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Contents

Session A1

A group theoretic approach to shear-free radiating stars

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A systematic group analysis of the junction condition, relating the radial pressure with the heat flow in a shear-free relativistic radiating star, is undertaken. This is a highly nonlinear partial differential equation in general. In spite of this, we obtain the Lie point symmetries that leave the boundary condition invariant. Using a linear combination of the symmetries, we transform the junction condition into ordinary differential equations. We present several new group invariant solutions to the junction condition. In each case we can identify the exact solution with the group generator. Some of the solutions obtained satisfy the linear barotropic equation of state. As a special case we regain conformally at models which were found previously. Our analysis highlights the interplay among group theory, nonlinear differential equations and applications to relativistic astrophysics.

Separable metrics and radiating stars

Gezahegn Zewdie Abebe

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We study the junction condition relating the pressure to heat flux at the boundary of an accelerating and expanding spherically symmetric radiating star. We transform the junction condition to an ordinary differential equation by making a separability assumption on the metric functions in the spacetime variables. The condition of separability on the metric functions yields several new exact solutions. A class of shear-free models is found which contains a linear equation of state and generalizes a previously obtained model. Four new shearing models are obtained; the gravitational potentials can all be written explicitly. A brief physical analysis indicates that the matter variables are well behaved.

Lie point symmetries, vacuum Einstein equations, and Ricci solitons

Mohammad Akbar

University of Texas at Dallas, USA

This talk will present an explicit one-parameter Lie point symmetry of the four-dimensional vacuum Einstein equations that enables one to construct particular one-parameter extended families of axisymmetric static solutions and cylindrical gravitational wave solutions from old ones, in a simpler way than most solution-generation techniques, including the only other available prescription for this system given by Ernst about thirty years ago. As examples, it will present the families that generalize the Schwarzschild solution and the C-metric. These in effect superpose a Levi-Civita cylindrical solution on the seeds. Exploiting a correspondence between static solutions of Einstein's equations and Ricci solitons (self-similar solutions of the Ricci flow), this also enables one to construct new steady Ricci solitons.

Open Access Non-Linear Electrodynamics Gedanken Experiment for Modified Zero Point Energy and Planck's Constant, h Bar, in the Beginning of Cosmological Expansion, So h(Today) = h(Initial).

Andrew Beckwith

Chongqing University, China

We initially look at a nonsingular universe representation of entropy, based in part on what is brought up by Muller and Lousto. This is a gateway to bring up information and computational steps (as defined by Seth Lloyd) as to what will be available initially due to a modified Zero Point Energy formalism. The Zero Point Energy formalism is modified as due to Vissers's setting of an angular plane number in early universe cosmology as k(maximum)   1/(Planck length), with a specific initial density giving rise to initial information content which may permit fixing the initial Planck's constant, h, which is pivotal to the setting of physical law. This will be in the spirit of Stoica's removal of initial conditions of non-pathological initial starting points in Cosmology. What we want are necessary and sufficient conditions so h(today) = h(initial). We also in addition make a brief survey into 5th force arguments in gravity which also has a strict entropy interpretation. i.e., how to link gravity, quantum mechanics, and E and M through entropy production.

Solving the Einstein-Maxwell Equations for the Propagation of Relativistic Energy during Kasner and other Anisotropic Early-Universe Models

Brett Bochner

Hofstra University, USA

The pre-homogenized very early universe generically experiences Mixmaster-like behavior as it approaches the Big Bang, featuring a sequence of anisotropically expanding Kasner epochs. To draw accurate conclusions about the transport of relativistic mass-energy in such environments, it is helpful to obtain as much information as possible about the detailed propagation of energy in rapidly and nonadiabatically expanding metrics for which the geometrical optics approximation substantially breaks down. Here we solve for the propagation of test particle electromagnetic fields through background spacetimes with various sets of Kasner expansion indices. In solving the Einstein-Maxwell equations, we obtain independent fourth-order differential equations for each of the electric and magnetic fields which can be individually solved to yield interesting information about how they are parametrically driven by the asymmetrically expanding early universe. Furthermore, we consider other anisotropic (and non-vacuum) models, including metrics related to the Vaidya and Szekeres-Szafron solutions, which include inhomogeneity as well as anisotropy.

Ergosphere of the Born-Infeld black hole

Nora Breton

Centro de Investigacin y de Estudios Avanzados del I.P.N., Mexico

We introduce the Born-Infeld (BI) black hole that is the nonlinear electromagnetic generalization of the Reissner-Nordstrom (RN) black hole. The differences between the BI and the RN black holes are significative only at short distances from the horizon. The effective potential for a test particle in the field of a BI black hole presents, for certain values of the parameters (extreme case), negative energy states, defining then an effective ergosphere.; this opens the possibility of extraction of energy.

Elastic waves in spherically symmetric elastic spacetimes

Irene Brito,Jaume Carot, and Estelita Vaz

University of Minho, Portugal

We consider spherically symmetric spacetimes with elastic matter and determine the propagation speed of elastic waves in the radial direction. The propagation speed depends on the density, radial pressure and elasticity tensor components. The local causality condition for the speed of elastic waves is analysed for shear free spherically symmetric elastic solutions of the Einstein field equations.

Cylindrically symmetric inhomogeneous dust collapse

Irene Brito, M. F. A. Da Silva, Filipe C. Mena and N. O. Santos
University of Minho, Portugal

We investigate the class of cylindrically symmetric inhomogeneous Lambda-dust spacetimes, which have a regular axis and zero expansion in some spatial direction. We find that the Senovilla-Vera exact solution (which has *Lambda*=0) is the unique non-stationary solution within that class, at least in a neighbourhood of the axis. We show that this solution can be locally matched to an Einstein-Rosen type of exterior.

Did GW150914 produce a rotating gravastar?

Cecilia Chirenti
UFABC, Brazil

The interferometric LIGO detectors have recently measured the first direct gravitational-wave signal from what has been interpreted as the inspiral, merger and ringdown of a binary system of black holes. The signal-to-noise ratio of the measured signal is large enough to leave little doubt that it does refer to the inspiral of two massive and ultracompact objects, whose merger yields a rotating black hole. Yet, room is left for alternative interpretations that do not involve black holes, but other objects that, within classical general relativity, can be equally massive and compact, namely, gravastars. We here consider the hypothesis that the merging objects were indeed gravastars and explore whether the merged object could therefore be not a black hole but a rotating gravastar. After comparing the real and imaginary parts of the ringdown signal of GW150914 with the corresponding quantities for a variety of gravastars, and notwithstanding the very limited knowledge of the perturbative response of rotating gravastars, we conclude it is not possible to model the measured ringdown of GW150914 as due to a rotating gravastar.

The Inverse spatial Laplacian of spherically symmetric backgrounds

Karan Fernandes
S. N. Bose National Centre for Basic Sciences, India

In the context of gauge fixing of theories on curved backgrounds and self-force calculations, the inverse spatial Laplacian has been invoked numerous times in the literature. As will be explained, these solutions are also expected to play an important role in the quantization of gauge theories on curved backgrounds with horizons, where the possibility of edge states and boundary conditions need to be determined. However, no explicit solution prior to our work appears to have been derived. We will find the exact solution for the inverse spatial Laplacian, defined on the hypersurfaces of spherically symmetric backgrounds, by using the method of multipole expansion. The closed form expressions for the Schwarzschild and pure de Sitter spacetimes are derived as special cases. Both solutions are found to be well defined on the horizon and yield the correct flat spacetime limit. A comparison of our result with the known expression for the inverse spacetime Laplacian of the Schwarzschild background will also be provided. In considering the gauge fixing of the Maxwell field as an example, we will demonstrate the relevance of the inverse spatial Laplacian in the quantization of this field on the Schwarzschild background.

Coordinate families for the Schwarzschild geometry based on radial timelike geodesics

Tehani Finch

NASA-Goddard Space Flight Center, USA

We explore the connections between various coordinate systems associated with observers moving inwardly along radial geodesics in the Schwarzschild geometry. Painlevé-Gullstrand (PG) time is adapted to freely falling observers dropped from rest from infinity; other time coordinates are adapted to observers who start at infinity with non-zero initial inward velocity, or observers dropped from rest from a finite distance from the black hole horizon. From these we construct two families of time coordinates, introducing new coordinates in the process. These families constitute distinct, but related, one-parameter generalizations of PG time.

Rotating black hole and quintessence

Sushant Ghosh

Centre for Theoretical Physics, Jamia Millia Islamia, New Delhi, India

We discuss spherically symmetric exact solutions of the Einstein equations for quintessential matter surrounding a black hole, which has an additional parameter (ω) due to the quintessential matter, apart from the mass (M). In turn, we employ the Newman-Janis complex transformation to this spherical quintessence black hole solution and present a rotating counterpart that is identified, for $\alpha = -e^2 \neq 0$ and $\omega = 1/3$, exactly as the Kerr-Newman black hole, and as the Kerr black hole when $\alpha = 0$. Interestingly, for a given value of parameter ω, there exists a critical rotation parameter ($a = a_E$), which corresponds to an extremal black hole with degenerate horizons, while for $a < a_E$, it describes a non-extremal black hole with Cauchy and event horizons, and no black hole for $a > a_E$. We find that the extremal value a_E is also influenced by the parameter ω and so is the *ergoregion*.

The Role of an Equation of State in Modeling Relativistic Compact Stars

Megandhren Govender
Durban University of Technology, South Africa

In this paper we present a new class of exact solutions of the Einstein field equations which describe relativistic compact objects in isotropic coordinates. The interior matter distribution is taken to be that of a perfect fluid in which the principal stresses are unequal. By employing various equations of states for the stellar fluid, we are in a position to solve the Einstein field equations and fully determine the gravitational and thermodynamical behaviour of our models. We match the interior spacetime to the vacuum Schwarzschild exterior by employing the Darmois junction conditions. The mass to radius ratio, compactification parameter, surface and central densities are computed and compared to observational data sets for strange star candidates such as Her. X-1, SAX J1808.4-3658(SS2), SAX J1808.4-3658(SS1) and PSR J1614-2230.

Causal structure of cosmological black holes under scalar-field accretion

Daniel Guariento
Perimeter Institute for Theoretical Physics, Canada

We show that the generalized McVittie solution, which represents a central time-dependent mass in an expanding cosmological background, is an exact solution of a subset of the so-called beyond Horndeskï class of scalar-tensor field actions and constitutes an important example of a time-dependent hairy black hole solution. We also demonstrate that a time-dependent central mass may have a significant impact on the overall causal structure and analytic extension. The metric always has an event horizon at future cosmological time infinity in the appropriate limits but the character of the horizon depends on the accretion and cosmological histories in the bulk. We also discuss the emergence and interpretation of this solution in other theories of gravity."

Rotating fields and the Newman-Janis algorithm in conformastatic space-times

Antonio C. Gutierrez-Pineres
Universidad Tecnologica de Bolivar, Colombia

It is shown that by means of the Newman-Janis formalism one can generate rotating solutions starting from conformastatic ones. As a result, we obtain different classes of rotating perfect-fluid configurations endowed with a Maxwell field. We investigate also the particular case when the seed solution is given by the Schwarzschild spacetime and show that the resulting rotating configuration cannot be a vacuum solution.

Quasi-local Energy for Black Holes

Yuan K. Ha
Temple University, USA

We investigate the quasi-local energy distribution of a black hole in various spacetimes. We find in each case corresponding to neutral, charged or rotating black hole, the horizon mass is always equal to twice the irreducible mass observed at infinity. This is known as the Horizon Mass Theorem. As a result, the electrostatic and rotational energy of a general black hole are all external quantities. This result could resolve the long-standing puzzle why entropy is proportional to area and not to volume of a black hole since matter carrying charges and spins could only lie outside the horizon.

Kinematic restrictions on particle collisions near extremal black holes–a unified analysis

Filip Hejda
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It has been known that the centre-of-mass collision energy between test particles around an extremal rotating black hole can grow without bound if one of the particles is "critical", and if the collision point is approaching the horizon. Since having been revived by Banados, Silk and West in 2009 (for Kerr black hole) this type of so-called "BSW effect" has been studied by a number of authors, and it is now known to be present in case of arbitrary ("dirty") extremal rotating black holes, as well as extremal charged non-rotating holes, as clarified by Zaslavskii. Hitherto, these two variants were examined separately. We consider a combination of the centrifugal and electrostatic mechanism for this generalized "BSW effect". We investigate kinematic restrictions which may prevent critical particles from reaching the desired point of collision and study qualitatively the dependence of these restrictions on the features of an arbitrary black-hole model. Applying these considerations, we analyze quantitatively particles in the field of Kerr-Newman black holes, reproduce some known results and obtain new ones. We also show how this analysis can be combined with our previous work (Phys. Rev. D 92, 104006 (2015)) about the near-horizon behavior of strongly magnetized Kerr-Newman holes and so study the influence of an external magnetic field.

Towards a charged Myers-Perry black hole

Eric Hirschmann

Brigham Young University, USA

We describe the development of a self-consistent field technique to solve for black holes in higher dimensions. Such a method has been used to find various matter configurations in four dimensions such as neutron stars in Newtonian gravity and general relativity. This is applied to five spacetime dimensions and charged Myers-Perry black holes with one and two rotations.

The Effect of Gravitational Waves on the Nearby Particles in Closed Spacetimes

Jafar Khodagholizadeh

Lecturer, Iran

In this paper we derive the deviation equation in the de Sitter spacetime by applying the first order perturbed metric. Then by using the solution of Gravitational wave equation in closed space time we investigate the effect of this wave on a circle of nearby particles and compare the results with the flat case. As a result, the detection of gravitational waves may be used to specify the curved spacetimes.

Short-Distance Gravity Interaction and Ostrogradski Formalism

Timur Kamalov

Moscow Institute of Physics and Technology, Russia

Ostrogradski Formalism describes mechanical systems by a Lagrange Function which depends on high-order time derivatives of coordinates. In this case all classical equations contain additional variables with high-order derivatives which play the role of non-local hidden variables (T.F. Kamalov, /textitJournal of Physics Conference Series, 442 (2013) 012051). To satisfy the Equivalence Principle one needs to add new variables in the equations of gravitational interaction which are strong at short distances. The corresponding metric for short-distance interaction is different from the Schwarzschild metric by additional terms and reproduces it if the addition terms are neglected. The short-distance metric at large distances reproduces the Schwarzschild metric and it grows exponentially at short distances. The characteristic size of the short-distance metric is around classical radius of the proton. The theory possesses a scale-dependent effective gravitational constant $G^(\lambda/r)$.

Higher dimensional spacetimes with a separable Klein-Gordon equation

Ivan Kolar

Institute of Theoretical Physics, Faculty of Mathematics and Physics, Charles University in Prague, Czech Republic

We study a class of higher dimensional spacetimes that lead to a separable Klein-Gordon equation. Motivated by Carter's work in four dimensions, we introduce an ansatz for the separable metric in higher dimensions and find solutions of the Klein-Gordon equation. For such a metric we solve the Einstein equations and regain the Kerr-NUT-(A)dS spacetime and an Einstein-Kahler metric of a Euclidean signature. We construct a warped geometry of two Klein-Gordon separable spaces with a properly chosen warped factor. We show that the corresponding Klein-Gordon equation can also be solved by separation of variables. By solving the Einstein equations for the warped geometry we find new solutions. We discuss general commutativity conditions for classical observables and analogous scalar field operators. Then we investigate the fulfillment of these conditions in the Kerr-NUT-(A)dS spacetimes (and related spaces) and find the most general form of the weak electromagnetic field compatible with the complete integrability of the particle motion and the commutativity of the scalar field operators. For such a field we solve the charged Hamilton-Jacobi and Klein-Gordon equations by separation of variables.

Various limits of Kerr-NUT-(A)dS spacetimes

Pavel Krtous

Charles University in Prague, Czech Republic

Kerr-NUT-(A)dS metric represents a highly symmetric solution of the Einstein equation in a general dimension. It is a generalization of the four-dimensional Carter-Plebaski form of the Kerr solution. The standard form of the metric is suitable mainly for the study of symmetry properties of the solution. One can write down explicitly a tower of Killing vectors and tensors which encode explicit and hidden symmetries of the geometry. However, a full interpretation of the solution in its general form is rather complicated. Depending on a choice of the parameters and coordinate ranges, the metric can describe a Euclidian instanton, a generally rotating black hole, geometry with NUT charges, just a maximally symmetric spacetime, or other geometries with an unclear interpretation. Employing suitable limits, the Kerr-NUT-(A)dS metric can describe even wider variety of geometries. We will demonstrate that by switching off the rotations while keeping non-trivial NUT charges in the spatial sector one obtains deformed black holes. It turns out that these are given by the warped product of off-shell Kerr-NUT-(A)dS metrics and they share most of the symmetry structures of the original geometry. Another limiting procedure reduces the Kerr-NUT-(A)dS metric to the NUTTY spacetimes - a generalization of the Taub solution. Finally, a similar limit in the Lorentzian sector leads to the metric describing near-horizon geometry.

Thermodynamics of Accelerating Black Holes

David Kubiznak
Perimeter Institute, Canada

We address a long-standing problem of describing the thermodynamics of accelerating black holes. We derive a standard first law of black hole thermodynamics, with the usual identification of entropy proportional to the area of the event horizon, even though the event horizon contains a conical singularity. This result not only extends the applicability of black hole thermodynamics to realms previously not anticipated, it also opens a possibility for studying novel properties of an important class of exact radiative solutions of Einstein equations describing accelerated objects. We discuss the thermodynamic volume, stability and phase structure of these black holes.

On Stability of the Static Charged Brans-Dicke Spacetimes

Anthony Lun
Monash University, Australia

In the static charged Brans-Dicke spacetimes, the Brans parameter λ, which is either real or purely imaginary in the Brans-Dicke solutions, is complex. We present all these nine branches of charged solution using the generalised Brans parameter. We then show that all these solutions are stable under the perturbation of a static electric charged in the sense that the exact perturbation solution is finite everywhere except at the position of the perturbed charge and everywhere where the background spacetime is defined.

Black Holes: Hovering vs falling perspectives

Colin MacLaurin
University of Queensland, Australia

Descriptions of a black hole are often given in absolute terms, for example the radial distance is $(1 - 2M/r)^{-1/2}dr$, the space part is represented by that familiar funnel shape, and the time of a far away observer is the Schwarzschild coordinate t. Though this language can be justified, it ignores the relativity of space, time, and simultaneity, and often omits who is doing the measuring (in fact these are hovering or "static" observers). A different perspective is offered by observers falling radially, with energy per mass e. For them, the radial distance generalises to $1/edr$, the funnel shape of space becomes a cone, and t is no longer the time of a distant observer. In particular, a distant observer measures only finite time for an object to cross the event horizon, by this simultaneity convention. Also the claim that time and space swap roles inside the event horizon is not true in this case, for which the r coordinate remains spacelike everywhere. This perspective is more readily apparent under a coordinate choice such as Gullstrand-Painlev or Lematre coordinates, and

their generalisations. Though the relativity community's appreciation for coordinates adapted to photons is justified, it has sometimes left an incomplete picture. Our purpose is pedagogy, a clearer articulation of misconceptions, and a broader perspective on black holes. [Based on research being prepared for publication with Prof. Geraint Lewis and Prof. Tamara Davis]

Stellar objects in the quadratic regime

Pedro Mafa Takisa

University of Kwazulu-Natal, South Africa

We model a charged anisotropic relativistic star with a quadratic equation of state. Physical features of an exact solution of the Einstein-Maxwell system are studied by incorporating the effect of the nonlinear term from the equation of state. It is possible to regain the masses, radii and central densities for a linear equation of state in our analysis. We generate masses for stellar compact objects and perform a detailed study of PSR J1614-2230 in particular. We also show the influence of the nonlinear equation of state on physical features of the matter distribution. We demonstrate that it is possible to incorporate the effects of charge, anisotropy and a quadratic term in the equation of state in modeling a compact relativistic body.

On the conditions for the formation of exotic compact objects from gravitational collapse

Daniele Malafarina

Nazarbayev University, Kazakhstan

Gravitational collapse models with semi-classical corrections in the strong field regime are known to lead to bouncing scenarios where the black hole turns into a white hole. Here we investigate under which conditions the complete collapse of an homogeneous and isotropic, spherical matter cloud with semi-classical corrections may lead to the formation of an exotic compact remnant. In particular we investigate the case of the so called 'dark energy star' and discuss its implications for astrophysical black holes.

Universal Walker metrics

Tomas Malek

Institute of Mathematics, Academy of Sciences of the Czech Republic, Czech Republic

Universal metrics solve, by definition, vacuum equations of all theories of gravitation with the Lagrangian described by any polynomial curvature invariant constructed from the metric, the Riemann tensor and its covariant derivatives of arbitrary order. Therefore, all quantum corrections to the vacuum Einstein equations vanish for these metrics. In Lorentzian case of any dimension, the known universal metrics belong to the Kundt class of non-expanding, non-shearing and non-twisting spacetimes. We discuss Walker metrics admitting a field of parallel null planes, specifically, four-dimensional Walker metrics with a field of parallel null 2-planes. These metrics of neutral signature possess a pair of mutually orthogonal null vector fields spanning the 2-planes. We show that Ricci-flat Walker metrics with vanishing self-dual part of the Weyl tensor are universal and they do not necessary belong to the Kundt class.

The Cartan Algorithm in Higher Dimensions with Applications

David McNutt

Dalhousie, Canada

Deciding when two metrics are equivalent is an important question for the study of exact solutions. In four dimensions this can be definitively answered using the Karlhede algorithm, which is an adaptation of the Cartan equivalence algorithm to four dimensional Lorentzian manifolds. Applying the Cartan algorithm in higher dimensions is considerably more difficult. In this talk we introduce the general Cartan Algorithm for Lorentzian manifolds in $N \lesssim 4$ dimensions. To give some concrete examples, the dimension will be fixed to be N=5 and we will discuss black hole solutions including the supersymmetric black ring.

Anisotropic dark energy cosmological model with a hybrid scale factor

Bivudutta Mishra

BITS-Pilani, Hyderabad Campus, India

Anisotropic dark energy model with dynamic pressure anisotropies along different spatial directions is constructed at the backdrop of a spatially homogeneous diagonal Bianchi type V (BV) space time in the framework of General Relativity. A time varying deceleration parameter generating a hybrid scale factor is considered to simulate a cosmic transition from early deceleration to late time acceleration. We found that the pressure anisotropies along the y- and z-axes evolve dynamically and continue along with the cosmic expansion without being subsided even at late times. The anisotropic pressure along the x-axis becomes equal to the mean fluid pressure. At a late phase of cosmic evolution, the model enters into a phantom region. From a state finder diagnosis, it is found that the model overlaps with CDM at late phase of cosmic time.

Radiating stars with exponential Lie symmetries

Rakesh Mohanlal

University of KwaZulu-Natal, South Africa

We analyze the general model of a radiating star in general relativity. A group analysis of the under determined, nonlinear partial differential equation governing the model's gravitational potentials is performed. This analysis is an extension of previous studies carried out and produces new group invariant solutions. We find that the gravitational potentials depend on exponential functions owing to the choice of the Lie symmetry generator. The fundamental boundary equation to be solved is in general a Riccati equation. Several new exact families of solutions to the boundary condition are generated. Earlier models of Euclidean stars and generalized Euclidean stellar models are regained as special cases. Linear equations of state can be found for shear-free and shearing spacetimes.

Stellar models generated via the horizon function

Riven Narain

Astrophysics and Cosmology Research Unit, School of Mathematics, Statistics and Computer Science, University of KwaZulu-Natal, South Africa

We study the stellar boundary condition of a radiating star in the presence of shear via a recently introduced transformation called the Horizon function. A detailed analysis of this function is performed. We show that the transformation is not general and when particular relationships between the gravitational potentials are assumed the transformation is not valid. In the case where it is valid, we apply the transformation to the original stellar boundary to obtain a simpler partial differential equation. We employ group theoretic methods to the transformed equation and reduce it to a Riccati equation. Several families of new exact solutions to the Riccati equation are generated. For particular parametric restrictions we are able to relate our models to previous generalized Euclidean star models. We show that certain restrictions arise when utilizing the horizon function.

Particle and photon orbits in flat and non-flat McVittie spacetimes

Brien Nolan

Dublin City University, Ireland

We present further results on the physical interpretation of McVittie's solution of the Einstein equations, which represents an embedding of the Schwazschild solution into an isotropic universe. We review recent results on particle and photon orbits in spatially flat McVittie spacetimes. These results, relying on centre manifold analysis of the geodesic equations, show that there are families of particles and photons whose motion is asymptotic to stable elliptical orbits around the central mass. We present new results which show how the metric of the spatially non-flat McVittie spacetimes may be written in terms of special functions, making these metrics amenable to the global analysis which has heretofore only been carried out for the spatially flat case.

Exact solutions to Einstein's equations in the (2+2) Hamiltonian reduction formalism

Seung Hun Oh

Konkuk University, Republic of Korea

In this talk, I will illustrate a new method of finding exact solutions to the Einstein's equations obtained by the Hamiltonian reduction based on the (2+2) formalism. In this Hamiltonian reduction, the Einstein's equations are written in the privileged spacetime coordinates, where the area element of the 2 dimensional cross-section of an out-going null hypersurface is used as a physical time, and spatial coordinates are chosen as suitable functions on the phase space of gravitational fields. The Hamiltonian constraint is solved to define a non-vanishing gravitational Hamiltonian in terms of conformal two metric and its conjugate momenta, which dictates the evolutions of the conformal two metric and its conjugate in the physical time. The momentum constraints are also solved to express local momentum densities of gravitational fields in the canonical form. Explicitly, I will find two particular solutions to the Einstein's equations in the privileged coordinates using ansatz, and show that they are just the Einstein-Rosen wave and the Schwartzschild solution by making suitable coordinate transformations to the standard coordinates.

Geodesically complete black hole space-times in arbitrary dimension.

Gonzalo J. Olmo

University of Valencia, Spain

I present a family of spherically symmetric electrovacuum solutions in which the central singularity is replaced by a wormhole structure. As such, these configurations can be naturally interpreted as geons, in Wheeler's sense. The resulting space-time is similar to the Reissner-Nordström solutions - with two, one, or no horizons - but turns out to be geodesically complete and, therefore, nonsingular. This is so despite the generic appearance of curvature divergences at the wormhole throat. These results arise in a Born-Infeld type extension of General Relativity.

Electromagnetic fields with vanishing scalar invariants

Marcello Ortaggio
Institute of Mathematics of the Czech Academy of Sciences, Czech Republic

We determine the class of p-forms which possess vanishing scalar invariants (VSI) at arbitrary order in a n-dimensional spacetime. In particular, we prove that the corresponding spacetime must belong to the "degenerate" Kundt family. Although the result is theory-independent, we discuss, in particular, the special case of Maxwell fields, both at the level of test fields and of the full Einstein-Maxwell equations. These describe various classes of non-expanding electromagnetic waves. We further point out that a subset of these solutions possesses a "universal" property, i.e., they also solve any generalized (non-linear and with higher derivatives) electrodynamics, possibly also coupled to Einstein's gravity. Reference: M. Ortaggio, V. Pravda, arXiv:1506.04538 [gr-qc]

Algebraic classification of spacetimes - recent developments

Vojtech Pravda
Institute of Mathematics, AS CR, Czech Republic

Over a decade ago, we introduced an algebraic classification of tensors on Lorentzian manifolds, which is in the case of the Weyl tensor in four dimensions equivalent to the well known Petrov classification. We will briefly review main results in this field with a focus on the recent developments. For example, we will discuss a generalization of the Goldberg-Sachs theorem to higher dimensional Einstein gravity, new algebraically special vacuum solutions to the Einstein equations, quadratic gravity and more general theories of gravity in four and higher dimensions, universal spacetimes etc.

Universal metrics in modified theories of gravity.

Alena Pravdova
Institute of Mathematics of the Czech Academy of Sciences, Czech Republic

Universal metrics are "immune" to all corrections to the Einstein equations. These metrics possess a remarkable property that they simultaneously solve vacuum field equations of any theory of gravity with the Lagrangian constructed from the metric, the Riemann tensor and its covariant derivatives of arbitrary order. It has been known since 1990s that type N Ricci-flat pp-waves are universal. We will show that in fact the class of universal metrics is much broader than pp-waves and that these metrics in general do not admit a covariantly constant null vector or a recurrent null vector. We will discuss necessary and sufficient conditions for Weyl type N and III universal metrics and present explicit examples of universal metrics representing gravitational waves propagating on flat or (A)dS backgrounds in arbitrary dimension. Main reference: S. Hervik, V. Pravda, A. Pravdova, Class. Quantum Grav. 31: 215005, 2014

Viability of some classes of static spherically symmetric exact interior solutions as models for compact objects.

Ambrish Raghoonundun

University of Calgary, Canada

In my previous work, several classes of static and spherically symmetric exact interior solutions to the Einstein field equations (EFE) generalising the quadratic density fall-off profile of the Tolman VII solution were constructed. This proceeded through the addition of an electric charge (through Maxwell's equations) and an anisotropic pressure (to allow for more complicated fluids) to the EFE. Here, the viability of the new solutions as candidates for modeling compact physical objects is investigated. All the known criteria of physical viability, including causality of pressure (sound) waves in the interior, are shown to be obeyed by some of the solutions. Additionally the generalised pulsation equation that can be used to determine the linear radial stability of the general EFE with charge and anisotropic pressures was derived, and utilised to prove the stability of the viable models. An advantage of the quadratic density fall-off is that it allows for an inversion of the density–radial relation in the energy-momentum tensor. An equation of state (EOS) relating the pressure to the density can thus be derived in all cases. This EOS depends on the arbitrary (but physically interesting) density–radial relation, with nuclear physics invoked only to fix the central density (one of the parameters) of the model. Self-bound objects (having non-zero boundary densities) can also be modeled as a side-effect of the generalising of the Tolman VII solution, and the predicted masses and radii of the models are compatible with recent observations of compact objects' masses and radii.

Vacuum thin shells in EGB brane-world cosmology

Marcos Ramirez

IFEG, CONICET - FaMAF, Universidad Nacional de Córdoba, Argentina

In this talk we construct new solutions of the EGB field equations in a SMS brane-world setting which represent a couple of Z_2 -symmetric vacuum thin shells splitting from the central brane, and explore the main properties of the dynamics of the system. The matching of the separating vacuum shells with the brane-world is as smooth as possible and all matter fields are restricted to the brane. Several implications for the effective Friedmann equations on the brane are discussed, and compared with standard cosmology. We also comment on the relation of this system with the thermodynamic instability of highly symmetric vacuum solutions of Lovelock theory.

Algebraically special solutions in five dimensions

Harvey Reall

University of Cambridge, United Kingdom

The classification of five-dimensional vacuum solutions with an algebraically special Weyl tensor has recently been completed. I will review this classification.

The effects of self-interactions on spinning boson stars and Kerr black holes with scalar hair

Helgi Freyr Rúnarsson

Universidade de Aveiro, Portugal

In this talk, I will discuss the effects of self-interactions for both spinning boson stars (BSs) and Kerr black holes with scalar hair (KBHsSH). It has been shown that both the BSs and KBHsSH have an increased ADM mass when one considers self-interactions but for the latter, this increased mass arises purely from the hair and not the black hole. I will explore further effects of self interactions on these solutions. Namely, their compactness, spatial distribution, energy densities and the existence of ergo-regions. Finally, I will discuss the inclusion of electric charge to the model. Phys. Rev. D 92, no. 8, 084059 (2015)

Hawking radiation from magnetized black holes

Khalid Saifullah

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Hawking radiation of charged scalar and Dirac particles from the event horizon of magnetized Kerr-Newman black holes is studied using the Hamilton-Jacobi method and WKB approximation. This is done by calculating tunneling probabilities of these particles from the horizons of magnetized black holes. This method yields the Hawking temperature of magnetized Kerr-Newman black holes as well. It is interesting to note that while the tunneling probabilities depend upon the background magnetic field, the Hawking temperature is not affected by magnetization.

Visualizing spacetime curvature for teaching/interpreting GR

Robert Scott

Universit de Bretagne Occidentale, France

A diagram is explored wherein spacetime is cut into approximately Minkowski pieces or "wedges" and plotted in physical coordinates. The curvature of the boundaries of the wedges reveals the curvature of the spacetime. This wedge diagram provides a more general tool to visual spacetime curvature than the familiar embedding diagram, the latter being restricted to spatial curvature only. The wedge diagram is applied first to the Schwarzschild spacetime to demonstrate the physical significance of the curvature of spacetime. In particular it is shown how gravitational time dilation results from curvature of a radial-time slice of spacetime. Then this diagram is applied to the Friedmann-Robertston-Walker (FRW) spacetime revealing how expansion of the universe results from a qualitatively similar curvature of a radial-time slice, but with the roles of space and time reversed. The analogy between the two spacetimes suggests novel interpretations of the two spacetimes. We interpret the Schwarzschild spacetime as time expanding with increasing distance from the horizon. And we interpret the FRW spacetime as the universe expanding as the influence of the big bang peters out. Tracing geodesics is a trivial exercise on the wedge diagrams, the turning of the boundaries between wedges providing a visual interpretation of the Christoffel symbols. We examine circular orbits in Schwarzschild to show of the dominant time curvature leads to turning of the wedge boundaries that balances the centripetal acceleration, resulting in acceleration-free circular motion.

Study of Thin-Shell Wormholes Stability

Muhammad Sharif

Punjab University, Pakistan

This work is devoted to construct thin-shell wormholes from regular ABG black hole using cut and paste technique and examine their stability. We assume a general equation of state to explore stability of these constructed wormholes. We consider linear, logarithmic and Chaplygin gas models for exotic matter and evaluate stability regions for different values of charge. We conclude that possibility of stable regions decreases by increasing charge and we have maximum stable regions for the generalized Chaplygin gas model.

Super-Entropic Black Holes: the Kerr-CFT Correspondence

Cedric Musema Sinamuli
University of Waterloo, Canada

We show that Kerr-CFT duality can be extended to super-entropic black holes, which are black holes of finite areas with non-compact horizons. We demonstrate that this duality is robust insofar as the ultra-spinning limit of a Kerr-AdS black hole commutes with the near-horizon limit. Consequently the Bekeinstein-Hawking and the CFT entropies are equivalent. We show that the duality holds for both singly-spinning super-entropic black holes in 4 dimensions and for doubly-spinning super-entropic black holes of gauged supergravity in 5 dimensions.

Explicit algebraic classification of Robinson-Trautman and Kundt geometries

Robert Svarc
Charles University in Prague, Czech Republic

In collaboration with Jiri Podolsky Without assuming any field equations, the Weyl tensor algebraic structure of a general family of Robinson-Trautman and Kundt geometries (which admit non-twisting and shear-free null vector field) is discussed. It is shown that in arbitrary dimension D any such spacetime is of type I(b), and explicit conditions are derived under which the spacetime becomes of algebraically more special type with respect to the optically privileged null direction. In the classic case D=4, even more suitable choice of the null frame is made and the complete Petrov classification is performed. The significance of our results is demonstrated both on standard solutions to the Einstein-Maxwell equations of general relativity, and on specific spacetimes in the context of modified theories of gravity. The first part of our contribution is based mainly on the paper Class. Quantum Grav. 32 (2015) 015001 while the second one contains recent results not yet published.

General Relativity and the Great War

Virginia Trimble
University of California Irvine & Queen Jadwige Observatory, USA

For astronomers, WWI began with the capture of Fruendlich's German eclipse expedition in the Crimea in August 1914, where they had gone to look for bending of starlight by the sun, at Einstein's request. The end came in 1919 with the measurement of that light bending and the founding of the International Astronomical Union. The four famous November 1915 papers (curiously, all submitted on Thursdays) and the more extended 1916 "Grundlage" were all written after he had returned to Berlin in March, soon to be sealed in German but in the company of a congenial coterie and their heritage. He mentions Minkowski, Gauss, Riemann, Christoffel, Ricci, Levi-Cevita, and Grossmann. But Besso, de Sitter, Weyl, and

especially Hilbert probably also belong. Before the war was over, there had also appeared important papers by Riessner, Nordstrom, Thirring, Lense, Schwarzschild, Kottler, de Sitter and Schroedinger, some written literally from the trenches. Serious historians say that only Einstein could have developed GR and only there and then. Relativity, under Eddington, was Commission 1 of the IAU and voted itself out of existence in 1925. I'll try to explain what happened when, if not why.

Late time Cosmic Acceleration with Unified Dark Fluid and a Hybrid Scale Factor

Sunil K. Tripathy

Indira Gandhi Institute of Technology, Sarang, India

It is now an accepted fact that, our universe is undergoing an accelerated phase of expansion in the present epoch. This fact has been supported by a lot of observational data from type Ia Supernovae, X-ray Clusters, Baryonic Acoustic Oscillations etc. The late time cosmic acceleration is usually attributed to an exotic dark energy whose nature and origin is not yet known. Also, it is believed that, the universe was decelerating earlier and has undergone a transit from the decelerating phase to an accelerating one. The redshift at which the transition occurred is of the order of unity. Another problem that concerns is the anisotropy in the CMBR. Many approaches have been adopted to handle both the problem of late time cosmic acceleration and the cosmic anisotropy. In the present work, we have considered a plane symmetric anisotropic universe in the frame work of generalized Brans-Dicke theory. The dark energy and dark matter are considered in a single platform of a unified dark fluid described through a linear equation of state. Also, we consider a hybrid scale factor that simulates an evolving deceleration parameter with early deceleration and late time acceleration. By exploring the predicted values of transition redshift from different calculations, we have constructed four accelerating models which are in conformity with observations.

Violation of cosmic censorship in dynamical p-brane systems

Kunihito Uzawa

Kwansei Gakuin University, Japan

We discuss the cosmic censorship of dynamical p-brane systems in a D-dimensional background. This is the generalization of the analysis in the Einstein-Maxwell-dilaton theory. We show that a timelike curvature singularity generically appears from an asymptotic region in the time evolution of the p-brane solution. Since we can set regular and smooth initial data in a dynamical M5-brane system in 11-dimensional supergravity, this implies a violation of cosmic censorship.

Interpretation of Generic Off-Diagonal Exact Solutions in Einstein Gravity and Modifications

Sergiu Vacaru

University Alexandru Ioan Cuza, Project IDEI, Romania and R. Moldova

We review and apply a geometric technique for constructing generic off-diagonal exact solutions in f(R, T)-modified gravity for systems of gravitational-Yang-Mills-Higgs equations. The corresponding classes of metrics and generalized connections are determined by generating and integration functions which depend, in general, on all space and time coordinates and may possess, or not, Killing symmetries. For nonholonomic constraints resulting in Levi-Civita configurations, we can extract solutions of the Einstein-Yang-Mills-Higgs equations. It is proven that for well-defined conditions massive ghost-free gravity f(R)-modified theories, MGFTs, can be encoded into generic off-diagonal Einstein spaces. Using "auxiliary" connections completely defined by the metric fields and adapted to nonholonomic frames with associated nonlinear connection structure, we decouple and integrate in certain general forms the field equations in MGFT. We find general parameterizations for generic off-diagonal spacetime metrics and matter sources in general relativity, GR, and modified gravity theories when the field equations decouple with respect to certain types of nonholonomic frames of reference. Such (modified) spacetimes display Killing and non-Killing symmetries, describe nonlinear vacuum configurations and effective polarizations of cosmological and interaction constants. Our method can be extended to higher dimensions, which simplifies some proofs for embedded and nonholonomically constrained four-dimensional configurations. We reproduce the Kerr solution and show how to deform it nonholonomically into new classes of generic off-diagonal solutions depending on 3-8 spacetime coordinates.

Non-aligned Einstein-Maxwell fields

Norbert Van den Bergh

Gent University, Belgium

A new characterisation is given of the Plebanski-Hacyan and Garcia-Plebanski metrics within the class of 'half-aligned' Einstein-Maxwell fields with a cosmological constant, as well as of the 'class D' metrics with non-vanishing cosmological constant within the general class of Einstein-Maxwell fields.

Caustic-singulartity-free scalar field theory with shift-symmetry

Yota Watanabe
Kavli IPMU, YITP, Japan

An argument on caustic singularity formations was recently done, where second derivatives of a field diverge and the theory should be replaced by another to describe motions, for a simple class of planar-symmetric, i.e. 1+1-dimensional non-linear wave solutions in shift-symmetric k-essense theory (whose Lagrangian is a function of the kinetic term of a scalar field) and Horndeski theory (whose Euler-Lagrange equations are second-order) on Minkowski spacetime by E. Babichev (arXiv:1602.00735). I will talk on its extension to find a healthy theory in which such solutions are free from the caustic singularity without tuning any initial condition.

Cylindrically Symmetric Static Perfect Fluid Solution of Petrov Type D

Muhammad Ziad
Sultan Qaboos University, Oman

Kramer (Class. Quantum Grav. 5(1988)393-398) found a Petrov Type I cylindrically symmetric static perfect fluid solution with the equation of state p=. This metric admits a G as the maximal group of isometries. Here, a Petrov type D static cylindrically symmetric perfect fluid solution given by the metric with the equation of state p= will be presented. This metric admits a G; as the maximal group of isometries. This metric is not part of the list of degenerate static perfect fluid metrics given by Barnes (J. Phys. A: Gen. Phys. 5(1972)374).

Session A2

Extremal black hole initial data deformations

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For initial data, there seems to be a close relation between the presence of a cylindrical end and certain extremality condition suggested in part, by the behavior of stationary solutions like Kerr-Newman and also by the fact that given a monoparametric family of conformally flat initial data having a wormhole structure, with given angular momentum and charges, then there exists a singular limit as the parameter goes to zero, where the asymptotic structure changes to trumpet-like and the angular momentum and charges are maximal for given mass. This reinforces the interest in studying initial data with cylindrical ends in an attempt to understand cosmic censorship issues, black hole formation, conical singularities appearing in stationary multi-black hole solutions, etc.

A study of positive energy condition in Bianchi universes via Noether symmetries

Sajid Ali

Dept. of Basic Sciences, School of Electrical Engineering and Computer Science, NUST University, Pakistan

Bianchi models can be used to address the problem of anisotropy at earlier epoch of our universe during its evolution. It is important to characterize Binachi universes on the basis of their geometrical and dynamical properties. The existence of Noether point symmetries not only helps us to specify a model but also provide us first integrals which can be used to reduce the dynamics. In this paper we first characterize all such models. Secondly we investigate the positive energy condition in all specified models which provides us critical bounds on the physical parameters. Lastly we discuss the possibilities of involving physical fields (perfect fluid, dust, or vacuum etc) such that the Einstein's field equations are satisfied and give physical understanding of these solutions.

Models for self-gravitating photon shells and geons

Håkan Andr(é)asson
University of Gothenburg, Sweden

I will present an existence result for spherically symmetric, static, self-gravitating photon shells as solutions to the massless Einstein-Vlasov system. The solutions are highly relativistic in the sense that the ratio $2m(r)/r$ is close to 8/9, where $m(r)$ is the Hawking mass and r is the area radius. In 1955 Wheeler constructed, by numerical means, so called idealized spherically symmetric geons, i.e. solutions of the Einstein-Maxwell equations for which the energy momentum tensor is spherically symmetric on a time average. The structure of these solutions is such that the electromagnetic field is confined to a thin shell for which the ratio $2m(r)/r$ is close to 8/9, i.e., the solutions are highly relativistic photon shells. The solutions presented in this talk provide an alternative model for photon shells. Moreover, recent results of a numerical study on axisymmetric solutions will also be discussed. The aim is here to construct massless toroidal solutions.

New 'hairy' black hole and soliton solutions to anti de-Sitter Einstein-Yang-Mills theories

J. Erik Baxter
Sheffield Hallam University, United Kingdom

The Einstein-Yang-Mills (EYM) equations couple the Yang-Mills equations for a gauge field of structure group G to Einstein's equations for gravity, yielding a non-Abelian generalisation of Einstein-Maxwell theory. Since the late '90s, the literature has identified a rich landscape of solutions that may be generated in asymptotically anti-de Sitter (adS) spacetimes. Here we present very recent results concerning hairy black holes and solitons, two species of solutions to the EYM equations, for some quite general cases. The results in question are mainly for the gauge group SU(N) and comprise analytical proofs and numerical analysis confirming the existence of stable solutions in some regimes. We also mention some results obtained for adS EYM theories with general semisimple gauge groups. The future potential of this work is very interesting in view of Bizon's modified 'no-hair' theorem, and also in light of some of Hawking's recent work concerning the 'black hole information paradox'. Also, these results may prove useful in condensed matter physics applications via the adS/CFT correspondence, by providing some extremely general gravitational models for possible adaptation and study.

Energy Density Irregularities in Self-gravitating systems

Muhammad Zaeem Ul Haq Bhatti
University of the Punjab, Pakistan

This paper explores some inhomogeneity factors that are responsible for creating irregularities in an initial homogeneous self-gravitating system. For this purpose, I shall explore Ellis equations and conservation laws. After that inhomogeneity factors for dissipative and non-dissiapative systems are explored.

On first integrals of the geodesic equations for spacetimes via Noether symmetry

Ugur Camci
Akdeniz University, Turkey

In this study, we argue that the first integrals of the geodesic equations can be obtained via the Noether symmetry approach, whenever such symmetry exist. We illustrate with some familiar spacetimes such as Gdel-type spacetimes, pp-wave spacetimes etc., calculating their Noether symmetries and deriving complete characterizations of their geodesic Lagrangians of motion, finally solving the geodesic equations.

Wormholes and nonsingular space-times in Palatini $f(R)$ gravity

Alejandro Cardenas-Avendano
Fundacion Universitaria Konrad Lorenz, Colombia

In this poster we reconsider the problem of $f(R)$ theories of gravity coupled to Born-Infeld theory of electrodynamics formulated in a Palatini approach, where metric and connection are independent fields. By studying electrovacuum configurations in a static and spherically symmetric space-time, we find solutions which reduce to their Reissner-Nordstrom counterparts at large distances but undergo important non-perturbative modifications close to the center. Our new analysis reveals that the point-like singularity is replaced by a finite-size wormhole structure which provides a geodesically complete and thus nonsingular space-time despite the existence of curvature divergences at the wormhole throat. Implications of these results in particular for the cosmic censorship conjecture are discussed.

Deflection of Light in Kerr-Taub-NUT space time

Sarani Chakraborty
Assam University, Silchar, India

According to General Relativity, there are three factors namely mass, rotation and charge that can influenced the path of light ray. Many author showed that there is another factor that can influence the path of light ray namely gravitomagnetism. Here we discuss the effect of a rotating body with non-zero (Kerr-Taub-NUT) magnetic field on the motion of light ray. We use the null geodesic of photon method and obtain the deflection angle of light ray for such a body. Our calculation shows that magnetism has a noticeable effect on the path of light ray. If we set the magnetism to zero our expression of bending angle reduces to the Kerr bending angle. However, we get non-zero bending angle for a hypothetical mass less, magnetic body.

The dawn of Relativistic Astrometry: what can we learn from Gaia

Mariateresa Crosta
INAF-OATo, Italy

Gaia will have a huge impact across many fields, from galactic and stellar astrophysics to fundamental physics. Indeed, at the microarcsecond level of accuracy, a fully relativistic inverse ray-tracing requires highly accurate astrometric models in accordance with the local geometrical environment affecting light propagation itself at the observer, i.e. a correct application of the precepts of the theory of measurement in General Relativity. This will provide not only a new relativistic rendition of stellar charts and anchors for the space-time navigation, but also an alternative thinking on how our local zero redshift position plays a fundamental role in reconstruction the space-time architecture around us.

Relativistic astrometric models in comparison for future space astrometry

Mariateresa Crosta
INAF-OATo, Italy

Thanks to Gaia, nowadays there exist different ways to model an astrometric observable in the context of general relativity (GR). Their availability is needed in order to rule out spurious coordinate effects and to consolidate the future experimental results, especially if one needs to implement gravitational source velocities and retarded time effects in the Solar System. From the computational and experimental point of view, in fact, relativistic astrometry opens a largely uncharted territory.

Then, accurate analytical solutions of light trajectories can be used in the relativistic modeling of astronomical observables. We will present two different but complementary methods in classical General Relativity RAMOD and TTF, to compute relativistic observables in Solar System, i.e. in the weak field regime, which turns to be "strong" already at the level of Gaia accuracy v^3/c^3.

Black hole nonmodal linear stability: the Schwarzschild (A)dS cases

Gustavo Dotti

Universidad Nacional de Crdoba, Argentina

The nonmodal linear stability of the Schwarzschild black hole established in Phys. Rev. Lett. 112 (2014) 191101 is generalized to the case of nonnegative cosmological constant. Two gauge invariant combinations (G,H) of perturbed scalars made out of the Weyl tensor and its first covariant derivative are found such that the map [h] (G,H), [h] an equivalence class under gauge transformations of a solution of the linearized Einstein's equation, is invertible. For arbitrary perturbations consistent with the background asymptote, G and H are bounded in the the outer static region. At large times, the perturbation decays to a linearized Kerr black hole around the Schwarzschild or Schwarschild de Sitter background solutions. In the case of negative cosmological constant, it is shown that there is a choice of boundary condition at the time-like boundary under which the Schwarzschild anti de Sitter black hole is unstable.

This talk is based on arXiv:1603.037493749

Gravitational Redshift in Kerr-Newman Geometry

Anuj Kumar Dubey

Assam University, India

Gravitational redshift has been reported by most of the authors without consideration of rotation, static electric and/or magnetic charges present in the rotating body. In the present paper, we considered the three parameters: mass, rotation parameter and charge to discuss their combined effect on redshift, for a charged rotating body by using Kerr-Newman metric. It has been found that the value of gravitational redshift is influenced by the direction of rotation of central body and also on the position (latitude) on the central body at which the photon is emitted. It has been also found that, the presence of electrostatic and magnetostatic charge increases the value of so-called gravitational redshift. The variation of gravitational redshift from equatorial to non- equatorial region has been calculated, for a given set of values of electrostatic and magnetostatic charges.

A New Area Law in General Relativity

Netta Engelhardt
University of California Santa Barbara, USA

We report a new area law in General Relativity. A future holographic screen is a hypersurface foliated by marginally trapped surfaces. We show that their area increases monotonically along the foliation. Future holographic screens can easily be found in collapsing stars and near a big crunch. Past holographic screens exist in any expanding universe and obey a similar theorem, yielding the first rigorous area law in big bang cosmology. Unlike event horizons, these objects can be identified at finite time and without reference to an asymptotic boundary. The Bousso bound is not used, but it naturally suggests a thermodynamic interpretation of our result.

The Einstein flow on closed surfaces

David Fajman
University of Vienna, Austria

Despite the high interest in 3-dimensional general relativity in the field of generalized theories of gravity, cosmological solutions to the 3-dimensional Einstein equations have been rarely studied in the context of the Cauchy problem. This is most likely related to the fact that this system only allows for few vacuum solutions, which do not exhibit the variety of global geometries occurring in the higher dimensional case.

However, this changes drastically when the non-vacuum equations are considered. For the Einstein-Vlasov system in three dimensions there is a large class of homogeneous cosmological spacetimes with arbitrary spatial topology. The global structure of those spacetimes depends on the mass of particles and, in the massless case, on the spatial topology.

The class contains spacetimes that emanate from an initial singularity and eternally expand towards the future as well as models that recollapse and terminate in a big crunch.

This new class provides a framework to study relevant problems which have been addressed in the higher dimensional case such as nonlinear stability of homogeneous solutions the “closed universe recollapse conjecture” and “strong cosmic censorship”. In this talk we present the construction of those models and discuss their global structure.

Constrained field theories on backgrounds with horizons

Karan Fernandes
S. N. Bose National Centre for Basic Sciences, India

We study the dynamics of constrained field theories on spherically symmetric and axisymmetric black hole backgrounds, which are either asymptotically flat or bounded by a cosmological horizon. The Hamiltonian analysis for all cases are carried out on hypersurfaces foliated by a time like vector whose norm vanishes on the horizons. Since the resulting hypersurfaces possess boundaries which correspond to the horizons of the spacetime, boundary conditions and contributions have to be determined carefully. We will use the Dirac-Bergman algorithm to derive the constraints, and the conditions under which the boundaries do contribute. By considering the Yang Mills theory on these backgrounds, relevant steps and results regarding constraints, gauge transformations and gauge fixing, will be illustrated in detail. The constraints will be used to further construct the BRST invariant action and the classical master equation, which will be shown to be different from the usual treatment in the absence of horizons. Results from our ongoing work on the quantum BRST treatment of the Yang Mills field will be briefly discussed to address its quantization and renormalization on these backgrounds.

The Space of Gravitational Degrees of Freedom

Arthur Fischer
Department of Mathematics, University of California, Santa Cruz, USA

In general relativity, physical states are represented by isometry classes of solutions of Einstein's field equations. The resulting space Grav(V) of the totality of such states on a 4-dimensional manifold V is known as the space of gravitational degrees of freedom. In this research, we investigate the structure of this space when V is diffeomorphic to R M, where M is a closed 3-dimensional manifold which represents the spatial cosmic topology of the universe. One of our main results is how the topology of M gets encoded into the structure of Grav(V). We give a simple generic topological condition on M such that for spacetimes with constant mean curvature hypersurfaces, Grav(V) has the natural structure of an infinite-dimensional symplectic manifold on an open dense subset and that on the complement of such a set, a nowhere dense subset, Grav(V) has singularities which are of orbifold type, that is, of a manifold modulo a finite group action. We discuss potential applications of our work to 3-manifold geometrization and cosmology, which if successful, would give a dynamical reason, provided by Einstein's equations, to explain the observed fact that the universe is spatially locally homogeneous and isotropic and in such a state so as to continue expanding forever. In this case, these physical aspects of our universe would be a temporal asymptotic consequence of Einstein's evolution equations, rather than having to be imposed as part of a cosmological principle, and thus would be a spectacular and dramatic cosmological confirmation of Einstein's equations.

Sharp asymptotics for Einstein-lambda-dust flows

Helmut Friedrich

Max-Planck-Institut fr Gravitationsphysik, Germany

For the Einstein-dust equations with positive cosmological constant lambda on manifolds with time slices diffeomorphic to an orientable, compact 3-manifold S it is shown that the set of standard Cauchy data for the Einstein-λ-dust equations on S contains an open subset of data that develop into solutions which admit a space-like conformal boundary scri+ at future time-like infinity. The extended conformal structure is smooth if the data are smooth and of correspondingly lower smoothness otherwise. This implies in particular a strong stability result for FLRW solutions. The solutions can conveniently be characterized in terms of their data induced on scri+. Only a linear equation needs to be solved to construct such data. If the energy density is assumed to be positive no differential equation needs to be solved on scri+ at all.

Size and angular momentum of axisymmetric objects

Maria Eugenia Gabach-Clement

FaMAF Universidad Nacional de Crdoba, Argentina

In this talk we present recent results on the size and shape of axisymmetric rotating objects. In particular we show how the inverse mean curvature flow is used to obtain a geometrical inequality connecting the area, the angular momentum and the mass of an ordinary object.

Static spherically symmetric thin shell wormhole colliding with a spherical thin shell

Sijie Gao

Beijing Normal University, China

We consider a static spherically symmetric thin shell wormhole that collides with another thin shell consisting of ordinary matter. By employing the geometrical constraint, which leads to the conservation of energy and momentum, we show that the state after the collision can be solved from the initial data. In the low speed approximation, the solutions are rather simple. The shell may either bounce back or pass through the wormhole. In either case, the wormhole shrinks right after the collision. In the ?bouncing? case, a surprising result is that the radial speeds before and after the collision satisfy an addition law, which is independent of other parameters of the wormhole and the shell. Once the shell passes through the wormhole, we find that the shell always expands. However, the expansion rate is the same as its collapsing rate right before the collision. Finally, we find the solution for the shell moving together with the wormhole. This work sheds light on the interaction between wormholes and matter.

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Vacuum type D initial data

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A vacuum type D initial data set is a vacuum initial data set of the Einstein field equations whose data development cointains a region where the space-time is of Petrov type D. In this work we give a systematic characterisation of a vacuum type D initial data set. By systematic we mean that the only quantities involved are those appearing in the vacuum constraints, namely the first fundamental form (Riemannian metric) and the second fundamental form. Our characterisation is a set of conditions consisting of the vacuum constraints and some additional differential equations for the first and second fundamental forms. These conditions can be regarded as a system of partial differential equations on a Riemannian manifold and the solutions of the system contain all possible regular vacuum type D initial data sets. As an application we particularise our conditions for the case of vacuum data whose data development is a subset of the Kerr solution (Kerr initial data). This has applications in the formulation of the non-linear stability problem of the Kerr black hole.

New conserved currents for vacuum space-times in dimension four with a Killing vector

Alfonso Garca-Parrado Gmez-Lobo

Fsica Terica, Universidad del Pas Vasco, Apartado 644, 48080 Bilbao, Spain

A new family of conserved currents for vacuum space-times with a Killing vector is presented. The currents are constructed from the superenergy tensor of the Mars-Simon tensor and given the positivity properties of the former we find that the conserved charges associated to the currents have natural positivity properties. Given the role played by the Mars-Simon tensor in local and semi-local characterisations of the Kerr solution the currents presented in this work are useful to construct non-negative scalar quantities characterising Kerr initial data (known in the literature as non-Kerrness).

Gravitational wave memory in the expanding universe

David Garfinkle

Oakland University, USA

The final configuration of a gravitational wave detector, after the gravitational wave passes, is different from the initial configuration. This difference is called gravitational wave memory. This talk describes the effect of the expansion of the universe on the memory due to a source at a significant redshift.

Shapes of rotating nonsingular shadows

Sushant Ghosh

Centre for Theoretical Physics, Jamia Millia Islamia, New Delhi, India

It is a belief that singularities are creation of general relativity, and in the absence of quantum gravity model of nonsingular black holes have received significant attention. We study the shadow, an optical appearance because of its strong gravitational field cast by a nonsingular black hole which is characterized by three parameters, i.e., mass (M), spin (a) and a constant deviation parameter (k). The nonsingular black hole is recognized as asymptotically ($r >> k, k > 0$), explicitly on the Kerr-Newman black hole, and in the limit $k \to 0$ as the Kerr black hole, and that the shadow of a nonsingular black hole is a dark zone covered by deformed circle. Further, it is shown that the shadow is affected due to the parameter k, and for a given parameter a, the size of the shadow reduces as the parameter k increases and there is an enlargement in the distortion due to increasing value of parameter k. The effect of parameter k on the ergoregion and the emission rate from black hole is also investigated.

Exploring black hole spacetimes with Sage Manifolds

Eric Gourgoulhon

CNRS / Observatoire de Paris / Univ. Paris Diderot, France

SageManifolds is a recent extension of the open-source mathematics software system SageMath for differential geometry, especially tensor and exterior calculus. It constitutes a high-level language (based on Python) for performing tensorial computations in different charts and vector frames. The computations can involve not only symbolic calculus but also numerical calculations. In particular, one of the aims of SageManifolds is tensor calculus on spacetimes arising from numerical relativity. Some specific examples involving analytic and numerical black hole spacetimes will be provided, such as the drawing of Carter-Penrose diagrams, the computation of the Simon-Mars tensor in stationary 4D spacetimes, the computation of black brane exact solutions in 5D gravity, and the computation of geodesics of exact and numerical metrics.

