Neutron stars and symmetry energy

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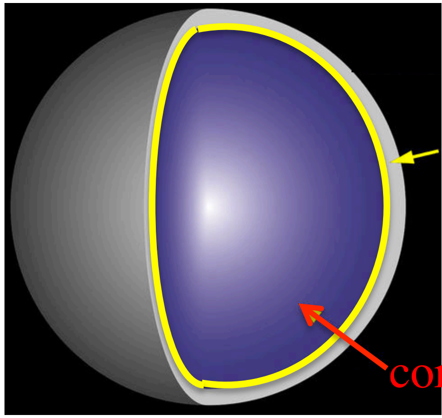
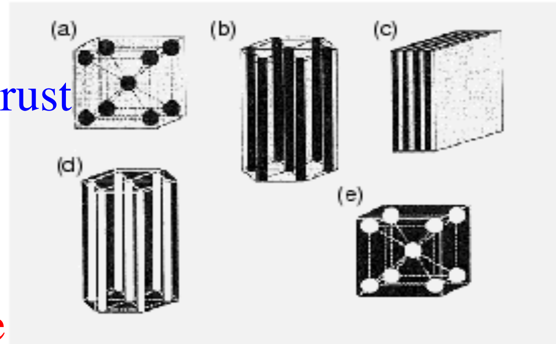
neutron stars

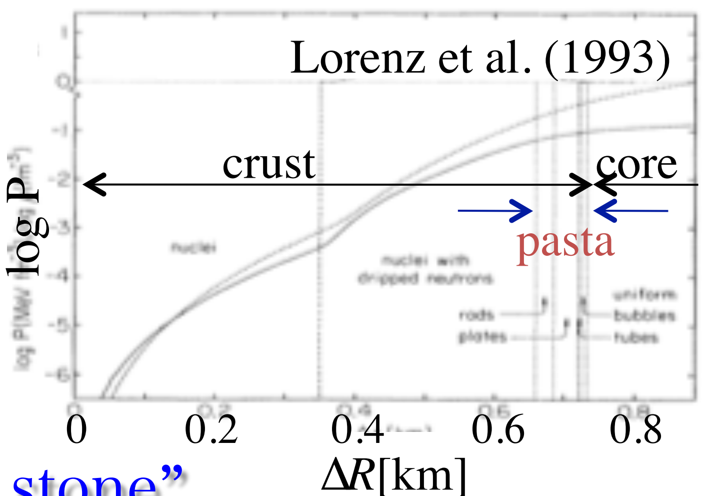
- Structure of NS
  - solid layer (crust)
  - nonuniform structure (pasta)
  - fluid core (uniform matter)
- Crust thickness $\lesssim$ 1km
- Determination of EOS for high density region could be quite difficult on Earth
- Constraint on EOS via observations
  - stellar mass and radius
  - stellar oscillations (& emitted GWs)

  "(GW) asteroseismology"
- NS can be considered as a "Rosetta stone" to see physics in ultra-high density region.





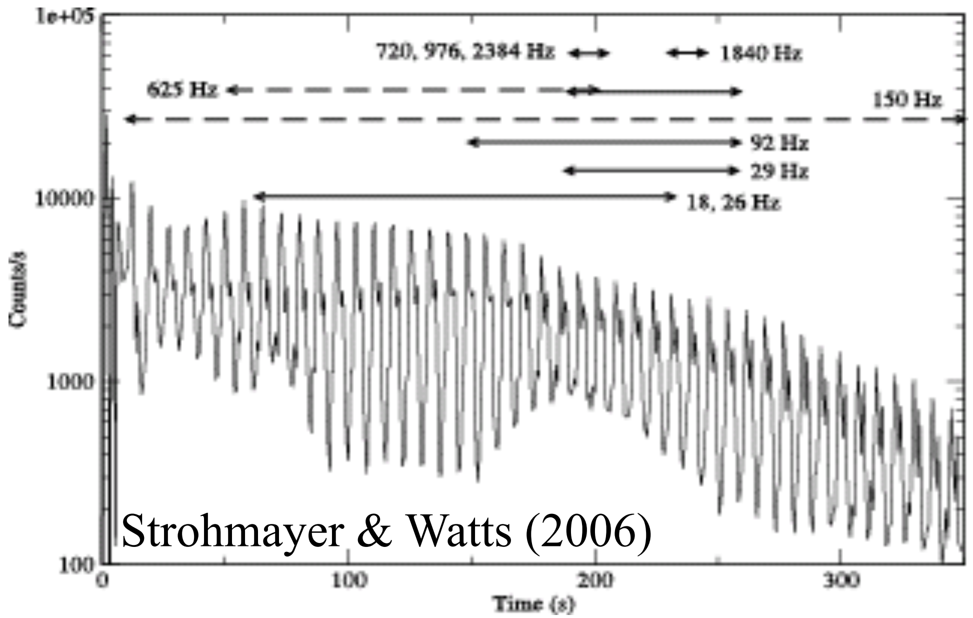
Oyamatsu (1993)



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)



Strohmayer & Watts (2006)

- Crustal torsional oscillation ?
- Magnetic oscillations ?

- Asteroseismology
  → stellar properties
  (M, R, B, EOS ⋯)

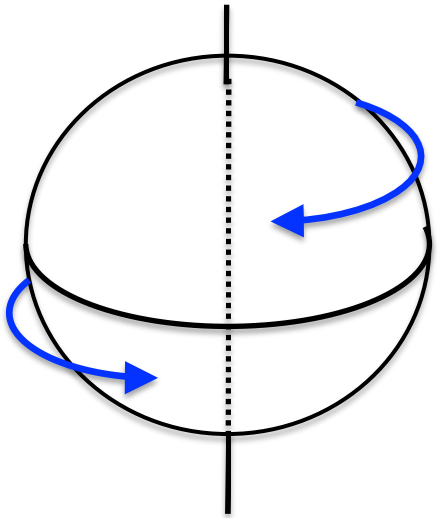
torsional oscillations

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

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

  - μ : shear modulus
  - frequencies ∝ shear velocity $v_s = \sqrt{\mu/\rho}$
  - overtones depend on crust thickness
- effect of magnetic field
  - frequencies become larger

(Sotani+ 07, Gabler+ 13)



