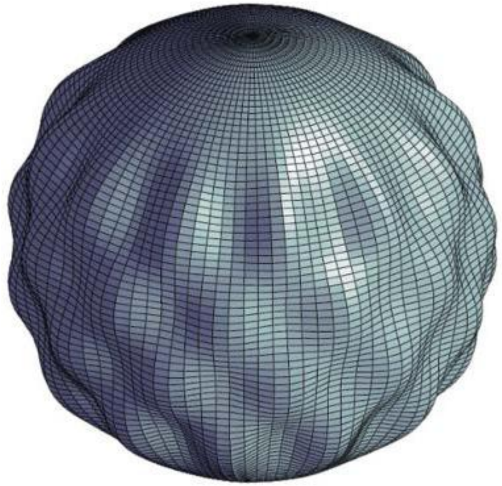
Astroseismology of NSs

Joint RIKEN/N3AS Workshop on Multi-Messenger Astrophysics

Hajime SOTANI (RIKEN ABBL/iTHMES)



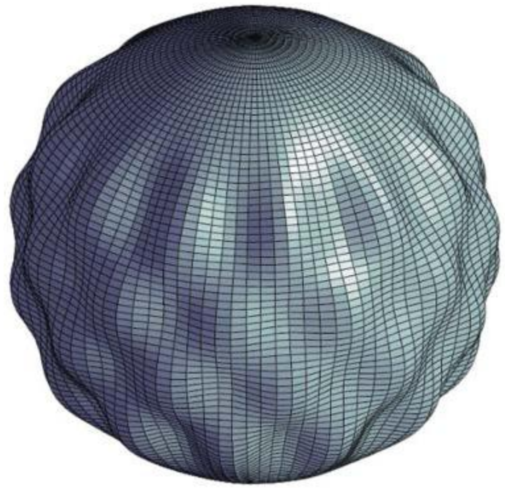
Asteroseismology

- how to know the best time to eat a watermelon?
  - inside can not be checked before cutting
- "empirical rule"
  - to check the best time, knock on a watermelon
    - high frequency "KIN-KIN"; too young
    - "BAN-BAN"; best time!
    - low frequency "BON-BON"; too old
  - may need many years to get this ability

- one could see the interior with specific sounds from objects.
  - asteroseismology
  - linear perturbation analysis is considered in this talk.

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

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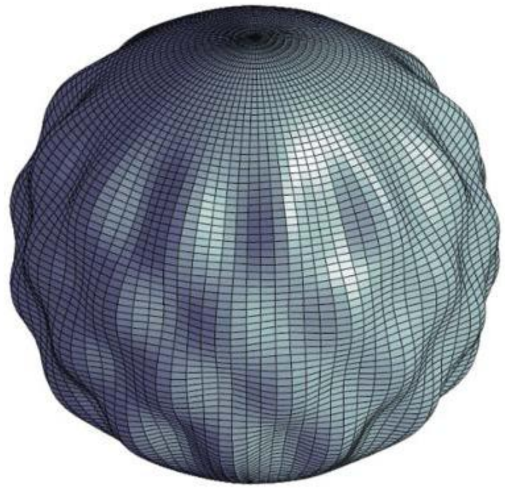

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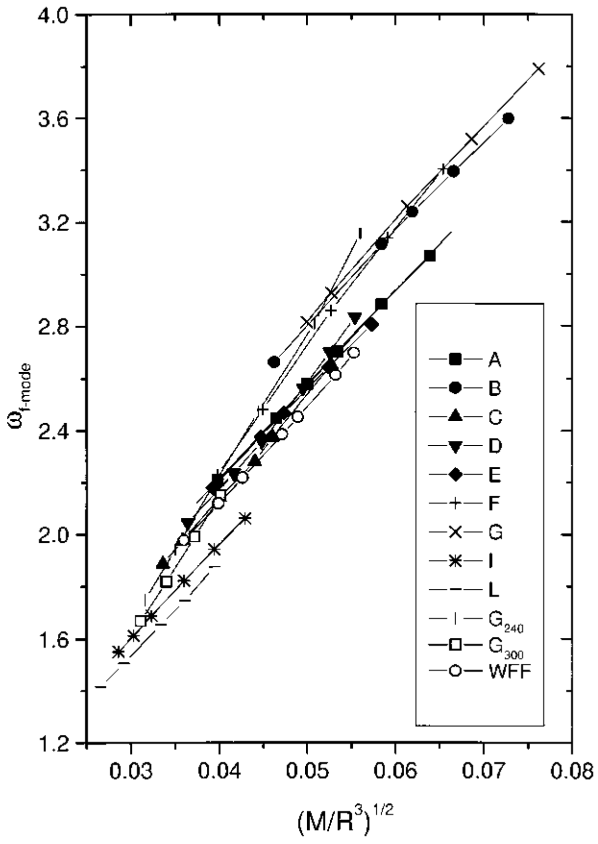
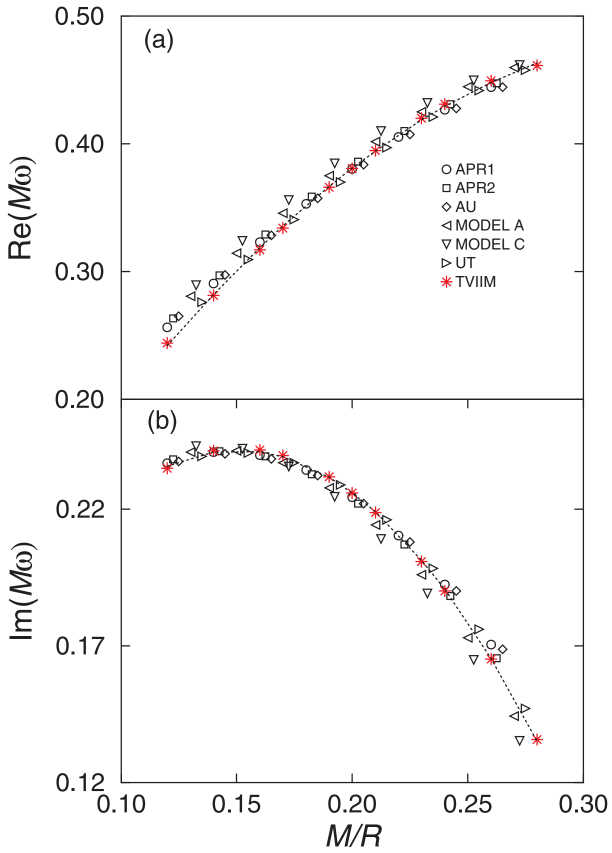
Universal (empirical) relations

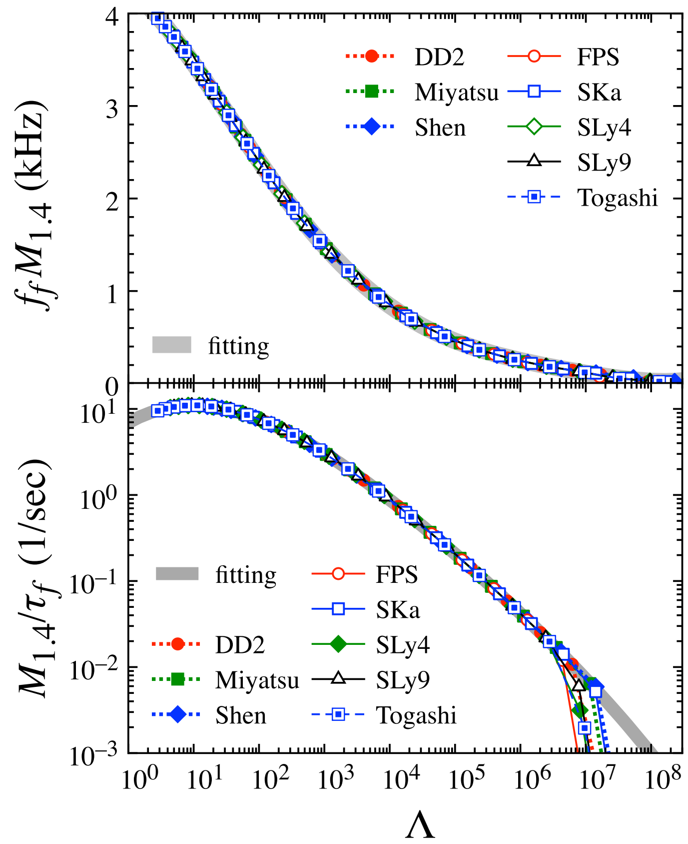
- To extract the physical properties from observables, a universal relation (independently of the EOS) must be important



Anderson & Kokkotas 98



Tsui & Leung 05

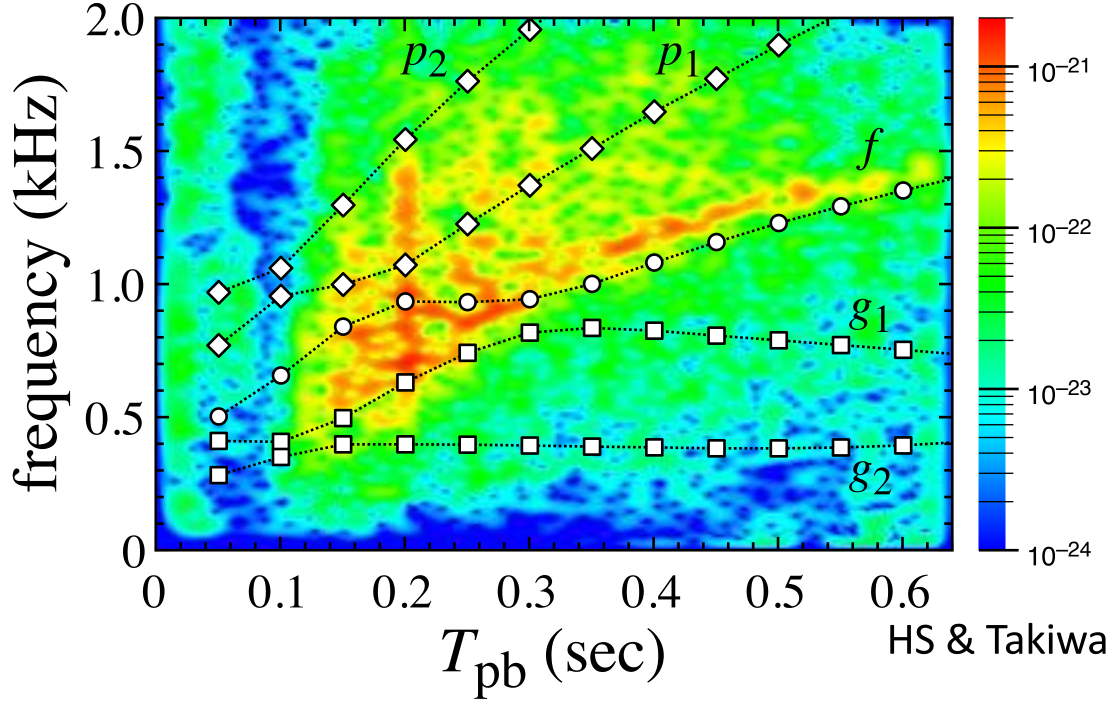


HS & Kumar 21

Contents

- supernova gravitational waves
- magnetar QPOs and torsional oscillations
- resonant shattering and shear/interface modes

