Crustal torsional oscillations and nuclear saturation parameters

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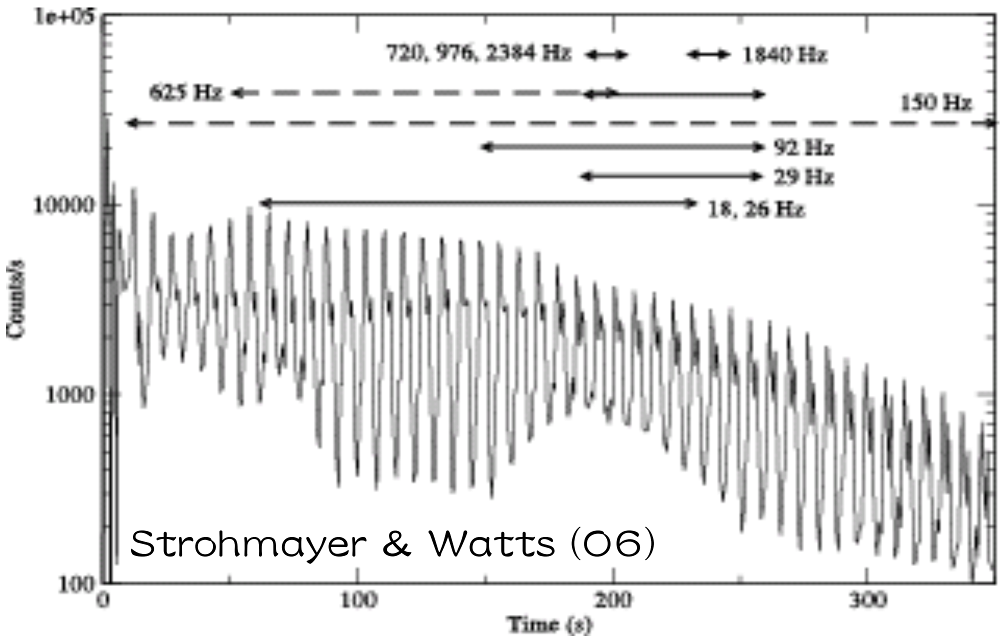
QPOs in SGRs

- Quasi-periodic oscillations (QPOs) in afterglow of giant flares from soft-gamma repeaters (SGRs)
  - 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

  (Barat+ 1983, Israel+ 05, Strohmayer & Watts 05, Watts & Strohmayer 06)
  - additional QPO in SGR 1806-20 is found : 57Hz (Huppenkothen + 2014)



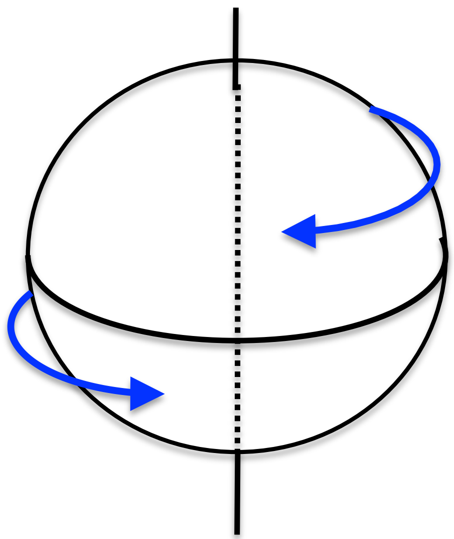
- Crustal torsional oscillation ?
- Magnetic oscillations ?

torsional oscillations

- axial parity oscillations
  - incompressible
  - no density perturbations (less associated with GWs)
- in Newtonian case (Hansen & Cioff 1980)

$$ {}_{\ell}t_0 \sim \frac{\sqrt{\ell(\ell+1)\mu/\rho}}{2\pi R} \sim 16\sqrt{\ell(\ell+1)}\ \text{Hz} \qquad {}_{\ell}t_n \sim \frac{\sqrt{\mu/\rho}}{2\Delta r} \sim 500 \times n\ \text{Hz} $$

  - μ : shear modulus
  - frequencies ∝ shear velocity $v_s = \sqrt{\mu/\rho}$
  - overtones depend on crust thickness
- torsional oscillations independently of core EOS
  - by integrating from the surface with (M, R)