EOS for curst region

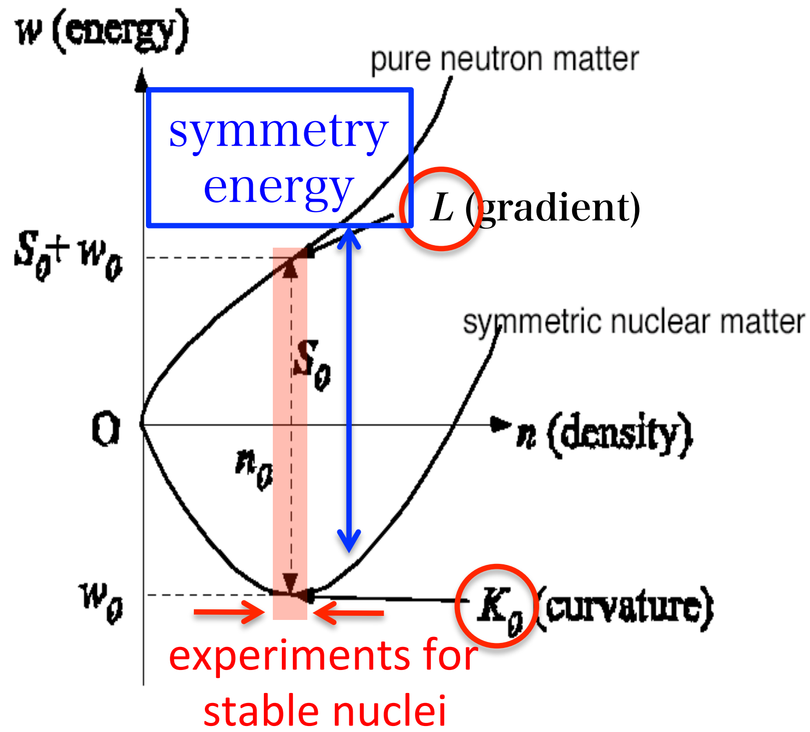
Oyamatsu & Iida 03, 07

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

incompressibility symmetry parameter

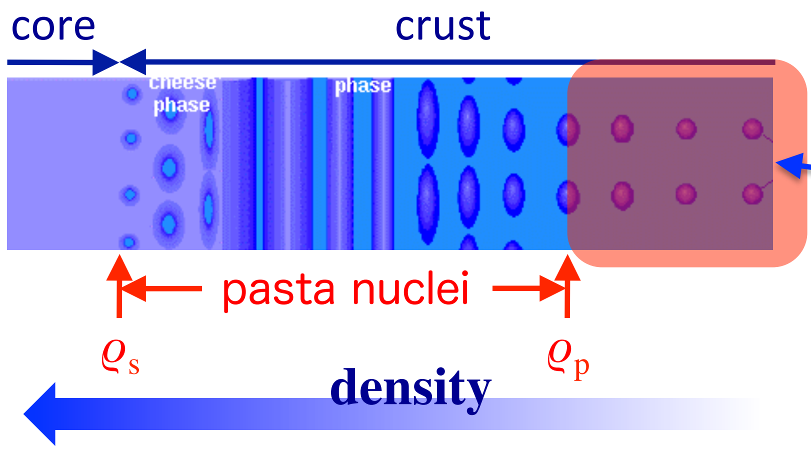
$$w = w_0 + \frac{K_0}{18n_0^2}(n-n_0)^2 + \left[S_0 + \frac{L}{3n_0}(n-n_0)\right]\alpha^2$$

- Calculations of the optimal density distribution of stable nuclei within Thomas Fermi theory.
- phenomenological, but cover the experimental data for stable nuclei.
- K_0 & L are associated with stiffness EOS of nuclear matter



what we do

- EOS for core region is still uncertain. (cf. Steiner & Watts 09)
- To prepare the crust region, we integrate from r=R.
  - ***M, R*** : parameters for stellar properties
  - ***L, K_0*** : parameters for curst EOS (Oyamatsu & Iida 03, 07)
- In crust region, torsional oscillations are calculated.
  - considering the shear only in spherical nuclei.
  - frequency of fundamental oscillation $\propto v_s$ ($v_s^2 \sim \mu/H$)
- Comparing frequencies with QPOs, we will put a constraint on EOS parameter.



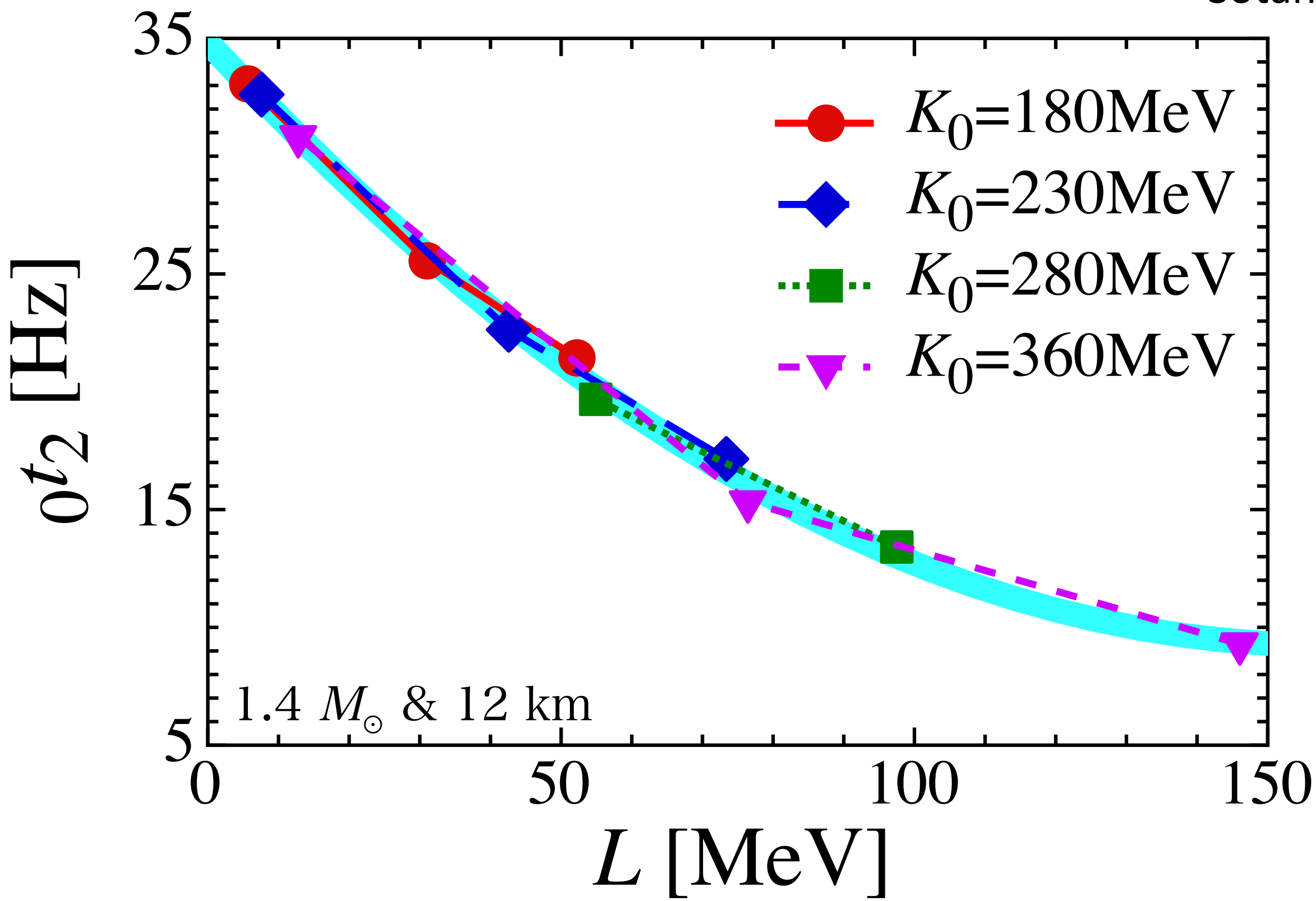
for bcc lattice (Strohmayer+ 1991)

