Astrophysical Implications of the Symmetry Energy

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Topics

Supernova explosion

Sumiyoshi-san's talk

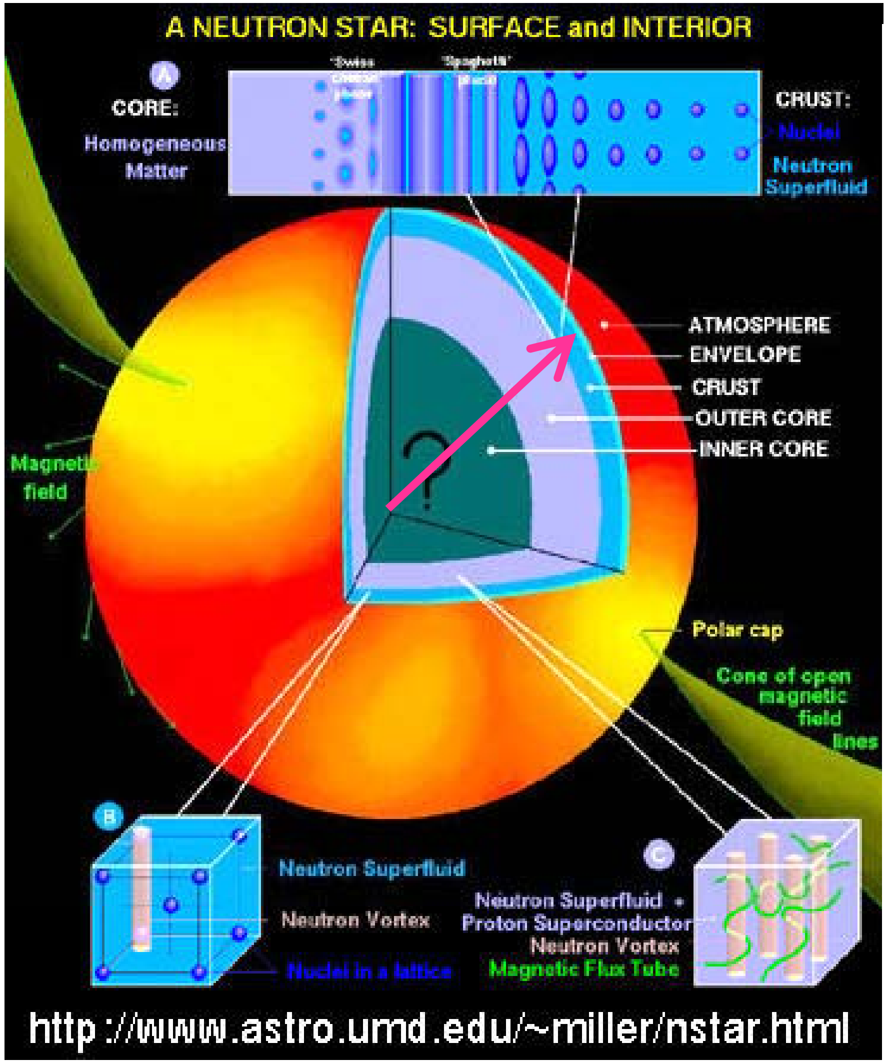
Hot (proto-)neutron star

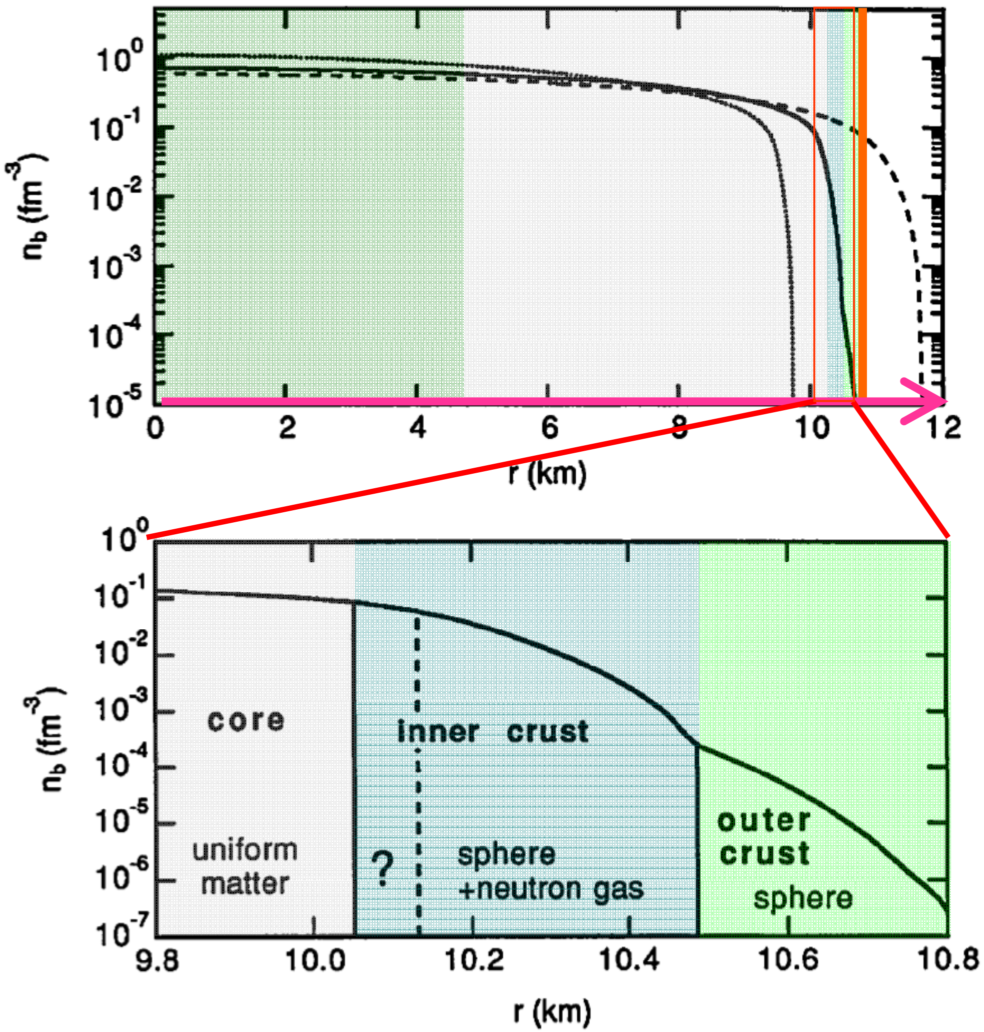
Neutron star

my topics

Interior of neutron stars

- Core（“packed” nuclear matter）＋ Crust（skin）





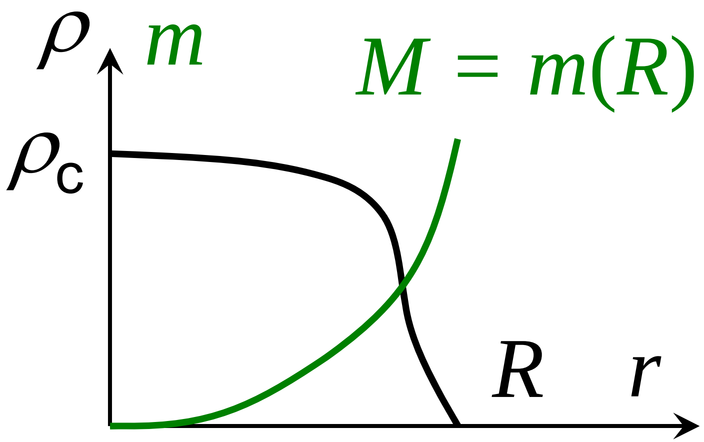
Neutron stars and EOS

- Structure of neutron stars（spherical case）
  - TOV equation（balance of gravity and pressure）

$$\frac{dP(r)}{dr} = -\frac{G\left\{m(r) + 4\pi r^3 P(r)/c^2\right\}}{r^2\left\{1 - 2Gm(r)/rc^2\right\}} \frac{\varepsilon(r) + P(r)}{c^2}$$

