Crustal oscillations and resonance shattering

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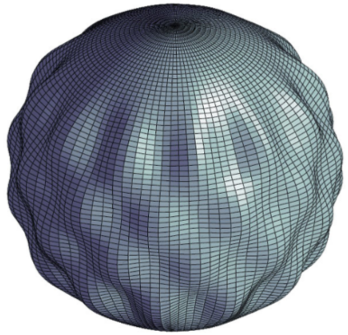
NS oscillation modes

- axial parity
  - spacetime (w-) modes
  - torsional (t-) modes
  - rotational (r-) modes
  - magnetic modes
- polar parity
  - fundamental (f-) modes
  - pressure (p-) modes
  - gravity (g-) modes
  - spacetime (w-) modes
  - shear (s-) modes
  - interface (i-) modes
  - inertial (i-) modes
  - magnetic modes



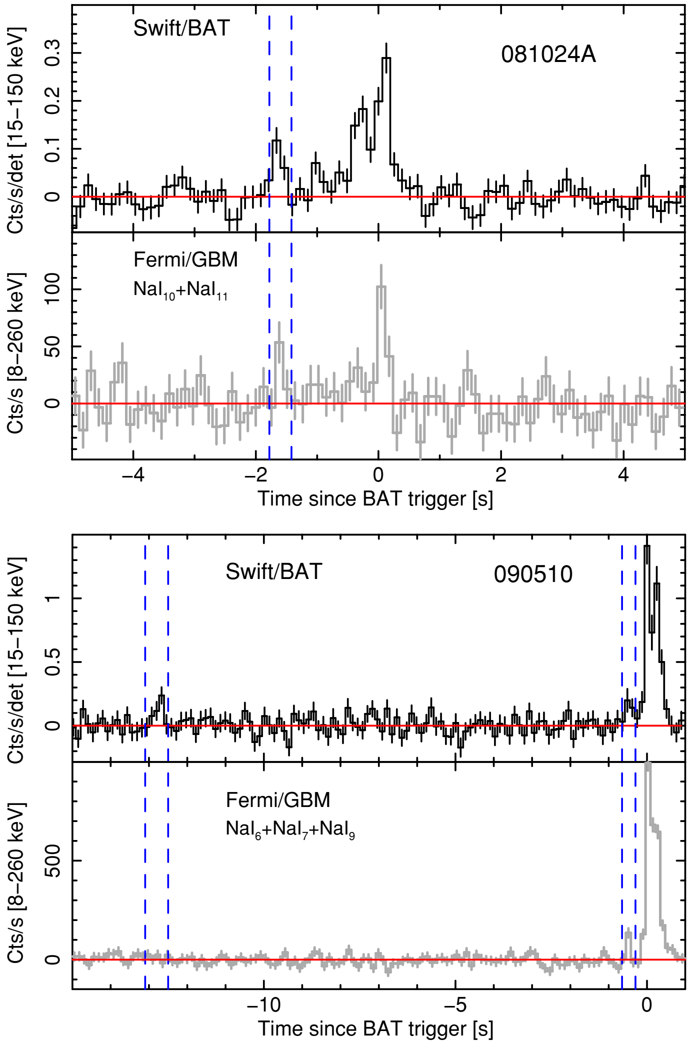
under the angular transformation
($\theta \rightarrow \pi - \theta$, $\phi \rightarrow \pi + \phi$),
a spherical harmonic function
with index ℓ transforms as
$(-1)^{\ell+1}$: axial parity / $(-1)^{\ell}$: polar parity

QPOs at 22^{+3}_{-2} Hz & 51^{+2}_{-2} Hz were detected
at the pre-merger stage preceding GRB211211
(Xiao+22)
↓
result of the resonant shattering
(due to tidal interactions)
of one of the stars' crust prior to coalescence,
leading to the excitation of crustal oscillations
(Tsang+12;13;Suvorov+22)?

