高密度物質と中性子星の物理
Physics of Neutron Star Matter

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- 中性子星の基本的性質
- 状態方程式を記述する理論模型
- 対称エネルギーと非対称核物質の状態方程式
- ハイパー核物理と高密度核物質の状態方程式
- 中性子星におけるエキゾチック自由度
- Supplementary Contents
  - 実験・観測・理論で解き明かす中性子星物質状態方程式
  - 重イオン衝突とハイパー核から中性子星へ

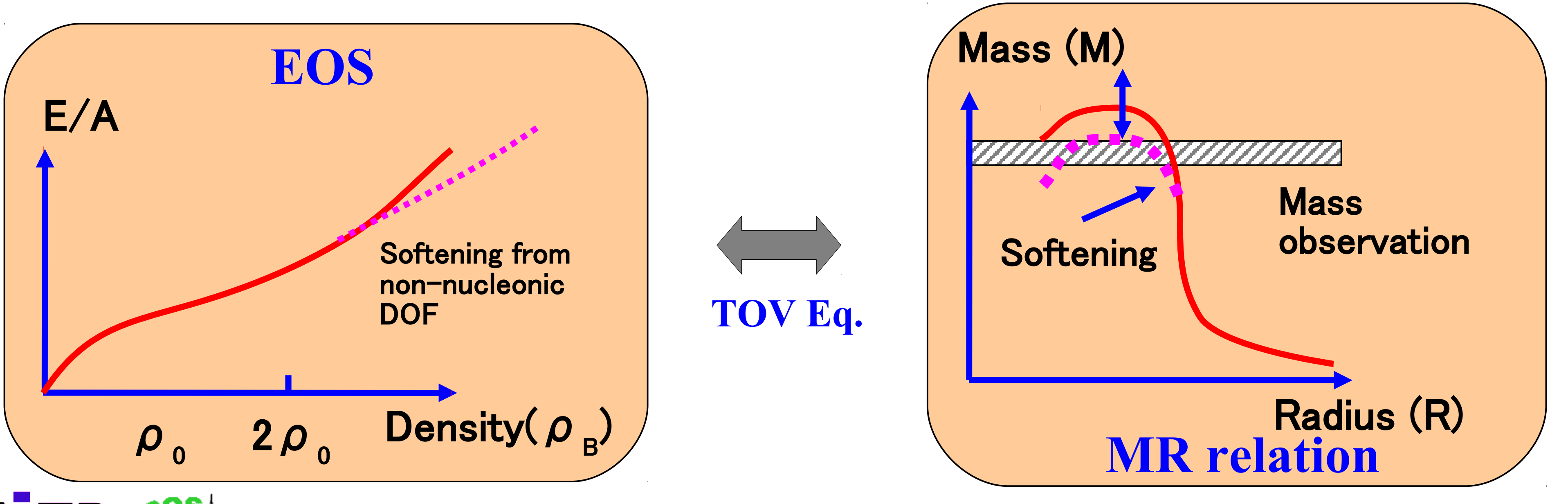
大阪大学集中講義　7/30-8/1

M-R Relation and EOS

- **Solving TOV eq.**
  starting from the "initial" condition, ε(r=0) = ε_c = given
  until the "boundary" condition P(r)=0 is satisfied.
  → M and R are the functions of ε(r=0)
  and functionals of EOS, P=P(ε).

$$M = M(\varepsilon_c)[P(\varepsilon)] \quad , \quad R = R(\varepsilon_c)[P(\varepsilon)]$$

→ M-R curve and NS matter EOS : 1 to 1 correspondence



Nuclear Mass

- **Bethe-Weizsacker mass formula**
  Nuclear binding energy is roughly given by Liquid drop.
  Nuclear size measurement → $R = r_0 A^{1/3}$

$$B(A,Z) = a_v A - a_s A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_a \frac{(N-Z)^2}{A} + a_p \frac{\delta_p}{A^\gamma}$$

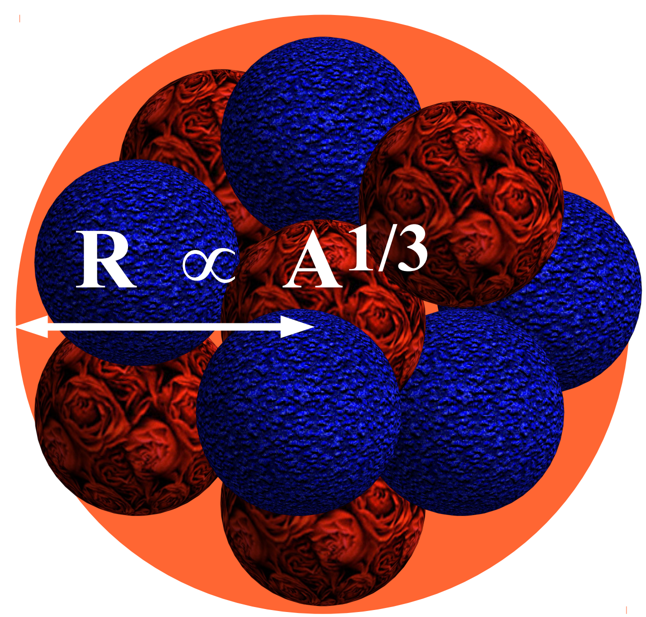
Volume **Surface** **Coulomb** **Symmetry** **Paring**

$A \propto \frac{4\pi}{3} R^3$ $A^{2/3} \propto 4\pi R^2$ $\propto \frac{Q^2}{R}$

- **Ignore Coulomb, consider A → ∞,**

$$B/A = a_v(\rho) - a_a(\rho)\delta^2 \quad , \quad \delta = (N-Z)/A$$

$$a_v \simeq 16\,\mathrm{MeV} \quad , \quad a_a \simeq 30\,\mathrm{MeV}$$



Coef. may depend on the number density ρ
→ Nuclear Matter EOS

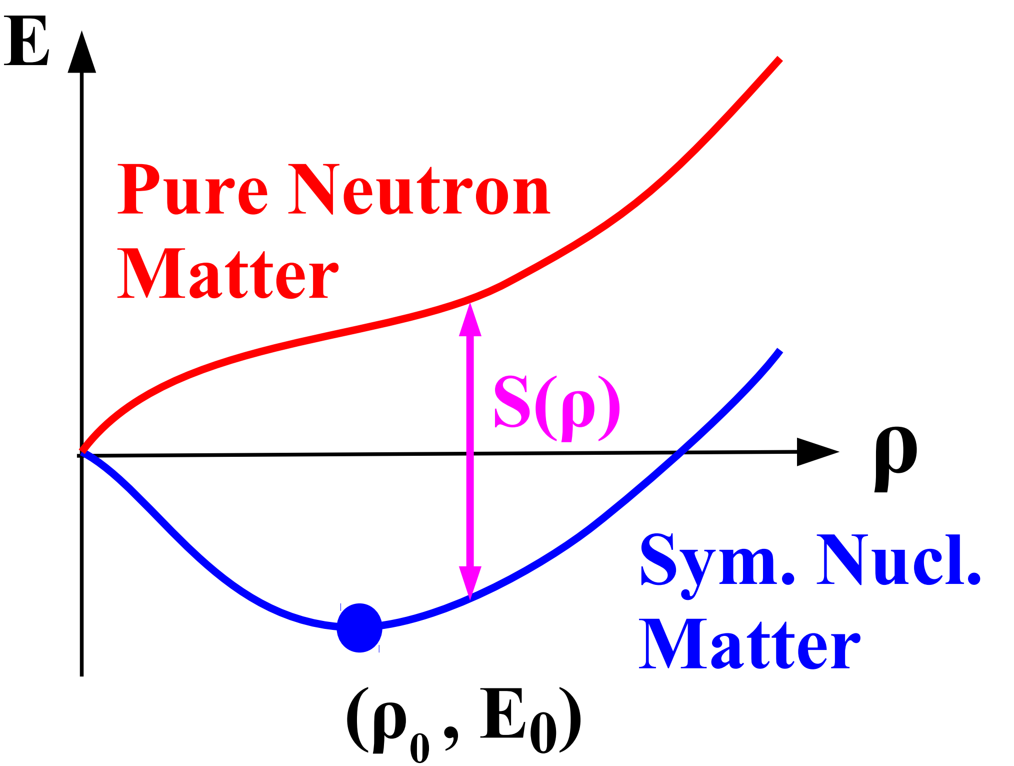
Nuclear Matter EOS

- **Energy per nucleon in nuclear matter**

$$E(\rho,\delta)=E_{\rm SNM}(\rho)+E_{\rm Sym}(\rho)\delta^2 \quad , \quad \delta=(N-Z)/A$$

- **Saturation point (ρ_0, E_0)**
  - $\rho_0 \sim 0.15\ \mathrm{fm}^{-3}$
  - $E_0 = -a_v \sim -16$ MeV
  - (nuclear radius and mass)

- **Symmetry energy**
  - $S(\rho) = E_{PNM}(\rho) - E_{SNM}(\rho)$
  - $= E(\rho, \delta=1) - E(\rho, \delta=0)$
  - $S_0 = S(\rho_0) \sim 30$ MeV
  - (mass formula)



> ***Nuclear Matter EOS can be, in principle, determined by terrestrial (laboratory) nuclear physics experiments !***

- **Additional two important parameters: K and L**
- **Pressure is given by the derivative of E via ρ**

$$P = \rho^2 (\partial E / \partial \rho)$$

At ρ_0, L determines P

$$P = \rho_0 L/3 \ (\text{at} \quad \rho = \rho_0)$$

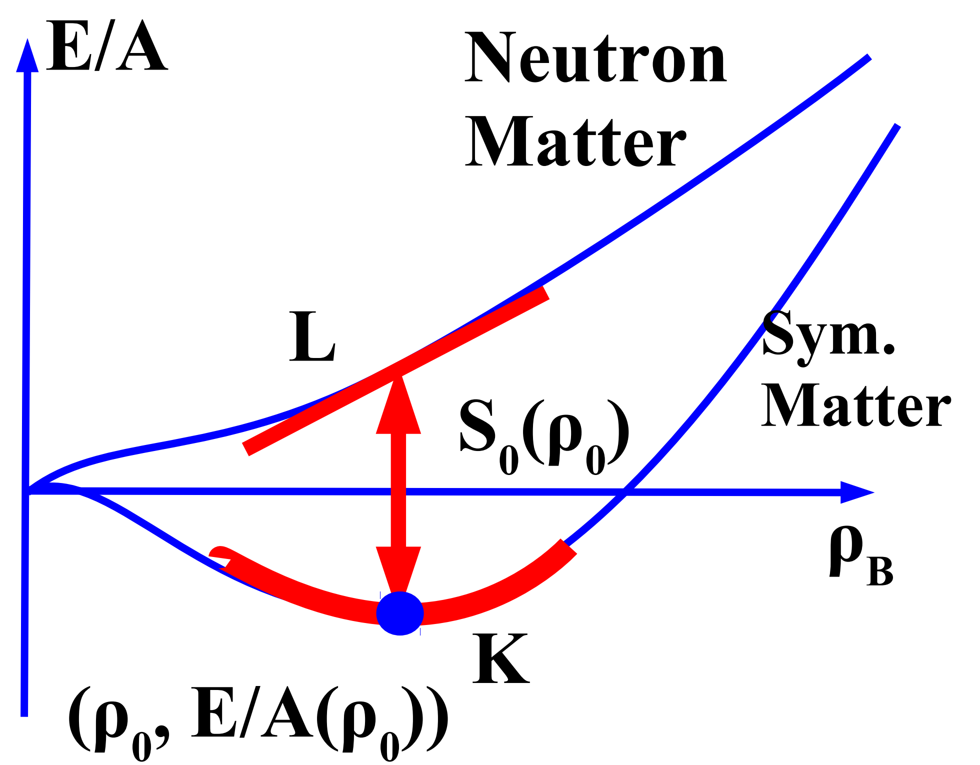
$$E/A(\rho, \delta) = \varepsilon(\rho) + E_{\text{sym}}(\rho)\delta^2 + O(\delta^4)$$

Symmetric Nuclear Matter

$$\varepsilon(\rho) = \varepsilon(\rho_0) + \frac{K(\rho-\rho_0)^2}{18\rho_0^2} + O((\rho-\rho_0)^3)$$

Symmetry Energy $\quad (\delta = (N-Z)/A = 1 - 2Y_p)$

$$E_{\text{sym}}(\rho) = S_0 + \frac{L(\rho-\rho_0)}{3\rho_0} + \frac{K_{\text{sym}}(\rho-\rho_0)^2}{18\rho_0^2} + O((\rho-\rho_0)^3)$$

