

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

Hajime Sotani (NAOJ)

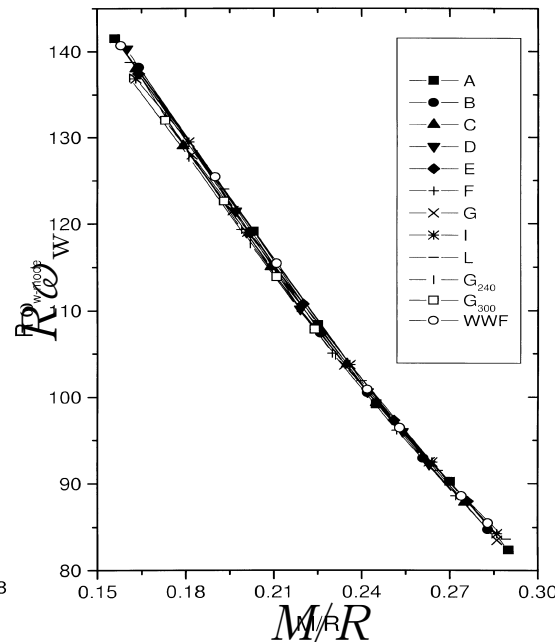
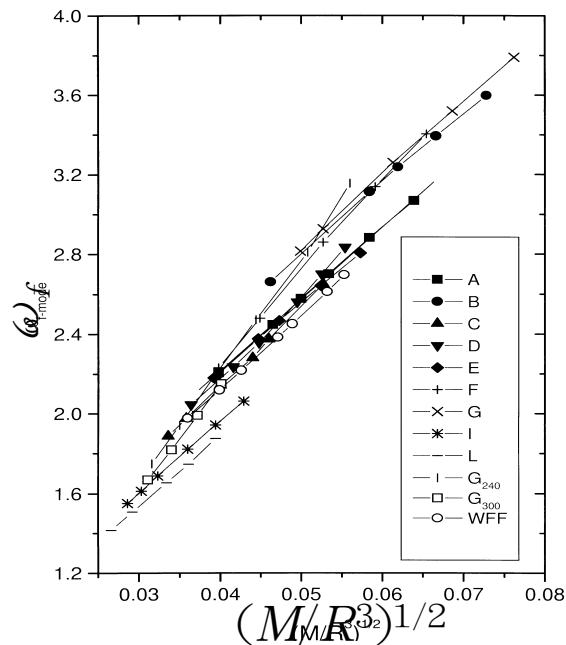
Tomoya Takiwaki (NAOJ)

Gravitational wave asteroseismology

- oscillation spectra are important information for extracting the interior information of star
 - seismology on the Earth
 - helioseismology on the Sun
 - GW asteroseismology on compact stars
- several attempts have been done for cold neutron stars
 - one can get the stellar mass, radius, EOS, and magnetic properties...

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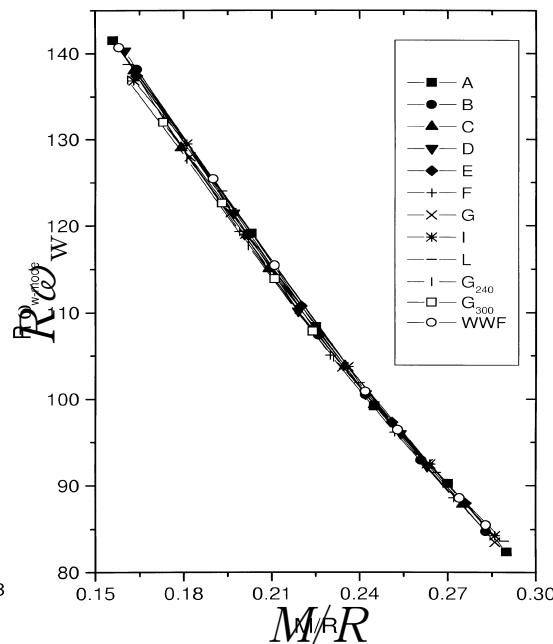
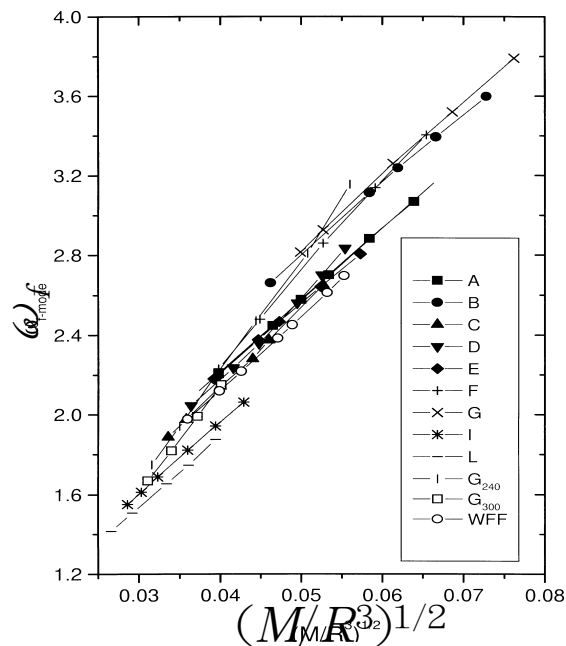
Andersson & Kokkotas (1998)

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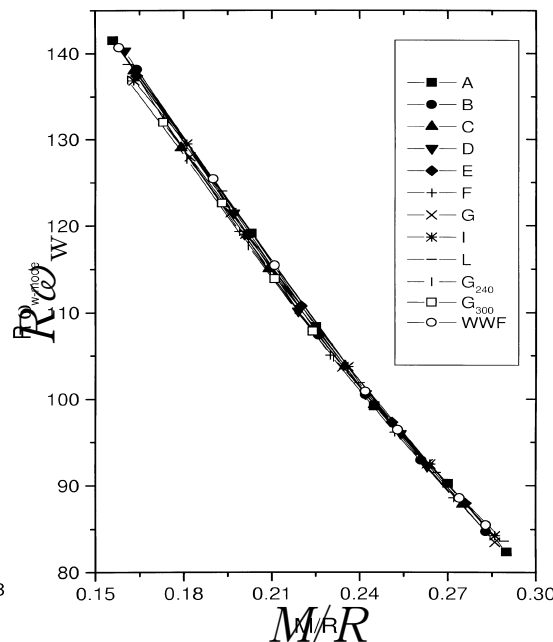
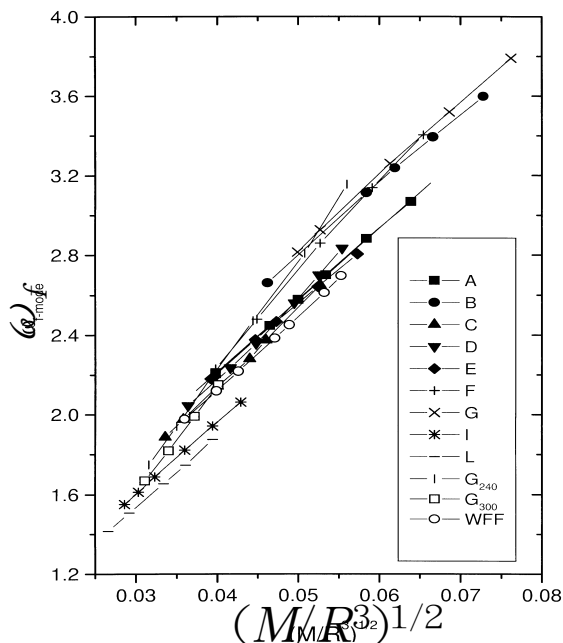
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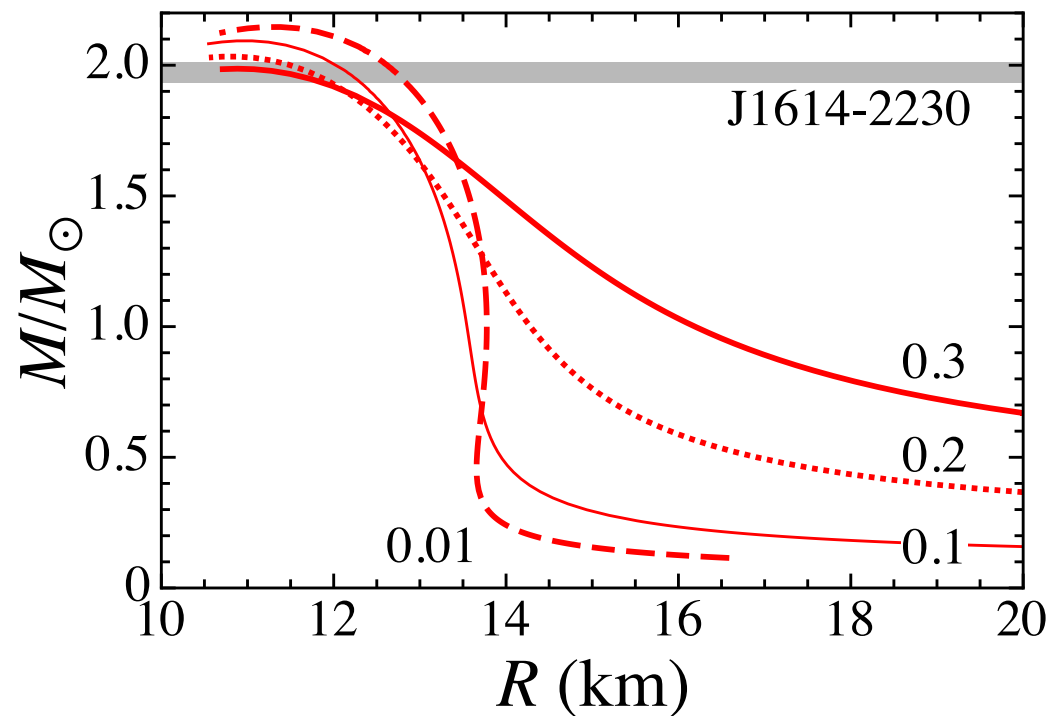
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How about protoneutron stars?

