Possibility to restrict on neutron star matter by using asteroseismology

Hajime Sotani (YITP)

K. Nakazato, K. Iida, & K. Oyamatsu

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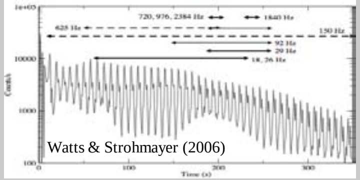
QPOs in giant flares

Recent observations of the quasi-periodic oscillations (QPOs) in giant flares from soft gamma repeaters (SGRs) suggest that long-awaited evidence for the neutron star (NS) oscillations. The QPOs with frequencies in the range from tens Hz up to kHz have been discovered. Many theoretical attempts to explain the observed evidences have been done...



Magnetars

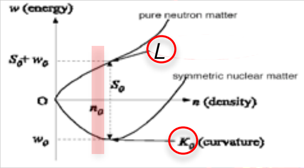
SGRs are promising candidate of magnetar, which is a NS with strong magnetic field, such as $B \gtrsim 10^{14}$G. Since interior region of NS is quite high density, NS is suitable laboratory to see the properties for high density region.

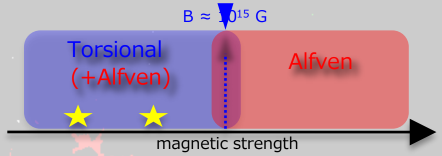
Considering the magnetic field strength of central object in SGRs, observed QPOs could be due to the crust torsional oscillations.

Comparing QPOs with frequencies of crust torsional oscillations, one can make a constraint on the crust EOS parameters. (asteroseismology)

Crust EOS

We adopt the crust EOS suggested by Oyamatsu & Iida (03,07), which is based on the extended Thomas-Fermi theory. As in their article, we adopt the parameter range $0 < L < 160$ MeV & $180 \leq K_0 \leq 360$ MeV.



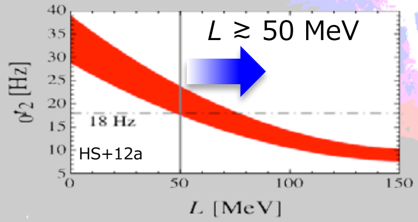


Constraint 1

We find that the fundamental frequencies are independent of the incompressibility K_0.

In order to explain the observed QPOs with the crust torsional oscillations, at least, the expected lowest frequency, ${}_0t_2$, should be lower than the lowest observed QPO frequency, 18Hz.

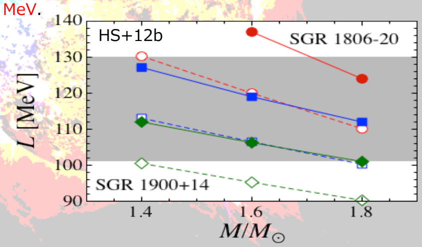
Concluding that we can make a constraint on L as $L \gtrsim 50$ MeV.



Constraint 2

Taking into account the effect of neutron superfluidity in the inner crust, the effective enthalpy should reduce and the shear velocity increases. As a result, the frequencies of torsional oscillations also increases, because the frequencies are proportional to shear velocity.

Comparing the observed QPOs with torsional modes, we can get the constraint on L as $100 \text{ MeV} \lesssim L \lesssim 130$ MeV.



astronomical observations

+

calculate torsional oscillations

constraint on L

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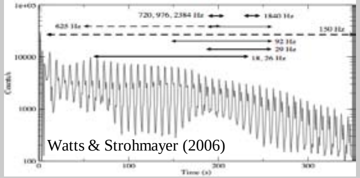

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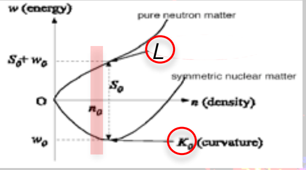

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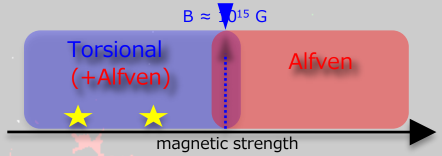

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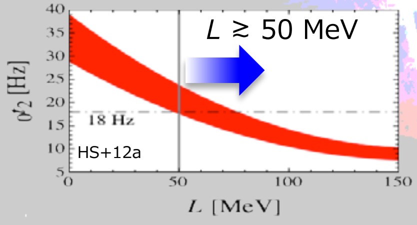

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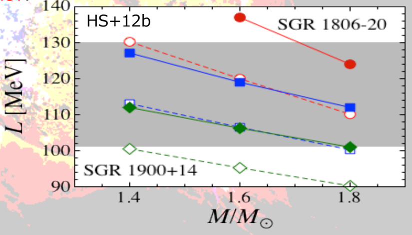
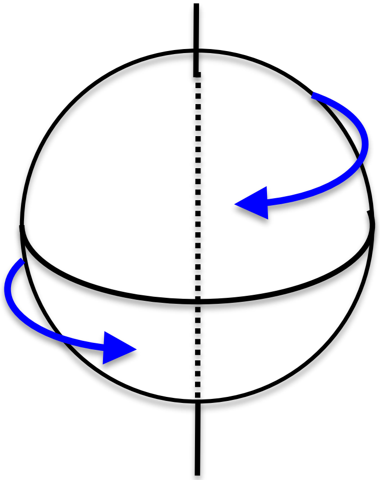
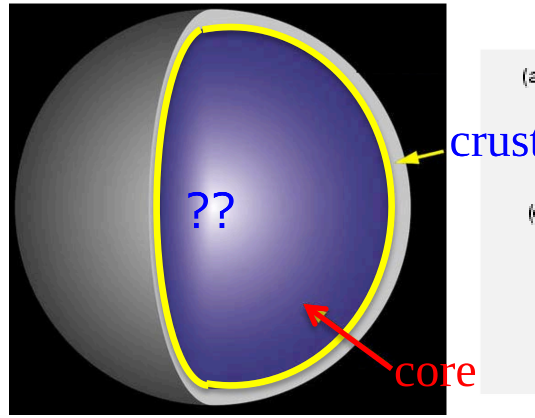


