Neutron stars and nuclear symmetry energy

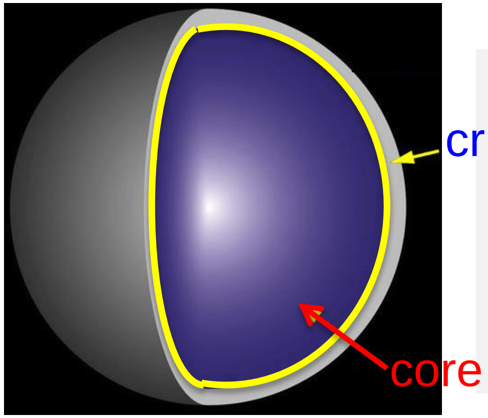
Hajime SOTANI (YITP, Kyoto U.)

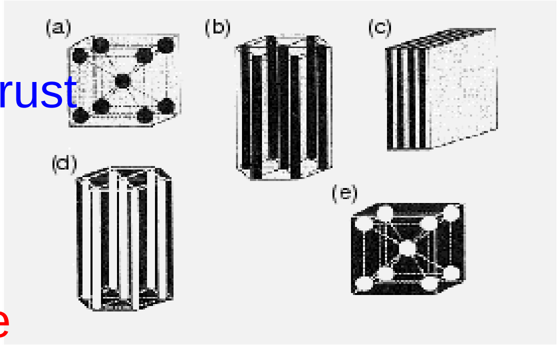
HS, Nakazato, Iida, Oyamatsu, PRL (2012)
HS, Nakazato, Iida, Oyamatsu, MNRASL (2013)
HS, Nakazato, Iida, Oyamatsu, MNRAS (2013)

neutron stars

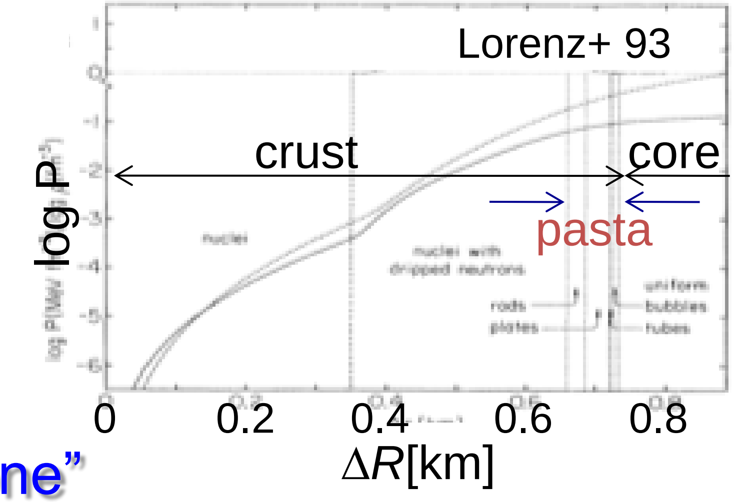
- Structure of NS
  - solid layer (crust)
  - nonuniform structure (pasta)
  - fluid core (uniform matter)
- Crust thickness $\lesssim$ 1km
  - Determination of EOS for high density region could be quite difficult on Earth
- Constraint on EOS via observations of neutron stars
  - stellar mass and radius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

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





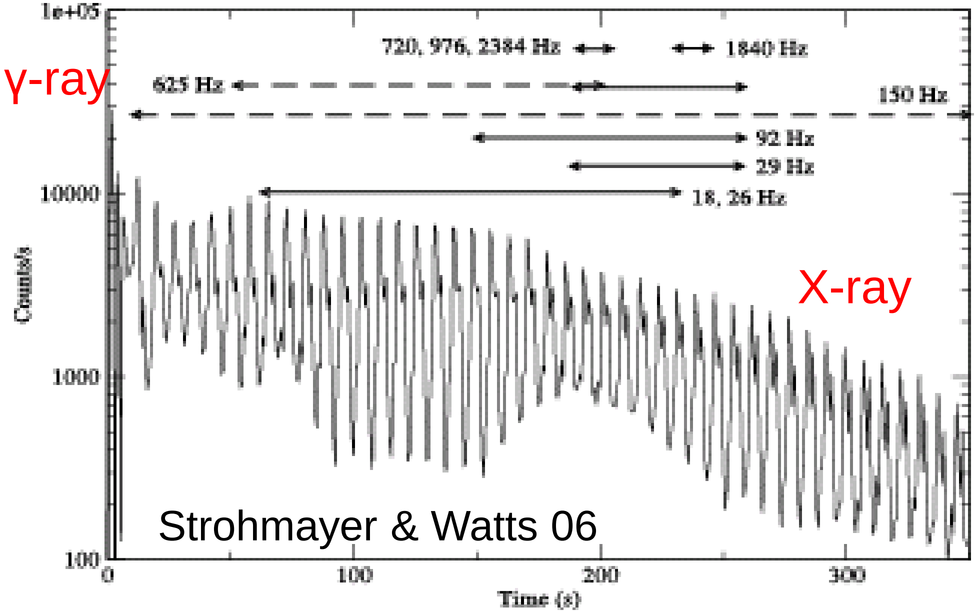
Oyamatsu 93



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 06

- Crustal torsional oscillation ?
- Magnetic oscillations ?

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

torsional oscillations

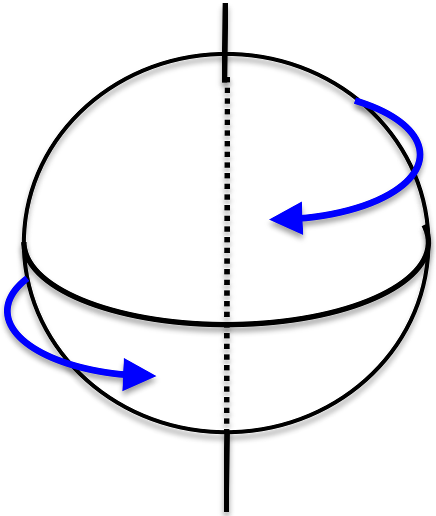
- axial parity oscillations
  - incompressible
  - no density perturbations
- in Newtonian case

(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 $v_s = \sqrt{m/ r}$
  - 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;

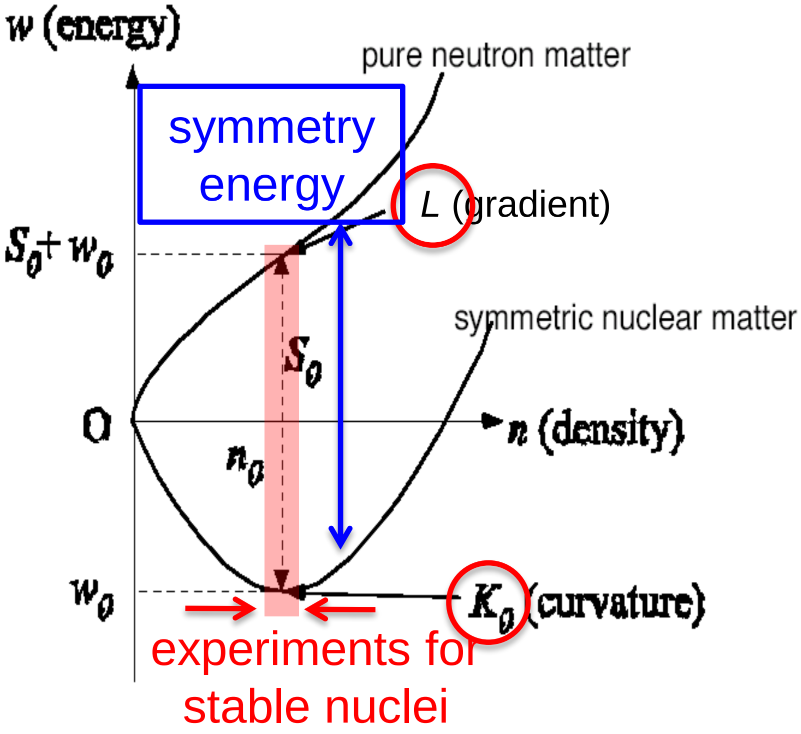
incompressibility

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



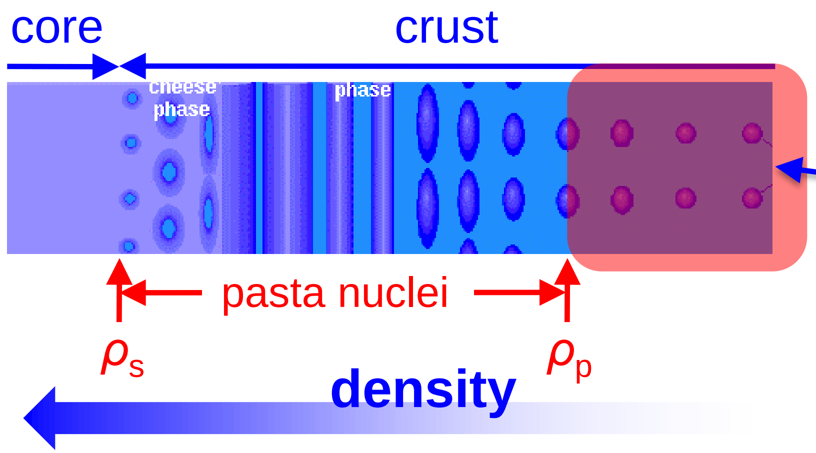
symmetry energy

L (gradient)

experiments for stable nuclei

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 ∝ v_s ($v_s^2 \sim \mu/H$)
- Comparing frequencies with QPOs, we will put a constraint on EOS parameter.



