Asteroseismology with protoneutron stars

Hajime Sotani (NAOJ)
Tomoya Takiwaki (NAOJ)

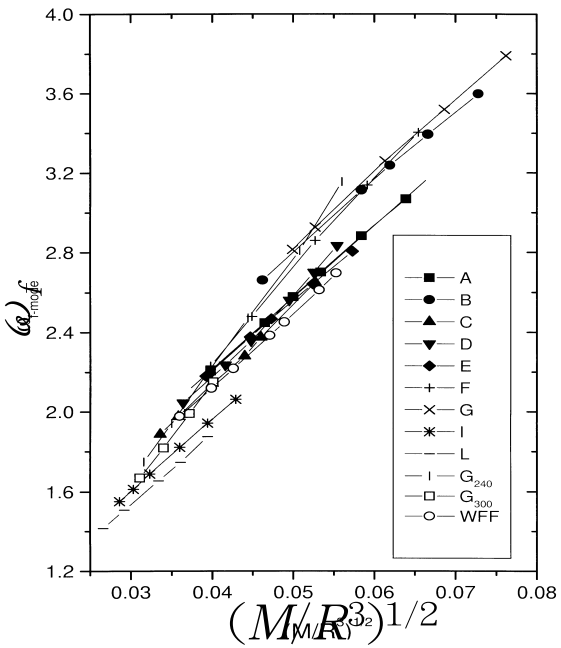
Gravitational wave asteroseismology

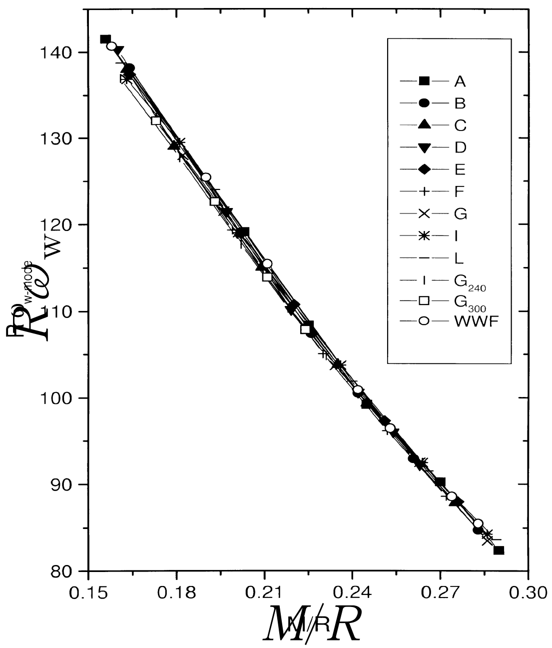
- oscillation spectra are important information for extracting the interior information of star
  - seismology on the Earth
  - helioseismology on the Sun

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

ars

c properties…





via the observations of f and w mode oscillations, one could determine the M and R *within ~10% accuracy.*

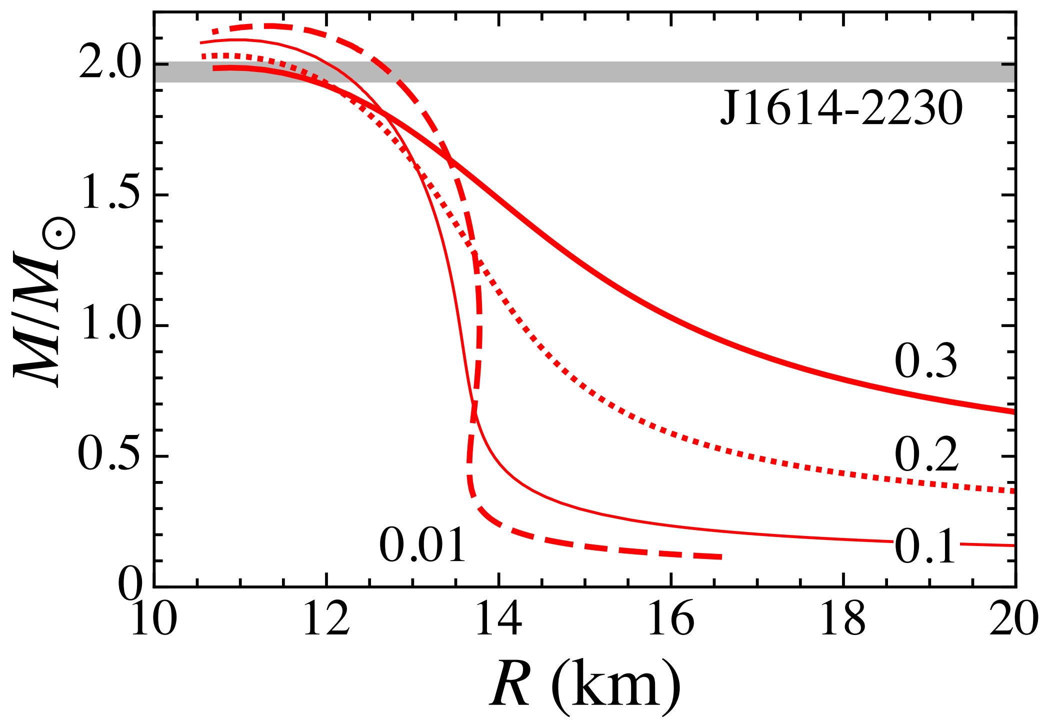
Andersson & Kokkotas (1998)

How about protoneutron stars?