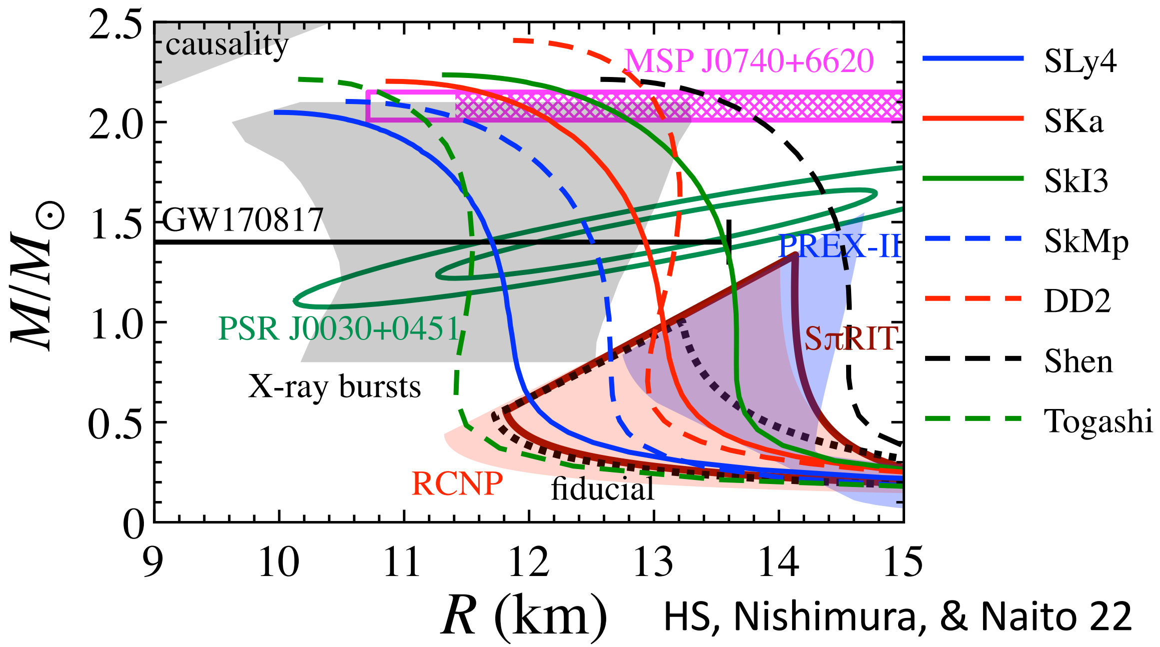
Supernova gravitational waves



HS & Takiwaki 20

Dawn of GW astronomy

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



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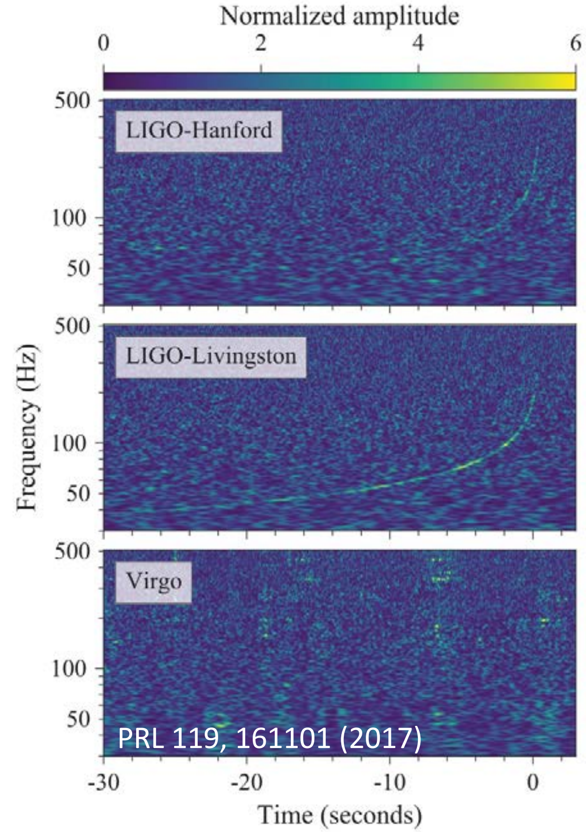
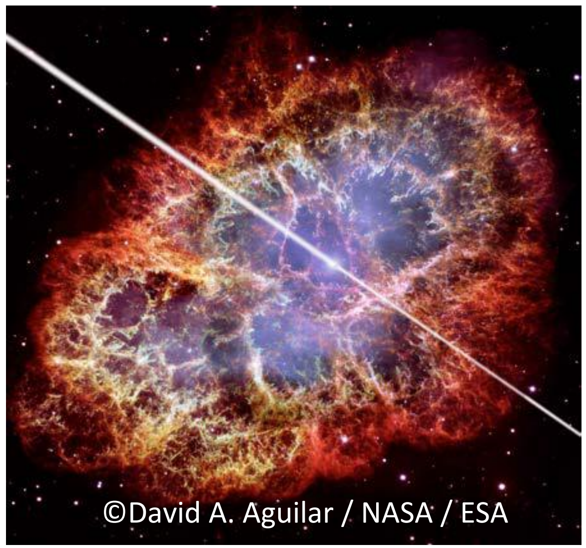
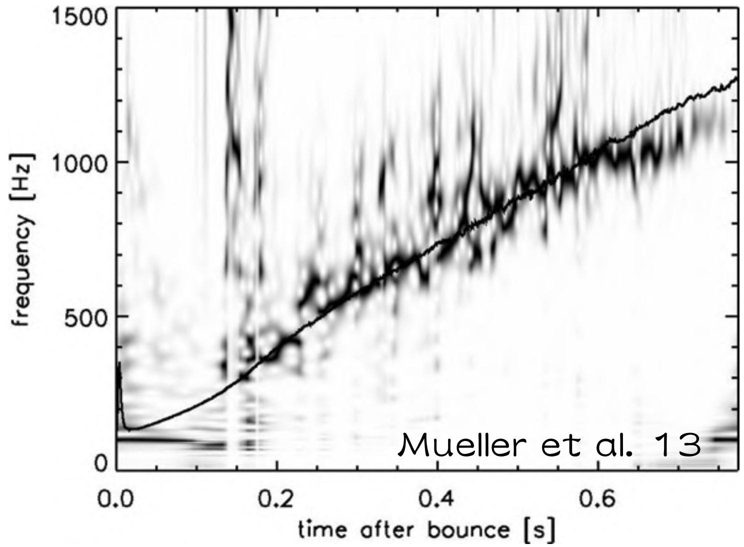


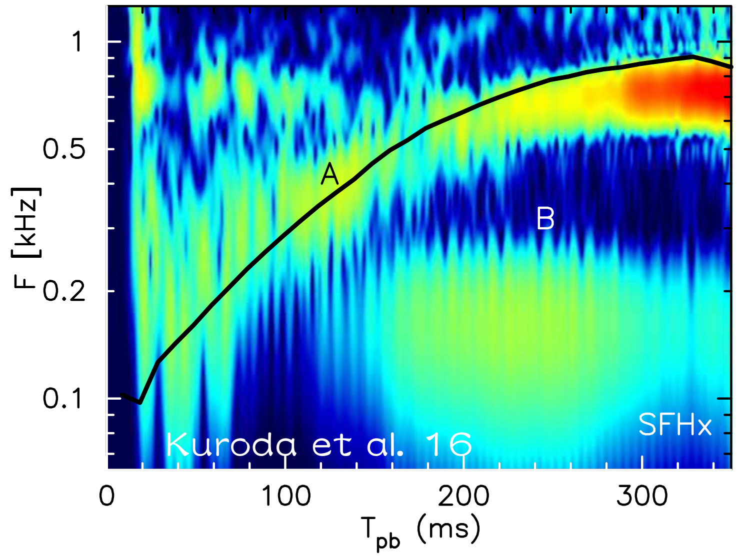


- The next candidate must be a supernova explosion.

Next candidate of GW sources

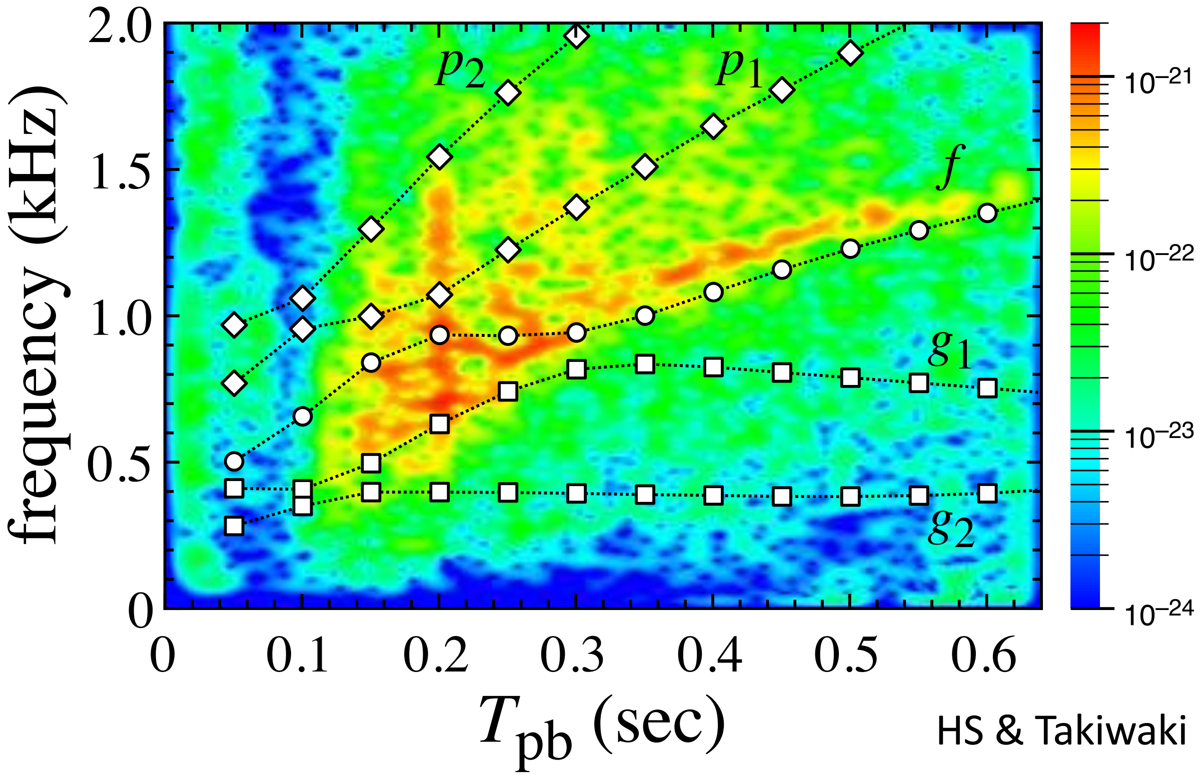
- core-collapse supernovae
  - compared to the binary merger, the system is almost spherically symmetric
    - less energy of gravitational waves
  - many numerical simulations show the existence of GW signals
  - SN GWs depend on the SN models, such as progenitor mass and EOS
    - how to extract the astronomical information from the GW observations?
    - what is the origin of the SN GWs?





