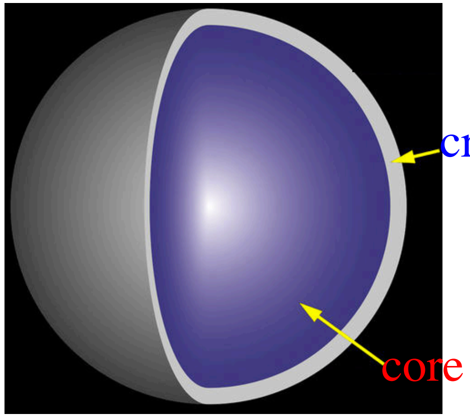
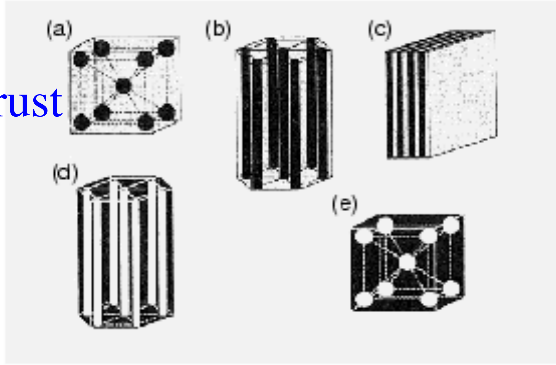
中性子星の振動と
クラスト状態方程式

祖谷 元　（国立天文台）
中里 健一郎　（東京理科大学）
飯田 圭　（高知大学）
親松 和浩　（愛知淑徳大学）

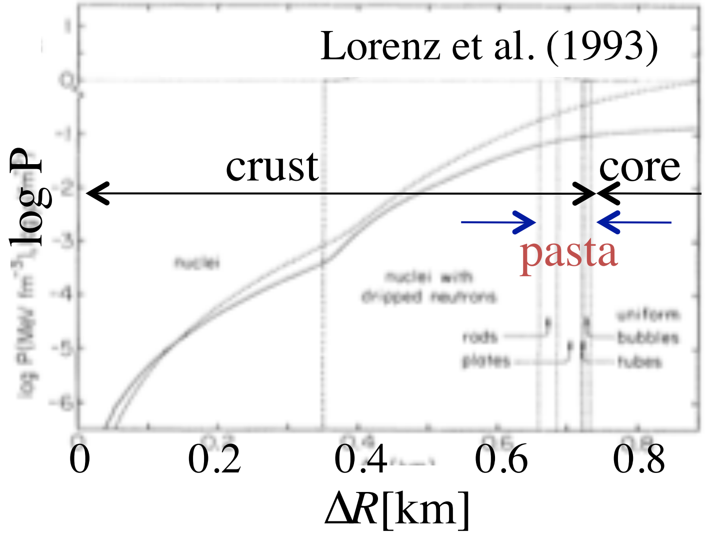
Neutron stars & asteroseismology

- Structure of NS
  - solid layer (crust)
  - nonuniform structure (pasta)
  - fluid core (uniform matter)
- Thickness of pasta ~ 100m
- 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 and emitted GWs
    "(GW) asteroseismology"
    cf.) seismology, helioseismology



