Constraints on the nuclear symmetry energy via asteroseismology

PRL **108**, 201101 (2012)

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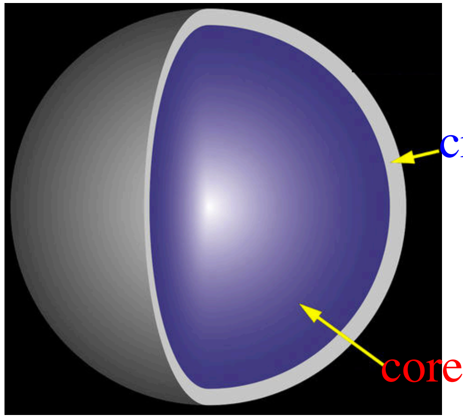
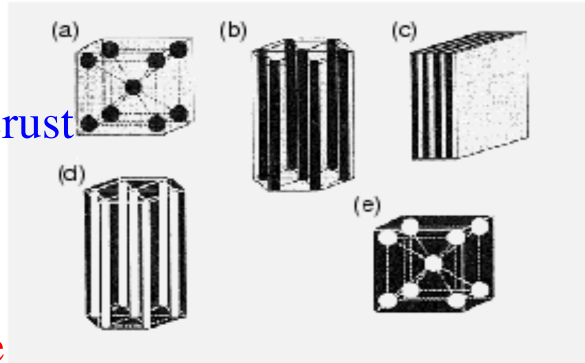
Neutron stars & asteroseismology

- 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

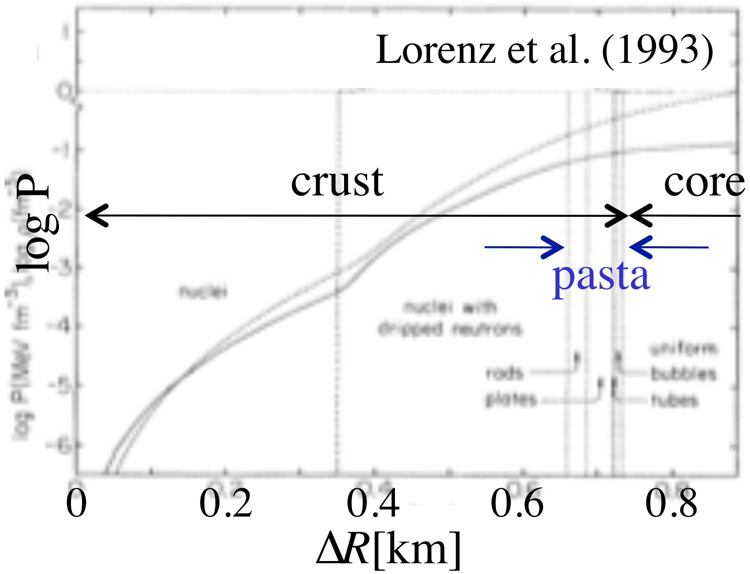
  "(GW) asteroseismology"