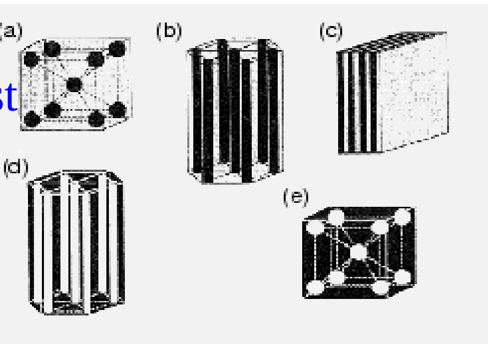


Neutron Stars

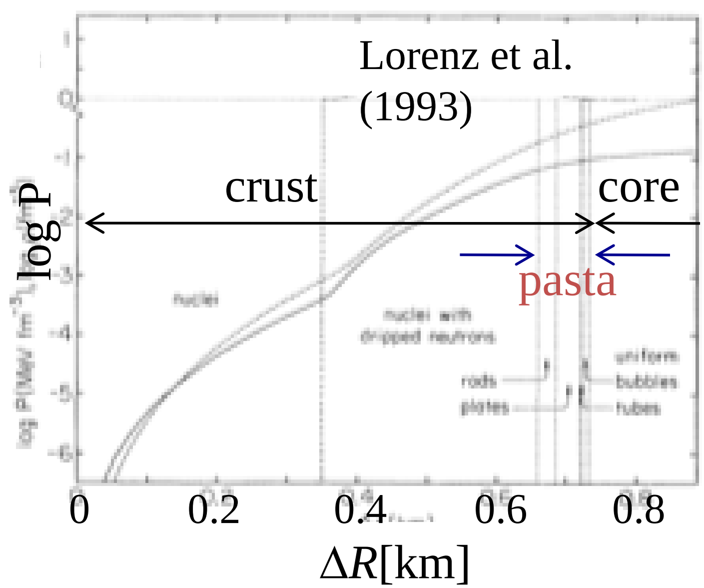
- Structure of NS
  - solid layer (crust)
  - nonuniform structure (pasta)
  - fluid core (uniform matter)
- Thickness of pasta ~ 70m
- Determination of EOS for high density region is quite difficult on Earth
- Constraint on EOS via observations of NS
  - stellar mass and radius
  - stellar oscillations (& emitted GWs)

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





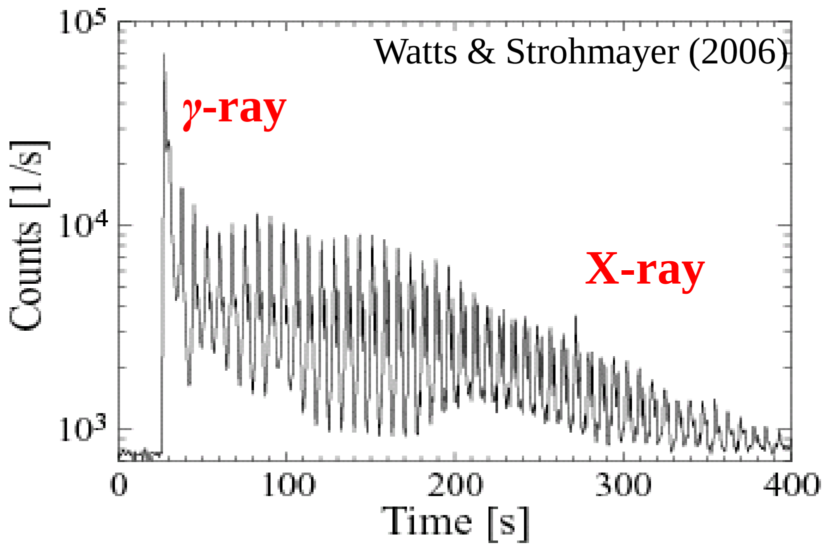
Oyamatsu (1993)

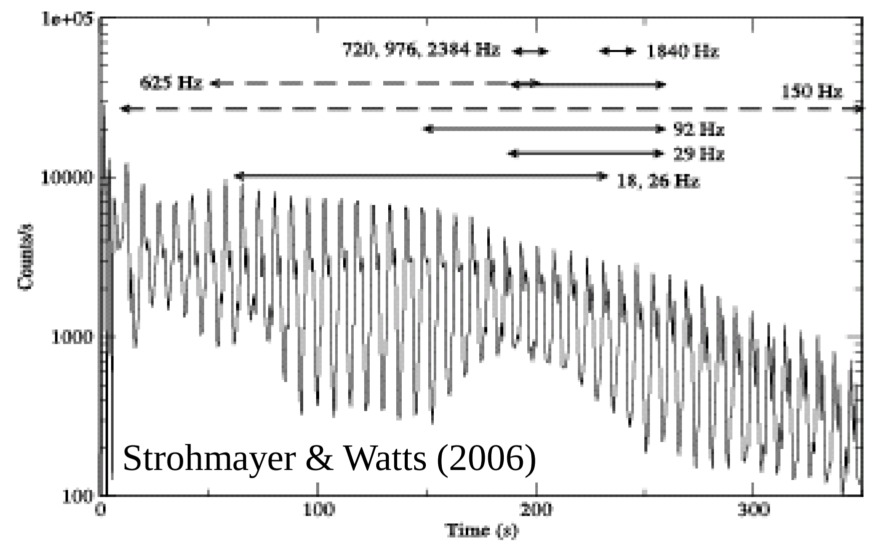


QPOs in giant flares 1

- Magnetars : $B > 10^{14}$G
- Candidates of magentars
  - Anomalous X-ray pulsars (AXPs)
  - Soft gamma repeaters (SGRs)

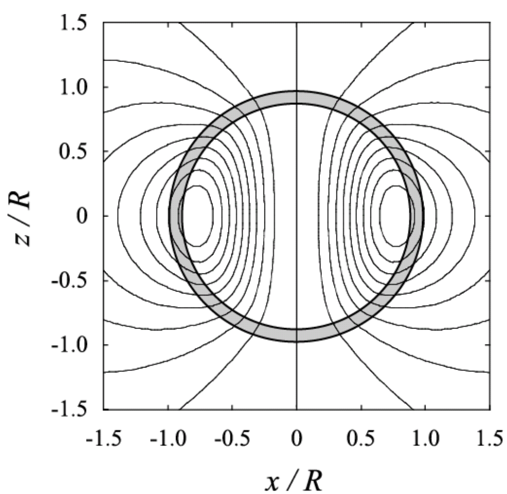
    ~ sporadic emission with X and γ-rays (~ 10^{41} erg/s)
- <u>Giant flares</u> from SGRs (10^{44}-10^{46} ergs/s)
  - SGR 0526−66 in March.5.1979
  - SGR 1900+14 in August.27.1998
  - SGR 1806−20 in December.27.2004