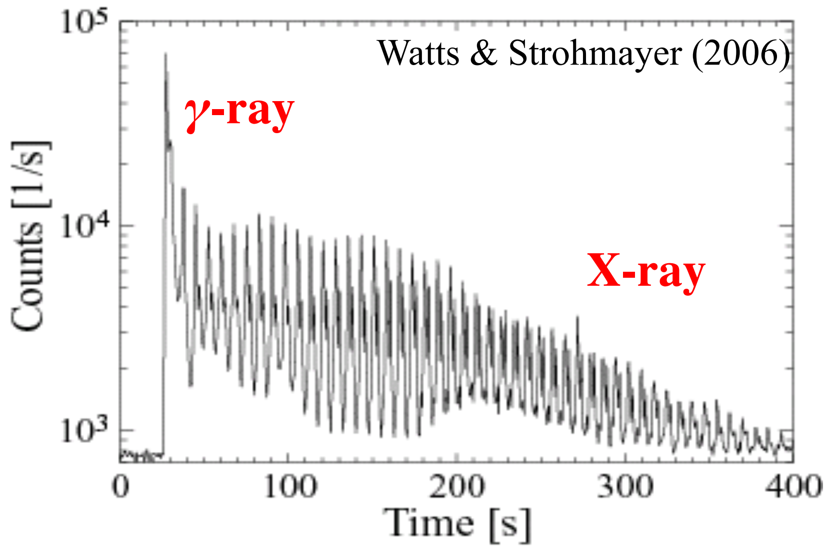


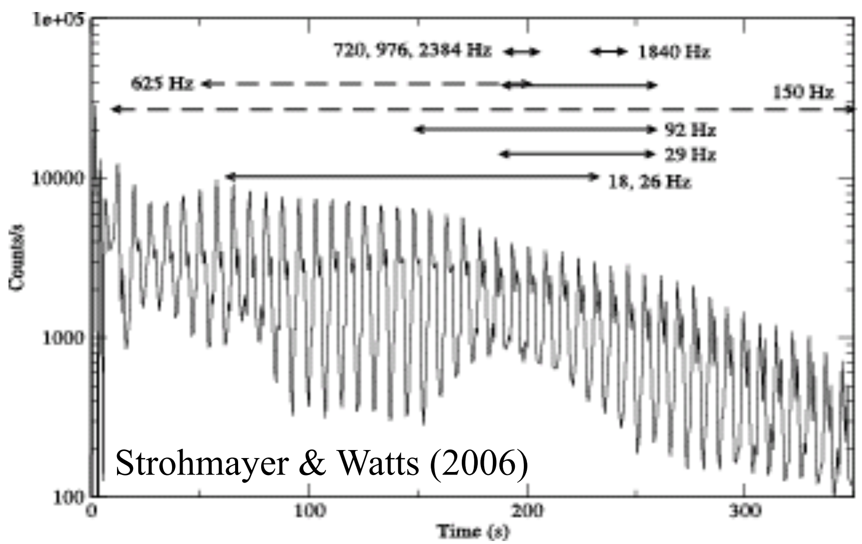
Oyamatsu (1993)



QPOs in giant flares 1

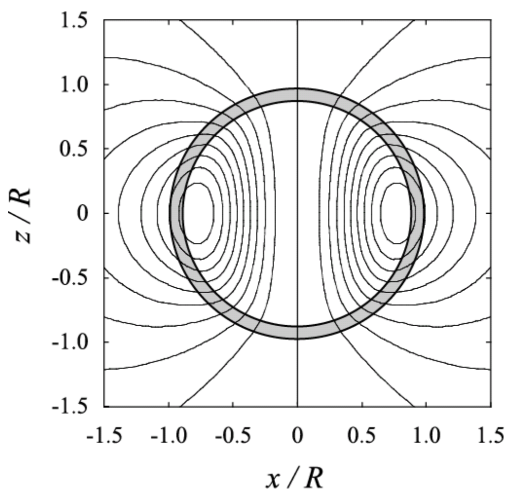
- Magnetars : $B > 10^{14}$G
- Candidates of magentars
  - Anomalous X-ray pulsars （AXPs）
  - Soft gamma repeaters（SGRs）
    ~ sporadic emission with X and γ-rays (~ 10^{41} erg/s)
- Giant flares from SGRs (10^{44}-10^{46} ergs/s)
  - SGR 0526–66 in March.5.1979
  - SGR 1900+14 in August.27.1998
  - SGR 1806–20 in December.27.2004

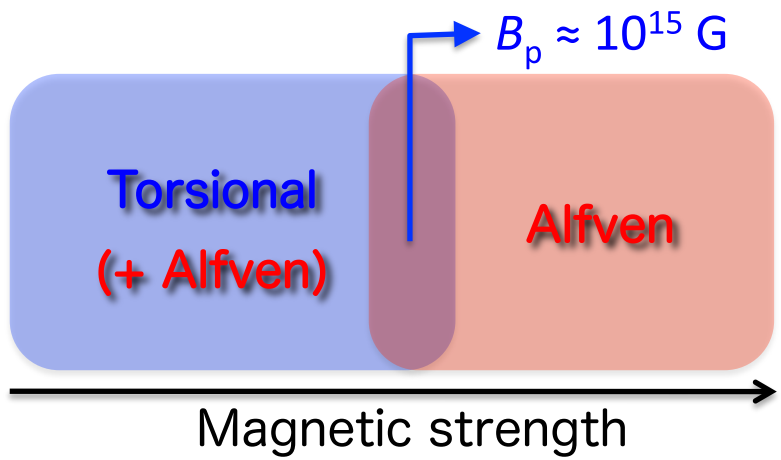




QPOs in giant flares 2

- 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 $\times 10^{14}$G
  - SGR 1900+14 : $B > 4 \times 10^{14}$G, 28, 54, 84, 155 Hz
  - SGR 1806–20 : $B \sim 8 \times 10^{14}$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)