Superradiant instabilities of asymptotically anti-de Sitter black holes

Stephen Green

Perimeter Institute for Theoretical Physics, Canada

We study the linear stability of asymptotically anti-de Sitter black holes in general relativity in spacetime dimension 4. Our approach is an adaptation of the general framework of Hollands and Wald, which gives a stability criterion in terms of the sign of the canonical energy, E. The general framework was originally formulated for static or stationary and axisymmetric black holes in the asymptotically flat case, and the stability analysis for that case applies only to axisymmetric perturbations. However, in the asymptotically anti-de Sitter case, the stability analysis requires only that the black hole have a single Killing field normal to the horizon and there are no restrictions on the perturbations (apart from smoothness and appropriate behavior at infinity). For an asymptotically anti-de Sitter black hole, we define an ergoregion to be a region where the horizon Killing field is spacelike; such a region, if present, would normally occur near infinity. We show that for black holes with ergoregions, initial data can be constructed such that $E \lesssim 0$, so all such black holes are unstable. To obtain such initial data, we first construct an approximate solution to the constraint equations using the WKB method, and then we use the Corvino-Schoen technique to obtain an exact solution. We also discuss the case of charged asymptotically anti-de Sitter black holes with generalized ergoregions.

Discrete cosmological models are piecewise silent

Daniele Gregoris

Dalhousie University, Canada

Continuous symmetries have been largely employed for the large scale modelling of the Universe. On the other hand discrete symmetries have played little role/no role at all in the cosmological modelling so far. In this talk I will discuss the importance of reflection symmetry in a class of discrete cosmological models in which the mass source is confined to a regular lattice of identical black holes. Such black hole lattice models have been largely considered in literature in recent years both numerically and analytically to provide a viable alternative to dark energy in the late time cosmology context. I will write the evolution equations for such reflection symmetric surfaces in terms of a set of Friedmann-like equations showing that the corresponding source term can be interpreted as a set of interacting effective fluids. I will show that this family of models is "piecewise silent": gravitational waves must be trapped within small chambers during all the time evolution and cannot propagate throughout the entire spacetime. This implies that the evolution of a chamber is as if it is not affected by the evolution the remaining Universe. The talk is based mainly on an original research by Clifton, Gregoris, Rosquist.

On Asymptotic Behaviour of 2+1 Einstein-Wave Map System

Nishanth Gudapati
Yale University, USA

Wave maps are nonlinear wave structures which are natural geometric generalizations of harmonic maps on the one hand and linear wave equations on the other. Such structures occur in several situations in gauge field theories. In particular, wave maps have applications in Einstein's equations of general relativity, most notably in the initial value formulation of Einstein's equations and in the Kaluza-Klein reduction. In this talk, after motivating the study of asymptotic behaviour of Einstein's equations, we shall discuss some recent results concerning the scattering of a 2+1 dimensional Einstein-wave map system.

Scalar field critical collapse in 2+1 dimensions

Carsten Gundlach
University of Southampton, United Kingdom

We present numerical and analytical progress on the critical collapse of a spherically symmetric massless scalar field in 2+1 spacetime dimensions with negative cosmological constant. We approximate the true critical solution as the n=4 Garfinkle solution, matched at the lightcone to a Vaidya-like solution, and corrected to leading order for the effect of. We conjecture that pointwise it is a good approximation to a yet unknown exact critical solution. With this conjecture, we derive a Ricci-scaling exponent of and a mass-scaling exponent of , compatible with our numerical experiments.

Gravitational lensing beyond geometric optics

Abraham Harte
Albert Einstein Institute, Germany

The vast majority of work on gravitational lensing assumes from its outset the rules of geometric optics: electromagnetic and gravitational signals travel on null geodesics, polarizations are parallel-propagated, and so on. Appropriate solutions to the underlying field equations do indeed obey these rules, but only "at infinite frequency." This talk explores how gravitational lensing is corrected at finite frequencies. There can be phase shifts, frequency-dependent changes in apparent source directions, and other effects. These effects are related to well-studied bitensors associated with Green functions in curved spacetimes, and can be determined simply by integrating ODEs along null geodesics. It is also pointed out that some wave-optical effects do not necessarily decay with distance.

Investigations of the shear-free conjecture: the roles of acceleration and the use of algebraic software

Peter Huf

Deakin University, Australia

P A Huf and J Carminati (Deakin University, Geelong, Australia) Abstract. In this paper we present results of our study of sub-cases of the shear-free conjecture for a perfect fluid. The kinematic and field equations used in our study are based on the work of Senovilla et al. (Gen.Rel.Grav. 30 (1998) 389-411), where the cases of (i) zero acceleration (a=0) and (ii) acceleration parallel to vorticity are shown to lead to. In addition we add the sub-case (iii) acceleration is orthogonal to vorticity. Our methods involves the use of TensorPack (a Maple-based software package) for the algebraic manipulation of tensors, which we have employed to provide alternative lines of proofs. In general these proofs are accessible and often shorter than that found in the literature. It is hoped that this approach will facilitate discussion of covariant proofs of exact solutions in general relativity.

A toy Penrose inequality and its proof

Emma Jakobsson

Stockholm University, Sweden

We formulate and prove a toy version of the Penrose inequality. The formulation mimics the original Penrose inequality in which the scenario is the following: A shell of null matter collapses in Minkowski space and a marginally trapped surface forms on it. Through a series of arguments relying on established assumptions, an inequality relating the area of this surface to the total energy of the shell is formulated. Then a further reformulation turns the inequality into a statement relating the area and the null expansions of surfaces in Minkowski space itself.

The inequality has been proven to hold true in many special cases, but there is no proof in general. In the toy version here presented, an analogous inequality in 2+1-dimensional anti-de Sitter space turns out to hold true.

The vector field methods for the relativistic transport equations

Jérémie Joudioux

University of Vienna, Austria

The vector field methods has been an important tools to handles the perturbations of the wave equation and ultimately prove the stabilty of Minkowski spacetime. The purpose of this talk is to present the tools to handle pertubatively the relativistic transport equations. In particular, we develop a commutator theory, simultaneously compatible with the wave equation and the massive transport equation. I will present in this talk the detailed asymptotic behavior for velocity averages of densities solutions to the massive transport equation in flat spacetime. As an application, the stability of the massive Vlasov-Nordstrom system in dimension 3 is discussed. This work is a collaboration between D. Fajman (Vienna) and J. Smulevici (Orsay).

Geometric Inequalities Involving Mass, Angular Momentum, and Charge

Marcus Khuri

Stony Brook University, USA

We establish mass-angular momentum-charge inequalities in higher dimensional general relativity, and also within the context of minimal supergravity. These in particular give variational characterizations of some well known stationary and static black holes. We also exhibit a special case of the Penrose inequality with angular momentum in the classical 4D setting.

Hairy black holes in the general Skyrme model

Olga Kichakova

University of Oldenburg, Germany

We study the existence of hairy black holes in the generalized Einstein-Skyrme model. It is proven that in the BPS model limit there are no hairy black hole solutions, although the model admits gravitating (and flat space) solitons. Furthermore, we find strong evidence that a necessary condition for the existence of black holes with Skyrmionic hair is the inclusion of the Skyrme term L4. As an example, we show that there are no hairy black holes in the L2 + L6 + L0 model and present a new kind of black hole solutions with compact Skyrmion hair in the L4 + L6 + L0 model.

Non-chaotic vacuum singularities without symmetries

Paul Klinger
University of Vienna, Austria

The BKL conjecture proposes a detailed description of the generic asymptotic dynamics of spacetimes as they approach a spacelike singularity. It predicts complicated chaotic behaviour in the generic case, but simpler non-chaotic one in cases with symmetry assumptions or certain kinds of matter fields. Here we use Fuchsian methods to construct a new class of four-dimensional vacuum spacetimes containing spacelike singularities which show non-chaotic behaviour. In contrast with previous constructions, no symmetry assumptions are made. Equivalent solutions exist for the case of non-zero cosmological constant and with timelike instead of spacelike singularity.

Singularity theorems in regularity $C^{1,1}$

Michael Kunzinger
University of Vienna, Austria

The singularity theorems of General Relativity, initiated by R. Penrose in 1965 and continued by S. Hawking, G.F.R. Ellis, R. Geroch, J. Senovilla and many others, constitute a major milestone in the understanding of solutions to the Einstein equations. They predict the existence of singularities (incomplete causal geodesics) for spacetimes that satisfy physically reasonable assumptions.

A shortcoming of the theorems is that they typically do not make statements on the character of the singularities they predict, e.g. whether curvature blows up at a singularity. In principle, a spacetime might be singular merely due to the differentiability of the spacetime metric dropping below C^2, with discontinuous but bounded curvature. Such a drop in the regularity from C^2 to $C^{1,1}$ would correspond, via the field equations, to a finite jump in the matter variables, a situation that could hardly be regarded as singular from the viewpoint of physics. Also for the singularity theorems themselves the natural differentiability class is $C^{1,1}$, as this is the minimal condition that ensures unique solvability of the geodesic equations.

Recent progress in low-regularity causality theory has allowed to show that, in fact, both the Penrose and the Hawking singularity theorem remain valid for

$C^{1,1}$-metrics. We will report on these developments and discuss open questions and further directions of research. This is joint work with M. Stojkovic, R. Steinbauer, and J. A. Vickers.

Multisymplectic Perspective on ADM Momentum and Black Hole Entropy

Eugene Kur
University of California, Berkeley, USA

We review multisymplectic geometry, which has become a powerful tool for describing classical field theories. We present a simple approach to performing a 3+1 decomposition of the theory and deriving a canonical formulation, with particular attention to what happens when the 3d surface has a 2d boundary. We clarify the resulting phase spaces and various boundary terms appearing in Noether charges. We apply these methods to general relativity to obtain the ADM momentum and derive the first law of black hole thermodynamics.

The advantage of this approach is that diffeomorphisms naturally generate conserved currents in the multisymplectic phase space. To our knowledge, this is the first approach which treats these multisymplectic currents in the presence of boundaries. This provides additional insight into the ADM charges and black hole entropy of the canonical formalism.

The global nonlinear stability of Minkowski space for the f(R) theory of modified gravity

Philippe G. LeFloch
Univ. Pierre et Marie Curie (Paris 6), France

We consider here the initial value problem for the so-called f(R)-theory of modified gravity for which the field equations are an extension to the classical Einstein equations of general relativity. Our main result concerns the nonlinear global stability of Minkowski spacetime for this theory and, as a corollary, also allows us to establish the nonlinear global stability of Minkowski spacetime for Einstein's theory in presence of a massive scalar field with sufficiently small mass. Our proof relies on the Hyperboloidal Foliation Method introduced earlier by the authors for the Einstein-scalar field system, but this method is significantly generalized by allowing here limited decay conditions at infinity for the scalar field. We express the problem as a system of coupled nonlinear wave-Klein-Gordon equations (with differential constraints) posed on a curved space, and we introduce a foliation of the spacetime by asymptotically hyperboloidal hypersurfaces. We prove sharp decay estimates for wave and Klein-Gordon equations on a curved space, as well as Sobolev and Hardy's inequalities on a hyperboloidal foliation. The quasi-null hyperboloidal structure of the Einstein equations is also essential in our analysis. By controlling the dependence in the defining function f(R) throughout the proof and establishing bounds for Klein-Gordon equations independently of the mass parameter, we are able to prove that the Cauchy developments of modified gravity converge to those associated with the Einstein equations when the function f(R) approaches R. This is a joint work with Y. Ma (Xi'an) and preprints are available at http://philippelefloch.org/

When near horizon geometries meet non-expanding horizons

Jerzy Lewandowski
Uniwersytet Warszawski, Poland

When near horizon geometries meet non-expanding horizons There is a mysterious relation between non-expanding null foliations of spacetimes and extremal isolated horizons. A lief of a non expanding null foliation satisfied conditions necessary for the existence of a transversal extremal isolated horizon. An example is near (extremal) horizon geometry which indeed admits a foliation by pieces of non-extremal Killing horizons. Whether this invitation for the transversal extremal horizon to exist is always satisfied or not we will be discussed in this talk.

Transverse deformations of extremal horizons

James Lucietti
University of Edinburgh, United Kingdom

Transverse deformations of extremal horizons I will discuss the inverse problem of determining the spacetime near an extremal Killing horizon with a prescribed, spatially compact, horizon geometry. In particular, the Einstein equations for infinitesimal deformations transverse to the horizon reduce to an elliptic PDE for the extrinsic curvature of a cross-section of the horizon, which implies there exists a finite dimensional moduli space of such deformations. This can also be used to establish a uniqueness theorem for transverse deformations of the extremal Kerr horizon. Furthermore, it is possible to determine all axisymmetric transverse deformations of a five-dimensional extremal Myers-Perry horizon, which reveals there are solutions with marginally trapped cross-sections of the horizon that are more general than the known black hole solutions.

Some applications of the theory of g-conjugation in the speeds space , relativity , cosmology and the phases space

Gheorghe Adrian Lupu
Decebal Technical College Drobeta Turnu Severin, Romania

In this paper, using the theory of the conjugated directions into a pseudo-riemannian structure (Mn,g), we will study the next items:

1) General properties and , as a particular case , special properties of the g-conjugated directions

2) How to use these properties to construct geometrical models , with applications in relativity

3) Some g-criteria for the classification of the relativistic models

4) The inclusion of the Einstein the symmetrical ones and the nonsymmetrical ones into a g-equivalence class and also the generalization of the nonsymmetrical Einstein model

5) Some interpretations in the speeds space and cosmology

6) For the first time we will study the conjugation in the phases space , including the demonstration of the existence of this posibility.

In this way we will give to the specialists in relativity and cosmology the opportunity to obtain new interpretations , using the results of the later researches on these fields.

Gravity, time and motion

Nadja Magalhaes

Federal University of Sao Paulo, Brazil

In this presentation the relationship between time and motion is analyzed. Once space is physically defined we argue that the fact that time can be defined in terms of space makes motion the key factor for physical transformations. The role of time as a counting parameter instead of a physically distinct quantity is presented. Consequences of this role in the context of gravity are discussed.

The (in)stability of anti-de Sitter spacetime–resonant approximation

Maciej Maliborski

Albert Einstein Institute, Potsdam, Germany

The anti-de Sitter (AdS) space is of great interest in contemporary theoretical physics due to the AdS/CFT correspondence. However, the question of (in)stability of AdS space is unanswered till now. The resonant approximation (also known as multiscale formalism) proved to be an efficient tool for studies of small perturbations of AdS. A review of this perturbative method with an emphasis on Einstein-massless-scalar field system will be presented. It will be demonstrated that for a large class of initial data solution of the resonant system develops an oscillatory singularity in finite time. The quasi-periodic solutions obtained within this approximation will also be discussed. Finally, comparison of resonant system with fully nonlinear evolution will be given.

Event Horizon Detection for the Supersymmetric Five Dimensional Black Ring

David McNutt

Dalhousie, Canada

In this presentation we extend the results by Page and Shoom for scalar polynomial curvature invariants (SPIs) as event horizon detectors for stationary horizons. We study regions of the 5D supersymmetric black ring which are not stationary and show the chosen SPI is able to detect the event horizon. Along with this result we will review the Cartan Equivalence algorithm and show that Cartan invariants provide a computationally simpler set of invariants for event horizon detection.

Through the Big Bang

Flavio Mercati

Perimeter Institute for Theoretical Physics, Canada

I consider the near-big-bang behaviour of a homogeneous but anisotropic cosmological model with S^3 spatial topology - the Bianchi IX model. This model is well-known to behave like a billiard ball (Misner called it 'mixmaster' behaviour), which goes through an infinite amount of bounces before reaching the big bang. However, assuming there is at least one massless scalar field, the mixmaster behaviour stops after a finite amount of bounces, and the shape degrees of freedom of the geometry stabilize around a Kasner-like solution as the singularity is reached (the so-called 'quiescent' case).

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I am able to prove that each solution of the quiescent model can be continued uniquely past the big-bang singularity, by demanding continuity of the shape degrees of freedom. The system goes through a degenerate shape (a 'pancake'- or 'cigar'-like shape), and comes out with an inverted orientation. Continued in this way, each solution of the system looks like two universes joined at the big bang. This makes GR compatible with the picture of the big bang being a 'Janus point' of the kind my collaborators and I studied in the context of Newtonian cosmological models in PRL 113, 181101, which provides a previously-unnoticed mechanism for the emergence of the arrow of time. This resolution of the big bang singularity is purely classical and does not require quantum effects. Finally I will discuss how, through the BKL conjecture, this new result generalizes to full General Relativity (relaxing the homogeneity hypothesis) with any kind of minimally-coupled matter.

Causal Nature and Dynamics of Trapping Horizons in Black Hole Collapse and Cosmology

Ilia Musco

Laboratoire Univers et Thories (LUTH), Observatoire de Paris, France

In calculations of gravitational collapse to form black holes, trapping horizons (foliated by marginally trapped surfaces) make their first appearance either within the collapsing matter or where it joins on to a vacuum exterior. Those which then move outwards with respect to the matter have been proposed for use in defining black holes, replacing the global concept of an "event horizon". We have studied the properties of trapping horizons within spherical symmetry, showing that their locations are then given by exactly the same condition (R=2M) as for the event horizon in the vacuum Schwarzschild metric, and the same condition also applies for cosmological trapping horizons. We have investigated the causal nature of these horizons (i.e. whether they are spacelike, timelike or null), making contact with the Misner-Sharp formalism, which has often been used for numerical calculations of spherical collapse. We follow two different approaches, one using a geometrical quantity related to the expansion of null geodesic congruence, and the other using the horizon velocity measured with respect to the collapsing (or expanding) matter. Each of these can be simply calculated in terms of local fluid parameters, and the connection between them allows a full description of the possible behaviours, depending on the initial density profile and the equation of state. After revisiting the FLRW universe model and the pressureless Oppenheimer-Snyder collapse model in the light of this, we have carried out numerical simulations for stellar collapse with non-zero pressure.

Mode Stability on the Real Axis

Claudio Paganini

Albert Einstein Institute, Germany

I will present a generalization of the mode stability result of Whiting (1989) for the Teukolsky equation for the case of real frequencies. I will focus on the core ideas that are needed to show that a separated solution of the Teukolsky equation governing massless test fields on the Kerr spacetime, which is purely outgoing at infinity, and purely ingoing at the horizon, must vanish.

Joint work with: Siyuan Ma, Lars Andersson, Bernard Whiting

Influence of a plasma on light propagation in general relativity

Volker Perlick
ZARM, University of Bremen, Germany

On a general-relativistic spacetime, light rays are lightlike geodesics of the spacetime metric as long as they are not influenced by matter. In a plasma, which is here considered to be pressureless and non-magnetised, they follow certain timelike curves which depend on the frequency of light. Some general features of light propagation in a plasma will be discussed, including the generalised Sachs equations which govern the geometry of light bundles. As an application, the influence of a plasma on the shadow of a black hole will be considered.

The part on the geometry of light bundles is based on a joint paper, now

in preparation, with Karen Schulze-Koops and Dominik Schwarz (U Bielefeld, Germany). The applications to the shadow of a black hole are based on joint work with Oleg Tsupko and Gennady S. Bisnovatyi-Kogan (Russian Space Institute, Moscow, Russia) which is partly published (Phys. Rev. D 92, 104031, 2015).

The Energy Conditions for Relativistic Magneto-Fluid Dynamics

Oscar Mauricio Pimentel Diaz
Universidad Industrial de Santander - UIS, Colombia

The energy conditions for a viscous fluid with heat flux and magnetic fields are presented. This conditions are computed under the assumption of infinite conductivity, so the electric field goes to zero. To establish the expressions for the energy conditions, the required physical quantities (energy density, energy flux density, etc.), as measured by an arbitrary observer, are computed. Using these quantities and following an algebraic procedure it is possible to find the conditions without doing any approximation or restriction (apart from the infinite conductivity) on the energy-momentum tensor of the fluid with magnetic field.

First Law for fields with Internal Gauge Freedom

Kartik Prabhu
The University of Chicago, USA

We extend the analysis of Iyer and Wald to derive the First Law of blackhole mechanics in the presence of fields charged under an 'internal gauge group'. We treat diffeomorphisms and gauge transformations in a unified way by formulating the theory on a principal bundle. The first law then relates the energy and angular momentum at infinity to a potential times charge term at the horizon. The gravitational potential and charge give a notion of temperature and entropy respectively.

Geometrothermodynamics of black holes with cosmological constant

MARIA QUEVEDO
Research professor, Colombia

We show that to investigate the thermodynamic properties of charged phantom spherically symmetric anti-de-Sitter black holes, it is necessary to consider the cosmological constant as a thermodynamic variable so that the corresponding fundamental equation is a homogeneous function defined on an extended equilibrium space.

We explore all the thermodynamic properties of this class of black holes by using the classical physical approach, based upon the analysis of the fundamental equation, and the alternative mathematical approach as proposed in geometrothermodynamics. We show that both approaches are compatible and lead to equivalent results.

Constraints as evolutionary systems

Istvan Racz
Wigner RCP, Hungary

The constraint equations for smooth $[n+1]$-dimensional (with $n \geq 3$) Riemannian or Lorentzian spaces satisfying the Einstein field equations are considered. It is shown, regardless of the signature of the primary space, that the constraints can be put into the form of an evolutionary system comprised either by a first order symmetric hyperbolic system and a parabolic equation or, alternatively, by a symmetrizable hyperbolic system and a subsidiary algebraic relation. In both cases the (local) existence and uniqueness of solutions are also discussed.

A simple method of constructing binary black hole initial data

Istvan Racz
Wigner RCP, Hungary

By applying a parabolic-hyperbolic formulation of constraint equations and superposing Kerr-Schild black holes, a simple method is introduced to initialize time evolution of binary systems. The data yielded fits to the needs of simulations with excision though in determining it no use of boundary conditions in the strong field regime is made. The proposed new method could also be applied to construct initial data for multiple black hole systems, and it offers an explicit control on the ADM parameters of the composite systems.

Strong Cosmic Censorship in cosmological Bianchi class B perfect fluids and vacuum

Katharina Radermacher
KTH Royal Institute of Technology, Sweden

Einstein's field equations of General Relativity can be formulated as an initial value problem, where the initial data corresponds to the metric and second fundamental form of a Cauchy hypersurface. This initial value problem has a maximal globally hyperbolic development which is unique up to isometry. The Strong Cosmic Censorship conjecture states that, at least for generic initial data, this development is inextendible, in the sense that there is no solution to the field equations larger than that determined by the initial data.

In this talk, I consider the case where the initial data is symmetric under the action of a three-dimensional Lie group (i.e. a Bianchi model), and the stress-energy tensor is assumed to be that of a perfect fluid or vacuum.

I present new results proving Strong Cosmic Censorship in a specific class of Bianchi models, namely non-exceptional Bianchi B spacetimes. I further discuss in more detail the asymptotic behaviour of such spacetimes towards the initial singularity.

Causality and hyperbolicity of Lovelock theories of gravity

Harvey Reall
Cambridge University, United Kingdom

In four spacetime dimensions, Lovelock's theorem asserts that the left hand side of the Einstein equation cannot be modified. However in higher dimensions extra terms can be added to give Lovelock theories of gravity. Characteristic surfaces in these theories are generically non-null. I will discuss causality and hyperbolicity of these theories and argue that they suffer from shock formation.

Accretion of a Relativistic Kinetic gas, into a Schwarzschild black hole

Paola Rioseco
Instituto de fisica y matematicas, Universidad Michoacana de San Nicolas de Hidalgo, Mexico

We analyze the accretion of gas into a black hole background space-time in the context of relativistic kinetic theory. The state of the gas is described by a distribution function which has to satisfy the general relativistic Boltzmann equation. In the first part of this work, we describe a method to find the most general solution of this equation in the collisionless case.

In the second part, we apply our result to the case of a radial flow propagating on a nonrotating black hole. We compute the accretion rate and compare it to the one of the Michel fluid flow solution, clarifying previous results in the literature.

Dynamics of confined double-shells systems, critical behavior and chaos

Jorge Rocha

University of Barcelona, Spain

I will present a study of gravitational collapse in confined spaces employing the simplest possible two-body setting: a system composed of two thin shells in spherical symmetry. Confinement is introduced either by putting the system inside a totally reflecting spherical cavity or by formulating the problem in anti-de Sitter (AdS) spacetime. The two shells interact only through their gravitational attraction. The problem amounts to solving just two decoupled ODEs but it features highly non-trivial dynamics: depending on initial data, one observes prompt collapse, perpetual oscillations or black hole formation on arbitrarily long timescales. This confined double-shell system exhibits critical behavior reminiscent of the turbulent dynamics of massless scalar fields in AdS as well as chaotic behavior. The AdS and the cavity settings show qualitatively similar dynamics but there are some quantitative differences.

On 2+1 Gravity, Topological M-Theory and Black Holes

Miguel Sabido

University of Guanajuato, Mexico

By determining the relation between topological M-theory and the Chern-Simons actions for a gauge field constructed from the Lie algebra of either $SL(2,\mathbb{R}) \times SL(2,\mathbb{R})$ or $SL(2,\mathbb{C}) \times SL(2,\mathbb{C})$, depending on the sign of the space-time curvature, we show that the partition function of topological M-theory evaluated on a particular space-time basis is equivalent to the partition function of 3-dimensional gravity. Furthermore, from this formalism we calculate the Entropy for the BTZ black hole.

Generalised Hyperbolicity for Singular Spacetimes

Yafet Sanchez Sanchez

University of Southampton, United Kingdom

A desirable property of any spacetime is that the evolution of any physical field is locally well-defined. For smooth metrics, this is guaranteed by standard local well-posedness results. Moreover, there are physically reasonable spacetimes for which the initial value problem is well-posed but the spacetime metric is rough.

In this talk we will show that in certain spacetimes with hypersurface and stringlike singularities one still has local well-posedness of the wave equation in the Sobolev space H^1. This function space is chosen as it allows us to define the energy-momentum tensor of the field distributionally. It is also the one needed for solutions of the linearised Einstein equations. The methods we employ are therefore

also relevant to finding low regularity solutions of the Einstein equations which, as shown by Dafermos, is an important issue when considering Strong Cosmic Censorship.

Motivated by this work we propose a definition of a strong gravitational singularity as an obstruction to the evolution of a test field rather than the usual definition as an obstruction to the evolution of a test particle along a causal geodesic. This definition has the advantage that it is directly related to the physical effect of the singularity on the field (the energy-momentum tensor fails to be Integrable) and also that it may be applied to situations where the regularity of the metric falls below $C^{1,1}$ where one no longer has existence and uniqueness of geodesics.

This is joint work with James Vickers

Susan Scott: The Australian National University, Australia The Abstract Boundary Singularity Theorem and its Generalisations The abstract boundary singularity theorem was proven by Ashley and Scott. It links the existence of incomplete causal geodesics in strongly causal, maximally extended space-times to the existence of abstract boundary essential singularities, i.e., non-removable singular boundary points. We will discuss this theorem and present two generalisations of the theorem: the first to continuous causal curves and the distinguishing condition, the second to locally Lipschitz curves in manifolds such that no inextendible locally Lipschitz curve is totally imprisoned.

Shear-free surfaces and distinguished dynamical horizons

Jos M M Senovilla

University of the Basque Country UPV/EHU, Spain

The concept of "shear-free" spacelike surface is introduced. They have a vanishing traceless second fundamental form along one normal direction. (They obviously generalize the surfaces orthogonal to a shear-free irrotational congruence). A simple, useful, way to characterize them is presented. Then, it is argued that they can be used to select a preferred marginally trapped tube (MTT) in dynamical black holes: the MTT foliated by shear-free surfaces. I will show that, in all known explicit examples, the expected natural preferred MTT is unique having this property. Finally, solid arguments in favour of the existence of such unique MTT will be discussed.

Charged rotating black holes at large D

Kentaro Tanabe
Rikkyo University, Japan

We discuss the charged rotating black holes in the Einstein-Maxwell theory by using the large D expansion method, where D is a spacetime dimension. The charged rotating black hole solution is constructed as the solution of large D effective equations. We also give stability analysis of charged rotating black holes by performing perturbation analysis of the large D effective equations. As a result we find that the ultraspinning instability of charged rotating black holes in de Sitter describes the instability of de Sitter Reissner-Nordstrom black hole.

Averaging of the Schwarzschild spacetime

Sergey Tegai
Siberian Federal University, Russia

Averaging the Newton potential gives the solution of the Poisson equation consisting of two parts. The interior is the field of the homogenious mass distribution and the exterior is again the Newton potential. We do the same exercise within the framework of general relativity applying several variants of the averaging scheme to the Schwarzschild spacetime. We show that with the suitable choice of the averaging operator it is possible to obtain the same behavior for the exterior region as in the newtonian case either by averaging the connection forms or the curvature forms.

The Cosmological Memory Effect

Alexander Tolish
University of Chicago, USA

The "memory effect" is the permanent change in the relative separation of test particles resulting from the passage of gravitational radiation. We investigate the memory effect for a general, spatially flat FLRW cosmology by considering the radiation associated with emission events involving particle-like sources. We find that if the resulting perturbation is decomposed into scalar, vector, and tensor parts, only the tensor mode contributes to memory. Furthermore, the tensor contribution to memory depends only on the cosmological scale factor at the source and observation events, not on the detailed expansion history of the universe. In particular, If locally similar radiation source events occur on flat and cosmological backgrounds, the resulting memory effect in the cosmological case will be exactly the same as in the Minkowski case provided that in both cases the detector is at the same distance to the source at the time of detection.

Causality theory for $C^{1,1}$ metrics

James Vickers
University of Southampton, United Kingdom

Much of the literature on causality theory assumes the metric to be at least C^2. However there are important mathematical and physical reasons for considering lower regularity. There are PDE theorems which show the existence of solutions of Einstein?s equations in Sobolev spaces where the metric need not be C^2. Also from the physical point of view one would like to study systems where the matter variables may not be continuous. On matching these regions across the boundary the energy-momentum tensor is no longer continuous which forces the differentiability of the metric to fall below C^2.

A $C^{1,1}$ (i.e. continuously differentiable with locally Lipschitz first derivatives - often written C^{2-}) allows for a finite jump in the matter variables and is also natural from the point of view of causality theory as it is the threshold for showing the existence and uniqueness of geodesics.

For $C^{1,1}$ metrics standard results only tell us that the exponential map is locally Lipschitz while to prove the existence of geodesically convex sets one requires the stronger condition that the exponential map is a bi-Lipschitz homeomorphism. This result has recently been established (by the authors below and also independently by E. Minguzzi). This talk will report on how this may be used to establish all the standard results of causality theory for $C^{1,1}$ metrics, why these results are important, and what causality results remain true below this threshold.

This is joint work with M. Kunzinger, M. Stojkovic and R. Steinbauer.

A lower bound for the mass of multiple charged rotating black holes

Gilbert Weinstein
Ariel University, Israel

S. Dain proved the lower bound $m^2 \geq |J|$ for axially symmetric data with one black hole, where m is the ADM mass and J the angular momentum. This was generalized to multiple black holes by Chrusciel, Li and Weinstein. Chrusciel and Costa generalized this to the charged rotating one black case proving the lower bound $m^2 \geq 1/2(q^2 + \sqrt{q^4 + 4J^2})$ where q is the total charge. Here we present joint work with M. Khuri generalizing this to multiple charged rotating black holes.

The threefold classification of spacetime tensors

Lode Wylleman
Ghent University, Belgium

Classification of tensors has been a very important tool to detect and describe the intrinsic geometric structure of spacetime physics. Well-known classifications are, for instance, the Petrov classification of the Weyl tensor in general relativity, and of antisymmetric (Faraday-like) or symmetric (Ricci-like) tensors. The Bel-Debever-Penrose viewpoint on the Weyl-Petrov classification has been generalized to the null alignment (boost order) classification of general tensors, even in arbitrary dimensions, by Milson, Coley, Pravda and Pravdová. For any given tensor, let N be the number of aligned null directions along which the boost order is at most zero (BOZANDs). Tensors may then be classified into three types: type A ($N = 0$, which is the generic type whenever the tensor is not fully antisymmetric), type B ($N = 1$) and type D ($N \geq 2$). In this talk I will prove that for type A tensors there exists a unique timelike direction relative to which Senovillaś super-energy density takes a minimal value; for type B tensors no such timelike direction exists, while for type D tensors minimality is precisely attained by all timelike directions within the space spanned by the BOZANDS. Hence the threefold classification generalizes the known classifications of specific tensors. Moreover, any type A tensor uniquely defines a $1 + (n - 1)$ structure of tangent space at a point of spacetime in $n \geq 4$ dimensions.

Nonaxisymmetric horizon instability of extremal black holes

Peter Zimmerman
University of Arizona, USA

Aretakis' discovery of a horizon instability of extremal black holes came as something of a surprise given earlier proofs that individual frequency modes are bounded. Is this kind of instability invisible to frequency-domain analysis? The answer is no: We show that the horizon instability can be recovered in a mode analysis as a branch point in the Green function at the horizon frequency. We use the approach to generalize to nonaxisymmetric perturbations of Kerr.

Session A3

Bigravitons as dark matter and gravitational waves

Katsuki Aoki
Waseda University, Japan

We consider the possibility that the massive graviton is a viable candidate of dark matter in the context of bimetric gravity. We first derive the energy-momentum tensor of the massive graviton and show that it indeed behaves as that of dark matter fluid. We then discuss a production mechanism and the present abundance of massive gravitons as dark matter. Since the metric to which ordinary matter fields couple is a linear combination of the two mass eigenstates of bigravity, production of massive gravitons, i.e. the dark matter particles, is inevitably accompanied by generation of massless gravitons, i.e. the gravitational waves. Therefore, in this scenario some information about dark matter in our universe is encoded in gravitational waves. For instance, if LIGO detects gravitational waves generated by the preheating after inflation then the massive graviton with the mass of about 0.01 GeV is a candidate of the dark matter.

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de Sitter special relativity and gravitation

Adriana Araujo
IFT UNESP, Brazil

As quotient spaces, Minkowski and de Sitter represent di erent non-gravitationalbackgrounds for the construction of physical theories. General relativity, for in-stance, can be constructed on any one of them. Of course, in either case gravi-tation will have the same dynamics, only their local kinematics will be di erent.If the underlying spacetime is Minkowski, the local kinematics will be ruled bythe Poincar e group of ordinary special relativity. If the underlying spacetime is deSitter, the local kinematics will be ruled by the de Sitter group, which amountsthen to replace ordinary special relativity by a de Sitter-ruled special relativity.Since the cosmological term is now encoded in the background local kinematics,it does not appear explicitly in Einstein equation. This means that, in contrast towhat happens in ordinary general relativity, the second Bianchi identity does notrequire to be constant. Such de Sitter-modied general relativity, in which is allowed to change with the cosmological time, provides a new scenario for the study of cosmology.

A conformally-invariant equal-footing description of Electromagnetism and Gravity

Carlos Barcel

Instituto de Astrofsica de Andaluca, Spain

In this work we revisit Weylś unified theory of Electromagnetism and Gravity. We highlight that at the mild cost of introducing an external volume element, one can construct a theory closely related to Einsteinś gravity but sharing the conformal invariance of four-dimensional Electromagnetism in the absence of matter. Our construction mixes ideas from Weyl-transverse gravity and Weylś unified theory. We argue that the former criticisms against Weylś unified theory loose most of their power in the present reincarnation of the theory. We also stress that the resulting theory is different enough from the Einstein-Maxwell theory so as to predict new observable effects.

Gedanken Experiment for Refining the Unruh Metric Tensor Uncertainty Principle via Schwartz Shield Geometry and Planckian Space-Time with Initial Nonzero Entropy and Applying the Riemannian-Penrose Inequality and Initial Kinetic Energy for a Lower Bound t

Andrew Beckwith

Chongqing University, China

First of all, we restate a proof of a highly localized special case of a metric tensor uncertainty principle first written up by Unruh. Unruh did not use the Roberson-Walker geometry which we do, and it so happens that the dominant metric tensor we will be examining, is variation in . The metric tensor variations given by , and are negligible, as compared to the variation . Afterwards, what is referred to by Barbour as emergent duration of time is from the Heisenberg Uncertainty principle (HUP) applied to in such a way as to give, in the Planckian space-time regime a nonzero minimum non zero lower ground to a massive graviton, mgraviton

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Gedanken Experiment Examining How Kinetic Energy Would Dominate Potential Energy, in Pre-Planckian Space-Time Physics, and Allow Us to Avoid the BICEP 2 Mistake

Andrew Beckwith
Chongqing University, China

We use Padmabhan?s ?Invitation to Astrophysics? formalism of a scalar field evolution of the early universe, from first principles, to show something which seems counter intuitive. How could, just before inflation, kinetic energy be larger than potential energy in pre-Planckian physics, and what physics mechanism is responsible for the Planckian physics result that Potential energy is far larger than kinetic energy. This document answers that question, as well as provides a mechanism for the dominance of kinetic energy in pre-Planckian space-time, as well as its reversal in the Planckian era of cosmology. The kinetic energy is proportional to , with initial degrees of freedom, and T the initial temperature just before the onset of inflation. Our key assumption is the smallness of curvature, as given in the first equation, which permits adoption of the Potential energy and Kinetic energy formalism used, in the Planckian and pre-Planckian space-time physics. Interpretation of this result, if done correctly, will be able to allow a correct distinguishing of relic gravitational waves, as to avoid the BICEP 2 pickup of galactic dust as a false relic Gravitational wave signal, as well as serve as an investigative template as to if quantum gravity is embedded in a deterministic dissipative system, as cited in the conclusion.

Partially massless gravitons on space-times beyond Einstein

Laura Bernard
Institut d'Astrophysique de Paris, France

Partial masslessness occurs when an additional scalar gauge symmetry is present in a massive gravity theory, reducing the number of propagating degrees of freedom to four. For example, this is known to happen at the Higuchi bound for a massive graviton on Einstein space-times. In this talk, I will introduce a new analysis of non linear partially massless gravity within the framework of dRGT massive gravity theories.

First, I will present the five covariant constraints in dRGT theories, that are obtained from the linearized equations of motion around general backgrounds. Then I will use this result to study partially massless gravity, by searching for space-times for which the scalar constraint vanishes identically. In particular, I will show that it is possible to obtain a partially massless graviton on a large class of space-times beyond Einstein.

Sub-Planckian black holes as a link between microphysics and macrophysics

Bernard Carr

Queen Mary University of London, United Kingdom

The Planck mass is usually regarded as marking the boundary between elementary particles and black holes, sub-Planckian black holes being excluded on the grounds that their Schwarzschild radius would be less than their Compton wavelength. However, the Black Hole Uncertainty Principle correspondence suggests a unified expression that asymptotes to the Compton wavelength below the Planck length and to the Schwarzschild radius above it. In this case, black holes could exist beneath the Planck mass but with radius of order the Compton scale rather than Schwarzschild scale, suggesting some connection with elementary particles. We present a modified, self-dual Schwarzschild-like metric that reproduces these features. The self-dual nature of this solution under M 1/M implies a Generalized Uncertainty Principle with the linear form . We also demonstrate a natural dimensional reduction feature in that the gravitational radius and thermodynamics of sub-Planckian objects resemble that of (1+1)-D gravity. The temperature of sub-Planckian black holes scales as M rather than 1/M and this suggests that relics of this mass could provide the dark matter.

Antisymmetric Curvature 2-tensors correspond to Angular Momentum and Charge Currents

John Bruce Davies

University of Colorado-Boulder, USA

The U4 spacetime geometrically possesses non-symmetric metric, curvature and torsion. The conservation laws obtained by 2-tensor linearization of the Bianchi Identities, Davies (1988), relates the non-symmetric metric to curvature and torsion terms and their respective gradients. A subset of this new set of equations governs the usual contribution of symmetric curvature to the gravitational field though with an added contribution due to torsion gradients. As in the previous 3-dimensional case, the antisymmetric curvature 2-tensor is shown to be related to the divergence of the torsion. Using a model of particle-antiparticle pair production, identification of certain torsion components with electroweak fields is proposed. These components obey equations, similar to Maxwell's, that are subsets of these linear Bianchi Identities. Because the additional torsion gradient term in Einstein?s equation contributes to the gravitational field, we expect and demonstrate that the electromagnetic field gradient affects measurements of the Gravitational Constant. This research is based on and extends the following published paper: Davies, J.B., 1988: "New Curvature-Torsion Relations through Decomposition of the Bianchi Identities", Foundations of Physics, 18, 5, 63.

Entropic Gravity and the Mandelbrot Set

Jonathan Dickau
USA

It is known that the Mandelbrot Set formula also gives rise to the Verhulst dynamic, such that the bifurcation diagram branches where an edge of the Set folds back on itself, going from (0.25,0i) to (-2,0i). There are also fractional basins of attraction opposite the Misiurewicz points, populating the periphery of the Set. These combine to form an alternative basis for Entropic Gravity, from the ideas put forward by Jacobson, Verlinde, or Padmanabhan, in the context of a Cosmology similar to Carroll and Chen's spontaneous inflation. This is seen to arise because observed behaviors extend beyond the Complex numbers into the Quaternion and Octonion domains, touching numerous areas of higher-dimensional Physics. The Mandelbrot Set has a fundamental asymmetry along the Real axis, and in addition to its many beautiful symmetries, it illustrates various types of symmetry-breaking phenomena moving along its edge from the cusp to the tail - or tip of the 'main antenna' at (-2,0i) - serving to complement symmetry-preserving objects like E8. This is seen to offer an essential piece of Gravity Physics, mostly unexplored until now.

Semigroup expanded algebras and gravity

Remigiusz Durka
Pontificia Universidad Catlica de Valparaso, Chile

Abelian semigroup expansion leads to non-trivial enlarging of the AdS algebra. It results in a wide class of the new Lie algebras (arXiv:1605.00059) and offers interesting modifications to the gauge gravity theories. Introducing the new generators and extended field content, along with the new invariant tensors, have an impact on the final form of terms in the Chern-Simons (CS) and Born-Infeld (BI) Lagrangians. Separation between various terms due to the different invariant tensor components was used to find the Einstein-Hilbert action as a particular limit of the CS theory in 5D (with later generalization to arbitrary odd dimensions) and was analogously repeated in odd for the BI theories. Recently (arXiv:1603.09424) this was further explored in the context of Pure Lovelock gravity, which action consists only of cosmological constant and a single higher order polynomial in the Riemann tensor.

The Kaluza Ansatz in Eddington-inspired Born-Infeld gravity

Karan Fernandes
S. N. Bose National Centre for Basic Sciences, India

Eddington-inspired Born-Infeld gravity is a higher curvature modified gravity theory whose action is of the Born-Infeld type involving the metric and Ricci tensors. We determine the coupling of electromagnetism to this theory geometrically by using the well known Kaluza-Klein ansatz. In doing so, an action is derived which contains both curvature and electromagnetic field strength tensors, as well as coupling terms between them. The key difference between our action and the usual coupling of electromagnetism to this theory is that the equations of motion involve non-trivial corrections to both Einsteinś and Maxwellś equations, and they are non-minimally coupled to one another. These equations can nevertheless be solved perturbatively. By considering the Reissner-Nordstrom de-Sitter solution as a background, we derive the leading order corrections to the metric and electromagnetic potential that results from our action. The solutions reveal that higher multipoles contribute perturbatively and their implication on the behaviour of electromagnetic fields in regions of high curvature will be elaborated on.

The Cost to Cancel the Cosmological Constant

Gregory Gabadadze
New York University, USA

ABSTRACT TBD

Compact objects in Lovelock gravity theory

Sudan Hansraj
University of KwaZulu Natal, South Africa

We investigate the problem of constructing compact star models within the Lovelock framework of gravity. Despite its successes, general relativity is still deficient in answering some core questions such as the late time accelerated expansion of the universe. In this spirit alternate and modified gravity theories are studied. Lovelock Lagrangians are known to generate at worst second order equations of motion notwithstanding the fact that they are constructed from quadratic forms of the Riemann tensor, Ricci tensor and Ricci scalar. It is worthwhile examining the N^{th} order Lovelock term as a generator of the Lagrangian since to first order general relativity and all its gains are recovered. After arduous calculations, we exhibit the full set of Lovelock equations for a spherically symmetric perfect fluid. It is shown that the constant density Schwarzschild interior metric continues to hold as the defining equation of pressure isotropy is independent of both the spacetime dimension d and the order of the Lovelock term N. We then postulate other forms for one of

the gravitational potentials to solve the seriously complicated master field equation. With the Finch-Skea ansatz, considered as physically reasonable in Einstein gravity, we are able to solve the isotropy equation in general in terms of d and N. The solution is given in terms of Bessel functions of half-integer order and is therefore expressible as elementary functions. We examine the behaviour of odd dimensional spacetimes $d = 2N + 1$ and find that no vanishing pressure surface can exist in general so the solution may model a cosmological fluid without bound. In the even case $d = 2N + 2$ it is found, empirically, that the six dimensional Finch Skea analogue resembles closely the profiles of its four dimensional counterpart in terms of pressure, density, speed of sound and energy conditions.

REFERENCES: S. Hansraj, et al EPJC DOI: 10.1140/epjc/s10052-015-3504-8, SD Maharaj, S Hansraj, ..PRD (DOI: 10.1103/PhysRevD.91.084049); Chilambwe, Hansraj, .. IJMPD (DOI: 10.1142/S0218271815500510); Dadhich, Hansraj .. PRD (Vol 93 to appear).

Cosmology based on Finsler geometry

Manuel Hohmann

University of Tartu, Estonia

We discuss a class of cosmological models based on a Finsler geometric extension to general relativity. Models of this type are motivated by the aim to describe dark energy and inflation from a gravity theory based on modified geometry. The basic ingredient of the extension we discuss here is a replacement of the metric geometry of spacetime by a Finsler geometry based on a length function, which generalizes the notion of proper time following the clock postulate. Within this geometrical framework we discuss different aspects of cosmology, in particular: 1. the notion of cosmological symmetry of Finsler spacetimes, 2. different realizations of such Finsler geometries from tensor fields, 3. the derivation of the geometry side of the cosmological equations of motion from a Finsler gravity action and vacuum solutions, 4. the dynamics of fluids in a cosmologically symmetric background based on the kinetic theory of fluids, 5. the role of such fluids as source terms in the gravitational equations of motion.

PPN parameter gamma for multiscalar-tensor gravity with a potential

Manuel Hohmann

University of Tartu, Estonia

For multiscalar-tensor gravity with completely general nonderivative couplings and potential we compute the parameterized post-Newtonian parameter gamma in the case of a static point source. As an application we use solar system measurements of gamma to draw constraints on some popular models that are equivalent to multiple scalar fields nonminimally coupled to curvature: Higgs dark energy, general hybrid metric-Palatini gravity, quadratic nonlocal gravity. In our formalism it is also relatively straightforward to identify and describe ghost and tachyonic degrees of freedom.

Galactic Shapiro delay for Gravitational waves

Emre Kahya

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A new window into gravitational waves has been opened by the detection of binary black holes from GW150914. We show how relative Shapiro delay between photons and GWs can be used to find evidence or rule out modified theories of gravity which dispense with the need for dark matter called dm emulators. We also show that for GW150914 using the fact that gravitons of different energies reached within 0.2 sec allows us to constrain any frequency dependent violations of Shapiro delay to 1 part in $10\hat{9}$.

A Non-Riemannian Space of Einstein-Cartan Theory of Gravitation

Laxman Katkar

Shivaji University, India

Abstract

The use of geometry in the description of relativity turns out to be necessary. Hence understanding of relativity involves considerable knowledge of underlying geometry on which it rests. Non-Riemannian geometry has its vital role in the development of Einstein-Cartan theory of gravitation, in which the spin of the gravitating matter is considered.

An expression for the Riemann curvature of a non-Riemannian space is derived. To set an example of a 2-dimensional non-Riemannian space, 2- null vector formalism is introduced; we here after refer to it as a dyad formalism. With the help of the dyad formalism a non-Riemannian sphere is constructed. It is shown that the Riemann Curvature of a non-Riemannian sphere is not constant. A new derivative operator d_* analogous to the exterior derivative is defined with respect to the asymmetric connections and Cartan?s equations of structure are obtained. The results thus obtained are corroborated by employing the techniques of differential forms. Geodesics on a non-Riemannian sphere are shown to be indistinguishable from the great circles as the curvature of the non-Riemannian sphere at a point $theta = pi/2$ of the sphere differs from the curvature of the Riemannian sphere by an infinitesimally small amount.

Key Words: Non-Riemannian space, Newman- Penrose tetrad formalism, Exterior calculus, Curvature of a space, Torsion tensor.

An Exact Solution of the Field Equations of Einstein-Cartan Theory of Gravitation

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Abstract:

The author of paper has introduced a new derivative operator d_* with respect to asymmetric connections and developed the techniques of differential forms. This technique is exploited to find the solution of the field equations of Einstein-Cartan theory of gravitation when the source of gravitation is Weyssenhoff fluid. The solution is shown to be Petrov type D. It is observed that in the absence of matter the solution reduces to the Minkowski space-time.

Primordial non-Gaussianities of gravitational waves beyond Horndeski

Tsutomu Kobayashi
Rikkyo University, Japan

We clarify the features of primordial non-Gaussianities of tensor perturbations in Gaoś unifying framework of scalar-tensor theories. The general Lagrangian is given in terms of the ADM variables so that the framework maintains spatial covariance and includes the Horndeski theory and Gleyzes-Langlois-Piazza-Vernizzi (GLPV) generalization as specific cases. It is shown that the GLPV generalization does not give rise to any new terms in the cubic action compared to the case of the Horndeski theory, but four new terms appear in more general theories beyond GLPV. We compute the tensor 3-point correlation functions analytically by treating the modification to the dispersion relation as a perturbation. The relative change in the 3-point functions due to the modified dispersion relation is only mildly configuration-dependent. When the effect of the modified dispersion relation is small, there is only a single cubic term generating squeezed non-Gaussianity, which is the only term present in general relativity. The corresponding non-Gaussian amplitude has a fixed and universal feature, and hence offers a "consistency relation" for primordial tensor modes in a quite wide class of single-field inflation models. All the other cubic interactions are found to give peaks at equilateral shapes."

Does the Gauss-Bonnet term stabilizes wormholes?

Takafumu Kokubu
Rikkyo University, Japan

The effect of the Gauss-Bonnet term on the existence and dynamical stability of thin-shell wormholes as negative tension branes is studied in the arbitrary dimensional spherically, planar, and hyperbolically symmetric spacetimes.

We consider radial perturbations against the shell for the solutions which have the Z_2 symmetry and admit the general relativistic limit.

It is shown that the Gauss-Bonnet term shrinks the parameter region admitting static wormholes.

The effect of the Gauss-Bonnet term on the stability depends on the spacetime symmetry.

For planar symmetric wormholes, the Gauss-Bonnet term does not affect their stability.

If the coupling constant is positive but small, the Gauss-Bonnet term tends to destabilize spherically symmetric wormholes, while it stabilizes hypebolically symmetric wormholes.

The Gauss-Bonnet term can destabilize hypebolically symmetric wormholes as a non-perturbative effect, however, spherically symmetric wormholes cannot be stable.

Parametrized post-Newtonian plus Yukawa (PPNY) approximation of nonminimally coupled gravity

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We consider a nonminimally coupled (NMC) curvature-matter model of gravity. The action functional involves two functions f$\hat{1}$(R)and f$\hat{2}$(R) of spacetime curvature R. The function f$\hat{1}$(R) is a nonlinear term in the action, analogous to f(R) gravity, and the function f$\hat{2}$(R) yields a NMC between the matter Lagrangian density and curvature R.

The model admits Minkowski spacetime as a background, and we derive the 1/c expansion of the metric assuming the functions f$\hat{1}$ and f$\hat{2}$ analytic at R=0. To compute the 00 component of the metric tensor up to order O(1c$\hat{4}$), we take into account up to cubic terms in the Taylor expansion of f$\hat{1}$(R), and quadratic terms in the expansion of f$\hat{2}$(R).

We consider a general distribution of matter with mass density, pressure and velocity. The nonrelativistic limit of the model is not Newtonian, but contains a Yukawa correction. We compute a parametrized post-Newtonian plus Yukawa (PPNY) approximation of the NMC model of gravity. Extra potentials are present that are not accounted for in the usual PPN formalism.

For applications on the scale of Solar System, we compute the metric around a static, spherically symmetric body. We look for trajectories of a test body around the

spherical body. Since in NMC gravity the energy-momentum tensor of matter is not covariantly conserved, then the trajectories deviate from geodesics. We compute the perihelion precession of planets and we constrain the parameters (coefficients of the power expansions of f1̂ and f2̂) of the NMC gravity model from radar observations of Mercury.

Finding Horndeski theories with Einstein gravity limits

Ryan McManus
University of Edinburgh, United Kingdom

Many scalar tensor gravity theories rely on screening mechanisms to pass local tests of gravity, which put tight restrictions on deviations from Einsteinś gravity. These screening mechanisms are non-linear self interactions which dominate near massive sources, suppressing modifications to gravity. To find predictions of such theories in the Newtonian limit, linearising the equations of motion is not sufficient in screened regions, thus making these theories hard to test. We present a new method for finding an expansion for scales where non-linear terms dominate by considering formal limits of the coefficients in the theory, a field expansion and a simple counting argument. A demonstration of its effectiveness for both a cubic galileon and a chameleon model is presented. Our method is used to find conditions to judge quickly whether a gravity theory from the Horndeski action contains an Einstein gravity limit.

Testing scalar-tensor theories of gravity with highly compact neutron stars

Raissa Mendes
University of Guelph, Canada

Scalar-tensor theories of gravity are extensions of General Relativity including an extra, non-minimally coupled scalar degree of freedom. A wide class of these theories, albeit indistinguishable from GR in the weak field regime, can predict a radically different phenomenology for neutron stars, due to the existence of a non-perturbative, strong-field effect referred to as spontaneous scalarization. This effect is known to occur for theories where the linear effective coupling β between the scalar and matter fields is sufficiently negative, i.e. $\beta \lesssim -4.35$, and has been strongly constrained by pulsar timing observations. In this talk, I discuss the possibility of testing scalar-tensor theories in the highly unconstrained region of coupling functions with $\beta > 0$, based on the fact that sufficiently compact neutron stars would be subject to a tachyonic-like instability according to these theories. In the case of $\beta < 0$, this instability is understood to be simply the test-field-limit manifestation of spontaneous scalarization; however, in the $\beta > 0$ case it can lead to different outcomes. I will discuss the equation of state dependence of this instability, its possible end-states and observational signatures. [1] R. F. P. Mendes, ”Possibility of setting a new constraint to scalar-tensor theories”, Phys. Rev. D **91**, 064024 (2015). [2] R. F. P. Mendes and N. Ortiz, in preparation.

Non-relativistic fields on curved backgrounds and their applications

Arpita Mitra

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Motivated by recent applications of non-relativistic field theories on curved spacetimes, we investigate the minimal coupling of massive matter fields to curved non-relativistic backgrounds. Unlike relativistic curved backgrounds, general covariance in the non-relativistic context requires careful consideration due to the absolute nature of Newtonian time. We have derived the coupling of fields by localizing the global spacetime symmetries of the matter action on the Euclidean background. The advantage of using this procedure is the simultaneous emergence of the curved background as well as the coupling of matter to it. The new fields introduced during the localization of the Galilean symmetry can be identified with the tetrads and spin connection of the Newton-Cartan spacetime, which is well known as the non-relativistic limit of the Riemann-Cartan spacetime. Further inclusion of the anisotropic scale transformation in the localization procedure gives the Weyl-rescaled Newton-Cartan geometry. These backgrounds possess two degenerate metrics as a direct consequence of the unequal footing of time and space. It will be of interest to study how these two metrics affect the dynamics of fields coupled to them. This will be illustrated through two specific applications - the thermodynamic description of ideal incompressible fluids on the Weyl-rescaled Newton-Cartan background, and the gravitational anomalies of the Schrodinger field theory on the Newton-Cartan background. In both cases, key differences with the analogous relativistic results are highlighted.

The Equivalence Principle in the Dark Sector

Neo Mohapi

Rhodes University, South Africa

The Einstein Equivalence Principle (EEP) is a fundamental principle of the theory of General Relativity. While the EEP has been thoroughly tested with standard matter, the question of its validity in the Dark sector remains open. In this talk we will discuss the constraints of the EEP in the Dark sector. We will place particular emphasis on galactic observations as they are considered good candidates to constrain an EEP violation in the Dark sector. Finally, we will discuss our ongoing work on the implications of a violation of the EEP within the framework of a general tensor-scalar theory with two different conformal couplings to standard matter and to Dark matter.

Scalar Gravitational Waves

Emil Mottola

Los Alamos National Laboratory, USA

General Relativity receives quantum corrections relevant at macroscopic distance scales and near event horizons. These arise from the conformal scalar degree of freedom in the extended effective field theory (EFT) of gravity generated by the trace anomaly of massless quantum fields in curved space. Linearized around flat space this quantum scalar degree of freedom combines with the conformal part of the metric and predicts the existence of scalar spin-0 “breather” propagating gravitational waves in addition to the transverse tensor spin-2 waves of classical General Relativity. Estimates of the expected strength of scalar gravitational radiation from compact astrophysical sources and the possibilities for their detection by LIGO and the new generation of gravitational wave detectors will be discussed.”

On Dirac Equation and Angular Momentum of Axially Symmetric of Rotating Neutron Stars in the Teleparallel Gravity

Mohamed Mourad

Minia University, Egypt

In this paper, we re interested in studying the teleparallel version of axially symmetric, uniformly rotating spacetime for two different sets of tetrad fields. For these sets, we obtained the expressions for the torsion vector, torsion axial-vector and the angular momentum in stationary axisymmetric space-time solutions. We found that the obtained expressions of torsion axial-vector and the angular momentum are, in general quite different in both two sets of tetrad fields. In addition, when the functions of the space time are only dependent of r or z, the torsion vectors vanish only in r or z direction while axial-vectors vanish only on z or r direction respectively. Finally, the vector part connected with Dirac spin which has been evaluated as well.