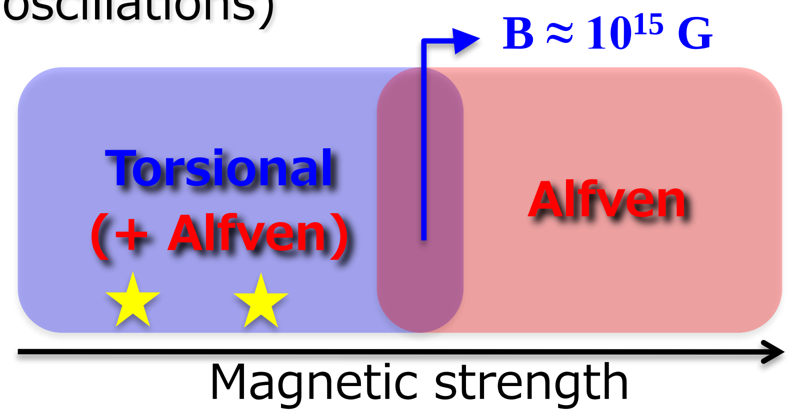




QPOs in giant flares 2

- Afterglow of giant flares → quasi periodic oscillations(QPOs)
  → Barat et.al. (1983); Israel et.al. (2005);
  Watts & Strohmayer (2005, 2006)
  - SGR 0526-66 : 23ms (43Hz), B ~ 4 ×10^{14}G
  - SGR 1900+14 : B > 4 ×10^{14}G, **28, 54, 84, 155 Hz**
  - SGR 1806−20 : B ~ 8 ×10^{14}G, L ~ 10^{46} ergs/s
    18, 26, 30, 92.5, 150, 626.5, 1837 Hz + something ?
- Theoretical attempts to explain···
  - torsional oscillations in neutron star crust.
  - magnetic oscillations (Alfven oscillations)





c.f.) fundamental modes of NS is order of kHz

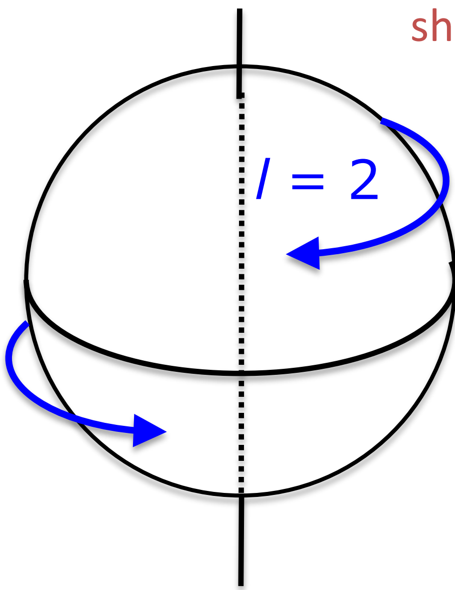
Torsional oscillations in curst

- Frequencies of torsional oscillations:
  - For Newtonian star; Hansen & Cioffi (1980), McDermott et al. (1998), Carroll et al. (1986), Storhmayer (1991), ⋯

→ in Newtonian case,

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

shear speed: v_s



- incompressible
- without stellar deformation
- without density deviation

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

v_s^{-2}

EOS for crust region

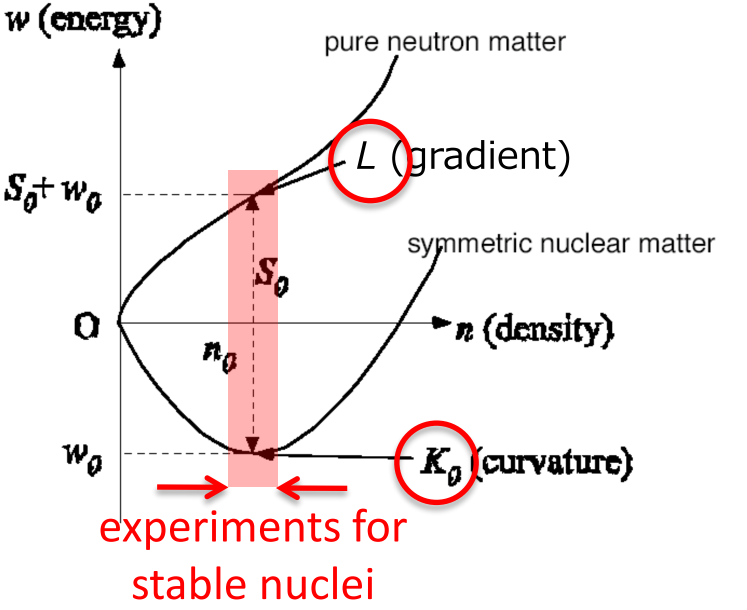
Oyamatsu & Iida (2003), (2007)

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

incompressibility — symmetry parameter

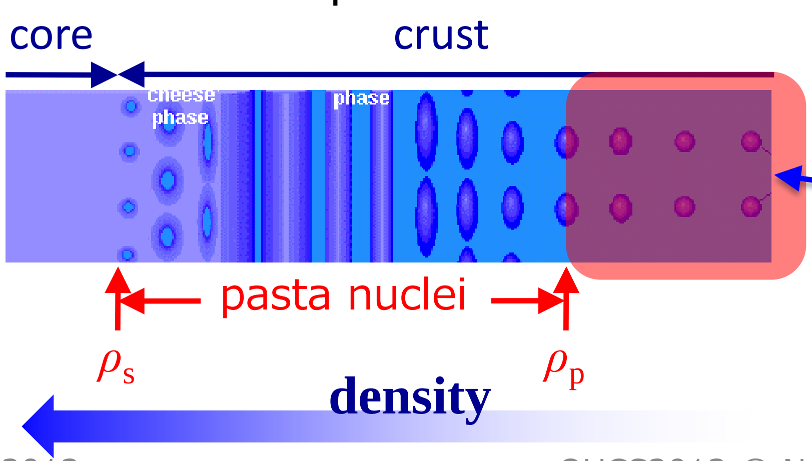
$$w = w_0 + \frac{K_0}{18n_0^2}(n - n_0)^2 + \left[S_0 + \frac{L}{3n_0}(n - n_0)\right]\alpha^2$$

- Calculations of the optimal density distribution of stable nuclei within Thomas Fermi theory.
  - Obtain the value of w_0, n_0, and S_0 for given L & K_0 by fitting Z, mass, & charge radius that can be calculated from the optimal density distribution to the empirical data for stable nuclei.
  - To constrain in L & K_0 with experiments on Earth is quite difficult.



