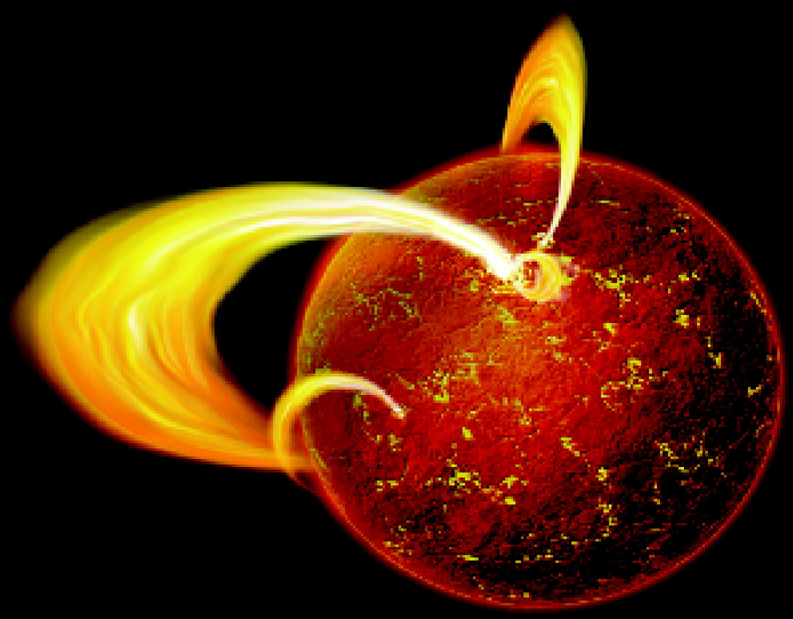
Neutron Skins and Magnetar Flare Oscillations: Taming the PREX with Starquakes



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PREX at ECT*

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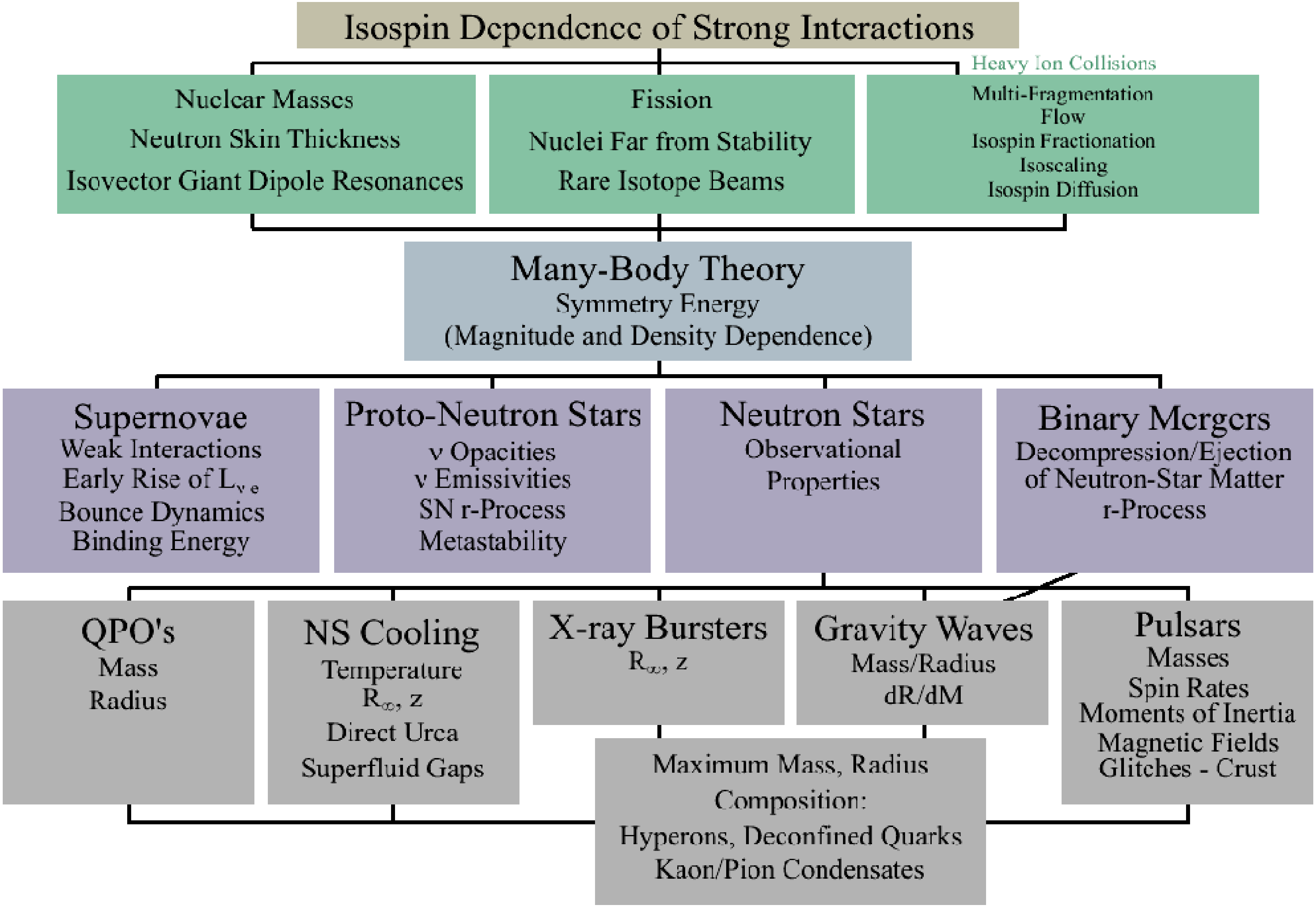
Outline