- it could be possible if one can construct stellar models

Protoneutron stars (PNSs)

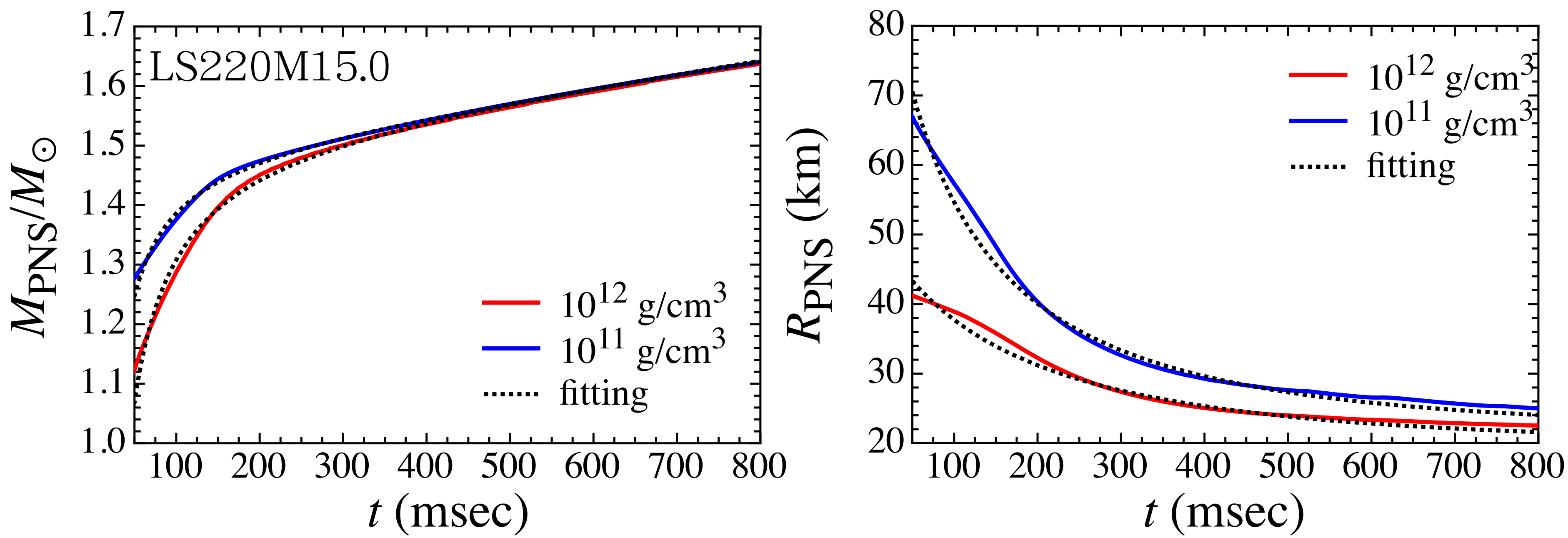
- Unlike cold neutron stars, to construct the PNS models, one has to prepare the profiles of Y_e and s.
  - for example, with LS220 and s =1.5 (k_B/baryon), but Y_e =0.01, 0.1, 0.2, and 0.3



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 ($M_{pro}/M_\odot$ = 11.2, 15, 27, 40), Shen ($M_{pro}/M_\odot$ = 15)

evolutions of mass and radius



- fitted with

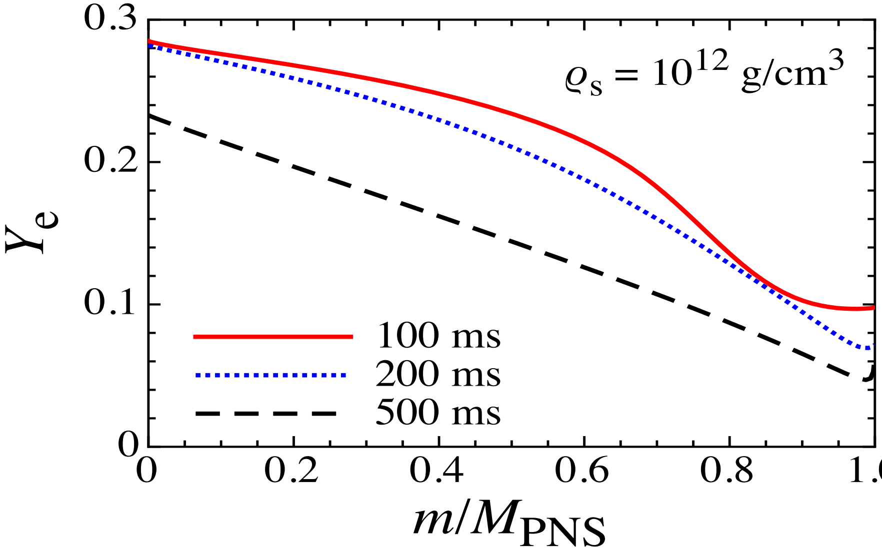
$$R_{\rm PNS}(t) = \frac{R_{\rm i}}{1 + \left[1 - \exp(-\frac{t}{\tau})\right]\left[\frac{R_{\rm i}}{R_{\rm f}} - 1\right]}$$