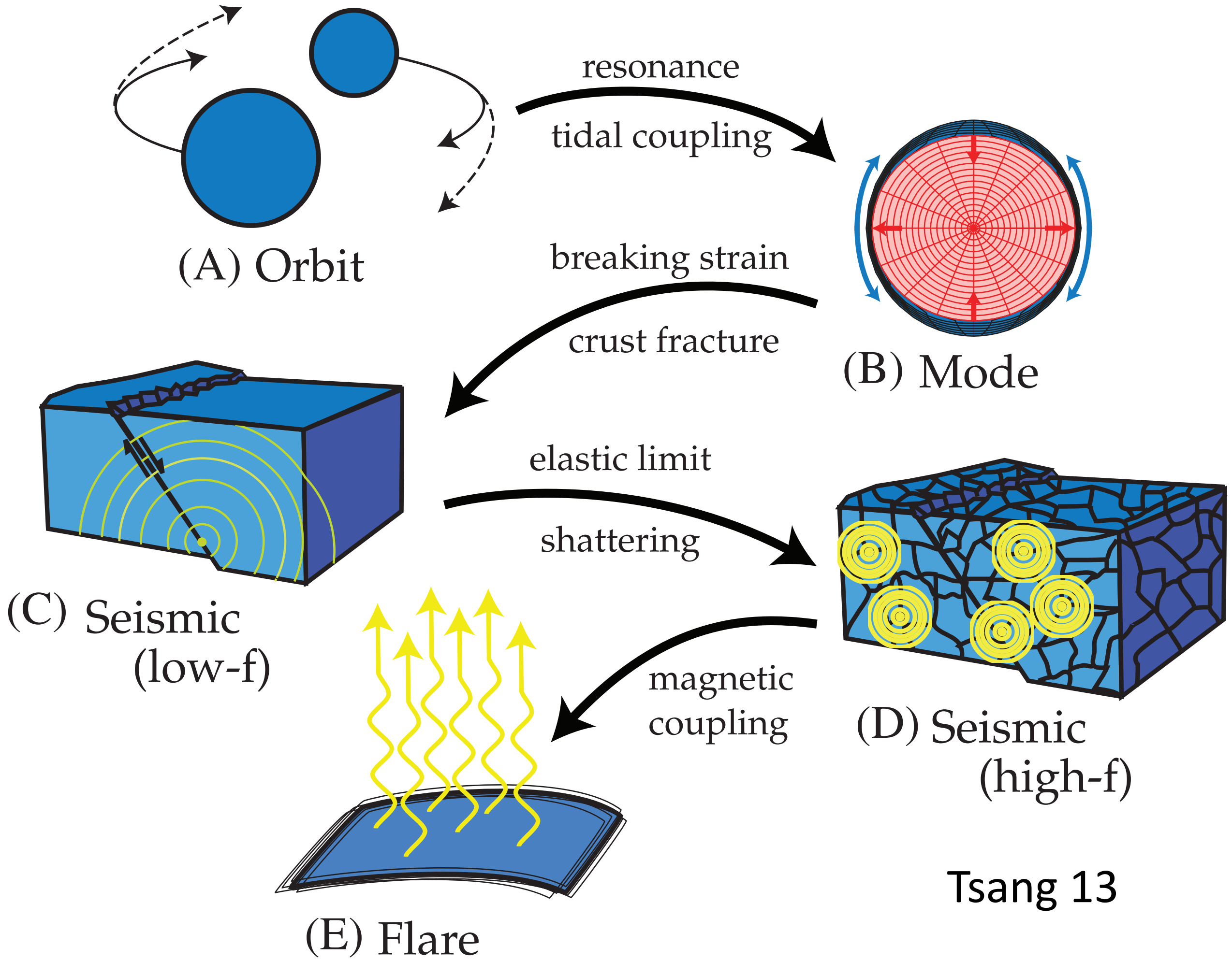
we focus on

Resonant shattering

- Precursors 1–10 s prior to the main flare were detected with high significance for three SGRBs out of the 49 (Troja+10)



Troja+10



Tsang 13

Double-layer model
(lasagna sandwich) HS+19

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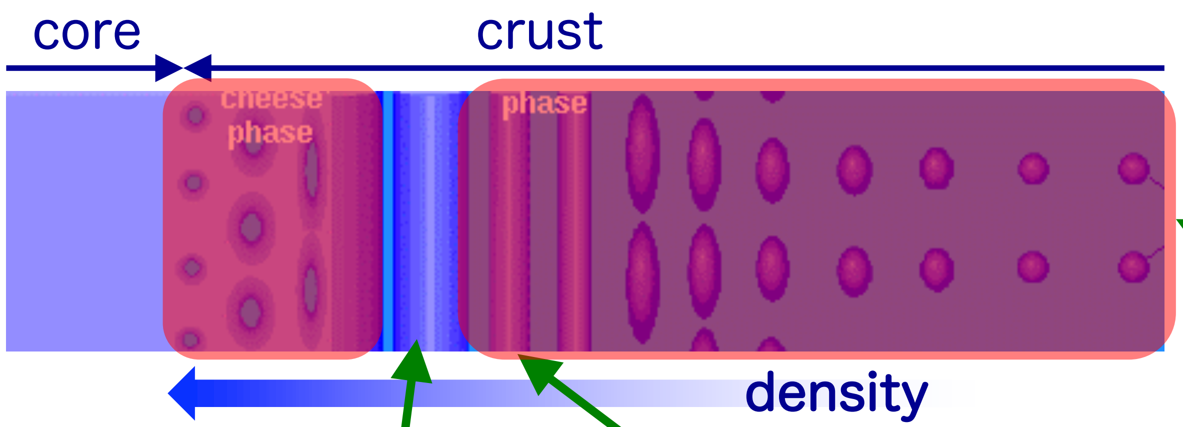


spherical (Strohmayer+ 91)

$$\mu = 0.1194\frac{n_i(Ze)^2}{a}$$

cylindrical (Potekhin+98)

$$\mu_{cy} = \frac{2}{3}E_{Coul} \times 10^{2.1(w_2-0.3)}$$

E_{Coul} : Coulomb energy per unit volume
w_2 : volume fraction

slab-like

linear response : fluid (Landau)

→two elastic regions
(i) spherical + cylindrical (sp+cy)
(ii) tube + bubble (tu+bu)

