Empirical relation in supernova gravitational waves

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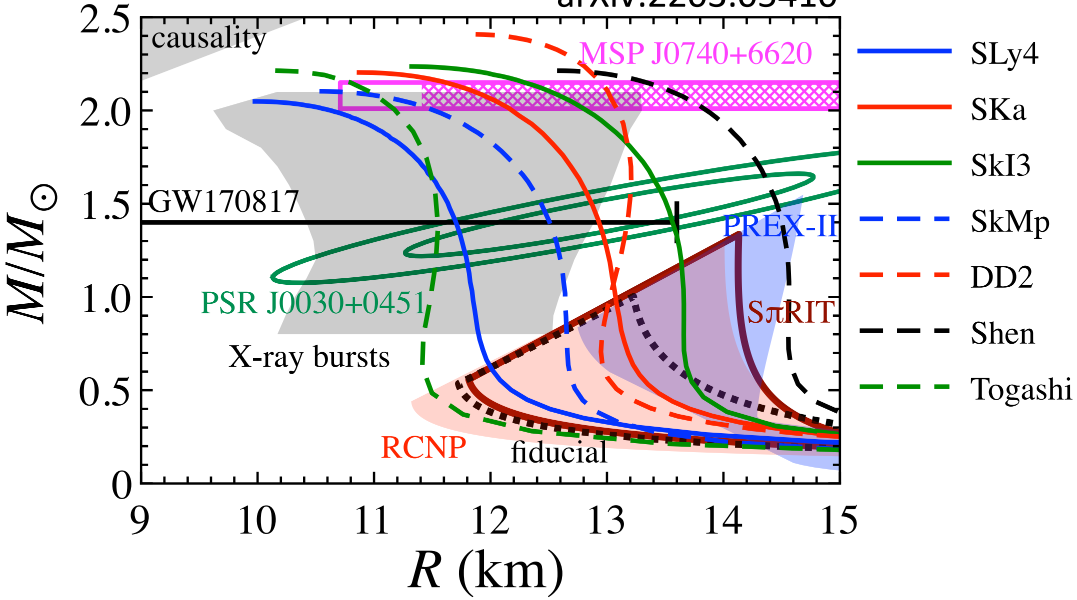
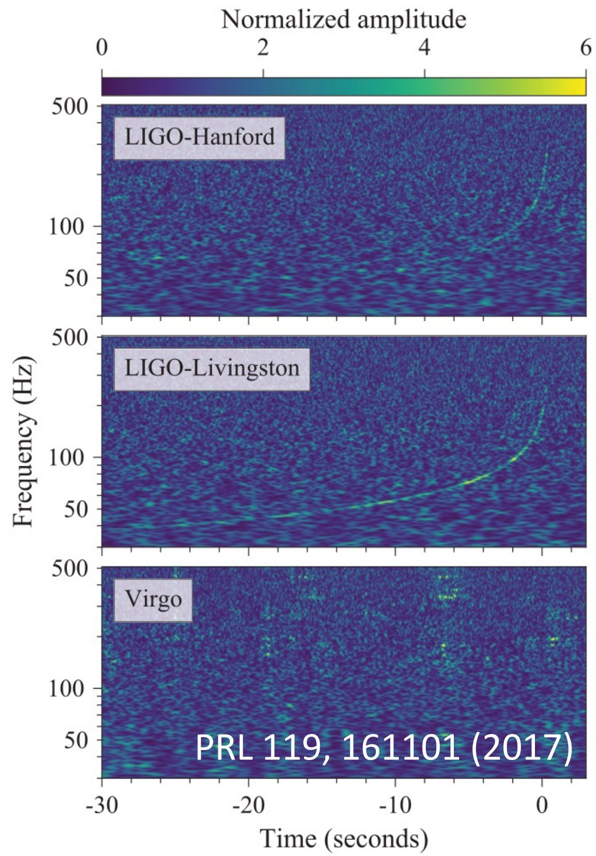
Dawn of GW astronomy

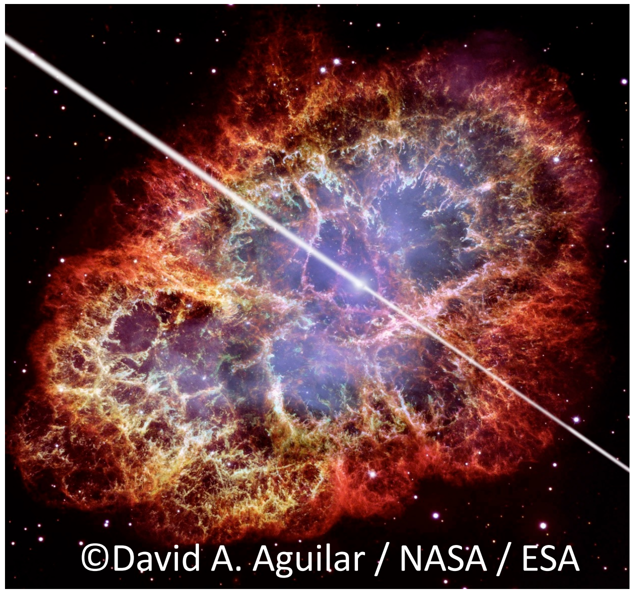
- GWs from compact binary merger have been detected.
  - GW becomes a new tool for extracting the astronomical information.