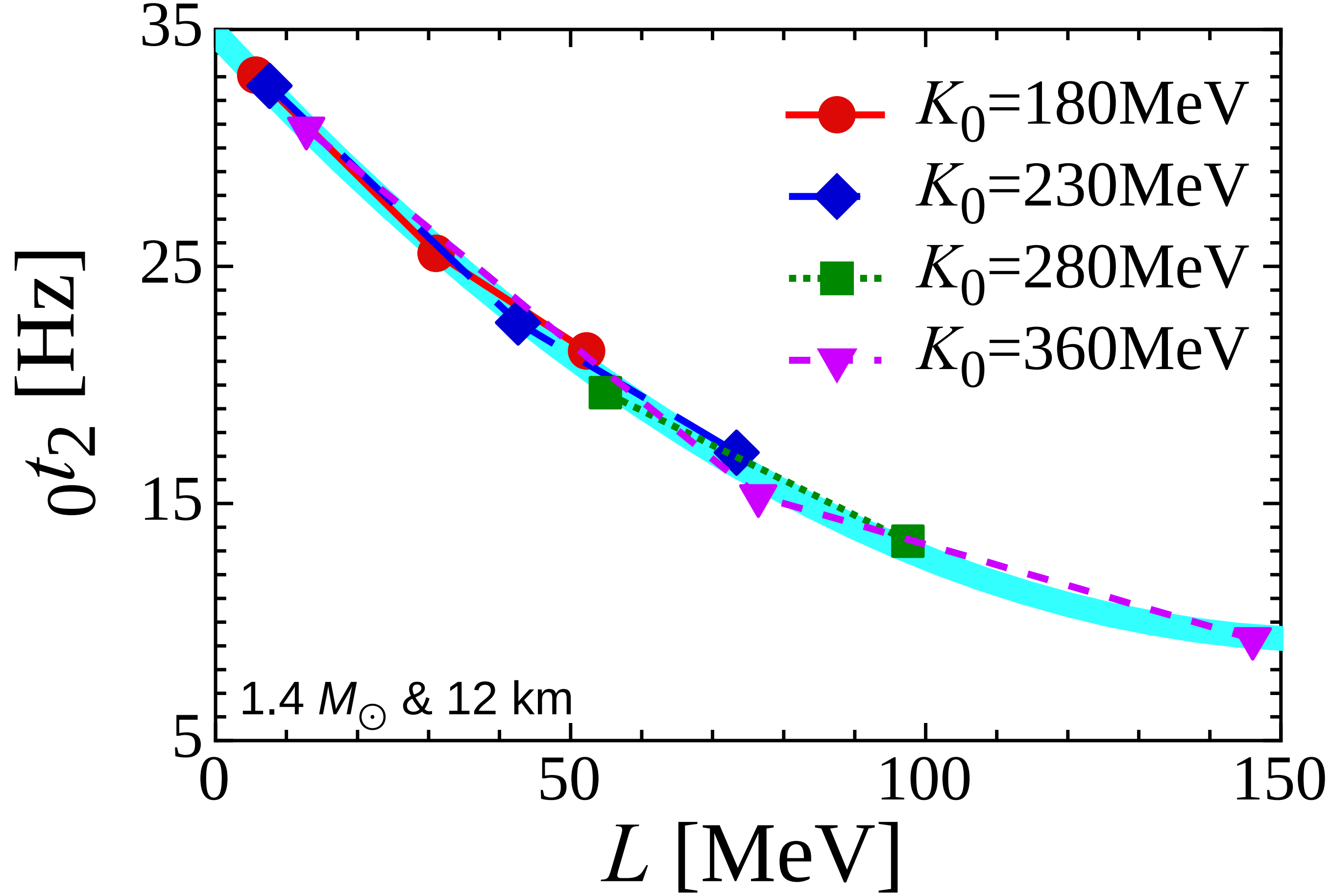
for bcc lattice (Strohmayer+ 91)

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

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

torsional oscillations

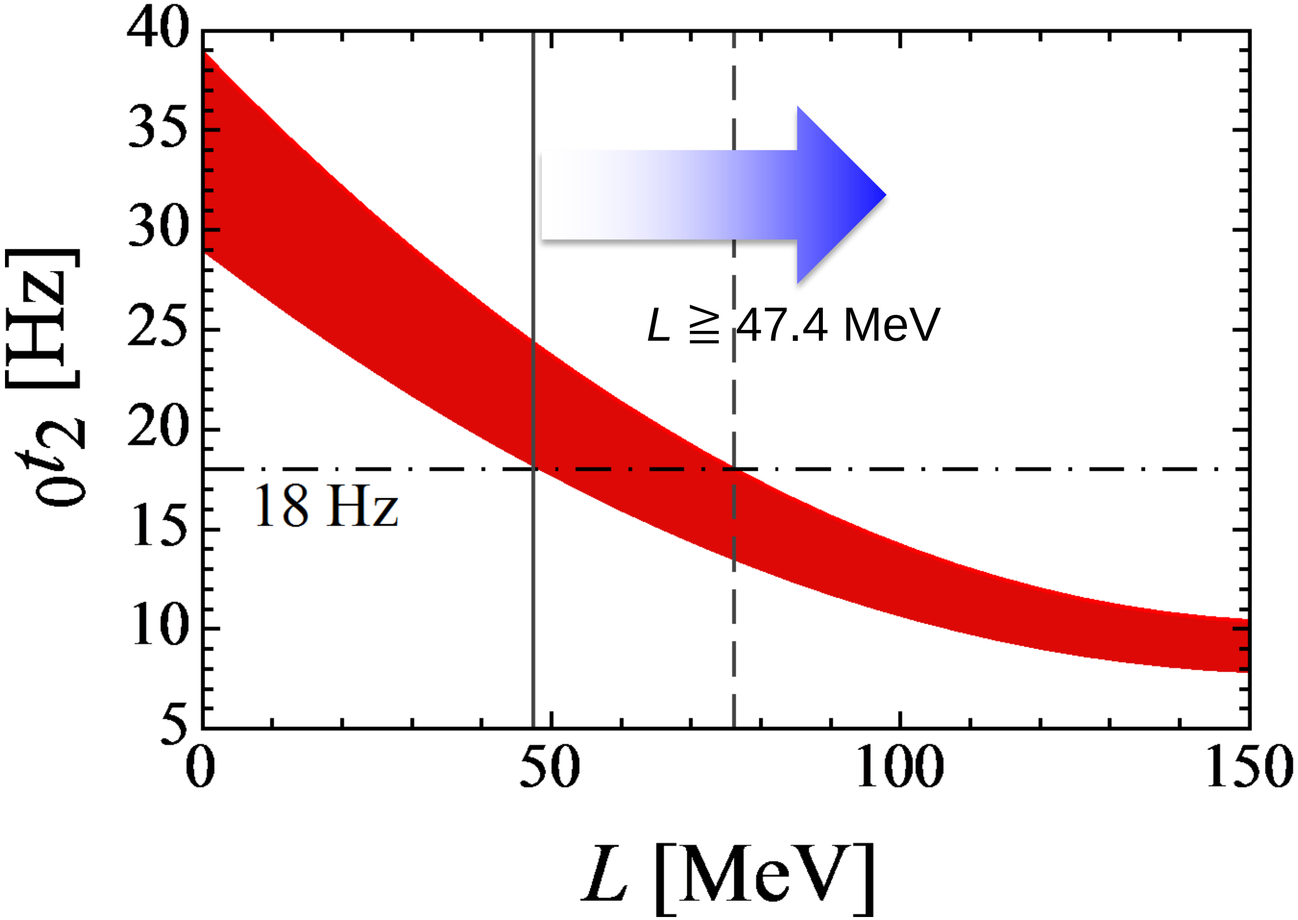
(HS, Nakazato, Iida, Oyamatsu13)



