Stability of collapsing protoneutron stars and gravitational waves

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collaborated with

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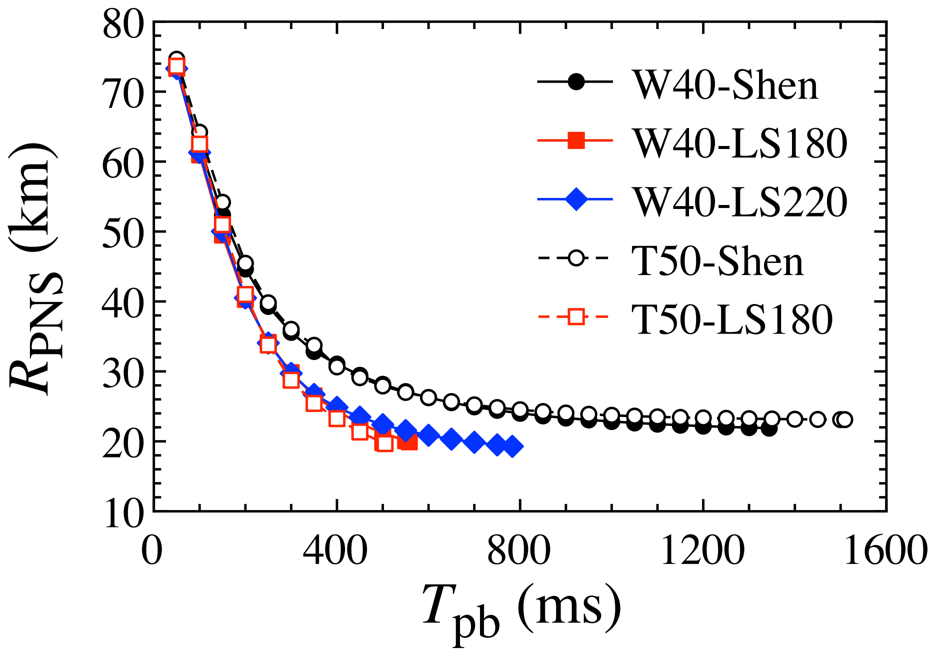
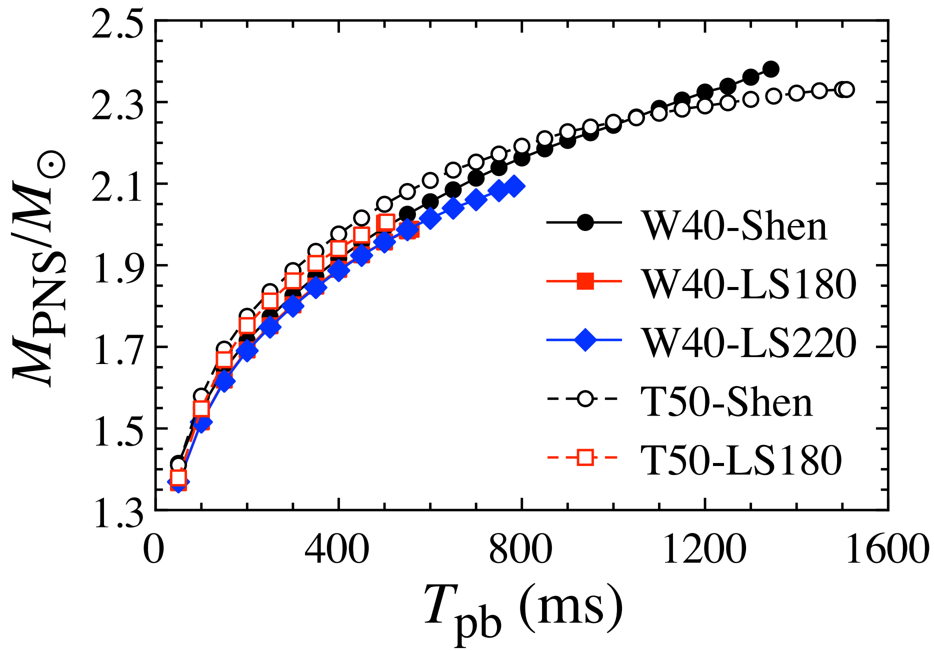
focusing on failed supernovae