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

n_i : number density of quark droplet
Z : charge of quark droplet
a : Wigner-Seitz radius

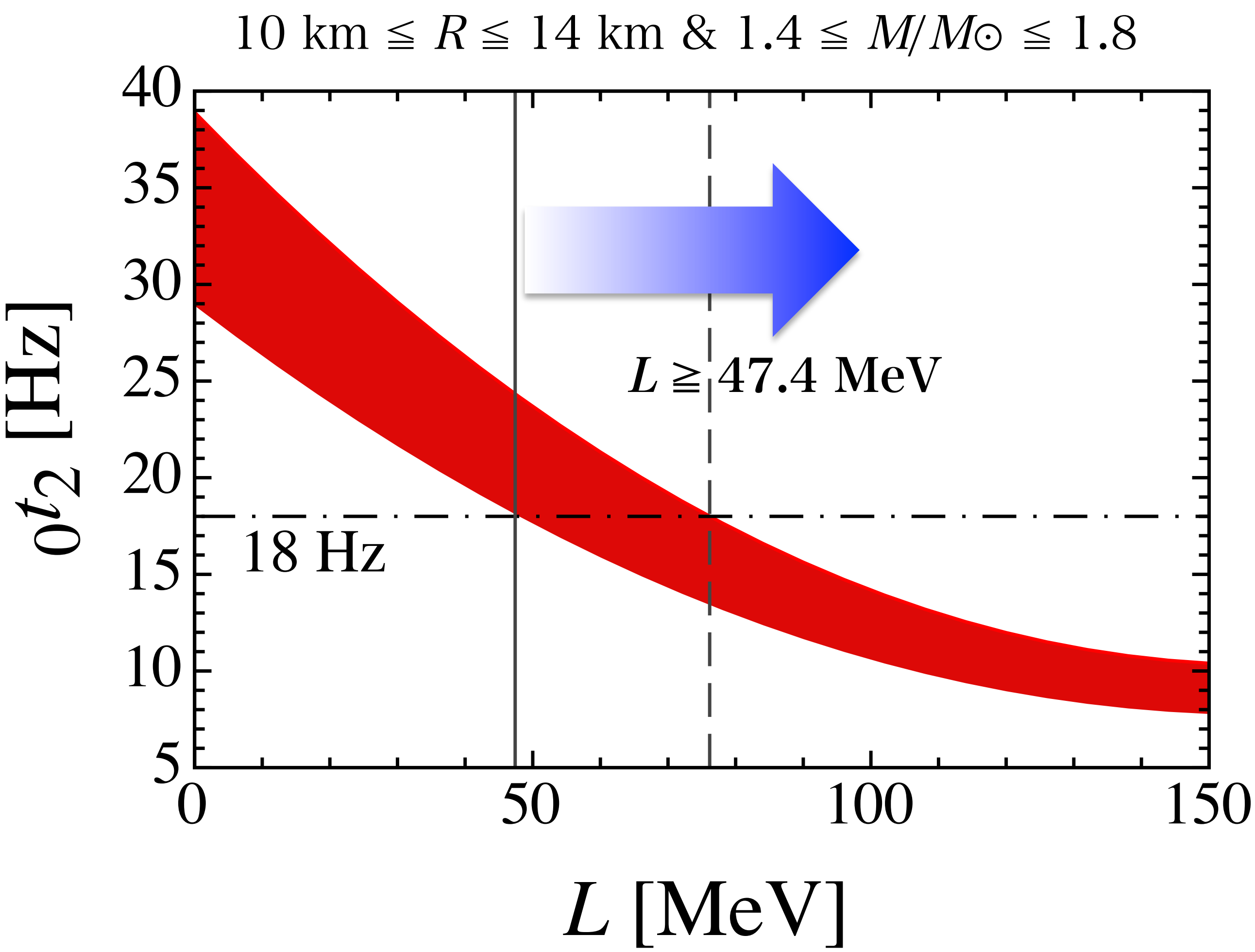
torsional oscillations

Sotani+ 13



➡ almost independent of the incompressibility K_0

robust constraint on L

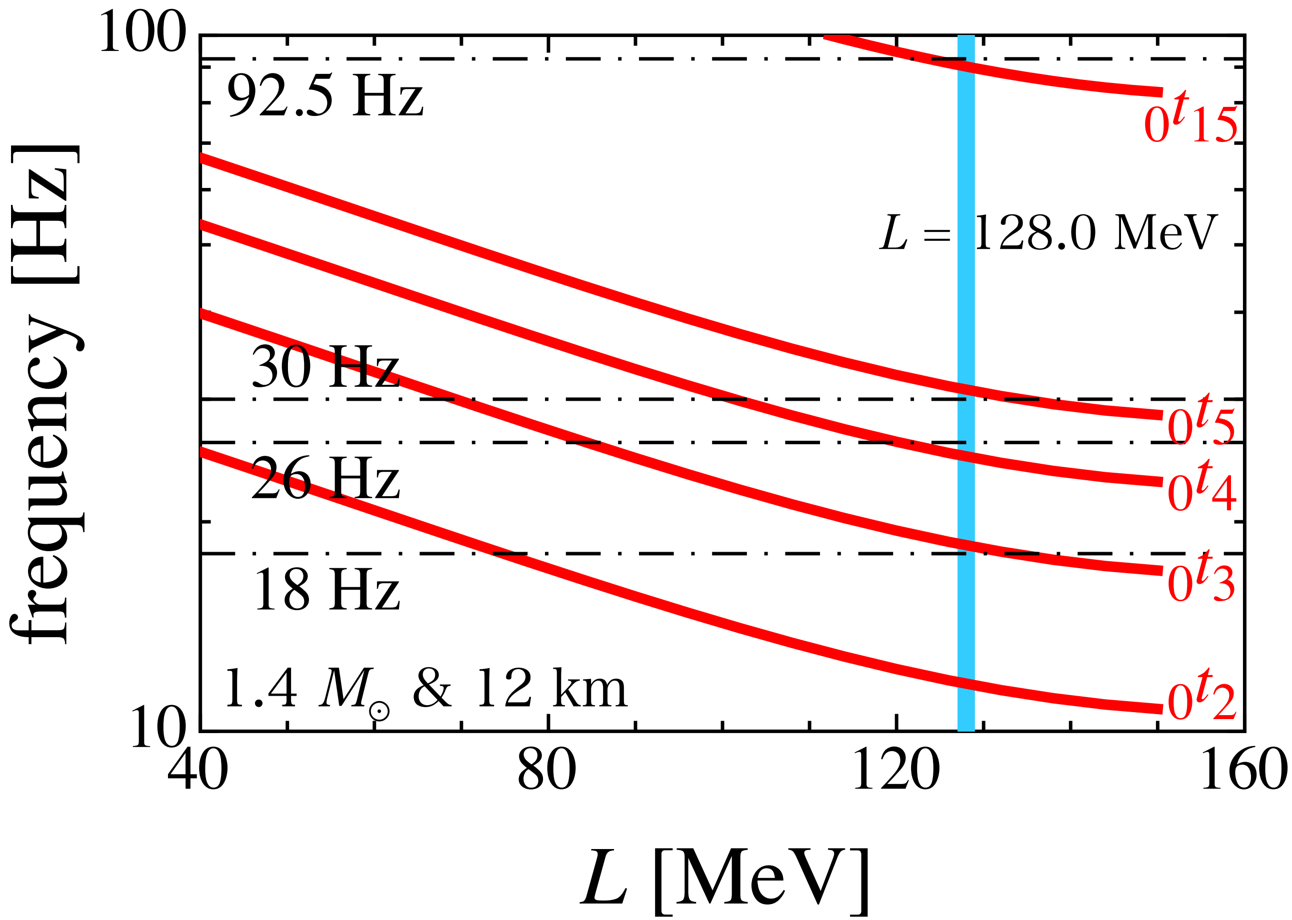


effect of superfluidity

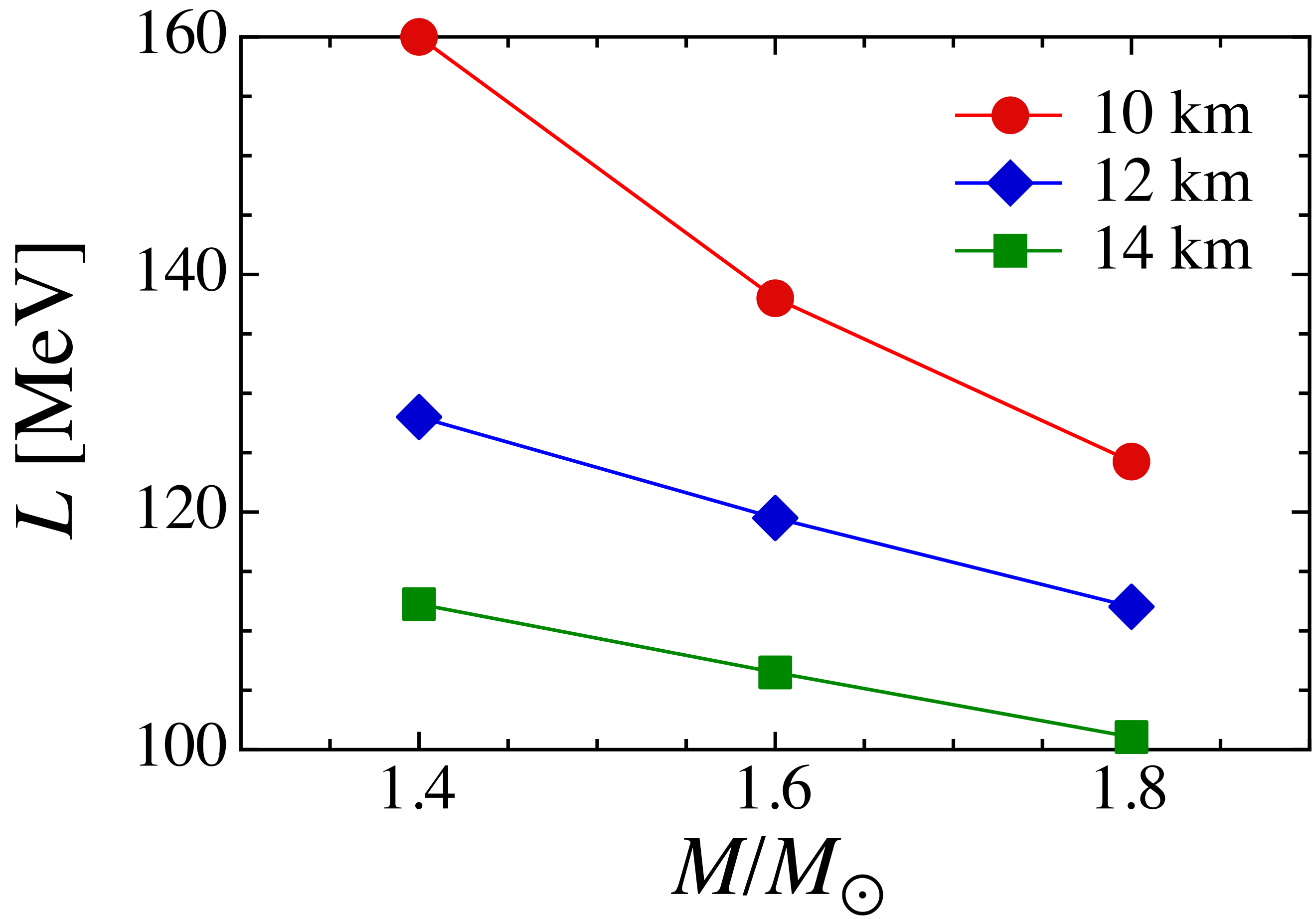
- $\rho \gtrsim 4\times10^{11}$ g/cm^3; neutrons start to drip out of nuclei
  - some of them play as superfluid
  - how many fraction of dripped neutrons behave as superfluid ?
  - major parts may be locked to the motion of protons in nuclei (Chamel 12)
  - depending on density, $N_s/N_d \simeq$ 10 - 30% @$n_b \sim 0.01 - 0.4n_0$
- since torsional oscillations are transverse, superfluid neutrons can not contribute to such oscillations.
  - one show introduce the effective enthalpy
  - at zero-temperature, $\mu_b = H / n_b$ → $\bar{H} = \left(1 - \frac{N_s}{A}\right) H$

