UNIVERSITY OF TRENTO - Italy

Trento Institute for
Fundamental Physics
and Applications

Binary neutron star mergers in GRMHD and short gamma-ray bursts

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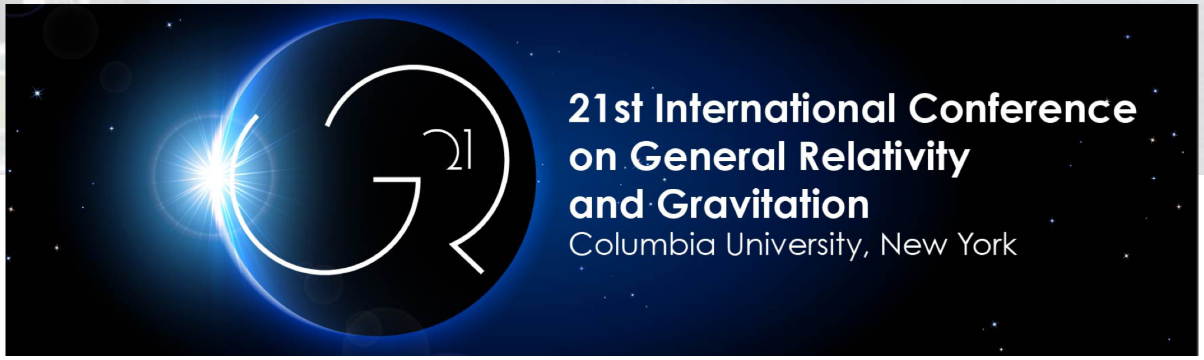
in collaboration with: T. Kawamura, B. Giacomazzo, W. Kastaun, A. Endrizzi (UNITN)
L. Baiotti (Osaka), R. Perna (Stony Brook)

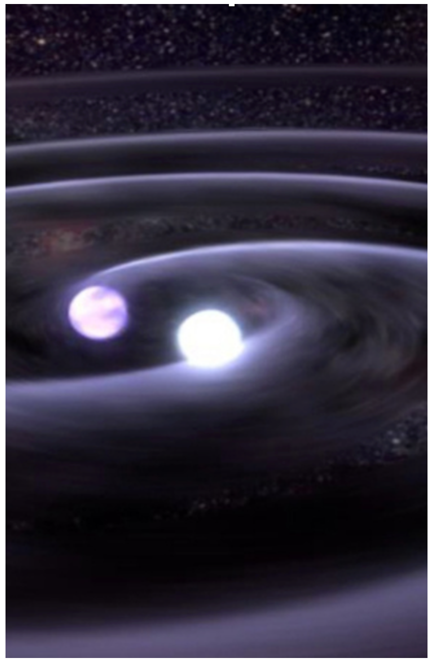
Kawamura et al. (2016) submitted, **Arxiv:1607.01791**



11th July 2016

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

INTRODUCTION

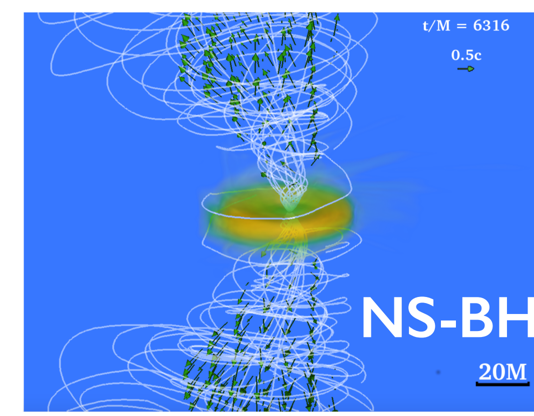


binary neutron star (BNS) mergers and neutron star-black hole (NS-BH) binary mergers ➡ **promising sources of GRAVITATIONAL WAVES** for advanced LIGO/Virgo

	detection rate	best guess
BNS	~(0.4-400)/yr	~40/yr
NS-BH	~(0.2-300)/yr	~10/yr

Abadie et al. 2010

Paschalidis et al. 2015

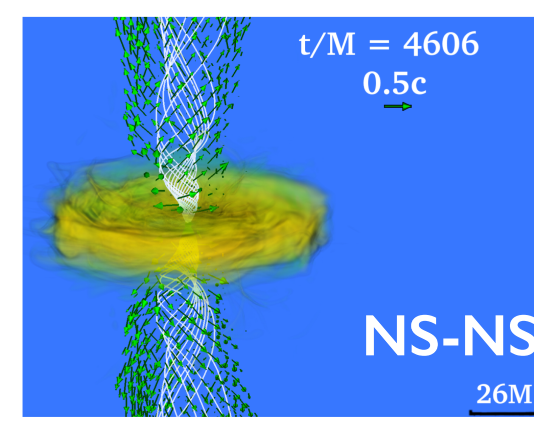


Short GRBs: "standard" model

central engine is a **black hole** surrounded by a massive **accretion torus**
⟶ end product of a **BNS or NS-BH binary merger**

Paczynski 1986, Eichler et al. 1989, Narayan et al. 1992, Barthelmy et al. 2005, Fox et al. 2005, Gehrels et al. 2005, ..

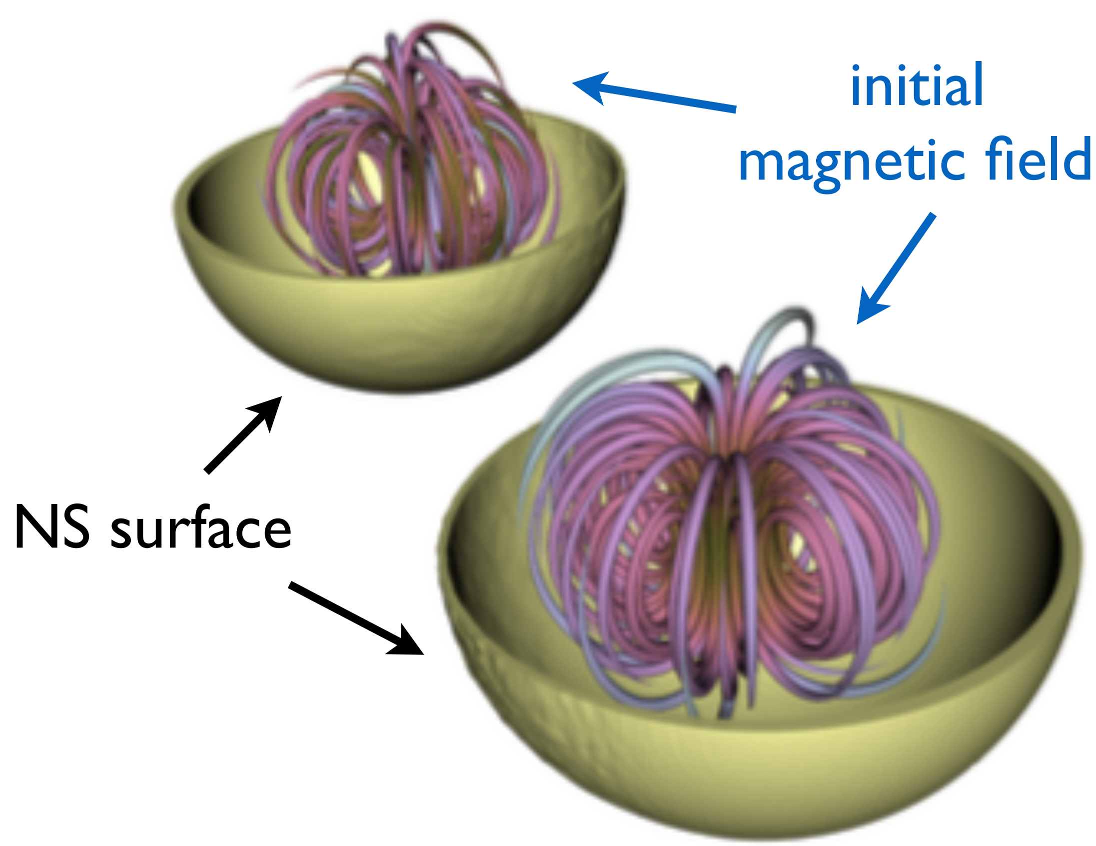
neutrino mechanism vs **magnetic mechanism (Blandford-Znajek?)**



Ruiz et al. 2016

SIMULATION SETUP

- Einstein Toolkit + WhiskyMHD
- 6 refinement levels
  (two levels following the stars during inspiral)
- fiducial resolution 222/186 m (IF/H4 EOS)
- also runs at different resolution
  (including higher resolution 177/150 m)
- computational domain >1000 km
- atmosphere floor level $\approx 6.2 \times 10^4 \mathrm{g\,cm}^{-3}$



OUR MODELS

Equation of state: ideal fluid and H4

Equal and unequal mass (mass ratio 1 and ~0.8)

Model	IF equal	IF unequal	H4 equal	H4 unequal
q	1	0.816	1	0.816
M_b^{tot} [$M_\odot$]	3.25	3.25	3.04	3.04
M_b [$M_\odot$]	1.63	1.44, 1.81	1.52	1.35, 1.69
M_g [$M_\odot$]	1.51	1.36, 1.67	1.40	1.26, 1.54
M_g/R_c	0.140	0.120, 0.164	0.148	0.132, 0.164
f_0 [Hz]	295	234	263	263
d [km]	59.3	68.0	61.0	61.0
E_B [10^{40}erg]	8.19	8.03	9.51	9.32
B_{max} [10^{12}G]	1.99	1.99	1.99	1.99
A_b	2.20	0.76, 5.36	1.97	1.21, 3.13

quasi-circular, irrotational BNS models (Lorene)

purely poloidal magnetic field added
on top with prescription

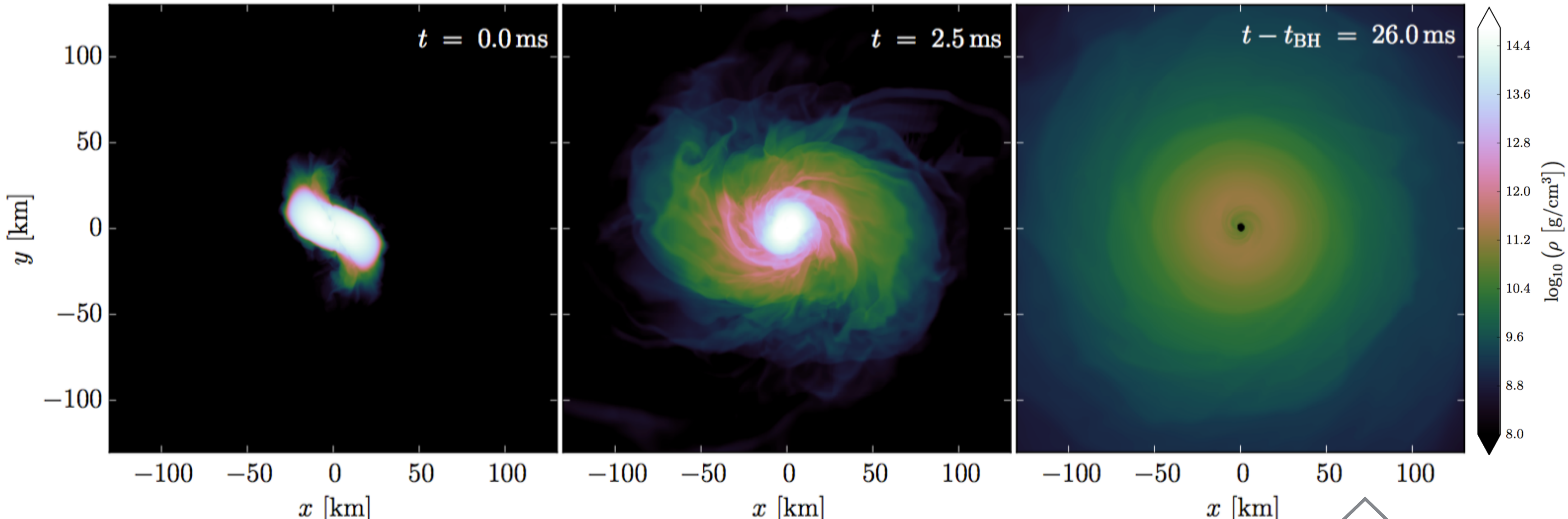
$$A_\phi \equiv \varpi^2 A_b \max(p - p_{\mathrm{cut}}, 0)^{n_s}$$

(confined inside the two stars)

different orientations
up-up (UU), up-down (UD), down-down (DD)