  - Equation of state（EOS）

$$P = P(\rho)$$



  - Boundary conditions

$m(r) = 0$ @ $r = 0$

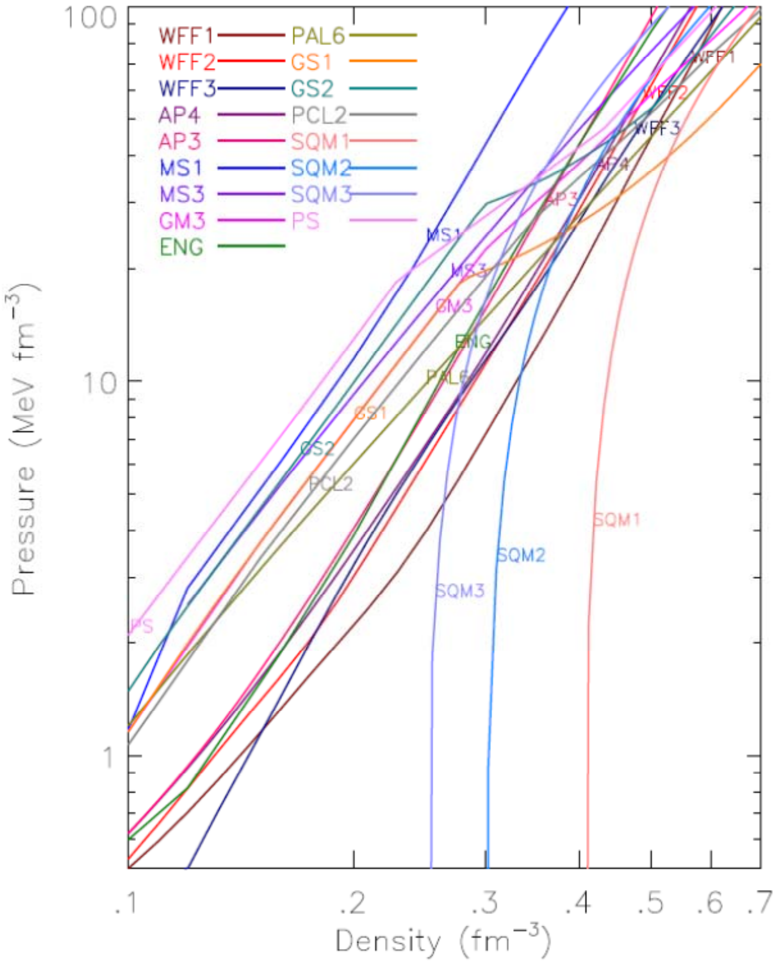
central density ρ_c

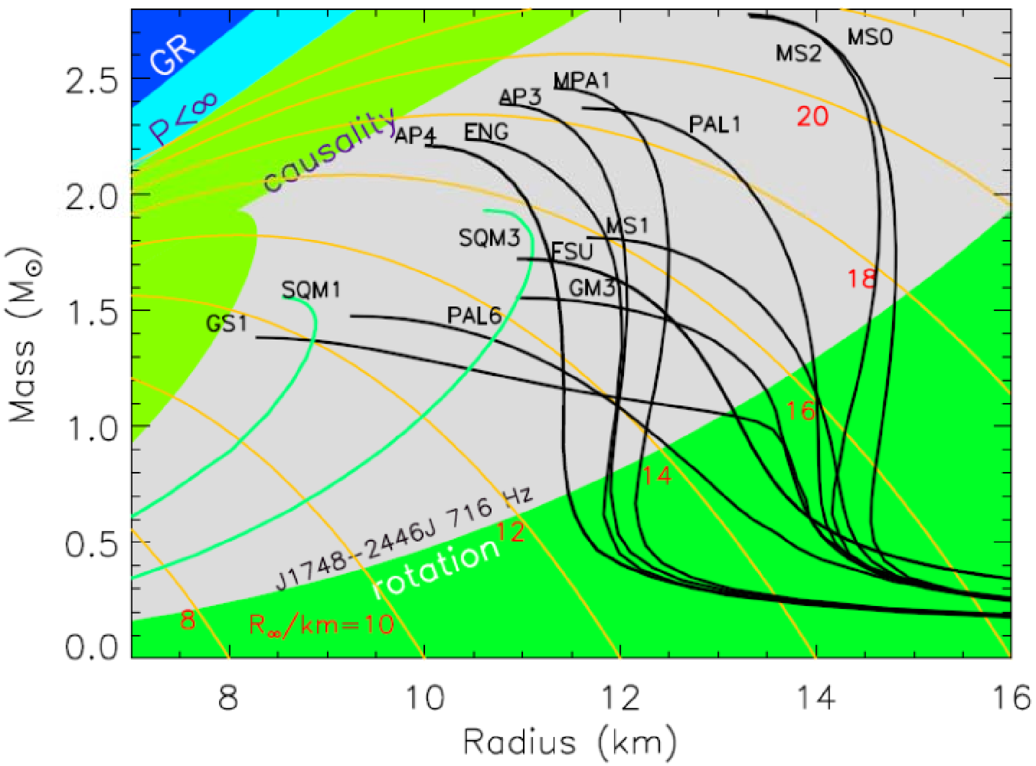
$\rho(R) = 0$ at surface

radius R, mass $M = m(R)$

EOS determines M-R relation

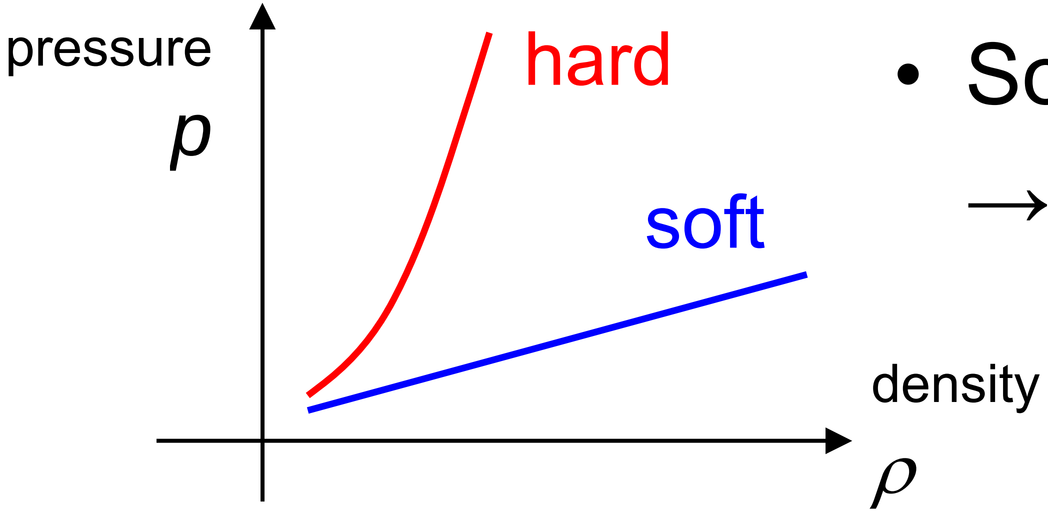
equation of state ⟷ mass-radius relation (*M-R*)





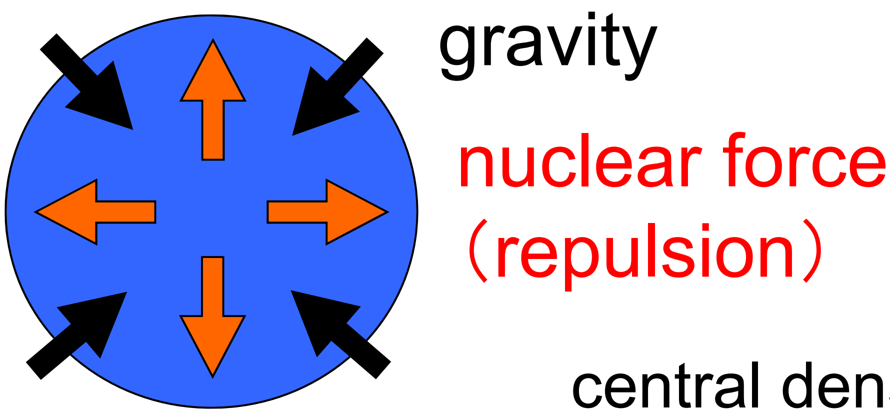
(Lattimer 2012)

