Neutron stars and nuclear matter parameters

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collaborated with

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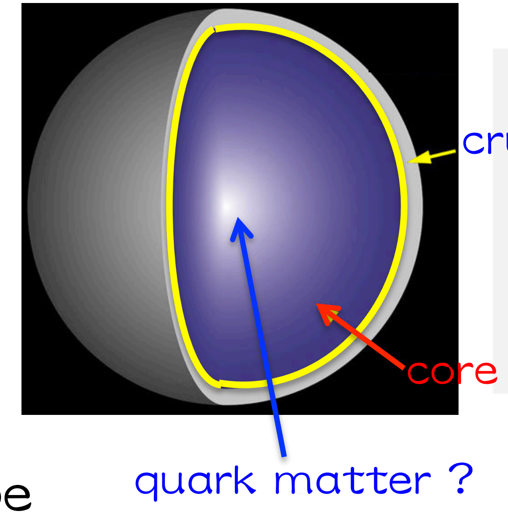
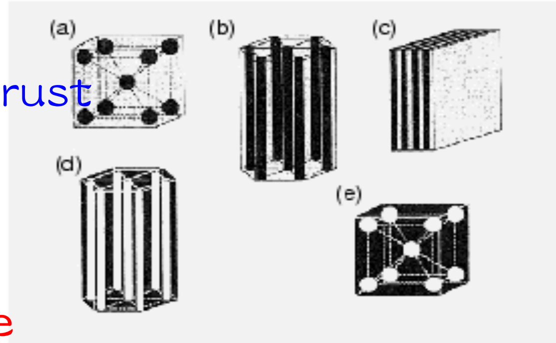
neutron stars

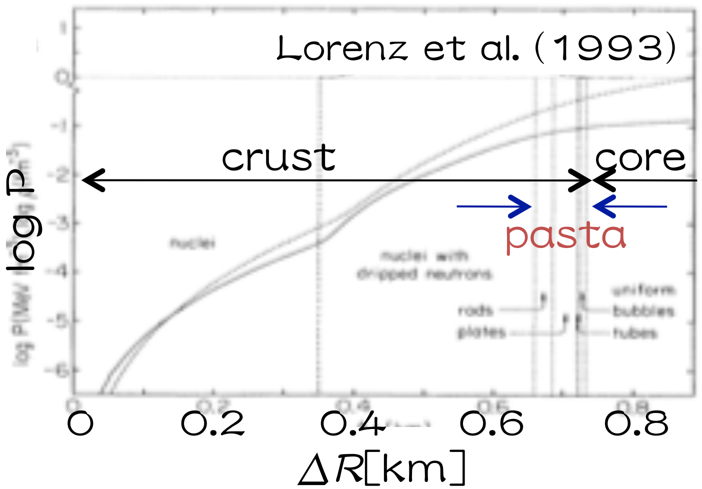
- Structure of NS
  - solid layer (crust)
  - nonuniform structure (pasta)
  - fluid core (uniform matter)
- Crust thickness ≲ 1km
- Determination of EOS for high density region could be quite difficult on Earth
- Constraint on EOS via observations of NSs
  - stellar mass and radius
  - stellar oscillations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

"(GW) asteroseismology"





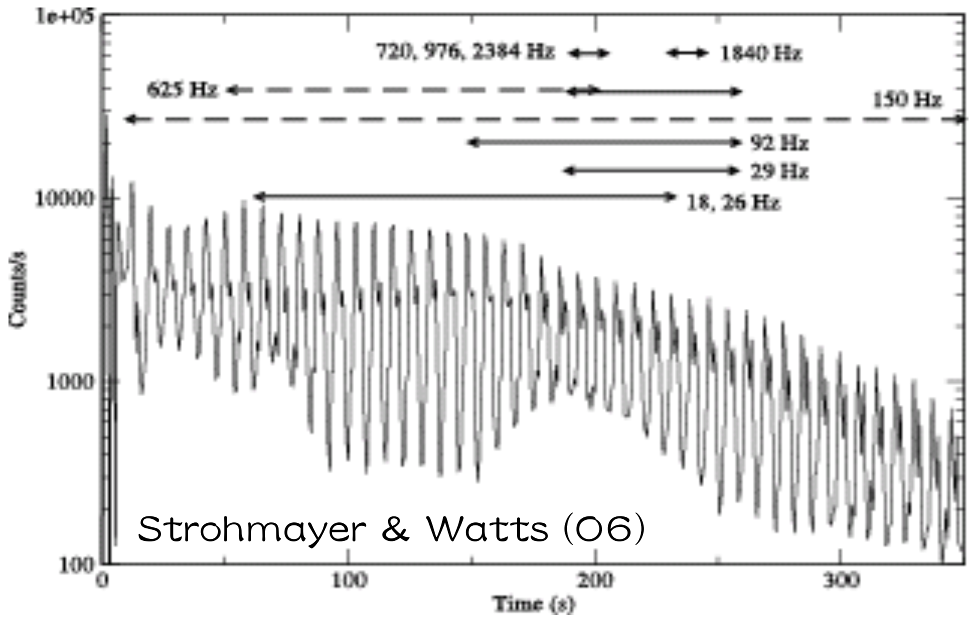
Oyamatsu (1993)



QPOs in SGRs

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

  (Barat+ 1983, Israel+ 05, Strohmayer & Watts 05, Watts & Strohmayer 06)



- Crustal torsional oscillation ?
- Magnetic oscillations ?

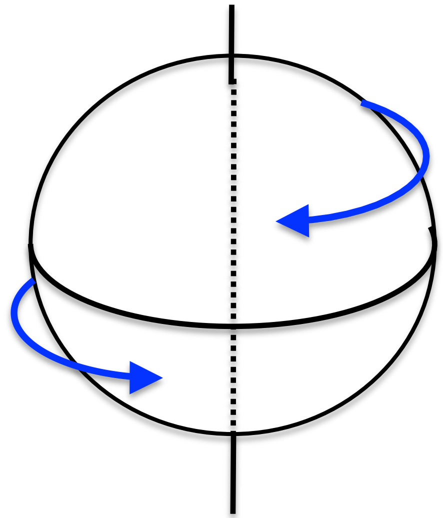
- Asteroseismology
  → stellar properties
  (M, R, B, EOS ...)

torsional oscillations

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

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

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



EOS near the saturation point

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

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

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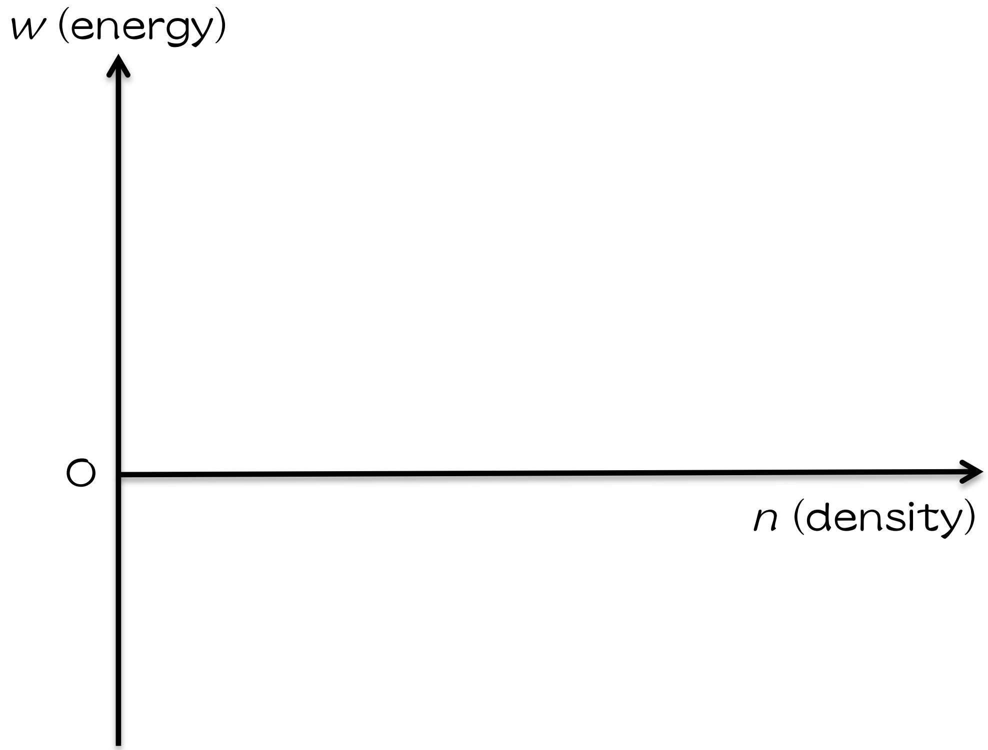

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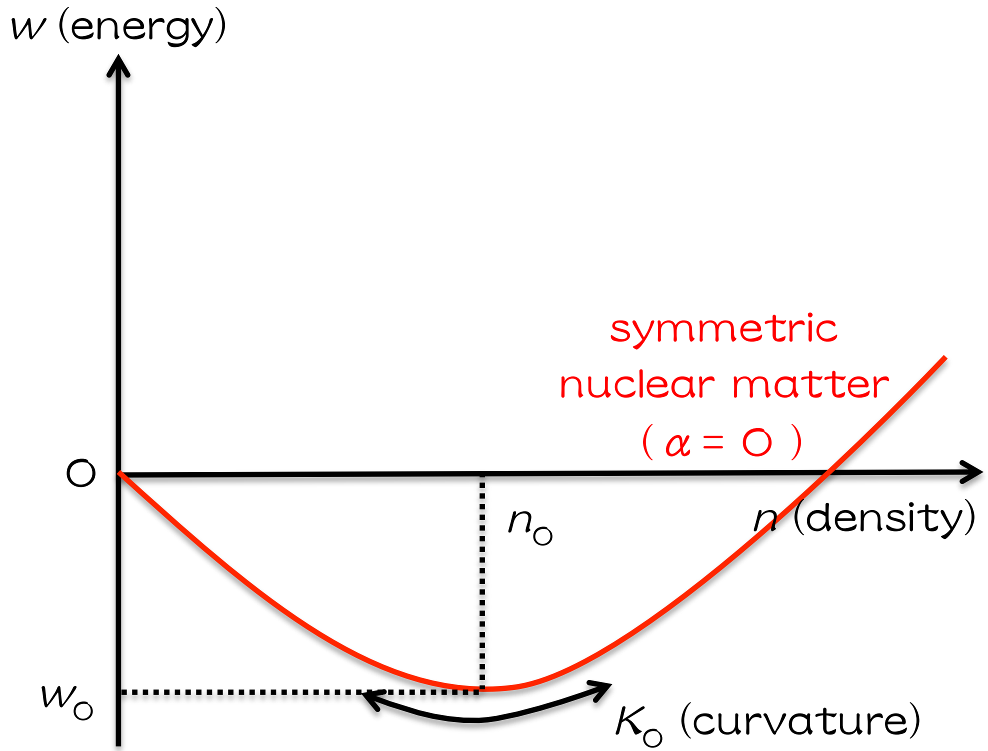

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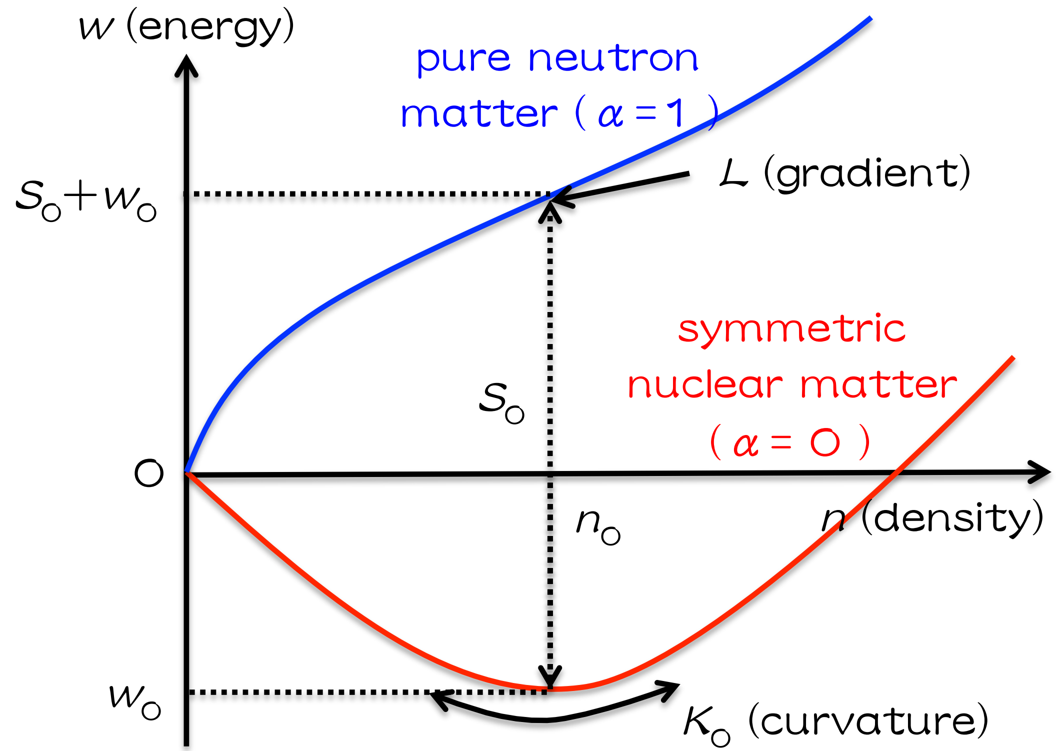

