Estimation of neutron star mass and radius from the high-frequency QPOs in GRB 200415A

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collaborate with

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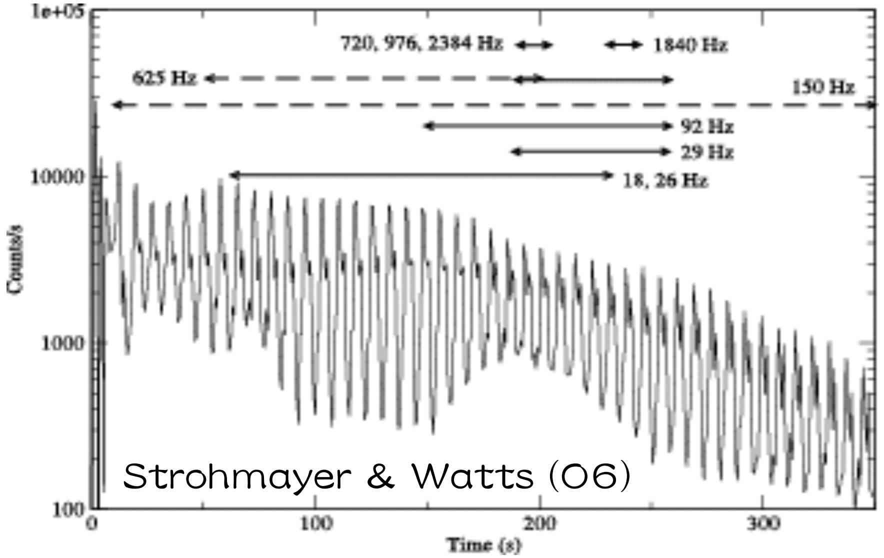
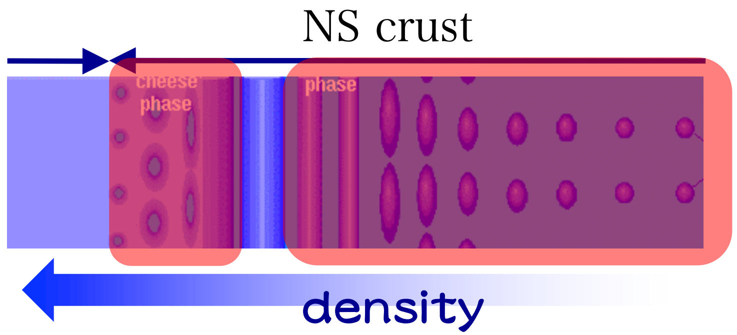
Magnetar QPOs & crust oscillations

- Quasi-periodic oscillations (QPOs) in 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)



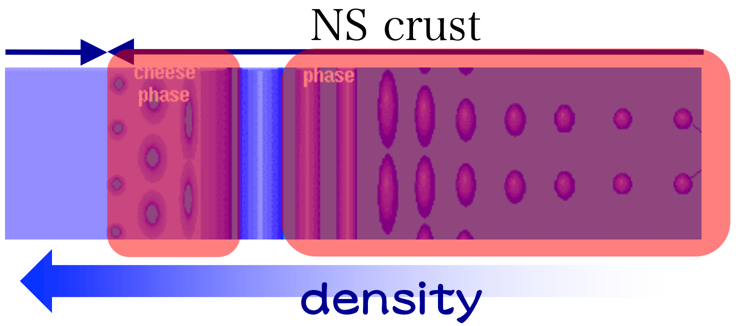
- Crustal torsional oscillation ?
- Magnetic oscillations ?



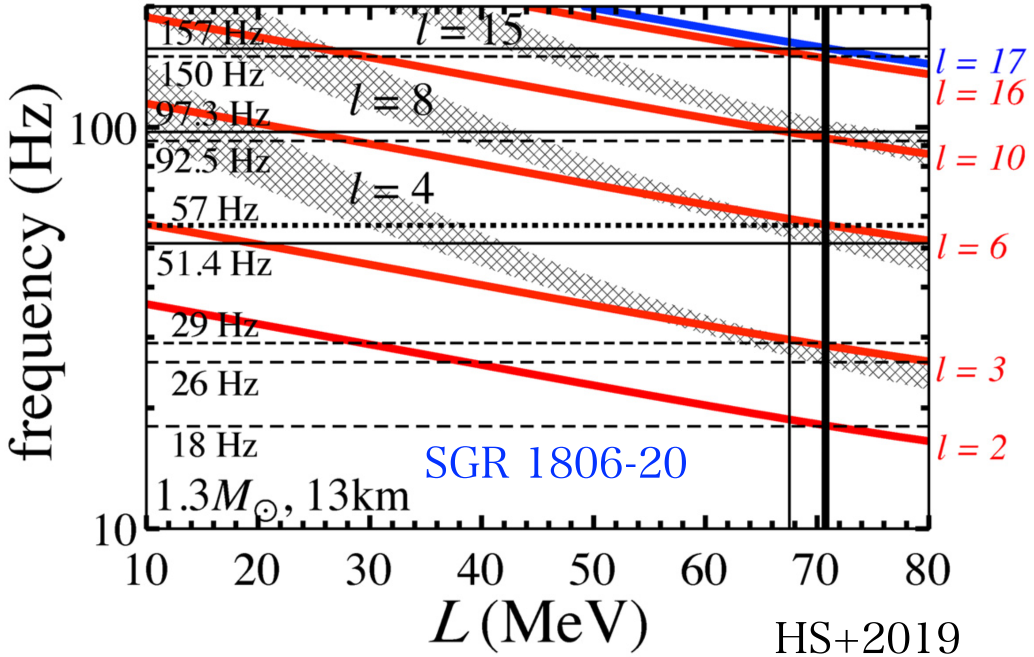
Constraint on L from magnetar QPOs

- nuclear saturation parameters

$$w = w_0 + \frac{K_0}{18n_0^2}(n_b - n_0)^2 + \left[S_0 + \frac{L}{3n_0}(n_b - n_0)\right]\alpha^2$$



- Constraint on K_0 : $K_0 = 240 \pm 20$ MeV (Shlomo+2006)
- Constraint on L
  - L = 60 ± 20 MeV : fiducial value (Li+2019)
  - L = 58 – 73 MeV : constraint from QPOs (HS+2019)