- stability analysis with radial perturbations
- gravitational waves from PNS until apparent horizon appears inside the PNS with linear perturbation analysis

failed supernovae simulations

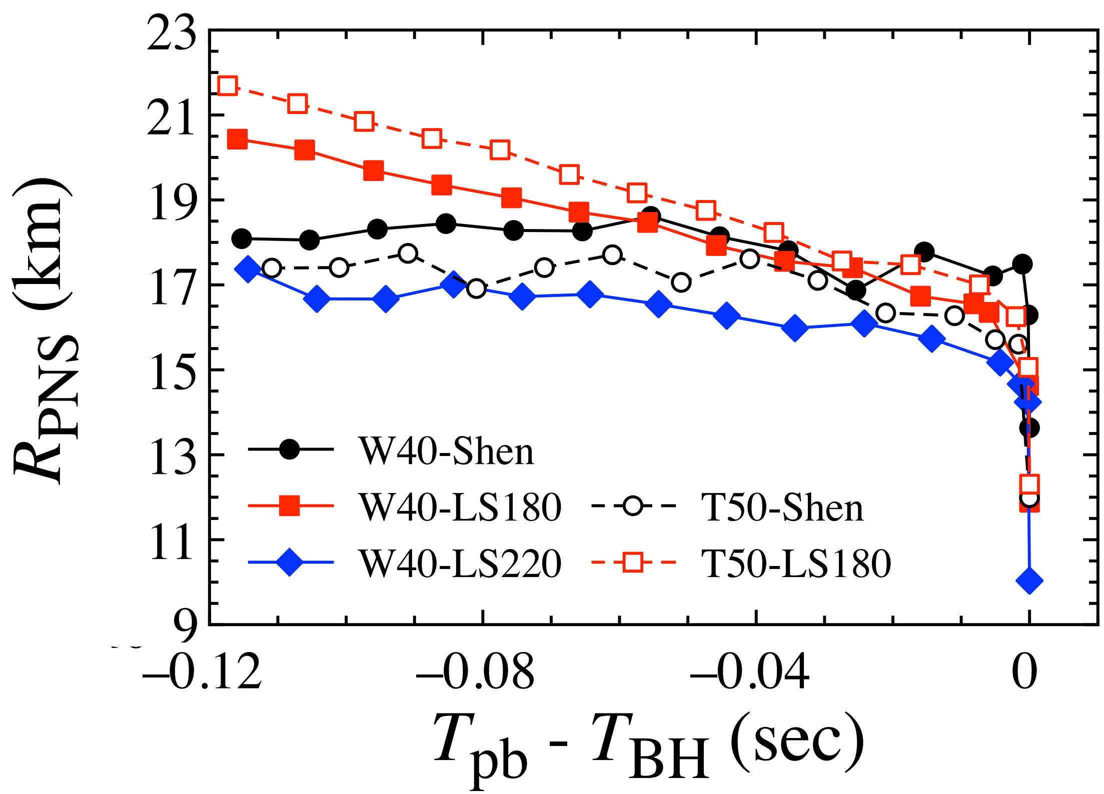
- 1D-GR core-collapse simulations (by Sumiyoshi)
  - $40M_\odot$ progenitor model (W40) based on Woosley & Weaver 95
  - $50M_\odot$ progenitor model (T50) based on Tominaga, Umeda & Nomoto 07
  - EOS: Shen ($2.2M_\odot$), LS180 ($1.8M_\odot$), LS220 ($2.0M_\odot$)
  - surface density ≈ 10^{11} g/cm^3