arXiv:2203.05410



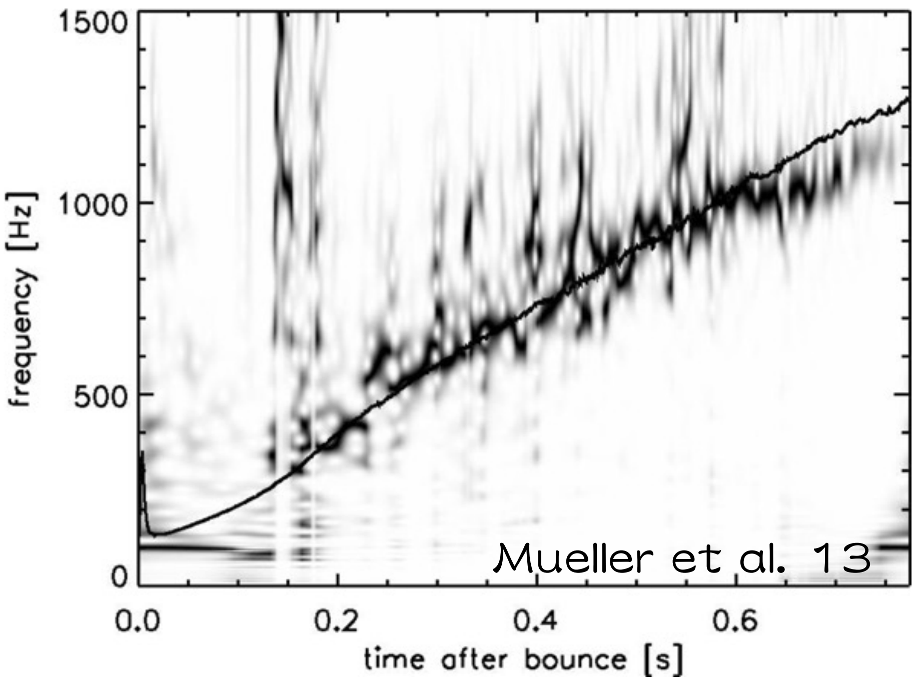


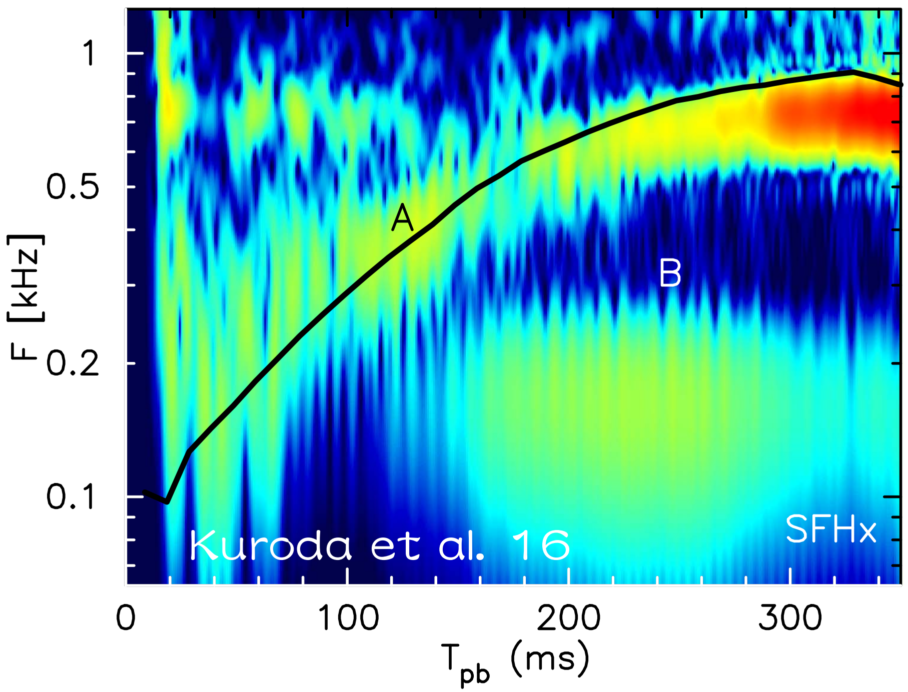
- The next candidate must be supernova explosion.
  - GW asteroseismology
  - universal relation



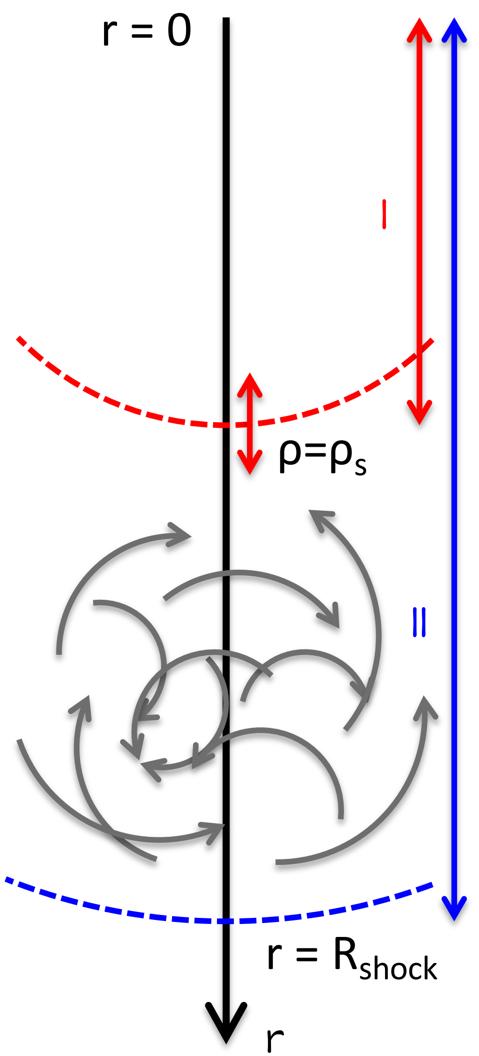
Next candidate of GW sources

- core-collapse supernovae
  - compered to the binary merger, the system is more spherically symmetric
    - less energy of gravitational waves
  - many numerical simulations show the existence of GW signals
  - to understand the physics behind GW signals, we adopt a perturbative approach, i.e., asteroseismology