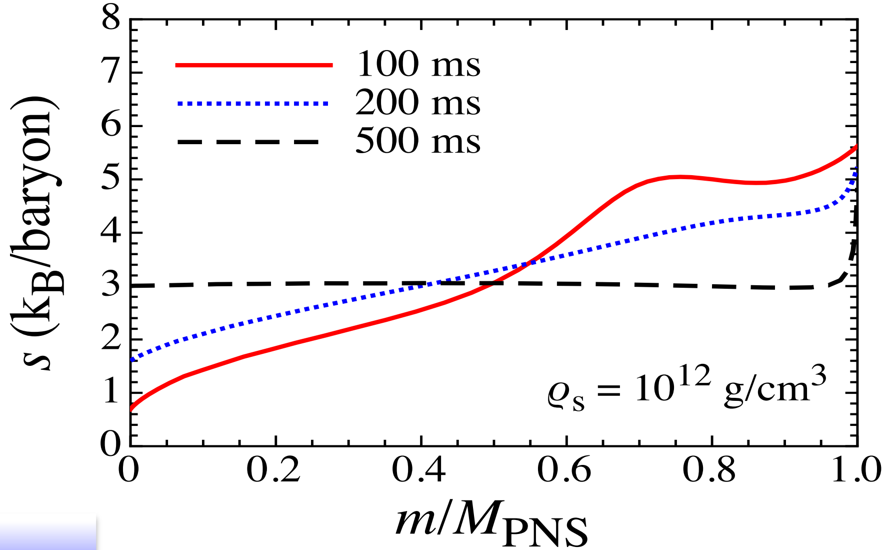
$$\frac{M_{\rm PNS}(t)}{M_\odot} = \frac{c_0}{t} + c_1 t + c_2$$

Scheck et al. (2006)

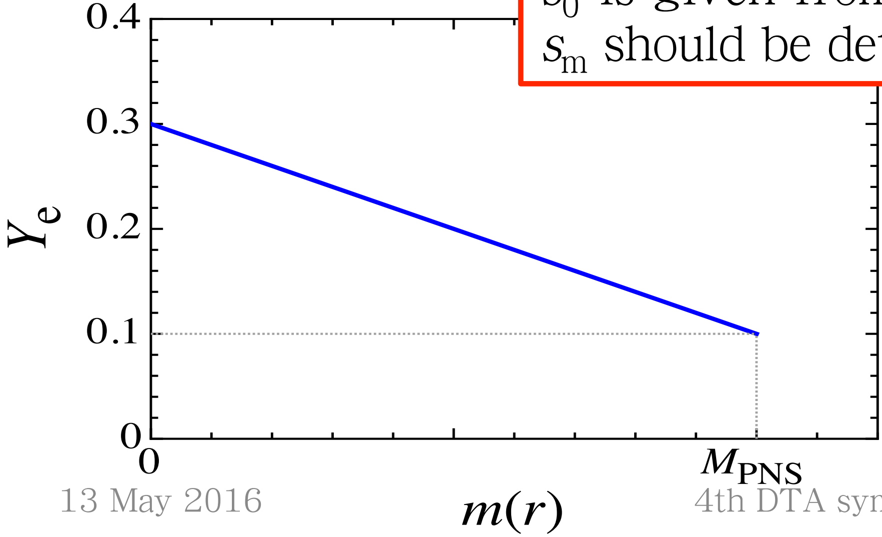
Y_e and s profiles

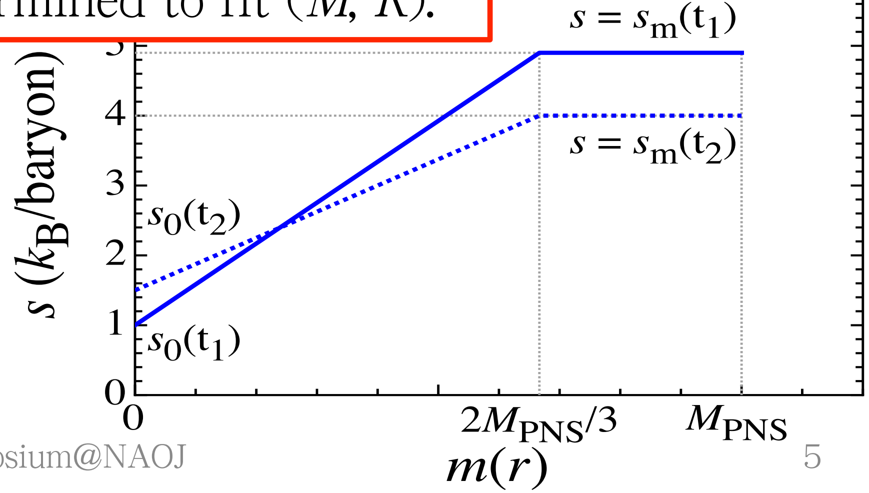
- the snap shot at t=100, 200, and 500ms after bounce





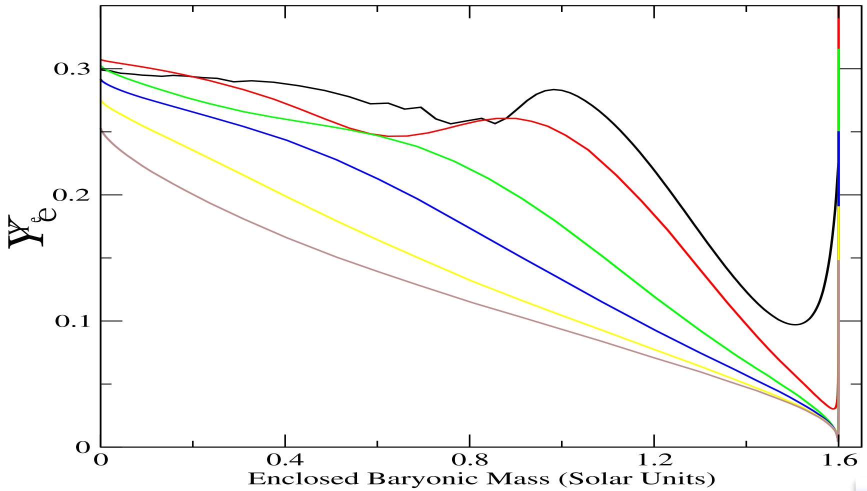
s_0 is given from numerical results, but s_m should be determined to fit (M, R).