➡ almost independent of the incompressibility K_0

robust constraint on *L*

10 km ≦ *R* ≦ 14 km & 1.4 ≦ *M*/*M*⊙ ≦ 1.8



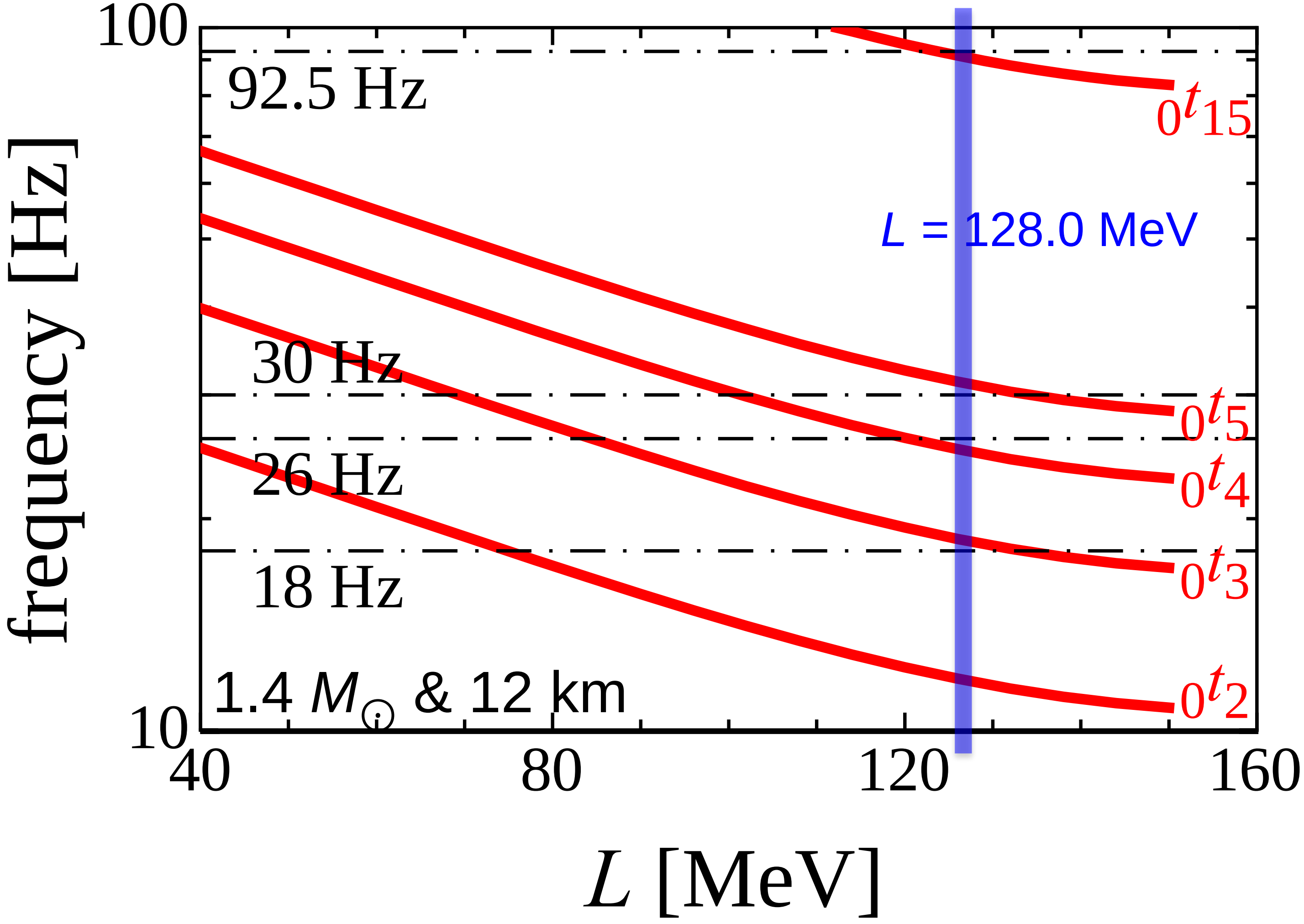
effect of superfluidity

- $\rho \gtrsim 4\times10^{11}$ 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, $N_s/N_d \simeq 10 - 30\%$ @$n_b \sim 0.01 - 0.4 n_0$
- since torsional oscillations are transverse, superfluid neutrons can not contribute to such oscillations.
  - one show introduce the effective enthalpy
  - at zero-temperature, $\mu_b = H / n_b$ →

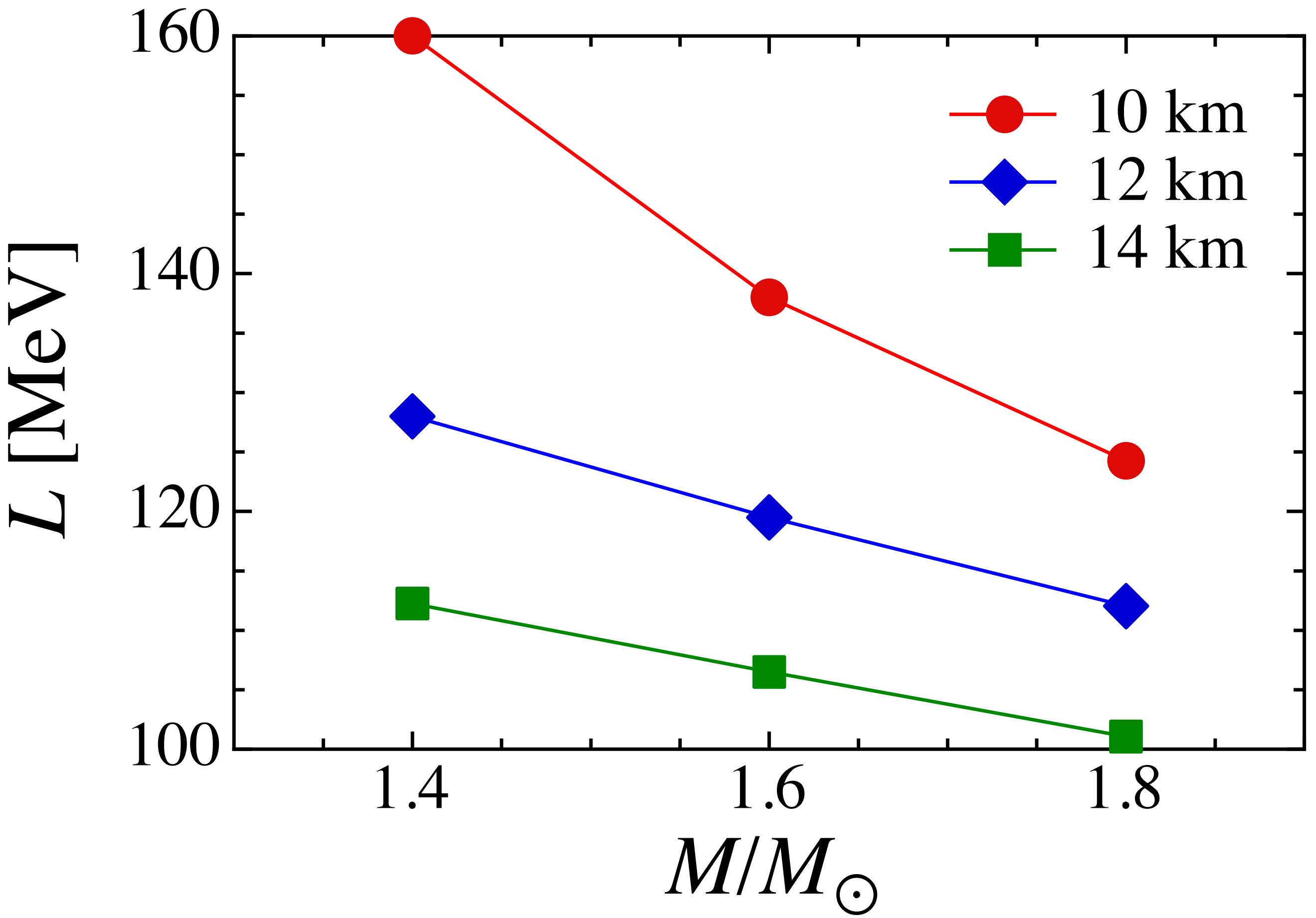
$$\bar{H} = \left(1 - \frac{N_s}{A}\right) H$$