HS+2019

QPOs are newly found

Article

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

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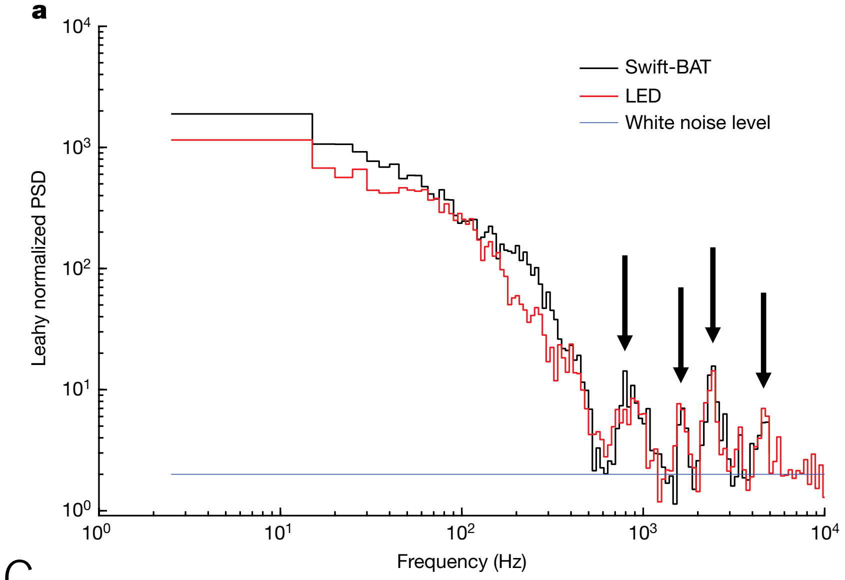


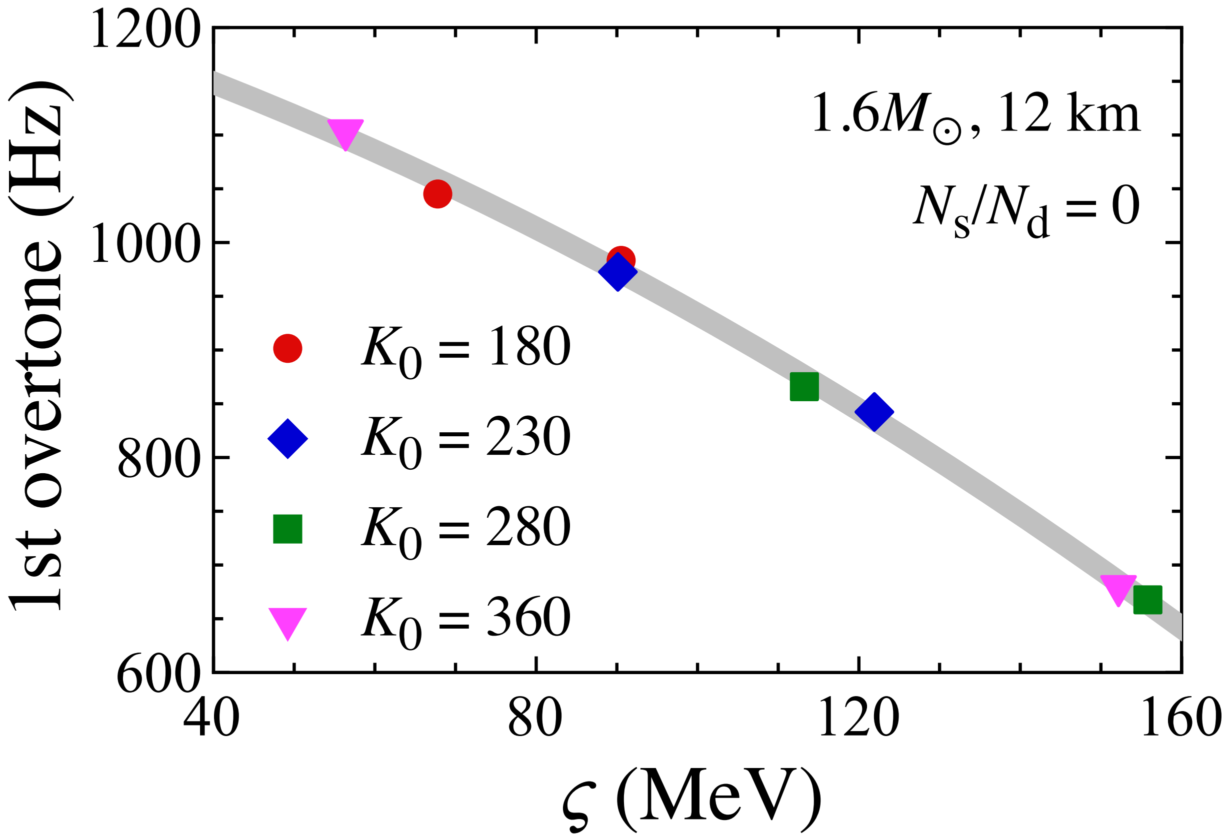
giant gamma-ray flare (GRB 200415A) in the direction of the NGC 253 galaxy, disappearing after 3.5 msec, on 15/4/2020.

	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 frequencies are high

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

1^{st} overtone



- two parameters in EOS, two in NS models
- overtones depend on K_0 & L
  - f ~ $v_s / \Delta R$ (Hansen & Cioffi 80)
  - ΔR depends on K_0 & L (HS+17)
- as in Sotani+ 19, frequencies can be well characterized by

