# クラスト振動によるGRB 200415Aの質量半径の制限

Hajime SOTANI (RIKEN)
collaborate with
K. D. Kokkotas (Tuebingen), N. Stergioulas (Thessaloniki)

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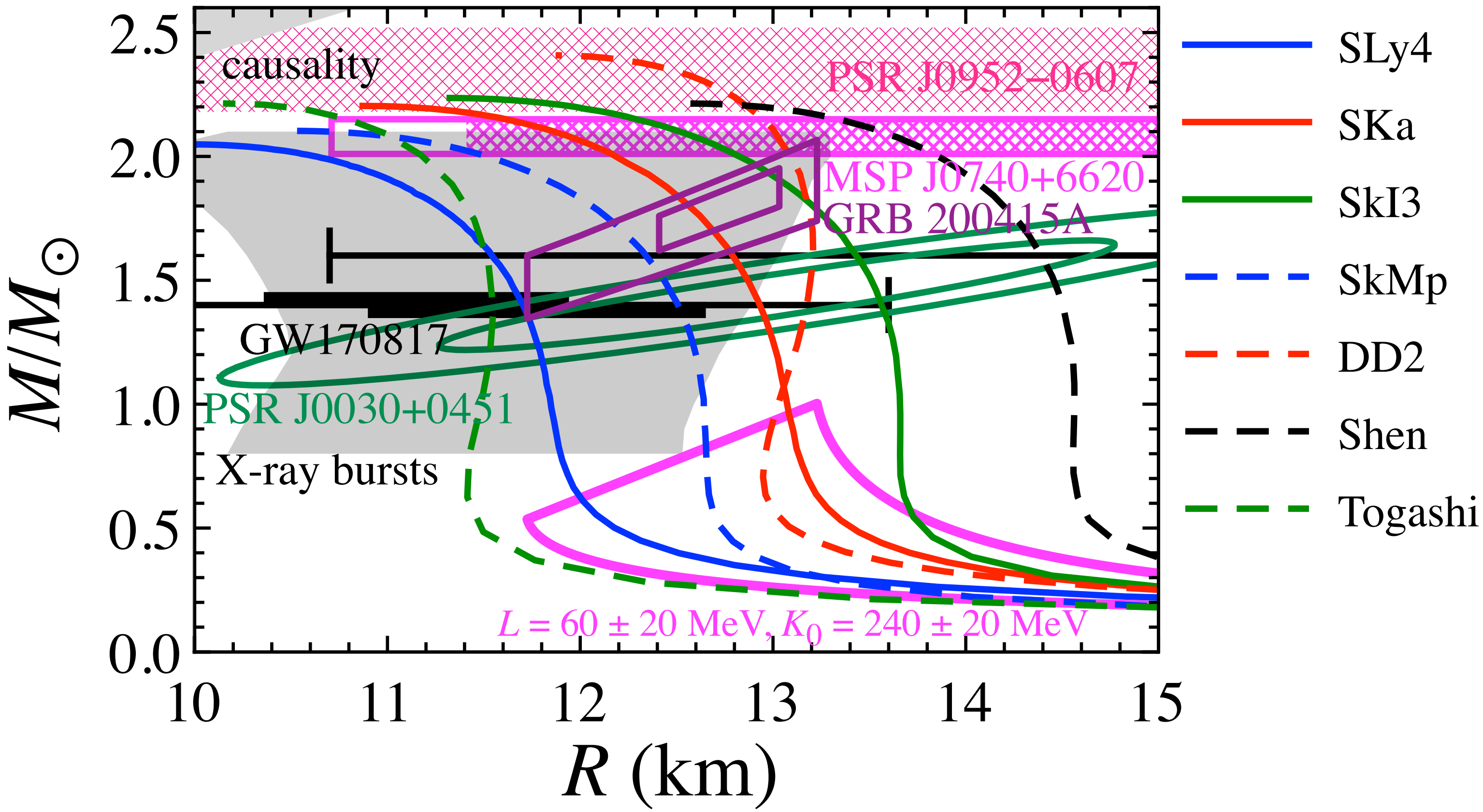
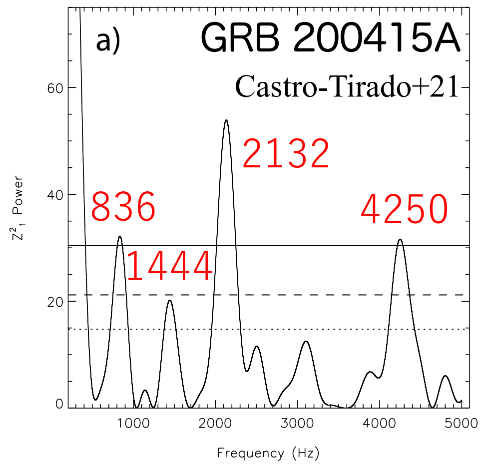
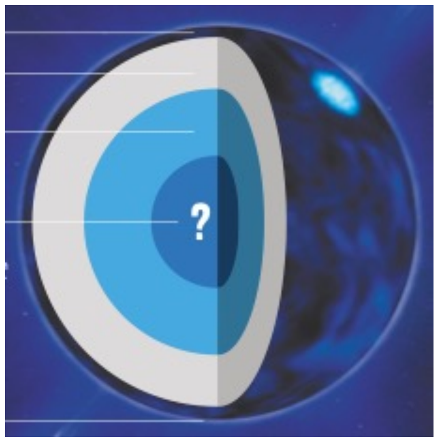
# Result



causality
PSR J0952−0607
MSP J0740+6620
GRB 200415A
GW170817
PSR J0030+0451
X-ray bursts
$L = 60 \pm 20$ MeV, $K_0 = 240 \pm 20$ MeV
$M/M_\odot$
$R$ (km)
SLy4
SKa
SkI3
SkMp
DD2
Shen
Togashi