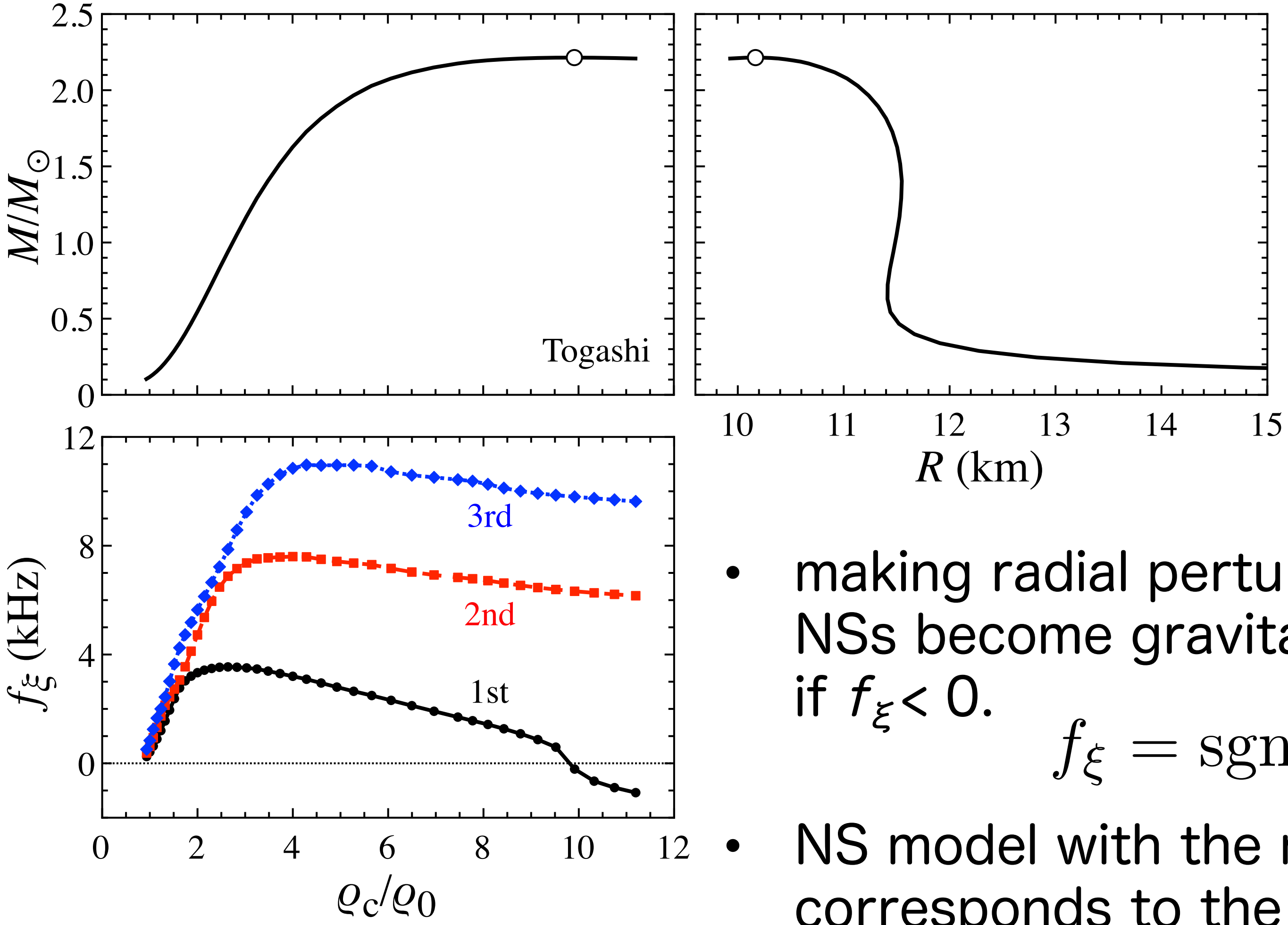


final phase

- at last, the PNS radius is rapidly shrinking.