Quasi-Static Solutions for Compact Objects in Chameleon Models

Ilia Musco

Laboratoire Univers et Thories (LUTH), Observatoire de Paris

It has been suggested that a scalar field non-minimally coupled to matter could be responsible for the observed accelerated expansion of the Universe. However, the fact that we are able to measure its effect only on cosmological scales but not on local ones, such as that of our solar system, might be the consequence of a screening mechanism. This is the essence of the Chameleon model. Understanding its viability requires solving the field equations in the transition regime where the scalar field transitions from a region of high density to the outer region where it plays the role of the Dark Energy. In this work we analyze quasi-static spherically symmetric solutions for objects such as standard stars and more compact objects like white dwarfs and neutron stars, by solving the Tolman-Oppenheimer-Volkoff equations coupled with the Klein-Gordon equation in a quasi static regime. We derive a solution that takes into account the background expansion without needing to introduce an artificial cosmic matter corresponding to a non-spatially flat metric. The interior of the star is characterized using a constant density (incompressible) model and a more realistic polytropic equation of state. The increase of compactness that we observe in case of a good screening (thin shell) allows to put serious constraints on the Chameleon mechanism and its viability using astrophysical compact objects.

Gravitational scalar-tensor theory

Atsushi Naruko

Tokyo Institute of Technology, Japan

We consider a new form of theories of gravity in which the action is written in terms of the Ricci scalar and its first and second derivatives. Despite the higher derivative nature of the action, the theory is free from ghost under an appropriate choice of the functional form of the Lagrangian. This model possesses 2 + 2 physical degrees of freedom, namely 2 scalar degrees and 2 tensor degrees. We also discuss the correspondence between these theories and generalized bi-Galileon theories.

Growing tensor perturbations on super horizon scales in Generalized Galilean Genesis

Sakine Nishi

Rikkyo University, Japan

Galilean genesis is an alternative to inflation, in which the universe starts expanding from Minkowski space-time with the stable violation of the null energy condition. We have constructed the generalized model of Galilean genesis, and we discussed the behaviour of background and perturbations in our previous study. In recently days, It has been discussed that Galilean genesis can be expanded so that the tensor perturbations grow on super horizon scale. By introducing extra parameter and terms in the genesis Lagrangian, we study the dynamics of perturbations in the general case and discuss how extra parameter and terms effect on the perturbations. After this discussion we take in account of the possibility that we can add more extra terms in genesis Lagrangian, and we consider the extended genesis model in GLPV scalar-tensor theory in ADM formalism.

Black Holes and Abelian Symmetry Breaking

Gustavo Niz

University of Guanajuato, Mexico

I examine exact black hole configurations in vector-tensor theories, originally proposed to explain dark energy by breaking the Abelian symmetry with a non-minimal coupling of the vector to gravity. The solutions evade the no-go theorems by Bekenstein on the existence of regular black holes in vector-tensor theories with Proca mass terms, and exhibit regular black hole solutions with a profile for the longitudinal vector polarization, characterised by an additional charge. I discuss the inclusion of a cosmological constant or having slow-rotation, and generalise these solutions to higher dimensions.

Instability of hairy black holes in shift-symmetric Horndeski theories

Hiromu Ogawa

Rikkyo University, Japan

Recently it was pointed out that in shift-symmetric scalar-tensor theories a black hole can have nontrivial scalar hair which depends linearly on time.

We develop black hole perturbation theory for such solutions and compute the quadratic action of odd-parity perturbations.

We show that around all the solutions known so far with such time-dependent scalar hair the perturbations trigger instabilities or are presumably strongly coupled.

Nestor Ortiz: Perimeter Institute for Theoretical Physics, Canada

Spontaneous scalarization of neutron stars in the unconstrained parameter regime of scalar-tensor theories

We use numerical simulations in order to study the evolution of neutron stars in the context of scalar-tensor theories of gravity, in the yet unconstrained parameter regime of
$beta_0 > 0$, where
$beta_0$ measures the linear effective coupling between the scalar field and regular matter. We focus on initial data corresponding to equilibrium configurations possessing unstable scalar modes, and investigate the nonlinear development of this instability for some representative coupling functions with
$beta_0 > 0$. We find that, contrary to the well-understood
$beta_0 < 0$ case, the final state of the instability is highly sensitive to the details of the coupling function, varying from gravitational collapse to spontaneous scalarization. In particular, this is the first demonstration of spontaneous scalarization in the case of
$beta_0 > 0$, which could give rise to novel astrophysical tests for this theories.

Einstein-Cartan Relativity in a 2-dimensional Non-Riemannian Space

D. Phadatare

Balasaheb Desai College Patan, Karad, Dist: Satara, Maharashtra, India

We describe the Einstein-Cartan theory of gravity in a 2- dimensional non-Riemannian space. To explore the implications and features of Einstein-Cartan field equations in a 2-dimensional non-Riemannian space, we introduce a formalism consisting of two real null vector fields. We here after referred to it as a dyad formalism. This formalism facilitates the computational complexity and will serve as an instructional tool to simplify mathematics. The results are derived by two different methods one based on the dyad formalism and one based on the techniques of differential forms introduced by the author by introducing a new derivative operator d_* defined with respect to the asymmetric connections. Both the methods will serve as an "amazingly useful" techniques to reduce the complexity of mathematics. We have proved that the Einstein tensor vanishes identically yet the Riemann Curvature of the non-Riemannian 2- space is shown to be functions of coordinates and involves the torsion terms.

Self gravitating medium and modified gravity

Luigi Pilo
University of L'Aquila and LNGS INFN, Italy

The effective field theory that describes the low-energy physics of self-gravitating media is formulated in terms of four derivatively coupled scalar fields that can be identified with the internal comoving coordinates of the medium. Imposing SO(3) internal spatial invariance, the theory describes supersolids. Stronger symmetry requirements lead to superfluids, solids and perfect fluids, at lowest order in derivatives. In the unitary gauge, massive gravity emerges, being thus the result of a continuous medium propagating in spacetime. Our results can be used to explore systematically the effects and signatures of modifying gravity consistently at large distances. The dark sector is then described as a self-gravitating medium with dynamical and thermodynamic properties dictated by internal symmetries. These results indicate that the divide between dark energy and modified gravity, at large distance scales, is simply a gauge choice.

Universal metrics - exact solutions to all theories of gravity

Alena Pravdova
Institute of Mathematics of the Czech Academy of Sciences, Czech Republic

Universal metrics are exact vacuum solutions to all theories of gravity with the Lagrangian constructed from the metric, the Riemann tensor and its covariant derivatives of arbitrary order. Many of these metrics represent gravitational waves propagating e.g. on flat, (A)dS or (anti-)Nariai backgrounds.

We will discuss various classes of universal metrics and related classes of metrics solving only specific field equations (e.g. Lovelock gravity or quadratic gravity).

While for type N and III, universal metrics exist in arbitrary dimension, we will show that type II universal metrics do not exist

in five dimensions. However, we will provide explicit examples of type II universal metrics in arbitrary composite number dimensions.

Ref: S. Hervik, T. Malek, V. Pravda, A. Pravdova, Class. Quantum Grav. 32: 245012, 2015

Double layers in quadratic theories of gravity

Borja Reina

UPV/EHU, Spain

The junction conditions for the most general gravitational theory with a Lagrangian containing terms quadratic in the curvature are derived. We include the cases with a possible concentration of matter on the joining hypersurface, as well as the proper matching conditions where only finite jumps of the energy-momentum tensor are allowed. In the latter case we prove that the matching conditions are more demanding than in General Relativity. In the former case, we show that generically the shells/domain walls are of a new kind because they possess, in addition to the standard energy-momentum tensor, a double layer energy-momentum contribution which actually induces an external energy flux vector and an external scalar pressure/tension on the shell. We prove that all these contributions are necessary to make the entire energy-momentum tensor divergence-free, and we present the field equations satisfied by these energy-momentum quantities. The consequences of all these results are briefly analyzed.

Supernova core collapse in scalar-tensor theory with massive fields

Roxana Rosca

DAMTP, University of Cambridge, United Kingdom

Though General Relativity has been successfully tested so far, concepts such as dark matter and string theory suggest the need of modifying it. Scalar-tensor theory is one of the most popular alternatives discussed. The key reason for looking at the ones with massive fields is that they are barely constrained by binary pulsar observations, in contrast to the massless case (Ramazano and Pretorius 2016). We study supernova core collapse in spherical symmetry generalizing the massless code of Gerosa et all 2016 to the massive case. We discuss the impact of the mass of the scalar on the collapse dynamics and wave emission by comparison with the GR and massless ST cases.

Newton Chern–Simons Cosmology

Gustavo Rubio
Universidad de Concepcin, Chile

Recently [arXiv: 1604.06313], was shown that is possible to obtain the nonrelativistic versions of the generalized Poincar algebras and of generalized AdS?Lorentz algebras. This algebras leads to a Chern?Simons lagrangian which coincides with the Einstein?Hilbert lagrangian in a certain limit, even if the new gauge field vanishes and therefore leads to newtonian gravity in the nonrelativistic limit. The nonrelativistic algebras are called, generalized Galilean algebras type I and type II. On other hand, was shown that the nonrelativistic limit of the five dimensional Einstein?Chern?Simons gravity the called Newton Chern–Simons gravity obtained from the Newton?Hooke algebra for S-expansion [arXiv: 0606215] modifies the Poisson equation. The generalization of the Newton gravity obtained could be compatible with the effects of Dark Matter, which leads us to think that Dark Matter can be interpreted as a nonrelativistic limit of Dark Energy.

Scalar field and Cosmological constant in $f(R, T)$ gravity for Bianchi type-I Universe

Pradyumn Sahoo
Birla Institute of Technology and Science-Pilani, Hyderabad Campus, India

In this article, we have tried to analyse the behaviour of scalar field and cosmological constant in f(R,T) theory of gravity. Here we consider simplest form of $f(R, T)$ i.e $f(R, T) = R+2f(T)$ and explore the spatially homogeneous and anisotropic Locally Rotationally Symmetric (LRS) Bianchi type-I cosmological model. It is assumed that the universe is filled with two noninteracting matter sources, scalar field (normal or phantom) with scalar potential and matter contribution due to $f(R, T)$ action. We have discussed two cosmological models according to power law and exponential law along with constant and exponential scalar potential as submodels. Power law models is compatible with normal (quintessence) and phantom scalar field where as exponential models is compatible with only normal (quintessence) scalar field. Cosmological constant is in agreement with the observation from literature for our models. Finally we discussed some physical and kinematical properties of both the models.

Modified f(R) Gravity and Thermodynamics of Time-Dependent Wormholes at Event Horizon

Hamidreza Saiedi: Florida Atlantic University, USA

I

n the context of modified f(R)gravity theory, we study time-dependent wormhole spacetimes in the radiation background. In this framework, we attempt to generalize the thermodynamic properties of time-dependent wormholes in f(R) gravity. Finally, at event horizon, the rate of change of total entropy has been discussed.

AdS-Weyl algebra and gravity

Sebastian Salgado: Universidad de Concepcion, Chile

W

e propose a method to obtain differents subalgebras from an original Lie algebra. The basic idea consists in considering a splitting the original algebra in subspaces and then to carry out a reduction of one of subspaces using orthogonal rectangular matrices.

This method allows us to find a new Lie algebra which we call Weyl-AdS algebra which modifies the usual Weyl algebra through the addition of a cosmological constant.

We construct a representation of this algebra in terms of Dirac matrices in four and six dimensions. This representation is used to obtain three and five dimensional actions for Chern-Simons gravity theories. The dynamical consequences and their differences with the usual Weyl gravities are also studied. Sebastian Salgado: Universidad de Concepcion, Chile Extended gauge theories for (super)gravity

Recently, Antoniadis, Konitopoulos and Savvidy have introduced a procedure to construct background-free gauge invariants, using non-abelian gauge potentials described by forms of higher degree (arXiv:1401.4812). The construction is particularly useful because it can be used in both, odd- and even-dimensional spacetimes. Following these ideas, we introduce an alternative technique to construct a new kind of Lie algebras and superalgebras which in some cases contains the structure proposed by Savvidy. This allows us to formulate the Chern–Weil theorem in the new framework and construct a four dimensional Chern-Simons action for a supergravity theory.

Bootstrapping a Lorentz-violating gravity theory

Michael Seifert: Connecticut College, USA

T

he Standard Model Extension (SME) has proved to be a valuable framework for the investigation of possible Lorentz-violating phenomena. However, the gravitational sector of the SME contains a set of coefficients whose role is still unclear, and which may not in fact be physically meaningful. An attempt to "bootstrap" a Lorentz-violating gravity theory, by coupling a Lorentz-violating rank-2 tensor to its own stress-energy, might shed some light on the role of these coefficients. I will discuss how such a theory can be constructed, with particular attention to the implications of this construction for non-standard gravitational wave theories.

Anisotropic Universe in $f(R)$ Gravity

Muhammad Farasat Shamir

National University of Computer & Emerging Sciences, Pakistan

Modified theories of gravity have attracted much attention of the researchers in the recent years. In particular, the $f(R)$ theory has been investigated extensively due to important $f(R)$ gravity models in cosmological contexts. This paper is devoted to explore anisotropic universe in metric $f(R)$ gravity.

Locally rotationally symmetric Bianchi type I cosmological model is considered for this purpose. Exact solutions of modified field equations are obtained for a well-known

$f(R)$ gravity model. The energy conditions are also discussed for the model under consideration. The viability of the model is investigated via graphical analysis using the present day values of cosmological parameters.

Model satisfies null energy, weak energy and dominant energy conditions for a particular range of anisotropic parameter while the strong energy condition is violated which shows that anisotropic universe in $f(R)$ gravity supports the crucial issue of accelerated expansion of universe.

Numerical black holes and mergers in dynamical Chern-Simons gravity

Leo Stein: California Institute of Technology, USA

I

n order to test general relativity in the dynamical strong-field regime, we would like to have predictions of gravitational waves from black hole mergers in beyond-GR theories. This is complicated by the fact that most ćorrectionsĺack a well-posed initial value formulation. Nonetheless by using the decoupling limit (motivated by the EFT paradigm) we have a well-posed system and thus can simulate black holes and binary mergers for certain theories. We focus on dynamical Chern-Simons gravity (dCS) though our methods are generic, and thus applicable to a broad class of theories. These are the first simulations of black hole binaries in dCS and indeed any beyond-GR theory (save for scalar-tensor theory).

Reshaping the Dispersion of a Gravitational Wave

Rhondale Tso: California Institute of Technology, USA

W

hen testing General Relativity (GR) through gravitational wave (GW) detections, two approaches are often taken: 1) modifying the source dynamics to account for possible non-GR effects, 2) modifying the propagation and dispersive properties of the GW. Often one can disentangle one from the other and investigate each independently. Our work looks at a new generic modification to the dispersion of GWs, irrespective of the source, to account for parametrized corrections to GR. This new model-independent approach encapsulates all previous studies, including massive graviton and Lorentz violating theories, and provides hints at additional theories to be included, e.g., Chern-Simons. In this talk the added features will be discussed, including frequency dependent dissipation, preferred space directions coupled to dissipation, and adjustments to the polarization content of the gravitational waveform during its time of flight. Furthermore, an overview of projected constraints will be presented.

The spacetime between Einstein and Kaluza-Klein

Chris Vuille

Embry-Riddle Aeronautical University, USA

In this paper I use a subalgebra of tensor multinomials to create a generalization of Einstein?s theory of general relativity that in a mathematical sense falls between Einstein?s original theory of general relativity in four dimensions and the Kaluza-Klein theory in five dimensions. Scalar, vector, and tensor constraints make precise the difference between standard Kaluza-Klein and the in-between theory. In the extended theory there are only four physical dimensions, but tensor multinomials are involved rather than tensors, resulting in expanded operators with transformation properties distinct from five-dimensional general relativity. One advantage over the original Kaluza-Klein is that the electromagnetic fields transform as vectors, as they should. The equivalent Ricci tensor of this geometry yields vacuum general relativity and electromagnetism, as well as a Klein-Gordon-like quantum scalar field. With a generalization of the stress-energy tensor, an exact solution for a plane-symmetric dust can be found where the scalar portion of the field drives early universe inflation, levels off for a period, then causes a later, continued universal acceleration. That suggests that some version of this theory, together with an appropriate stress-energy, might explain some of the effects of the inflaton or dark energy.

Testing the Dark Universe

Amanda Weltman

University of Cape Town, South Africa

In this talk I will discuss alternative approaches to solving the dark matter and dark energy problems as well as novel ways to test these theories.

In an era of ever increasing precision in cosmology and particle physics experiments, we should be subjecting our theories to rigorous and complementary tests. I will focus in particular on chameleon gravity as well as macro dark matter as case studies.

Nonlocal Metric Realizations of MOND

Richard Woodard
University of Florida, USA

This is based on arXiv:1403.6763 and 1405.0393. We consider a class of nonlocal, pure-metric modified gravity models which were developed to reproduce the Tully-Fisher

relation without dark matter and without changing the amount of weak lensing predicted by general relativity. Previous work gave only the weak field limiting form of the field equations specialized to a static and spherically symmetric geometry. Here we derive the full field equations and specialize them to a homogeneous, isotropic and spatially flat geometry. We also discuss the problem of fitting the free function to reproduce the expansion history. Results are derived for models in which the MOND acceleration a_0 is a fundamental constant and for the more phenomenologically interesting case in which the MOND acceleration changes with the cosmological expansion rate.

Suppressing the primordial tensor amplitude without changing the scalar sector in quadratic curvature gravity

Kohji Yajima
Rikkyo University, Japan

We address the question of how one can modify the inflationary tensor spectrum without changing at all the successful predictions on the curvature perturbation. We show that this is indeed possible, and determine the two quadratic curvature corrections that are free from instabilities and affect only the tensor sector at the level of linear cosmological perturbations. Both of the two corrections can reduce the tensor amplitude, though one of them generates large non-Gaussianity of the curvature perturbation. It turns out that the other one corresponds to so-called Lorentz-violating Weyl gravity. In this latter case one can obtain as small as 65% of the standard tensor amplitude. Utilizing this effect we demonstrate that even power-law inflation can be within the 2? contour of the Planck results.

Constraint on ghost-free bigravity from Cherenkov radiation

Yashuo Yamashita
YTIP, Kyoto University, Japan

We investigate the gravitational Cherenkov radiation in a healthy branch of background solutions in the ghost-free bigravity model. In this model, because of the modification of dispersion relations, each polarization mode can possess subluminal phase velocities, and the gravitational Cherenkov radiation could be potentially emitted from a relativistic particle.

We derive conditions for the process of the gravitational Cherenkov radiation to occur and estimate the energy emission rate for each polarization mode. We found that the gravitational Cherenkov radiation emitted even from an ultrahigh energy cosmic ray is sufficiently suppressed for the gravitonś effective mass less than 100eV.

Dynamical instability and Cavity Evolution

Zeeshan Yousaf
University of the Punjab, Lahore, Pakistan

This paper explores dynamical instability of relativistic self-gravitating systems in modified gravity. For this purpose, I shall use perturbation scheme and then explore collapse equation from the dynamical equations. I shall then calculate instability constraints at both Newtonian and post-Newtonian approximations.

Derivation of the Gravitational Field Equations solely by First Quantization of the Relativistic Energy-Momentum Relation

Ramin Zahedi
Hokkaido University, Japan

Using a new primary algebraic axiomatic approach (presented in Ref. [1]: http://eprints.lib.hokudai.a https://inspirehep.net/record/1387680/; 2015) ? which has been formulated on the basis of ring theory and the generalized Clifford algebra ? by first quantization of the linearized (and simultaneous parameterized)forms of relativistic energy-momentum relation (as a mere special relativistic algebraic relation), a unique massive form of the gravitational field equations (with a complex torsion) is derived directly. It is shown that the massless case of these field equations is equivalent to the Einstein field equations (including a cosmological constant). Moreover, the geometric algebra formulation (via a symmetric matrix representation) of the derived gravitational field is presented. Alexander Zakharov: Institute of Theoretical and Experimental Physics, Russia Bounding the graviton mass with observations of S2 like stars near the Galactic Center Recently LIGO collaboration discovered gravitational waves (Abbott et al. 2016) predicted 100 years ago by A. Einstein. Moreover, in the key paper reporting about the discovery, the joint LIGO & VIRGO team presented an

upper limit on graviton mass such as $m_g < 1.2 \times 10^{-22} eV$ (Abbott et al. 2016). Since the graviton mass limit is so small the authors concluded that their observational data do not show violations of classical general relativity.

We consider another opportunity to evaluate a graviton mass from phenomenological consequences of massive gravity and show that an analysis of bright star trajectories could bound graviton mass with a comparable accuracy with accuracies reached with gravitational wave interferometers and expected with forthcoming pulsar timing observations for gravitational wave detection. It gives an opportunity to treat observations of bright stars near the Galactic Center as a wonderful tool not only for an evaluation specific parameters of the black hole but also to obtain constraints on the fundamental gravity law such as a modification of Newton gravity law in a weak field approximation. In particular, we obtain bounds on a graviton mass based on a potential reconstruction at the Galactic Center.

The Lambda_2 limit of massive gravity

Shuang-Yo Zhou
Case Western Reserve University, USA

Lorentz-invariant massive gravity is usually associated with a strong coupling scale Lambda_3. By including non-trivial effects from the Stueckelberg modes, we show that about these vacua, one can push the strong coupling scale to higher values and evade the linear vDVZ-discontinuity. For generic parameters of the theory and generic vacua for the Stueckelberg fields, the Lambda_2-decoupling limit of the theory is well-behaved and free of any ghost or gradient-like instabilities. We also discuss the implications for nonlinear sigma models with Lorentzian target spaces.

Session A4

Asymptotics with a positive cosmological constant

Beatrice Bonga

Penn State, USA

The framework that allows the study of isolated systems is well-developed for space-times with a vanishing cosmological constant
Lambda and it lies at the foundation of research in diverse areas in gravitational physics. The standard extension of this framework to space-times with a positive
Lambda fails for non-stationary space-times as there is no physically useful notion of conserved quantities. I will outline a new physically meaningful proposal and illustrate it by applying it to linearized gravity. In particular, I will discuss the quadrupole formula for gravitational radiation and its implications. This linear analysis provides a first step to study the errors one makes by assuming
$Lambda = 0$ when studying general relativistic gravitating systems.

A geometric characterisation of black hole spacetimes using Killing spinors

Michael Cole

Queen Mary University of London, United Kingdom

We investigate the implications of the existence of Killing spinors in spacetimes. We show that in vacuum and electrovacuum a Killing spinor can be used to characterise the Kerr and Kerr-Newman solutions respectively. Using the space spinor formalism, we find a set of spatial conditions on a spacelike Cauchy hypersurface which guarantee the existence of a Killing spinor on the resulting development. From these conditions, we construct a geometric invariant for the initial data set, which vanishes if and only if the initial data corresponds to data for the Kerr-Newman solution.

Parity-odd surface anomalies and correlation functions on conical defects

Maro Cvitan
Faculty of Science, University of Zagreb, Croatia

Using cohomology analysis we construct an expression for the most general parity-odd surface trace anomaly on a singular 2-dimensional surface in 4-dimensional spacetimes. When the singular surface is a conical defect we show that the bulk Pontryagin trace anomaly induces such a surface trace anomaly given purely by the outer curvature tensor. On two flat space examples we show that the surface contact terms appear in the energy-momentum tensor correlators of the lower rank than the corresponding bulk surface terms.

Using the generalised conformal field equations to study the ‘ringingóf a Schwarzschil black hole

Joerg Frauendiener
University of Otago, New Zealand

Friedrichś generalised conformal field equations are an ideal tool to access the asymptotic regions of a space-time. In this talk I will describe a setup which has allowed us to study the interaction of incoming gravitational waves with an (initially) static black hole. In particular, we have been able to extract the scattered gravitational waves on null-infinity and to compute the decay of the Bondi mass.

Conformal properties of the Schwarzschild-de Sitter spacetime

Edgar Gasperin Garcia
Queen Mary University Of London, United Kingdom

Conformal methods constitute a powerful tool for the global analysis of spacetimes, e.g., in the proof of the global non-linear stability of de Sitter and the semiglobal non-linear stability of the Minkowski spacetime. In this talk we will briefly discuss the conformal Einstein field equations and conformal Gaussian systems. In addition, we will discuss how to use this formalism to pose an asymptotic initial value problem (the initial hypersurface is the conformal boundary) and analyse non-linear perturbations close to the Schwarzschild-de Sitter spacetime in the asymptotic region. In particular, it will be shown that small enough perturbations of asymptotic initial data for the Schwarzschild de-Sitter spacetime give rise to a solution to the Einstein field equations which exists to the future and has an asymptotic structure similar to that of the Schwarzschild-de Sitter spacetime.

arXiv:1506.00030v2

Comparing transverse-traceless decompositions of symmetric tensors

Jeffrey Hazboun

Hendrix College, USA

The transverse-traceless (TT) components of symmetric tensors in three spacial dimensions are well known as carrying physically relevant information about the gravitational field. Finding these modes has been studied in the context of the initial value problem and linear perturbations, of which the most common application is gravitational waves. A number of distinct recipes for finding the TT part of a given symmetric tensor exist. These include various differential recipes that are true in general - but often cumbersome to solve explicitly - and an algebraic method that relies on a projection operator, which is computationally simpler but only applicable for plane waves.

Recent work by Ashtekar, Bonga and Kesavan has made it apparent that one needs to pay careful attention to linear perturbations in asymptotically de Sitter spacetimes since the $1/r$-expansion is not useful at a space-like $mathcal I^+$. There is little reason to expect, a priori, that the projection operator usually used to find the TT components of a tensor in asymptotically flat spaces will accurately characterize the physical degrees of freedom in an asymptotically de Sitter spacetime. We investigate this question by presenting solutions of the differential recipes for extracting the TT modes of a quadrupolar gravitational wave in asymptotically flat spacetimes, keeping the full dependence on retarded time. We will compare these solutions to those obtained by employing the projection operators. Finally we will discuss these results in the context of understanding the asymptotics of a spacetime with positive cosmological constant and using conformal methods to transform known solutions.

The conformally invariant wave equation near the cylinder at spacelike infinity

Joerg Hennig

University of Otago, New Zealand

We study the scalar, conformally invariant wave equation on a four-dimensional Minkowski or Schwarzschild background in spherical symmetry. This can be considered as a toy model for the conformal field equations. Even though the wave equation is a much simpler equation, it already mirrors important mathematical properties and difficulties of the general problem. Our main interest is in a suitable treatment of spatial infinity, which is represented as a cylinder. We solve the problem numerically with a fully pseudospectral scheme, in which spectral expansion with respect to space and time are used, and the solution is obtained at all grid points simultaneously. In the Minkowski case, this allows us to find highly accurate numerical solutions. For Schwarzschild, where logarithmic singularities form at the future boundary, we still obtain solutions of good accuracy. We also describe how initial data can be chosen that avoid the leading-order logarithmic terms, which further improves the numerical accuracy.

Conformal Wave Equations for the Einstein Trace-free Matter System

Adem Hursit

Queen Mary, University of London, United Kingdom

The Conformal Field Equations (CFEs) are a conformal representation of the Einstein Field Equations (EFEs). These equations imply a solution to the EFEs whenever the conformal factor is different from zero. We show that the CFEs coupled to a matter model with an energy momentum tensor of vanishing trace implies a system of wave equations for the conformal geometric fields. We also show that under very general assumptions on the matter model the solutions to these wave equations imply a solution to the CFEs (propagation of the constraints). We analyze in particular, the cases where the matter content is described the Maxwell equations, the Yang Mills fields and conformally invariant scalar fields.

Complexified MOTS-stability operator: an approach to the spectral problem

Jose Luis Jaramillo

Institut de Mathmatiques de Bourgogne (IMB), France

The reaction of a dynamical horizon,foliated by marginally outer trapped surfaces (MOTS), to an influx of radiation and matter is controlled by the so-called MOTS-stability operator. Having a qualitative insight into the spectrum of this elliptic non-self-adjoint operator may provide clues on generic properties of the MOTS-evolution, in particular at late times. In this context we conjecture that the MOTS-stability operator spectrum can be obtained from the stationary states of a quantum charged particle subject to magnetic and electric fields, by complexifying the corresponding electric charge. This is supported by the construction of a complex one-parameter family of elliptic operators containing both the MOTS-stability operator and the relevant quantum Hamiltonian. This approach would permit to recast the MOTS-spectral problem in terms of the analysis of a better understood self-adjoint operator.

New tensorial charge for BMS symmetries

Aruna Kesavan
The Pennsylvania State University, USA

Conservation laws of asymptotic symmetries are essential to quantify the amount of energy-momentum and angular momentum carried away by gravitational radiation from isolated systems. The asymptotic symmetry group of asymptotically flat spacetimes at null infinity is the Bondi-Metzner-Sachs (BMS) group. While the flux associated to an arbitrary BMS vector field was provided by Ashtekar and Streubel (1981) using symplectic methods, a corresponding tensorial expression for a two-dimensional charge integral linear in an arbitrary BMS vector field has not been available in the literature. We fill this gap by providing such a charge. I will discuss its properties and relation to Gerochś supermomentum and the charge of Dray and Streubel (1984).

Parametrized theories, making EM even gaugier

Juan Margalef
UC3M-CSIC, Spain

Parametrized field theories provide interesting examples of relatively simple diff-invariant systems, which can be then used as good toy models to understand some subtle features of General Relativity. In this talk, relying on the space of embeddings, I will explain some interesting aspects of the parametrized electromagnetic field, as it is one of the simplest models with gauge symmetries. In particular I will focus on how its primary constraint submanifold can be divided into sectors where different Hamiltonian dynamics take place, and show how the Gauss law comes into play (spoiler alert, it is not a constraint).

Conformal regularity and non-linear stability of spatially homogeneous spacetimes with a positive cosmological constant

Filipe Mena
University of Minho, Portugal

We investigate the stability of spatially homogeneous spacetimes with a positive cosmological constant by using and further developing geometric conformal methods in General Relativity. For a large class of source fields, including imperfect fluids, we prove that those spacetimes are globally conformally regular. We use that result in order to prove the non-linear stability of a Cauchy problem for Einstein-Maxwell-Yang-Mills systems as well as Einstein-radiation fluids. This provides a proof of the cosmic no-hair conjecture in these settings.

Conserved charges of the extended Bondi-Metzner-Sachs algebra

David Nichols

Cornell University, USA

In general relativity, the conserved charges associated with the Bondi-Metzner-Sachs (BMS) group characterize an isolated system. Specifically, these charges are the Bondi 4-momentum, the relativistic angular momentum, and an infinite number of supermomentum charges related to the supertranslation symmetries. There is a recent proposal that the BMS symmetry algebra should be enlarged to include an infinite number of additional symmetries known as superrotations. We compute the corresponding "super-center-of-mass" charges and show that they are finite and well defined in stationary regions of future null infinity. The supermomentum charges are associated with ordinary gravitational-wave memory, and the super-center-of-mass charges are associated with total (ordinary plus null) gravitational-wave memory, in the terminology of Bieri and Garfinkle. For black holes, these charges constitute a type of black-hole hair, as noted by Strominger and Zhiboedov. We point out how this hair evades the no-hair theorems.

Future stability of the FLRW fluid solutions with a positive cosmological constant

Todd Oliynyk

Monash University, Australia

In this talk, I will outline a new method for establishing the future non-linear stability of perturbations of FLRW solutions to the Einstein-Euler equations with a positive cosmological constant and a linear equation of state. The method is based on a conformal transformation of the Einstein-Euler equations that compactifies the time domain thereby reducing the global problem to a local one, albeit singular. I will discuss how a variation of the usual approach to establishing the local-in-time existence and uniqueness of solutions to symmetric hyperbolic systems can be used to obtain the existence and uniqueness of solutions to our local singular problem and obtain the asymptotic behaviour in the far future. Some advantages of the method over previous approaches are the conciseness of the resulting stability proof and the fact that the equation of state parameter values can be handled in a uniform manner. Due to the compactified time domain, I expect this method will also be useful for numerically simulating solutions globally to the future.

Characterization of (asymptotically) Kerr-de Sitter-like spacetimes at null infinity

Tim-Torben Paetz

University of Vienna, Austria

The Kerr-de Sitter spacetime, and related metrics such as the Kerr-NUT-de Sitter family, can be characterized, among vacuum spacetimes with positive cosmological constant admitting a Killing vector field, in terms of the vanishing of a suitable geometric tensor, the so-called Mars-Simon tensor. Based on this local characterization, the geometric data at null infinity corresponding to those spacetimes will be identified and analyzed. Particular attention will be devoted to those spacetimes which admit a conformally flat null infinity.

Along the way, a larger class of spacetimes, which we call "asymptotically Kerr-de Sitter-like" arises naturally, which will also be characterized in terms of asymptotic data at null infinity.

Center of Mass and spin for isolated sources of gravitational radiation

Gonzalo Damian Quiroga

Universidad Industrial de Santander, Colombia

We define the center of mass and spin of an isolated system in General Relativity. The resulting relationships between these variables and the total linear and angular momentum of the gravitational system are remarkably similar to their Newtonian counterparts, though only variables at the null boundary of an asymptotically flat spacetime are used for their definition. We also derive equations of motion linking their time evolution to the emitted gravitational radiation. The results are then compared to other approaches. In particular one obtains unexpected similarities as well as some differences with results obtained in the Post Newtonian literature. These equations of motion should be useful when describing the radiation emitted by compact sources such as coalescing binaries capable of producing gravitational kicks, supernovas, or scattering of compact objects.

The structure of spaces of null geodesics

George Sparling

University of Pittsburgh, USA

I will discuss aspects of the geometry of spaces of null geodesics, concentrating on the conformal and group theoretic structure of Penrose limits and their interpretation in terms of the constructs of twistor theory.

The conformal constraints as an evolution system

Jarrod Williams
QMUL, United Kingdom

The conformal constraints are the intrinsic equations implied by Friedrich?s conformal Einstein field equations on a spacelike hypersurface. Their solutions provide initial data for the conformal evolution equations. We show, using a 1+2 spinorial decomposition and introducing suitable gauge source functions, that the conformal constraints imply an evolution system on the hypersurface for which certain components of the Weyl tensor need to be prescribed as free data. Under suitable assumptions, this evolution system implies a solution to the full conformal constraint equations. We use this formulation of the conformal constraint equations to construct initial data describing perturbations of hyperboloidal data for the Schwarzschild spacetime.

Session B1

Life under a black sun

Pavel Bakala
Silesian University in Opava, Czech Republic

Life is dependent on the income of energy with low entropy and the disposal of energy with high entropy. On Earth, the low-entropy energy is provided by solar radiation and the high-entropy energy is disposed as infrared radiation emitted into the cold space. Here we turn the situation around and assume cosmic microwave background (CMB) radiation as the low-entropy source of energy for a planet orbiting a black hole into which the high-entropy energy is disposed. We estimate the power that can be produced by thermodynamic processes on such a planet, with a particular interest in planets orbiting a near-extreme Kerr black hole (as in the science fiction movie Interstellar). We show, that for exoplanets orbiting near ISCO of massive and fast rotating Kerr black hole, a interplay of gravitational and Doppler frequency shift significantly changes the CMB temperature map of the sky and allows to harvest enough power to drive life processes far from thermodynamic equilibrium. We used relativistic raytracing code LSDplus for a construction of the CMB temperature map in the frame of the exoplanet orbiting near-extreme Kerr black hole.

Discovering the QCD Axion with Black Holes and Gravitational Waves

Masha Baryakhtar
Perimeter Institute, Canada

Advanced LIGO was be the first experiment to detect gravitational waves. Through superradiance of stellar black holes, it may also be the first experiment to discover the QCD axion with decay constant above the GUT scale. When an axion's Compton wavelength is comparable to the size of a black hole, the axion binds to the black hole, forming a "gravitational atom." Through the superradiance process, the number of axions occupying the bound levels grows exponentially, extracting energy and angular momentum from the black hole. Axions transitioning between levels of the gravitational atom and axions annihilating to gravitons can produce observable gravitational wave signals. The signals are long-lasting, monochromatic, and can be distinguished from ordinary astrophysical sources. We estimate up to O(1) transition events at aLIGO for an axion between 10ˆ-11 and 10ˆ-10 eV and up to 10ˆ4 annihilation events for an axion between 10ˆ13 and 10ˆ11 eV. In the event of a null search, aLIGO can constrain the axion mass for a range of rapidly spinning black hole formation rates. Our projections for aLIGO are robust against perturbations from the black hole environment and account for our updated exclusion on the QCD axion of $6 * 10^{-13} eV < ma < 2 * 10^-11$ eV suggested by stellar black hole spin measurements. Further constraints on – or evidence of – a light axion will be achieved with upcoming measurements of black hole masses and spins in binary detections at aLIGO. Note: this is not a modification of gravity, but an addition of an extra particle to the Standard Model.

Astrophysical Mini-Disks during General Relativistic Black Hole Binary Inspiral

Dennis Bowen
Rochester Institute of Technology, USA

GW150914 represents the first direct detection of a black hole binary.

During galaxy mergers, as a result of dynamical friction (stars, gas, etc.) and gravitational slingshot, the supermassive black holes (SMBHs) from each galaxy will become gravitationally bound and eventually merge due to gravitational radiation.

It is expected that gas will form a circumbinary accretion disk around the SMBH binary that will persistently feed individual ?mini-disks? via dense streams out to their tidal truncation radii. We present simulations of SMBH binaries in this astrophysical environment during the general relativistic inspiral regime. We place particular emphasis on the dynamics of the individual ?mini-disks? where violent shocks via disk-disk and disk-stream interactions will likely produce intense electromagnetic emission. Signals emanating from the mini-disks will prove instrumental in direct detections of SMBH binaries with currently available observatories.

A model for testing strong gravity via X-ray reflection spectroscopy

Alejandro Cardenas
Fundacion Universitaria Konrad Lorenz/Fudan University, Columbia

Astrophysical black hole candidates are thought to be the Kerr black holes of general relativity. However, a direct observational evidence is still lacking. The X-ray radiation produced in the inner part of the accretion disk can be a powerful tool to test the Kerr nature of these objects. In this talk, we present a new model for testing the Kerr black hole hypothesis via X-ray reflection spectroscopy. We employ the formalism of the transfer function proposed by Cunningham 40 years ago, where the transfer function acts as an integration kernel and takes into account all the relativistic effects. We have developed a code to compute transfer functions in arbitrary stationary and axisymmetric spacetimes. These transfer functions are tabulated in FITS files and combined with XILLVER. The result is best model that we can have today for testing black hole candidates via X-ray reflection spectroscopy.

A new numerical approach to force-free electrodynamics

Frederico Carrasco
FaMAF-Universidad Nacional de Cordoba, IFEG-CONICET., Argentina

Force-Free Electrodynamics (FFE) is a non-linear system of equations modeling the evolution of the electromagnetic field, in the presence of a magnetically dominated relativistic plasma. This configuration arises on several astrophysical scenarios which represent exciting laboratories to understand physics in extreme regimes.

We present here a new numerical implementation of the FFE around a Kerr black hole, which reproduced standard results regarding jet formation and energy extraction by means of a truly stationary electromagnetic configuration.

The novelty of our approach is three-folded: (i) We use the ?multi-block? technique [1] to represent a domain with S^2
$timesR^+$ topology within a stable numerical scheme. (ii) We employ as evolution equations those arising from a covariant hyperbolization of the FFE system [2] (that we have developed using the generalized symmetric hyperbolic formalism of Geroch [3]). (iii) We implement stable and constraint-preserving boundary conditions, which represents an outer region given by a uniform magnetic field aligned/misaligned with the symmetry axis.

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Scotland , pages 19-60, 1996.

Equation of State of Strange Quark Matter with Density dependent B parameter in pseudo-spheroidal space-time with anisotropy

Pradip Kumar Chattopadhyay
Alipurduar College, India

A class of relativistic solutions for compact cold stars with strange matter in a pseudo-spheroidal space-time is presented here. Considering strange matter equation of state namely, $p =$
$frac13($
$rho - 4B)$, where
rho, p and B are energy density, pressure and MIT Bag parameter respectively, stellar models are obtained. In the presence of anisotropy with a pseudo-spheroidal geometry described by Vaidya-Tikekar metric stellar models are explored, where the Bag parameter varies with the energy density (
rho) inside the compact object. We determine the density dependence of B for

different anisotropy including isotropic case. It is noted that although B varies with anisotropy inside the star, finally at the surface it attains a value which is independent of the anisotropy. The Bag parameter B is found to increase with an increase in anisotropy for a given compactness factor (M/b) and spheroidicity (
lambda). It is also noted that for a star with given mass and radius, the parameter B increases with the increase of
lambda and finally at large value of
lambda it attains a constant value. We note that in this model equation of state (EoS) obtained from geometrical consideration with allowable value of ?B? is similar to that obtained by earlier investigators from consideration of micro-physics. The stability of the stellar models for compact stars with anisotropy in hydro-static equilibrium is also studied.

Maximum Mass of Relativistic Star in Higher Dimensions in presence of Anisotropy

Pradip Kumar Chattopadhyay

Alipurduar College, India

A class of relativistic solutions of cold compact anisotropic stars in hydro-static equilibrium in the framework of higher dimensions using spheroidal geometry is investigated in this paper. The solutions obtained with Vaidya-Tikekar metric are used to construct stellar models of compact objects and studied their physical features. The effects of anisotropy and extra dimensions on the global properties namely, compactness, mass, radius, equation of state are determined in terms of the spheroidicity parameter (
lambda). It is noted that for a given configuration, compactness of a star is found smaller in higher dimensions compared to that in four space-time dimensions. It is also noted that the maximum mass of compact objects increases with the increase of space-time dimensions (D) which however attains a maximum value when D = 5 for any spheroidicity parameter (
lambda), thereafter it decreases as one increases the number of extra dimensions (D). The effect of extra dimensions on anisotropy is also studied.

CAF relativistic astrophysics code

Alejandro Cruz

Universidad Nacional Autnoma de Mxico, Mxico

We present CAFE, a code designed to solve the equations of relativistic ideal magnetohydrodynamics (RMHD) in three cartesian dimensions. We present the standard tests for the relativistic RMHD regime. The tests include among the 2D and 3D tests with magnetic field. The code uses high-resolution shock-capturing methods, and we present the error analysis for a combination that uses the Harten, Lax, van Leer, and Einfeldt flux formula combined with a linear, PPM and WENO5 reconstructors. We use the flux-constrained transport and the divergence cleaning methods to control the divergence-free magnetic field constraint.

Lensing by boson stars and shadows of Kerr black holes with scalar hair

Pedro V.P. Cunha

Aviero University & IST Lisbon, Portugal

Kerr BHs, which are BHs with rotation, are presently the most ?standard? Black Hole (BH) solutions, and possibly also the most realistic ones. However, in order to provide alternative shadow templates for upcoming astronomical observations, namely for the observation of the supermassive BH candidate Sgr A* in the center of our galaxy by the Event Horizon Telescope, it is timely to also consider different types of solutions. Hence, a novel class of BHs in equilibrium with a massive scalar field, Kerr BHs with scalar hair, was considered. This class exhibits intriguing properties, some of which are shadows that differ significantly from the Kerr prediction. For an observer, a shadow is a BH?s apparent shape in the sky due to gravitational lensing of nearby radiation, emitted by an external source. It was discovered that these ?hairy? BHs possess smaller shadows than the corresponding Kerr BHs. Additionally, under some conditions novel exotic shadow shapes can arise. Thus, hairy BHs could potentially provide new shadow templates for the aforementioned experiments. These hairy BH solutions are also continuously connected to Boson Stars, described by the massive Klein-Gordon equation in curved space-time. Thus, the gravitational lensing of the latter is of especial interest to understand the new shadow shapes of the hairy BHs.

Gravitational waves from pulsars with measured braking index

Jose de Araujo

Instituto Nacional de Pesquisas Espaciais, Brazil

We study the putative emission of gravitational waves (GWs) in particular for pulsars with measured braking index. We show that the appropriate combination of both GW emission and magnetic dipole brakes can naturally explain the measured braking index, when the surface magnetic field and the angle between the magnetic dipole and rotation axes are time dependent. Then we discuss the detectability of these very pulsars by aLIGO and the Einstein Telescope.

A Task-based Discontinuous Galerkin Code for Solving Multiphysics Problems in General Relativity

Scott Field

Cornell University, USA

Multi-messenger observations of the merger of compact binary coalescences with matter and of supernova explosions will probe fundamental physics. Modeling these systems requires a relativistic treatment of hydrodynamics, including magnetic fields, as well as neutrino transport and nuclear reactions. The accuracy, efficiency, and robustness of current codes that treat all of these problems is not sufficient to keep up with the observational needs. We are building a new computational framework that uses a Discontinuous Galerkin method together with a task-based parallelization strategy, a promising combination that will allow multiphysics applications to be treated both accurately and efficiently on petascale and exascale machines. The code scales to more than 100,000 cores allowing for high-fidelity simulations and efficient exploration of the parameter space of potential sources and allowed physics. I will discuss the current status of the development of this new code as well as first applications.

Can magnetic-field windup kill the r-mode instability of neutron stars?

John Friedman
University of Wisconsin-Milwaukee, USA

AUTHORS: John Friedman, Lee Lindblom, Luciano Rezzolla

At second order in perturbation theory, the unstable r-mode of a rotating star includes growing differential rotation whose form and growth rate are determined by gravitational radiation reaction. With no magnetic field, the angular velocity of a fluid element grows exponentially until the mode reaches its nonlinear saturation amplitude and remains nonzero after saturation. With a background magnetic field, the differential rotation winds up and amplifies the field, and previous work suggests that the amplification may damp out the instability. A background magnetic field, however, turns the time-independent perturbations corresponding to adding differential rotation into perturbations whose characteristic frequencies are of order the Alfven frequency. We argue that magnetic field growth stops soon after the mode reaches its saturation amplitude. We show that this is the case for a toy model, where magnetic amplification for small saturation amplitude is too small to damp the r-mode. For a more realistic model of a cold, rotating neutron star, an analogous upper limit depends on the assumption that there are no marginally unstable perturbations.

Statistical ensembles of Schwarzschild black holes and weak gravitational lensing

Hossein Ghaffarnejad
Semnan University, Iran

According to the ideas presented by Chevalier et al [Physica A 376 (2007), 293-307] we use mean metric of Schwarzschild black holes ensembles to study weak gravitational lensing of bending lights rays. Mean metric is obtained through exact computations of energy distribution of the black holes ensembles. We study physical effects of the ensembles parameter of the mean metric on deflection angle of bending light rays, locations of non-relativistic images and their magnifications. Our method which is used in this work will be perturbation method. Averaging on metrics of the black hole ensembles causes to change the corresponding photon sphere radius and so this will be affect on the images positions and other gravitational lensing parameters as deflection angle and magnifications.

Twin peak QPOs: modulation of accretion disc and boundary layer radiation by oscillating cusp torus

Katerina Goluchova

Research Centre for Computational Physics and Data Processing, Institute of Physics, Faculty of Philosophy and Science, Silesian University in Opava, Czech Republic

Serious effort has been devoted to explain the observed frequencies of twin-peak quasi-periodic oscillations (QPOs) observed in low-mass X-ray neutron star binaries. We propose a new model of high-frequency QPOs. We consider an oscillating torus with cusp that changes location of its centre around radii very close to innermost stable circular orbit. The observed variability is assigned to global modes of accreted fluid motion that may give strong modulation of both accretion disc radiation and the accretion rate. For a given spacetime geometry, the model predicts that QPO frequencies are functions of a single parameter. We illustrate that the model can provide fits of data comparable to those reached by other models, or even better. Moreover, we show that the model consideration is compatible with the consideration of models of a rotating neutron star in the atoll source 4U 1636-53.

ISCO frequencies for rotating neutron stars - simple and accurate formulae

Katerina Goluchova

Research Centre for Computational Physics and Data Processing, Institute of Physics, Faculty of Philosophy and Science, Silesian University in Opava, Czech Republic

Keplerian frequency at the innermost stable circular orbit (ISCO frequency) has been within several astrophysical studies frequently assumed as the characteristic orbital frequency. For simplicity, the relativistic formula linear in neutron star angular momentum is often considered when expressing its value for a rotating neutron star. The ISCO frequency however depends on the interplay between strong gravity effects and effects given by neutron starś oblateness. Consequently, for a given neutron star mass and equation of state this frequency may increase as well as decrease when the spin and angular momentum of the star increase. We present simple fitting quadratic formulae for the ISCO frequency. We further present formulae based on universal neutron star relations.

Friction forces: formulation and applications in general relativity

Daniele Gregoris

Dalhousie University, Canada

In this talk I will derive a manifestly covariant expression for a friction force in general relativity applying the formalism of Poynting and Robertson. I will show that it reduces to the Stokesformula as a limit in the non-relativistic regime. Astrophysical applications to the motion of massive test particles inside a photon gas and massive gas clouds respectively undergoing frictional effects are discussed emphasizing differences with the pure geodesic case. Finally a cosmological application to the modelling of peculiar velocities within this framework is discussed. The talk is based mainly on four papers by Bini, Geralico, Gregoris, Succi on EPL 2012, GRG 2012, CQG 2013, EPJC 2013.

Relativistic Hydrodynamics in the Context of the Hadron-Quark Phase Transition in Compact Stars

Matthias Hanauske

Goethe University Frankfurt / Frankfurt Institute for Advanced Studies, Germany

The properties of compact stars are mainly determined by two fundamental forces: Quantum chromodynamics (QCD) and general relativity. Relativistic hydrodynamical simulations of collapsing neutron stars and binary neutron star mergers depend strongly on the high density properties of the equation of state (EoS) of hadronic and quark matter. The emergence of the QCD - phase transition (the transition

from confined hadronic to deconfined quark matter) will change the properties of neutron stars. The appearance of a disconnected mass-radius relation emerging from a hybrid star model implies the existence of a third family of compact stars, so called twin stars. Usually it is assumed that the loss of stability of a neutron star, exceeding its maximum mass, leads to the collapse into a black hole. However, realistic calculations within QCD-motivated models show that a neutron star collapse could be, at first, stopped before the black hole forms. Within such a collapse scenario the neutron star would be transformed into a hybrid star with a deconfined quark matter phase at its inner core. Several astrophysical observables of the Quark-Gluon-Plasma will be discussed during the talk. Whether these observables will be visible with telescopes and gravitational wave detectors depends strongly on the EoS and on the order and construction of the phase transition.

Correspondence between sonic points of ideal photon gas accretion and photon spheres

Tomohiro Harada
Rikkyo University, Japan

In an accretion of fluid, its velocity may transit from subsonic to supersonic. The point at which such transition occurs is called sonic point and often mathematically special. We consider a steady-state and spherically symmetric accretion problem of ideal photon gas in general static spherically symmetric spacetime neglecting back reaction. We prove exact correspondence between its sonic point and the photon sphere of the spacetime. We also prove that this correspondence holds for spacetimes of arbitrary dimensions. We discuss the physical implications of this result.

Relativistic burning on neutron stars

Alice Harpole
University of Southampton, United Kingdom

Type I X-ray bursts are thermonuclear deflagrations which begin in a localised region in the ocean of an accreting neutron star, before rapidly spreading across the entire surface. The strong gravitational field on the surface of the neutron star means general relativistic effects will affect the propagation of this burning front. As the front propagates at a speed much less than the acoustic speed in the ocean, an approximation that filters out acoustic waves will give considerable computational speed up when modelling the system. We have extended the Low Mach Number Approximation to the general relativistic case, in a way that naturally builds on the approach successfully used in the Newtonian limit to model X-ray bursts, white dwarf burning and core convection in massive stars. We will also present numerical simulations of relativistic burning in a segment of the neutron star ocean using this relativistic Low Mach approximation, and discuss potential applications to other astrophysical systems.

Modelling gravitational wave emission from LMXBs

Brynmor Haskell
Nicholas Copernicus Astronomical Center, Poland

Rapidly rotating neutron stars in Low Mass X-ray Binaries are promising sources of gravitational radiation, and the next detection challenge now that ground based detectors have proved their capabilities. I will discuss the detection prospects of the most promising emission scenarios, including crustal and magnetic mountains. I will then focus on the r-mode instability in particular; review how electromagnetic observations can guide our theoretical understanding of the different possible emission scenarios and discuss the contribution of these sources to the astrophysical gravitational wave stochastic background.

Beyond ideal MHD: resistive, reactive and relativistic plasmas

Ian Hawke

University of Southampton, United Kingdom

The relativistic MHD approximation has been widely employed in global general-relativistic simulations of neutron stars, black hole accretion, and other strong field problems. However, the effects of plasma inertia, resistivity and/or interactions between particle species have been largely neglected in the majority of these works. These effects could be extremely important around neutron stars and black holes, especially in their magnetosphere where particles can accelerate to relativistic speeds. Whilst the ideal-MHD approximation fails to address these issues, employing a resistive-MHD set of equations brings the additional burden of having to choose a suitable Ohm?s law. We have extended the MHD framework in general relativity to include plasma inertial effects and particle species interactions through reaction and scattering processes. The additional microphysics, incorporated in this novel formulation of the equations describing the phenomena in general relativity, can lead to instabilities essential for particle acceleration in compact-object magnetospheres. We have investigated a class of such possibilities by performing local simulations of a charged multi-fluid plasma with a new code implementing a reduced set of equations in our formalism. In addition to presenting a detailed set of numerical tests, we discuss the implications of the formalism for the accuracy of GRMHD simulations of neutron stars.

Viewing the shadow of a black hole through a magnetized plasma

Anslyn John

Stellenbosch University, South Africa

We determine the effects of a magnetized plasma on the shadow of a black hole. The shadow of a Schwarzschild black hole is a circular disk corresponding to the radius of its photon sphere viz $r = 3M$. An observer infers a shadow?s angular diameter as a function of the black hole?s mass and its radial distance. Astrophysical black holes, however, are not observed in a vacuum but invariably inhabit an environment consisting of plasma. Since a plasma is a dispersive and refractive medium the radius of a shadow will be frequency-dependent. We extend recent results on plasma effects on shadow measurements by incorporating magnetic fields. We determine the equation of motion for light rays, photon deflection angle, radii of photon spheres and the angular size of the shadow. Given the presence of a large magnetic field around Sag A* these results will be useful in efforts to resolve its shadow using very long baseline interferometry.

Accretion of gaseous clumps from the Galactic Centre Mini-spiral onto Milky Way?s supermassive black hole

Vladimir Karas

Astronomical Institute, Czech Academy of Sciences, Czech Republic

Evidence for reflection of X-rays on molecular clouds in the vicinity of Sagittarius A* super-massive black hole (Sgr A* SMBH) suggests that the center of Galaxy was active in its recent history. We investigate the idea of gaseous Mini-spiral pattern as the origin of material triggering this enhanced activity. Collisions between clumps of gas in the Mini-spiral can reduce their angular momentum and set some of the clumps on a plunging trajectory towards Sgr A* SMBH. It turns out that the amount of material in the Mini-spiral region is sufficient to sustain the required level of luminosity. We examine a possibility of Thermal Instability onset to describe the mechanism for elevated accretion during the past period. Our contribution extends a recent paper (Rozanska et al., Astronomy and Astrophysics, vol. 581, id. A64, 2015; arXiv:1507.01798) by including the effect of the Nuclear Star Cluster, which provides additional important contribution to the energy balance of the inter-stellar medium.

Ionized particles around Kerr black holes in the presence of uniform magnetic field

Martin Kolo

Institute of Physics and Research Centre of Theoretical Physics and Astrophysics, Silesian University in Opava, Czech Republic

We study the dynamics of the charged test particles in the vicinity of a black hole immersed into an asymptotically uniform magnetic field. Ionization of test particles forming a neutral accretion disc, can lead to acceleration and escape of charged particle along the magnetic field lines, or to quasi-periodic oscillations close to equatorial plane, or to charged particle capture by black hole. We test if such processes could serve as a model of relativistic jets, quasi-periodic oscillation phenomena observed near black holes or black hole accretion disc destruction. Andrea Kotrlova: Research Centre for Computational Physics and Data Processing, Institute of Physics, Faculty of Philosophy and Science, Silesian University in Opava, Czech Republic Super-spinning compact objects and models of high-frequency quasi-periodic oscillations

We applied several models of high-frequency quasi-periodic oscillations (HF QPOs) to estimate the spin of the central compact object in the three Galactic microquasars. We explore the alternative possibility that the central compact body is a super-spinning object (or a naked singularity) with the external space-time described by Kerr geometry with a dimensionless spin parameter a* ¿ 1. We calculate the relevant spin intervals for a large set of HF QPO models and discuss their astrophysical relevance

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Charged fluid tori in spherically symmetric gravitational and dipolar magnetic fields

Jiri Kovar

Institute of Physics, Silesian University in Opava, Czech Republic

We present our study of electrically charged perfect fluid toroidal structures encircling relativistic spherically symmetric gravitating object endowed with a dipole magnetic field. After a short general introduction of the model, we discuss a variety of possible topologies of the toroidal fluid configurations. Along with the charged equatorial tori forming interesting coupled configurations that cannot occur in the case of electrically neutral configurations, we reveal unique, the so-called 'levitating; off-equatorial tori; we pay attention to the orbiting structures with constant specific angular momentum, and on those in permanent rigid rotation. Finally, we try to put our work into an astrophysical context by identifying the central object with an idealization of non-rotating magnetic neutron star. Constraining ranges of its parameters and also parameters of the circling matter, we discuss a possible astrophysical relevance of the studied toroidal structures, presenting along with their geometry also their pressure, density, temperature and charge profiles.

Approximating waveforms of rapidly rotating neutron stars

Scott Lawrence

Department of Astronomy, University of Maryland, College Park, USA

Modeling of energy-dependent waveforms presents a robust, potentially systematic-free way to determine the mass and radius of an individual neutron star, and therefore a way to constrain the high-density, low-temperature nuclear equation of state. Computing exact waveforms is time-consuming, and so an effective statistical analysis procedure for extracting masses and radii requires the use of a more efficient, but still sufficiently accurate, approximation. We will present a code for computing raytraced lightcurves in a numerically computed, exact spacetime. By comparison with this code, we investigate the conditions under which various approximations to the exact solution are sufficient, in the context of attempts to accurately determine the masses and radii of individual neutron stars.

Cosmological Constant and Gravitational Lensing

Dimitri Lebedev
Queenś University at Kingston Ontario, Canada

Whether or not the cosmological constant plays a role in gravitational lensing has recently been a subject of an ongoing debate, yet to be definitively settled. Following N. J. Islam?s work of 1983, it was generally believed that the cosmological constant has no effect on the bending of light. However, in 2008 W. Rindler and M. Ishak questioned the definition of the bending angle itself in the context of non-asymptotically flat spacetime. They offered a fresh perspective on the issue, and pointed out the importance to recognize the influence of curvature on local measurements. Effectively showing that there is more than one place from where the cosmological constant can enter gravitational lensing, they challenged the generally held opinion. Rindler and Ishak?s work was met with much enthusiasm and scepticism, sparking the ongoing debate on the contribution of the cosmological constant to lensing.

It is our aim to present the fundamentals of this topic as well as our own research in which we build on Rindler and Ishak?s work and derive some important generalized expressions. Furthermore, through showing exactly how the cosmological constant can enter the gravitational lens equation, we hope to finally settle the ongoing debate. We developed a general technique which allows finding observable intersection angles of null trajectories analytically, and as one of its applications we?ve established a general relativistic aberration relationship. We have provided a clear answer to whether or not the cosmological constant affects orbits of light, observable intersection angles, and gravitational lensing phenomena in general.