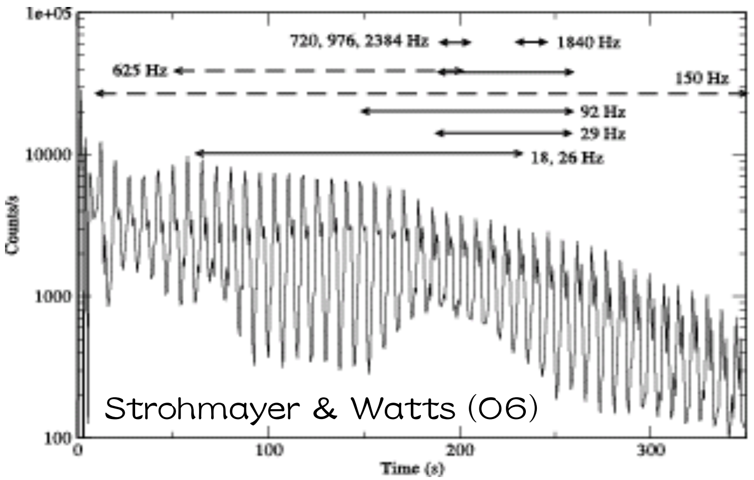



a) GRB 200415A
Castro-Tirado+21
836
1444
2132
4250
Frequency (Hz)

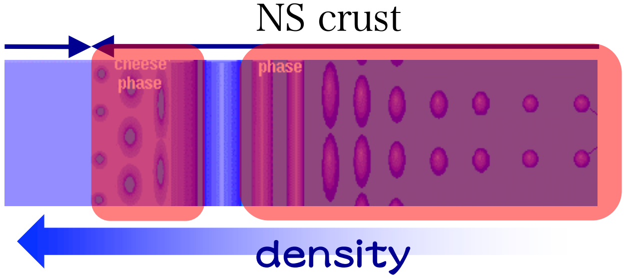



# Magnetar QPOs & crust oscillations

- 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 ($5^{th}$/3/1979) : 43 Hz
  - SGR 1900+14 ($27^{th}$/8/1998) : 28, 54, 84, 155 Hz
  - SGR 1806-20 ($27^{th}$/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 ?

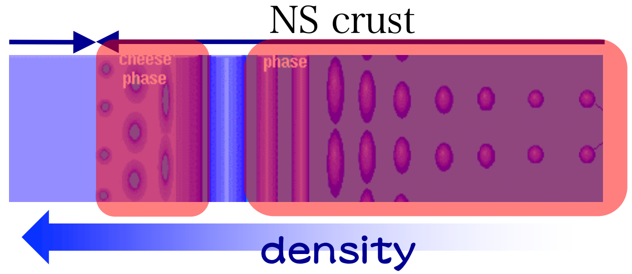


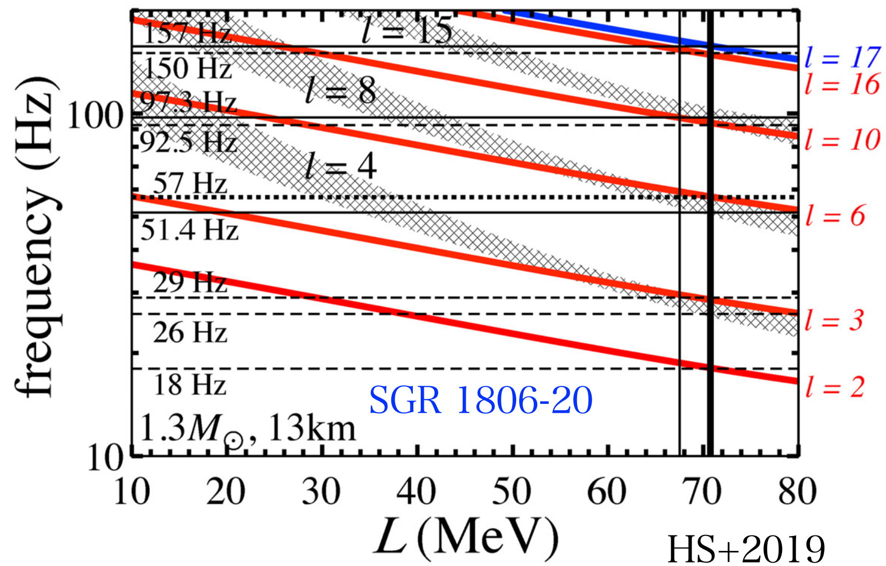
# Constraint on L from magnetar QPOs

- nuclear saturation parameters

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

- Double-layer model (lasagna sandwich)
  - L = 58-73 MeV (HS+ 2019)
- Constraint on $K_0$ : $K_0$ = 240 ± 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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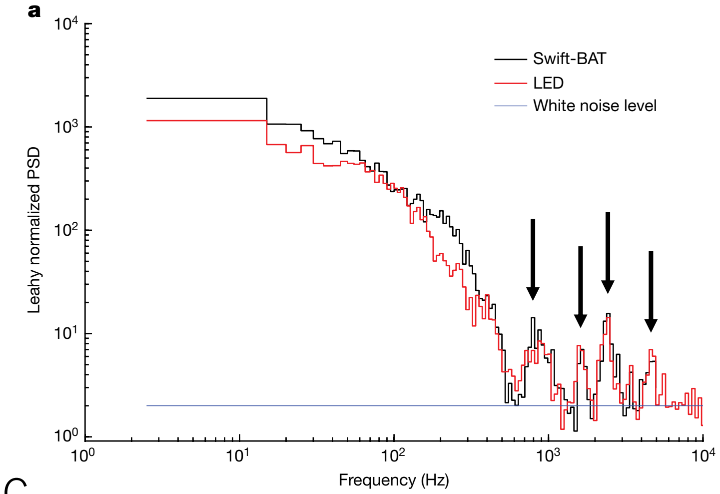
A. J. Castro-Tirado[1,2], N. Østgaard[3✉], E. Göğüş[4✉], C. Sánchez-Gil[5], J. Pascual-Granado[1], V. Reglero[6,7], A. Mezentsev[3✉], M. Gabler[6✉], M. Marisaldi[3,8✉], T. Neubert[9], C. Budtz-Jørgensen[9], A. Lindanger[3], D. Sarria[3], I. Kuvvetli[9], P. Cerdá-Durán[6], J. Navarro-González[7], J. A. Font[6,10], B.-B. Zhang[11,12,13], N. Lund[9], C. A. Oxborrow[9], S. Brandt[9], M. D. Caballero-García[1], I. M. Carrasco-García[14], A. Castellón[2,15], M. A. Castro Tirado[1,16], F. Christiansen[9], C. J. Eyles[7], E. Fernández-García[1], G. Genov[3], S. Guziy[17,18], Y.-D. Hu[1,19], A. Nicuesa Guelbenzu[20], S. B. Pandey[21], Z.-K. Peng[11,12], C. Pérez del Pulgar[2], A. J. Reina Terol[2], E. Rodríguez[1], R. Sánchez-Ramírez[22], T. Sun[1,23,24], K. Ullaland[3] & S. Yang[3]