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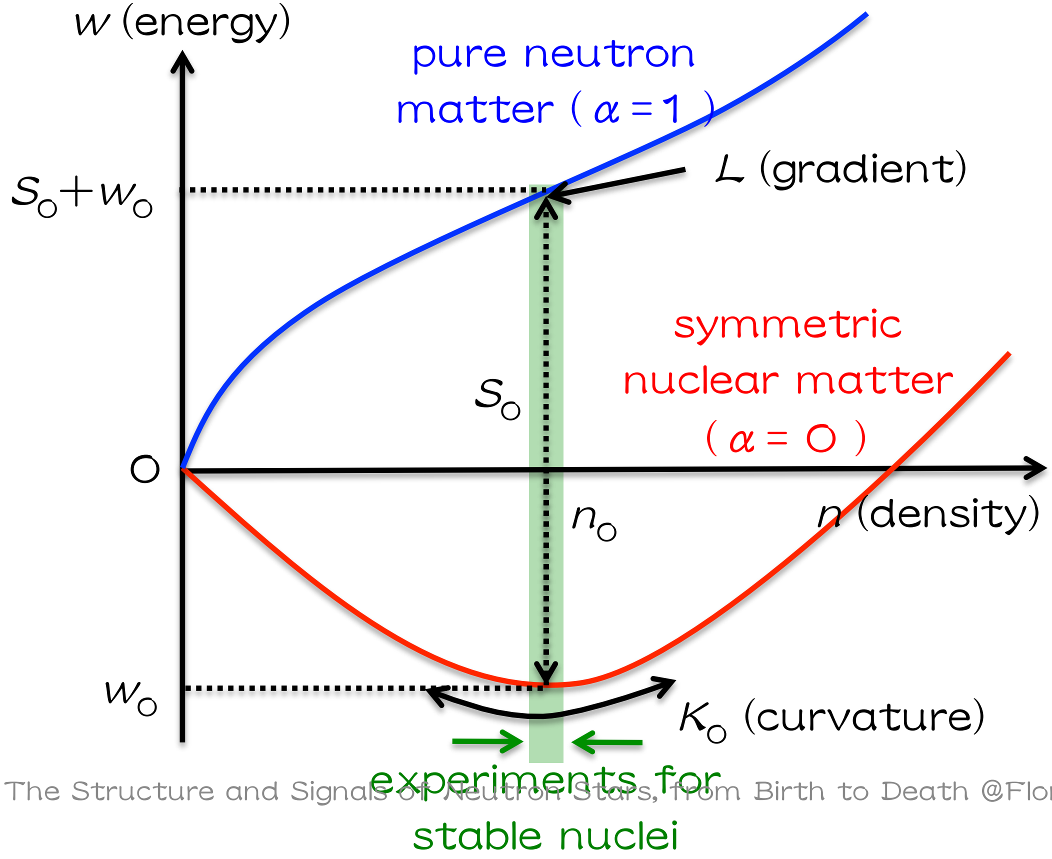


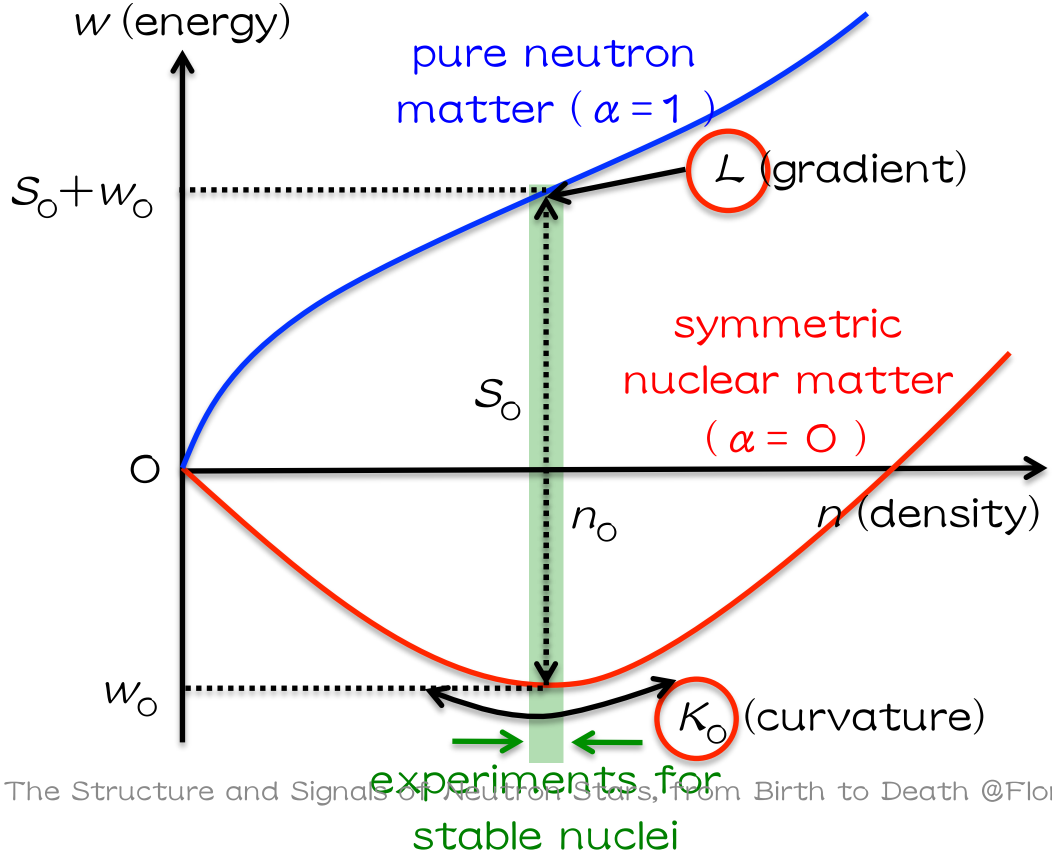
EOS near the saturation point

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

incompressibility

symmetry parameter

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



what we do

- EOS for core region is still uncertain. (cf. Steiner & Watts 09)
- We especially adopt the **phenomenological EOSs**, which are consistent with the terrestrial nuclear experiments, proposed by Oyamatsu & Iida (03, 07).
- 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)

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  - M, R : parameters for stellar properties
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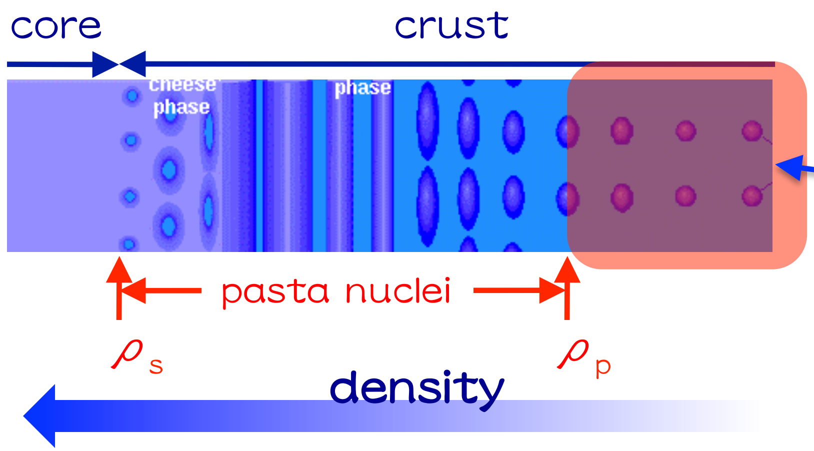
- In crust region, torsional oscillations are calculated.
  - considering the shear only in spherical nuclei.
  - frequency of fundamental oscillation $\propto v_s$ ($v_s^2 \sim \mu / H$)
- Comparing frequencies with QPOs, we will put a constraint on EOS parameter.



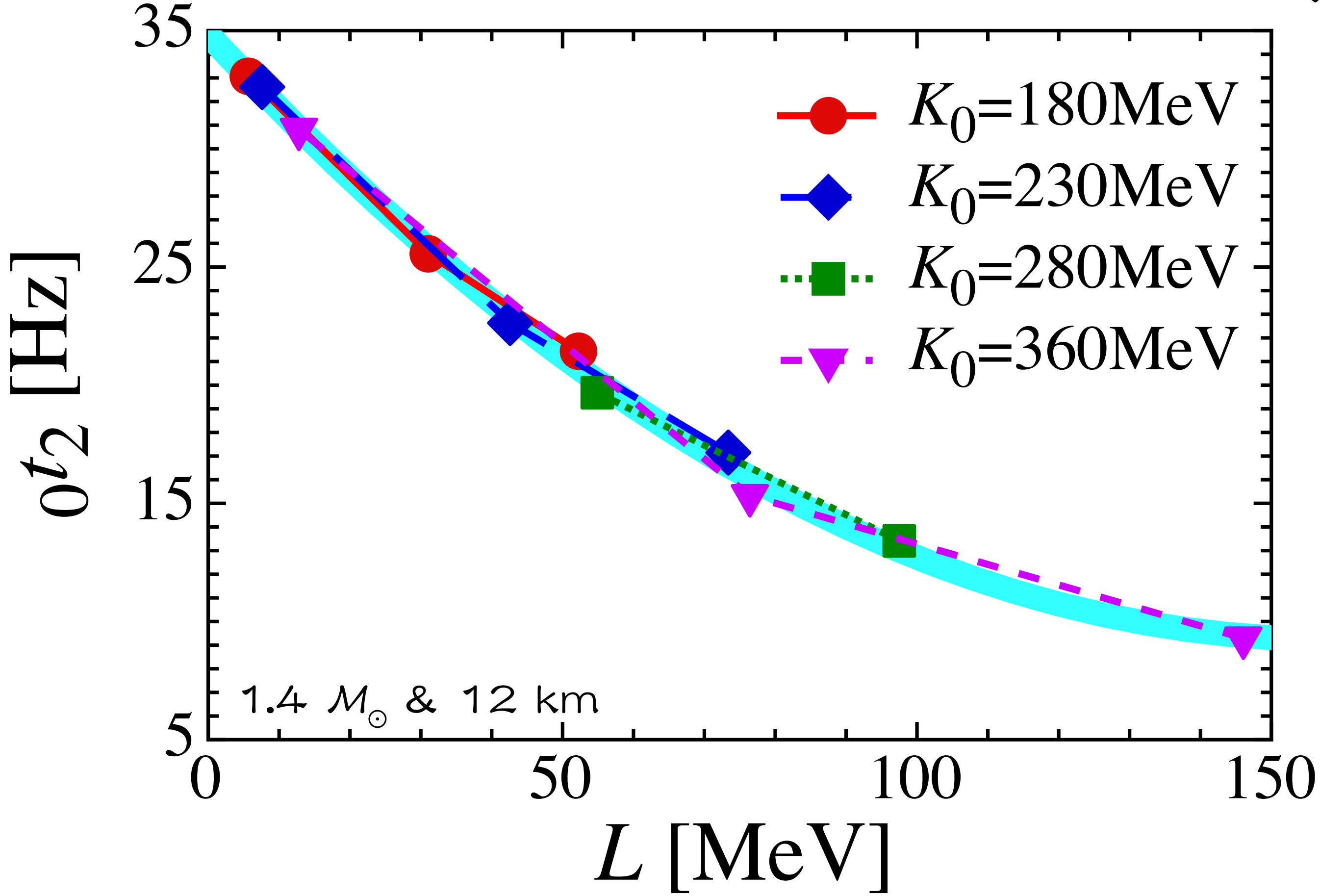
for bcc lattice (Strohmayer+ 1991)