$$\varsigma = (K_0^4 L^5)^{1/9}$$

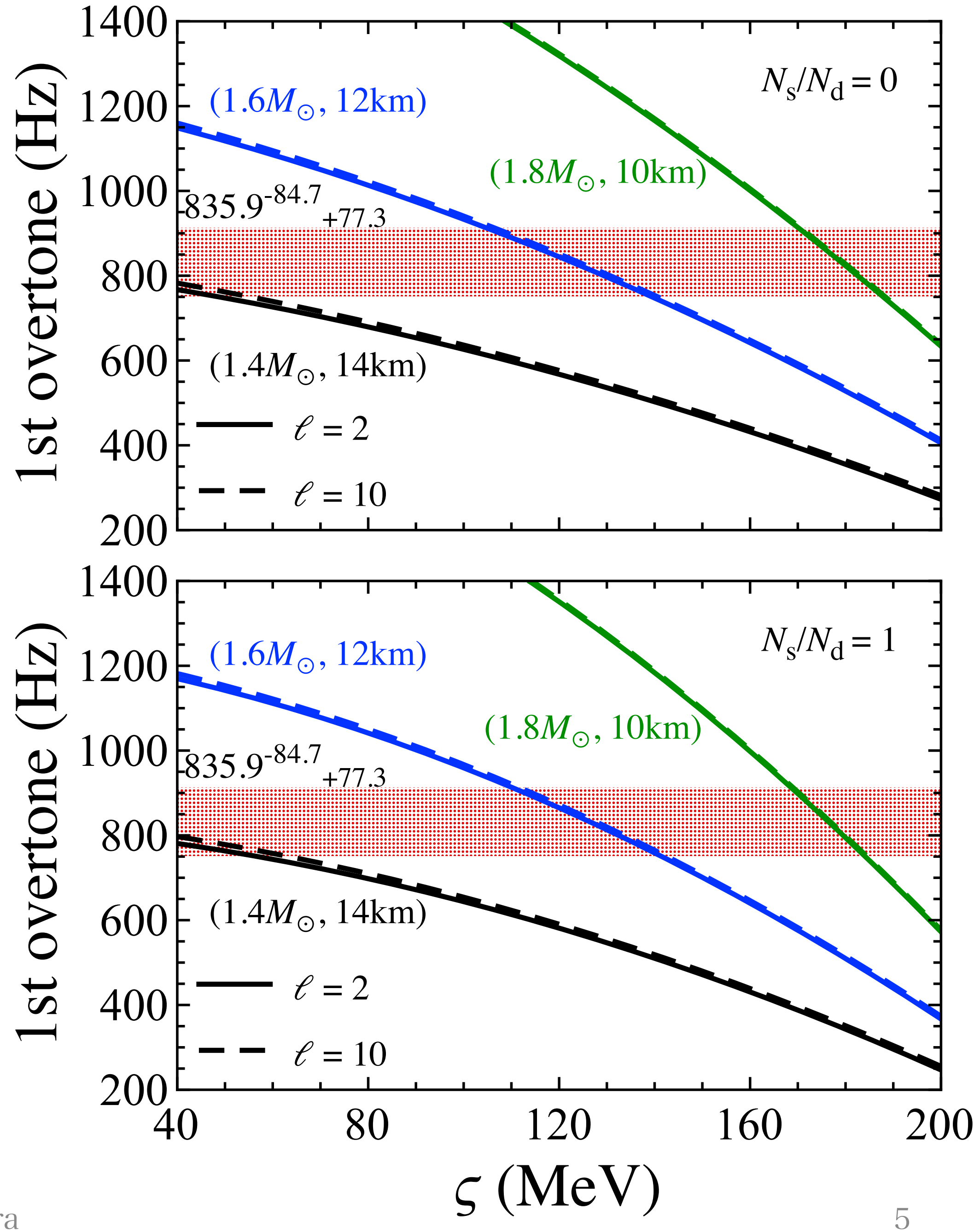
- In fact, fre. can be expressed as

$$ {}_\ell t_n = d_{\ell n}^{(0)} + d_{\ell n}^{(1)} \varsigma_{100} + d_{\ell n}^{(2)} \varsigma_{100}^2$$

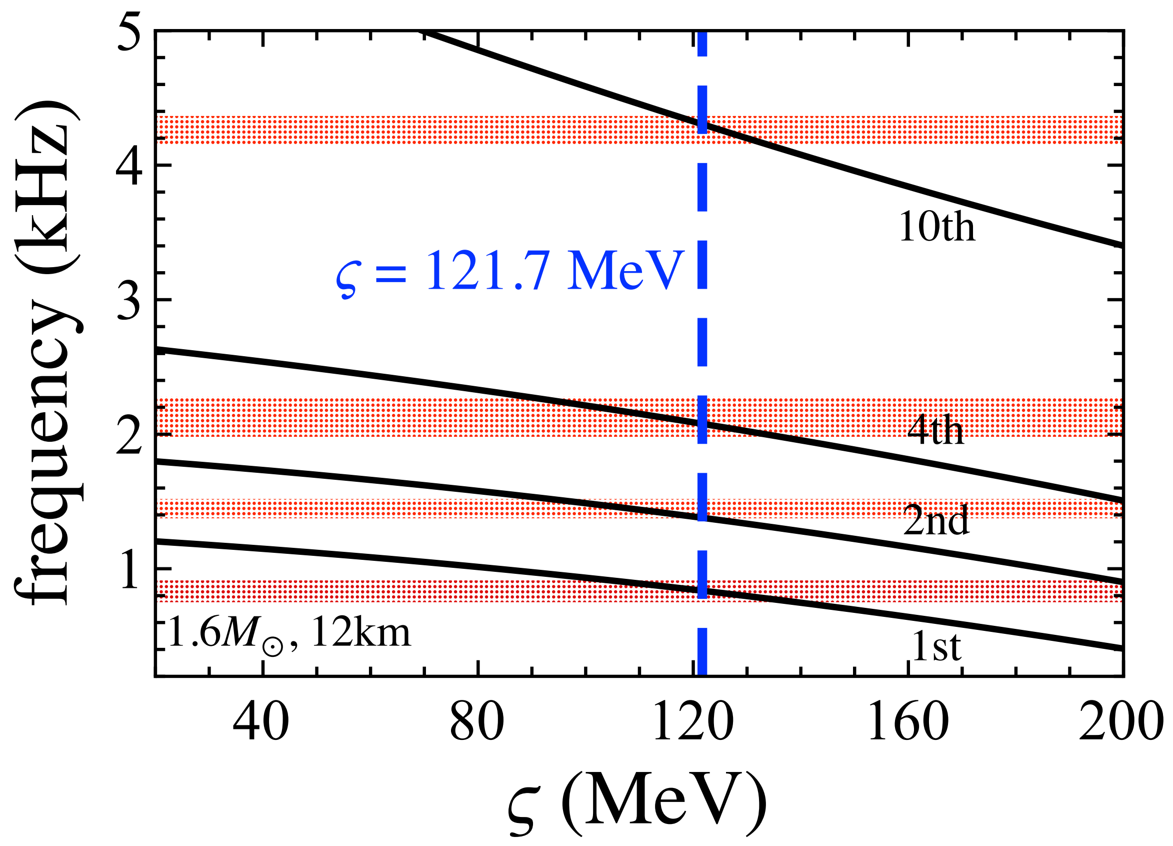
$$\varsigma_{100} \equiv \varsigma/(100\mathrm{MeV})$$

1st overtone

- frequencies increases with M/R
  - f ~ $v_s / \Delta R$ (Hansen & Cioffi 80)
  - $\Delta R/R$ ~ R/M (HS+ 17)
- one can neglect the ℓ-dep. & N_s/N_d-dep.
  - hereafter, we consider only the ℓ =2 mode with N_s/N_d=0
- to identify the 836 Hz QPO with the 1st overtone frequency, one must determine a specific value of ς, depending on (M,R)