  cf.) seismology, helioseismology



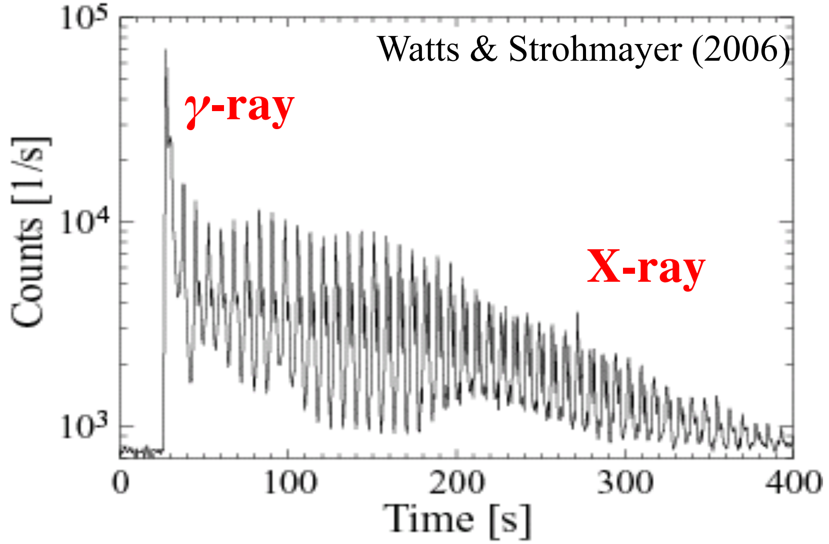


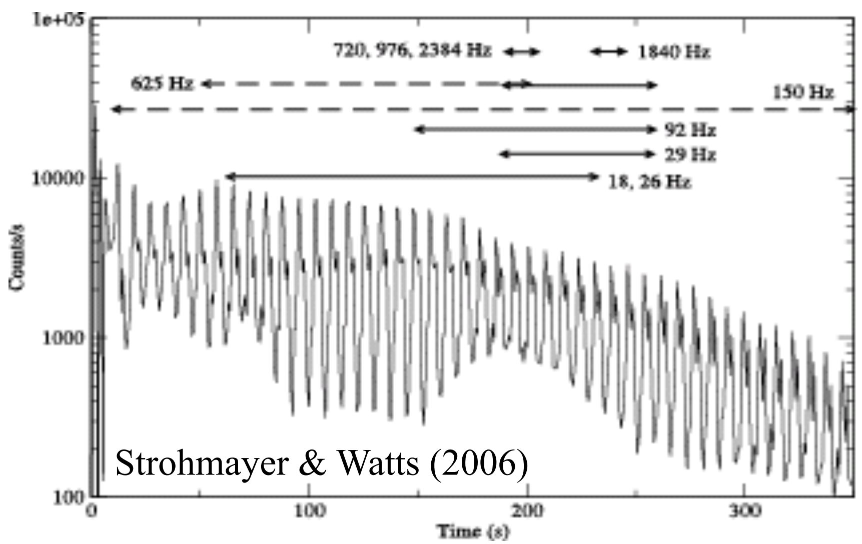
Oyamatsu (1993)



QPOs in giant flares 1

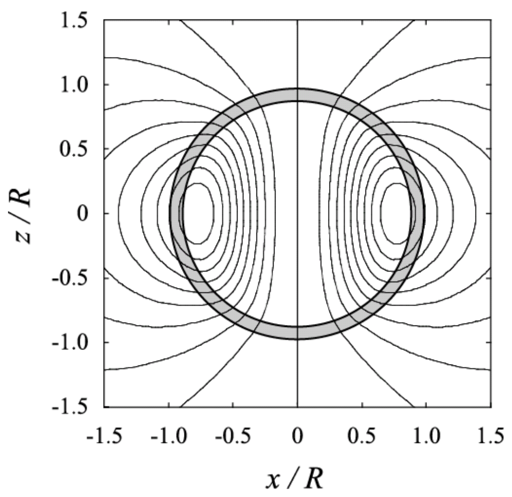
- Magnetars : $B > 10^{14}$G
- Candidates of magentars
  - Anomalous X-ray pulsars （AXPs）
  - Soft gamma repeaters（SGRs）
    ~ sporadic emission with X and γ-rays (~ 10^{41} erg/s)
- Giant flares from SGRs (10^{44}-10^{46} ergs/s)
  - SGR 0526–66 in March.5.1979
  - SGR 1900+14 in August.27.1998
  -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