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

identification of SGR 1806-20

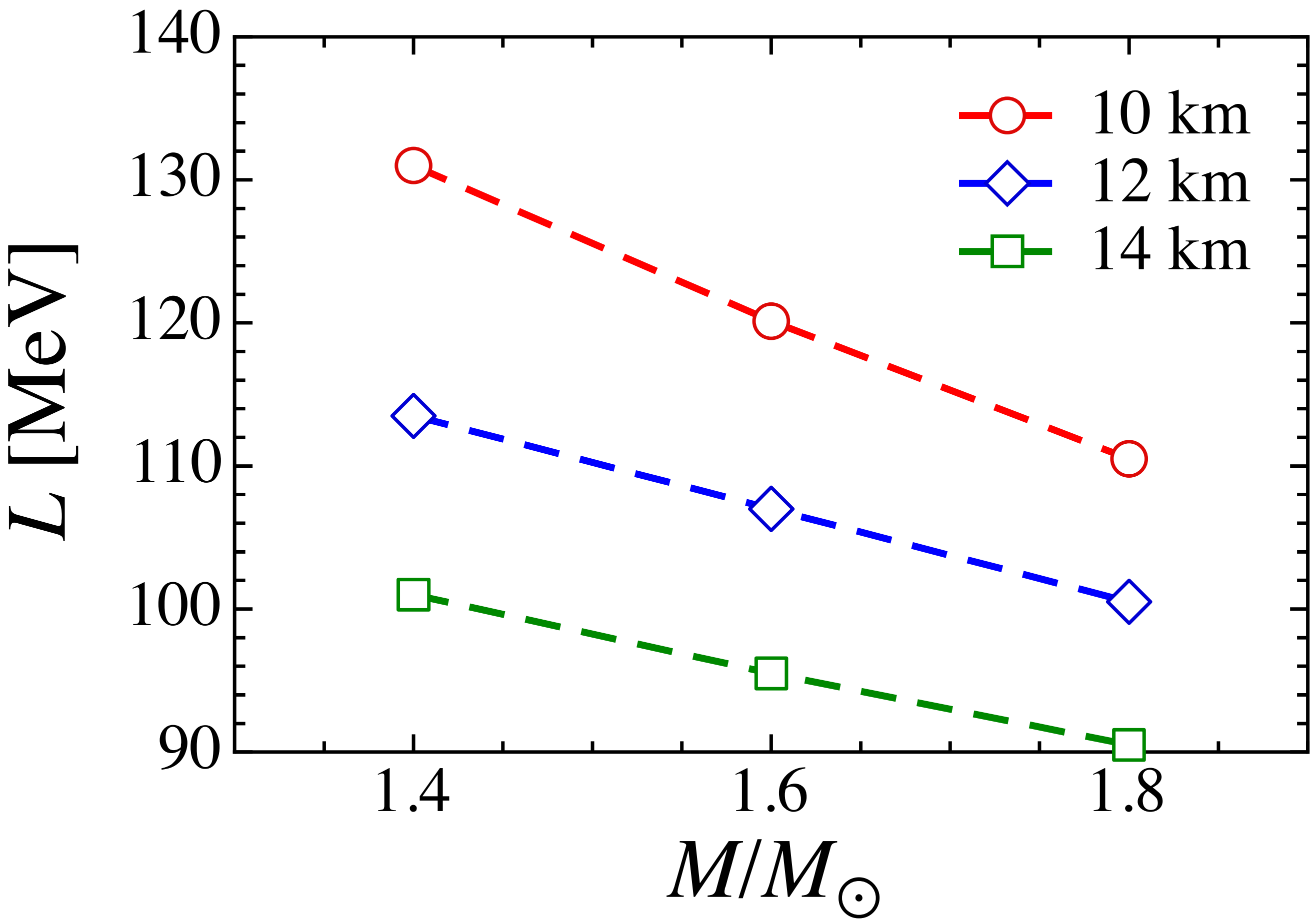


constraint on *L* via SGR 1806-20



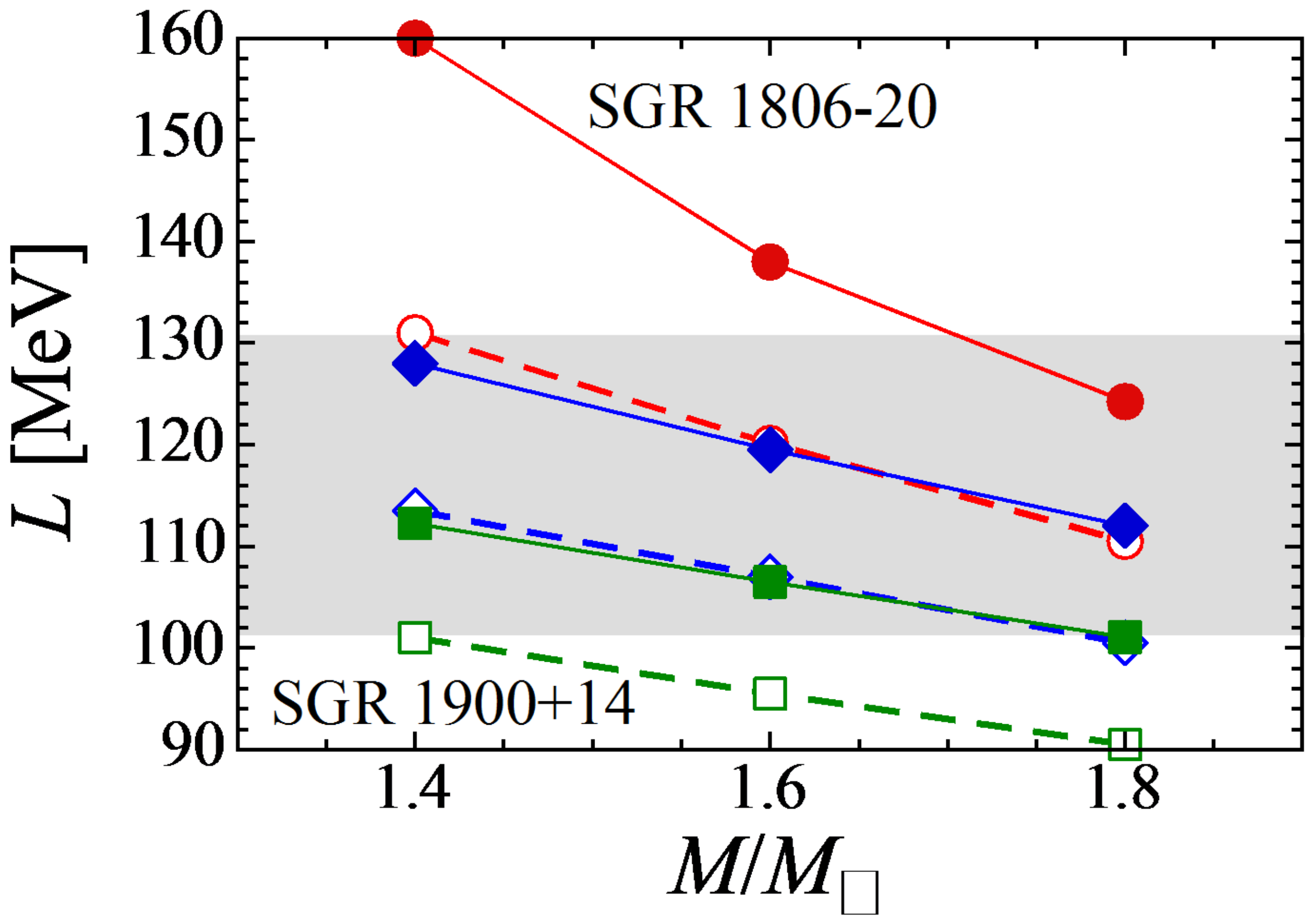
➡ 101.1 MeV $\leqslant L \leqslant$ 160.0 MeV

constraint on *L* via SGR 1900+14



➡ 90.5 MeV ⩽ L ⩽ 131.0 MeV

allowed region for *L*



➡ 101.1 MeV ⩽ *L* ⩽ 131.0 MeV

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)

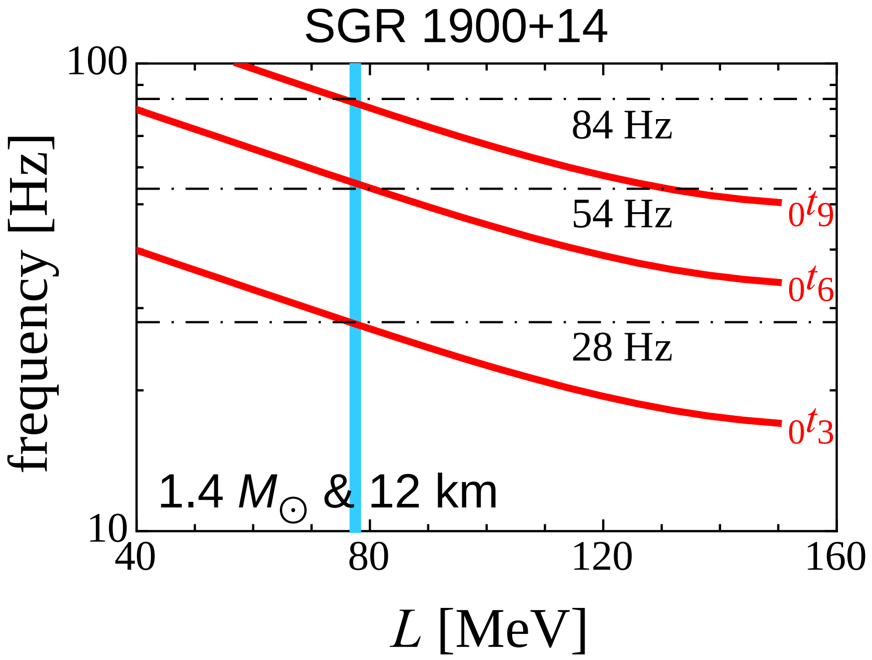
- emission mechanism ??

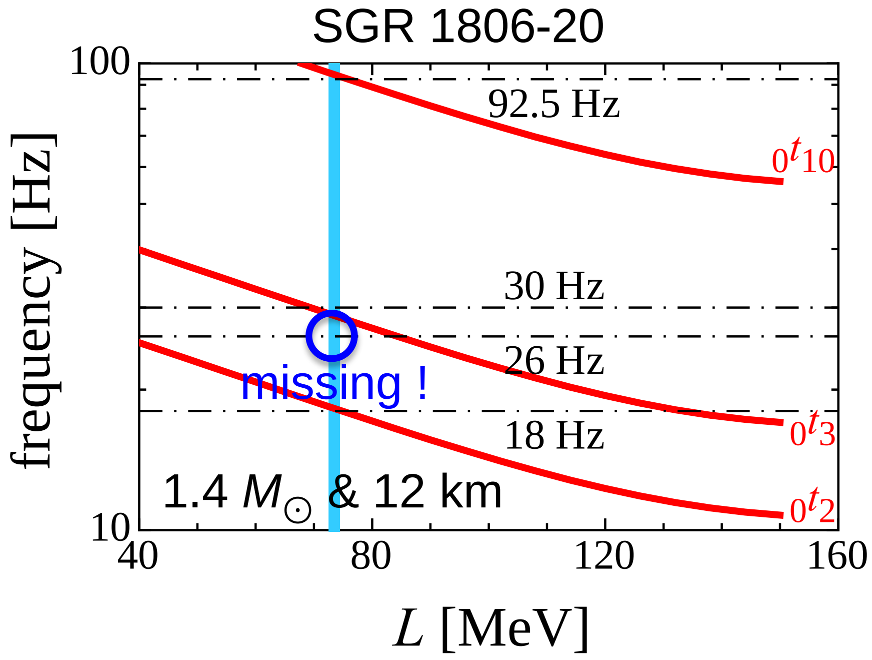
summary

- 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 missing effects.