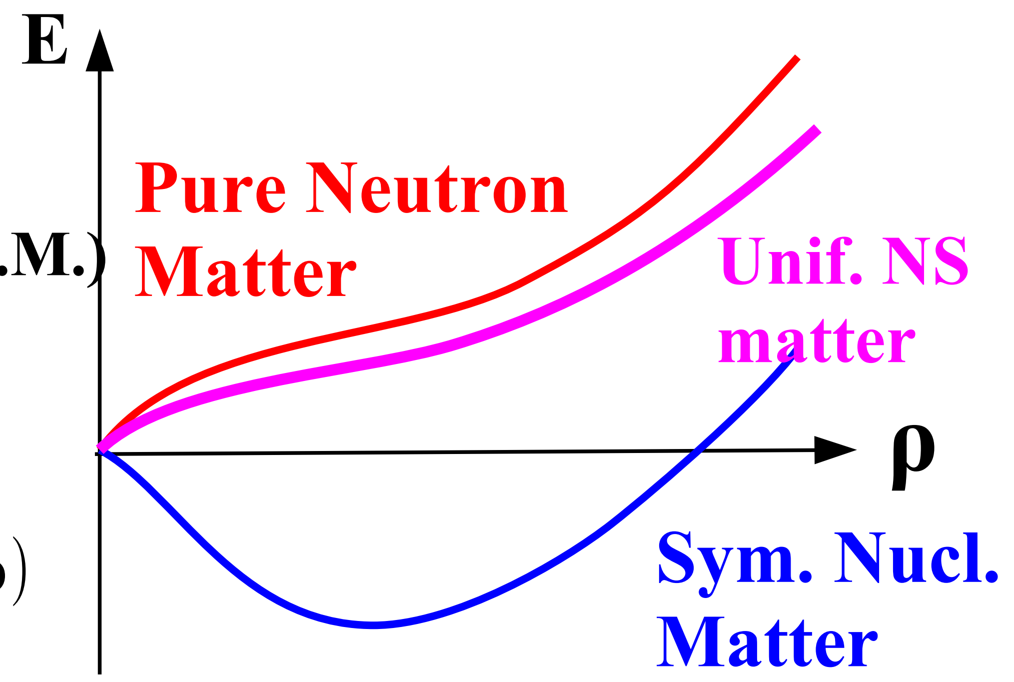


Neutron Star Matter EOS

- **What happens in low-density uniform neutron star matter ?**
  - **Constituents = proton, neutron and electron**
  - **Charge neutrality → # of electons= # of protons ($\rho_e=\rho_p=\rho(1-\delta)/2$)**

$$E_{\rm NSM}(\rho)=E_{\rm NM}(\rho,\delta)+E_e(\rho_e=\rho_p)$$
$$=E_{\rm SNM}(\rho)+S(\rho)\delta^2+\frac{\Delta M}{2}\delta+\frac{3}{8}\hbar k_F(1-\delta)^{4/3}$$

**(electron mass neglected,
neutron-proton mass diff. incl.
k_F= Fermi wave num. in Sym. N.M.)**



  - **δ is optimized to minimize energy per nucleon**

$$E_{\rm NSM}(\rho)\leq E_{\rm NM}(\rho,\delta=1)=E_{\rm PNM}(\rho)$$

対称エネルギーの起源

- **Fermi Gas model での核子あたりの運動エネルギー**

$$E_{\mathrm{sym},K} = \frac{Z}{A}\frac{3}{5}\frac{\hbar^2 k_{\mathrm{F}p}^2}{2m} + \frac{N}{A}\frac{3}{5}\frac{\hbar^2 k_{\mathrm{F}n}^2}{2m} = \frac{3}{5}E_{\mathrm{F}}\frac{1}{2}\left[(1-\delta)^{5/3} + (1+\delta)^{5/3}\right]$$

$$\simeq \frac{3}{5}E_{\mathrm{F}} + \frac{1}{3}E_{\mathrm{F}}\delta^2 + \mathcal{O}(\delta^4)$$

a_{sym} (FG)=E_F/3 ~ 11 MeV となり、質量公式の a_{sym} ~ 23 MeV (surface を考えると a_{sym} (vol) ~ 30 MeV) と比べて半分程度。残りは相互作用。

- **残りの半分の対称エネルギーを RMF で評価してみましょう。**

$$\Delta E_{\mathrm{sym},\rho} = \frac{1}{2}\frac{m_\rho^2 R^2}{\rho_B} = \frac{1}{2}\frac{g_\rho^2}{m_\rho^2}\rho_B\delta^2 = \Delta a_{\mathrm{sym}}\delta^2 \quad \left(R = \frac{g_\rho(\rho_n - \rho_p)}{m_\rho^2} = \frac{g_\rho \rho_B \delta}{m_\rho^2}\right)$$

$$g_\rho^2 = \frac{2m_\rho^2 \Delta a_{\mathrm{sym}}}{\rho_B} \simeq (4.3)^2 \quad (a_{\mathrm{sym}} = 30\,\mathrm{MeV})$$

← **RMF par. より少し小さめ**

$$L \simeq E_F + 3\Delta a_{\mathrm{sym}} \simeq 90\,\mathrm{MeV}$$

← **Optimal value より少し大きい**

Simple parametrized EOS

- **Skyrme int. motivated parameterization**

$$E_{\rm SNM} = \frac{3}{5} E_F(\rho) + \frac{\alpha}{2}\left(\frac{\rho}{\rho_0}\right) + \frac{\beta}{2+\gamma}\left(\frac{\rho}{\rho_0}\right)^{1+\gamma}$$

$$\alpha = \frac{2}{\gamma}\left(E_0(1+\gamma) - \frac{E_F(\rho_0)(1+3\gamma)}{5}\right) \ , \quad \beta = \frac{2+\gamma}{\gamma}\left[-E_0 + \frac{1}{5}E_F(\rho_0)\right] \ .$$

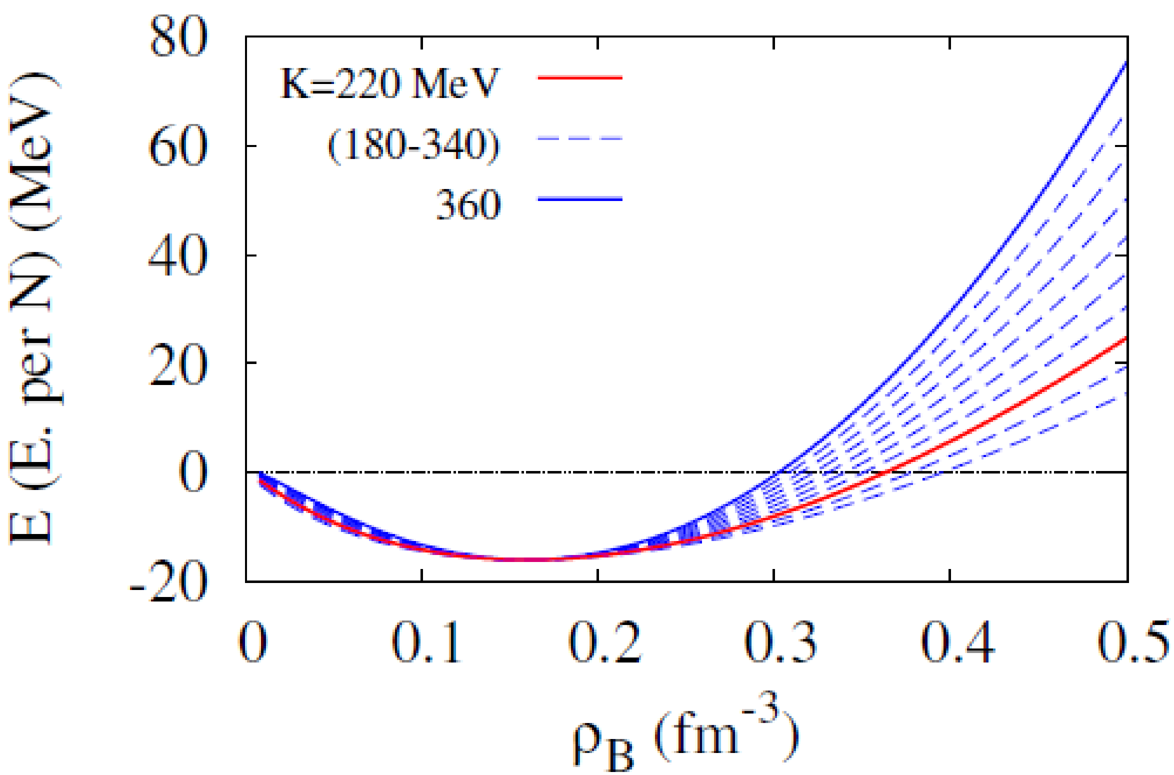
$$K = \frac{1+3\gamma}{5} E_F(\rho_0) - 3E_0(1+\gamma) \ .$$

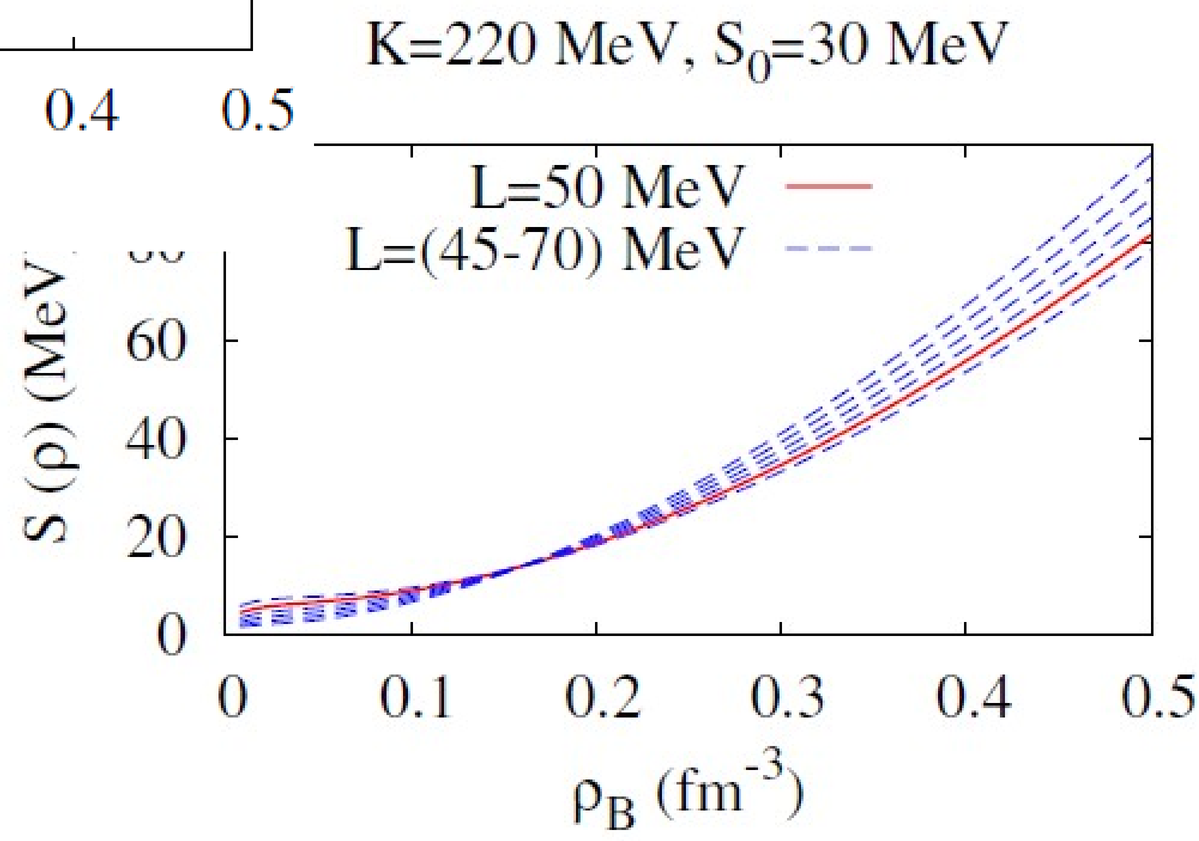
- **Symmetry energy parameterization**

$$S(\rho) = \frac{1}{3} E_F(\rho) + \left[S_0 - \frac{1}{3}E_F(\rho_0)\right]\left(\frac{\rho}{\rho_0}\right)^{\gamma_{\rm sym}}$$

