原始中性子星における星震学

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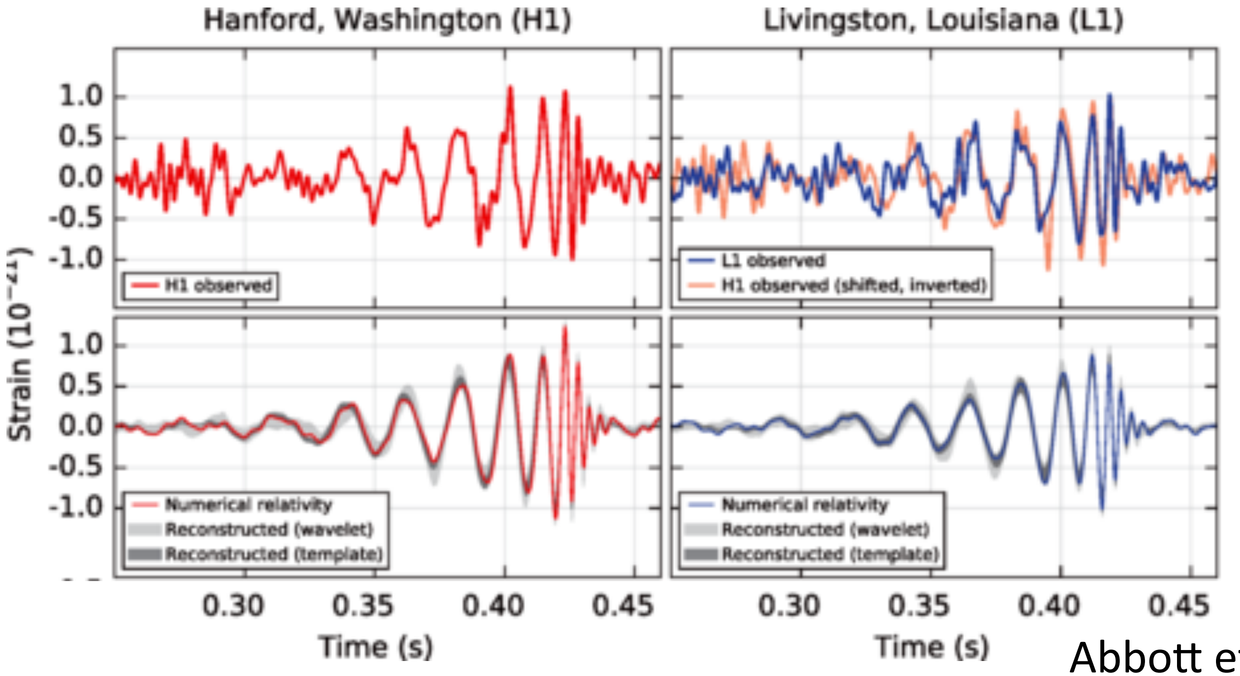
Dawn of GW astronomy era

- First detection of GWs from BH-BH merger (GW150914)