- it could be possible if one can construct stellar models
- Ferrari et al. (2003)

Protoneutron stars (PNSs)

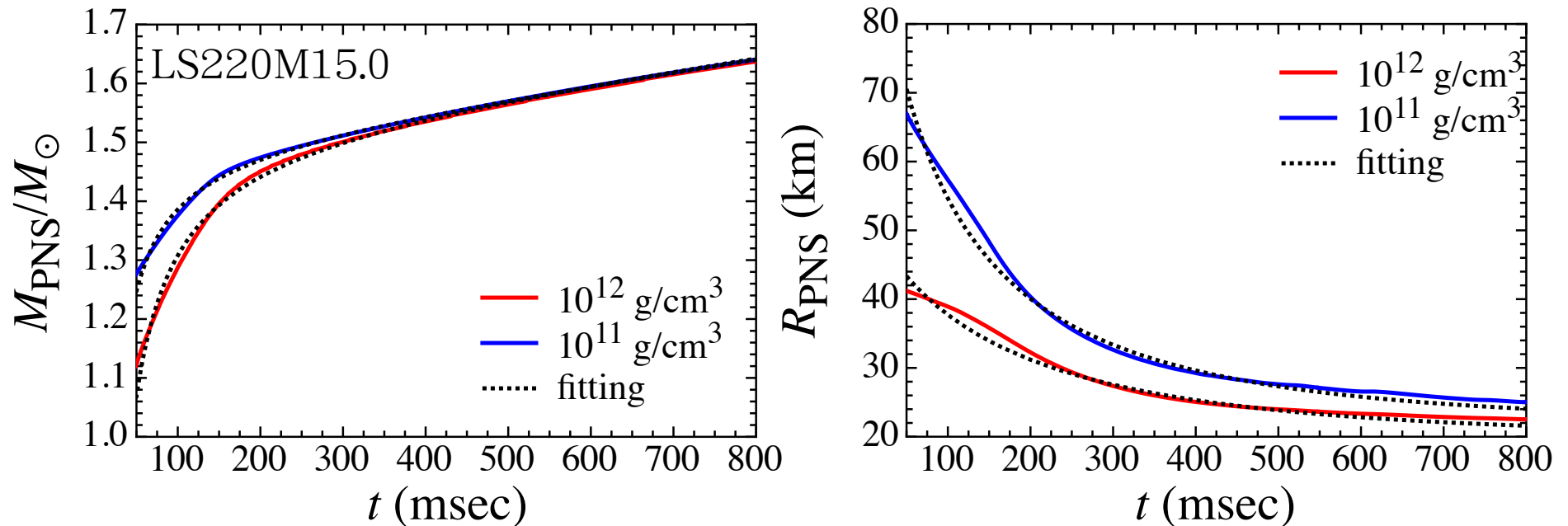
- Unlike cold neutron stars, to construct the PNS models, one has to prepare the profiles of Y_e and s .
 - for example, with LS220 and $s=1.5$ (k_B /baryon), but $Y_e=0.01, 0.1, 0.2$, and 0.3



strategy

- calculate the 1D simulation of core-collapse supernova (by Takiwaki)
 - time evolutions of radius and mass of PNS are determined
 - radius and mass of PNS are fitted by simple formula
- PNS models are constructed in such a way that the radius and mass of PNS are equivalent to the expectation from the fitting
 - with the assumption that the PNS is quasi-static at each time step
 - with the profiles of Y_e and s
- calculate the eigen-frequencies via the eigen-value problems on PNS models
 - dependence of the frequencies on the profiles of Y_e and s
 - dependence on the average density of PNS
 - dependence on the progenitor models
 - LS220 ($M_{\text{pro}}/M_{\odot} = 11.2, 15, 27, 40$), Shen ($M_{\text{pro}}/M_{\odot} = 15$)

evolutions of mass and radius



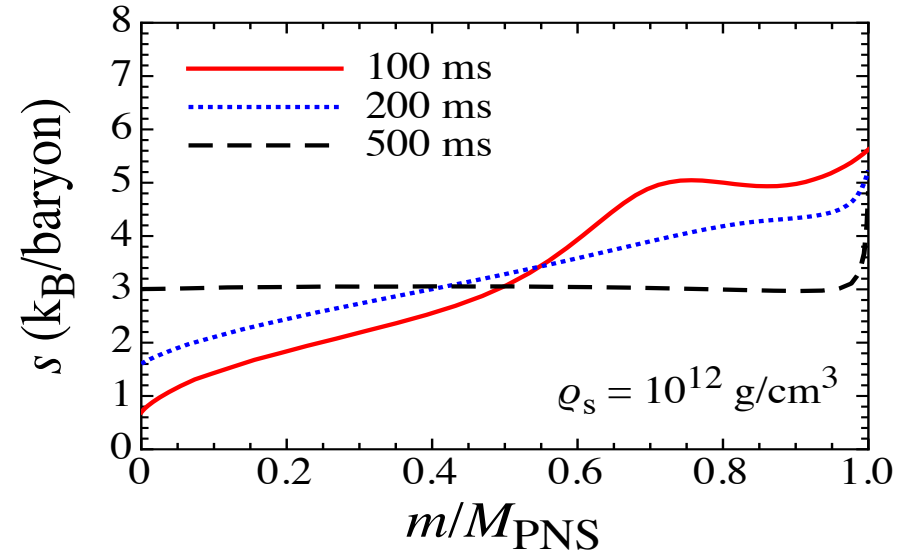
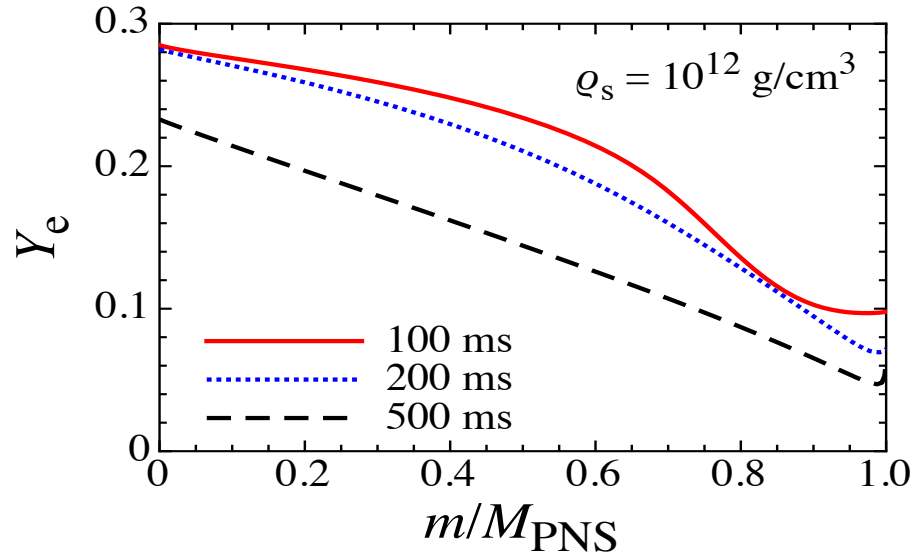
- fitted with

$$R_{\text{PNS}}(t) = \frac{R_i}{1 + [1 - \exp(-\frac{t}{\tau})] \left[\frac{R_i}{R_f} - 1 \right]}$$