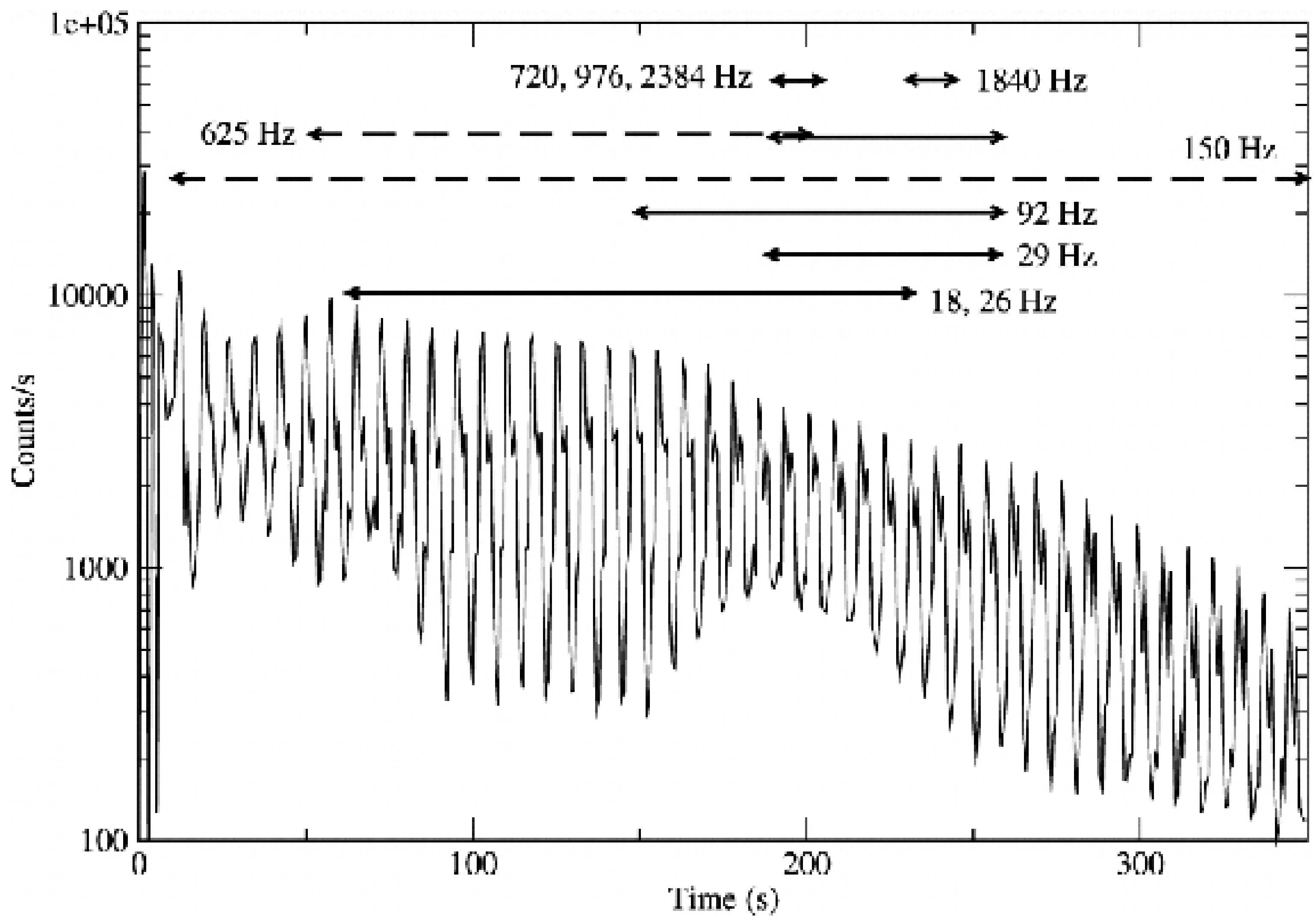
- Symmetry Energy
- Magnetars, Giant Flares, and Shear Oscillations
- Neutron Star Crust Model
- Neutron Skin Thickness of Lead
- Shear Oscillation Frequencies



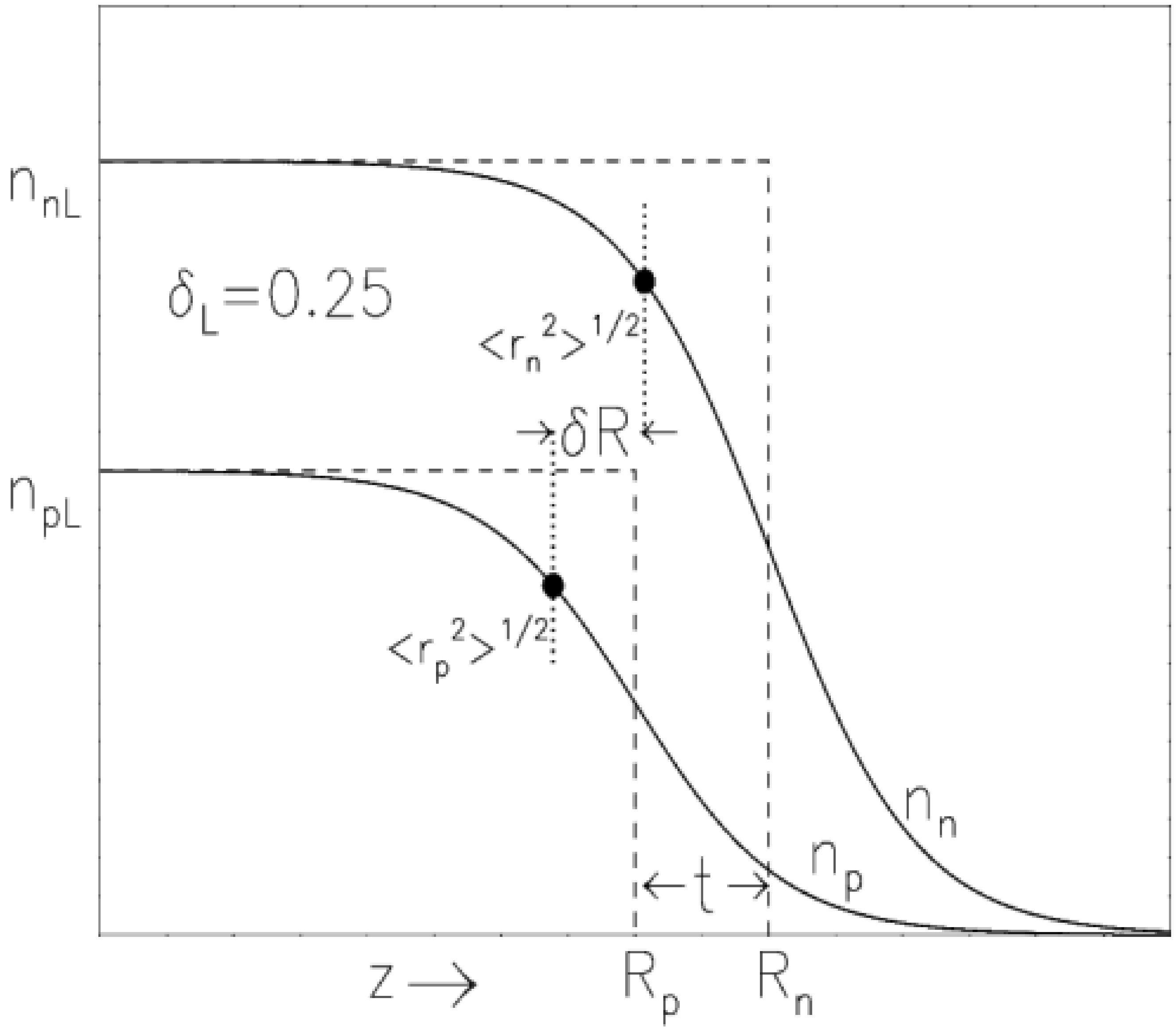
Adapted from Steiner, et al., Phys. Rep. 411 (2005) 325.