EOS for crust region

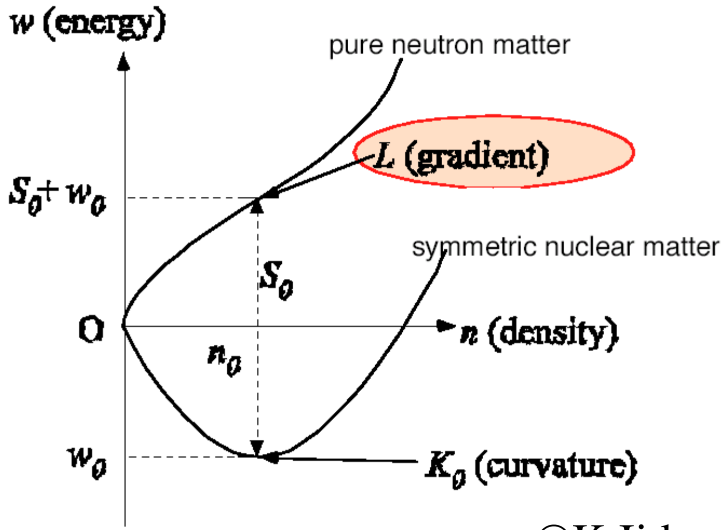
Oyamatsu & Iida (2003), (2007)

- 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 rather difficult.



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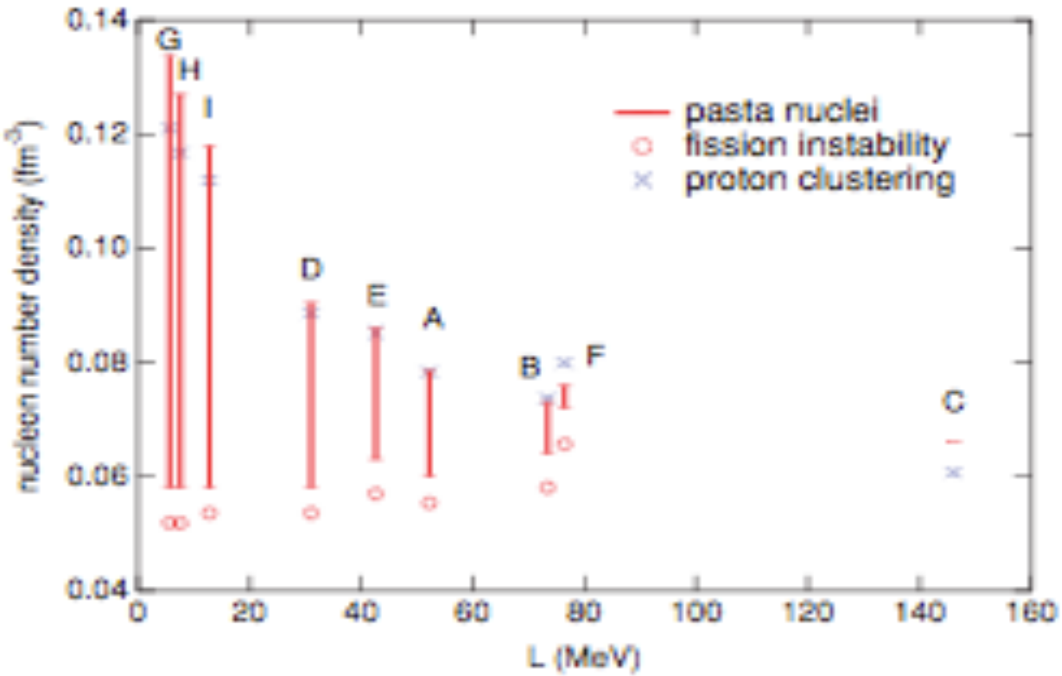
Pasta structure

Oyamatsu & Iida (2003), (2007)