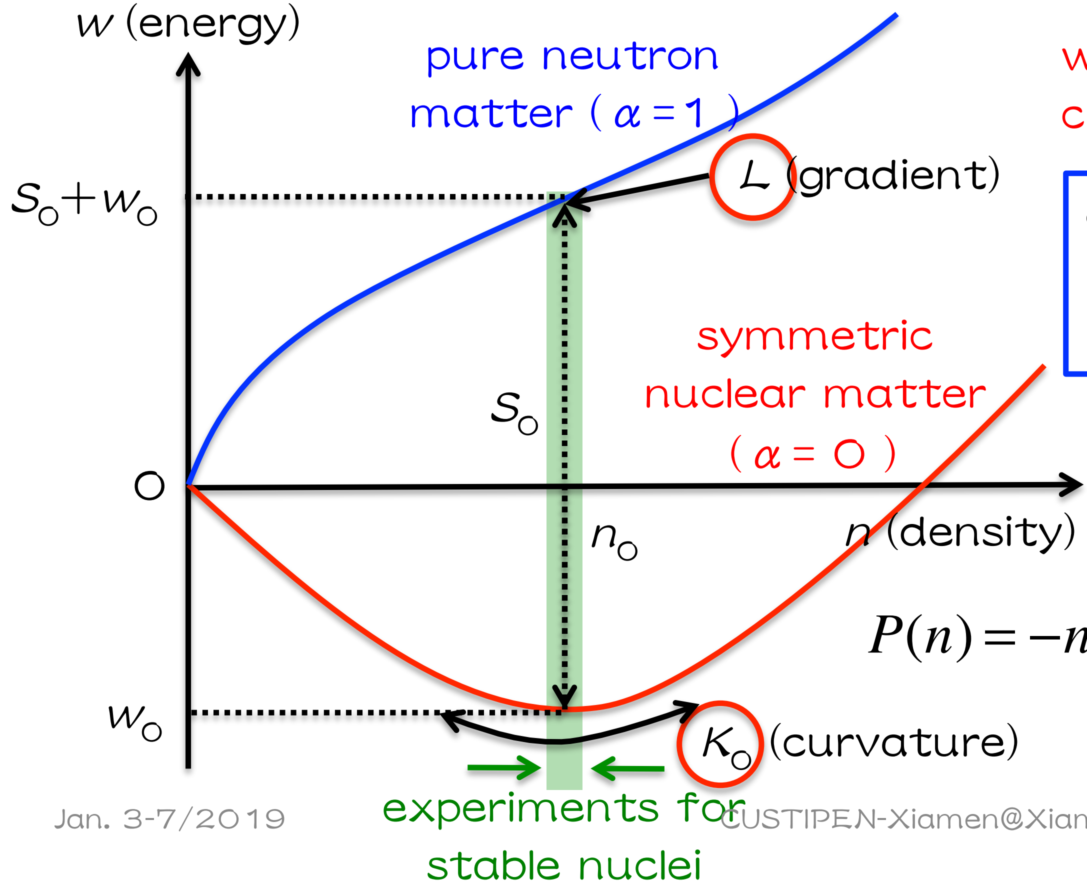


EOS near the saturation point

- Bulk energy per nucleon near the saturation point of symmetric nuclear matter at zero temperature;

incompressibility — symmetry parameter

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



$$P(n) = -n^2 \frac{dw}{dn}$$

we adopt a phenomenological EOS, characterized by (K_0, L)

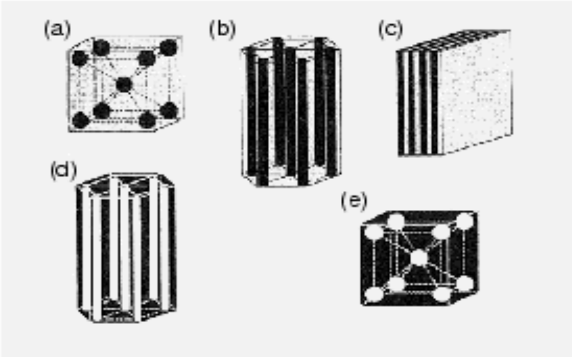
current constraints on K_0 & L
- K_0 = 230 ± 40 MeV (Khan+13)
- 40 ≲ L ≲ 80 MeV (Li+ 13)

bcc lattice

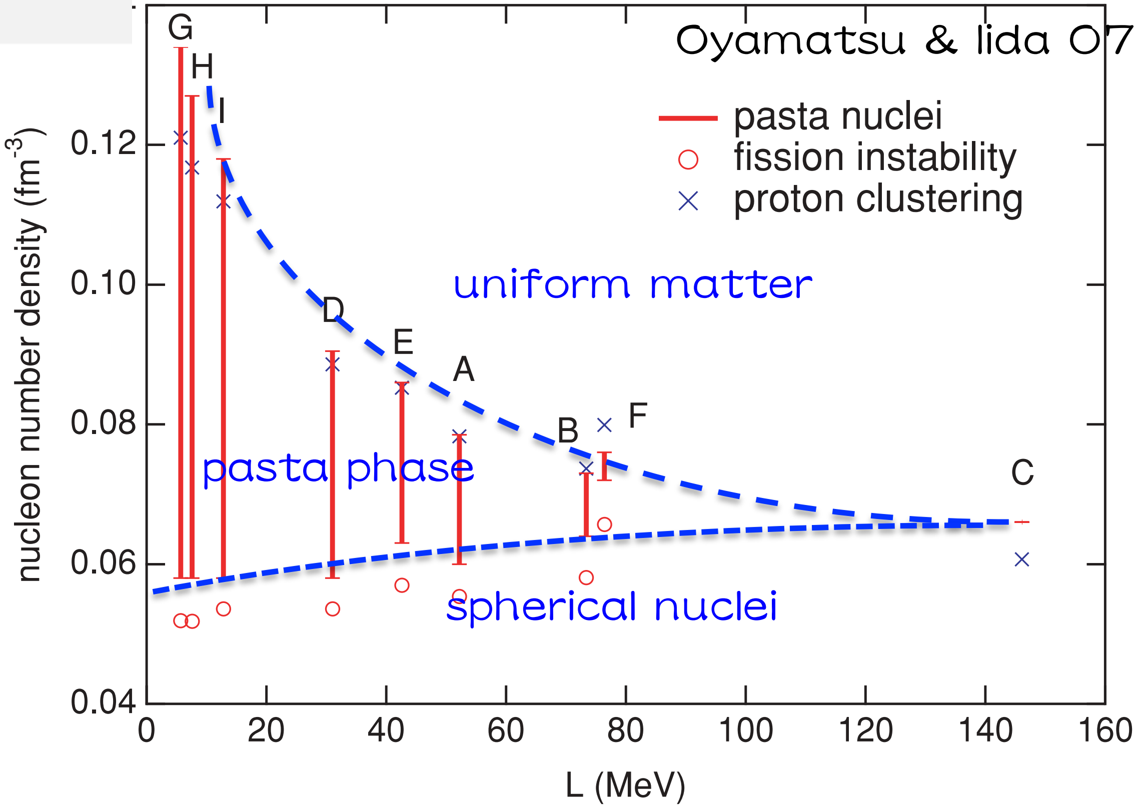
$$\mu = 0.1194\frac{n_i(Ze)^2}{a}$$

n_i : ion number density
Z : charge of nuclei
a : Wigner-Seitz radius
(Strohmayer+91)