IDEAL FLUID, EQUAL-MASS MODEL

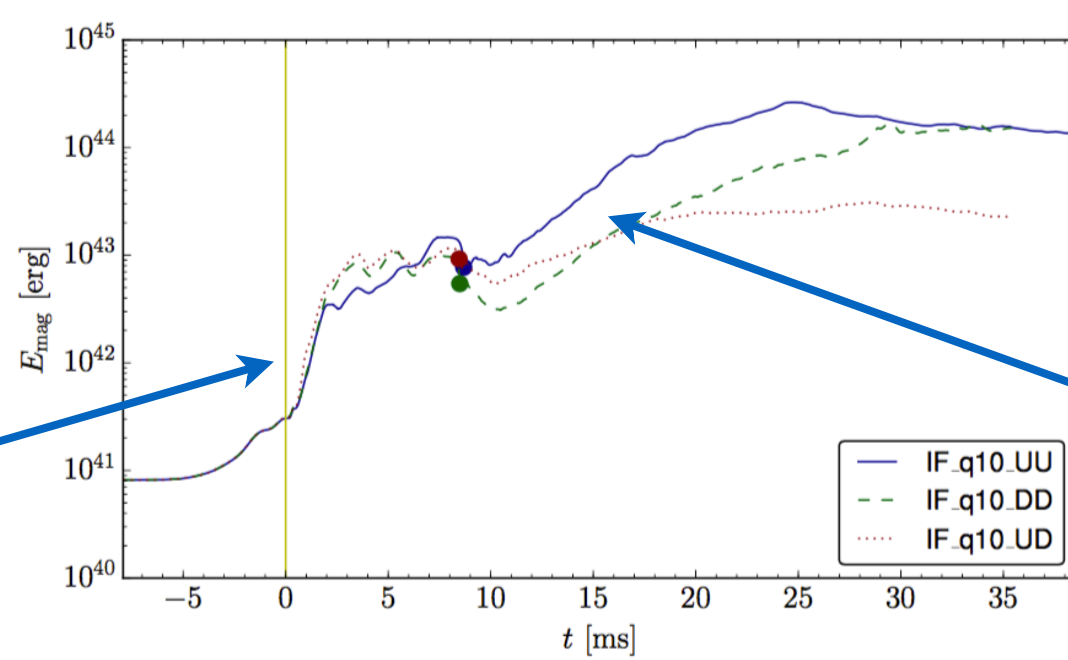
rest-mass density



disk mass ~0.04 Msun

BH spin ~0.8

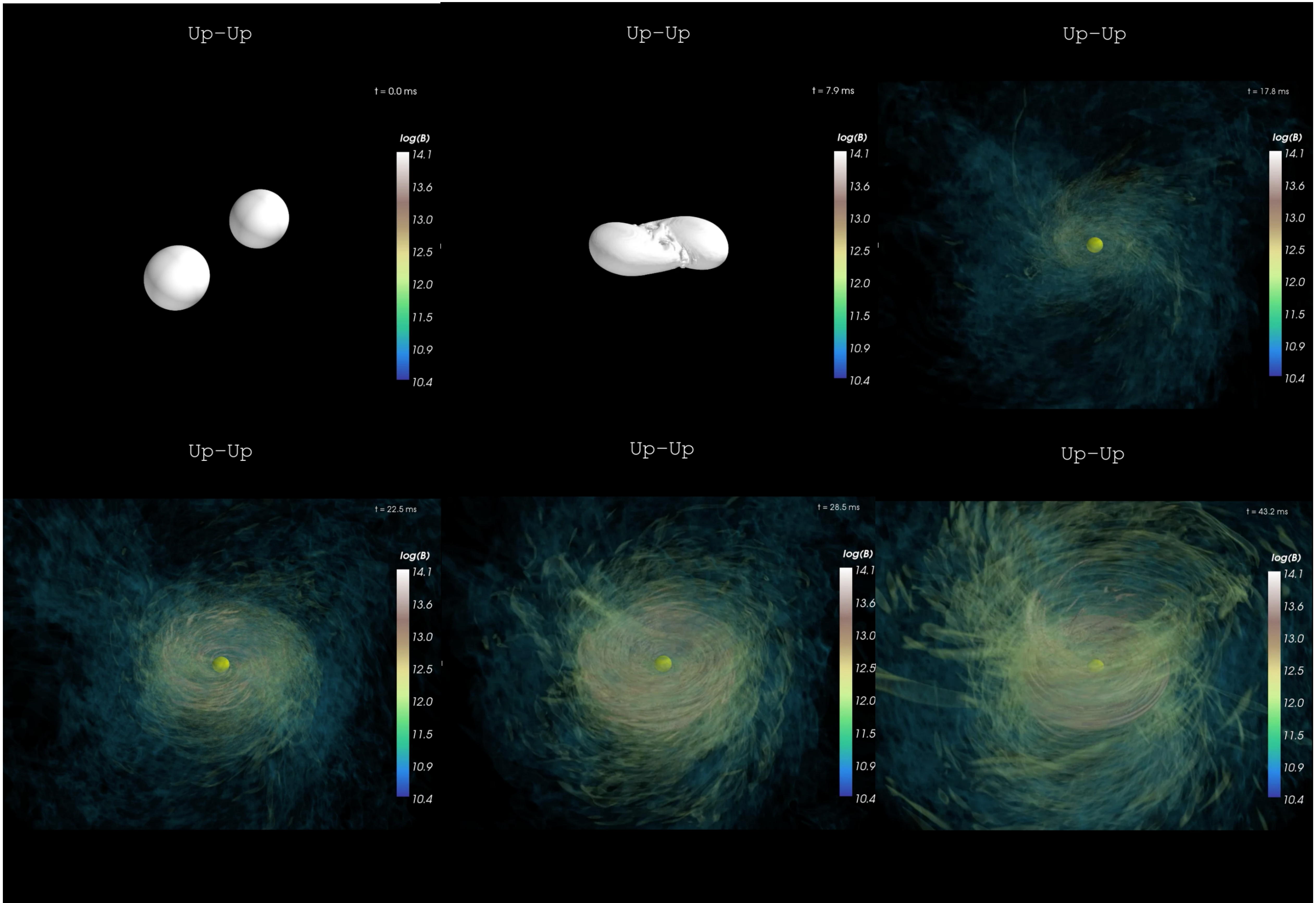
magnetic energy



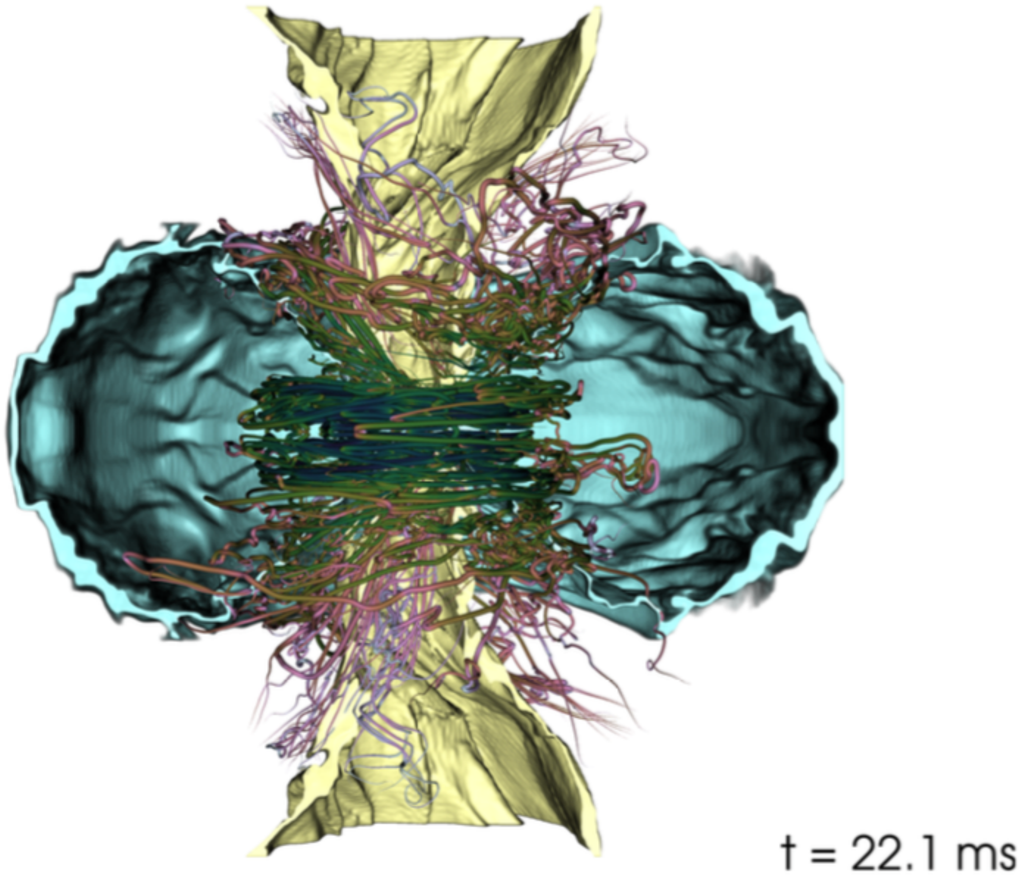
Kelvin-Helmholtz instability

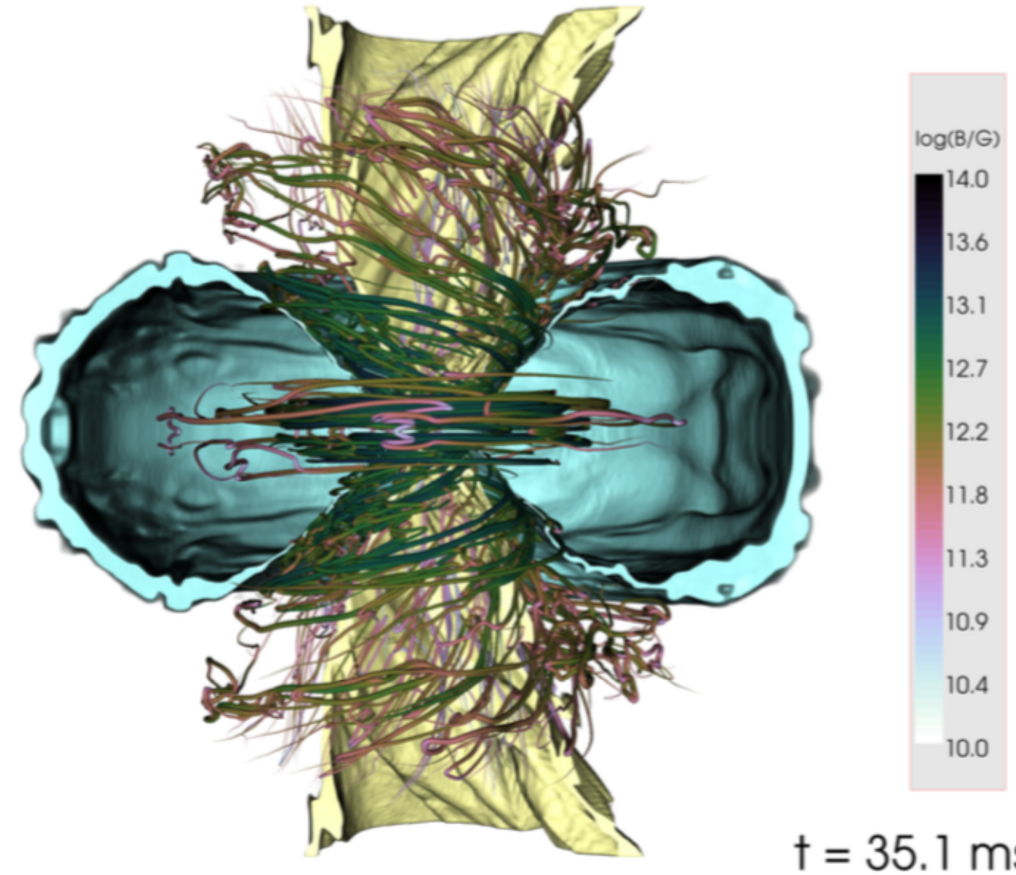
magnetic field amplification in the disk