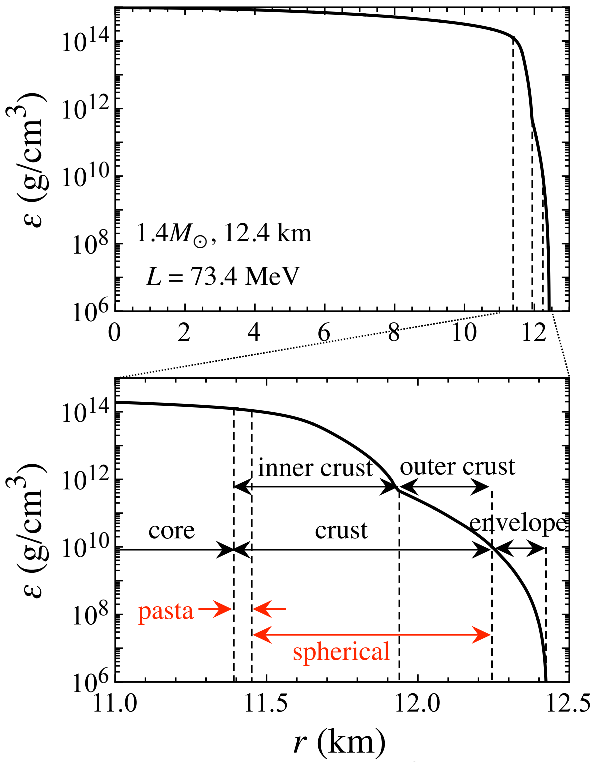
→bubble ~ spherical
tube ~ cylindrical

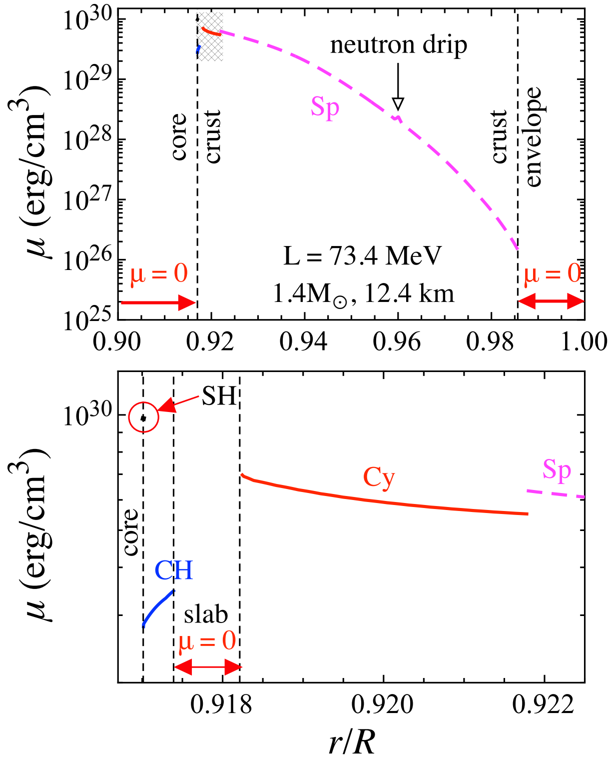
EOSs & NS properties

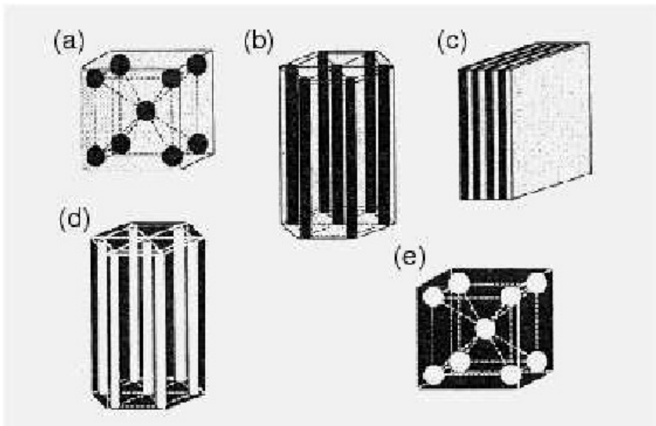
- we simply adopt two OI-EOSs

K_0 (MeV)	L (MeV)	SP-C (fm^{-3})	C-S (fm^{-3})	S-CH (fm^{-3})	CH-SH (fm^{-3})	SH-U (fm^{-3})	$\Delta R_{\mathrm{SpCy}}/R$	$\Delta R_{\mathrm{CHSH}}/R$
230	42.6	0.06238	0.07671	0.08411	0.08604	0.08637	0.0007731	0.05406
230	73.4	0.06421	0.07099	0.07284	0.07344	0.07345	0.0003773	0.06740

- crust thickness strongly depends on L and M/R
  - as L and M/R increase, crust thickness decreases