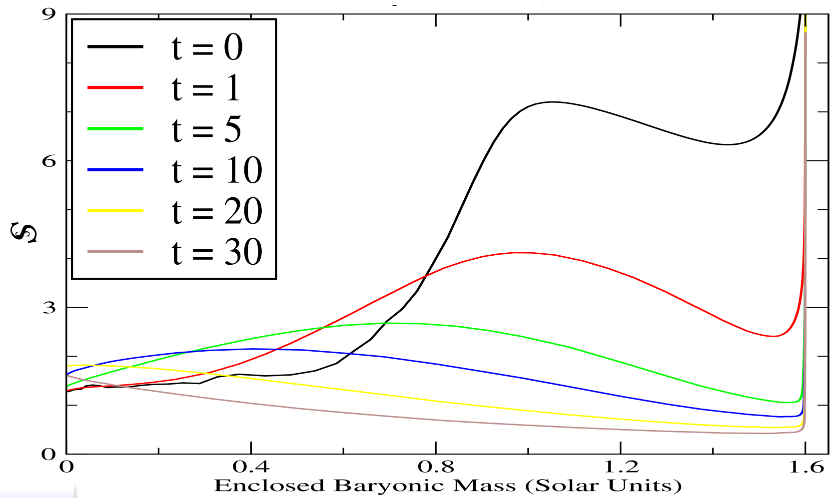




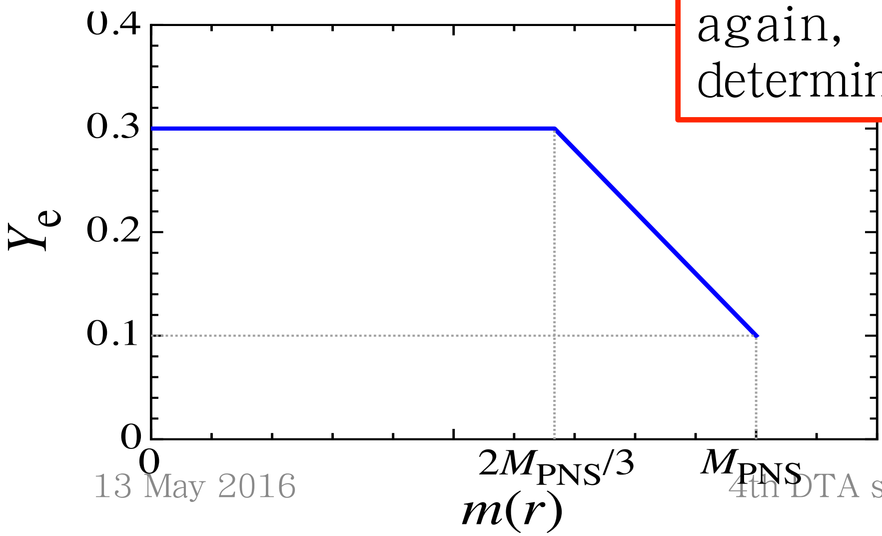
comparison with other results

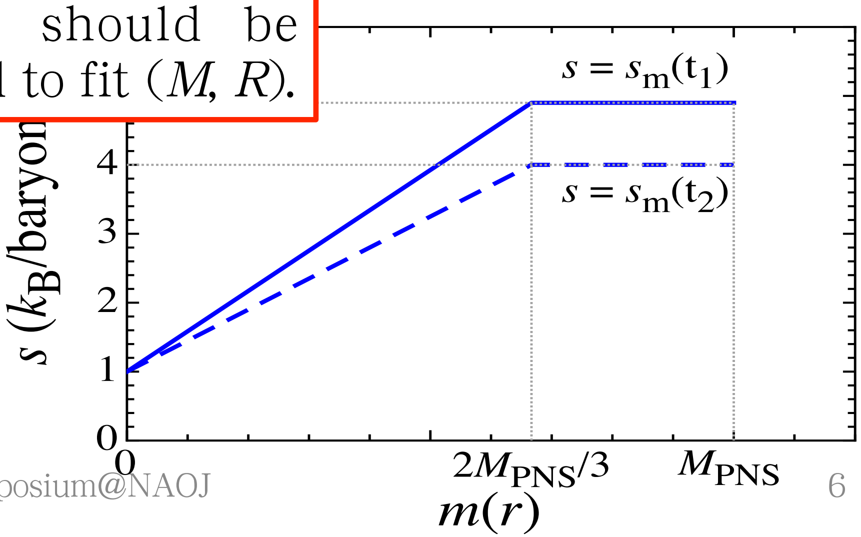
- results by Roberts (2012), where he has done the 1D simulations for long-term.