difference in two approaches

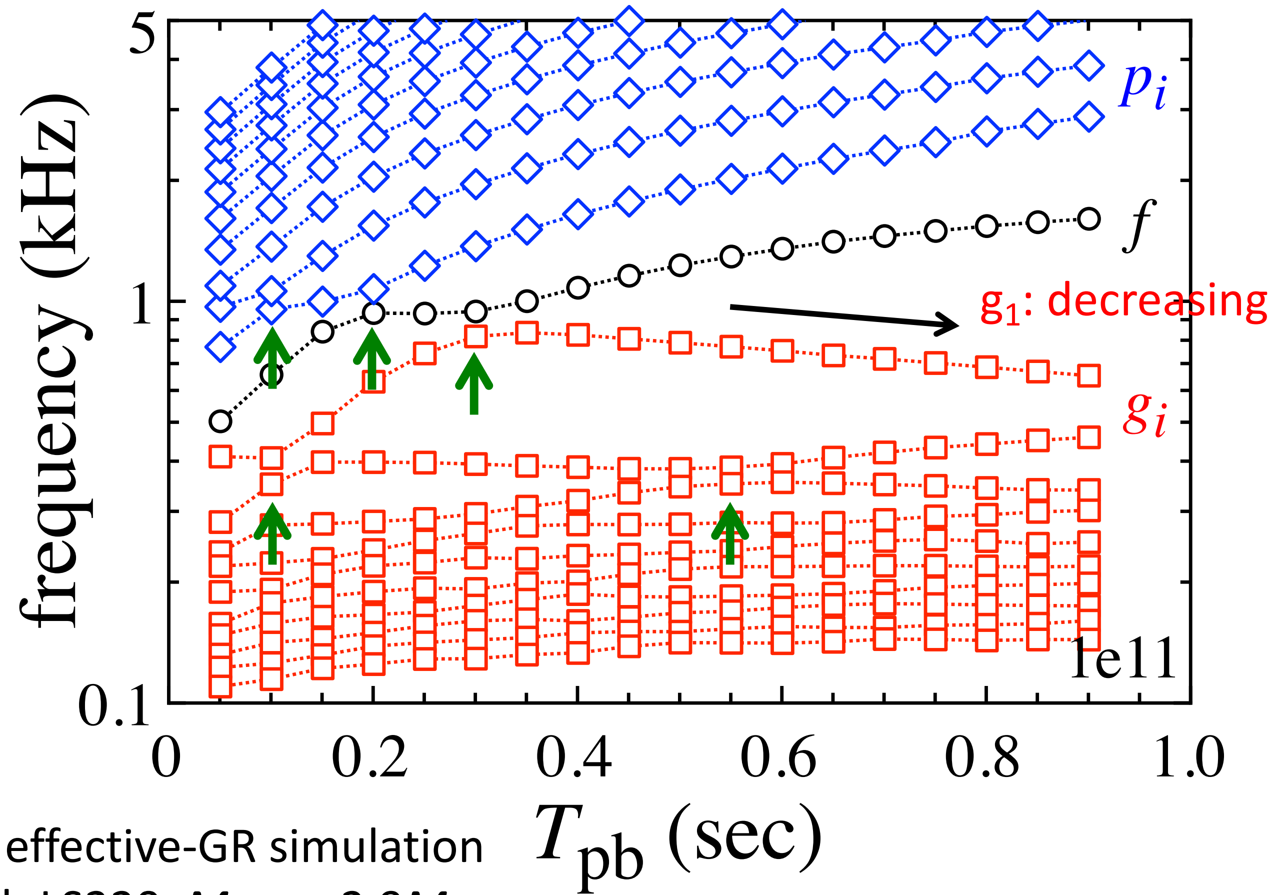


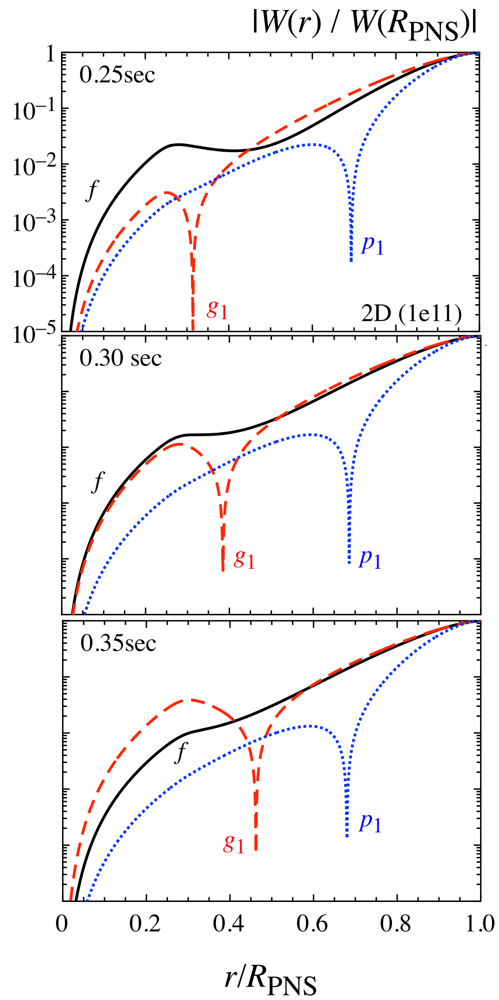
- computational domain
  - Model I : only inside R_{PNS} defined by ρ_s
  - Model II : up to R_{shock}
- Boundary condition for solving the eigenvalue problem
  - Model I : $\Delta p = 0$ @$r = R_{PNS}$
  - Model II : $\delta\xi^r = 0$ @$r = R_{shock}$
  - mathematically, problem to solve is completely different
  - for the both models, the BC is a kind of assumption (not exact one)
- advantage
  - Model I : matter motion is relatively small
    mode classification is as usual
  - Model II : boundary is uniquely determined
- disadvantage
  - Model I : uncertainty in choice of ρ_s
  - Model II : matter motion may not be negligible outside R_{PNS}
    mode classifications is different from the standard one.

avoided crossing in GW frequency

(Sotani&Takiwaki 20b)

- one can observe the phenomena of avoided crossing between the eigenmodes.
- the f- & g_1-modes frequencies are almost independent from the selection of ρ_s (Morozova+ 18; HS, Takiwaki 20b).