The Origins of Stellar-Mass Black Holes in the Milky Way

Nathan Leigh
American Museum of Natural History, USA

In this talk, we explore some of the ramifications for stellar-mass black holes (BHs) of recently proposed revisions to primordial globular cluster (GC) formation in the Milky Way. Given the discovery of multiple stellar populations, the observations now suggest a prolonged (100 Myr) initial gas-embedded phase to fuel the formation of the second generation of stars. Indirectly, this implies that any stellar-mass BHs formed from the first generation of stars should have spent non-negligible time orbiting within a dense gas-rich environment. After a brief review of what is known about the initial conditions, we quantify the impact of a gas-embedded phase on the BH mass distribution, the relevant dynamical rates, their retention fractions, etc. Our key point is that the initial conditions in massive star clusters, which are still poorly known, could significantly impact the distributions of BH masses, their binary fractions and even their locations in the Galaxy. This is critical since, given the observed correlation between the total mass of a star cluster and the mass of its most massive star, (arguably) every stellar-mass BH in the Universe originated in a

massive cluster. These issues relate directly to understanding the origins of future gravitational wave detections.

Non Axisymmetric Relativistic Wind Accretion with Velocity and Density Gradients onto a Rotating Black Hole

Fabio Lora

Universidad Industrial de Santander, Colombia

In this work, we present, for the first time, a numerical study of the Bondi-Hoyle accretion with density and velocity gradients in the fully relativistic regime. In this context, we consider accretion onto a Kerr Black Hole (BH) of a supersonic ideal gas, which has density and velocity gradients perpendicular to the relative motion. The set of parameters of interest in this study are the Mach number, the spin of the BH and the density-gradient parameter of the gas. We show that, unlike in the Newtonian case, all the studied cases, especially those with density and velocity gradient, approach a stationary flow pattern. To illustrate that the system reaches steady state we calculate the mass and angular momentum accretion rates on a spherical surface located almost at the event horizon.

Pulsars at the Center of the Galaxy

Walid Majid

JPL, Caltech, USA

Over the past few years, a number of groups using data from NASA?s space-borne Fermi LAT instrument have identified excess gamma-ray flux toward the inner 1 of the Galactic Center (GC), with an even larger significant excess within 0.2 degrees. At present there are two leading candidates for this excess: dark matter annihilation and a population of unresolved millisecond pulsars (MSPs). We are currently developing dedicated instrumentation to carry out a sensitive search for the pulsars in this region of the galaxy using a newly developed front end and receiver on a Deep Space Network large diameter antenna in Australia. In this presentation, we will provide an overview of the challenges encountered with pulsar searches at the GC region and a summary of previous and ongoing efforts to survey this region with radio telescopes. We will also provide preliminary results from our recent observations of the GC region at 2 and 8 GHz and will conclude with prospects for detection of perhaps hundreds of pulsars in this region with new generations of radio telescopes now under construction.

Signatures of Neutron Star Mergers in the Era of Gravitational Wave Astronomy

Brian Metzger

Columbia University, USA

ABSTRACT TBD

An Upper Bound on Neutron Star Masses from Models of Short Gamma-Ray Bursts

Cole Miller

University of Maryland, USA

The discovery of neutron stars with gravitational masses 2Msun has placed a strong lower limit on the maximum mass of nonrotating neutron stars, and with it a strong constraint on the properties of cold matter beyond nuclear density. Current upper mass limits are much looser. Here, we note that if most short gamma-ray bursts are produced by the coalescence of two neutron stars, and if the merger remnant collapses quickly, then the upper mass limit is constrained tightly, to 2-2.2 Msun if the masses of neutron stars that coalesce to produce gamma-ray bursts are in the range seen in Galactic double neutron star systems. Future coincident detection of short gamma-ray bursts with gravitational waves will strengthen these arguments because they will produce tight bounds on the masses of the components for individual events. If these limits are accurate, then a reasonable fraction of double neutron star mergers might not produce gamma-ray bursts. In that case, or in the case that many short bursts are produced instead by the mergers of neutron stars with black holes, the implied rate of gravitational wave detections involving neutron stars will be increased.

The Influence of Initial Conditions during Dissipative collapse

Nolene Naidu

Astrophysics and Cosmology Research Unit, University of KwaZulu-Natal, South Africa

Starting off with two distinct initially static stellar cores (i) Florides interior (constant density, vanishing radial pressure) and (ii) Wyman interior (constant density, nonvanishing radial pressure), we explore the dynamics of these two models once hydrostatic equilibrium is lost. We show that although the time of formation of horizon, evolution of the mass and proper radius are independent of the chosen initially static configurations, there is a significant difference in the temperature profiles of the radiating bodies as the

collapse proceeds.

Lighting Up Inspiraling Binary Black Hole Systems

Scott Noble
University of Tulsa, USA

Accretion disks around supermassive binary black holes offer a rare opportunity to probe the strong-field limit of dynamical gravity using turbulent plasma as a lighthouse. Accurate simulations of these systems using a variety of configurations will be critical to interpreting future observations of them. In this talk, we will present our latest results of 3-d general relativistic magnetohydrodynamic supercomputer simulations of accreting binary black holes during the post-Newtonian inspiral phase of their evolution. The goal of our work is to explore whether these systems provide a unique means to identify and characterize them with electromagnetic observations. We will present results that show how our predicted light curves vary with respect to mass ratio, binary separation, amount of accreting magnetic flux, and the order of accuracy in the post-Newtonian approximation. Post-processing calculations of the electromagnetic spectrum from these accreting supermassive black holes will also be presented. Our results will provide a start to understanding what electromagnetic signatures we may expect in the future. We will also provide a context for our results and describe our future avenues of exploration.

High efficiency of collisional Penrose process requires heavy particle production

Kota Ogasawara
Rikkyo University, Japan

The center-of-mass energy of two particles can become arbitrarily large if they collide near the event horizon of an extremal Kerr black hole, which is called the Banados-Silk-West effect.

We consider such a high-energy collision of two particles which started from infinity and follow geodesics in the equatorial plane and investigate the energy extraction from such a high-energy particle collision and the production of particles in the equatorial plane.

We analytically show that, on the one hand, if the produced particles are as massive as the colliding particles, the energy-extraction efficiency is bounded by 2.19 approximately. On the other hand, if a very massive particle is produced as a result of the high-energy collision, which has negative energy and necessarily falls into the black hole, the upper limit of the energy-extraction efficiency is increased to13.9.

Thus, higher efficiency of the energy extraction, which is typically as large as 10, provides strong evidence for the production of a heavy particle.

SUPERMASSIVE BLACK HOLES BINARIES, GRAVITATIONAL WAVES AND THE DYNAMICAL EFFECTS IN THE HOST GALAXY

Fabrcia Pereira
University of Vale do Paraba, Brazil

The recent first direct detection of gravitational waves by the LIGO detector is consistent with an emission by a binary system of two massive stellar black holes. On the other hand, binary systems of supermassive black holes (SMBHs) with masses from emit gravitational waves in a frequency range only accessible by the projected space-borne gravitational wave detectors and by Pulsar Timing Arrays. Binary systems of SMBHs are expected to reside at the center of most galaxies and are formed during a galaxy merger. In this respect, the aim of this work is to investigate the dynamical effects in the binary environment during the relativistic phase of their orbits. We look for possible dynamical counterparts in the host galaxy due gravitational wave emission, such as in the velocity profile of stars and in the dynamics of the surrounding gas. To this end, we concentrate our analysis on the inspiral phase by using the Post-Newtonian expansion up to order 2.5PN. The expansion terms of order 1PN and 2PN correspond to relativistic conservative terms while the 2.5PN order is dissipative term responsible by gravitational wave radiation reaction. In order to model the host galaxy, N-body simulations were performed by using the GADGET-3 code.

Ringed accretion disks

Daniela Pugliese
Institute of Physics, Faculty of Philosophy & Science, Silesian University in Opava, Czech Republic

The possibility that several toroidal accretion configurations (rings) may be orbiting on the equatorial plane of one central super massive Kerr black hole has been addressed. Such tori may be formed during different stages of the Kerr attractor accretion history. We consider the relative rotation of the tori and the corotation or counterrotation of a single torus with respect to the Kerr attractor. We provide constraints on the model parameters for the existence and stability of various ringed configurations and discuss occurrence of accretion onto the Kerr black hole. We give classification of the couples of accreting and non-accreting tori in dependence on the Kerr black hole dimensionless spin. The discussion of the rings stability in different spacetimes lead to identify particular classes of central Kerr attractors accordingly to their dimensionless spins. As a result of this analysis we set constraints on formations, morphology and relative rotation of the two rings and to the central black hole. We demonstrate that only in few cases a double accretion tori system may be formed under specific conditions. The dynamics of the unstable phases of the ringed disk evolution seems to be promising in relation to high energy phenomena demonstrated in active galactic nuclei.

Gravitational Spinning Particle and Gravitational Radiation

Gonzalo Damian Quiroga
Universidad Industrial de Santander, Colombia

We introduce the concept of gravitational spinning particle in General Relativity. For this definition we use the available fields at the null boundary of an asymptotically flat spacetime describing an isolated source of gravitational radiation. The resulting construction has some similarities with the Mathisson-Papapetrou approach although it does not describe a particle in a given background, rather it describes some global aspects of the asymptotically flat spacetime from which it is constructed. We also derive equations of motion linking their time evolution to the emitted gravitational radiation. These equations of motion are valid even for relativistic speeds and thus should be useful when describing the final moments of binary coalescence.

Dynamical ejecta from binary neutron star mergers

David Radice
California Institute of Technology, USA

Binary neutron star mergers can drive dynamical outflows of neutron rich material. These ejecta might be the astrophysical site of production of the r-process elements. In this talk, I will present very recent full-GR, numerical relativity, simulations of binary neutron star mergers with microphysical equation of state and a simplified treatment of neutrino radiation done with the WhiskyTHC code. I will discuss the mechanisms driving the mass ejection, the role played by neutrino cooling and heating in shaping composition and morphology of the ejecta, as well as the impact on the final yields of the r-process nucleosynthesis.

Minidiscs in Circumbinary Black Hole Accretion

Geoffrey Ryan
New York University, USA

Newtonian calculations have demonstrated circumbinary black hole accretion is mediated by minidiscs around each black hole, fed by streams from the global circumbinary disc. We study the structure of black hole minidiscs using general relativistic hydrodynamics calculations of minidiscs with the moving mesh hydro code Disco. Torques from the binary companion induce spiral shocks in the disc which can effectively dissipate energy and transport angular momentum outwards; inducing accretion onto the central black hole. The disc is cooled with a local blackbody prescription, allowing evolution to a self-consistent temperature profile. The shock structure agrees well with the relativistic dispersion relation for tightly-wound linear waves. We measure the shock induced dissipation, find effective alpha parameters on the order of 0.01, and produce disc spectra from the blackbody emission.

Motion of Photons in Bardeen and ABG Regular Spacetimes

Jan Schee

Silesian University in Opava, Czech Republic

We discuss how is the regularity of Bardeen and ABG spacetimes reflected in the motion of photons. There is a characteristic phenomena we call "ghost image" which we illustrate on properties of spacetimes in question on null geodesics analysis and the Keplerian disc images. Although the spacetimes are generated by non-linear electromagnetic system we approximate the motion of photons as geodetical. We also discuss the impact of non-linearity of the field on photon motion when treated properly as non-geodetical.

A toy model for relativistic accretion ow in Kerr-Newman space-time

Kris Schroven

ZARM, University of Bremen, Germany

Building on the work of E. Tejeda, P. Taylor and J. C. Miller (2013), we present a relativistic toy model for the stationary accretion flow of a rotating cloud of dust like particles falling on to a Kerr-Newman black hole. We express the streamlines as time-like geodesics using Jacobian elliptic functions. Furthermore the local velocity field and the density field is calculated and restrictions to the initial conditions of the model are discussed. This model provides a good way to present the influence of the specific angular momentum and the charge of the black hole on the course of the accretion flow, the density field and the outer edge of a forming accretion disc in a strong gravitational field.

Black hole spin inferred from orbital models of high-frequency quasi-periodic oscillations

Eva Sramkova

Research Centre for Computational Physics and Data Processing, Institute of Physics, Faculty of Philosophy and Science, Silesian University in Opava, Czech Republic

Estimations of spin a* of black holes in the three Galactic microquasars GRS 1915+105, GRO J1655-40, and XTE J1550-564 have been carried out based on several models of 3:2 high-frequency quasi-periodic oscillations (QPOs). Several of the so far calculated QPO spin estimates have been implied by models that deal with geodesic accretion flow. Non-geodesic accretion flow described by the model of a pressure-supported torus has been recently considered for obtaining non-geodesic corrections to mass-spin estimates based on the QPO model assuming internal 3:2 resonance between disc oscillation axisymmetric epicyclic modes. It has been shown for this particular model that the presence of pressure forces affects predicted QPO

frequencies only slightly when a*¡0.9. On the contrary, when a*¿0.9, the pressure influence is non-negligible. Here we extend the consideration of non-geodesic flow to 15 other QPO models and show that for several of them the pressure influence can be quite significant even for low values of a*.

Electromagnetic Signatures of Supermassive Black Hole Binaries

Takamitsu Tanaka

Stony Brook University, USA

I will present analytic and semi-analytic arguments for spectral features and transient emission from compact, accreting supermassive black hole binaries. The transient signatures are detectable by current and planned time-domain observatories. I will also discuss physical mechanisms that are expected to play key roles in producing and shaping these signatures, but have not yet been captured by numerical simulations on this subject.

Constraining models of twin peak quasi-periodic oscillations with realistic neutron star equations of state

Gabriel Torok

Research Centre for Computational Physics and Data Processing, Institute of Physics, Faculty of Philosophy and Science, Silesian University in Opava, Czech Republic

Twin-peak quasi-periodic oscillations (QPOs) have been observed in the X-ray power density spectra of several accreting low-mass neutron star binaries. It is believed that QPOs are in a fundamental way connected to orbital motion in strong gravity. We confront several QPO models with various neutron star equations of state and present results of detailed calculations considering the influence of the starś oblateness in Hartle-Thorne spacetimes. Considering a particular spin frequency close to 580 Hz measured in the atoll source 4U 1636-53, we show that 51 out of 90 considered combinations of EoS and QPO models can be excluded.

Influence of a plasma on the shadow of a spherically symmetric black hole and other chromatic effects of gravitational lensing in presence of plasma

Oleg Tsupko

Space Research Institute of Russian Academy of Sciences, Russia

We consider an influence of plasma on gravitational lensing. In presence of both gravity and plasma the deflection angle is physically defined by mutual combination of different phenomena: gravity, dispersion, refraction. While effects of deflection by gravity in vacuum and the refractive deflection in non-homogeneous medium are well known, the new effect is that in case of homogeneous plasma, in absence of refractive deflection, the gravitational deflection differs from vacuum deflection and depends on the photon frequency. In presence of non-homogeneity in plasma the chromatic refractive deflection also occurs, so the presence of plasma always makes gravitational lensing chromatic. For strong lens systems with multiple images, the presence of plasma leads to difference in angular position of the same image if observed at different wavelengths. Shift of angular position can be significant for observation in radio band. Influence of plasma on the shadow of spherically symmetric black hole is also considered. It is the first attempt to investigation of the shadow in matter based on analytical calculations. Our main result is an analytical formula for the angular size of the shadow. As a plasma is a dispersive medium, the radius of the shadow depends on the photon frequency. The effect of the plasma is significant only in the radio regime. We find that for an observer far away from a Schwarzschild black hole, the plasma has a decreasing effect on the size of the shadow.

Bounded motion of charged particles near Kerr black hole in external magnetic field

Arman Tursunov

Silesian University in Opava, Czech Republic

The detailed analysis of the dynamics of charged particles in the combined field of Kerr black hole and external asymptotically uniform magnetic field is presented. Focusing on the epicyclic quasi-circular orbits near the equatorial plane we separate the circular orbits into four qualitatively different classes according to the sign of the canonical angular momentum of the motion and the orientation of the Lorentz force. We analytically calculate the energy, angular momentum and fundamental frequencies of the oscillatory motion of charged particle in the vicinity of equatorial circular orbits. We demonstrate that in the case of the retrograde circular orbits with outward oriented Lorentz force there exists a new phenomenon of toroidal epicyclic motion when the orbital frequency of a particle is much lower than the corresponding radial and vertical frequencies.

The Role of the Kozai-Lidov Mechanism in Black Hole Binary Mergers in Galactic Centers

John VanLandingham

University of Maryland College Park, USA

In order to understand the rate of merger of stellar-mass black hole binaries (BHBs) by gravitational wave (GW) emission it is important to determine the major pathways to merger. We use numerical simulations to explore the evolution of BHBs inside the radius of influence of supermassive black holes (SMBHs) in galactic centers. In this region the evolution of binaries is dominated by perturbations from the central SMBH. In particular, as originally suggested by Antonini and Perets (2012) the Kozai-Lidov (KL) mechanism trades relative inclination of the BHB to the SMBH for eccentricity of the BHB, and if the orientation is correct, can bring the BHB to an eccentricity near unity. At very high eccentricities, GW emission from the BHB can become efficient, causing the members of the BHB to coalesce. In some cases, this may result in a merger that still has significant eccentricity when observable by ground based GW detectors. We use a novel combination of two N-body codes to follow this evolution. We find that all simulated BHBs undergo KL oscillations and that some of them may be driven to merger via this mechanism. None of these BHBs would have coalesced in this time without the influence of the KL mechanism. Under optimistic conditions, this mechanism could result in a detection rate of a few per year by advanced LIGO from this pathway alone.

From Relativity to QCD: the Equation of State of Neutron Stars

Anna Watts

University of Amsterdam, The Netherlands

Neutron stars provide a unique test bed for nuclear physics, quantum chromodynamics, and quantum superfluidity. Determination of the fundamental interactions that govern matter under such extreme conditions is one of the major unsolved problems of modern physics and - since it is impossible to replicate these conditions on Earth - a major motivation for future telescopes. Relativity, however, plays a key role in efforts to measure the equation of state. It is using relativistic effects that we measure neutron star mass and radius, and it is the relativistic equations of stellar structure that relate mass and radius to the equation of state. I will review the intricate links between Special and General Relativity and our efforts to understand the behaviour of matter at the highest densities.

Crustal dynamics of magnetars and its connection to magnetar bursts

Huan Yang

Perimeter Institute for Theoretical Physics, Canada

We propose a model describing the crustal motion in magnetars and its connection to various kind of magntar bursts, including giant flares, soft gamma-ray repeaters and quasi-periodic oscillations (QPOs). In this model, there are regions within the crust where the Maxwell stress is strong enough to force the crustal solid into plastic motion. We show that these plastic zones are natural launch stations to release part of the magnetic energy to the magnetar magnetosphere, when crustal elastic waves pass by. The disconnected yielding patches could introduce a super-radiance mechanism, convertng magnetic energy of the core field to the crustal elastic wave to support the
$sim 100s$ QPOs. We also argue that the giant flares are related to the long-term instability of the core and sudden meltdown of certan extended plastic zones of the crust.

Accretion in Radiative Equipartition (AiRE) Disks

Yasaman Yazdi

Perimeter Institute for Theoretical Physics, Canada

Standard accretion disk theory (Shakura & Sunyaev 1973) predicts that the total pressure in disks at typical (sub-)Eddington accretion rates becomes radiation pressure dominated. However, radiation pressure dominated disks are thermally unstable. Since these disks are observed in a steady state, this suggests that our disk models in the radiation pressure dominated regime (i.e. inner disk) need to be modified. In this talk I will present a modification to the SS model, where radiation pressure is in equipartition with gas pressure in the inner region. We call these disks Accretion in Radiative Equipartition (AiRE) disks. I will introduce the basic properties of AiRE disks and show how they modify disk quantities such as the Toomre parameter and radiation flux.

Possible alternatives to the supermassive black hole at the Galactic Center

Alexander Zakharov

Institute of Theoretical and Experimental Physics, Russia

Now there are two basic observational techniques to investigate a gravitational potential at the Galactic Center, namely, a)

monitoring the orbits of bright stars near the Galactic Center to reconstruct a gravitational potential; b) measuring a size and a shape of shadows around black hole giving an alternative possibility

to evaluate black hole parameters in mm-band with VLBI-technique. At the moment one can use a small relativistic correction approach for stellar orbit analysis (however, in the future the approximation will not be not precise enough due to enormous progress of

observational facilities) while now for smallest structure analysis in VLBI observations one really needs a strong gravitational field approximation. We discuss results of observations, their

conventional interpretations, tensions between observations and models and possible hints for a new physics from the observational data and tensions between observations and interpretations. We will

discuss an opportunity to use a Schwarzschild metric for data interpretation or we have to use more exotic models such as Reissner

– Nordstrom or Schwarzschild – de-Sitter metrics for better fits.

Collisional super-Penrose process

Oleg Zaslavskii

Kharkov V. N. Karazin National University, Ukraine

If two geodesic particles collide near a rotating black hole, their energy in the centre of mass frame $E_c m$ can become unbound under certain conditions.

We show that for any scenario with collision of particles having finite masses and angular momenta, the Killing energy E of debris at infinity remains restricted.

Meanwhile, unbound E and, correspondingly, unbound efficiency of energy extraction (so-called the super-Penrose process) is possible in the spacetime with a naked singularity.

The above statements apply to generic axially symmetric rotating metrics.

Session B2

Title

Author
Affiliation, Country

Abstract Text

Schwarzschild scalar wigs: spectral analysis and late time behavior

Juan Barranco
Universidad de Guanajuato, Mexico

Using the Green?s function representation technique, the late time behavior of localized scalar field distributions on Schwarzschild spacetimes is studied. Assuming arbitrary initial data we perform a spectral analysis, computing the amplitude of each excited quasibound mode without the necessity of performing dynamical evolutions. The resulting superposition of modes is compared with a traditional numerical evolution with excellent agreement; therefore, we have an efficient way to determine final black hole wigs. The astrophysical relevance of the quasibound modes is discussed in the context of scalar field dark matter models and the axiverse.

Cosmological modelling with numerical relativity

Eloisa Bentivegna
Universit degli Studi di Catania, Italy

Cosmological observations have reached the era of sub-percent measurements, and their interpretation demands accurate modelling of even the finest cosmic history details. Furthermore, the first detection of a gravitational-wave signal, announced in February, opens a new chapter in the exploration of the elaborate role played by general relativity in our Universe.

A number of recent studies have addressed the inclusion of general-relativistic effects in the description of large-scale cosmological processes using numerical relativity [1-9]; in particular, the first studies of cosmological spacetimes containing pressureless fluids with three-dimensional density profiles have now appeared [10-12]. I will first review the techniques used in these works, presenting the open-source

Einstein Toolkit and its extensions necessary to build well-behaved simulations of cosmological spacetimes. I will then illustrate the departures of these exact spacetimes from the modelling approximations commonly used to describe the evolution of the late Universe, thereby providing a first estimate of the systematic errors involved in these approximations.

Schwarzschild black holes can wear scalar wigs

Argelia Bernal

Universidad Autonoma del Estado de Hidalgo, Mexico

We study the evolution of a massive scalar field surrounding a Schwarzschild black hole and find configurations that can survive for arbitrarily long times, provided the black hole or the scalar field mass is small enough. In particular, both ultra-light scalar field dark matter around supermassive black holes and axion-like scalar fields around primordial black holes can survive for cosmological times. Moreover, these results are quite generic, in the sense that fairly arbitrary initial data evolves, at late times, as a combination of those long-lived configurations.

HOW LOUD ARE NEUTRON STAR MERGERS IN THE GRAVITATIONAL WINDOW?

Sebastiano Bernuzzi

Parma U & INFN, Italy

Neutron stars binary mergers are among the main targets for ground-based gravitational-wave (GW) interferometers like Advanced LIGO and Virgo. The development of GW astronomy with these sources requires a detailed theoretical understanding of the merger dynamics. In this talk, I will report about recent developments in the numerical and analytical modeling of neutron star mergers. I will first discuss a new tidal effective-one-body model for the description of the inspiral phase and up to merger and in agreement with high-precision numerical relativity simulations. I will then present results from the first large parameter postmerger study using fully general relativistic simulations with finite-temperature microphysical equations of state and neutrino cooling. These data show that the GW energy emitted during the early evoluton period of the hypermassive neutron star produced during merger is about twice the energy emitted over the entire inspiral history of the binary. Thus, considering also the postmerger, the total radiated energy per binary mass is comparable to or larger than that of nonspinning black hole mergers.

Recent results in Smooth Lattice Relativity

Leo Brewin
Monash University, Australia

In this talk I will present some recent theoretical and numerical results on the smooth lattice method in 3+1 numerical relativity. I will review the theoretical basis of the method followed by detailed results for the Kasner, Gowdy, Brill and Teukolsky spacetimes. The results will be compared with finite difference methods in both the ADM and BSSN formulations. The results are very encouraging and show that the smooth lattice method is competitive with contemporary methods in numerical relativity.

Solving 3D relativistic hydrodynamical problems with WENO discontinuous Galerkin methods

Bernd Bruegmann
University of Jena, Germany

Discontinuous Galerkin methods coupled to WENO algorithms allow high order convergence for smooth problems and for the simulation of discontinuities and shocks. We investigate WENO-DG algorithms in the context of numerical general relativity, in particular for general relativistic hydrodynamics. To evaluate the performance of different numerical schemes, we study non-relativistic, special relativistic, and general relativistic testbeds. The most important testbed is a single TOV-star in three dimensions, showing that long term stable simulations of single isolated neutron stars can be obtained with WENO-DG methods.

Gravitational Wave Emission in Higher Dimensional Black Hole Collisions

William Cook
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, United Kingdom

Gravitational waves are a key diagnostic in the study of the properties of black holes (BHs). In four dimensional General Relativity the properties of gravitational waves emitted in BH-BH mergers have been extensively studied using numerical relativity, largely in astrophysical settings. Understanding higher dimensional BH-BH collisions is also an important goal for numerical relativity, firstly in order to observe the behavior of the theory in its most extreme, non-linear regime, and also due to its applications to areas of high energy physics. One such example is that of TeV gravity theories, in which it is proposed that high energy collisions in particle accelerators could cause black hole creation. In this work we present for the first time full non-linear simulations of head-on BH-BH collisions in up to 10 dimensions and present an analysis of the gravitational radiation emitted. We use a new method

for analysis of the radiation, analogous to the well known Weyl scalar method based on the Newman-Penrose formalism in 4D. We find that as the number of dimensions is increased the energy emitted in gravitational radiation is significantly suppressed. We also present a comparison of our numerical data with point particle calculations.

Global Sphere Reconstruction (GSR) of the Astrometric Verification Unit at the Italian data center (DPCT)

Mariateresa Crosta

INAF-OATo, Italy

The main goal of the Gaia ESA will be reached by means of high-precision astrometric measurements conducted by a satellite sweeping continuously the celestial sphere during its 5-years mission. A fundamental step toward the realization of this catalog is the so-called "Sphere Reconstruction", which determines the celestial reference frame using the observations of a subset of up to 100 million "primary stars" among those observed by Gaia. This represents an extremely challenging problem because of the high accuracy of the observations and of the large number of unknowns involved. The former issue implies that an adequately accurate relativistic astrometric model has to be used, while the huge number of unknowns and observations puts this task at the forefront of the High-Performance Computing problems. These challenges, and the absolute character of the Gaia measurements and results, calls for a careful scientific validation of the sphere reconstruction. For these reasons the Gaia Data Processing and Analysis Consortium (DPAC) decided to replicate the baseline process, named AGIS (Astrometric Global Iterative Solution) with another independent solution, named GSR (Global Sphere Reconstruction) which uses a different astrometric model and different algorithms for the system solution.

Final dynamical state of unsestable charged black holes

Juan Carlos Degollado

Institute for Physical Sciences, UNAM, Mexico

A Reissner-Nordstrom black hole is superradiantly unstable against spherical perturbations of a charged scalar field, enclosed in a cavity, with frequency lower than a critical value.

We follow the development of this unstable system into the non-linear regime, solving the full Einstein-Maxwell-Klein-Gordon equations, in spherical symmetry.

Our results show that the process stops before all the charge is extracted from the BH and the system settles down into a hairy Black hole configuration.

Generic Binary Neutron Stars Systems

Tim Dietrich

Max Planck Institute for Gravitational Physics, Germany

Binary neutron star mergers are associated with a variety of observable phenomena in the gravitational and electromagnetic spectra. We investigate binary neutron stars in the last milliseconds before and after their merger with full 3D numerical simulations using the BAM code. We explain how we access previously unaccessible regions of the binary neutron star parameter space, e.g. precessing, eccentric, and high mass ratio setups, and we discuss first simulations with generic setups.

We also show that recent upgrades allow us to improve the accuracy of the simulation and decrease the phase error of the obtained gravitational waveforms. With this updates our waveforms can be used for validating and improving semi-analytical waveform models.

Dynamics of the Inflationary Higgs Vacuum Instability

William East

Stanford/SLAC, USA

If the Standard Model is extrapolated to very high energy scales, it indicates that the Higgs field should become unstable at large values. Though the electroweak vacuum is metastable on timescales that are long compared to the age of the Universe, during a period of inflation the Higgs field would have experienced large fluctuations which could have driven it towards its true vacuum at negative energy in some regions. Using the tools of numerical general relativity, we elucidate the dynamics and growth of unstable Higgs fluctuations in an expanding spacetime, illustrating how they can halt inflation in the regions they develop, and lead to the development of singularities. By combining this with a detailed treatment of the stochastic development of such unstable Higgs fluctuations, we place bounds on the inflationary energy scale relative to that of the Higgs instability based on the existence of our current Universe.

Explosion and final state of the charged black hole bomb

Jose Antonio Font Roda
University of Valencia, Spain

A Reissner-Nordstrm black hole (BH) is superradiantly unstable against spherical perturbations of a charged scalar field, enclosed in a cavity, with frequency lower than a critical value. We use numerical relativity techniques to follow the development of this unstable system – dubbed charged BH bomb – into the non-linear regime, solving the full Einstein–Maxwell–Klein-Gordon equations, in spherical symmetry. We show that: i) the process stops before all the charge is extracted from the BH; ii) the system settles down into a hairy BH: a charged horizon in equilibrium with a scalar field condensate, whose phase is oscillating at the (final) critical frequency. For low scalar field charge, q, the final state is approached smoothly and monotonically. For large q, however, the energy extraction overshoots and an explosive phenomenon, akin to a bosenova, pushes some energy back into the BH.

A numerical implementation of the Corvino-Schoen gluing method in spherical symmetry

Joerg Frauendiener
University of Otago, New Zealand

In 2000 J. Corvino presented a method for gluing two initial data sets which is based on the exploitation of the underdeterminedness of the constraint equations. It can be used to glue an arbitrary solution of the constraint equations to a Schwarzschild asymptotic end, thereby producing an initial data set which is identical to Schwarzschild near infinity. We present a numerical implementation of this method and show first results.

Fast and accurate prediction of numerical Green?s functions in black hole spacetimes using surrogate models

Chad Galley
California Institute of Technology, USA

The fundamental nature of linear wave propagation in curved spacetime is described by the retarded Greenś function (or propagator). Greenś functions are useful tools because many quantities of interest, even in perturbation theories, can be computed via convolution integrals with a source. Recently, numerical approximations for propagators in black hole spacetimes have been found that are globally valid and accurate for computing physical quantities. However, the data generated is too large for practical use because the propagator depends on two spacetime points that must be sampled finely to yield accurate convolutions. I describe how to build a reduced-order model that can be evaluated as a substitute, or surrogate, for numerically solving the curved spacetime Greenś function equation. The resulting surrogate is

fast to evaluate and accurately models the original and out-of-sample data. I discuss applications of the surrogate, including the self-consistent dynamics and waveforms of extreme mass ratio binaries. Greenś function surrogate models provide a new and practical way to handle problems involving wave propagation and radiation reaction in curved spacetimes.

Gravitational Waves Induced by Plasma Turbulence in the Early Universe: Nonlinear and Linear Calculations

David Garrison
University of Houston Clear Lake, USA

This work is a follow-up to the paper, "Numerical Relativity as a Tool for Studying the Early Universe". In this report we determine the accuracy of linearized gravity in primordial gravitational wave calculations. We calculate the normalized energy density strain and degree of polarization of gravitational waves produced by a simulated turbulent plasma similar to what was believed to have existed shortly after the electroweak scale. This calculation is completed using two numerical codes one which utilizes full General Relativity calculations based on modified BSSN equations while the other utilizes a linearized approximation of General Relativity. Our results show that there is a noticeable difference between the normalized energy densities of gravitational waves calculated using a nonlinear code as opposed to that calculated with a linear approximation. This does not however imply that the strain and polarization calculations that do not take into account nonlinear effects give unreliable results."

Nearly extremal binary black hole simulations

Matthew Giesler
Caltech, USA

Astrophysical black holes could have nearly extremal spins; therefore, nearly extremal black holes could be among the binaries that Advanced LIGO detects. Predicting the gravitational waves emitted by merging black holes requires numerical-relativity simulations, but these simulations are especially challenging when one or both holes have mass m and spin S exceeding the Bowen-York limit of $S/m^2 = 0.93$. With improved methods for simulating high-spin black holes in the Spectral Einstein Code (SpEC) we perform simulations of binary black holes with spins above the Bowen-York limit including a nearly extremal non-precessing binary black hole coalescence, where both black holes have $S/m^2 = 0.998$, reaching the Novikov-Thorne upper bound for holes spun up by thin accretion disks. We discuss numerical convergence and estimate the numerical errors of the waveforms; we compare numerical waveforms from our simulations with post-Newtonian and effective-one-body waveforms; and we analyze the extremality of the individual and common apparent horizons at merger.

Critical collapse of rotating radiation fluids

Carsten Gundlach
University of Southampton, United Kingdom

We present results from the first fully relativistic simulations of the critical collapse of rotating radiation fluids. We observe critical scaling both in subcritical evolutions, in which case the fluid disperses to infinity and leaves behind flat space, and in supercritical evolutions that lead to the formation of black holes. We measure the mass and angular momentum of these black holes, and find that both show critical scaling with critical exponents that are consistent with perturbative results. The critical exponents are universal; they are not affected by angular momentum, and are independent of the direction in which the critical curve, which separates subcritical from supercritical evolutions in our two-dimensional parameter space, is crossed. In particular, these findings suggest that the angular momentum decreases more rapidly than the square of the mass, so that, as criticality is approached, the collapse leads to the formation of a non-spinning black hole. We also demonstrate excellent agreement of our numerical data with new closed-form extensions of power-law scalings that describe the mass and angular momentum of rotating black holes formed close to criticality.

Gravitational waves and rotational properties of hypermassive neutron stars from binary mergers

Matthias Hanauske
Goethe University Frankfurt / Frankfurt Institute for Advanced Studies, Germany

Based on a large number of numerical-relativity simulations of merging neutron star binaries, the differential rotation profiles of the hyper massive neutron stars (HMNS) in the post-merger phase have been analyzed. All simulations have been performed in full general relativity using the "Einstein Toolkit" together with the WHISKY and WhiskyTHC code for the general-relativistic hydrodynamic equations. The HMNS properties have been analysed for a variety of different equation of states (EoS) and two initial neutron star mass values. The time evolution of the HMNS rotation profiles show a structural uniqueness in respect to a variation of the EoS and initial neutron star mass. By using a particular kind of time average the differential rotation profiles of the various simulations have been compared and several dependencies with characteristic EoS-properties have been found. Gravitational waves emitted from merging neutron star binaries are on the verge of their first detection with advanced gravitational-wave interferometers. This talk will focus on the internal HMNS properties (e.g. differential rotation profiles structure of the space-time metric particle composition) and their connection with the emitted gravitational-wave signal. The emitted gravitational-wave signals produced by the HMNSs comprise specific characteristics of the equation of state of matter which can be analysed from the spectral properties of the post-merger gravitational-wave signal. A strong correlation of the maximum value of the averaged rotation profile with the f_2-peak of the emitted gravitational wave spectrum have been found."

Zooming in on black holes: numerical-relativity follow-up to GW observations

Mark Hannam
Cardiff University, United Kingdom

Following the first GW detection, GW150914, we performed a series of follow-up numerical-relativity simulations of merging black-hole binaries, to gain improved understanding of the detailed phenomenology of the waveforms in the neighboring volume of parameter space, over that provided by current waveform models. The ultimate goal is to produce a more accurate local model that could be used to improve parameter estimates. We report on the status of that work.

Binary black hole simulations for surrogate modeling

Daniel Hemberger
California Institute of Technology, USA

Analytic or data-driven models of binary black hole coalescences are used to densely cover the full parameter space, because it is computationally infeasible to do so using numerical relativity (NR). However, these models still need input from NR, either for calibration or because the model is agnostic to the underlying physics. We use the Spectral Einstein Code (SpEC) to provide a large number of simulations to aid the construction of a NR surrogate model in a 5-dimensional subset of the parameter space. I will present an analysis of the simulations that were used to construct the surrogate model. I will also describe the infrastructure that was needed to efficiently perform a large number of simulations across many computational resources.

An eccentric binary black hole inspiral-merger-ringdown gravitational waveform model from post-Newtonian and numerical relativity

Ian Hinder
Max Planck Institute for Gravitational Physics, Germany

I present a prescription for generating gravitational waveforms for non-spinning eccentric binary black hole systems including the inspiral, merger and ringdown portions calibrated to new numerical relativity simulations. I first show that the eccentric waveform sufficiently close to merger from numerical relativity, in the mass-ratio range studied, is the same as the circular case, and therefore combine an eccentric post-Newtonian inspiral waveform with a circular merger waveform. I assess the agreement of the resulting inspiral-merger-ringdown waveform with the numerical relativity results, and discuss the implications for gravitational wave detections of eccentric binary systems.

Systematic numerical relativity fits to gravitational-wave peak luminosity and final states of binary black hole mergers

Xisco Jimenez

University of the Balearic Islands, Spain

We present a hierarchical method to construct fits to numerical relativity data for binary black hole coalescence, considering in particular the examples of peak luminosity, final spin and radiated energy. We use input data obtained from different numerical relativity codes, and pay special attention to evaluate the systematic errors from numerical relativity across different input data sets, and to consider the effect of the systematic errors on the fits. We also comment on
applications to gravitational wave data analysis.

Merger of spinning neutron stars with nuclear physics EOS

Wolfgang Kastaun

University Trento, Italy

One of the most interesting aspects of future GW detections from NS binaries might be the observation of a post-merger waveform emitted by a metastable supra- or hyper-massive NS. The influence of the equation of state on the remnant properties has been the subject of many studies, while fewer results are available addressing the initial NS spins. We present results from general relativistic simulations for selected models with different initial NS spins and a nuclear physics EOS, with focus on the remnant structure and dynamics. In detail, we investigate the rotation profile, oscillations, and the thermal structure. We discuss the evolution of hot spots and their possible impact on the GW signal. We also study the influence of the initial NS spin on the GW signal and the amount of ejected matter.

Unequal mass binary neutron star mergers and multimessenger signals

Steven Liebling

Long Island University, USA

We study the merger of binary neutron stars with different mass ratios adopting three different realistic, microphysical nuclear equations of state, as well as incorporating neutrino cooling effects. In particular, we concentrate on the influence of the equation of state on the gravitational wave signature and also on its role, in combination with neutrino cooling, in determining the properties of the resulting hypermassive neutron star, of the neutrinos produced, and of the ejected material. The ejecta we find are consistent with other recent studies that find that small mass ratios produce more ejecta than equal mass cases (up to some limit) and this ejecta

is more neutron rich. This trend indicates the importance with future kilonovae observations of measuring the individual masses of an associated binary neutron star system, presumably from concurrent gravitational wave observations, in order to be able to extract information about the nuclear equation of state.

A Discontinuous Galerkin Method Compatible with the BSSN Formulation of the Einstein Equations

Jonah Miller

Perimeter Institute for Theoretical Physics, Canada

The BSSN formulation of the Einstein equations has repeatedly demonstrated its robustness. The formulation is not only stable but allows for puncture-type evolutions of black hole systems. Discontinuous Galerkin Finite Element (DGFE) methods offer a mathematically beautiful, computationally efficient, and highly parallelizable way to solve hyperbolic PDEs. These properties make them highly desirable for numerical relativity. To-date no one has been able to solve the full (3+1)-dimensional BSSN equations using DGFE methods. This is partly because DGFE discretization often occurs at the level of the equations, not the derivative operator, and partly because DGFE methods are traditionally formulated for manifestly flux-conservative systems. By discretizing the derivative operator, we generalize a particular flavor of DGFE methods, Local DG methods, to solve arbitrary second-order hyperbolic equations. This generalization allows us to solve the BSSN equations.

Co-moving frames for BSSNOK evolutions of dynamical spacetimes

Dumsani Ndzinisa

Rhodes University, South Africa

Numerical models of relativistic simulations for both vacuum (black holes) and hydrodynamical (stellar) models often make use of Cartesian grids which are fixed to a global background. A set of coordinates which are co-moving with bulk, essentially orbital motion, has the chance of significantly reducing the dynamics of variables relative to the computational grid. With current high-order finite difference schemes, this may be a dominant source of phase error in computing orbital trajectories, rotational flows, and the resulting gravitational waveforms. We revive a method for implementing a co-moving frame using the shift vector in the BSSNOK formalism, providing a very generally applicable framework which is easily integrated into existing mesh-refinement codes.

Numerical Tests of Cosmic Censorship

Maria Okounkova
Caltech, USA

We present our results of numerical tests of the weak cosmic censorship conjecture (CCC), which states that generically, singularities of gravitational collapse are hidden within black holes, and the hoop conjecture, which states that black holes form when and only when a mass M gets compacted into a region whose circumference in every direction is C
$leq4$
piM. We built a smooth particle methods module in SpEC, the Spectral Einstein Code, to simultaneously evolve spacetime and collisionless matter configurations. We monitor $R_{abcd}R^{abcd}$ for singularity formation, and probe for the existence of apparent horizons. We also consider probing for the existence of event horizons from null evolution after singularity formation. We include in our simulations the prolate spheroid configurations considered in Shapiro and Teukolský 1991 numerical study of the CCC.

Merger of weakly-interacting compact objects

Carlos Palenzuela
Universitat de les Illes Balears, Spain

We study the merger of compact objects, which only interact gravitationally, by performing dynamical simulations of two different perfect fluids. We focus on the influence of the radii of these compact objects on the gravitational wave signature produced during the coalescence. Although the LIGO detection GW150914 agrees very well with a binary black hole merger, our goal is to explore a possible degeneracy with these weakly interacting objects.

Comparing Space-time using Geometric Scalars

Jam Sadiq
Rochester Institute of Technology, USA

Einsteiń Theory of General relativity is one of the two cornerstones of modern physics. One of the issues with this theory is that it is a coordinate invariant theory. So dealing with the same space-time using different coordinates will not give the same expression, and it is hard to understand physics in different coordinates. One has to chose different coordinates to explain different parts of space-time. In order to understand how space-times are similar or different in different coordinates we are proposing a new technique of constructing scalars from geometric quantities that will remain invariant in any coordinate system. This will help us analyze and compare space-times in different coordinates at different locations. This technique will be helpful in understanding the numerical error in the calculation of these space-times.

Simulating higher dimensional black holes with GRChombo

Saran Tunyasuvunakool
DAMTP, University of Cambridge, United Kingdom

The study of general relativity in higher dimensions has revealed a range of surprising behaviours. This is especially true in the highly nonlinear, dynamical regime, and numerical relativity has been established as an effective tool for the study of gravitation in this setting. Recently, we have achieved a stable simulation of ring-shaped black holes in five dimensions, thus providing a concrete evidence that the weak cosmic censorship conjecture can be violated in asymptotically flat spacetimes. The additional freedom in black hole horizon topology in higher dimensions, along with extreme geometries which typically arise from dynamically-emerging physical features, pose new challenges to existing numerical relativity techniques which have been tremendously successful in astrophysical settings. In this talk, I will give an account of the various difficulties that we encountered, along with the tools and techniques which were developed in response. These include the GRChombo adaptive mesh refinement code, a singularity diffusion scheme inspired by shock-capturing techniques, a modification to the standard gauge condition, and a flexible apparent horizon finder.

Free hyperboloidal evolution of strong field initial data in spherical symmetry

Alex Vano-Vinuales
Cardiff University, United Kingdom

The present work addresses the hyperboloidal initial value problem in numerical relativity, where the Einstein equations are evolved on a foliation of smooth spacelike slices that reach future null infinity, which allows to study global properties of spacetimes, such as to unambiguously extract radiation signals. The hyperboloidal initial value problem for the Einstein equations can be addressed through conformal compactification methods, which we express in terms of unconstrained evolution schemes based on the BSSN and conformal Z4 formulations. The main difficulty of the implementation is that the resulting system of PDEs includes formally diverging terms at null infinity that require a special treatment and a careful choice of gauge conditions. This first step is restricted to spherical symmetry, although the regularization in the radial direction is expected to also apply to the full 3D case, at least to some extent. We present stable numerical evolutions of a massless scalar field coupled to the Einstein equations for different types of initial data, including the collapse of a scalar field perturbation of flat spacetime into a black hole, as well as a scalar field perturbing a Schwarzschild trumpet geometry. In the second scenario the simulations were followed long enough to measure the scalar fieldś power-law decay tails at future null infinity at the expected convergence order. These successful results make this approach of the hyperboloidal initial value problem a good candidate for more general numerical setups.

Computing Binary Black Hole Initial Data in the Damped Harmonic Gauge

Vijay Varma

Caltech, USA

Binary black hole evolution in the Spectral Einstein Code (SpEC) is currently done in the damped harmonic (DH) gauge, which has proven very useful for merger simulations. However, the initial data for the simulation is constructed in a different gauge. Once the evolution starts we need to perform a smooth gauge transformation to the DH gauge, introducing additional gauge dynamics into the evolution. In this work, we construct the initial data in the DH gauge itself, which allows us to avoid the above gauge transformation. This can have added benefits such as possibly reducing junk radiation, making it easier to achieve a desired orbital eccentricity, reducing the runtime of simulations, and being able to start evolution closer to the merger.

Modeling the Remnant Black Hole from the Merger of Precessing Black-Hole Binaries

Yosef Zlochower

Rochester Institute of Technology, USA

In this talk, I present results from the modeling of the remnant mass, spin, spin orientation, and gravitational recoil as a function of both the parameters of the binary near merger, and those at very far separations. Such models are useful for both studies of the astrophysical implications of black hole mergers, as well as the modeling of gravitational wave signals from such mergers.

Session B3

Dynamics of non-spinning compact binaries at the fourth post-Newtonian order

Laura Bernard

Institut dÁstrophysique de Paris, France

The coalescence of compact binary systems are among the most promising sources of gravitational waves for the current and next generations of interferometers. Due to the faintness of the signal, both the detection and precise determination of the physical parameters require highly accurate template banks of theoretical waveforms, which are then filtered against the detector data.

During the inspiral phase of the coalescence, when the two objects are widely separated, the perturbative post-Newtonian approach allows one to describe the dynamics of the binary system and to compute the radiation energy flux, from which the orbital phase evolution can be derived.

In this talk, I will address the question of the equations of motion at the fourth post-Newtonian order in harmonic coordinates. I will present a method based on a Fokker action, adapted to the specificities of the post-Newtonian formalism in harmonic coordinates. In particular I will focus on the treatment of the so-called tail effects which appear for the first time in the dynamics at 4PN.

Gravitational waves in de Sitter spacetime

Nigel Bishop

Rhodes University, South Africa

The construction of exact linearized solutions to the Einstein equations within the Bondi-Sachs formalism is extended to the case of linearization about de Sitter spacetime. The gravitational wave field as measured by distant observers is constructed, leading to two conclusions. Firstly, the effect of using a de Sitter rather than a Minkowski background for gravitational waves in the LIGO frequency band, is negligible. Secondly, a somewhat counter-intuitive result is found for the gravitational wave energy: energy conservation does not normally apply to inertial observers, but can be formulated for a class of accelerated observers, i.e. with worldlines that are timelike but not geodesic.

An updated Effective-One-Body model for non-precessing binary black holes

Alejandro Boh

AEI Potsdam, Max Planck Institute, Germany

The Effective-one-body (EOB) formalism, which describes semi-analytically the dynamics of coalescing binary black holes and the associated gravitational radiation, has undergone several refinements since its original formulation, gradually extending the region in parameter space over which the model provides highly accurate predictions for the gravitational waveforms. As a result, EOB waveforms have played a central role in the detection and subsequent analysis of the first gravitational-wave observation announced earlier this year. In this talk, I will present an updated version of the EOB model calibrated to a set of recently produced numerical-relativity waveforms and a description of multipolar waveform modes beyond the dominant quadrupole mode for non-precessing binary black holes.

Interaction between bosonic dark matter and stars

Richard Brito

Instituto Superior Tcnico, Portugal

Searches for dark matter imprints are one of the most active areas of current research. We focus here on light fields with mass mB, such as axions and axionlike candidates. Using perturbative techniques and full-blown nonlinear numerical relativity methods, we show the following. (i) Dark matter can pile up in the center of stars, leading to configurations and geometries oscillating with a frequency that is a multiple of $f = 2.510^14(mB{*}c^2/eV)$ Hz. These configurations are stable throughout most of the parameter space, and arise out of credible mechanisms for dark-matter capture. We also show that (ii) collapse of the host star to a black hole is avoided by efficient gravitational cooling mechanisms.

Master equation solutions in the linear regime of characteristic formulation of general relativity

Jose de Araujo

Instituto Nacional de Pesquisas Espaciais, Brazil

From the field equations in the linear regime of the characteristic formulation of general relativity, Bishop, for a Schwarzschildś background, and Madler, for a Minkowskiś background, were able to show that it is possible to derive a fourth order ordinary differential equation, called master equation, for the J metric variable of the Bondi-Sachs metric. Once
beta, another Bondi-Sachs potential, is obtained from the field equations, and J is obtained from the master equation, the other metric variables are solved integrating directly the rest of the field equations. In the past, the master equation was

solved for the first multipolar terms, for both the Minkowskiś and Schwarzschildś backgrounds. Also, Madler recently reported a generalization of the exact solutions to the linearised field equations when a Minkowskiś background is considered, expressing the master equation family of solutions for the vacuum in terms of Besselś functions of the first and the second kind. Here, we report new solutions to the master equation for any multipolar moment l, with and without matter sources in terms only of the first kind Besselś functions for the Minkowski, and in terms of the Confluent Heunś functions (Generalised Hypergeometric) for radiative (nonradiative) case in the Schwarzschildś background. We particularize our families of solutions for the known cases for l =2 reported previously in the literature and find complete agreement, showing the robustness of our results.

Progress on the numerical calculation of the self-force in the time domain.

Peter Diener

Louisiana State University, USA

Extreme Mass Ratio Inspirals (EMRIś), the inspiral of a small compact object into a massive black hole, promises to be one of the main sources for future space based gravitational wave detectors. In order to model such systems, it is necessary to take into account the interaction of the small object with its own back scattered field (the self-force problem).

The effective source approach to the self-force problem has proven to be a valuable tool in numerical calculations of the self-force in the time domaain. The first self-consistent evolutions of a scalar charge in orbit around a Schwarzschild black hole were performed a few years ago using a finite difference code on a full multi-patch 3D grid. The main limitation of those simulations was the limited accuracy caused by the non-smoothness of the effective source across the particle.

In this talk I will present the ideas and main ingredients of a new code based on the Discontinuous Galerkin method that overcomes the accuracy issue and present some new results.

Post-Newtonian tidal dynamics of a rotating neutron star

Jean Douot

Ecole normale suprieure, Paris, France

The study of the tidal deformations of compact objects has been recently pursued actively because of the implications for the gravitational waves emitted by binary systems. For nonrotating stars, the response to an external tidal field is characterized by the so-called Love numbers. The case of rotating stars is more complex because of couplings between the spin and the tidal perturbation.

A perturbative analysis in general relativity reveals dynamical fluid motions in the starś interior, but cannot distinguish between a response that is bounded or linearly growing in time. Further insight into the problem is given by a post-Newtonian analysis. In this framework, considering a gravitomagnetic tidal field, explicit expressions for the fluidś velocity perturbation can be obtained at first post-Newtonian order, which give the fully dynamical evolution of the fluid. The approach remains valid for non-stationary tidal fields, which is relevant for the orbital evolution of a binary system.

Averaging the average: multi-timescale analysis of precessing black-hole binaries

Davide Gerosa

University of Cambridge, United Kingdom

Spinning black-hole binaries are powerful gravitational-wave sources. Their dynamics is deeply characterized by a timescale hierarchy: the orbital timescale is very short compared to the spin-precession timescale which, in turn, is much shorter than the radiation-reaction timescale on which the orbit is shrinking due to gravitational-wave emission. We use multi-timescale techniques to formulate a new post-Newtonian approach which efficiently disentangles these three dynamical features: orbit, precession and inspiral. Our findings improve our understanding of spin precession in much the same way that the conical sections for Keplerian orbits provide additional insights beyond Newtonś $1/r^2$ law. Our theoretical breakthrough lets us unveil a variety of dynamical features (including morphological phase transitions and precessional instabilities) and allows for an enormous computational speed up. Precession-averaged post-Newtonian inspirals can be calculated from arbitrarily large separations, thus bridging the gap between astrophysics and numerical relativity. More on PRL 114 (2015) 081103 and PRL 115 (2015) 141102.

Gravity waves from plunges into rapidly rotating black holes via Kerr/CFT

Shahar Hadar

DAMTP, University of Cambridge, United Kingdom

Massive objects orbiting a near-extreme Kerr black hole plunge into the horizon after passing the innermost stable circular orbit. The near horizon dynamics of such rapidly rotating black holes is governed by a conformal symmetry. In the talk I will show how this symmetry can be exploited to analytically compute the outgoing gravitational radiation in this process, using a conformal mapping of the plunge to a circular orbit. I will also discuss the holographic interpretation of the process.

Dynamical Tidal Response of a Rotating Neutron Star

Soichiro Isoyama

University of Guelph, Canada

The gravitational wave phase of a neutron star (NS) binary is sensitive to the deformation of the NS that results from its companion's tidal influence. In a perturbative treatment, the tidal deformation can be characterized by a set of dimensionless constants, called Love numbers, which depend on the NS equation of state. For static NSs, one type of Love number encodes the response to gravitoelectric tidal fields (associated with mass multipole moments), while another does likewise for gravitomagnetic fields (associated with mass currents). A NS subject to a gravitomagnetic tidal field develops internal fluid motions through gravitomagnetic induction; the fluid motions are irrotational, provided the star is non-rotating. When the NS is allowed to rotate, the situation is complicated by couplings between the tidal field and the starś spin. The problem becomes tractable in the slow-rotation limit. In this case, the fluid motions induced by an external gravitomagnetic field are fully dynamical, even if the tidal field is stationary: interior metric and fluid variables are time-dependent, and vary on the timescale of the rotation period. Remarkably, the exterior geometry of the NS remains time-independent, though additional types of Love numbers are needed to fully characterize it."

Dynamical Tidal Response of a Rotating Neutron Star

Philippe Landry
University of Guelph, Canada

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When the NS is allowed to rotate, the situation is complicated by couplings between the tidal field and the starś spin. The problem becomes tractable in the slow-rotation limit. In this case, the fluid motions induced by an external gravitomagnetic field are fully dynamical, even if the tidal field is stationary: interior metric and fluid variables are time-dependent, and vary on the timescale of the rotation period. Remarkably, the exterior geometry of the NS remains time-independent, though additional types of Love numbers are needed to fully characterize it.

Gravitational radiation from compact binaries in scalar-tensor gravity

Ryan Lang
University of Wisconsin-Milwaukee, USA

Prior to September 2015, general relativity (GR) had been extensively tested in the solar system and in binary pulsars, but never in the strong-field, dynamical regime. Advanced LIGO's detection of gravitational waves (GWs) from coalescing compact binaries has opened the door to brand-new tests of GR. One particularly interesting alternative to GR is scalar-tensor gravity. We present the calculation of tensor and scalar waveforms for inspiraling compact binaries in a general class of scalar-tensor theories. The waveforms are constructed using a standard GR method known as "Direct Integration of the Relaxed Einstein equations," appropriately adapted to the scalar-tensor case. The tensor waveforms are calculated to second post-Newtonian (2PN) order, where "0PN" is equivalent to the lowest order GR result. The scalar waveforms are calculated to 1.5PN order. We also calculate to 1PN order the rate at which both tensor and scalar waves carry energy away from the system.

Tail-of-tail-of-tail terms in the 4.5 Post-Newtonian radiative mass quadrupole moment

Alexandre Le Tiec
Observatoire de Paris, France

Post-Newtonian theory enables us to predict the gravitational waveform emitted by a system of two coalescing compact objects in its inspiral phase. State-of-the-art works provide the full gravitational emission of compact binaries up to 3.5PN (i.e. up to $1/c^7$). Comparison with numerical relativity, as well as the promising improvement of the gravitational wave detector network, motivate us to push this computation to a higher order. In our current attempt to reach the 4.5PN order (i.e. $1/c^9$), we have computed new contributions to the radiative mass quadrupole at 4.5PN. This radiative quadrupole describes the non-linear interactions of the metric during its propagation from the compact source to future null infinity. One difficulty of this computation is the high-order interactions between the mass of the system and its mass quadrupole, which are commonly called tails. Among these terms, the tail terms and the tail-of-tail terms occurring respectively at 1.5PN and 3PN in the radiative mass quadrupole were already known. Our work (T. Marchand, L. Blanchet and G. Faye in preparation) was to compute the tail-of-tail-of-tail terms occurring at 4.5PN in the radiative mass quadrupole.

A Model for Quasinormal Mode Excitation

Zachary Mark
California Institute of Technology, USA

It is known that the late time gravitational waveform produced by a particle plunging into a Kerr black hole is well described by a sum of quasinormal modes. However, due to the complicated form of the frequency domain Greenś function, it is not yet understood how the early part of the waveform gives way to the quasinormal mode description, which diverges at early times, nor how the inhomogenous part of the waveform contributes. Motivated by Price, Nampalliwar, and Khanna (2016), we offer a model for quasinormal mode excitation by a particle plunging into a Schwarzschild black hole. To develop our model we study approximations to the Regge-Wheeler equation that allow for a closed-form expression of the frequency-domain Greenś function, which we use to isolate the component of the waveform that should be identified with quasinormal ringing. In our description, each quasinormal mode behaves like a damped simple harmonic oscillator which is driven by the plunging particle and then reradiates gravitational waves. Within our model, it is possible to predict and quantify the relative size of the different quasinormal mode contributions. The conventional late time picture of the ringdown as a sum of decaying sinusoids is recovered via general observations of the plunging particle behavior.