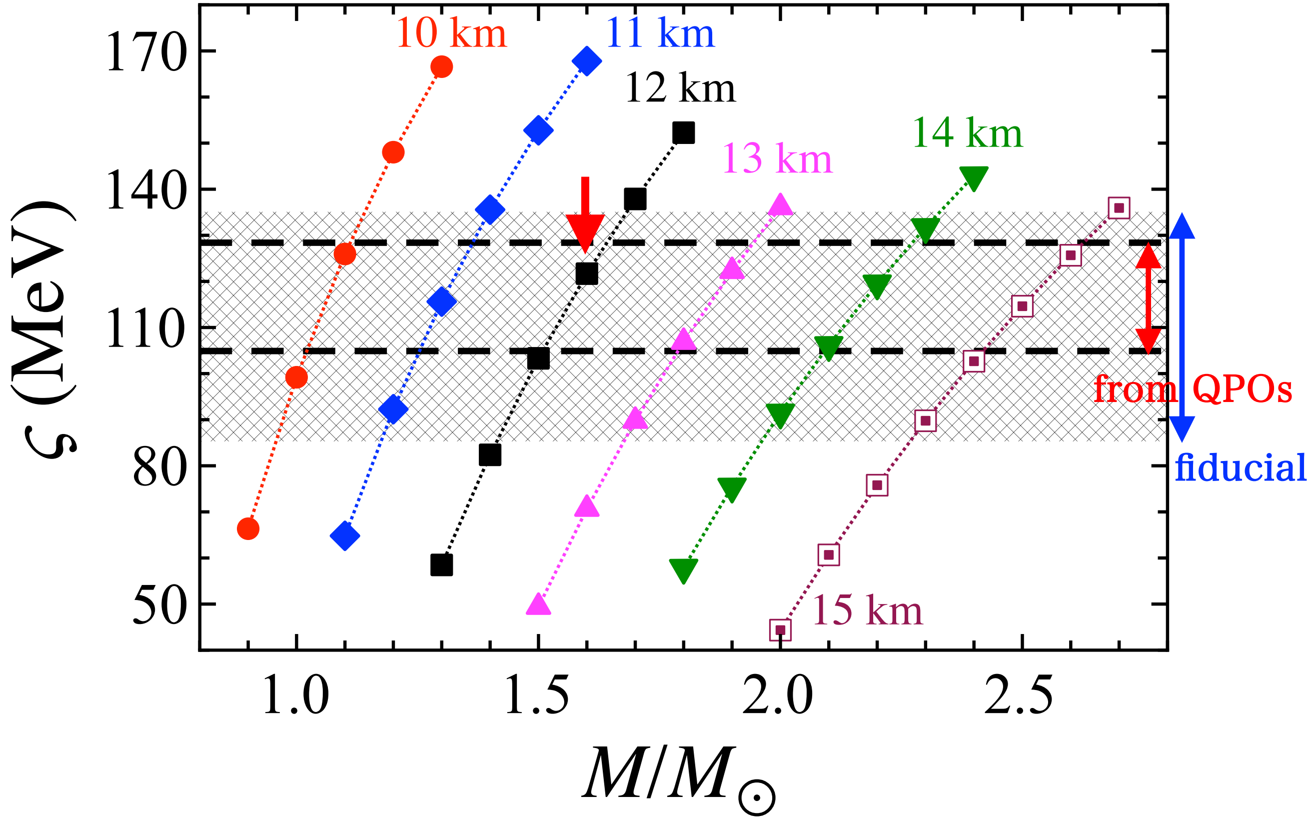


identification of all QPOs



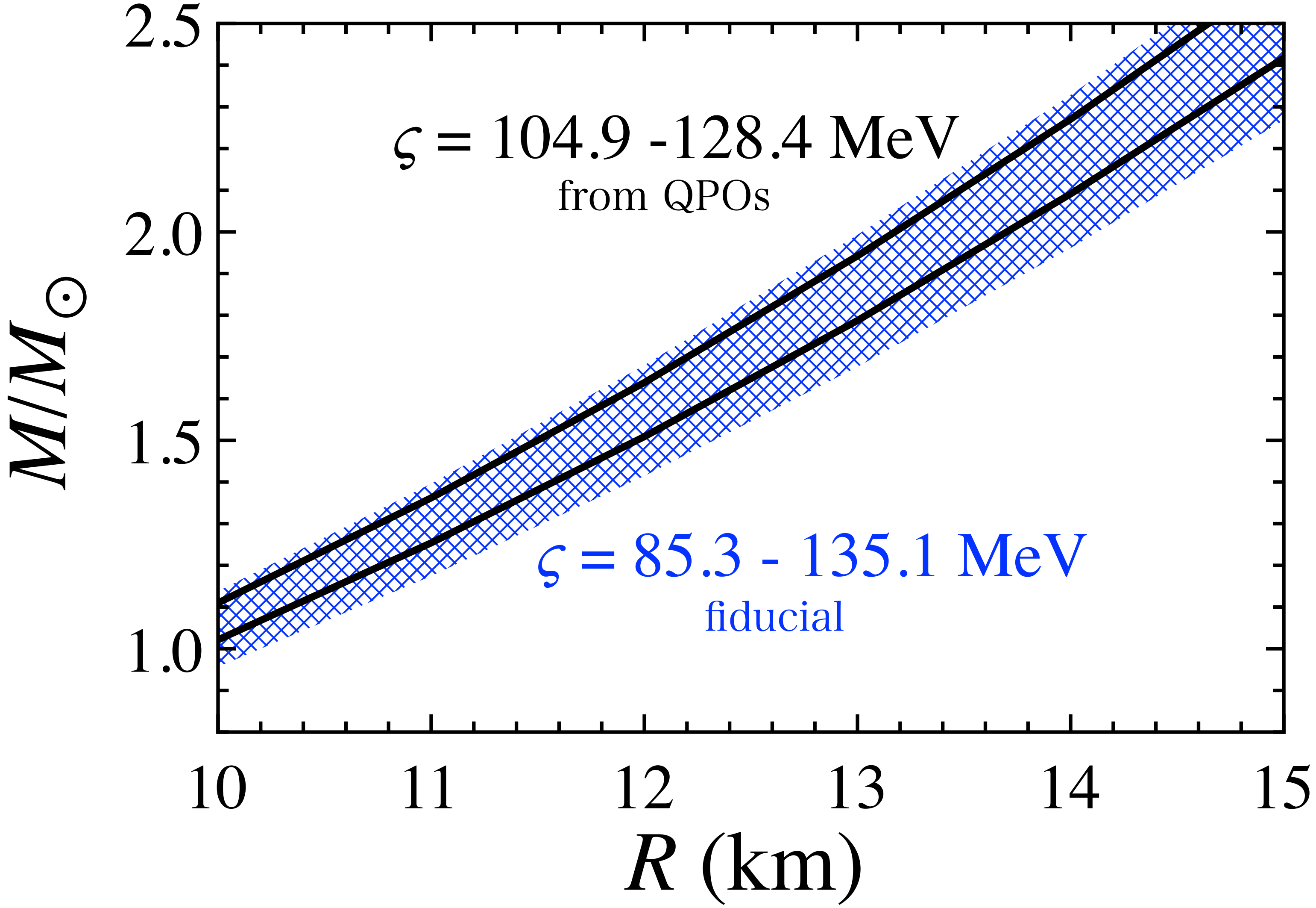
- the observed QPOs in GRB 200415A can be identified with the 1st, 2nd, 4th, and 10th overtones of crustal torsional oscillations
- for NS models with $1.6M_\odot$ and 12km, ς should be 122 MeV for the identification.
- with different NS models, fre. shift up and down, which leads to ς for identification also shifts right and left.
  - frequencies increases with M/R