EMERGING MAGNETIC FIELD STRUCTURE

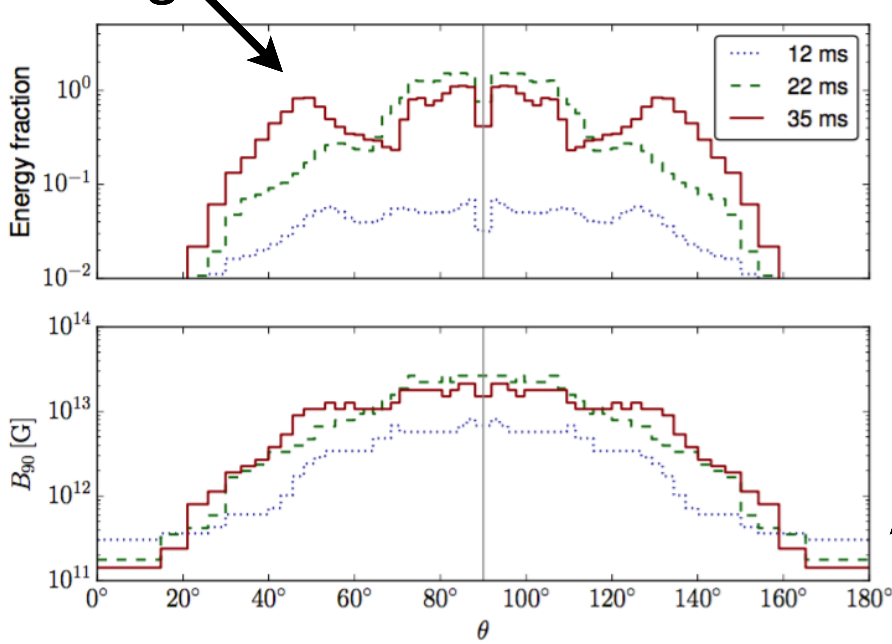


EMERGING MAGNETIC FIELD STRUCTURE





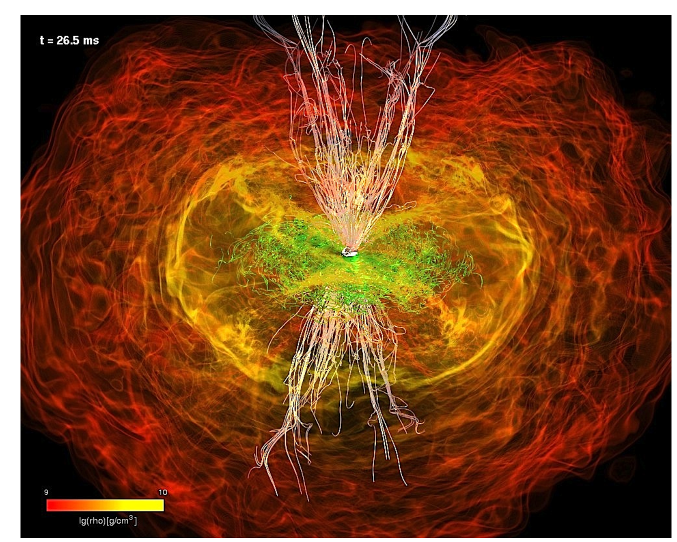
~50 deg



polar angle distribution
of magnetic energy and
magnetic field strength

weak field of ~2x10^{11} G
along the BH axis

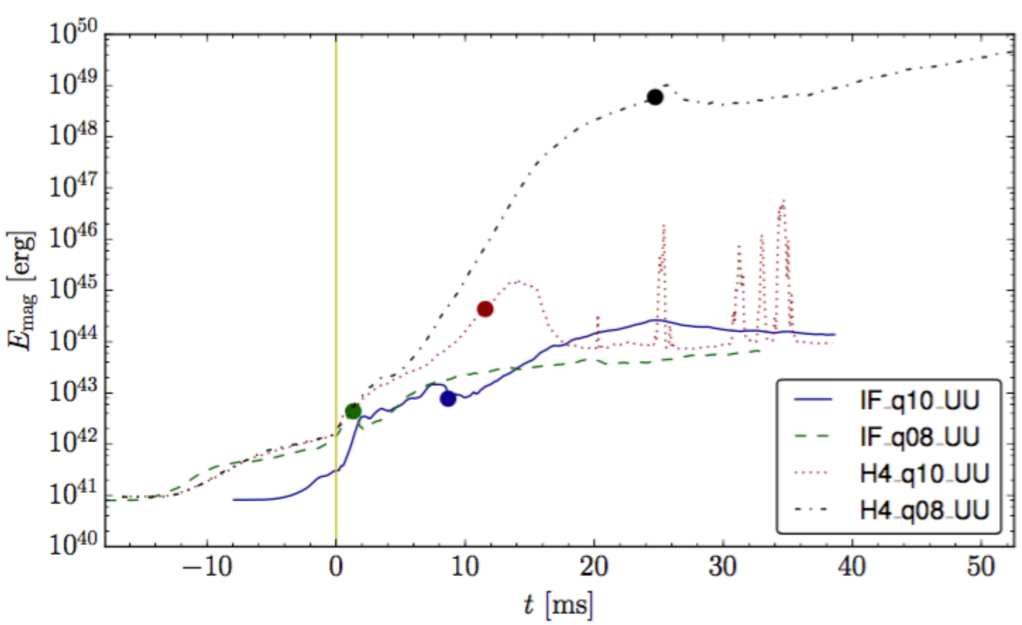
same model of
Rezzolla et al. 2011



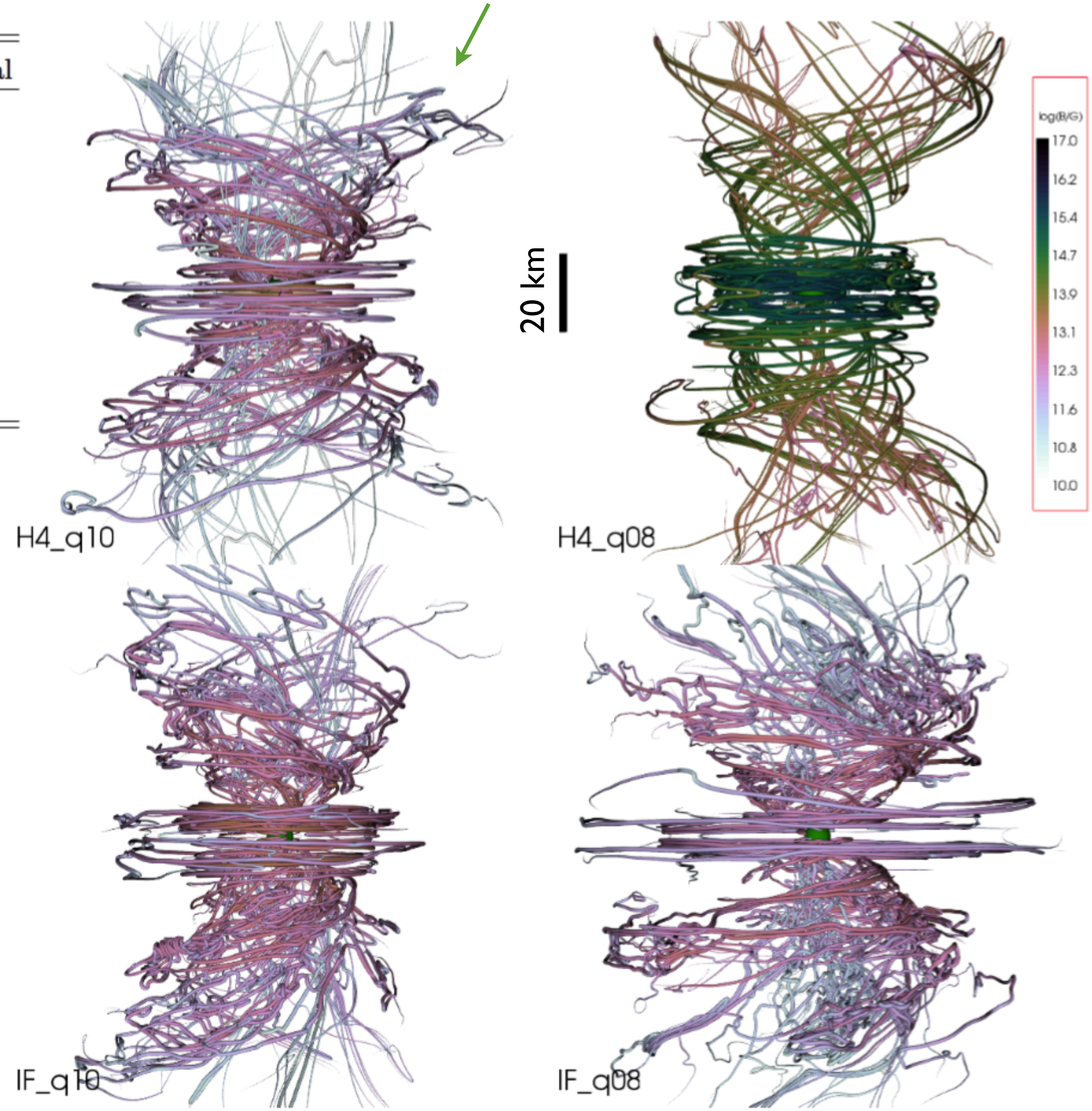
RESULTS WITH DIFFERENT EOS/MASS RATIOS

Model	IF equal	IF unequal	H4 equal	H4 unequal
$M_{\rm BH}$ [$M_\odot$]	2.92	2.78	2.67	2.50
$a_{\rm BH}$	0.81	0.77	0.71	0.63
$M_{\rm disk}$ [$M_\odot$]	0.04	0.21	0.04	0.23
$\dot{M}$ [$M_\odot$/s]	0.8	2.6	1.1	1.8
$\tau_{\rm acc}$ [s]	0.05	0.08	0.03	0.13
$t_{\rm BH}$ [ms]	8.7	1.3	11.6	24.7
$f_{\rm merger}$ [kHz]	1.36	0.96	1.43	1.62
$f_{\rm HMNS}$ [kHz]	–	–	2.47	2.69

magnetic energy



same model of Kiuchi et al. 2014



H4 UNEQUAL-MASS MODEL

Model	IF equal	IF unequal	H4 equal	H4 unequal
$M_{\rm BH}$ [$M_\odot$]	2.92	2.78	2.67	2.50
$a_{\rm BH}$	0.81	0.77	0.71	0.63
$M_{\rm disk}$ [$M_\odot$]	0.04	0.21	0.04	0.23
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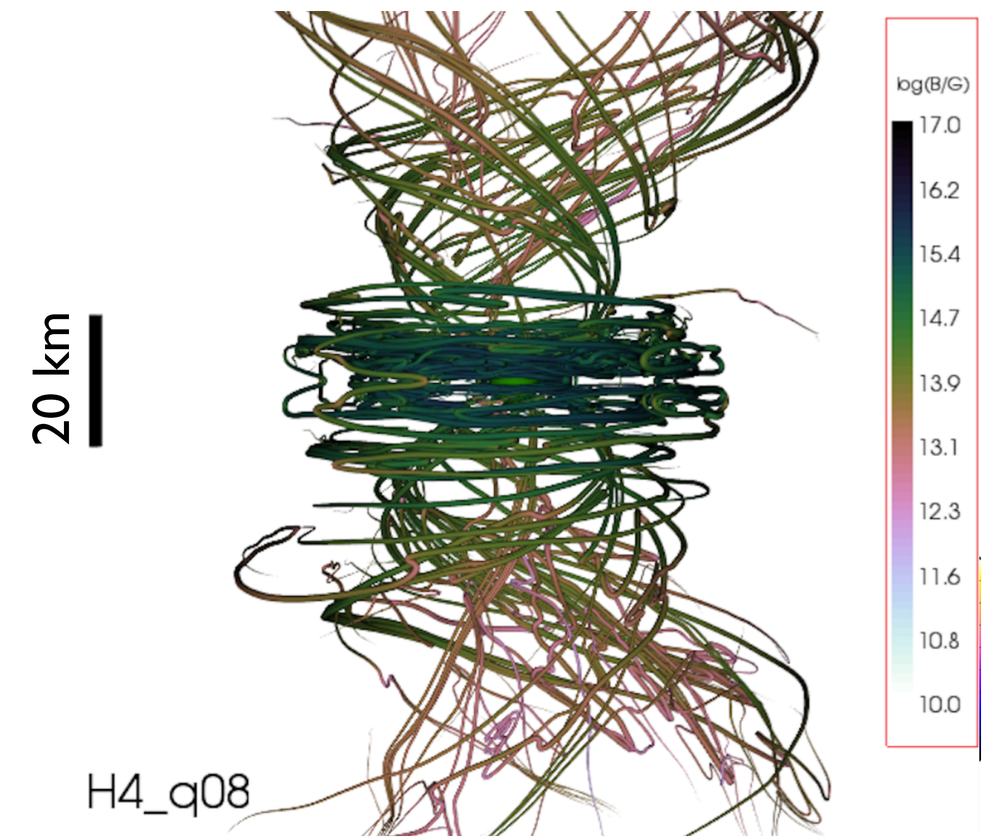
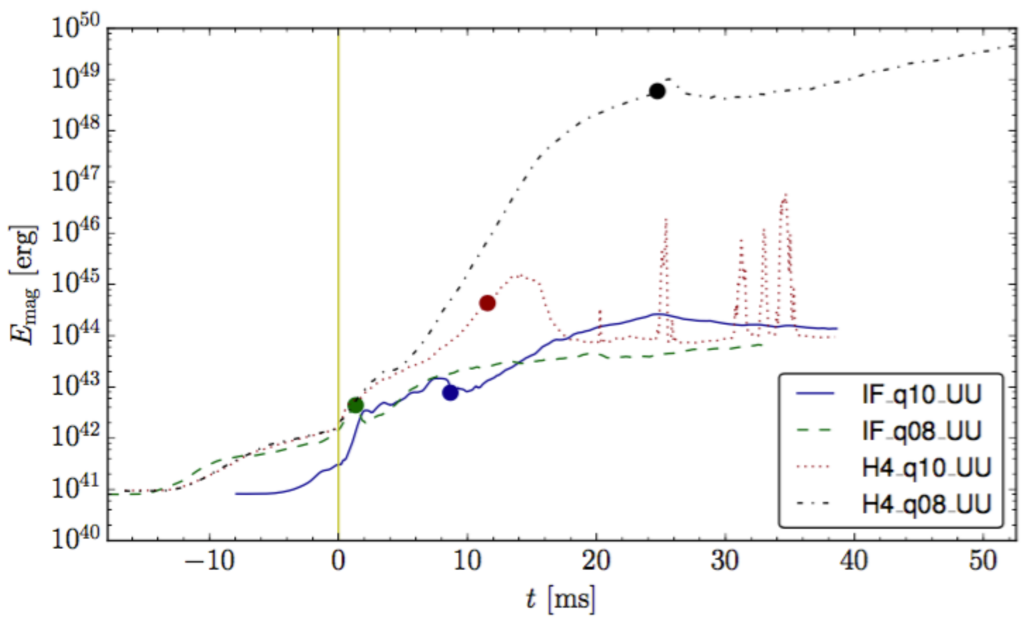
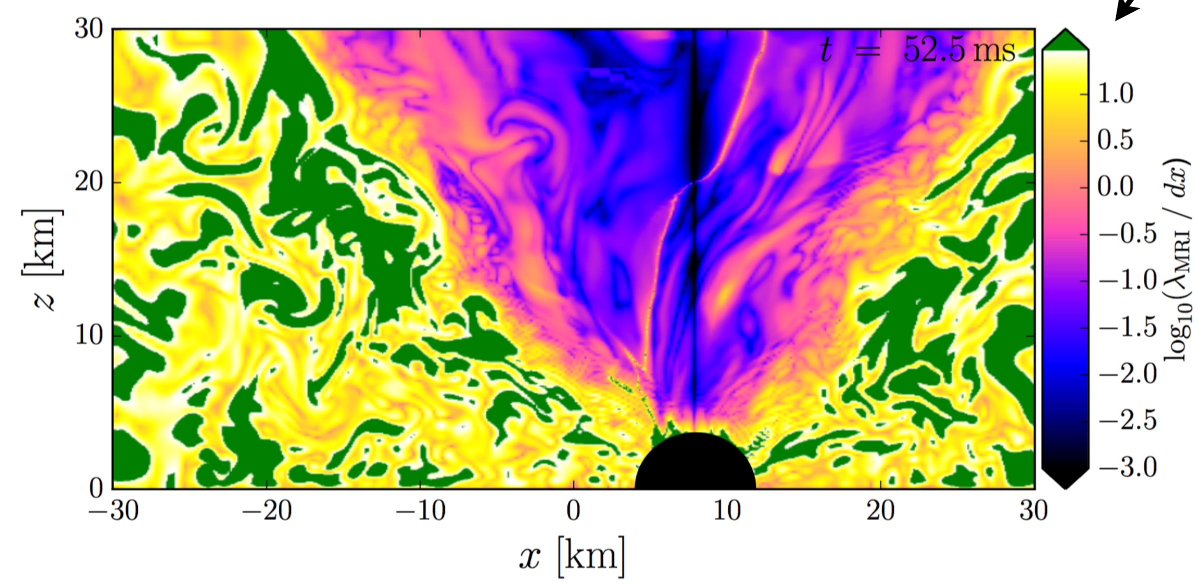