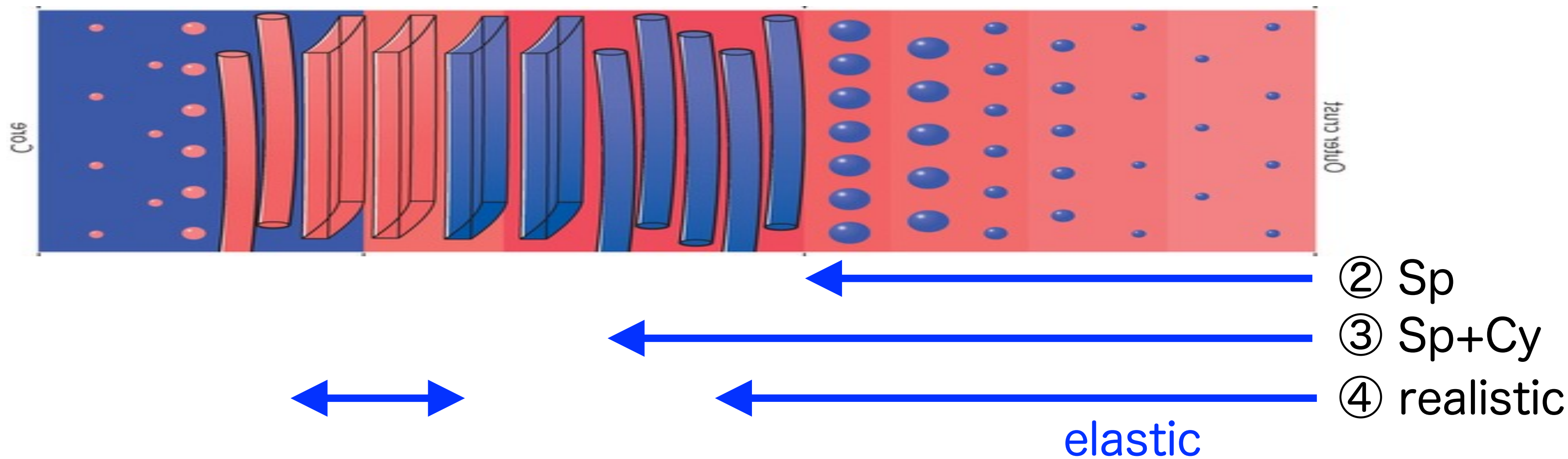




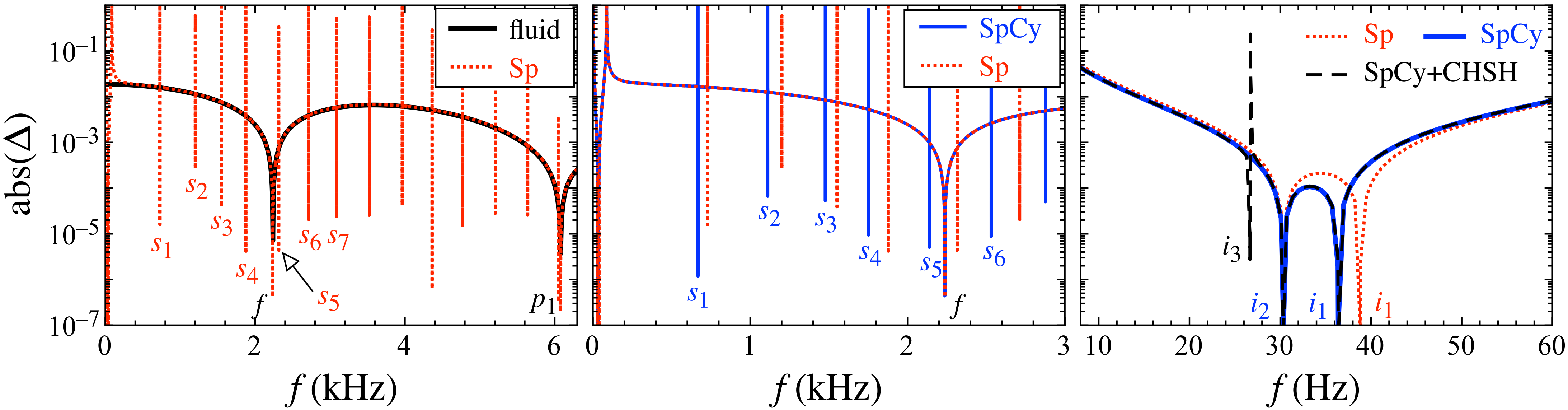
Oyamatsu 93

Stellar models

- To understand the dependence of eigenfrequencies excited in NSs on the presence of elasticity, we consider four models
  - ① NS composed of fully zero-elastic "fluid"
  - ② NS with elastic phase composed of spherical nuclei, "Sp"
  - ③ NS with elastic phase composed of spherical and cylindrical nuclei, "Sp+Cy"
  - ④ "realistic" NS model with elastic phase composed of Sp, Cy, CH, & SH nuclei
- First, we focus on a specific NS model with $1.4M_{\odot}$ and 12.4 km constructed with L = 73.4 MeV