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

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

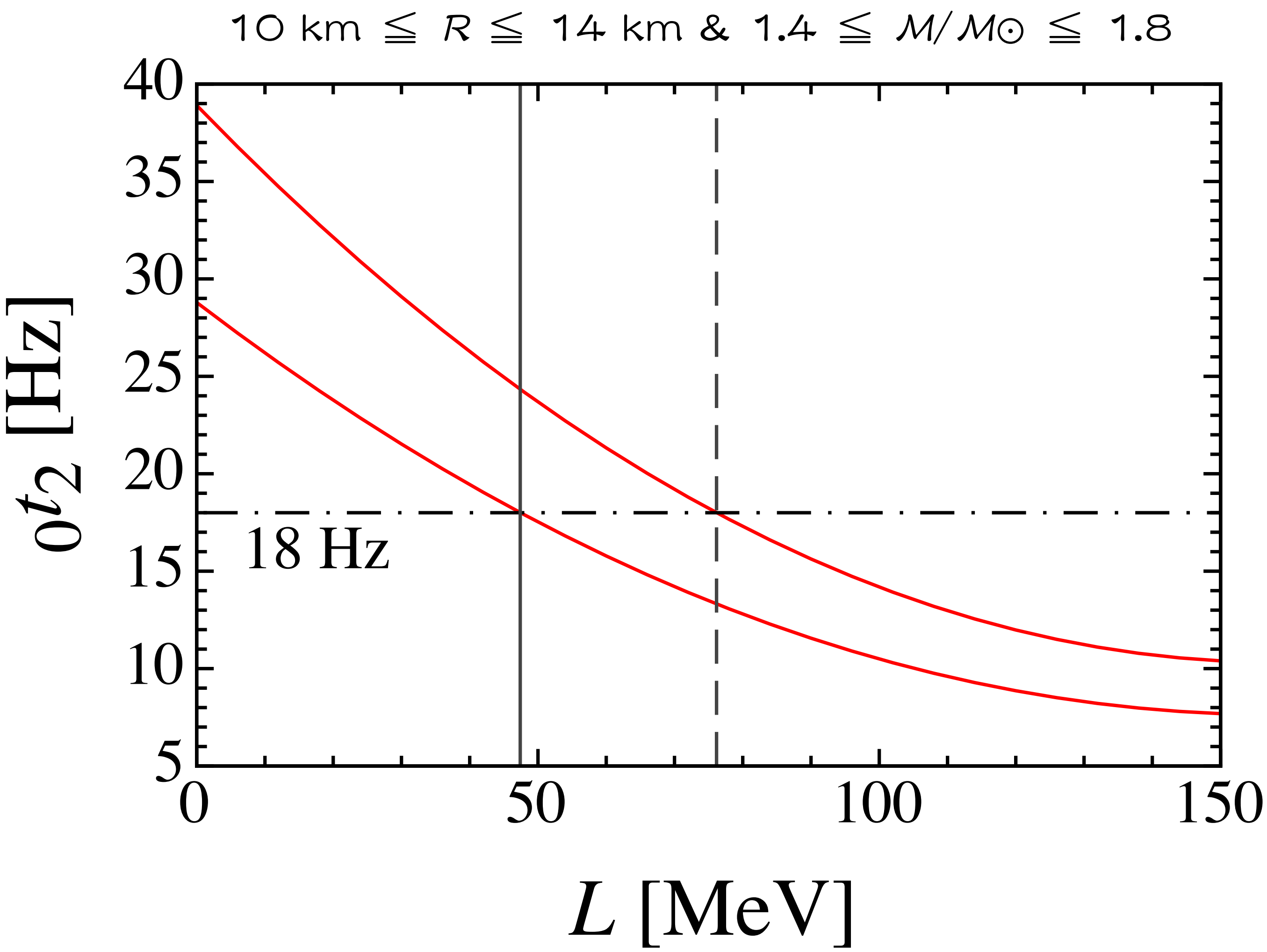
torsional oscillations

HS, Nakazato, Iida, Oyamatsu 13



➡ almost independent of the incompressibility K_0

constraint on L



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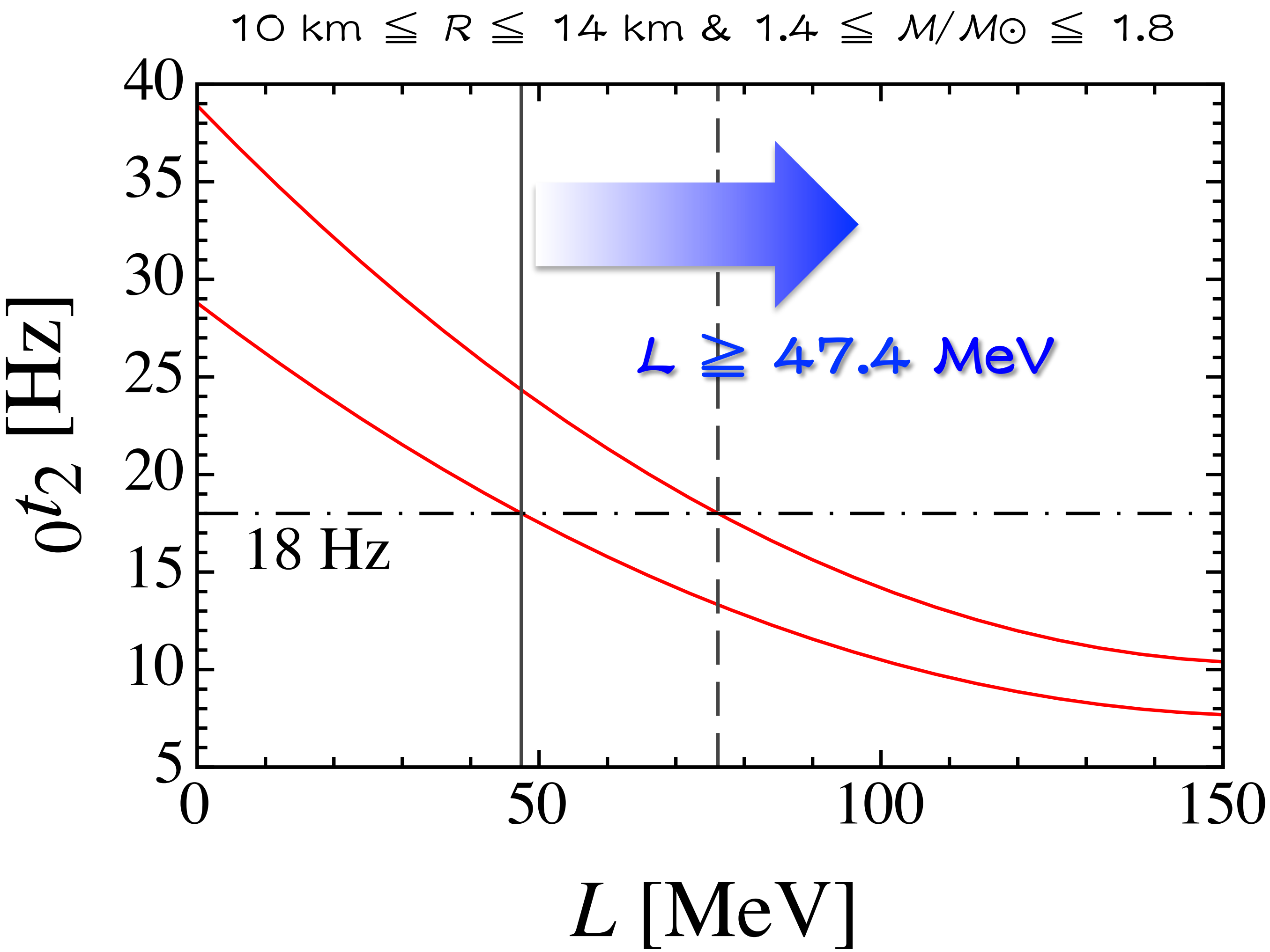
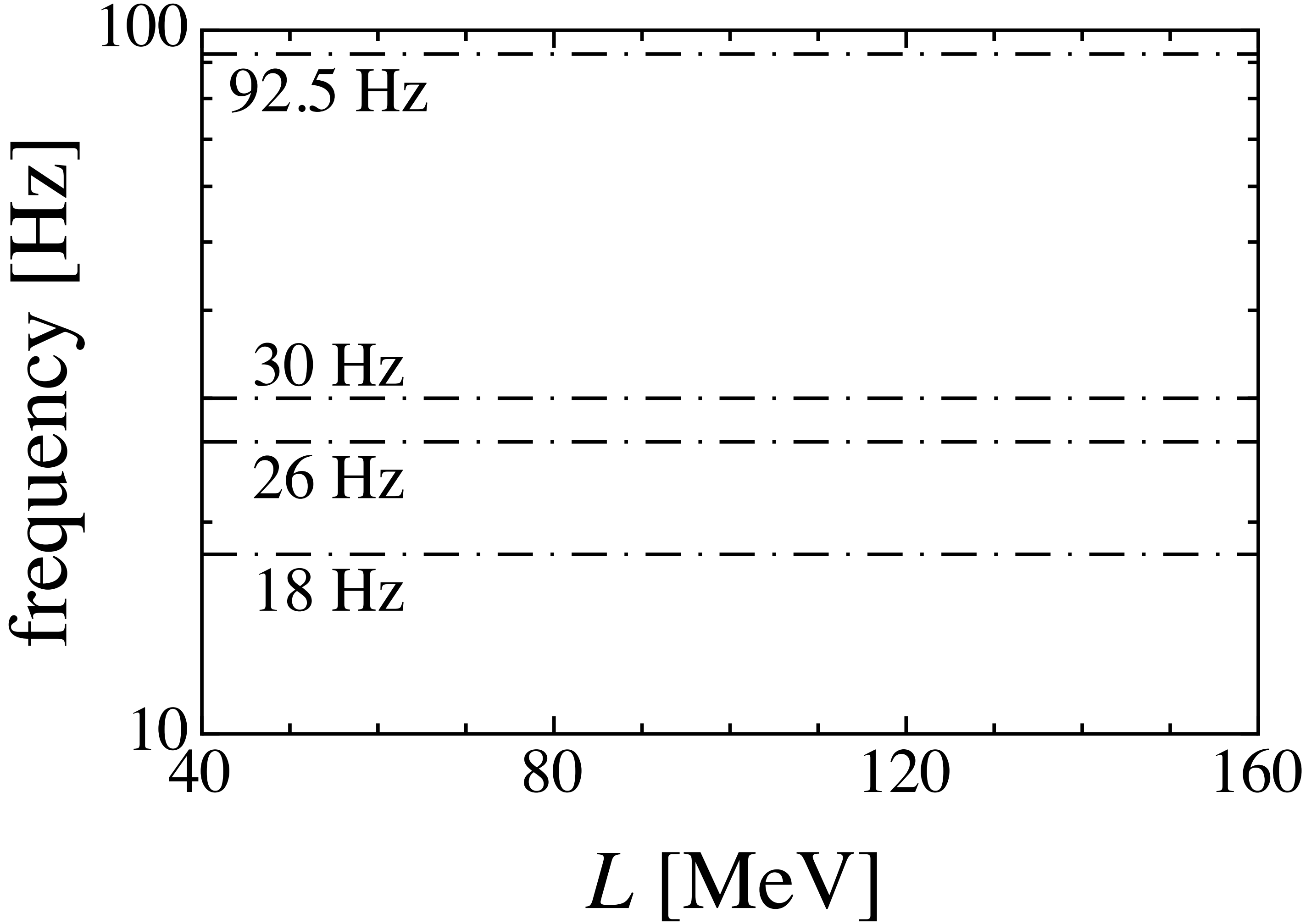


effect of superfluidity

- $\rho \gtrsim 4 \times 10^{11}$ 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, $\mu_b = H / n_b$ $\Rightarrow$ $\bar{H} = \left(1 - \frac{N_s}{A}\right) H$

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

identification of SGR 1806-20



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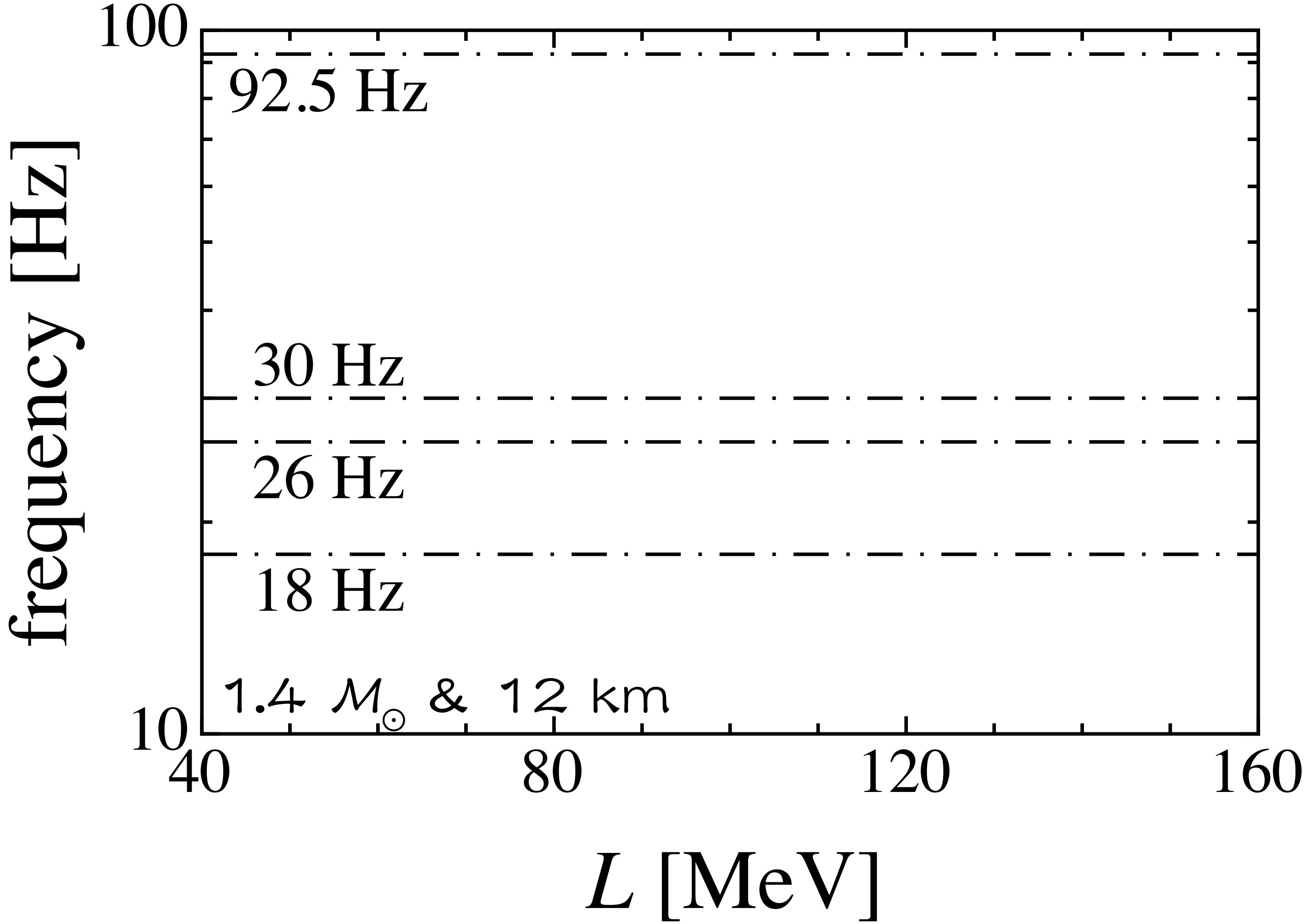