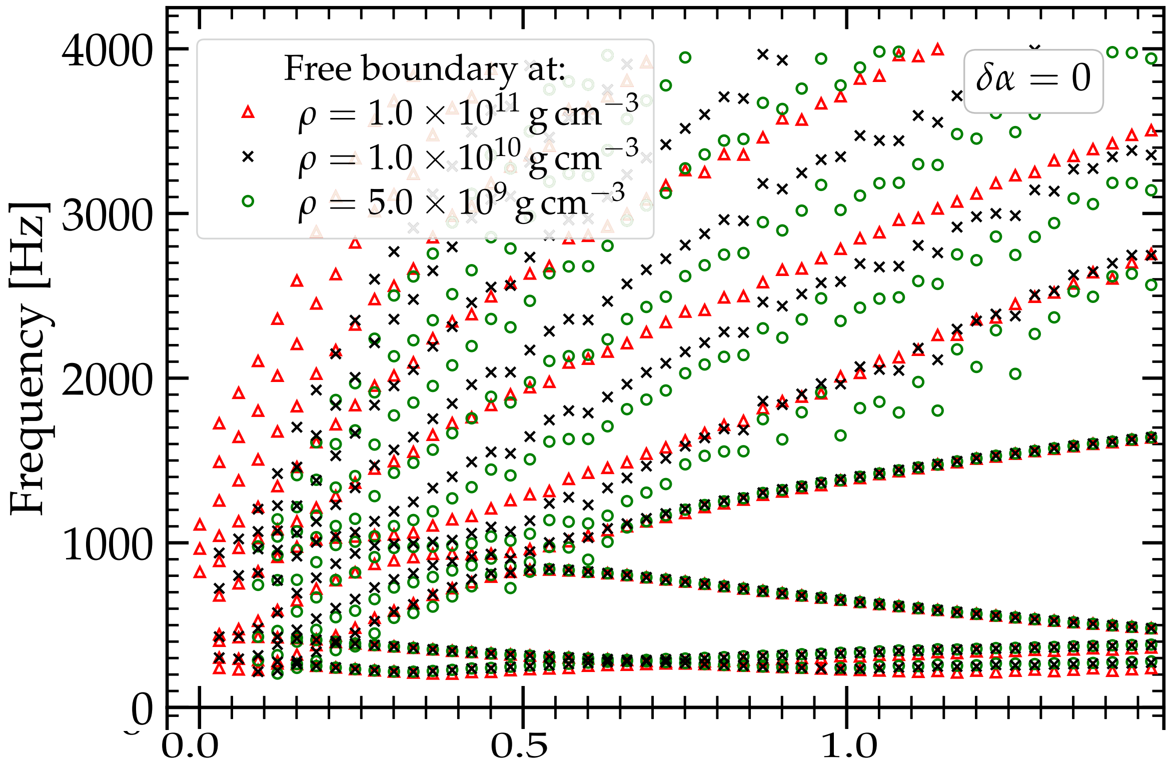




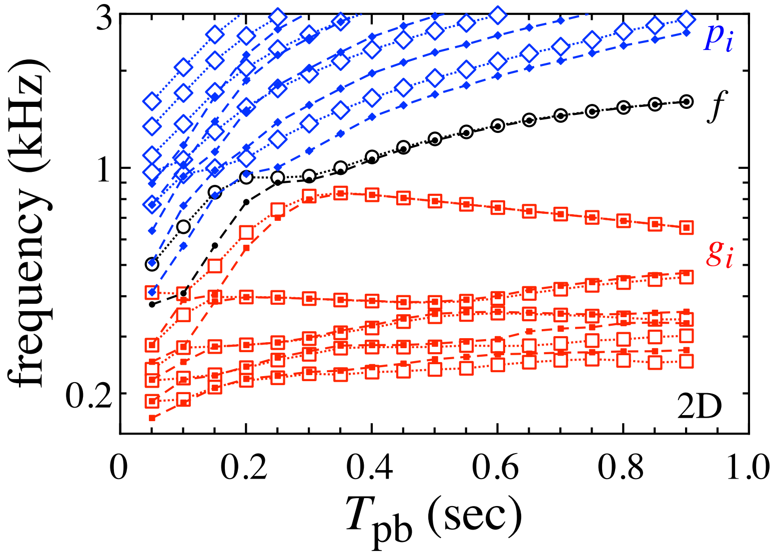
2D effective-GR simulation with LS220, $M_{prog} = 2.9M_\odot$

Comment on uncertainty in ρ_s for Model I

- in the late phase after core bounce, e.g., ~ 500ms, f-mode freq. becomes almost independent of the choice of ρ_s (Morozova+18)
- we also confirm this feature, i.e., f- & g_1-modes in later phase are almost independent of ρ_s, where g_1-mode decreases with time (Sotani & Takiwaki 20b).