$$\mathcal{Y}'' + \left[\left(\frac{4}{r} + \Phi' - \Lambda'\right) + \frac{\mu'}{\mu}\right]\mathcal{Y}' + \left[\frac{\epsilon + p}{\mu}\omega^2 e^{-2\Phi} - \frac{(\ell+2)(\ell-1)}{r^2}\right] e^{2\Lambda}\mathcal{Y} = 0.$$

identification of SGR 1806-20

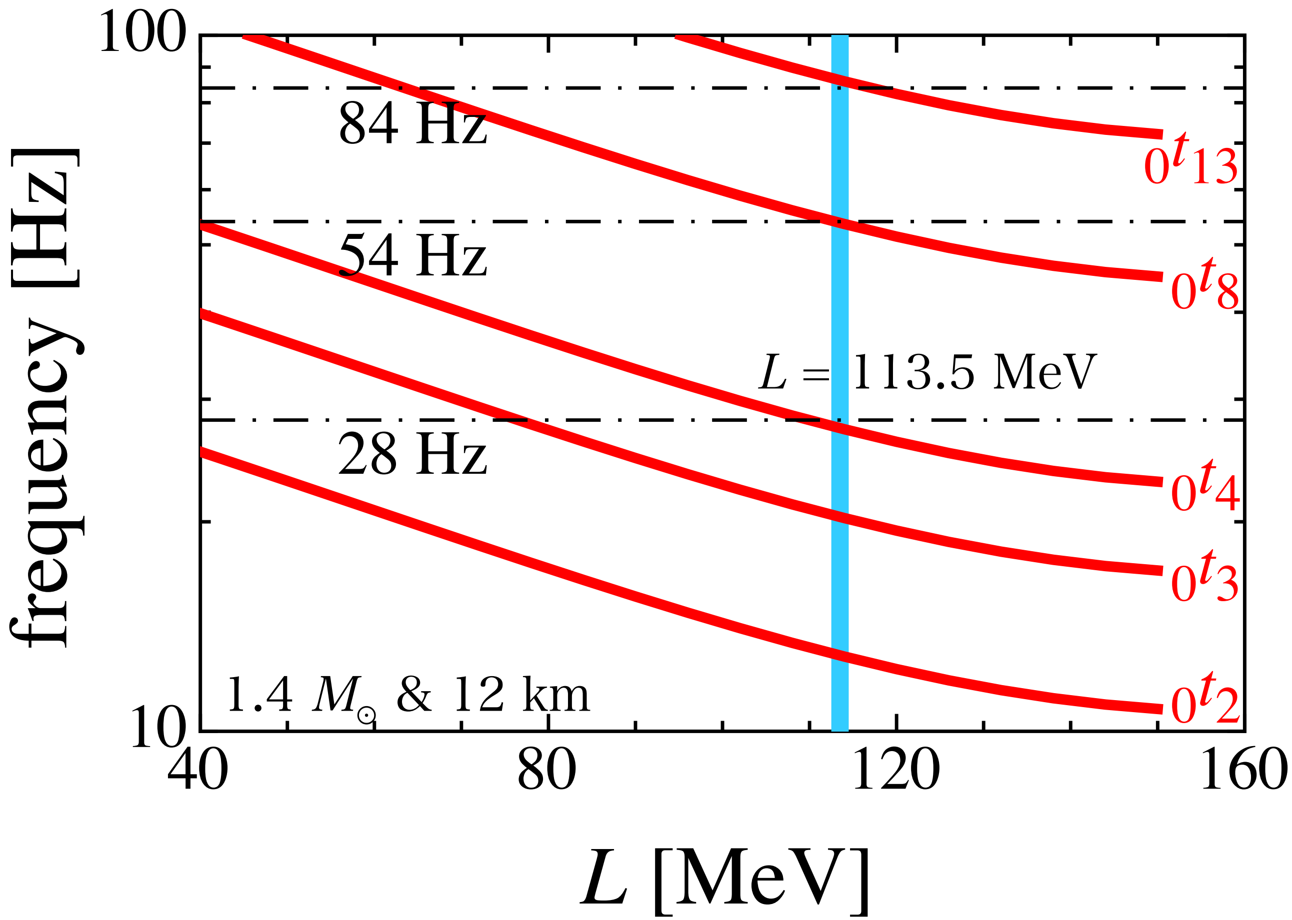


constraint on L via SGR 1806-20

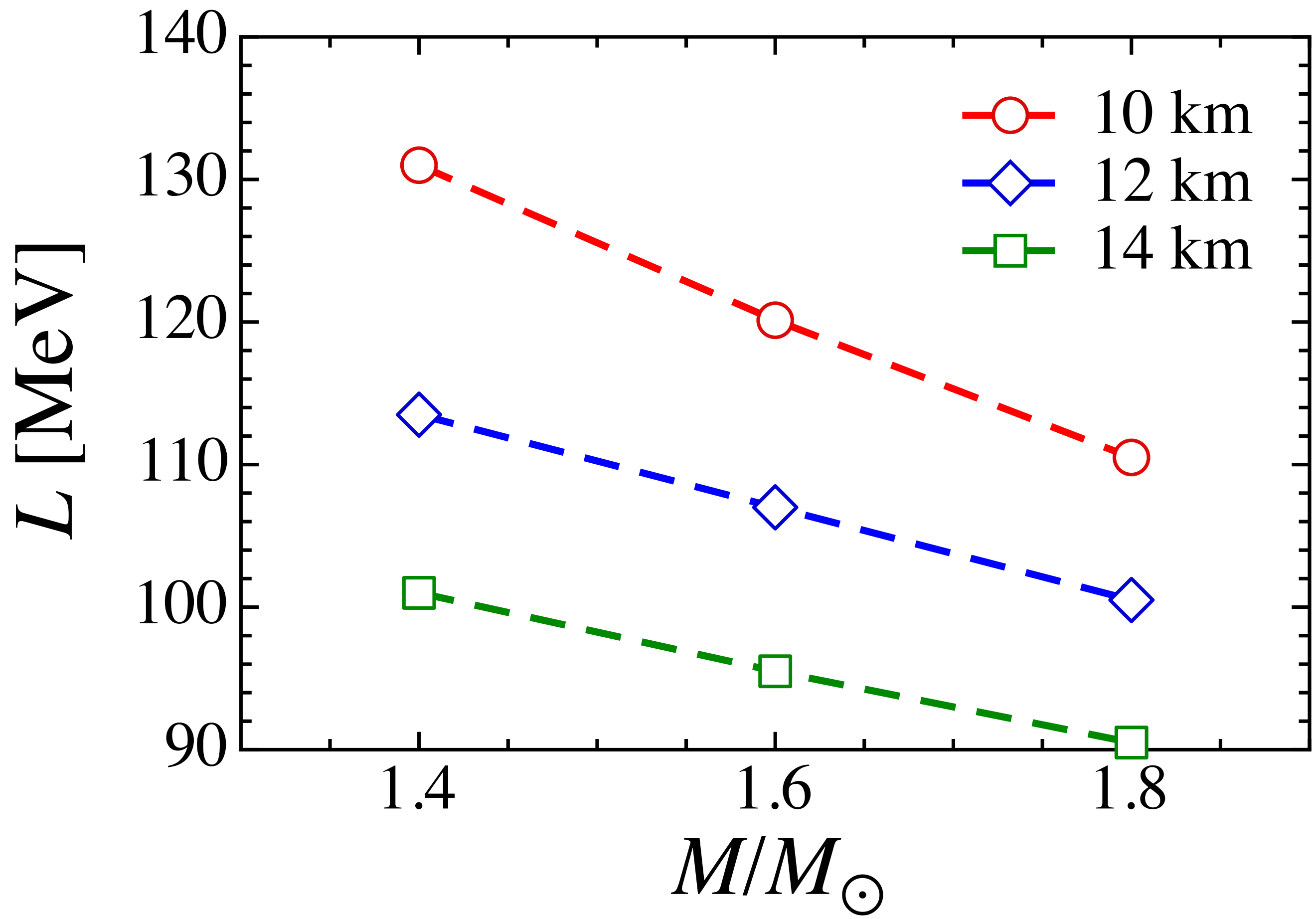


➡ 101.1 MeV ≤ L ≤ 160.0 MeV