What we do

- EOS for core region is still uncertain.
- 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 (2003), (2007))
    $\rightarrow$ For $L \gtrsim$ 100MeV, pasta structure almost disappears
- In crust region, torsional oscillations are calculated.
  - considering the shear only in spherical nuclei.
  - frequency of fundamental oscillation $\propto v_s$ ($v_s^2 \sim \mu/H$)
  - calculated frequencies could be lower limit



for bcc lattice

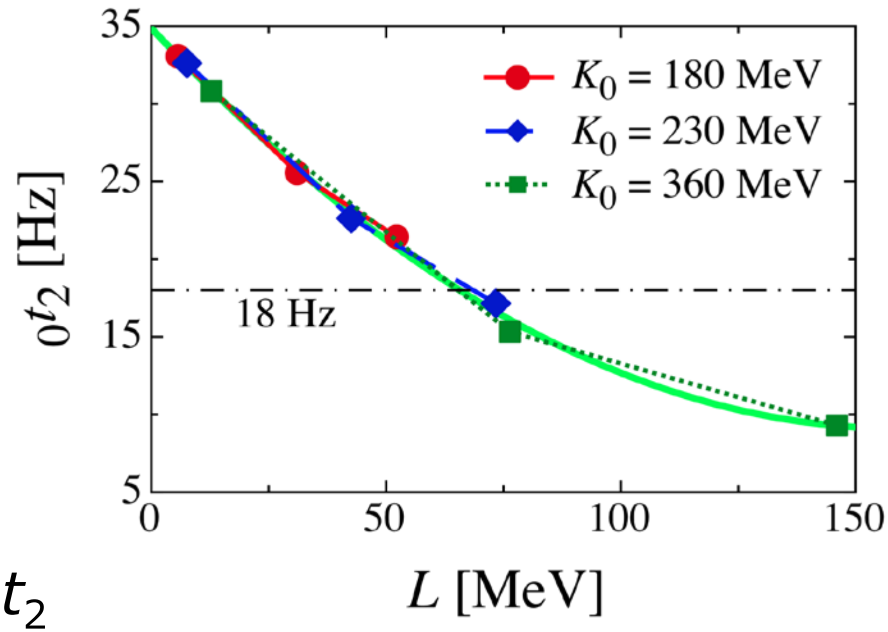
$$\mu = 0.1194 \frac{n_i (Ze)^2}{a}$$

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

${}_0t_2$ without superfluidity

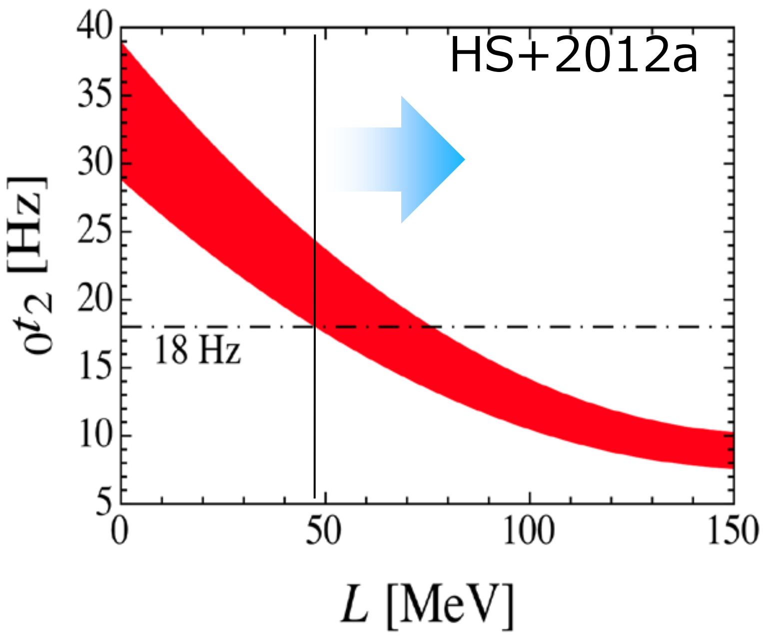
HS+2012a

- For M=1.4$M_\odot$ & R=12km, calculated frequencies ${}_0t_2$
- ${}_0t_2$ is almost independent of the value of K_0
- For R=10~14 km and $M/M_\odot$=1.4~1.8, similar dependence on K_0
- One can write fitting line
- Focus on L dependence of ${}_0t_2$
- ${}_0t_2$ becomes smaller with larger R and M.



Constraint on L

- For R=10km~14km & M/M$_\odot$=1.4~1.8, ${}_0t_2$ are calculated
- Assuming that the observed QPOs would come from torsional oscillations
- ${}_0t_2$ is the smallest frequency among a lot of torsional oscillations
  - ${}_0t_2$ should be equal to or smaller than the smallest observed QPOs frequency



- Consequently, $L \gtrsim 47.6$ MeV.
  - For $L \gtrsim 47.6$ MeV, pasta region could be very narrow
  - Modification due to the pasta effect should be small
  - This is first constraint in the symmetry parameter with astronomical observations

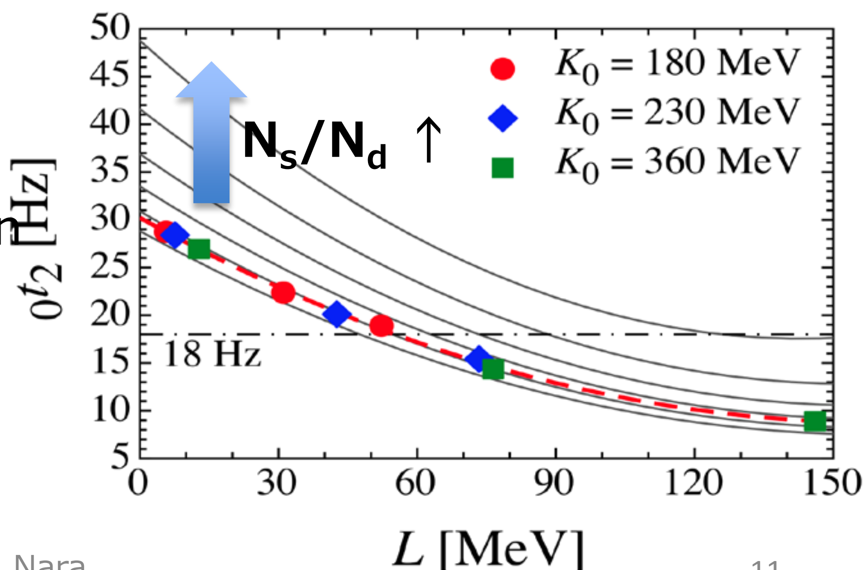
Effect of superfluidity

HS+2012b

- For $\rho \gtrsim 4 \times 10^{11}$ g cm^{-3}, neutron could drip from nuclei
- Some of dripped neutron play a role as superfluid
- Effective enthalpy affecting on the shear oscillations could be reduced
  - shear speed ($v_s^2 \sim \mu/H$) increases due to the effect of superfluidity

