Crust EOS in Neutron Stars & Asteroseismology

公募研究「重力波観測を用いた中性子星内部における物質構造への制限の可能性 」

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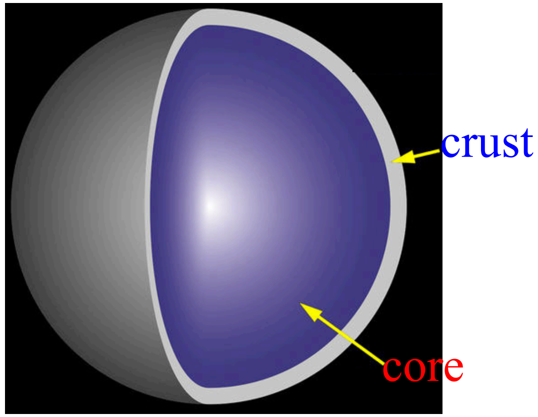
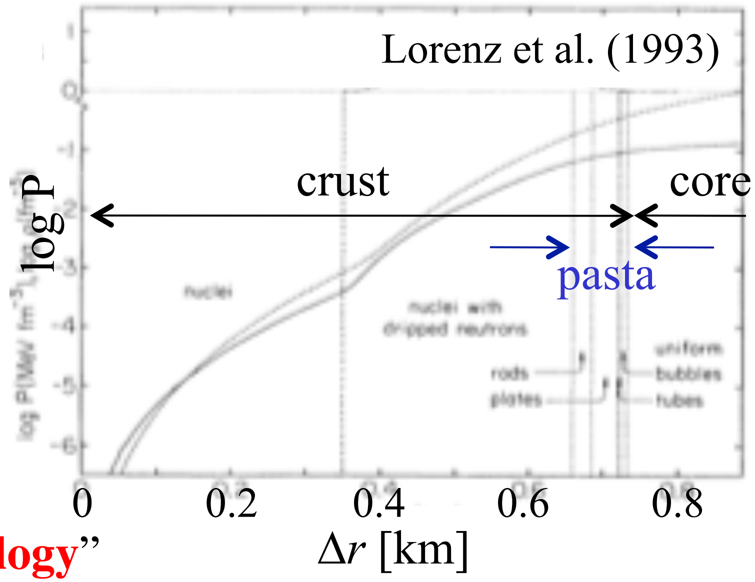
NSs and asteroseismology

- In neutron stars (NSs), the nuclear structure forms
  - Body center cubic (bcc) lattice in crust region
  - Uniform matter in core region
- It is also considered that the nonuniform nuclear structure could exist at the basis of crust.
  - *so-called "**Pasta**".*
- The thickness of pasta phase is quite small, which is ~ 100 m.
- It is quite difficult to see the properties of pasta via the observations of M and/or R.
- One could know those via the observations of neutron star oscillations (or GWs).
  - "**asteroseismology**" or "**GW asteroseismology**"



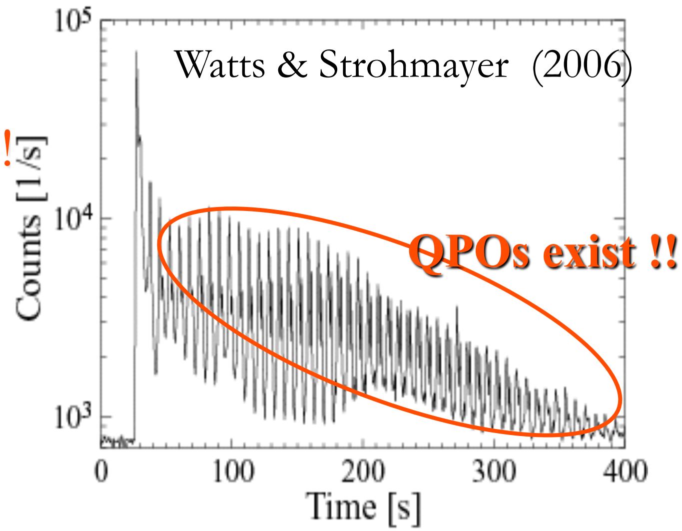


QPOs in SGRs

- **Soft gamma Repeaters** (SGRs) : objects that arise the gamma-ray flare activity.
  - Source…**Magnetar** ?? (neutron stars with strong magnetic fields > 10^{14} G)
- **Giant Flare 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
- In the decaying tail after the flare, QPOs are found !