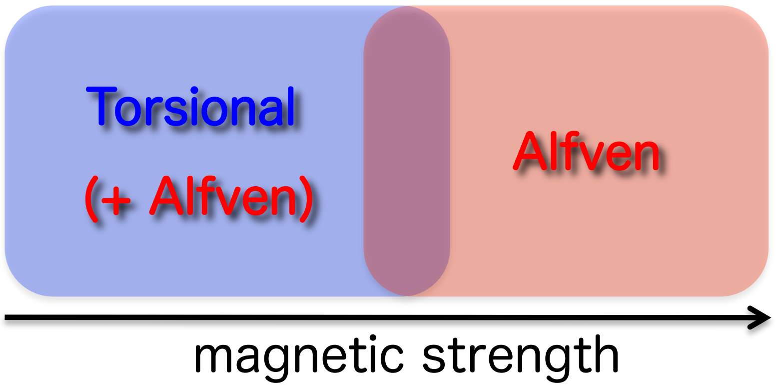




QPOs in giant flares 2

- 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 ~ 8 $\times 10^{14}$G, L ~ 10^{46} ergs/s
    18, 26, 30, 92.5, 150, 626.5, 1837 Hz
- Theoretical attempts to explain…
  - torsional oscillations in neutron star crust
  - magnetic oscillations (Alfven oscillations)





We consider the QPOs as torsional oscillations

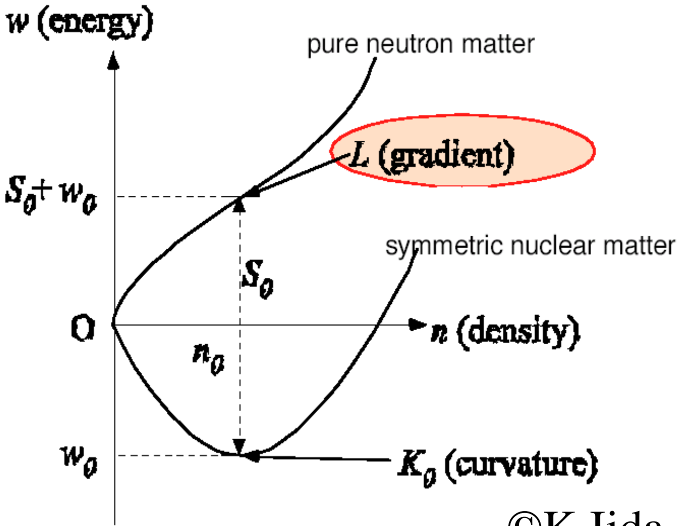
EOS for crust region

Oyamatsu & Iida (2003), (2007)

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

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

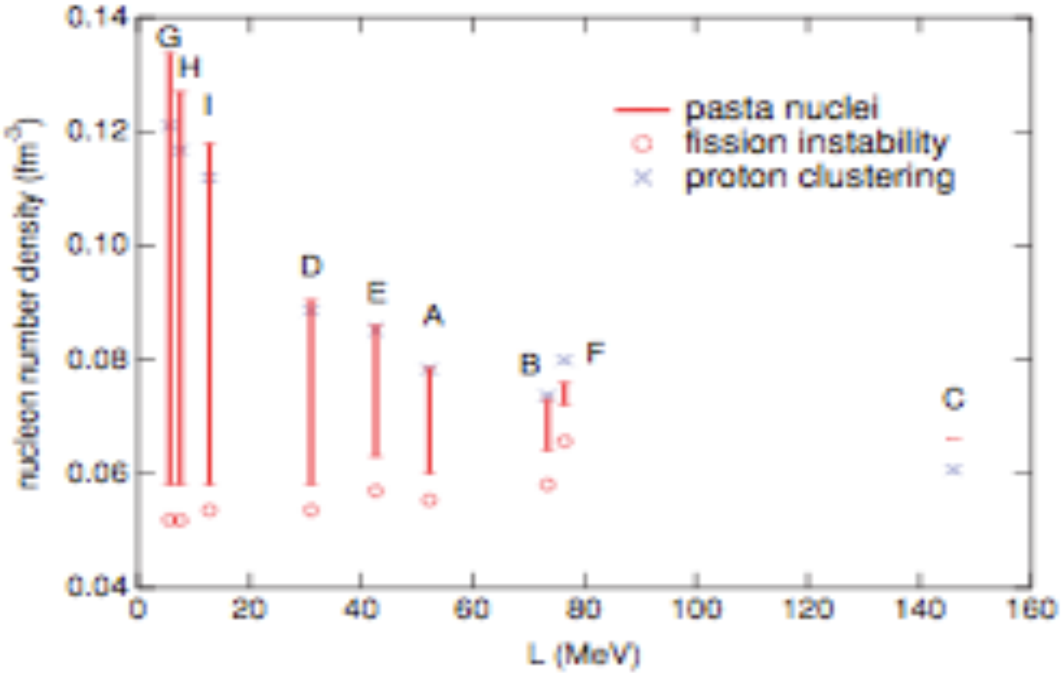
- Calculations of the optimal density distribution of stable nuclei within Thomas Fermi theory.
  - We know Z, mass, & charge radius that can be calculated from the optimal density distribution to the empirical data for stable nuclei.
  - Obtain the value of w_0, n_0, and S_0 for given L & K_0 by fitting such Z, mass, charge radius