Magnetars

- Magnetars - Class of highly magnetized neutron stars, as inferred from spin-down
- Emit giant flares of hard X-rays/gamma rays
- Flares originate in reconfigurations of a magnetized crust
- Flares obey log-normal distribution also observed in terrestrial earthquakes
- Quasi-periodic oscillations are embedded in the giant flares
- Some of the oscillation frequencies are thought to be shear modes of the crust



The Neutron Star Crust Model



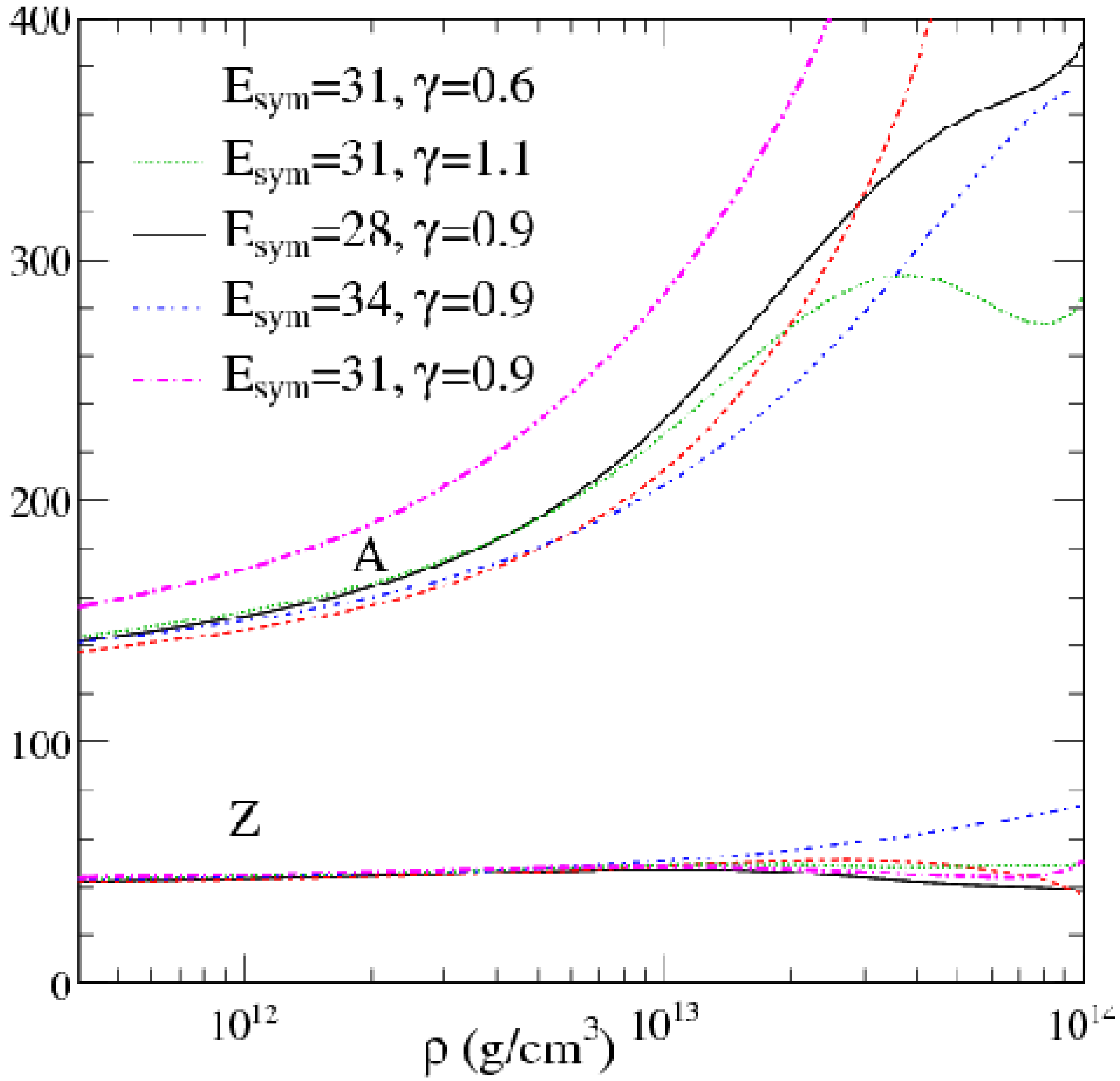
- Liquid droplet model, but with bulk energy determined from a specified EOS for homogeneous nucleonic matter (mostly Skyrme models)
- Coulomb energy - modified appropriately for finite density
- Surface energy - Typically quadratic in the isospin asymmetry $\delta = 1 - 2\frac{n_p}{n_n + n_p}$. Now cubic to correct for the medium
- The mass of the nucleus depends on the medium (forces one to iterate)
- Simple and quick, yet includes most of the physics we expect in the $N \rightarrow \infty$ limit
- 6 parameters
- Transition to nuclear matter at a fixed transition density (0.07 fm^{-3})