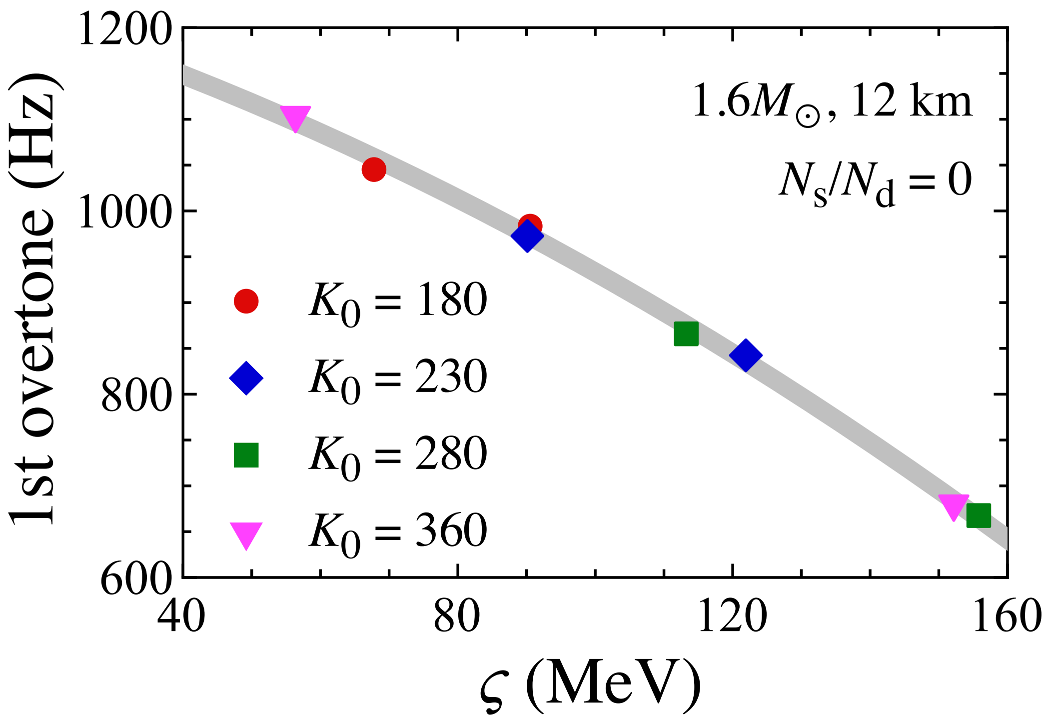

giant gamma-ray flare (GRB 200415A) in the direction of the NGC 253 galaxy, disappearing after 3.5 msec, on 15/4/2020.

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

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 ~ $v_s$ / ΔR (Hansen & Cioffi 80)
  - ΔR depends on $K_0$ & L (HS+17)
- as in Sotani+ 19, frequencies can be well characterized by