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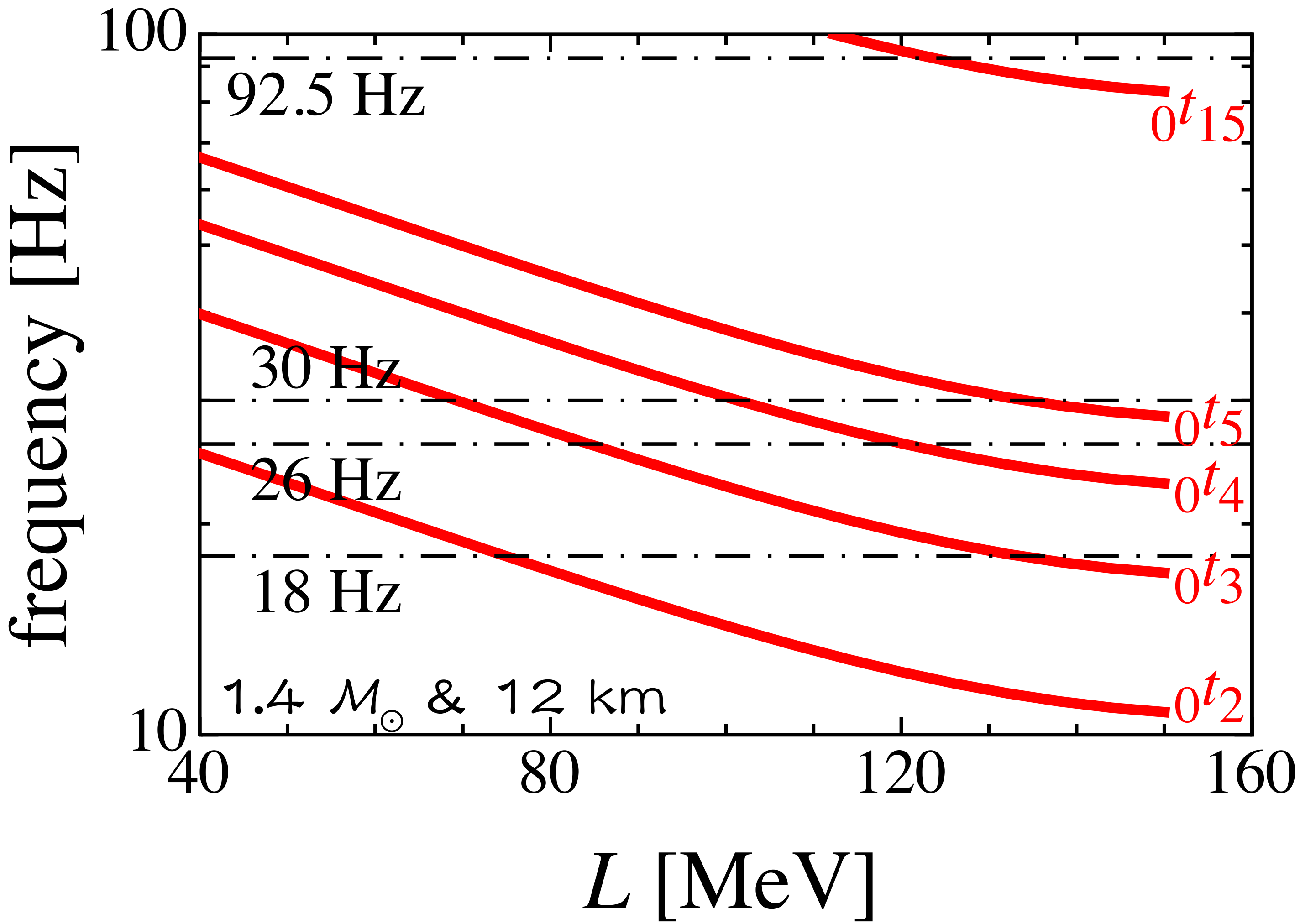

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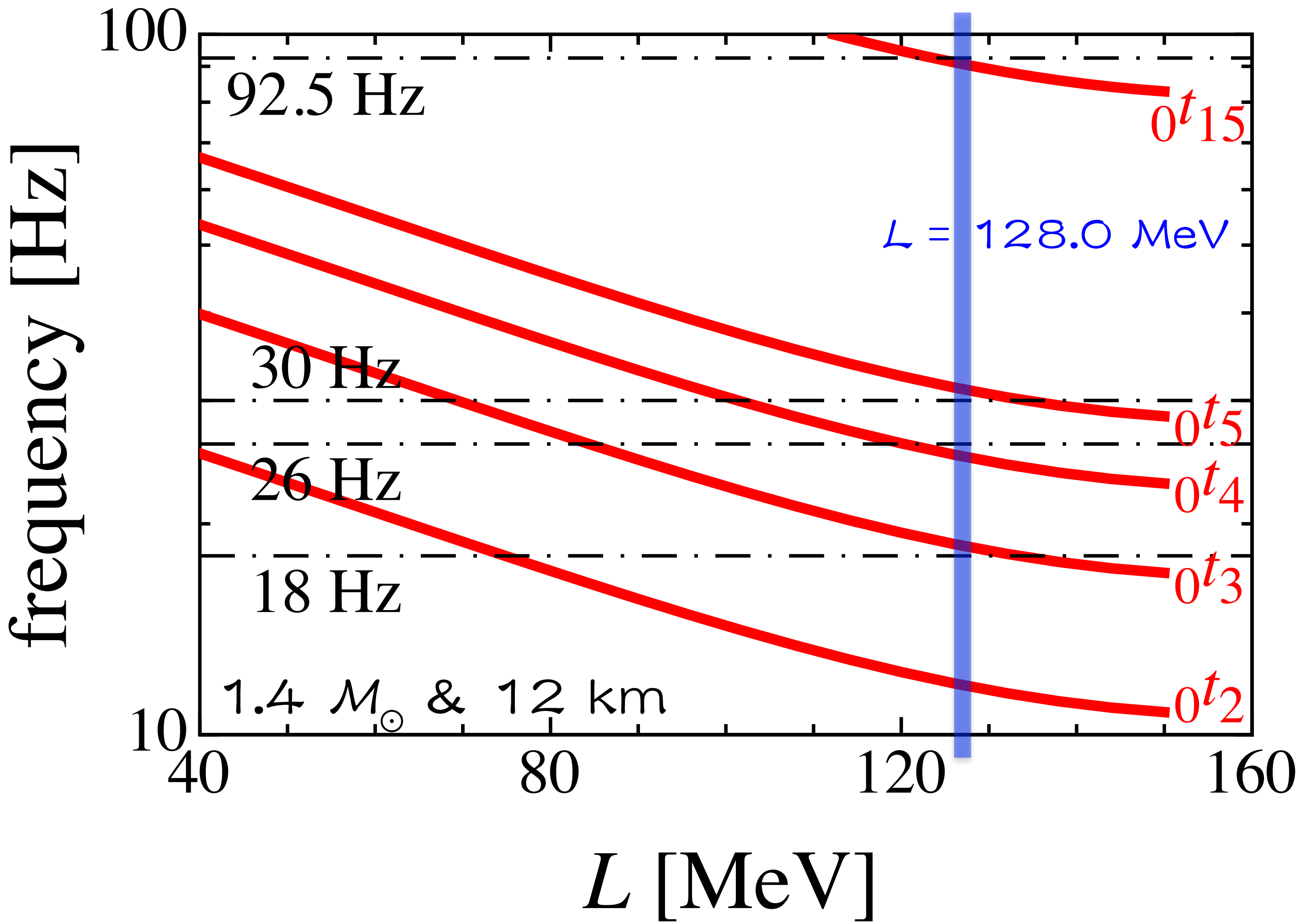
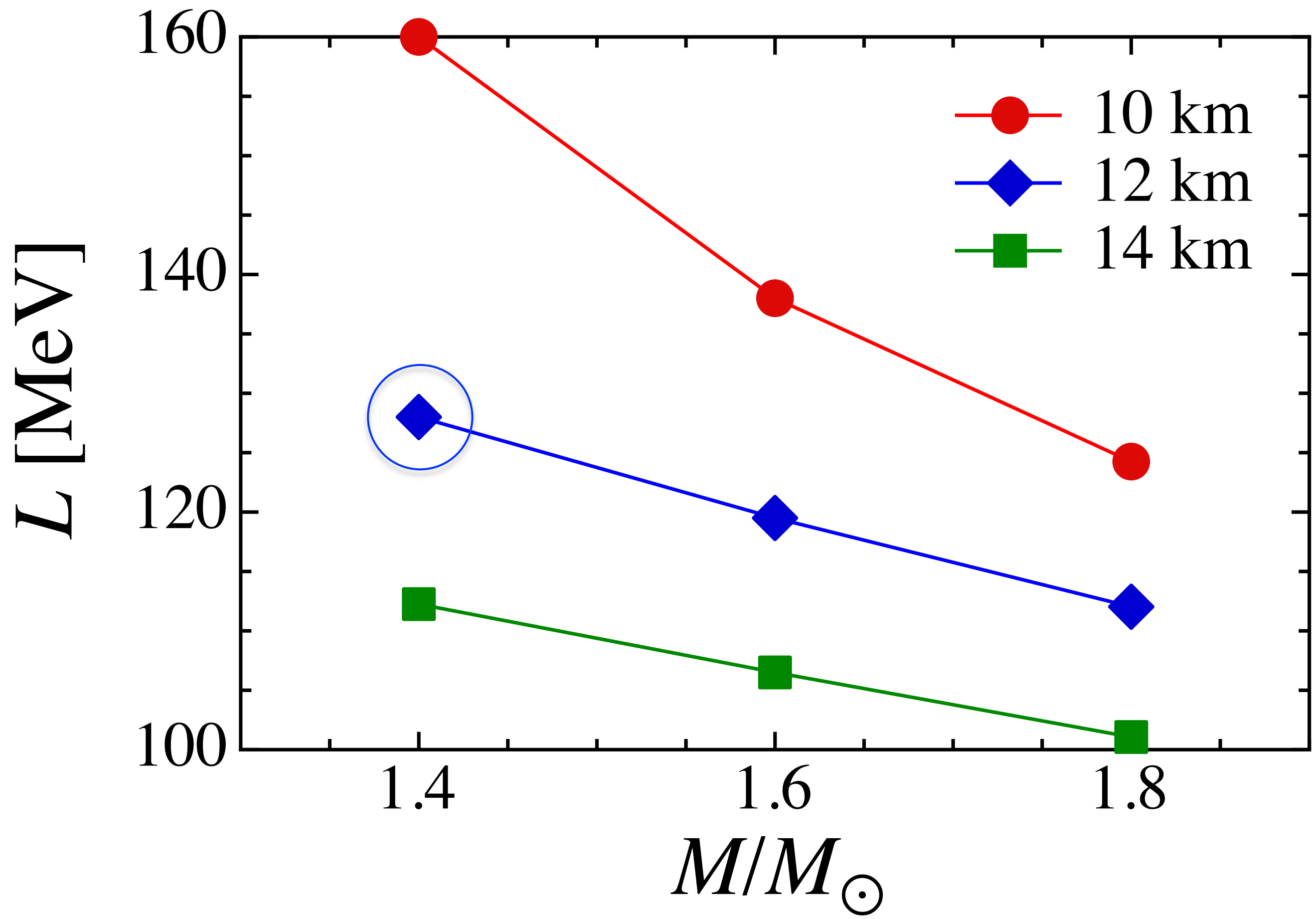
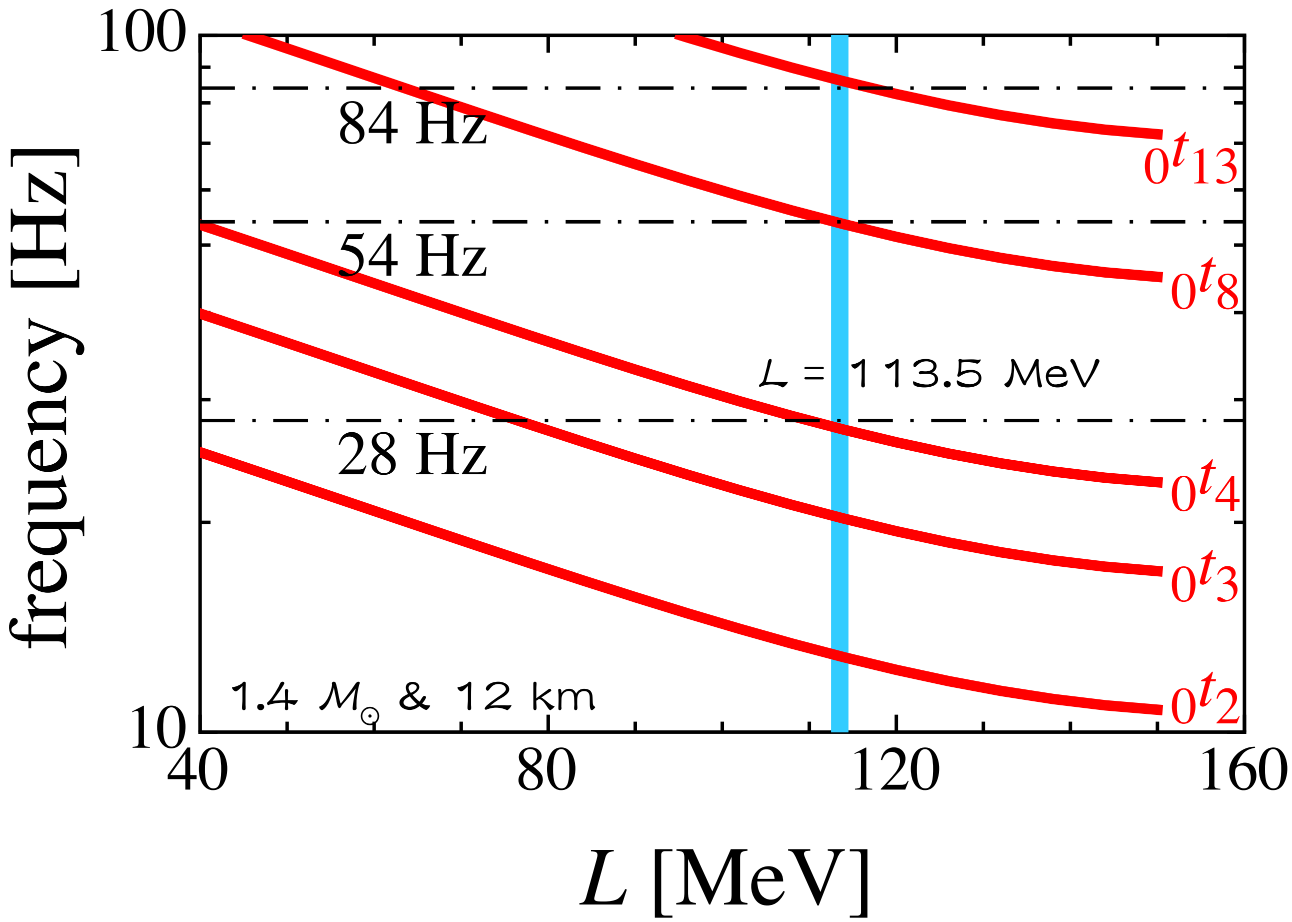