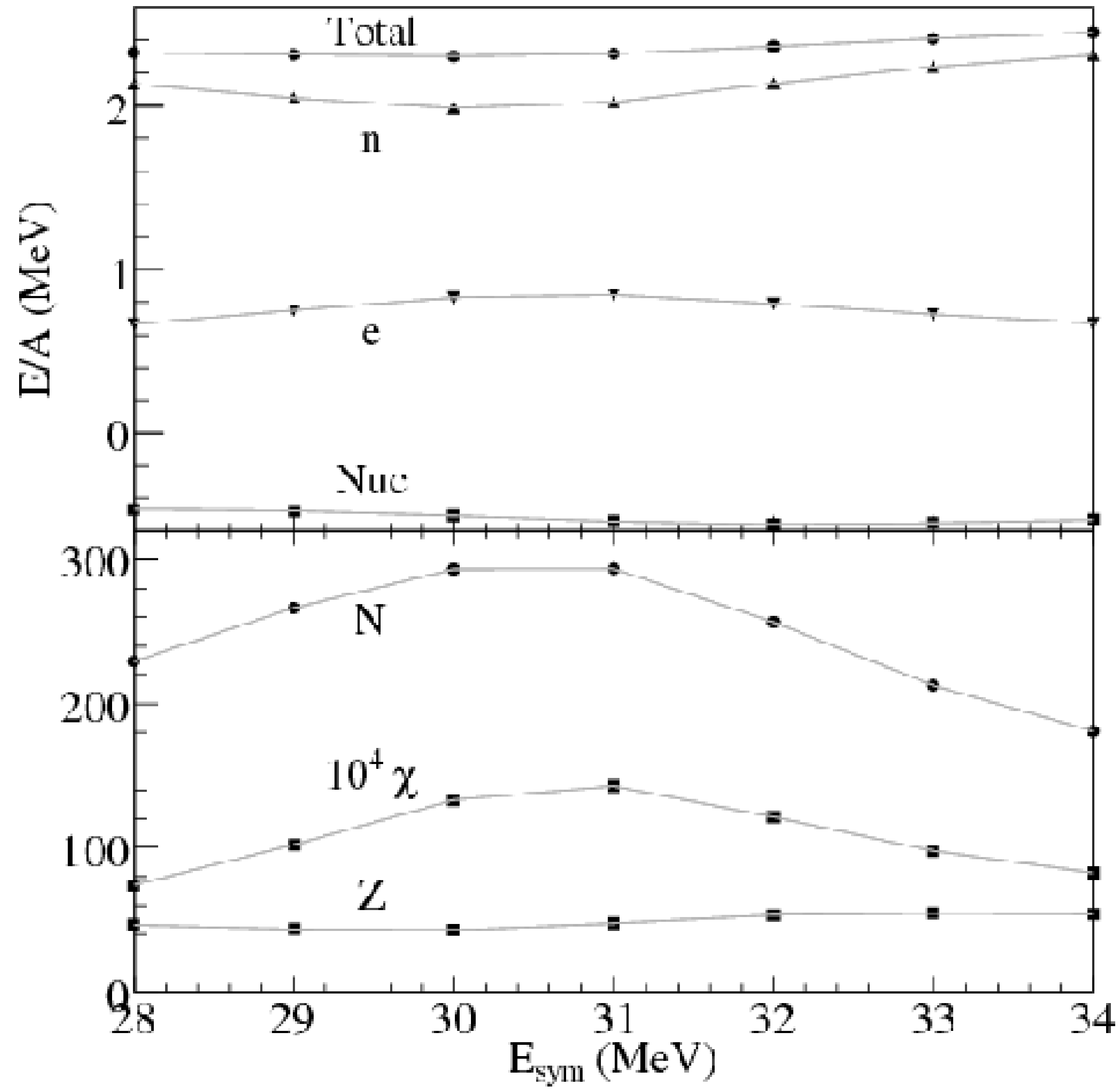
The Neutron Star Crust Model

- Self-consistency:
  - Separately fit liquid drop parameters for each model of homogeneous matter
  - Bulk part of the nuclear energy computed from same EOS as the neutron drip
  - Excluded volume corrections correctly account for the neutron skin
  - Can consistently vary symmetry energy
- Nuclear structure:
  - Obeys the expected correlation between the symmetry energy and the surface symmetry energy
  - Matches RMS mass excess of entire AME '03 set to within 2.7 MeV
  - Predicts Z=34-36, N=74-82 for the last nucleus before neutron drip
    (vs. z=34-38, N=82-84 for Rüster, et al. Phys. Rev. C (2006))
  - No shell effects or pairing

Steiner, Phys. Rev. C 77 (2008) 035805.