magnetic energy



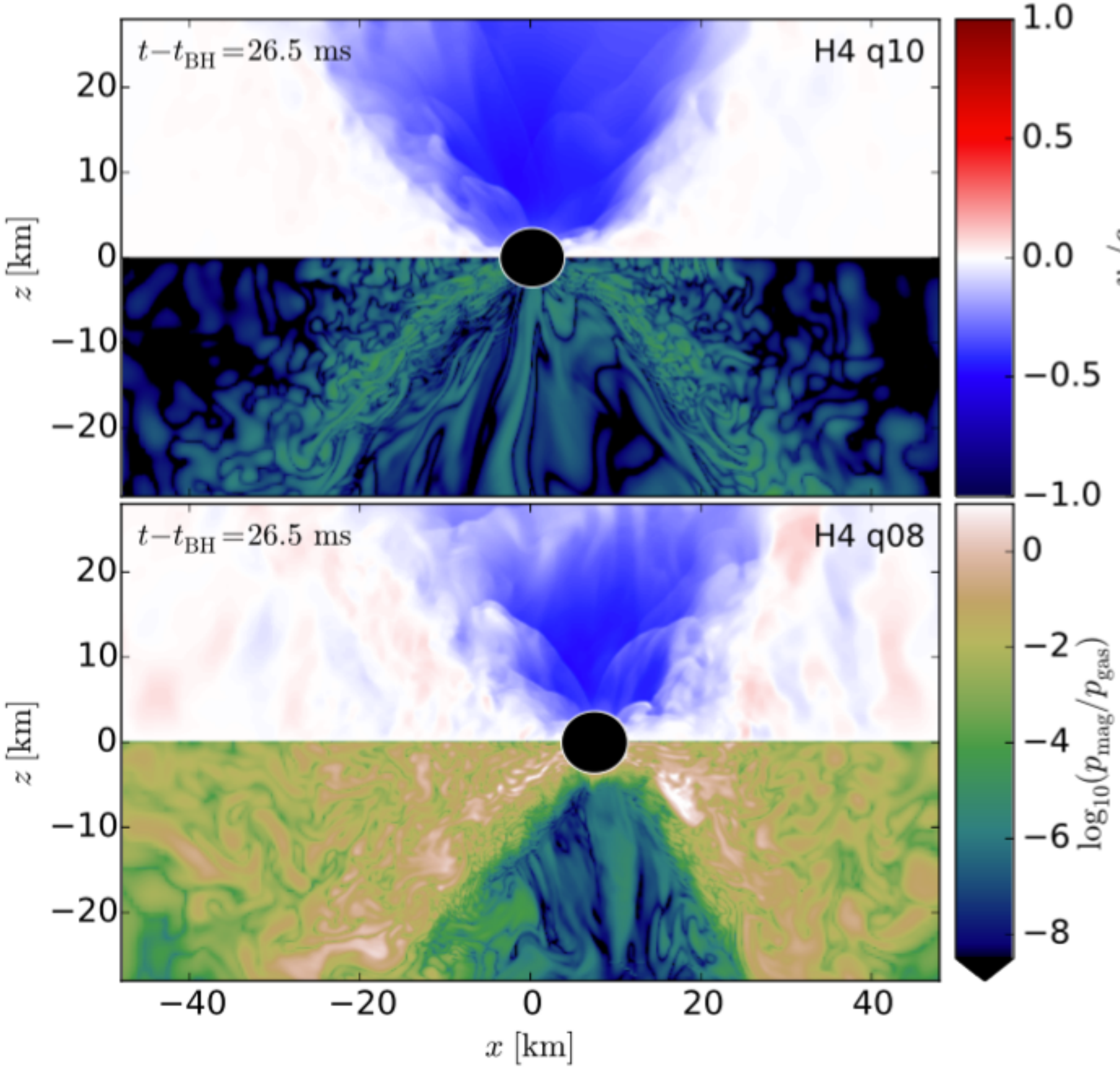
magnetorotational instability

MRI wavelength over dx

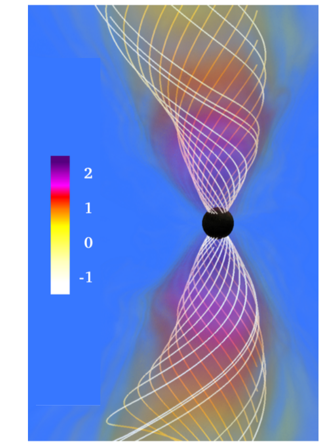


CONDITIONS FOR INCIPIENT JET?

fluid velocity (along z) and MHD ratio



..some necessary conditions are met, but



- NO OUTFLOW
- NO MAGNETICALLY DOMINATED FUNNEL

missing ingredients?

- HIGHER RESOLUTION (or SUBGRID MODEL) to fully account for magnetic field amplification
- LONGER SIMULATIONS (several tens of ms after BH formation)

UNIVERSITY OF TRENTO - Italy

INFN Istituto Nazionale di Fisica Nucleare

TIFPA Trento Institute for Fundamental Physics and Applications

WORKSHOP

SHORT GAMMA-RAY BURSTS
FROM OBSERVATION TO NUMERICAL SIMULATIONS

University of Trento, 8-9 September 2016
www.unitn.it/event/sgrb2016

INVITED SPEAKERS

Maria Grazia Bernardini (U. Montpellier)
Marica Branchesi (U. Urbino)
Pablo Cerda-Duran (U.Valencia)
Paolo D'avanzo (INAF Brera)
Bruno Giacomazzo (U.Trento)
Wolfgang Kastaun (U.Trento)
Kenta Kiuchi (U. Kyoto)
Paul O'Brien (U. Leicester)
Tsvi Piran (Hebrew U. Jerusalem)
Stephan Rosswog (U. Stockholm)
Ruben Salvaterra (INAF IASF)
Daniel Siegel (Columbia)
Giulia Stratta (U. Urbino)

ORGANIZERS

Riccardo Ciolfi (U.Trento)
Giancarlo Ghirlanda (INAF Brera)

SUMMARY

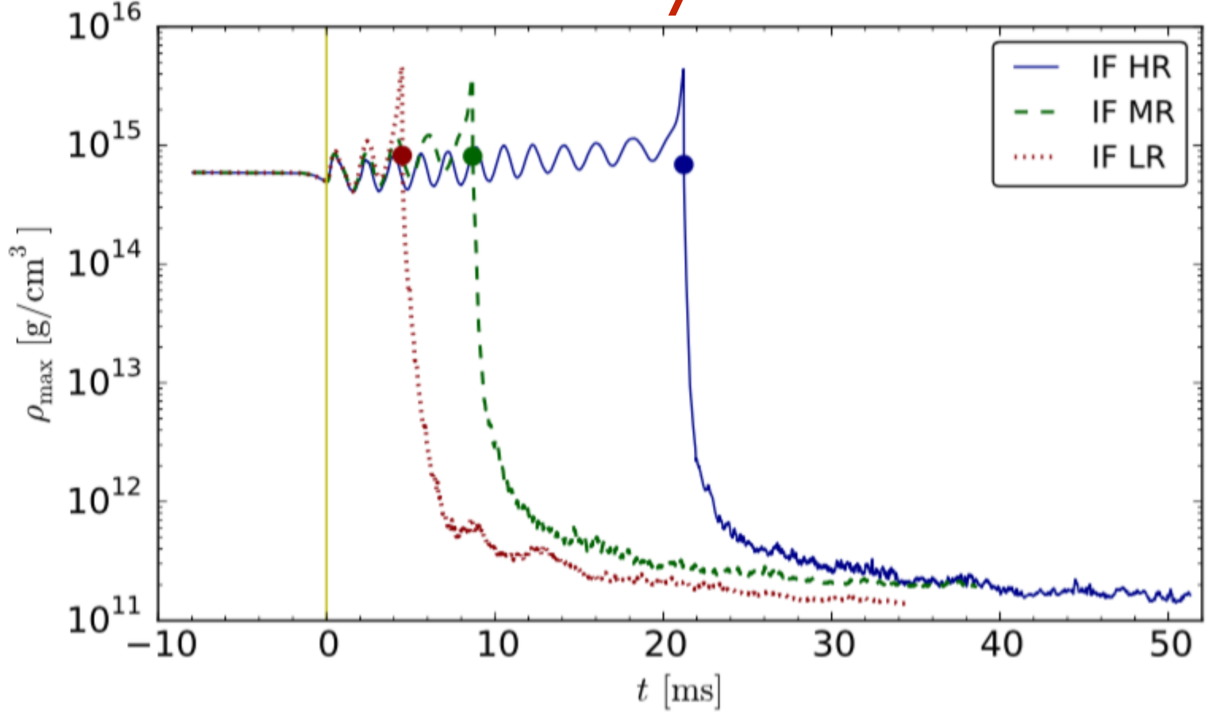
- studied magnetized BNS mergers forming a BH with different EOS, mass ratios, and magnetic field orientations, focusing on the conditions to produce SGRB jets
- twister-like ordered structure emerging after BH formation
- high disk masses and accretion rates can be obtained with unequal mass BNS mergers
- HMNS lifetime (depending on EOS and total mass) has a major impact on magnetic field amplification and on the properties of the final BH-disk system, longer-lived HMNSs provide more favorable conditions to form a jet
- we find no outflow and no magnetically dominated funnel, thus no evidence (yet) for an "incipient jet"
- need stronger field? magnetic field amplification not fully resolved..
- need more time (>20 ms) to generate an outflow?
- made direct comparisons with some previous results