Comparison with GW signals in numerical simulation

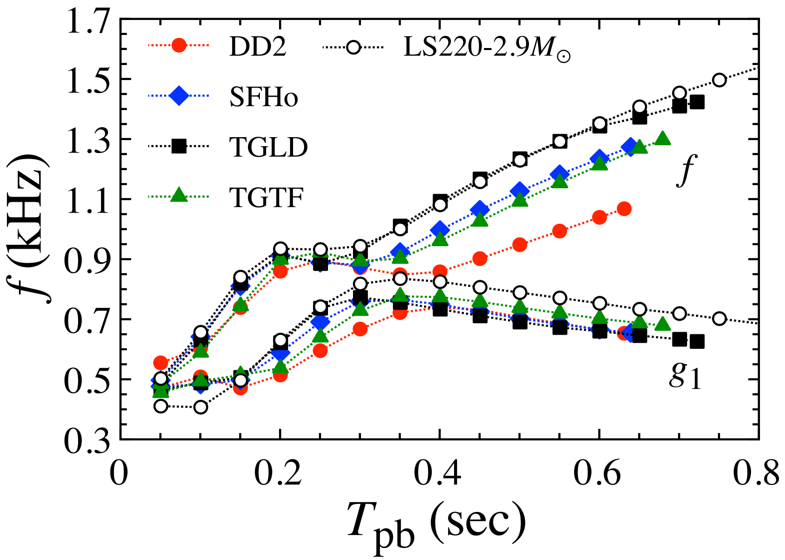
- GW signals correspond to g_1-mode in early phase and f-mode after avoided crossing.
  - similar correspondence has been seen even in various SN models

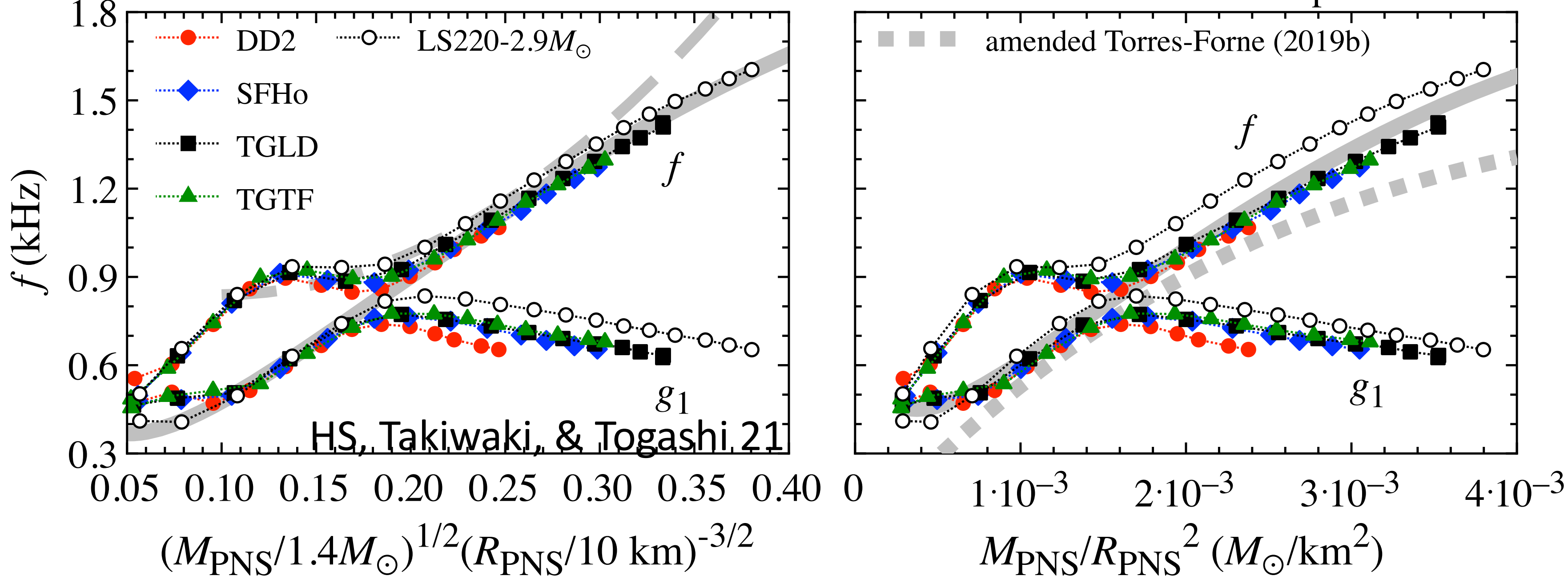


HS & Takiwaki 20

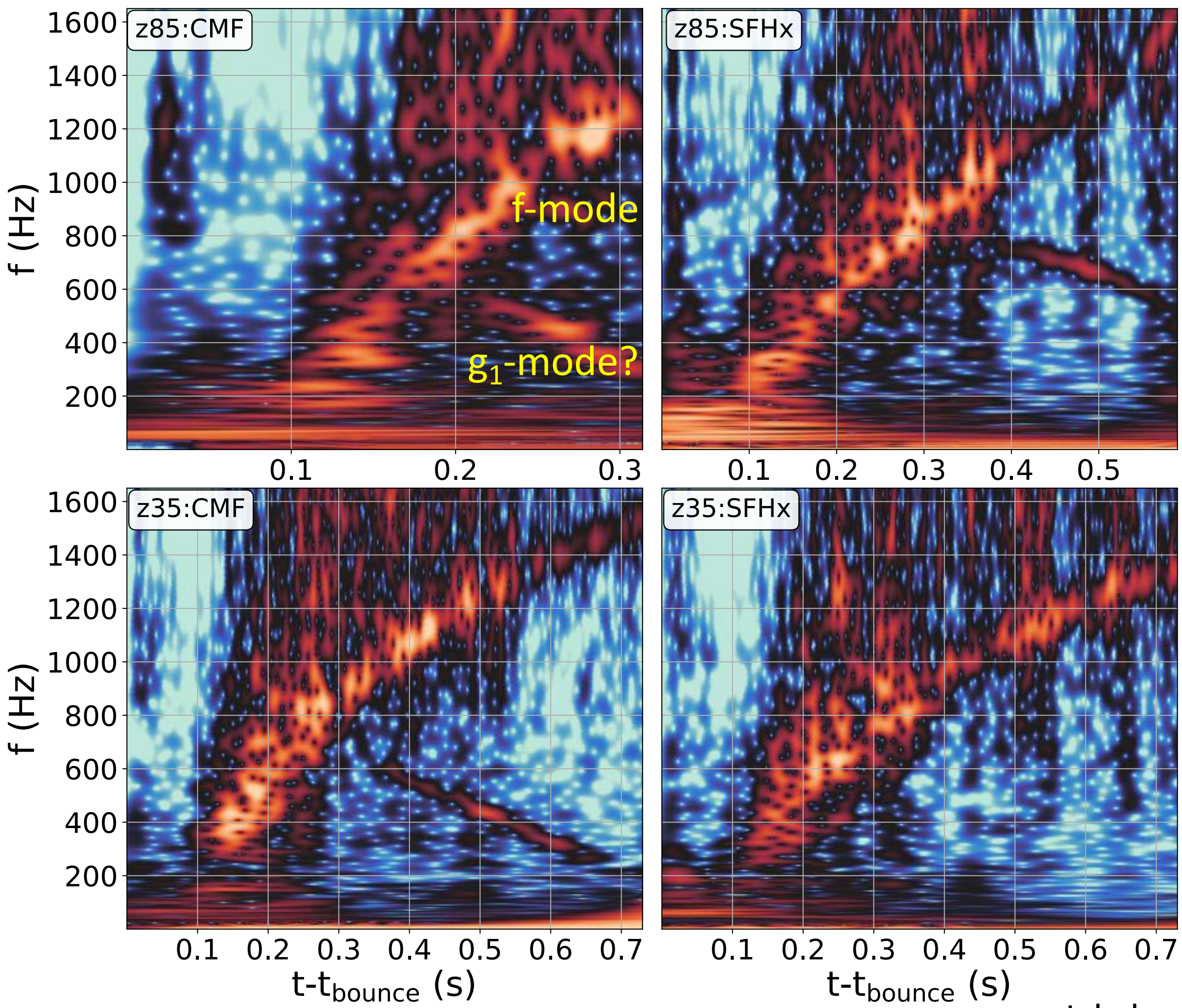
What can we learn from SN GWs

- GW freqs. evolution strongly depend on SN models, but…
- well expressed with average density or surface gravity of PNS





Signal of the g_1-mode oscillations?