The Crust and the Nuclear Symmetry Energy





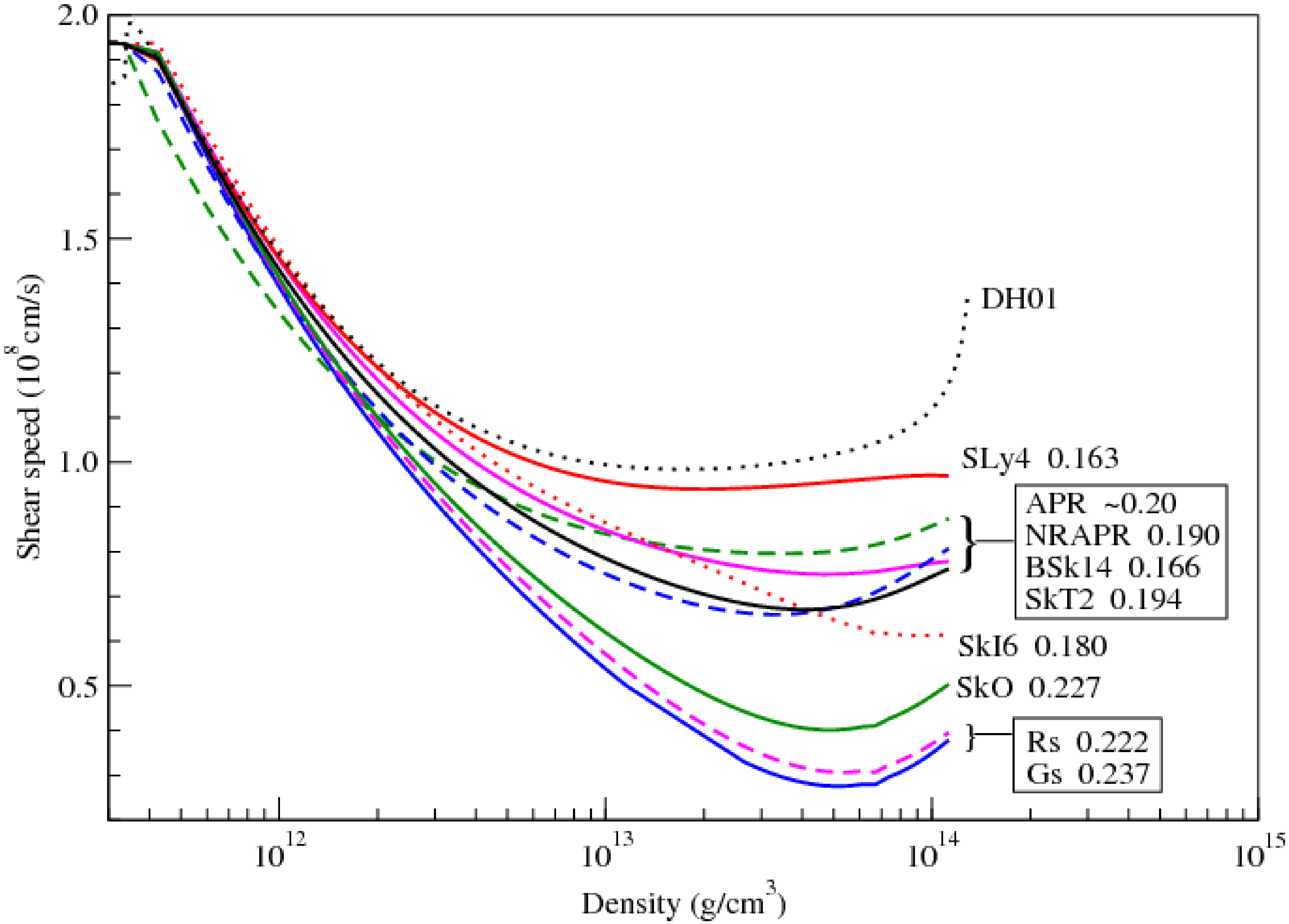
- $E_{sym} = A(n/n_0)^{2/3} + B(n/n_0)^{\gamma}$
- Fix A=17, A+B=E_{sym}, and γ.
- Non-monotonic behavior becomes clear with self-consistency

Steiner, Phys. Rev. C 77 (2008) 035805.

Shear moduli and shear speeds

The shear modulus is $\mu = \frac{0.12}{1+0.6(173/\Gamma)^2}\frac{n(Ze)^2}{a}$; $v_s = (\mu/\rho)^{1/2}$

T. Stromayer et al., Ap J 375 (1991) 679, T. Piro Ap. J Lett. 634 (2005) 153,

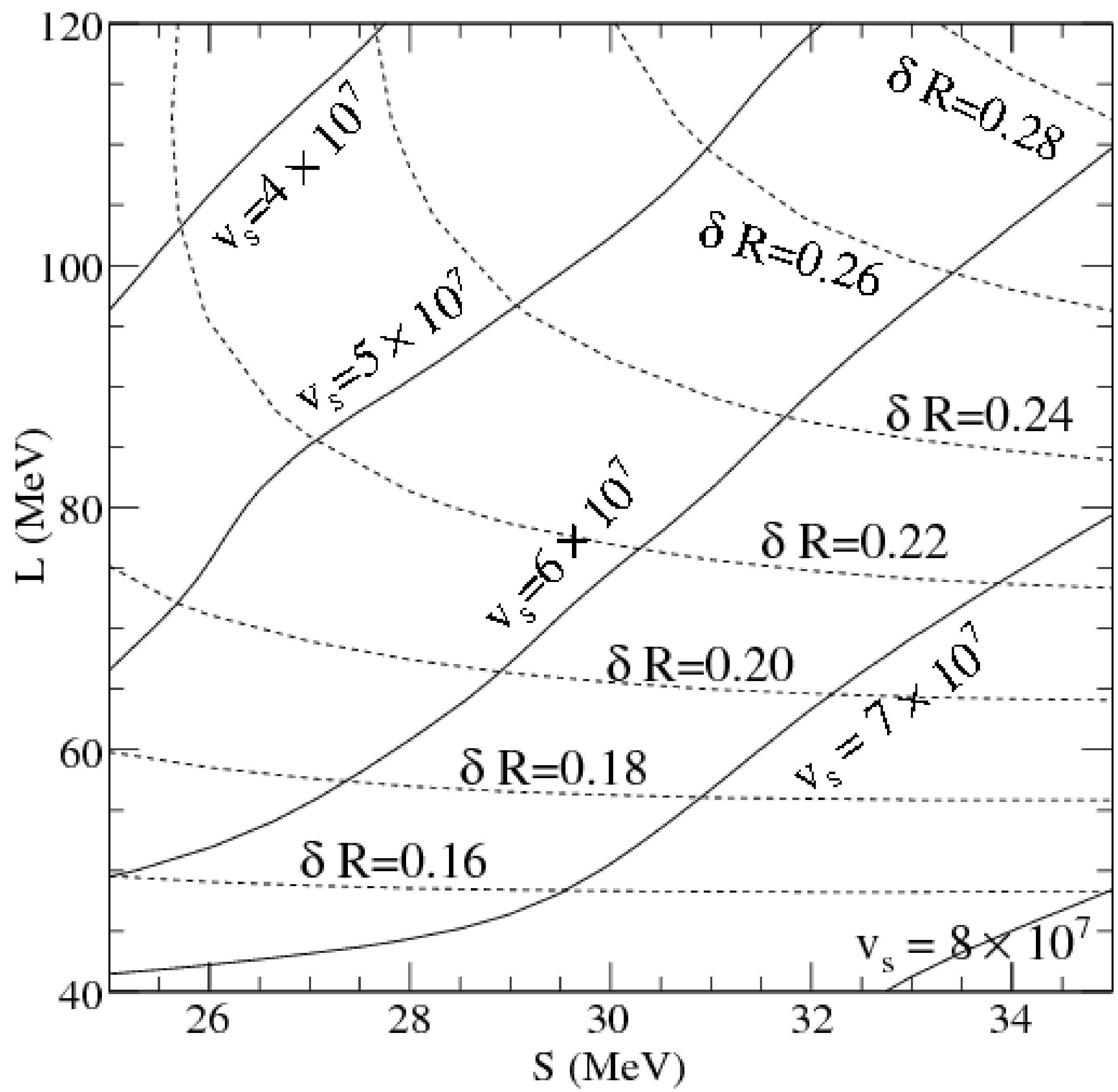


Steiner and Watts, arXiv.org: 0902.1683

- Monte Carlo calculations of a Coulomb solid
- Ignore the neutrons, superfluidity
- Outer crust identical for all models
- Red vs. black-dotted lines show uncertainty due to model