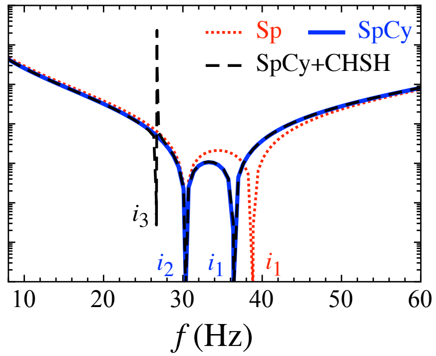


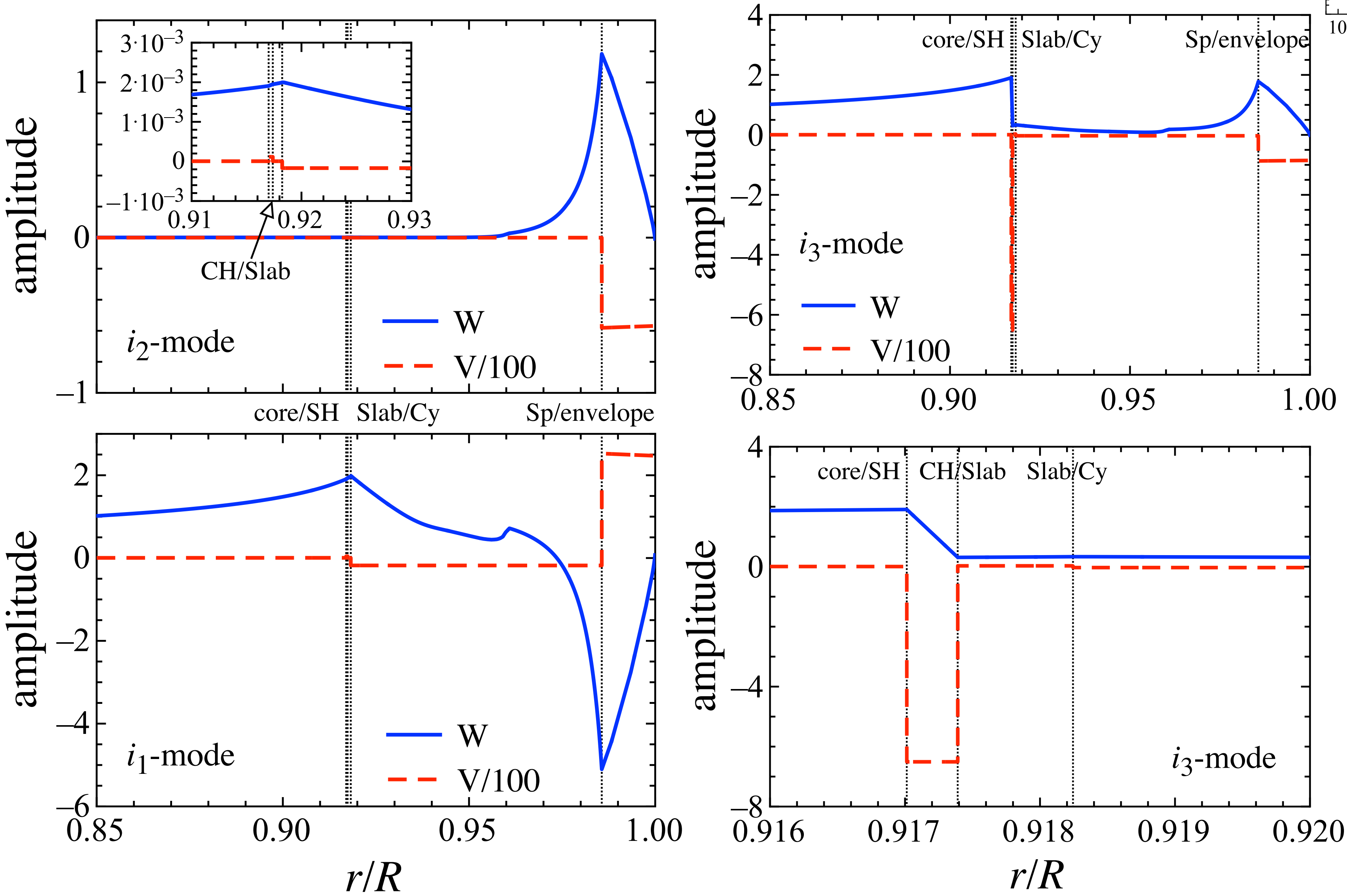
Behavior of eigenfrequencies



- Frequencies with Δ=0 correspond to the eigenfrequencies

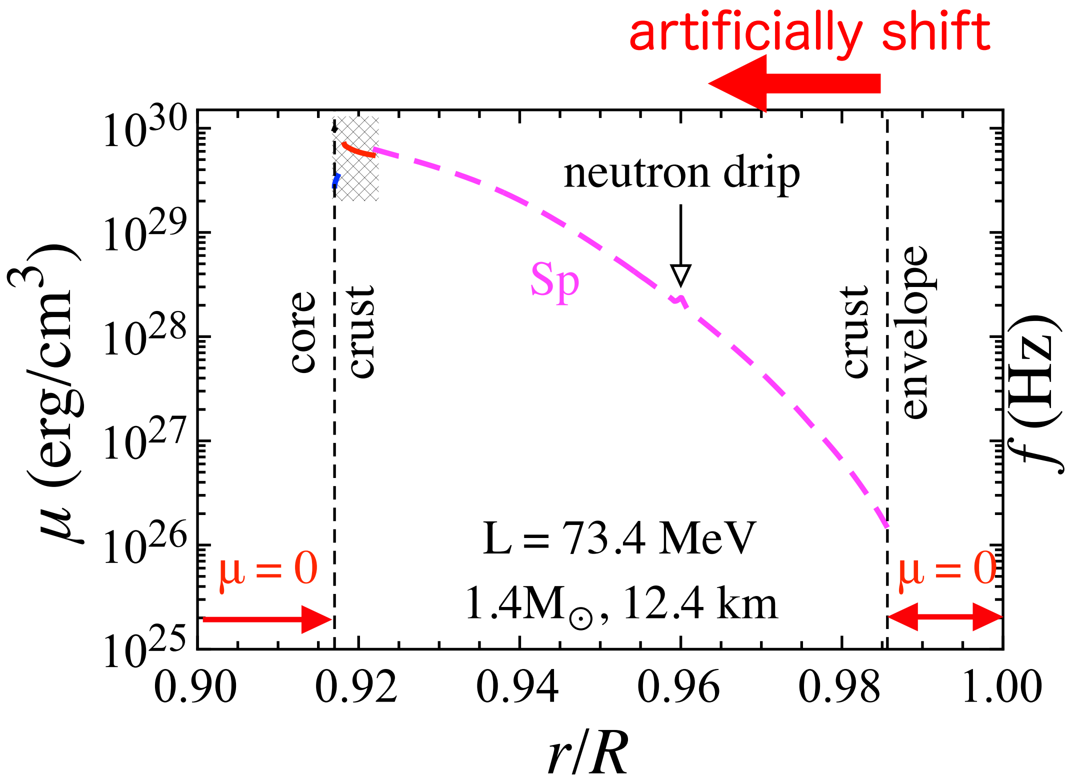
Eigenfunctions (i-modes)