  → Barat et.al., 1983; Israel et.al., 2005; Watts & Strohmayer, 2005, 2006

  - SGR 0526-66 : **43Hz**, $B \sim 4 \times 10^{14}$G, $L \sim 10^{44}$ ergs/s
  - SGR 1900+14 : $B > 4 \times 10^{14}$G, **28, 54, 84, and 155 Hz**
  - SGR 1806–20 : $B \sim 8 \times 10^{14}$G, $L \sim 10^{46}$ ergs/s, **18, 26, 30, 92.5, 150, 626.5, and 1837 Hz**



- **These QPO frequencies could be due to the oscillations of magnetars.**
  - **Crust torsional oscillations ??**
  - **Identification of QPO frequencies could tell us the stellar properties.**

Crustal Oscillations without Pasta vs QPO Frequencies

HS, K.Kokkotas, N.Stergioulas (2007)

- SGR 1900+14

f [Hz]	28	54	84	155
torsional	${}_3t_0$	${}_6t_0$	${}_9t_0$	${}_{17}t_0$

- SGR 1806-20

f [Hz]	18	26	30	92.5	150	626.5	1837
torsional	${}_2t_0$	???	${}_3t_0$	${}_9t_0$	${}_{15}t_0$	${}_lt_1$	${}_lt_4$

- Missing frequencies exist
  - Difficulty to explain two QPO frequencies 26 and 30 Hz with a stellar model
  - *What's problem ??*