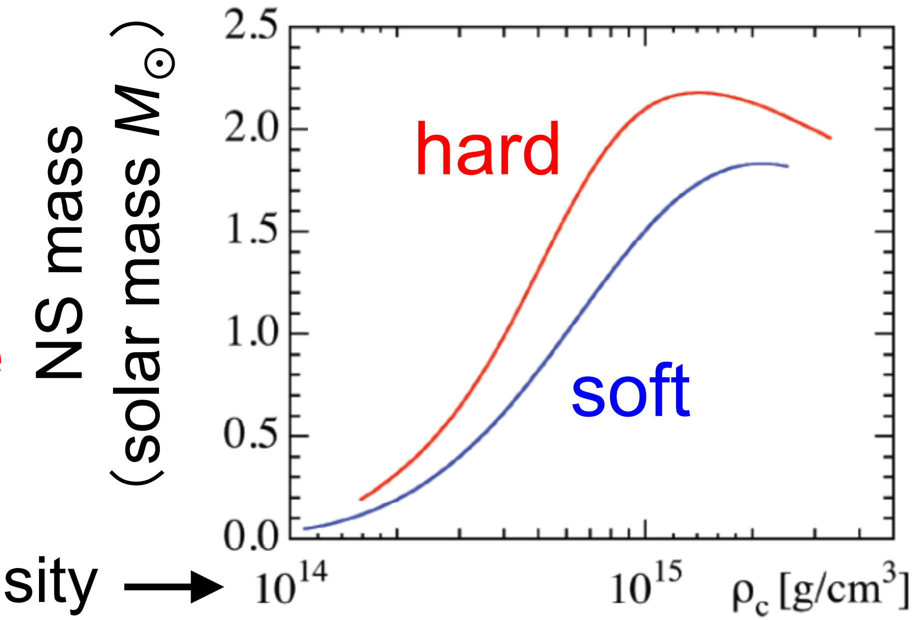
EOS and NS maximum mass



- Soft = compressible
  → easy to raise density

- Hard EOS have high NS maximum mass





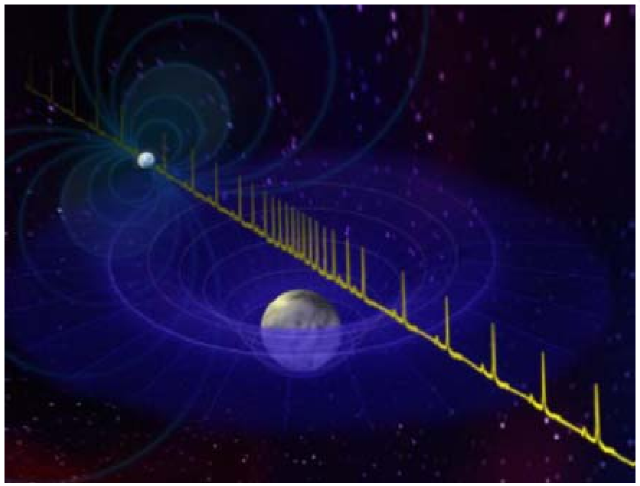
central density →

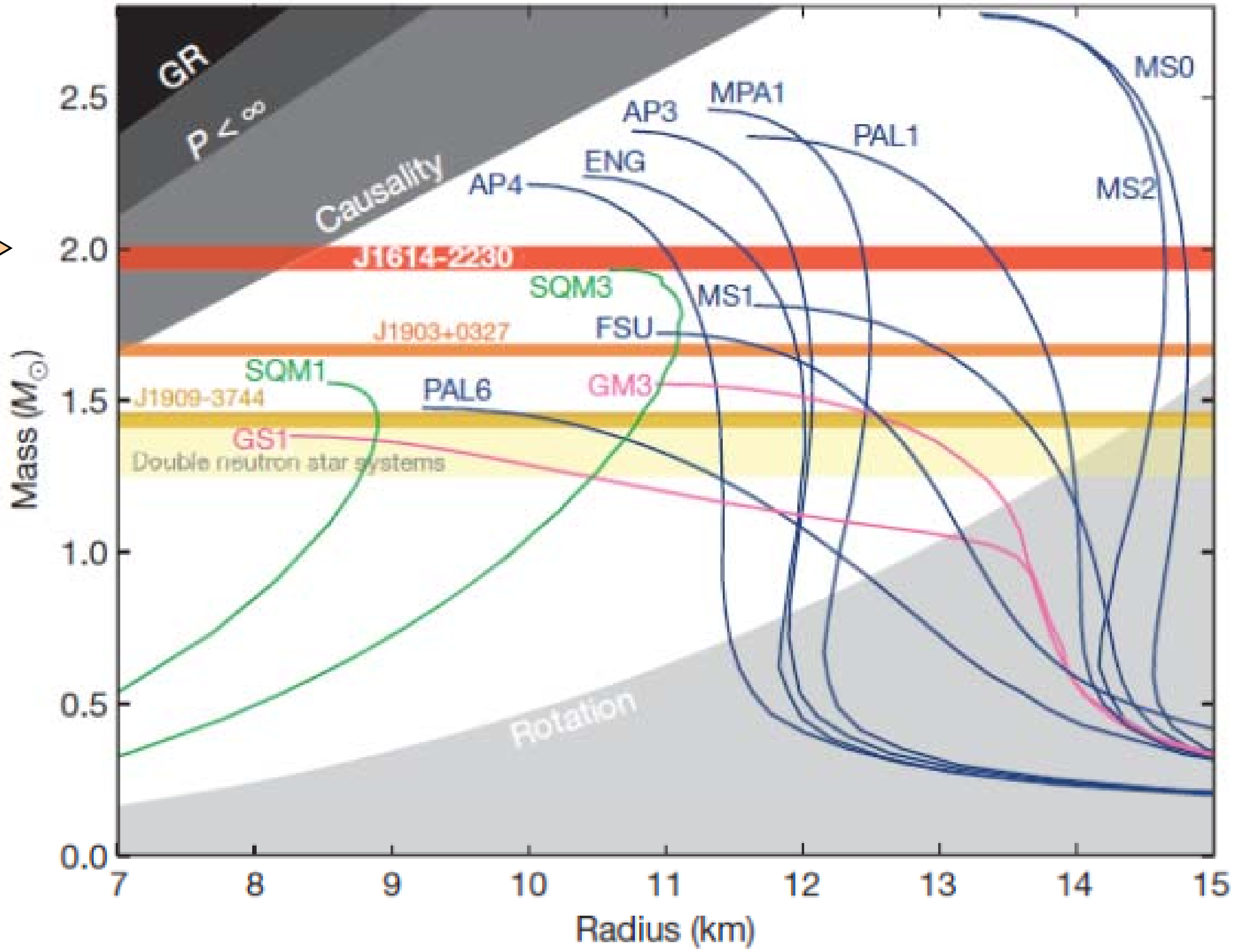
Discovery of $2M_\odot$ neutron star

- Pulsar J1614-2230 puts a tight constraint on EOS!