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

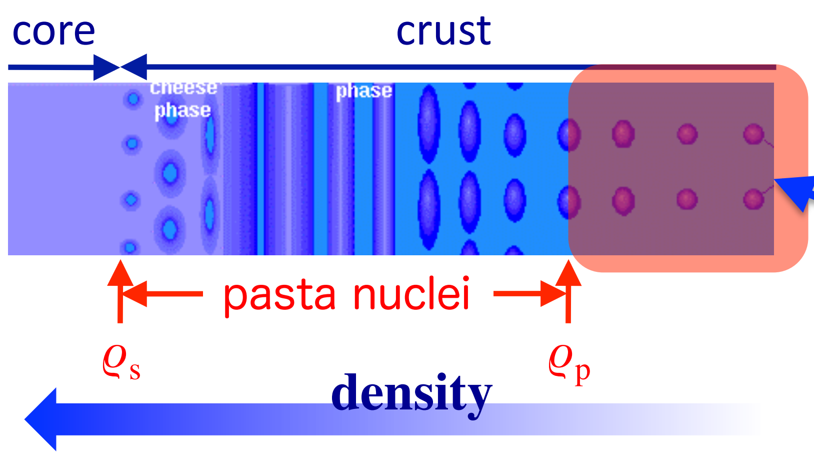


- Whether pasta phase exists or not depends strongly on L.
- For $L \gtrsim$ 100MeV, pasta structure almost disappears.

What we do

HS+(2012), HS+ submitted

- EOS for core region is still uncertain.
- To prepare the crust region, we integrate from stellar surface.
  - M, R : parameters for stellar properties
  - L, K_0 : parameters for curst EOS
- In crust region, torsional oscillations are calculated.
  - considering the shear only in spherical nuclei.
  - frequency of fundamental oscillation $\propto v_s$ ($v_s^2 \sim \mu/\rho$)
  - calculated frequencies could be lower limit



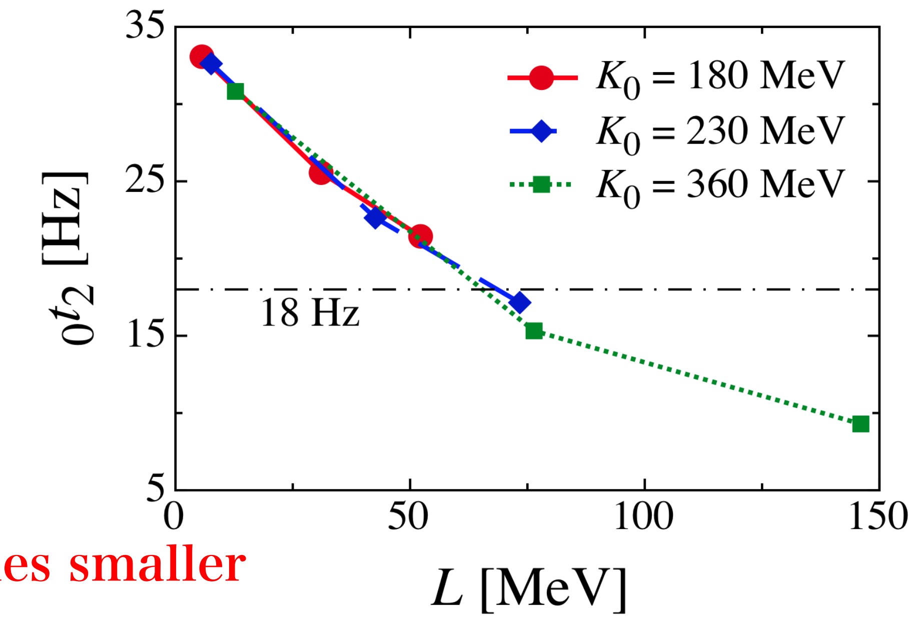
for bcc lattice

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

Strohmayer et al. (1991)

Fundamental oscillation ${}_0t_2$

- 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 of K_0
  - With larger M & R, ${}_0t_2$ becomes smaller
- One can write fitting line
- Focus on L dependence of ${}_0t_2$
  - Z decreases with respect to L
  - μ also decreases with respect to L
  - As a result, ${}_0t_2$ also decreases with respect to L



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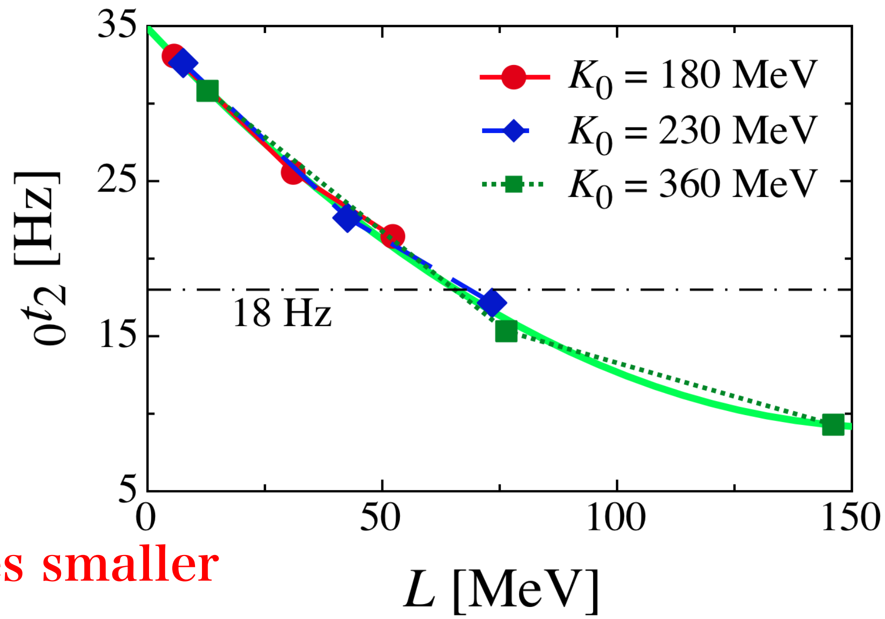