$$\frac{M_{\text{PNS}}(t)}{M_{\odot}} = \frac{c_0}{t} + c_1 t + c_2$$

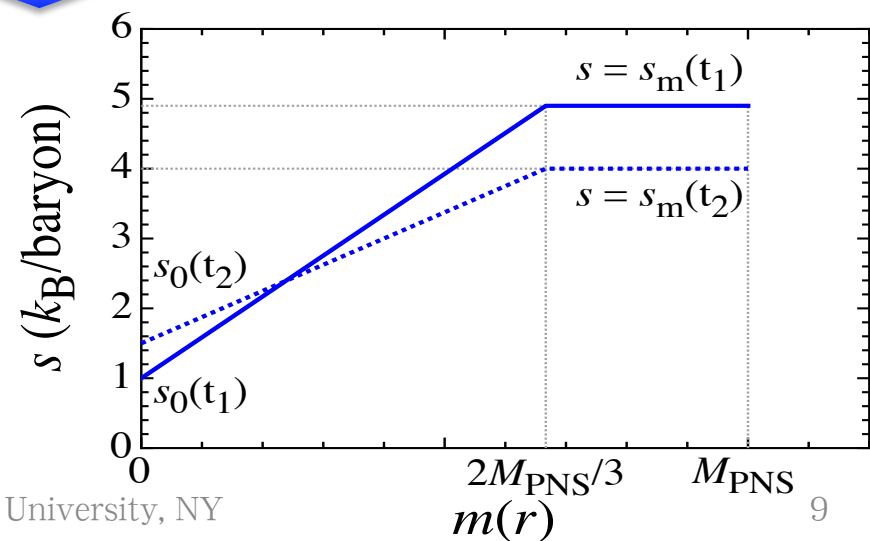
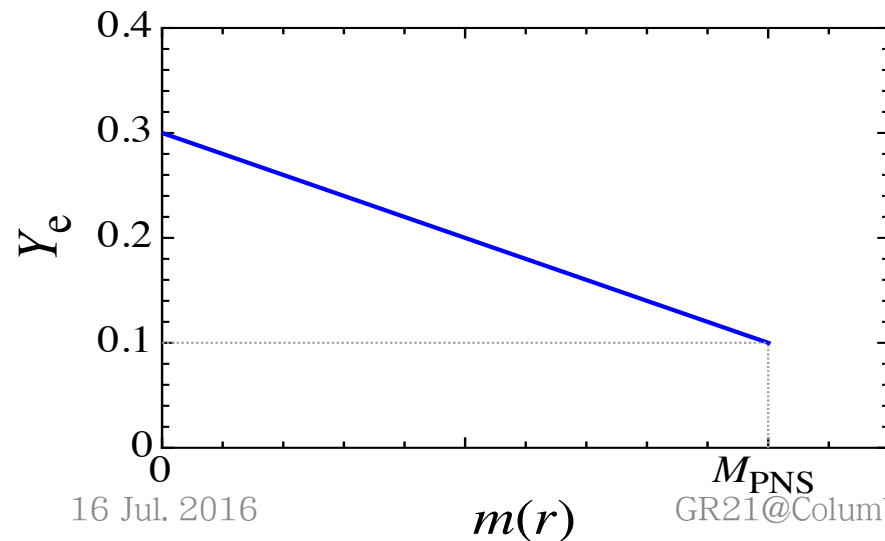
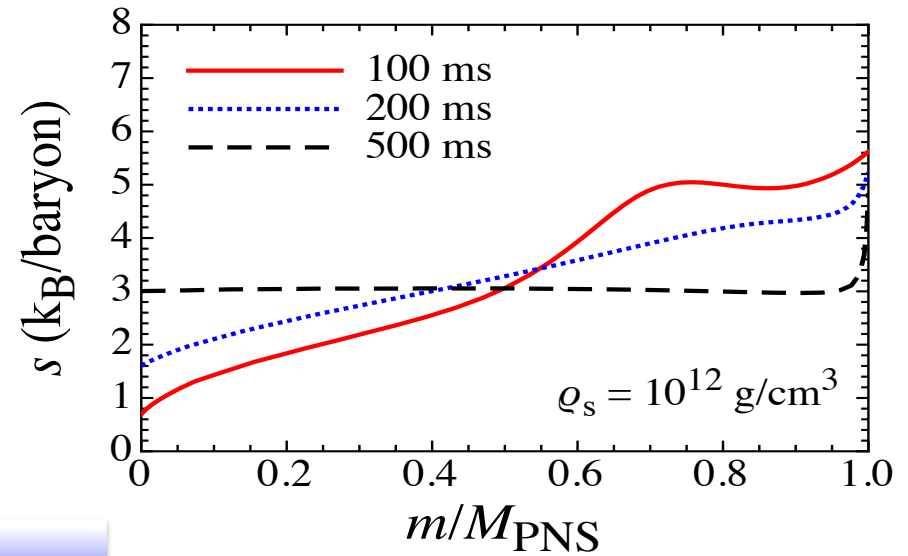
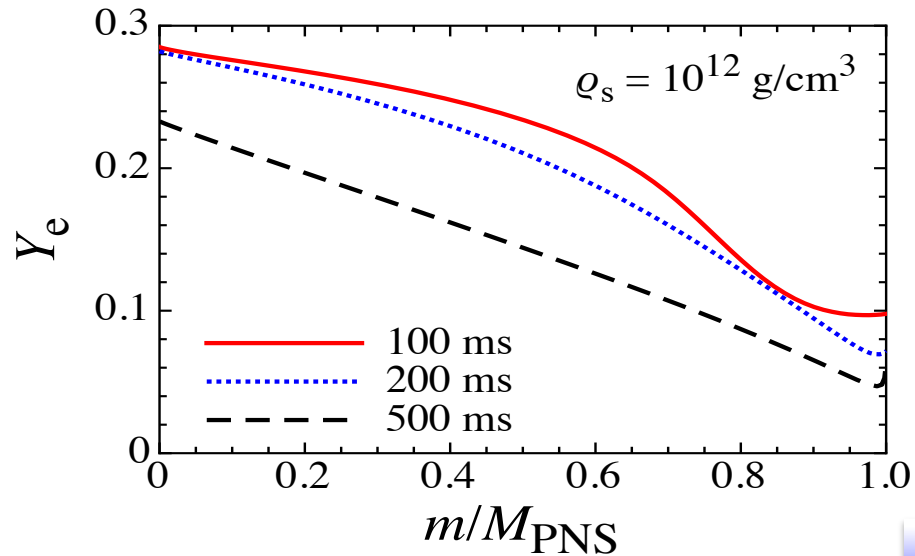
Y_e and s profiles