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


SGR 1900+14


SGR 1806-20

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

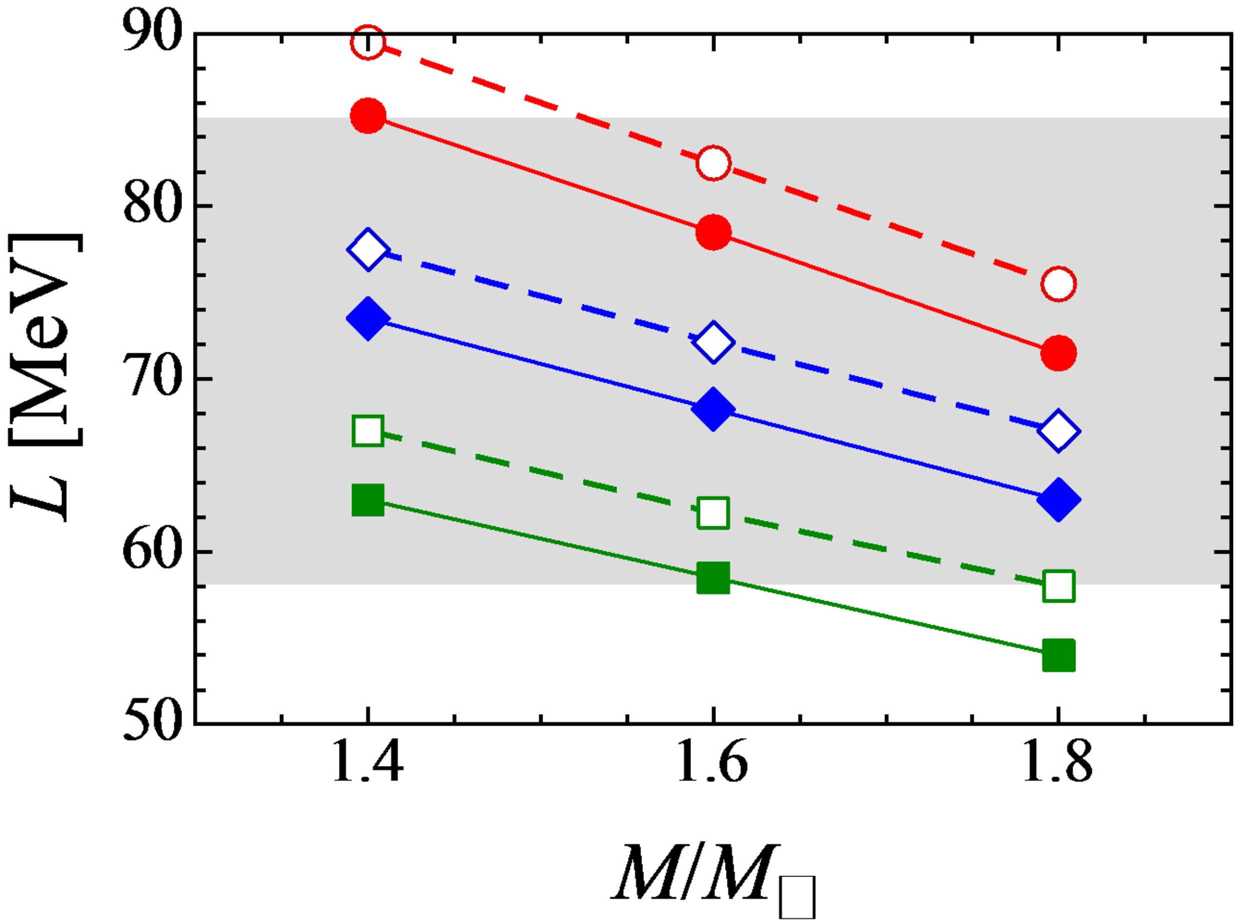
QPOs (Hz)	l	${}_0t_l$ (Hz)	error (%)
28	4	27.26	2.63
54	8	53.76	4.50
84	13	86.18	-2.60

- 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*

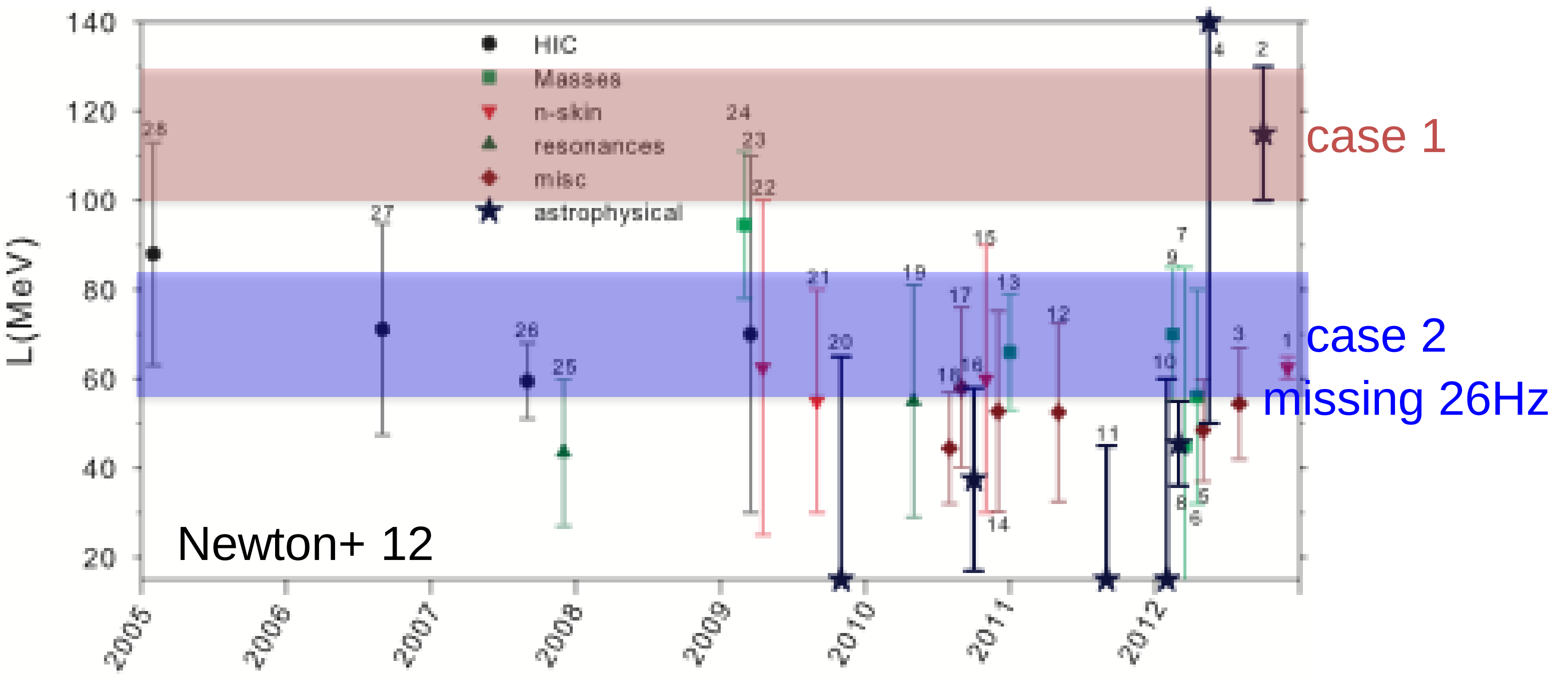


➡ 58.0 MeV ⩽ L ⩽ 85.3 MeV

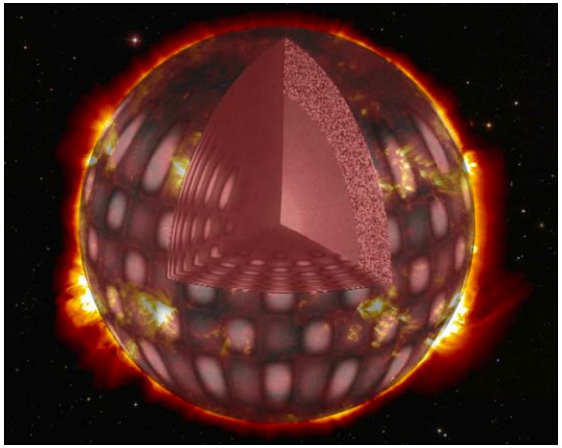
(32.4 MeV ⩽ S_0 ⩽ 34.4 MeV)