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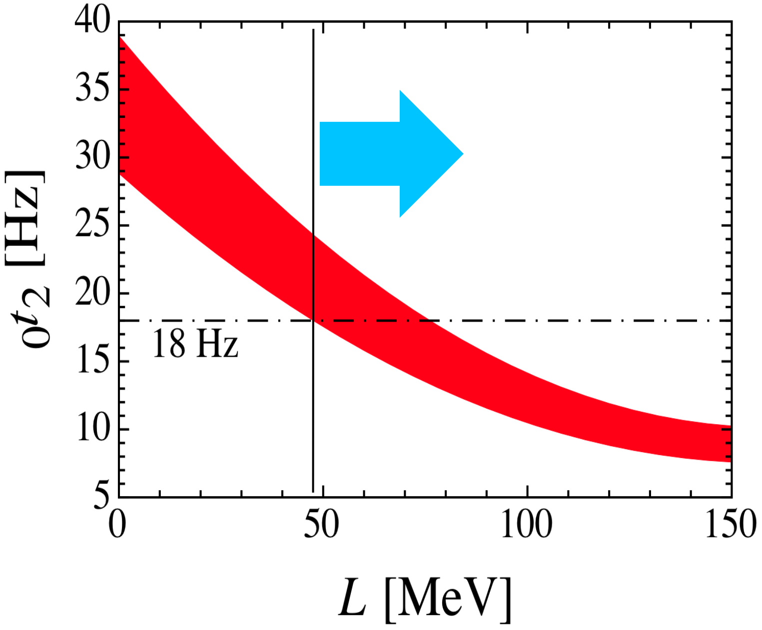
Constraint on L

- 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

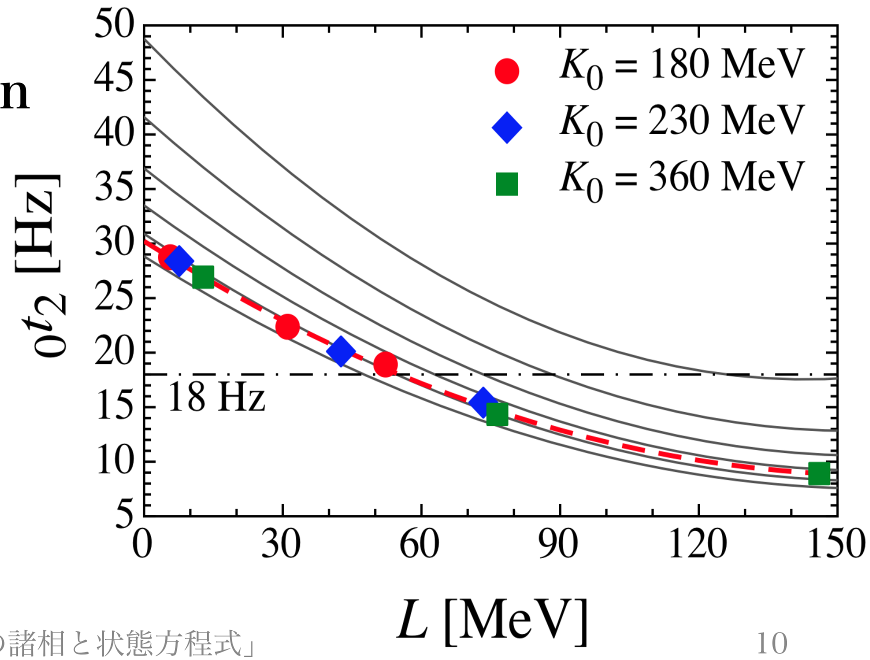


- Consequently, $L \gtrsim 47.6$ MeV.
  - For $L \gtrsim 47.6$ MeV, pasta region could be very narrow
  - Modification due to the pasta effect should be small
  - This is first constraint in the symmetry parameter with the observations of NS oscillations