The Neutron Star Crust and The Neutron Skin Thickness of Lead

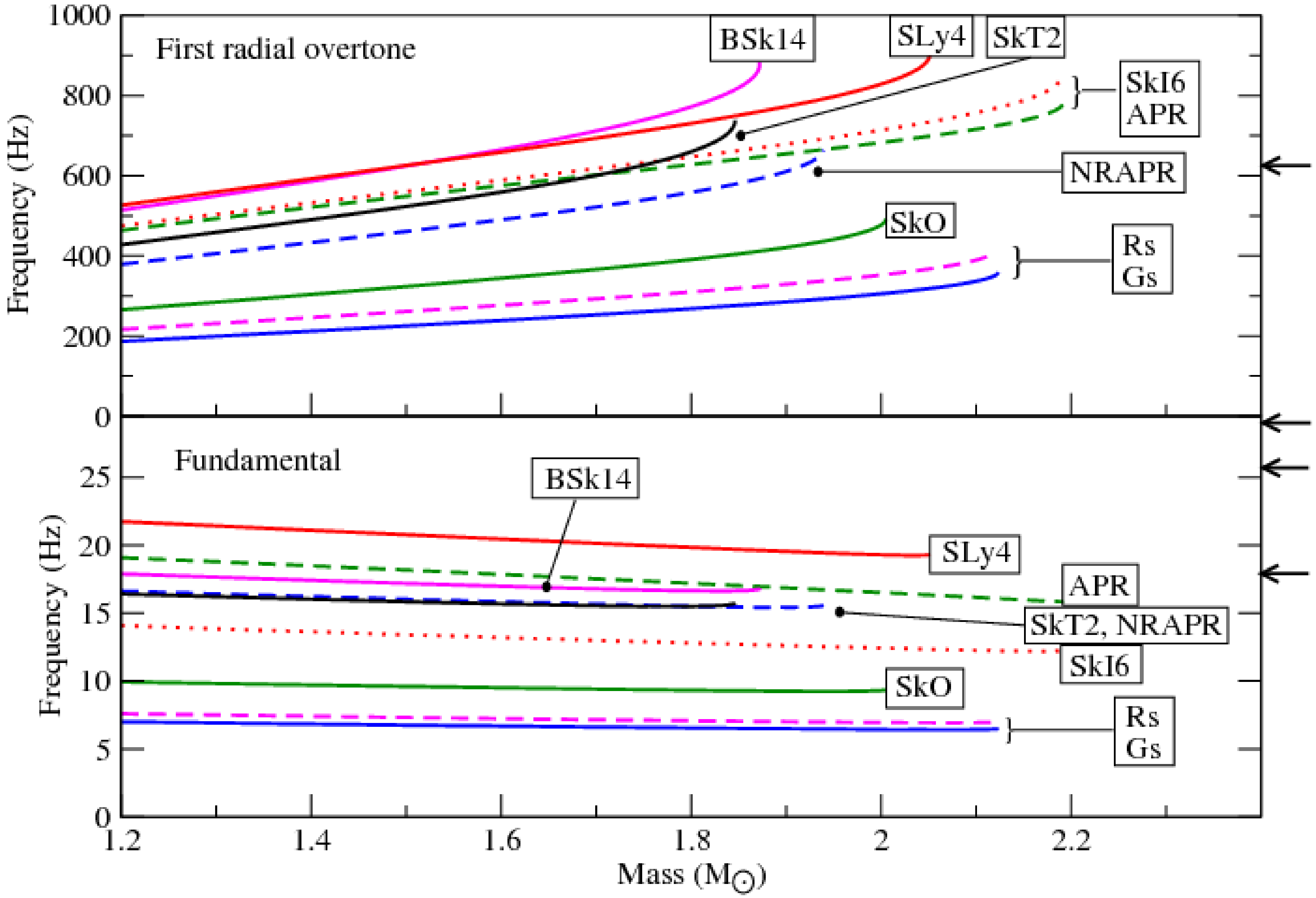
- Determine skin thicknesses through the Typel Brown correlation
- S is the magnitude of the symmetry energy at the saturation density, L is the derivative
- Related to the neutron skin thickness of lead, to be measured at JLab in the PREX experiment



Steiner and Watts, arXiv.org: 0902.1683

Matching the Observed Frequencies

- Only models with symmetry energies which depend weakly on density ("soft") match the data
- Typically, lowest frequencies are assigned to Alfven core modes
- Problem: This implied quite low neutron star masses
- Solution: This mode assignment could be incorrect!



Steiner and Watts, arXiv.org: 0902.1683

- Electron screening corrections (Horowitz) lower shear modulus
- Outer crust doesn't matter
- Transition density is important for overtone - this may limit mass determinations
- Lower fundamental frequencies will imply larger masses

Connection between the direct Urca process

- The isospin dependence of the three-body force is not well understood.
- No measurement of a neutron skin thickness is likely to shed light on the threshold for the direct Urca process
- How to modify the direct Urca threshold?