constraint on L via SGR 1806-20

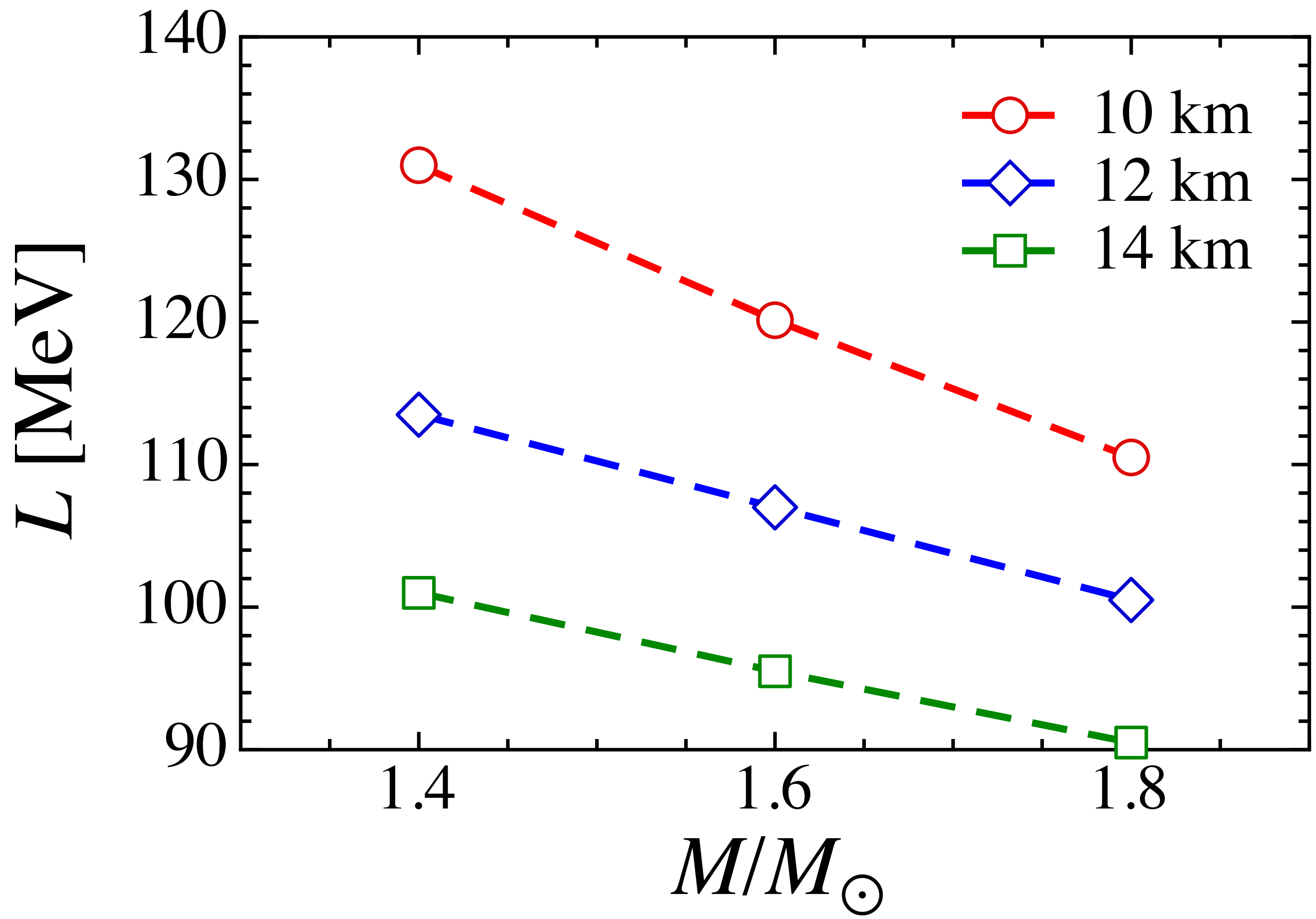


➡ 101.1 MeV ≤ L ≤ 160.0 MeV

identification of SGR 1900+14

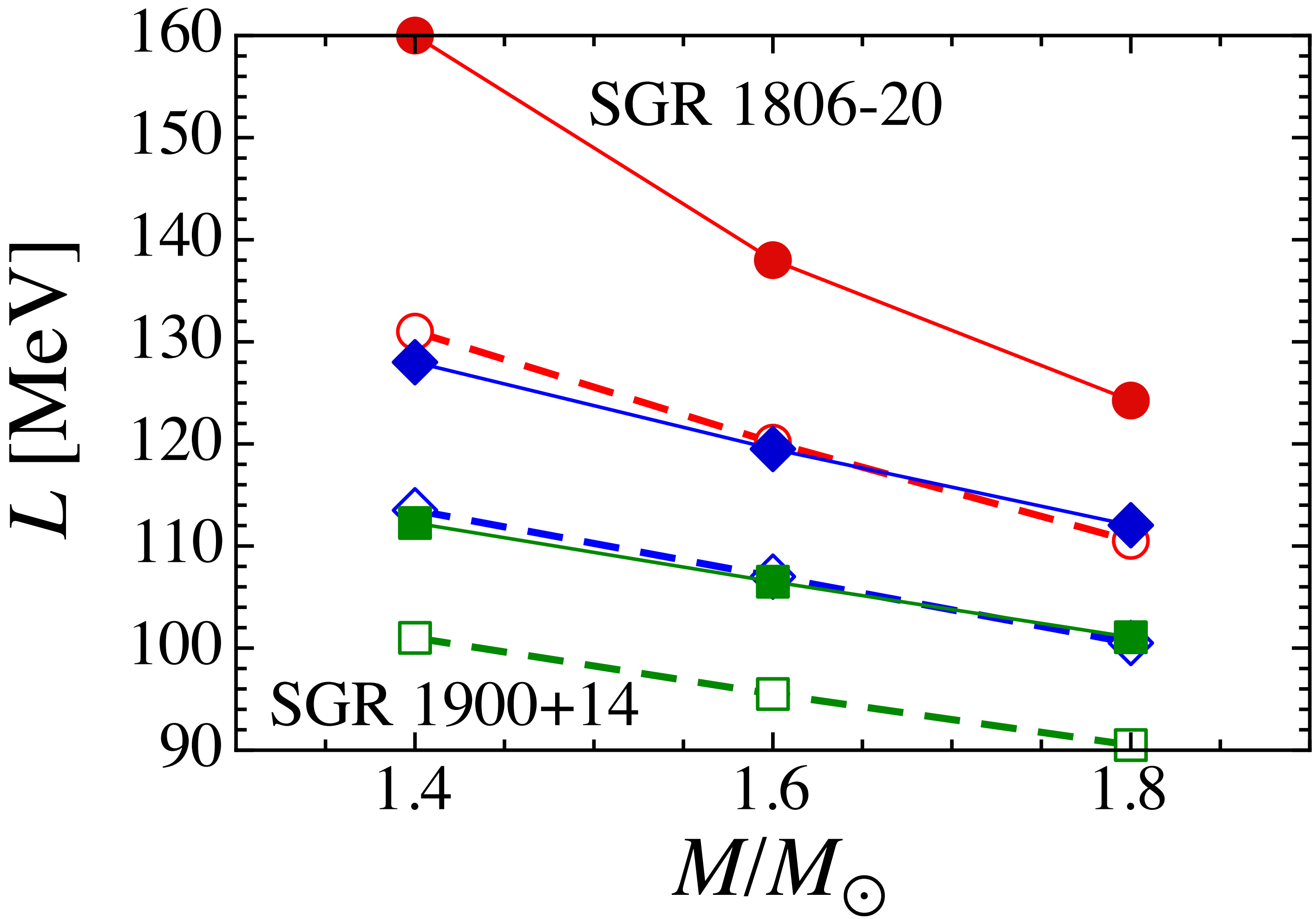


constraint on L via SGR 1900+14



➡ 90.5 MeV ≤ L ≤ 131.0 MeV

allowed region for L



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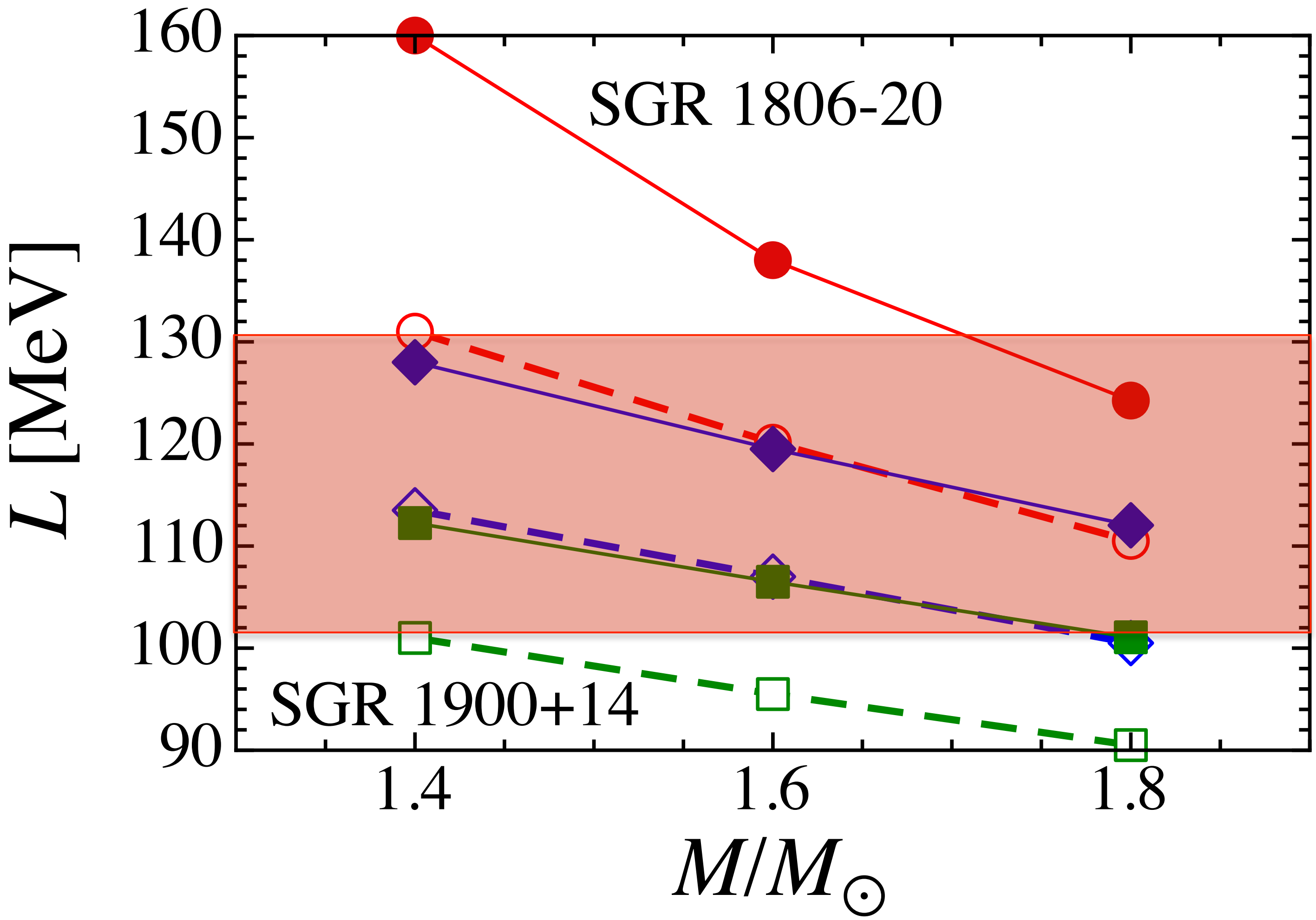


➡ 101.1 MeV ≤ L ≤ 131.0 MeV

missing effects ??

blue : decrease

red : increase

- modification of shear modulus
  - size of nuclei