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 nuclei.
  - $0 < L < 160$MeV, $180\text{MeV} \leqq K_0 \leqq 360\text{MeV}$

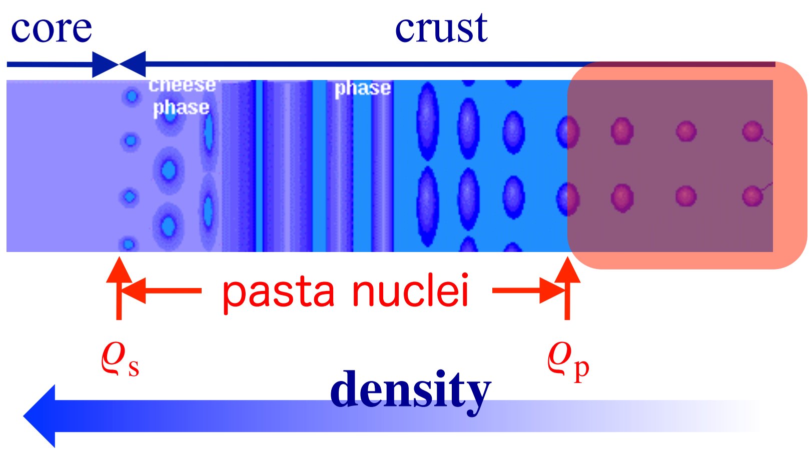


- Whether pasta phase exists or not depends strongly on L.
- For $L \gtrsim 100$MeV, pasta structure almost disappears.

What we do

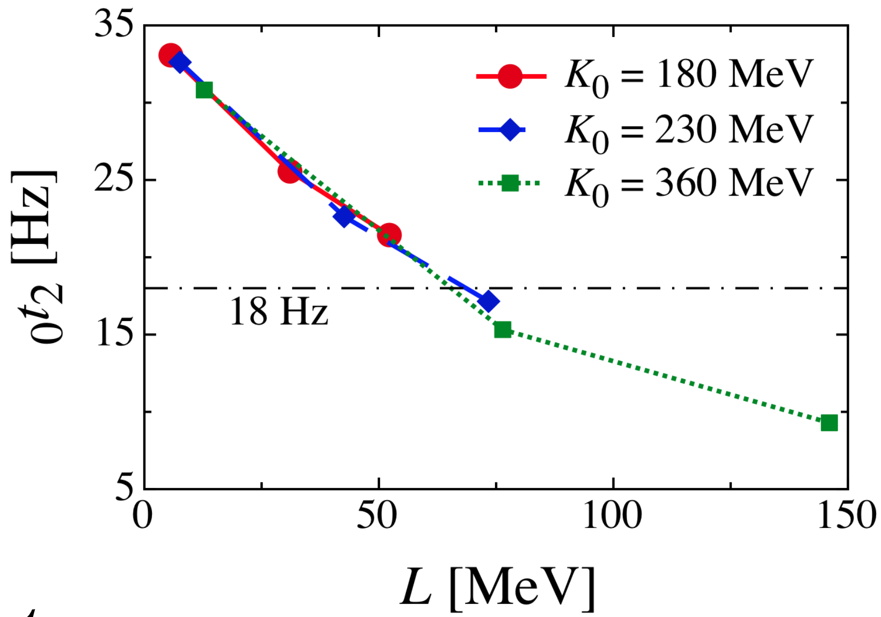
- EOS for core region is still uncertain.
- To prepare the crust region, we integrate from stellar surface.
  - M, R : parameters for stellar properties
  - L, K_0 : parameters for curst EOS
- In crust region, torsional oscillations are calculated.
  - considering the shear only in spherical nuclei.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