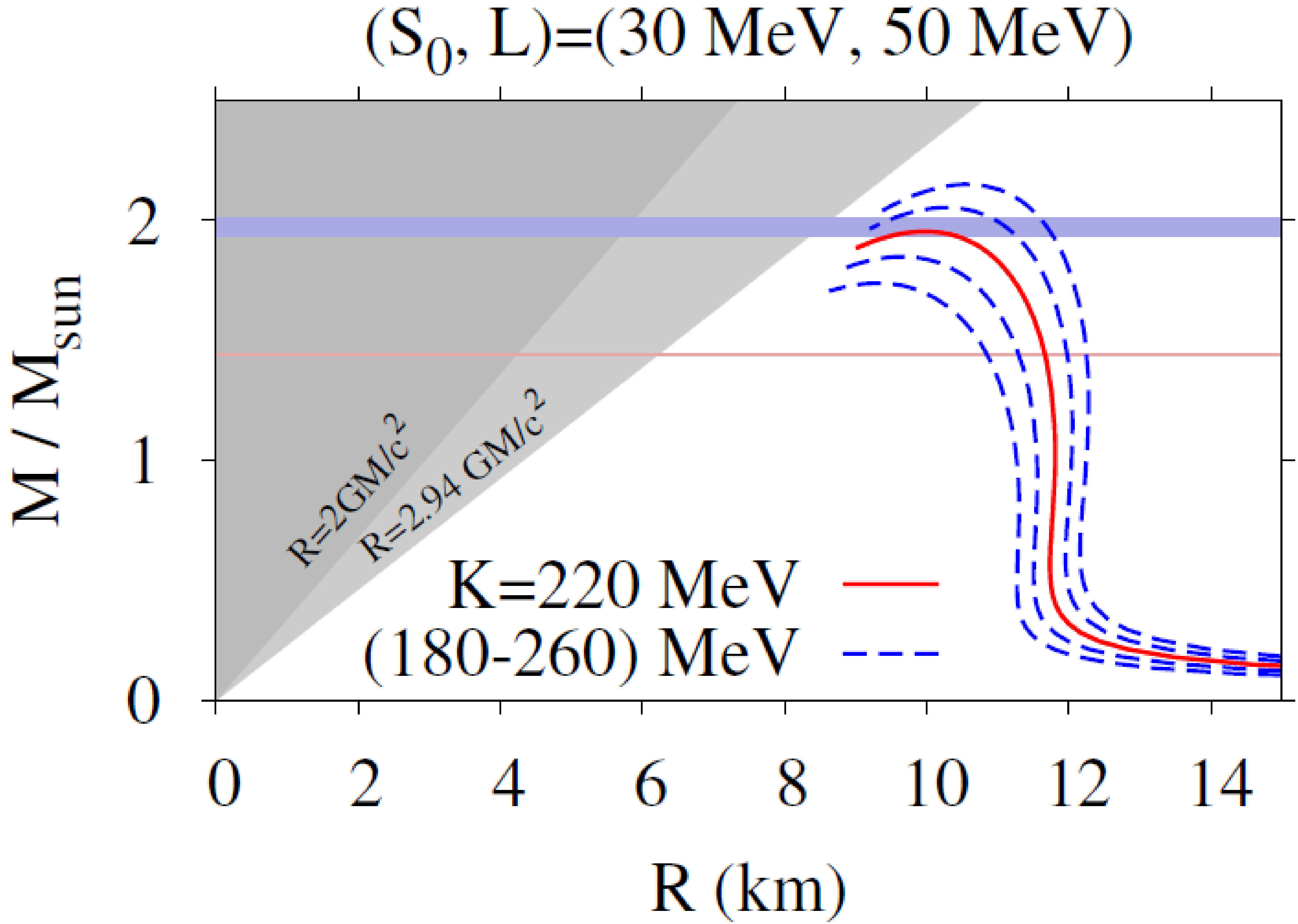
$$\gamma_{\rm sym} = \frac{L - \frac{2}{3}E_F(\rho_0)}{3S_0 - E_F(\rho_0)}$$

Simple parametrized EOS

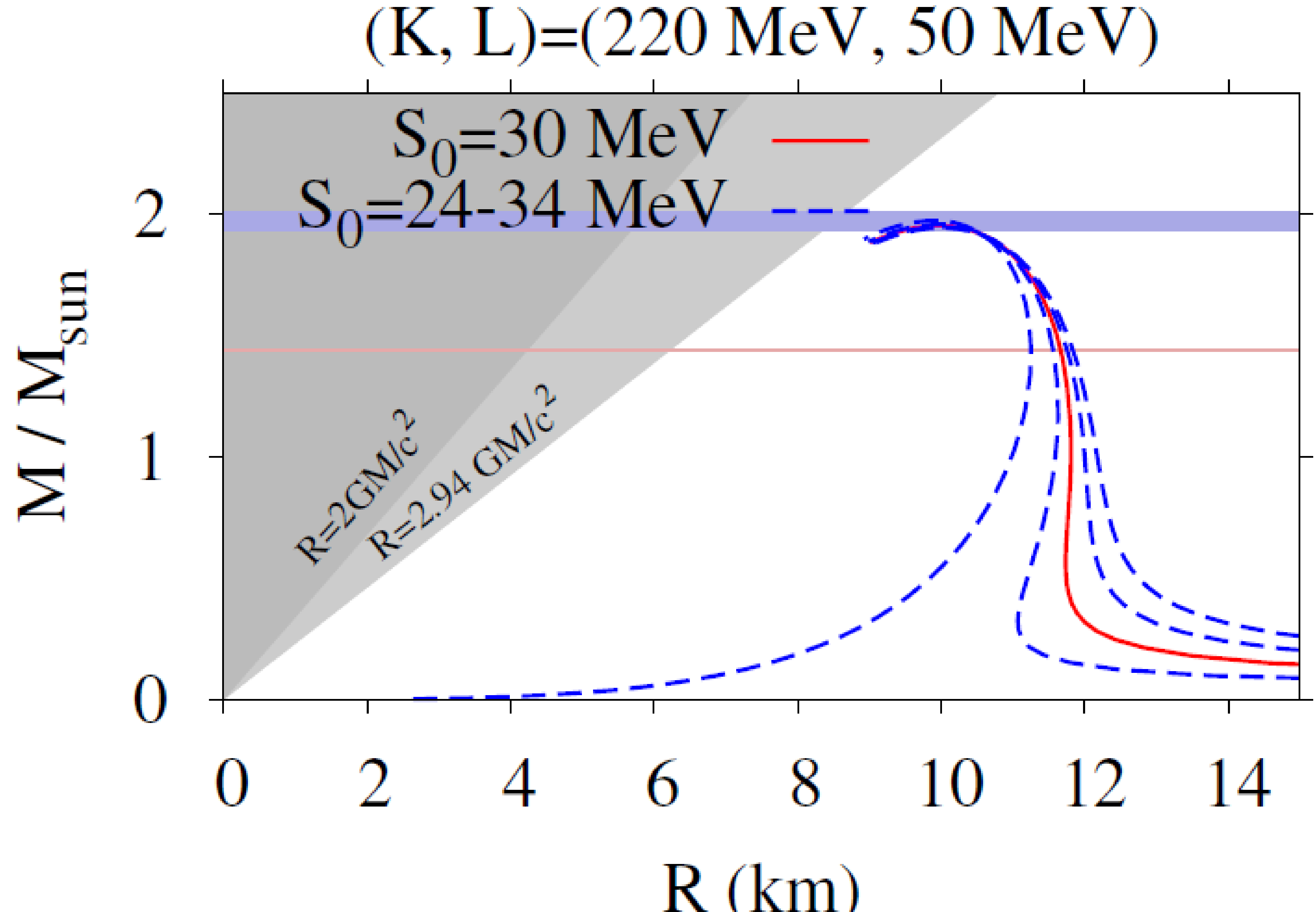




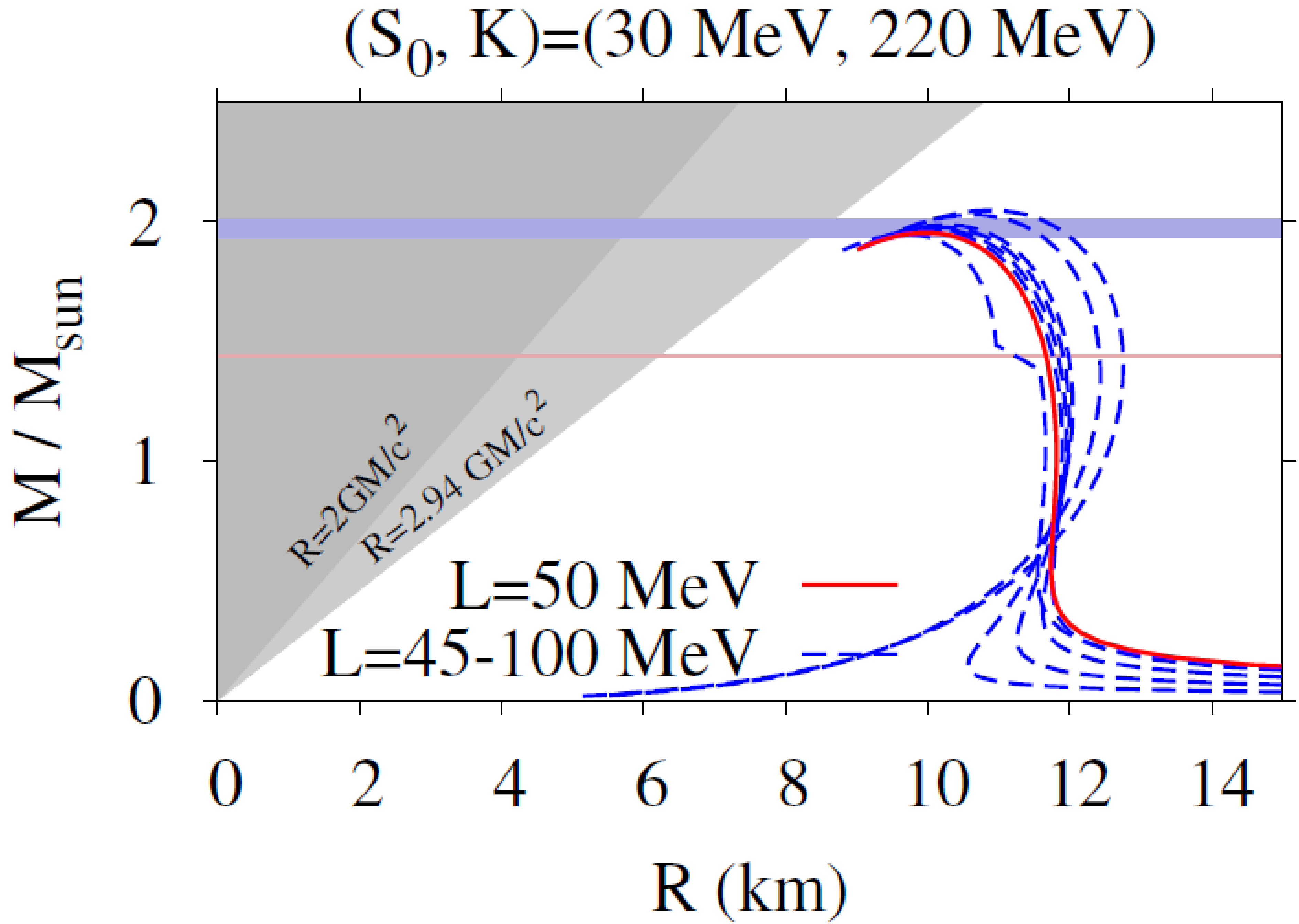
Simple parametrized EOS



Simple parametrized EOS

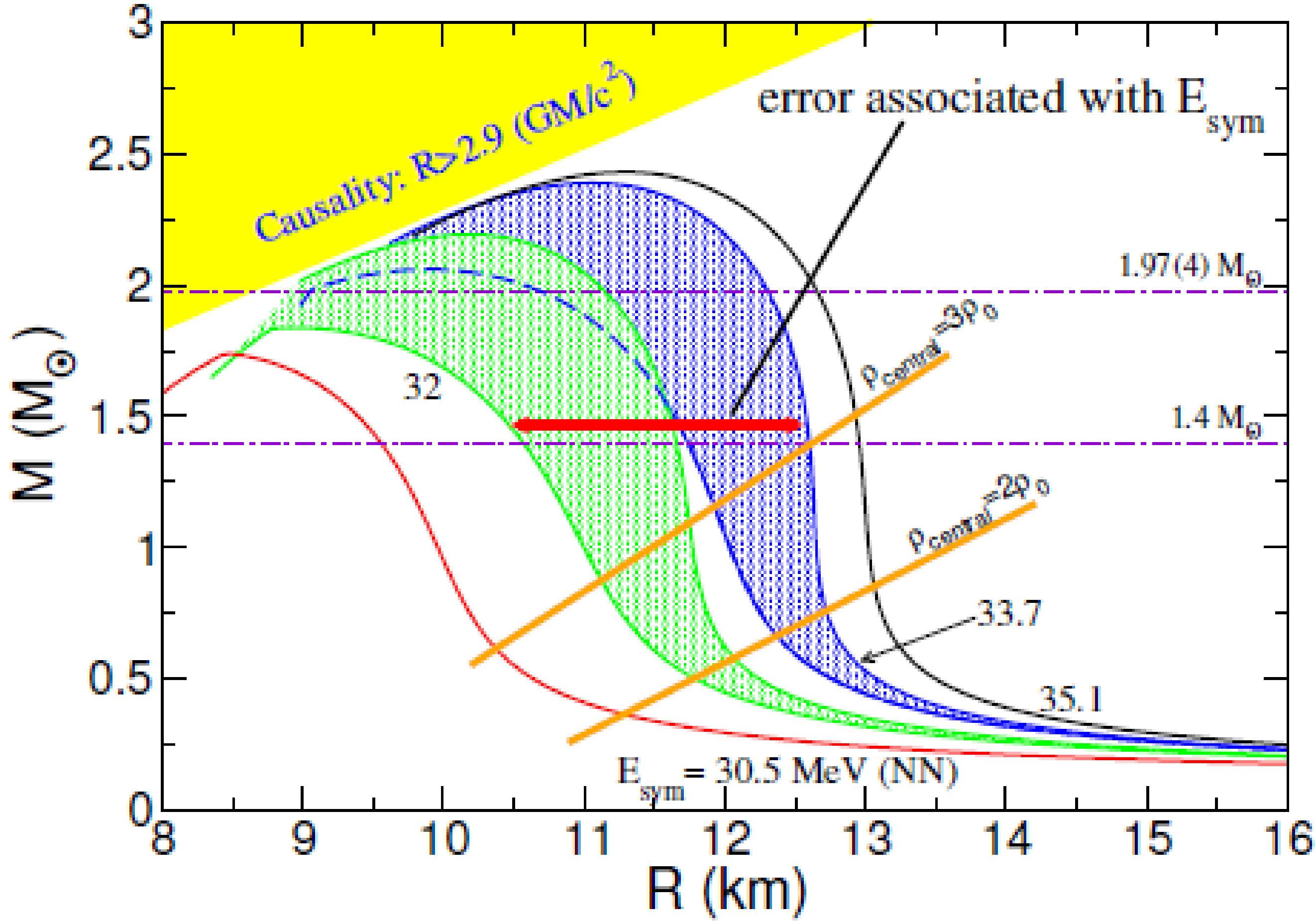


Simple parametrized EOS



Symmetry Energy affects MR Relation of NS

- **Nuclear pressure at ρ_0 comes ONLY from Esym, then Esym dominates pressure around ρ_0 !**
- **5 MeV Difference in Esym results in (3-4) km difference in R_{NS} prediction.**