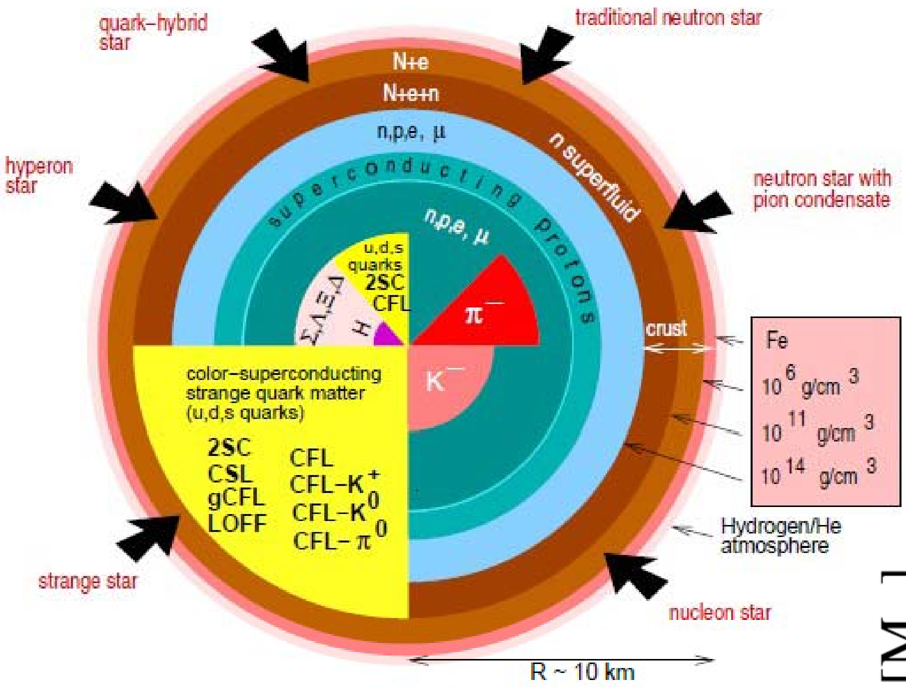
Demorest et al., Nature 467 (2010) 1081

Shapiro delay





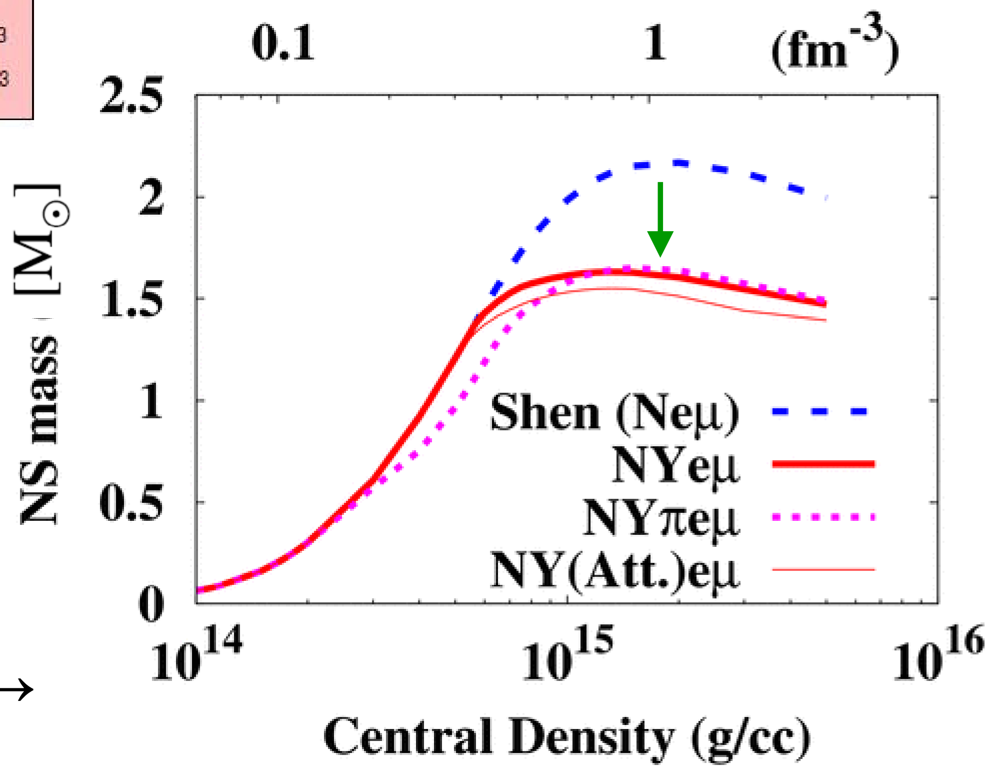
Most of NS mass is core



- Not only new degrees of freedom, but also supra-nuclear density EOS are important!

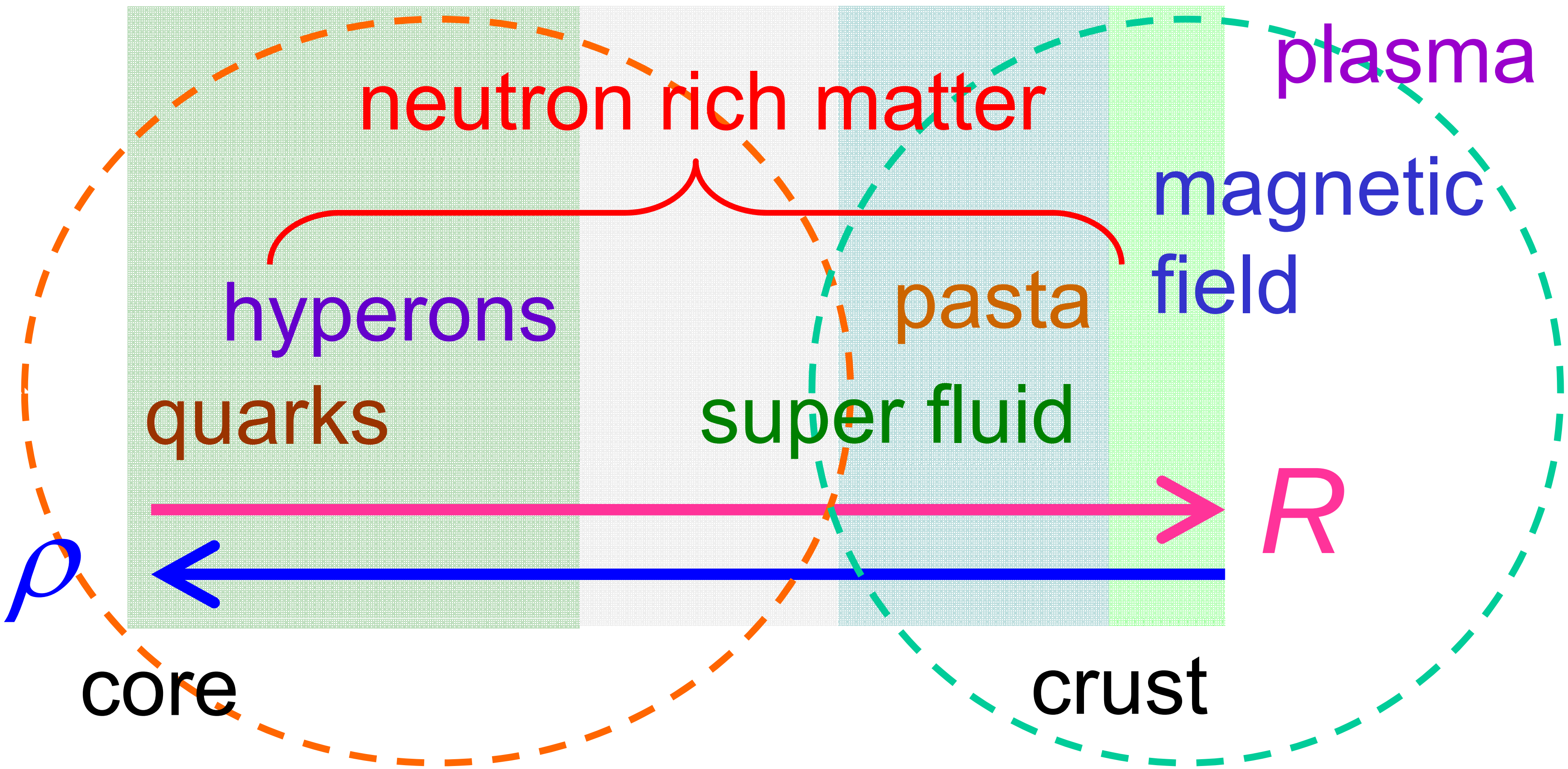
effects of hyperon and/or pion inclusion

Ishizuka et al. (2008) →



Physics in neutron stars

Symmetry Energy!!