pasta phase

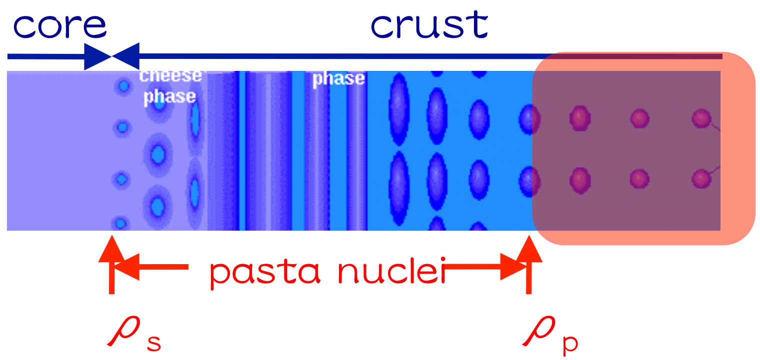


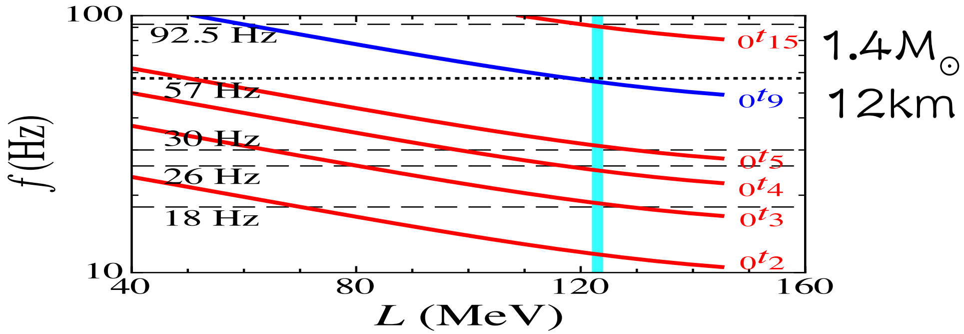
Oyamatsu (1993)



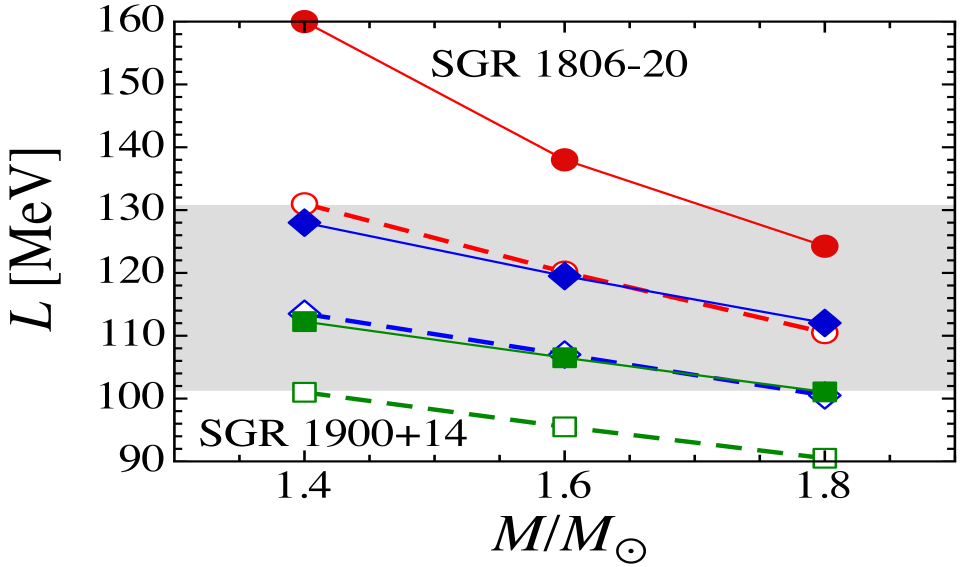
- with larger L, pasta phase becomes narrower
  - For $L \gtrsim$ 100MeV, pasta structure almost disappears.

constraint on L via QPO frequencies





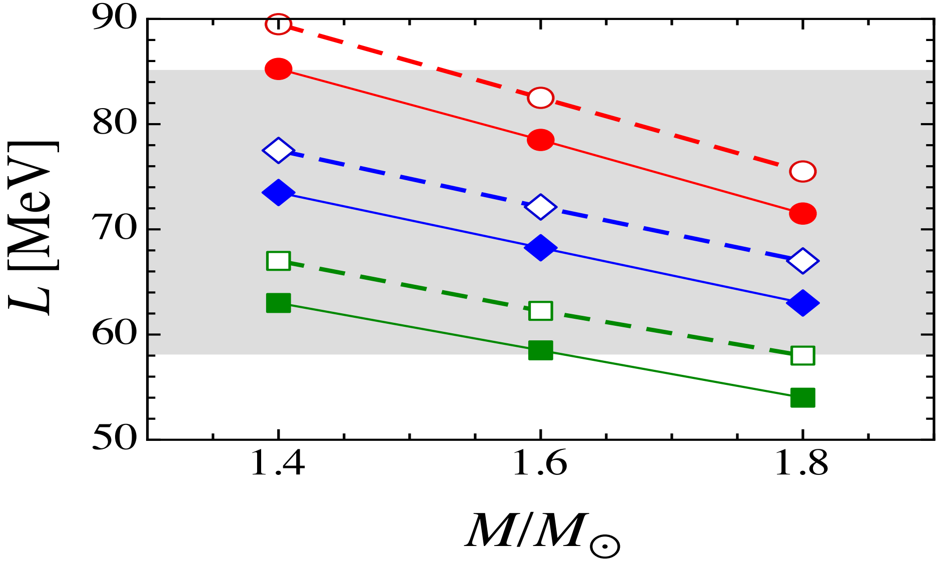
1) all QPOs come from crustal torsional oscillations (HS+13a)



➡ $101.1 \leq L \leq 131.0$ MeV

cf) L = 40 ~ 80 MeV ??

2) QPOs except for 26Hz come from crustal torsional oscillations (HS+13b)



➡ $58.0 \leq L \leq 85.3$ MeV

one needs another oscillation mechanism to explain the 26Hz QPO.

elastic properties in pasta

Pethick & Potekhin 98

- cylindrical nuclei

uniform transverse compression; transverse shear

$$E_d = \frac{B}{2}\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}\right)^2 + \frac{C}{2}\left[\left(\frac{\partial u_x}{\partial x}-\frac{\partial u_y}{\partial y}\right)^2 + \left(\frac{\partial u_x}{\partial y}+\frac{\partial u_y}{\partial x}\right)^2\right] + \frac{K_3}{2}\left(\frac{\partial^2 \boldsymbol{u}}{\partial z^2}\right)^2$$