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

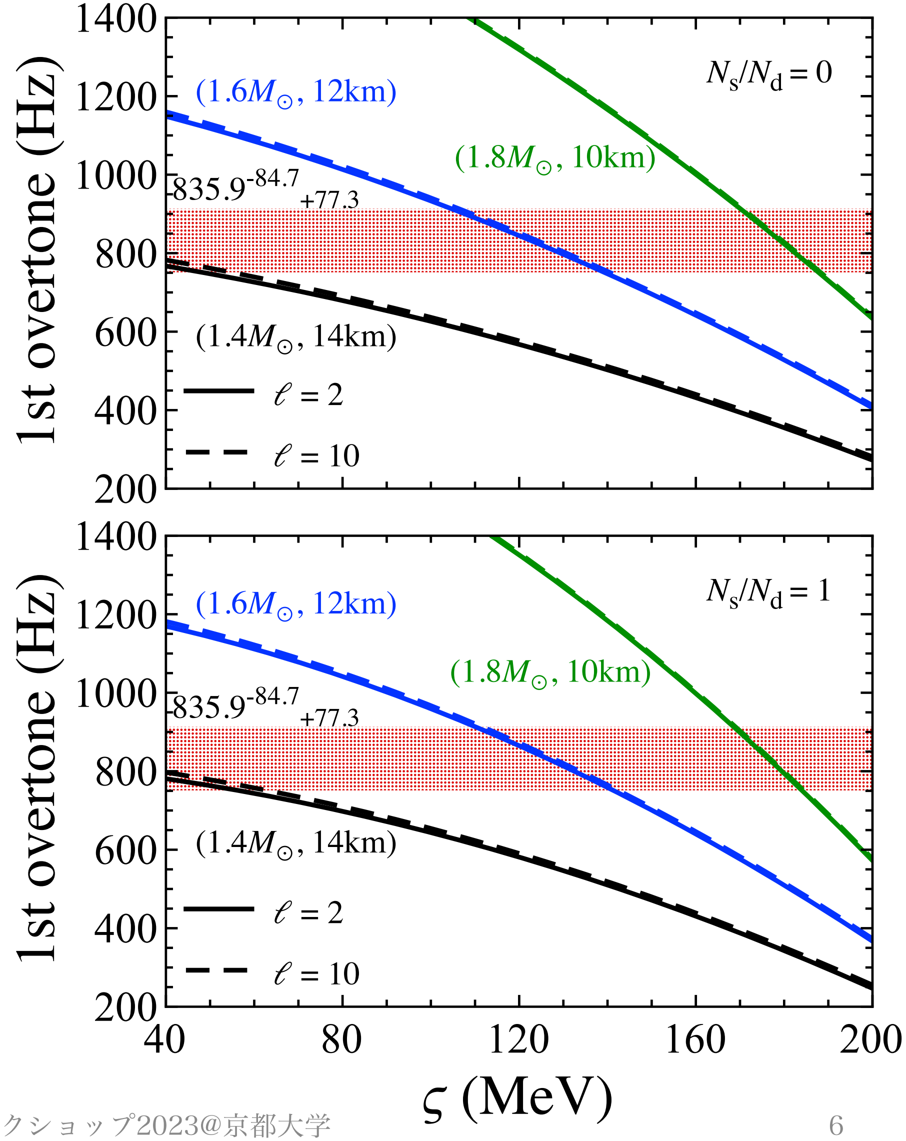
- In fact, fre. can be expressed as

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

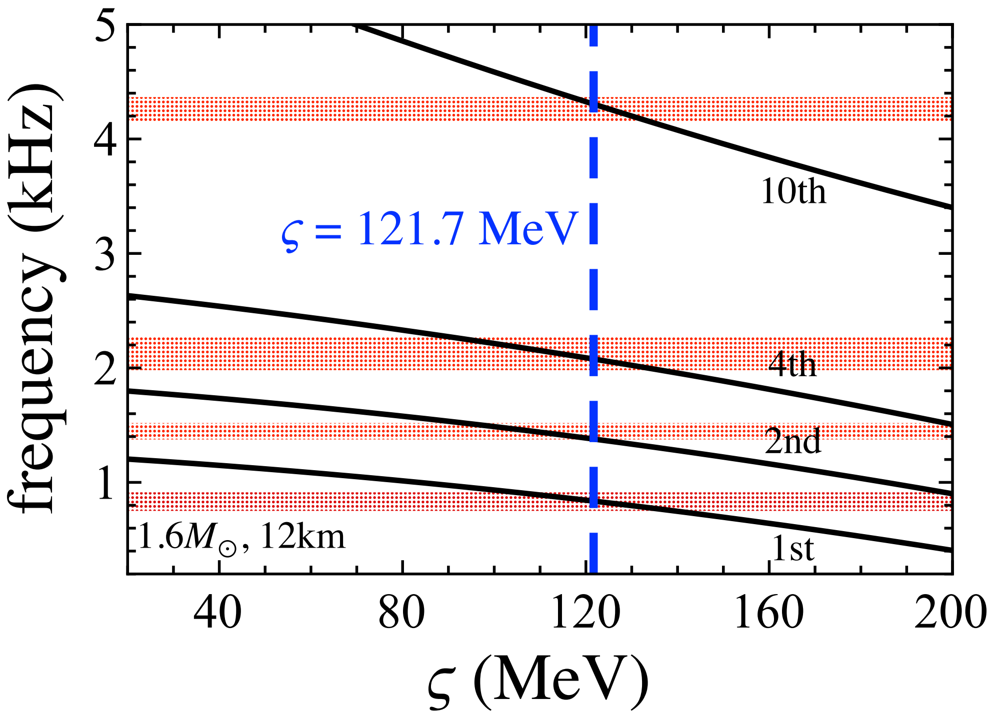
$$\varsigma_{100} \equiv \varsigma/(100\mathrm{MeV})$$