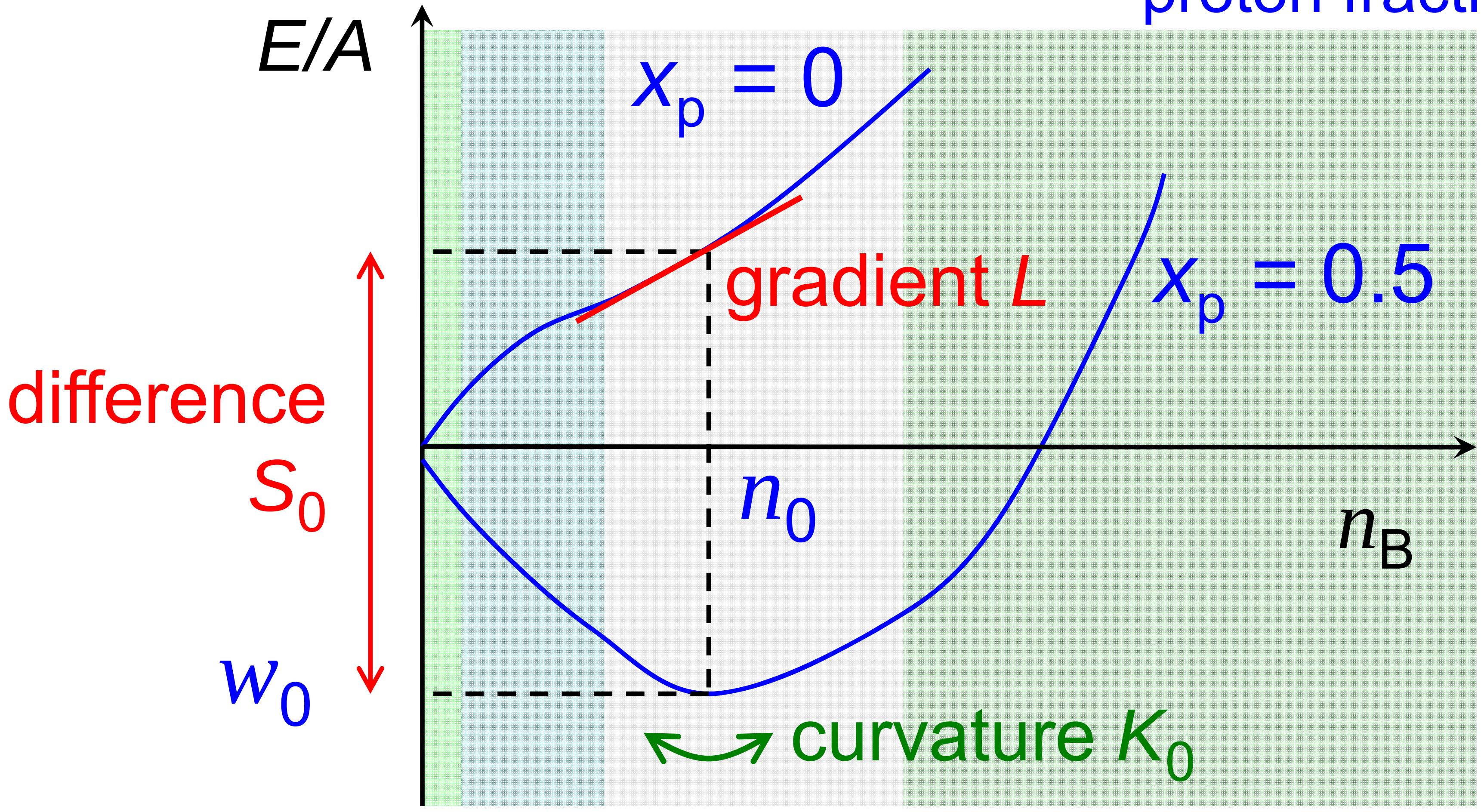
determine *M* and *R*   important for emission

EOS and saturation parameters

- Saturation parameters characterize EOS.

$$w = w_0 + \frac{K_0}{18n_0^2}(n-n_0)^2 + \left[S_0 + \frac{L}{3n_0}(n-n_0)\right](1-2x_p)^2$$