Kawamura et al. (2016) submitted, **Arxiv:1607.01791**

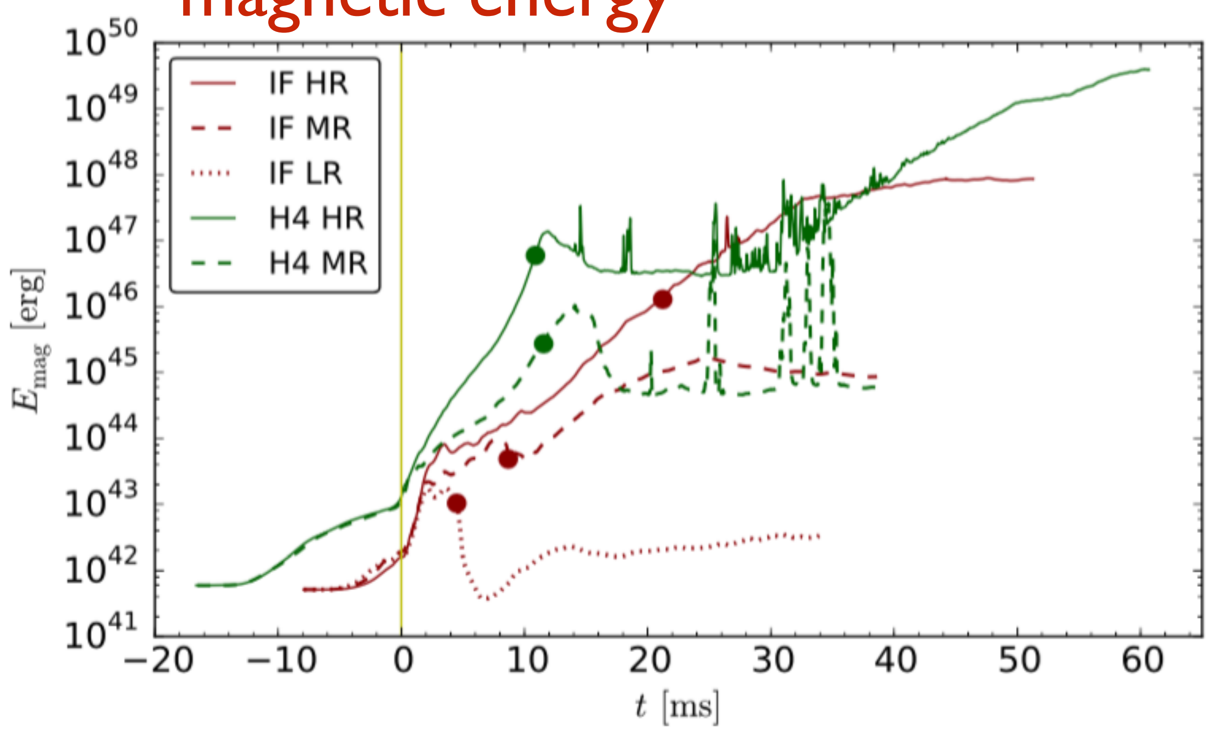
BACKUP SLIDES

Influence of resolution and MRI

rest-mass density

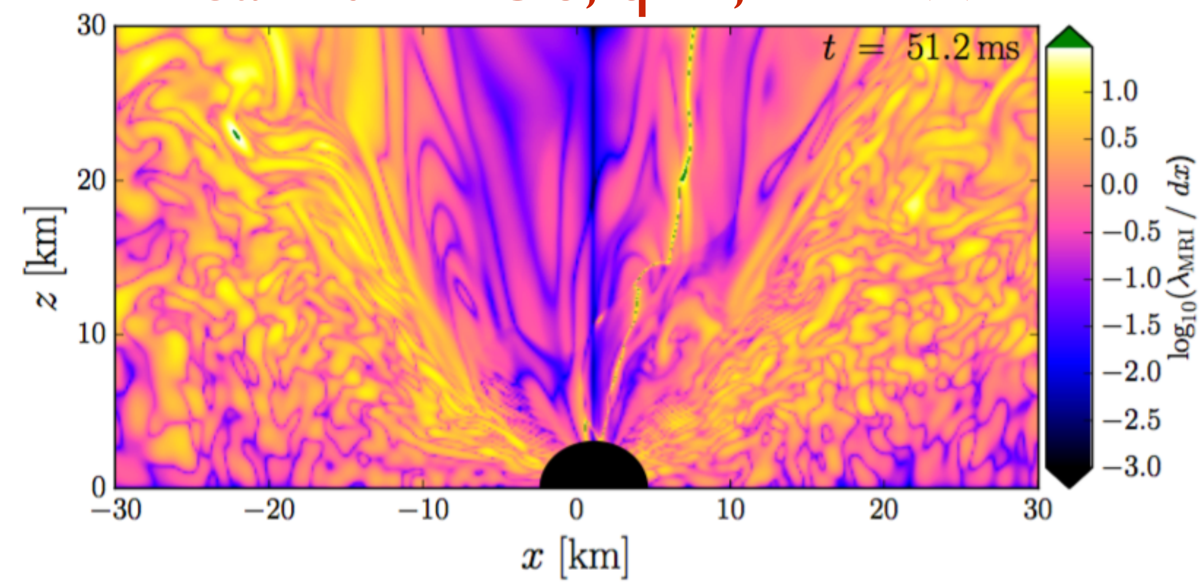


magnetic energy

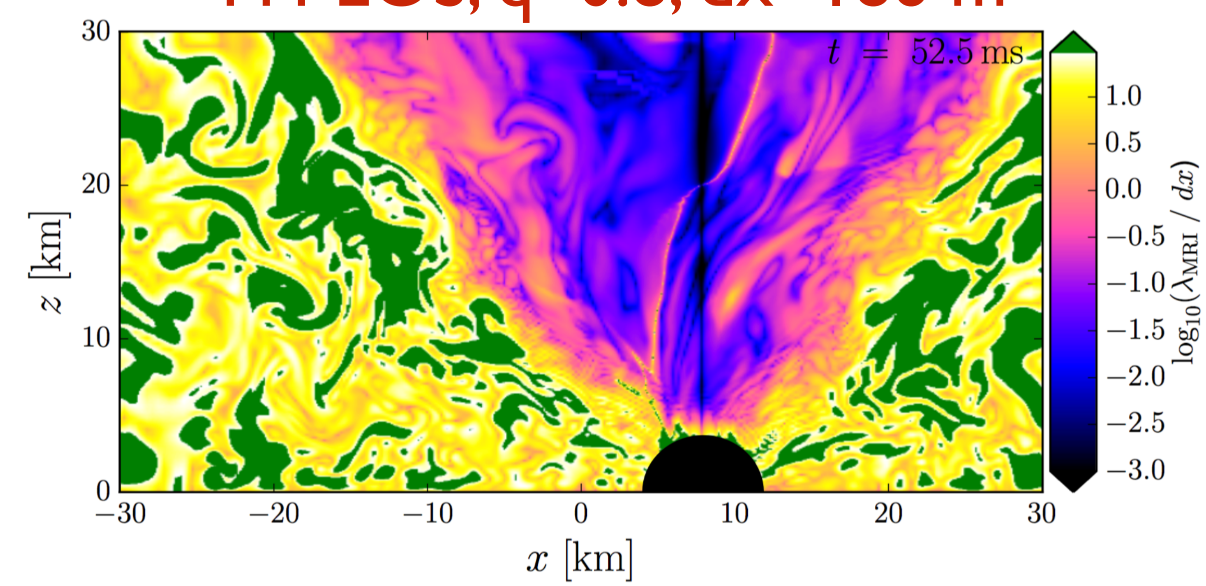


magnetorotational instability
how well resolved?