NS models for identifying QPOs



- ς for identifying the QPOs with various NS models
- fiducial value of ς = 85.3 - 135.1 MeV
  - L = 60 ± 20 MeV
  - K_0 = 240 ± 20 MeV
- constrained from QPO obs.; ς = 104.9 – 128.4 MeV
  - L = 58 – 73 MeV (HS+2018)
  - K_0 = 240 ± 20 MeV
- compared to the fiducial value of ς, one can get the constraints on NS mass and radius

NSs constrained from GRB 200415A

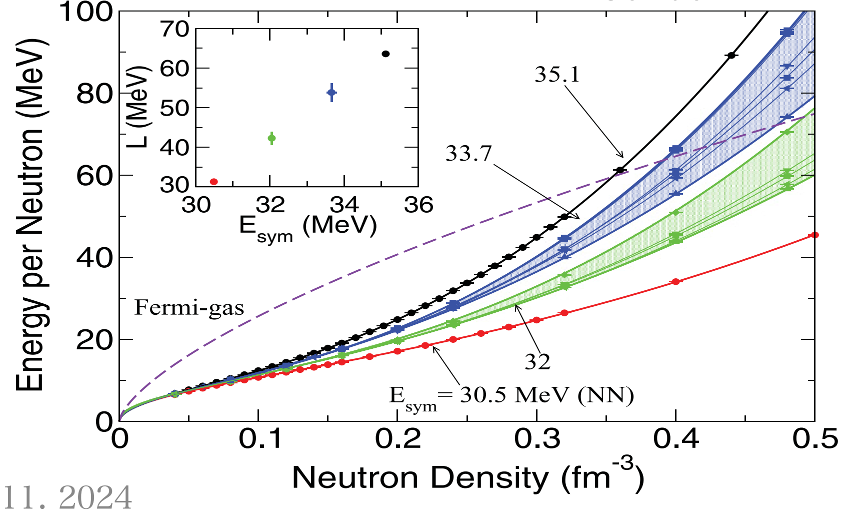


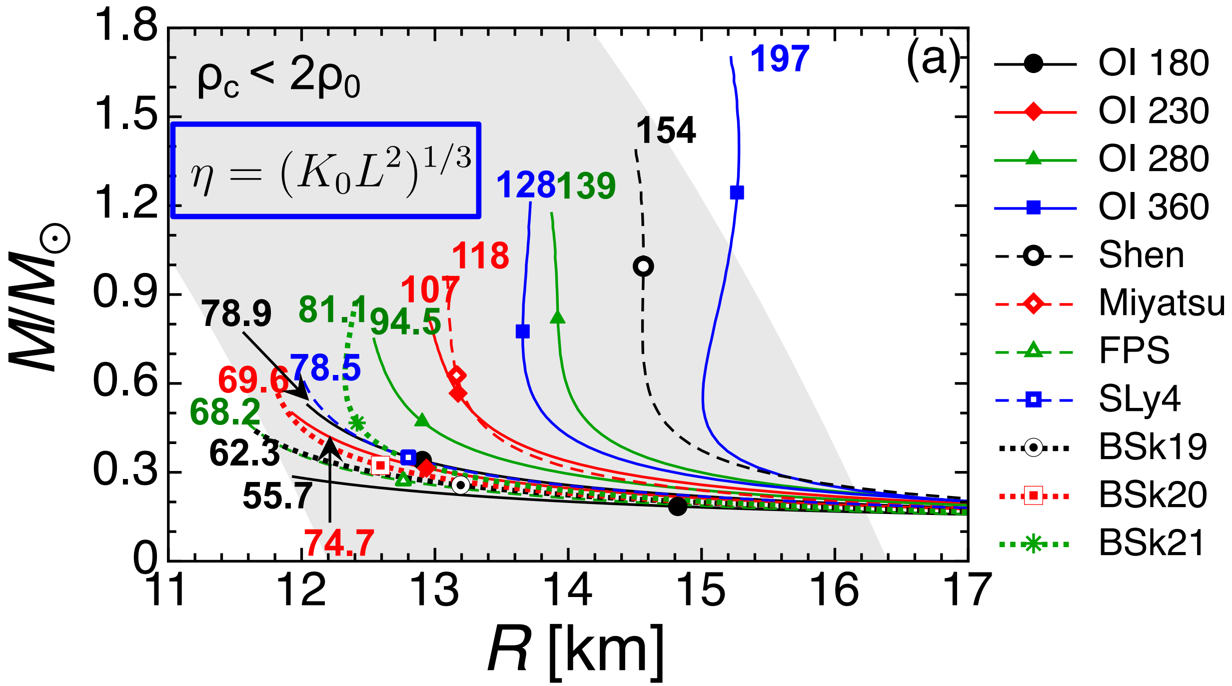
Mass formula (HS+14)