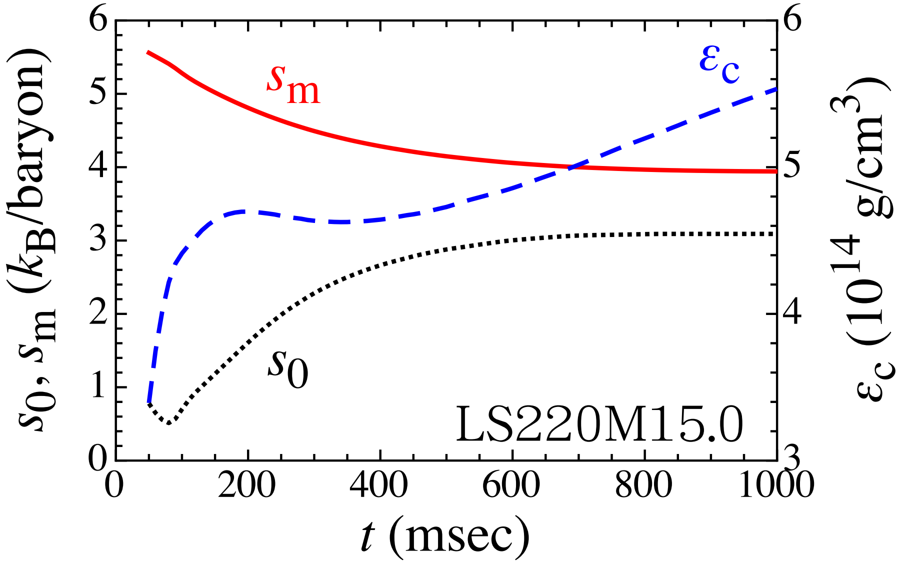
again, s_m should be determined to fit (M, R).

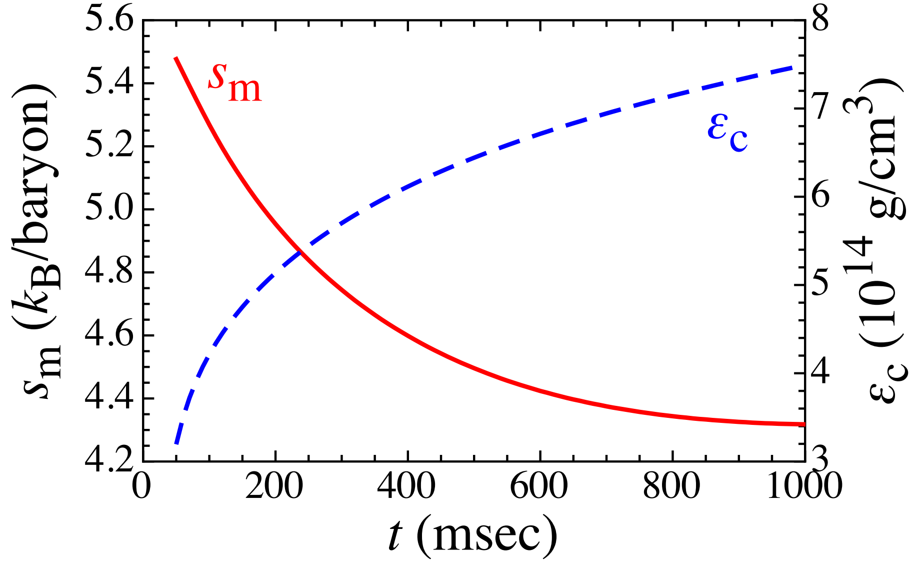




PNS models

- 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.

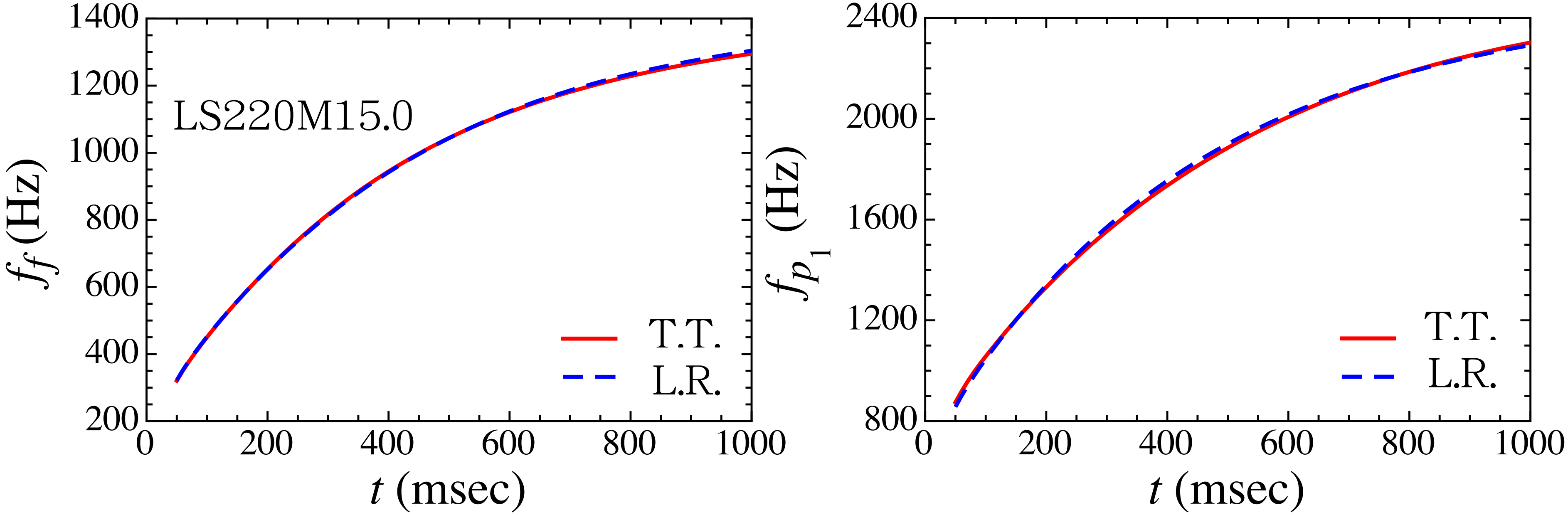




- evolutions of ε_c and s_m depend strongly on the profiles of Y_e and s.