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…



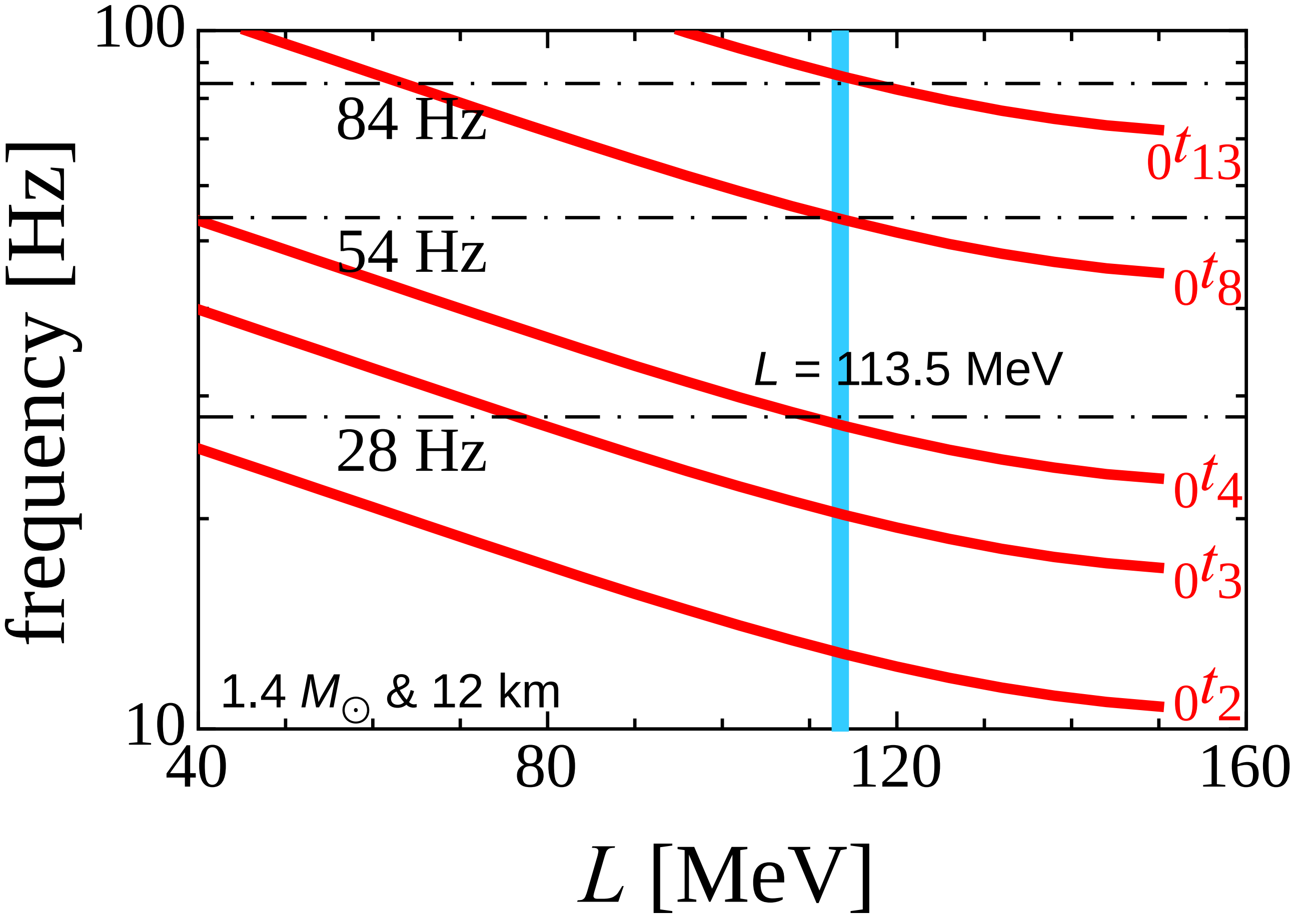
oscillations in NSs



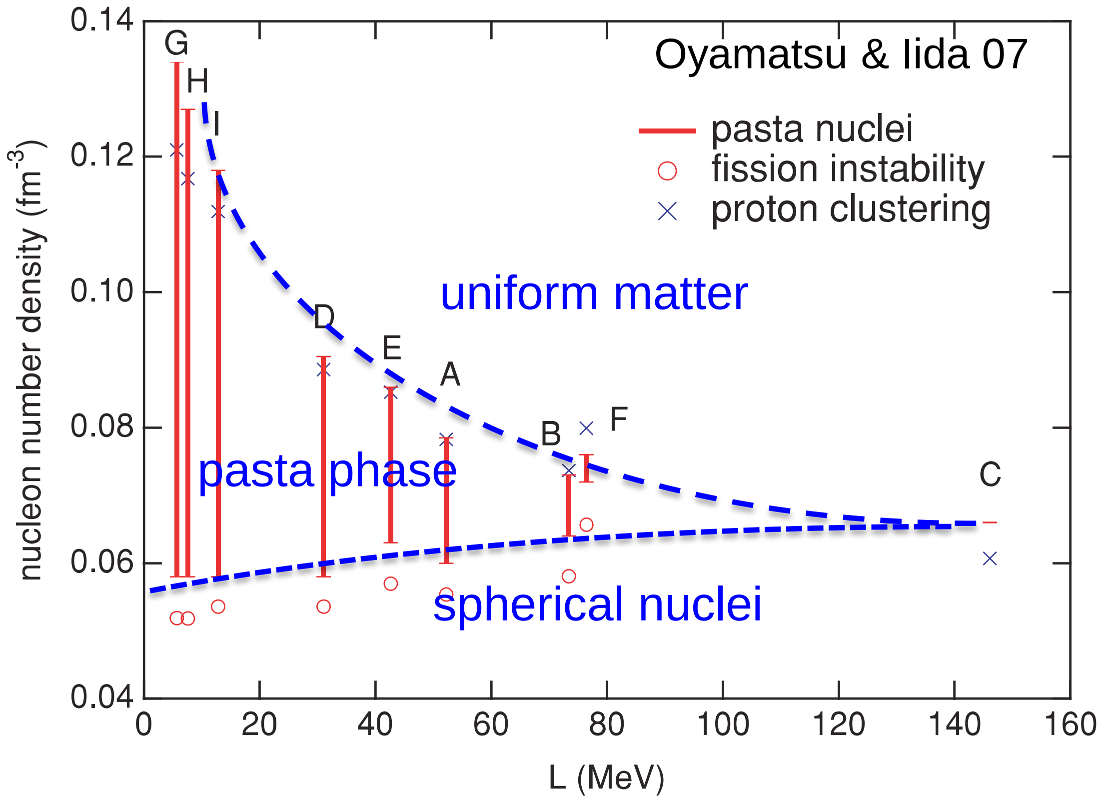
©NASA

- polar oscillations
  - fluid modes
    - ✓ fundamental mode (f -mode) … ~ kHz
    - ✓ pressure mode (p-mode) … > a few kHz
    - ✓ gravity mode (g-mode) … < a few 100 Hz
    - ✓ rotational mode (r-mode) … ~ rotation frequency
  - relativistic modes
    - ✓ spacetime mode (w-mode) … > a few tens kHz
- axial oscillations
  - fluid modes; **torsional mode (t-mode)** … > ten Hz
  - relativistic modes; w-mode … > a few tens kHz

identification of SGR 1900+14



pasta phase



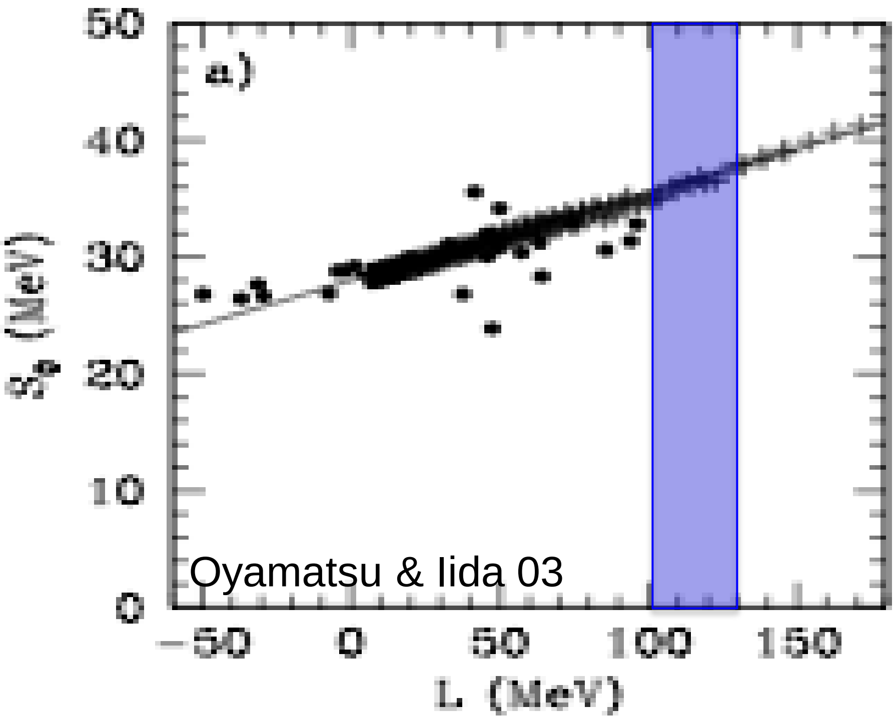
- region of pasta phase depends strongly on *L*
- for *L* ≳ 100MeV, pasta structure almost disappears