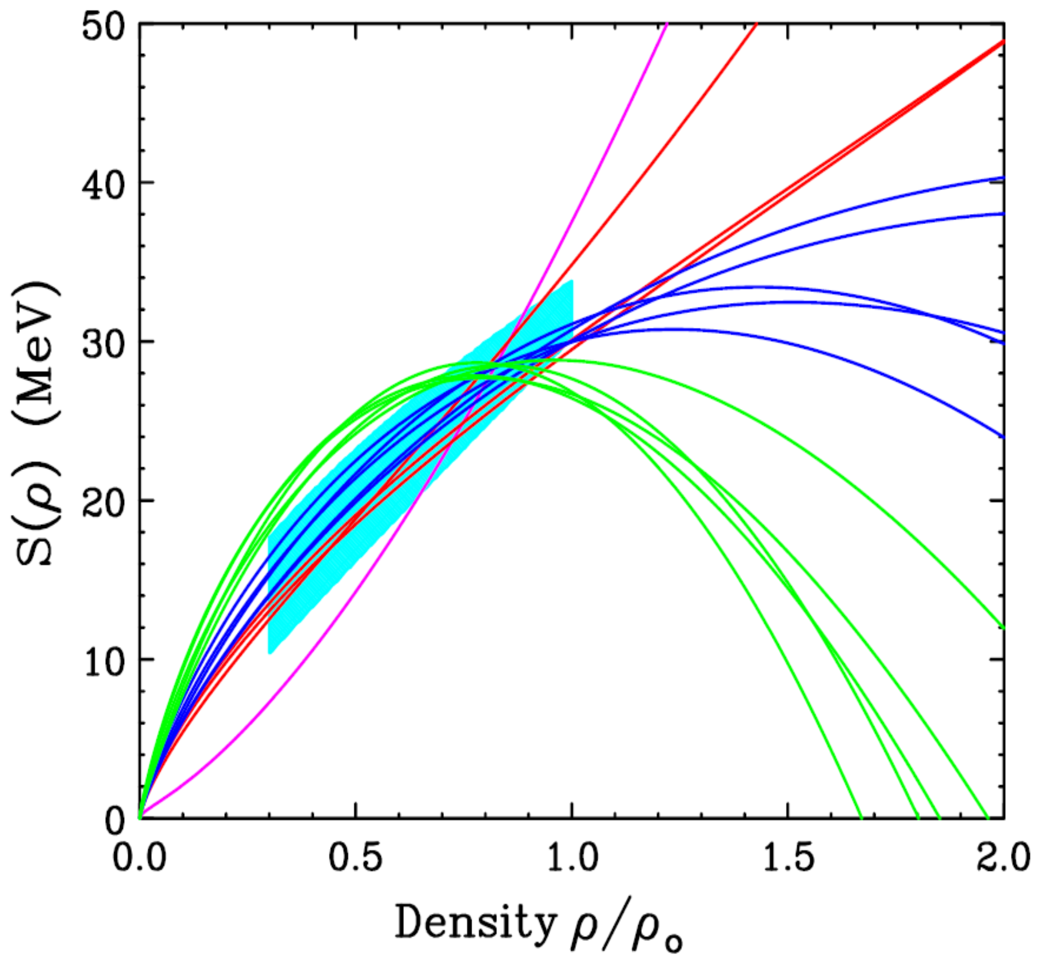
Gandolfi, Carlson, Reddy, PRC 032801, 85 (2012).

Symmetry Energy

- Summary of Nuclear Symmetry Energy workshop NuSym11 http://www.smith.edu/nusym11

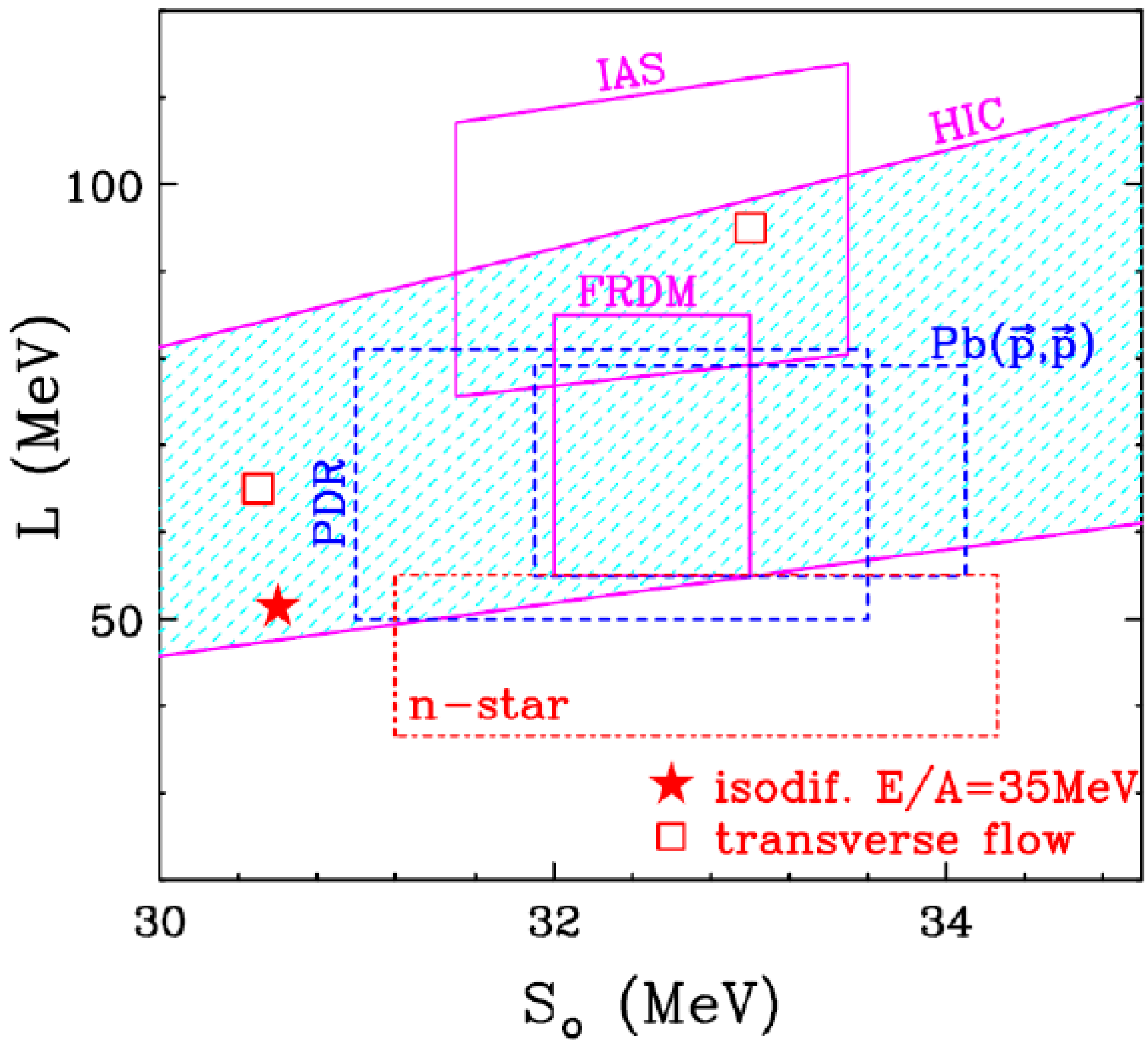
  $E_{sym}(\rho_0)$ = 31-34 MeV, L = 50-110 MeV

  extracted from various observations.
  - Mass formula *Moller ('10)*
  - Isobaric Analog State *Danielewicz, Lee ('11)*
  - Pygmy Dipole Resonanc *Carbone+ ('10)*
  - Isospin Diffusion *Tsang et al. ('04)*
  - Neutron Skin thickness *J.Zenihiro+ ('10)*
- これらの多くは ρ_0 以下の密度での Esym に敏感。



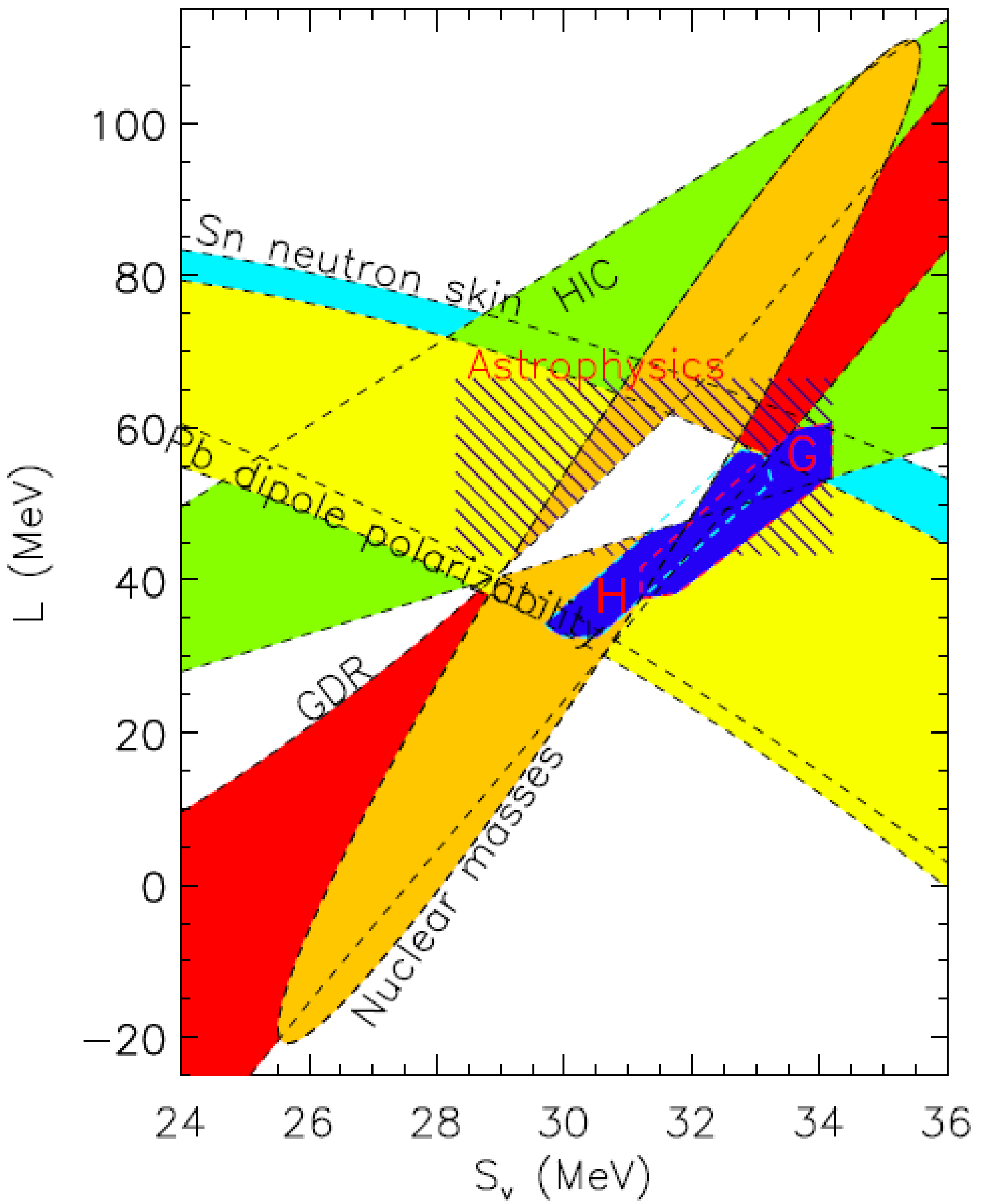
M. B. Tsang et al., Phys. Rev. C 86 (2012) 015803.