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 ~ a few hundred hertz, which is good for gravitational wave detectors.

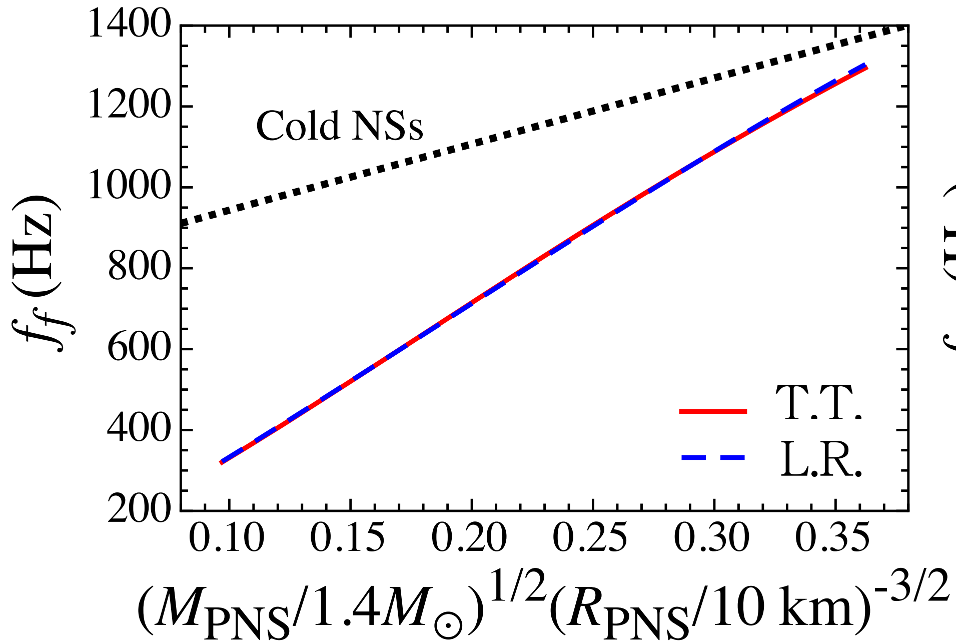
characterized by average density

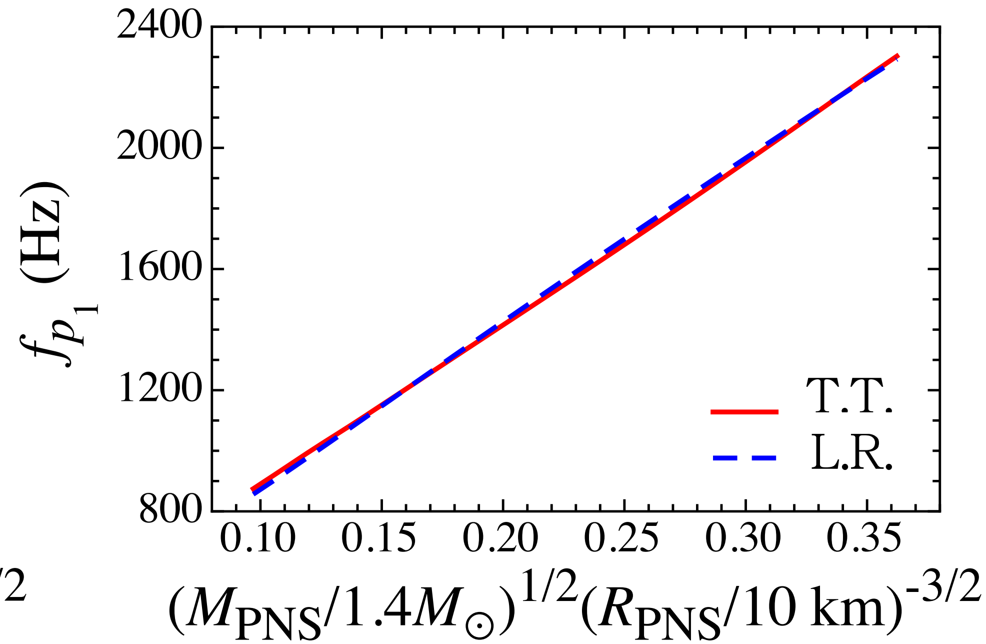
- frequencies of f-mode for cold neutron stars:

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

Andersson & Kokkotas (1998)