Effect of superfluidity

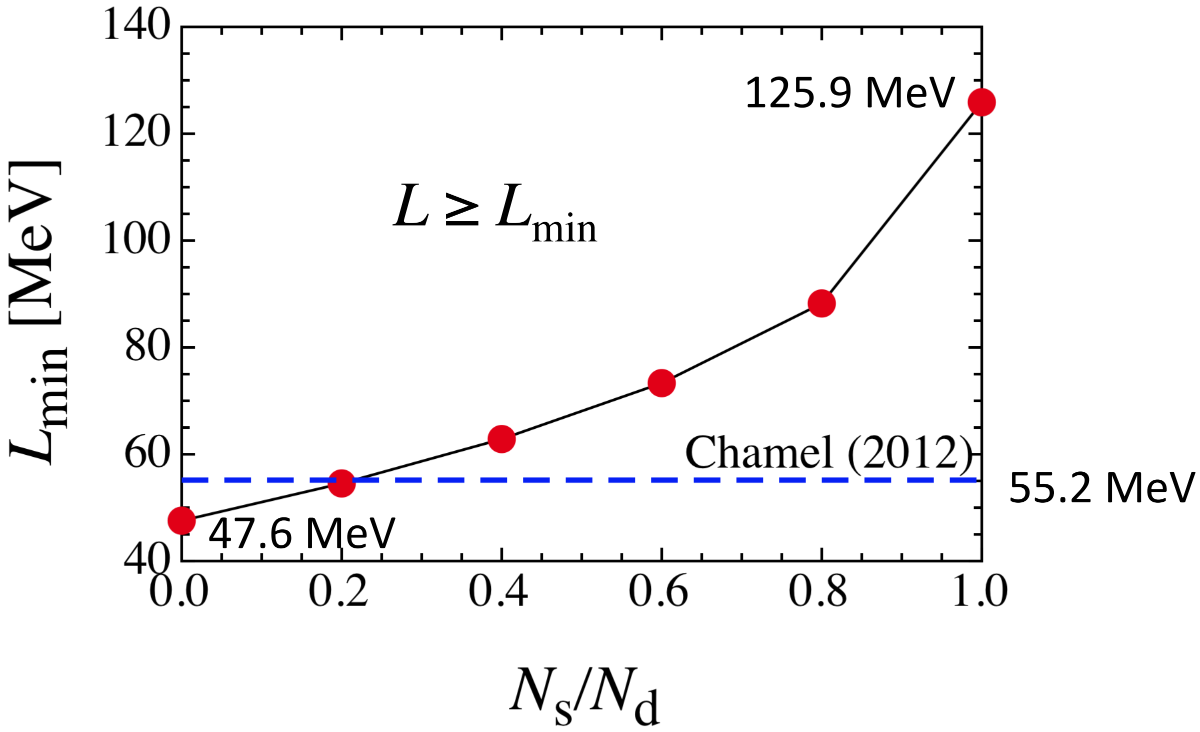
HS+ submitted

- 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
- ${}_0t_1$ could 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%?)
- We calculate ${}_0t_1$ with using a parameter of N_s/N_d for R=14km & M=1.8$M_\odot$