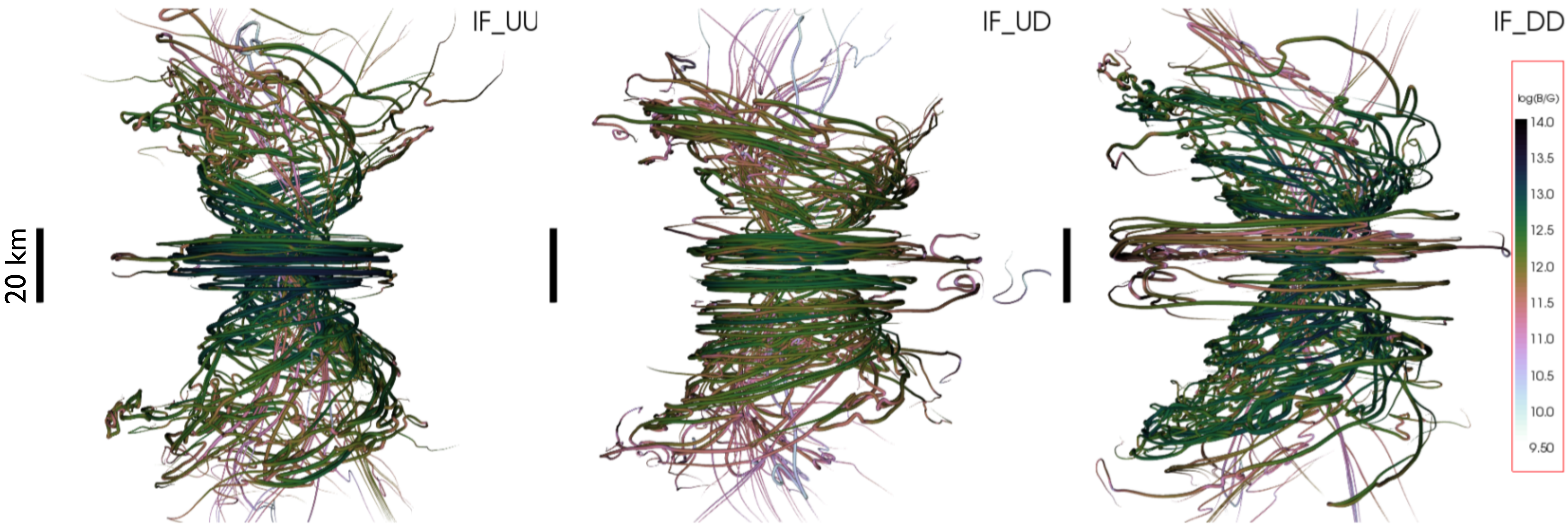
ideal fluid EOS, q=1, dx=177 m



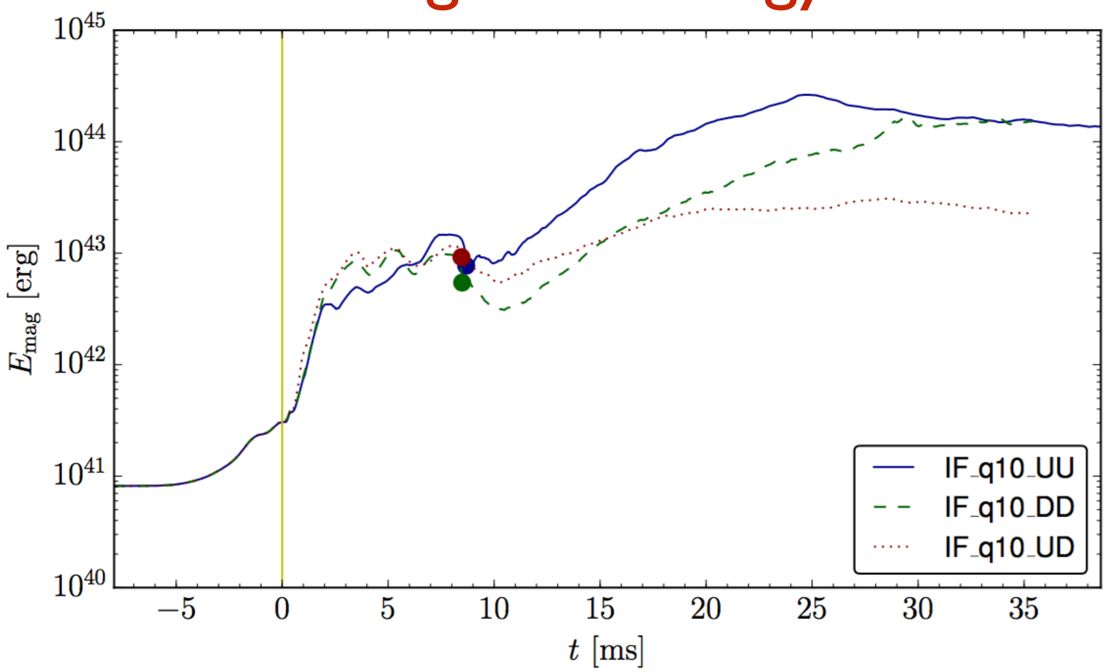
H4 EOS, q~0.8, dx=186 m



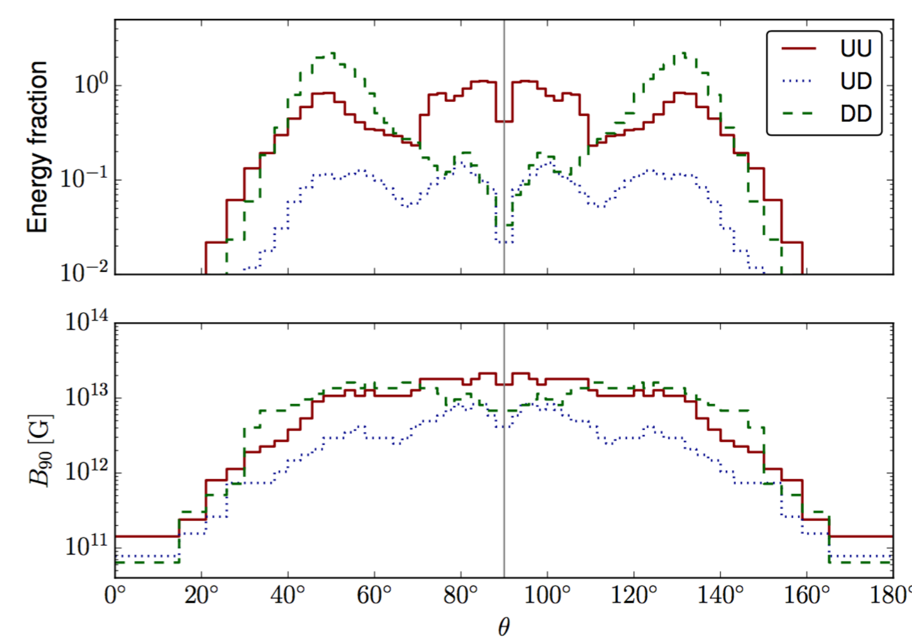
Magnetic field orientations



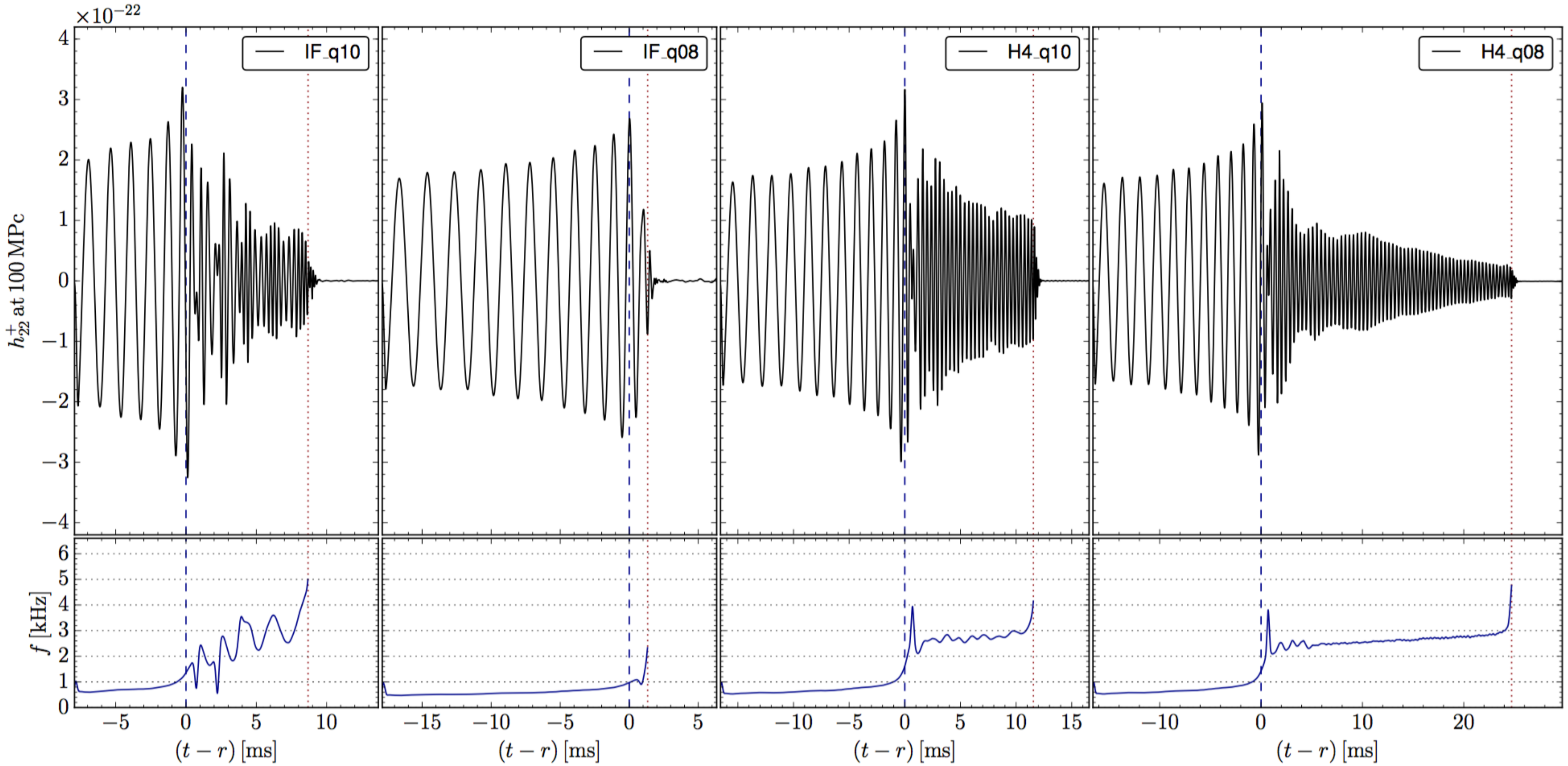
magnetic energy



polar angle dependence



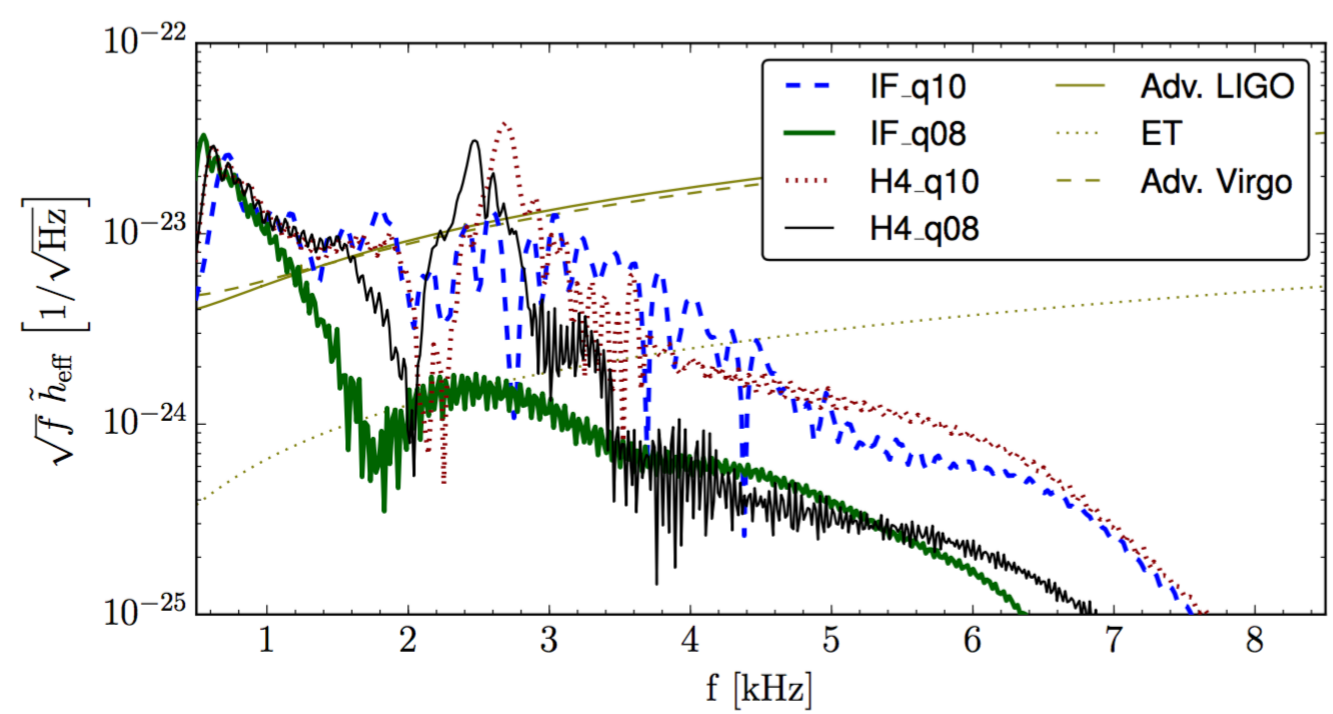
Gravitational waves



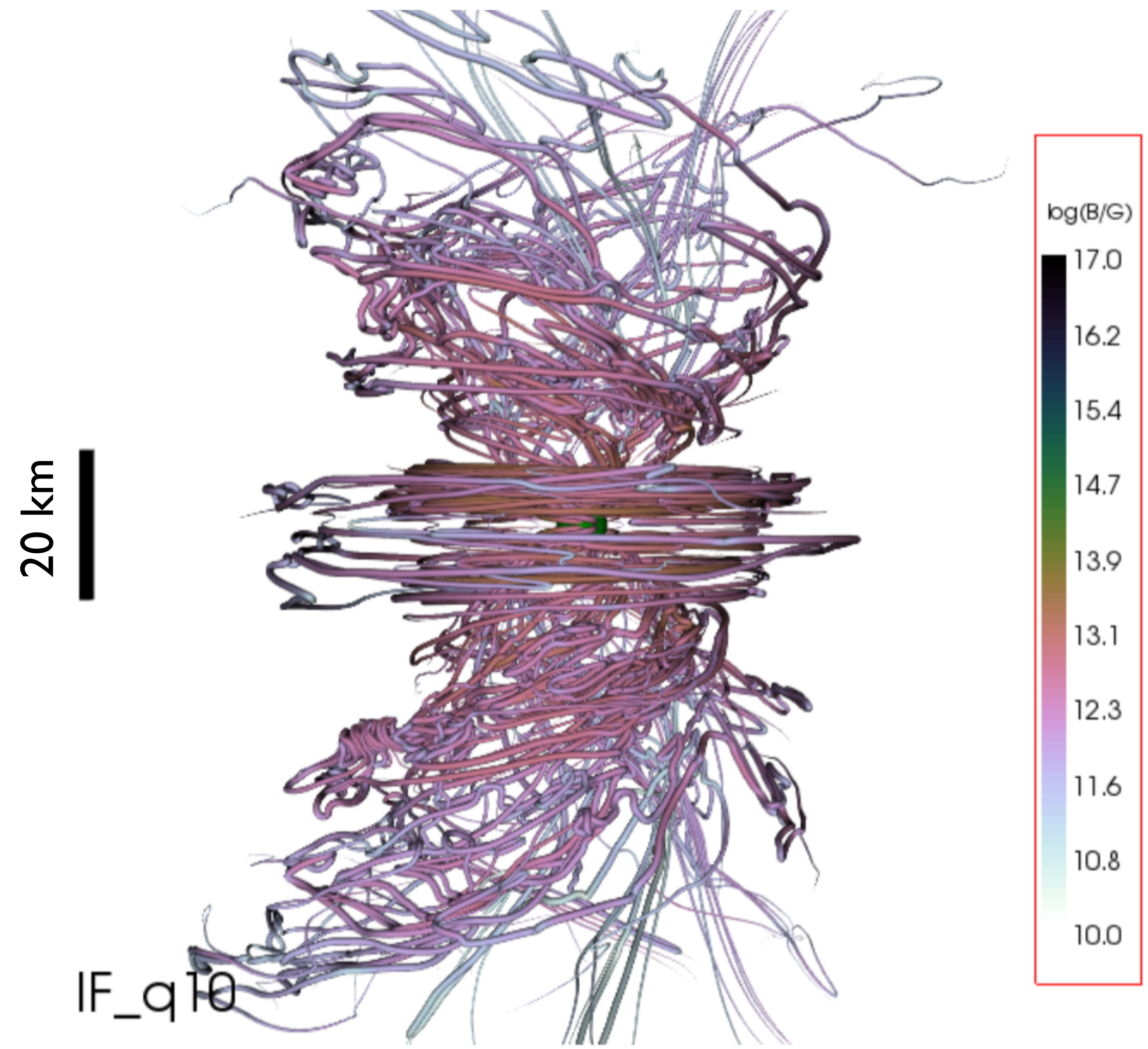
GW
strain

instantaneous