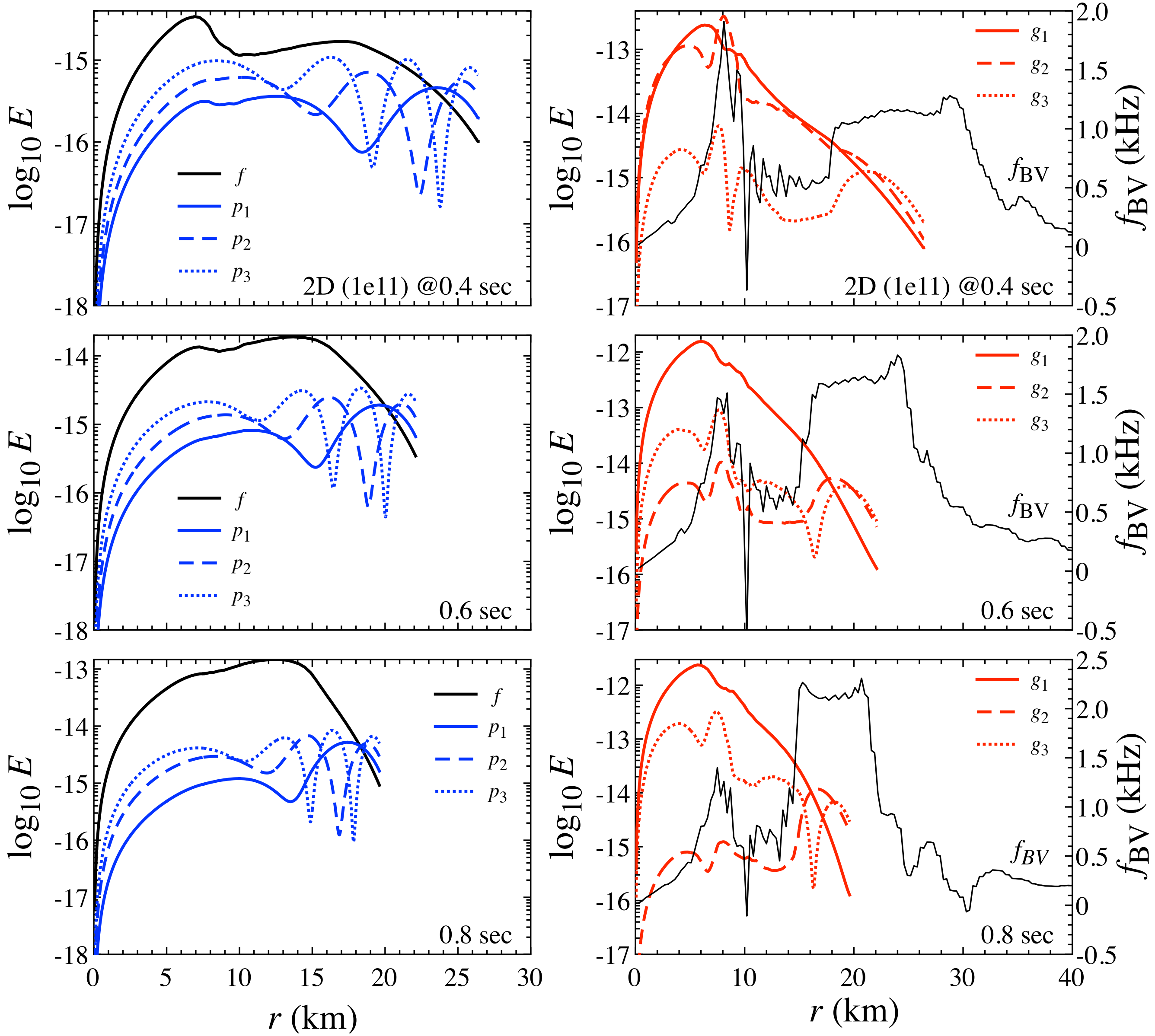


Morozova+18



dotted : 10^{11} g/cm^3
dashed : 10^{10} g/cm^3

pulsation energy density



$$E(r) \sim \frac{\omega^2 \varepsilon}{r^4}\left[W^2 + \ell(\ell+1) r^2 V^2\right]$$

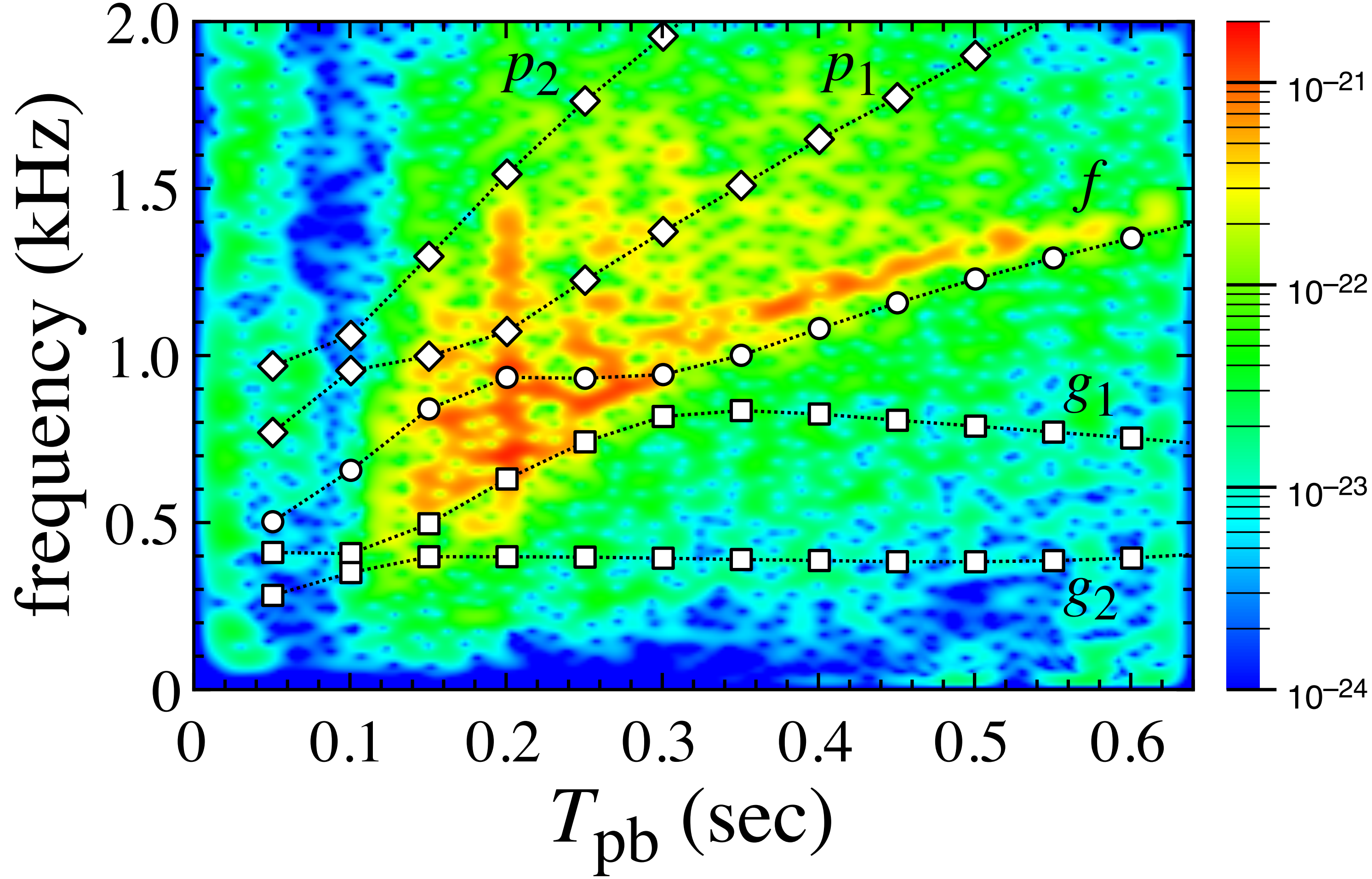
$$f_{\rm BV} = {\rm sgn}(\mathcal{N}^2)\sqrt{|\mathcal{N}^2|/2\pi}$$

$$\mathcal{N}^2 = -e^{2\Phi - 2\Lambda}\frac{\Phi'}{\varepsilon + p}\left(\varepsilon' - \frac{p'}{c_s^2}\right)$$