Nuclear Symmetry Energy (NuSYM 2011)



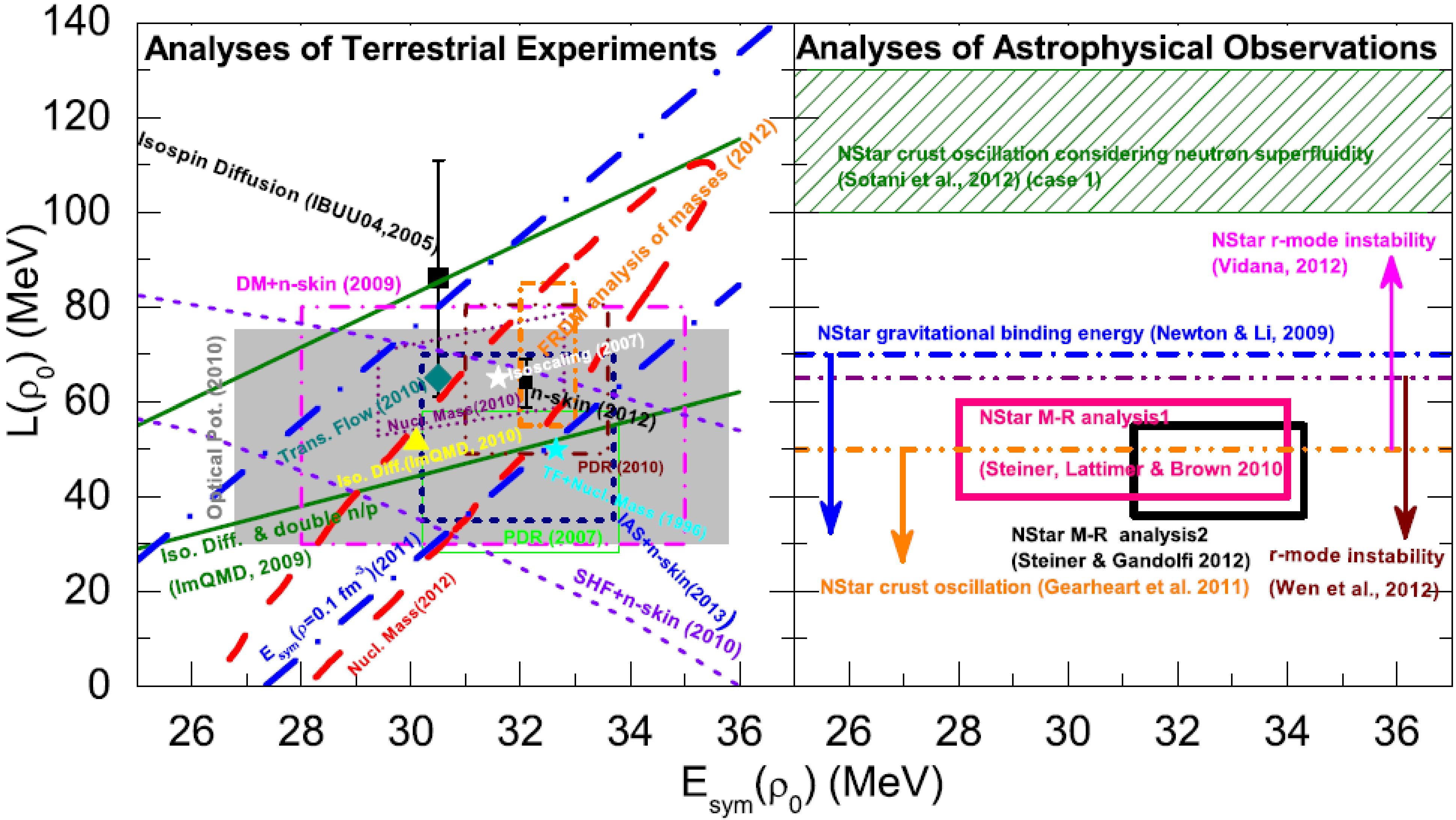
Tsang et al. ('12): NuSYM 2011

Nuclear Symmetry Energy (Lattmier-Lim, 2013)



Lattimer, Lim ('13)

Nuclear Symmetry Energy (NuSYM 2013)



B. A. Li et al. ('13)

Nuclear Mass

- **Larger symmetry energy → B.E. of n-rich nuclei become smaller.**
  - **Volume and surface symmetry energy**

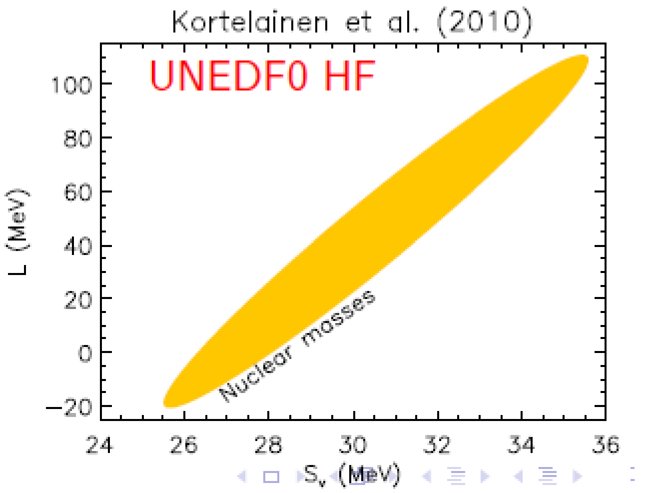
$$E_{\rm sym}(A)=a_a(A)=S_v-S_s A^{-1/3}$$
$$(\delta=(N-Z)/A=1-2Y_p)$$

$$B(A,Z)=a_v A - a_s A^{2/3} - a_C\frac{Z^2}{A^{1/3}} - a_a\frac{(N-Z)^2}{A} + a_p\frac{\delta_p}{A^\gamma}$$

  - **Finite Range Droplet Model**
    P.Moller, W.D.Myers, H.Sagawa, S.Yoshida, Phys. Rev. Lett. 108, 052501 (2012)

$$S_v=32.5\pm0.5\,\mathrm{MeV}\,,\ L=70\pm15\,\mathrm{MeV}$$

  - **Density Functional (UNEDF)**
    Kortelainen et al. (2010)



Lattimer, Lim ('13)

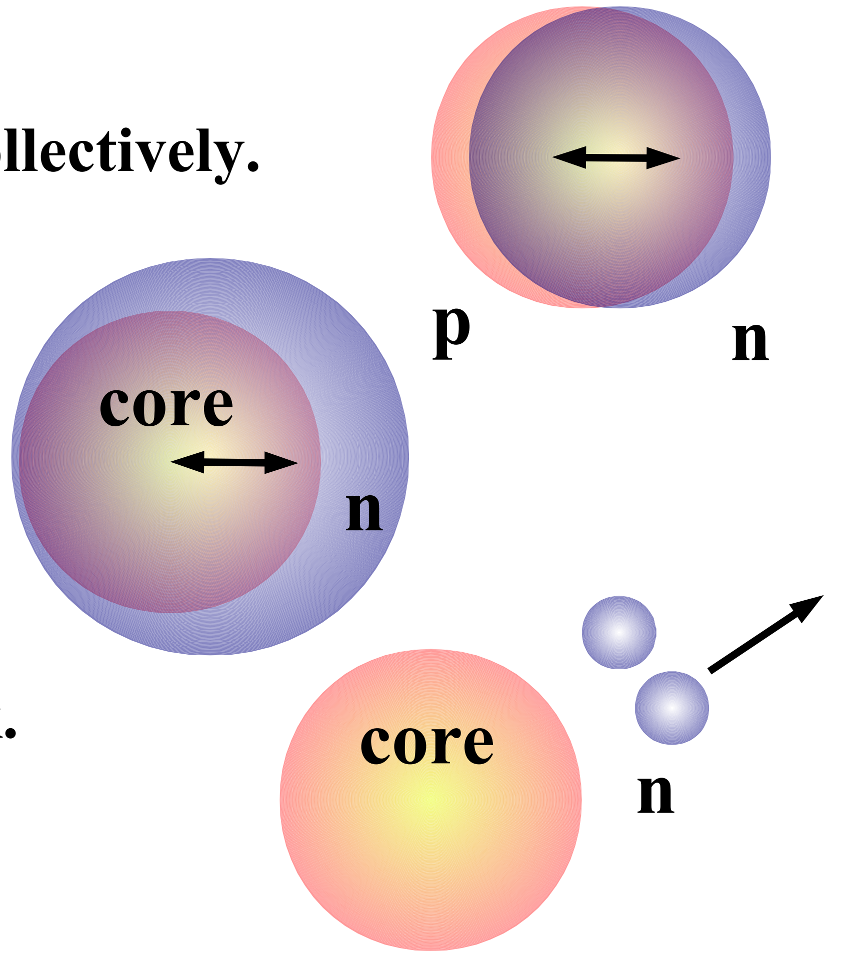
Well, relax (rough idea)

- When L and Sv are linearly correlated as
  $L = a\,S_v + b$,
  Symmetry energy is given as
  $E_{sym}(x) = Sv + L(x-1)/3 = Sv\,(1+a(x-1)/3) + \text{const. (indep. of Sv)}$
  $(x = \rho/\rho_0)$
  → That observable determines symmetry energy
  most effectively at $x = 1 - 3/a$.

- Nuclear mass: $a \sim 14$
  原子核質量は $x \sim 1 - 3/14 = 0.78$ 近辺の対称エネルギーを
  よく決める

Pigmy Dipole Resonance

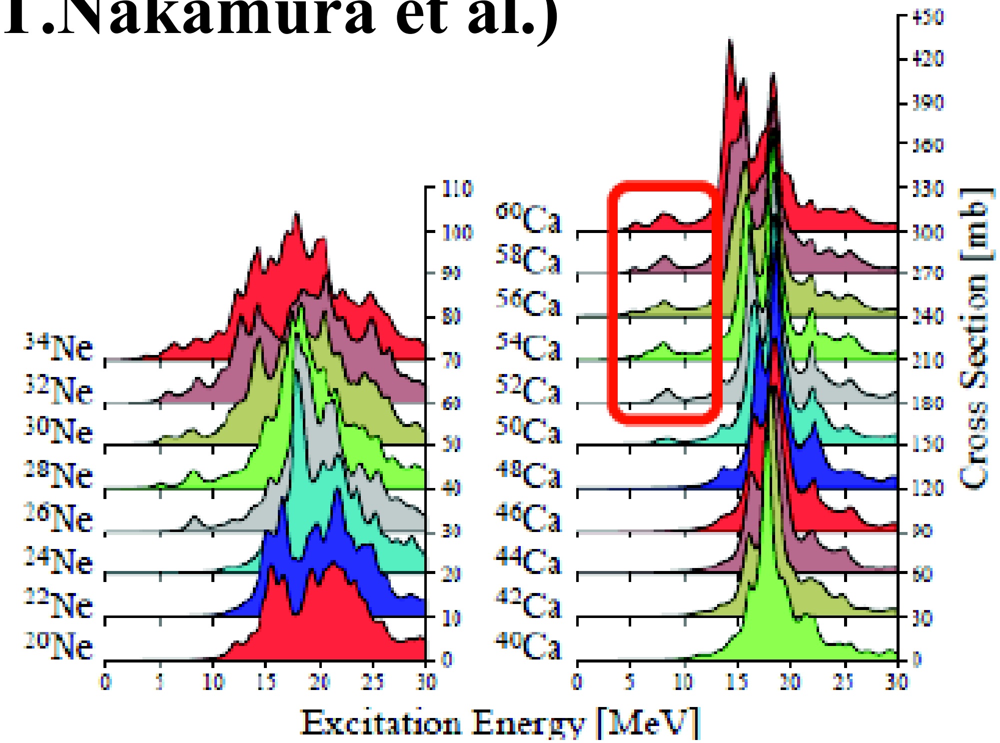
- **E1 response of nuclei**
  - **Giant Resonance: p and n oscillates collectively.**
    $E^* \sim 80\ A^{-1/3}$ MeV
  - **Pigmy Dipole Resonance:**
    Core oscillates in neutron skin/halo
    $E^* \sim (5\text{-}10)$ MeV
  - **Soft E1 excitation**
    When n wf is extended,
    direct dissociation σ also shows a peak.