identification of SGR 1900+14

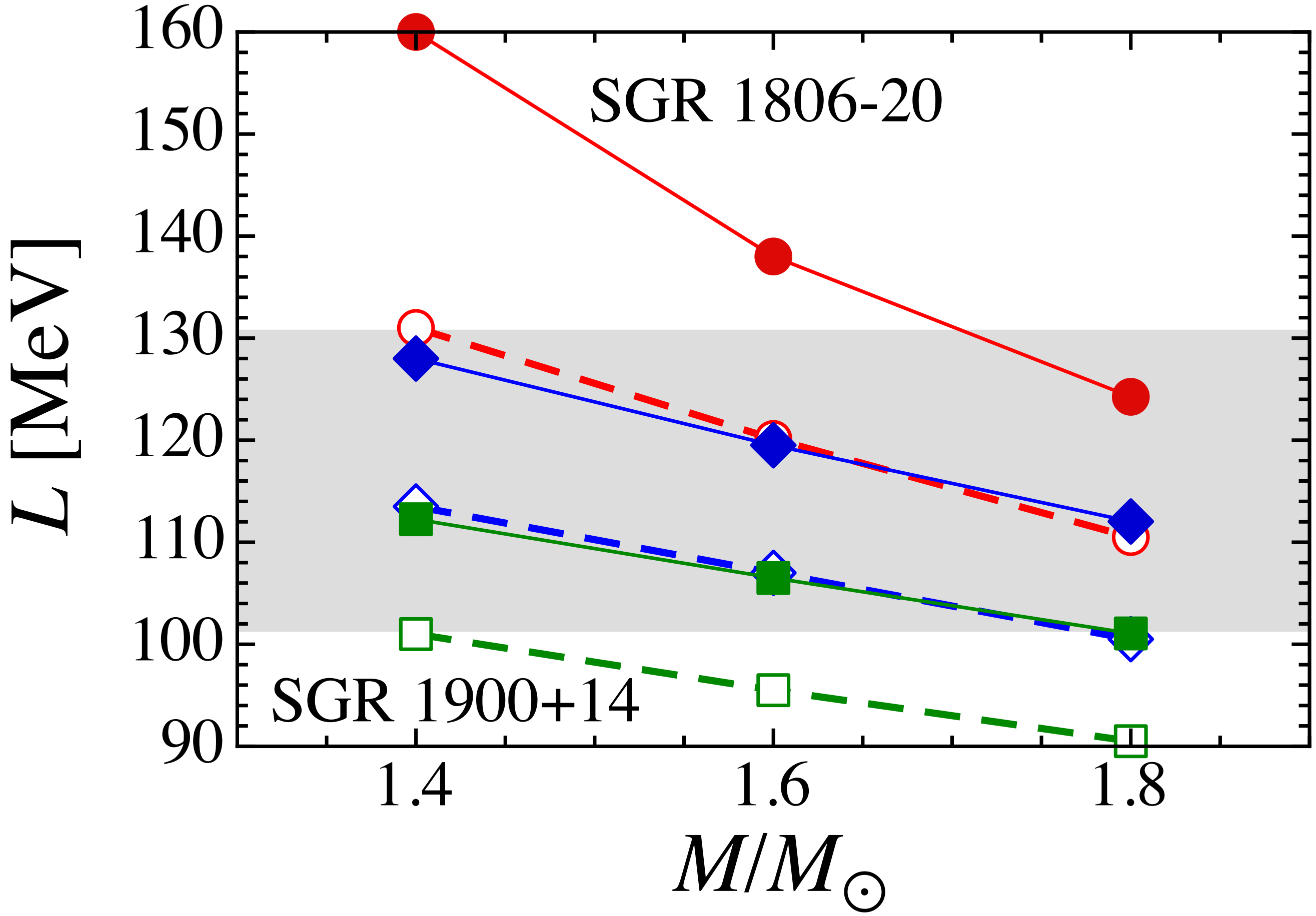


constraint on L via SGR 1900+14



➡ 90.5 MeV $\leqslant L \leqslant$ 131.0 MeV

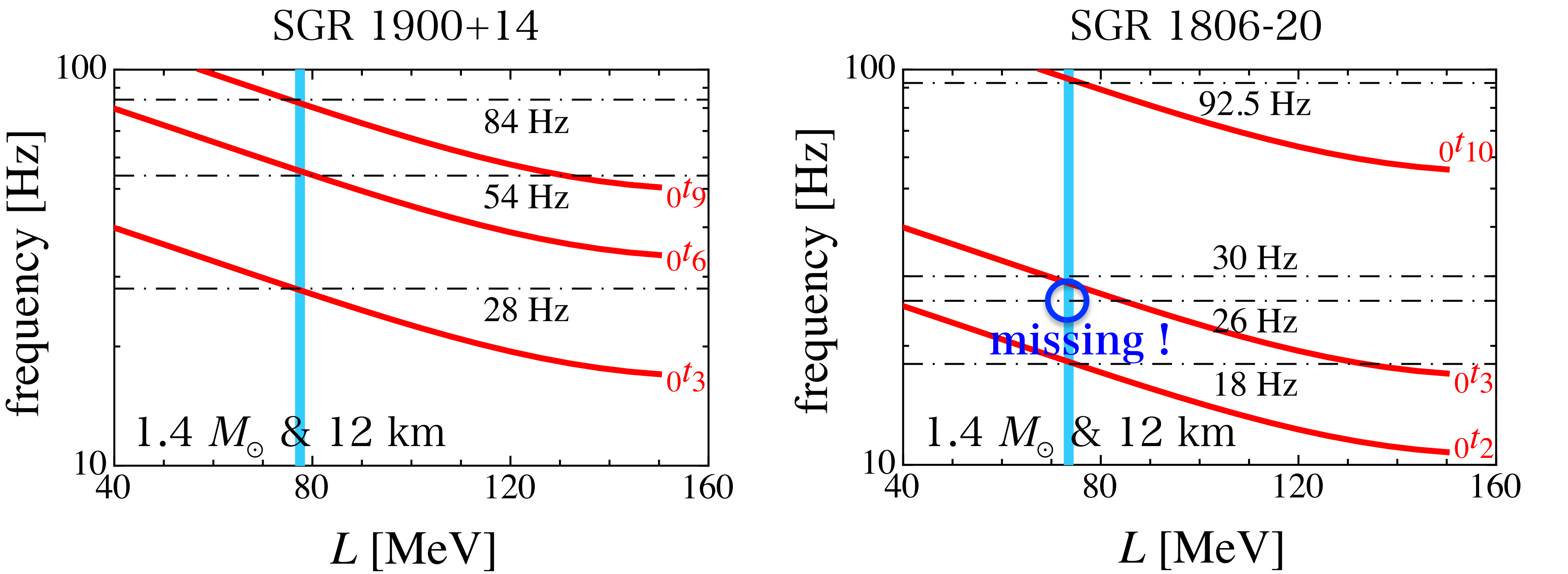
allowed region for *L*



➡ $101.1\ \mathrm{MeV} \leq L \leq 131.0\ \mathrm{MeV}$

alternative possibility

instead of previous correspondence, i.e., l = 4, 8, 13 for SGR 1900+14, and l = 3, 4, 5, 15 for SGR 1806-20, we may consider alternative possibility as