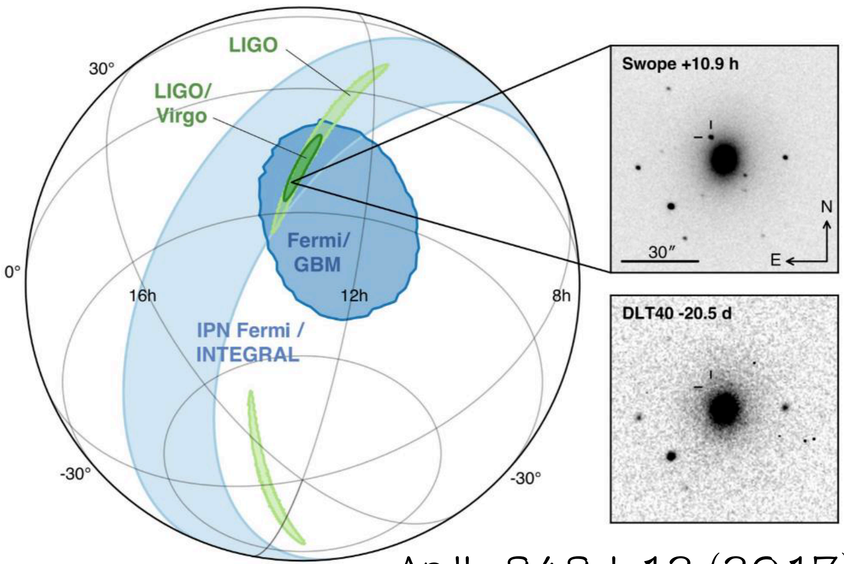


Abbott et al. 16

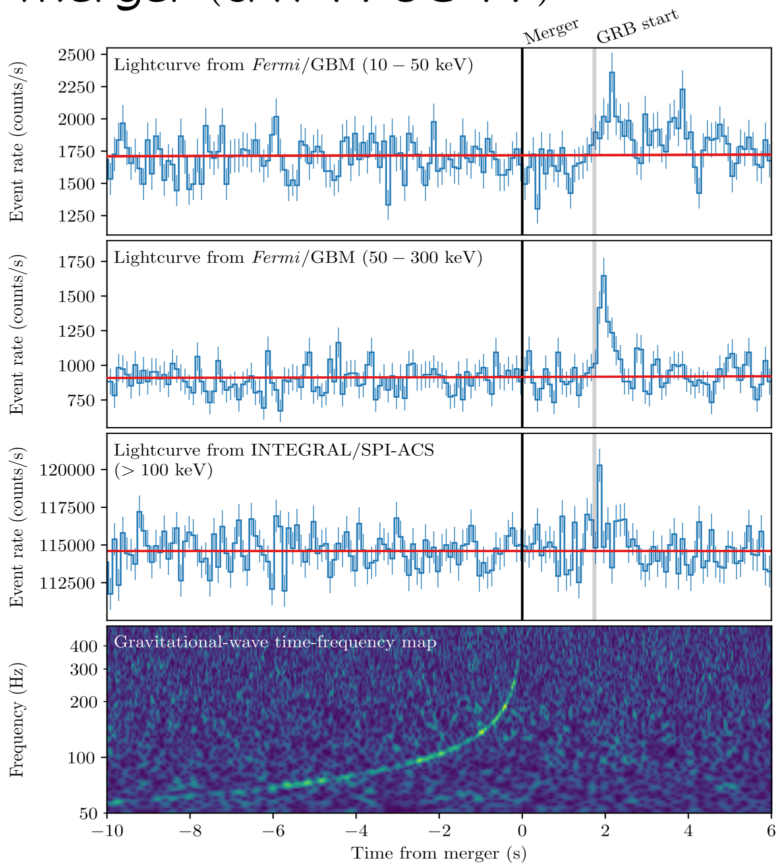
  - $36M_{\odot}$-$29M_{\odot}$ binary BH merger (410Mpc)
- GW151226 (Abbott et al. 16) : $14M_{\odot}$-$7.5M_{\odot}$ BBH (440Mpc)
- GW170104 (Abbott et al. 17) : $31M_{\odot}$-$19M_{\odot}$ BBH (880Mpc)

Dawn of GW astronomy era

- First detection of GWs from NS-NS merger (GW170817)
  - first BNS + EM counter part
  - total mass = $2.74M_\odot$ (40Mpc)



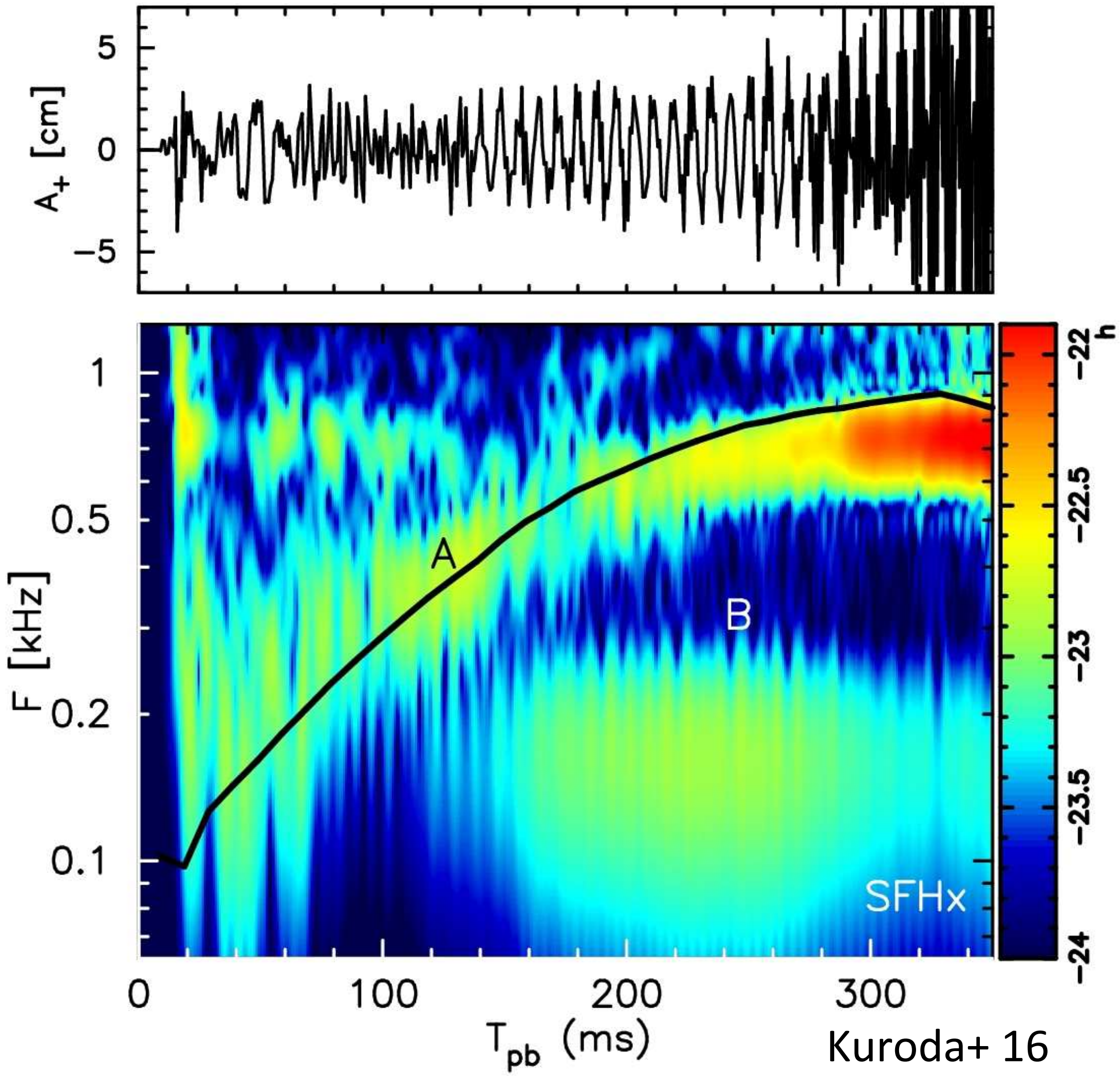
ApJL 848 L12 (2017)