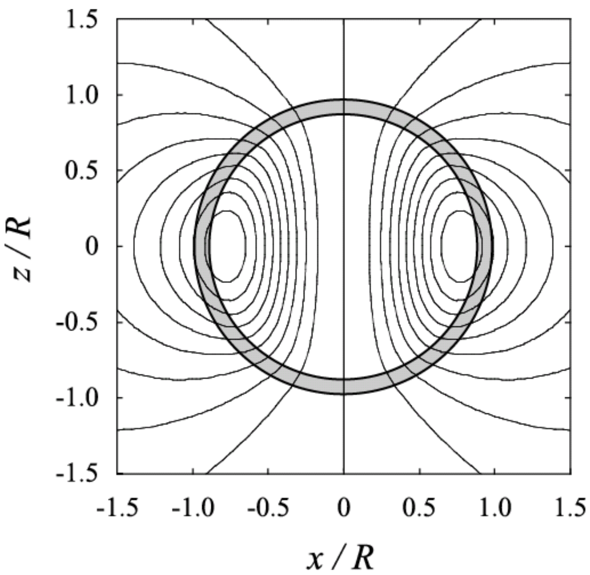
Shear modulus in crust region

- isotropic shear modulus : μ
- Body center cubic (bcc) is assumed

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

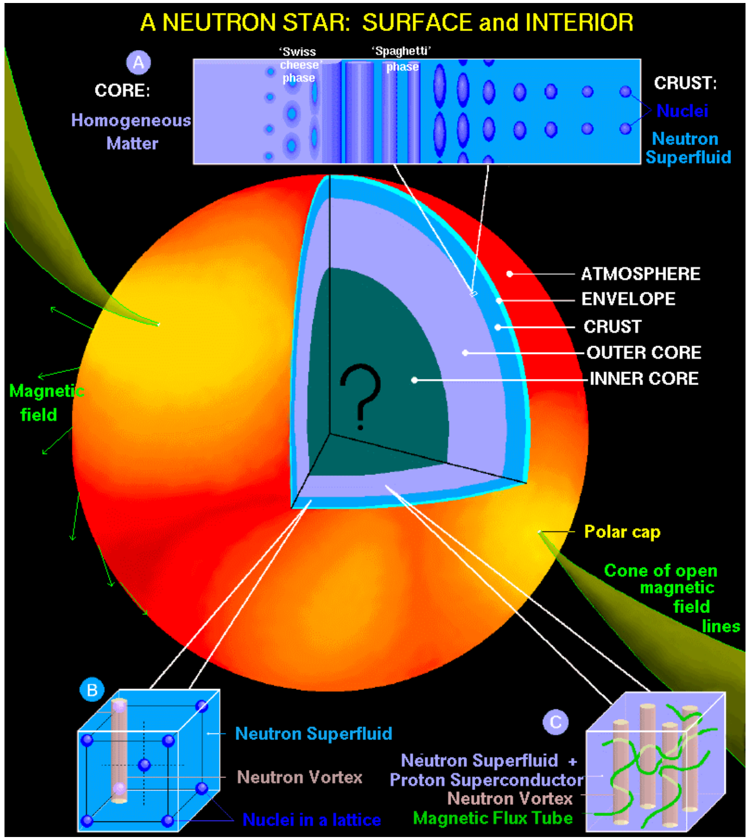
n_i : number density of ions
$+Ze$: average charge of ions
$a^3 = 3/4\pi n_i$: average space between ions

Strohmayer, et al. (1991)



Shear modulus in Pasta phase 1

- Nonuniform structure "pasta" exists
  - – shear modulus in pasta could be different from that with bcc structure.
- Pethick & Potekhin (1998)
  - – behavior like "liquid crystal"
  - – smaller shear modulus
- Density that pasta structure appears
  - – ~ 10^{13} g/cc (ex. Lorenz et al. (1993))
- Realistic shear modulus in pasta phase is still unknown…



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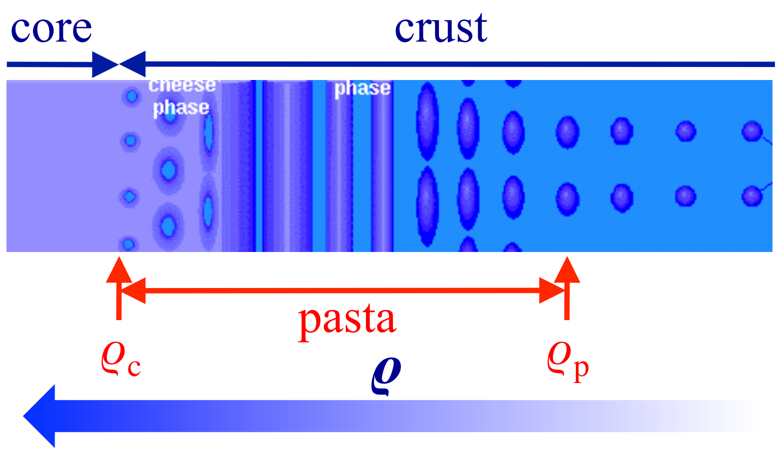
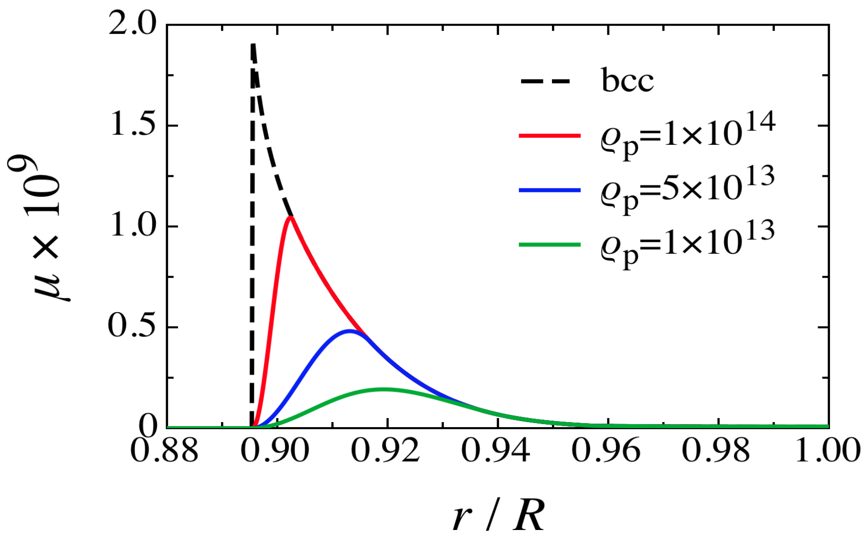
Shear modulus in Pasta phase 2