Jakobus+23

Strong correlations M/R^2 & M/R^3

- Unlike cold NSs, we find the strong correlations in PNS properties

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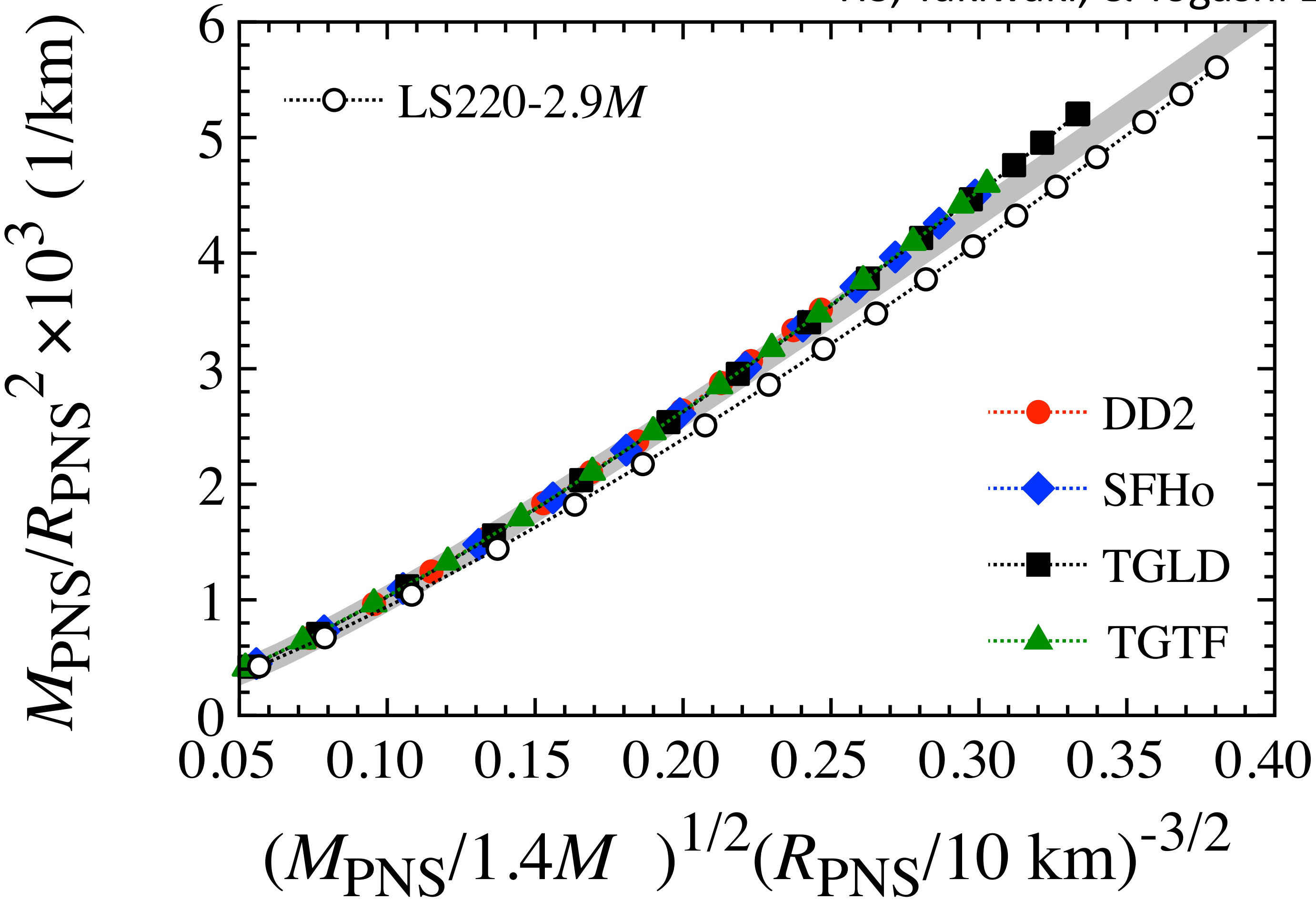
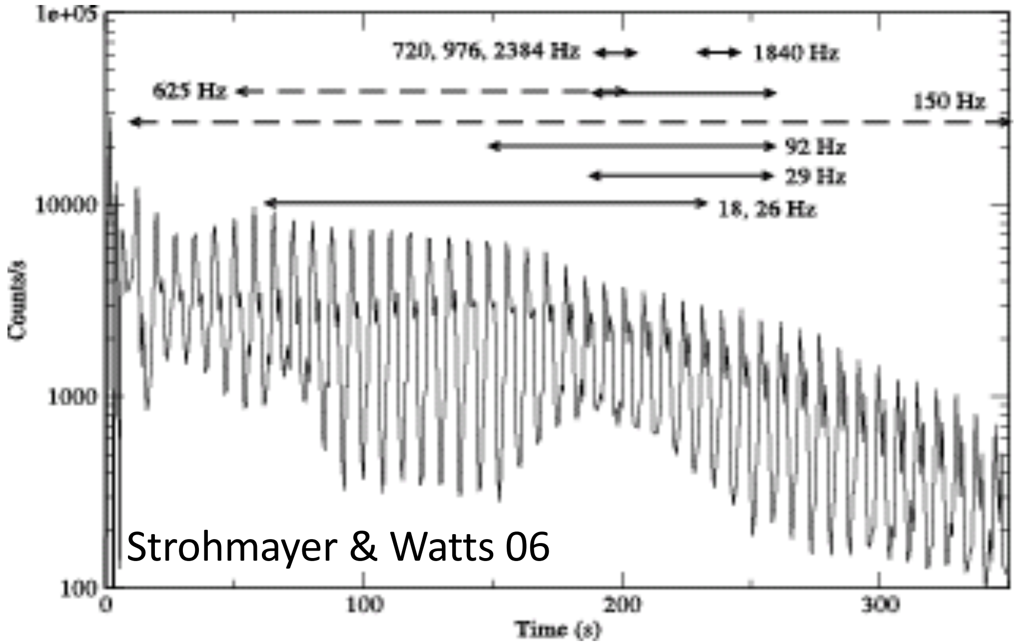
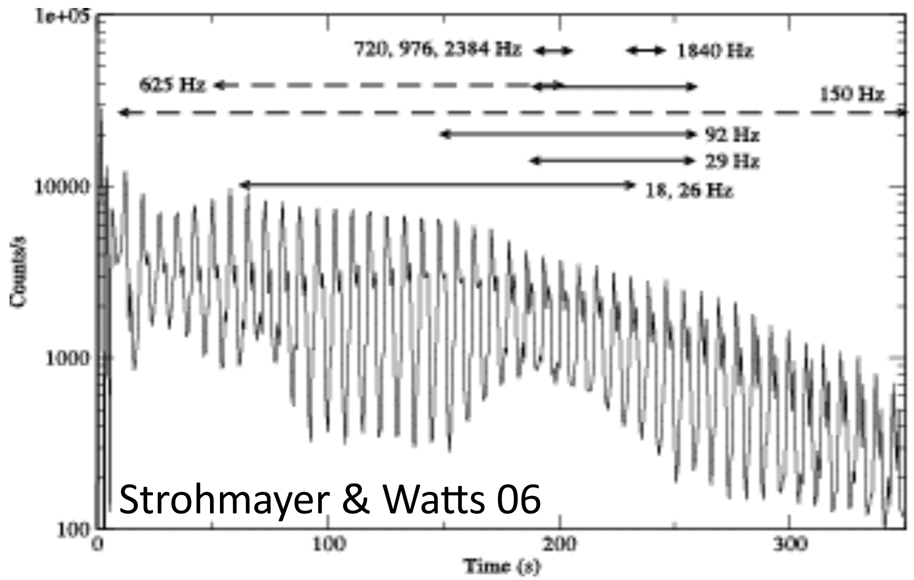


Magnetar QPOs and torsional oscillations

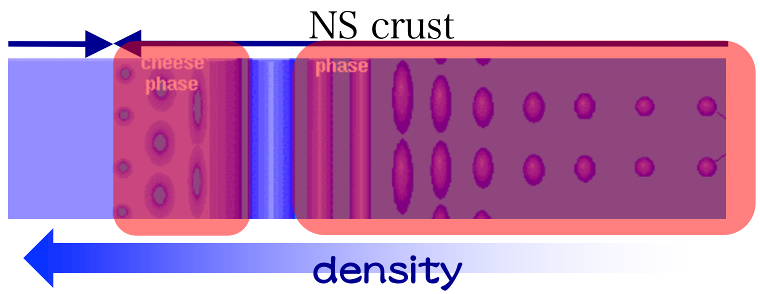


Magnetar QPOs

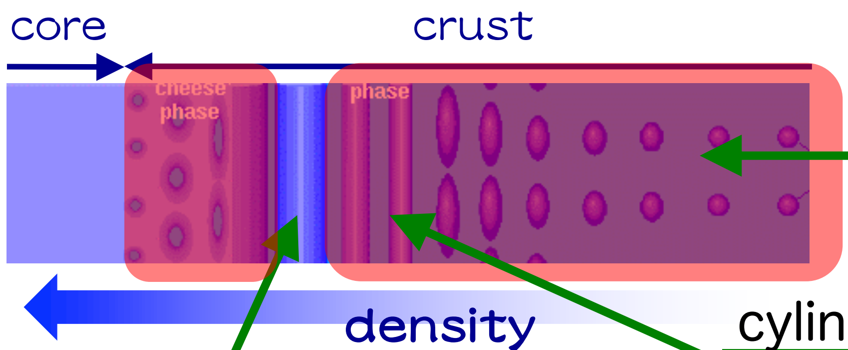
- Quasi-periodic oscillations (QPOs) in the afterglow of giant flares from soft-gamma repeaters (SGRs)
  (Barat+83, Israel+05, Strohmayer & Watts 05, Watts & Strohmayer 06)
  - SGR 0526-66 (5th/3/1979) : 43 Hz
  - SGR 1900+14 (27th/8/1998) : 28, 54, 84, 155 Hz
  - SGR 1806-20 (27th/12/2004) : 18, 26, 30, 92.5, 150, 626.5, 1837 Hz
    - additional QPO in SGR 1806-20 : 57 Hz (Huppenkothen+14)
    - additional QPOs : 51.4, 97.3, 157 Hz (Miller+18)



- Crustal torsional oscillation ?
- Magnetic oscillations ?