Stability analysis for cold NSs



HS, Sumiyoshi submitted

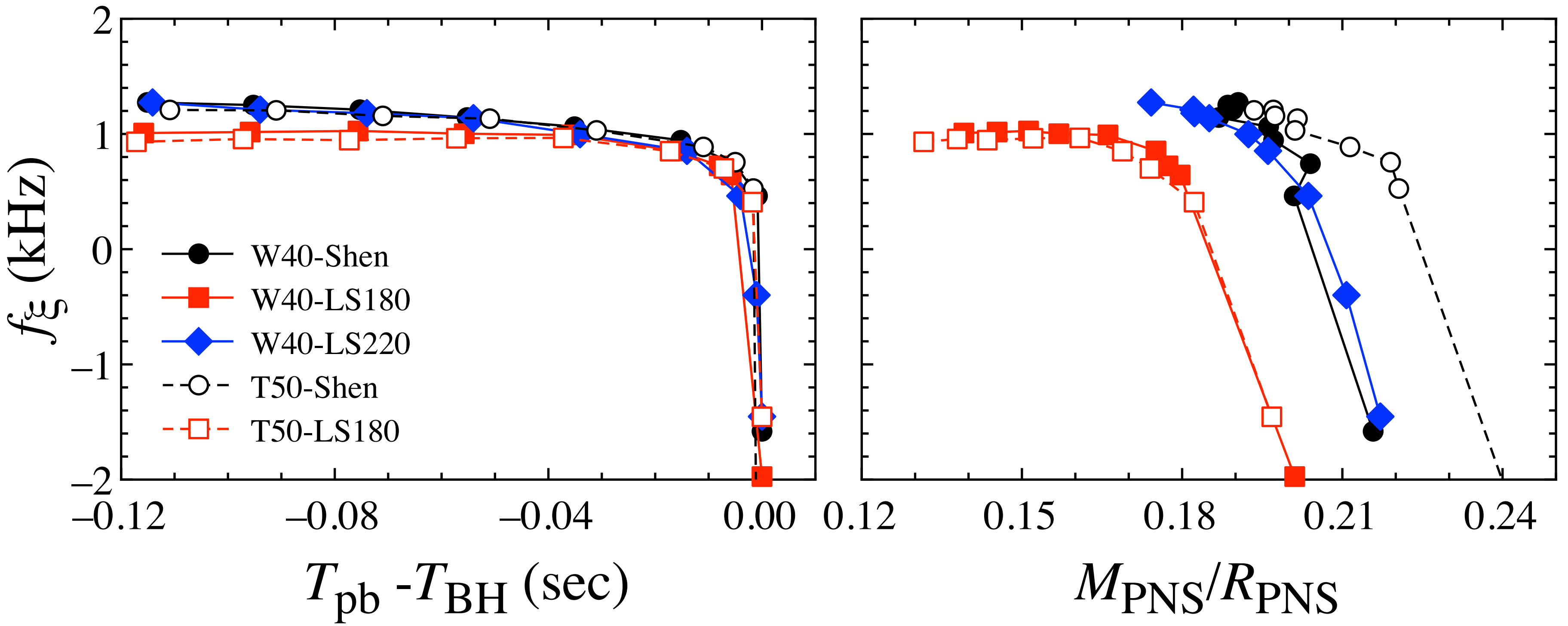
- making radial perturbation analysis, NSs become gravitationally unstable, if $f_\xi < 0$.

$$f_\xi = \mathrm{sgn}(\omega^2)\sqrt{|\omega^2|}/2\pi$$

- NS model with the maximum mass corresponds to the onset of instability.