- the snap shot at $t=100, 200,$ and 500 ms after bounce



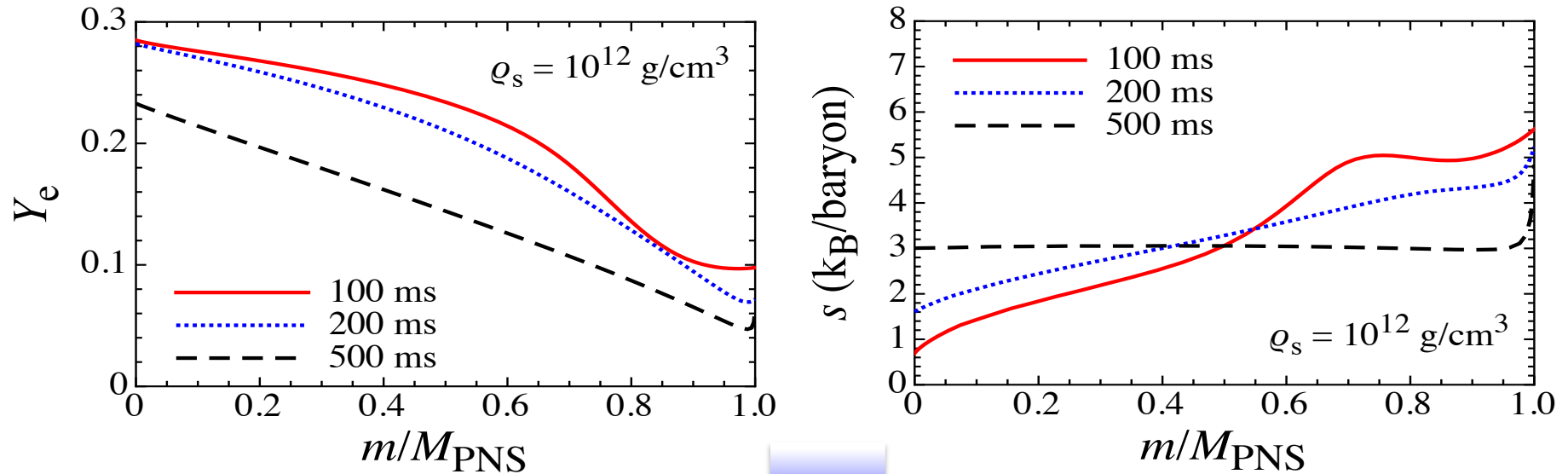
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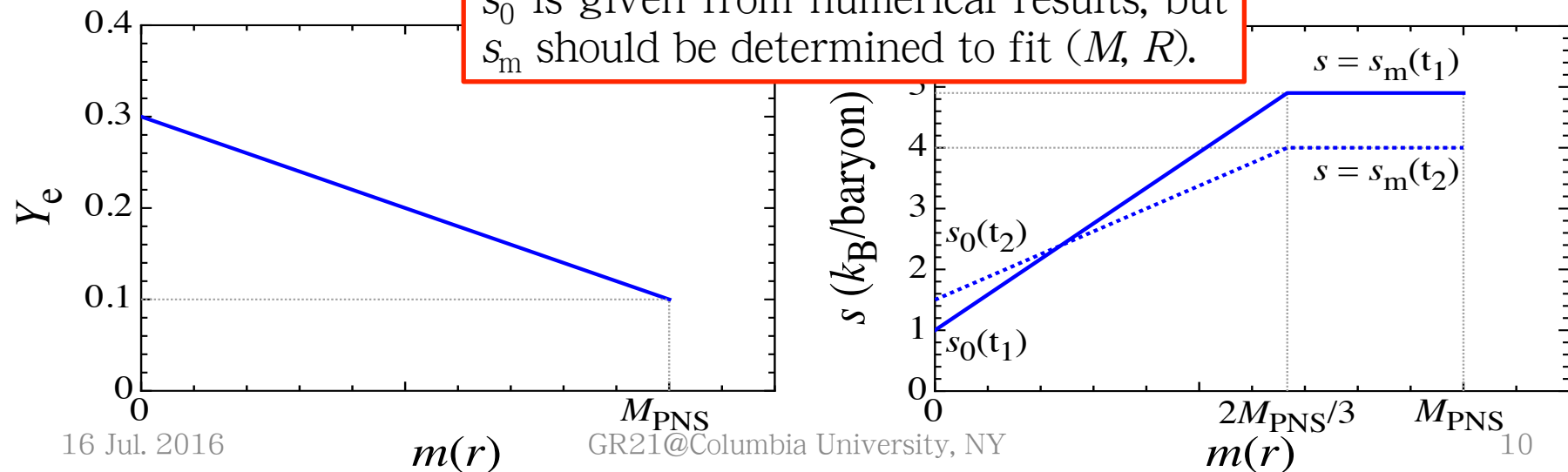


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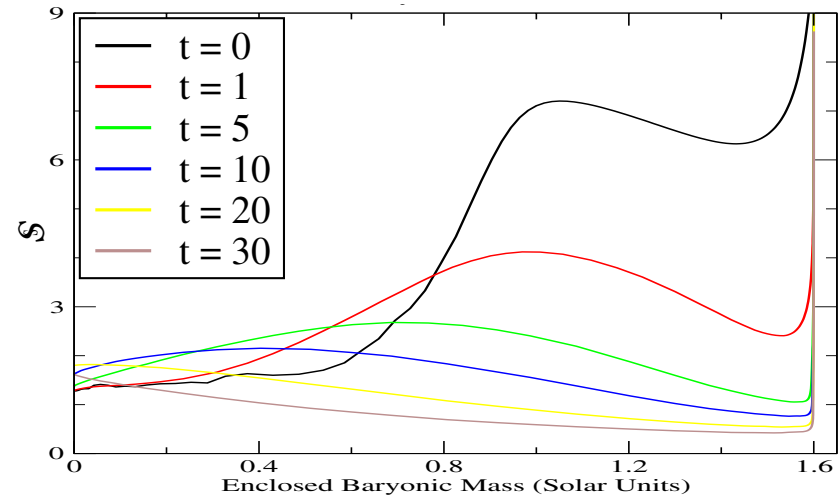
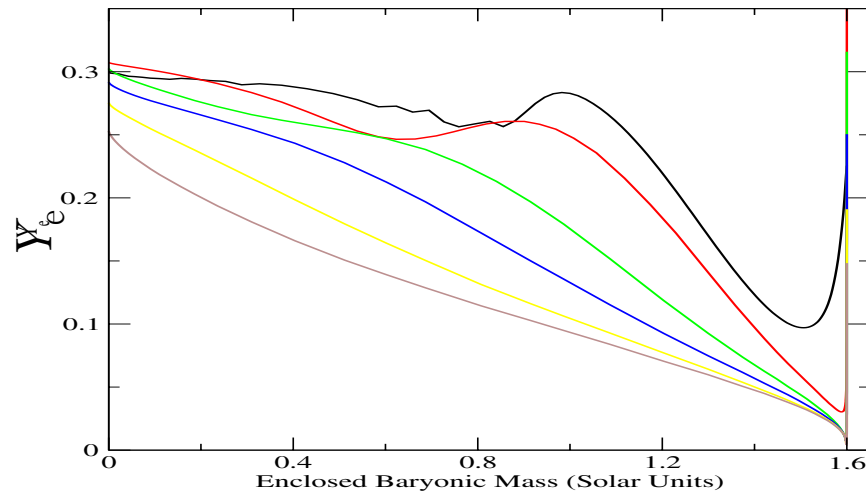


s_0 is given from numerical results, but s_m should be determined to fit (M, R) .



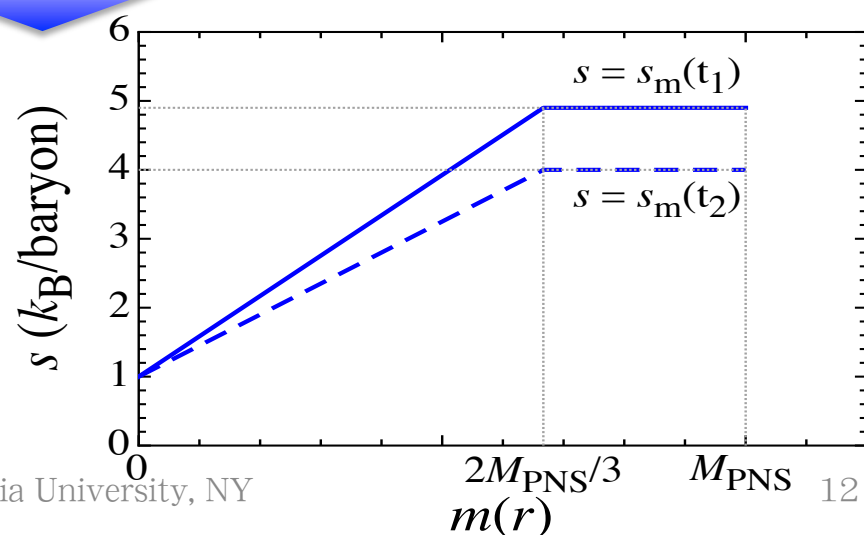
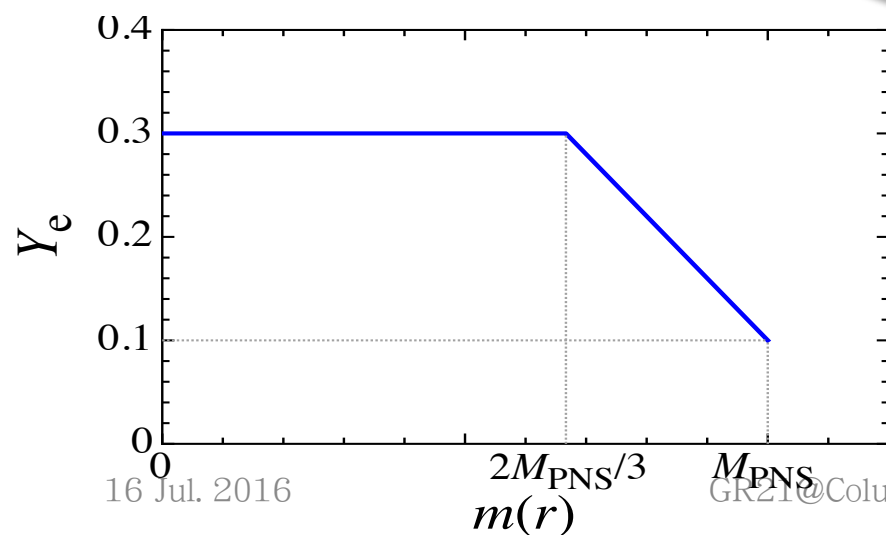
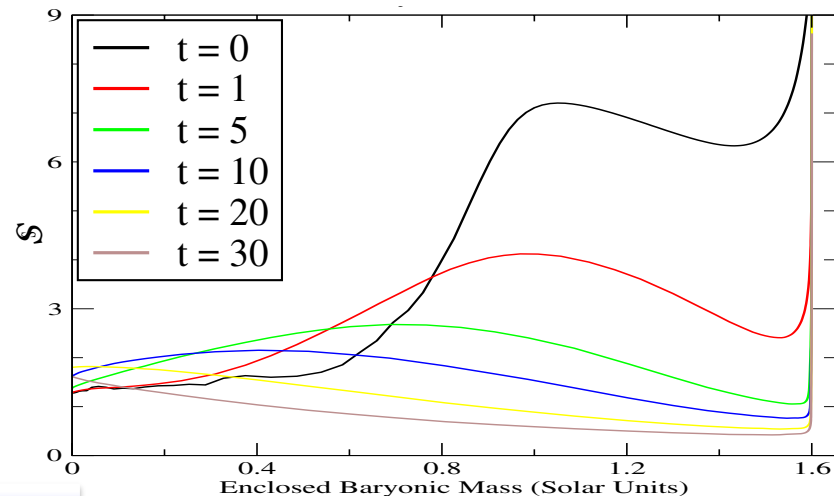
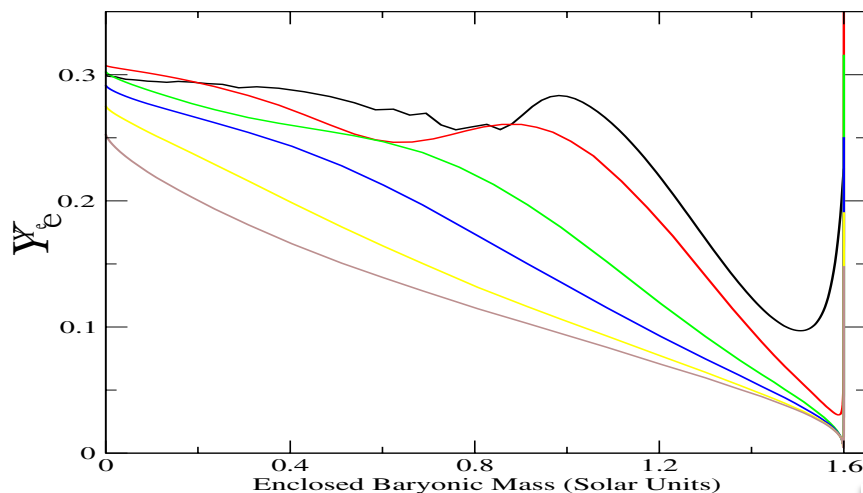
comparison with other results