Elasticity in NS crust



spherical (Strohmayer+ 91)

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

cylindrical (Potekhin+ 98)

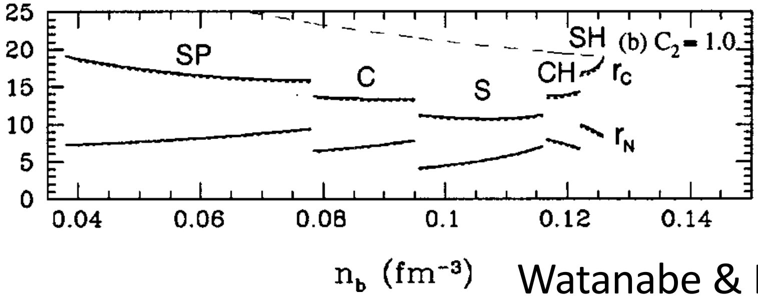
$$\mu_{cy} = \frac{2}{3} E_{Coul} \times 10^{2.1(w_2 - 0.3)}$$

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

slab-like

linear response : fluid (Landau)

→ two independent oscillations
(i) sphericzal + cylindrical (sp+cy)
(ii) tube + bubble (tu+bu)
→ bubble ~ spherical
tube ~ cylindrical



Watanabe & Iida 03

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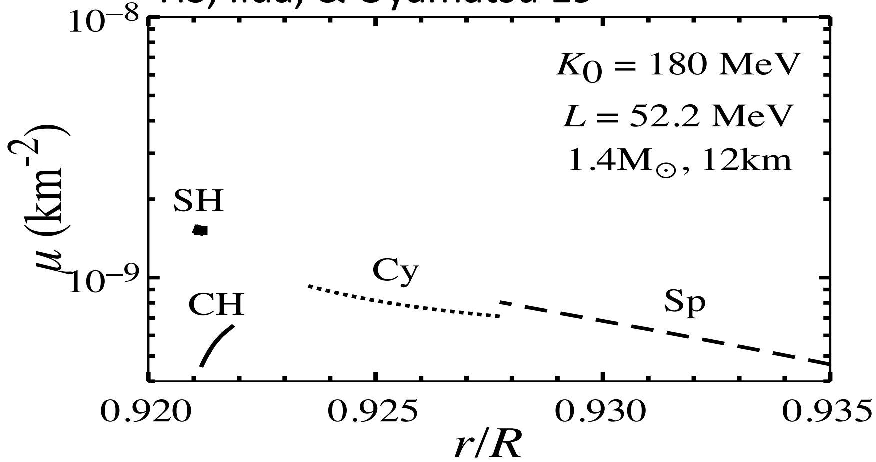
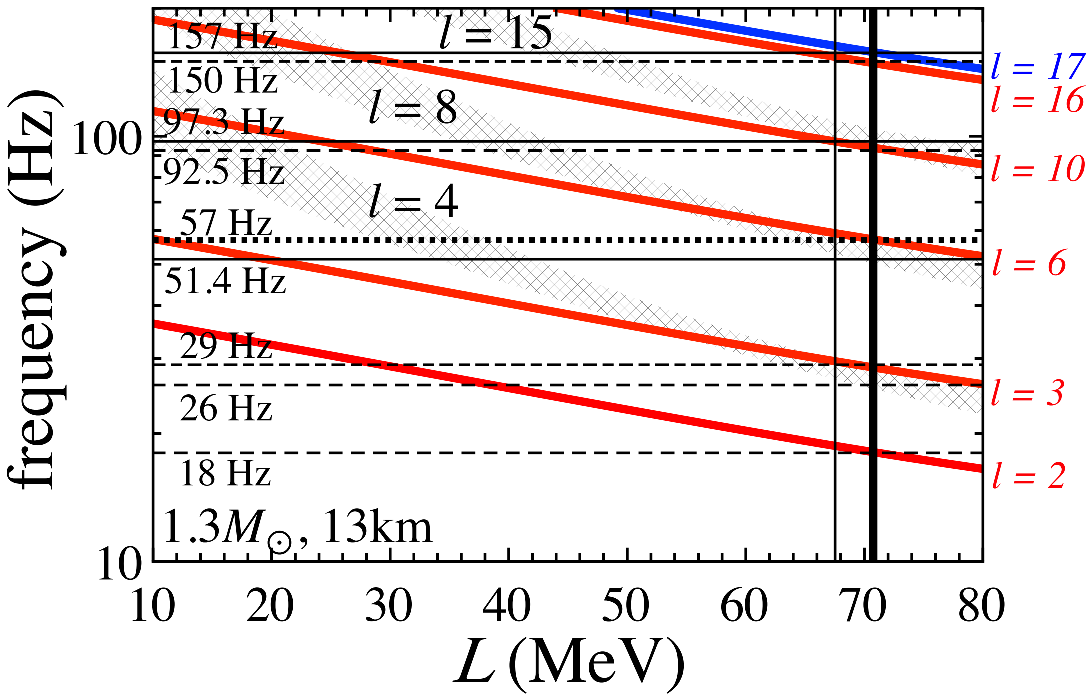
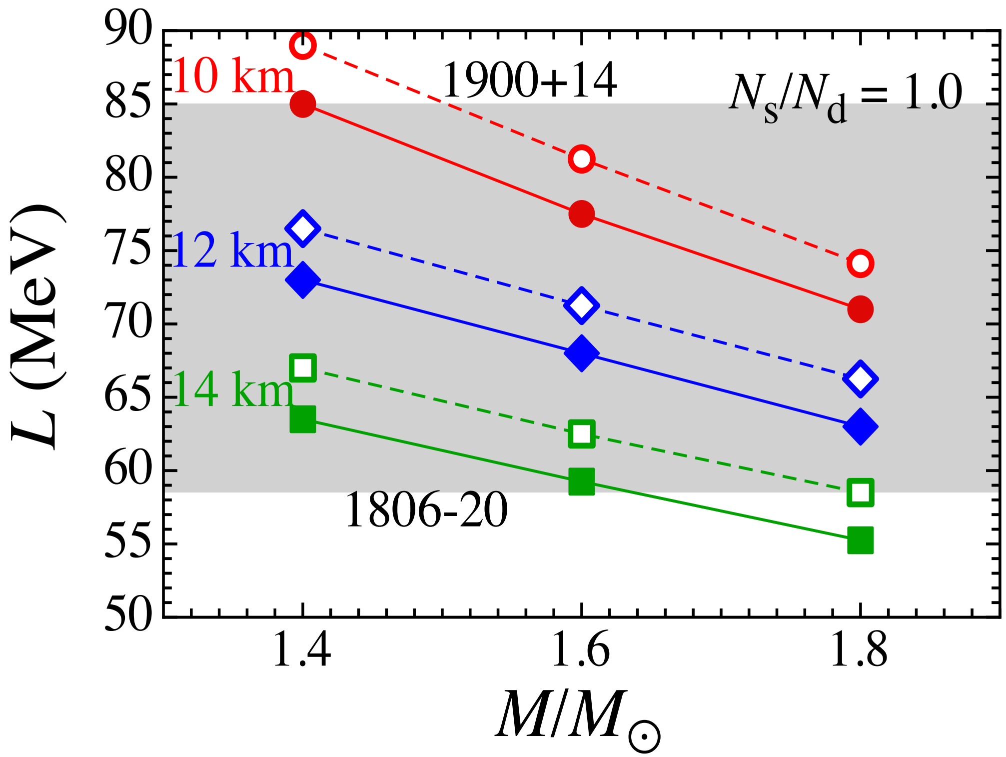


Constraint on nuclear parameters

- observed freq. are well identified with crustal torsional oscillations, which tell us the constraint on L





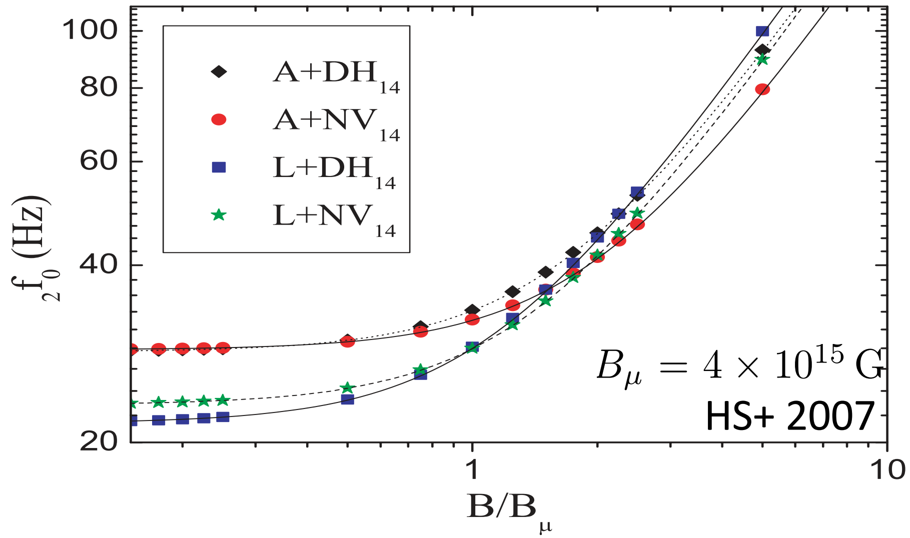
Magnetic effects

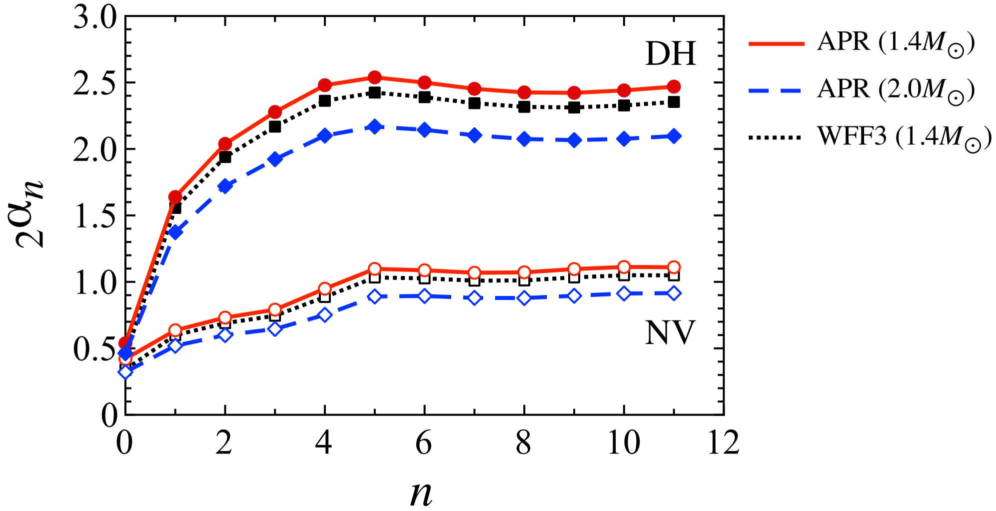
- the shift in the torsional oscillation freqs. obeys the following formula (HS+2007; Gabler+2018)

$$\frac{{}_\ell f_n}{{}_\ell f_n^{(0)}} \approx \left[1 + {}_\ell\alpha_n \left(\frac{B}{B_\mu}\right)^2\right]^{1/2} \qquad B_\mu = 4 \times 10^{15}\,\mathrm{G}$$