ApJL 848 L13 (2017)

- promising GW sources;
  - BH-BH, BH-NS, and NS-NS mergers
  - supernovae

GW from SN?

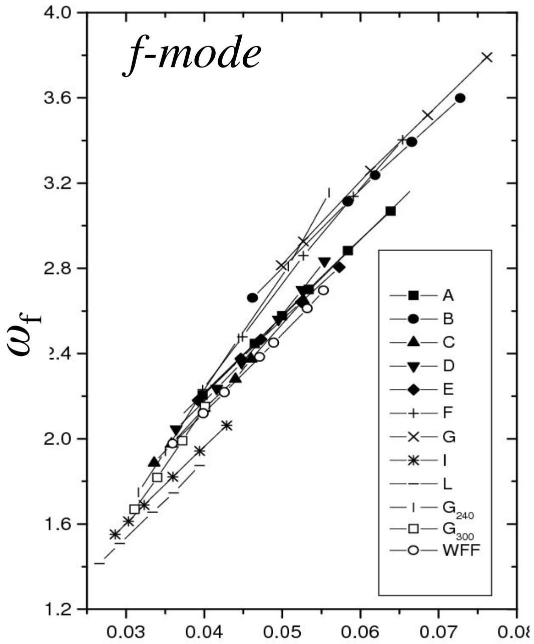


Kuroda+ 16

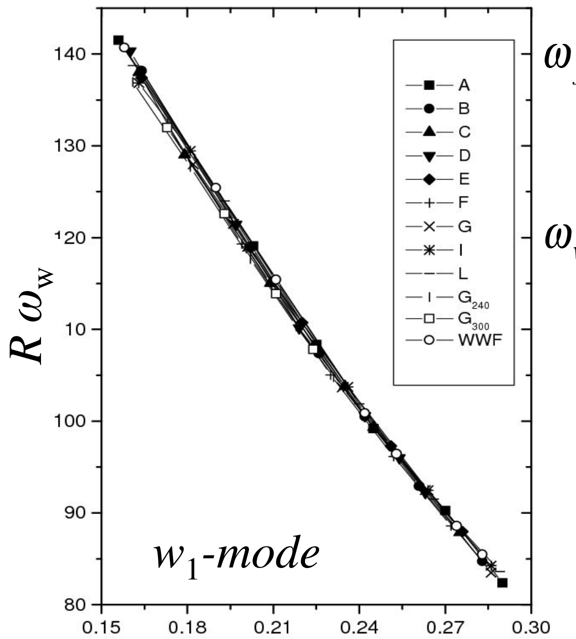
- Numerical simulations tell us the GW spectra.
- difficult
  - to extract physics of PNS and/or SN mechanism
  - to make a long-term numerical calculations
- We adopt the perturbation approach to determine the freq. from PNS.

Asteroseismology on Cold NSs

- via the observations of GW frequencies, one might be able to see the properties of NSs



average density



compactness

Andersson & Kokkotas (1998)

$$\omega_f \approx 0.78 + 1.64\left[\left(\frac{M}{1.4M_\odot}\right)\left(\frac{10\mathrm{km}}{R}\right)^3\right]^{1/2}$$