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

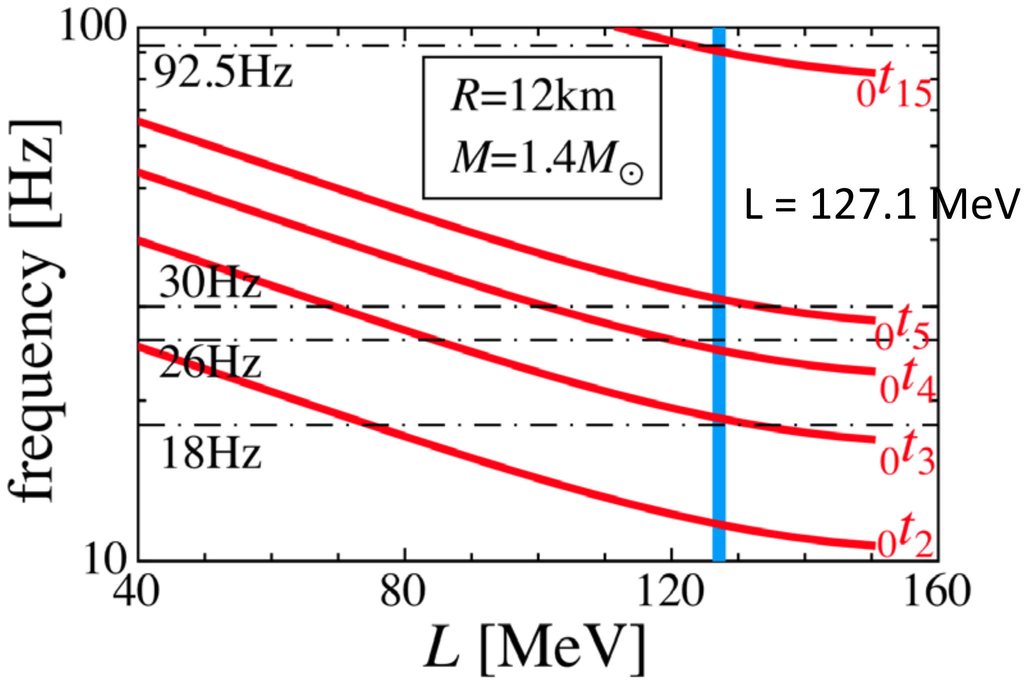
- ${}_0t_l$ could also increase due to the effect of superfluidity
- While, the fraction of superfluid neutron in dripped neutron is unknown…
  - Chamel (2012): superfluid neutron are not so much (~10-30%?)
- ${}_0t_l$ with using a parameter of N_s/N_d for R=14km & M=1.8$M_\odot$



Comparison with QPO frequencies

HS+2012b

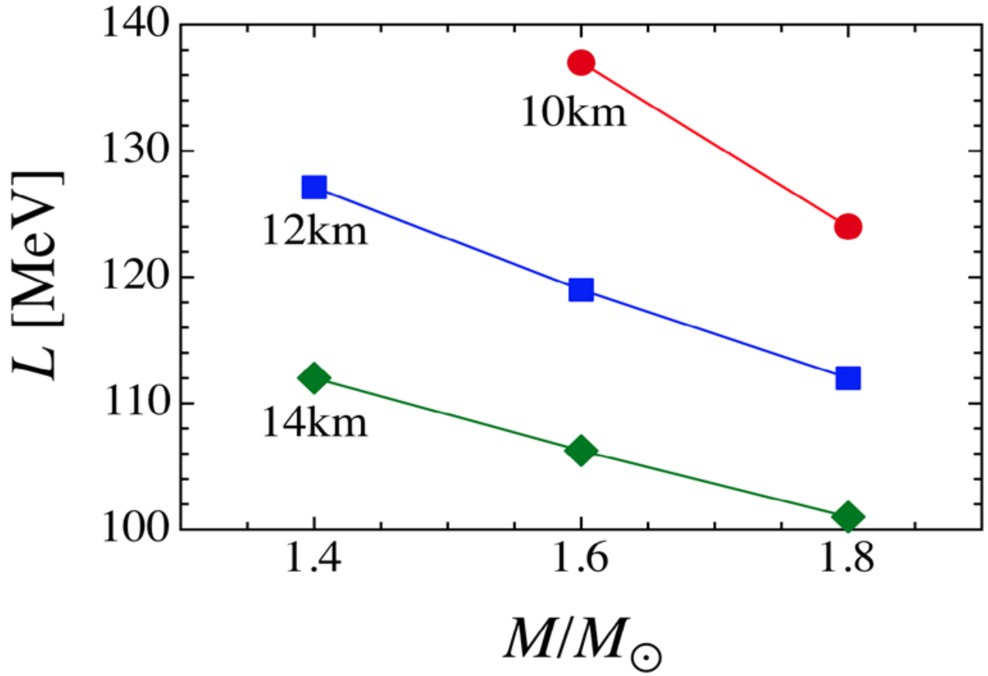
- Comparison of frequencies of torsional oscillations with the QPO frequencies observed in SGR 1806-20



- less than 5% accuracy

expected values of *L* HS+2012b

- Comparison with the observations in SGR 1806-20
  - independently of the stellar models, we can get a constraint on *L* as 100 MeV ≲ *L* ≲ 140 MeV.
  - with the help of the observation of (*M*,*R*) of oscillating star, one may make a severer constraint in the value of *L*.