26 Hz QPO observed in SGR 1806-20 remains a complete puzzle !!

relative error

- previous identification

QPOs (Hz)	l	${}_0t_l$ (Hz)	error (%)
18	3	18.50	-2.79
26	4	24.82	4.53
30	5	30.96	-3.19
92.5	15	90.18	2.51

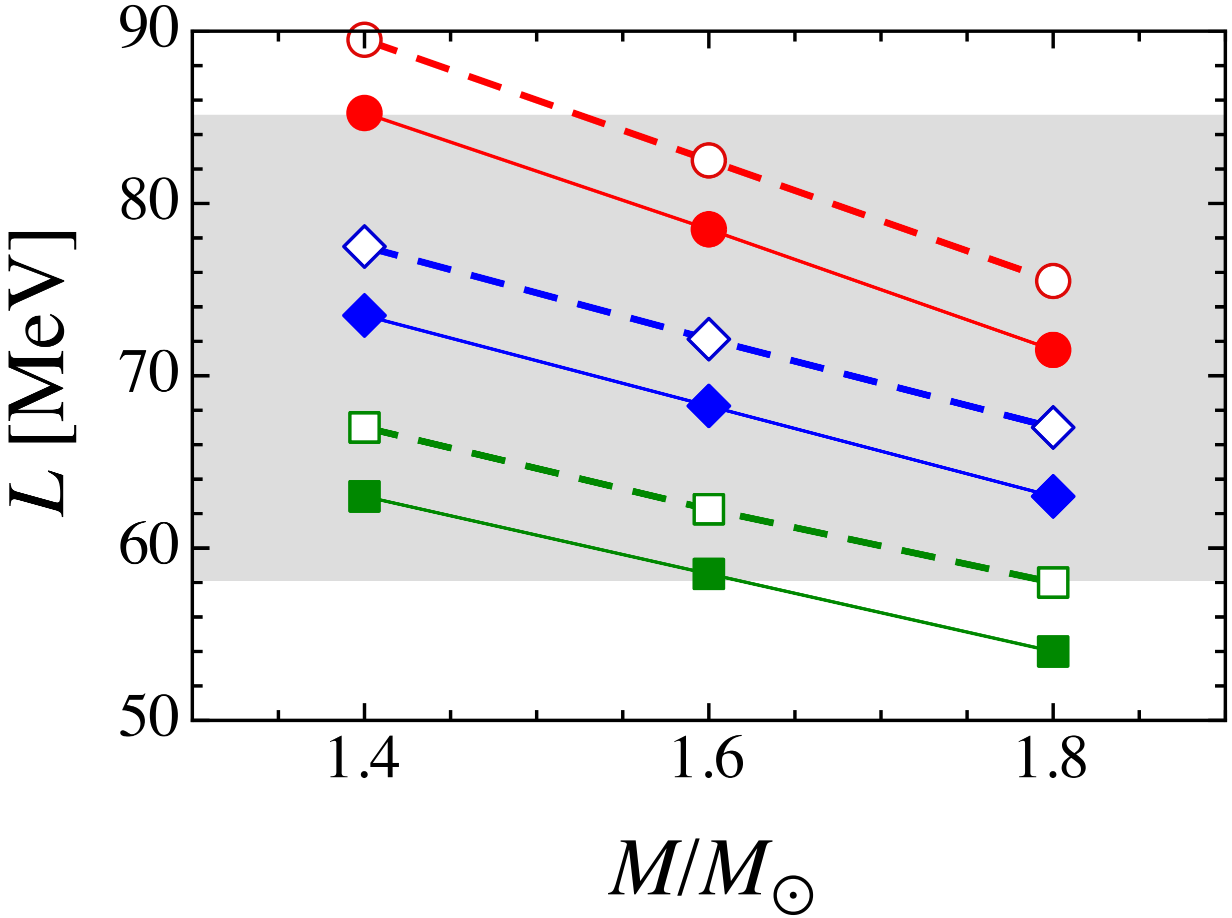
QPOs (Hz)	l	${}_0t_l$ (Hz)	error (%)
28	4	27.26	2.63
54	8	53.76	4.50
84	13	86.18	-2.60