constraint on S_0

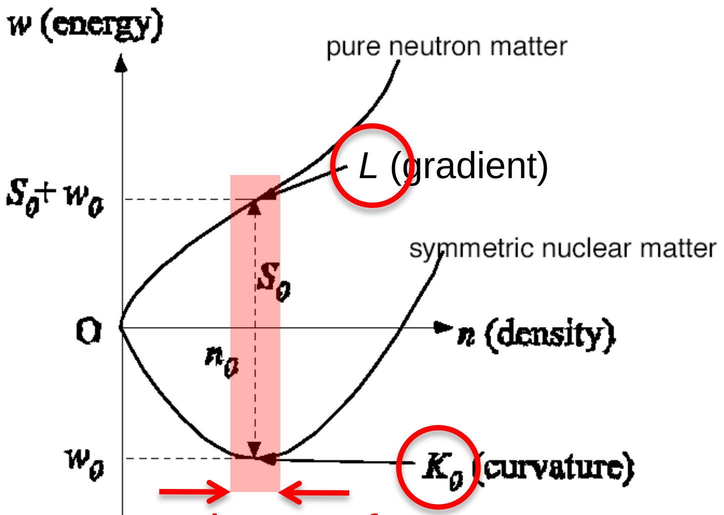
- by using the empirical relation : $$S_0 = 28 + 0.075L$$

(Oyamatsu & Iida 03)

➡ 35.6 MeV ⩽ S_0 ⩽ 37.8 MeV



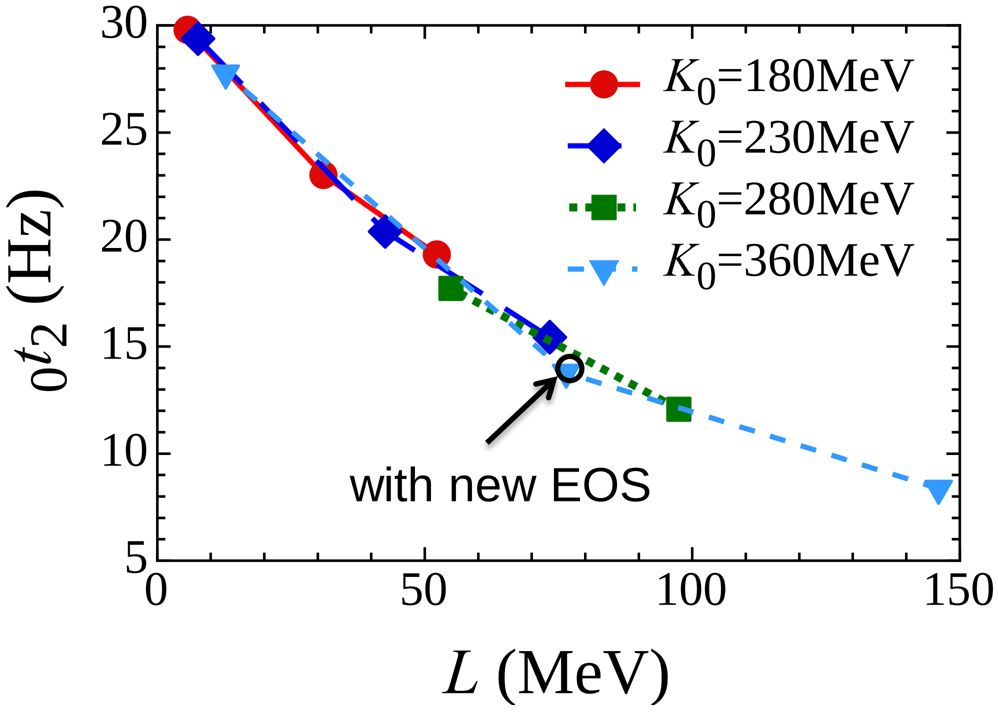
Oyamatsu & Iida 03



experiments for stable nuclei

comparing with other EOS

- new EOS (Miyatsu+ 13)
  - core : RMF calculation
  - crust : TF theory
- EOS parameters
  - L = 77.1 MeV
  - K_0 = 274 MeV
- even with new EOS, the dependence of torsional oscillations on L is same as the previous results.



effect of electron screening

- contribution due to Coulomb interaction
  - Ogata & Ichimaru 90; Strohmayer+ 91

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

- including effect of electron screening
  - Horowitz & Hughto 08 : 10% reduction
  - Kobyakov & Pethick 13

$$\mu = 0.1194 \left[1 \boxed{- 0.010 Z^{2/3}} \right] \frac{n_i (Ze)^2}{a}$$

effect of electron screening

  - ~11.7% reduction for *Z* = 40
- phonon contribution is much smaller (Baiko 12)

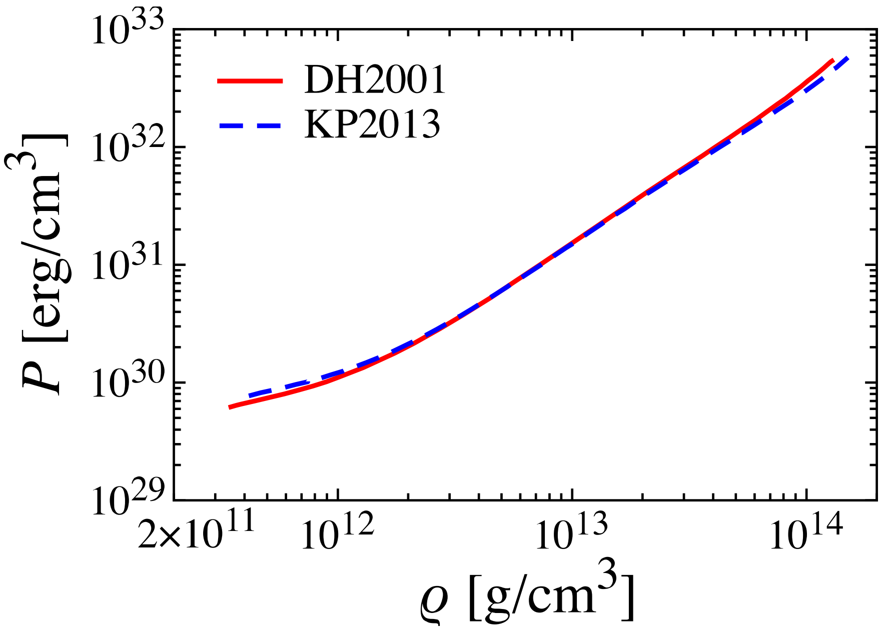
adopted EOS

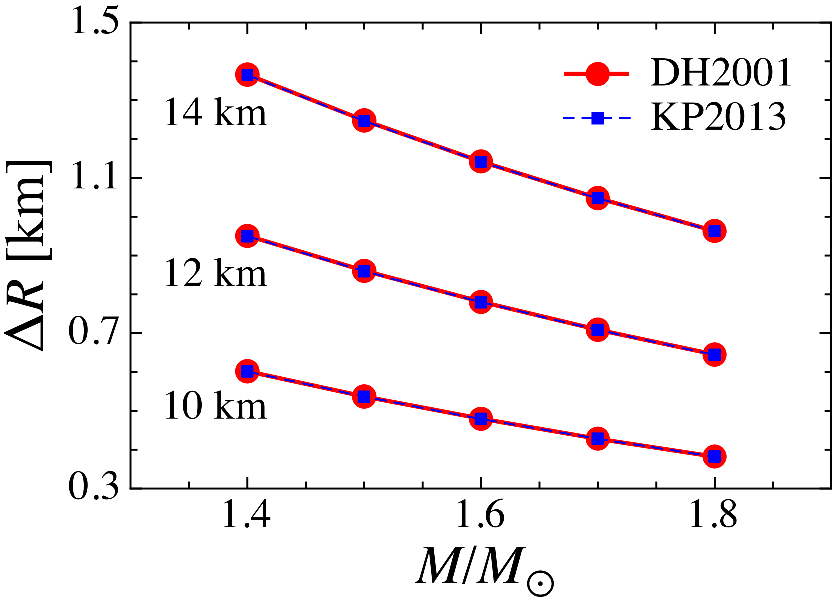
- outer crust
  - Haensel & Pichon 94
- inner crust
  - compressible liquid drop model (CLDM)
  - Kobyakov & Pethick 13 (KP2013) based on Lattimer & Swesty 91
  - Douchin & Haensel 01 (DH2001)