frequency

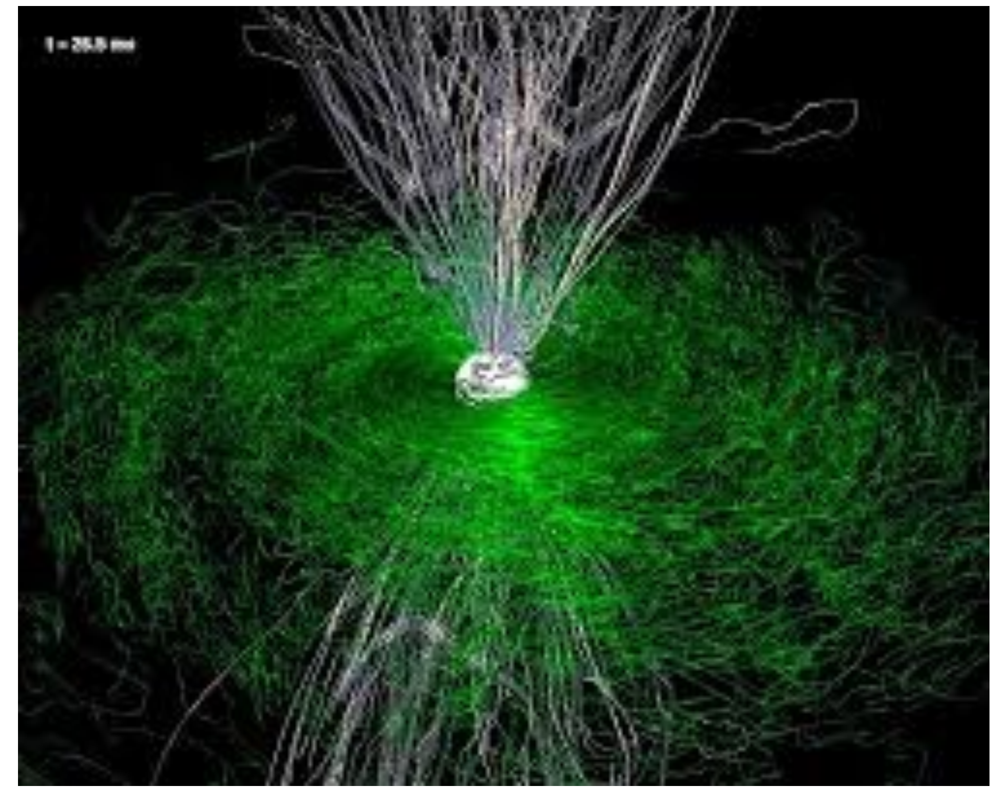
GW spectrum
vs
advanced and ET

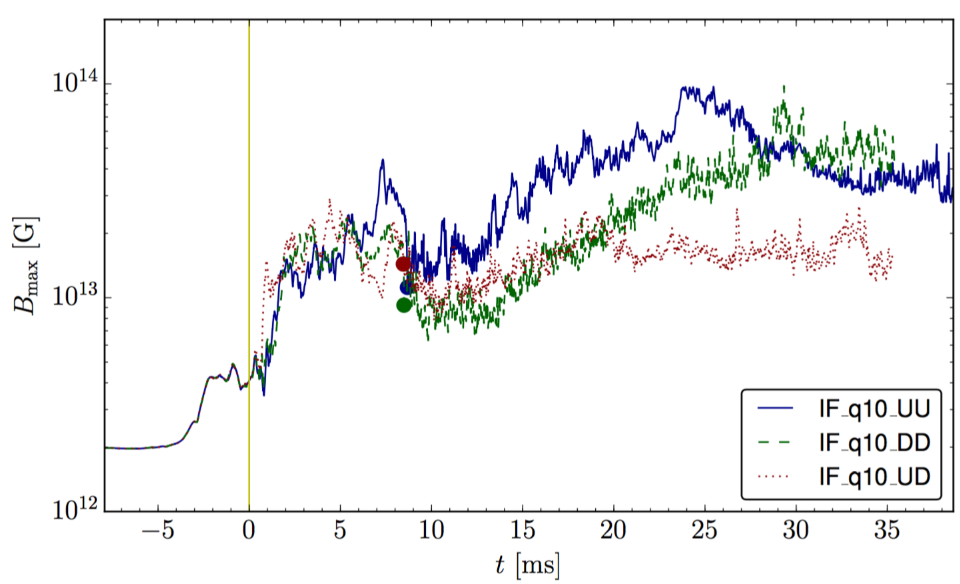


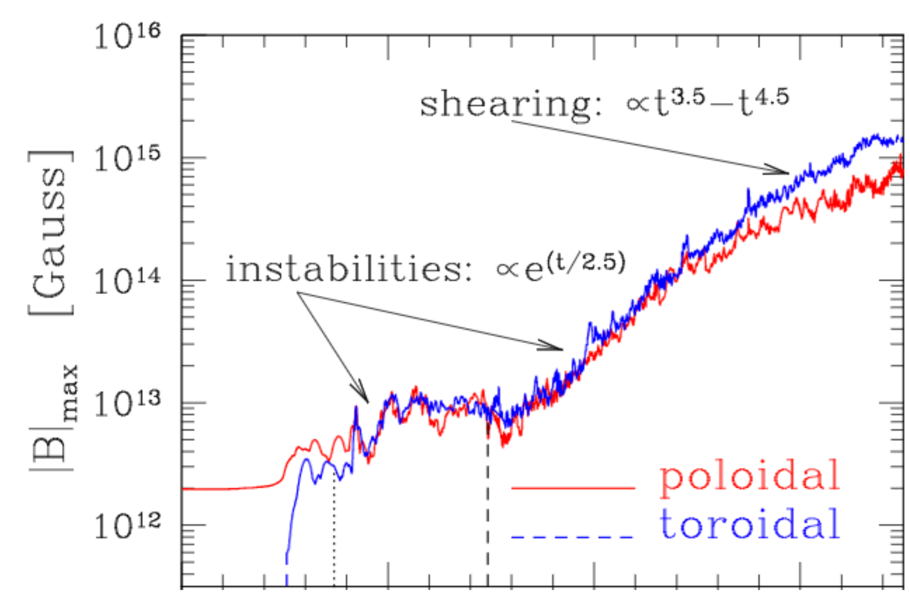
Comparison with Rezzolla et al. 2011



equal mass, ideal fluid EOS

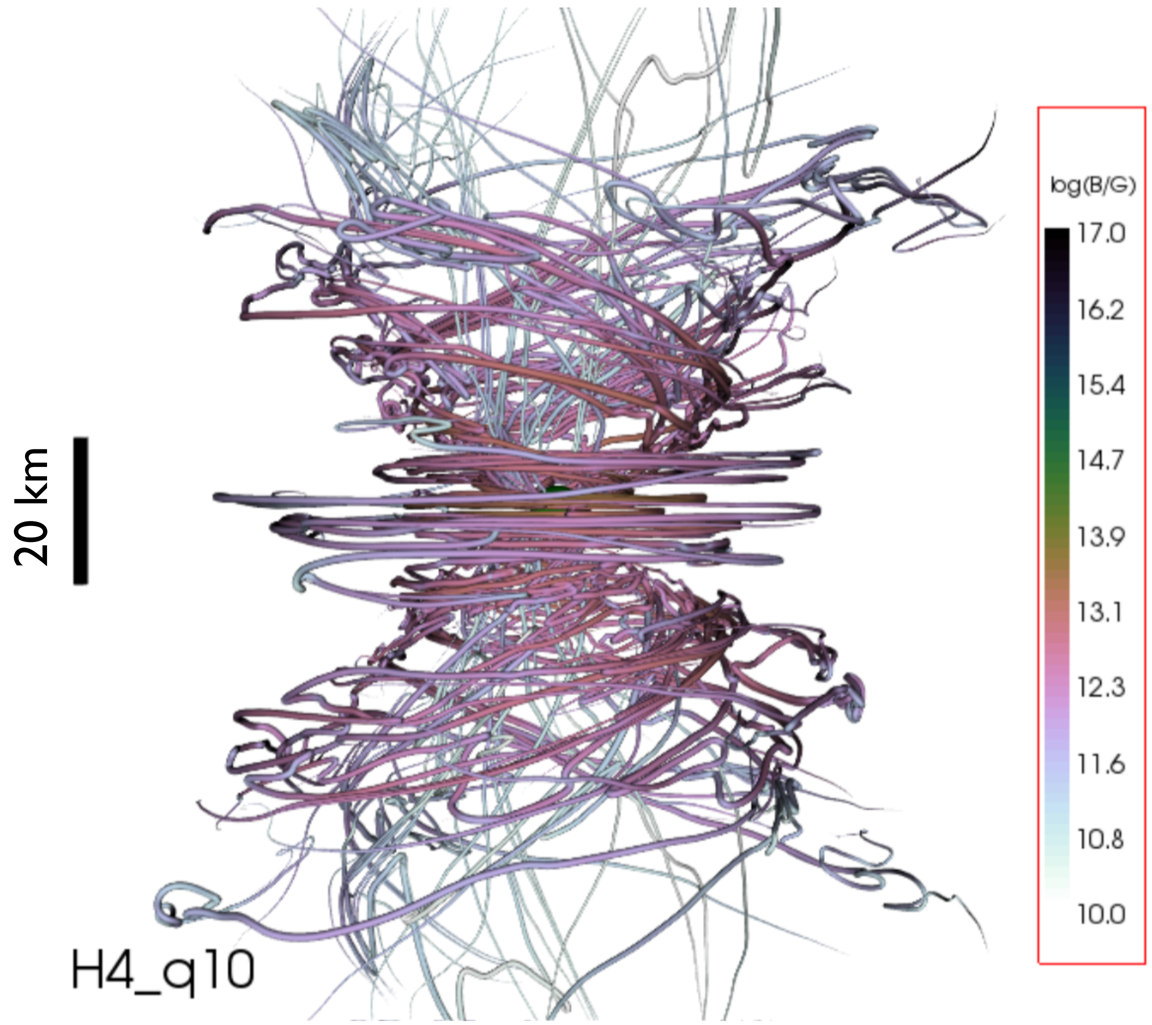


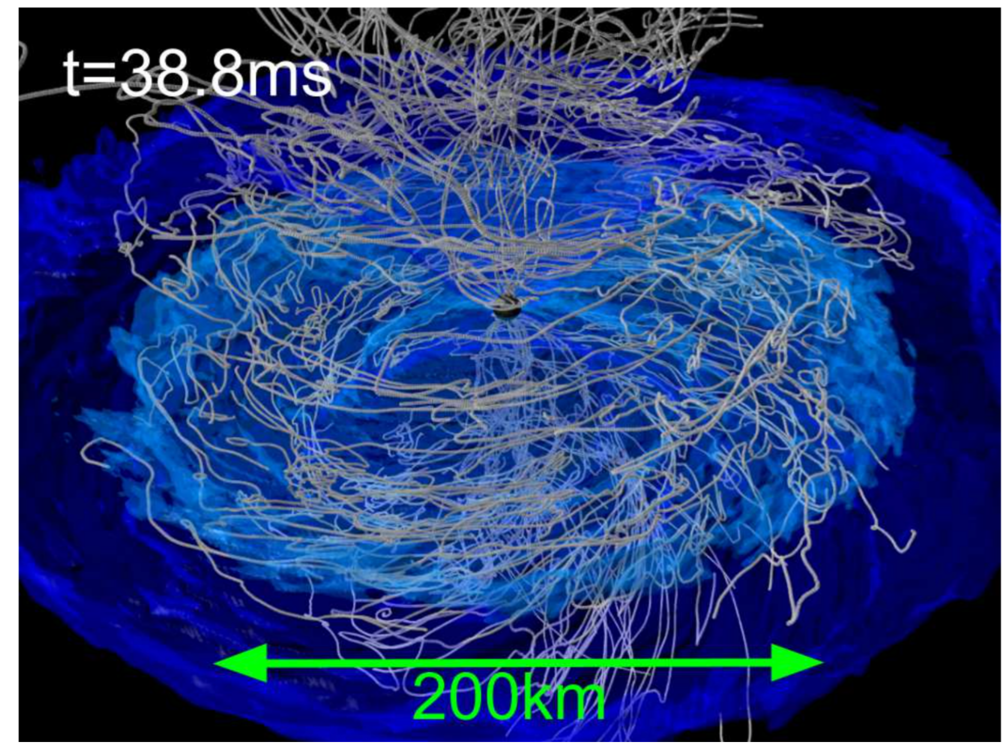


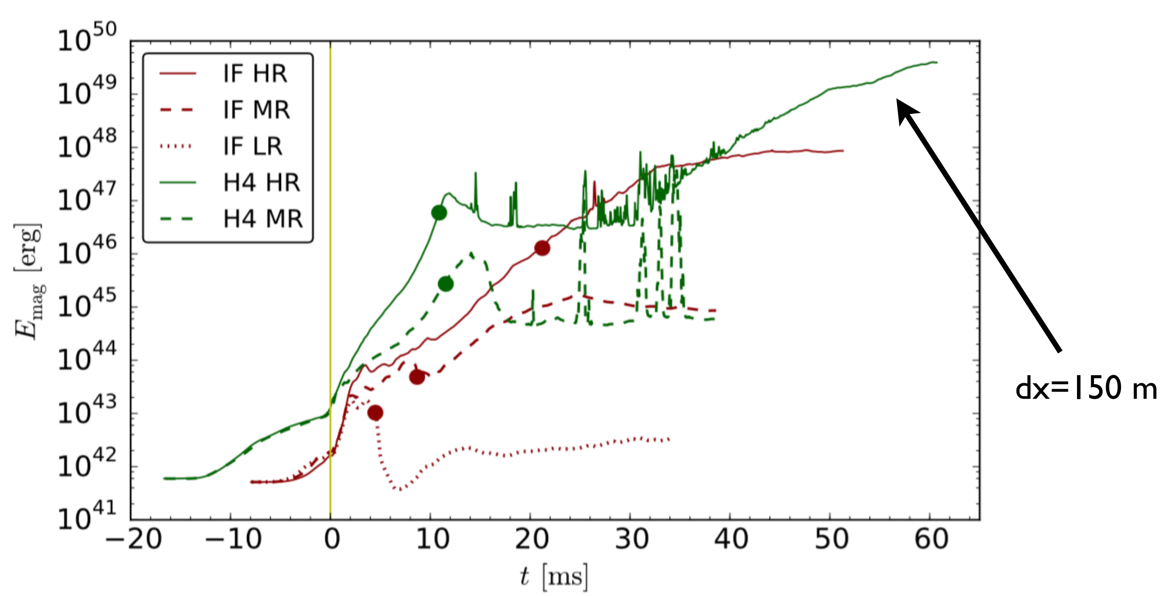


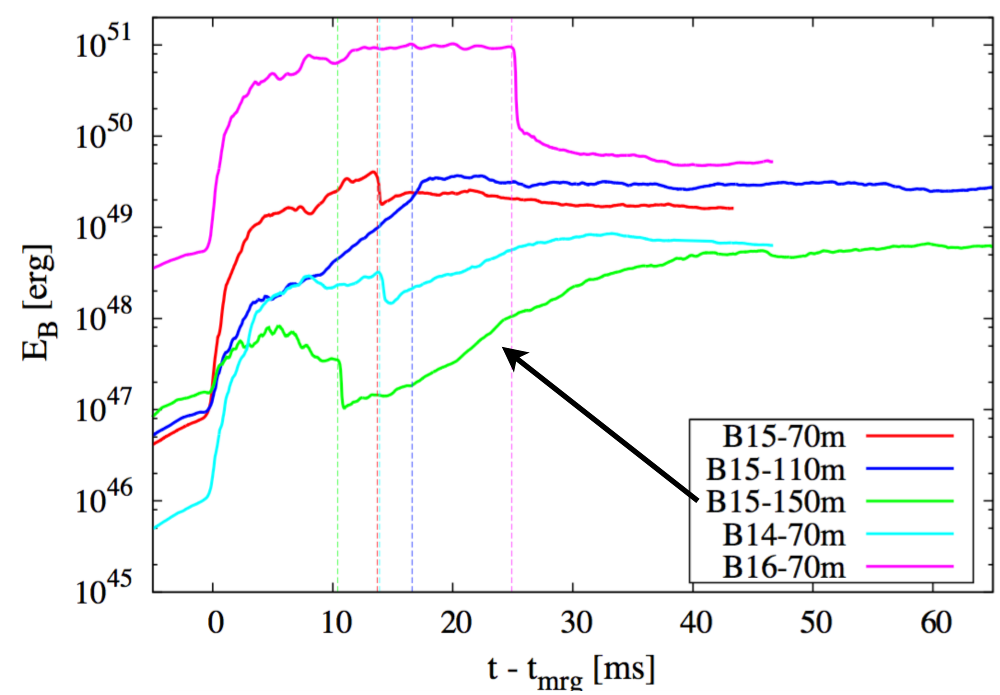
Comparison with Kiuchi et al. 2014