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



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
- 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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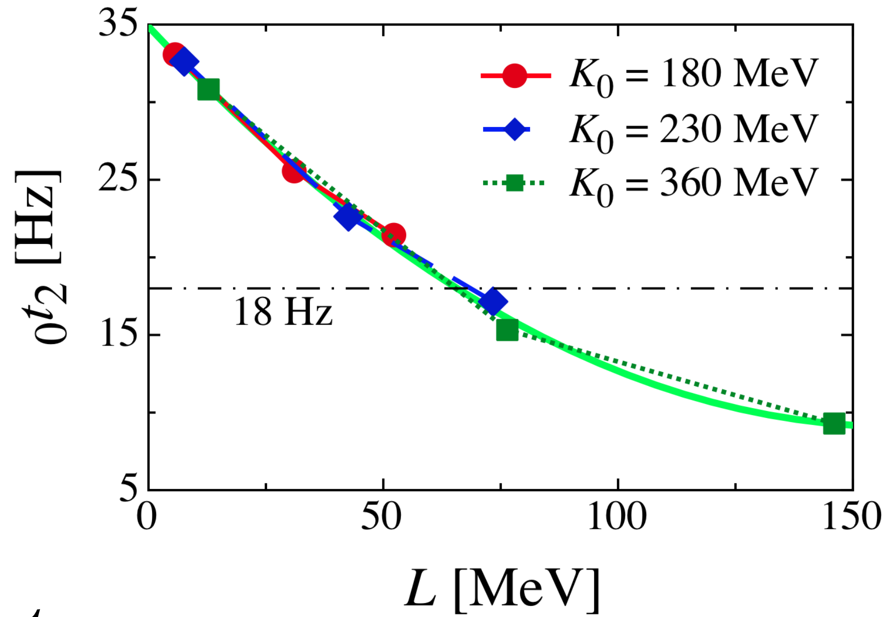
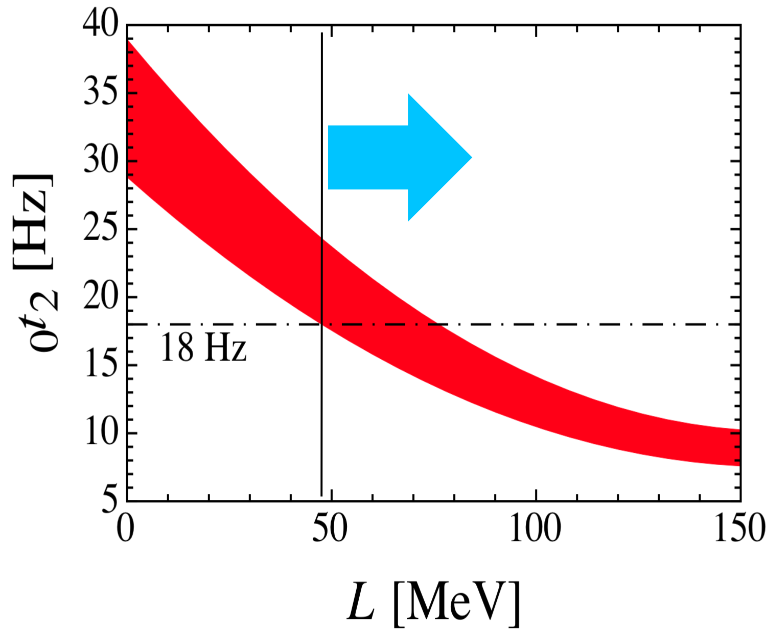