# $1^{st}$ overtone

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

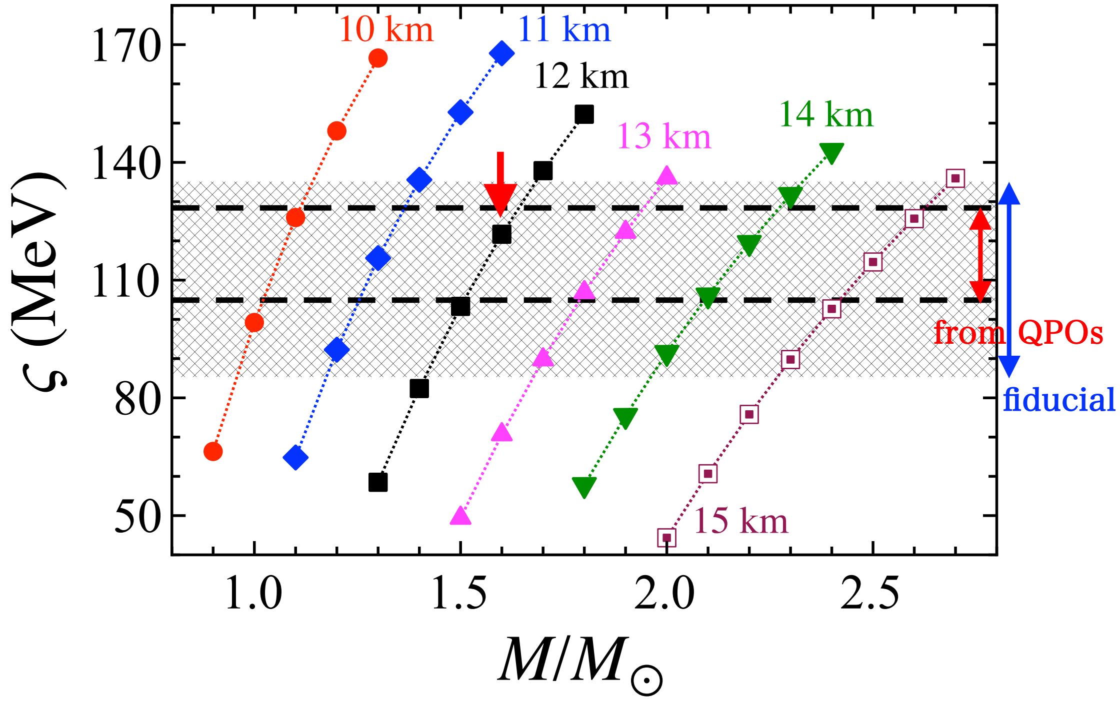


# identification of all QPOs



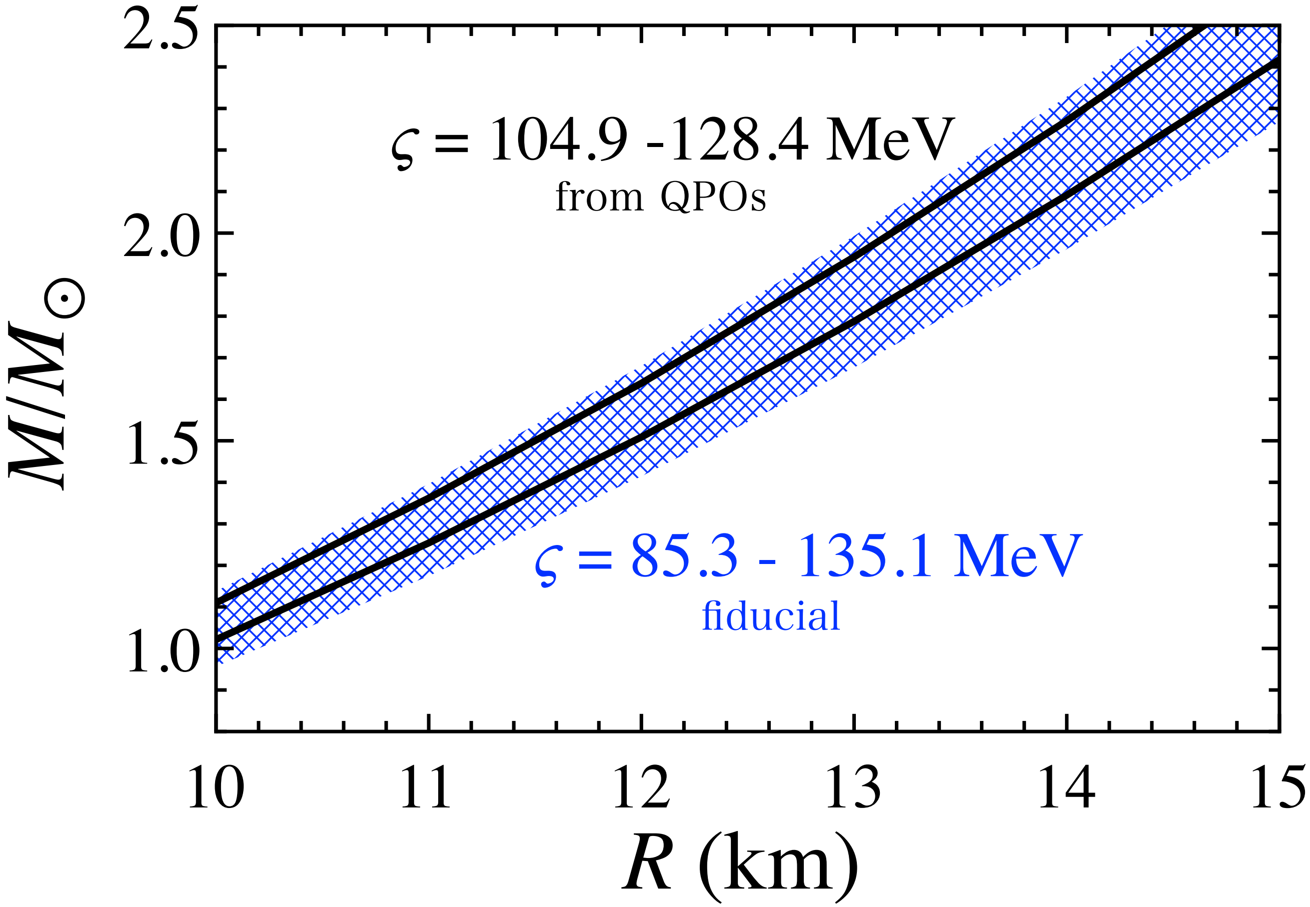

- the observed QPOs in GRB 200415A can be identified with the 1$^{st}$, 2$^{nd}$, 4$^{th}$, and 10$^{th}$ overtones of crustal torsional oscillations
- for NS models with 1.6$M_\odot$ and 12km, ς should be 122 MeV for the identification.
- with different NS models, fre. shift up and down, which leads 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