	KP2013	DH2001
model	CLDM	CLDM
neutron skin	×	○
n_{bc} [1/fm^3]	8.913×10^{-2}	7.596×10^{-2}
ρ_c [g/cm^3]	1.504×10^{14}	1.285×10^{14}

crust models

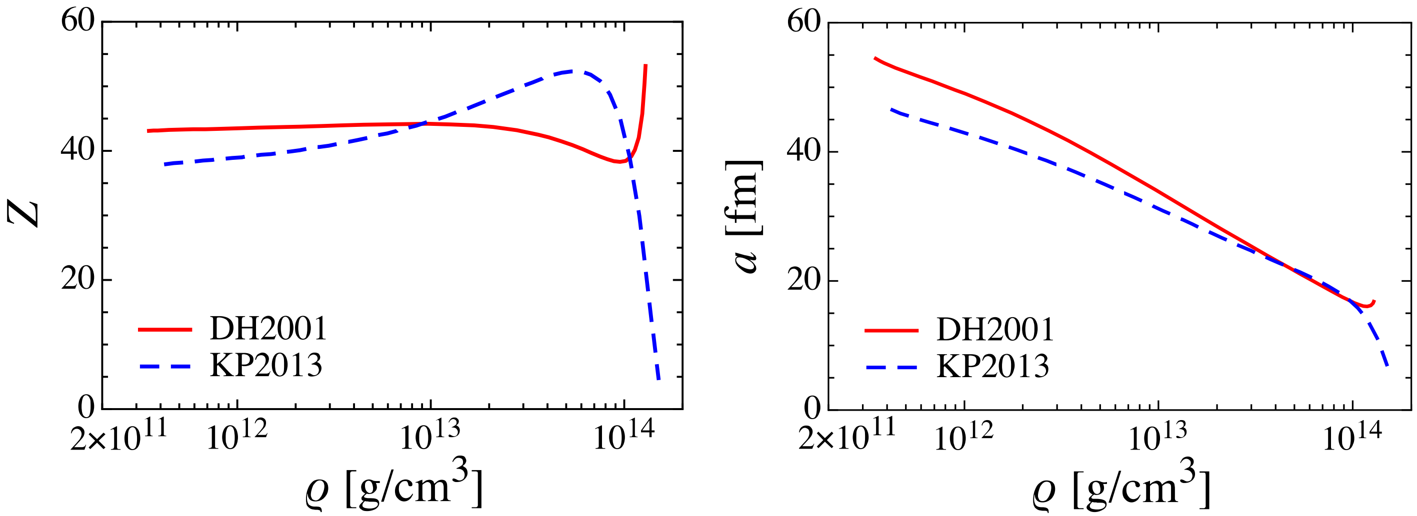
- quite difficult to distinguish the difference in crust thickness with DH2001 and with KP2013





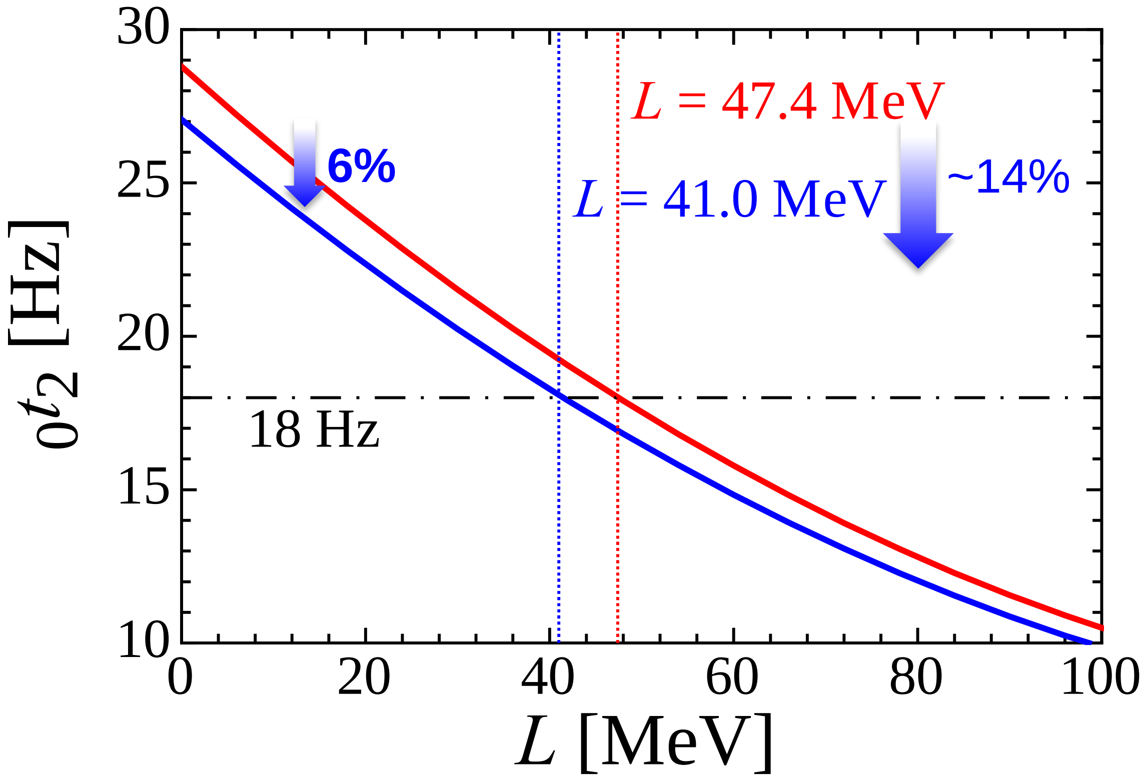
other properties

- charge depends strongly on the EOS at the crust basis
- radius of WS cell also depends on the EOS



constraint on *L*

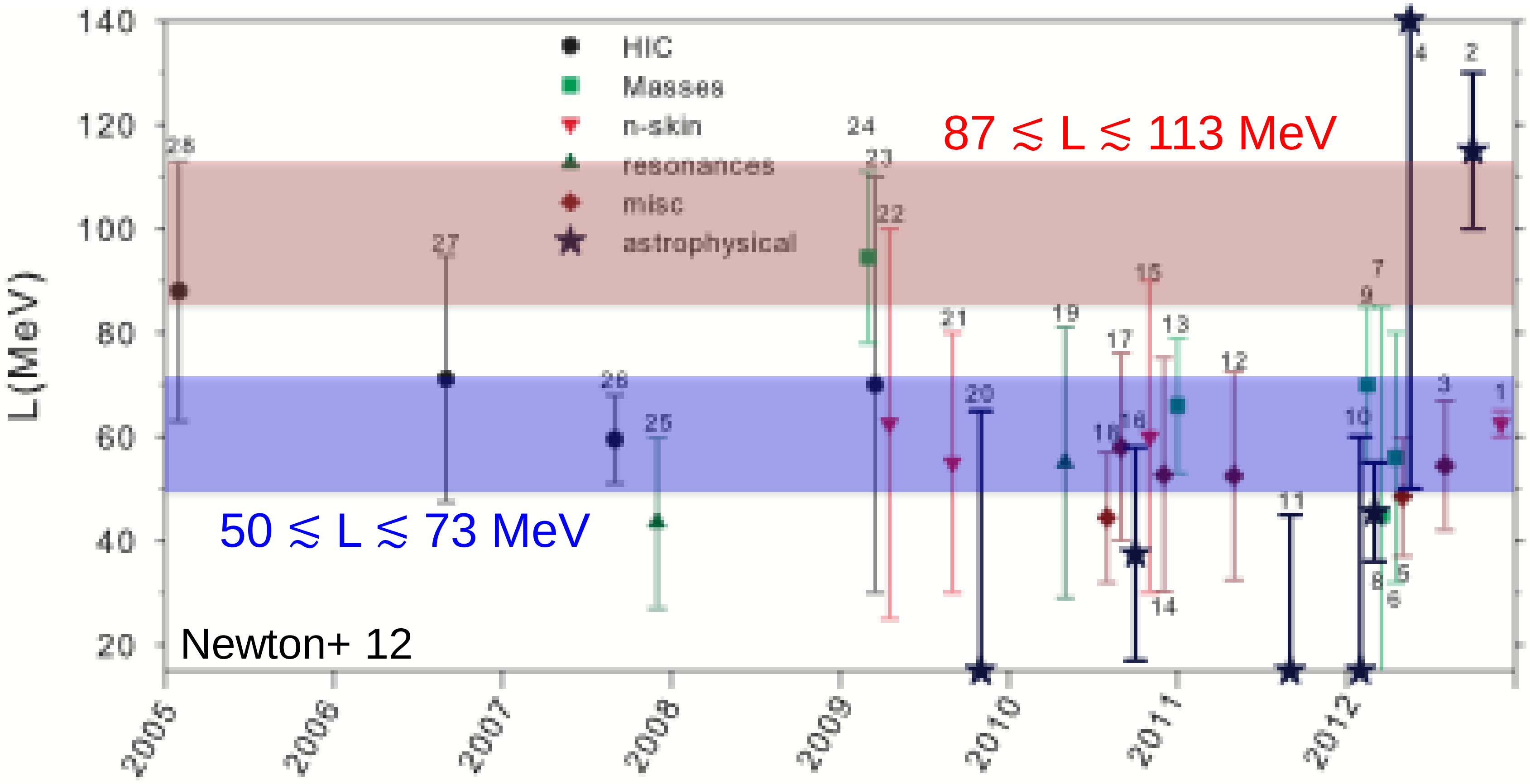
- due to the electron screening effect, constraint of *L* shifts ~14% smaller value



$L \gtrsim 47.4$ MeV → $L \gtrsim 41.0$ MeV

modified constraints on *L*

- adopting the reduction of frequencies due to the electron screening effect, constraints on *L* become as follows;



fundamental oscillations

(HS 13)

- one may be identify the EOS using the observations of crustal oscillations
- independent of the stellar mass and the crust EOS, the effect of electron screening can reduce 6% of the frequencies