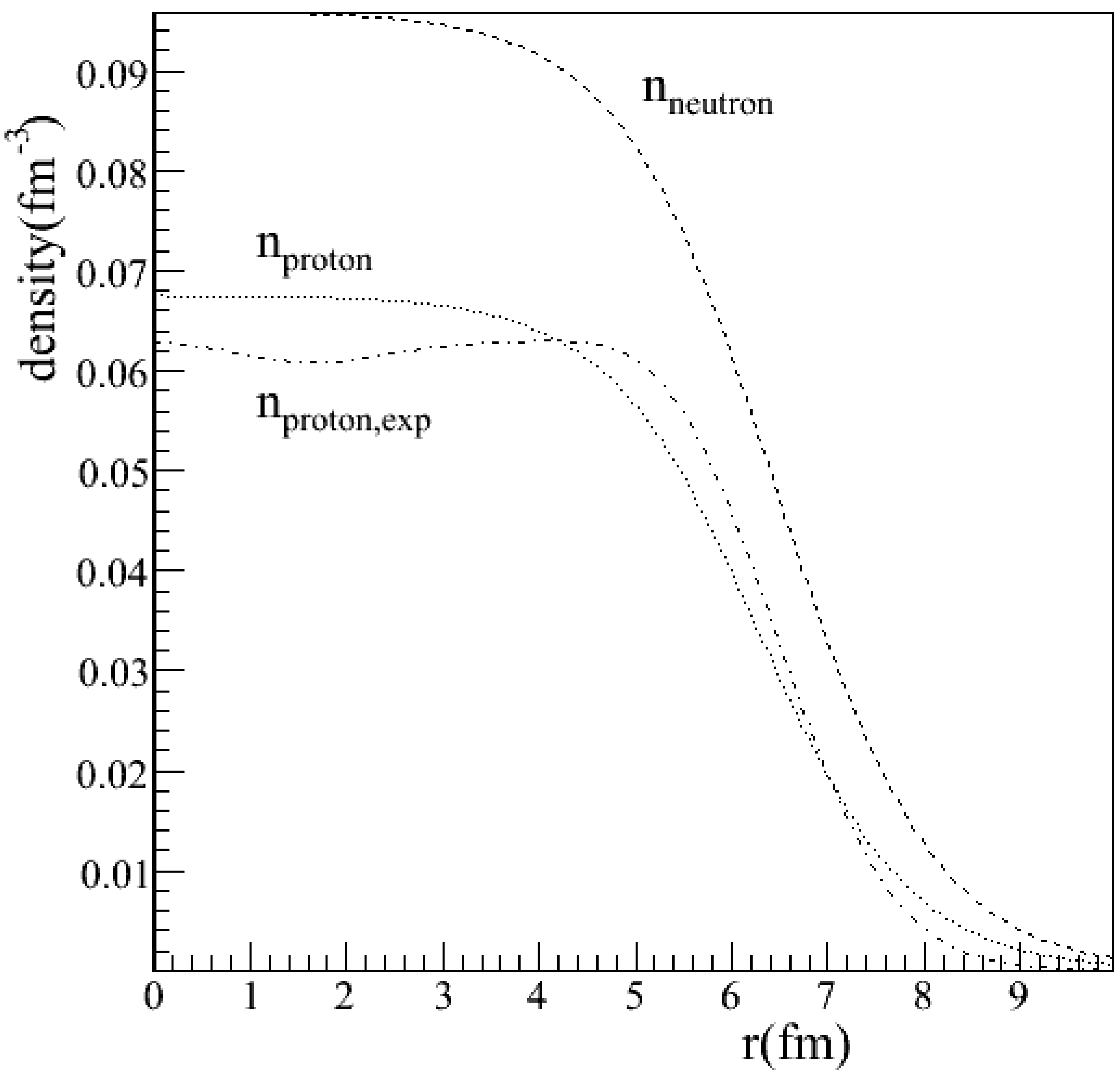
  Steiner, Phys. Rev. C 74 (2006) 045808.

Summary

- Shear oscillation frequencies may be able to constrain the nuclear physics of the neutron star crust below the saturation density.
- Either the symmetry energy is soft (i.e. the neutron skin thickness is small), or the fundamental mode has been assigned incorrectly.
- In the latter case, our model predicts we ought to observe more flares with sub-20 Hz oscillations. We've searched for these oscillations in the 1900 flare, and cannot rule them out
- This also implies larger inferred neutron star masses and better frequency scaling
- While these initial studies offer promise, there is a lot to do:
    - More complete understanding of the flare generation mechanism
    - Superfluidity and entrainment
    - Better nuclear structure
    - Better descriptions of the shear modulus
- PREX is an important part of helping us resolve the nature of matter in the neutron star crust