Quasinormal Mode Excitation in Extreme Mass Ratio Inspirals

Zachary Mark

California Institute of Technology, USA

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Spin supplementary conditions for spinning compact binaries

Balzs Mikczi

Wigner Research Centre for Physics, HAS, Hungary

It is well-known that the system of Mathisson-Papapetrou equations is incomplete for a spinning test particle, thus choosing some kind of spin supplementary condition (SSC) is necessary. In the literature there are 4 types of SSCs, 2 of which are equivalent considering the spin-orbit interaction. In my presentation I review the classical dynamics of spinning compact binaries with leading-order spin-orbit interaction in all SSCs where the corresponding Lagrangians are

acceleration dependent in two cases. We will construct the generalized Lagrangian and Hamiltonian dynamics for each SSC and then present the orbital motion with the help of conserved quantities. With concrete examples we show how one can eliminate the acceleration terms from the Lagrangian in some cases. Finally, we demonstrate the evolution of the conserved and observed quantities under gravitational radiation (i.e. energy and angular momentum losses and waveform) and discuss their SSC dependence.

Gravitational and electromagnetic responses from a charged black hole

Claudia Moreno
University of Guadalajara, Mexico

We investigate the generation of electromagnetic and gravitational radiation in the vicinity of a perturbed Reissner-Nordstrom black hole. The gravitational and electromagnetic perturbations are studied by solving the Teukolsky master equation with sources, which we take to be locally charged, radially infalling, matter. We obtain a system of four first-order linear partial differential equations that can be solved by separation of variables. This scenario allows us to compare the gravitational and electromagnetic signals that are generated by a common source.

How close can we approach the event horizon of the Kerr black hole from the detection of the gravitational quasinormal modes?

Takashi Nakamura
Kyoto University, Japan

Using the WKB method, we show that the peak location (r_{peak}) of the potential, which determines the quasinormal mode (QNM) frequency of the Kerr black hole (BH), obeys an accurate empirical relation as a function of the specific angular momentum a and the gravitational mass M. I, for example, the QNM with $a/M = 0.9999$ is observed by gravitational wave detectors, we can confirm the space-time around $r_{peak} = 1.01445M$. While if the QNM is different from that of general relativity, we are forced to seek the true theory of gravity and/or face to the existence of the naked singularity.

Tidal deformations of compact objects and their impact for gravitational-wave astronomy

Paolo Pani
Sapienza University of Rome & CENTRA-IST, Lisbon, Italy

The deformability of a compact object induced by a perturbing tidal field is encoded in the tidal Love numbers, which depend sensibly on the objectś internal structure. So far these numbers have been computed only for static, spherically-symmetric objects. We present recent work on the theory of tidal deformability and the tidal Love numbers of a slowly spinning compact object within general relativity. Angular momentum introduces couplings between distortions of different parity and new classes of spin-induced, tidal Love numbers emerge. All tidal Love numbers of a Kerr black hole are exactly zero to first order in the spin and also to second order in the spin, at least in the axisymmetric case. For a binary system close to the merger, various components of the tidal field become relevant. Preliminary results suggest

that spin-tidal couplings can introduce important corrections to the gravitational waveforms of coalescing neutron-star binaries, which are one of the main targets of advanced gravitational-wave detectors.

Applicability of the geodesic deviation equation in GR

Dennis Philipp

ZARM, University of Bremen, Germany

Within the theory of General Relativity we study the solution and range of applicability of the standard geodesic deviation equation in highly symmetric spacetimes. The deviation equation is used to model satellite orbit constellations around the earth. In particular, we reconsider the deviation equation in Newtonian gravity and then determine relativistic effects within the theory of General Relativity. The deviation of nearby orbits, as constructed from exact solutions of the underlying geodesic equation, is compared to the solution of the geodesic deviation equation to assess the accuracy of the latter. Furthermore, we comment on the so-called Shirokov effect in Schwarzschild spacetime.

Dynamic anti-dragging effect in post-newtonian description of stationary, self-gravitating disks

Michal Pirog

Jagellonian University, Poland

I?m going to present the first post-newtonian correction to the angular velocity in stationary, self-gravitating disks systems. It contains three different components ? each of them corresponds with a different phenomenon, has different origin and physical interpretation. The analysis which I?m going to present revealed an utterly new effect of weak gravitational field which slows the rotation down and works against conventional frame dragging. This so called ?anti-dragging? effect is a function of specific enthalpy of the fluid and doesn?t appear for a dust. I will discuss the meaning of each correction and explain the role which they are playing for our understanding the concept of ?keplerian rotation? in general relativity.

Second-order self-force calculations: a progress report

Adam Pound
University of Southampton, United Kingdom

Perturbative self-force calculations have proven to be an important tool in efforts to model binary inspirals. By interfacing with other methods, they can improve models of comparable-mass binaries, and they are currently the only viable method of accurately modeling extreme-mass-ratio inspirals (EMRIs). However, concrete self-force calculations of binary dynamics have until now been restricted to first perturbative order in the binarys̈ mass ratio, which limits their power to assist other models and renders them insufficiently accurate to model EMRIs. In this talk I discuss ongoing work toward self-force computations at second perturbative order, which are expected to be sufficiently accurate for EMRI modeling. These calculations introduce several new difficulties on both the large and small scales of the system. I describe these new obstacles, how they are overcome, and some results for the case of a small, nonspinning object in quasicircular orbit around a Schwarzschild black hole.

Modeling dynamical scalarization of neutron-star binaries

Noah Sennett
University of Maryland, College Park, USA

Direct observations of gravitational waves allow us to probe the highly-relativistic, strong-field regime of gravity for the first time. A promising signal for which to search is the process of “dynamical scalarization” that neutron-star binary systems undergo in certain scalar-tensor theories of gravity. Ground-based gravitational-wave detectors will require highly accurate and reliable analytic models of dynamical scalarization to uncover this effect. Previous efforts to model this phenomenon have spliced non-linear models of scalarization onto existing approximations of the inspiral of a binary system. In this talk we develop a new perturbative formalism that incorporates dynamical scalarization from first principles by partially resumming the post-Newtonian expansion. We calculate the next-to-leading order corrections to the equations of motion and scalar mass of a binary system. By comparing with recent numerical-relativity results we verify that this new approximation scheme can accurately predict dynamical scalarization. This work represents the first steps towards a full waveform model that includes dynamical scalarization in a consistent and conceptually streamlined manner.”

Gravitational waves of core-collapse supernova at post-bounce phase

Hajime Sotani

National Astronomical Observatory of Japan, Japan

We examine the spectra of gravitational waves radiating from protoneutron stars after bounce of core-collapse supernova, where we adopt the relativistic Cowling approximation. To calculate the frequencies of photoneutron stars, we construct the stellar models with the assumption that the protoneutron stars would be quasi-static at each moment. Solving the eigenvalue problem numerically, we obtain the frequencies. Then, we find that the frequencies of f-mode are almost independent from the distributions of electron fraction and entropy per baryon, but depend on the mass and radius of protoneutron stars. In addition, the frequencies are almost proportional to the average density of protoneutron stars, whose proportional constant is completely different from that for cold neutron stars. Thus, combining the observations for the so-called g-mode oscillations around protoneutron stars, one could determine the radius and mass of protoneutron stars via the observation of f-mode oscillations. We will also show the results how the frequencies depend on the progenitor mass and equation of state.

Adiabatic approach to the second order orbital evolution in black hole spacetime

Takahiro Tanaka

Graduate School of Science, Japan

To obtain an accurate template for the gravitational wave form from extreme mass-ratio inspirals of binaries, we need to develop a practical scheme of the second order black hole perturbation caused by a satellite particle. So far, many studies have been done, and the knowledge is actually almost matured. Wed́ like to present a doable approach to compute the long-term phase evolution accurately based on an adiabatic expansion and the decomposition of the Green function into radiative and conservative parts. The necessary computations can be reduced to what we know how to deal with.

Revisiting Hartleś model using perturbed matching theory to second order: amending the mass of rotating stars

Ral Vera

University of the Basque Country UPV/EHU, Spain

Hartle's model describes the equilibrium configuration of a rotating isolated compact body to second order in perturbation theory in GR. The interior is a perfect fluid with a barotropic equation of state, no convective motions and rigid rotation, which is matched across its surface to an asymptotically flat vacuum exterior. Perturbations are taken around a static and spherically symmetric background configuration. Apart from the explicit assumptions, the model is built upon some implicit premises, as the continuity of the functions describing the perturbation in terms of some radial coordinate. We have revisited the model within a recent consistent theory of perturbative matchings to second order, independent of the coordinates and gauges used in the two regions. The matching conditions are explored up to second order in full, and put on firm grounds. However, we find that a function at second order (the "radial" m_0 in the original work), presents a jump at the surface of the star proportional to the value of the interior energy density there. That jump appears in the computation of the total mass of the rotating configuration in terms of the central energy density.

Hamiltonian for an extended test body in curved spacetime: To quadratic order in spin

Justin Vines: Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Germany

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e derive a Hamiltonian for an extended spinning test-body in a curved background spacetime, to quadratic order in the spin, in terms of three-dimensional position, momentum, and spin variables having canonical Poisson brackets. This requires a careful analysis of how changes of the spin supplementary condition are related to shifts of the bodyś representative worldline and transformations of the bodyś multipole moments, and we employ bitensor calculus for a precise framing of this analysis. We apply the result to the case of the Kerr spacetime and thereby compute an explicit canonical Hamiltonian for the test-body limit of the spinning two-body problem in general relativity, valid for generic orbits and spin orientations, to quadratic order in the test spin. This fully relativistic Hamiltonian is then expanded in post-Newtonian orders and in powers of the Kerr spin parameter, allowing comparisons with the test-mass limits of available post-Newtonian results. Both the fully relativistic Hamiltonian and the results of its expansion can inform the construction of waveform models, especially effective-one-body models, for the analysis of gravitational waves from compact binaries.

Inspiral into Gargantua

Niels Warburton
Massachusetts Institute of Technology, USA

We model the inspiral of a compact object into a more massive black hole rotating very near the theoretical maximum. We find that once the body enters the near-horizon regime the gravitational radiation is characterized by a constant frequency, equal to (twice) the horizon frequency, with an exponentially damped profile. This contrasts with the usual "chirping" behavior and if detected would constitute a "smoking gun" for a near-extremal black hole in nature."

Gauge invariant perturbations of Petrov type D space-times

Bernard F Whiting
University of Florida, USA

Gauge invariance is an important property when considering perturbations of geometries in general and black hole spacetimes in particular. The Regge-Wheeler and Zerilli equations are satisfied by gauge invariant perturbations of the Schwarzschild black hole geometry. Both the perturbation of the imaginary part of (a component of the Weyl curvature), and its time derivative, are gauge invariant and solve the Regge-Wheeler equation with different sources. The and perturbations of the Weyl curvature are not only gauge, but also tetrad, invariant. Starting in Schwarzschild, we explore the framework in which these results hold, and consider what generalizations may extend to the Kerr geometry, and presumably to Petrov type D space-times in general.

Gravitational Wave Physics with Binary Love Relations

Kent Yagi
Princeton University, USA

Gravitational waves from the late inspiral of neutron star binaries encode rich information about their internal structure at supranuclear densities through their tidal deformabilities. However, extracting the individual tidal deformabilities of the components of a binary is challenging with future ground-based gravitational wave interferometers due to degeneracies between them. We overcome this difficulty by finding new, approximate universal relations between the individual tidal deformabilities that depend on the mass ratio of the two stars and are insensitive to their internal structure. Such relations have applications not only to gravitational wave astrophysics, but also to nuclear physics as they improve the measurement accuracy of tidal parameters. Moreover, the relations improve our ability to test extreme gravity and perform cosmology with gravitational waves emitted from neutron star binaries.

Evolution of Lagrangeś orbit in the three-body problem due to gravitational radiation reaction

Kei Yamada

Kyoto University, Japan

The gravitational radiation reaction to Lagrangeś equilateral triangular orbit in the three-body problem are investigated. It is found that the configuration of three bodies does not break up at the 2.5 PN order if the mass ratio satisfies the Newtonian stability condition. Also, the triangle adiabatically shrinks and the orbital frequency of the system increases due to the radiation reaction.

Analytic, Frequency-Domain Waveform Models for Generic, Spin-Precessing, Compact Binary Inspirals

Nicolas Yunes

Montana State University, USA

Parameter estimation studies of compact binary gravitational wave signals require fast and accurate waveform models. The gravitational waves emitted by compact binaries with spin angular momenta misaligned with the orbital angular momentum are very difficult to model analytically due to spin-precession. In this talk, I will describe a new method that uses multiple-scale analysis and shifted uniform asymptotics to allow for the construction of accurate, analytic waveform models in the time- and frequency-domain. I will show how these new, frequency-domain waveform models for generic, spin-precessing systems have a typical overlap with numerical models that is higher than 0.999.

Measuring the redshift factor in binary black hole simulations

Aaron Zimmerman

Canadian Institute for Theoretical Astrophysics, Canada

The redshift factor z is an invariant quantity of fundamental interest in Post-Newtonian and self-force descriptions of circular binaries. It allows for interconnections between each theory, and plays a central role in the Laws of Binary Black Hole Mechanics, which link local quantities to asymptotic measures of energy and angular momentum in these systems. Through these laws, the redshift factor is conjectured to have a close relation to the surface gravity of the event horizons of black holes in circular orbits. We have implemented a novel method for extracting the redshift factor on apparent horizons in numerical simulations of quasicircular binary inspirals. Our results confirm the conjectured relationship between z and the surface gravity of the holes. This redshift factor allows us to test PN and self-force predictions for z in spacetimes where the binary is only approximately circular, and

allows for an array of new comparisons between analytic approximations and numerical simulations. I will present our new method, our initial results in using z to verify the Laws of Binary Black Holes Mechanics, and discuss future directions for this work.

Session B4

Baryon Acoustic Oscillations from the SDSS galaxies angular correlation function

Jailson Alcaniz
OBSERVATRIO NACIONAL, Brazil

The 2-point angular correlation function w (2PACF), where; is the angular separation between pairs of galaxies, provides the transversal Baryon Acoustic Oscillation (BAO) signal almost model-independently. In this work we use a sample of luminous red galaxies in the redshift range z=[0.4,0.7], obtained from the tenth and eleventh data release of the Sloan Digital Sky Survey, to estimate BAO(z) from the 2PACF at eleven redshift shells. Since noise and systematics can hide the BAO signature in the plane, we also discuss some criteria to localize the acoustic bump as well as possible sources of model-dependence in the analysis, such as the correction in the BAO(z) position due to projection effects and the CMB estimates of the acoustic scale. Constraints on the dark energy equation-of-state parameter from the BAO(z) diagram are derived in a joint analysis with current CMB measurements. We find that the standard CDM model as well as some of its extensions are in good agreement with these BAO(z) measurements.

Gedanken Experiment Examining How Kinetic Energy Would Dominate Potential Energy, in Pre-Planckian Space-Time Physics, and Allow Us to Avoid the BICEP 2 Mistake

Andrew Beckwith
Chongqing University, China

We use Padmabhan?s ?Invitation to Astrophysics? formalism of a scalar field evolution of the early universe, from first principles, to show something which seems counter intuitive. How could, just before inflation, kinetic energy be larger than potential energy in pre-Planckian physics, and what physics mechanism is responsible for the Planckian physics result that Potential energy is far larger than kinetic energy. This document answers that question, as well as provides a mechanism for the dominance of kinetic energy in pre-Planckian space-time, as well as its reversal in the Planckian era of cosmology. The kinetic energy is proportional to , with initial degrees of freedom, and T the initial temperature just before the onset of inflation.

Our key assumption is the smallness of curvature, as given in the first equation, which permits adoption of the Potential energy and Kinetic energy formalism used, in the Planckian and pre-Planckian space-time physics. Interpretation of this result, if done correctly, will be able to allow a correct distinguishing of relic gravitational waves, as to avoid the BICEP 2 pickup of galactic dust as a false relic Gravitational wave signal, as well as serve as an investigative template as to if quantum gravity is embedded in a deterministic disipative system, as cited in the conclusion.

The CMB spectrum, inflation and quantum-gravity modified dispersion relation

Stefano Bianco
Max Planck Institute for Gravitational Physics, Germany

The recent Planck results tells us two clear features for the CMB: almost scale invariance and a bound on the scalar-to-tensor ratio. We find that a class of quantum-gravity deformed dispersion relations improve the current inflationary model especially for the description of the scale-to-tensor ratio. (COMMENT from ZSUZSA: THis abstract was submitted to both B4and D4. The author asks the chairs to consider in either session whichever fist better. Joanne and Ralf, please discuss. Many thanks!)

Superhorizon effects on the observable universe using numerical relativity

Jordan Braden
University College London, United Kingdom

Although the local universe is well described by a homogeneous and isotropic cosmological model with an early stage of inflation, theoretical considerations suggest that our observable universe may be embedded within a much larger landscape of ultra-large scale superhorizon density fluctuations. If present, this superhorizon complexity encodes information on both the initial conditions for and dynamics of inflation, which themselves depend on the microphysical laws governing our universe. This provides an interesting framework to investigate anomalies in cosmological data, as well as to constrain models of fundamental physics. It is therefore of great interest to investigate the effects of this superhorizon structure on local observables. Using planar symmetric numerical relativity simulations, we investigate the ultra-large scale structure arising from superhorizon fluctuations present at the beginning of inflation. We focus specifically on the CMB quadrupole, an effect known as the Grischuk-Zeldovich effect, although our framework is easily generalised to include additional correlated anomalies. Due to the gravitational nonlinearities, we find the contribution of the superhorizon fluctuations to the local quadrupole becomes increasingly non-Gaussian as the amplitude of the initial fluctuations is increased. This superhorizon contribution is combined with the usual Gaussian contribution

generated by the inflationary phase to produce the observed quadrupole. We find the non-Gaussianity induced by the gravitational nonlinearities significantly alters the predictions of the observed CMB quadrupole power relative to the case of Gaussian superhorizon fluctuations. In a wide range of inflationary models, this in turn significantly alters inferences about the scale of approximate homogeneity.

Gauge inflation with Chern Simons term - 2

Suddhasa Brahma
Fudan University, China

In a previous talk, it was shown that we can have inflation from a particular interaction term between fermionic currents and SU(2) gauge fields, along with a CP violating Chern Simons term. In this talk, I shall derive a small tilt in the spectral index of scalar perturbations as well as the power spectrum for the tensor modes in this model. As is expected in the presence of such terms, the dynamics are different for left and right-polarized primordial gravitational waves.

Precision Predictions for Primordial Power Spectra

Daniel Brooker
University of Florida, USA

We exploit a new numerical technique for evaluating the tree order contributions to the primordial scalar and tensor power spectra for scalar potential models of inflation. Among other things we develop a good analytic approximation for the nonlocal corrections from evolution before and after horizon crossing.

Primordial black holes and the Galactic gamma-ray background

Bernard Carr
Queen Mary University of London, United Kingdom

The fraction of the Universe going into primordial black holes (PBHs) with initial mass g, such that they are evaporating at the present epoch, is strongly constrained by observations of both the extragalactic and Galactic gamma-ray backgrounds. However, while the dominant contribution to the extragalactic background comes from the time-integrated emission of PBHs with initial mass the Galactic background is dominated by the instantaneous emission of those with initial mass slightly larger than and current mass below. Even a tiny initial spread of mass around would generate a low-mass tail of PBHs below today and the mass function of this tail can be predicted very precisely. Also, the instantaneous emission of PBHs smaller than is dominated by secondary particles produced by the decay of directly emitted quark and gluon jets. These points were missed in earlier analyses. We calculate the Galactic background for a variety of scenarios and infer constraints on these scenarios by comparison with the Fermi LAT data. These are stronger than the limits from the extragalactic gamma-ray background or searches for PBH bursts.

Coalescence of Supermassive Black Holes Binaries in AGNs

Claudio Castro
University of Vale do Paraba, Brazil

Recent studies about Active Galactic Nuclei (AGNs) have contributed to a better understanding of our more distant universe. Whereas, one of the most important features of the AGNs is the presence of supermassive black holes (SMBHs) as the main source of its energy and that among the known and classified galaxies as AGNs, some may have binary systems of black hole coalescing. During this coalescence, there is the emission of gravitational waves that, among other processes, are responsible for driving the binary to the merger. Thus, we consider here a promising approach to the study of binary systems immersed in the centers of different types of AGN. In this respect, the goals of this work are to analyze of the reasons for the intensity of emission lines of AGNs and the estimate of coalescence time of SMBHs binaries from these sources. With this, we will show whether certain properties or type of AGNs influence the coalescence time of their SMBHs binary. We will check also the relationship between the black hole and its host galaxy.

Rapid oscillation of gravitational constant G in scalar-tensor theory of gravity: Cosmic evolution and constraints on its early properties

Po-Wen Chang
National Taiwan University, Taiwan

In the scalar-tensor theory of gravity, the concept of gravitational constant G can be replaced with a scalar field non-minimally coupled to gravity. This turns out to be an additional degree of freedom compared to General Relativity and is possible to induce periodic variations (i.e. oscillations) in G by a homogeneous and isotropic massive scalar field. In this talk, we show the equation of motion of can be cast into a fairly graceful formula and the dissipation rate of its effective energy density $l(t)$ behaves differently in three epochs of cosmic evolution: I. , II. and III. where h is the frequency of oscillations. During the epoch I and epoch II, the non-minimal coupling and cosmic expansion could lead to non-trivial effects on the dynamics of scalar field, which make l(t) dissipate much slower than in epoch III. As the universe enters the epoch III, $l(t)$ is in average proportional to $a^($) or $a^($) (a is the scale factor) , depends on the form and the strength of non-minimal coupling. To be consistent with local experiments on G and observational cosmology, we give constraints on the amplitude of G oscillation at the end of reheating in the Higgs inflation and electroweak phase transition from the dynamical behavior of in both linear and quadratic coupling cases. We finally discuss the impact of the constraints on physics in the early universe.

Rapid Oscillation of Gravitational Constant in the Scalar-Tensor Theory of Gravity: the early-time constraints on its induced energy density from cosmology

Po-Wen Chang

National Taiwan University, Taiwan

In the scalar-tensor theory of gravity, the concept of gravitational constant G can be replaced with a scalar field non-minimally coupled to gravity. This turns out to be an additional degree of freedom compared to general relativity and is possible to induce periodic variations (i.e. oscillations) in G by a homogeneous and isotropic massive scalar field. In this research, we show the equation of motion of can be cast into a fairly graceful formula and the dissipation rate of its effective energy density $rho(t)$ behaves differently in three epochs of cosmic evolution. During the epoch I and epoch II, the non-minimal coupling and cosmic expansion could lead to non-trivial effects on the dynamics of scalar field, which make
$rho(t)$ dissipate much slower than in epoch III. As the universe enters the epoch III, $\rho(t)$ is in average proportional to $a^(-2)$ or $a^(-3)$ (a is the scale factor) , depends on the form and the strength of non-minimal coupling. To be consistent with local experiments on G and observational cosmology, we give constraints on the effective energy density contributed from G oscillation at the end of reheating in the Higgs inflation and electroweak phase transition from the dynamical behavior of in both linear and quadratic coupling cases. We finally discuss the impact of the constraints on physics in the early universe.

Density profiles of galaxy clusters in the CFHT Stripe 82 survey from weak gravitational lensing

Maria Elidaiana de Silva Pereira

Brazilian Center for Physics Research, Brazil

Galaxy clusters are important tools to study the matter distribution in the Universe. The only direct mass estimator that can be constructed from this data alone is Weak Lensing (WL), which also has the advantage of being insensitive to the dynamical state of the cluster and is a direct probe of the total mass. To perform WL measurements a high quality imaging survey is mandatory, which is the case of CFHT Stripe 82 (CS82) survey. The CS82 survey covered an area of 170 square degrees on Stripe 82 region in the i-band to a depth of mag AB and mean seeing of 0.6. In this work we focus on the WL measurements - stacking the tangential shear profile - around galaxy clusters, which allows one t o obtain high signal-to-noise profiles even for low mass clusters. In our analysis, the shear measurements of galaxies were computed with the Lensfit code and the cluster identification was made using the redMaPPer algorithm. We fit the derived mean radial profiles by models such as the Navarro-Frenk-White to obtain the mass in each bin and then fit a mass-observable relation. We are also interested in discriminating different theoretical models using these data as well as assessing biases arising from the fact that a bin in the observable combines clusters of different masses with very different numbers. Finally, we

propose a new method to combine the weak lensing signal of clusters without any binning, yielding directly a mass-observable relation.

On the possibility of forming Supermassive Black Holes from Bose-Einstein condensation of dark bosons

Patrick Das Gupta

Department of Physics & Astrophysics, University of Delhi, India

Observed active galactic nuclei at redshifts of about 6 strongly suggest that supermassive black holes (SMBHs) had formed early on. Accretion of matter onto remnants of Population III stars leading to SMBHs is a very slow process, and therefore such models encounter difficulties in explaining distant quasars detected at $z \gtrsim 6$. In this paper, we invoke Bose-Einstein condensation of dark bosons to demonstrate that existence of very light dark matter bosons can lead to generation of SMBHs of mass $m \gtrsim 10^{10} M_{\odot}$ at $z \gtrsim 6$. We predict that scalar/pseudo-scalar particles with mass $\sim 10^{-23}$eV may not only generate SMBHs of mass $m \gtrsim 10^{12} M_{\odot}$ at $z \gtrsim 6$ but also can masquerade as dark matter as well as dark energy. Collapse of such Bose-Einstein condensates with asymmetric configurations can also generate low frequency gravitational waves. We study constraining such scenarios using pulsar timing data.

On our way to a full GR n-body code, gevolution and LAtfield2

David Daverio

African Institute for Mathematical Sciences, South Africa

Cosmological structure formation is a highly non-linear process that can only be studied with the help of numerical simulations. This process is mainly governed by gravity, which is the dominant force on large scales. A century after the formulation of general relativity, numerical codes for structure formation still use Newton?s law of gravitation. In my talk I will present the first n-body code based on equation consistently derived from general relativity, gevolution, and the c++ library used by this code to manage the fields and particles, LATfield2. The first result (CDM and neutrinos) obtained with the gevolution code will be exposed. Finally the future development of LATfield2, with the though of a BSSN n-body code, will be shortly discussed.

Intrinsic Initial Inflation Defines the Finite Mass of a Flat Universe

John Bruce Davies
Dept. of Physics (retd), University of Colorado, Boulder, USA

General relativity governs the large-scale gravitational properties of continuum space-time, while the particle and field history of the universe is governed at the microscopic level by quantum mechanics and component phase transitions. Using our extension of FLRW to the earliest continuum Universe, we show that an exponentially accelerating solution for the Scale Factor approaches a flat Universe for any initial condition, resulting in an equation of state similar to that of Dark Energy. The largest total energy density of the expanding observable Universe is due to the inflation solution of a constant Planck energy density initiated at the earliest Planck time. Assuming that this initial inflation ends in the phase change that results in the constituents attaining the finite mass of the observable Universe, the time of this phase change is determined at about 10-22 secs. At this time it has been postulated that the existing form of matter starts changing from a quark-antiquark-gluon plasma to that of hadrons thereafter. This time is also the mean life-time of the Higgs boson, which particle is considered to mediate the Higgs Field that gives mass to the constituent particles of the Universe. The effect of the Uncertainty Principle is investigated as to the relic energy left after this phase change. This research is based on essays that were awarded Honorable Mentions in the 2014 and 2015 GRF competitions.

Cosmic variance in inflation with two light scalars

Anne-Sylvie Deutsch
Pennsylvania State University, USA

We examine the squeezed limit of the bispectrum when a light scalar with arbitrary non-derivative self-interactions is coupled to the inflaton. We find that when the hidden sector scalar is sufficiently light (m ¡0.25H), the coupling between long and short wavelength modes from the series of higher order correlation functions (of arbitrary order contact diagrams) causes the statistics of the fluctuations to vary in sub-volumes. This means that observations of primordial non-Gaussianity cannot be used to uniquely reconstruct the potential of the hidden field. However, the local bispectrum induced by mode-coupling from these diagrams always has the same squeezed limit, so the field?s locally determined mass is not affected by this cosmic variance.

Unified DE-DM Laden Cosmology in LQC Perspective

Balendra Kumar Dev Choudhury

Pub Kamrup College, India

Observational evidences are strong enough to support the existence of dark matter (DM) and dark energy (DE). But lack of direct detection of them, their existence is, till now, posing a great challenge to researcher, - both in theoretical and experimental field. Instead of classical cosmology, loop quantum cosmology (LQC) might be capable of throwing some light forwarding new cosmological implications. In our proposed work, modified Friedmann equation in LQC is considered incorporating effective density term for a unified DE-DM candidate. Thus some new results come out forwarding new understanding. In addition, remembering thermodynamic study is the common approach to understand dark energy (DE) and dark matter (DM) riddle, it is proposed to pursue this angle in loop quantum cosmology (LQC) aiming to have the status of generalized second law (GSL) in unified DE-DM dominated LQC scenario.

Semiclassical theory of cosmological perturbation

Pietro Dona

Fudan University, China

Motivated by the quantum statistical mechanics definition of coherent state we show that cosmological perturbations can be addressed in term of the semiclassical limit of the expectation value of quantum fields. In particular cosmological linear quantum perturbations can actually be accounted for in terms of composite quantum operator, which must be treated as fundamental quantum objects, and their dynamics. We first test our tools by taking into account cosmological perturbations originated by a quantum scalar field, and then extend our formulation to account for the expectation values of bilinears of Dirac fermion fields. Will will than illustrate other application of coherent states in the study of non-Bunch?Davies vacuum inflations and BCS-like inflation.

The Phase Space of a Cosmological Scalar Field

David Edwards
University of Edinburgh, United Kingdom

When considering a Friedmann-Robertson-Walker universe containing a scalar field the phase space of such a system would appear to be 4 dimensional. Motivated by the attractor nature of simple, slowly rolling inflationary trajectories Remmen and Carroll recently showed that it is possible to consider the space of the scalar field and its time derivative as an effective two dimensional phase space when dealing with the "vanilla" model of a canonical, minimally coupled scalar field. In this talk I will review this previous work, paying particular attention to the question of why this previous result is important. After this, I will move on to more recent work, extending the result to the general Horndeski theory. I will finish with specific examples of common cosmological models where this can be applied.

First-order cosmological perturbations engendered by point-like masses: all scales covered

Maxim Eingorn
North Carolina Central University, CREST and NASA Research Centers, USA

In the framework of the concordance cosmological model the first-order scalar and vector perturbations of the homogeneous background are derived without any supplementary approximations in addition to the weak gravitational field limit. The sources of these perturbations (inhomogeneities) are presented in the discrete form of a system of separate point-like gravitating masses. The obtained expressions for the metric corrections are valid at all (sub-horizon and super-horizon) scales and converge in all points except the locations of the sources, and their average values are zero (thus, first-order backreaction effects are absent). Both the Minkowski background limit and the Newtonian cosmological approximation are reached under certain well-defined conditions. An important feature of the velocity-independent part of the scalar perturbation is revealed: up to an additive constant it represents a sum of Yukawa potentials produced by inhomogeneities with the same finite time-dependent Yukawa interaction range. The suggesting itself connection between this range and the homogeneity scale is briefly discussed along with other possible physical implications.

Anisotropic pressures in cyclic universes

Chandrima Ganguly
University of Cambridge, United Kingdom

Cyclic universe scenarios, like the ekpyrotic model have often been considered as a contender to conventional inflationary scenarios. In this talk, I shall present the results of an investigation on whether scenarios which incorporate a non-singular bounce, do indeed lead to isotropisation on approach to a singularity (or bounce) in the presence of dominant ultra-stiff pressure anisotropies. This study then specialises to consider the closed Bianchi type IX universe and shows that when the anisotropic pressures are stiffer on average than any isotropic ultra-stiff fluid then, they dominate on approach to the singularity. An isotropic ultra-stiff ghost fluid with negative energy density is also included in order to create a cosmological bounce at finite volume in the absence of the anisotropic fluid. When the dominant anisotropic fluid is present it leads to an anisotropic cosmological singularity rather than an isotropic bounce. The inclusion of anisotropic stresses generated by collisionless particles in an anisotropically expanding universe is therefore essential for a full analysis of the consequences of a cosmological bounce or singularity in cyclic universes.

Black holes from cosmic inflation

Jun Zheng
Universitat de Barcelona, Spain

Vacuum bubbles may nucleate and expand during the inflationary epoch in the early universe. After inflation ends, the bubbles quickly dissipate their kinetic energy; they come to rest with respect to the Hubble flow and eventually form black holes. The fate of the bubble itself depends on the resulting black hole mass. If the mass is smaller than a certain critical value, the bubble collapses to a singularity. Otherwise, the bubble interior inflates, forming a baby universe, which is connected to the exterior FRW region by a wormhole. A similar black hole formation mechanism operates for spherical domain walls nucleating during inflation. As an illustrative example, we studied the black hole mass spectrum in the domain wall scenario, assuming that domain walls interact with matter only gravitationally. Our results indicate that, depending on the model parameters, black holes produced in this scenario can have significant astrophysical effects and can even serve as dark matter or as seeds for supermassive black holes.

Cosmological applications of the Shan-Chen equation of state

Daniele Gregoris

Dalhousie University, Canada

In my talk I will address the open question of providing a physical picture of dark energy. I will consider a Friedmann universe whose matter content is given by dust plus a fluid obeying the Shan-Chen equation of state. Such nonideal equation of state exhibits "asymptotic freedom" both at high and low densities; the physical meaning of the free parameters of the Shan-Chen equation of state will be discussed. I will show that it is possible to account for the presence of dark energy at present time in terms of the Shan-Chen fluid without the need of invoking a cosmological constant term. Comparison between the model and the type Ia supernova data will be shown. The stability of the model is also considered. I will also present a cosmological application of the Shan-Chen equation of state for the modeling of the inflationary epoch of our universe within the slow-roll approximation. Comparison between astrophysical data (ratio of tensor to scalar perturbations, scalar spectral index and its running) and model is discussed. The talk is based on the papers Bini, Geralico, Gregoris, Succi, PRD, 2013 & 2014.

Inflationary perturbations in a closed FLRW universe and CMB anomalies

Brajesh Gupt

Pennsylvania State University, USA

We study gauge invariant perturbations in an inflationary FLRW universe with positive spatial curvature. The resulting two point function at the end of inflation shows suppression of power at large scales (corresponding to
$ell < 30$ at CMB). By comparing our results with the recent Planck data we revisit the constraints of spatial curvature and discuss the role of spatial curvature on the estimation of other cosmological parameters. We also highlight the main differences from the standard inflationary scenario in a flat FLRW model and potential implications for non-gaussianity and future observations.

Degeneracy between primordial non-Gaussianity and interaction in the dark sector

Mahmoud Hashim
University of the Western Cape, South Africa

If dark energy and dark matter interact via exchange of energy and momentum, then this may affect the galaxy power spectrum on large scales. When this happens, it may be degenerate with the signal from primordial non-Gaussianity via a scale-dependent bias. We consider a class of interacting dark energy models and show that the matter overdensity is scale dependent on large scales. We estimate the effective non-Gaussianity arising from the large-scale effects of interaction in the dark sector. The signal of dark sector interaction can be disentangled from a primordial non-Gaussian signal by measuring the power at two redshifts.

Ramon Herrera

Pontificia Universidad Catolica de Valparaiso, Chile

A

n inflationary universe scenario in the context of a tachyon field is studied. This study is carried out using an Ansatz for the effective potential of cosmological perturbations $U($
$eta)$. We describe in great detail the analytical solutions of the scalar and tensor perturbations for two different Ansatze for the effective potential of cosmological perturbations: the Eastherś model and an effective potential similar to power law inflation. Also we find from the background equations that the effective tachyonic potentials $V($
$varphi)$ in both models satisfy the properties of a tachyonic potential. We consider the recent data from the Planck to constrain the parameters in our effective potential generating the cosmological perturbations.

Observable effects of general relativistic non-linearities in cosmology, primordial and present

Matthew Johnson
Perimeter Institute and York University, Canada

The dramatic success of Lambda CDM with inflationary initial conditions in describing our observable Universe is predicated on a linearized treatment of Einstein?s equations around an FRW background. But precisely how do we recover the nearly homogeneous, flat, and isotropic Universe that we observe from a spacetime that could be far from homogeneous on large or small scales? How do we obtain quantitative predictions for cosmological observables this context, and what role does the intrinsic non-linearity of GR play? In this talk, I will present a general prescription for extracting locally FRW patches, with the leading corrections, from the output

of fully relativistic cosmological simulations of inflation and non-linear structure formation in a variety of gauges. Many versions of inflationary cosmology predict large inhomogeneities on scales much larger than the observable Universe. Using simulations, I characterize the effect that non-linear fluctuations on large scales have on small scales, testing the ?Separate Universes? assumption. In non-linear structure formation, fluctuations on small scales influence the behavior of the space-time on large scales. For example, a uniform distribution of many compact objects should yield an approximately matter dominated FRW Universe on large scales. By simulating the fragmentation of a scalar field condensate into pseudo-stable bound overdensities known as oscillons, I characterize the degree to which this statement is true. I conclude with a summary of future directions for strong gravity in cosmology.

The Rotation Problem

Michael Jones

University of Colorado-Boulder, USA

On a large scale, inertial frames seem not to rotate relative to the average matter distribution in the universe. Three classical (non-quantum) arguments have been proposed to explain why: (1) existence of absolute space; (2) very special initial conditions; or (3) that gravitational fields (including inertial fields) be completely determined by the matter distribution, with no independent degrees of freedom for the gravitational field. None of those three is a likely explanation. However, a semi-classical approximation to quantum gravity shows that phase interference would cancel out cosmologies with significant relative rotation. A generic general estimate for a perfect fluid cosmology with a realistic variation of vorticity with cosmological scale factor and a specific calculation using a Bianchi model, shows that only cosmologies with a present relative rotation smaller than a value proportional the Planck length and to the square of the Hubble parameter (about 10 to the -71 radians per year) could contribute significantly to a measurement of relative rotation rate.

Time-Dependent Scalar Mode Functions effect to Non-Gaussianity

Emre Onur Kahya

Instanbul Technical University, Turkey

I will discuss quantum gravitational loop effects to observable quantities such as curvature power spectrum and primordial non-gaussianity of Cosmic Microwave Background (CMB) radiation. We first review the previously shown case where one gets a time dependence for zeta-zeta correlator due to loop corrections. Then we investigate the effect of these loop corrections to primordial non-gaussianity of CMB.

On homogeneous and isotropic universe

Mikhail Katanaev
Steklov Mathematical Institute, Moscow, Russia

We give a simple example of spacetime metric, illustrating that homogeneity and isotropy of space slices at all moments of time is not obligatory lifted to a full system of six Killing vector fields in spacetime, thus it cannot be interpreted as a symmetry of a four dimensional metric. The metric depends on two arbitrary and independent functions of time. One of these functions is the usual scale factor. The second function cannot be removed by coordinate transformations. We prove that it must be equal to zero, if the metric satisfies Einsteinś equations and the matter energy momentum tensor is homogeneous and isotropic. A new, equivalent, definition of homogeneous and isotropic spacetime is given.

Stochastic cosmological lensing

Julien Larena
Rhodes University, South Africa

For small cosmological sources like supernovae, the matter distribution along the line of sight cannot accurately be described as a smooth fluid. This questions the applicability of standard cosmological lensing to that type of sources. In this talk, I will present a new method to take into account the granularity of the lensing matter. This method relies on a description of small-scale lensing as a diffusion process; the Sachs and Jacobi equations are recast in the form of Langevin equations for which Fokker-Planck-Kolmogorov equations will be derived. I will then use this formalism to derive some analytical properties of the average and dispersion of the angular diameter distance. Finally, applying the formalism to a particular case of random Swiss-Cheese models, I will present the results of a post Kantowski-Dyer-Roeder approximation, and discuss the shortfalls and future outlooks for the method.

Chern-Simons Inflation: Inflation from fermionic matter interacting with a gauge field

Antonio Marciano
Fudan University, China

I present results from works in collaboration with S. Alexander, A. Kosowsky and D. Spergel, in which a model of Inflation has been developed relying on a U(1) gauge field and on standard fermionic matter. The model is based on the interaction between a homogeneous and isotropic configuration of the U(1) gauge field and the fermionic charge density. The regulated fermionic charge density is found to redshift as the inverse of the gravitational scale factor. The time-like component of the gauge field is sourced by the fermionic charge, leading to a growth in the gauge field proportional to the scale factor. Consistency of the model is ensured via the

Stueckelberg mechanism. There exists exactly one stable solution, the stability of which can be demonstrated numerically. Inflation arises then without fine tuning, and does not require postulating any effective potential or non-standard coupling. I close the overview mentioning recent work with collaborators at Fudan University on a generalization involving Yang-Mills fields which is phenomenologically richer.

Toward a unification between standard particle physics inspired models for Dark Energy and Dark Matter

Antonio Marciano
Fudan University, China

In collaboration with S. Alexander and Z. Yang we shown that the late time acceleration of the universe can be accounted for by an extension of the QCD color to a SU(3) invisible sector (IQCD). We will review there results and we will discuss a unified framework where the scale of dark chiral-breaking dictates both the accelerated expansion of the universe, and the origin of dark matter that has been developed with S. Alexander and A. Addazi. The strong and gravitational dynamics of dark quarks and gluons evolve to eventually form exotic dark stars, the dynamical complexity of these dark compact objects will be discussed in light of dark big bang nucleosynthesis. We will also discuss possible phenomenological implications in dark matter searches and argue that dark supernovae and dark binaries can emit very peculiar gravitational waves signal testable by the LIGO/VIRGO collaboration and future projects dedicated to these aspects.

Graceful exit in Topological Inflation

Anja Marunovic
Utrecht University, Netherlands

We investigate a class of models of topological inflation in which a super-Hubble-sized global monopole seeds inflation. These models are attractive since inflation starts from rather generic initial conditions, but their not so attractive feature is that, unless symmetry is again restored, inflation never ends. In this work we show that, in presence of another nonminimally coupled scalar field, that is both quadratically and quartically coupled to the Ricci scalar, inflation naturally ends, representing an elegant solution to the graceful exit problem of topological inflation. While the monopole core grows during inflation, the growth stops after inflation, such that the monopole eventually enters the Hubble radius, and shrinks to its Minkowski space size, rendering it immaterial for the subsequent Universeś dynamics. Furthermore, we find that our model can produce cosmological perturbations that source CMB temperature fluctuations and seed large scale structure statistically consistent (within one standard deviation) with all available data. In particular, for small and (in our convention) negative nonminimal couplings, the scalar spectral index can be as large as n_s
$simeq 0.955$, which is about one standard deviation lower than the central value quoted by the most recent Planck Collaboration.

Galaxies Simulations with Scalar Field Dark Matter

Tonatiuh Matos

Departamento de Fisica, Centro de Investigacion y de Estudios Avanzados del IPN, Mexico

The Scalar Field Dark Matter (SFDM) model (also called Wave Dark Matter, Ultra-Light Axion dark matter or Bose-Einstein Condensate dark matter) has shown to be an excellent candidate to be the dark matter of the universe. This model is in excellent agreement with cosmological observations like the mass power spectrum, the CMB observations, etc. The model predicts core central density profiles in galaxias and a natural cut of in the structure formation. Using the SFDM model we recover spiral and barred spiral patterns in disk galaxy simulations. We show how the interaction between a baryonic disk and its Dark Matter Halo triggers the formation of spiral structures when the halo is allowed to have a triaxial shape and angular momentum. This is a more realistic picture within the SFDM model since a nonspherical rotating halo seems to be more natural. By performing hydrodynamic simulations, along with earlier test particles simulations, we demonstrate another important way in which SFDM is consistent with observations. The common existence of bars in these simulations is particularly noteworthy.

Possible geometrical origin of the accelerated expansion of the universe

Ariadna Montiel

Physics Department, Cinvestav, Mexico

The modified geodetic brane cosmology (MGBC) is tested with observational data. The MGBC is derived from the geodetic brane gravity action corrected by the extrinsic curvature of the braneworld. The density parameter coming from this additional term produces an accelerated expansion of geometrical origin. Subject to the Supernovae Ia, Observable Hubble parameter, Baryon Acoustic Oscillations and Cosmic Microwave Background probes, the obtained fit provides enough evidence in the sense that the extrinsic curvature effect is able to reproduce the accelerated expansion of the universe without need of invoking dark energy, exotic matter or cosmological constant. Moreover the MGBC is free of the problems present in other braneworld models.

Litmus Test for Cosmic Hemispherical Asymmetry from CMB B-mode polarization

Suvodip Mukherjee
IUCAA, India

Recent measurements by WMAP and Planck have confirmed more than 3 *sigma* departure from Statistical Isotropy (SI) in the temperature field of cosmic microwave background (CMB) at large angular scales, which is popularly known as Hemispherical Asymmetry. Cosmological origin of such an anomalous signal is beyond the standard LCDM cosmological model and is a challenge to one of the fundamental assumption of cosmology. Speaker will discuss about an inevitable effect arising from the weak lensing of CMB photons by cosmic hemispherical asymmetry imprinted Large Scale Structure. Presence of this asymmetry in the scalar perturbations can naturally put its signatures also in the matter distribution at very large angular scales, which in turn can generate B mode polarization by converting E mode polarization through weak lensing. This mechanism can induce statistical isotropy violated B mode polarization at small angular scales which can be measured from future CMB mission like CMB Stage IV. The property of this phenomena to translate the effects of hemispherical asymmetry from large angular scales in matter distribution to small angular scales in B mode polarization makes it a clinching window to explore the origin of this asymmetry.

Curvature perturbation, gravitational collapse and primordial black hole formation

Ilia Musco
Laboratoire Univers et Thories (LUTH), Observatoire de Paris, France

Cosmological perturbations, of the type expected to have come from inflation, have been shown to collapse after horizon crossing and give rise to primordial black holes (PBHs) in the early universe if the perturbation amplitude is larger than a threshold which depends on the equation of state and the perturbation profile. The connection between the abundance of PBHs and the critical amplitude is very sensitive and provides a strong tool to constrain different models of inflation. I will present results coming from my personal simulations, where a time independent curvature profile has been used to to generate initial conditions during the regime of the linear growth of cosmological perturbations in the early universe, when perturbation length-scales are much larger than the cosmological horizon. This method to impose initial conditions in a cosmological settings, is interesting beyond the PBH scenarios, to study more in general the formation of structure in LCDM early universe. I will clarify how this approach is related to the gauge choice of the curvature perturbation, investigating then how the threshold for PBH formation is changing when two perturbations specified on two different length sales are coupled together.

Slow roll inflation and BB mode angular power spectrum of CMB

Malsawmtluangi N

University of Hyderabad, India

The BB-mode correlation angular power spectrum of CMB is obtained by considering the primordial gravitational waves in the squeezed vacuum state for various inflationary models and results are compared with the joint analysis of the BICEP2/Keck Array and Planck 353 GHz data. The present results may constrain several models of inflation.

Anisotropies of Gravitational-Waves from Black-Hole Binaries as a Tracer of Dark Matter

Atsushi Nishizawa

University of Mississippi, USA

Recent detection of the gravitational waves (GWs) emitted from a black hole (BH) binary implies a higher merger rate of BH binaries than the expectation. An important astrophysical test for the BH binaries is to statistically analyze the properties of their host galaxies and to see how they trace the matter inhomogeneities in the Universe. So far no observational evidence exists for the clustering properties of the BH binaries because of the difficulty to observe them with electromagnetic waves. In this presentation, based on the method to detect the anisotropies of luminosity distance observed by GWs, which was proposed in our recent paper [Namikawa, Nishizawa, & Taruya, to be published in Physical Review Letters], we discuss whether the second-generation GW detector network can find the evidence of BH binary clustering, showing how significantly the BH binaries trace the cosmological matter density fluctuations. We find that by cross-correlating with other cosmological observations such as galaxy surveys, the clustering signals of the BH binaries can be detected for the intermediate merger rate of BH binaries and allow us to estimate the galaxy bias (how much the BH binaries trace the matter density fluctuations). We also show that future GW detectors such as Einstein Telescope are able to precisely measure source luminosity distances out to high redshifts and extract cosmological information at very high redshifts (z 2), where the identification of the electromagnetic counterpart is typically difficult.

On the Creation of Emergent Universe with Dynamical Wormhole

Bikash Candra Paul
University of North Bengal, India

We investigate the emergent universe scenario in the presence of interacting fluids. The non-linear equation of state (EoS) considered in the general theory of relativity for obtaining emergent universe is effectively a cosmological model with a composition of three fluids. In this paper we consider two models to realize viable cosmological scenarios, *viz.*, (i) a two-fluid model with interaction of a pressure-less fluid with the fluid having the non-linear EoS needed for the emergent universe, and (ii) a three-fluid model with interaction among the three fluids which originate from the EoS of the emergent universe. It is found that realistic cosmological models in accordance with observations are not ruled out for both the above cases. The origin of a static de Sitter phase needed for an emergent Universe is obtained making use of a dynamical wormhole in massive gravity theory.

Dark energy from non-unitarity in quantum theory

Alejandro Perez
Centre de Physique Theorique, France

We consider a scheme whereby it is possible to reconcile semi-classical Einsteinś equation with the violation of the conservation of the expectation value of energy-momentum that is associated with dynamical reduction theories of the quantum state for matter. The very interesting out-shot of the formulation is the appearance of a nontrivial contribution to an effective cosmological constant (which is not strictly constant). This opens the possibility of using models for dynamical collapse of the wave function to compute its value. Another interesting implication of our analysis is that tiny violations of energy-momentum conservation with negligible local effects can become very important on cosmological scales at late times.

DE as self gravitating medium

Luigi Pilo
Dept. of Physical and Chemical Sciences Univ. of L'Aquila, Italy

A unifying picture for dark energy (DE) is proposed. If DE is not a cosmological constant new degrees of freedom in the gravitational sector should be introduced. Such new degrees of freedom can be interpreted as coordinates describing as a self-gravitating medium with dynamical and thermodynamic properties dictated by symmetries with observational distinguishable signatures. Interesting examples of self-gravitating media are: fluids, super fluids and solids. The dark sector is then described as a self-gravitating medium with dynamical and thermodynamic properties dictated by internal symmetries. In addition, it appears that the divide between dark energy and modified gravity, at large distance scales, is simply a gauge choice. The presented result are based on arXiv:1603.02956 and two forthcoming papers.

Quantum Cosmological Perturbations of Multiple Fluids and Application to Bouncing Models

Nelson Pinto-Neto

Centro Brasileiro de Pesquisas Fisicas - CBPF, Brazil

The formalism to treat quantization and evolution of cosmological perturbations of multiple fluids is described. The final Hamiltonian is obtained without assuming any equations of motion for the background variables. This general formalism is applied to the special case of two fluids, having in mind the usual radiation and matter mix which made most of our current Universe history. Quantization is achieved using an adiabatic expansion of the basis functions. This allows for an unambiguous definition of a vacuum state up to the given adiabatic order. Using this basis, we show that particle creation is well defined for a suitable choice of vacuum and canonical variables, so that the time evolution of the corresponding quantum fields is unitary. This provides constraints for setting initial conditions for an arbitrary number of fluids and background time evolution. We also show that the common choice of variables for quantization can lead to an ill-defined vacuum definition. Our formalism is not restricted to the case where the coupling between fields is small, but is only required to vary adiabatically with respect to the ultraviolet modes, thus paving the way to consistent descriptions of general models not restricted to single-field (or fluid). The formalism is then aplied to bouncing models with dust and radiation and a comparison with current observations concerning the anisotropies of the CMBR is made, showing that such models can be competitive with usual inflationary models.

Constraining the mysterious dark matter with recent cosmological and galactic observations

Victor Hugo Robles

Federal University of Rio de Janeiro - UFRJ, Brazil

So far, the predictions of general relativity (GR) have been confirmed in the local universe, thanks to recent high-resolution cosmological observations we can test the theory at large and galactic scales at different stages of the evolution, but in order to do this we need to know the nature of the dark matter (DM), a necessary component that is not explained with any known matter but whose existence is required in the theory of GR. I will show that assuming the standard collision-less DM model leads to some discrepancies with galaxy observations at small scales despite successfully reproducing the cosmological expansion, however, I will show that these issues may find a natural explanation in the scalar field dark matter (SFDM) model where DM is a spin-0 scalar field with a very small mass that leads to a quantum behavior at galactic scales, this stresses the importance of obtaining observations at different scales and epochs to understand DM and then use it as a test to the General Relativity theory.

Adiabaticity and gravity theory independent conservation laws for cosmological perturbations

Antonio Romano
NONE GIVEN

So far, the predictions of general relativity (GR) have been confirmed in the local universe, thanks to recent high-resolution cosmological observations we can test the theory at large and galactic scales at different stages of the evolution, but in order to do this we need to know the nature of the dark matter (DM), a necessary component that is not explained with any known matter but whose existence is required in the theory of GR. I will show that assuming the standard collision-less DM model leads to some discrepancies with galaxy observations at small scales despite successfully reproducing the cosmological expansion, however, I will show that these issues may find a natural explanation in the scalar field dark matter (SFDM) model where DM is a spin-0 scalar field with a very small mass that leads to a quantum behavior at galactic scales, this stresses the importance of obtaining observations at different scales and epochs to understand DM and then use it as a test to the General Relativity theory.

Cosmological Model and Higher Deritatives for the scalar field

Joel Saavedra
Pontificia Universidad Catolica de Valparaiso, Chile

We would like to show a model involving higher deritavive ins the scalar sector and show that we can elimanted the instability associated, and therefore obtain one well behaver model, where the ghost ans linear instability are moved out of the model

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Cosmic Inflation with and without Viscous Pressure

Rabia Saleem
Government College, Lahore, Pakistan

The aim of this work is to study the warm inflation during intermediate era. We assume that the universe is composed of inflaton and imperfect fluid having radiation and bulk viscous pressure. A necessary condition is developed for the realization of the anisotropic model using slow-roll parameters. We assume both dissipation and bulk viscous coefficients variable as well as constant. We evaluate entropy density, scalar (tensor) power spectra, their corresponding spectral indices, tensor-scalar ratio and running of spectral index in terms of inflation. These cosmological parameters are constrained using recent Planck observations.

Relativistic cosmological modelling for non-linear structure formation

Viraj Sanghai
Queen Mary University of London, United Kingdom

We construct a framework to probe the effect of non-linear structure formation on the large-scale expansion of the universe. We take a bottom-up approach to cosmological modelling by splitting up our universe into cells. The matter content within each cell is described by the post-Newtonian formalism. We assume that most of the cell is in the vicinity of weak gravitational fields, so that it can be described using a perturbed Minkowski metric. Our cells are patched together using the Israel junction conditions. We impose reflection symmetry across the boundary of these cells. This allows us to calculate the equation of motion for the boundary of the cell and, hence, the expansion rate of the universe. At Newtonian order, we recover the standard Friedmann-like equations. At post-Newtonian orders, we obtain a correction to the large-scale expansion of the universe. As an example, we use this framework to investigate the cosmological evolution of a large number of regularly arranged point-like masses. At post-Newtonian orders, for a late time dust dominated universe, we get corrections to the dust term and we get an additional term that takes the same form as radiation. The radiation-like term is a result of the non-linearity of Einsteinś equations, and is due to the inhomogeneity present in our model. We then include a cosmological constant, radiation and spatial curvature in our model and study its influence on this radiation-like correction.

What do the cosmological supernova data really tell us?

Ibrahim Semiz
Bogazici Univ. Physics Dept, Turkey

We try to reconstruct the scale factor $a(t)$ of the universe from the SNe Ia data, i.e. the luminosity distance $d_L(z)$, using only the cosmological principle and the assumption that gravitation is governed by a metric theory. In our hence *model-independent*, or *cosmographic* study, we fit functions to $d_L(z)$ rather than $a(t)$, since $d_L(z)$ is what is measured. We find that the acceleration history of the universe cannot be reliably determined in this approach due to the irregularity and parametrization-dependence of the results. However, adding the GRB data to the dataset cures most of the irregularities, at the cost of compromising the model-independent nature of the study slightly. Then we can determine the redshift of transition to cosmic acceleration as $z_t \sim 0.50 \pm 0.09$ for a flat universe (larger for positive spatial curvature). If Einstein gravity (GR) is assumed, we find a redshift at which the density of the universe predicted from the $d_L(z)$ data is independent of curvature. We use this point to derive an upper limit on matter density, hence a lower limit on the density of dark energy. While these limits do not improve the generally accepted ones, they are derived without using an EoS.

Inflationary Models: Viability and the Quantum-Classical Transition.

Daniel Sudarsky
ICN-UNAM, Mexico

The stringent bounds on the tensor primordial perturbations in the CMB spectrum are being used to assess the viability of various inflationary models. However these kind of analysis ignore the fact that the connection of models to observations depend on a rather particular views regarding the quantum/classical transition leading to the primordial seeds of cosmic structure. I will discuss the issue, presenting various alternative options leading to radically different expectations regarding the tensor modes, while preserving those regarding the scalar perturbations.

A fully relativistic Zeldovich approximation to describe multiple structures

Roberto Sussman
ICN-UNAM, Mexico

We examine the evolution and collapse of multiple 30-100 Mpc sized "pancake" and "filament" shaped CDM structures constructed with the Szekeres dust models. The dynamics of these structures follows from a fully relativistic generalization of the Zeldovich approximation, thus allowing for a fully relativistic generalization of the Newtonian "spherical" and "elliptic" collapse models used in numerical simulations. The Szekeres multi-structure models are potentially useful in fitting observations whenever a non-perturbative and fully relativistic approach is needed.

Late time cosmology with eLISA

Nicola Tamanini
Institut de Physique Thorique - CEA/Saclay, France

In this talk I will consider the application of eLISA as a probe of the late-time cosmological expansion. In particular I will first review the concept of standard sirens and how these can be used to investigate the distant-redshift relation. I will then discuss the best strategies to obtain as many standard sirens as possible, taking into account what kinds of electro-magnetic counterparts could reasonably be detected and by which instruments. Finally, employing realistically simulated data, I will present the eLISA forecasted constraints on the cosmological parameters of LambdaCDM and alternative cosmological models.

Explore the early universe via relic gravitational waves constrained by pulsar timing arrays, cosmic microwave background and big bang nucleosynthesis

Minglei Tong
National Time Service Center, Chinese Academy of Sciences, China

Relic gravitational waves (RGWs) generated at the end of inflation, carry abundant information about the very early universe. One can understand the scenario of the early universe through RGWs constrained by the current various observations. In this paper, we will constrain the RGWs using the observations from pulsar timing arrays (PTAs), cosmic microwave background (CMB) and big bang nucleosynthesis (BBN), combining with the theories of the generation of RGWs. From the current NANOGrav, we constrained the inflation index to be $\lesssim 11.71$ for $r = 0.11$. We also got upper limit curves depending on the reheating temperature for given values of the tensor-to-scalar ratio r from the observations of CMB/BBN. Besides, we obtained another upper limit curve depending the reheating temperature from the origination of RGWs. Applying these constraints, we obtained the corresponding constraints on the reheating processes under the validity of the quantum normalization condition. We also discussed the detection on RGWs in future by the method of the PTAs. It is found that, the future SKA will have the ability to rule out some models of RGWs or give a more stringent upper bound, rendering an important probe to the very early universe.