  - electron screening (Horowitz & Hughto 08; Kobyakov & Pethick 13; Sotani 14)
  - 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)

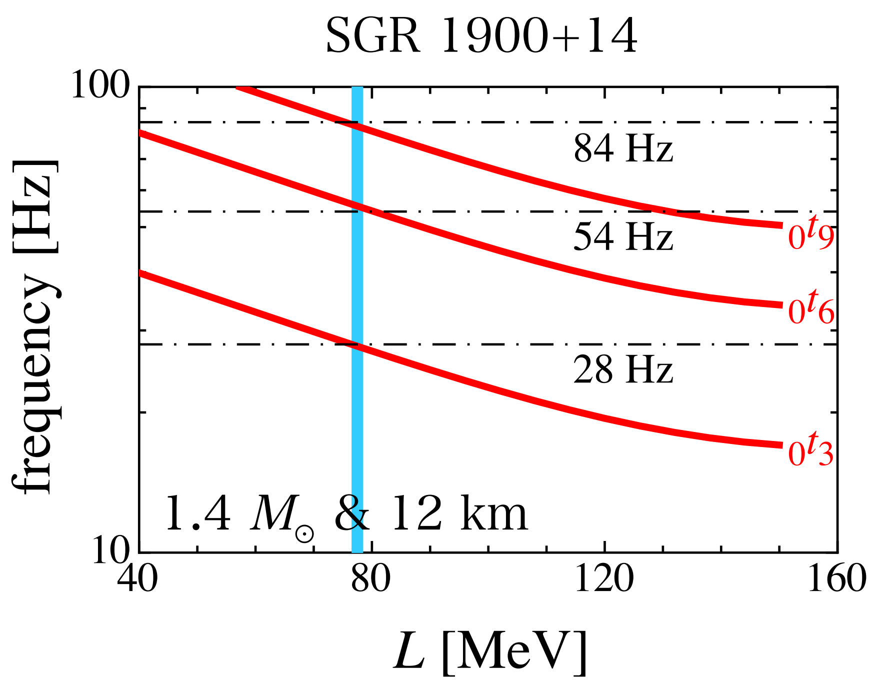
- emission mechanism ??

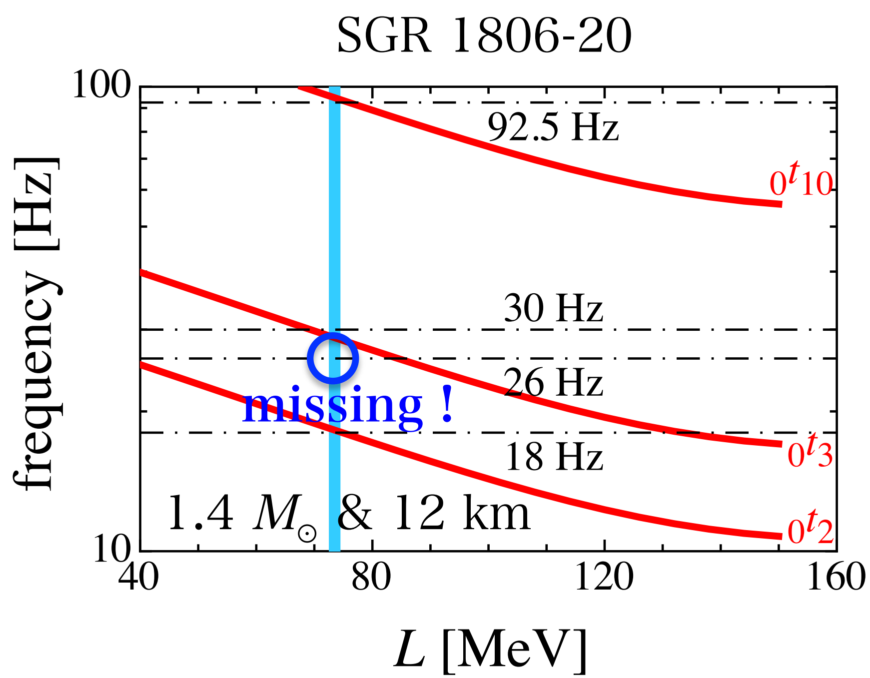
summary

- 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.

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

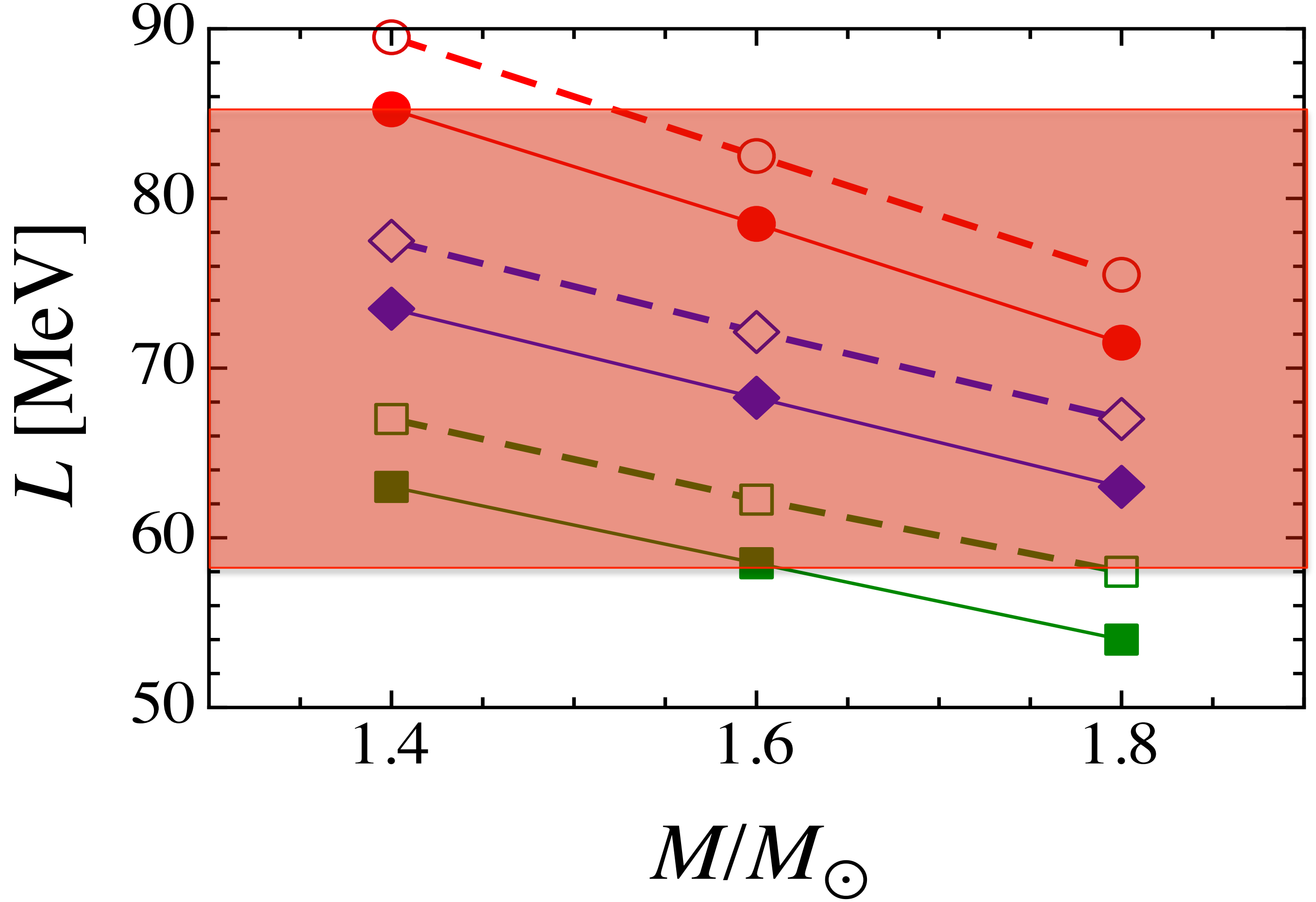
QPOs (Hz)	l	${}_0t_l$ (Hz)	error (%)
28	4	27.26	2.63
54	8	53.76	4.50
84	13	86.18	-2.60