- for the overtones,
  - for EOS NV $\;{}_2\alpha_n \approx 0.8 - 1.1$
  - for EOS DH $\;{}_2\alpha_n \approx 2 - 2.5$
- Deviation of the magnetized NS freqs. from those of the non-magnetized ones
  - $\lesssim$ 3.4% for the EOS NV
  - $\lesssim$ 7.5% for the EOS DH,

if we assume B ≈ 10^{15}G





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QPOs are newly found

Article

Very-high-frequency oscillations in the main peak of a magnetar giant flare

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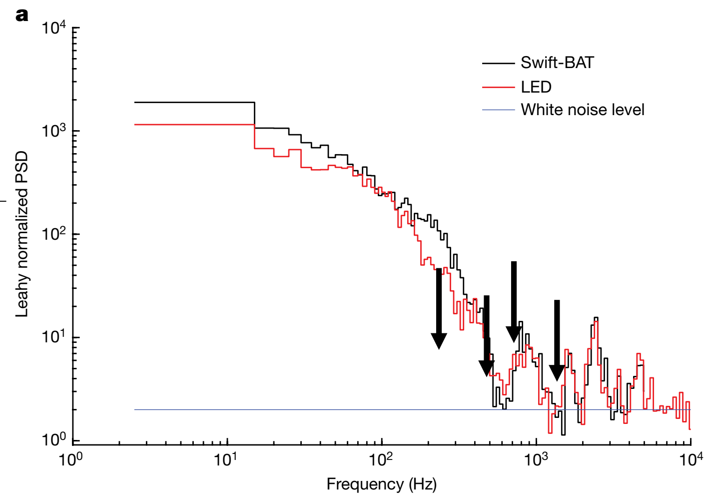

giant gamma-ray flare (GRB 200415A) in the direction of the NGC 253 galaxy, disappearing after 3.5 msec, on 15/4/2020.

	LED		HED	
Interval (Hz)	Peak Frequency (Hz)	Chance probability	Peak Frequency (Hz)	Chance probability
500 - 1100	$835.9^{-84.7}_{+77.3}$	1.2×10^{-4}	-	-
1100 - 1700	$1443.7^{-68.7}_{+74.8}$ [a]	4.9×10^{-2}	$1353.5^{-230.7}_{+217.7}$	1.2×10^{-12}
1800 - 2400	$2131.7^{-151.0}_{+148.2}$	2.4×10^{-9}	$2095.1^{-277.5}_{+180.8}$	5.0×10^{-8}
3900 - 4500	$4249.7^{-102.7}_{+116.0}$	1.7×10^{-4}	$4126.8^{-71.1}_{+73.0}$	1.1×10^{-2}

Observed fres. are high

- polar type oscillations, such as f, p_i-modes
- overtones of torsional modes

Constrains on M & R

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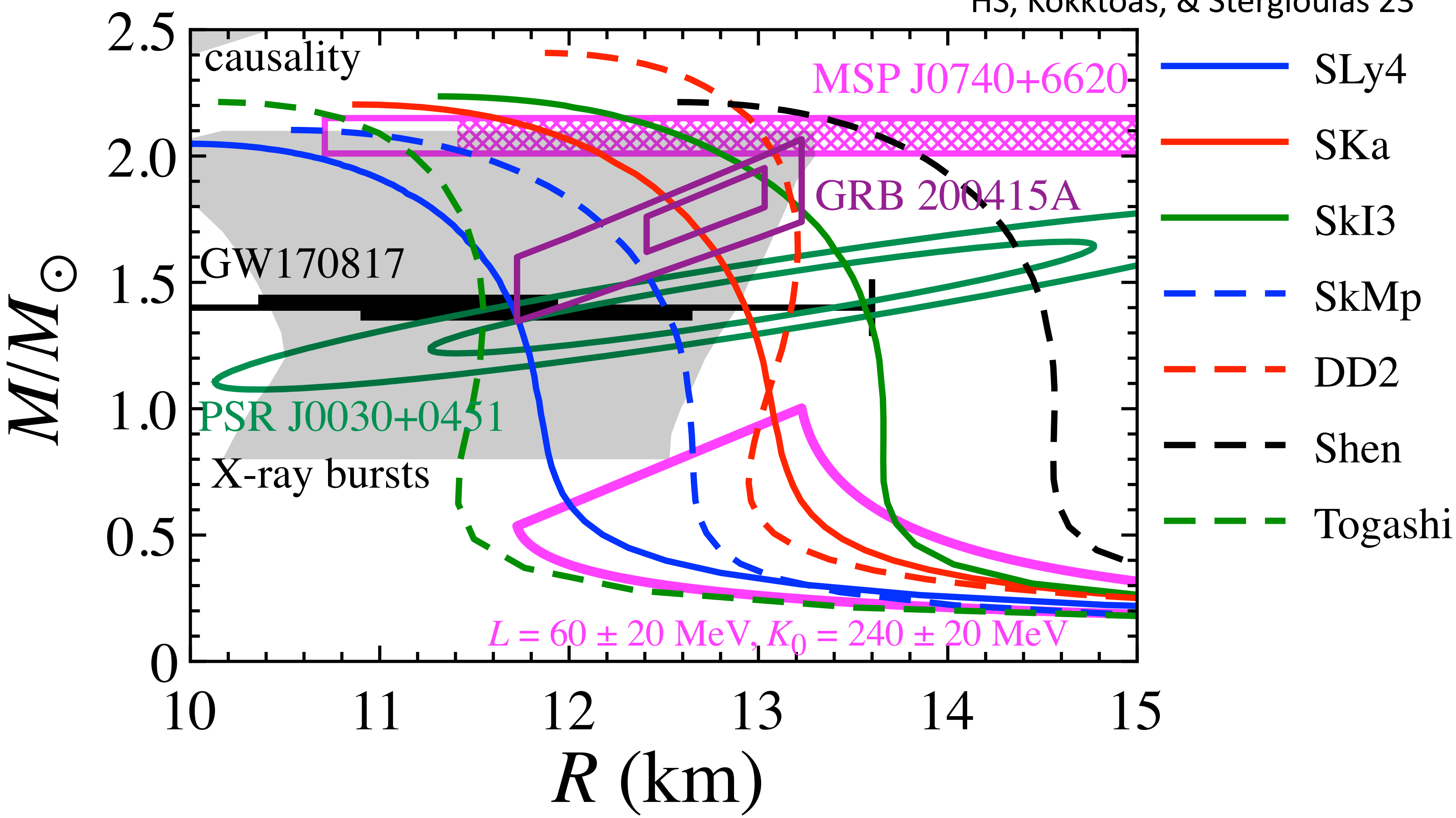
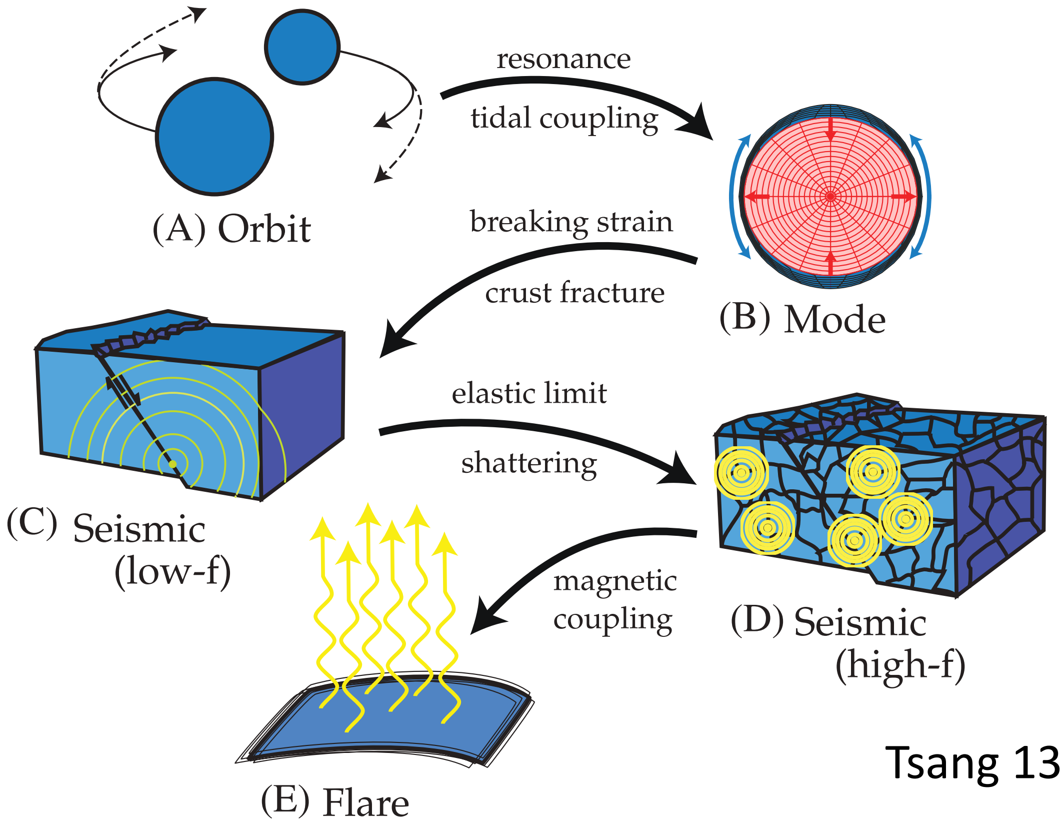


- See in Session D08: Minisymposium: Solid State Physics in Neutron Stars: Crystallography and Superfluidity on <u>Nov. 29th</u>