- results by Roberts (2012), where he has done the 1D simulations for long-term.



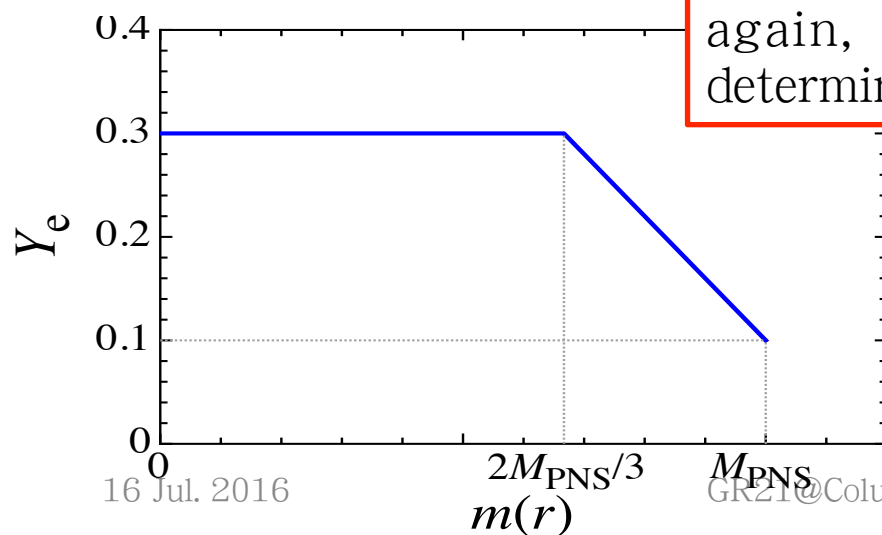
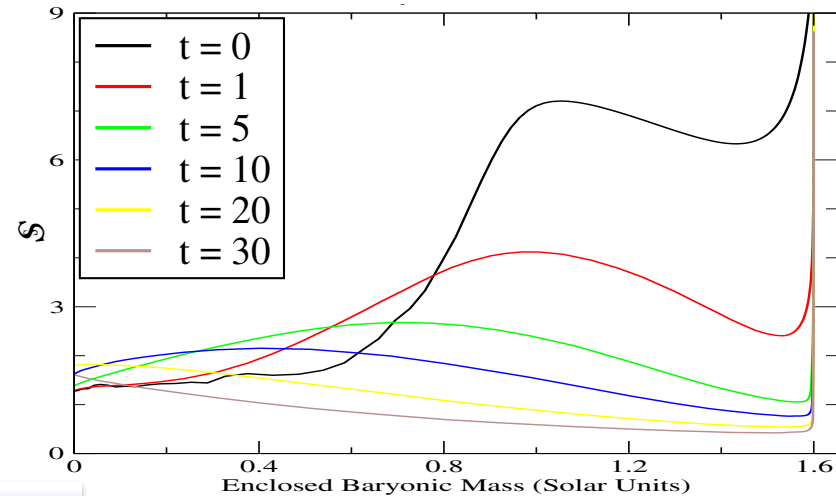
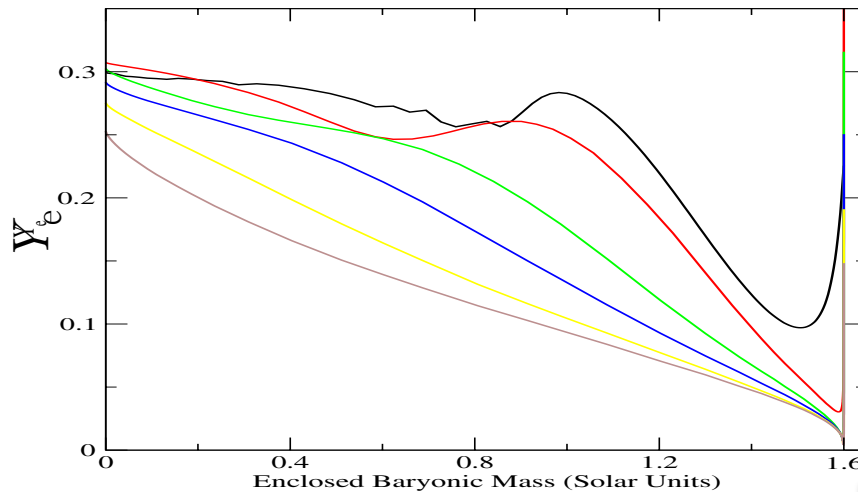
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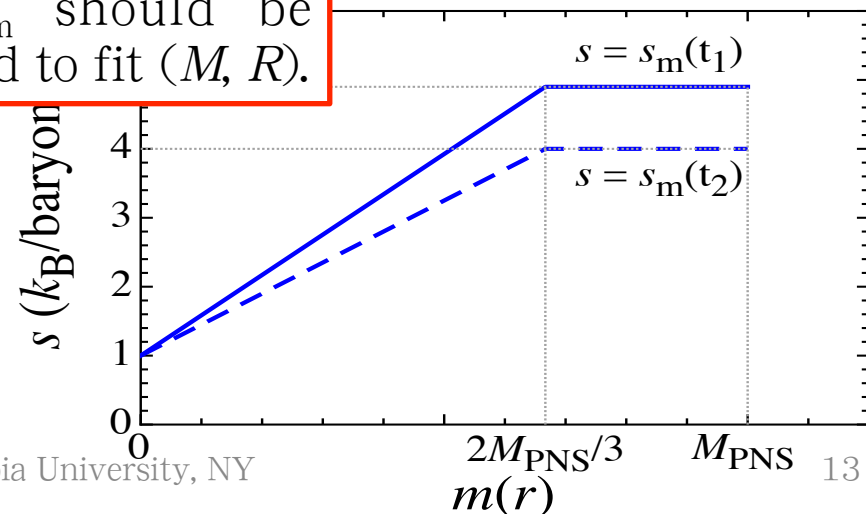


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again, s_m should be determined to fit (M, R) .