- 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

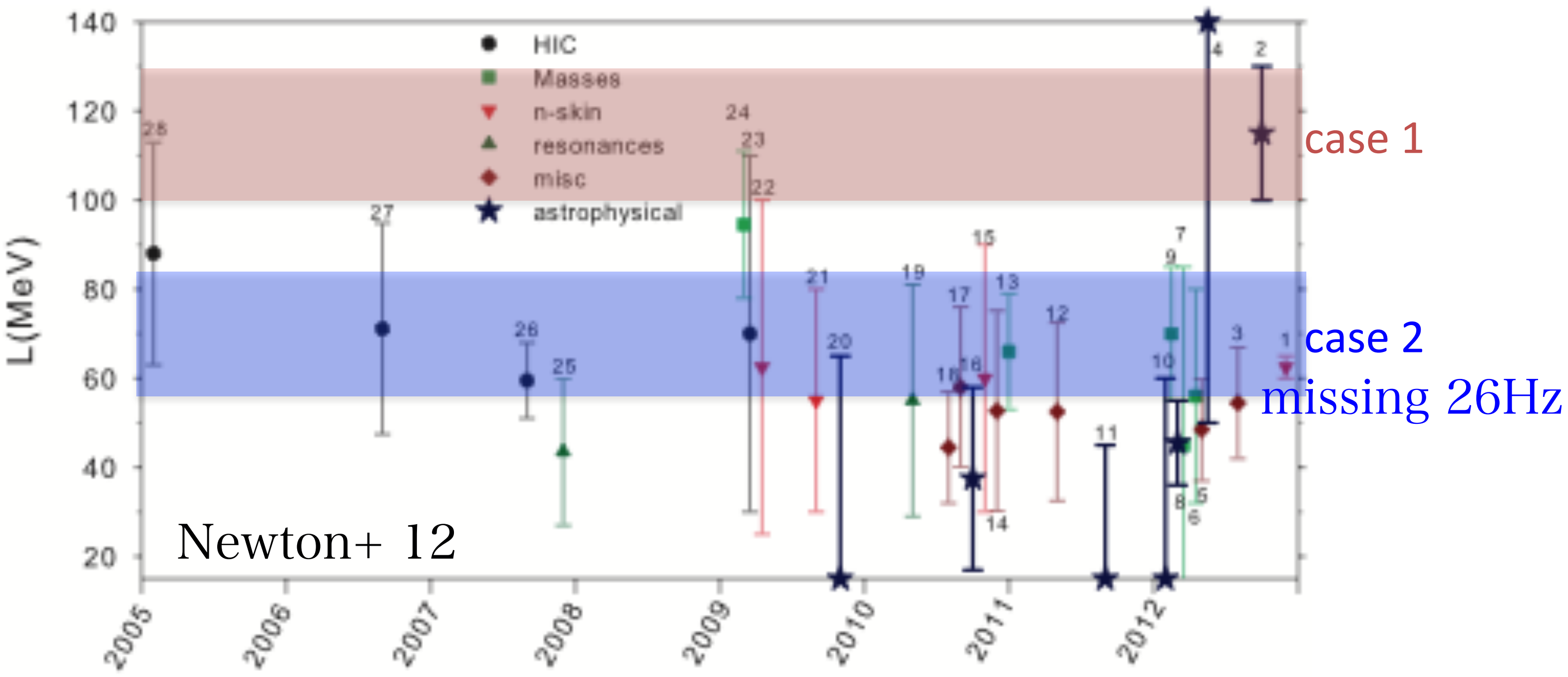


➡ $58.0\ \mathrm{MeV} \leqslant L \leqslant 85.3\ \mathrm{MeV}$

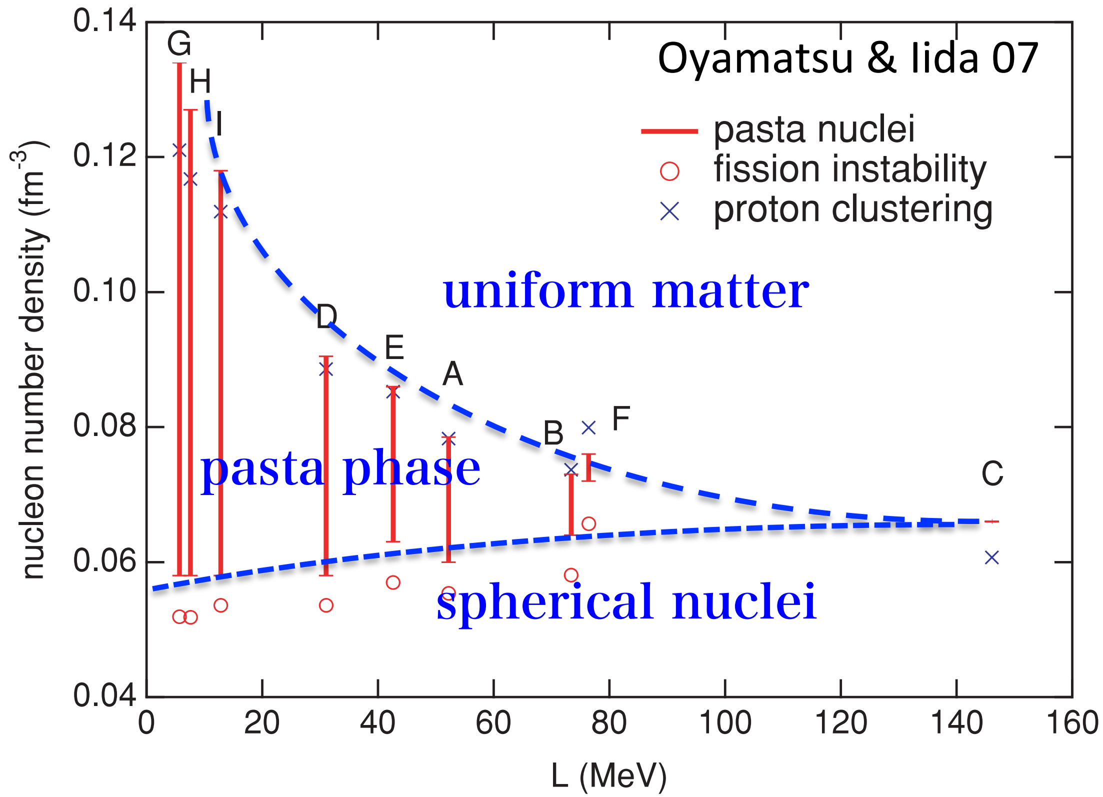
($32.4\ \mathrm{MeV} \leqslant S_0 \leqslant 34.4\ \mathrm{MeV}$)

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…



pasta phase



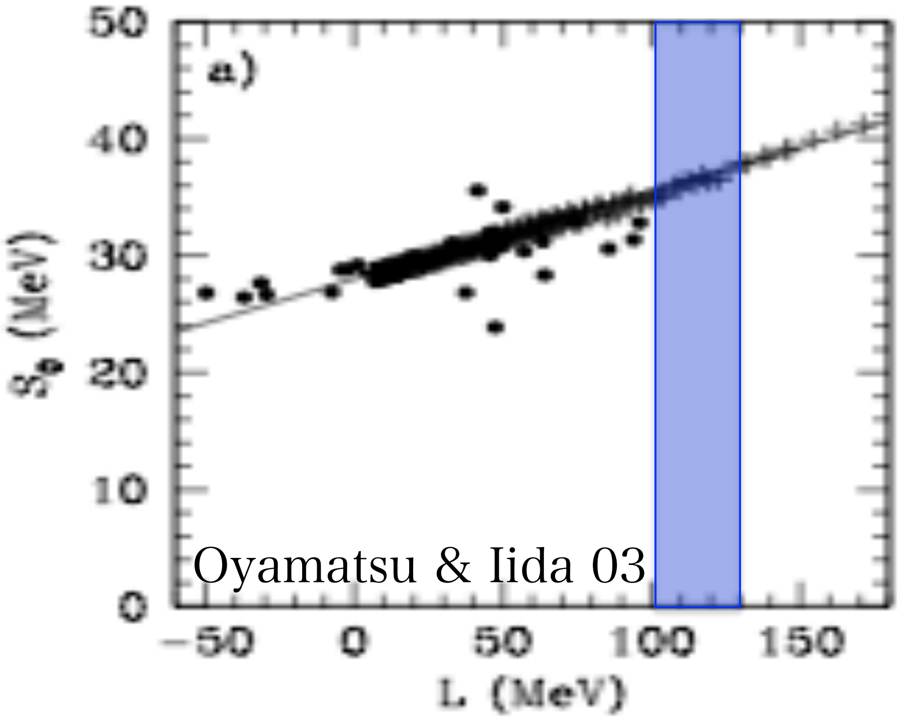
- region of pasta phase depends strongly on L
- for $L \gtrsim 100$MeV, pasta structure almost disappears

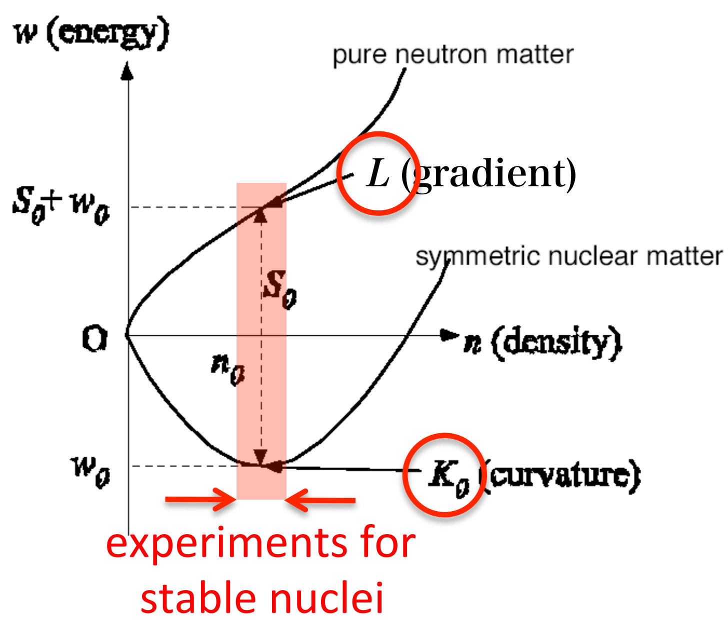
constraint on S_0

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

(Oyamatsu & Iida 03)

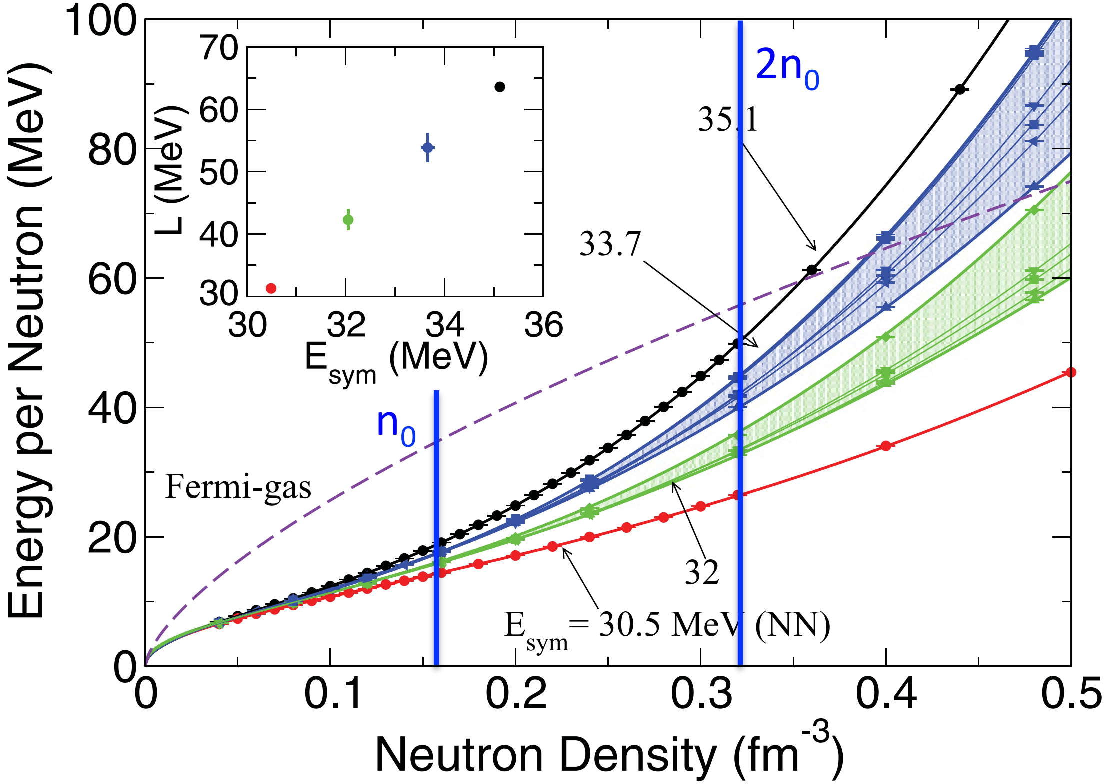
➡ $35.6\ \text{MeV} \leqslant S_0 \leqslant 37.8\ \text{MeV}$





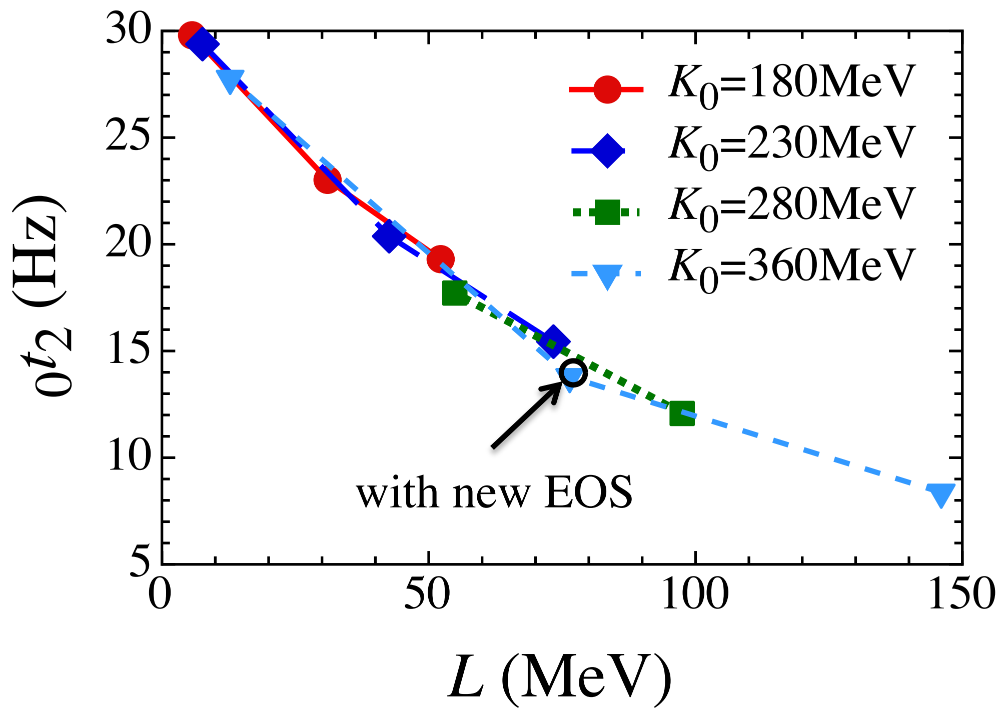
three-nucleon interactions

- for $\rho \lesssim 2\rho_0$, the uncertainty from three-nucleon interactions in EOS is not so relevant (Gandolfi+ 2012).



comparing with other EOS

- new EOS
  - 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 1990; Strohmayer+ 1991

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

- including effect of electron screening
  - Horowitz & Hughto 2008 : 10% reduction
  - Kobyakov & Pethick 2013

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

effect of electron screening

  - ~11.7% reduction for $Z = 40$
- phonon contribution is much smaller (Baiko 2012)