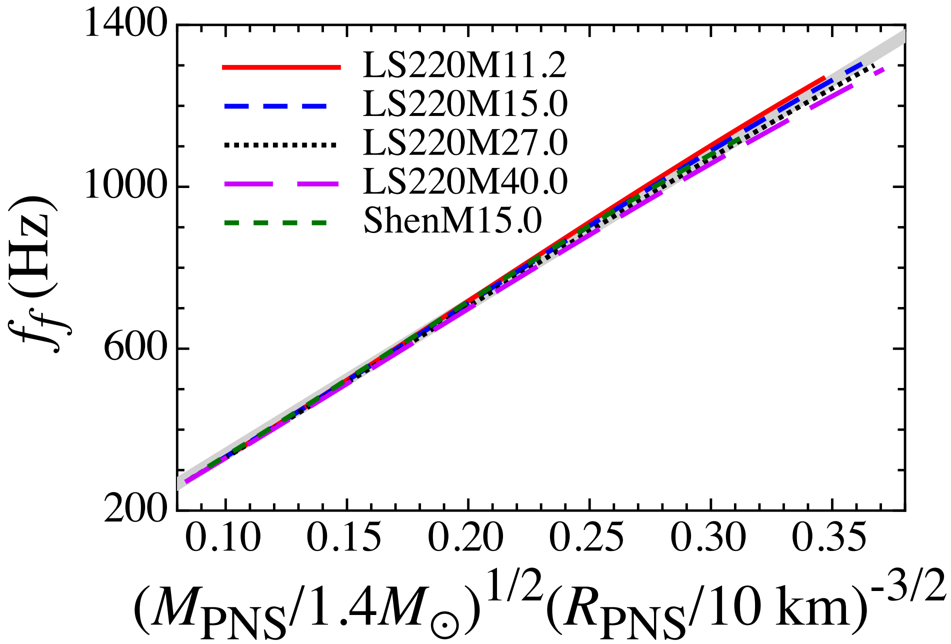
- Similarly, frequencies for PNS can be characterized by average density, but obviously different from those for neutron stars.

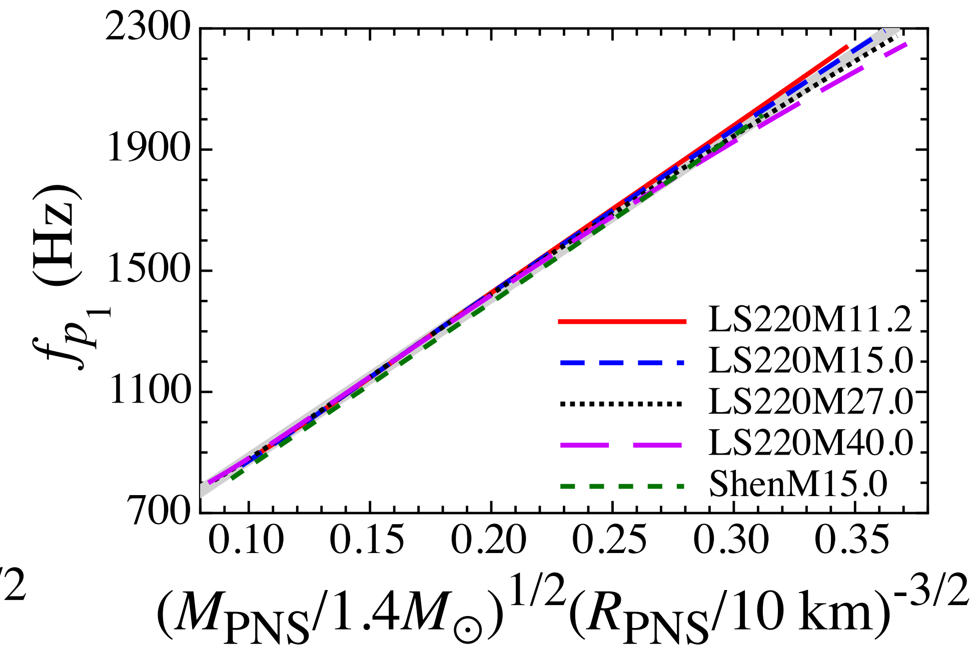




dependence on progenitor models

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





- progenitor model dependence is quite weak.

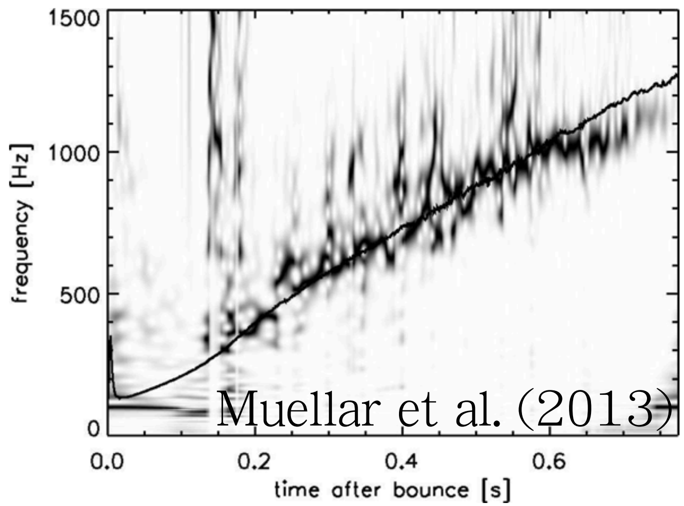
$$f_i^{(\mathrm{PNS})}(\mathrm{Hz}) \approx c_i^0 + c_i^1 \left(\frac{M_{\mathrm{PNS}}}{1.4M_{\odot}}\right)^{1/2} \left(\frac{R_{\mathrm{PNS}}}{10\ \mathrm{km}}\right)^{-3/2}$$

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.