Stability of PNS @final phase

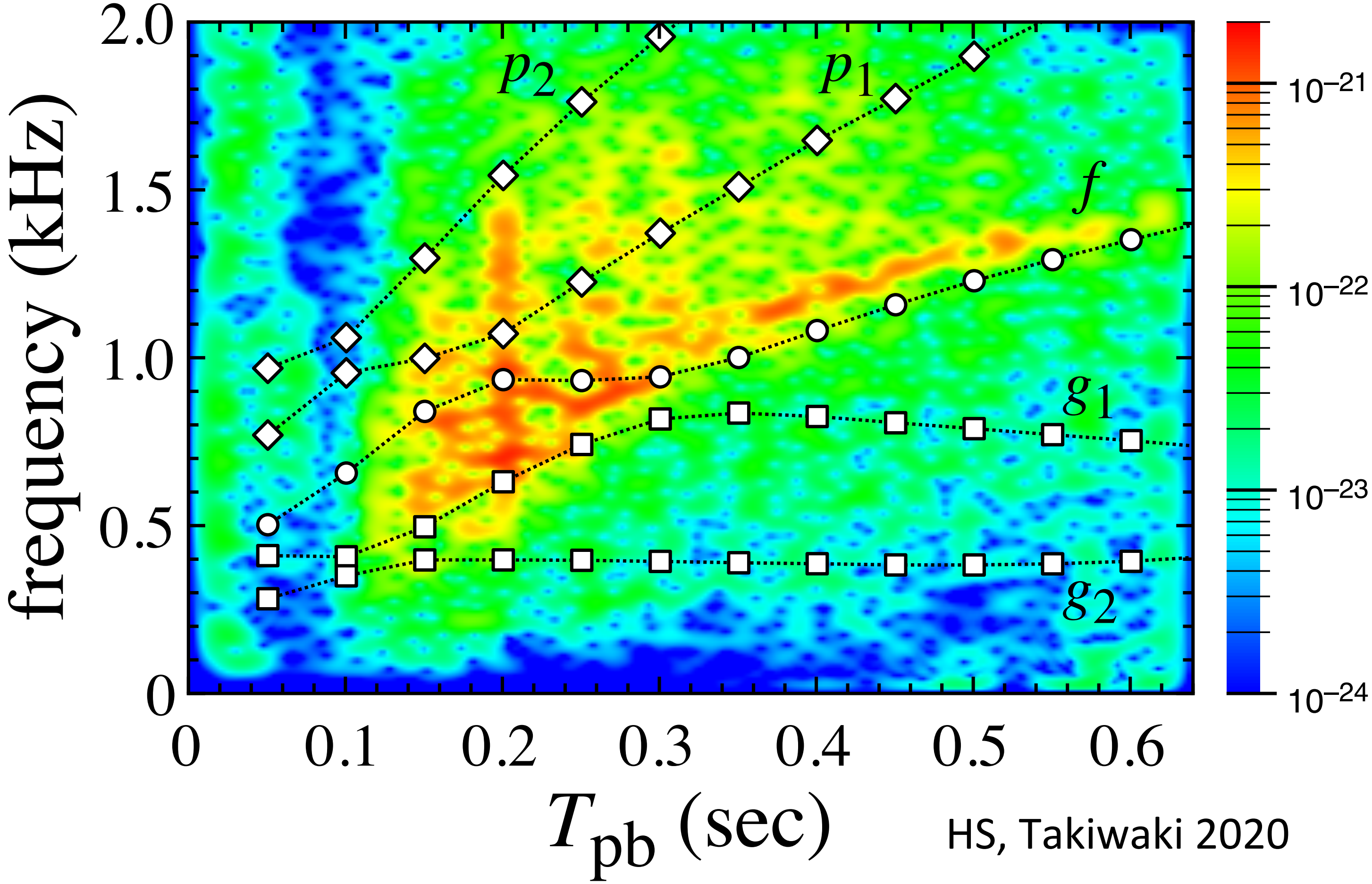
- before the apparent horizon appears inside the PNS, the PNS seems to become gravitationally unstable



HS, Sumiyoshi submitted

GWs from PNS in successful supernova

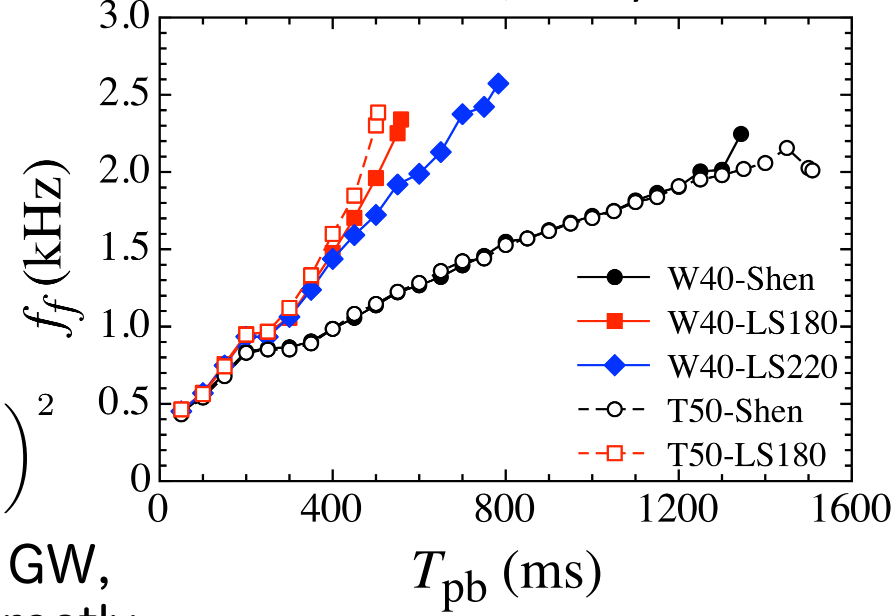
- GW signals correspond to g_1-mode in early phase and f-mode after avoided crossing.