HS (2011)

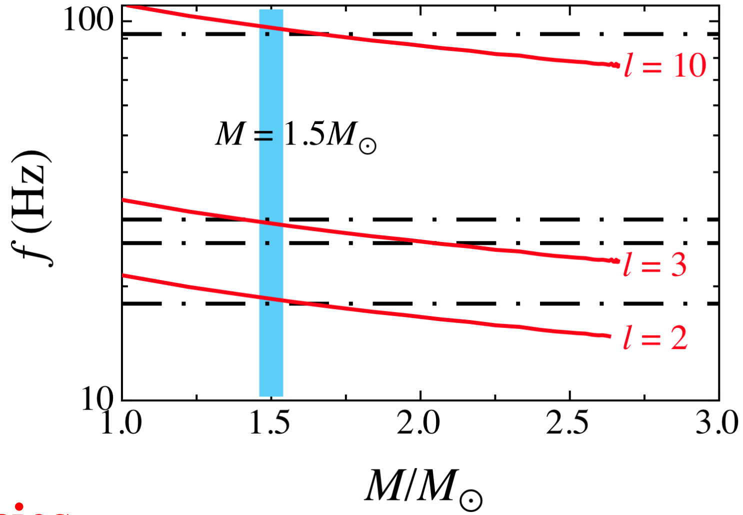
- We assume toy model for the shear modulus in pasta phase
  - ϱ_p : density that non-uniform nuclear structure appears
  - $\varrho_p = 10^{13} - 10^{14}$ g/cm^3
  - ϱ_c : density between the crust and core region ($\varrho_c = 1.24 \times 10^{14}$ g/cm^3)
  - $\varrho < \varrho_p$: nuclear structure forms bcc lattice
  - $\varrho_p < \varrho < \varrho_c$: non-uniform nuclear structure (pasta phase)
  - $\varrho > \varrho_c$: core fluid region



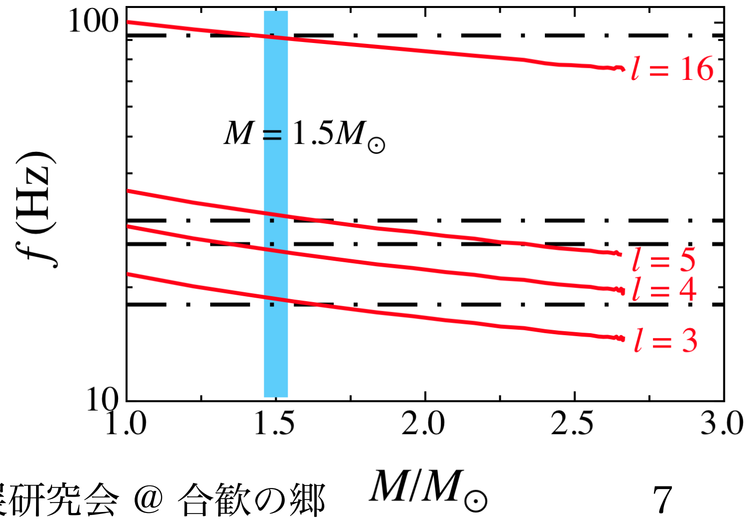


Comparison with QPO frequencies

- For $\varrho_p = 1 \times 10^{14}$ g/cm^3
  - some of QPOs are impossible to explain
  - similar difficulty to the previous study without pasta structure



- For $\varrho_p = 2 \times 10^{13}$ g/cm^3
  - **possible to explain the all QPO frequencies**



- **One needs to consider the effect of pasta**
- **Do more systematic analysis**

Crust EOSs & Pasta Structure

Oyamatsu & Iida (2003), (2007)