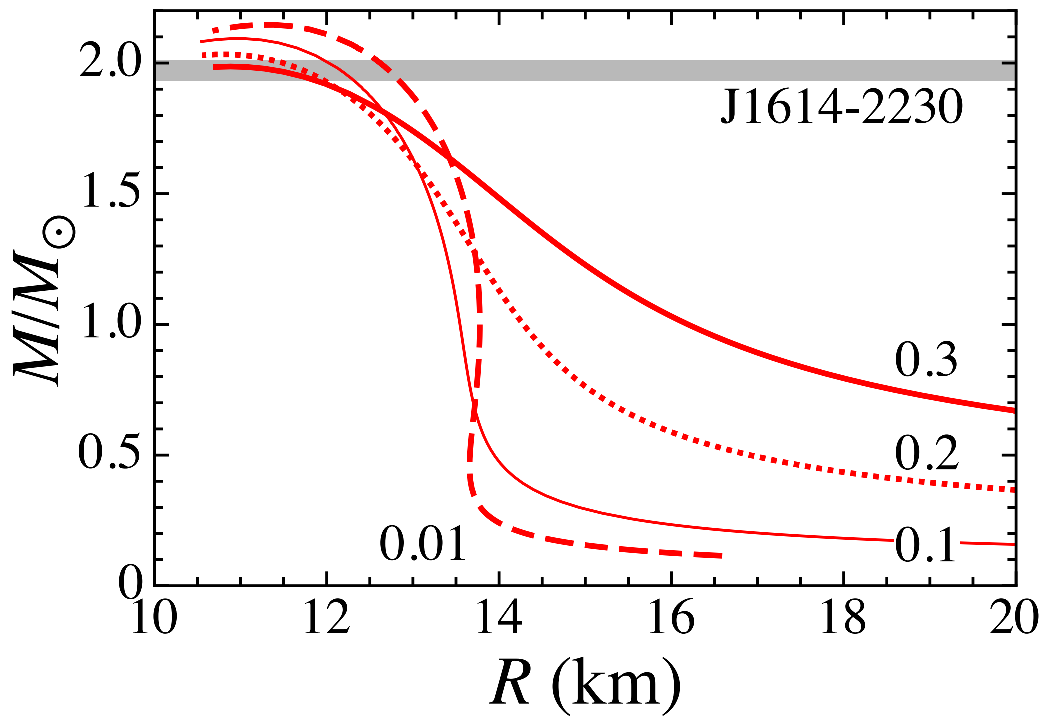
$$\omega_w \approx \left(\frac{10\mathrm{km}}{R}\right)\left[20.92 - 9.14\left(\frac{M}{1.4M_\odot}\right)\left(\frac{10\mathrm{km}}{R}\right)\right]$$

determination of (M, R)

For PNS,
- Muellar et al. (13);
- Cerda-Duran et al. (13);
- Fuller et al. (15);
- Kuroda et al. (16)

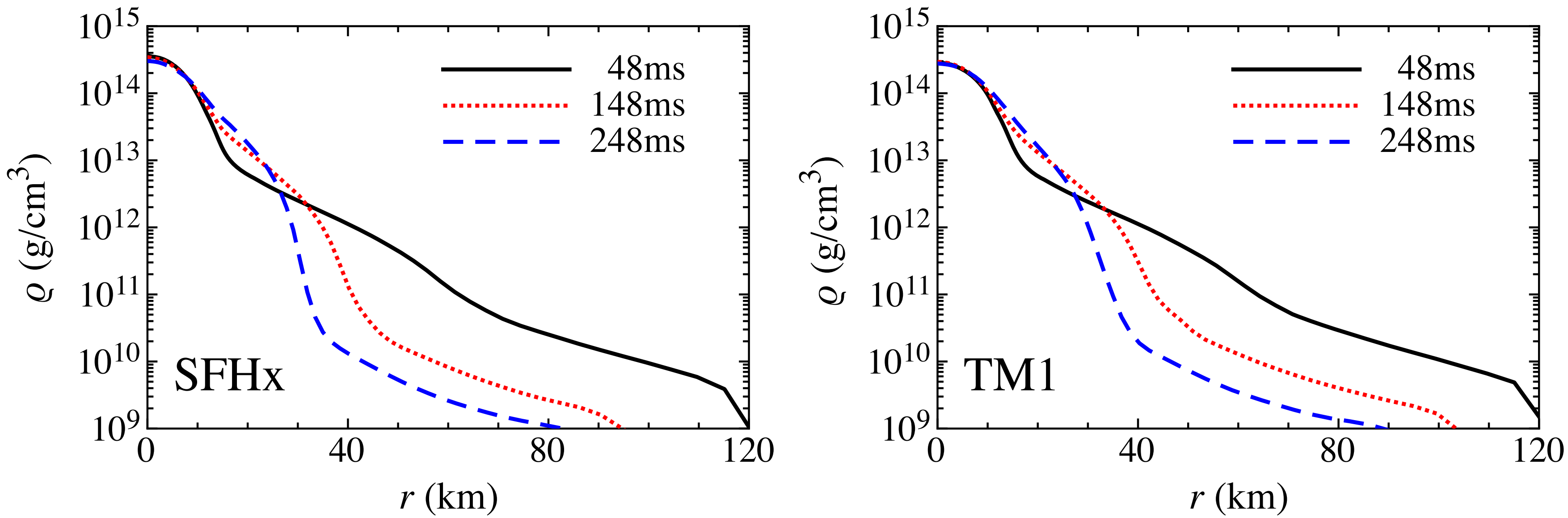
Protoneutron stars (PNSs)