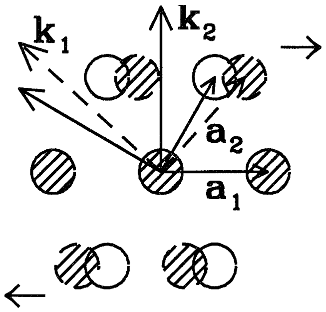
bending

$$+B'\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}\right)\left(\frac{\partial \boldsymbol{u}}{\partial z}\right)^2 + \frac{B''}{2}\left(\frac{\partial \boldsymbol{u}}{\partial z}\right)^4 .$$

higher order term

$$\log_{10}(C/E_{C0}) \approx 2.1(w-0.3)$$

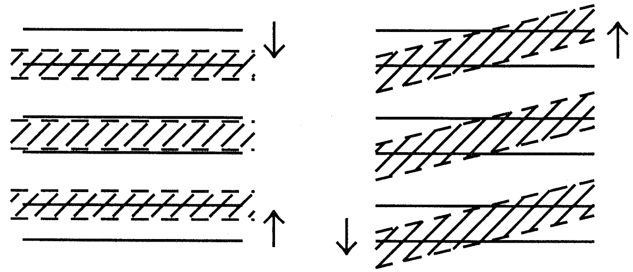
E_{C0}: Coulomb energy per unit volume
w : volume fraction



- slab-like nuclei

$$E_d = \frac{B}{2}\left[\frac{\partial u}{\partial z} - \tfrac{1}{2}(\nabla_\perp u)^2\right]^2 + \frac{K_1}{2}(\nabla_\perp^2 u)^2$$

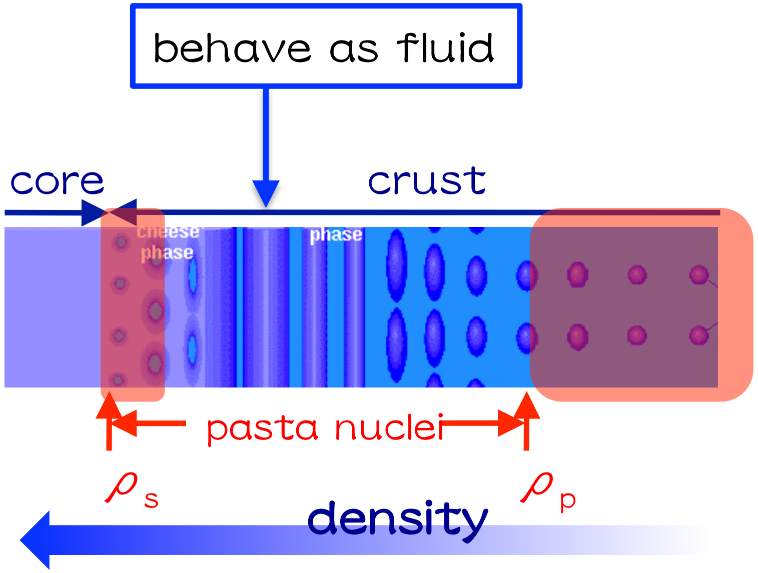
compression; shear; splay deformation



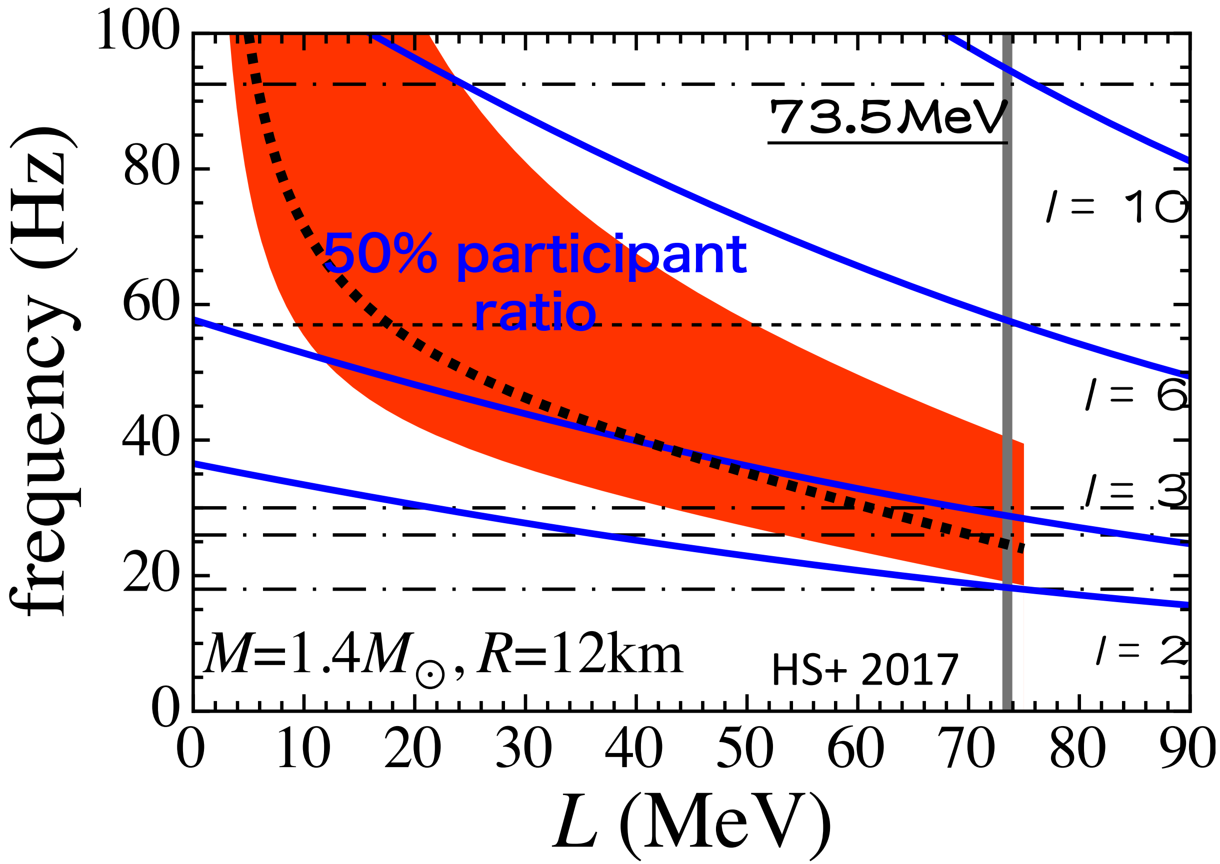
a compression   b shear

shear property in slab-like nuclei becomes higher order effect!
→ linear response behaves as fluid

as a possibility of 26Hz...