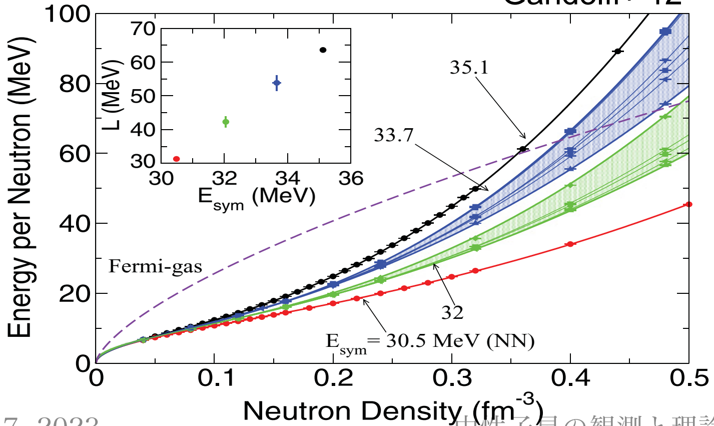


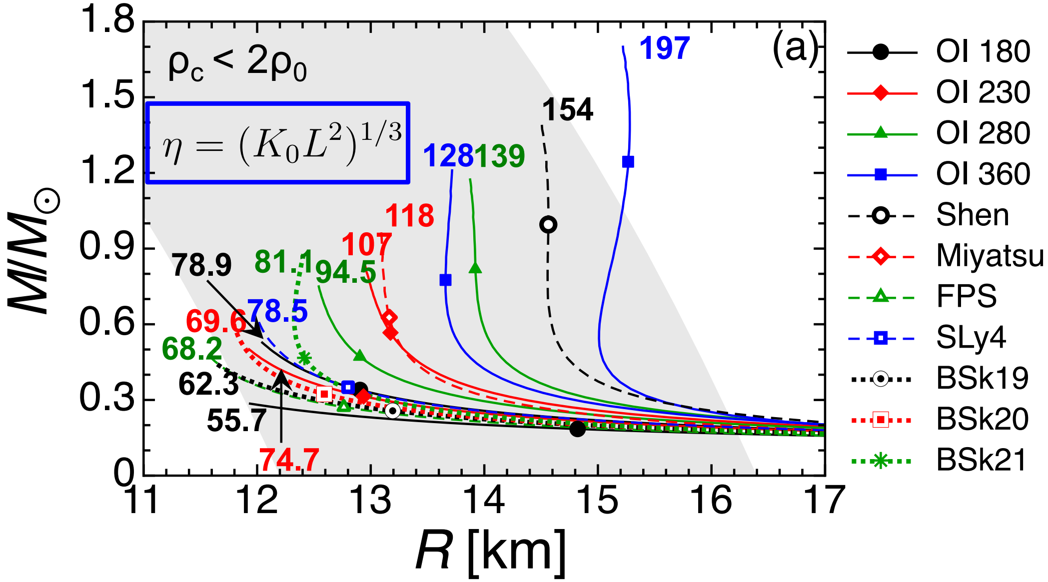
# Mass formula (HS+14)

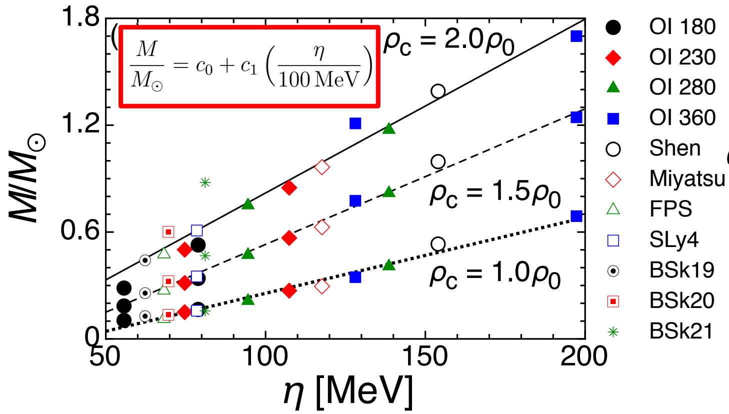
- low-mass NSs
  - low-central density
  - EOS for a low-density region plays an important role
  - may be able to discuss the stellar models without the core EOS
  - $1.174M_\odot$ NS exists (Martinez+ 15)
- we focus on the NS models for $\rho \lesssim 2\rho_0$

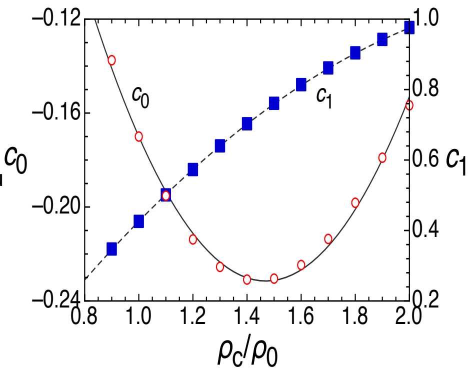
$$w = w_0 + \frac{K_0}{18n_0^2}(n-n_0)^2 + \left[S_0 + \frac{L}{3n_0}(n-n_0)\right]\alpha^2$$