A Geometrical Non-Inflationary Interpretation of Cosmic Microwave Background Uniformity

Branislav Vlahovic
North Carolina Central University, USA

A large scale homogeneity and isotropy is not required by classical GR theory. It is well known that in the BB models homogeneity of space cannot be explained, it is simply assumed in the initial conditions. We will show that the observed uniformity in the CMB does not mean that space was uniform at the time of decoupling. In the framework of the CDM model supplemented in the spherical space with an additional perfect fluid (namely, quintessence with the constant parameter u in the linear equation of state) there is an elegant solution [1] of the horizon problem without inflation: under the proper choice of the parameters light travels between the antipodal points during the age of the Universe. Consequently, one may assume that the observed CMB radiation originates from a very limited antipodal space region, which explains its uniformity. Therefore, measuring the same CMB by looking in the opposite directions of the Universe does not represent or reflect the uniformity of the Universe at the time of decoupling. There are some difficulties when one tries to adjust the proposed concept to the CMB anisotropy arriving at the necessity to change the amplitude of the initial power spectrum. However, the changes that should be done are well inside experimentally allowed constrains. The model also

satisfies supernovae data at the same level of accuracy as the ECDM model. [1] B. Vlahovic, M. Eingorn, C. Ilie, Modern Physics Letters A, Vol. 30, No. 35 (2015) 1530026.

Differential expansion of space and the Hubble flow anisotropy

David Wiltshire
University of Canterbury, New Zealand

In general relativity inhomogeneities generically produce differential expansion of space which is not equivalent to a homogeneous isotropic cosmology plus local boosts, as assumed in the current standard model. We present the first ray tracing simulations of small scale structure constrained by both actual large galaxy surveys (the COMPOSITE sample) and the Cosmic Microwave Background (CMB). We use exact Szekeres solutions on scales $\lesssim 70/h$ Mpc which asymptote to a Planck-satellite normalized FLRW model on scales $\gtrsim 100/h$ Mpc. The simulations are consistent with the hypothesis that the component of the CMB dipole anisotropy usually attributed to a 635 km/sec boost of the Local Group of galaxies is better modelled as a differential expansion of space induced by inhomogeneities including the Local Void and Great Attractor. Our simulations are able to model features of the local expansion that the FLRW assumption does not account for. While we still need additional structures to account for a sub-dominant Hubble expansion quadrupole, our approach if further substantiated is likely to have a significant impact on observational and theoretical cosmology. As one example, our results will potentially impact on large angle anomalies in the angular power spectrum. With further refinement our models can be tested directly for their effect on the anomalies in the CMB map making pipeline. Reference: K. Bolejko, M.A. Nazer and D.L. Wiltshire, arXiv:1512.07364

Fine Tuning May Not Be Enough

Richard Woodard
University of Florida, USA

This talk is based on arXiv:1506.07306. We argue that the fine tuning problems of scalar-driven inflation may be worse than is commonly believed. The reason is that reheating requires the inflaton to be coupled to other matter fields whose vacuum fluctuations alter the inflaton potential by terms which are not Planck-suppressed. The usual response has been that even more fine-tuning of the classical potential $V(\varphi)$ can repair any damage done in this way. We point out that the effective potential in de Sitter background actually depends in a complicated way upon the dimensionless combination of φ/H. We also show that the factors of H^2 which occur in de Sitter do not correspond to $R/12$ for a general metric, which is the one dependence which would be allowed for a counterterm. In fact, the dependence is not even local so it cannot be subtracted, although it might be nulled at one instant.

Gauge inflation with Chern Simons term - 1

Zhi Yang
Fudan University, China

We propose a model for inflation which does not assume any fields outside the standard model of particle physics. In this talk, I would demonstrate how an interaction term between the fermionic currents and the gauge fields can drive the inflationary background. The spectra of scalar perturbations would also be derived and be shown to be scale invariant as required. The associated Chern-Simons term of the SU(2) gauge fields will lead to a slight tilt in the spectral index, as will be shown in a companion talk.

Cosmic bulk viscosity through backreaction

Winfried Zimdahl
Universidade Federal do Esprito Santo, Brazil

We consider an effective viscous pressure as the result of a backreaction of inhomogeneities within Buchert's formalism. The use of an effective metric with a time-dependent curvature radius allows us to calculate the luminosity distance of the backreaction model. This quantity is different from its counterpart for a "conventional" spatially flat bulk viscous fluid universe. Both expressions are tested against the SNIa data of the Union2.1 sample with only marginally different results for the distance-redshift relation and in accordance with the Λ CDM model. Future observations are expected to be able to discriminate among these models on the basis of indirect measurements of the curvature evolution. Reference: R.M. Barbosa, E.G.Chirinos, W. Zimdahl, O.F. Piattella, arXiv: 1512.07835 to be published in GRG

Session C1

Developments in low-frequency gravitational-wave searches in the European Pulsar Timing Array

Nicolas Caballero

Max Planck Institute for Radio Astronomy, Germany

The recent detection of gravitational waves (GWs) by the LIGO collaboration was a great example of how to work towards a robust GW detection. In this talk I will discuss recent work and results from the European Pulsar Timing Array as part of our efforts to efficiently use our data to find any possible evidence for GWs, which are expected to first appear at low significance, and our approach to ensure the robustness of future detections.

A population of periodic quasars from PTF as milliparsec supermassive black hole binaries-Prospects for PTA discovery

Maria Charisi

Columbia University, USA

Supermassive Black Hole Binaries (SMBHBs) are the natural result of galaxy mergers and are thought to be fairly common in galactic nuclei. Compact SMBHBs are strong sources of low-frequency gravitational radiation, which will be detected by near-future Pulsar Timing Arrays. Hydrodynamical simulations of circumbinary disks predict that the mass accretion rate onto the BHs is periodically modulated on timescales comparable to the orbital period of the binary. Therefore, SMBHBs may be recognized by the periodic modulation of their brightness. We performed a systematic search for periodic variability in a large sample of quasars, in the photometric database of the Palomar Transient Factory. We identified 33 quasars with statistically significant periodicity and short periods of a few hundred days. Assuming that the observed periods correspond to the redshifted orbital periods of SMBHBs, we conclude that our findings are consistent with a population of unequal-mass SMBHBs, with a typical mass ratio as low as $q = M2/M1 \sim 0.01$. I will discuss the prospects for discovery of gravitational waves from our SMBHB candidates with current and future Pulsar Timing Arrays.

Fast Radio Bursts: Searching for needles in a very large haystack

Shami Chatterjee
Cornell University, USA

Searches for pulsars at radio wavelengths have turned up intriguing single pulses whose dispersion measure indicates a probable extragalactic origin. Their energy budget remains unclear, and many scenarios have been proposed for their origin, from the local and mundane to the cosmological and exotic. In particular, the repeating Fast Radio Burst, FRB 121102, demonstrates that the sources of at least some FRBs survive the events, but the wide range of spectral shapes and scattering properties of FRBs is as yet unexplained. The identification of a host galaxy by interferometric localization or the detection of a multiwavelength counterpart remains the key to progress. Here we present an overview of these Fast Radio Bursts and the ongoing quest to localize them on the sky, identify their hosts, and understand their origins.

A Gravitational Wave Processing-Enabled Archive

Robert Ferdman
McGill University, Canada

Pulsar timing array data sets comprise pulsar timing data and data products from a continuing decades-long campaign of observations and high-precision analysis of over 40 millisecond pulsars, conducted with the intent to detect nanohertz gravitational waves. Employing a team of developers, researchers and undergraduates, the North American Nanohertz Gravitational Wave Observatory (NANOGrav) have built an open-source interface based on iPython/Jupyter notebooks, allowing for detailed processing and analysis via direct access to archived raw data and data products.
We also provide a separate web visualization interface, primarily developed by undergraduates, that allows the user to perform natural queries for data table construction and download, and providing an environment for plotting both primary science and diagnostic data; the next iteration of this interface will allow for real-time analysis tools such as model fitting, high-precision timing, and of course, gravitational-wave searches.
This flexible and powerful framework will certainly enhance science throughput, and address issue of both data provenance, as well as analysis transparency and reproducibility. Importantly, it will also provide an intuitive "sandbox" environment with a growing standard suite of pulsar and astronomical data analysis software , enhance learning opportunities for students, and drive the development and sharing of new open-source analysis tools that we aim to expand to other telescope data and collaborations.

Peculiar results of long-term millisecond pulsar timing

Gemma Janssen
ASTRON, The Netherlands Institute for Radio Astronomy, The Netherlands

I will present results of the long-term timing campaign with the European Pulsar Timing Array. With our data set being extended both back in time by including the first timing instruments, as well as being improved with the next-generation observations, we have discovered some interesting and unexpected results. Since gravitational wave detection in the nanohertz regime with pulsars is dependent on having very stable and well-modelled pulsars, any surprise feature in the data needs to be understood to be able to push our limits towards detection levels. This results in interesting science ranging from the interior of neutron stars to the evolution of an extremely long binary system.

The International Pulsar Timing Array

Andrea Lommen
Franklin & Marshall University

The Bridge is a web-based portal designed to foster an ever-broadening community of researchers willing to engage with and investigate gravitational wave data, and in particular the pulsar timing array data of NANOGrav. The Bridge makes data products and tools available to the broader astronomical community in an elegant, user-friendly, and efficient package. The portal also leverages the public?s interest in the enterprise by enabling their ability to participate in gravitational wave science in the post-detection era.

Pulsar Timing Arrays Beyond the Stochastic GW Background

Dustin Madison
National Radio Astronomy Observatory, USA

Orthodox models for the nanohertz gravitational wave (GW) stochastic background are increasingly in tension with current pulsar timing array (PTA) upper limits. As such, nearby supermassive black hole mergers may occur more frequently than previously thought, eccentricity may play an integral role in binary black hole evolution, and unconventional sources of GWs may prove key to an initial GW detection by PTAs. I will discuss recent efforts to detect localized burst-like sources of GWs using PTAs and near-future prospects for improving PTA sensitivity to such sources.

NANOGrav High-Precision Pulsar Timing and the Search for Nanohertz Gravitational Waves

David Nice

Lafayette College, USA

The NANOGrav collaboration makes high-precision radio telescope observations of an array of millisecond pulsars with the goal of detecting gravitational waves in the nanohertz band, i.e., gravitational waves with periods of several years. Gravitational waves will be detected via small perturbations in measured pulse arrival times correlated across the pulsars in the array.

We use the Green Bank Telescope and Arecibo Observatory to observe 54 millisecond pulsars at intervals of three to four weeks. Arrival time measurement accuracy for individual pulsars ranges from 50 nanoseconds to 1 microsecond (daily post-fit RMS). Observations are made over wide bands with two receivers at each telescope to aid in mitigating interstellar dispersion. We have not yet detected gravitational waves, but we are putting meaningful limits on astrophysical sources of gravitational waves in the nanohertz band. In this talk we will give an overview of the NANOGrav observing program; describe our most recent data releases; present upper limits on gravitational waves from our data, along with astrophysical implications; and describe prospects for the future.

Linking Galaxy Evolution Parameters and Pulsar Timing Array Observations

Joseph Simon

University of Wisconsin Milwaukee, USA

Recent Pulsar Timing Array (PTA) upper limits on the gravitational wave strain in the nanohertz frequency band are impacting our understanding of the binary supermassive black hole population. But as upper limits grow more constraining, what can be implied about galaxy evolution? In this talk, I will present work which provides a simple framework to directly translate between measured values for the parameters of galaxy evolution and PTA limits, including the M-M_{bulge} relation and binary stalling. Additionally, we investigate how modeling the gravitational wave background with different galaxy evolution parameters effects the characterization of the signal. Finally, I will briefly discuss the potential for detecting multi-messenger sources in the PTA band, and show how electromagnetic observations can help to characterize the binary population in our universe.

Gravity tests with the Square Kilometre Array

Gilles Theureau
Paris Observatory Station de Radioastronomie

The Square Kilometre Array (SKA) is in the final phase of its design; when complete it will be the most powerful telescope in the world. The SKA will revolutionise our understanding of the Universe in many areas. In particular the field of pulsar astronomy, and the study of gravity using pulsars will be transformed in the SKA era. The SKA will be capable of detecting all radio pulsars in the Milky Way which are beamed towards Earth. The very best of these cosmic superclocks will be monitored in a Pulsar Timing Array (PTA), which acts as a gravitational wave detector: each Earth-Pulsar being essentially the arms of a Galaxy-scale interferometer. The sensitivity of current PTAs is dominated by a handfull of best timers, measured with a typical precision of 100 ns. SKA will discover a few tens of those rare pearls and its much greater collecting area will allow to gain an order of magnitude on their timing accuracy with respect to the present radio telescope generation. True gravitational wave astronomy may then become possible beyond the scope of the first detection or the set of robust limits in the nanohertz-microherzt regime. The properties of the source population and the fundamental properties of the gravitational waves themselves will be revealed. Additionally, gravity studies with the SKA will be performed in the strong field regime. Pulsars in compact binary systems where post-Keplerian effects of GR, or alternative theories of gravity, are magnified, are a key target for the SKA. A pulsar orbiting a stellar mass black hole is a high priority aim of the pulsar search, with which the no-hair theorem and cosmic censorship could be tested. Furthermore, in its search for the ultimate gravity laboratories, the SKA will perform the most sensitive search of for pulsars in the vicinity Sgr A*, the Milky Way's supermassive black hole. SKA talk

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Detection and parameter estimation of continuous GW signals in pulsar timing arrays

Yan Wang
School of Physics, Huazhong University of Science and Technology, China

Supermassive black hole binaries are one of the primary targets of gravitational wave (GW) searches using pulsar timing arrays (PTAs). GW signals from such systems are well represented by parameterized models, allowing the standard Generalized Likelihood Ratio Test (GLRT) to be used for their detection and estimation. However, there is a dichotomy in how the GLRT can be implemented for PTAs: there are two possible ways in which one can split the set of signal parameters for semi-analytical and numerical extremization. The straightforward extension of the method used for continuous signals in ground-based GW searches, where the so-called pulsar phase parameters are maximized numerically, was addressed in Wang et al. (2014). In this talk, we report the first study of the performance of the second approach where the pulsar phases are maximized semi-analytically. This approach

is scalable since the number of parameters left for numerical optimization does not depend on the size of the PTA. Our results show that for the same array size (9 pulsars), the new method performs somewhat worse in parameter estimation, but not in detection, than the previous method where the pulsar phases were maximized numerically. The origin of the performance discrepancy is likely to be in the ill-posedness that is intrinsic to any network analysis method. However, the scalability of the new method allows the ill-posedness to be mitigated by simply adding more pulsars to the array. This is shown explicitly by taking a larger array of pulsars, and can be extend to the PTA scenario in the SKA era.

Measurements of Gravitational Waves and other Relativistic Parameters in the Binary Pulsar PSR B1913+16

Joel Weisberg
Carleton College, Northfield, MN, USA

We discuss the history and current status of 35 years of measurements and analyses of the first binary pulsar, PSR B1913+16, along with future projections. We have now extracted ten significant measurables from time-of-arrival measurements, while only seven are required to completely specify the orbiting system aside from its unknown orientation on the plane of the sky. The three "excess" parameters yield three independent tests of relativistic gravitation; one the rate of orbital period change is caused by gravitational radiation emission while two additional ones characterize the "Shapiro" gravitational propagation delay. All three measurements are consistent with general relativity. We have also recently accomplished marginal measurements of two additional relativistic orbital parameters – the time derivative of projected semimajor axis; and a post-Keplerian correction to the shape of the nominally elliptical orbit. The latter measurement however is affected by a comparable pulsar emission beam aberrational correction which is currently unquantified. Geodetic precession of the pulsar spin axis is secularly altering the pulsar's pulse profile which we continue to monitor and to model. Most but not all analyses suggest the pulsar emission beam will stop intersecting our line of sight within the next several years at which time it would disappear.

Session C2

Gravitational waves detection from inspiral compact binaries injected during the science experiments of the Laser Interferometer Gravitational-wave Observatory (LIGO)

Javier M. Antelis

Tecnolgico de Monterrey, Campus Guadalajara, Mexico

Since the discovery of gravitational waves (GW) by Albert Einstein one hundred years ago, scientists have been working in the search of these ripples in the space-time. After several improvements and upgrades of LIGO interferometer, the scientists reported the first detection of a GW emitted 1.3 billion years ago by a binary system composed of two merging black holes of masses 36 and 29 the sunś mass possibly located in the Magellanic cloud. This remarkable achievement demonstrated that Einsteinś theory is right and opens a new era in astronomy to explore and to study our universe. In this work, we analyzed GW generated by inspiral compact binaries, a system composed of a pair of neutron stars and/or black holes in their late stage of evolution. Then, we perform the detection of this type of GW injected in the freely available LIGO data. We present a comprehensive data analysis methodology based on the Matched Filter, which is the optimal detection technique of GW emitted by these astrophysical sources. Finally, the results of the detection experiments are presented and discussed.

Accuracy of gravitational-wave models for coalescing Black-hole Neutron-star systems

Swetha Bhagwat

Syracuse University, USA

Detection of gravitational wave involves extracting extremely weak signal from noisy data and their detection depends crucially on the accuracy of the signal models. The most accurate models of compact binary coalescence are known to come from solving the Einsteinś equation numerically without any approximations. However, this is computationally formidable. As a more practical alternative, several analytic or semi analytic approximations are developed to model these waveforms. However, the work of Nitz et al. (2013) demonstrated that there is disagreement between these models. We present a careful follow up study on accuracies of different waveform families for spinning black-hole neutron star binaries, in context of both detection and parameter estimation and find that SEOBNRv2 to be the most faithful model. Post Newtonian models can be used for detection but we find that they could lead to large parameter bias.

Surrogate Models of Precessing Binary Black Hole Waveforms from Numerical Relativity Simulations

Jonathan Blackman
California Institute of Technology, USA

With the recent detection of gravitational waves from a binary black hole (BBH) system, we begin the era of gravitational wave astronomy. To infer the black hole and orbital parameters, the observed gravitational wave signal must be compared to waveforms predicted by general relativity for millions of binary configurations. Numerical relativity (NR) simulations may accurate waveforms, but are prohibitively expensive for parameter estimation. Other waveform models may be fast enough but sacrifice accuracy in portions of the parameter space, especially during the merger phase which can be the dominant contribution to the signal for more massive BBH systems. As detectors improve and time goes on, we will receive increasingly loud signals and will be able to place tighter constraints on the source parameters, making any biases due to waveform errors more obvious and important. NR surrogate models attempt to rapidly predict the results of a NR code with a small or negligible modeling error, after being trained on a set of input waveforms. We have built two such surrogates using waveforms from the Spectral Einstein Code (SpEC): one for the simple case of non-spinning black holes, and a new surrogate for spinning and precessing systems which uses 250 input waveforms. We have also constructed frequency-domain reduced-order models (ROMs) of these time-domain surrogates which are suitable for gravitational wave parameter estimation.

Prospects for observing multiple ringdown modes in a binary black hole detection and testing the Kerr nature of the final black hole

Miriam Cabero Mueller
Albert Einstein Institute Hannover, Germany

For astrophysical Kerr black holes, the ringdown spectrum is completely characterized by the black hole mass and angular momentum. If general relativity were not the correct theory of gravity, or if the source of the emitted gravitational radiation was not a traditional black hole, this spectrum would be different. In order to confirm the Kerr nature of the black hole based on the ringdown portion of a binary coalescence waveform with minimal additional assumptions, it is essential to observe at least two quasi-normal modes. In this talk, we will discuss techniques for observing multiple quasi-normal modes in a binary black hole detection candidate in advanced LIGO data, and the prospects for having detecting multiple modes and testing the Kerr-nature of the final black hole.

Impact of higher order modes in gravitational wave searches for binary black holes

Juan Calderon Bustillo
Georgia Institute of Technology, USA

In February 2016, LIGO announced the first discovery of a binary black hole via the direct detection of its gravitational wave emission, GW150914. Gravitational wave signal models used in current searches for such sources only consider the dominant quadrupolar mode of the full emitted signal, omitting the so called higher order modes. In this talk I discuss the impact of this omission in current and future searches in terms of both event losses and bias in the inferred parameters of the source. In particular it will be shown that higher modes are needed for both purposes for the case of unequal mass binary black holes whose total mass is above 70 solar masses, known as intermediate mass binary black holes.

Results of searching for binary black holes in the first observing run of Advanced LIGO

Collin Capano
Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Hannover, Germany

The first observing run of Advanced LIGO completed in January 2016. I discuss the results of searching this data for gravitational waves from binary black holes with total masses up to 100 solar masses, using modeled waveforms. The first 16 days of this data included GW150914, as well as a second, marginal event LVT151012. I discuss what can be learned from these results, and estimates of the expected detection rate in future observing runs.

An improved analytic extreme-mass-ratio inspiral waveform model

Alvin Chua
Institute of Astronomy, University of Cambridge, Singapore

The mission design for the future space-based gravitational-wave detector eLISA will be finalised by the end of this decade. Several outstanding data analysis questions will be addressed during the next round of mock LISA data challenges, which will require fast and accurate waveform models for the extreme-mass-ratio inspirals of stellar-mass compact objects into massive black holes. The computationally affordable waveforms of Barack and Cutler have been used in previous data challenges; these dephase relative to more accurate waveforms within hours due to their mismatched radial, polar and azimuthal frequencies. We introduce an augmented Barack-Cutler model that uses a frequency map to the correct Kerr frequencies, along with updated evolution equations and a simple fit to a more accurate model. The augmented waveforms stay in phase for months and may be generated with virtually no additional cost.

The mass distribution of coalescing binary black holes from ground-based GW observations

Thomas Dent

AEI Hannover, Germany

After the epochal discovery of a high-mass stellar black hole coalescence in 2015, the ground-based network of GW detectors is expected to observe tens of black hole merger events in the coming years. The rate and distribution of coalescing BH binaries over intrinsic (component masses and spins) and extrinsic (redshift) parameters are key outputs from these observations, which will enable us to test models of compact binary formation and evolution.

We show that a Bayesian analysis using outputs from existing pipelines is able to reconstruct the rate and mass distribution of a set of simulated signals injected into recolored data from an early commissioning run of Advanced LIGO, with appropriate uncertainty estimates.

Denoising of gravitational wave signals via dictionary learning

Jose Antonio Font Roda

University of Valencia, Spain

Dictionary learning algorithms have been extensively developed in the last years.

We have recently applied a machine learning algorithm based on dictionaries to denoise gravitational wave signals embedded in non-white Gaussian noise. The dictionaries are built from numerical relativity waveform templates of two types of signals, namely binary black holes mergers and magneto-rotational stellar core collapse. In this talk we show the performance of dictionary learning techniques to denoise this type of gravitational wave signals.

An inspiral-merger-ringdown waveform model for compact binaries on eccentric orbits

Eliu Huerta

NCSA/University of Illinois at Urbana-Champaign, USA

The detection of compact binaries with significant eccentricity in the sensitivity band of gravitational wave detectors will provide critical insights on the dynamics and formation channels of these events. In order to search for these systems and place constraints on their rates, we present a time domain, inspiral-merger-ringdown waveform model that describes the gravitational wave emission from compact binaries on orbits with low to moderate values of eccentricity. We use this model to explore the detectability of these events in the context of advanced LIGO.

Phenomenological waveform models for the advanced detector era

Sascha Husa

University of the Balearic Islands, Spain

This talk discusses the current status of accurate phenomenological waveform models for the coalescence of non-precessing black hole binary systems, and the extension of such models to precession. These models describe the gravitational wave signal in terms of explicit functions of the mass ratio and spins, and their low computational cost facilitates the use in Bayesian parameter estimation. Open source implementations are available in the LIGO Algorithms library and as a Mathematica package.

Binary black hole remnants of First stars for the gravitational wave source

Tomoya Kinugawa

Institute for Cosmic Ray Research, University of Tokyo, Japan

Using our population synthesis code, we found that the typical chirp mass of binary black holes (BH-BHs) whose origin is the first star (Pop III) is 30Msun with the total mass of 60Msun so that the inspiral chirp signal as well as quasi normal mode (QNM) of the merging black hole are interesting targets of LIGO,VIRGO and KAGRA (Kinugawa et al.2014 and 2016). The detection rate of the coalescing Pop III BH-BHs is $\sim$ 180 events/yr $(SFR_p/(10^{-2.5}Msun/yr/Mpc^3)) * ([f_b/(1+f_b)]/0.33) * Err_{sys}$ in our standard model where SFR_p, f_b and Err_sys are the peak value of the Pop III star formation rate, the binary fraction and the systematic error with $Err_sys = 1$ for our standard model, respectively.

Furthermore, We found that the chirp mass has a peak at $\sim$30Msun in most of parameters and distribution functions (Kinugawa et al.2016). This result predicted the gravitational wave events like GW150914 and LIGO paper said recently predicted BBH total masses agree astonishingly well with GW150914 and can have sufficiently long merger times to occur in the nearby universe (Kinugawa et al. 2014) (Abbot et al. ApJL 818,22 (2016)). Nakano, Tanaka & Nakamura 2015 show that if S/N of QNM is larger than 35, we can confirm or refute the General Relativity more than 5 sigma level.

In our standard model, the detection rate of Pop III BH-BHs whose S/N is larger than 35 is 3.2 events/yr $(SFR_p/(10^{-2.5}Msun/yr/Mpc^3)) * ([f_b/(1+f_b)]/0.33) * Err_{sys}$. Thus, there is a good chance to check whether GR is correct or not in the strong gravity region.

Learning with Future Gravitational Wave Detections

Lionel London
Cardiff University, USA

Future gravitational wave detections will enable us to directly learn which binary black hole populations are astrophysically relevant. In turn, increased knowledge of these populations allows us to perform targeted modeling studies that enable the inference of bulk features, such as radiated energy and peak luminosity. In this talk I will discuss strategies to followup future detections with targeted modeling studies. In particular, I will present a new method for determining which Numerical Relativity simulations are useful for modeling.

Fourier-domain modulation and delay of gravitational wave signals: application to the response of LISA-type detectors and to precessing binaries

Sylvain Marsat
Albert Einstein Institute - Potsdam-Golm, Germany

Future space-based gravitational wave observatories following the LISA concept will detect mergers of massive black hole binaries at cosmological distances with unprecedented signal-to-noise ratios. Detailed Bayesian analysis are needed to better assess the prospects of parameter recovery by the future mission in its various proposed designs, but they have so far been limited by their computational cost. Due to the orbital motion of the detector array, the response of the instrument is time-dependent, which induces a modulation and delay of the signal. We propose an analytical framework to efficiently represent these effects directly in the Fourier domain. By combining our approach with recently developed reduced order models to accurately represent Effective-One-Body waveforms, and with accelerated overlap computations in the no-noise approximation, we are able to bring this cost down to a few milliseconds per likelihood evaluation. As an application, we discuss the impact of higher-harmonics for non-spinning binaries.

Modulations also play an important role in modelling the signals of spinning, precessing binaries, which are well represented as a time-dependent rotation of a non-precessing waveform. We will discuss how our formalism allows to recover and generalize recently proposed treatments of the precession in the Fourier domain, and we will explore the treatment of the merger-ringdown phase.

Tests of General Relativity in the Advanced Detector Era

Jeroen Meidam
Nikhef, The Netherlands

The detection of GW150914, the gravitational-wave signal of the merger of two black holes, by the Advanced LIGO detectors has opened the possibility to probe the strong field regime of gravity for the first time. We will discuss the latest results on the verification of the predictions of general relativity done by the LIGO-Virgo Collaboration.

Estimating spins of aligned-spin binary black holes using Gravitational Wave Observations

Krishnendu N. V.
Chennai Mathematical Institute, India

Advanced gravitational wave (GW) detectors can detect binary black hole (BH) mergers up to large distances. We consider a sub-population of these binaries where spins of the component BHs are aligned or anti-aligned with respect to the orbital angular momentum of the binary. We investigate the accuracies with which the spins of the component BHs can be estimated using GW observations. We use the recently computed post-Newtonian (PN) waveforms which have 3.5PN accurate phasing and 2PN accurate amplitude including spin effects up to these orders. An important feature of this waveform model is that it contains sub-dominant GW modes, in addition to the leading quadrupolar mode, and hence is a more accurate model of the GW signal expected from the binary black holes. We show that the presence of sub-dominant modes significantly improves the spin estimation enabling estimation of component spins to a few percent for many source configurations. We also report the results of our comprehensive study on how these errors change as a function of total mass of the BH, mass ratio of the binary and value of the component spins. We then consider a special case of neutron star - BH binaries and discuss how inclusion of sub-dominant modes help to break the mass-spin degeneracy.

Improved all-sky Hough search for continuous gravitational waves

Miquel Oliver
University of the Balearic Islands, Spain

In this talk we will review the basics of the Hough search for continuous gravitational waves and present an improved algorithm, including candidate selection, based on population clustering, that improves efficiency and parameter estimation, reducing the parameter volume to be followed up and computational cost of the search. Results will be presented based on the all-sky mock data challenge performed within the LIGO-Virgo continuous wave search group.

Is the gravitational-wave ringdown a probe of the event horizon?

Paolo Pani

Sapienza University of Rome & CENTRA-IST, Lisbon, Italy

It is commonly believed that the ringdown signal from a binary coalescence provides a conclusive proof for the formation of an event horizon after the merger. This expectation is based on the assumption that the ringdown waveform at intermediate times is dominated by the quasinormal modes of the final object. We point out that this assumption should be taken with great care, and that basically any compact object with a light ring will display a similar ringdown stage, even when its quasinormal-mode spectrum is completely different from that of a black hole. In other words, universal ringdown waveforms indicate the presence of light rings, rather than of horizons. Only precision observations of the late-time ringdown signal, where the differences in the quasinormal-mode spectrum eventually show up, can be used to rule out exotic alternatives to black holes and to test quantum effects at the horizon scale.

Prospects for joint GW and high-energy EM observations of BNS mergers

Barbara Patricelli

University of Pisa and INFN - Sezione di Pisa, Italy

On September 14th, 2015 the era of gravitational wave (GW) astronomy has begun: the two Advanced LIGO interferometers detected for the first time a transient signal. The event, labeled GW150914, is consistent with the inspiral and the merger of a binary system of black holes (BBH). A possible high-energy electromagnetic counterpart to this event has been observed by Fermi-GBM.

In the next years the 2nd generation interferometers will increase their sensitivity: many other GW events are expected to be detected, expanding the frontiers of the multimessenger investigations of the universe.

Besides the merger of BBH systems, one of the most promising candidates for the direct GW detection is the coalescence of binary neutron stars (BNS) and black holes (NSBH). These mergers are thought to be connected with short Gamma Ray Bursts (GRBs), the most energetic events in the universe: but a definitive probe of this association is still missing. Combined observations of gravitational and electromagnetic signals from these events will provide an unique opportunity to unveil the progenitors of short GRBs and study the physics of compact objects. In particular, large field-of-view instruments such as Fermi will be crucial to observe the high-energy electromagnetic counterparts of transient gravitational wave signals and provide a robust identification based on a precise sky localization. We will present the prospects for joint GW and high-energy EM observations of merger of binary systems with Advanced LIGO and Virgo and with Fermi, with focus on BNS.

Electromagnetic counterparts from long-lived binary neutron star merger remnants

Daniel Siegel

Columbia Astrophysics Laboratory & Center for Theoretical Physics, Columbia University, USA

With the discovery of a binary black hole merger by advanced LIGO, the era of gravitational wave (GW) astronomy and multimessenger astronomy has begun. In the next few years, exciting discoveries will be made, including binary neutron star mergers, which are among the most promising events for multimessenger astronomy. Recent studies indicate that in a large fraction of binary neutron star mergers a long-lived neutron star may be formed rather than a black hole. In this talk, I will present a model that provides a self-consistent evolution of such a post-merger system and its electromagnetic (EM) emission. The resulting EM signals provide unique information about the post-merger evolution on timescales that are inaccessible to GWs. Lightcurves and spectra from this model will be discussed in the context of multimessenger astronomy and be compared to other potentially promising EM counterparts. Implications for short gamma-ray bursts and their X-ray afterglows are also pointed out.

Search for Continuous Wave Transients: Toward Neutron Star Equation of State

Avneet Singh

Max-Planck-Institut für Gravitationsphysik, Germany

Glitches in the rotational frequency of a spinning neutron star could be promising sources of gravitational wave signals lasting between a few micro-seconds to a few weeks. The emitted signals and their properties depend upon the internal properties of the neutron star. In stellar models that assume a super-fluid core for the neutron star, the most important physical properties are the viscosity of the super-fluid, the stratification of flow in the equilibrium state and the adiabatic sound speed. We present one of the many promising models for 'Continuous Wave Transient' emission (CW-transients); specifically one where the post-glitch relaxation phase is driven by the well-known process of 'Ekman Pumping'. We explore the hydrodynamic properties of the flow of super-fluid during this phase following liberal assumptions on the stratification of flow and/or the pressure-density gradients within the neutron star than previously studied. We calculate the time-scales of duration as well as the characteristic strengths of the resulting gravitational wave signals, and we detail their dependence on the physical properties of the super-fluid core. We find that it is possible for the neutron star to emit gravitational wave signals in a wide range of decay time-scales and within the detection sensitivity of advanced-LIGO for selected domains of Equation of State. Further, we present formalism(s) for conducting dedicated searches for such gravitational wave signals on the Einstein@Home framework. We detail the detection statistic(s) employed for such CW-transient searches, and possibly elaborate on preliminary results from such searches.

Core-Collapse Supernova Science with Advanced LIGO and Virgo

Marek Szczepanczyk

Embry-Riddle Aeronautical University, USA

Core-Collapse Supernovae (CCSNe) are the spectacular end stage of dying large stars. Gravitational Waves produced by CCSNe could elucidate critical aspects of the inner physics of CCSNe like the shock wave evolution. In this presentation I will summarize activities of the LIGO and Virgo supernova group to analyze the first and second scientific runs of Advanced LIGO (O1 and O2) and Virgo. The presentation will cover the main emission models we are considering and the approaches to detect Gravitational Waves emitted from CCSNe. I will also talk about our efforts to estimate the limits on emission models as well as reconstruction of the emitted Gravitational Wave waveforms.

Advanced Virgo Data Quality and Online Monitoring

Didier Verkindt

Virgo-LAPP-CNRS, France

After the first observation of a gravitational wave with the two Advanced LIGO detectors, one important next step is the start of Advanced Virgo and its participation to the interferometric detectors network during the second LIGO science run. Several tools have been developed in Virgo for online monitoring and detector characterization. They are important items to improve the detector during the commissioning and to better discriminate real gravitational wave events from background due to transient noises during the scientific runs. I will present some of those tools, their impact during the previous Virgo runs, their current improvements or development and how they can help Advanced Virgo to reduce its false alarm rate and to better contribute to any future detection by the interferometric detectors network.

Accelerating CBC parameter estimation with multi-band frequency domain waveforms

Serena Vinciguerra

University of Birmingham, United Kingdom

As demonstrated by advanced LIGO and, in general, by the design planned for future generations of GW detectors, the low frequency sensitivity of GW interferometers is constantly improving. This will both enhance the SNR of CBC signals and increase their total duration in the sensitive band of the detections. This increased duration results in a greater amount of data to be analysed for parameter estimation of CBC sources, in particular for lighter BNS systems, which will increase the run-time of these analyses. Here we report on a new approach which exploits the known frequency evolution to optimise the waveform generation. We divide the frequency range of the signal into several chunks where we apply different sampling resolutions, exploiting the limited bandwidth of the source at different times. We therefore calculate the waveform with the dedicated algorithms at a reduced set of frequencies and interpolate the phase to the original sampling rate necessary for likelihood calculations. Unlike reduced order models, this generic approach is readily applicable to any frequency domain waveform. We find gains in speed of template generation up to $\sim$10 for TaylorF2 waveforms, and of $\sim$30 adopting a lower frequency cut off of 40Hz for IMRPhenomPv2 waveforms.

First Einstein@Home all-sky search for continuous gravitational waves in advanced LIGO data

Sinead Walsh

Albert-Einstein-Institut Potsdam-Golm, Germany

Rapidly rotating neutron stars are promising sources of continuous gravitational waves for the LIGO and Virgo interferometers. All-sky searches offer the potential to detect gravitational waves from compact objects, for example neutron stars, that have not been observed electromagnetically. The broad parameter space of these all-sky searches presents a significant computational challenge. The computing power amassed via the Einstein@Home project facilitates the most sensitive all-sky searches for continuous gravitational waves. In this talk, I describe the first all-sky search for such signals on Einstein@Home with advanced LIGO data. This search covers the low frequency range of 20 Hz to 100 Hz, much of which was not explored by Einstein@Home in initial LIGO.

Building the next Einstein@Home search code for continuous gravitational waves

Karl Wette

Albert Einstein Institute (Hannover), Germany

With the every-increasing sensitivity of the LIGO detectors, and longer observing runs on the horizon, prospects for detecting continuous gravitational waves from rapidly-rotating neutron stars remain promising. I describe the development of a new semicoherent search code for continuous gravitational waves from isolated sources, based on the associated parameter-space metric, which will be deployed on the Einstein@Home volunteer computing project in the near future.

A stochastic gravitational-wave background from binary black hole mergers

Bernard F. Whiting

University of Florida, USA

The whole world was excited to hear that the first discovered of gravitational waves arose from the merger of two black holes of about 30 solar masses. The existence of black holes of such mass, and of binaries composed of such black holes, raises new questions about the abundance of such sources and of their possible origins. In this talk we will discuss implications of the existence of such sources and the potential that, at higher redshifts, they may create an unresolved stochastic background of gravitational waves.

A directed Einstein@Home search for continuous gravitational waves from Cassiopeia A

Sylvia Zhu

AEI Potsdam-Golm / AEI Hannover, Germany

Rapidly rotating compact objects are the most promising sources of continuous gravitational-wave emission for the LIGO and Virgo interferometers. Directed searches for signals from nearby sources with known sky positions allow us to probe weaker signal strengths than do comparable all-sky searches. The supernova remnant Cassiopeia A (CasA) is both nearby (at 3.4 kpc) and young (a few hundred years old), and its compact central object is likely to be a neutron star; these attributes make it a good candidate for a directed search. In this talk, I will present an Einstein@Home search for a continuous gravitational-wave signal from CasA using LIGO S6 data, and discuss the astrophysical implications.

Theoretical Physics Implications of the Binary Black-Hole Merger GW150914: Kerr Hypothesis and Smaller-confidence Observations

Kent Yagi

Princeton University, USA

Advanced LIGO's discovery of the direct detection of gravitational waves from a binary black hole coalescence allows us to probe extreme gravity for the first time. In this talk, I will describe additional implications of the GW150914 event on the strong-field nature of gravity and compact objects. I will first demonstrate what information one can obtain on theoretical physics mechanisms from smaller-confidence observations, namely the LVT151012 trigger and possible electromagnetic counterpart signals associated with GW150914 or with future events. I will next show how GW150914 can inform us about constraints on the Kerr hypothesis through inferences on the properties of the inner-most stable circular orbits. I will then discuss how GW150914 constrains the properties of exotic, compact-object alternatives to black holes, such as boson stars, in particular if the remnant does not promptly collapse to a black hole upon coalescence.

Theoretical Physics Implications of the Binary Black-Hole Merger GW150914: Gravitational-wave Generation and Propagation

Nicolas Yunes

Montana State University, USA

The gravitational-wave observation GW150914 by Advanced LIGO provided the first opportunity to learn about theoretical physics mechanisms that may be present in the extreme gravity environment of coalescing binary black holes. The LIGO collaboration verified that this observation is consistent with Einstein's theory of General Relativity and the Kerr hypothesis, constraining the presence of parametric anomalies in the signal. In this talk, I will discuss the plethora of additional inferences that can be drawn on theoretical physics mechanisms from the absence of such anomalies in the LIGO observation. I will classify these inferences in those that inform us about the generation of gravitational waves, the propagation of gravitational waves and the structure of exotic compact object alternatives to black holes. I will then focus on how GW150914 constrains the generation of gravitational waves (e.g. the activation of scalar fields, black hole graviton leakage into extra dimensions, the variability of Newton's constant, the breakage of Lorentz invariance and parity invariance) as well as the propagation of gravitational waves (e.g. the speed of gravity and the existence of large extra dimensions).

Session C3

R&D for the gravitational wave detector KAGRA

Yoichi Aso
University of Tokyo, Japan

KAGRA is a gravitational wave detector currently being built in the Kamioka mine in Japan. It is based on a laser interferometer with arms 3 km in length. It will be first km-scale interferometer to be operated at cryogenic temperature. This talk will present the research and development ongoing to complete the detector and prepare some of its possible future upgrades.

Progress on the demonstration of a quantum speed meter

Bryan Barr
University of Glasgow, United Kingdom

As we enter the era of gravitational wave astronomy, we are approaching a regime where the limit to detector sensitivity is the Heisenberg uncertainty principle - the so-called Standard Quantum Limit (SQL) of position measurement. Improving detector sensitivity will require the use of new detector topologies, capable of bypassing this limit, increasing detection range and ultimately expanding our ability to observe the gravitational universe. One promising approach for surpassing this limit over a broad frequency range is the speedmeter, designed to measure speed rather than position. In Glasgow, the prototype interferometry group is currently pursuing an extensive experimental and theoretical research programme into the practical limits of speedmeter systems. We discuss our current experimental work on sub-SQL measurements with conventional ring-Sagnac interferometry, theoretical and experimental investigations into the viability of polarisation topologies, and our recent developments on novel śloshingśpeedmeter configurations.

Complementarity of Earth- and space-based detectors: binary populations and tests of strong gravity

Emanuele Berti
University of Mississippi, USA

The recent detection of gravitational waves by the LIGO/Virgo Collaboration calls for an updated assessment of the relative role of Earth- and space-based detectors. I will present my own perspective on this issue, focusing in particular on two aspects where the complementarity of Earth- and space-based detectors will be crucial: tests of strong-field gravity and our understanding of compact binary populations.

Development of advanced gravitational reference sensor technologies for LISA

John Conklin
University of Florida, USA

The Laser Interferometer Space Antenna is the most mature concept for detecting gravitational waves from space. LISA consists of three Sun-orbiting spacecraft that form an equilateral triangle, with each side measuring 1-5 million kilometers in length. Each spacecraft houses two free-floating test masses, which are protected from all disturbing forces so that they follow pure geodesics. A single test mass together with its protective housing and associated components is referred to as a gravitational reference sensor. A drag-free control system commands micronewton thrusters to force the spacecraft to fly in formation with the test masses. Laser interferometry is used to measure the minute variations in the distance, or light travel time, between these purely free-falling test masses, caused by gravitational waves. LISA Pathfinder, launched in December of 2015, will test key technologies for LISA, including the gravitational reference sensor and its closed loop drag-free operation. However, the design of the Pathfinder payload was solidified more than a decade ago. An advanced charged management system utilizing ultraviolet LEDs is a new technology that can potentially reduce complexity and technological risk for LISA beyond what LISA Pathfinder has already achieved. The charge management system controls the bulk potential of the test mass relative to its housing, which is vital for reducing spurious force noise acting on the test mass below the required level. This presentation will describe new test mass charge control techniques enabled by UV LEDs and evaluations of their efficacy using unique laboratory experiments at the University of Florida.

Fundamental Level of Noise in Electro-optic modulators of advance-LIGO

Alfredo Eduardo Dominguez

Instituto Universitario Aeronautico, Argentina

From a theoretical point of view we obtain a fundamental level of noise (FLN) which is inherently associated with phase modulation processes of laser beams based on electro-optic effects. This FLN states a threshold to the value of the radio frequency amplitude modulation (RFAM) effect. RFAM effect is a spurious phenomenon observed in a laser beam outgoing of an electro-optic modulator of aLIGO. The effect appears as an unwanted amplitude modulation of the intensity of the laser beam. As we know electro-optic modulators are used in aLIGO to modulate the phase of the laser beam. These modulators are built as a serial array of three pairs of electrodes placed over an RTP crystal. The AC voltage applied on each pair of electrodes produces an electric field inside the crystal which in turn modulates its index of refraction.

We show that there exists an FLN in the three processes of modulation. We model each single modulator as two different media with constant index of refraction separated by another medium which index refraction changes because of electro-optic effects.

We solve Maxwell equations for electromagnetic fields of laser using a WKB approximation scheme in the three different media. The matching conditions for fields in both interfaces of media allow us to obtain the solution.

Then the theoretical relative RFAM values are calculated and it can be understood as an FLN of the phase modulation process itself. Finally we compare theoretical and observational of RFAM values for different situations.

Modeling and detectability of the gravitational wave memory

Marc Favata

Montclair State University, USA

Gravitational wave memory refers to a non-oscillating component of a gravitational wave signal. All gravitational-wave sources have a memory component. The largest sources of memory waves are the merger of two black holes. These produce the so-called nonlinear or Blanchet-Damour-Christodoulou memory. I will provide an update on recent work to model the memory signal and discuss the prospects for its detection.

Limitation of gravitational wave detector Niobe sensitivity by the frequency tracking noise

Carlos Frajuca
IFSP, Brazil

This work studies the influence of the frequency tracking noise of the Niobe gravitational wave (GW) detector. The University of Western Australia operated the GW detector Niobe at Perth, Australia. It was a resonant-mass bar detector made of niobium operating at a temperature of 5 K. It was sensitive around the frequency of 700 Hz and had a burst sensitivity of h 7 x 10-19 with a long term operation from 1993 to early 1998. It had the lowest observed noise temperature. Using the characteristics of the detector, NIOBE should had reached a much better sensitivity that the one measure. It seems that the noise introduced in the system by the frequency tracking device was not taken into at the time, this noise gives a value of 2.5 x 10-18 m/(Hz) -1/2, what is the value that limited the detector sensitivity to the one measured.

Cryogenics for future GW detectors

Giles Hammond
University of Glasgow, United Kingdom

In this presentation, I will elaborate on current cryogenic detector upgrades.

First Test Operation of Underground Gravitational-Wave Detector, iKAGRA, and future plans

Keiko Kokeyama
KAGRA Observatory, ICRR, University of Tokyo, Japan

KAGRA project is Japanese large-scale gravitational-wave detector. Its features are quiet underground site and cryogenic operation. As an initial phase of the project, "iKAGRA" test operation had been done from March 25th, 2016, for one month, with a simple optical configuration at a room temperature. In this talk, our experiences for installation, commissioning, data acquisition and data analysts at the underground site will be presented. Our next bKAGRA plan, the cryogenic detector with full configuration, will be also presented.

Arm cavity filter cavity via EPR entanglement

Yiqui Ma
California Institute of Technology, USA

Investigating Newtonian noise: TorPeDO and the LHO seismometer array

David McManus
Australian National University, Australia

Recent detections of gravitational waves by Advanced LIGO have established the field of gravitational wave astronomy. In the future, Newtonian noise could limit the sensitivity of Advanced LIGO and other second generation gravitational wave detectors at low frequencies.

I will give an update on the TorPeDO system from ANU, and the current LHO seismometer array: two current investigations into Newtonian noise.

TorPeDO is a dual torsion pendulum sensor designed to measure local gravitational forces to high precision. Gravitational forces induce a differential rotation between the two torsion bars, which is measured with an optical read-out. The torsion bars are designed to have a high mechanical common mode cancellation.

I will also discuss current progress and results from a seismometer array being tested at the LIGO Hanford Observatory. This array is used to characterise the ground motion, and may be used for feed forward cancellation of seismic Newtonian noise. This type of cancellation scheme would rely on accurate modelling of NN effects from seismic data obtained by the array.

Squeezed states of light for Advanced LIGO and beyond

John Miller
MIT, USA

The quantum nature of light imposes one of the principal limits on the performance of gravitational-wave interferometers. Squeezed vacuum injection can mitigate this problem and is now an assumed component of all proposed ground-based detectors. I will describe the design and status of the Advanced LIGO squeezed light source and discuss how current methods and technologies must be modified for the future.

Status of laser for next generation cryogenic silicon optics

Volker Quetshke
University of Texas, USA

The push for going to cryogenic optics, possibly with silicon test masses, requires the assessment of the availability and properties with respect to the demanding specifications of interferometric gravitational wave detectors. The talk will present the state of the art of 1550nm and 2 micrometer laser systems using fiber amplifier technology. Stabilization techniques and challenges, as well as the prospects for future power increases will be addressed.

The Impact of GW150914 on Interferometer Design

Dave Reitze
California Institute of Technology, United States

Impact of first detection on interferometer design.

Prospects of eLISA for Detecting Galactic Binary Black Holes Similar to GW150914

Naoki Seto
Kyoto University, Japan

We discuss the prospects of eLISA for detecting gravitational waves (GWs) from Galactic binary black holes (BBHs) similar to GW150914. For a comoving merger rate that is consistent with current observation, eLISA is likely to identify at least one BBH with a sufficient signal-to-noise ratio. In addition, eLISA has a potential to measure the eccentricity of the BBH as small as $e \times 0.02$, corresponding to the residual value $e \times 10^{-6}$ at 10Hz. Therefore, eLISA could provide us with a crucial information to understand the formation processes of relatively massive BBHs like GW150914. We also derive a simple scaling relation for the expected number of detectable Galactic BBHs.

A geostationary Laser Interferometer Space Antenna

Massimo Tinto
Jet Propulsion Laboratory, USA

We present a gravitational wave mission concept that relies on an array of satellites in geostationary orbit, coherently tracking each other with laser light. The scientific capabilities of our proposed detector have been estimated to be comparable to those characterizing interplanetary missions, and it could be flown by the beginning of the next decade as it relies on existing technology.

LISA Pathfinder results

Stefano Vitale
University of Trento and TIFPA, Italy

LISA Pathfinder is the precursor to ESA's space based gravitational wave detector planned as the third large mission of the Cosmic Vision program. By the time of the conference the mission will have completed its nominal science phase. The talk will give the results and present their impact on the sensitivity of the gravitational wave observatory.

Session C4

Testing Gravity with the Standard Model Extension (SME)

Robert Bluhm
Colby College, USA

Einstein's general relativity is invariant under local Lorentz transformations and diffeomorphisms, and as a result the theory is dynamical and background independent. However, ideas in quantum gravity and modified theories of gravity suggest that Lorentz invariance might not hold exactly at all scales, and many models introduce background fields at the level of effective field theory. The Standard Model Extension (SME) is the most general effective field theory describing particle and gravitational interactions that can incorporate violations of local Lorentz invariance and diffeomorphisms while maintaining general covariance. It serves as a phenomenological framework that is used in experimental tests of fundamental spacetime symmetries. This presentation describes some theoretical issues affecting the construction of the gravity sector of the SME. In particular, the background fields (or SME coefficients) that are introduced are assumed to arise as vacuum expectation values of dynamical fields through a process of spontaneous Lorentz and diffeomorphism breaking as opposed to explicit breaking caused by nondynamical backgrounds. Examples of how the SME is used in laboratory, astrophysical, and gravitational wave experiments are given, and results of some recent investigations are summarized.

Relativistic Astrometry: The Gaia Experiment

Mariateresa Crosta
INAF-OATo, Italy

Missions like Gaia demand the proper treatment of gravity when compiling stellar catalogues to micro-arcsecond accuracy. High-precision measurements, by demanding suitable relativistic modeling, need to be validated. In this regard, it is of capital importance to allow the existences of different and cross-checked models which exploit different solutions to interpret the same experimental data. The realization of the celestial sphere is not only a scientific validation of the absolute parallax and proper motions in Gaia, but also, given the number of celestial objects (a real Galilean method applied on the sky!) and directions involved (the whole celestial sphere!), the largest experiment in General Relativity ever made with astrometric methods (since 1919).

With Gaia, almost one century from the formulation of the General Relativity Theory, Astrometry becomes part of Fundamental Physics and, in particular, in that of Gravitation.

Global Astrometry with Gaia as tool to prove dilation runway scenario

Mariateresa Crosta
INAF-OATo, Italy

The use of highly accurate astrometry models will a) help scrutinize (among several alternatives) the theory providing the route to quantum gravity and, from a different but equally crucial perspective, b) testing locally current cosmological models.

As far as the GR testing is concerned, a mission like Gaia, repeatedly observing over 5 years millions of bright and stable stars uniformly scattered across the sky to a precision of $\sim$ 10-20 micro-arcsecond, will constitute by far the largest and most thorough astronomical experiment in testing GR ever attempted since its formulation (one century ago), possibly with the sensitivity for testing the dilaton-runaway scenario. Gravity theories alternative to GR require the existence of this scalar field and predict it fades with time, so that this residue would manifest itself through very small deviations from Einstein's GR in the weak field regime. In fact, very accurate global astrometry is a very powerful and independent tool to unveil the presence of the scalar field.

Differential astrometry with Gaia for Quadrupole light deflection detection

Mariateresa Crosta
INAF-OATo, Italy

As far as Gia is concerned, while global tests will be done toward mission's end, when most of the observations will be collected, differential experiments, exploiting the precision of the elementary measurements, can be implemented also in the form of repeated Eddington-like experiments by comparing the evolution of angular distances in bright stellar asterisms consecutively observed by the satellite within a few planet's radii from the limb of a giant planet like Jupiter. Results based on simulated observations of actual star fields near Jupiter's orbit prove Gaia's ability to detect the light deflection due to Jupiter's quadrupole, predicted by GR and yet to be detected, with opportunities quite early into the mission in 2017.

ASTRA

Mariateresa Crosta
INAF-OATo, Italy

Astrometric Short Term Reconstruction and Analysis (ASTRA) uses the Relativistic Astrometric MODel (RAMOD) to analysis short time period observations of Gaia satellite. Since the final astrometric precision have to use many months of observation data, and reduce in a global and interleaved way, the ASTRA results can be used to check the measurement precision and instrument stability using a short time period observation data. This can make us aware if there is any unperceived, subtle effects arise during the mission. Besides, ASTRA is useful for the comparison of intermediate results with the other astrometric solution using a different model.

BOOST: Testing Lorentz Invariance in Space

Norman Gürlebeck
ZARM University of Bremen, Germany

The proposed satellite mission BOOST (Boost Symmetry Test) will perform a test of special relativity. By comparing an absolute to a length-based frequency reference, BOOST will carry out a Kennedy-Thorndike type experiment testing the boost dependency of the speed of light exploiting the large velocity modulation in low Earth orbit. Using clocks with instabilities below the 10E-15 level at orbit averaging time, the Kennedy-Thorndike coefficient will be measured with an up to two orders of magnitude higher accuracy than current ground-based experiments. In the current baseline design, an absolute frequency reference based on modulation transfer spectroscopy of molecular iodine near 532nm is compared to a high finesse optical cavity made of ultra-low expansion glass as length based frequency reference. Variations between the two references are analyzed at the orbit frequency. The iodine clock is based on DLR-funded setups on Elegant Breadboard and Engineering Model level reaching a frequency stability below 5×10^{-15} at orbit time. The cavity is based on the space-qualified cube cavity setup of NPL. A design with amongst others an adapted thermal shielding is currently realized at ZARM (University of Bremen). BOOST is at present investigated in a DLR-funded phase A study together with the Humboldt University of Berlin, the Leibniz University in Hannover and Airbus Defense and Space (Friedrichshafen).

Fundamental physics with space clocks in highly elliptic orbits

Philippe Jetzer
University of Zurich, Switzerland

The test of the Einstein Equivalence Principle (EEP) is of crucial importance as a deviation from it could hint to quantum effects in gravity or to unification with the other fundamental forces. One aspect of EEP is the local position invariance (LPI), which can be tested by measuring the gravitational red-shift. We will discuss a recently proposed satellite experiment, E-GRIP (Einstein Gravitational Red-Shift Probe), whose aim is to test LPI using an hydrogen maser atomic clock on a highly elliptic orbit around Earth and compare the on-board clock to clocks located on Earth via a microwave link. E-GRIP primary goal is to test the Earth field red-shift with an accuracy of $2x10^{(} - 6)$, taking also advantage of the frequency modulation along the highly elliptic orbit. A further goal is to measure the time dilation due to Sun's and Moon's gravitational fields with an accuracy of $5x10^{-5}$ and 1 x 10^{-2}, respectively, thereby testing its independence on the nature of the mass producing the gravitational field. The latter measurements are performed by comparing ultra-precise ground clocks, linked via the microwave link on-board of E-GRIP.

Testing gravitomagnetism with clocks

Claus Laemmerzahl
ZARM University of Bremen, Germany

The gravitomagnetic field of the Earth which within General Relativity is related to the rotation of the Earth has been observed by satellite orbits (LAGEOS, LARES) as well as by the precession of spinning gyroscopes (GP-B). Being encoced in the space-time metric the gravitomagnetic components should also have an effect on clocks. This has first been observed by Cohen and Mashoon for a pair of satellites counter-orbiting the Earth [Phys. Lett. A 181, 353 (1993)]. We report on a generalization of this effect for arbitrary pairs of satellites [Phys. Rev. D 90, 044059 (2014)]. This may also be used for testing gravitomagnetism using pulsar timing. In addition to that, we will show that clocks on Earth are also sensitive to the gravitomagnetic field. Clock networks which are in the state of being established around the world will be crucial for that. We also can use a comparison of clocks in space with clocks on Earth in order to measure the gravitomagnetic field. For each case we calculate the effect and discuss its measurability.

Breakdown of the Equivalence between Passive Gravitational Mass and Energy for a Quantum Body: Theory and Suggested Experiment

Andrei Lebed

Department of Physics, University of Arizona, USA

We calculate passive gravitational mass operator for a hydrogen atom in a weak gravitational field. As shown, it does not commute with energy operator of the atom in the absence of the gravitational field. Nevertheless, we demonstrate that the expectation value of passive gravitational mass of a hydrogen atom is equivalent to the total energy for stationary quantum states. On the other hand, in the presence of quantum fluctuations, the above mentioned equivalence is shown to be broken and unexpected radiation can be observed from a macroscopic ensemble of the atoms. We suggest a concrete experiment on the Earth's orbit to detect this radiation from solid sample of Hellium-4 under pressure. If such experiment is done, it will be the first direct observation of quantum effects in General Relativity. [See, for example: Andrei G. Lebed, Int. J. Mod. Phys. D, vol. 24, 1530027 (2015).]