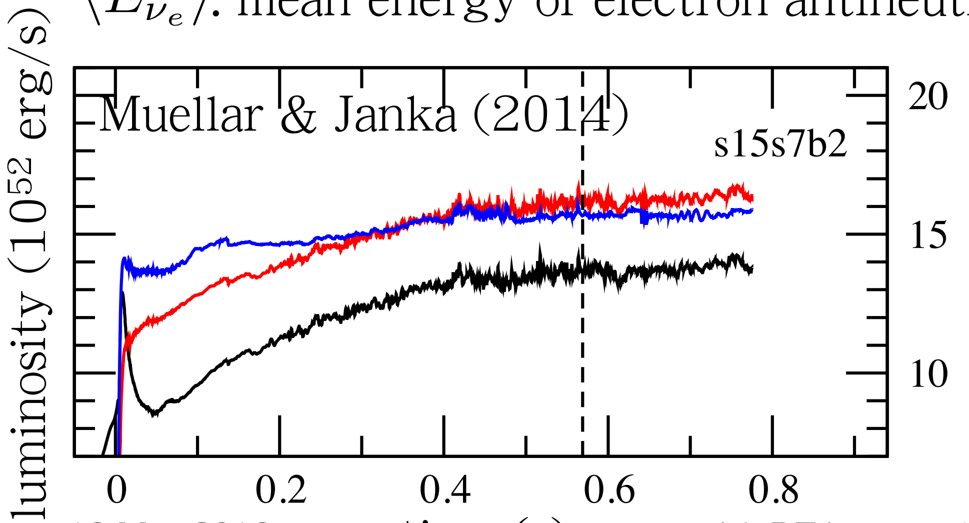
$$f_g \approx \frac{1}{2\pi}\frac{GM_{\rm PNS}}{R_{\rm PNS}^2}\left(\frac{1.1 m_n}{\langle E_{\bar{\nu}_e}\rangle}\right)^{1/2}\left(1-\frac{GM_{\rm PNS}}{c^2 R_{\rm PNS}}\right)^2$$

Muellar et al. (2013)



m_n: neutron mass

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



black: electron neutrinos

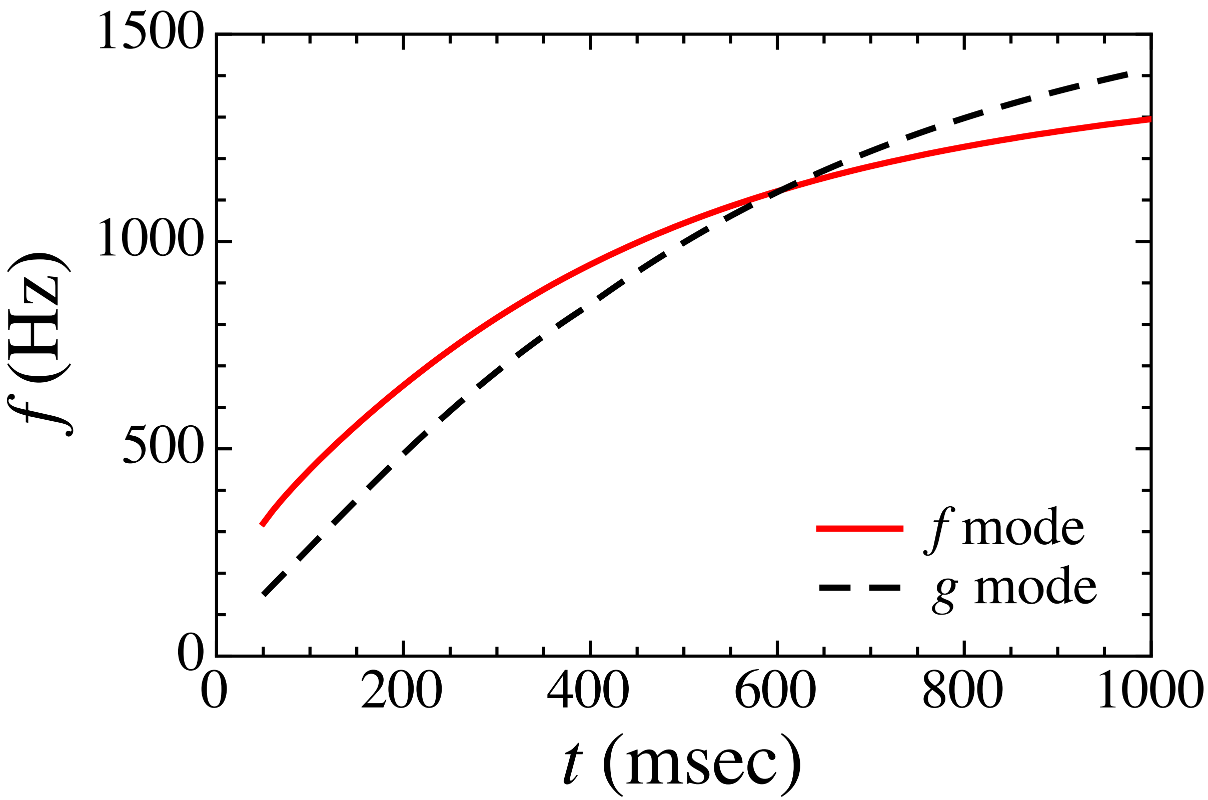
red: electron antineutrinos

blue: μ / τ neutrinos

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

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
- f… …om t…

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

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

- p…
  - … 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.