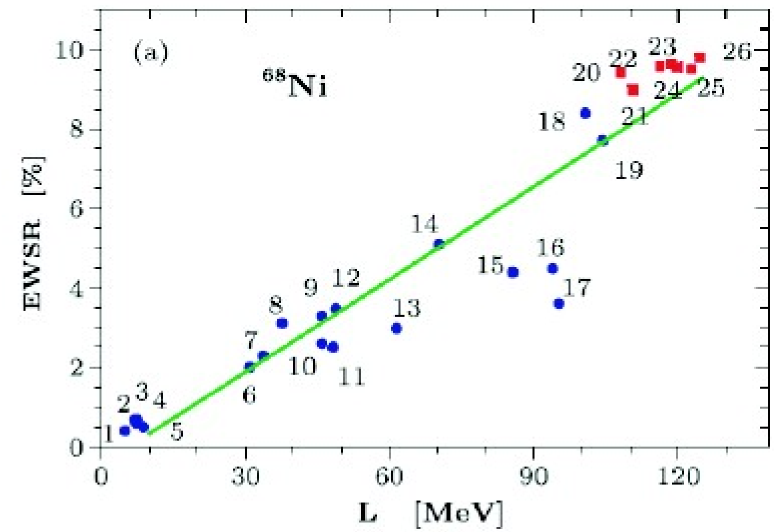
PDR would be sensitive to Esym

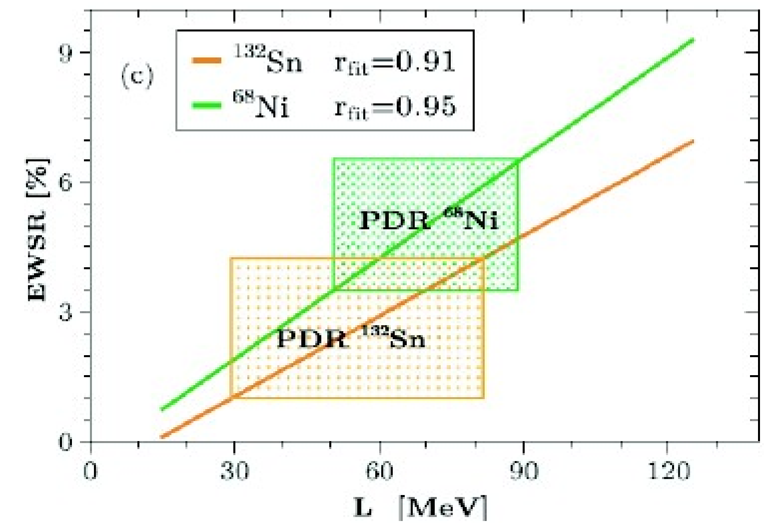
PDR of neutron skin nuclei

- **Energy Weighted Sum Rule value of PDR would has linear dep. on L**
- **PDR of very neutron rich nuclei will be measured at RIBF-SAMURAI (T.Nakamura et al.)**



T.Inakura, T.Nakatsukasa, K.Yabana
Phys.Rev. C 84, 021302(R) (2011)





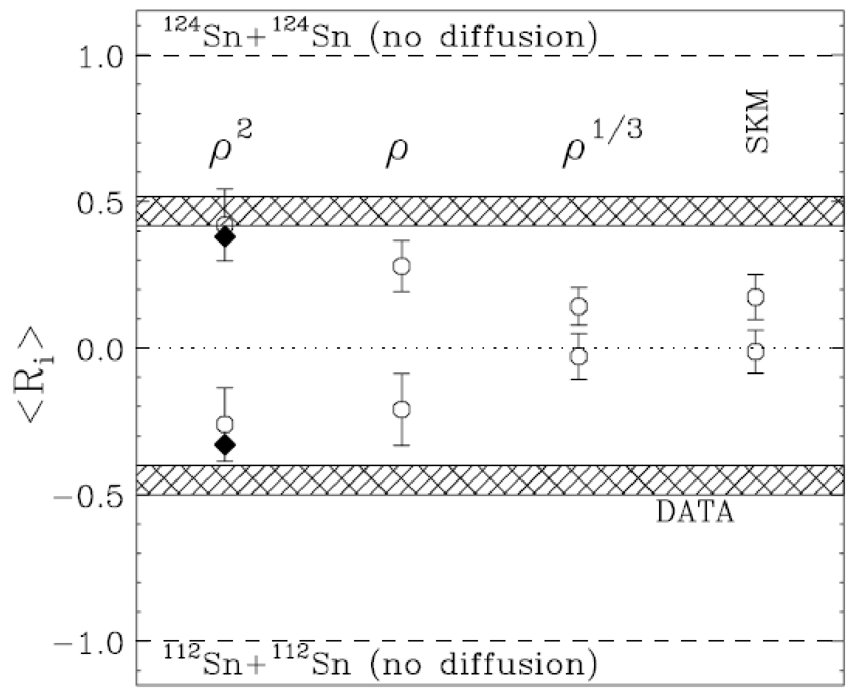
P. Adrich et al., PRL 95, 132501 (2005) .(GSI) 130,132Sn
O.Wieland et al., PRL 102, 092502 (2009) . (GSI) 68Ni

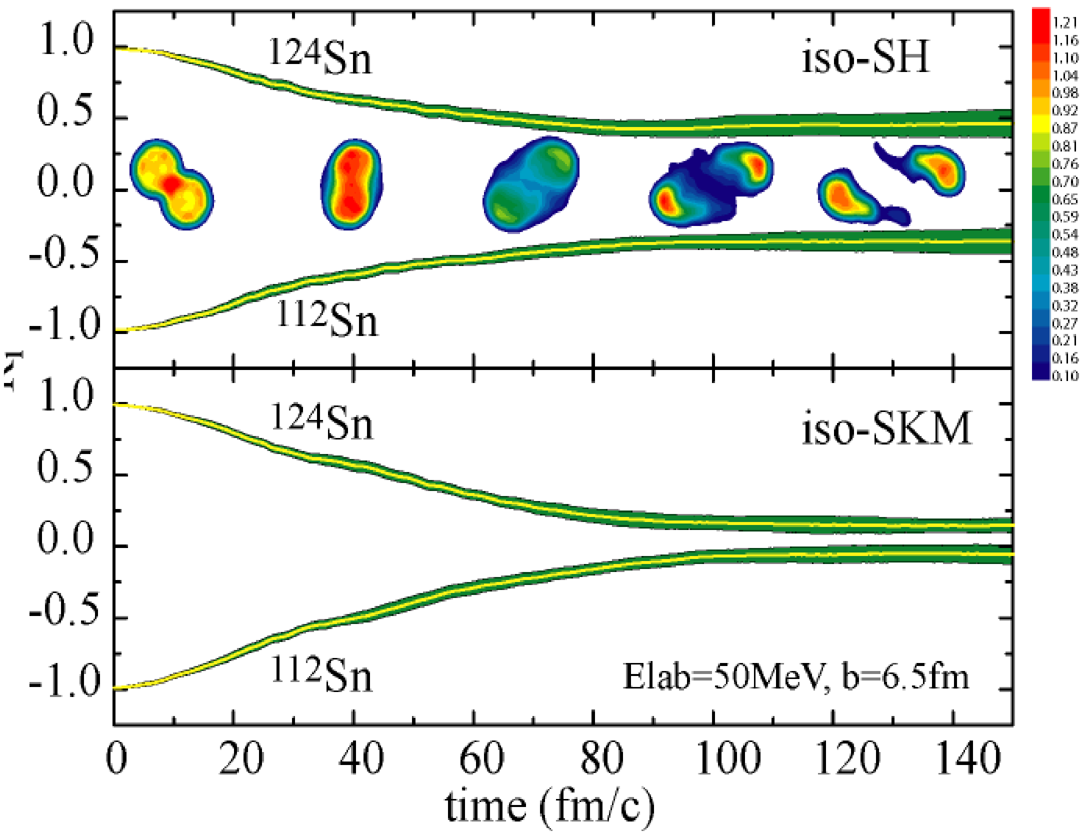
Isospin Diffusion

- **Collision of nuclei having different n/p ratio**
  → fragments with medium n/p ratio will be formed
  (Isospin diffusion)

- **Driving force of isospin diffusion**
  = Symmetry energy

$$R_i = \frac{2x - x_{124+124} - x_{112+112}}{x_{124+124} - x_{112+112}}$$





Tsang et al. ('04)

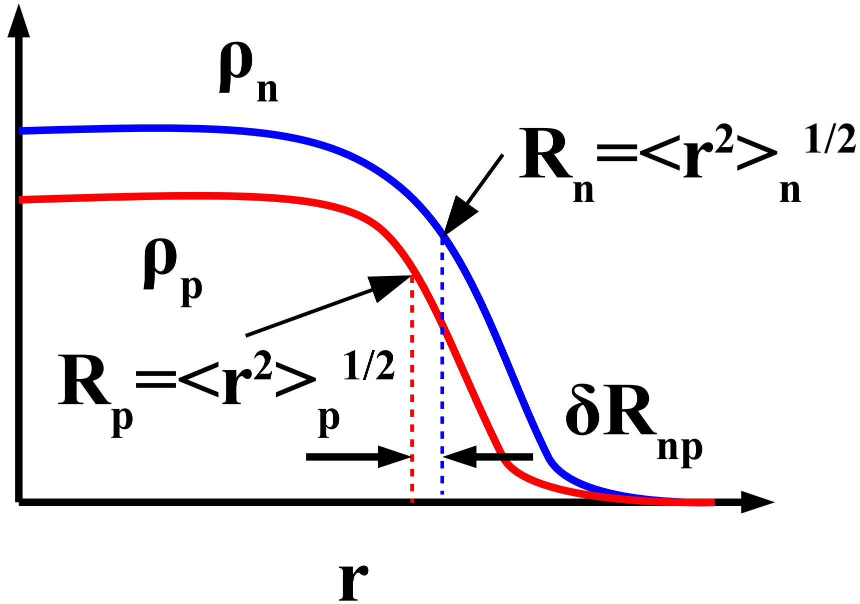
Skin Thickness & Dipole Polarizability

- **Skin Thickness δR_{np}**
  - **Larger L**

    → Small E_{sym} at low ρ

    Large E_{sym} at high ρ

    → Larger δR_{np}



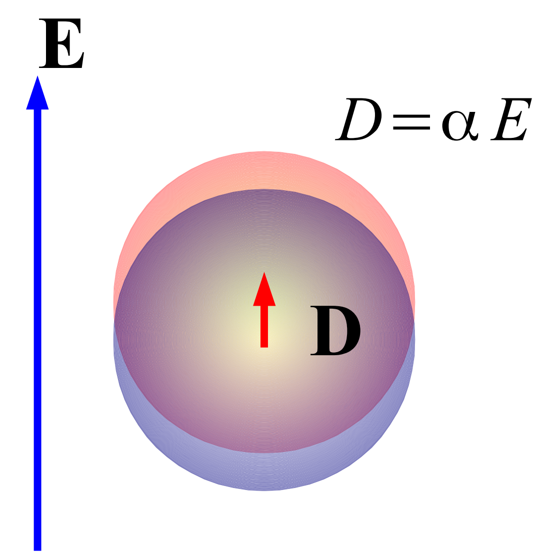
- **Electric Dipole Polarizability α**

$$H = H_0 - eE \sum_{i \in p} x_i = H_0 - E\hat{D}$$

$$|\psi\rangle = |0\rangle - \sum_{n>0} \frac{|n\rangle\langle n|V|0\rangle}{E_n - E_0} + O(E^2)$$

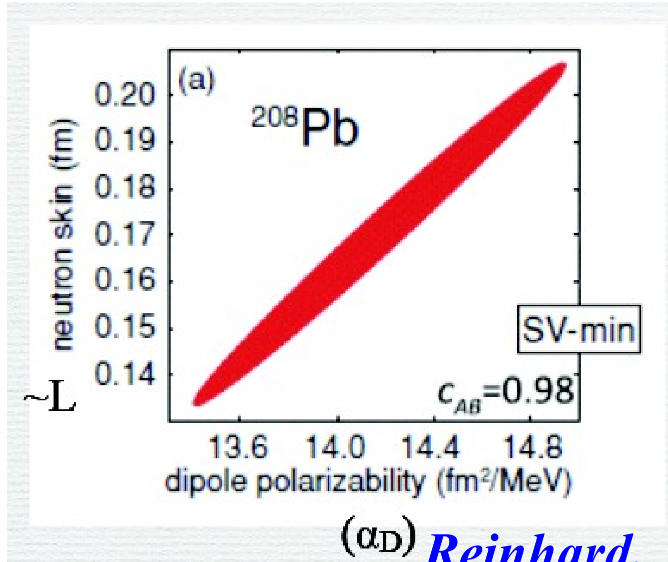
$$D = \langle\psi|\hat{D}|\psi\rangle = 2E \sum_{n>0} \frac{\langle 0|\hat{D}|n\rangle\langle n|\hat{D}|0\rangle}{E_n - E_0}$$

$$\alpha = \frac{8\pi}{9} \int \frac{dB(E1)}{\omega}$$

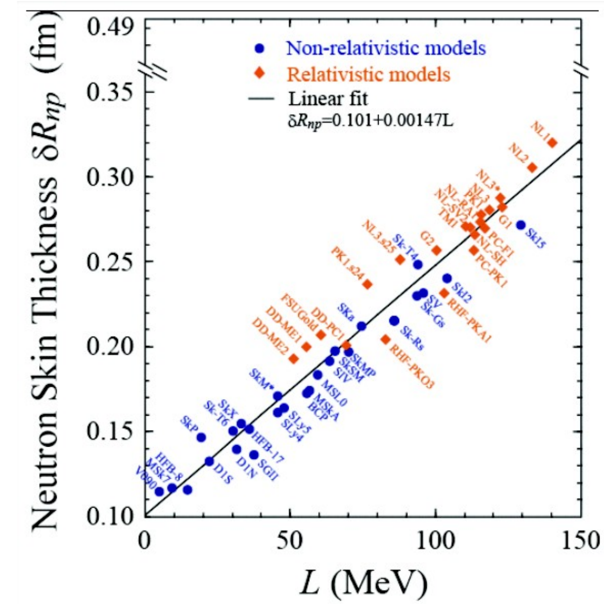


Skin Thickness & Dipole Polarizability

- **Strong corr. btw α and skin thickness (smaller restoring force → soft)**
- **Skin thickness is also correlated with L.**