HS, Takiwaki 2020

Dependence on PNS models

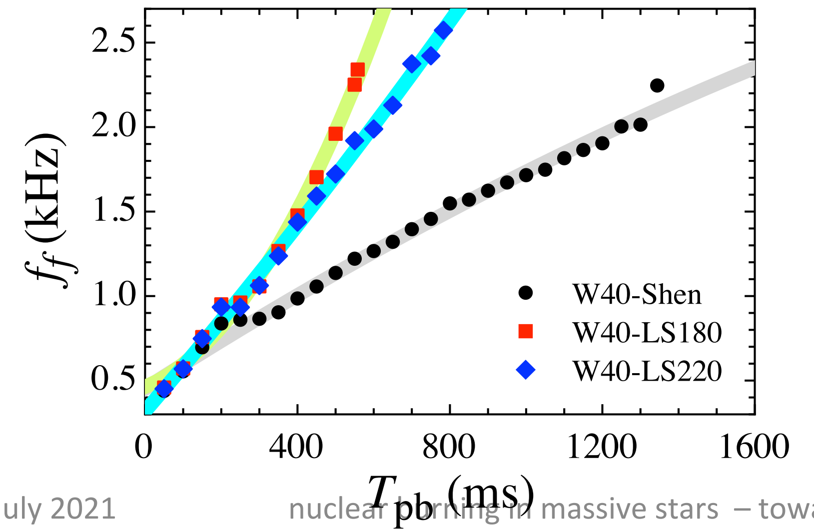
HS, Sumiyoshi 2019

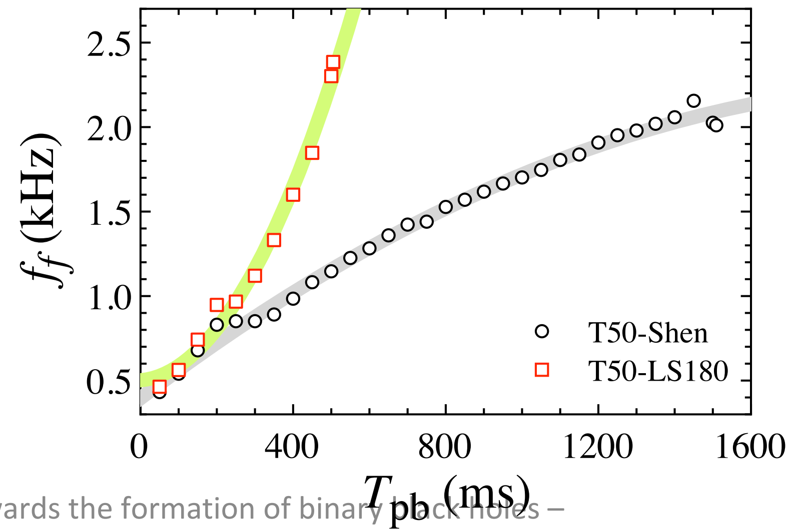


- Time evolution of f-mode GW strongly depends on the progenitor models.
- In any case, it can be well fitted as a function of T_{pb}, such as

$$f_f(\mathrm{kHz}) = c_0 + c_1 \left(\frac{T_{\rm pb}}{1000\,\mathrm{ms}}\right) + c_2 \left(\frac{T_{\rm pb}}{1000\,\mathrm{ms}}\right)^2$$

  - one can expect high fre. f-mode GW, even though it is not detected directly.