- alternative identification

QPOs (Hz)	l	${}_0t_l$ (Hz)	error (%)
18	2	18.23	-1.27
26	---	---	---
30	3	28.82	3.93
92.5	10	94.70	-2.38

QPOs (Hz)	l	${}_0t_l$ (Hz)	error (%)
28	3	27.74	0.93
54	6	55.48	-2.74
84	9	82.29	2.04

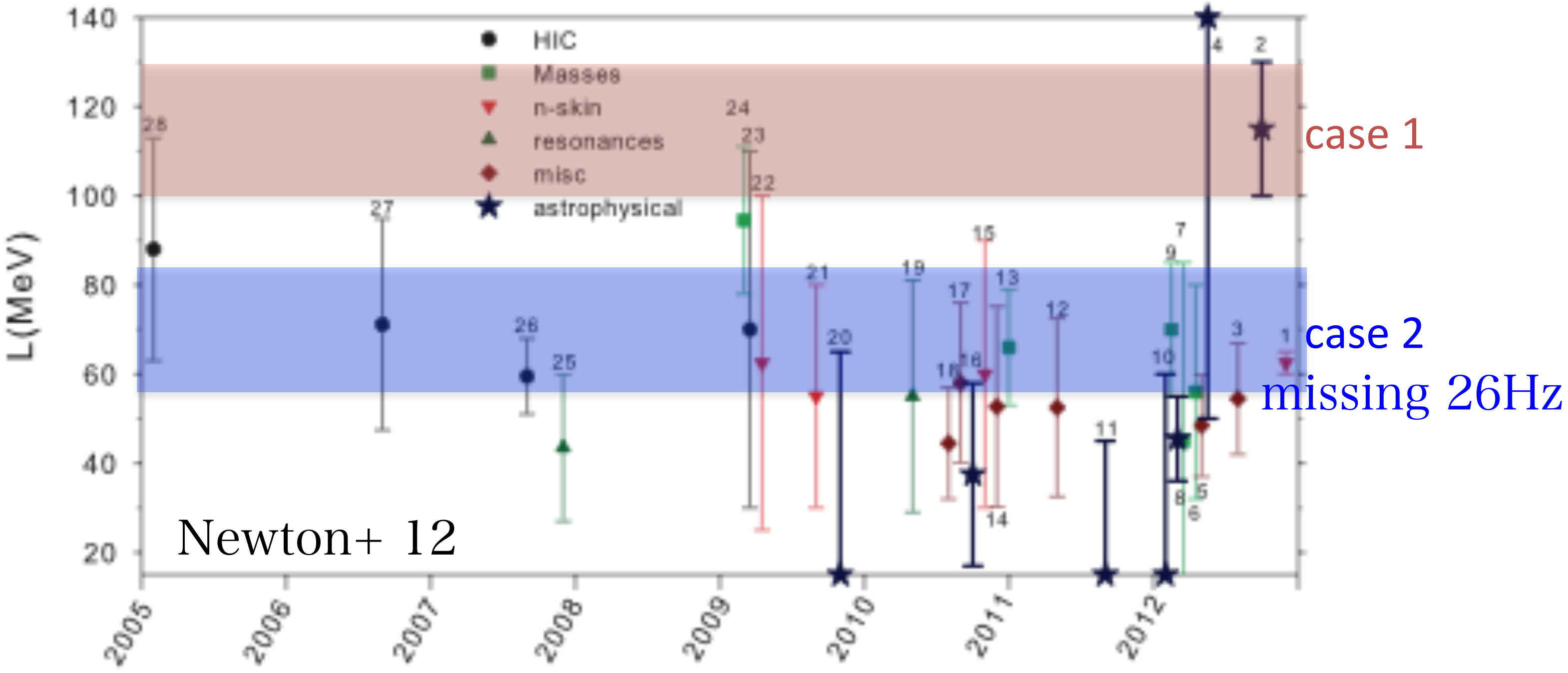
alternative allowed region for L



➡ 58.0 MeV ≤ L ≤ 85.3 MeV
(32.4 MeV ≤ S_0 ≤ 34.4 MeV)

other constraints on *L*

- other constraints suggests *L* ~ 60±20 MeV ?
  - this means case 2 may be faivored ??
  - if so, one has to prepare another oscillation mechanism···



missing effects ??

blue : decrease
red : increase

- modification of shear modulus
  - size of nuclei
  - electron screening (Horowitz & Hughto 08; Kobyakov & Pethick 13)
  - existence of pasta phase (Sotani 11; Gearheart+11; Newton+13)
- paring effect and shell effect (Deibel+13)
- superfluidity (Chamel 12, 13; Sotani+12; Deibel+13)
- magnetic field (Sotani+; Colaiuda & Kokkotas; Gabler+; Passamonti+; Lander+; Deibel+13)

- emission mechanism ??

summary

- asteroseismology could be powerful approach to see the interior properties of neutron stars.
  - QPOs in SGRs may be good examples to adopt the asteroseismology
- compering the torsional oscillations to the observational evidences, we can get the constraint on L as $L \gtrsim 50$ MeV.
- superfluid effect enhances the frequencies of torsional oscillations.
  - **$100 \lesssim L \lesssim 130$ MeV**, if all QPOs come from torsional oscillations
  - **$58 \lesssim L \lesssim 85$ MeV**, if QPOs except for 26 Hz QPO coms from torsional oscillations
- we should take into account additional effects.