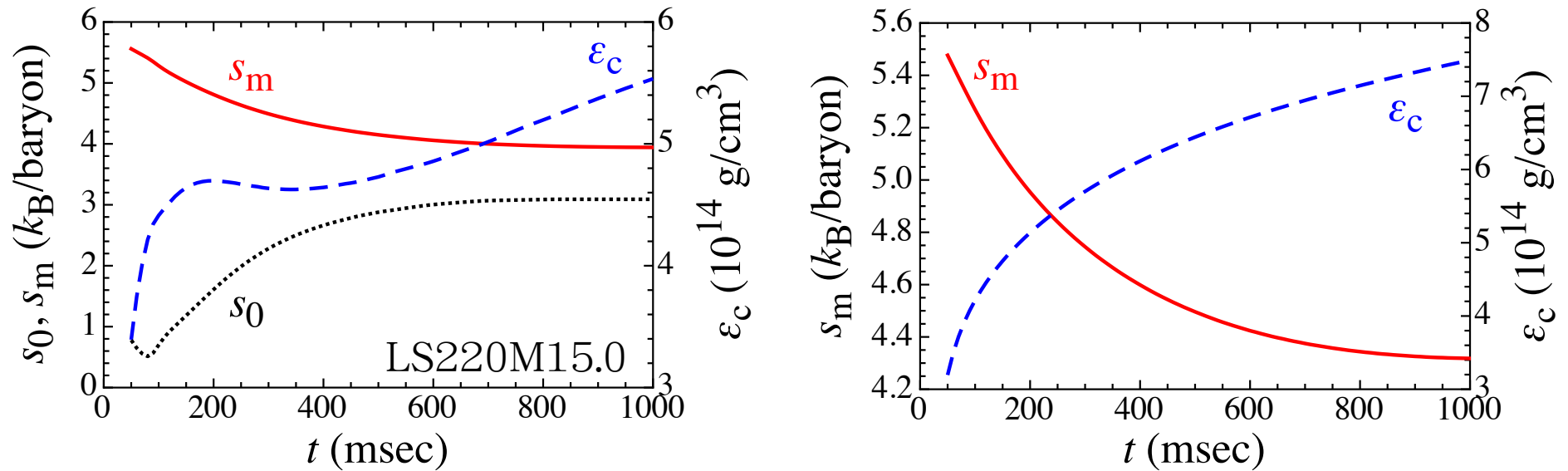


PNS models

- adopting two different profiles of Y_e and s inside the PNS, we construct the PNS models.
 - unknown parameter: ε_c & s_m
 - to reproduce the PNS models with given (M, R) , ε_c and s_m are fixed.

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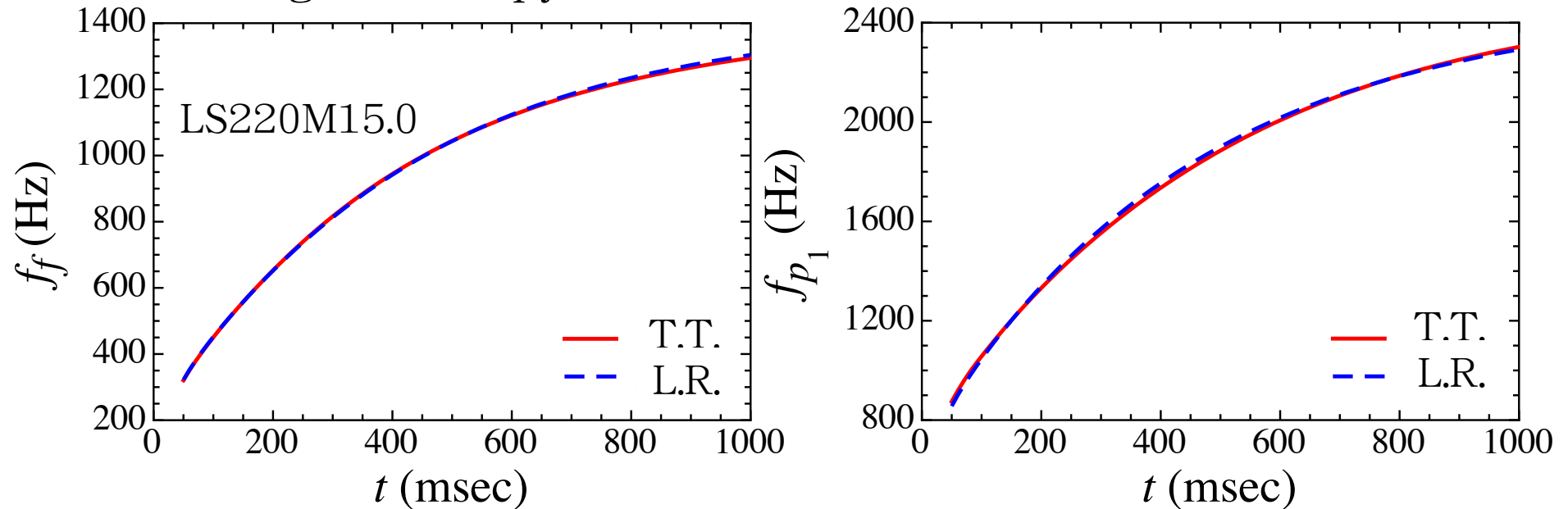
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- evolutions of ε_c and s_m depend strongly on the profiles of Y_e and s .

oscillations in PNS

- with relativistic Cowling approximation
- omitting the entropy variation



- frequencies depend on mass and radius of PNS, but weakly depend on (Y_e, s) profiles.
- in the early stage, the typical frequencies of f -mode is \sim a few hundred hertz, which is good for gravitational wave detectors.

characterized by average density

- frequencies of f-mode for cold neutron stars:

$$f_f^{(\text{NS})} \text{ (kHz)} \approx 0.78 + 1.635 \left(\frac{M}{1.4M_\odot} \right)^{1/2} \left(\frac{R}{10 \text{ km}} \right)^{-3/2}$$

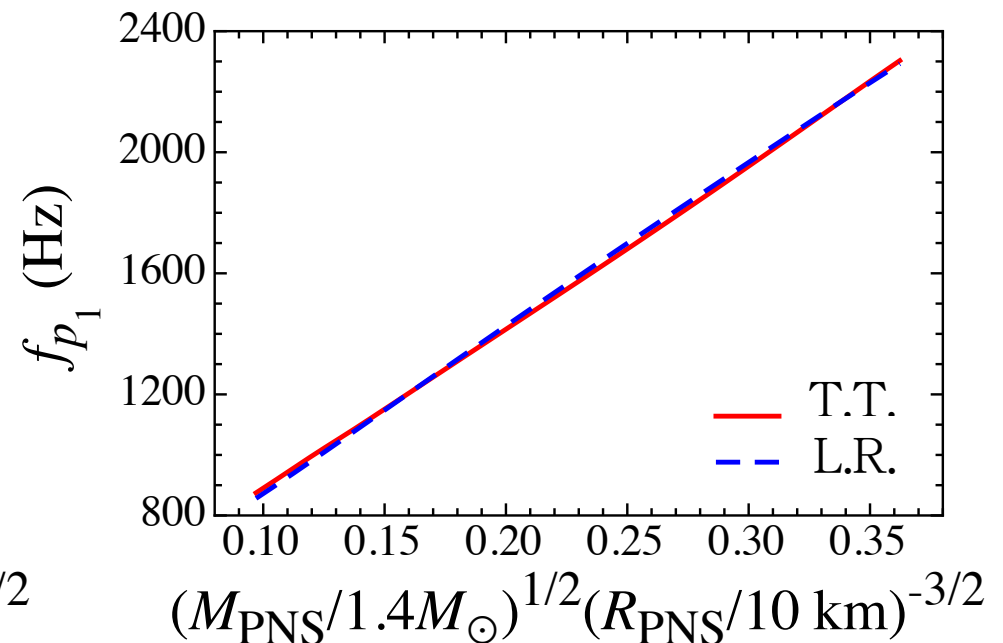
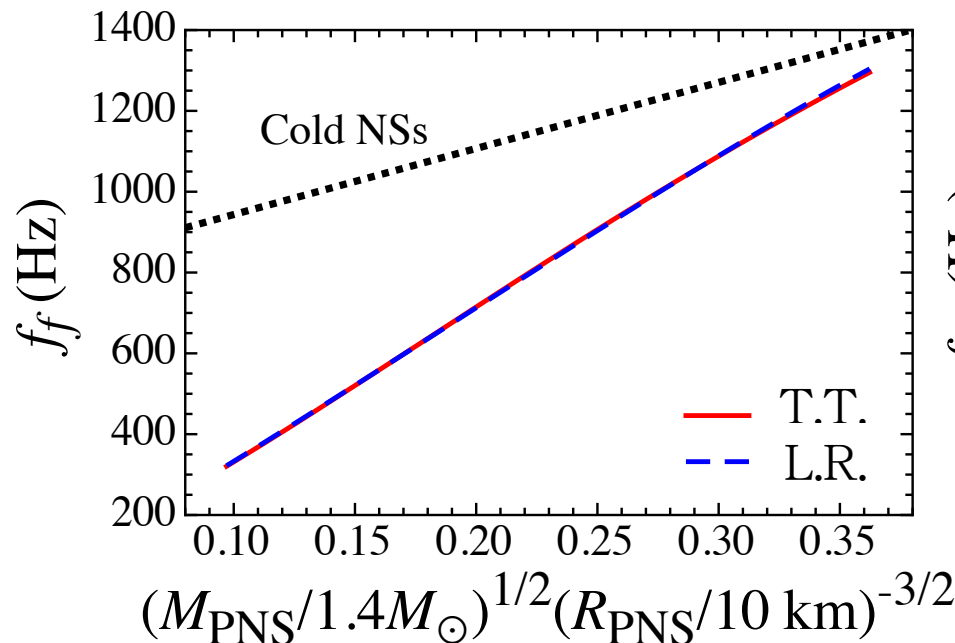
Andersson & Kokkotas (1998)