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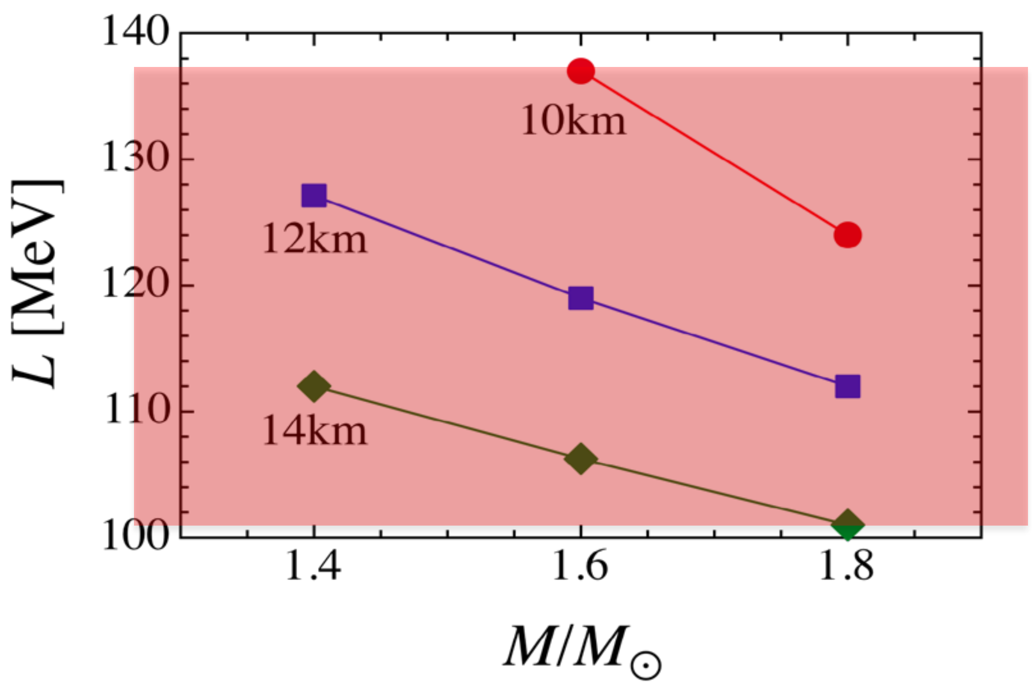
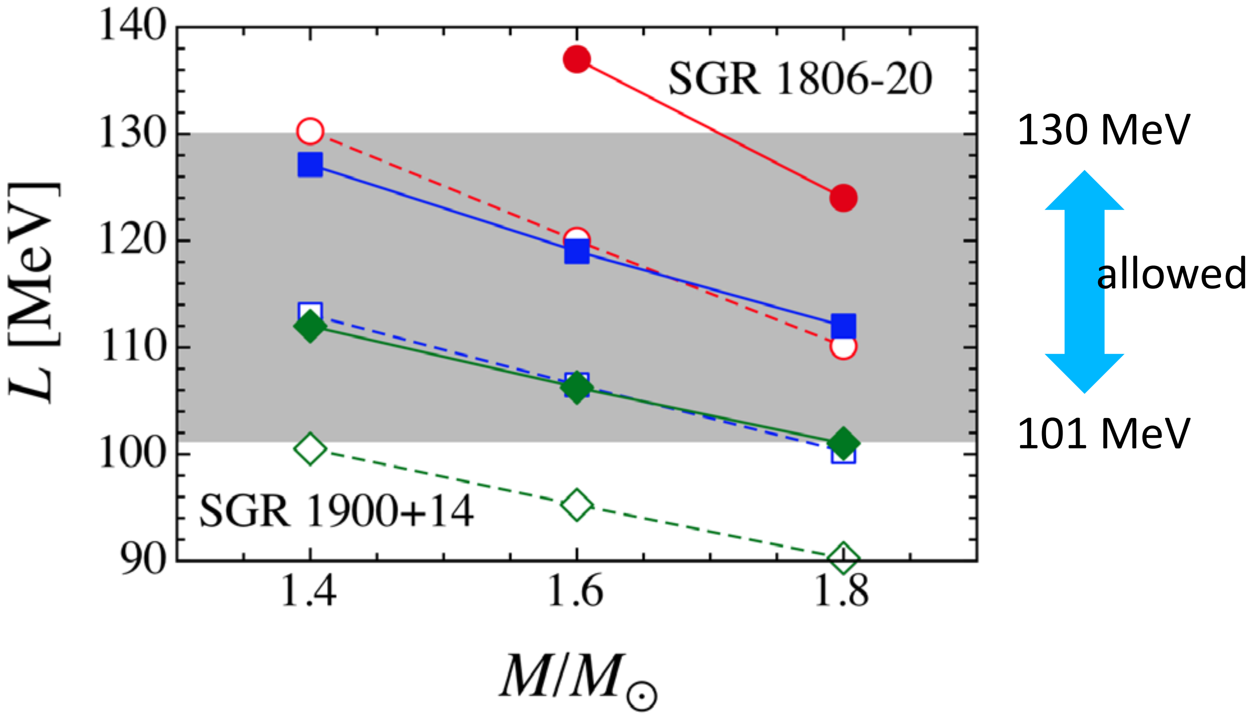


allowed region from SGR 1806-20 observation.

Allowed values of L

HS+2012b

- Comparisons with the both observations in SGR 1806-20 & SGR 1900+14



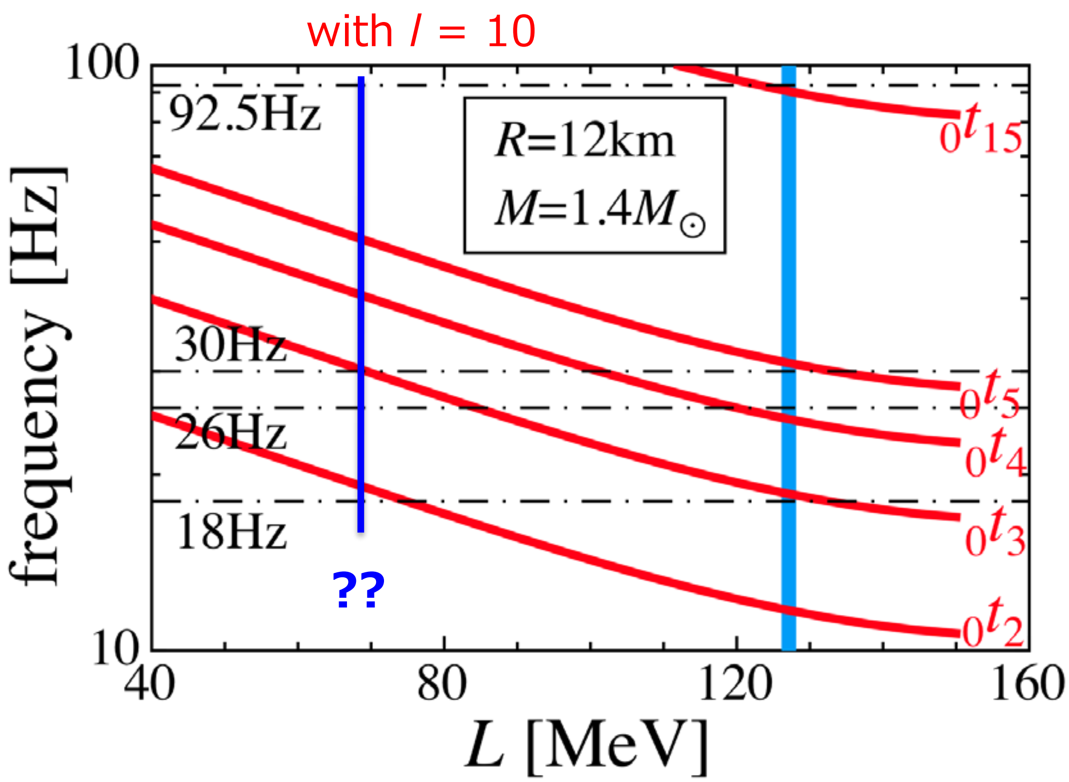
Conclusion

- QPOs are found in afterglow of giant flares
- We examined the frequencies of torsional oscillations as varying the stellar and EOS parameters with/without the *effect of superfluidity*.
- Fundamental frequencies are almost independent of the incompressibility K_0, depend only on L.
- Assuming the QPOs are associated with crustal oscillations, we can make a constraint on EOS as
  - $L \lesssim 50$ MeV
  - 100 MeV $\lesssim L \lesssim$ 130 MeV
- We are successful to constrain L with the astronomical observations.
  - This is completely different approach from the experiments on Earth