Gandolfi+ 12



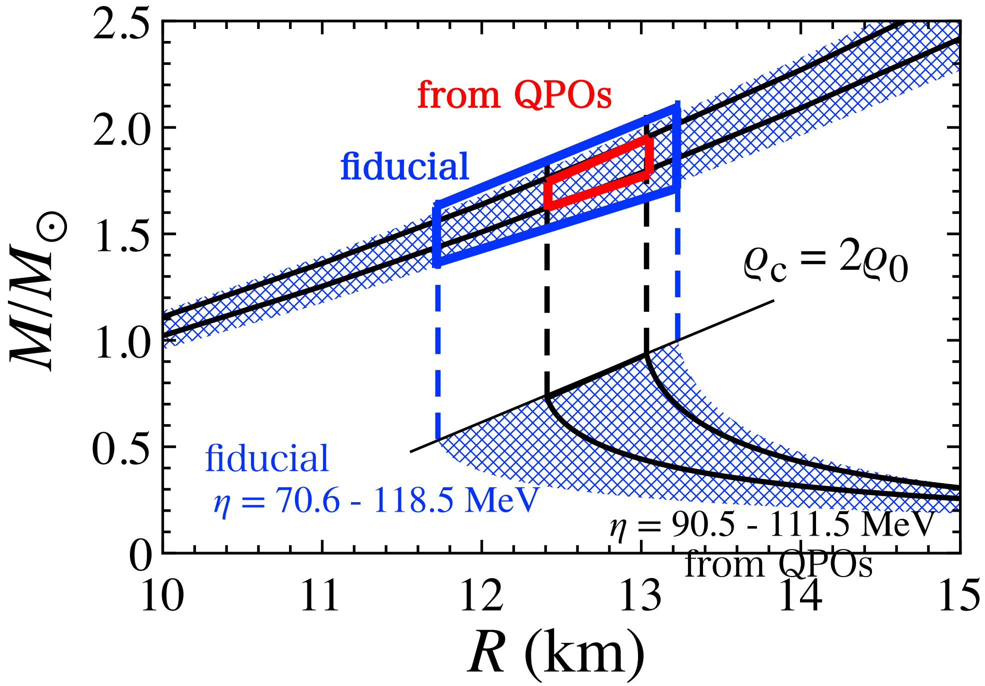




$z = 1/\sqrt{1-2GM/Rc^2} - 1$

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

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

# make constraint more severe




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

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

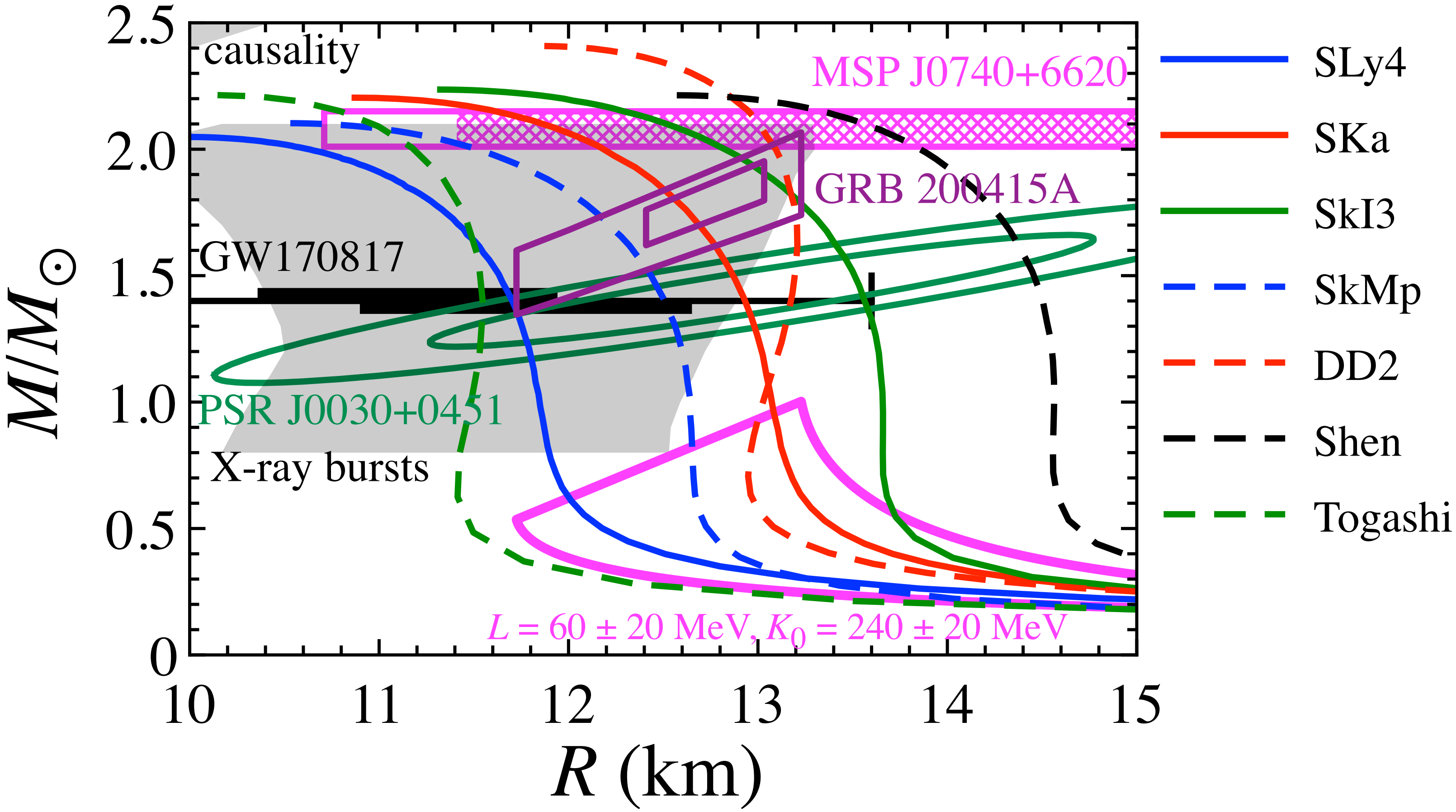
$$z = 0.00859 - 0.0619u_c + 0.0255u_c^2 - (0.0429 - 0.108u_c + 0.0120u_c^2)\left(\frac{\eta}{100\,\mathrm{MeV}}\right)$$