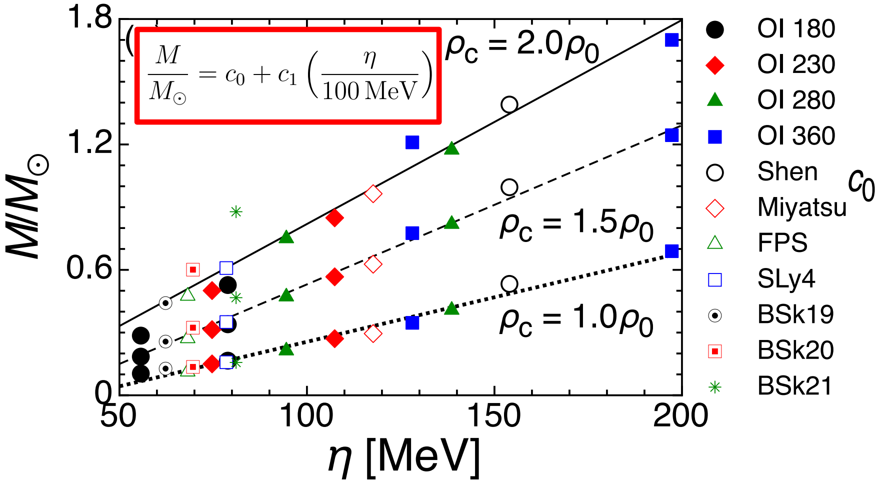
- low-mass NSs
  - low-central density
  - EOS for a low-density region plays an important role
  - may be able to discuss the stellar models without the core EOS
  - $1.174 M_\odot$ NS exists (Martinez+ 15)
- we focus on the NS models for $\rho \lesssim 2\rho_0$

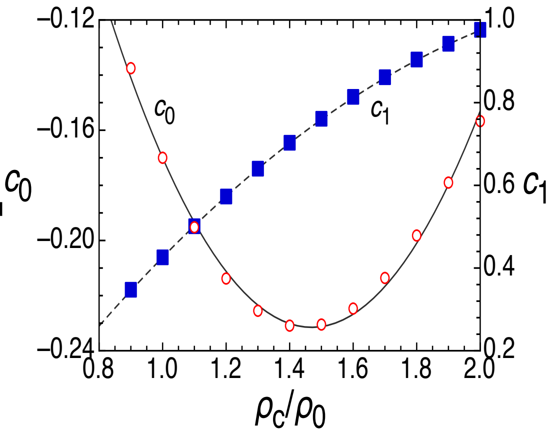
$$w = w_0 + \frac{K_0}{18n_0^2}(n-n_0)^2 + \left[S_0 + \frac{L}{3n_0}(n-n_0)\right]\alpha^2$$

Gandolfi+ 12







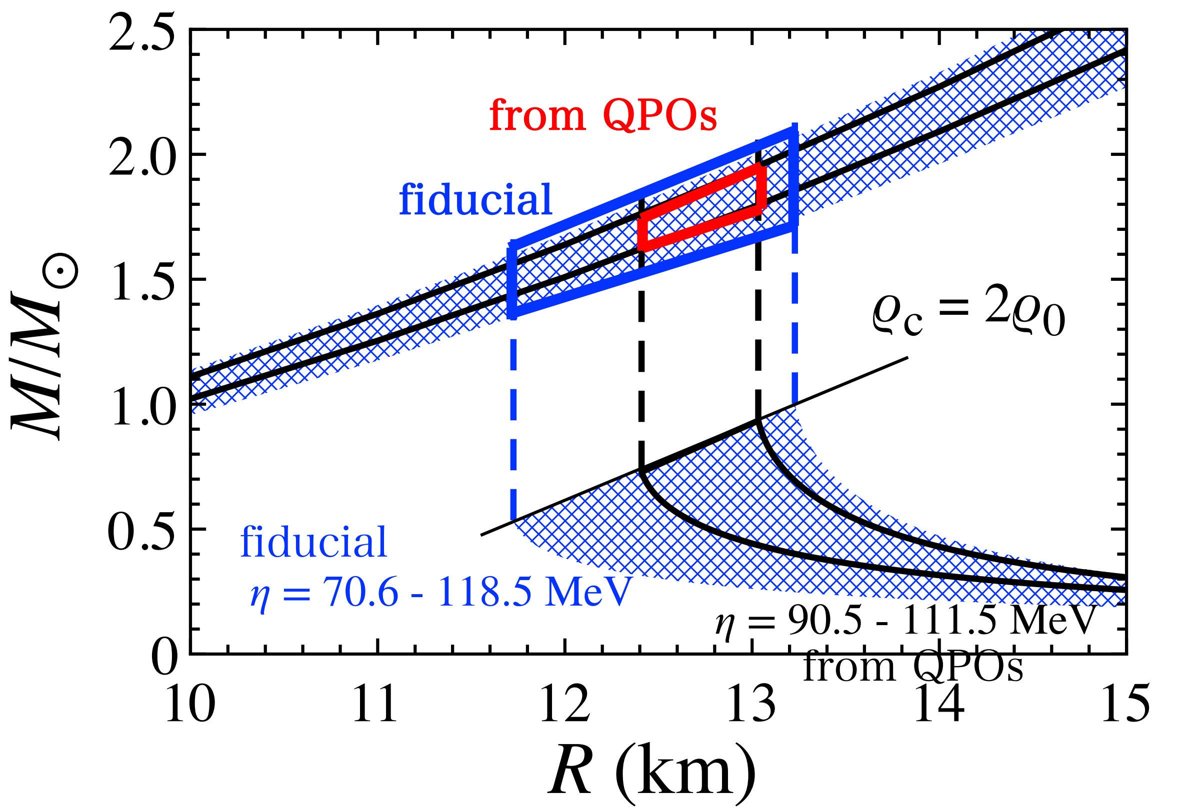


$z = 1/\sqrt{1 - 2GM/Rc^2} - 1$

$$\frac{M}{M_\odot} = 0.371 - 0.820u_c + 0.279u_c^2 - (0.593 - 1.254u_c + 0.235u_c^2)\left(\frac{\eta}{100\,\mathrm{MeV}}\right)$$

$$z = 0.00859 - 0.0619u_c + 0.0255u_c^2 - (0.0429 - 0.108u_c + 0.0120u_c^2)\left(\frac{\eta}{100\,\mathrm{MeV}}\right)$$

make constraint more severe



- low-mass NS can be expressed with η and ρ_c up to $\rho_c = 2\rho_0$ (HS+ 14); $\eta = (K_0 L^2)^{1/3}$ & $u_c \equiv \rho_c/\rho_0$

$$\frac{M}{M_\odot} = 0.371 - 0.820u_c + 0.279u_c^2 - (0.593 - 1.254u_c + 0.235u_c^2)\left(\frac{\eta}{100\,\mathrm{MeV}}\right)$$