Constraint on L

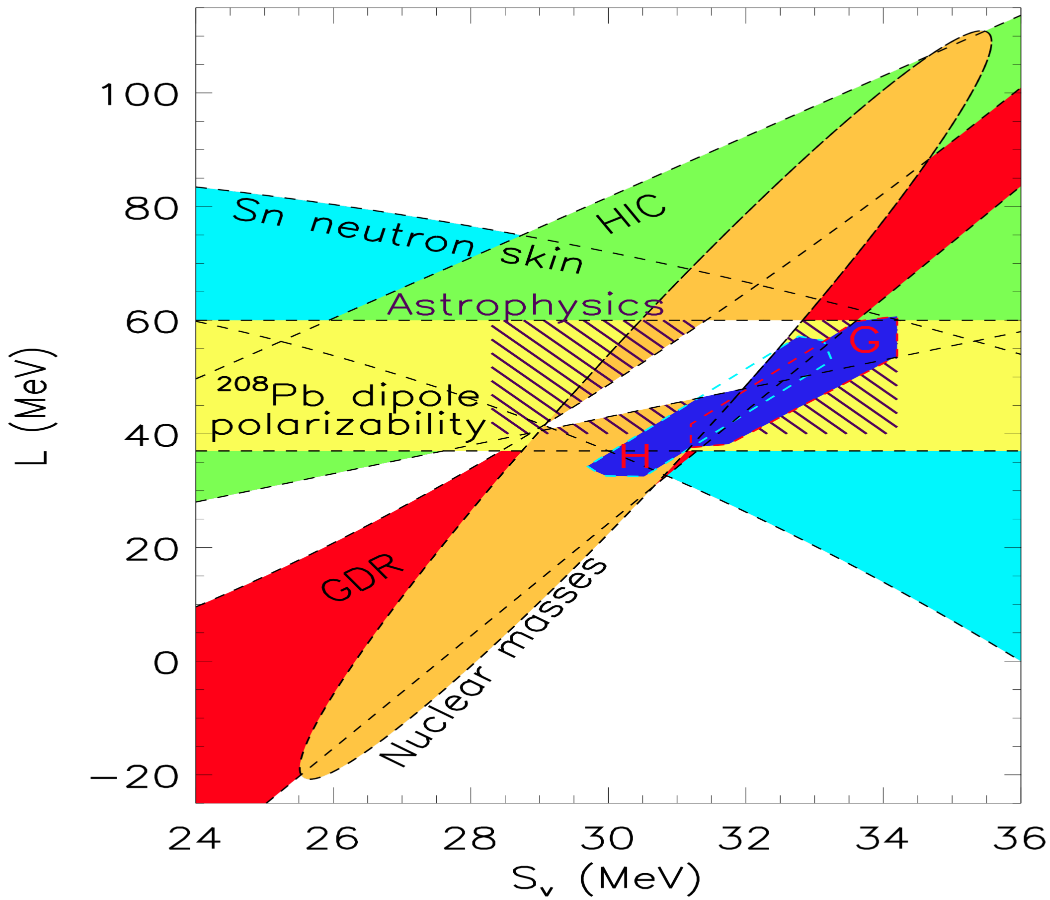
- For R=10km~14km & $M/M_\odot$=1.4~1.8, ${}_0t_2$ are calculated
- Assuming that the observed QPOs would come from torsional oscillations
- ${}_0t_2$ is the smallest frequency among a lot of torsional oscillations
  - ${}_0t_2$ should be equal to or smaller than the smallest observed QPOs frequency



- 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

Compared with other constraints

- Lattimer & Lim (2012)