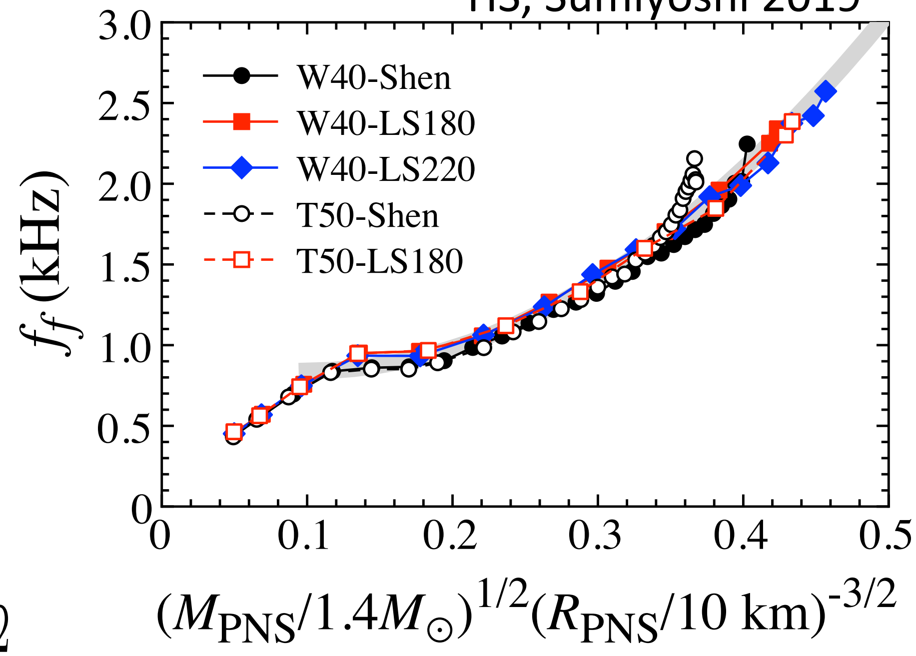
Universality in f-mode GWs

- The f-mode frequencies are well-expressed as a function of stellar average density, <u>independently of progenitor models.</u>

$$f_f(\mathrm{kH}) = 0.9733 - 2.7171X + 13.7809X^2$$

$$X \equiv (M_{\mathrm{PNS}}/1.4M_\odot)^{1/2}(R_{\mathrm{PNS}}/10\,\mathrm{km})^{-3/2}$$

HS, Sumiyoshi 2019

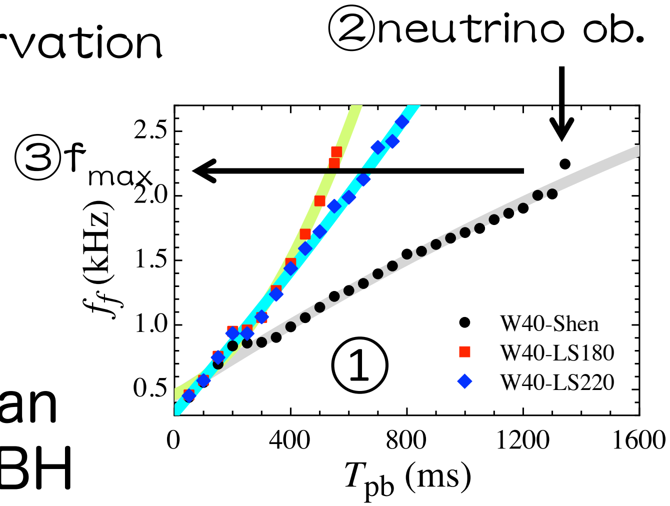


- Through the f-mode GW obs., one can extract the PNS average density, which leads to the time evolution of PNS average density.

For PNS with maximum mass

- PNS <u>at the moment when it collapses to BH</u>, corresponds to the PNS model with maximum mass.↑

one can know via neutrino observation



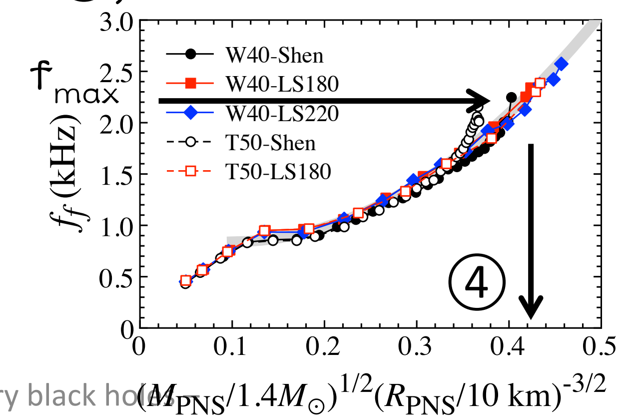
- How to determine the PNS property

① With the data of the f-mode GW, one can fit the time evolution of the f-mode GW

② Owning to the neutrino observation, one can know the moment when PNS collapses to BH

③ The f-mode frequency is expected via ① and ②, <u>even if the f-mode freq. at the final phase would not be detected</u>.

④ Via the universal relation of the f-mode, one can extract the average density of PNS with maximum mass



summary

- We made a stability analysis on PNS
  - PNS becomes gravitationally unstable before the apparent horizon appears inside the PNS.

- we examine the GW freq. from PNSs for failed supernova
  - f-mode frequency can be expressed well as a function of PNS average density independently of the PNS models
  - Owning to the neutrino observation, one would estimate the average density of PNS with maximum mass, even if the corresponding f-mode GW could NOT be detected.

- We will taken into account the effect of the radial velocity as background properties.