proton fraction



Values of saturation parameters

$\boldsymbol{n}_0$ = 0.15 - 0.16 fm^{-3}

$\boldsymbol{w}_0 \sim -16$ MeV

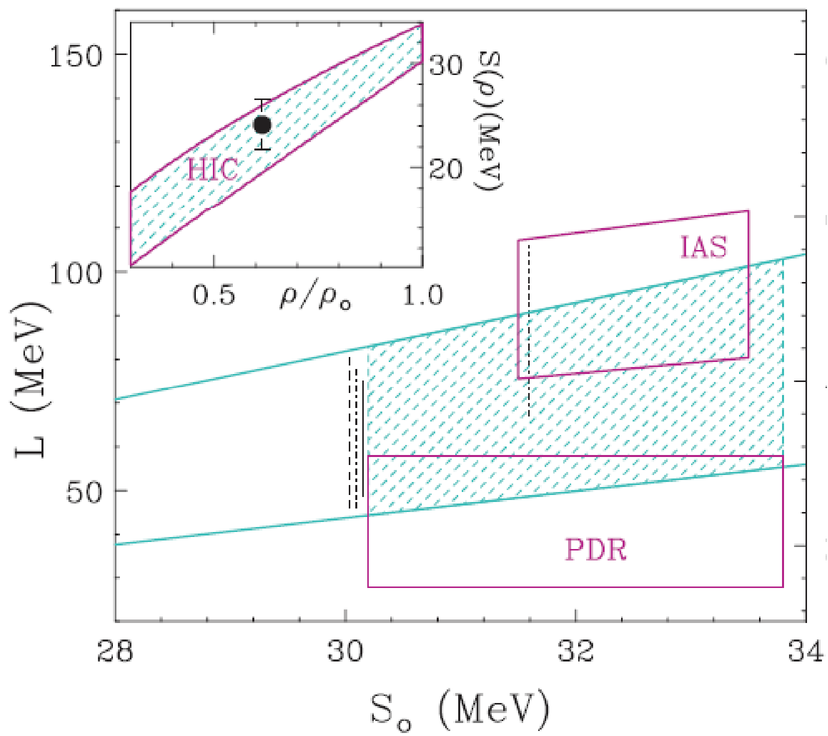
K_0 = 230 - 250 MeV（Piekarewicz 2010）

S_0 = 30 - 34 MeV（Tsang et al. 2009）

L = 20 - 100 MeV ？？？

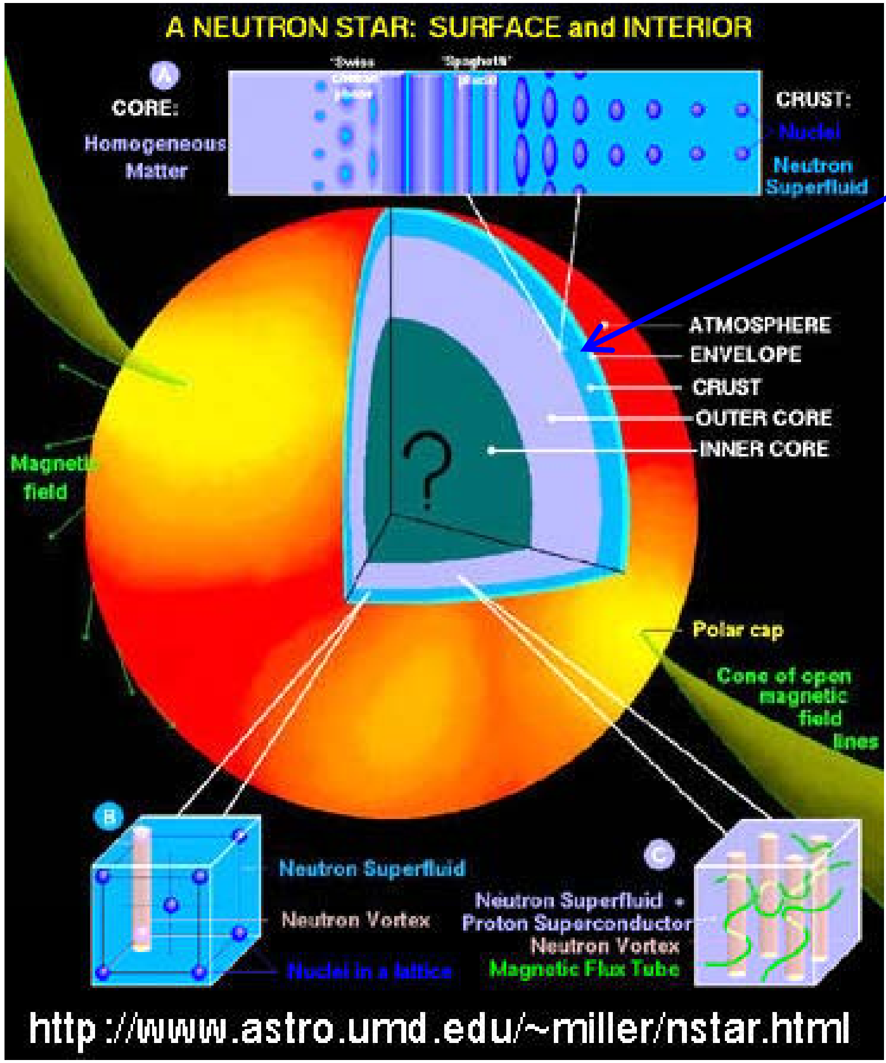
related to
symmetry energy!!

→ Are important for
neutron stars?

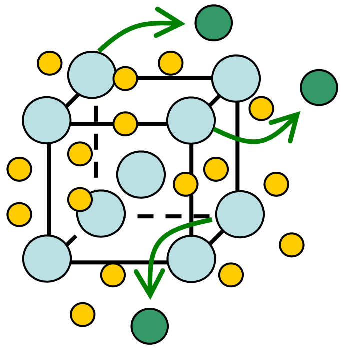


Neutron star crust

- Crystalline structure of nuclei



crust



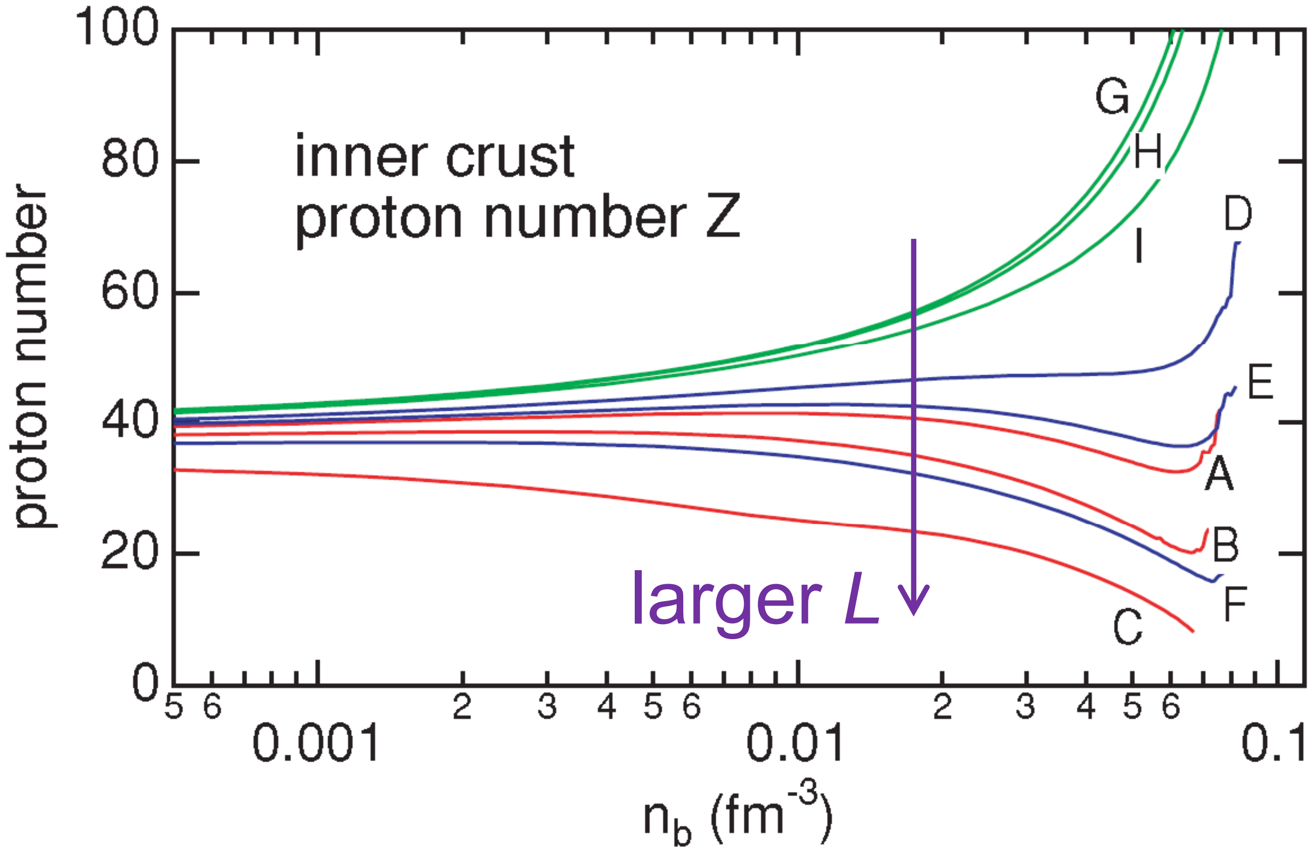
nuclei

electrons

dripped neutrons

Crust nuclei and L parameter

- Proton number of crust nuclei depends on *L*.

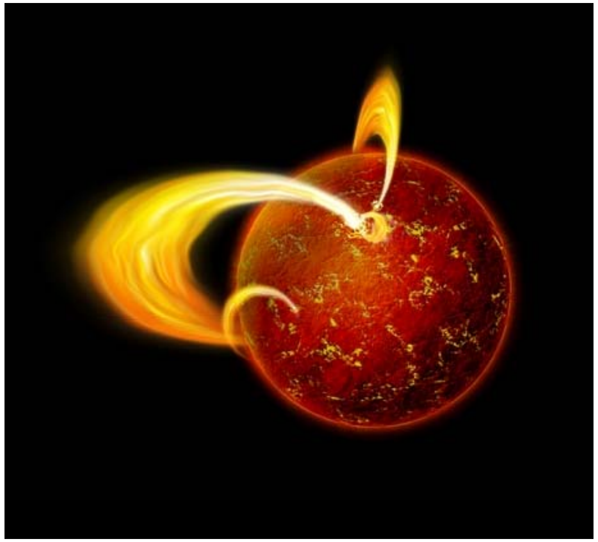


Oyamatsu & Iida (2007)

Proton number is small, if *L* is large.