- We are hoping to observe nest giant flare & QPOs
  - SGR 0526−66 in March.5.1979
  - SGR 1900+14 in August.27.1998
  - SGR 1806−20 in December.27.2004
- Next observation might be possible soon...

another possibility

- Otherwise, to realize 60 MeV ≲ L ≲ 80 MeV,
  one needs to consider another oscillation mechanism

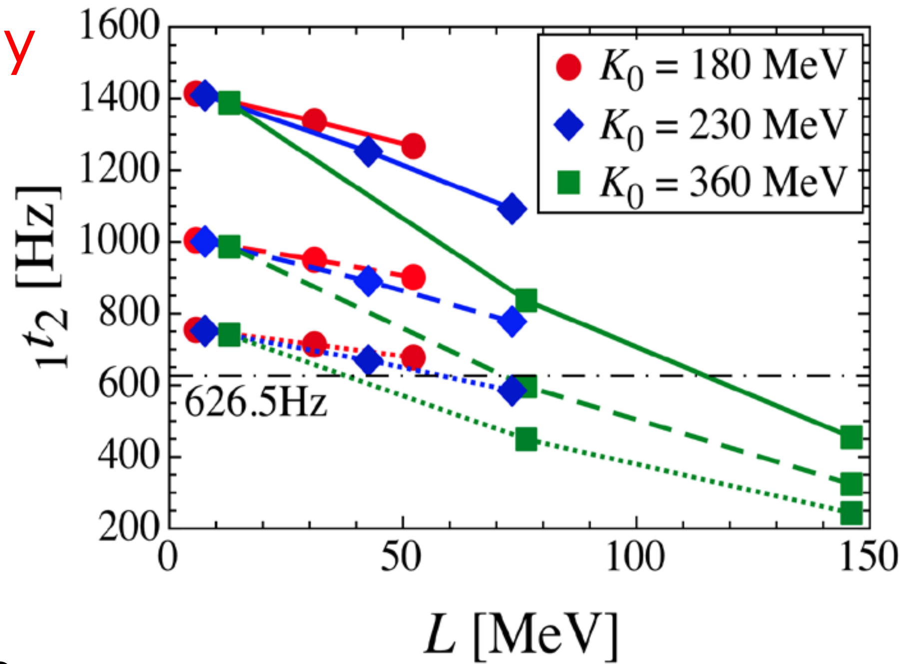


Outlook

- Examine overtones of crust torsional oscillations
- Consider the more realistic μ
  - effect of nonuniform nuclear (pasta) structure
- Take into account the ratio of N_s/N_d
- γ-ray emission mechanism
- Estimate the emitted GWs

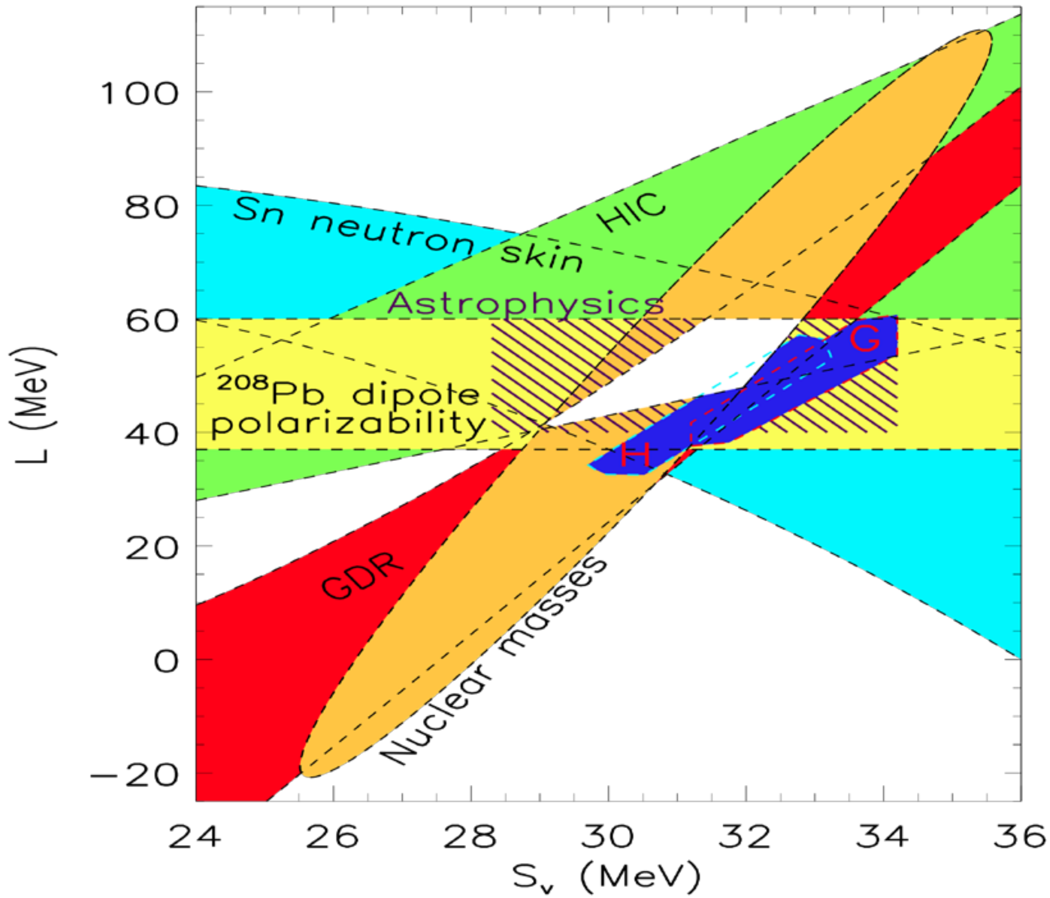
1st overtone ${}_1t_2$

- For M=1.4$M_\odot$& R=10, 12, 14 km, ${}_1t_2$ are calculated
- Unlike ${}_0t_2$, ${}_1t_2$ depends not only on L, but also K_0 & R.
- Dependence of R :
  - ${}_0t_2 \propto 1/\Delta R$
  - $\Delta R \propto R^2$ (Ravenhall & Pethick (1994))
- Dependence of K_0 :
  - Dependence of K_0 to determine the density of pasta phase?
  - Depend on shear in pasta phase?
- now making an analysis···