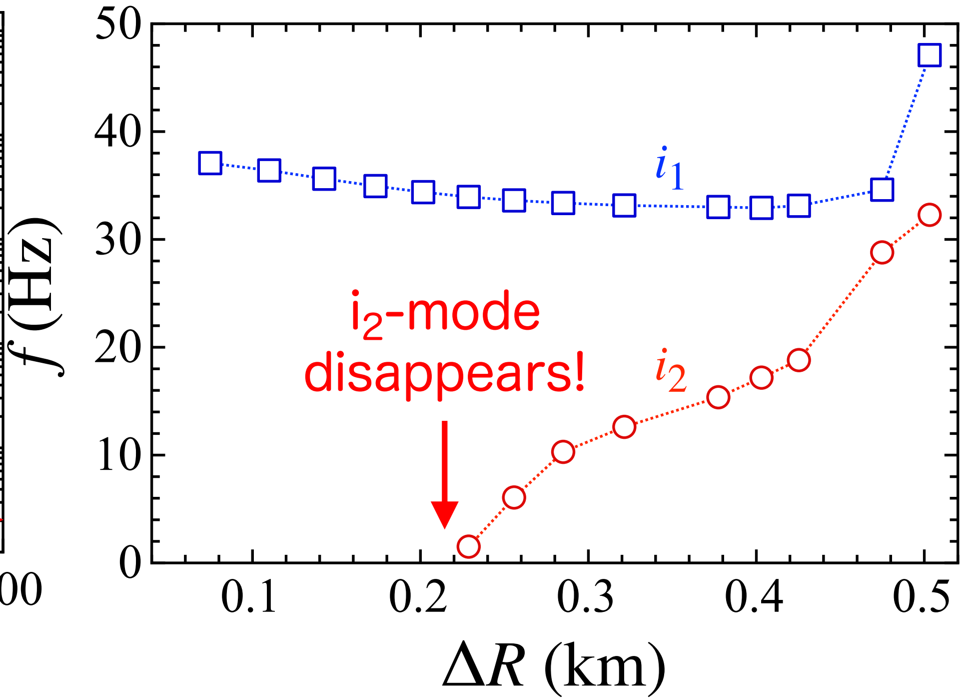




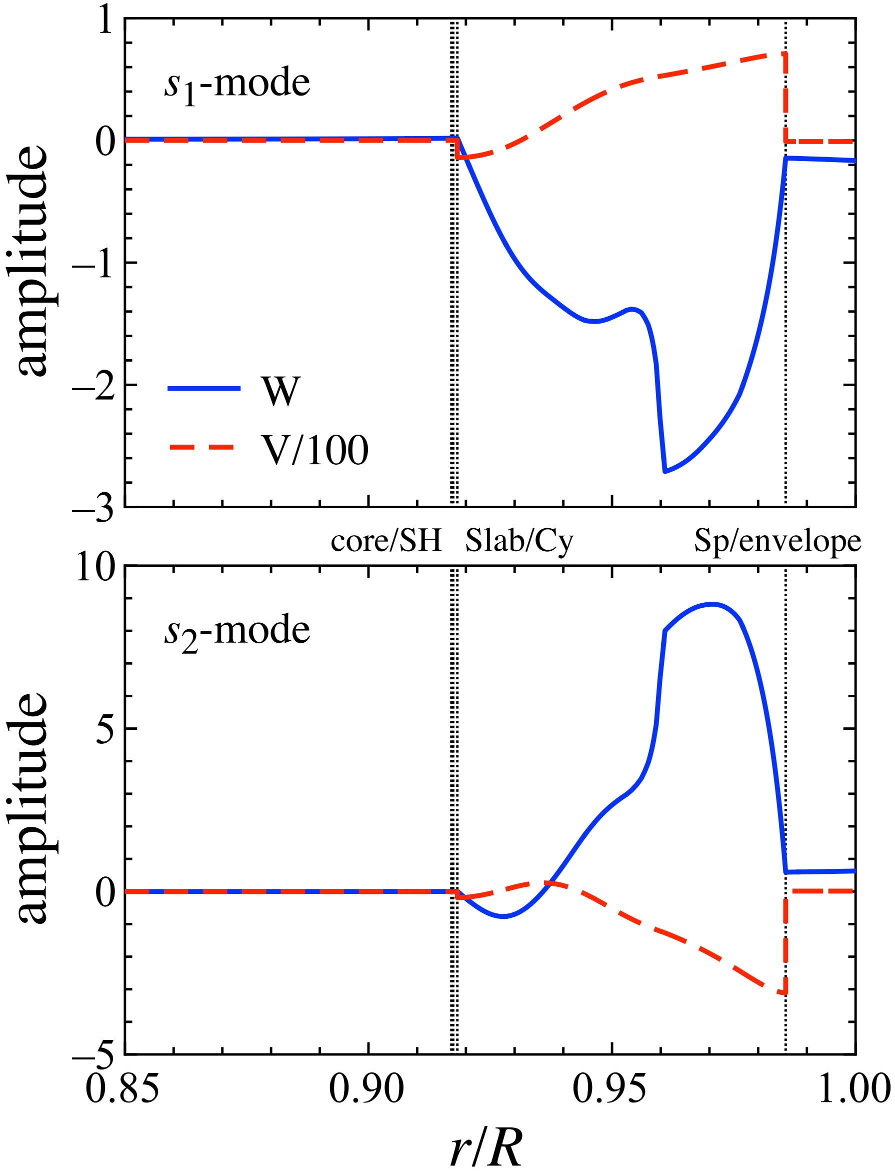
why only three i-modes

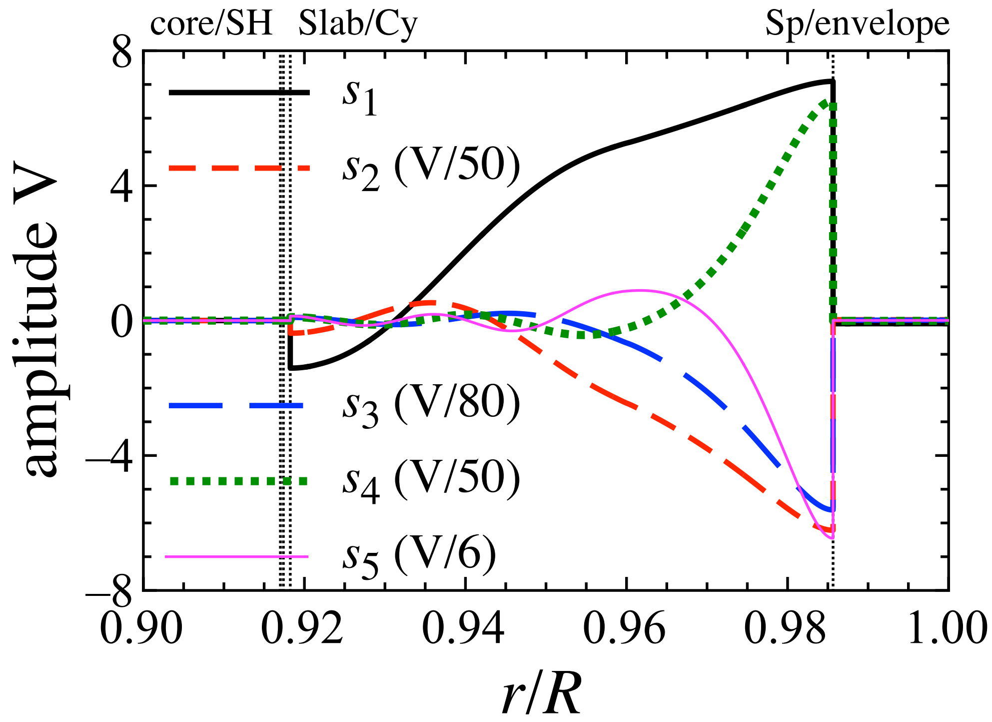
- The number of the i-modes is the same as the number of interfaces?
- Dependence of the i-mode frequencies on the thickness of an elastic region





Eigenfunctions (s-modes)