Giant flare and QPO of SGR

- Soft gamma-ray repeater (SGR)
  - Neutron stars with high magnetic field（ $>10^{14}$G）
- 3 giant flares are detected from SGRs.
  - SGR 0526－66（1979）
  - SGR 1900＋14（1998）
  - SGR 1806－20（2004）

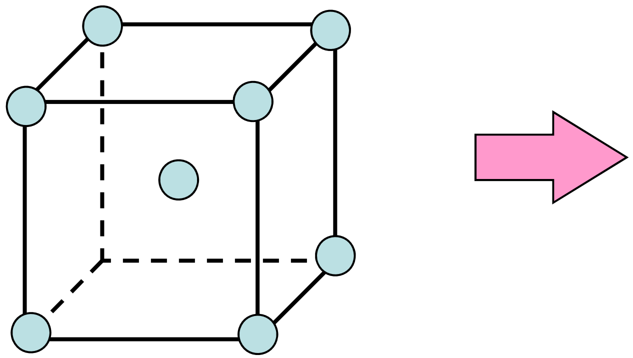


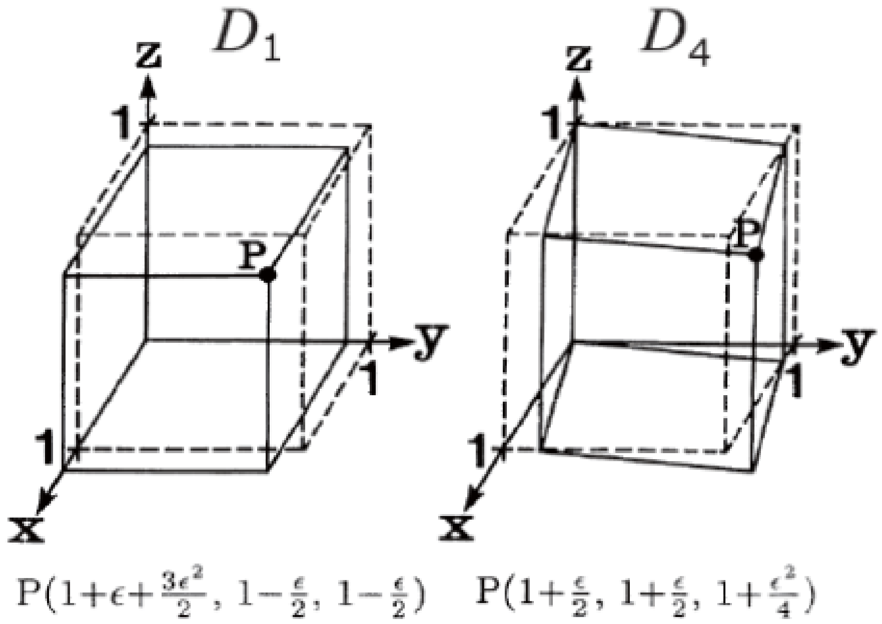
- Quasi periodic oscillation (QPO) is discovered in a decaying tail of giant flare.（SGR 1806－20）

Origin of QPOs

- Crustal shear mode
  - Note: other hypotheses also exist
- The oscillation frequency of Coulomb lattice depends on proton number

→ depends on *L*!!



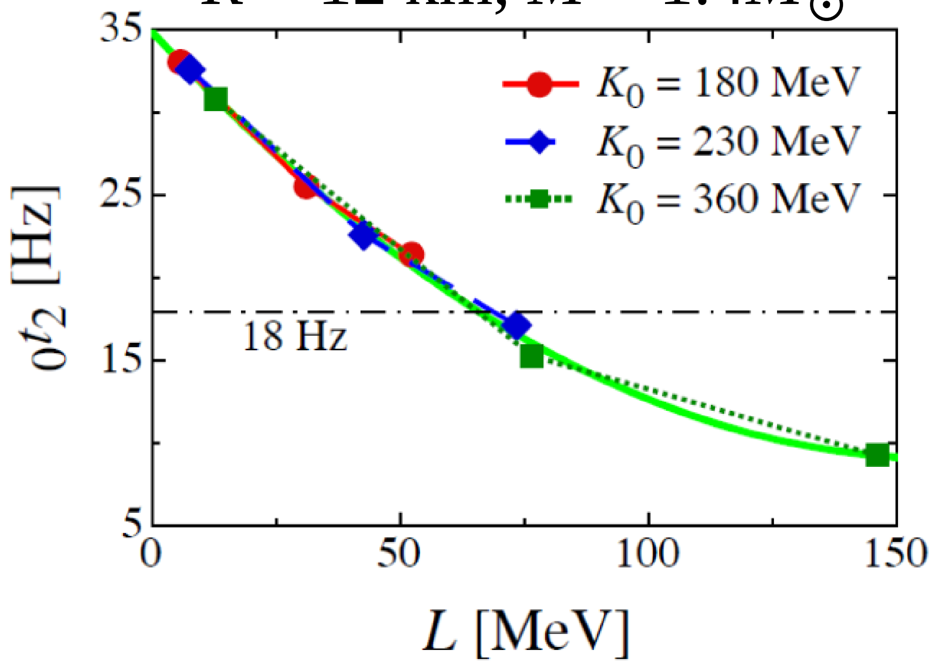


(Ogata and Ichimaru 1990)

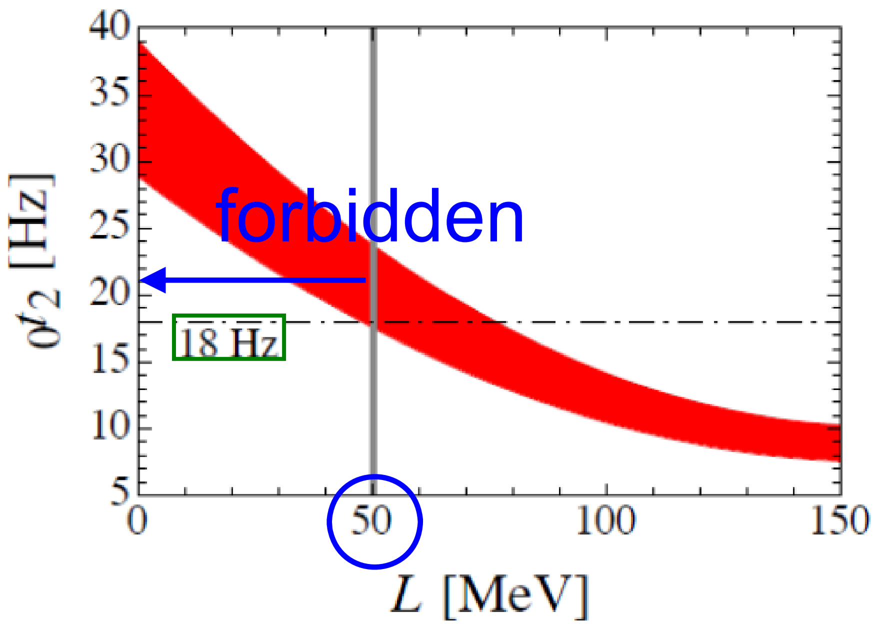
Constraint on L parameter

- General relativistic perturbative calculation to find eigenfrequencies for various *L*.
- To reproduce 18 Hz（lowest frequency）QPO, *L* > 50 MeV.

$R = 12$ km, $M = 1.4 M_\odot$



（Sotani et al. 2012）

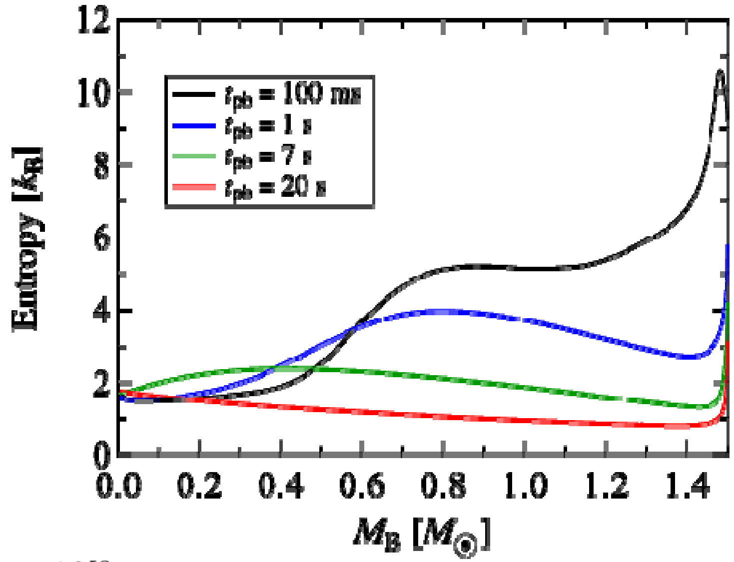


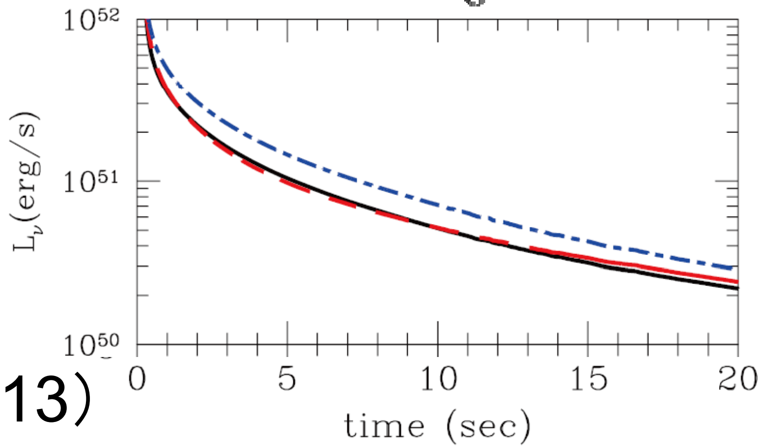
Hot (proto-)neutron stars

- Nascent hot neutron star（proto-neutron star：PNS）just after supernova is cooled by neutrino emission.
- Neutrino-nucleus scattering cross section depends on the mass number

$$\sigma \propto A^2$$

→ depends on *L*!?