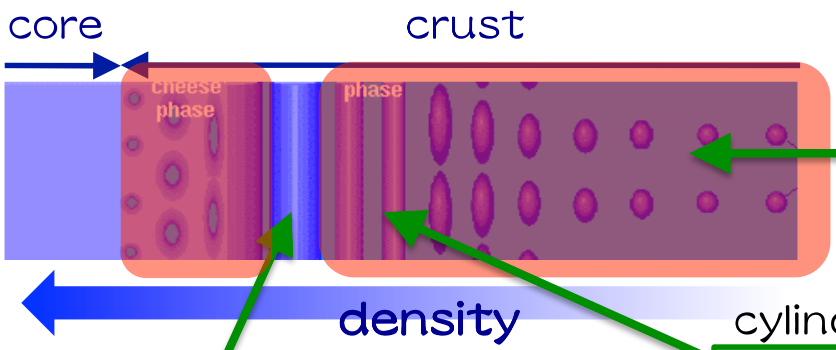
oscillations in bubble phase??



- Oscillation in bubble might be possible to correspond to 26Hz QPO, depending on the entrainment rate.
- Observational evidence for showing the existence of pasta phase!?

effect of pasta structure

HS+ 18



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)

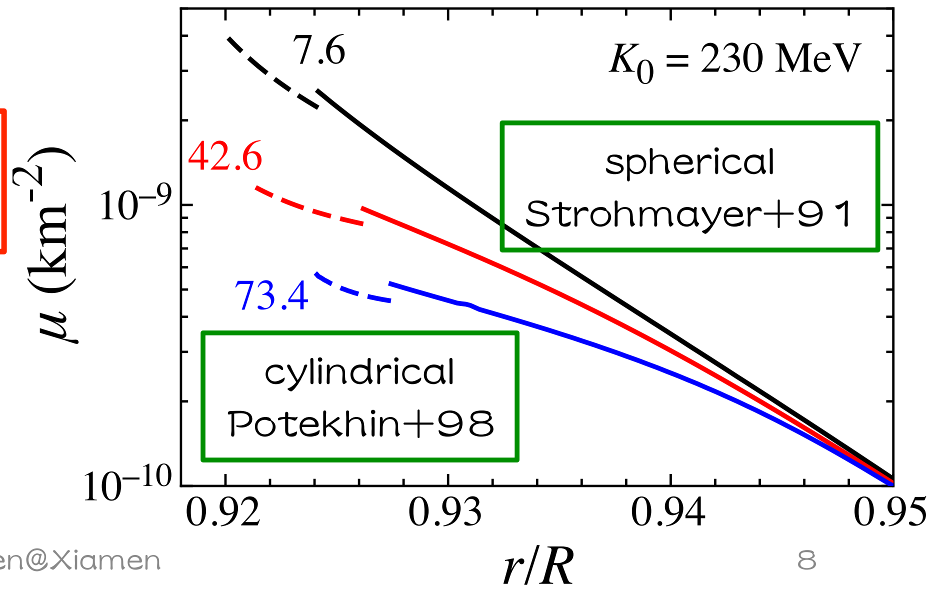
→ two independent oscillations
(i) spherical + cylindrical
(ii) cylindrical-hole + bubble → 26Hz?

identification of fundamental oscillations
→ constraint on L (?)

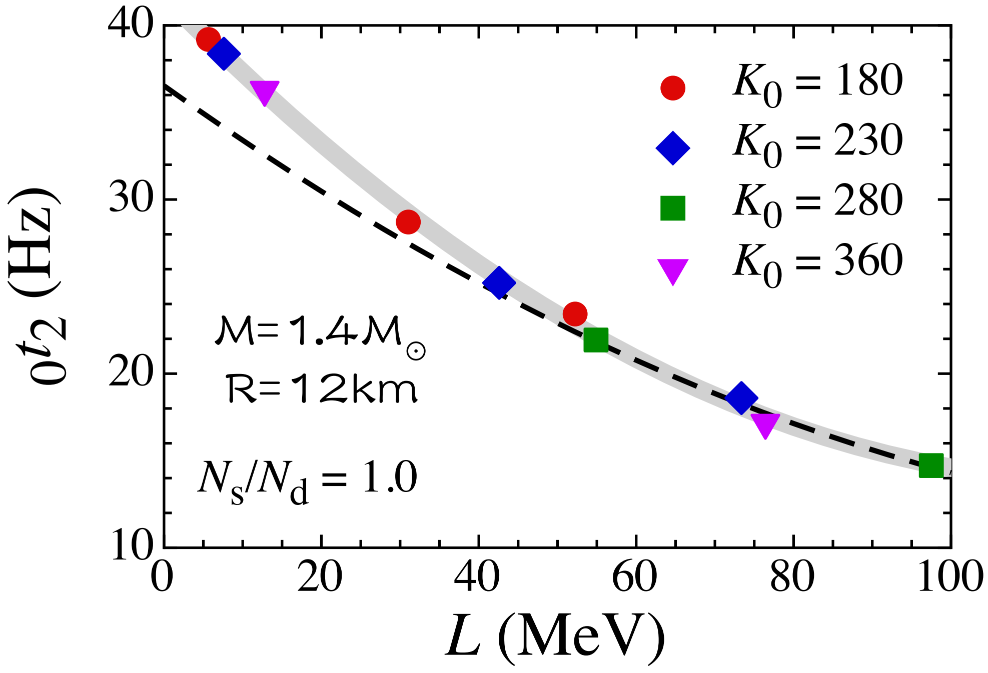
identification of overtone (?)