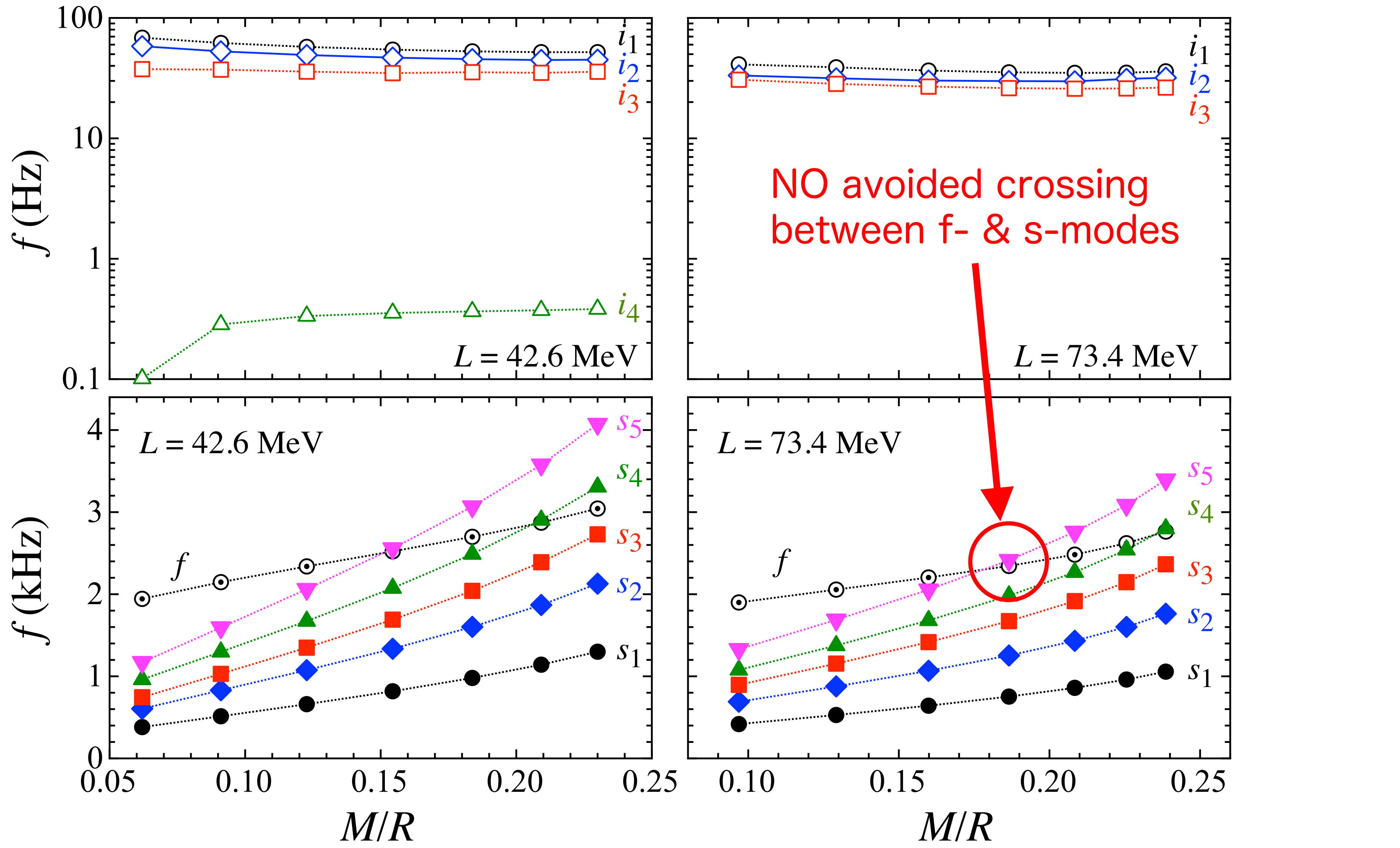




s-modes are confined only inside the elastic region

- wavelength of s_i-mode: $\lambda_i \simeq 2\Delta R/i$
- frequency: $f_i \approx v_s/\lambda_i$

Dependence on M/R



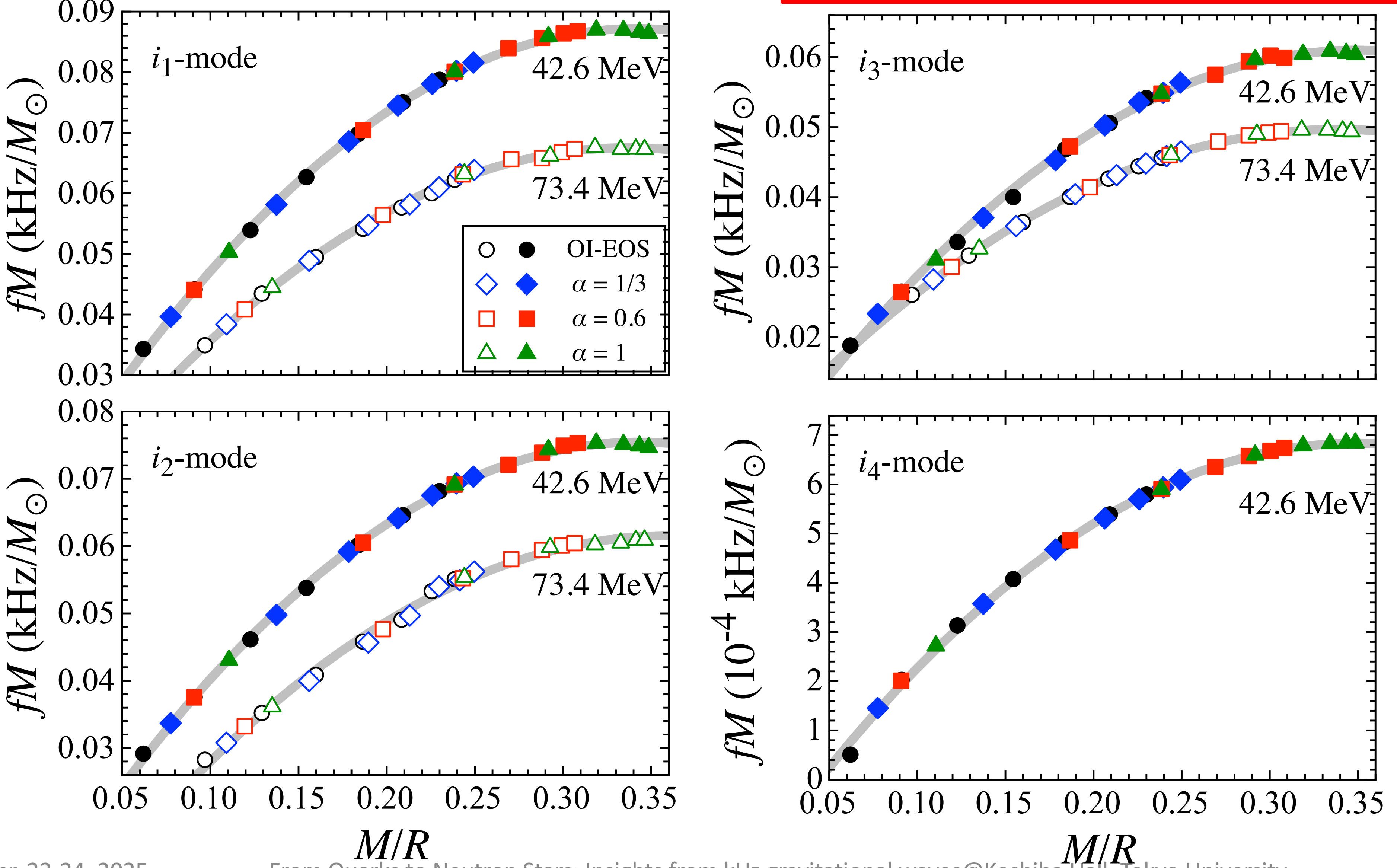
Uncertainties in core EOS

- To see the dependence on the EOS stiffness in a higher-density region, we adopt not only the original OI-EOSs but also the one-parameter EOS, such as
  for a lower-density region ($\varepsilon \leq \varepsilon_t$): original OI-EOSs
  for a higher-density region ($\varepsilon \geq \varepsilon_t$): $p = \alpha(\varepsilon - \varepsilon_t) + p_t$.
- α is associated with the sound velocity as $c_s^2 = \alpha$
- we consider in the range of $1/3 \leq \alpha \leq 1.$