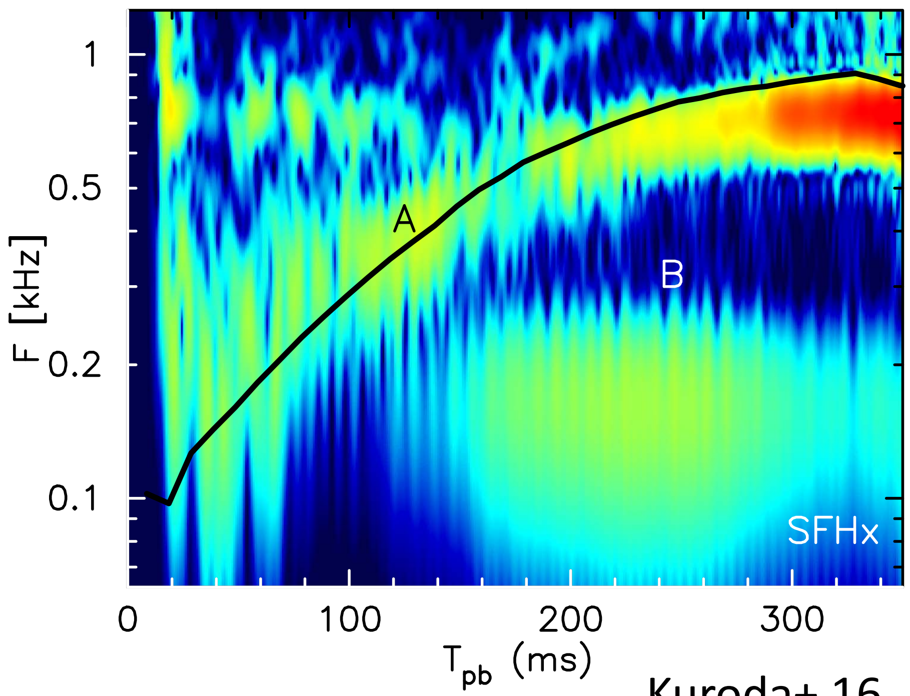
- f- & g_1-modes are not dominant @PNS surface
  → f- & g_1-modes weakly depend on ρ_s
- g_i-modes related to $f_{\rm BV}$
- g_1-mode is strongly associated with BV freq. @r=8km, which decreases with time
  → decrease of g_1-mode

comparison with GW signals in numerical simulation

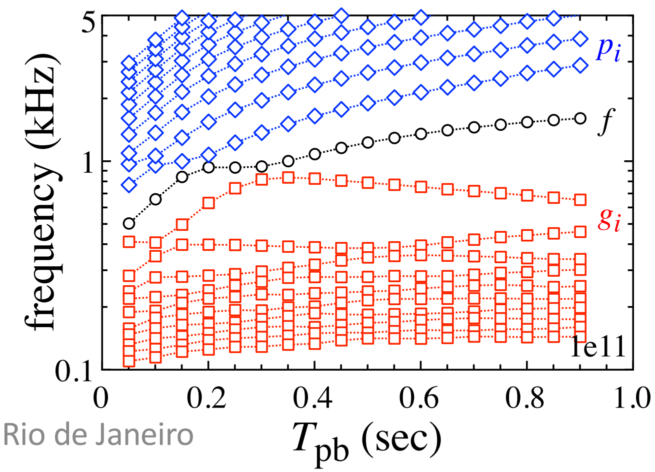
- GW signals correspond to g_1-mode in early phase and f-mode after avoided crossing.

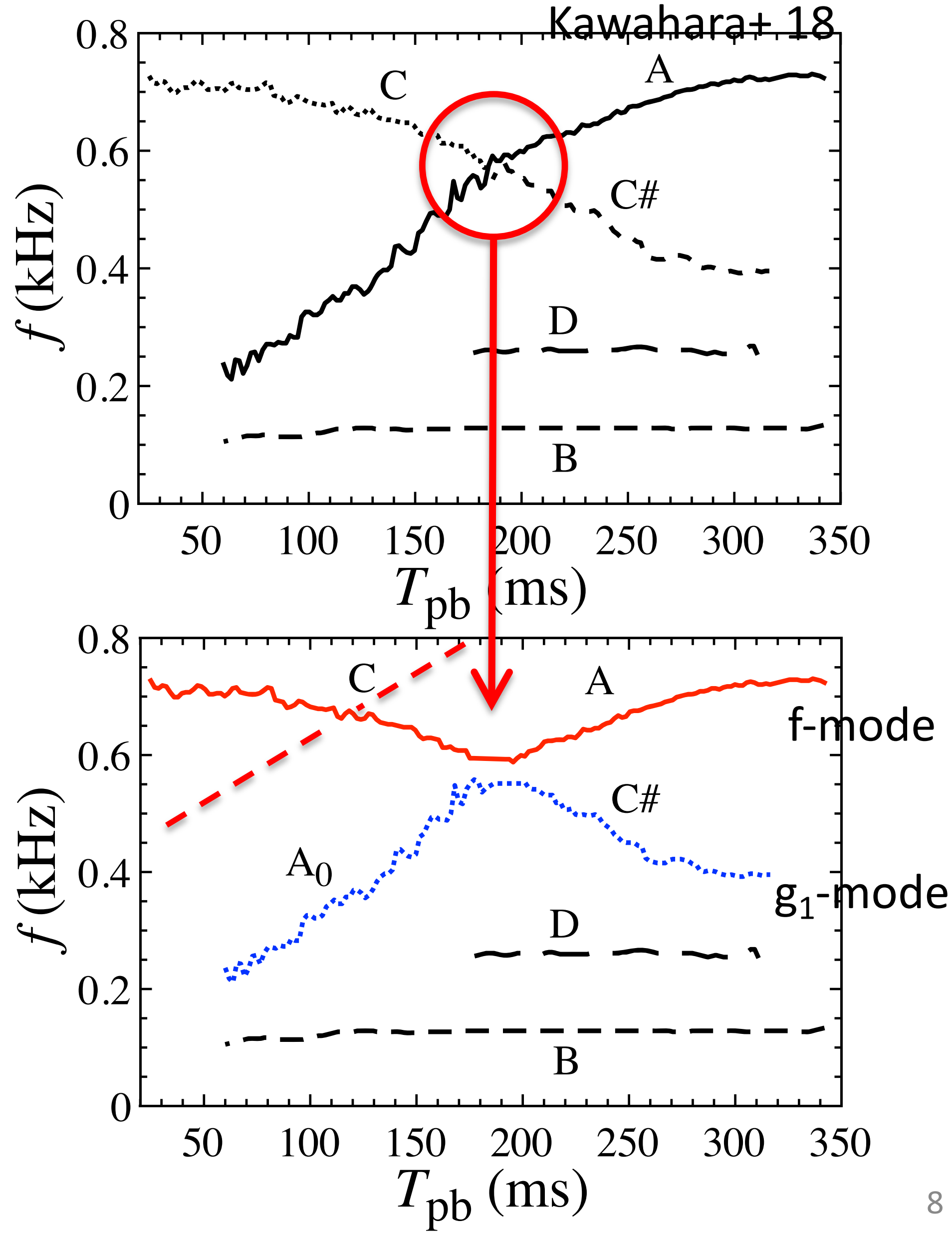


avoided crossing in GW signal?