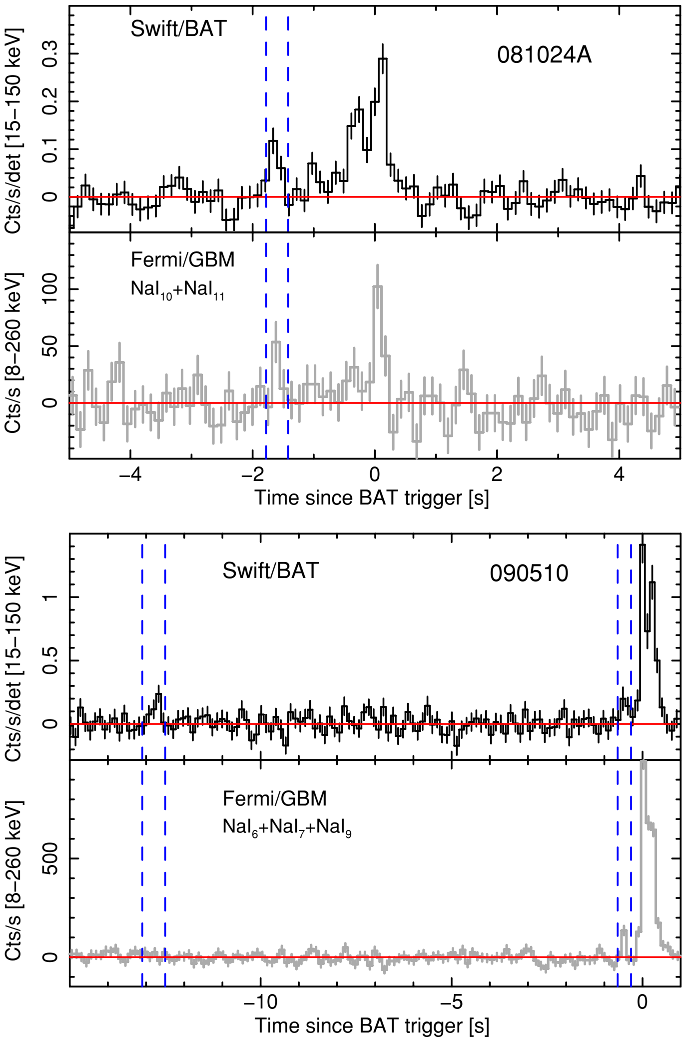
Resonant shattering and shear/interface modes

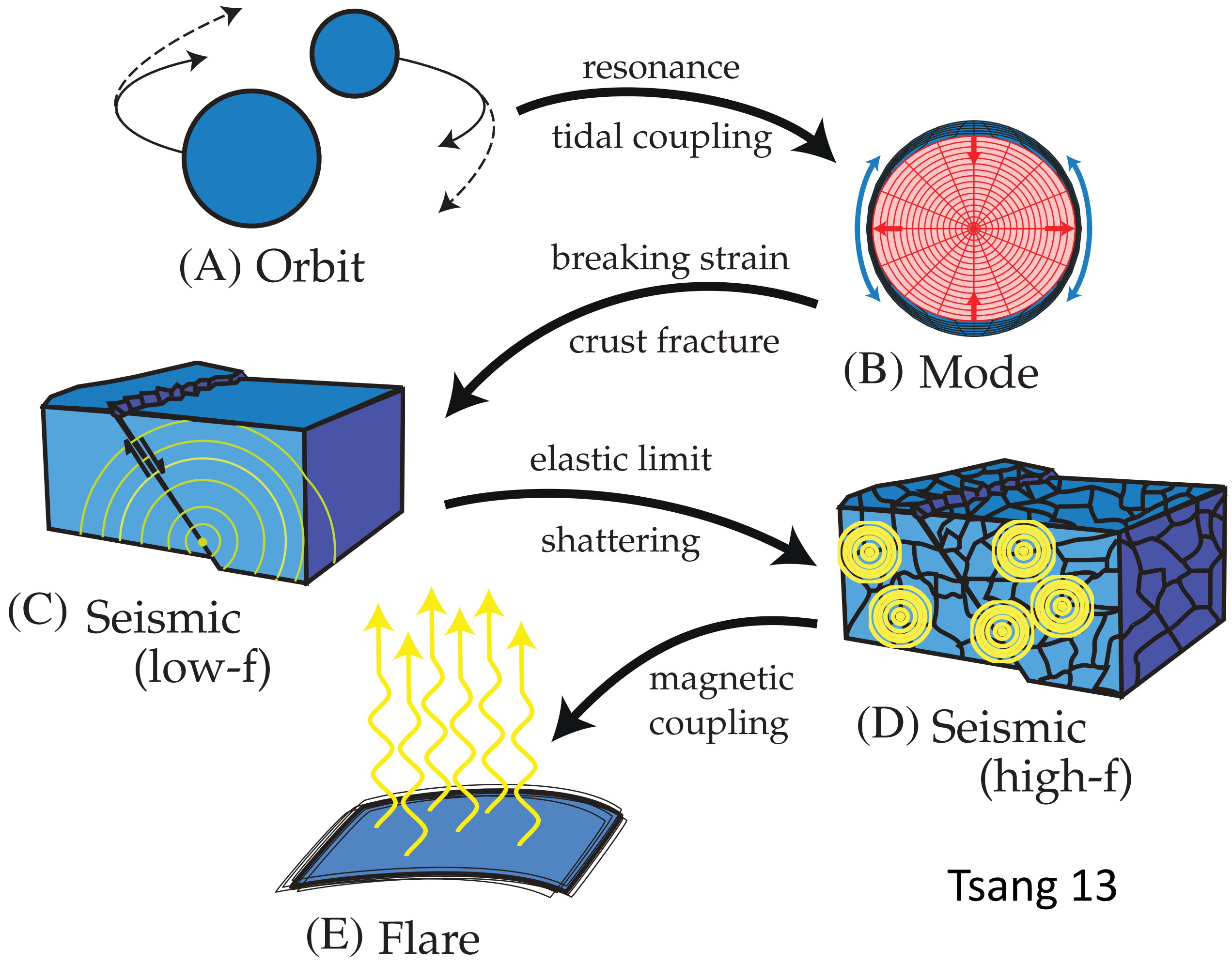


Tsang 13

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)