- 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



PNS models

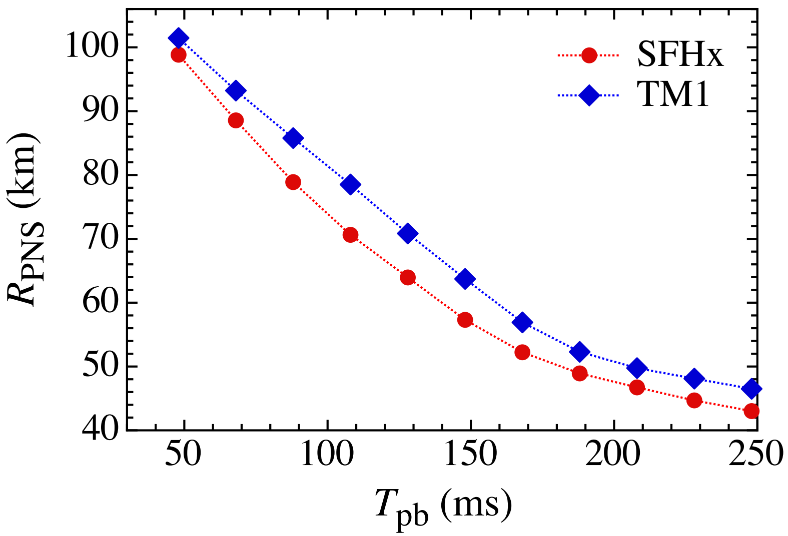
- we adopt the results of 3D-GR simulations of core-collapse supernovae (Kuroda et al. 2016)
  - progenitor mass = $15M_\odot$
  - EOS : SFHx ($2.13M_\odot$) & TM1 ($2.21M_\odot$)

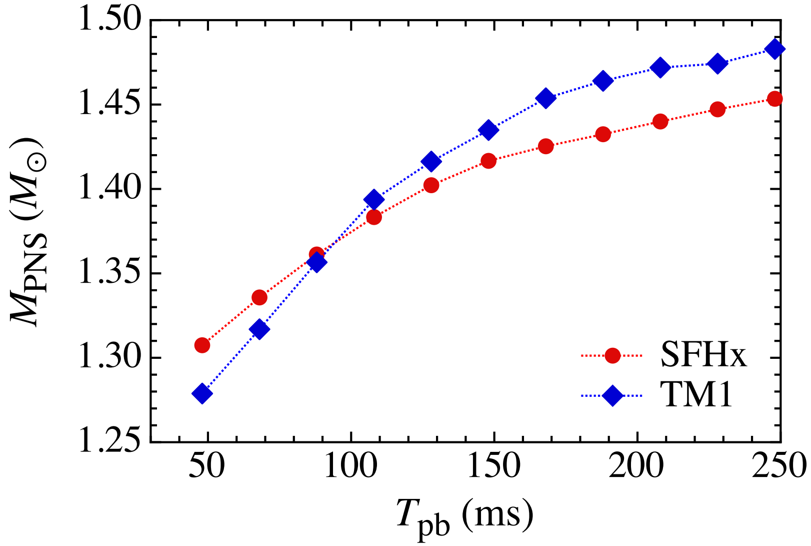


  - R_{PNS} is defined with $\rho_s = 10^{10}$ g/cm^3
  - using the radial profiles as a background PNS model, the eigen-frequencies are determined.