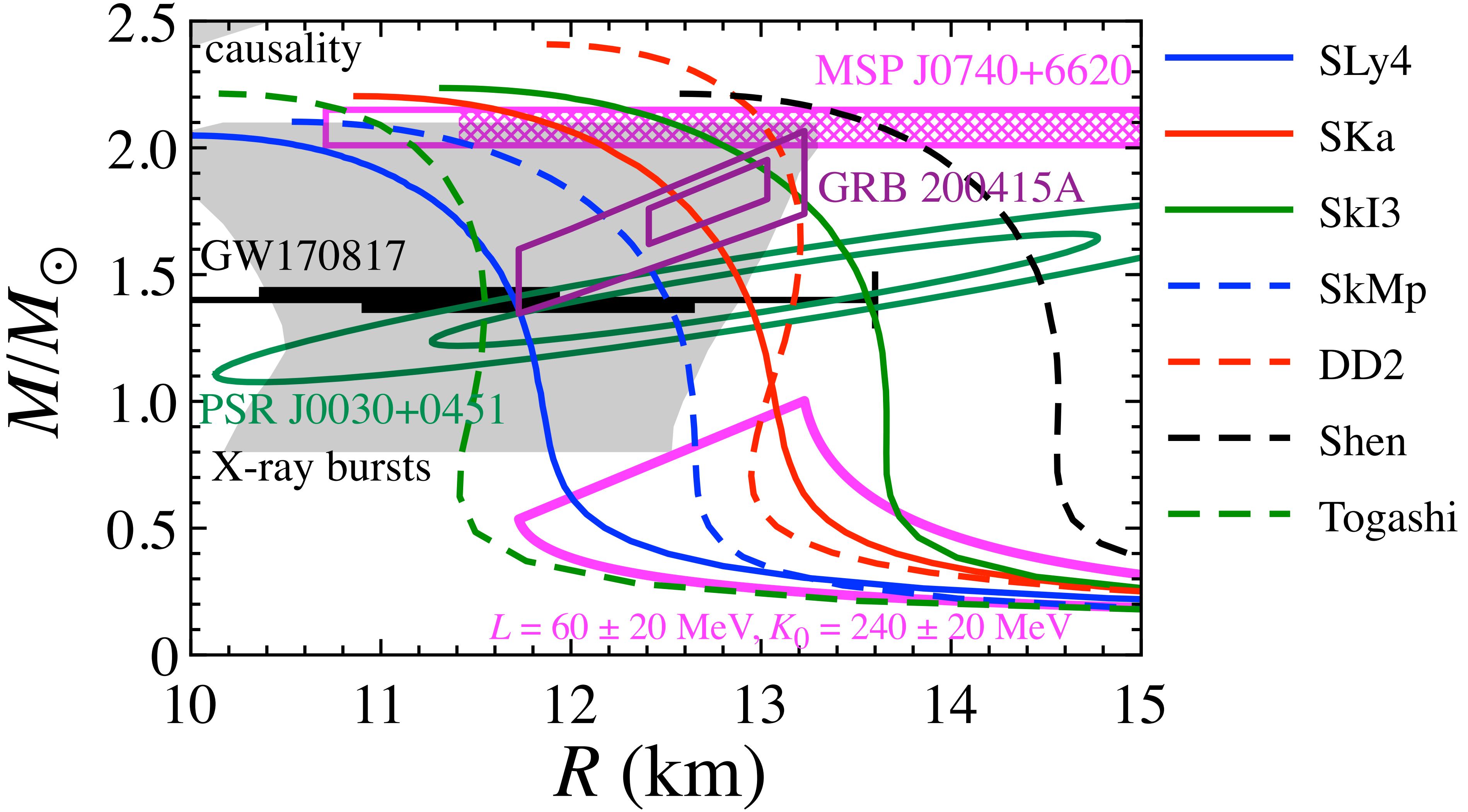
$$z = 0.00859 - 0.0619u_c + 0.0255u_c^2 - (0.0429 - 0.108u_c + 0.0120u_c^2)\left(\frac{\eta}{100\,\mathrm{MeV}}\right)$$

- we focus on
  - η = 70.6 – 118.5 MeV (ς = 85.3 - 135.1 MeV)
  - η = 85.3 – 135.1 MeV (ς = 104.9 - 128.4 MeV)

$$z = 1/\sqrt{1 - 2GM/Rc^2} - 1$$

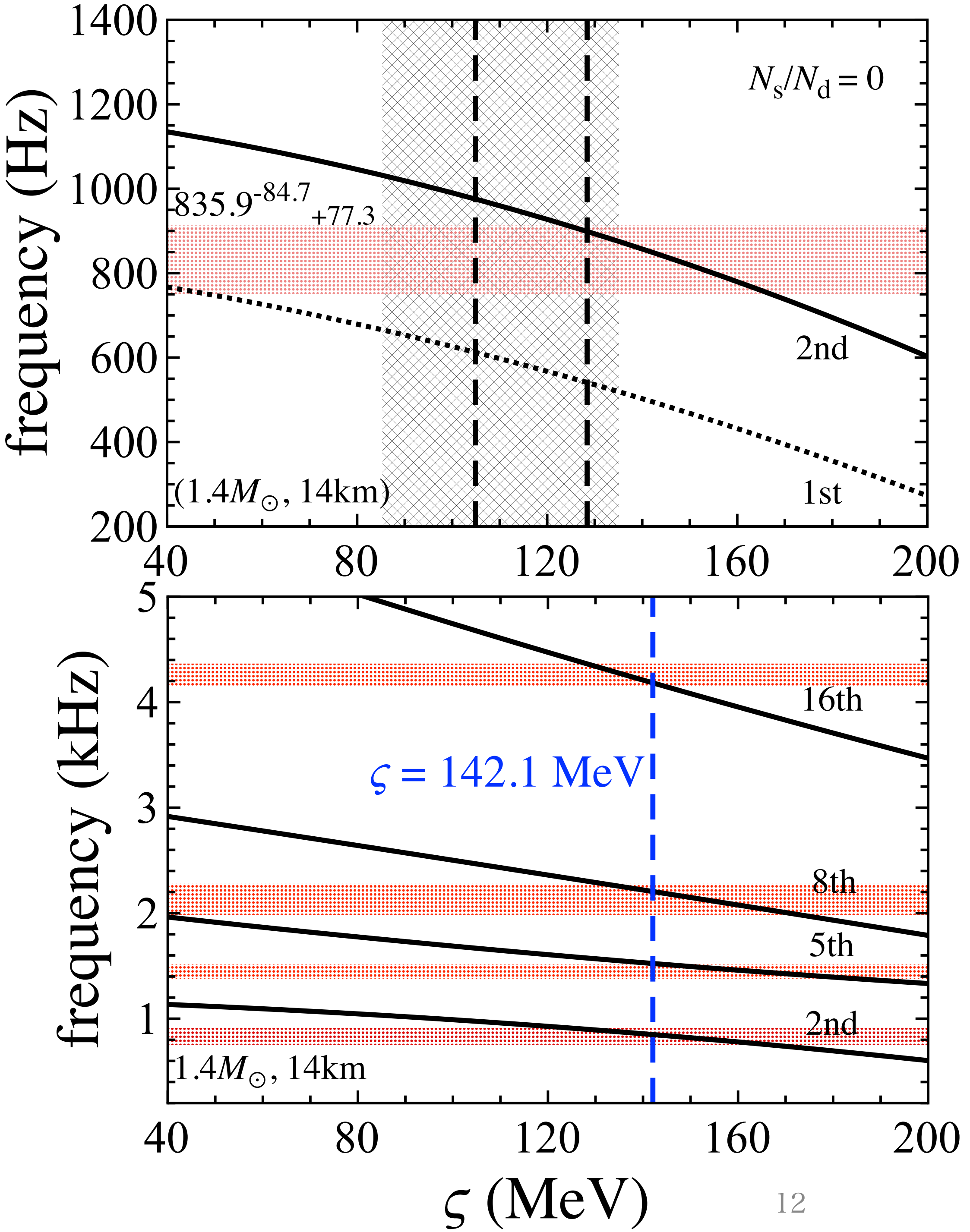
- suppose that the radius of NS with $\rho_c \geq 2\rho_0$ is constant
- then, we can get the NS mass and radius constraint as an intersection