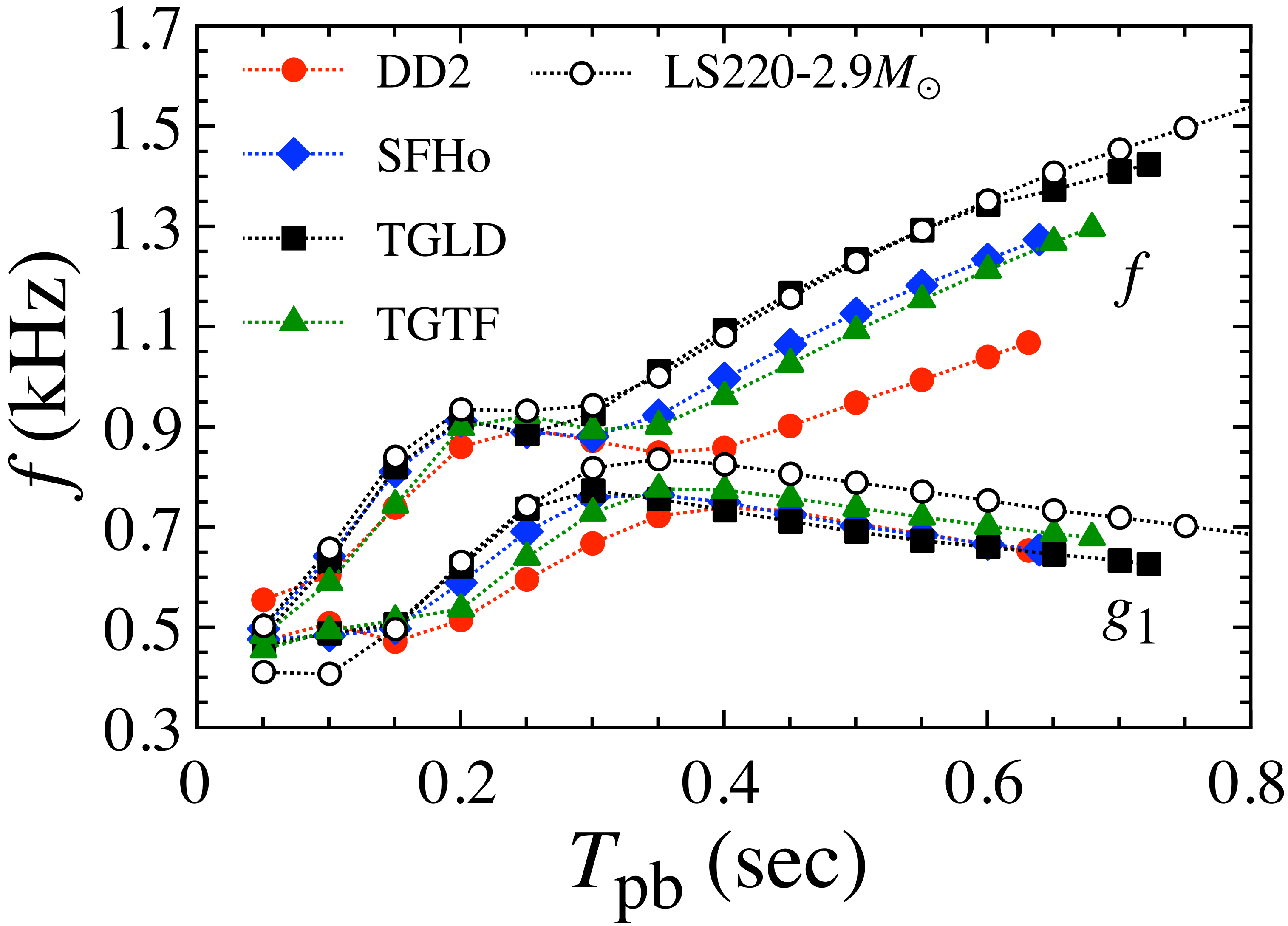


Kuroda+ 16

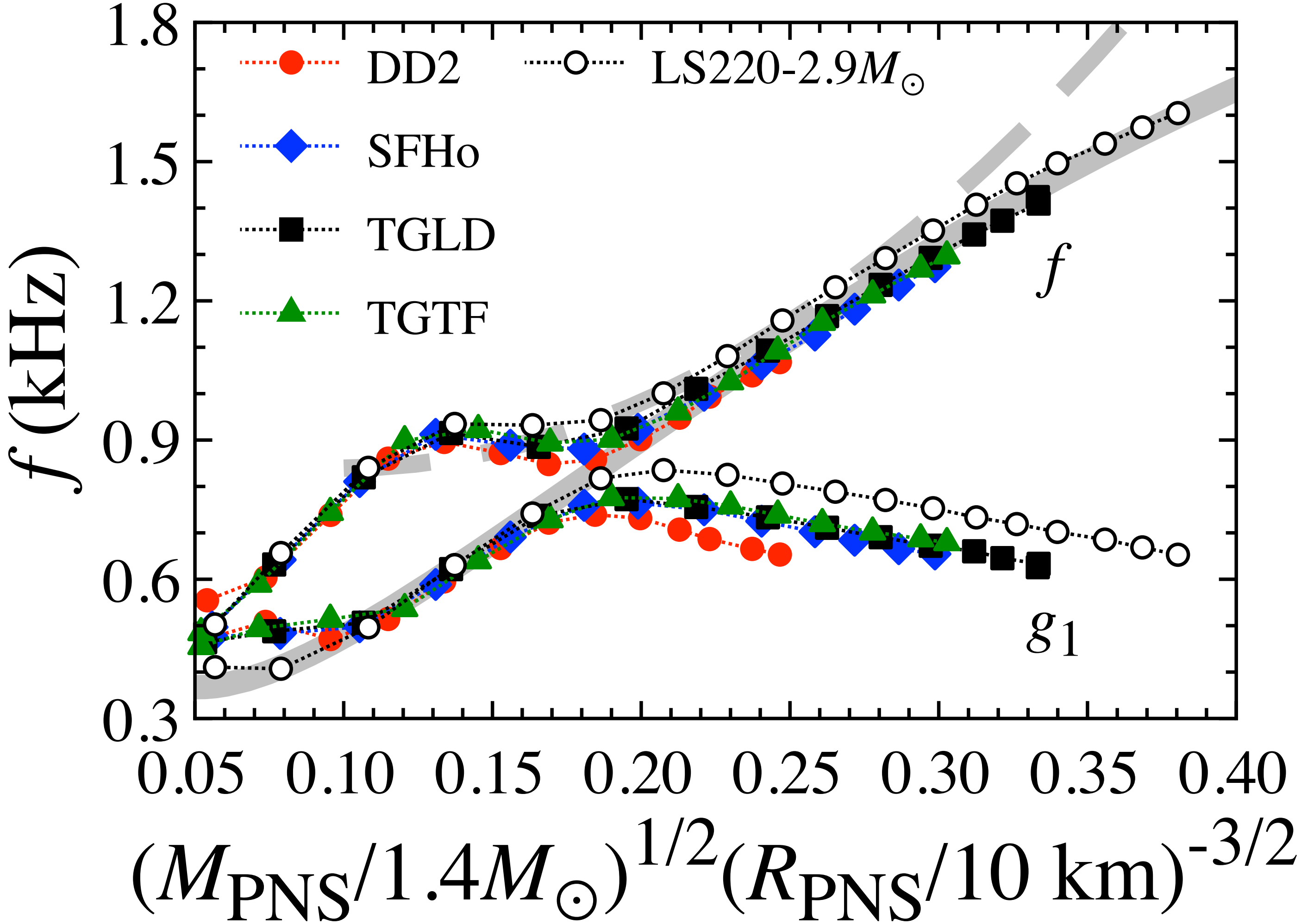




dep. of GW signals on PNS models

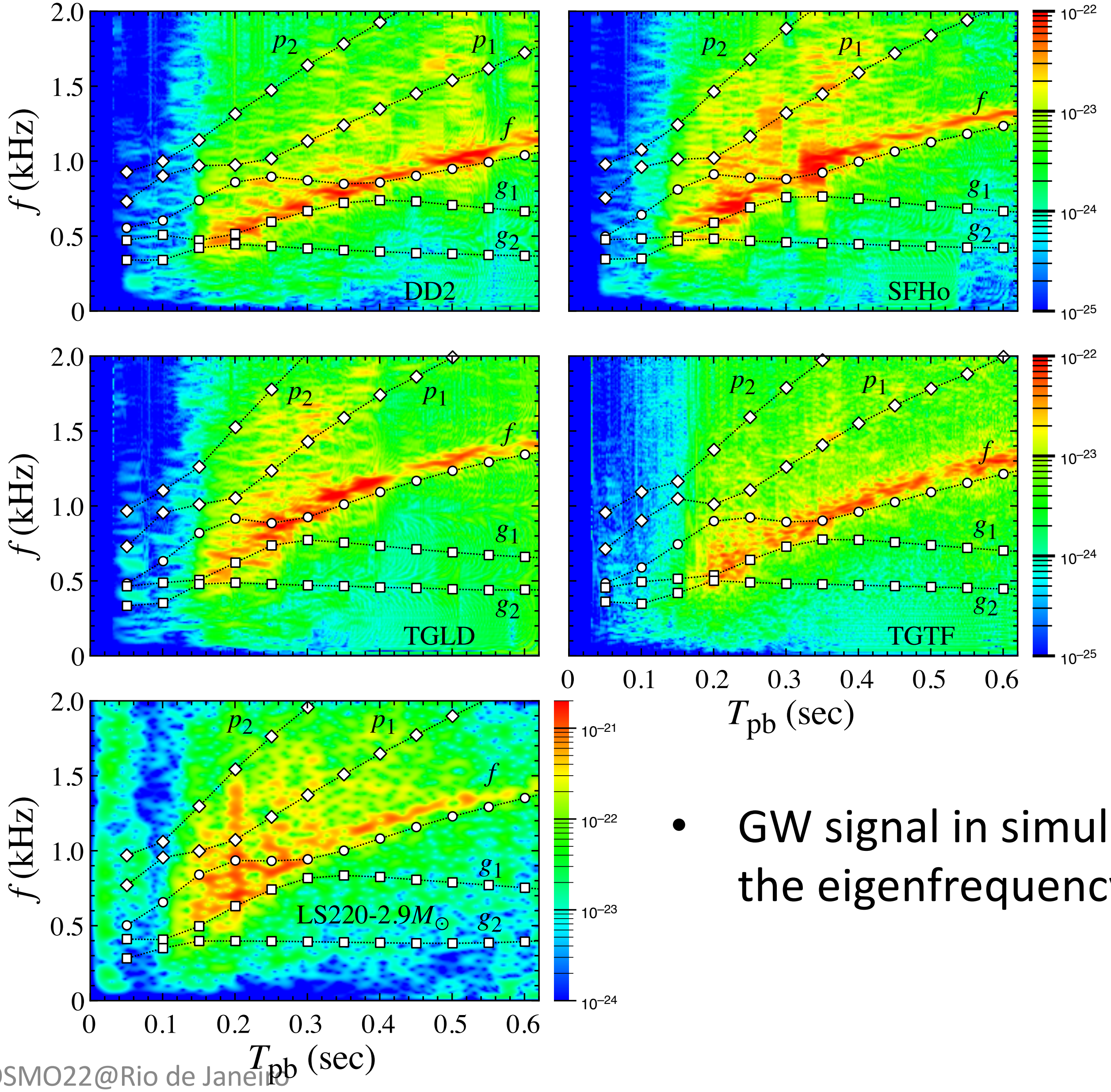


universal relation



$$f\ (\mathrm{kHz}) = -1.410 - 0.443\ln(x) + 9.337x - 6.714x^2$$

still systematical deviation



- GW signal in simulation deviates from the eigenfrequency ~ 100Hz.

summary

- we examine the GW freq. from PNSs
- GW signals in numerical simulations correspond to g_1- & f-modes
  - we find the empirical formula for GW signals
  - via the GW observations, one could extract the PNS average density
- For the BH formation, owning to the neutrino observation, one would determine the average density of PNS with maximum mass by detecting the f-mode GW.

- Still, there are some open problems;
  - systematical deviation between the GW signal and PNS frequencies.
  - difference in the universal relation for BH formation and successful SN

- We will take into account
  - the effect of the radial velocity as background properties.
  - the rotational effects