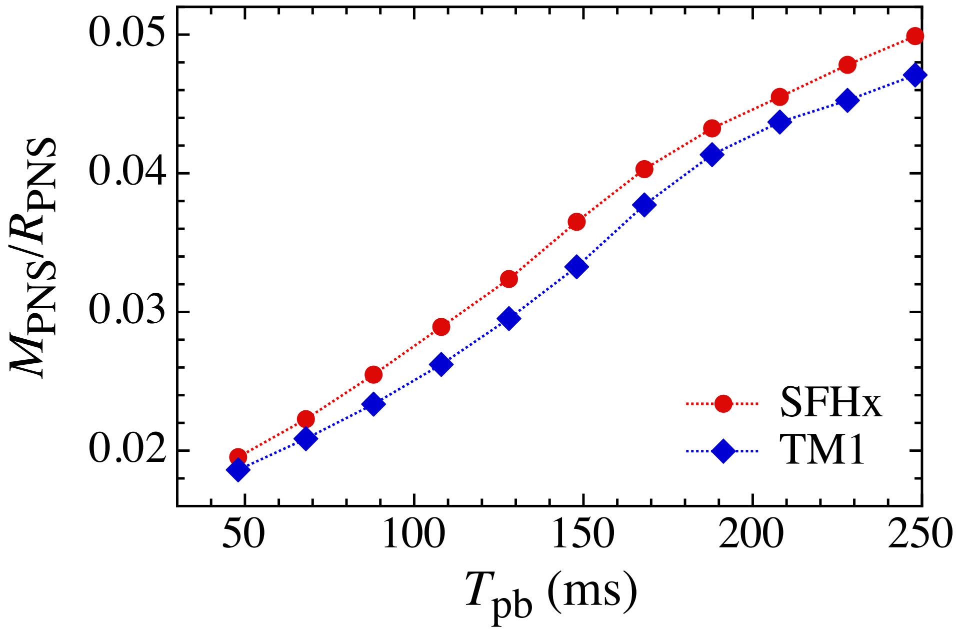
Mass & Radius

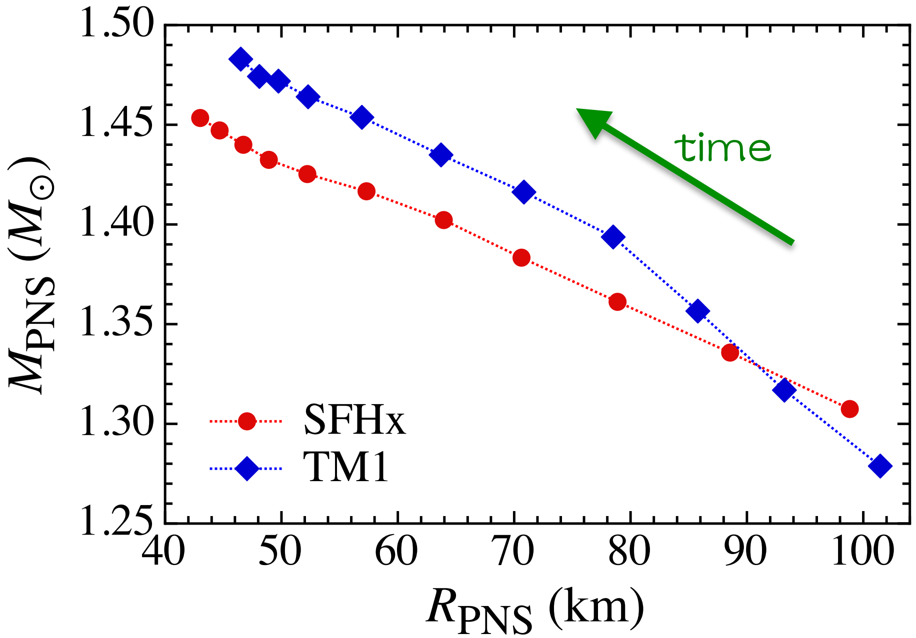
- M_{PNS} is increasing by mass accretion
- R_{PNS} is decreasing due to the cooling





M/R & M-R relation

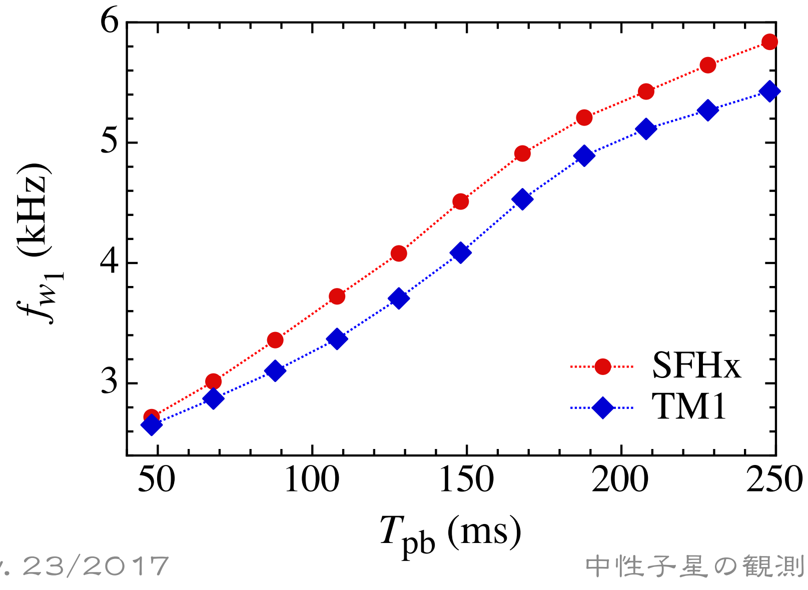


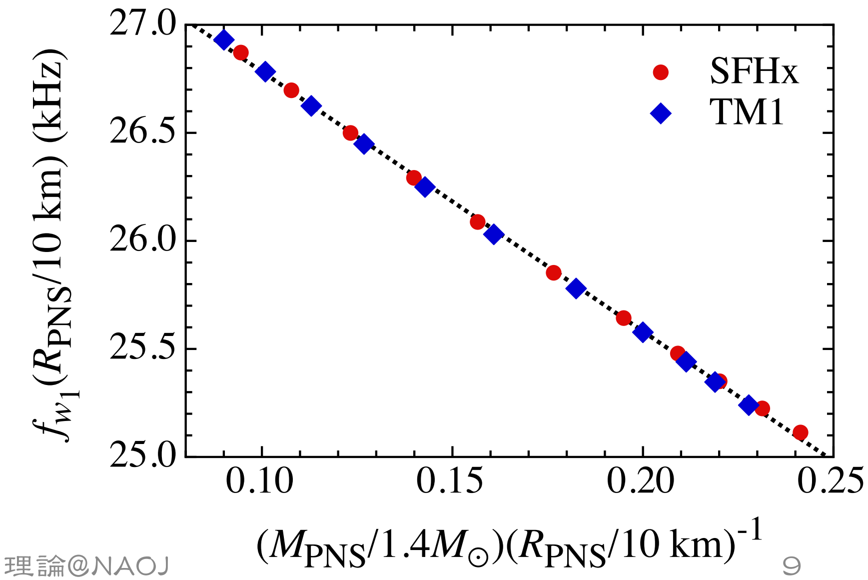


evolution of w_1-modes

- frequencies depend on the EOS.
  - increasing with time
  - can be characterized well by M/R
- as for cold NS, we can get the fitting formula, almost independent from EOS

$$f_{w_1}^{(\mathrm{PNS})}(\mathrm{kHz}) \approx \left[27.99 - 12.02\left(\frac{M_{\mathrm{PNS}}}{1.4\ M_\odot}\right)\left(\frac{R_{\mathrm{PNS}}}{10\ \mathrm{km}}\right)^{-1}\right] \times \left(\frac{R_{\mathrm{PNS}}}{10\ \mathrm{km}}\right)^{-1}$$