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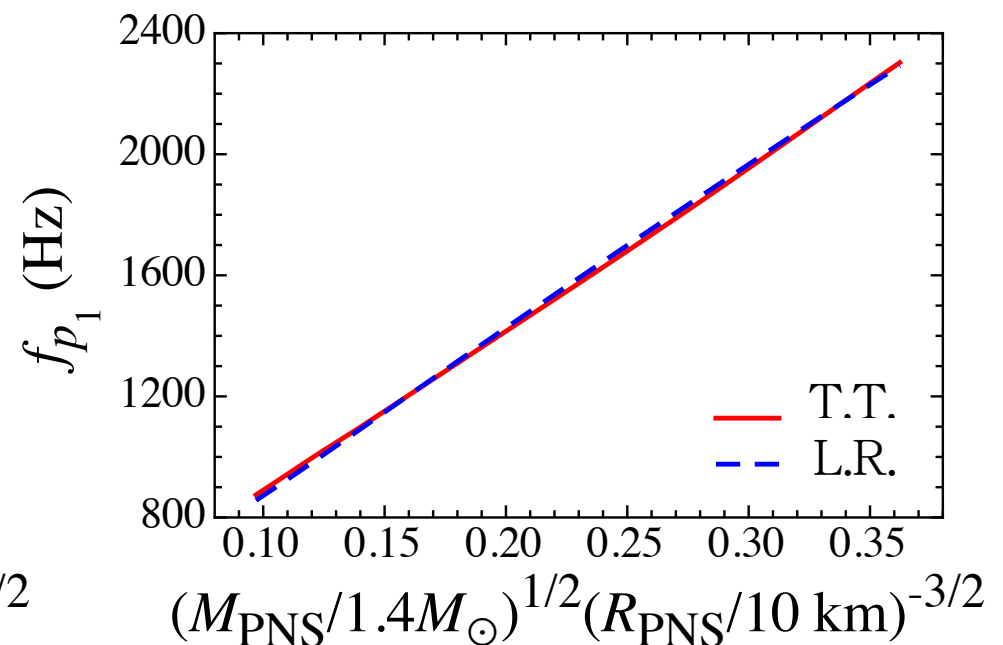
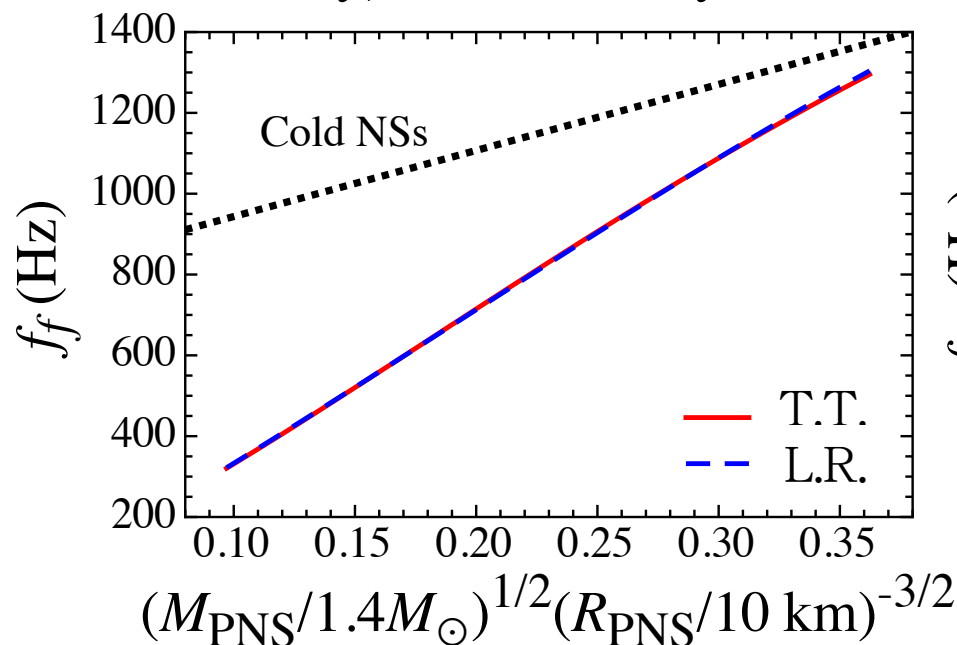
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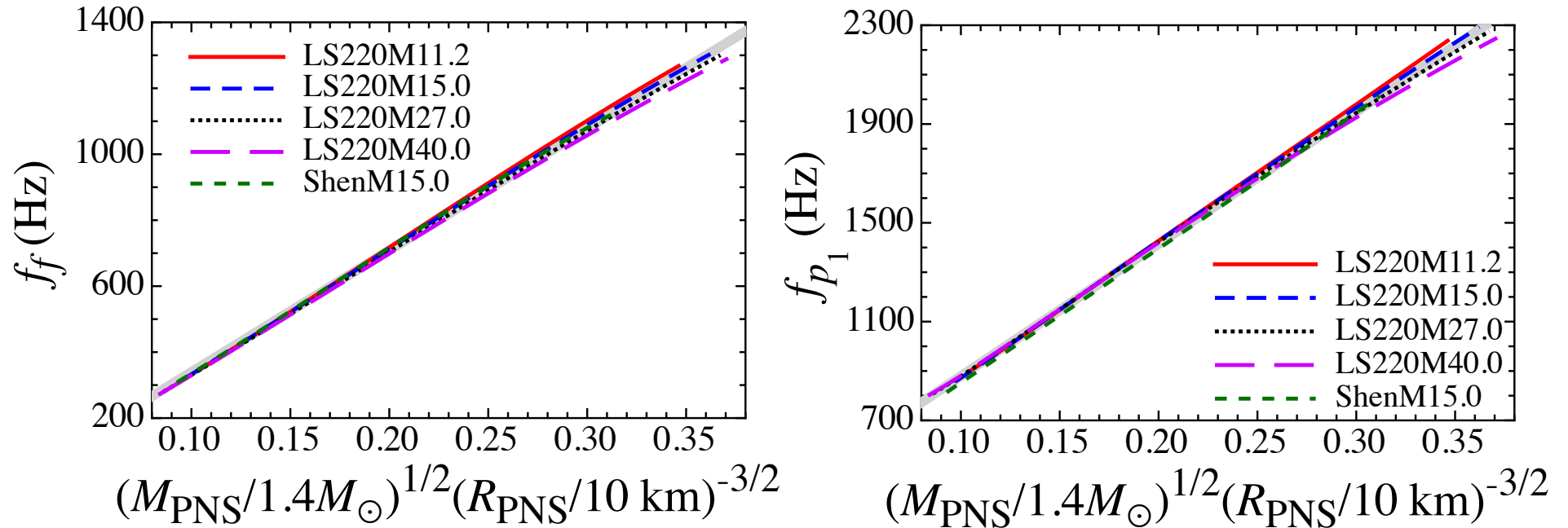
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- Similarly, frequencies for PNS can be characterized by average density, but obviously different from those for neutron stars.



dependence on progenitor models

- results for LS220 with $M_{\text{pro}}/M_{\odot}=11.2, 15, 27, \text{ and } 40$, for Shen with $M_{\text{pro}}/M_{\odot}=15$



- progenitor model dependence is quite weak.

$$f_i^{(\text{PNS})} (\text{Hz}) \approx c_i^0 + c_i^1 \left(\frac{M_{\text{PNS}}}{1.4M_{\odot}} \right)^{1/2} \left(\frac{R_{\text{PNS}}}{10 \text{ km}} \right)^{-3/2}$$