- we focus on

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

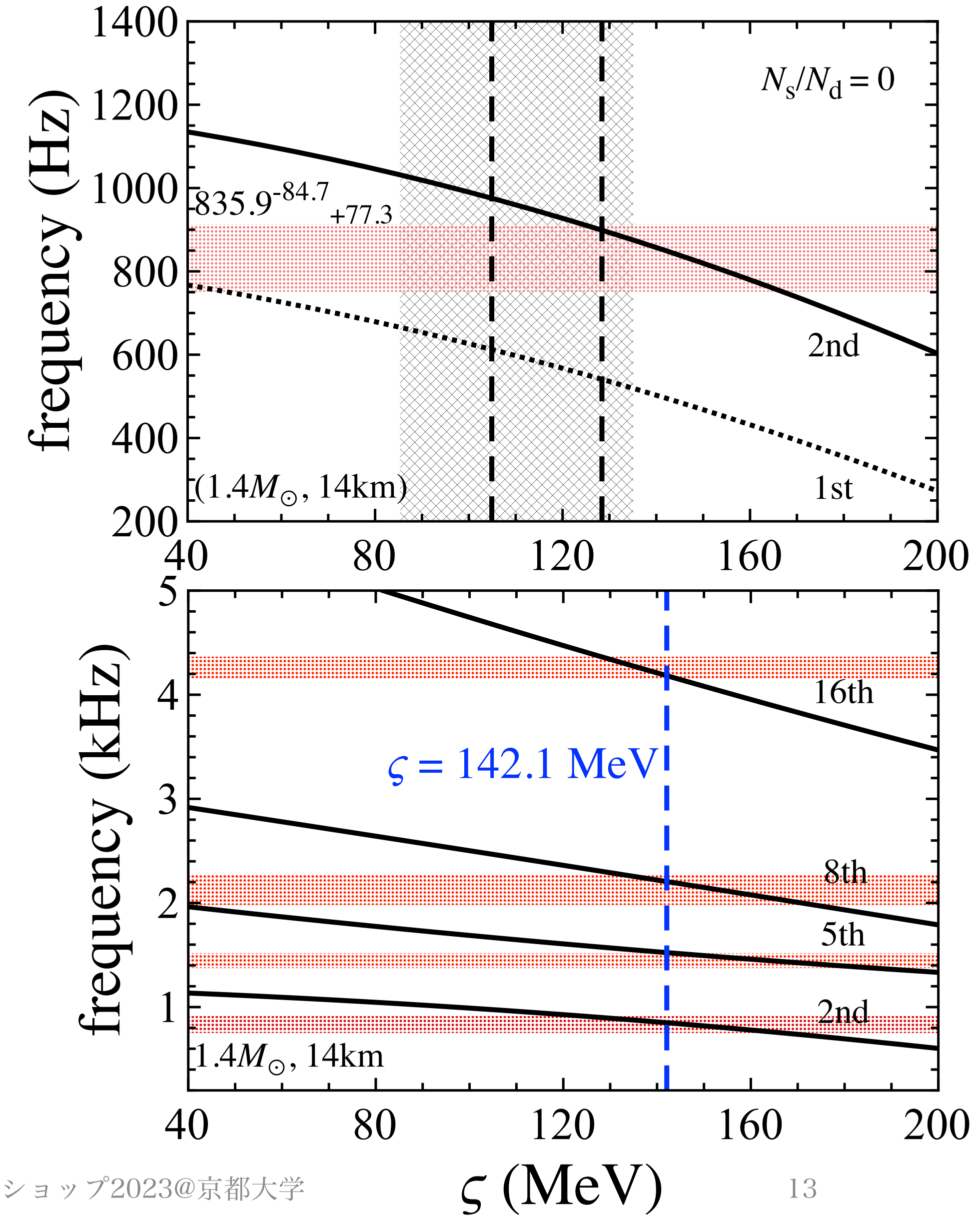
  - $\eta$ = 70.6 – 118.5 MeV ($\varsigma$ = 85.3 - 135.1 MeV)
  - $\eta$ = 85.3 – 135.1 MeV ($\varsigma$ = 104.9 - 128.4 MeV)
- suppose that the radius of NS with $\rho_c \geq 2\rho_0$ is constant
- then, we can get the NS mass and radius constraint as an intersection

# 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
    - $\varsigma$ 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 $\varsigma$



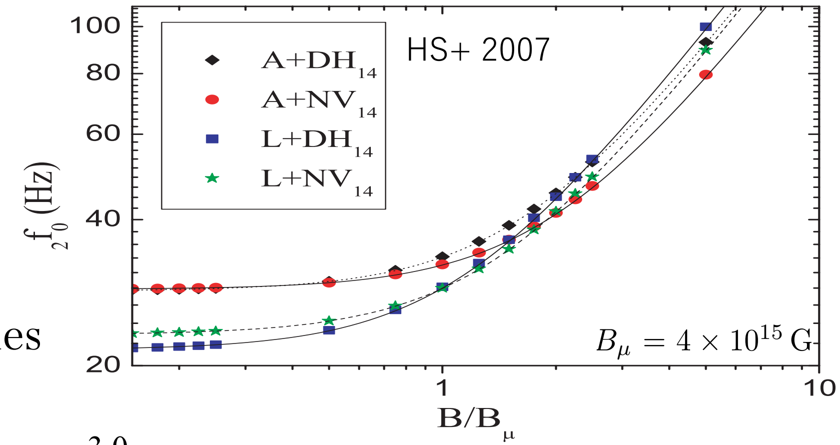
# Magnetic effects

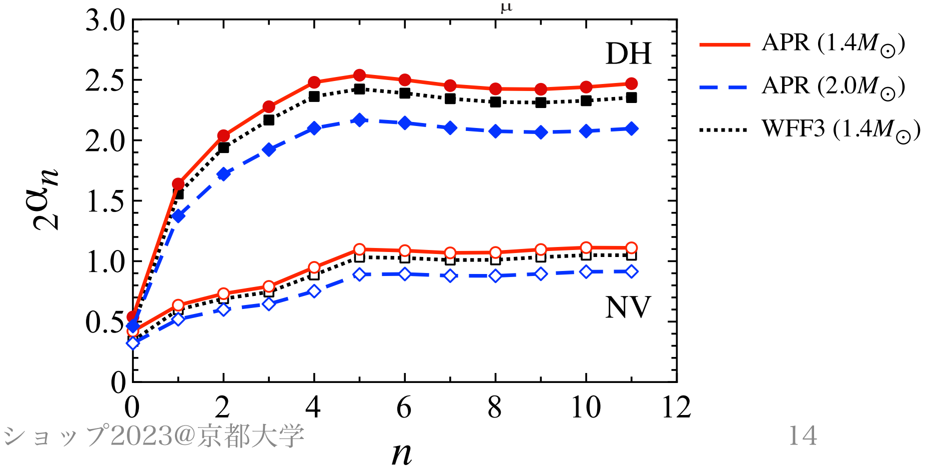
- the shift in the torsional oscillations frequencies obeys the following formula (HS+2007; Gabler+2018)

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

- 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

- kHz QPOs found from other short GRBs (Chirenti +23)
  - 1113, 2649 Hz in GRB 910711
  - 877, 2612 Hz in GRB 931101B