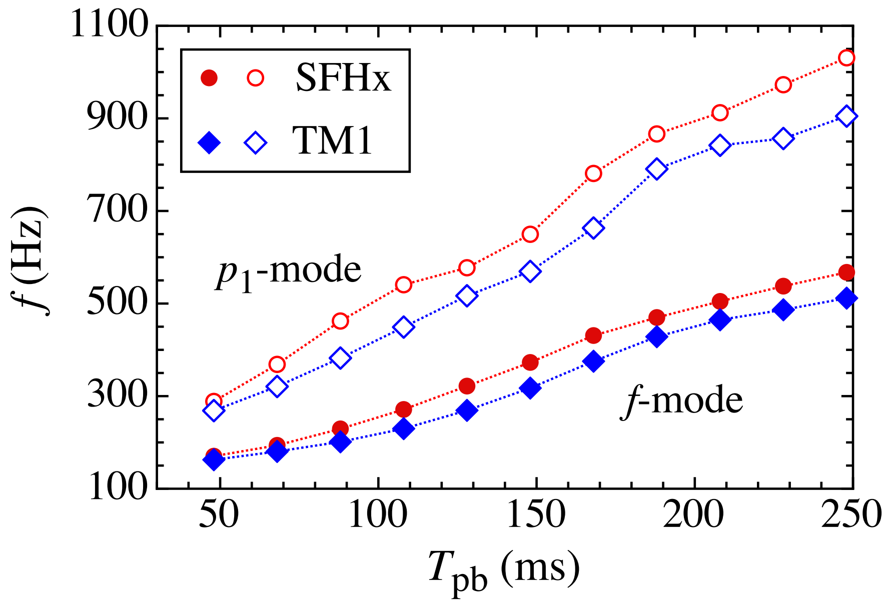


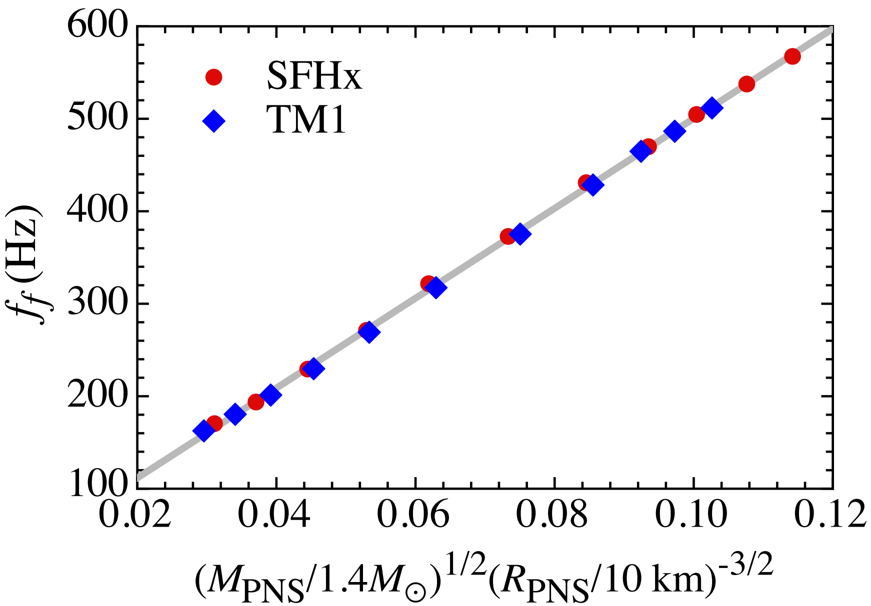


evolution of f-mode

- frequencies can be expressed well by the average density independent of the EOS (and progenitor mass)
- we derive the fitting formula as a function of M/R^3