Compared with other constraints

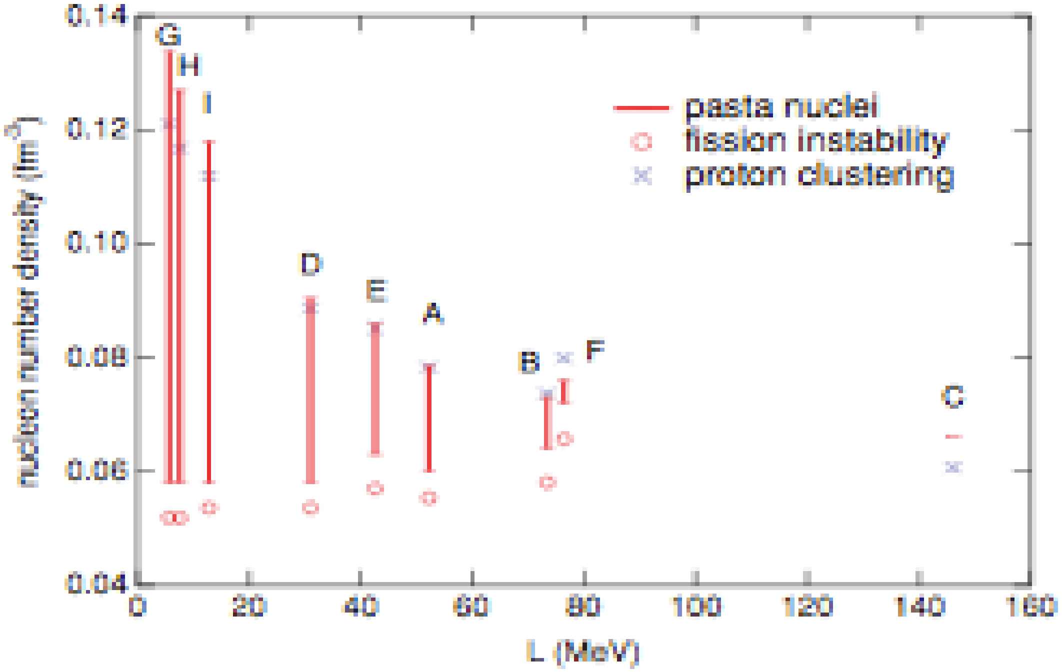
- Lattimer & Lim (2012)



Pasta structure

Oyamatsu & Iida (2003), (2007)

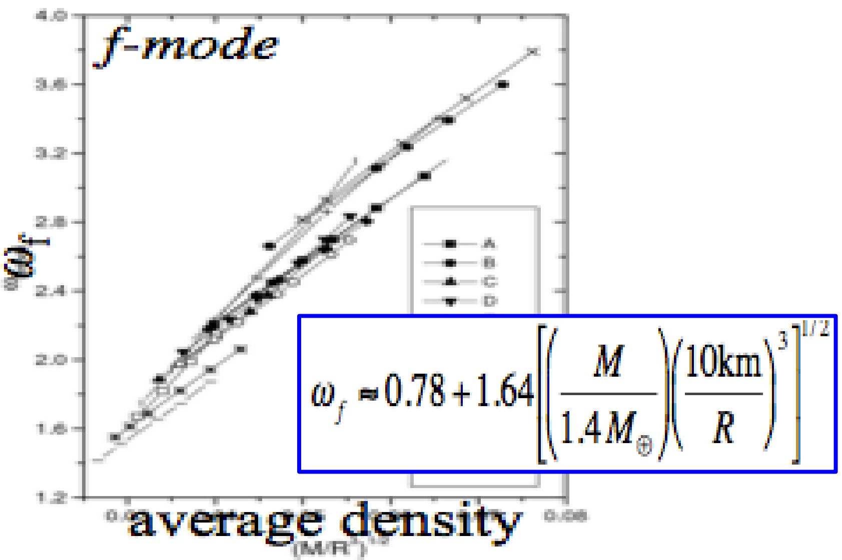
- Adopt the values of (L , K_0), with which can be reproduced the mass and radius data for stable.
  - 0 < L < 160MeV, 180MeV ≦ K_0 ≦ 360MeV



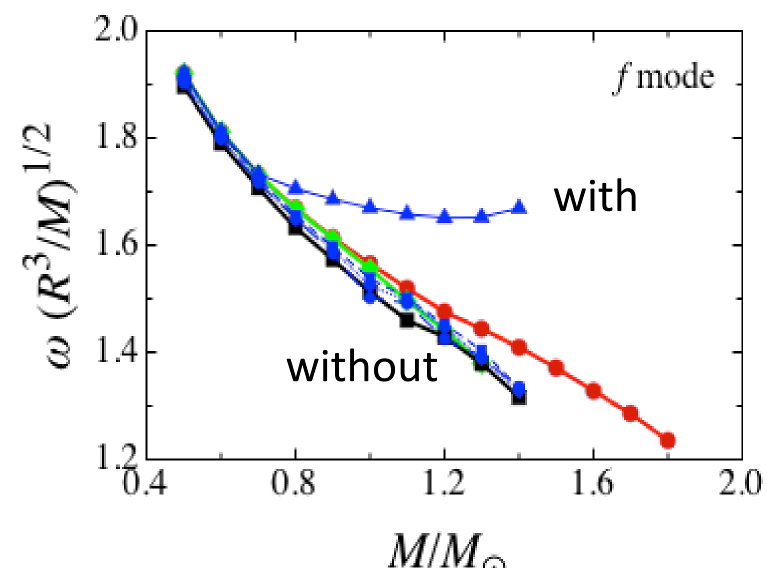
- Whether pasta phase exists or not depends strongly on L.
- For L ≳ 100MeV, pasta structure almost disappears.

Asteroseismology

- Via the observations of stellar oscillations
  → One can get the interior information (**asteroseismology**)
  e.g., helioseismology for Sun
- With this technique, the possibilities to get the information of NSs have been suggested.



Andersson & Kokkotas (1998)



HS+2011

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