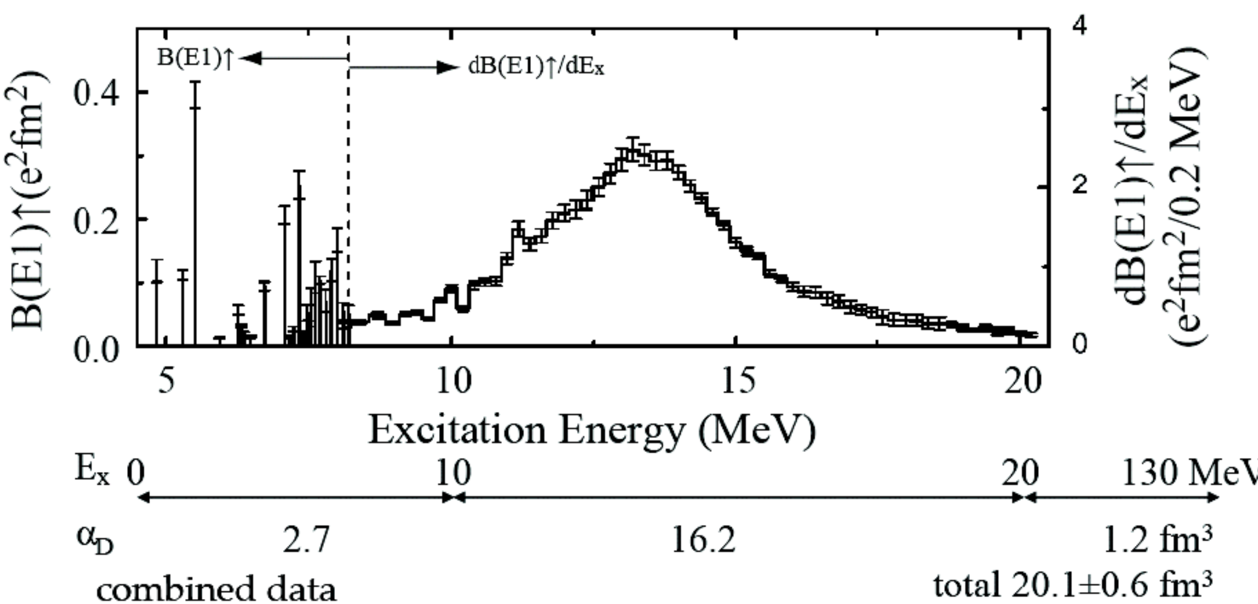


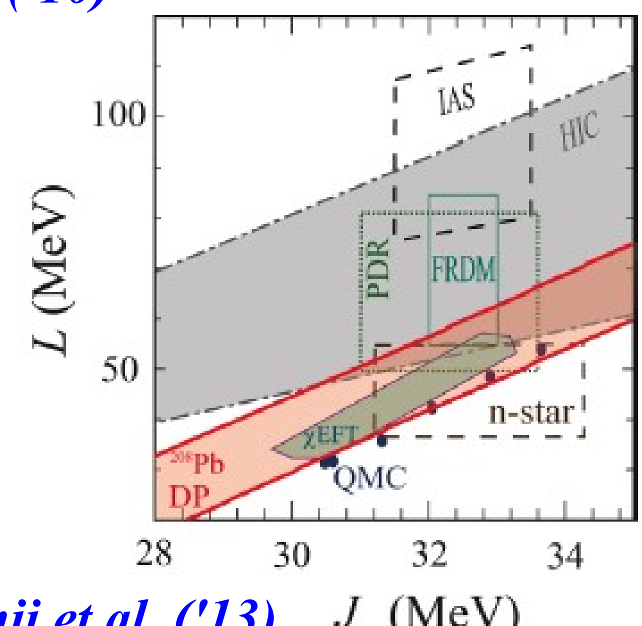
Reinhard, Nazarewicz ('10)



Roca-Maza et al. ('11)

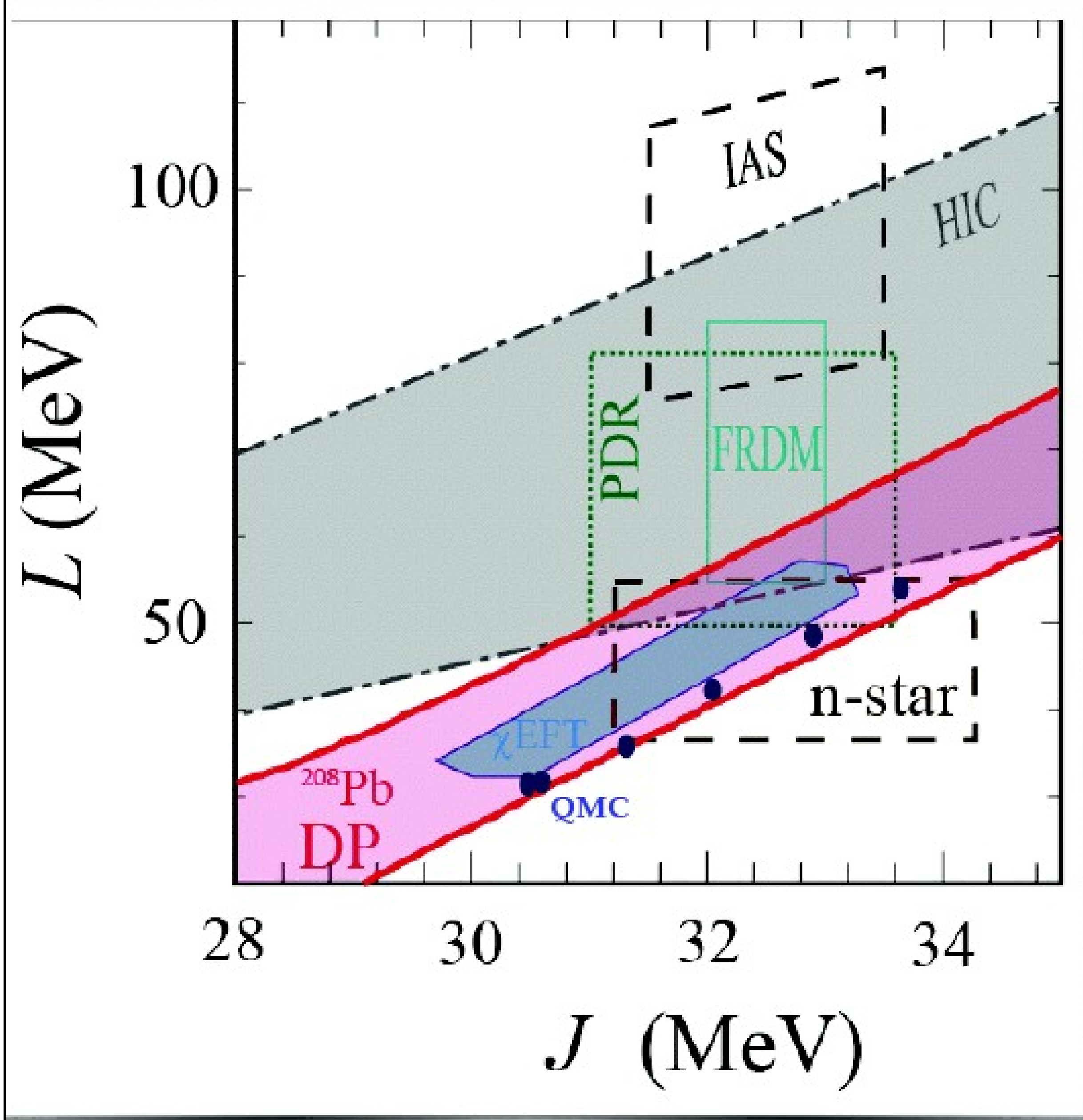
- **Precise data from RCNP**





Tamii et al. ('13)

Constraints on J and L



AT *et al.*, to be published in EPJA.

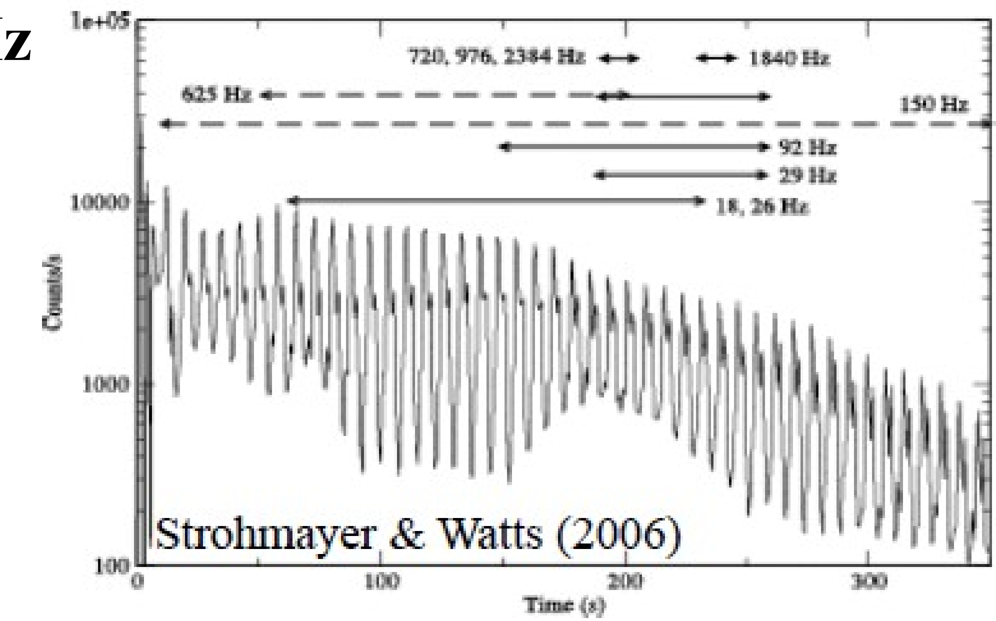
M.B. Tsang *et al.*, PRC86, 015803 (2012).

I. Tews et al., PRL110, 032504 (2013)

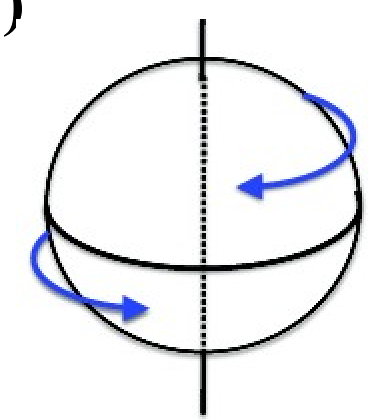
DP: Dipole Polarizability (this work)
HIC: Heavy Ion Collision
PDR: Pygmy Dipole Resonance
IAS: Isobaric Analogue State
FRDM: Finite Range Droplet Model (nuclear mass analysis)
n-star: Neutron Star Observation (A.W. Steiner et al.,)
cEFT: Chiral Effective Field Theory
QMC: Quantum Monte-Carlo Calc.