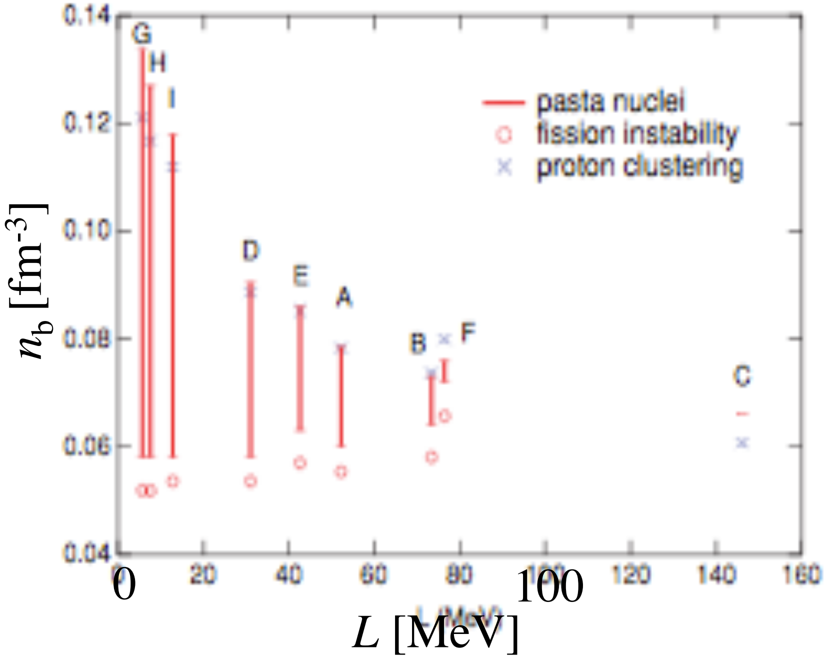
- Bulk energy per nucleon;

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

  - w_0, n_0, and S_0 might be fixed experimentally.
  - adopt two parameters; L & K_0.

- Whether the pasta phase appear or not depends strongly on L.
  - $L \gtrsim 100$MeV, pasta phase could vanish.

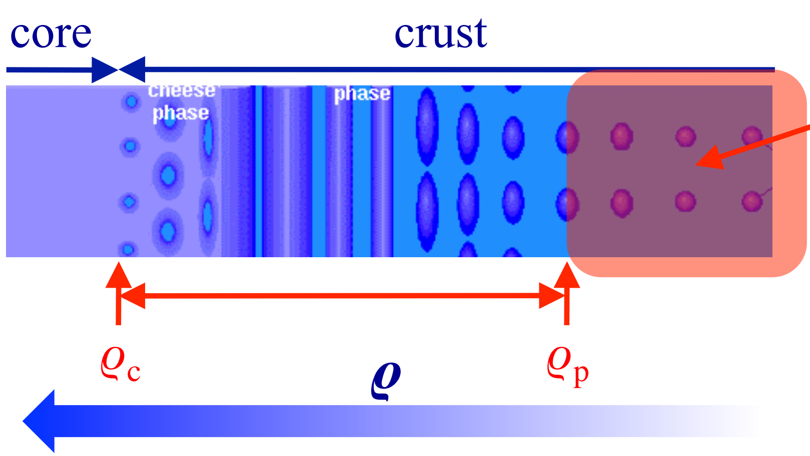
- How do the parameters L & K_0 affect on the stellar oscillations ?



Strategy

HS, Nakazato, Iida, Oyamatsu, in prep.

- EOS for inner core is still uncertain.
- We construct the stellar model by integrating TOV eqs. from $r = R$ inward.
  - M and R become parameters
  - L and K_0 are parameters for curst EOS
- In the crust region, we calculate the shear oscillations
  - We will see the relation between the frequencies and parameters.
  - It might be possible to know something…