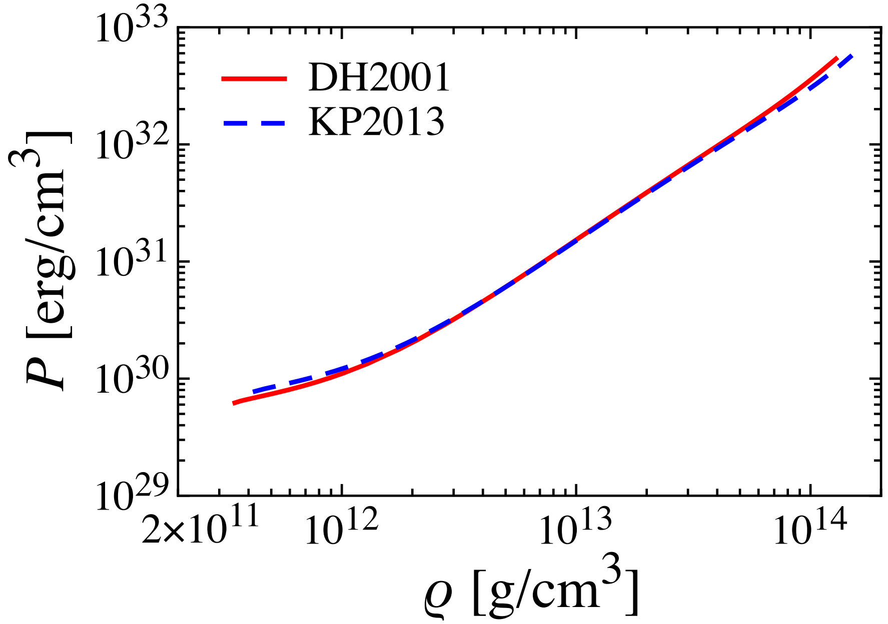
adopted EOS

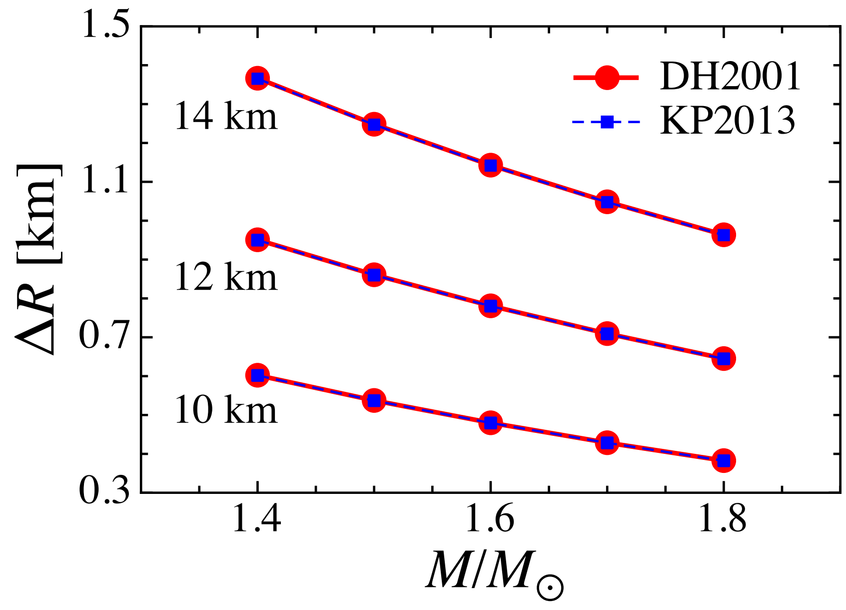
- outer crust
  - Haensel & Pichon 1994
- inner crust
  - Kobyakov & Pethick 2013 based on Lattimer & Swesty 1991
  - Douchin & Haensel 2001
  - compressible liquid drop model (CLDM)

	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

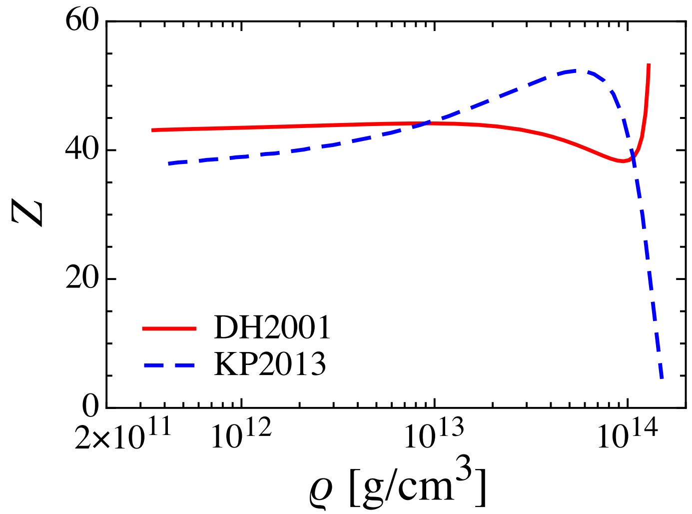
- quite difficult to distinguish the difference in crust thickness with DH2001 and with KP2013

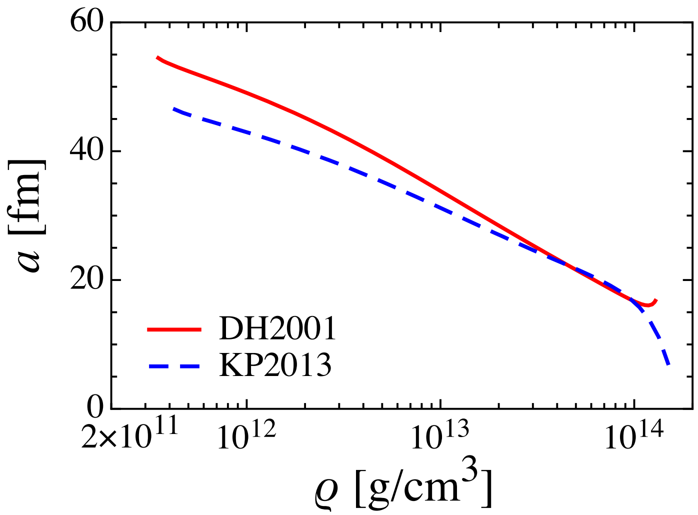




other properties

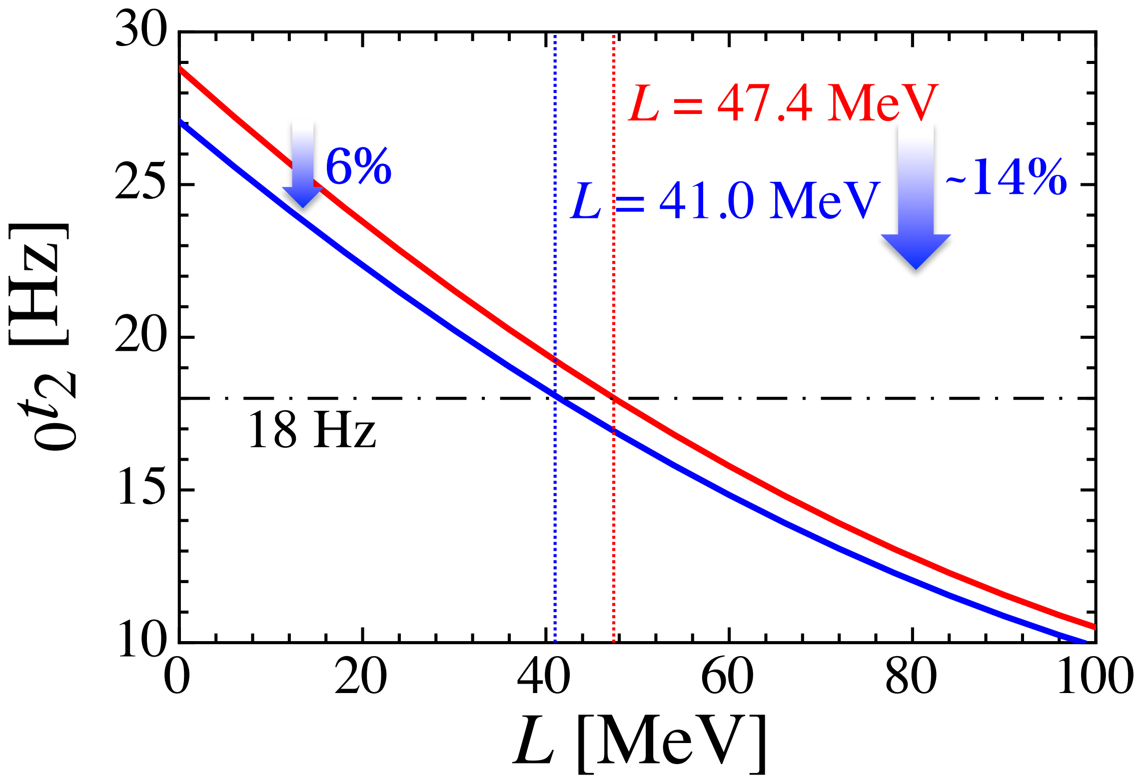
- charge depends strongly on the EOS at the crust basis
- radius of WS cell also depends on the EOS





constraint on L

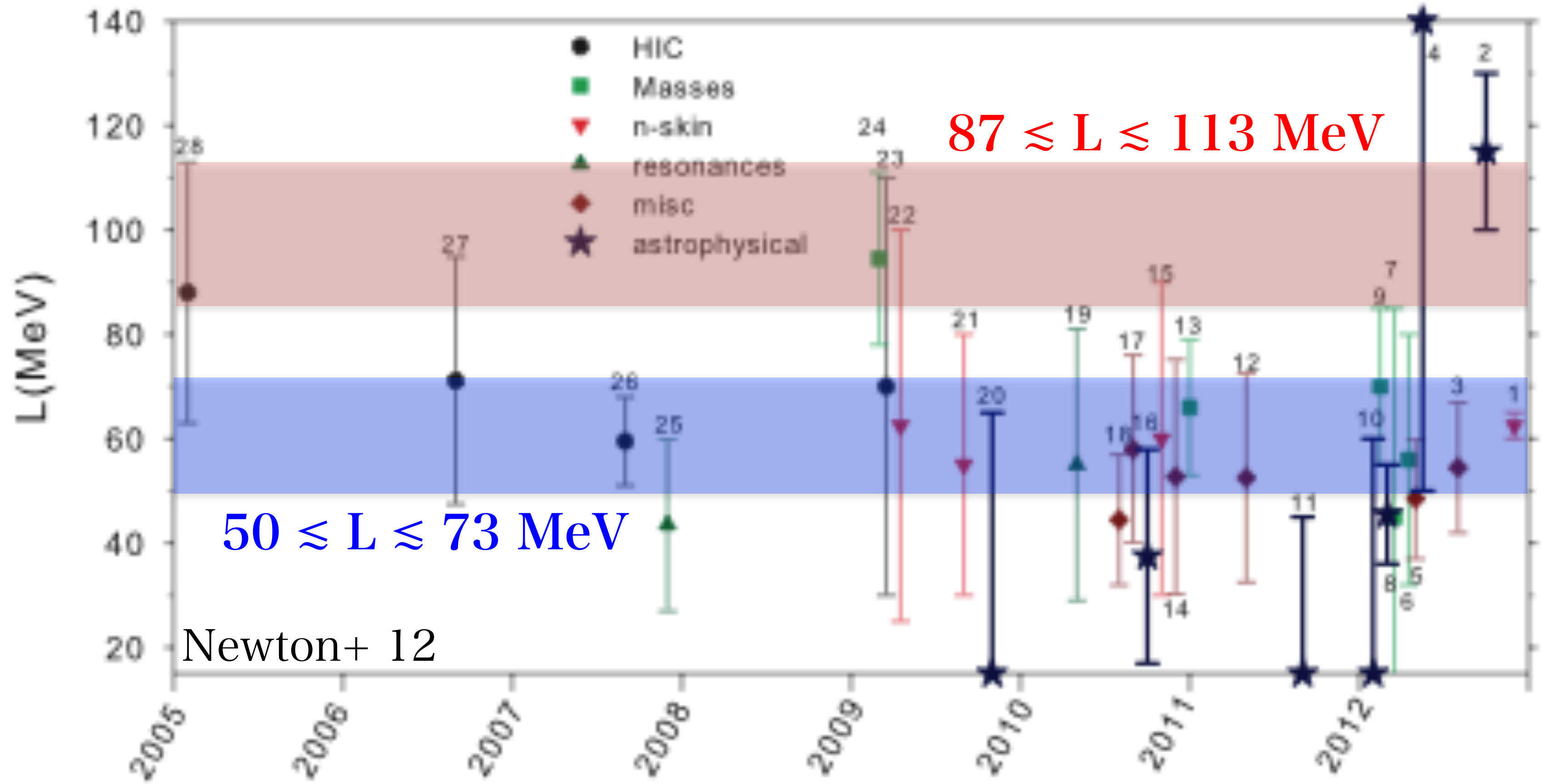
- due to the electron screening effect, constraint of L shifts ~14% smaller value



$L \gtrsim 47.4$ 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 (Sotani 14)

- 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