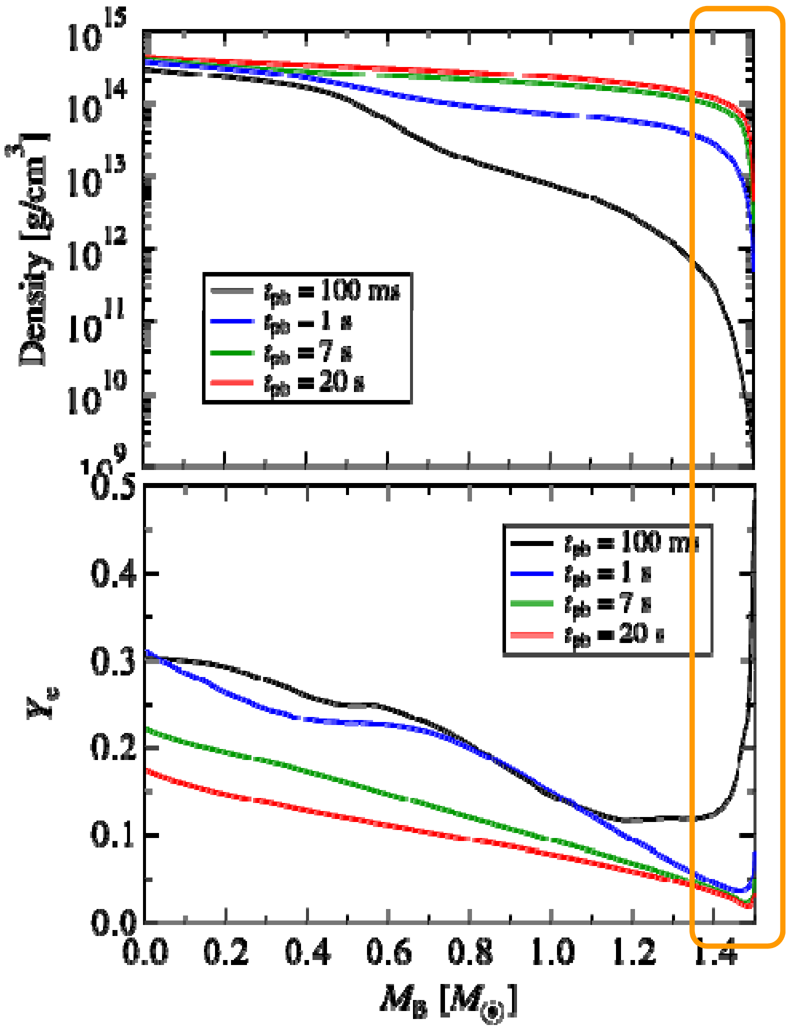




（Nakazato et al. 2013）

Nuclei in proto-neutron stars

- Inhomogeneous phase will appear during the proto-neutron star（PNS）cooling.



→ Nucleation

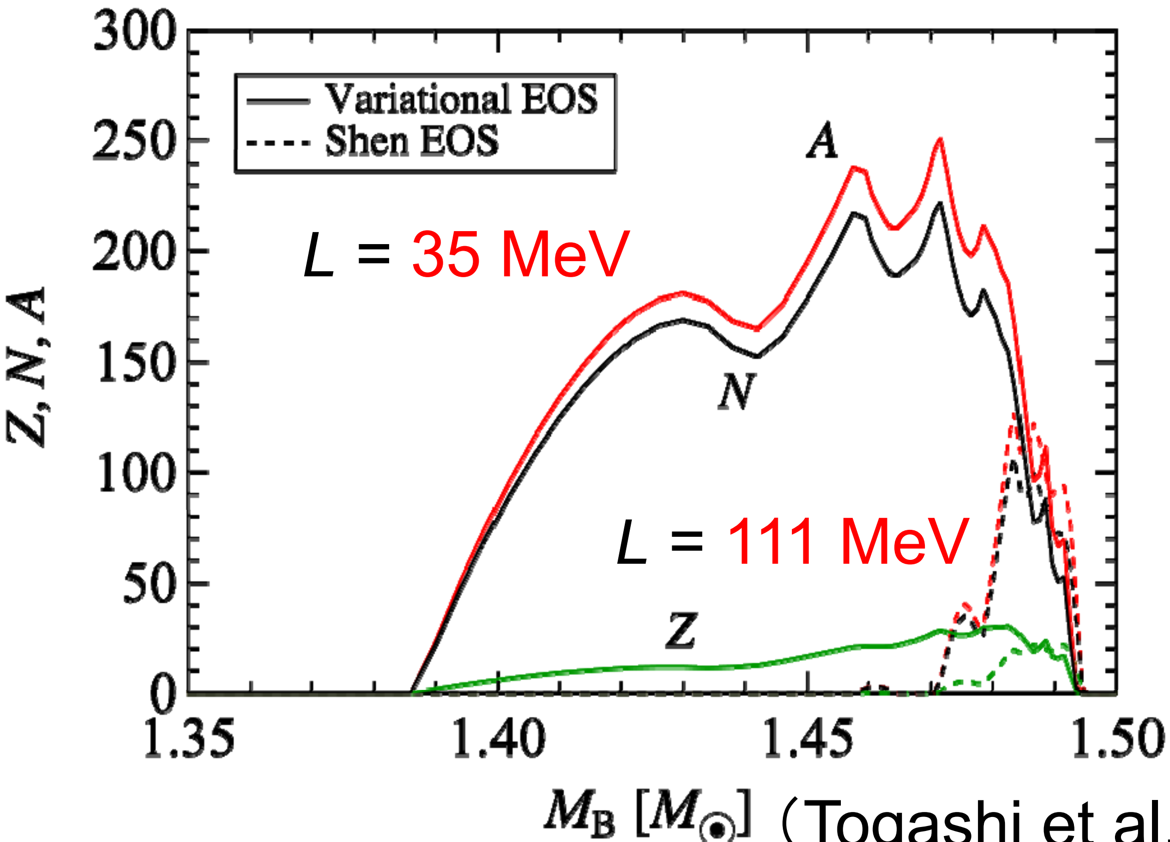
near the surface, low density and neutron rich

↓

transition to inhomogeneous phase（proto-crust）

Size of nuclei in PNS

- Comparing two EOS's with different *L*.
  - variational method (Togashi et al. in prep.), *L* = 35 MeV
  - relativistic mean field (Shen et al. 1998), *L* = 111 MeV



(Togashi et al. in prep)

Inhomogeneous phase is wide & mass number is large for small *L*.

↓

crucial for ν (future work!)

Summary

- Symmetry energy is important for astrophysics.
- Supra-nuclear density EOS is crucial for *M*-*R* relation of neutron stars, as well as exotic components（hyperons, quarks etc.）.
- Symmetry energy is characterized by S_0 and L.
- L determines nuclear size in inhomogeneous phase of neutron stars and proto-neutron stars.

  → L > 50 MeV according to crust oscillation

  → cooling by neutrinos will be affected by L