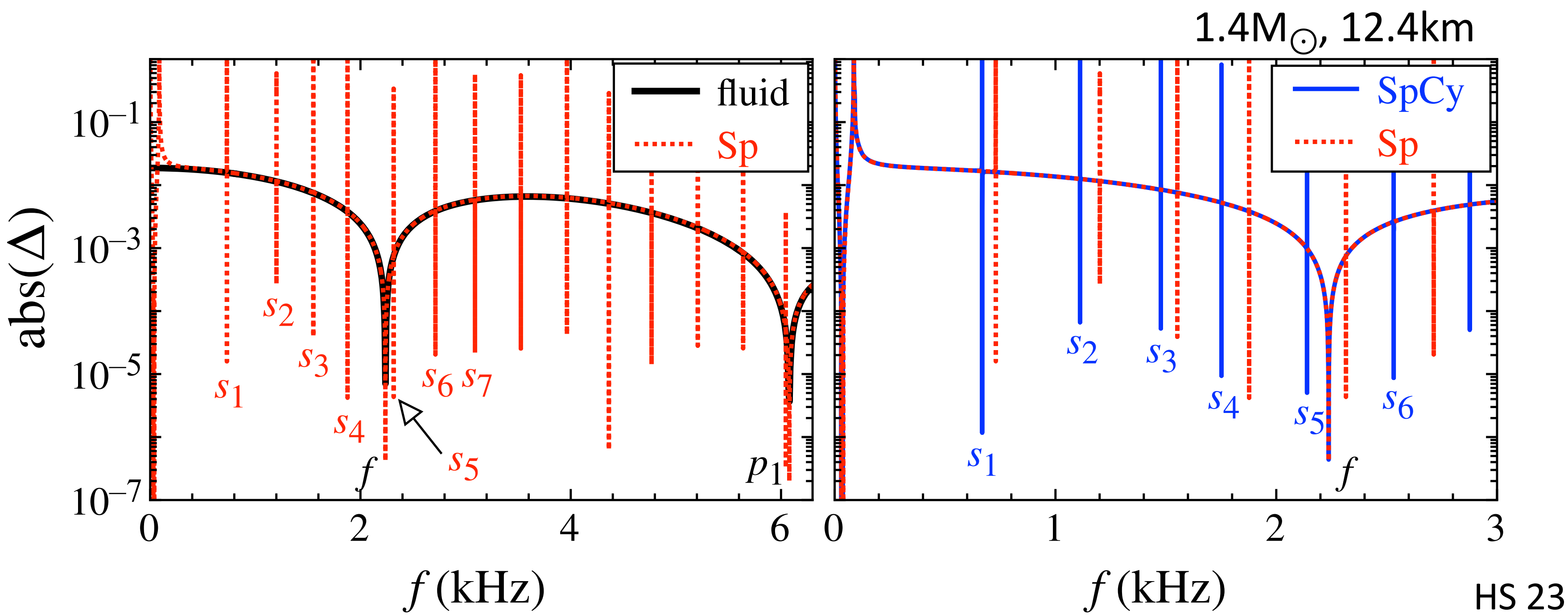




Tsang 13

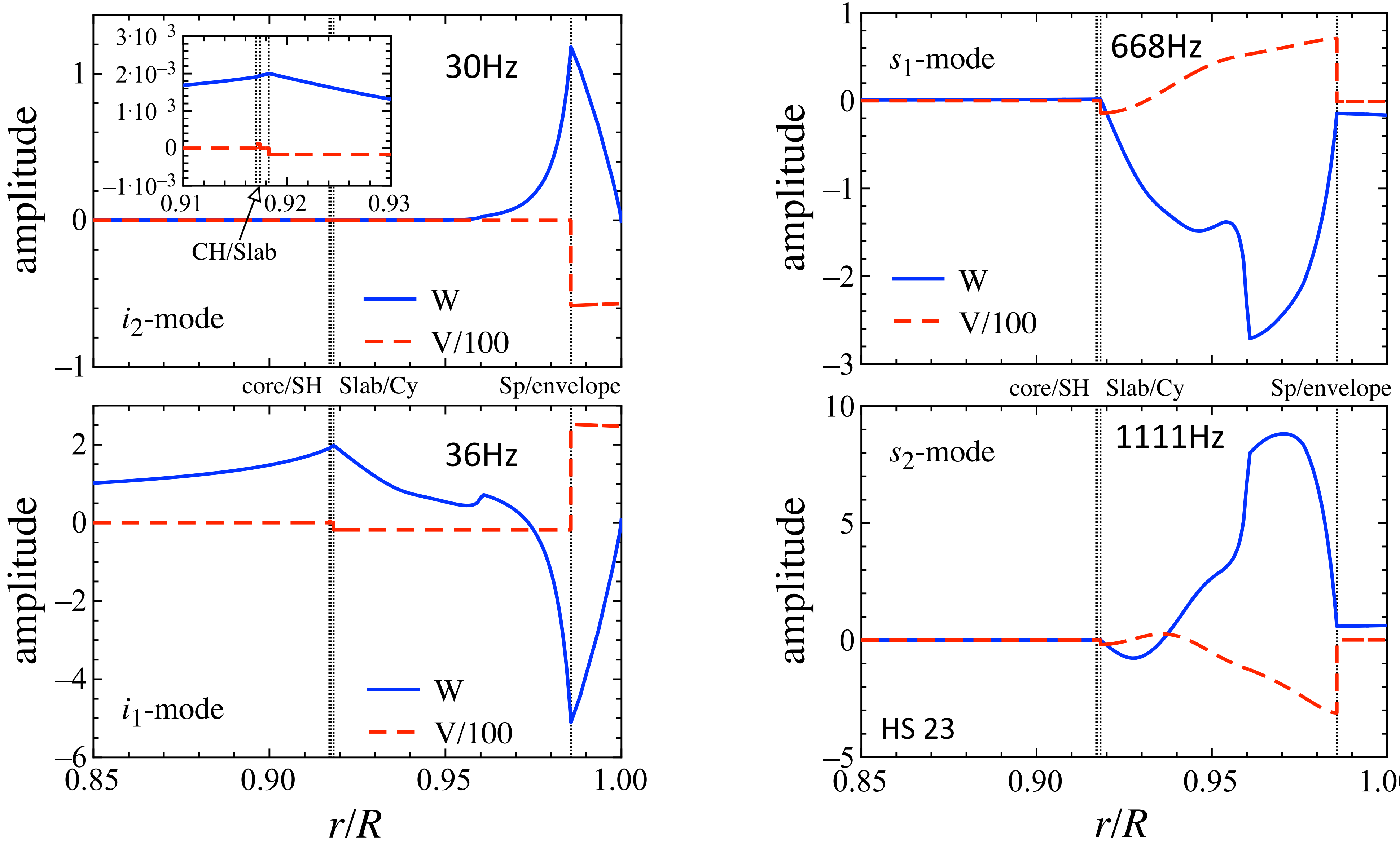
Troja+10

Behavior of eigenfrequencies



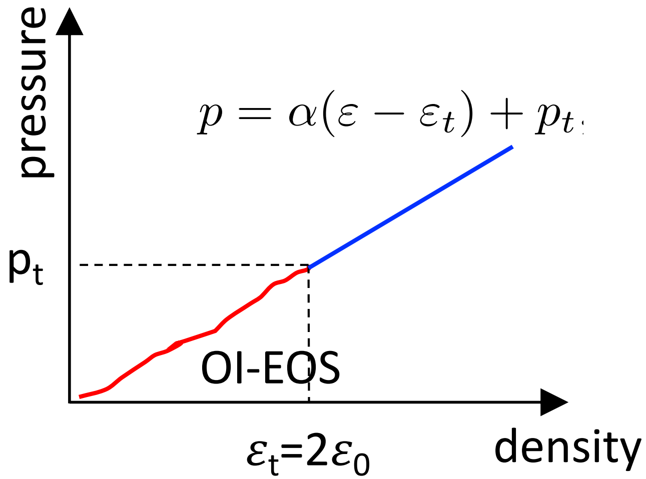
- Frequencies with Δ=0 correspond to the eigenfrequencies
- f- and p_1-mode freqs. hardly depend on the crust elasticity
- s_i-mode freqs. strongly depend on the density of interface(s)

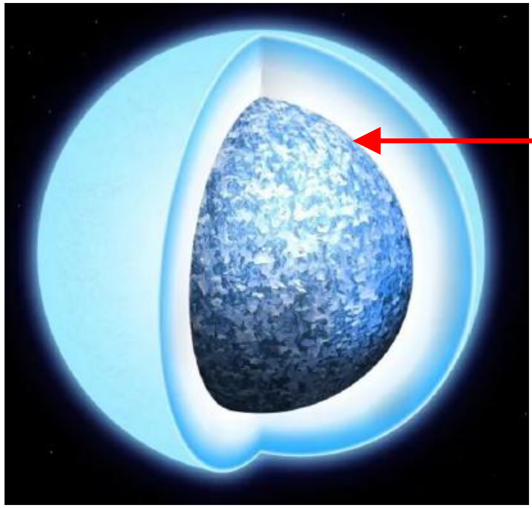
Eigenfunctions (i/s-modes)



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 $1/3 \leq \alpha \leq 1$.





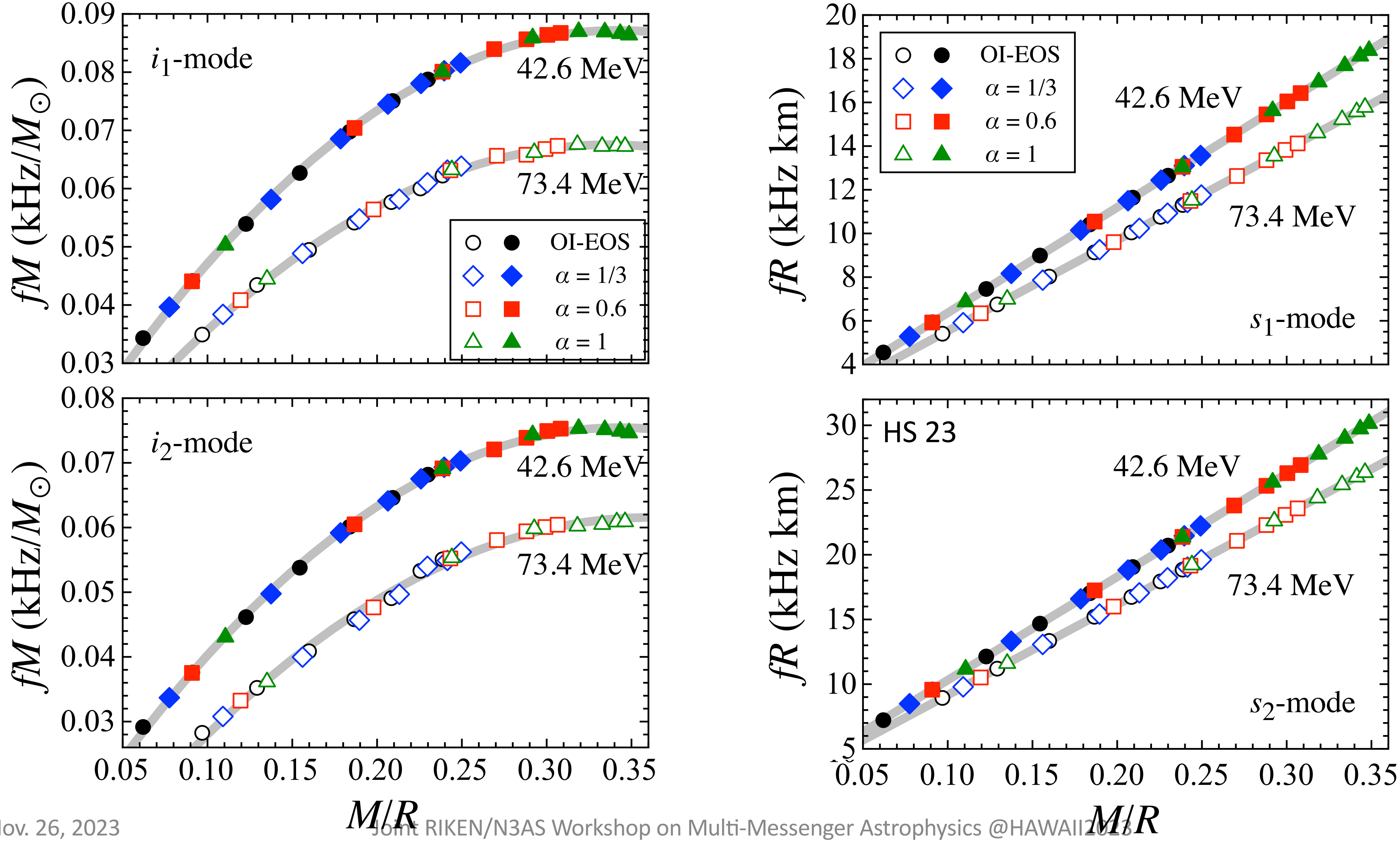
crust/core transition density
$\simeq$ (0.3-0.5)n_0

Empirical relation (i/s-modes)

$x = M/R$

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

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



- we find two different types of fitting formulae for the i- and s-mode freqs.
    - 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.

- Moreover, it may affect the binary evolution

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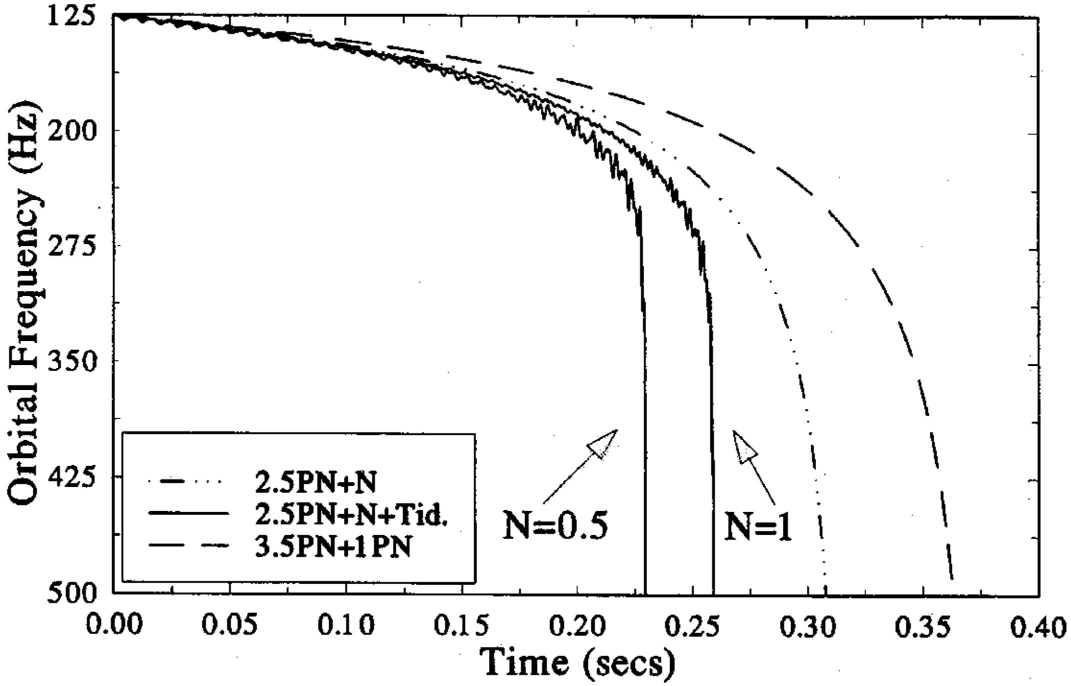

Conclusion

- Asteroseismology is a powerful technique for extracting the NS properties

- In this talk, we focus on
  - supernova gravitational waves
  - magnetar QPOs
  - resonant shuttering in binary NSs

- We are looking forward to getting new signals from NSs, which may help us to understand NS physics well by using the asteroseismology approach.