equal mass, H4 EOS



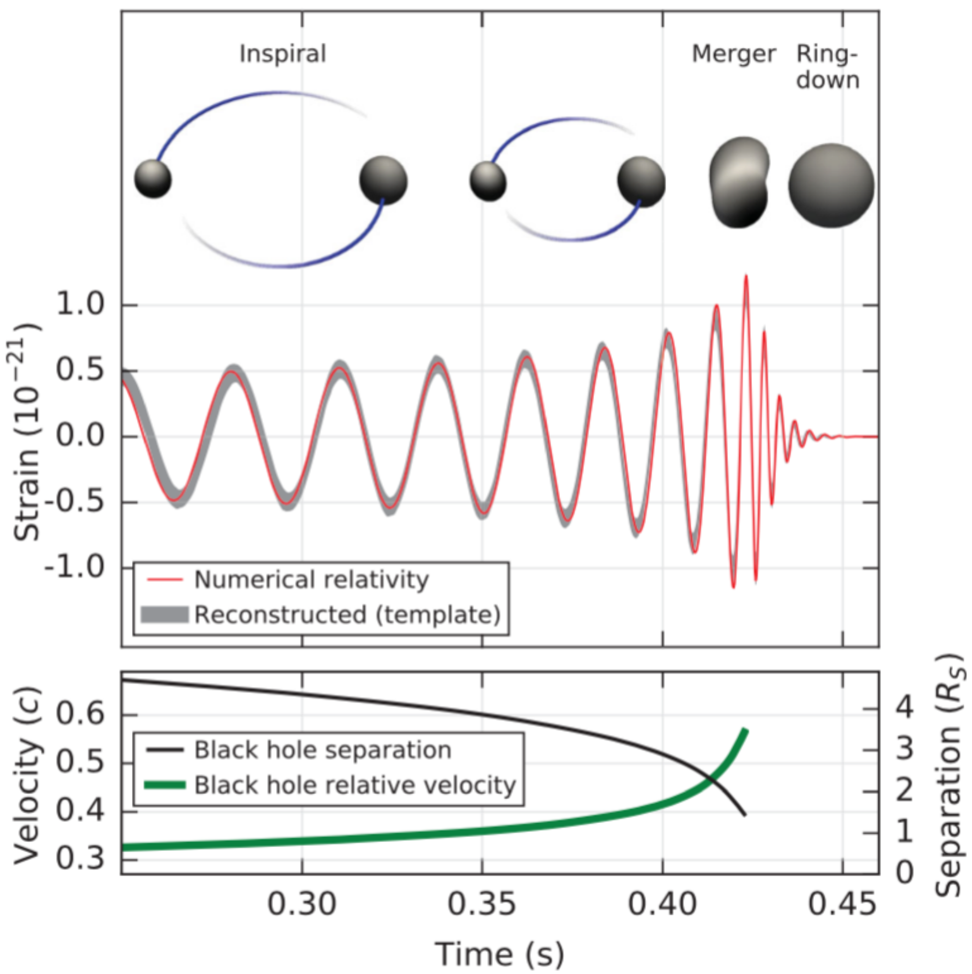


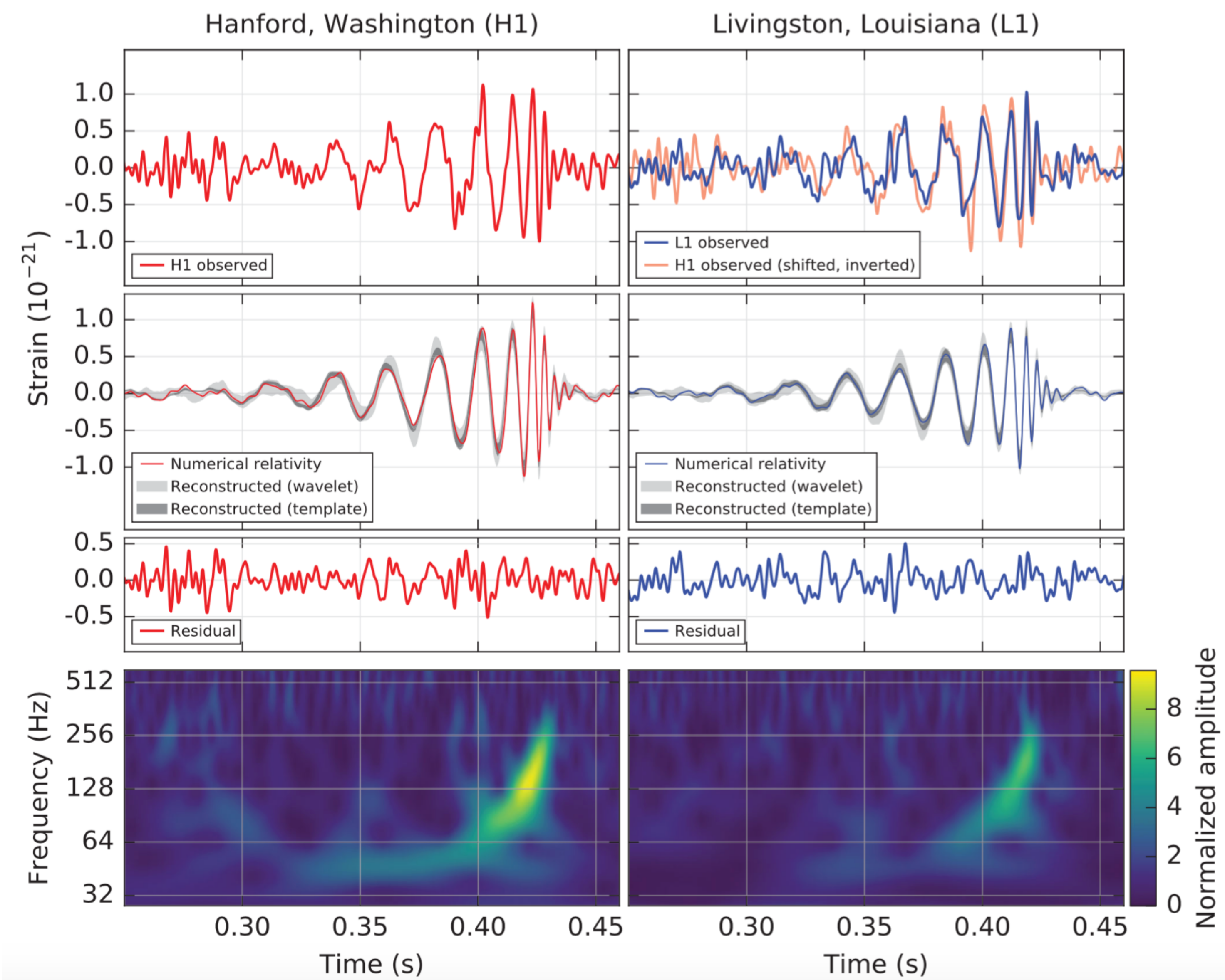




FIRST GRAVITATIONAL WAVE DETECTION

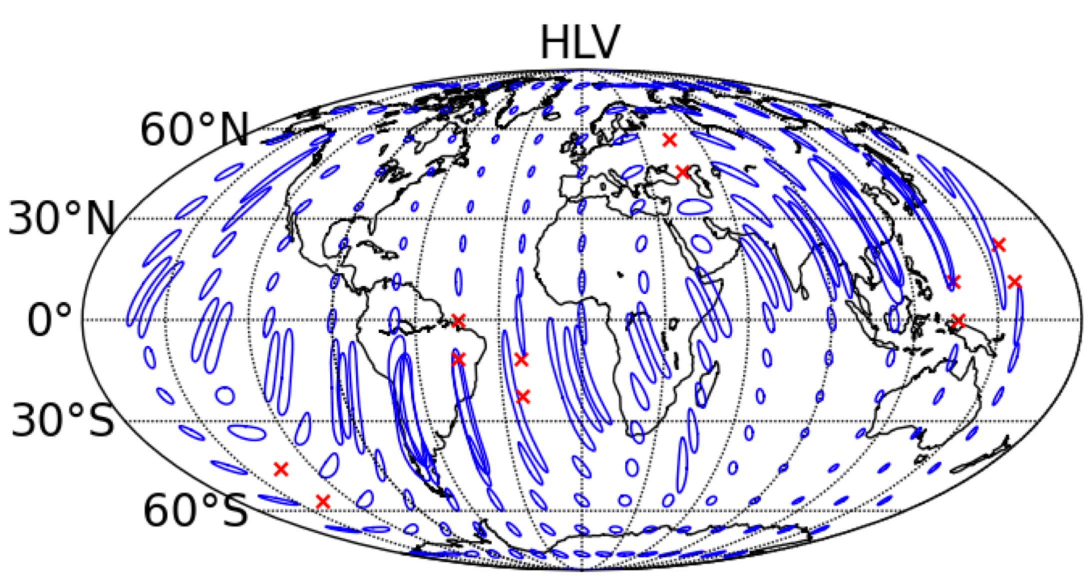
LIGO Scientific Collaboration & Virgo Collaboration, PRL 116, 061102 (2016)

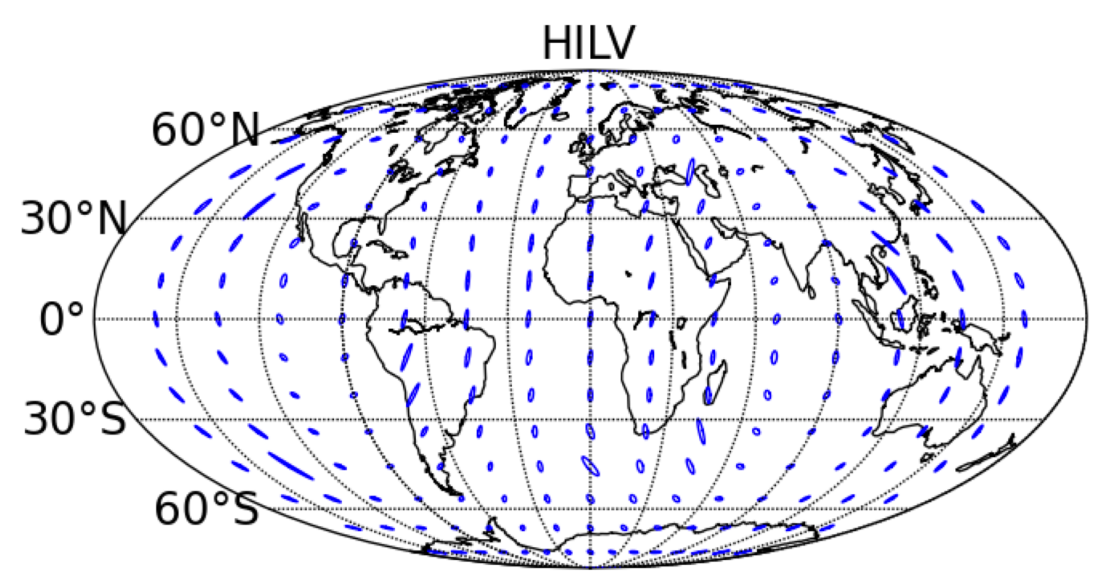




a black hole binary merger!

GW detector network





3 detectors

4 detectors

sky localization (90% confidence level)