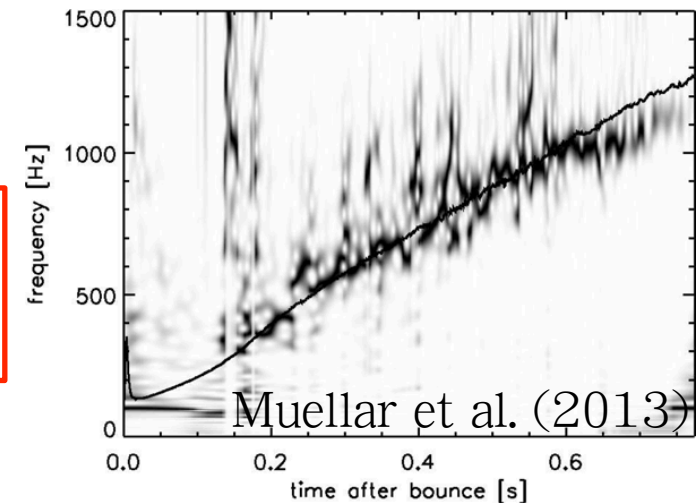
comparison with g-modes

- as characteristic GWs from core-collapse supernova, [the excitation of g-modes around PNS has been reported](#) (Muellar et al. (2013); Cerda-Duran et al. (2013))
 - due to the convection and the standing accretion-shock instability.

$$f_g \approx \frac{1}{2\pi} \frac{GM_{\text{PNS}}}{R_{\text{PNS}}^2} \left(\frac{1.1m_n}{\langle E_{\bar{\nu}_e} \rangle} \right)^{1/2} \left(1 - \frac{GM_{\text{PNS}}}{c^2 R_{\text{PNS}}} \right)^2$$

m_n : neutron mass
 $\langle E_{\bar{\nu}_e} \rangle$: mean energy of electron antineutrinos

Muellar et al. (2013)



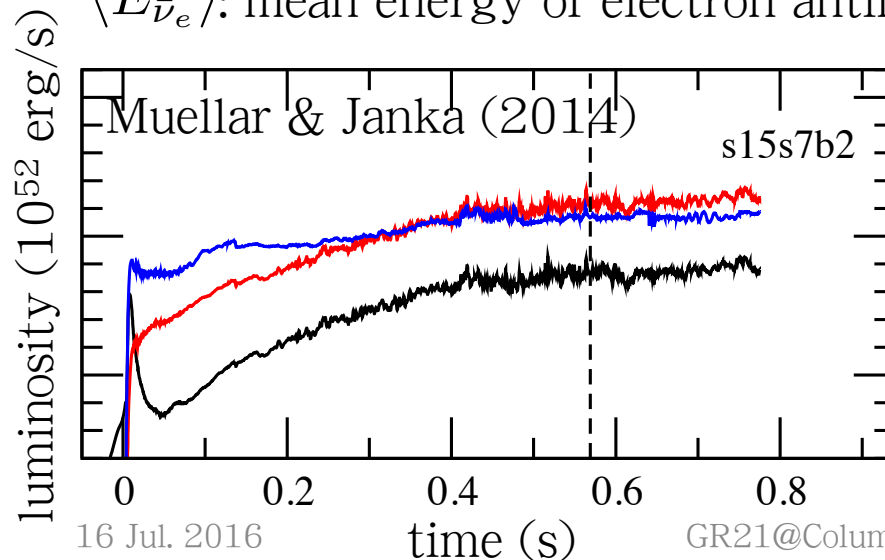
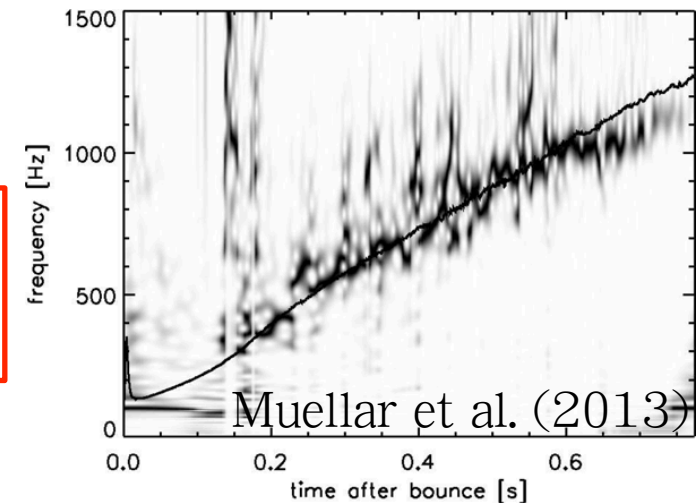
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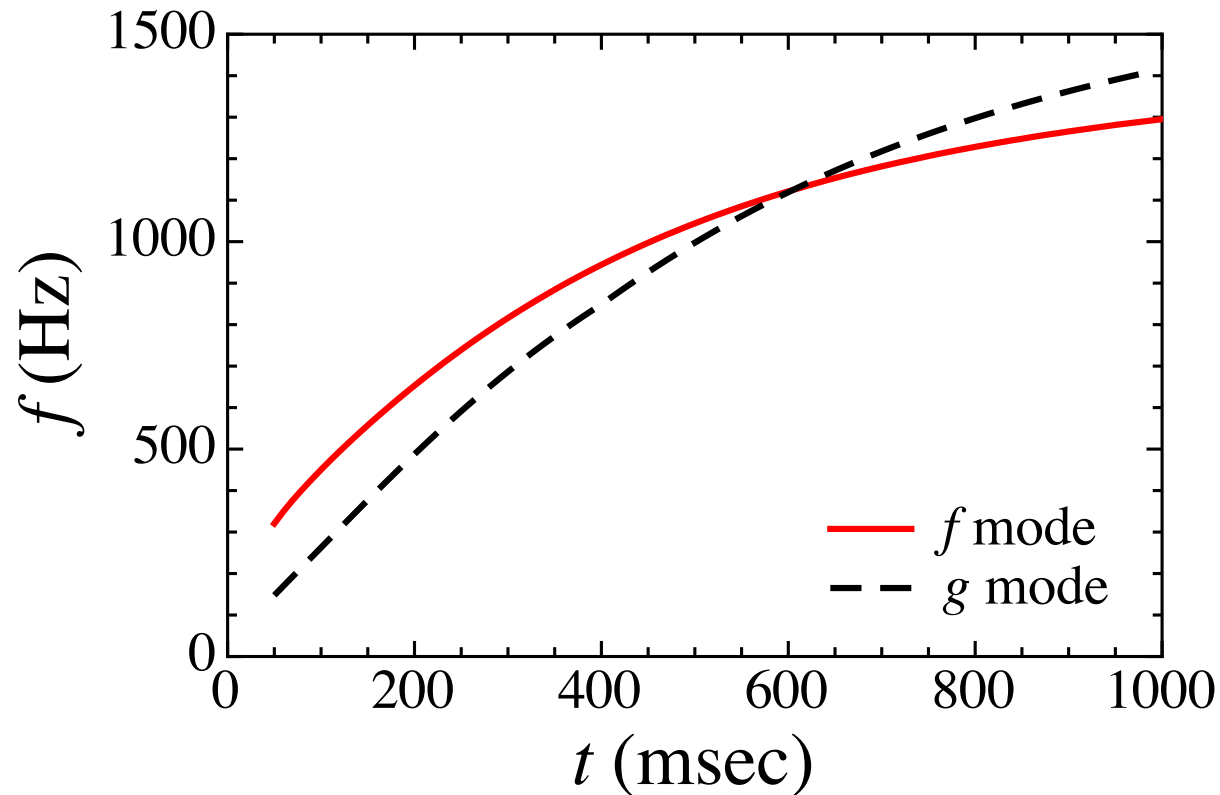


black: electron neutrinos
 red: electron antineutrinos
 blue: μ / τ neutrinos

$$\langle E_{\bar{\nu}_e} \rangle = \begin{cases} 3t/400 + 13 & (0 \leq t \leq 400 \text{ msec}) \\ 16 & (400 \text{ msec} \leq t) \end{cases}$$

comparison with g-modes

- careful observing the gravitational wave spectra after core-collapse supernova, one might see the different sequences in spectra
 - which tells us the radius and mass of PNS



conclusion

- We examine the frequencies of gravitational waves radiating from PNS after bounce.
- The PNS models are constructed in such a way that the mass and radius obtained from 1D simulation are reconstructed.
 - two different profiles of Y_e and s are considered
- frequencies of gravitational waves are almost independent from the profiles of Y_e and s , but sensitive to the mass and radius.
 - characterized by average density
 - different from that expected for cold neutron stars
- progenitor dependence is quite weak.
 - find an universal relation for frequencies of f - and p -modes as a function of average density
 - different dependence for g -mode around PNS
- one might be possible to determine the mass and radius of PNS via careful observations of time evolution of gravitational wave spectra.

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t
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