Quasi Periodic Oscillation of Neutron Stars

- **QPOs in afterglow of giant flares from soft-gamma repeaters (SGRs)** *(Barat+ 83, Israel+ 05, Strohmayer & Watts 05, Watts & Strohmayer 06)*
  - **SGR 0526-66 (5th/3/1979) : 43 Hz**
  - **SGR 1900+14 (27th/8/1998) :**
    28, 54, 84, 155 Hz
  - **SGR 1806-20 (27th/12/2004) :**
    18, 26, 30, 92.5, 150,
    626.5, 1837 Hz



- **Asteroseismology**
  - **From star quake to stellar properties (M, R, B, EOS …)**
  - **Low frequency (e.g. 28 Hz) requires long wave mode.**
    → Torsional oscillations of the crust

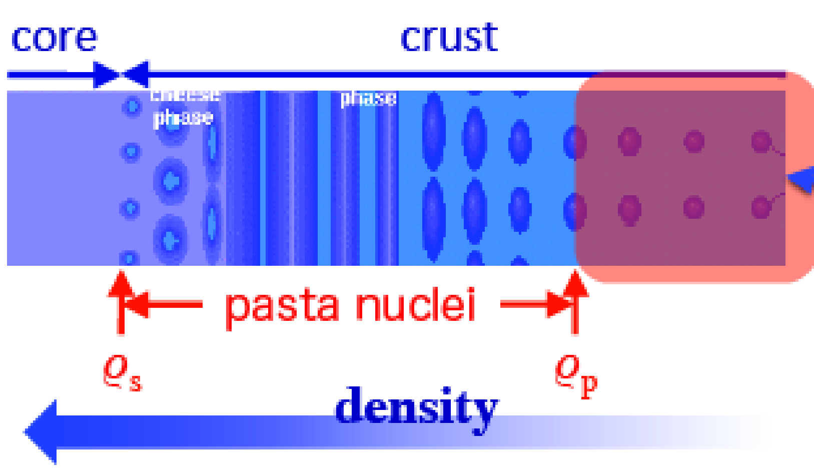


QPO and Symmetry Energy

- **Torsional oscillations (ねじれ振動)**
  - **incompressible (no density perturbations)**
  - **Frequency** $\quad {}_l t_0 = \sqrt{l(l+1)}\dfrac{v_s}{2\pi R} \quad , \quad v_s = \sqrt{\mu/\rho}$

  μ: shear modulus, vs: shear velocity
  (Hansen & Cioff 1980)

- **Shear modulus of bcc lattice depends on nuclear charge**
  → Dependence on the symmetry energy



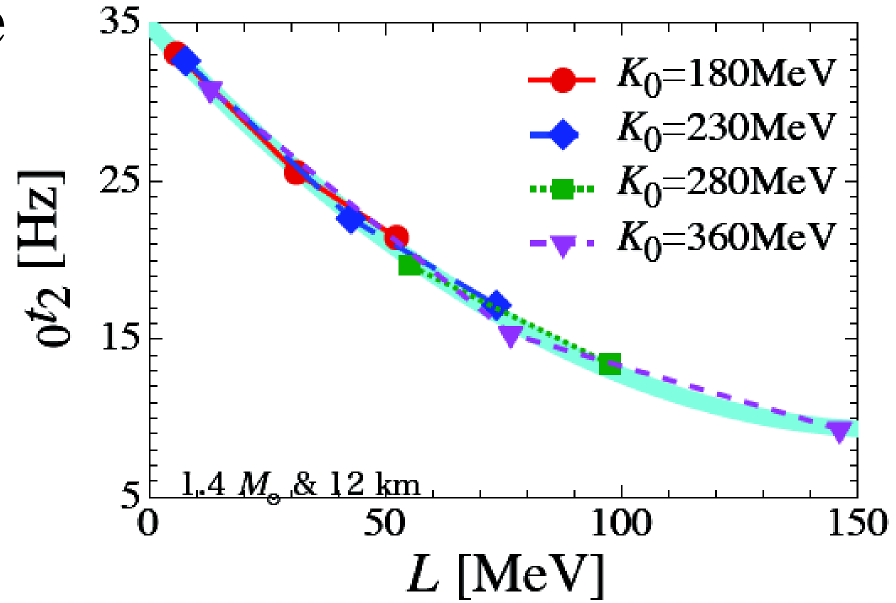
for bcc lattice (Strohmayer+ 1991)

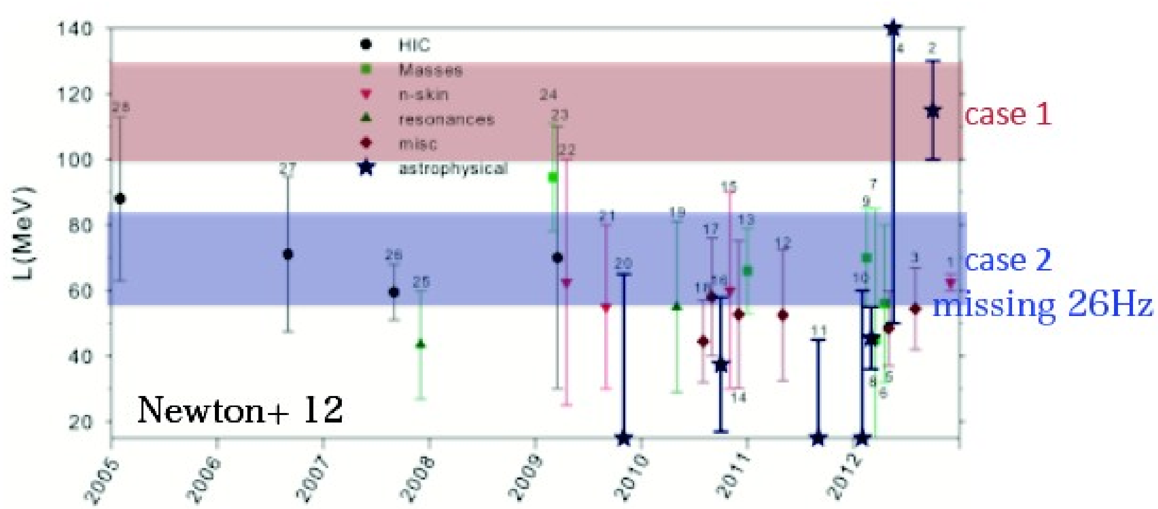
$$\mu = 0.1194 \frac{n_i (Ze)^2}{a}$$

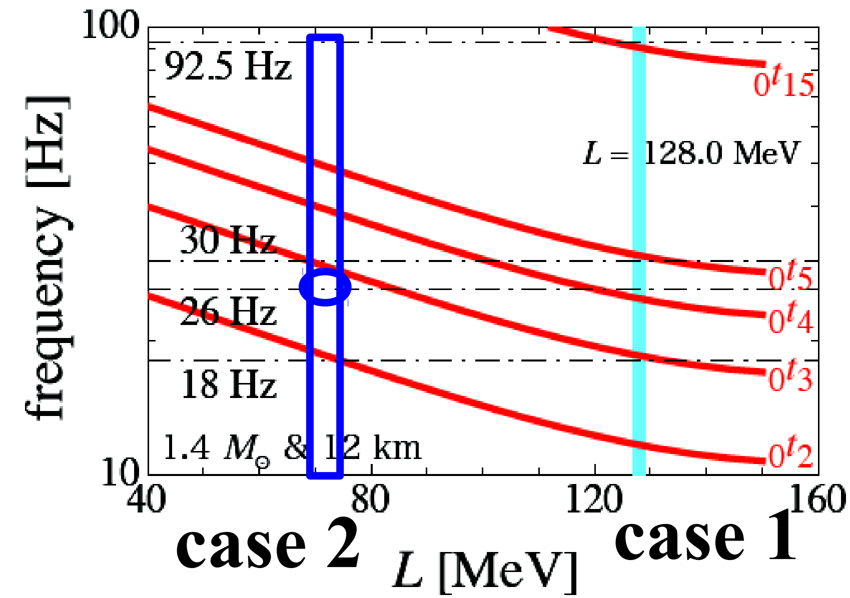
n_i : number density of quark droplet
Z : charge of quark droplet
a : Wigner-Seitz radius

QPO and Symmetry Energy

- **For a given set of (M,R), we can solve TOV equation from the surface.**
- **Torsional oscillation frequencies are calculated using EOSs with various (L,K).**
  Oyamatsu, Iida ('03,'07)
- **Compared with observed freq.**
  → constrains on L (small dep. on K)





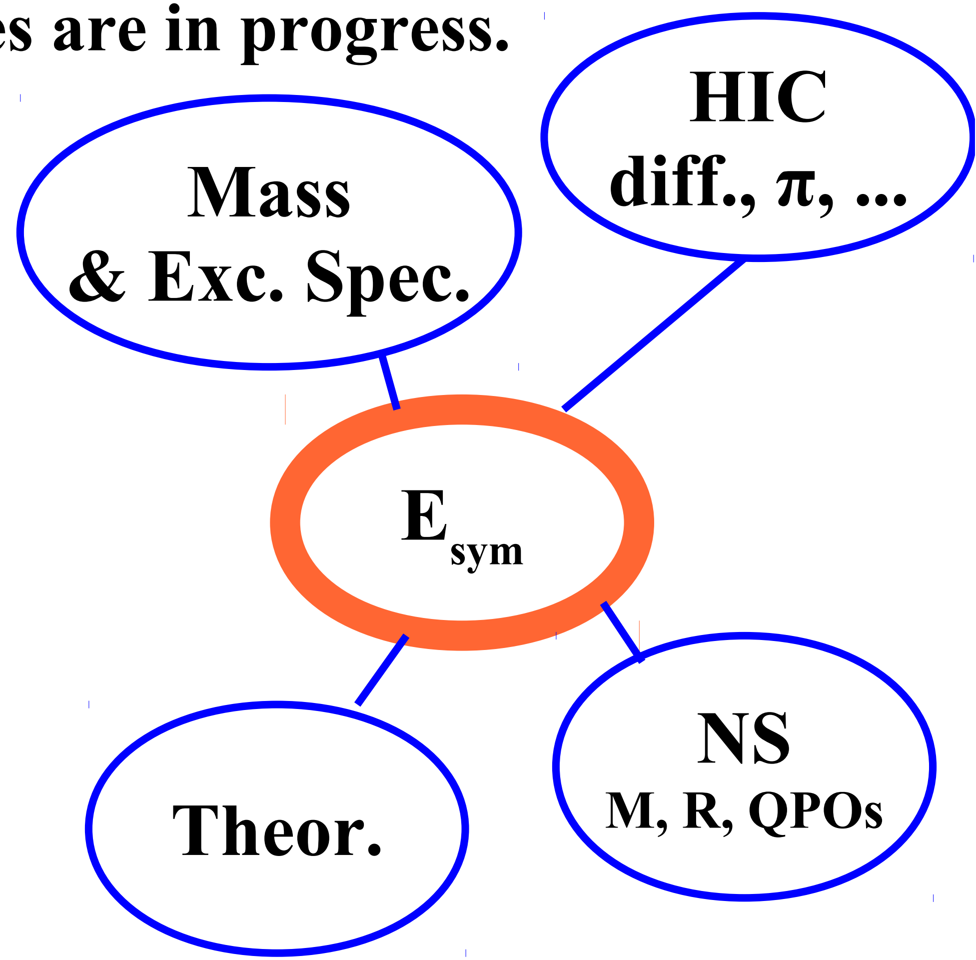


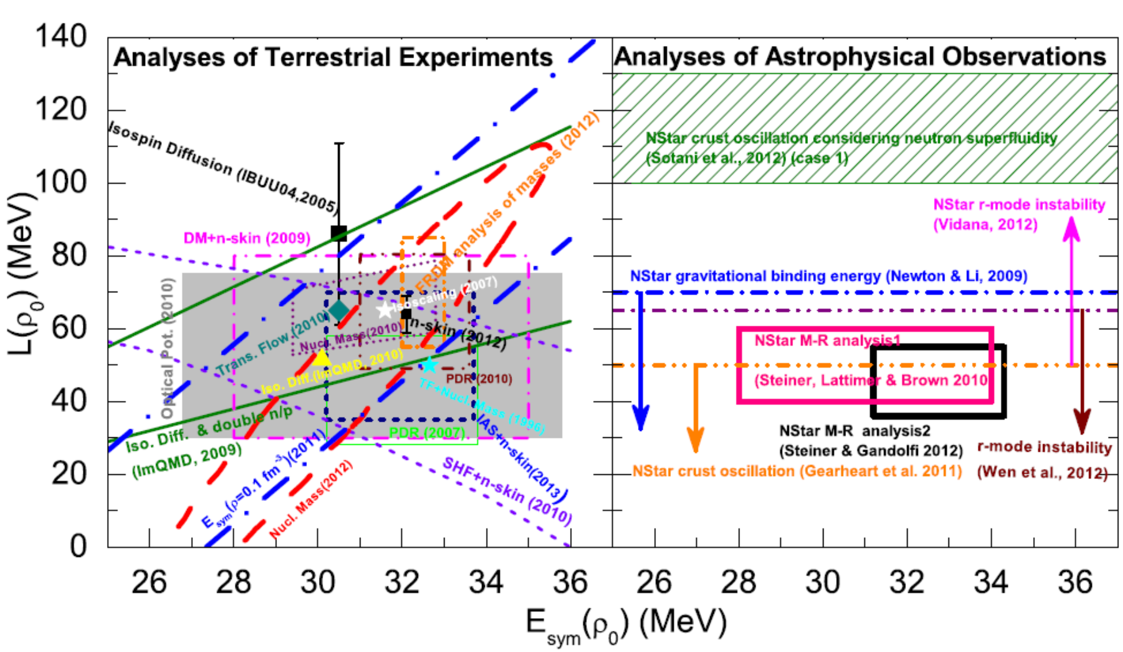
Large L or missing 26 Hz

Sotani+ '13

Summary

- Symmetry energy is decisive in neutron star matter EOS, and is related to various properties of nuclei.
- Experimental & Theoretical studies are in progress.
- If you have a new idea
  to determine Esym,
  please propose as soon as possible.





Thank you !