$${}_1t_2 \sim v_s / \Delta R$$

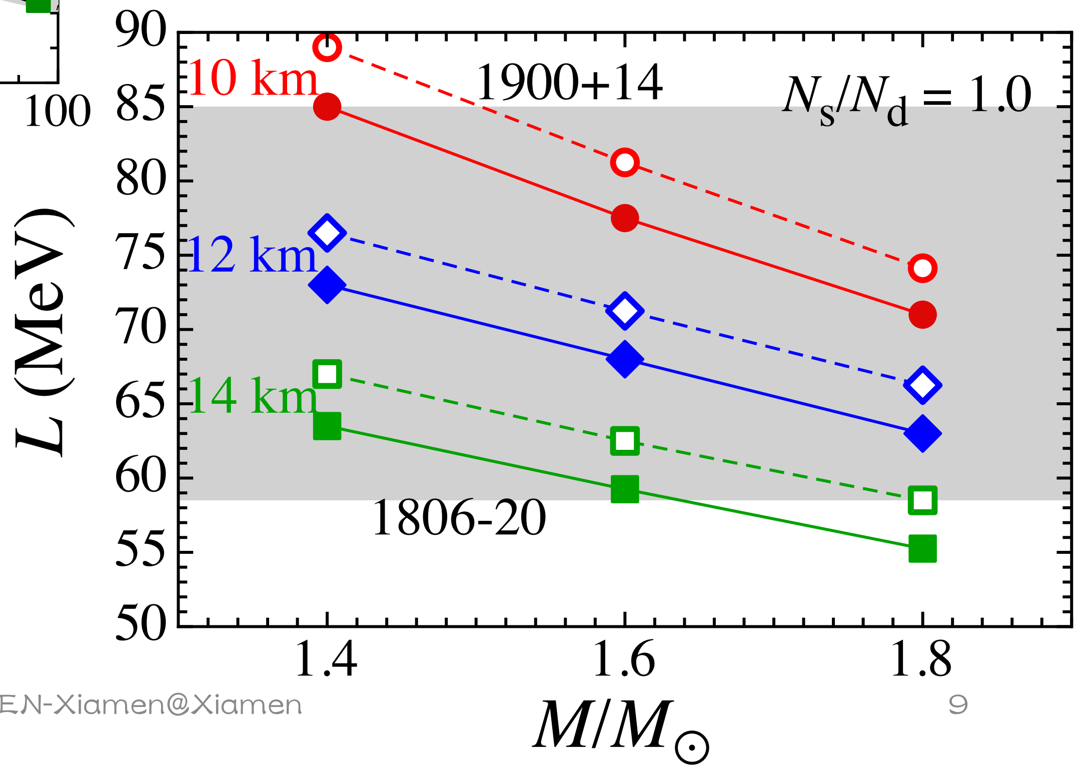
→ additional information



constraint on L



- fundamental oscillations weakly depend on the existence of cylindrical phase.
- all of QPOs except for 26Hz can be identified as same as the previous calculations.