MICROSCOPE - Testing the Weak Equivalence Principle in Space

Meike List

ZARM University of Bremen, Germany

On April 25, 2016, the French satellte mission MICROSCOPE was successfully sent to orbit from Arianespace's launch pad in French Guiana. MICROSCOPE is part of the micro-satellite line of CNES. Its objective is to test the Weak Equivalnce Principle (WEP) by measuring the so-called Etvs factor eta with an accuracy two orders better than the accuracy of present ground based tests. The satelliteś experiment consists of two extremely sensitive capacitive acceleration sensors developed by ONERA. The relative motion of the concentric cylindric test masses will be studied and residuals in the differential mode signal may indicate a violation of the WEP. To achieve the required measurement accuracy the satellite is operated in drag free mode which reduces perturbations due to space environmental effects to a minimum. First measurements are underway, The test masses were released and sucessfully servo-looped on May 2, 2016. First science data will be available in late summer, after the missionś calibration phase and a orbit dependent eclipse phase, ZARM is a member of the Science Working Group. ZARM contributes to the missionś data analysis by developing methodes based on wavelet transformations as well as detailed simulations of environmental disturbances. The present status of ongoing work will be presented.

Testing QG-modified laws of propagation for neutrinos with IceCube data

Niccoló Loret
Institut Ruer Boškovi (Zagreb), Croatia

Two recent studies (Astrophys.J.806(2015)269 and Phys.Rev.D91(2015)045009) have argued that some aspects of IceCube reported neutrino data might be manifestations of quantum-gravity-modified laws of propagation for neutrinos. We here analyze IceCube data from 2010 to 2014, testing the hypothesis that some IceCube neutrinos were produced at gamma-ray bursts but were not identified as such because of their anomalous propagation properties.

Testing general relativity with satellite laser ranging and the LAser RAnged Satellites Experiment (LARASE) research program: current results and perspectives

David M. Lucchesi
National Institute for Astrophysics (INAF-IAPS), Italy

LARASE aims to perform reliable measurements of the gravitational interaction in the weak-field and slow-motion limit of General Relativity (GR) by means of the laser tracking of the two LAGEOS and LARES satellites. These satellites are orbiting the Earth at a rather high altitude and their trajectory is known with an accuracy of a few cm level. By a least-squares fit of the ranging data it is possible to extract the GR effects on the orbital elements, namely in the Euler angles that define the orientation in space of the orbit, and by means of suitable combinations of such observables it is therefore possible to obtain the measurements of the GR precessions that arise from the Earth's gravitoelectric and gravitomagnetic fields, as well as from the de Sitter effect. These measurements represent the first step to obtain constraints of selected post-Newtonian parameter values in the field of the Earth, as well as to check the predictions of GR with respect to those of other theories for the gravitational interaction. In order to obtain these precise measurements of relativistic effects it is of primary importance to provide a reliable error budget based on an accurate evaluation of the main systematic error sources due to gravitational and non-gravitational perturbations. In this talk the various ongoing LARASE activities will be presented and discussed, along with the current results regarding satellites dynamics modeling improvements, precise orbit determination and preliminary measurements of relativistic effects, with the perspectives for the final goals of this research program.

Testing the MONDian alternative to GR with STEP

James Overduin
Towson University, USA

The proposed Satellite Test of the Equivalence Principle (STEP) will strengthen existing constraints on any possible difference in acceleration between different test materials in the same gravitational field by five orders of magnitude, testing the foundation of Einstein?s theory of General Relativity (GR). Here we remark that STEP will also give us a powerful probe of the absolute motions of the test masses, with a sensitivity to common-mode acceleration of order $10^{-18} \times g$. This sensitivity gives us a new way to test Modified Newtonian Dynamics (MOND), which has been proposed as an alternative to GR in the regime of accelerations below about $10^{-11} \times g$. We find reductions of order 10^{-5} to 0.1 in the period of oscillation of the STEP test masses if the Strong Equivalence Principle (SEP) is satisfied. If the SEP is not satisfied, as is generally expected in the context of MOND, we still find that STEP will be able to exclude some versions of the MONDian alternative to GR.

Experimental upper limits to generalized Heisenberg uncertainty relations using harmonic oscillators

Giovanni A. Prodi
INFN and University of Trento, Italy

A minimal observable length is a common feature of theories that aim to merge quantum physics and gravity. Quantum mechanically, this concept is associated with a nonzero minimal uncertainty in position measurements, which is encoded in deformed commutation relations. These can give effects potentially measurable in low-energy experiments, such as intrinsic non-linearities in the dynamics of isolated harmonic oscillators. We will present the best bounds to the parameters quantifying the commutator's deformation, achieved by direct measurements on harmonic oscillators with masses spanning a wide range around the Planck mass. We will overview the progresses toward further dedicated experiments on mechanical oscillators at the quantum regime, where the modal motion is preliminarily cooled down to a thermal occupation number around unity by means of optical cooling techniques. These experiments would set limits to quantum gravity effects even under the hypothesis that such effects are destroyed by decoherence of the wavefunction.

Search for Space-Time Correlations from the Planck Scale with the Fermilab Holometer

Jonathan Richardson
University of Chicago, USA

Measurements are reported of high-frequency cross-spectra of signals from the Fermilab Holometer, a pair of co-located 40-m, power-recycled Michelson interferometers. The instrument obtains differential position sensitivity to cross-correlated signals far exceeding any previous measurement in a broad frequency band extending to 7.6 MHz, twice the inverse light crossing time of the apparatus. General experimental constraints are placed on parameters of a set of models of universal exotic spatial shear correlations, with a sensitivity that exceeds the Planck-scale holographic information bound of space-time position states by a significant factor.

Solar Radiation Pressure Modeling for a Gravitational Redshift Test with Galileo

Benny Rievers
Center of Applied Space Technology and Microgravity (ZARM), University of Bremen, Germany

A launch anomaly of the navigation satellites GSAT-5 and GSAT-6 (European Galileo System) offers a unique opportunity for relativistic research. Although efforts have been underway to obtain a nominal circular orbit, both satellites remain at an eccentricity of about 0.15. Together with high precision clocks aboard an improved test of the gravitational redshift is feasible. However, the quality of clock data depends on an accurate modeling of the satellite position and behaviour. As a consequence, high precision approaches need to be employed for the modeling of the involved non-gravitational disturbances acting on the satellite motion. In this respect the modeling of Solar radiation pressure (SRP) is of particular importance since SRP introduces a major part of the expected disturbances. We show a high precision approach for an a-priori model of the SRP which includes the influence of the actual satellite geometry, attitude and the distribution of optical properties throughout the satellite surface. The results for the modeled SRP are evaluated with respect to commonly used models such as box-wing or cannonball. The influence and benefits of our SRP approach are discussed with respect to the evaluation of the gravitational redshift from Galileo clock data.

Hydrodynamic simulations of rotating black holes

Theo Torres Vicente
University of Nottingham, United Kingdom

In 1981, Unruh dressed an analogy between the propagation of fields in the vicinity of astrophysical black holes and the one of small excitations in fluids. This analogy allows one to test, challenge and verify, in tabletop experiments, the elusive processes of black hole mass and angular momentum loss. We are currently running various scattering experiments in effective rotating black holes from stationary draining fluid flows. This poster will report on those ongoing experiments.

Strong Field Tests of Gravity Using the Pulsar White Dwarf Binary J1141-6545

Vivek Venkatraman Krishnan
Swinburne University of Technology, Australia

Pulsars in relativistic binary systems provide some of the most stringent tests of gravity in the strong field regime to date. While pulsars like the double neutron star B1913+16 and the double pulsar J0737-3039A/B provide significant tests for the predictions of the general theory of relativity, their gravitational symmetry makes them less sensitive to test the predictions of alternative theories of gravity such as scalar-tensor theories. Pulsars in gravitationally asymmetric binaries such as pulsars with white dwarf or black hole companions are one of the best laboratories to test such alternative theories. J1141-6545 is one such pulsar in a 4.8-hour relativistic binary orbit around a white dwarf. In this presentation, I will report the results of 13-yr timing of this pulsar with the CSIRO Parkes 64m radio telescope and the UTMOST telescope and discuss how the observations constrain different scalar tensor theories of gravity.

Session D1

Loop Quantum Cosmology and the CMB

Ivan Agullo
Louisiana State University, USA

This talk will provide an up-to-date summary of phenomenological explorations in loop quantum cosmology. The possibility of a quantum gravity origin of the anomalies observed in the cosmic microwave background at large angular scales will be discussed.

Loop Quantum Gravity: Some Recent Advances

Abhay Ashtekar
Pennsylvania State University, USA

Vertex renormalisation in spin foams

Andrzej Banburski
Perimeter Institute for Theoretical Physics, Canada

Recent work on rewriting 4d spin foam amplitudes in terms of gaussian integrals over spinors has resulted in a model which allows us to evaluate amplitudes on arbitrary triangulations to a good approximation. We find that the amplitude after a 5-1 Pachner move cannot be written as a local product of edge propagators, but can give us a renormalization condition for the spin foam vertex. We discuss the physical implications of this renormalization flow.

Entanglement and the architecture of spacetime

Eugenio Bianchi
Penn State, USA

I discuss the role of entanglement in the reconstruction of a spacetime geometry in loop quantum gravity. In particular I show that semiclassical solutions of the Hamiltonian constraint are highly-entangled superpositions of spin-network states. Quantum squeezing of the Ashtekar-Lewandowski vacuum provides a new variational tool for solving the constraints and describing a semiclassical spacetime with graviton fluctuations.

Covariance in midisuperspace models of LQG

Suddhasattwa Brahma
Fudan University, Shanghai, China

Non-perturbative corrections arising from Loop Quantum Gravity can modify the structure functions in the hypersurface deformation algebra, thereby giving rise to a deformed notion of general covariance for the underlying "effective" spacetime. On incorporating (local) holonomy corrections, recently some no-go theorems have been derived in certain inhomogeneous models. In this talk, we discuss these obstructions and possible ways to overcome them, with a specific example where this shall be demonstrated for the spherically symmetric case by choosing self-dual Ashtekar variables.

Bulk amplitude and degree of divergence in 4d spin foams

Lin-Qing Chen
Perimeter Institute, Canada

We study the 4-d holomorphic Spin Foam amplitude on arbitrary connected 2-complexes and degrees of divergence. With recently developed tools and truncation scheme, we derive a formula for a certain class of graphs, which allows us to write down the value of bulk amplitudes simply based on graph properties. We then generalize the result to arbitrary connected 2-complexes and extract a simple expression for the degree of divergence only in terms of combinatorial properties and topological invariants. The distinct behaviors of the model in different regions of parameter space signal phase transitions. In the regime which is of physical interest for recovering diffeomorphsim symmetry in the continuum limit, the most divergent configurations are melonic graphs. We end with a discussion of physical implications.

Black Hole Singularity Resolution: Lesson from LQC

Alejandro Corichi
UNAM, Mexico

We review our understanding of black hole resolution as provided by loop quantum cosmology. We focus on the asymmetry of the bounce process yielding a 'white hole mass' very different from the original black hole mass. We discuss possible implications for information loss.

A new basis for Loop Quantum Gravity and application to coarse-graining.

Clement Delcamp
Perimeter Institute, Canada

Spin networks arise in the context of Loop Quantum Gravity as an orthonormal basis for the Hilbert space of functionals satisfying the Gauss constraint. Though well established, this basis presents certain drawbacks if we are interested in the large scale behavior of the theory. For instance, it has been recently found that torsion degrees of freedom might emerge under coarse-graining based on Alexander moves, such degrees of freedom being hard to capture on the usual spin network basis. In the context of 2+1d BF representation of the theory, we present here an alternative basis. The emphasis is now on excitations which correspond to violations of the constraints, namely curvature and torsion. The elementary excitations can then be interpreted as quasi-particles carrying a mass and a spin. This basis offers new opportunities to design states as well as controlling their behavior at all scales. Within this framework, the coarse-graining amounts to a merging of defects localized on the vertices of the triangulation. This merging is described by a fusion of the corresponding quasi-particles. (Work in collaboration with Bianca Dittrich)

Propagator in the rotor regimen of the scalar field through polymer path integral.

Ernesto Flores
Universidad Autnoma Metropolitana, Mexico

Polymer Quantum Mechanics (PQM) is a model that is obtained by quantizing a mechanical system adapting techniques used in Loop Quantum Gravity. This quantization is inequivalent to Schrdinger one, but it includes the latter, either as a certain limit or upon renormalization of a parameter appearing in the model. Recently, PQM has been used to study Polymer Quantum Field Theory. Hossain, Husain and Seahra calculated the propagator of the scalar field in flat spacetime applying PQM to each of the Fourier modes of the field; this within Hamiltonian framework. This has been used to study Lorentz violation in recent works. In addition, Kajuri studied the path integral version of PQM to calculate the corresponding action for a

scalar field, again Lorentz invariance is modified. In this work we calculated the propagator in the rotor regime for each pendulum corresponding to every one of the infinite Fourier modes of the field. Finally, some possible physical consequences are discussed.

Conformal Loop quantization of gravity coupled to the standard model

Rodolfo Gambini

Universidad de la República, Uruguay

We consider a local conformal invariant coupling of the standard model to gravity free of any dimensional parameter. The theory is formulated in order to have a quantized version that admits a spin network description at the kinematical level like that of loop quantum gravity. The Gauss constraint, the diffeomorphism constraint and the conformal constraint are automatically satisfied and the standard inner product of the spin-network basis still holds. The resulting theory has resemblances with the Bars-Steinhardt-Turok local conformal theory, except it admits a canonical quantization in terms of loops. By considering a gauge fixed version of the theory we show that the Standard model coupled to gravity is recovered and the Higgs boson acquires mass. This in turn induces via the standard mechanism masses for massive bosons, baryons and leptons.

Squeezed Vacua in Loop Quantum Gravity

Jonathan Guglielmon

The Pennsylvania State University, USA

Semiclassical states in loop quantum gravity are expected to exhibit long range correlations and it is important to develop tools suited to the construction of such states. In this talk, I will present a new class of states in loop quantum gravity that have controllable correlations. These states, called squeezed vacua, are most naturally defined by working in the bosonic representation, where they are generated by squeezing the vacuum via the action of a quadratic exponential. The resulting state is then projected down onto the gauge-invariant, area-matched subspace, yielding states in the Hilbert space of loop quantum gravity. I will give an explicit expression for the expansion of these states in terms of loops and spin networks, and present some simple examples that demonstrate the presence of correlations.

Phenomenology of loop quantum cosmology and CMB observations

Brajesh Gupt
Penn State, USA

An important feature of the singularity resolution in loop quantum cosmology (LQC) is the occurrence of the quantum bounce when the space-time curvature becomes Planckian leading the pre-inflationary evolution of the universe to be greatly modified. Due to the modified dynamics in the pre-inflationary era the initial conditions for both the background and cosmological perturbations are different from those in the standard inflationary scenario. We find that such modifications can lead to observational signatures on the cosmic microwave background (CMB) anisotropy spectrum, and provide a new window to explore the CMB anomalies. In this talk, we describe these initial conditions, discuss their consequences on the inflationary power spectrum, and compare our results with data from recent CMB experiments.

Can chaos be observed in quantum gravity?

Philipp Hoehn
Austrian Academy of Sciences, Vienna, Austria

There is strong evidence that a generic general relativistic spacetime features chaotic dynamics. This has severe (and often ignored) repercussions for the quantization and interpretation of the dynamics as a chaotic (Hamiltonian) constrained system generally does not give rise to a Poisson algebra of Dirac observables. Nevertheless, in certain cases one can explicitly quantize such systems. By means of toy models, I will discuss general challenges and some surprising consequences for the quantum theory of chaotic constrained systems which presumably will also appear in canonical quantum gravity. (Based on arXiv:1602.03237, 1508.01947)

Resistance distance in discretized gravity

Mikhail (Mike) Kagan
Penn State University, Abington, USA

A general expectation of loop quantum gravity is that quantized space-time should be discrete, and there are examples in which this structure is represented by graphs. In this talk, I would like to propose a new approach from graph theory that may provide a new handle on the issue of canonical quantization. Since distance (metric) is the fundamental notion in general relativity, its definition for graphs is a necessary ingredient for quantum space-time. The standard notion of distance on graphs is simply defined as the length of the shortest path between two given vertices. It turns out, however, that when graphs are used in scientific modeling there exists a more natural way to introduce distance, known as the 'resistance distance' (Klein, 1993).

The main idea behind this concept is based on the fact that multiple paths between two vertices in an electrical circuit imply a smaller effective resistance between the vertices, thus effectively decreasing the distance between them. A recently obtained closed formula for the resistance distance of an arbitrary graph is particularly simple and it appears very promising to use it as a substitute for the standard graph-theoretical (shortest-path) distance and the resulting metric. It is essentially non-local, depends on all possible paths between two vertices on a graph/lattice and thus constitutes an emerging quantity. This approach can be combined, for example, with Regge calculus and with the elegant idea of quantum graphity (Konopka et al.).

Holography: From Discretum to Continuum

Seth Kurankyi Asante

Peimeter Institute for Theoretical Physics, Canada

In recent work, Bonzom and Dittrich used Regge calculus to find the one-loop partition function of 3d gravity with finite boundaries. This initial work used the topological invariance of 3d and thus a maximally coarse triangulation. We will redo this construction with a triangulation admitting also a bulk continuum limit. This offers connection to so- called MERA tensor networks. We will also present first steps to evaluate 4D partition functions with finite boundaries in the framework of Regge calculus. These considerations will help to Address the continuum limit of spin foams and related models.

Projective State Spaces for Quantum Gravity

Suzanne Lanry

Universidad Nacional Autnoma de Mxico, Mexico

Instead of formulating the states of a Quantum Field Theory (QFT) as density matrices over a single large Hilbert space, it has been proposed by Kijowski to construct them as consistent families of partial density matrices, the latter being defined over small 'building block' Hilbert spaces. In this picture, each small Hilbert space can be physically interpreted as extracting from the full theory specific degrees of freedom (aka. 'coarse-graining' the continuous theory). This allows to reduce the quantization of a classical field theory to the quantization of finite-dimensional sub-systems, while obtaining robust and well-controlled quantum states spaces. I will explain how this formalism can be applied to background-independent Quantum Gravity, and discuss what can be gained by doing so, especially with respect to the study of the semi-classical and cosmological sectors of the theory, and as a way to connect canonical and covariant approaches to exploit their respective strengths.

Canonical Loop Quantum Gravity

Jerzy Lewandowski
Uniwersytet Warszawski, Poland

The goal of this talk is to give a review of and the update for the canonical Loop Quantum Gravity. The talk will be focused on the full theory with all the local degrees of freedom. There will be outlined newest results concerning the quantum scalar constraint operators, their solutions, physical Hamiltonians, the Dirac observables and other structures of the canonical quantum gravity. A part of the results was obtained by the speaker in collaboration with: Sahlmann, Lin, Alesci, Assanioussi, Dapor, Makinen, Swiezewski, Duch, Bodendorfer, Kaminski.

Quantization of Plane Gravitational Waves: An update

Seth Major
Hamilton College, USA

We investigate plane fronted gravitational wave space-times as model systems to study loop quantization techniques and dispersion relations. Starting with planar symmetric space-times in the real connection formulation, we formulate the constraint algebra of the model in such that it is first class and without structure functions. Quantization of the diffeomorphism and scalar constraints are discussed.

Primordial fluctuations in Quantum Cosmology

Mercedes Martin-Benito
Radboud University Nijmegen, Netherlands

A lot of attention has been devoted lately to the consideration of quantum corrections to the power spectrum of primordial fluctuations, as a possible window to unveil quantum geometry phenomena in the Early Universe. We review the derivation of these corrections, starting from a formalism designed to describe the cosmological perturbations in terms of gauge invariants without freezing the gauge degrees of freedom of the system. We show how a Born-Oppenheimer ansatz leads then to the recovery of a Mukhanov-Sasaki equation in which the coefficients are provided by expectation values on the background geometry. We also discuss technical tools and develop a procedure to deal with these quantum corrections beyond the most direct semiclassical approximation. The case of hybrid Loop Quantum Cosmology is commented in detail, but the presented treatment is general, and aims at increasing the ability to discriminate between the predictions of different quantization proposals for cosmological perturbations.

Spherically symmetric quantum spacetimes coupled to a thin null-dust shell

Javier Olmedo

Louisiana State University, USA

In this contribution I will describe the loop quantization of a spherically symmetric spacetime coupled to a spherical thin null-dust shell. Concretely, I provide a quantum constraint algebra free of anomalies. The solutions to the constraints are not known yet, but it is possible to identify quantum Dirac observables. Presently, some of them lack a selfadjoint representation on the polymeric kinematical space. However, if we assume a standard one for them, a quantization in terms of parametrized observables provides a quantum covariant formalism free of singularities and with a fundamental discretization of the geometry. Finally, I will comment on other possible physical outcomes, like a rigorous study of dynamical black hole formation in quantum gravity, and future prospects.

Black hole entropy, 2d CFTs, and quantum geometry

Alejandro Perez

Centre de Physique Theorique, France

I will show that there is a natural relationship between quantum geometry degrees of freedom on an (isolated) horizon and 2-dimensional CFTs. This relationship might play a central role in the understanding of BH entropy in LQG.

Spacetime emergence through a geometric renormalization method

Saeed Rastgoo

Universidad Autonoma Metropolitana, Mexico

We present a method of coarse graining graphs, such that it would lead to a limit space that under certain conditions may look like a manifold representing the semiclassical spacetime. The idea is based on the convergence of a hierarchical sequence of graphs built upon each other, such that each is the coarse grained version of the previous one in the hierarchy. The convergence is measured by the Gromov-Hausdorff distance between metric spaces, and the coarse graining is based on quasi-isometry. We show that for a large class of graphs, this sequence converges to a limit space called the Hausdorff limit. We also define a dimension for the graphs that is both integer and stable under this coarse graining process. Finally we comment on the criteria under which this limit space is a manifold.

Computing black hole's lifetime with LQG

Carlo Rovelli
Aix-Marseille University, France

Black holes can explode via a quantum tunneling process, after reaching the Planck-star stage. The astrophysical relevance of this process depends on the time its takes. To compute this time, a background-free quantum gravity theory is needed. I show how covariant LQG can be used for this. The calculation is a concrete example of how realistically observable quantities can be computed in a background-free quantum theory gravity.

On the effective loop quantum FLRW model with positive cosmological constant

Juan Carlos Ruelas Vázquez
Universidad Autnoma Metropolitana, Mexico

In loop quantum cosmology the path integral formalism allows to define an effective action leading to corrections to the equations of motion not only capable of avoiding the initial singularity but describing pretty well several physical features. On the other hand, in the case of the hamiltonian loop quantization of the FLRW model with positive cosmological constant, the Hamiltonian constraint has a family of selfadjoint extensions related to different boundary conditions. In this work we describe our progress in studing the fate of the selfadjoint extensions of this model using the effective description descending from the path integral version of the loop quantization.

Boundedness of curvature invariants and lack of strong singularities in loop quantization of Kantowski-Sachs spacetime

Sahil Saini
Louisiana State University, Baton Rouge, Louisiana, USA

The Kantowski-Sachs spacetime is singular in classical General Relativity. Assuming the validity of effective Hamiltonian approach, we examine the behavior of the curvature invariants in loop quantum cosmology. Our results show that classical divergences in curvature invariants are resolved in the sense that they are found to be finite for any finite proper time, given that the pressure is finite. Analysis of the strength of singularities indicates that strong singularities are resolved but weak singularities can occur. These results are in tune with similar resolution of physical singularities in results obtained earlier for loop quantization of isotropic and Bianchi-I spacetimes.

On the relationship between the modifications to dynamical equations, and canonical Hamiltonian structures & polymerization

Parampreet Singh

Louisiana State University, USA

We study the problem of obtaining canonical Hamiltonian structures from modified dynamical equations of motion without any knowledge of action, in Friedmann-Robertson-Walker models. Canonical structure of the modified theories is determined demanding that the total Hamiltonian be a linear combination of gravity and matter Hamiltonians. We show that a repulsive quadratic modification to energy density in Raychaudhuri equation fixes the canonical canonical phase space of gravity as a polymerized phase space with canonical momentum as inverse trigonometric function of Hubble rate; the canonical Hamiltonian can be identified with the effective Hamiltonian in loop quantum cosmology. The repulsive cubic modification results in a 'generalized polymerized' canonical phase space. In contrast, the quadratic and cubic attractive modifications result in a canonical phase space in which canonical momentum is non-trigonometric and singularities persist. Our results hint on connections between repulsive/attractive nature of modifications to gravity arising from gravitational sector and polymerized/non-polymerized gravitational phase space.

The Thermodynamics of quantum spacetime histories

Lee Smolin

Perimeter Institute for Theoretical Physics, Canada

We show that the simplicity constraints, which define the dynamics of spin foam models, imply, and are implied by, the first law of thermodynamics, when the latter is applied to causal diamonds in the quantum spacetime. This result reveals an intimate connection between the holographic nature of gravity, as reflected by the Bekenstein entropy, and the fact that general relativity and other gravitational theories can be understood as constrained topological field theories. To state and derive this correspondence we describe causal diamonds in the causal structure of spin foam histories and generalize arguments given for the near horizon region of black holes by Frodden, Gosh and Perez and Bianchi. This allows us to apply a recent argument of Jacobson to show that if a spin foam history has a semiclassical limit described in terms of a smooth metric geometry, that geometry satisfies the Einstein equations. These results suggest also a proposal for a quantum equivalence principle. This will be developed.

Quantum-gravity signals from primordial black holes

Francesca Vidotto

Radboud University Nijmegen, Netherlands

The possibility that quantum gravity allow black holes to tunnel into white holes has recently raised much interest. This could open to a new window for quantum-gravity phenomenology, in connection with the existence of primordial black holes. I discuss the power of the expected black hole explosion and the possibility to observe astrophysical signals in the radio and in the gamma wavelengths.

Evolution of perturbations in anisotropic loop quantum cosmology

Sreenath Vijayakumar

Louisiana State University, USA

In loop quantum cosmology the big bang singularity is replaced by a quantum bounce. The evolution of primordial perturbations through such a bounce in an FLRW universe has been studied in great detail. However, it is well known that bouncing cosmologies are unstable in the presence of anisotropies, in the sense that any tiny anisotropy will grow as the universe contracts and undergo a bounce. Anisotropies will then decrease and eventually dilute in the expanding branch, but quantum perturbation may retain memory of the anisotropic bounce. In this talk, we present our efforts in understanding the evolution of primordial perturbations in the anisotropic (Bianchi-I) bounce of loop quantum cosmology, and in exploring its phenomenological implications.

Cosmological transition amplitudes with Proper Vertex

Ilya Vilensky

Florida Atlantic University, USA

Recently a modification of the EPRL vertex amplitude - so-called, the proper vertex amplitude - was introduced to enable correct semi-classical behavior to match classical Regge calculus. We use the proper vertex amplitude to investigate transition amplitudes between coherent quantum boundary states of cosmological geometries. We study the interplay between the choice of coherent boundary data and the selection of the gravitational sector ensured by the proper vertex.

Angular momentum and centre of mass from generalised Witten equations

Wolfgang Wieland
Perimeter institute for Theoretical Physics (Waterloo, ON), Canada

Witten?s three-surface spinor equations provide a definition for the ADM energy-momentum vector at spatial infinity. I give a generalisation for the remaining six Poincaré charges, which are the angular momentum and the centre of mass. I show that the defining differential equations for these generalised Witten spinors are well-defined on surfaces or arbitrary signature and I study them on the entire boundary of a compact four-dimensional region. The resulting quasi-local charges for energy and angular momentum are two-dimensional surface integrals over an arbitrary cross-section of the boundary. For any two consecutive cross-sections, I present conservation laws that determine the influx (outflow) of matter and gravitational radiation. The formalism is surprisingly similar to recent developments in loop quantum gravity: During the last couple of years a new framework for loop quantum gravity was constructed by Simone Speziale, Laurent Freidel, myself and others. In this new representation, the fundamental configuration variables are SL(2,C) spinors that live on a one-dimensional graph in the boundary of spacetime, and I will give evidence that the three-surface spinors that are used in Witten's formalism are nothing but the spinorial degrees of freedom that appear in loop quantum gravity at the boundary of spacetime.

Bouncing cosmologies from quantum gravity condensates

Edward Wilson-Ewing
Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Germany

We study the effective cosmological dynamics, emerging as the hydrodynamics of simple condensate states, of a group field theory model for quantum gravity coupled to a massless scalar field and reduced to its isotropic sector. The quantum equations of motion for these group field theory condensate states are given in relational terms with respect to the scalar field, from which effective dynamics for spatially flat, homogeneous and isotropic space-times can be extracted. The result is a generalization of the Friedmann equations, including quantum gravity modifications, in a specific regime of the theory. The classical Friedmann equations of general relativity are recovered in a suitable semi-classical limit for some range of parameters of the microscopic dynamics. An important result is that the quantum geometries associated with these GFT condensate states are non-singular: a bounce generically occurs in the Planck regime. For some choices of condensate states, these modified Friedmann equations are very similar to those of loop quantum cosmology.

Long range correlations in loop quantum gravity

Nelson Yokomizo

Pennsylvania State University, USA

I discuss the long range behavior of correlations of quantum fluctuations of the geometry in semiclassical spin network states based on regular cubulations. For coherent spin networks, area-area correlations are shown to decay exponentially with a small correlation length in lattice units. States with an inverse square law decay of correlations are shown to exist in the family of squeezed vacua in the bosonic model of loop quantum gravity.

Session D2

AdS nonlinear instability: moving beyond spherical symmetry

Oscar Dias
STAG, Southampton University, United Kingdom

AdS is conjectured to be nonlinear unstable to a weakly turbulent mechanism that develops a cascade towards high frequencies, leading to black hole formation. We give evidence that the gravitational sector of perturbations behaves differently from the scalar one. In contrast with the spherically symmetric scalar sector, we find that not all gravitational normal modes of AdS can be nonlinearly extended into periodic horizonless smooth solutions of the Einstein equation. In particular, we show that even seeds with a single normal mode can develop secular resonances, unlike the spherically symmetric scalar field collapse. Moreover, if the seed has two normal modes, more than one resonance can be generated at third order, unlike the spherical collapse. We also show that weak turbulent perturbative theory predicts the existence of direct and inverse cascades, with the former dominating the latter for equal energy two-mode seeds.

Entanglement, Gravity, and Quantum Error Correction

Xi Dong
Institute for Advanced Study, United States

Over the last few years it has become increasingly clear that there is a deep connection between quantum gravity and quantum information. The connection goes back to the remarkable discovery that black holes carry entropy with an amount given by the horizon area. I will present new evidence that this is only the tip of the iceberg, and prove that a similar area law applies to more general Renyi entanglement entropies. To demonstrate the simplicity of my prescription, I will use it to provide the first holographic calculation of the mutual Renyi information between two disks of arbitrary dimension. I will comment on the prospect of verifying this area law experimentally in light of recent advances in measuring Renyi entropies. Furthermore, I will provide quantum corrections to the area law and use it to solve a long-standing problem in quantum gravity: what region of the dual spacetime is described by a subregion in a holographic theory. The answer to this question lies in a new perspective that I will advocate: holography is a quantum error correcting code.

Black holes at large D: Things we've learned so far

Roberto Emparan
ICREA & Universitat de Barcelona, Spain

The dynamics of black holes and black branes greatly simplifies in the limit in which the number of spacetime dimensions D grows very large. I will give an overview of some of the main things we have learned and of results we have achieved so far in the development of this program.

Bulk Consequences of Boundary Causality

Sebastian Fischetti
Imperial College London, United Kingdom

Causality is a fundamental property of QFTs, which in AdS/CFT is manifested in a gravitational time delay: the "fastest" signal from one point on the boundary of AdS to another must travel through the boundary. A well-known result of Gao and Wald shows that the averaged null energy condition (ANEC) in the bulk is sufficient to ensure this property. However, quantum fields may violate the ANEC, so it is not clear their theorem applies outside of a classical regime. Here I study the converse problem: what does boundary causality imply for the bulk? I will show that a necessary and sufficient condition for linear perturbations of pure AdS to preserve boundary causality is that they cause light cones to close in an averaged, gauge-invariant sense. I will show that this condition is strictly weaker than the ANEC, and so it can be interpreted as an inequality that any quantum gravitational perturbation of pure AdS must obey (as long as it is dual to a causal boundary CFT).

Infrared Effects in the Late Stages of Black Hole Evaporation

Eanna Flanagan
Cornell University, United States

As a black hole evaporates, each outgoing quantum carries away some of the holes energy, linear momentum, angular momentum, BMS supermomentum and BMS super center-of-mass. Fluctuations in the black hole's charges thus grow over the course of the evaporation. We estimate the scale of these fluctuations using a simple model. The late-time results are: The black hole position has a uncertainty of order the square of the initial mass M_i (previously estimated by Page); The mass has fractional fluctuations of order unity when the expected mass is $M_i^{2/3}$; The fluctuations in supermomentum are negligible; The fluctuations in the super center-of-mass charges (soft hair) are of order unity for multipoles of order unity, but fall off exponentially at large multipole order. These large infrared effects complicate the usual, sharp arguments for the information loss paradox. However, we argue

that the usual arguments can be generalized and that the paradox is persistent and robust. The infrared effects do suggest a new scenario for how the paradox might be resolved: information starts to emerge once there is an amplitude of order unity for the black hole mass to be at the Planck scale, which happens when the expected mass is $M_i^{2/3}$. Then, over a timescale M_i^2, the state makes a transition to a thermal gas of gravitons and other quanta of total mass $M_i^{2/3}$, spatial extent M_i^2, temperature $M_i^{-4/3}$ and entropy M_i^2. Some new ingredient would be required for the viability of this scenario.

Polarised Black Holes in AdS

Lauren Greenspan
University of Porto, Portugal

I will discuss solutions of Einstein-Maxwell theory with a negative cosmological constant that asymptote to global AdS_4 with a dipolar electrostatic potential turned on at infinity. The potential gives rise to two new geometries: an AdS soliton that includes the full backreaction of the electric field on the AdS geometry, and a neutral black hole that is deformed by the electric field. Boundary data such as the charge density and stress tensor, as well as black hole horizon quantities will be presented. The free energies of the black hole and soliton phases give rise to a phase diagram that generalizes the Hawking-Page phase transition, with the soliton dominating the low temperature phase and the black hole dominating the high temperature phase. Coupling this geometry to a scalar field allows us to construct the supergravity duals to ABJM theory, providing a nontrivial example of the gauge/gravity duality.

First law for solitons in five dimensional spacetime

Sharmila Gunasekaran
Memorial University of Newfoundland, Canada

The mass variation formula and Smarr relation for black holes contains terms involving conserved charges and their corresponding potentials. Recently, a mass variation formula and Smarr relation was derived for more general five dimensional asymptotically flat stationary spacetimes with non-trivial topology (2-cycles) in the exterior region. Additional terms appear in these expressions arising from the fluxes and associated potentials coupled to these 2-cycles. In this presentation, these results will be reviewed and examined in detail for examples of spacetimes containing solitons.

Entanglement production and Lyapunov exponents

Lucas Hackl
Pennsylvania State University, United States

Entanglement entropy plays an important role when one studies correlations in quantum field theory. In this talk, I discuss the relation between entanglement production of quantum systems and instabilities in their classical counterpart. In particular, I present a new theorem stating that in classically unstable linear systems the entanglement entropy grows linearly. Its slope is given by a sum over the Lyapunov exponents of the system. [based on work with Eugenio Bianchi and Nelson Yokomiza]

Acoustics of a simple holographic model with momentum relaxation

Shahar Hadar
DAMTP, University of Cambridge, United Kingdom

The linear axion model, proposed by Andrade and Withers, is the simplest extant holographic model of transport with momentum relaxation in a strongly coupled field theory without quasiparticles. On the gravity side it is an asymptotically Anti-de Sitter black brane solution of General Relativity with additional matter fields which have a nonzero profile at equilibrium. We develop a gauge-invariant formalism for studying the perturbations of this solution and compute its quasinormal modes. We find strong evidence for the model's stability and find an interesting critical behaviour of a certain family of modes. For a special value of the parameters the symmetry is enhanced, allowing an analytical computation of the full quasinormal spectrum.

Thinking outside the truncation: new hair for holographic superconductors

Gavin Hartnett
University of Southampton, United Kingdom

There has been a significant amount of work in recent years on modelling superconductors and superfluids using the gauge/gravity correspondence. Much of this work has been done via so-called bottom-up approaches wherein the action is chosen freely, and is not constrained to be derivable from a dimensional reduction of 10- or 11-dimensional supergravity, where the gauge/gravity dictionaries are best understood. Alternatively, in top-down approaches the lower dimensional action does in fact come from a reduction of 10- or 11-dimensional supergravity, but these approaches often only consider a consistent truncation of all possible Kaluza-Klein modes in the lower dimensional theory. In this talk, I show that, at least in certain classes of compactifications, the dominant superconducting instability comes from a mode that lies outside any known truncation. An important consequence of this fact is that the superconducting phase is necessarily described by an infinite number of VEV's, corresponding in the bulk to the infinite tower of Kaluza-Klein fields sourced by the unstable mode.

New Insights into Quantum Gravity from Gauge/gravity Duality

Gary Horowitz
UC Santa Barbara, United States

Using gauge/gravity duality, we deduce several nontrivial consequences of quantum gravity from simple properties of the dual field theory. These include: (1) a version of cosmic censorship, (2) restrictions on evolution through black hole singularities, and (3) the exclusion of certain cosmological bounces. In the classical limit, the latter implies a new singularity theorem. (Based on work with Netta Engelhardt.)

Quantum chaotic string in AdS geometry

Yuichiro Hoshino
Waseda University, Japan

Recently, integrability structure have gathered much attention in the context of AdS/CFT correspondence. Therefore classical string integrability in the sense of Liouville has been studied in various background and shows chaotic behavior in several cases. However, its quantum effects have not been sufficiently discussed. In this presentation, we show that a cohomogeneity-one string in 5-dimensional AdS black hole exhibits chaos and phase transition-like relationship between Lyapunov exponents and black hole mass. Then we quantize this system with minisuperspace prescription and then discuss how its chaotic characteristics appear in its level-spacing distribution.

Black hole non-uniqueness from spacetime topology

Hari Kunduri
Department of Mathematics and Statistics, Memorial University, Canada

The domain of outer communication of $D = 5$ asymptotically flat stationary spacetimes may possess non-trivial 2-cycles, leading to a gross violation of black hole uniqueness beyond the existence of black rings. I will sketch the derivation of a mass variation formula for such spacetimes, which can be considered as a 'first law' for black hole and soliton mechanics. Secondly, I will discuss a simple example of a family of supersymmetric black holes with spherical horizon and a 2-cycle in the exterior. There are black holes within this class with identical conserved changes to the BMPV black hole that have a larger entropy.

Dynamics of Black Rings and Weak Cosmic Censorship

Markus Kunesch

DAMTP, University of Cambridge, United Kingdom

In this talk I will present the results of our numerical simulations of black rings in five dimensions. The endpoint of a Gregory-Laflamme-type instability in very thin rings provides concrete evidence that the weak cosmic censorship conjecture can be violated in five dimensional asymptotically flat spacetimes. The process is qualitatively similar to what was observed by Lehner and Pretorius in their remarkable work on the Kaluza-Klein black string. As part of this work, we simulated a number of perturbed black rings which cover the whole range of the thickness parameter. In this process, we discovered a new instability which stretches the horizon without substantially changing its thickness. This instability completely dominates the evolution for rings of intermediate thickness and results in the collapse to a black hole of spherical topology. Only for very thin rings does the Gregory-Laflamme instability become dominant and eventually gives the ring a fractal structure of bulges connected by necks which become ever thinner over time. I will argue that this suggests that very thin black rings break and hence violate weak cosmic censorship. More on PRL 116, 071102 (2016).

The Exact SL(K + 3;C) Symmetry of String Scattering Amplitudes

Jen-Chi Lee

National Chiao-Tung University, Taiwan

We discover that the 26D open bosonic string scattering amplitudes (SSA) of three tachyons and one arbitrary string state can be expressed in terms of the D-type Lauricella functions with associated SL(K + 3;C) symmetry. As a result, SSA and symmetries or relations among SSA of different string states at various limits calculated previously can be rederived. These include the linear relations conjectured by Gross and proved by Taiwan group in the hard scattering limit, the recurrence relations in the Regge scattering limit and the extended recurrence relations in the nonrelativistic scattering limit discovered recently. Finally, as an application, we calculate a new recurrence relation of SSA which is valid for all energies.

The Dirac observables in general relativity

Jerzy Lewandowski
Uniwersytet Warszawski, Poland

We present a new scheme of defining invariant observables for general relativistic systems. The scheme is based on the introduction of an observer which endows the construction with a straightforward physical interpretation. The observables are invariant with respect to spacetime diffeomorphisms which preserve the observer. The limited residual spatial gauge freedom is studied and fully understood. A full canonical analysis of the observables is presented: we analyze their variations, Poisson algebra and discuss their dynamics. Bibliography: "The algebra of observables in Gaussian normal spacetime coordinates", N. Bodendorfer, P. Duch, J. Lewandowski, J. Swiezewski. JHEP 1601 (2016) 047. "Observables for General Relativity related to geometry" P. Duch, W. Kaminski, J Lewandowski, J. Swiezewski. JHEP 1405 (2014) 077.

Black lenses

James Lucietti
University of Edinburgh, United Kingdom

I will discuss a novel class of supersymmetric, asymptotically flat, black hole solutions to five dimensional supergravity, which are regular on and outside an event horizon of lens space topology $L(2,1)$. These black lenses uplift to new D1-D5-P solutions of type IIB supergravity and carry three charges, three dipoles and two angular momenta with one constraint relating these. The entropy of the system can be exactly accounted for by the degeneracy of the near-horizon CFT states, despite the absence of a (locally) AdS(3) factor in the decoupling limit.

Quantum mechanical models for black holes

Juan Maldacena
Institute for Advanced Study, United States

We will describe some condensed matter inspired quantum mechanical models that have some properties similar to near extremal black holes. We will discuss the match between the emergent almost conformal symmetry of the quantum mechanical system and the black hole.

Hairy Black Holes in AdS5S5

Julija Markeviciute
University of Cambridge, United Kingdom

We use numerical methods to exhaustively study a novel family of hairy black hole solutions in AdS5. These solutions can be uplifted to solutions of type IIB supergravity with AdS5S5 asymptotics and are thus expected to play an important role in our understanding of AdS/CFT. We find an intricate phase diagram, with the aforementioned family of hairy black hole solutions branching from the Reissner-Nordstrom black hole at the onset of the superradiance instability. We analyze black holes with spherical and planar horizon topology and explain how they connect in the phase diagram. Finally we detail their global and local thermodynamic stability across several ensembles.

Comments on Causal Holographic Information and the Coarse-grained Quantum Null Energy Conjecture

Donald Marolf
UCSB, United States

We present additional evidence that the area of causal horizons (aka Causal Holographic Information, or CHI) defined relative to regions of an asymptotically locally AdS boundary computes a coarse-grained of the dual CFT. In particular, for regions of the CFT outside a Killing horizon, a finite CHI is obtained by subtracting precisely the same counter-terms used to renormalize the area of extremal Ryu-Takayanagi or Hubeny-Rangamani-Takayanagi surfaces. We also discuss the possibility that CHI may satisfy a quantum null energy condition in the dual CFT. This condition would be a great surprise from the bulk point of view, where it would require an unprecedented constraint on the rate at which horizon areas can grow along caustics. Nevertheless, we show it to hold in simple AdS_3 examples.

Entanglement Entropy of Jammed CFTs

Eric Mefford
University of California, Santa Barbara, United States

We present new static, spherically symmetric solutions to the vacuum Einstein equations with negative cosmological constant in five, six, and seven dimensions. The (d+1) dimensional solutions are asymptotically locally Anti de Sitter with the corresponding d dimensional Reissner-Nordstrom metric on the boundary.

Holographic general relativity

Eric Perlmutter
Princeton University, United States

We present a computation of quantum corrections to the thermal entropy of small black holes in general relativity in AdS_3, and their implications for the spectrum of a putative dual 2d CFT.

Instability of supersymmetric microstate geometries

Harvey Reall
Cambridge University, United Kingdom

Microstate geometries are smooth, time-independent, asymptotically flat, horizon free solutions of type IIB supergravity. in the fuzzball conjecture, they are supposed to provide a geometrical description of certain black hole microstates. Some non-BPS microstate geometries have an ergoregion, which implies that they suffer a linear instability. BPS microstate geometries have no ergoregion so one might expect linear stability. However, I will argue that they suffer a nonlinear instability.

Lumpy $AdS_5 \times S^5$ black holes and black belts.

Jorge Eduardo Santos
DAMTP - University of Cambridge, United Kingdom

We numerically construct asymptotically global AdS5 $\times$ S5 black holes that are localised on the S5. These are solutions to type IIB supergravity with S8 horizon topology that dominate the theory in the microcanonical ensemble at small energies. At higher energies, there is a first-order phase transition to AdS5-Schwarzschild $\times$ S5. By the AdS/CFT correspondence, this transition is dual to spontaneously breaking the SO(6) R-symmetry of $N = 4$ super Yang-Mills down to SO(5). We extrapolate the location of this phase transition and compute the expectation value of the resulting scalar operators in the low energy phase.

String loop around black hole – applications

Sdeněk Stuchlík
Institute of Physics and Research Centre of Theoretical Physics and Astrophysics, Silesian University in Opava, Czech Republic

Axially symmetric current carrying string loop dynamics around rotating Kerr black hole will be presented. Such extended linear object is governed by two parameters only - an outer tension barrier and an inner angular momentum barrier. We assume that such a string loop could be useful for the description of axial symmetric matter distribution forming a special region of black hole accretion disc. We test if the string loop ejection from the equatorial plane region and the transitional motion along the symmetry axis could serve as possible explanation of relativistic jet. The string loop oscillations near the equatorial plane could be related to high-frequency quasi-periodic oscillations observed near black holes.

Black Resonators

Benson Way
DAMTP, University of Cambridge, United Kingdom

We numerically construct asymptotically anti-de Sitter (AdS) black holes in four dimensions that contain only a single Killing vector field. These solutions, which we coin black resonators, link the superradiant instability of Kerr-AdS to the nonlinear weakly turbulent instability of AdS by connecting the onset of the superradiance instability to smooth, horizonless geometries called geons. Furthermore, they demonstrate non-uniqueness of Kerr-AdS by sharing asymptotic charges. Where black resonators coexist with Kerr-AdS, we find that the black resonators have higher entropy. Nevertheless, we show that black resonators are unstable and comment on the implications for the endpoint of the superradiant instability.

Crossing the duality: the turbulence and statistics of gravity

Ryan Westernacher-Schneider
Perimeter Institute / University of Guelph, Canada

The fluid-gravity duality provides a means to import results from fluid turbulence into gravitational physics, and vice versa. The fluid side is conformal, and thus intrinsically relativistic. Therefore, in order to import familiar results from turbulence, those results must first be generalized to relativistic fluids. These efforts have given rise to the notion of a gravitational Reynolds number and the discovery of purely gravitational turbulent behaviour of black holes, both in asymptotically AdS and flat spacetimes. I will review this research program, with emphasis on present efforts to import recently discovered statistical correlations in relativistic turbulence across the duality.

Holographic Heavy Ion Collisions in Non-Conformal Theories

Miguel Zilhao

Universitat de Barcelona, Spain

Understanding the dynamics of out-of-equilibrium matter in strongly coupled systems is an important and challenging problem in theoretical physics. A particularly interesting example is the Quark-Gluon Plasma formed in relativistic colliders such as RHIC or the LHC, which motivates the study of the relaxation process in strongly coupled non-abelian field theories. We use holography to map the evolution of plasma in a non-conformal gauge theory to a gravitational system, namely to the collision of two gravitational shockwaves in Einstein-scalar field theory with an asymptotically Anti-de Sitter geometry, and study the effect of the non-conformality in the relaxation times of the resulting plasma.

Session D3

Open question. Could a Causal Discontinuity Explain Fluctuations in the CMBR Radiation Spectrum?

Andrew Beckwith
Chongqing University, PRC

Could a causal discontinuity lead to an explanation of fluctuations in the CMBR radiation spectrum? Is this argument valid if there is some third choice of set structure (for instance do self referential sets fall into one category or another?). The answer to this question may lie in (entangled?) vortex structure of space time, along the lines of structure similar to that generate in the laboratory by Ruutu. Self-referential sets may be part of the generated vortex structure, and we will endeavor to find if this can be experimentally investigated. If the causal set argument and its violation via this procedure holds, we have the view that what we see a space time 'drum' effect with the causal discontinuity forming the head of a 'drum' for a region of about 10^{10} bits of information before our present universe up to the instant of the big bang itself for a time region less than $\sim 10^{-44t}$ seconds in duration, with a region of increasing bits of 'information' going up to 10^{120} bits of 'information' due to vortex filament condensed matter style forming through a symmetry breaking phase transition

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Causal Sets and Nonlocality: Recent Developments

Dionigi Benincasa
SISSA, Italy

Non-locality in causal set theory arises from the interplay between fundamental discreteness and Lorentz invariance. After giving a brief review of the exact nature of the non-locality in causal sets, I will proceed to outline recent developments in the field that make explicit use of this non-locality. In particular, I will talk about nonlocal quantum field theories, dimensional reduction in the UV, and finally the possibility of using experiments on macroscopic quantum oscillators to detect this kind on non-locality.

The quantum clock: a critical discussion on space-time

Luciano Burderi
University of Cagliari, Italy

We critically discuss the measure of very short time intervals. By means of a Gedanken experiment, we describe an ideal clock based on the occurrence of completely random events. Many previous thought experiments have suggested fundamental Planck-scale limits on measurements of distance and time. Here we present a new type of thought experiment, based on a different type of clock, that provide further support for the existence of such limits. We show that the minimum time interval dt that this clock can measure scales as the inverse of its size dr. This implies an uncertainty relation between space and time: $drdt > Gh/(2\varpi c^4)$, where G, h, and c are the gravitational constant, the Planck constant, and the speed of light, respectively. We outline and briefly discuss the implications of this uncertainty conjecture.

The dynamics of boundary diffeomorphisms

Steven Carlip
UC Davis, United States

General relativity is invariant under diffeomorphisms, and excitations of the metric corresponding to diffeomorphisms are nonphysical. In the presence of a boundary, though – including a boundary at infinity – the Einstein-Hilbert action with suitable boundary terms is no longer fully invariant, and certain diffeomorphisms are promoted to physical degrees of freedom, with a boundary action induced from the bulk action. I will describe how this works in (2+1)-dimensional AdS gravity, where the boundary action is a Liouville action, and in (2+1)-dimensional asymptotically flat gravity, where the relevant diffeomorphisms are related to the BMS group.

Non-Perturbative Renormalization of Graviton Vertex Functions

Nicolai Christiansen
Heidelberg University, Germany

The asymptotic safety scenario provides a framework for non-perturbative renormalization of a quantum field theory of gravity. A non-trivial ultraviolet fixed point renders the theory finite at arbitrarily high energy scales and the theory can be considered as truly fundamental. We investigate the scale- and momentum-dependence of the graviton two- and three-point function, including four-derivative interactions. The fixed point structure of the couplings and the properties of the renormalization group flow are analyzed.

A finite-size scaling analysis of the spectral dimension in causal dynamical triangulations

Joshua Cooperman

Bard College, United States

The spectral dimension measures the scale-dependent dimensionality of a space as witnessed by a random walker diffusing through this space. Within the causal dynamical triangulations approach to the quantization of gravity, the spectral dimension exhibits physically interesting scale-dependent behavior, dynamically reducing towards 2 on sufficiently small scales, matching the topological dimension of 4 on intermediate scales, and decaying exponentially in the presence of positive curvature on sufficiently large scales. Although these results have been known for several years, a comprehensive finite-size scaling analysis of the spectral dimension is lacking. I present the results of such an analysis–both the dependence on the diffusion time and on the diffusion constant–for the test case of 3 topological dimensions.

Searching for a Continuum Limit in CDT Quantum Gravity

Daniel Coumbe

Niels Bohr Institute, Denmark

We search for a continuum limit in the causal dynamical triangulation (CDT) approach to quantum gravity by determining the change in lattice spacing using two independent methods. The two methods yield similar results that may indicate how to tune the relevant couplings in the theory in order to take a continuum limit.

Spectral dimension in non-commutative geometry

Lisa Glaser

University of Nottingham, United Kingdom

The spectral dimension of a mode is an intuitive measure that gives us information about both its short and long range properties. Having been introduced as a tool to extract information from simulations in CDT it is now used in many different theories of quantum gravity. Non-commutative geometry, in the way Alain Connes envisioned it, describes manifolds through the algebra of functions on them. This description implements a shortest wavelength cut-off, and hence a discretisation of space-time. It can be studied using Monte Carlo simulations of a matrix model, and in doing so we find random geometries and a phase transition. In this context we use the spectral dimension to better understand the structure of our geometries. To usefully extend the spectral dimension to Dirac operators we introduce the spectral variance, and show it's application to different geometries.

Phases of Gravity with Anisotropic Scaling

Kevin Grosvenor

Niels Bohr Institute (NBI), University of Copenhagen, Denmark

We analyze the phase structure of gravity with Lifshitz-type anisotropic scaling, as a function of the coupling constants and the spatial topology, in the mean field approximation. For concreteness, we consider Friedman-Lematre-Robertson-Walker solutions to the projectable theory in 2+1 dimensions around an ultraviolet fixed point characterized by a dynamical critical exponent $z = 2$. As in many condensed matter systems, under the influence of relevant deformations, the theory flows from the short-distance fixed point with dynamical critical exponent $z \gtrsim 1$ to one of several long-distance phases characterized by $z = 1$. The special case when the spatial slices are spheres is of particular interest for comparison with the Causal Dynamical Triangulations approach to lattice gravity and explains the gross aspects of the phase diagram observed therein despite its living in one fewer dimension than do the simulations. The phase structure is much richer in 3+1 dimensions, in which the theory can naturally support $z = 3$ scaling, as well as in the non-projectable case. In both of these cases, gradient terms in the action inevitably lead to spatially modulated phases, which remain largely unexplored. A number of interesting directions of inquiry arise naturally from this work. For example, in 2+1 dimensions, one can consider the theory both in real as well as in imaginary time. In the latter, a forbidden region opens up in which no solutions exist. We suggest some interpretations of and possible resolutions for this phenomenon.

Entanglement time in causal sets

Lucas Hackl

Pennsylvania State University, United States

Rafael Sorkin computed the entanglement entropy of a scalar field on a causal set from its correlation function. In this talk, I will introduce a notion of time that can be derived from the entanglement entropy of causal diamonds with the same volume. In particular, I will discuss its relation to the time of an initial observer in simple cosmological models and explain how entanglement can be produced by classical instabilities.

Ground state of the universe and the cosmological constant

Viqar Husain
University of New Brunswick, Canada

The physical Hamiltonian of a gravity-matter system depends on the choice of time, with the vacuum naturally identified as its ground state. We study the expanding Universe with scalar field in the volume time gauge. We show that the vacuum energy density computed from the resulting Hamiltonian is a nonlinear function of the cosmological constant and time. This result provides a new perspective on the relation between time, the cosmological constant, and vacuum energy.[V. Husain and B. Qureshi PRL 116, 061302 (2016)]

Causal Dynamical Triangulations – a progress report

Renate Loll
Radboud University, Netherlands

I will summarize and discuss progress in nonperturbative quantum gravity, based on Causal Dynamical Triangulations (CDT), with emphasis on the physical case of four spacetime dimensions, and covering the most important developments since the last GR meeting. These include a refined understanding of CDT's phase structure and second-order phase transitions, further evidence of semi-classical behaviour and the applicability of renormalization group methods in the 'background-free' Planckian regime of the theory.

Dark energy from energy-momentum conservation violations

Alejandro Perez
Centre de Physique Theorique, France

We consider a scheme whereby it is possible to reconcile semi-classical Einstein's equation with the violation of the conservation of the expectation value of energy-momentum that could arise in from fundamental discreteness (e.g. phase space diffusion in causal sets) or could also be associated with dynamical reduction theories of the quantum state for matter. The very interesting out-shot of the formulation is the appearance of a nontrivial contribution to an effective cosmological constant (which is not strictly constant). An interesting implication of our analysis is that tiny violations of energy-momentum conservation with negligible local effects can become very important on cosmological scales at late times.

Energetic causal sets

Lee Smolin

Perimeter Institute for Theoretical Physics, Canada

We discuss energetic causal set models proposed with Marina Cortes. These are causal set models which incorporate intrinsic properties such as energy-momentum. We highlight the relationships to spin foam models and pure causal set models, as well as to relative locality models. We discuss the conditions under which spacetime geometries emerge in the semiclassical limit. We also highlight the time asymmetry of these models and discuss how time symmetric phenomena emerge in terms of limit cycles of discrete dynamical systems. This is based on arXiv:1307.6167 , arXiv:1308.2206, arXiv:1407.0032 and work in progress.

The Hartle Hawking Wave Function in Causal Set Quantum Gravity

Sumati Surya

Raman Research Institute, India

The 2-dimensional version of causal set quantum gravity defined over the sample space of 2d orders has proved to be a useful testing ground for the full theory. It exhibits a 2nd order phase transition which interpolates between a continuum phase and a "crystalline" non-manifoldlike phase. These phases play an important role in determining the nature of the Hartle-Hawking wavefunction. Combining analytic and numerical techniques we find that the wave function has a low temperature peak over causal sets which have no continuum counterpart. However, these geometries exhibit physically interesting behaviour. In particular, they show a rapid spatial expansion with respect to the discrete proper time, as well as a high degree of spatial homogeneity due to extensive overlap of the causal past. While our results are limited to 2 dimensions they provide a concrete example of the role played by non-perturbative quantum gravity in generating the initial conditions for our observable universe.

Entanglement Entropy in Causal Set Theory

Yasaman Yazdi
Perimeter Institute/University of Waterloo, Canada

Entanglement entropy is now widely accepted as having deep connections with quantum gravity. It is therefore important that we understand it in the context of causal sets. Most definitions of entanglement entropy rely on quantities defined on hypersurfaces. Since canonical data on a hypersurface are not defined in causal sets, we need a spacetime definition of entanglement entropy. Recently, such a definition has been found for a scalar field in a Gaussian state, that expresses the entropy in terms of the field's spacetime correlation function. In this case, the cutoff that renders the entropy finite is also of a spacetime and Lorentz-invariant nature. I will present results from the application of the new definition to causal sets in 1+1 dimensions, finding in particular that the entropy obeys a spacetime-volume law instead of the expected (spatial) area law. I will discuss how to recover an area law, and I will describe results, from the application of this definition to continuum spacetimes and other discrete models, which provide further clues to the significance of the causal set results.