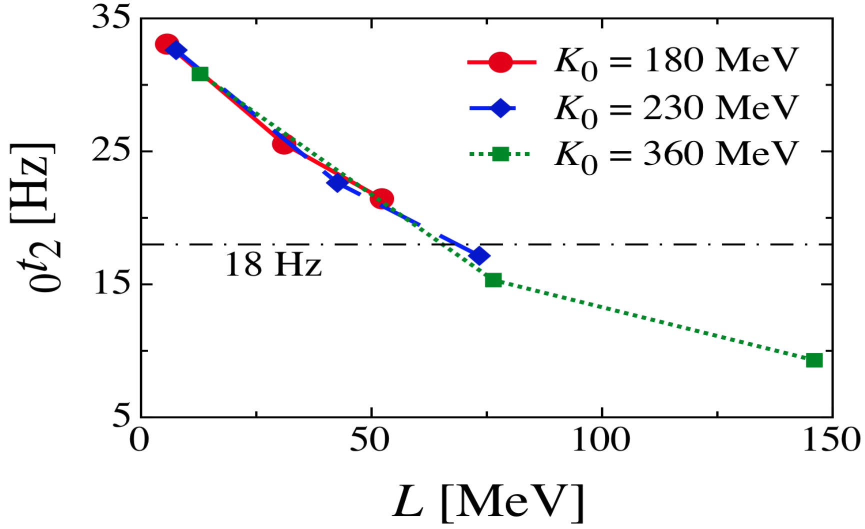
$$\mu = 0.1194\frac{n_i(Ze)^2}{a}$$

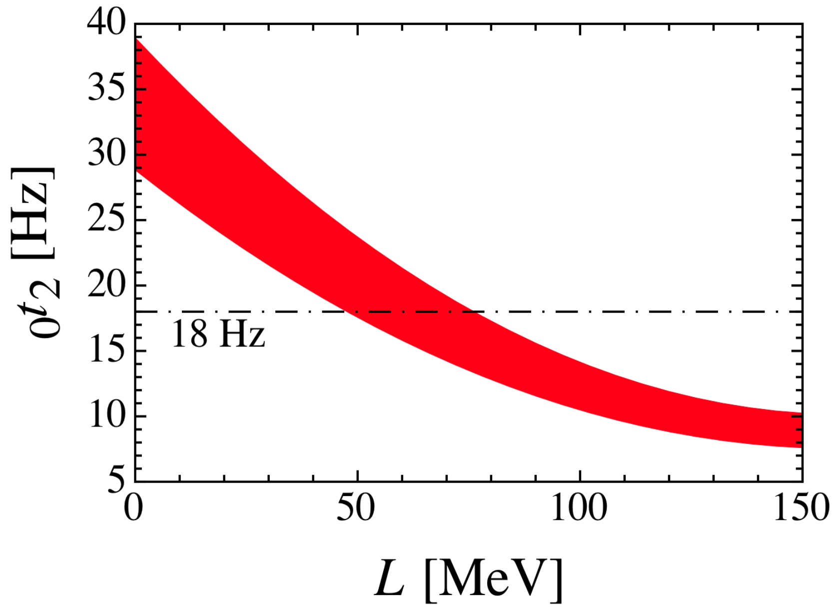
* Frequencies correspond to the lower limit

Fundamental l=2 oscillations

- Fundamental l=2 torsional frequency with M=1.4$M_\odot$ & R=12km.
- Frequencies of torsional oscillations could be independent of K_0.
- One can derive the fitting formula;

$$ {}_0t_2 = c_0 - c_1 L + c_2 L^2 $$





- Expected frequencies for the stellar model with 1.4$M_\odot \leq M \leq$ 1.8$M_\odot$ and 10km $\leq R \leq$ 14km.
- l=2 fundamental oscillation is the lowest frequency in torsional oscillations.
- Via the observed QPO frequencies, *L* should be more than 50 MeV independent of the stellar models.

Summary

- Asteroseismology is powerful tool to see the interior properties of star.
- In the giant flares, the QPO frequencies are discovered.
  - It is impossible to explain the observed QPO frequencies theoretically by using only crustal oscillations without pasta phase.
- We show the possibility to explain the all observed QPO frequencies with considering the pasta structure.
- It could be possible to see the properties of crust EOS via stellar oscillations.

Future works

- Consideration of realistic shear modulus μ
- Effect of Magnetic fields
- Mechanism of gamma-ray burst
- Possibility to detect GWs from magnetars