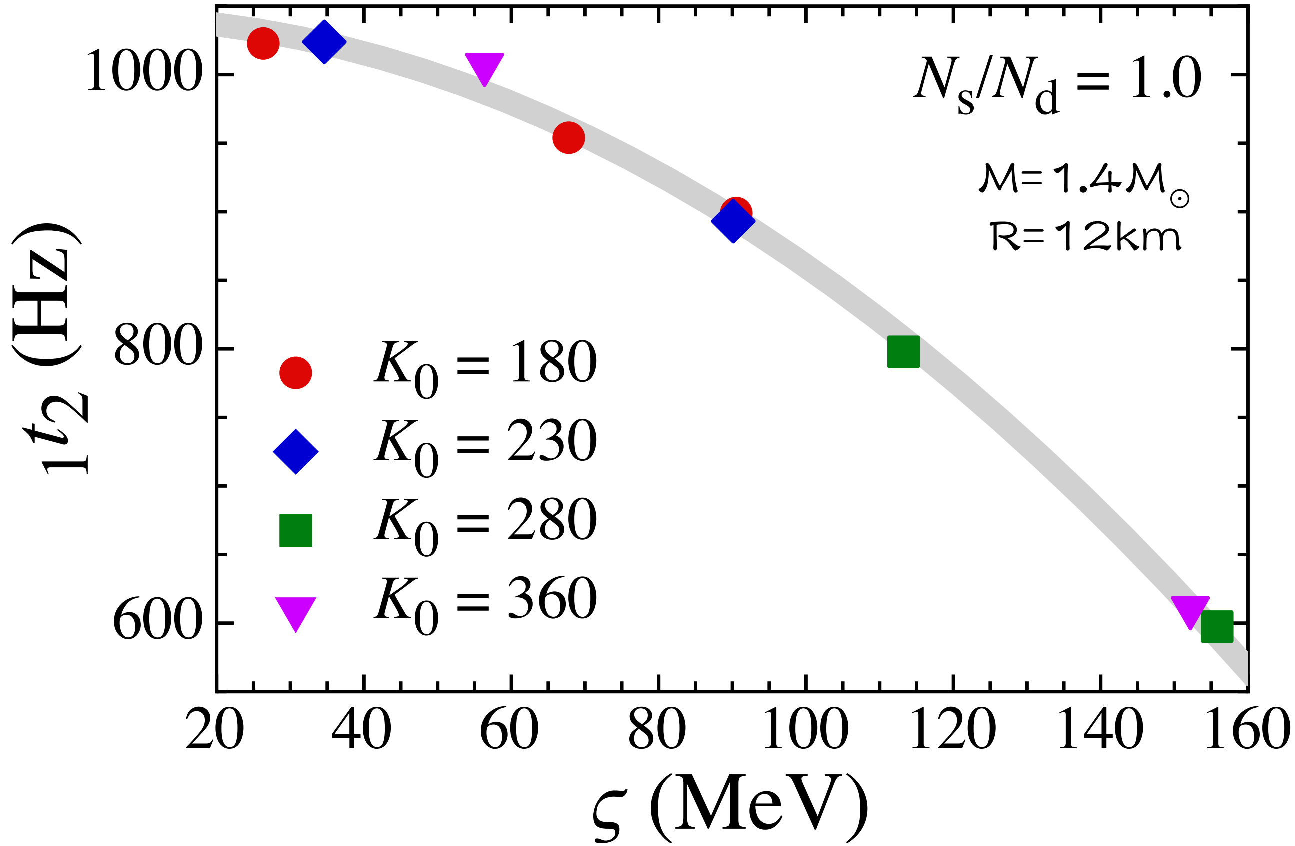


1^{st} overtone

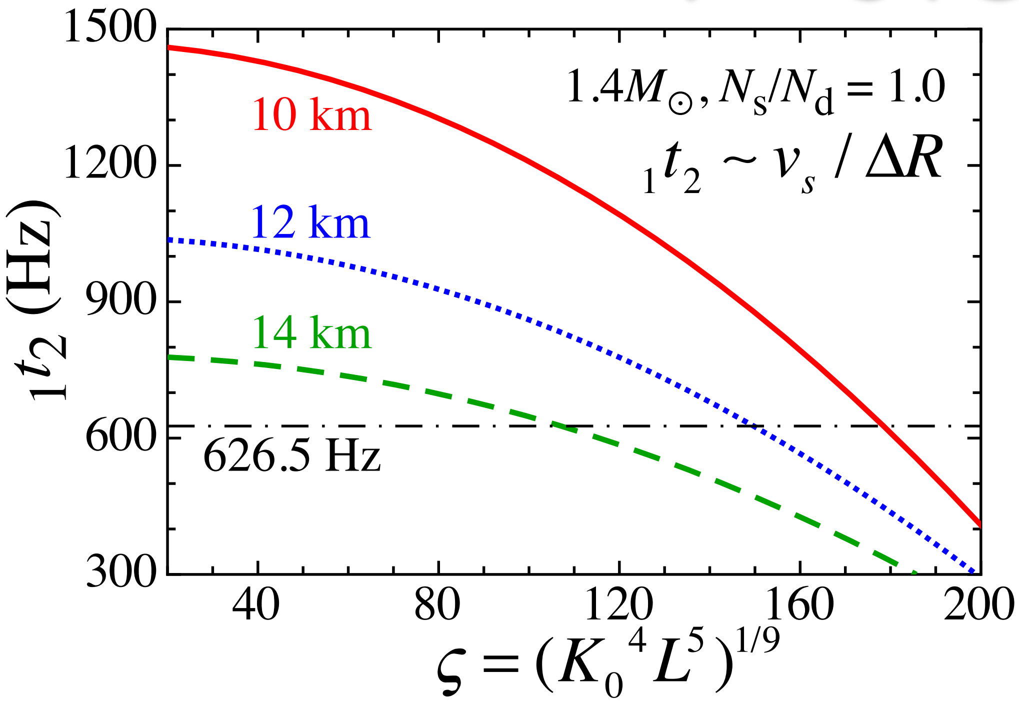
HS+ 18

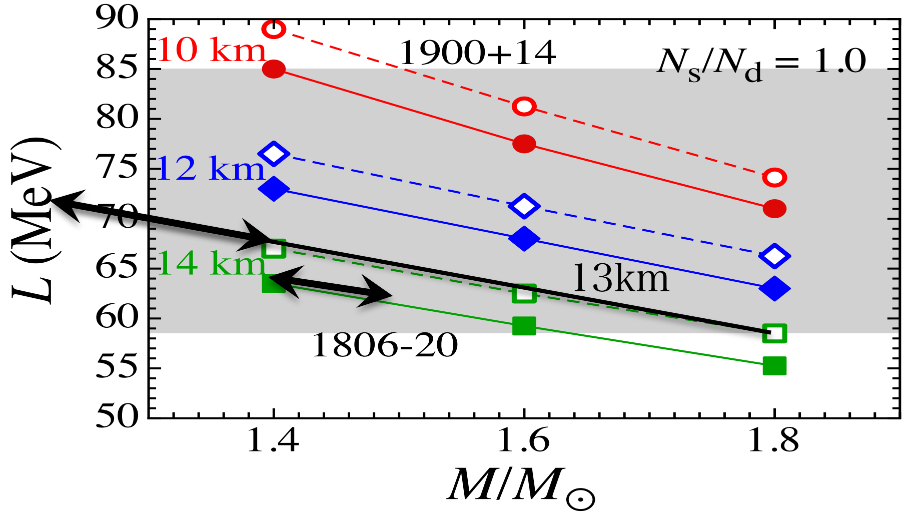
- frequencies of 1^{st} overtone depend on K_0 & L
- we find the good combination of K_0 & L for expressing the 1^{st} overtone frequencies.