Thermodynamic entropy as a Noether invariant

Yuki Yokokura
iTHES-RIKEN, Japan

We study a classical many-particle system with an external control represented by a time-dependent extensive parameter in a Lagrangian. We show that thermodynamic entropy of the system is uniquely characterized as the Noether invariant associated with a symmetry for an infinitesimal non-uniform time translation $t \to t+\eta\hbar\beta$, where η is a small parameter, $\hbar$ is the Planck constant, β is the inverse temperature that depends on the energy and control parameter, and trajectories in the phase space are restricted to those consistent with quasi-static processes in thermodynamics. [Phys.Rev.Lett.116,140601(2016)]

Session D4

Thermodynamic Metrics for Black Hole Physics

Jan E. Aman
Stockholm University, Sweden

We give a brief survey of thermodynamic metrics, in particular the Ruppeiner and Weinhold geometries constructed from the Hessian of the entropy function, and how they apply to black hole thermodynamics. We then provide a detailed discussion of the Gibbs surface of Kerr black holes. In particular, we analyze its global properties and extend it to take the entropy function of the inner horizon into account. We find a coordinate system where the Weinhold geometry for a Kerr black hole is manifestly flat. In this coordinate system we find the geodesics of the Ruppeiner geometry. Comparison between mass and entropy illustrates the Penrose process. If the state of a thermodynamic system is changed the least entropy increase is obtained if the change follows a geodesic in Ruppeiner geometry. This approach can be used to find the maximal amount of energy that can be extracted from a Kerr black hole in a finite time. Reference: Jan E. Aman, Ingemar Bengtsson, Narit Pidokrajt: "Thermodynamic Metrics and Black Hole Physics". Entropy, 17 (2015) 6503-6518, arXiv:1507.06097.

Method to compute the stress tensor for quantum fields outside of a black hole that forms from collapse

Paul Anderson
Wake Forest University, United States

A method is given to compute the stress-energy tensor for a massless minimally coupled scalar field in the case in which a spherically symmetric null shell collapses to form a black hole. The method works for the region outside the shell and outside of the event horizon. A comparison with the stress-energy tensor for the Unruh state in Schwarzschild spacetime will be made.

A Stochastic Extension to the Schrodinger-Newton Equation in Semiclassical Gravity and its Role in Wavefunction Evolution

Sayantani Bera
Tata Institute of Fundamental Research, India

The unification of gravity and quantum mechanics and how they affect each other has been a long-standing problem in physics. One approach to understand the interplay between gravity and quantum mechanics is 'semiclassical gravity' where gravity is treated as classical whereas matter fields are quantum. This approach is very useful in order to understand the full quantum theory of gravity. In this work, we discuss how gravity affects the evolution of the wavefunction in the context of semiclassical gravity and its role in explaining the 'measurement problem'. The Schrodinger-Newton equation describes the effect of self-gravity on the evolution of a quantum system. It has been proposed that this self-gravity acts as a source of decoherence which finally drives the system into a classical state. However, the equation by itself lacks a decoherence mechanism, because it does not possess any stochastic feature. In the present work we derive a stochastic modification of the Schrodinger-Newton equation, starting from the Einstein-Langevin equation in the theory of stochastic semiclassical gravity. For the case of a massive point particle, we derive the Diosi-Penrose criterion for the decoherence time which is the characteristic time for the system to lose quantum coherence. For an extended mass, we find that the decoherence time is dependent also on the length scale of the object apart from Planck length. The issue of superluminal signalling is also addressed. [Ref : S. Bera et al., Phys. Rev. D 92, 025054 (2015); arXiv: 1504.05892]

Entanglement entropy during inflation

Eugenio Bianchi
Penn State, United States

I present new analytic results about the time evolution of the renormalized entanglement entropy of quantum fields in a region of space. In particular I show that asymptotically the entropy grows linearly in time in the presence of instabilities and of parametric resonances. In this talk I discuss the relevance of these two new results to slow-roll inflation and reheating, and estimate the rate of growth of the entropy for a sub-Hubble region of space.

The CMB spectrum, inflation and quantum-gravity modified dispersion relation

Stefano Bianco
Max Planck Institute for Gravitational Physics, Germany

The recent Planck results tells us two clear features for the CMB: almost scale invariance and a bound on the scalar-to-tensor ratio. We find that a class of quantum-gravity deformed dispersion relations improve the current inflationary model especially for the description of the scale-to-tensor ratio.

Using Effective Field Theory to test Lorentz Invariance: self-consistency tests in curved spacetime

Yuri Bonder
Universidad Nacional Autonoma de Mexico, Mexico

Local Lorentz invariance is one of the fundamental principles of general relativity, and, as such, it must be empirically tested. In addition, Lorentz violation has been suggested, by some quantum gravity candidates, as a possible signal of nontrivial spacetime structures. Effective Field Theory is a robust tool from which it is possible to get a general parametrization of Lorentz violation. This parametrization is a guide for the experimental tests, but it also provides an arena to perform theoretical tests, which are particularly interesting in curved spacetime. In particular, I will talk about the compatibility with diffeomorphism invariance, the possibility of taking a Palatini point of view, a construction of a Gibbons-Hawking term, and the Cauchy problem, where several objections to extend standard physics to include Lorentz violations are revealed.

A Simple Model for Graviton Opacities through Astrophysical Media

Claia Bryja
City College of San Francisco, United States

I present arguments that the opacity of a medium to a single graviton– i.e. the graviton's probability of interaction per unit mass– will scale as the product of the energy of the graviton and a volume that is proportional to the cube of the graviton's wavelength. Conceptualizing the graviton as a quantum of spacetime distortion, this volume represents the graviton's effective "size" for possible interactions. The mean free path of the graviton is then inversely proportional to the product of the opacity and the density of the medium. A counter-intuitive result is that gravitons of lower energy will have shorter mean free paths. Yet, when high density obstacles are encountered that are smaller in size than the wavelength of a low energy graviton, higher energy gravitons will find these obstacles more difficult to penetrate. I discuss some example astrophysical implications of this model.

Traversable Wormholes and Scalar Fields

Luke Butcher
University of Edinburgh, United Kingdom

We do not know whether traversable wormholes are allowed by the laws of nature. This represents a potential challenge to our understanding of causality in physics, as there appears to be no fundamental obstacle to prevent these 'bridges' of curved spacetime being used as time machines. As such, there is a strong desire to settle the matter one way or the other: to either provide a believable mechanism by which a traversable wormhole could form and be maintained, or to use known laws to formulate a rigorous argument that would forbid their existence altogether. In this talk I will examine whether scalar fields might generate the negative energy needed to permit the existence of a traversable wormhole. I will first sketch a new theorem that prevents a *classical scalar field from being used to this end: even when coupled non-minimally to gravity, and in violation of the average null energy condition, the classical scalar field cannot support a well-behaved, spherically symmetric traversable wormhole. However, the quantum scalar field shows significantly more promise. I will explain my work on long thin wormholes, wherein the curvature and topology of the long thin throat induces a negative Casimir energy in a quantum scalar field, and this energy is used to keep the wormhole open. Although the wormhole cannot be completely stabilised, preliminary calculations suggest that the collapse is sufficiently slow to allow the transmission of information.*

Quantum dress for a naked singularity

Marc Casals
Brazilian Center for Research in Physics (CBPF), Brazil

We investigate semiclassical backreaction on a conical naked singularity space-time with a negative cosmological constant in (2+1)-dimensions. In particular, we calculate the renormalized quantum stress-energy tensor for a conformally coupled scalar field on such naked singularity space-time. We then obtain the backreacted metric via the semiclassical Einstein equations. We show that semiclassical backreaction dresses the naked singularity with an event horizon, thus enforcing Penrose's Cosmic Censorship hypothesis. Finally, on a similar but different setting, we obtain the semiclassical backreaction on a rotating BTZ black hole space-time and study its properties.

Quantised Curvature of Regge Calculus yields the Fundamental Particle Structure

John Bruce Davies
Dept. of Physics, University of Colorado, Boulder, United States

Feynman, as well as numerous other famous physicists, has postulated that space-time could be discrete rather than a continuum at the quantum level. However, this hypothesis has been only applied at the Planck level where Wheeler, Hawking and others argue for a spacetime foam. We show that a discrete space-time, governed by Regge calculus, can model the fundamental particles and their interaction. In this calculus, curvature is distributed over the 2-simplex defect with energy-momentum concentrated on the legs of the 2-simplex. We show that a baryon, composed of 3 quarks, is equivalent to the triangular 2-simplex, where the quarks compose the legs. Mesons and leptons correspond to collapsed line and point 2-simplices, respectively, where curvature and Action remain well-behaved through the collapse. There are 6 invariants of the 2-simplex that we argue correspond to the 6 quark flavors. The 3 on-diagonal invariants have inner products of 2/3 while the 3 off-diagonal invariants have -1/3 inner products. The closure condition on these invariants yields confinement of the quarks. We show that a discrete analogue of the Uncertainty Principle is a direct consequence of our approach. This research extends that which was awarded an Honorable Mention in the 1997 GRF essay competition.

Boundary Effects on the Thermodynamics of Quantum Fields Near a Black Hole

Birses Debir
PhD Student, Turkey

We study the thermodynamics of a quantum field in a spherical shell around a static black hole. We implement brick wall regularization by imposing Dirichlet boundary conditions on the field at the boundaries and analyze their effects on the free energy and the entropy. We also consider the possibility of using Neumann boundary conditions. We examine both bosonic and fermionic fields in Schwarzschild, Reissner-Nordstrom (RN), extreme RN, and dilatonic backgrounds. We show that the horizon divergences get contributions from the boundary (brick wall) which at the Hawking temperature are comparable to the bulk contributions. It is also shown that the leading divergence is the same for all the backgrounds considered and that the subleading logarithmic divergence is given by a specific function of surface gravity and horizon area. We will also consider the near horizon geometry and show the existence of a finite term generated by the logarithmic divergence which involves the logarithm of the horizon area. The thermodynamics of quantum fields is examined in the ultrarelavisitc regime through the high temperature/small mass expansion. We derive the high temperature expansion in the presence of chemical potential by Mellin transform and heat kernel methods as applied to the harmonic sum representation of the free energy

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Electromagnetic duality symmetry in curved space-times.

Adrian del Rio Vega
IFIC (University of Valencia - CSIC), Spain

In an arbitrary gravitational field the source-free Maxwell action is invariant under U(1) electric-magnetic duality rotations. This leads to a classical conserved Noether current. We investigate whether this conservation law is respected at the quantum level or, on the contrary, a duality anomaly arises in curved space-times. This is in fact what happens for the analogue case of massless Dirac fermions with the well-known chiral anomaly. Indeed, Maxwell equations can be recast as Weyl-type equations for spin-1 fields, and much of the machinery developed to compute the chiral anomaly for 1/2 fermions can be translated to the electromagnetic potential. Physical consequences of a duality anomaly would be a non-conservation of the difference in the number of right and left circularly polarized photons in those space-times having a non-zero Chern-Pontryagin $R_{abcd} \times R^{abcd}$ invariant.

Undulations in a BEC black hole analog model

Richard Dudley
Wake Forest University, United States

The two-point function for phonons in a BEC, Bose-Einstein condensate, analog black hole is calculated using the formalism of quantum field theory in curved space. The BEC is assumed to have constant flow velocity while the speed of sound is modified in such a way as to create regions of subsonic and supersonic flow. Excitations of the modes occur in the direction of flow and the transverse direction. The excitations in the transverse direction contribute a mass-like term in the mode equation and result in undulations inside the sonic horizon which appears as a distinctive pattern in the two point function.

Including Exotic Smoothness in Semiclassical Gravity

Christopher Duston
Merrimack College, United States

Recent work on exotic smooth structures (homeomorphic but non-diffeomorphic manifolds) has revealed that the presence of such structures can mimic gravitational interactions, and therefore must be included in our spacetime models. This talk will present a semiclassical partition function for gravity which is complete in the sense that it takes these structures into account. It is based on the branched covering of a codimension 2 foliation of the 4-sphere, which is further characterized by a pair of spinor fields. This partition function also naturally includes cosmic strings. These cosmic strings define the topological structure of the foliations, suggesting a deep connection between symmetry breaking in the early universe and large-scale topological structure.

Uniqueness of the Fock quantization of Dirac fields with unitary dynamics

Beatriz Elizaga Navascus
Institute for the Structure of Matter (IEM) – CSIC, Spain

It is well known that linear canonical transformations are not generally implemented as unitary operators in QFT. Such transformations include the dynamics that arises from the field equations on the background spacetime. This evolution is specially relevant in nonstationary backgrounds, where there is no time-translational symmetry that can be exploited to select a quantum theory. We investigate whether it is possible to find a Fock representation for the canonical anticommutation relations of a Dirac field, propagating on a homogeneous and isotropic cosmological background, such that the field evolution is unitarily implementable. First, we restrict our attention to Fock representations that are invariant under the group of spatial isometries of the background. Then, we prove that there indeed exist Fock representations such that the dynamics is implementable as a unitary operator. Finally, once a convention for the notion of particles and antiparticles is set, we show that these representations are all unitarily equivalent.

Probability and Effects of Large Stress Tensor Fluctuations

Larry Ford
Tufts University, United States

Recent results on the probability distributions of quantum stress tensor fluctuations will be presented. A meaningful probability distribution requires that the stress tensor operator be averaged in time or in spacetime. This averaging can be viewed as a description of the measurement process. Realistic measurements are expected to occur in finite time or spacetime regions, and hence be described by functions with compact support. We show that the probability for large fluctuations is determined by the Fourier transform of the averaging function. In the case of averaging along an inertial observer's worldline, this probability can fall considerably slower than might have been expected, as an exponential of a fractional power of the dimensionless averaged stress tensor. This means that large positive energy density fluctuations are less rare than expected. Averaging in spacetime, rather than time alone, somewhat decreases the probability of large fluctuations, but it remains larger than would have been the case with an exponentially decreasing distribution. Large quantum stress tensor fluctuations in turn induce large passive quantum geometry fluctuations through large Ricci tensor fluctuations. The physical effects can include large expansion fluctuations along a congruence of timelike geodesics. This and other possible effects will be discussed.

Light bending in superrenormalizable higher-derivative gravity

Breno Giacchini

Centro Brasileiro de Pesquisas Físicas, Brazil

Local gravitational theories with more than four derivatives have remarkable quantum properties, namely they are superrenormalizable and possibly unitary in the Lee-Wick sense. Therefore, these theories solve an old conflict between UV renormalizability and unitarity in quantum gravity, and the main problem is certainly the possibility of making experimental tests. We explore the light bending in the sixth-order gravity and show that under some circumstances it would be possible to perceive the contribution of the higher-order sectors through the dependence of the scattering angle on the energy of the photon. This analysis is carried out in the semiclassical context, by using Feynman diagrams to describe interaction of external classical gravity with photons. We especially analyze the situations which are completely impossible in fourth-order gravity, such that the massive extra degrees of freedom correspond to the complex poles in the propagator. (Work in collaboration with A. Accioly and I.L. Shapiro.)

Effective Tolman temperature induced by trace anomaly

Yongwan Gim

Department of Physics, Sogang University, Republic of South Korea

Despite the finiteness of the renormalized stress tensor for a scalar field on a four-dimensional Schwarzschild black hole in the Israel-Hartle-Hawking vacuum, the Tolman temperature defined in a proper frame in thermal equilibrium is certainly divergent on the horizon due to the infinite blueshift of the Hawking temperature. We pose that the Tolman temperature to rest upon the traceless stress tensor appears incompatible with the renormalized stress tensor accommodating the trace anomaly responsible for the Hawking radiation. So we present a modified Stefan-Boltzmann law relating the renormalized stress tensor to a corresponding effective Tolman temperature. The effective Tolman temperature induced by the trace anomaly turns out to be finite everywhere outside the horizon, and so there does not appear infinite blueshift of the Hawking temperature any more. In particular, it is vanishing on the horizon, so that the equivalence principle is recovered at the horizon. Moreover, the present calculations support that the origin of the outgoing Hawking radiation is a near-horizon quantum region.

Matching of the vacuum solution to spherically symmetric static interiors implies uniqueness of the black hole absorption cross section

Graeme Gossel

Icahn Institute, United States

We consider the implications of Israel's matching conditions when joining the metric of a static, spherically symmetric mass to the vacuum solution at the boundary of the body. We show that satisfying these conditions has direct implications for the uniqueness of the black hole absorption cross section. Previously it was shown that in the limit the interior metric becomes singular as $r_s \to R$, massless scalar particles scattering from the body's gravitational potential develop a dense spectrum of narrow resonances. Using the optical theorem, the low-energy cross section for capture into these resonances was calculated and found to be equal to the pure black hole case. We re-visit the previous resonance results in the context of these matching conditions and show that a metric for which the dt coefficient, tends to zero for $r \lesssim R$ may reasonably become singular only if the singular limit corresponds to the black hole limit. Additionally, we find that in cases where the dt coefficient vanishes only over some portion of the interior, the resonances are suppressed by the existence of an energy dependent barrier, giving a vanishing low energy cross section. Together these results imply that for a metric to acquire the black hole absorption cross section, it must have the dt metric coefficient vanish which in turn requires that the singular limit be the black hole limit. Collectively these results suggest that a non-zero gravitational absorption cross section may only be possible in the black hole limit.

Entanglement production and Lyapunov exponents

Lucas Hackl

Pennsylvania State University, Institute for Gravitation & the Cosmos, United States

Squeezed vacua play a prominent role in quantum field theory in curved spacetime. Instabilities and resonances that arise from the coupling in the field to the background geometry, result in a large squeezing of the vacuum. In this talk, I discuss the relation between squeezing and Lyaponov exponents of the system. In particular, I derive a new formula for the rate of growth of the entanglement entropy expressed as the sum of the Lyapunov exponents. As an example, we illustrate these features for the Schwinger effect. [Joint work with E. Bianchi and N. Yokomizo.]

Low energy Lorentz violation from modified dispersion at high energies

Viqar Husain
University of New Brunswick, Canada

Many quantum theories of gravity propose Lorentz-violating dispersion relations of the form $= kf(k/M)$ with recovery of approximate Lorentz invariance at energy scales much below M. We show that a quantum field with this dispersion predicts drastic low energy Lorentz violation in atoms modeled as Unruh-DeWitt detectors, for any f that dips below unity somewhere. [V. Husain and J. Louko, PRL 116, 061301 (2016)]

Quantum Gravitational Force Between Polarizable Objects

Johanna Karouby
Tufts University, United States

Since general relativity is a consistent low energy effective field theory, it is possible to compute quantum corrections to classical forces. I will present the computation of a quantum correction to the gravitational potential between a pair of polarizable objects. I will show the case of two distant bodies and compute a quantum force from their induced quadrupole moments due to two graviton exchange. The effect is in close analogy to the Casimir-Polder and London-van der Waals forces between a pair of atoms from their induced dipole moments due to two photon exchange. The new effect is computed from the shift in vacuum energy of metric fluctuations due to the polarizability of the objects. I will how the computation for the potential energy at arbitrary distances compared to the wavelengths in the system, including the far and near regimes. In the far distance, or retarded, regime, the potential energy takes on a particularly simple form that I will show. I will provide estimates of this effect when applied to astrophysical objects such as neutron stars.

Quantum resolution of timeline, classical singularities

Deborah Konkowski
U.S. Naval Academy, United States

Horowitz and Marolf, following pioneering work by Wald, proposed a way to resolve singularities in static spacetimes with timelike singularities. They termed a static spacetime to be quantum mechanically non-singular if the spatial portion of the relevant wave operator is essentially self-adjoint on C_o in the space of square-integrable functions L^2, where ; is a spatial slice. We have confirmed that their definition of quantum non-singularity for static spacetimes can be extended to the case of conformally static spacetimes. Here we review the applications of this technique to both static and conformally static spacetimes. In particular, the dynamical, classical timelike singularity in a class of continuously self-similar, conformally-static,

spherically-symmetric, power-law spacetimes is probed using massless scalar test fields. Ranges of metric parameters for which these classical singularities may be resolved quantum mechanically are determined. Using Weyl's limit point, limit circle criterion, the wave operator is shown not to be essentially self-adjoint, so in this class of spacetimes the wave packet evolution still has the usual ambiguity associated with scattering off singularities. In other words, these spacetimes are not healed quantum mechanically. In light of this result, we review the successes and failures of this method in general.

Tunneling of squeezed states with an eye to evaporating black holes

Eleni-Alexandra Kontou

Bard College, United States

In this work we study how tunneling time depends on the squeezing parameter of quantum states. Squeezed quantum states are investigated for optical communications and appear in the emission from black holes. A surprising property of these states is reduced tunneling time. Treating Hawking radiation as a quantum tunneling process, we study the interplay of squeezing with the radiation process.

From quantum to classical instability in relativistic stars

Andre Landulfo

Federal University of ABC, Brazil

It has been shown that gravitational fields produced by realistic classical-matter distributions can force quantum vacuum fluctuations of some nonminimally coupled free scalar fields to undergo a phase of exponential growth. The consequences of this unstable phase for the background spacetime have not been addressed so far due to known difficulties concerning backreaction in semiclassical gravity. It seems reasonable to believe, however, that the quantum fluctuations will 'classicalize' when they become large enough, after which backreaction can be treated in the general-relativistic context. Here we investigate the emergence of a classical regime out of the quantum field evolution during the unstable phase. By studying the appearance of classical correlations and loss of quantum coherence, we show that by the time backreaction becomes important the system already behaves classically. Consequently, the gravity-induced instability leads naturally to initial conditions for the eventual classical description of the backreaction. Our results give support to previous analyses which treat classically the instability of scalar fields in the spacetime of relativistic stars, regardless of whether the instability is triggered by classical or quantum perturbations.

Towards solution of negative mode problem in quantum tunnelling with gravity

George Lavrelashvili

A.Razmadze Mathematical Institute, I.Javakhishvili Tbilisi State University, Georgia

Negative mode problem in quantum tunneling with gravity was recognized about thirty years ago. In spite of much work done during these years in this direction fully satisfactory solution of the problem is not found yet. In my talk I briefly review historical development of the subject and discuss recent progress towards solution of the problem.

Inequivalence between Active Gravitational Mass and Energy for a Composite Quantum Body

Andrei Lebed

Department of Physics, University of Arizona, United States

In the framework of semiclassical theory of gravity, we define active gravitational mass operator of the simplest composite quantum body a hydrogen atom. It occurs that it does not commute with energy operator. Nevertheless, we show that the expectation value of the mass operator is equivalent to energy for stationary quantum states. On the other hand, for superposition of quantum states with the constant expectation values of energy, active gravitational mass operator exhibits quantum time-dependent oscillations. They create time-dependent gravitational field, which can be experimentally measured for laser induced ensemble of coherent superpositions of the atoms. These oscillations could be the first quantum effect directly observed in General Relativity. [See the review: Andrei G. Lebed, Int. J. Mod. Phys. D, vol. 24, 1530027 (2015).]

Stress tensor regularization & BH evaporation

Adam Levi

Technion, Israel

The regularization of the stress tensor is the main obstacle in studying interesting semi-classical dynamic phenomena such as BH evaporation. A recently developed regularization scheme now enables one to compute the stress-tensor in any background that admits a single symmetry, e.g. stationary, spherically symmetric or azimuthally symmetric background. I'll describe the new regularization scheme by showing regularization of the ϕ^2, which is a simpler quantity to regularize, and give examples where it can be used focusing on backgrounds where thus far we were unable to do regularization. I'll present new results computed using the scheme, including regularization in Kerr spacetime. In addition I'll describe the path and the difficulties still ahead towards full numerical BH evaporation.

Quantum Gravity Phenomenology with and without Lorentz

Stefano Liberati

SISSA - International School for Advanced Studies, Italy

In seeking for relic physics of a quantum gravitational regime much attention has been dedicated to tests of deviations from exact Lorentz invariance. Nonetheless, this is not the only possible scenario emerging from current quantum gravity models. In particular, some form of non-locality seems to ubiquitously appear as a needed ingredient for conciliating special relativity and quantum discreteness. In my talk, I will review were we stand in searches for deviations from exact Lorentz invariance as well as discuss what we can do to test quantum gravity induced non locality up to the Planck scale.

Radiation by an Unruh-DeWitt Detector in Oscillatory Motion

Shih-Yuin Lin

National Changhua University of Education, Taiwan

We calculate quantum radiated energy flux emitted by an Unruh-DeWitt detector, with the internal harmonic oscillator coupled to a massless scalar field, in linear oscillatory motion in (3+1) dimensional Minkowski space. Our results show that, when the averaged proper acceleration is sufficiently low, the signal of the Unruh effect can be greatly suppressed by quantum interference. In contrast, the Unruh-like effect can be pronounced in quantum radiation in the highly non-equilibrium regime with high averaged acceleration and short oscillatory cycle. While the averaged radiated energy flux over a cycle is always positive as guaranteed by the quantum inequalities, an observer at a fixed angle may see short periods of negative radiated energy flux in each cycle of motion, which indicates that the radiation is squeezed. We analyze the asymptotic state of the field to examine this.

Black Hole Entropy Perspective on Neutron Star Mass

Partha Sarathi Majumdar
Department of Physics, RKM Vivekananda University, India

The observed absence of neutron stars heavier than 2 solar masses is often explained based on an adaptation of Chandrasekhar's hydrostatic equilibrium ideas of a limiting mass for white dwarf stars. This adaptation involves two crucial augmentations of the theoretical framework : handling a strongly-coupled quantum field theory and the inclusion of general relativity. We briefly survey the complications that these introduce to the issue of determining the equation of state of this superdense system as an essential part of hydrostatic equilibrium. We then describe an alternative perspective, to this problem, based on certain results from the analysis of (quantum) black hole entropy and thermal stability. These results have been derived from a non-perturbative, background-independent formulation of canonical quantum gravity, and will be discussed in some detail, especially in the context of black hole entropy. We will then present a scenario whereby these results can be useful for the analysis of the neutron star maximum mass problem. This involves a formulation of the issue of neutron star instability in terms of the stability and growth of a nascent quantum horizon deep inside a collapsing neutron star. If this perspective works, this might be a first indirect evidence of quantum gravity playing an important role in the gravitational collapse of neutron stars.

Inertial Frame Dragging in a Rotating Analogue Black Hole

Partha Sarathi Majumdar
Professor, Department of Physics, RKM Vivekananda University, India

We present an incipient exploration of the Lense-Thirring precession effect in a rotating acoustic analogue black hole spacetime. An exact formula is deduced for the precession frequency of a gyroscope due to inertial frame dragging, close to the ergosphere of a 'Draining Bathtub' acoustic spacetime. Prospects of experimental detection of this new 'fixed-metric' effect in acoustic geometries, are briefly discussed.

Electrodynamic Effects from Inflationary Gravitons

Shun-Pei Miao
National Cheng Kung University, Taiwan

This talk is based on arXiv:1504.00894.I present an intuitive picture of how the vacuum polarization due to inflationary gravitons can be understood. I discuss the issue of dependence upon the graviton gauge, and describe the conjecture that it may drop out of the leading secular corrections. The main part of this talk reports on an explicit computation of the vacuum polarization in the most general de Sitter invariant family of gauges, and the demonstration (complete but not yet written up) that the leading secular enhancement to the photon field strength indeed shows no dependence upon the gauge parameter.

Bounds on the curvature coupling parameter around a cosmic string

Edisom Moreira
Itajub Federal University, Brazil

A recent publication regarding the low temperature behavior of a scalar field near a reflecting wall in flat space has shown that the values of the curvature coupling parameter ξ must be restricted to a certain range when stable thermodynamic equilibrium is required. Perhaps the next step to investigate further this phenomenon would be to examine a less trivial background, preferably one with genuine curvature. A natural candidate seems to be the background of a cosmic string which is locally flat but globally curved as is well known. The present work considers the thermal behavior of the scalar radiation in the conical spacetime of a cosmic string. Using formulas in the literature for the expectation value of the stress-energy-momentum tensor, it was possible to determine the corresponding low temperature regime. Then, by requiring stable thermodynamic equilibrium, it results that not all values of ξ are physically acceptable as long as the conical singularity is present. The way the bounds on ξ vary with the deficit angle is determined.

Integrable QFTs in inflation

Ian Morrison
McGill University, Canada

We present a class of integrable quantum field theories on de Sitter spacetime. These theories provide playgrounds to explore non-perturbative phenomena such as the screening of the effective cosmological constant. The models we consider possess both local and non-local higher-spin symmetries which, although not realized in nature, allow tight control over the theories. For example, the late-time expectation values (i.e. cosmological spectra) and de Sitter scattering matrices of these theories may be computed exactly.

Thermo Field Dynamics, Boulware and Hartle-Hawking States

Diego Felipe Muñoz Arboleda
Universidad Nacional de Colombia, Colombia

A detailed review of t-Hooft brick wall model is made in order to understand the Bekenstein-Hawking entropy as a thermal entropy due to quantum fields existing in the neighborhood of the event horizon of a black hole. The ground state is correctly identified (Boulware state) from the original model to eliminate the existing divergences. Finally, using the ThFD (Thermo Field Dynamics) formalism an extended brick wall model is made.

Gravitationally Induced Quantum Transitions

Manu Paranjape
Université de Montréal, Canada

We calculate the probability for resonantly induced transitions in quantum states due to time dependent gravitational perturbations. Contrary to common wisdom, the probability of inducing transitions is not infinitesimally small. We consider a system of ultra cold neutrons (UCN), which are organized according to the energy levels of the Schrodinger equation in the presence of the earth's gravitational field. The driving force is created by oscillating a macroscopic mass in the neighbourhood of the system of neutrons. The optimal strategy is to drive the system for 2 lifetimes. The transition amplitude then is of the order of 1.06×10^7 hence with a million ultra cold neutrons one should be able to observe transitions.

The geometry of spacetime from (modified) dispersion relations

Christian Pfeifer
Institute for Theoretical Physics, Leibniz University Hannover, Germany

One feature how quantum gravity is expected to manifest itself in observations is an effective modification of the standard dispersion relation of fundamental point particles in metric spacetime geometry. Since the point particle dispersion relation and the geometry of spacetime are closely intertwined any modification of the dispersion relation leads to a, possibly energy and momentum dependent, modification of the geometry of spacetime. In this talk I will interpret the dispersion relation as Hamilton function on the phase space of test particles on spacetime and demonstrate how the geometry of phase space is derived from the Hamiltonian, similarly as the geometry of spacetime is derived from a metric. Since phase space is composed out of spacetime (configuration space) and momentum space the result for a general Hamiltonian is that not only the spacetime is curved but also the momentum space. Moreover, both, the curvature of spacetime and that of momentum space, depend in

general on positions and momenta. I will demonstrate this framework on the example of a perturbation of the metric Hamiltonian $H = g(p,p)+h(p,p,p)$. This form of a modified dispersion relation contains as special cases the first order q-De Sitter and kappa Poincare modified dispersion relations from quantum gravity phenomenology. Moreover it will become clear that for a Hamiltonian of the form $H = g(p,p)$ the Hamilton geometry of phase space is nothing but metric spacetime geometry with flat momentum spaces. The talk is based on the article "Hamilton geometry: Phase space geometry from modified dispersion relation" (arXiv:1507.00922)

The Potential in General Linear Electrodynamics: Causal Structure, Propagators and Quantization

Christian Pfeifer

Institute for Theoretical Physics, Leibniz University Hannover, Germany

From an axiomatic point of view, the fundamental input for a theory of electrodynamics are Maxwell's equations $dF = 0$ (or $F = dA$) and $dH = J$, and a constitutive law $H = F$, which relates the field strength 2-form F and the excitation 2-form H. In this talk we consider general linear Electrodynamics, the theory of Electrodynamics which is defined through a liner constitutive law. The best known application of this theory is the effective description of Electrodynamics inside (linear) media including for example birefringence. We will analyse the classical theory of the electromagnetic potential A thoroughly before we use methods familiar from mathematical quantum field theory in curved spacetimes to quantise it. Our analysis of the classical theory contains the derivation of retarded and advanced propagators, the analysis of the causal structure on the basis of the constitutive law (instead of a metric) and a discussion of the classical phase space. This classical analysis then sets the stage for the construction of the quantum algebra of observables and quantum states. In the future this work sets the stage to study non-minimally coupled electrodynamics, axion electrodynamics and electrodynamics in media on curved spacetime. The talk is based on the article 'The Potential in General Linear Electrodynamics: Causal Structure, Propagators and Quantization' (arXiv:1602.00946)

Analogue cosmology in thin sheets of metamaterial

Angus Prain

Heriot-Watt University, United Kingdom

Experimental results for the observation of a time variation of the real and imaginary parts of the refractive index in a meta-material induced by a propagating laser pulse indicate conditions quite different to those normally assumed for a cosmological analogue. This talk explores what kind of phenomenology is possible and how it may be interpreted in cosmological terms. Such systems have been of interest also for black hole analogues which we also briefly address.

Quantum Scalar Corrections to the Gravitational Potentials on de Sitter Background

Tomislav Prokopec

Utrecht University, Netherlands

This talk is based on arXiv:1510.03352 with S. Park and R. P. Woodard. We employ the graviton self-energy induced by a massless, minimally coupled (MMC) scalar on de Sitter background to compute the quantum corrections to the gravitational potentials of a static point particle with a mass M. The Schwinger-Keldysh formalism is used to derive real and causal effective field equations. When evaluated at the one-loop order, the gravitational potentials exhibit a secular decrease in the observed gravitational coupling G. This can also be interpreted as a (time dependent) anti-screening of the mass M.

Dark Energy from inflationary perturbations

Tomislav Prokopec

Utrecht University, Netherlands

This talk is based on a work with D. Glavan and Tomo Takahashi, arXiv:1512.05329 and on work in prograss with D. Glavan and A. Starobinsky. We consider the one-loop quantum backreaction from inflationary fluctuations of a non-minimally coupled light. We show that, for suitably chosen non-minimal coupling and mass, these fluctuations can mimic the late time dark energy.

Quantum Vacuum Polarization in Large Dimensional Spacetimes

Gonalo Quinta

Superior Technical Institute - University of Lisbon, Portugal

The vacuum polarization φ^2 is the simplest measurement of quantum activity in curved space. In this work we present its computations in the vicinity of D-dimensional black holes and discuss its relevance in the context of the large D approximation to General Relativity.

Vacuum polarization near Lifshitz black holes

Gonçalo Quinta

Superior Technical Institute - University of Lisbon, Portugal

In this work we study quantum polarization effects in Lifshitz spacetimes for massive, non-minimally coupled scalar fields. To that aim, we adapt to the present situation an analysis previously developed for the case of asymptotically anti de Sitter black holes, where a mix of analytic and numerical computations are used to obtain an explicitly finite renormalized result. Some examples of numerical computations for particular values of the parameters are given. The interest of our work stems from the current application of the gauge/gravity duality to condensed matter theories, in particular gravity duals, i.e., Lifshitz spacetimes, of theories that exhibit anisotropic scaling, and from the further developments incorporating black hole solutions with Lifshitz asymptotics designed to understand finite temperature effects in the condensed matter systems.

How light gravitates: a brief exploration

Dennis Rätzel

University of Potsdam, Germany

As Einstein's equations tell us that all energy is a source of gravity, light must gravitate. However, because changes of the gravitational field propagate with the speed of light, the gravitational effect of light differs significantly from that of massive objects. In particular, the gravitational force induced by a light pulse is due only to its creation and annihilation and decays with the inverse of the distance to the pulse. We can expect the gravitational field of light to be extremely weak. However, the properties of light are premisses in the foundations of modern physics: they were used to derive special and general relativity and are the basis of the concept of time and causality in many alternative models. Studying the back-reaction of light on the gravitational field could give new fundamental insights to our understanding of space and time as well as classical and quantum gravity. In this talk, a brief overview is given of the gravitational field of light pulses in the framework of general relativity. A glimpse is caught of the gravitational interaction of two single photons which turns out to depend on the degree of their polarization entanglement.

Quantum Unitarity Preservation for General Relativity.

Joseph Rudmin
James Madison University, United States

Quantum unitarity fails in general relativity because the magnitude of angular momentum, and therefore Planck's constant, is affected by the metric. The magnitude of angular momentum is invariant, and quantum unitarity thus preserved if the momentum-energy equation has a metric conjugate to that for space-time, with rest mass playing the role of a length.

Local vs. global temperature for QFT in curved spacetimes.

Ko Sanders
Leipzig University, Germany

The concept of temperature and how to measure it in curved spacetimes play a fundamental role in the understanding of the Unruh effect and black hole thermodynamics. In this presentation we compare a local and a global notion of temperature, making use of the positive mass theorem of Schoen and Yau. We focus especially on massless free scalar fields in 4 dimensions with scalar curvature coupling between 0 (minimal) and 1/6 (conformal). The global temperature is given by $1/\beta$ (up to a constant) for any β-KMS state on a stationary spacetime. The local temperature at a point x is given (up to a constant) by the square-root of the expectation value of the Wick square (renormalized in a generally covariant way). The latter definition, proposed by Buchholz, Ojima and Roos, is ill-defined when the expectation value of the Wick square is negative. It is well-known that general states have a negative expectation value. This raises the question whether KMS states have a local temperature. To relate the local and global temperatures we consider ultra-static spacetimes with a compact Cauchy surface and non-negative scalar curvature everywhere. We show that in that case all stationary states (including KMS states) do have a local temperature in any flat region of spacetime. This initial result is insensitive to any renormalization freedom or local physical effects like acceleration. When negative curvature is allowed, counter-examples exist.

Vacuum polarization throughout subtracted black hole spacetimes

Alejandro Satz
Penn State University, United States

Subtracted black holes are modified black hole solutions on which the scalar wave equation is exactly solvable. We take advantage of this to compute analytic expressions for the vacuum polarization of a quantum field on these backgrounds. The results are valid both inside and outside the horizon, and for black holes that can include rotation and charge. We discuss the behavior close to the singularity and compare with known results for conventional black holes.

Graviton Creation by Small Scale Factor Oscillations in an Expanding Universe

Enrico D. Schiappacasse

Tufts Institute of Cosmology, Tufts University, United States

We treat quantum creation of gravitons by small scale factor oscillations around the average of an expanding universe. Such oscillations are predicted both by modified gravity theories with a term proportional to the square of the Ricci scalar in the gravitational action, and by semiclassical gravity in which a renormalized expectation value of a quantum matter stress tensor is the source of gravity. A perturbative method due to Birrell and Davies involving an expansion in a conformal coupling parameter is used. We obtain expressions for both the number and energy density creation rates on an average background of flat spacetime. We extend our analysis to an expanding universe, including two effects: damping on the metric oscillations and density dilution and redshifting of the created gravitons. We use the equivalence between f(R) theories and the scalar tensor gravity to analyze the behavior of the scale factor in an expanding background spacetime. We find that the oscillation frequency in comoving time is unchanged, but the amplitude of the oscillations decays. Cosmological constraints on the present graviton energy density are discussed, which indicate an upper bound of the order of 4% of the total mass-energy density of the universe. This constraint leads to an upper bound on the dimensionless amplitude of the oscillations. We also discuss decoherence of quantum systems produced by the spacetime geometry fluctuations due to such a graviton bath, and find a lower bound on the decoherence time resulting from this process.

Sparsity of the Hawking Flux

Sebastian Schuster

School of Mathematics and Statistics, Victoria University Wellington, New Zealand

Although known since the 1970s, the sparsity of particles emitted in black hole evaporation remains under-appreciated. By identifying the differences in time scales natural to the process and the time between emission of successive quanta, it is possible to quantify and thereby further elucidate this phenomenon. We did this semi-analytically and numerically for different particle statistics, several black-hole scenarios, and varying levels of description. It turns out that the process of superradiance can and should be considered separate to this aspect of the Hawking effect. In the end of this talk, we will discuss the consequences of taking note of this sparsity in black hole physics.

Test matter fields, (near-)extremal black holes and weak cosmic censorship

Ibrahim Semiz

Bogazici Univ. Physics Dept, Turkey

In absence of a comprehensive and conclusive proof of the cosmic censorship conjecture (CCC), gedanken experiments have been devised as tests. The first one was by Wald (1974), attempting to push an extremal Kerr-Newman black hole into a naked singularity by absorption of a test particle, concluding that CCC is preserved. Hubeny (1999) argued that a Reissner-Nordstrom black hole can be overcharged if one starts in a near-extremal state instead of extremal. This was later (2009) repeated for the Kerr black hole. Here we report similar thought experiments, where test fields are used instead of particles. We consider scalar, spin-1/2 and EM test fields, extremal and near-extremal black holes. We mention self-force, radiative and backreaction arguments by several authors, and quantum considerations. We show that a classical fermion field, if it makes sense, can give an unambiguous violation of CCC; the transmission coefficients and absorption probabilities are confused in the literature; the Zeldovich-Unruh effect can both be understood classically for scalars, and makes single-quantum-particle thought experiments meaningless; it also makes the scalar wave thought experiments inconclusive. We discuss the effect of the Hawking radiation.

Observation of quantum Hawking radiation and its entanglement in an analogue black hole

Jeff Steinhauer

Technion, Israel

We observe spontaneous Hawking radiation, stimulated by quantum vacuum fluctuations, emanating from an analogue black hole in an atomic Bose-Einstein condensate. The Hawking radiation is observed via the correlations between the Hawking radiation exiting the black hole and the partner particles falling into the black hole. The quantum nature of the Hawking radiation is observed through entanglement, by comparing the Fourier transform of the correlations to a measurement of the population. This comparison shows that the experiment is well within the quantum regime, since the measured Hawking temperature determined from the population distribution is far below the upper limit for quantum entanglement. A broad energy spectrum of entangled Hawking pairs are observed. Maximal entanglement is observed for the high energy part of the Hawking spectrum, while the lowest energies are not entangled.Thermal behavior is seen at very low energies where the finite extent of the correlation function implies frequency dependence. Thermal behavior is also seen at high energies through the agreement of the correlation spectrum with the appropriate function of the Planck distribution. Further insight is obtained by a preliminary experiment in which the horizon is caused to oscillate at a fixed frequency, which stimulates waves traveling into and out of the black hole. The

rate of particle production by the oscillating horizon is consistent with the measured Hawking temperature. Furthermore, the observed ratio of the phase velocities of the Hawking and partner particles are consistent with this preliminary experiment, as is the width of the Hawking/partner correlation feature. Additional confirmation of the results is obtained through a numerical simulation, which demonstrates that the Hawking radiation occurs in an approximately stationary background. It also confirms the width of the Hawking/partner correlation feature. The measurement reported here verifies Hawking's calculation, which is viewed as a milestone in the quest for quantum gravity. The observation of Hawking radiation and its entanglement verifies important elements in the discussion of information loss in a real black hole.

The black hole information paradox in the light of quantum theories involving dynamical spontaneous state reduction.

Daniel Sudarsky
UNAM, Mexico

We will briefly review the question of information loss during Hawking evaporation of a Black hole and argue that the so called dynamical reduction theories which have been developed in order to address the so called "measurement problem" in quantum mechanics, when used together with simple assumptions abut quantum gravity, possess the elements to resolve the issue in full. We will also discuss some further developments of this research line. References Found. of Phys. 45, 461 (2015). Phys. Rev. D, 91, 124009 (2015); Gen. Rel. & Gravitation 47 , 120 (2015).

A practical and efficient mode-sum renormalization scheme for computing vacuum polarization in black hole spacetimes in arbitrary dimensions

Peter Taylor
University College Dublin, Ireland

The renormalized stress-energy tensor acts as the source term in the semi-classical Einstein equations and hence efficient methods to compute such renormalized quantities are extremely important. Although formal expressions for renormalized quantities are well known, actual calculations are fraught with practical difficulties and standard approaches are cumbersome and usually have to be done on a case-by-case basis. Indeed, calculating renormalized vacuum polarization on the Kerr background remains elusive. Inspired by mode-sum regularization in self-force calculations, I will present an extremely efficient mode-sum renormalization scheme for computing vacuum polarization. I will focus on static, spherically symmetric spacetimes in arbitrary dimensions, though the general method is likely to be useful for Kerr. The method involves extending the locally valid Hadamard parametrix to a globally valid

mode-sum representation, which can be subtracted from the Feynman (or in practice the Euclidean) propagator mode-by-mode. Despite the increasing severity and number of singularities to be renormalized as the number of dimensions increase, this method of expressing the singular terms as mode-sums is mostly agnostic to number of dimensions. Hence most of the details can be worked out for arbitrary dimensions once and for all. Finally, some explicit results for Schwarzschild-Tangherlini spacetimes will be presented.

On Symmetry Breaking and the Unruh Effect

Cesar Uliana

Instituto de Fisica de So Carlos, Universidade de São Paulo, Brazil

It has been forty years since Unruh elucidated the intrinsic relation between the Minkowski vacuum and thermal behavior from the reference frame of uniformly accelerated observers. Nevertheless questions still remain regarding the nature of certain phenomena, one of them being spontaneous symmetry breaking. In inertial thermal field theory broken symmetries are restored by a finite temperature, and therefore is natural to ask if the Unruh temperature can also perform this role. Despite early work arguing on the negative there is a string of recent papers that purport that the Unruh effect indeed can restore a broken symmetry just as any thermal bath. By focusing on the algebra of symmetries we will present a new argument showing how the Unruh effect is manifestly incapable of restoring broken symmetries in the usual field theoretical definition, as well as discussing the source of the controversy. We will also discuss the related, but distinct, question of a accelerated probe with different phases coupled to the Unruh bath. In this case we show that, contrary to the field situation with broken symmetries, we do expect to see a phase transition induced on the probe due to the Unruh effect.

Excitation of Photons by Inflationary Gravitons

Changlong Wang

Department of Physics, University of Florida, United States

This talk is based on arXiv:1408.1448. Inflation produces a vast ensemble of horizon-scale gravitons. It is natural to expect that these gravitons should alter the kinematics of photons in the same way that gravitational radiation should affect pulsar timing. We use a one loop contribution of the quantum gravitational contribution to the vacuum polarization to solve the in-in effective field equation for a dynamical photon during inflation. Our results show that its electric field experiences a secular enhancement which must eventually become nonperturbatively strong. We also derive an absolute minimum for primordial inflation to seed cosmic magnetic fields.

A Self-consistent Description of Black Hole Evaporation

Yuki Yokokura
iTHES-RIKEN, Japan

We analyze time evolution of a spherically symmetric collapsing matter taking the back reaction from evaporation into account, and find that the collapsing matter evaporates without forming a horizon. Nevertheless, a Hawking-like radiation is created in the metric, and the object looks the same as a conventional black hole from the outside. We then discuss how the information of the matter is recovered. We also consider a black hole that is adiabatically grown in the heat bath and obtain the interior metric. We show that it is the self-consistent solution of the semi-classical Einstein equation, and that the 4-dimensional Weyl anomaly induces the radiation and a strong angular pressure. [arXiv: 1509.08472]

Session O

The Vector Volume of Black Holes

William Ballik
Queen's University at Kingston, Canada

By examining the rate of growth of an invariant four-volume V of some spacetime region along a divergence-free vector field v_a, we introduce the concept of a "vector volume" V_v. This volume can be defined in various equivalent ways. For example, it can be given as $dV(\mu)/d\mu$, where $v_a d_a = d/d(\mu)$ and μ is a parameter distance along the integral curve of v. Equivalently, it can be defined as the integral of $v_a d\sigma_a$, where $d\sigma_a$ is the directed surface element. We find that this volume is especially useful for the description of black holes, but it can be used in other contexts as well. This volume has several properties of interest. Among these is the fact that the vector volume is linear with respect to the choice of vector v_a. As a result, for example, in stationary axially symmetric spacetimes with timelike Killing vectors t_a and axially symmetry Killing vectors ϕ_a, the vector volume of an axially symmetric region with respect to the vector $t_a + \Omega \times \phi_a$ is equal for any value of Ω, a consequence of the result that ϕ_a does not contribute to V_a. In Kerr-Schild spacetimes the vector volume element for the full spacetime is equal to that of the background spacetime. We discuss different ways of using the vector volume to define volumes for black holes. We also relate this work to the recent widespread thermodynamically motivated study of the "volumes" of black holes associated with nonzero values of the cosmological constant (Λ).

Dynamical radiating stars with equations of state

Byron Brassel
University of KwaZulu-Natal, South Africa

We model the dynamics of spherically symmetric radiating stars. The local atmosphere is a two-component system consisting of standard pressureless (null) radiation and an additional type II null fluid with energy density and nonzero pressure. A large family of solutions to the field equations are presented for various equations of state. We demonstrate that it is possible to obtain solutions via a direct integration of the second order equations resulting from the assumption of an equation of state. A comparison of our solutions with earlier well known results is undertaken and we show that all these solutions, including those of Husain, are contained in our family. We then generalise our class of solutions for higher dimensional spacetimes.

Gravitational-wave parameter estimation with Gaussian process regression

Alvin Chua

Institute of Astronomy, University of Cambridge, Singapore

The theoretical uncertainty in waveform models must be accounted for when performing Bayesian parameter estimation on gravitational-wave data, especially as it could be the dominant source of error at high signal-to-noise ratios. A recently introduced method deals with model error by marginalising over it, using a prior distribution that is constructed through the technique of Gaussian process regression. The method is general and has various applications in the analysis of LIGO-Virgo and LISA data; we summarise the status of several projects in this area.

Special relativistic rotating electromagnetic fields

Paulo Javier Domínguez Chávez

University of Guadalajara, Mexico

Rotating electromagnetic fields are defined by having Poynting vectors on the tangents of closed integral lines around a rotation axis when a family of inertial reference frames is used and by vanishing Poynting vectors when a family of rotating reference frames is employed. This means that an angular momentum density can be associated to these fields only in the inertial reference frames. In this work, we consider a pure electric field and a pure magnetic field in a family of rotating reference frames. The latter frames are introduced through a time-like rotating congruence in the Minkowski space-time whose associated four-velocity vector field is called the monad vector and charaterizes these frames. Herein are used the usual and monadic versions of the four-dimensional Maxwell equations for the obtention of pure electromagnetic fields.

Pulsar Timing Array Portal Online: The Bridge

Andrea Lommen

Franklin and Marshall College, USA

The Bridge is a web-based portal designed to foster an ever-broadening community of researchers willing to engage with and investigate gravitational wave data, and in particular the pulsar timing array data of NANOGrav. The Bridge makes data products and tools available to the broader astronomical community in an elegant, user-friendly, and efficient package. The portal also leverages the public's interest in the enterprise by enabling their ability to participate in gravitational wave science in the post-detection era.

Entanglement Entropy of Jammed CFTs

Eric Mefford
University of California, Santa Barbara, United States

We present new static, spherically symmetric solutions to the vacuum Einstein equations with negative cosmological constant in five, six, and seven dimensions. The (d+1) dimensional solutions are asymptotically locally Anti de Sitter with the corresponding d dimensional Reissner-Nordstrom metric on the boundary.

Statistical Geometrothermodynamics of Black Holes

Viridiana Pineda Reyes
Institute of Nuclear Sciences, National Autonomous University of Mexico, Mexico

From the point of view of the thermodynamics, the quantization of gravity has been an open issue by forty years. Nowadays, there have been different approaches to the microscopic structure of black holes, with the aim of finding a path to solve this problem. Such approaches have been built, in essence, proposing partition functions and statistical models that could be consistent with what already is known of black holes thermodynamics. The purpose of our work is to provide one more approach, but within the Geometrothermodynmics formulation(GTD). We introduce the already known thermodynamics of black holes in the GTD formalism. Therefore, at foreseeable future, we would build a partition function that will be consistent and that lead us a statistical model that could give us a clue to get closer the problem of quantization of gravity.

GW150914 Highlights

Complementarity of Earth- and space-based detectors: binary populations and tests of strong gravity

Emanuele Berti

University of Mississippi, USA

The recent detection of gravitational waves by the LIGO/Virgo Collaboration calls for an updated assessment of the relative role of Earth- and space-based detectors. I will present my own perspective on this issue, focusing in particular on two aspects where the complementarity of Earth- and space-based detectors will be crucial: tests of strong-field gravity and our understanding of compact binary populations.

Results of searching for binary black holes in the first observing run of Advanced LIGO

Collin Capano

Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Hannover, Germany

The first observing run of Advanced LIGO completed in January 2016. I discuss the results of searching this data for gravitational waves from binary black holes with total masses up to 100 solar masses, using modeled waveforms. The first 16 days of this data included GW150914, as well as a second, marginal event LVT151012. I discuss what can be learned from these results, and estimates of the expected detection rate in future observing runs.

The mass distribution of coalescing binary black holes from ground-based GW observations

Thomas Dent

AEI Hannover, Germany

After the epochal discovery of a high-mass stellar black hole coalescence in 2015, the ground-based network of GW detectors is expected to observe tens of black hole merger events in the coming years. The rate and distribution of coalescing BH binaries over intrinsic (component masses and spins) and extrinsic (redshift) parameters are key outputs from these observations, which will enable us to test models of compact binary formation and evolution.

We show that a Bayesian analysis using outputs from existing pipelines is able to reconstruct the rate and mass distribution of a set of simulated signals injected into recolored data from an early commissioning run of Advanced LIGO, with appropriate uncertainty estimates.

Zooming in on black holes: numerical-relativity follow-up to GW observations

Mark Hannam

Cardiff University, United Kingdom

Following the first GW detection, GW150914, we performed a series of follow-up numerical-relativity simulations of merging black-hole binaries, to gain improved understanding of the detailed phenomenology of the waveforms in the neighboring volume of parameter space, over that provided by current waveform models. The ultimate goal is to produce a more accurate local model that could be used to improve parameter estimates. We report on the status of that work.

Binary black hole remnants of First stars for the gravitational wave source

Tomoya Kinugawa

Institute for Cosmic Ray Research, University of Tokyo, Japan

Using our population synthesis code, we found that the typical chirp mass of binary black holes (BH-BHs) whose origin is the first star (Pop III) is 30Msun with the total mass of 60Msun so that the inspiral chirp signal as well as quasi normal mode (QNM) of the merging black hole are interesting targets of LIGO,VIRGO and KAGRA (Kinugawa et al.2014 and 2016). The detection rate of the coalescing Pop III BH-BHs is $\sim$ 180 events/yr $(SFR_p/(10^{-2.5}Msun/yr/Mpc^3)) * ([f_b/(1+f_b)]/0.33) * Err_{sys}$ in our standard model where SFR_p, f_b and Err_sys are the peak value of the Pop III star formation rate, the binary fraction and the systematic error with $Err_sys = 1$ for our standard model, respectively.

Furthermore, We found that the chirp mass has a peak at ∼30Msun in most of parameters and distribution functions (Kinugawa et al.2016). This result predicted the gravitational wave events like GW150914 and LIGO paper said recently predicted BBH total masses agree astonishingly well with GW150914 and can have sufficiently long merger times to occur in the nearby universe (Kinugawa et al. 2014) (Abbot et al. ApJL 818,22 (2016)). Nakano, Tanaka & Nakamura 2015 show that if S/N of QNM is larger than 35, we can confirm or refute the General Relativity more than 5 sigma level.
In our standard model, the detection rate of Pop III BH-BHs whose S/N is larger than 35 is 3.2 events/yr $(SFR_p/(10^{-2.5}Msun/yr/Mpc^3)) \times ([f_b/(1+f_b)]/0.33) \times Err_{sys}$. Thus, there is a good chance to check whether GR is correct or not in the strong gravity region.

Modeling merging black holes with numerical relativity in the era of first gravitational-wave observations

Geoffrey Lovelace

California State University, Fullerton, United States

Merger of weakly-interacting compact objects

Carlos Palenzuela

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We study the merger of compact objects, which only interact gravitationally, by performing dynamical simulations of two different perfect fluids. We focus on the influence of the radii of these compact objects on the gravitational wave signature produced during the coalescence. Although the LIGO detection GW150914 agrees very well with a binary black hole merger, our goal is to explore a possible degeneracy with these weakly interacting objects.

Is the gravitational-wave ringdown a probe of the event horizon?

Paolo Pani
Sapienza University of Rome & CENTRA-IST, Lisbon, Italy

It is commonly believed that the ringdown signal from a binary coalescence provides a conclusive proof for the formation of an event horizon after the merger. This expectation is based on the assumption that the ringdown waveform at intermediate times is dominated by the quasinormal modes of the final object. We point out that this assumption should be taken with great care, and that basically any compact object with a light ring will display a similar ringdown stage, even when its quasinormal-mode spectrum is completely different from that of a black hole. In other words, universal ringdown waveforms indicate the presence of light rings, rather than of horizons. Only precision observations of the late-time ringdown signal, where the differences in the quasinormal-mode spectrum eventually show up, can be used to rule out exotic alternatives to black holes and to test quantum effects at the horizon scale.

The Impact of GW150914 on Interferometer Design

Dave Reitze
California Institute of Technology, United States

Impact of first detection on interferometer design.

A stochastic gravitational-wave background from binary black hole mergers

Bernard F. Whiting
University of Florida, USA

The whole world was excited to hear that the first discovered of gravitational waves arose from the merger of two black holes of about 30 solar masses. The existence of black holes of such mass, and of binaries composed of such black holes, raises new questions about the abundance of such sources and of their possible origins. In this talk we will discuss implications of the existence of such sources and the potential that, at higher redshifts, they may create an unresolved stochastic background of gravitational waves.

Theoretical Physics Implications of the Binary Black-Hole Merger GW150914: Kerr Hypothesis and Smaller-confidence Observations

Kent Yagi

Princeton University, USA

Advanced LIGO's discovery of the direct detection of gravitational waves from a binary black hole coalescence allows us to probe extreme gravity for the first time. In this talk, I will describe additional implications of the GW150914 event on the strong-field nature of gravity and compact objects. I will first demonstrate what information one can obtain on theoretical physics mechanisms from smaller-confidence observations, namely the LVT151012 trigger and possible electromagnetic counterpart signals associated with GW150914 or with future events. I will next show how GW150914 can inform us about constraints on the Kerr hypothesis through inferences on the properties of the inner-most stable circular orbits. I will then discuss how GW150914 constrains the properties of exotic, compact-object alternatives to black holes, such as boson stars, in particular if the remnant does not promptly collapse to a black hole upon coalescence.

Theoretical Physics Implications of the Binary Black-Hole Merger GW150914: Gravitational-wave Generation and Propagation

Nicolas Yunes

Montana State University, USA

The gravitational-wave observation GW150914 by Advanced LIGO provided the first opportunity to learn about theoretical physics mechanisms that may be present in the extreme gravity environment of coalescing binary black holes. The LIGO collaboration verified that this observation is consistent with Einstein's theory of General Relativity and the Kerr hypothesis, constraining the presence of parametric anomalies in the signal. In this talk, I will discuss the plethora of additional inferences that can be drawn on theoretical physics mechanisms from the absence of such anomalies in the LIGO observation. I will classify these inferences in those that inform us about the generation of gravitational waves, the propagation of gravitational waves and the structure of exotic compact object alternatives to black holes. I will then focus on how GW150914 constrains the generation of gravitational waves (e.g. the activation of scalar fields, black hole graviton leakage into extra dimensions, the variability of Newton's constant, the breakage of Lorentz invariance and parity invariance) as well as the propagation of gravitational waves (e.g. the speed of gravity and the existence of large extra dimensions).