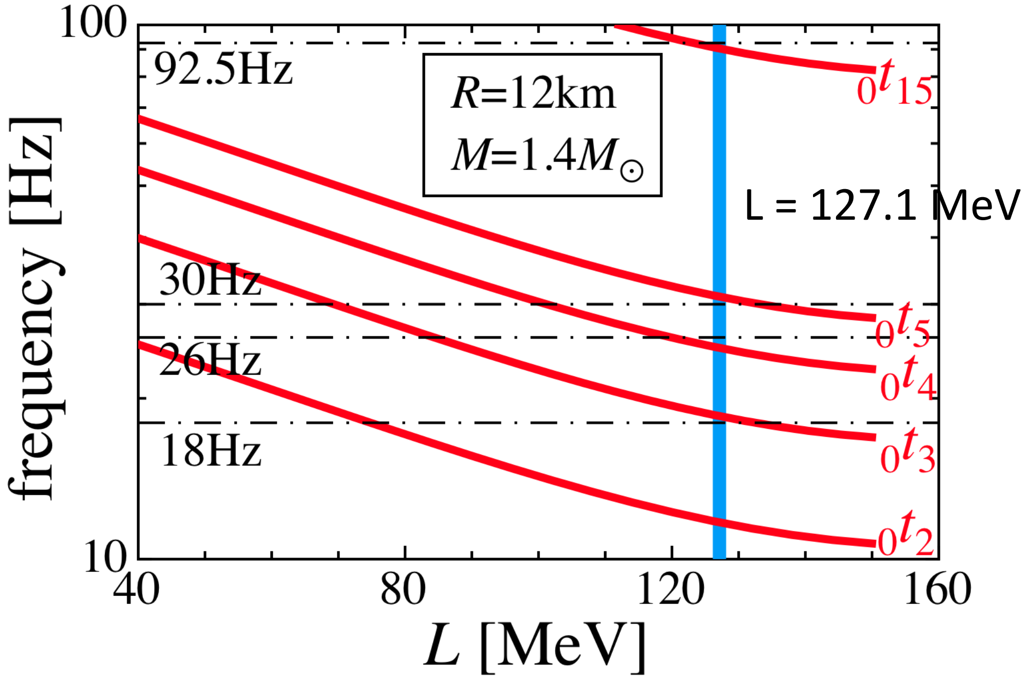
Lower limit of *L*

- The lower limit of L allowed from 18 Hz in SGR 1806-20:



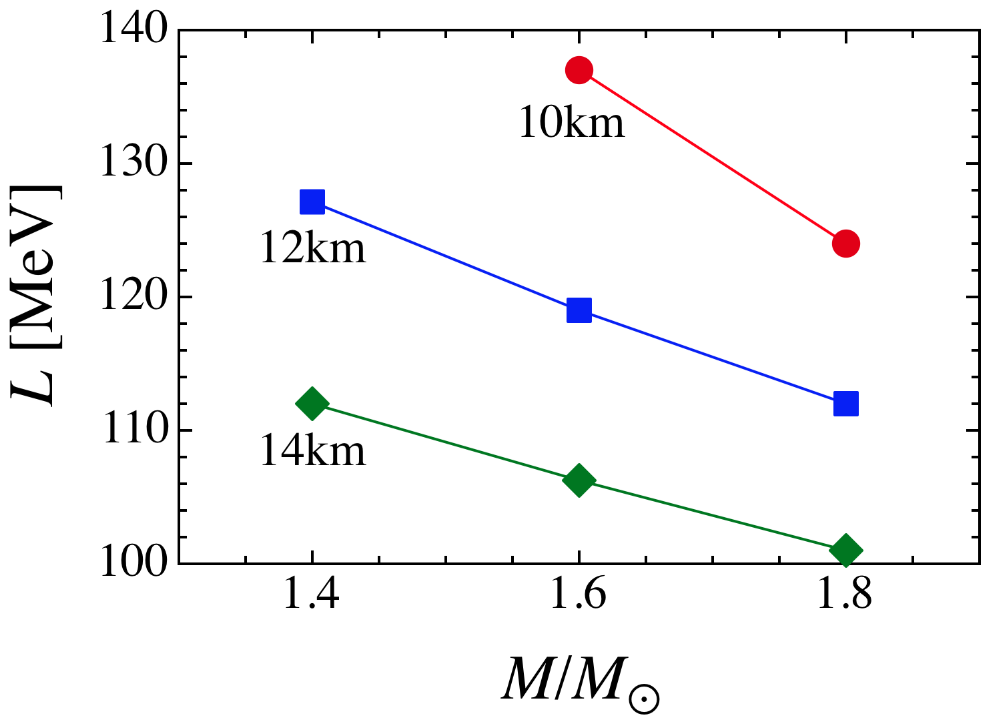
Comparison with QPO frequencies

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



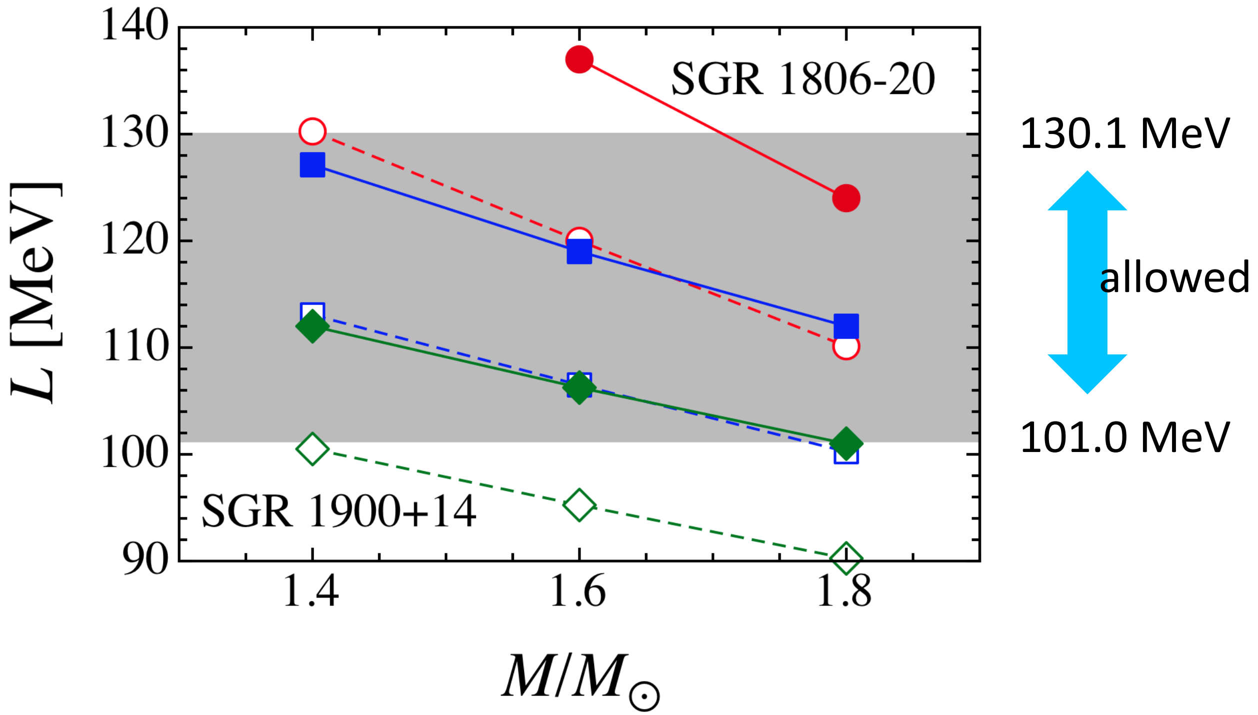
expected values of *L*

- Comparison with the observations in SGR 1806-20
  - with the help of the observation of (M,R) of oscillating star, one may make a constraint in the value of L.



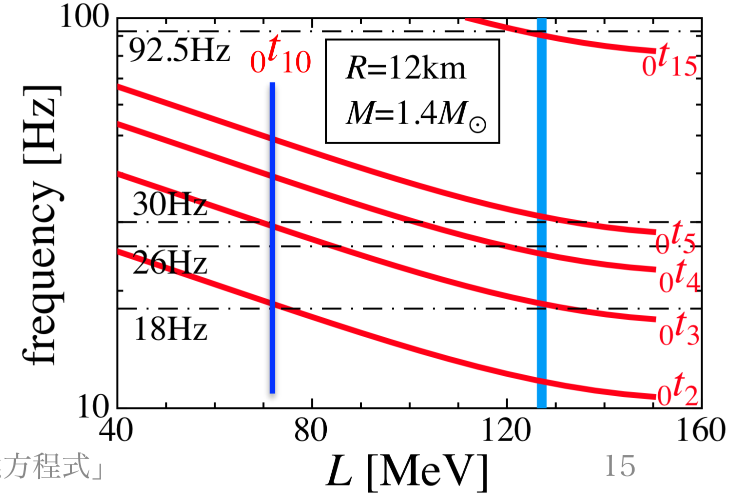
Allowed values of *L*

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



Conclusion

- QPOs are found in afterglow of giant flears
- We examined the frequencies of torsional oscillations as varying the stellar and EOS parameters.
- Fundamental frequencies are almost independent of the incompressibility K_0
- Assuming the QPOs are associated with crustal oscillations, we can make a constraint on EOS as
  - $L \gtrsim 47.6$ MeV without superfluid effect
  - $L \gtrsim 55.2$ MeV with realistic superfluid effect
  - $101.0 \text{ MeV} \lesssim L \lesssim 130.1$ MeV via comparison with obs.
- Otherwise, to realize $L \lesssim 80$ MeV, one needs to consider another oscillation mechanism



- It is becoming that the observations of NS can be adopted as a tool to see the interior region.
- The future observations will tell us information about the exact properties of NS matter.

Outlook

- Examine overtones of crust torsional oscillations
- Consider the more realistic μ
  - effect of nonuniform nuclear (pasta) structure
- Estimate the emitted GWs
- γ -ray emission mechanism