Empirical relation (i-modes)

$$fM\ (\mathrm{kHz}/M_\odot) = a_0 + a_1(x/0.1) + a_2(x/0.1)^2$$

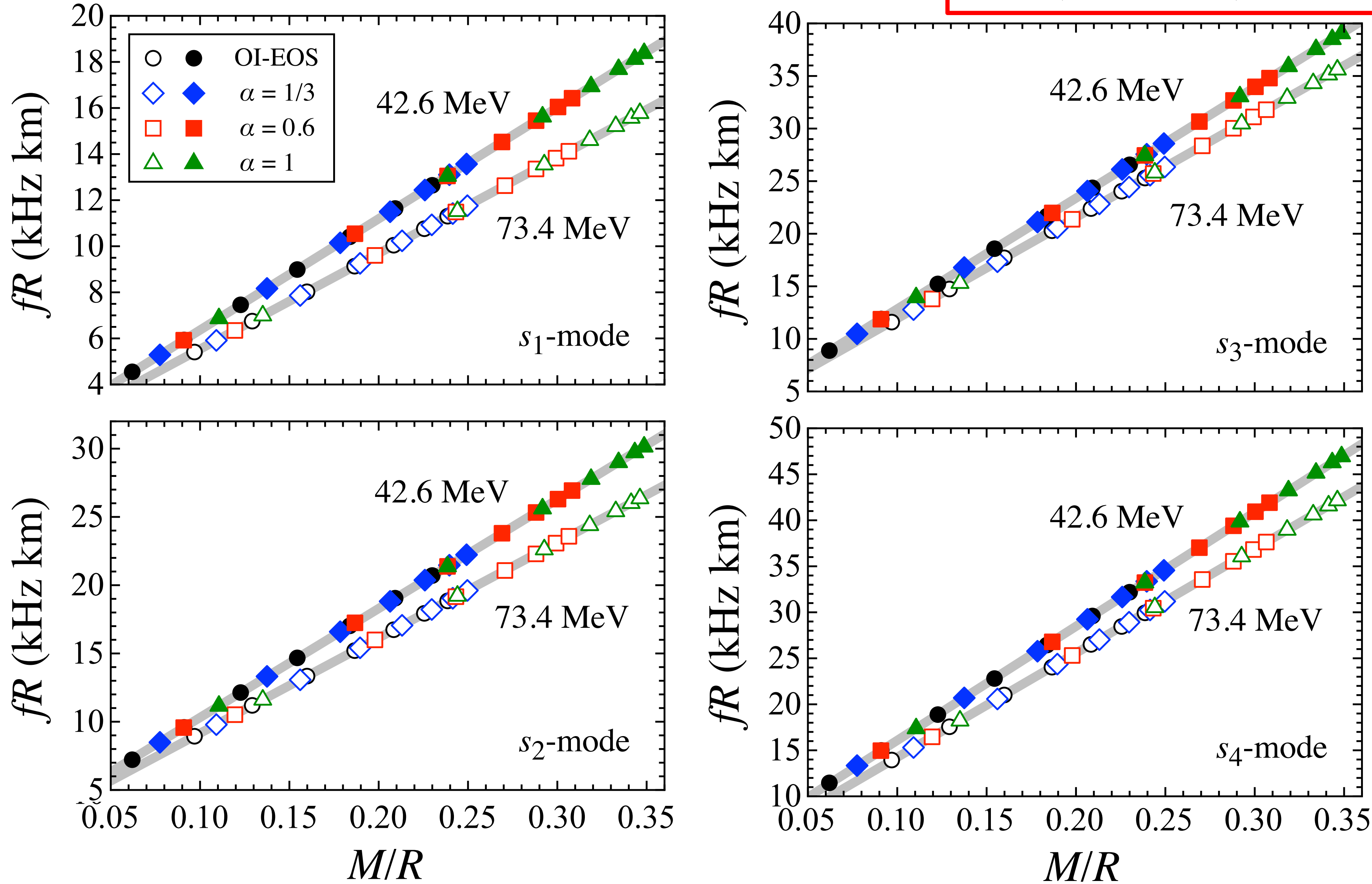
$x = \mathrm{M/R}$



Empirical relation (s-modes)

$$fR\ (\text{kHz km}) = b_0 + b_1(x/0.1)$$

x = M/R



- we find two different types of fitting formulae for the i- and s-mode freq.
  - depend only on the crust stiffness (crust EOS)

- If one would simultaneously observe the i- and s-modes, one might extract the stellar mass and radius with the help of the constraint on the crust stiffness from the terrestrial experiments.

Conclusion

- We carefully examine the s- and i-mode frequencies in realistic NS models
- s-mode frequencies are almost independent of the presence of CH and SH phases, at least up to a few kHz
- i-mode frequencies strongly depend on the presence of CH and SH phases
- We find the empirical relations for i- and s-mode frequencies
    - i-modes: $fM \ (\mathrm{kHz}/M_{\odot}) = a_0 + a_1(x/0.1) + a_2(x/0.1)^2$
    - s-modes: $fR \ (\mathrm{kHz\ km}) = b_0 + b_1(x/0.1)$ $x = \mathrm{M/R}$

  which depend only on the crust stiffness
- If one would simultaneously observe the i- and s-modes, one might extract the stellar mass and radius with the help of the constraint on the crust stiffness from the terrestrial experiments.