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

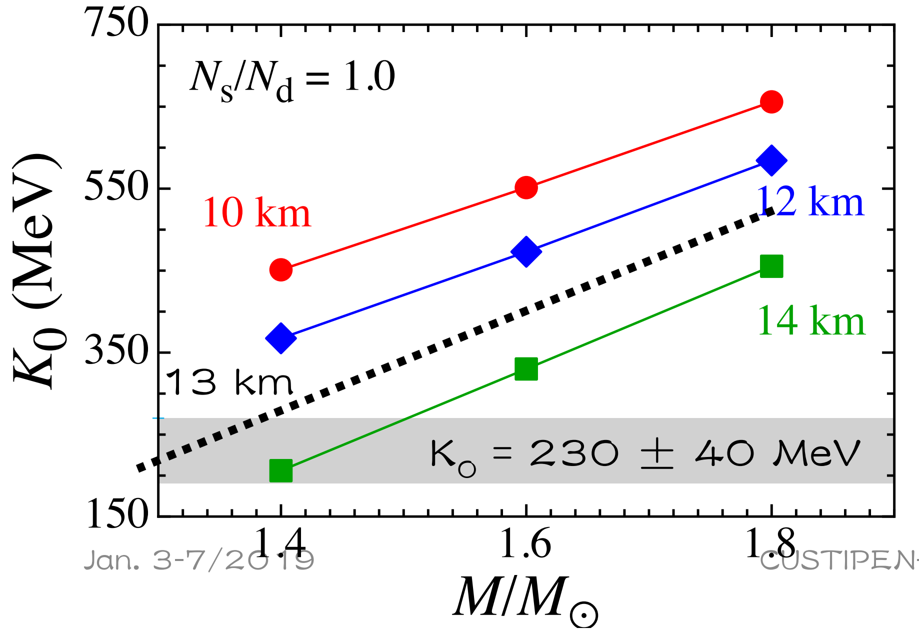


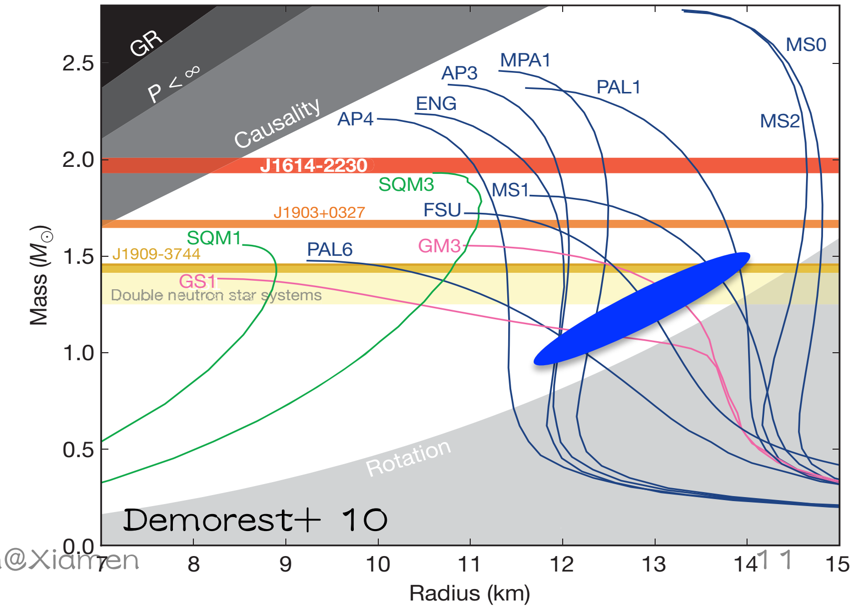
1^{st} overtone



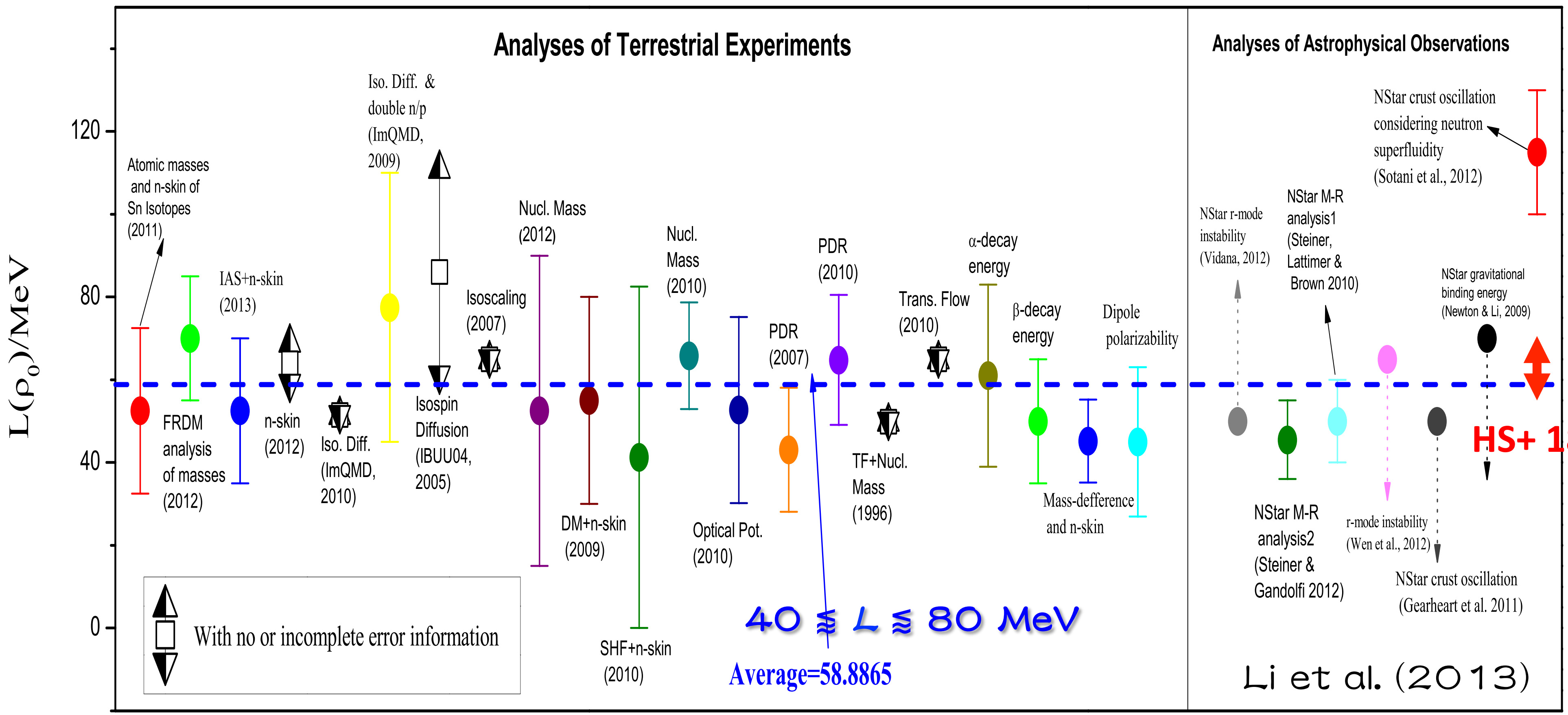


SGR 1806-20 : 1.2-1.4$M_\odot$(13km)
1.4-1.5$M_\odot$(14km) → L ≃ 61-73MeV





constraints on *L*



- 26Hz : bubble (${}_0t_2$), 626.5Hz : spherical + cylindrical (${}_1t_2$)
  → SGR1806-20 should be relatively low mass NS ($M \sim 1.2$-$1.4 M_\odot$, R~13km??)
  → L ~ 58-73MeV

summary

- QPOs in SGR could be strongly associated with the NS oscillations.
- taking into account the effect of pasta structure, we calculate the crustal torsional oscillations
  - spherical + cylindrical nuclei phase
- constraint on L is almost independent of the existence of pasta
- Identifying the 626.5Hz QPO with the overtone, we can obtain a new constraint on $\varsigma = (K_0{}^4 L^5)^{1/9}$
  - together with the constraint on L, we obtain the constraint on K_0
  - considering the terrestrial constraint on K_0, we find
    - SGR1806-20 should be relatively low mass NS ($M \sim 1.2\text{-}1.4 M_\odot$(13km), $\sim 1.4\text{-}1.5 M_\odot$(14km))
    - L ~ 58-73MeV