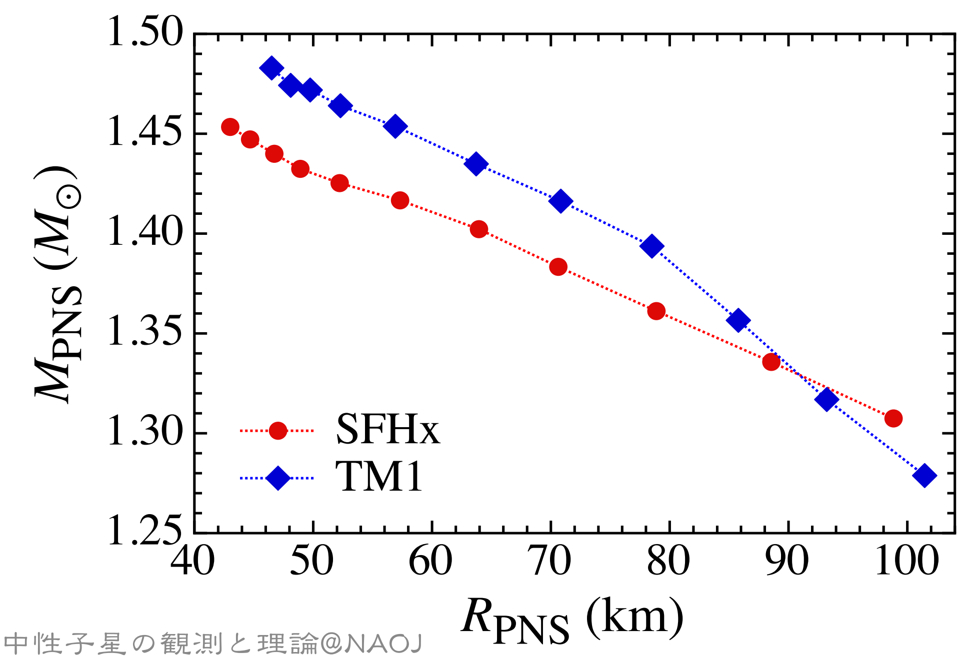
$$f_f^{(\mathrm{PNS})}(\mathrm{Hz}) \approx 14.48 + 4859 \left(\frac{M_{\mathrm{PNS}}}{1.4\ M_\odot}\right)^{1/2} \left(\frac{R_{\mathrm{PNS}}}{10\ \mathrm{km}}\right)^{-3/2}$$





determination of EOS

- with *f*- & w_1-modes GW observations, one can get two independent properties at each time after core bounce, which are combination of M_{PNS} & R_{PNS}
- one can determine (M_{PNS}, R_{PNS}) at each time after core bounce
  → determination of the EOS
- unlike cold NS cases, in principle one can determine the EOS even with ONE GW event !



detectability of w_1-modes

- effective amplitude of w_1-modes

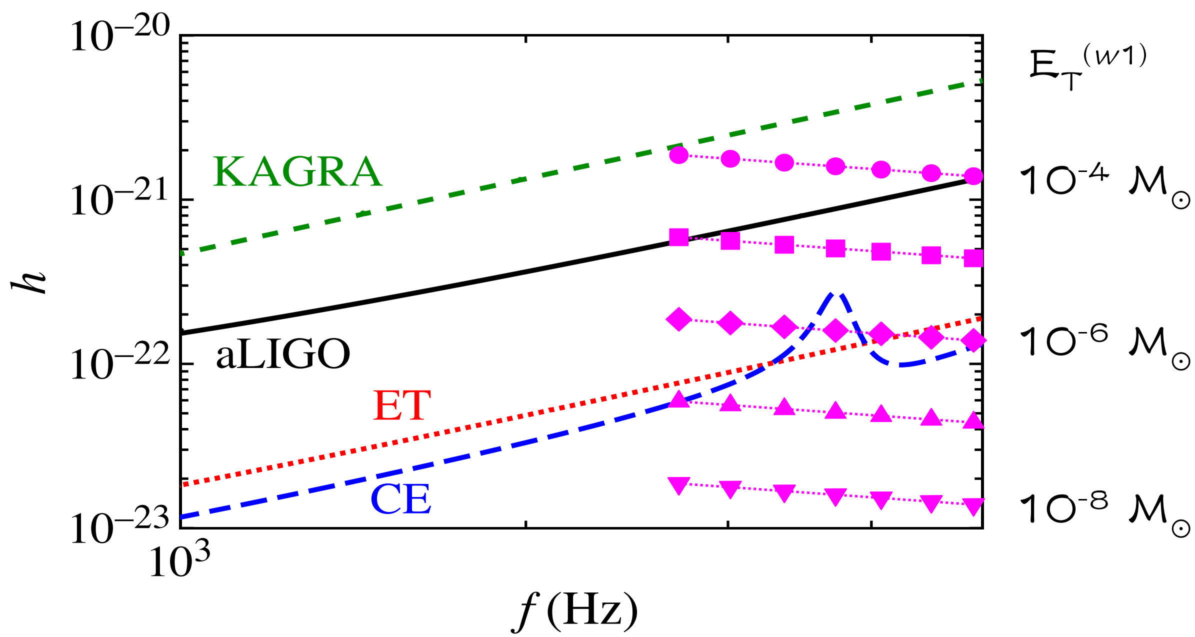
$$h_{\rm eff}^{(w_1)} \sim 7.7 \times 10^{-23} \left(\frac{E_{w_1}}{10^{-10}\, M_\odot}\right)^{1/2} \left(\frac{4\,{\rm kHz}}{f_{w_1}}\right)^{1/2} \left(\frac{10\,{\rm kpc}}{D}\right)$$

Andersson & Kokkotas (1996, 1998)

$$\frac{E_{w1}}{E_T^{(w1)}} \approx \frac{\tau_{w1}}{T_{w1}}$$

E_{w1} : energy for each time step

$E_T^{(w1)}$: total radiation energy in w_1-modes



conclusion

- We examine the frequencies of gravitational waves radiating from PNS after bounce.
  - we derive the empirical formula of w_1- & f-modes independent of the EOS
  - via the GW observation from PNS, one would see M_{PNS} & R_{PNS} evolution
- in principle, even with ONE GW event from supernova, one could determine the EOS for high density region.