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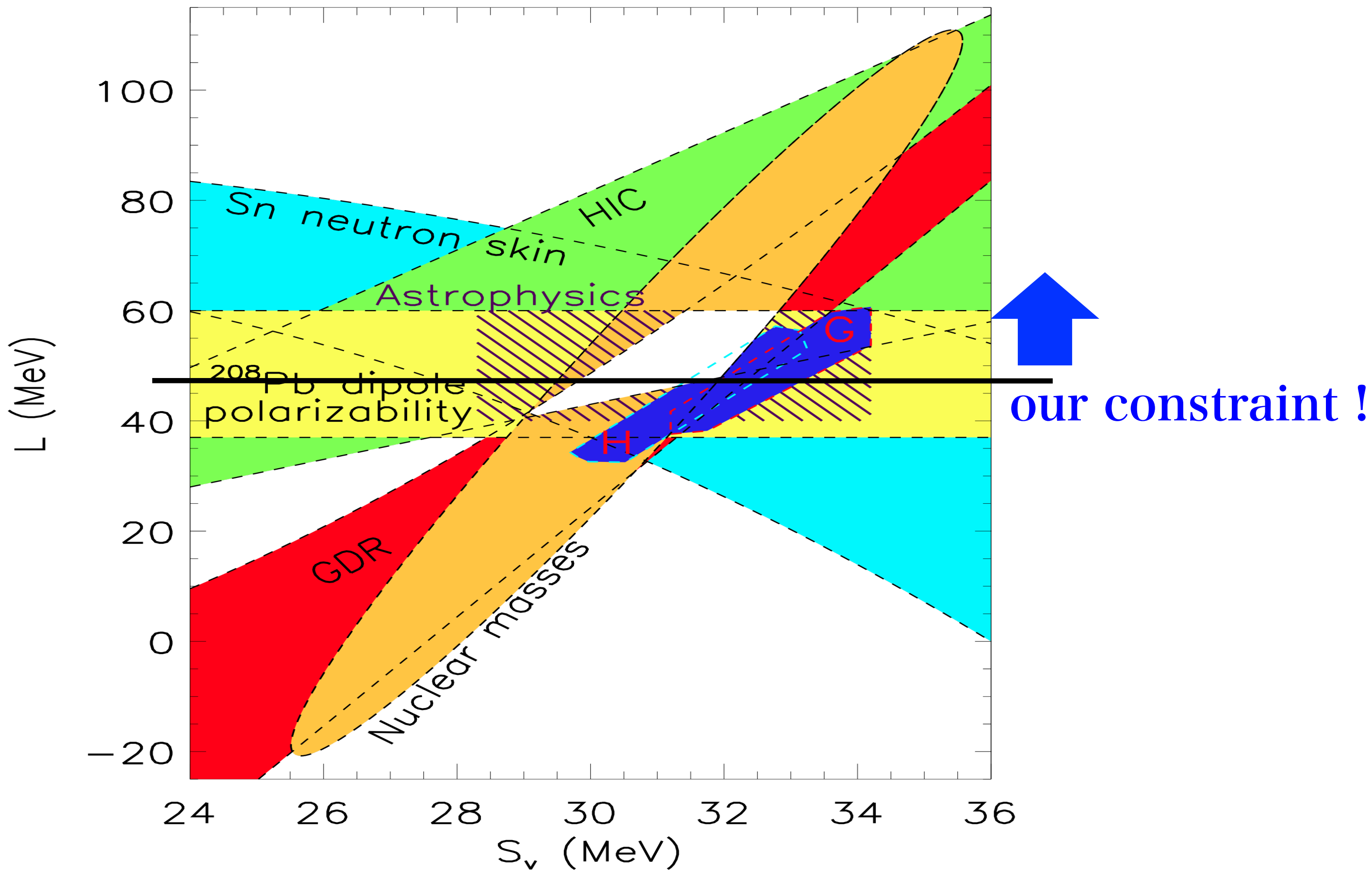

Conclusion

- 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
  - consistent with the previous examinations