Comparison with other constraints



Another possibility

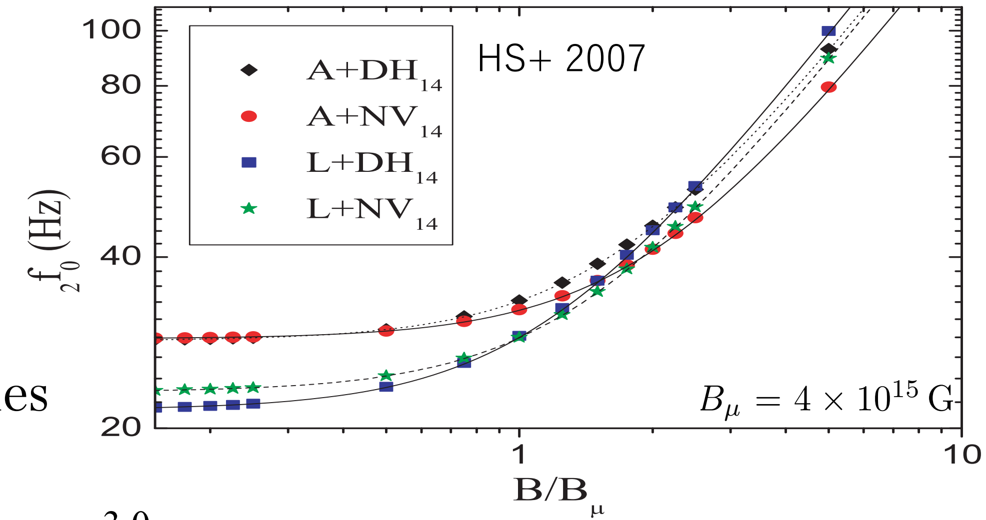
- up to now, we identify the lowest QPO in GRB 200415A with the 1st overtone
- the identification with the 2nd overtone is also possible
  - ς for this identification for NS models with $1.4M_\odot$ and 14 km is relatively large
  - frequency increases with M/R
  - to identify with this correspondence, standard NS models must give us out of the fiducial value of ς



Magnetic effects

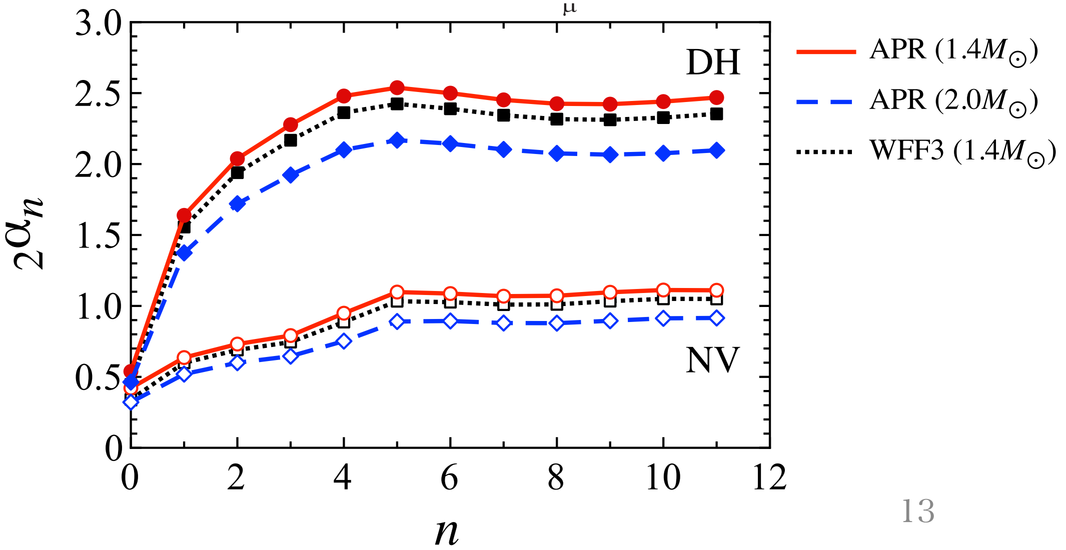
- the shift in the torsional oscillations frequencies obeys the following formula (HS+2007; Gabler+2018)

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



- for the overtones,
  - for EOS NV ${}_2\alpha_n \approx 0.8 - 1.1$
  - for EOS DH ${}_2\alpha_n \approx 2 - 2.5$
- the deviation of the magnetized neutron star frequencies from those of the non-magnetized ones are
  - $\lesssim$ 3.4% for the EOS NV
  - $\lesssim$ 7.5% for the EOS DH,

  if we assume B ≈ 10^{15}G
- These values are still within the limits of uncertainty (~ 10%) estimated in Castro-Tirado+ (2021)
- So, simply we neglect the magnetic effects here.



Conclusion

- magnetar QPOs are newly found in a giant gamma-ray flare (GRB 200415A)
- they can be identified with the overtones of the crustal torsional oscillations
- we get the constraint on NS mass and radius