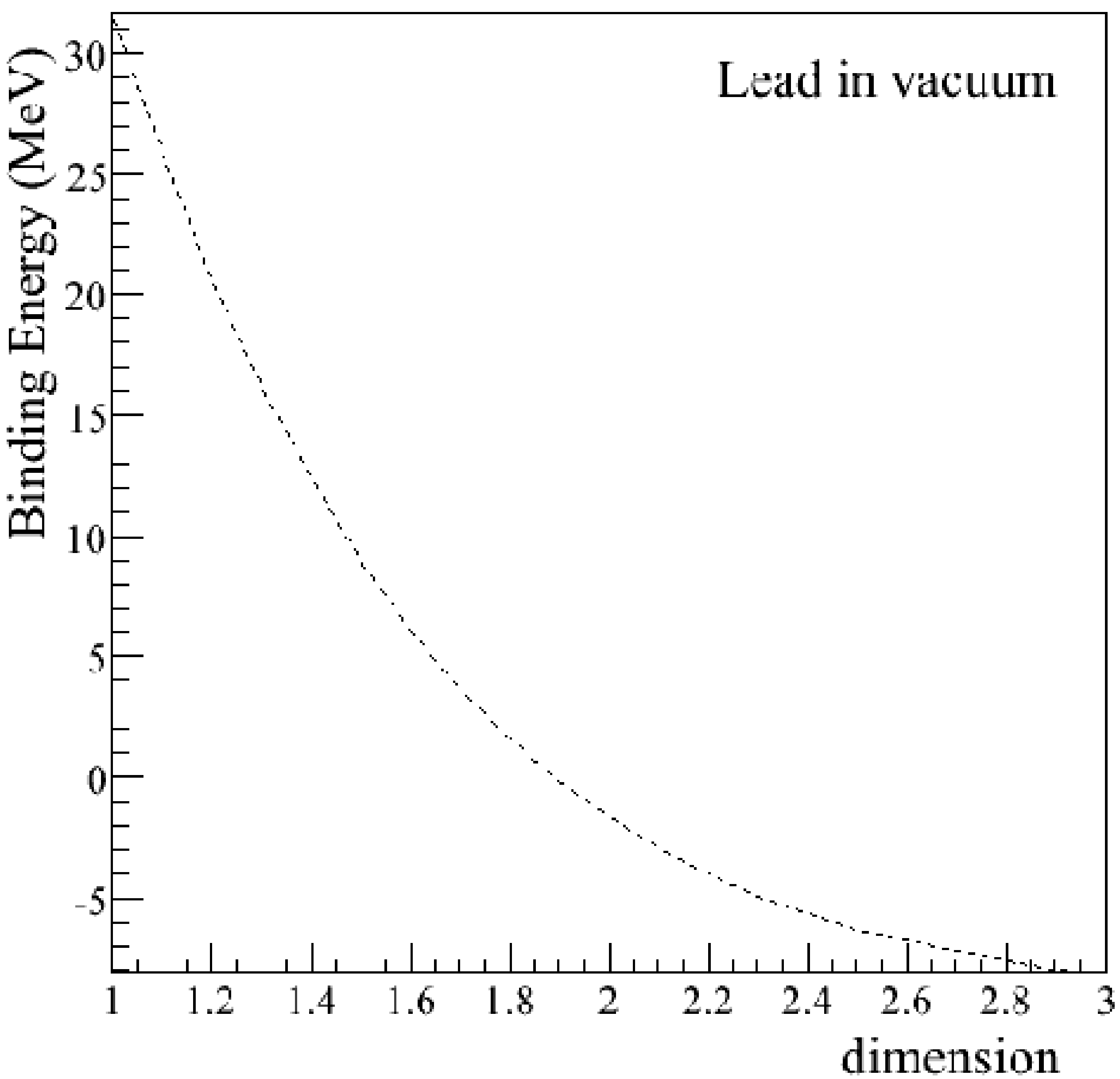
Fuzzy Pasta Crust Model

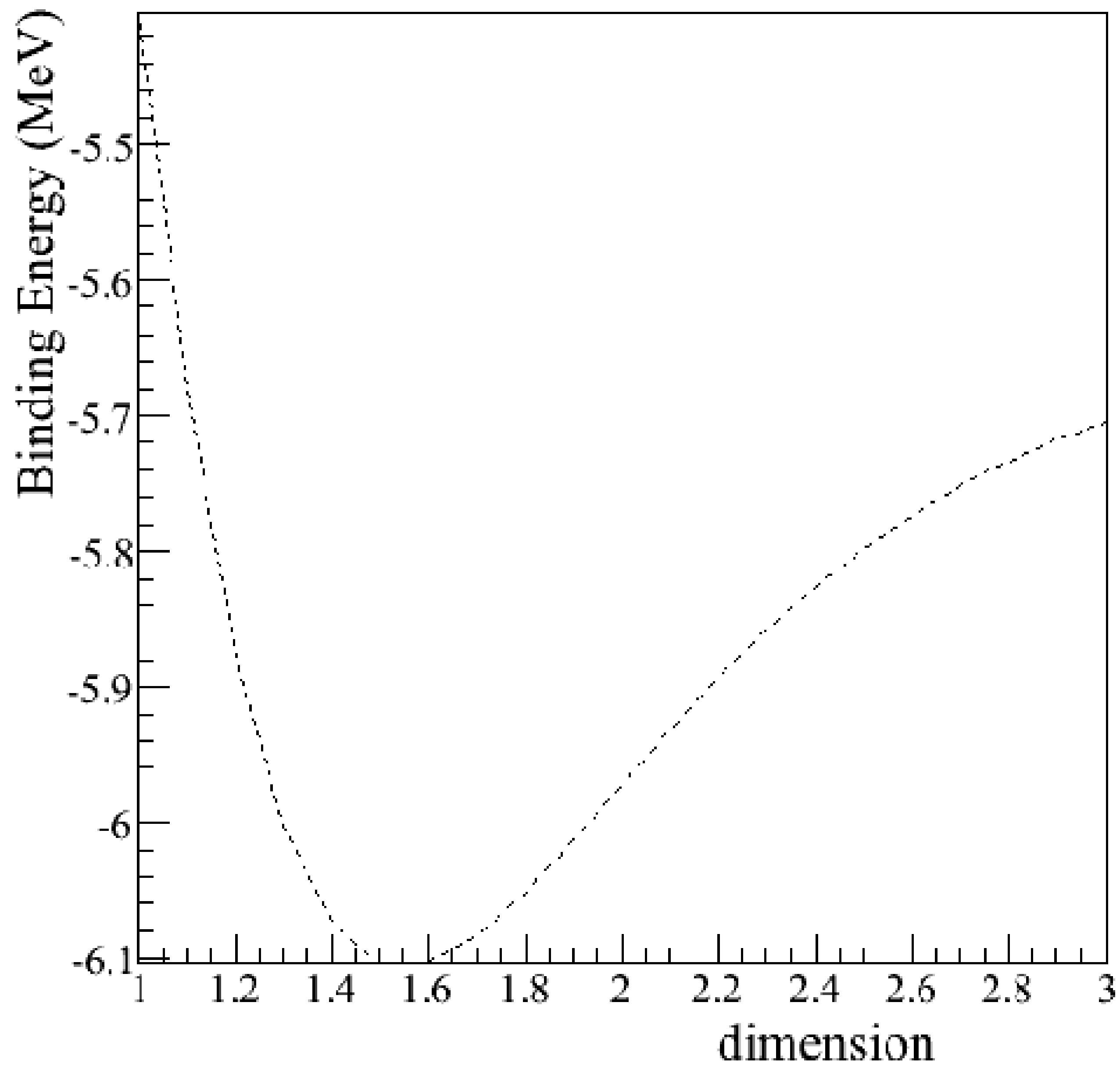
- Real nuclei are fuzzy, i.e. their density distribution has a "diffusiveness"
- Thomas-Fermi like model with a variable "dimensionality" of nuclei
- Spherically-symmetric nuclei in d dimensions, while the remaining 3-d dimensions are infinite
- Surface terms are replaced by gradient terms, no ambiguity in the location of the "surface"
- Form of gradient terms guided by DME expansion of pion-exchange interaction



Lead nucleus

Fuzzy Pasta Crust Model II

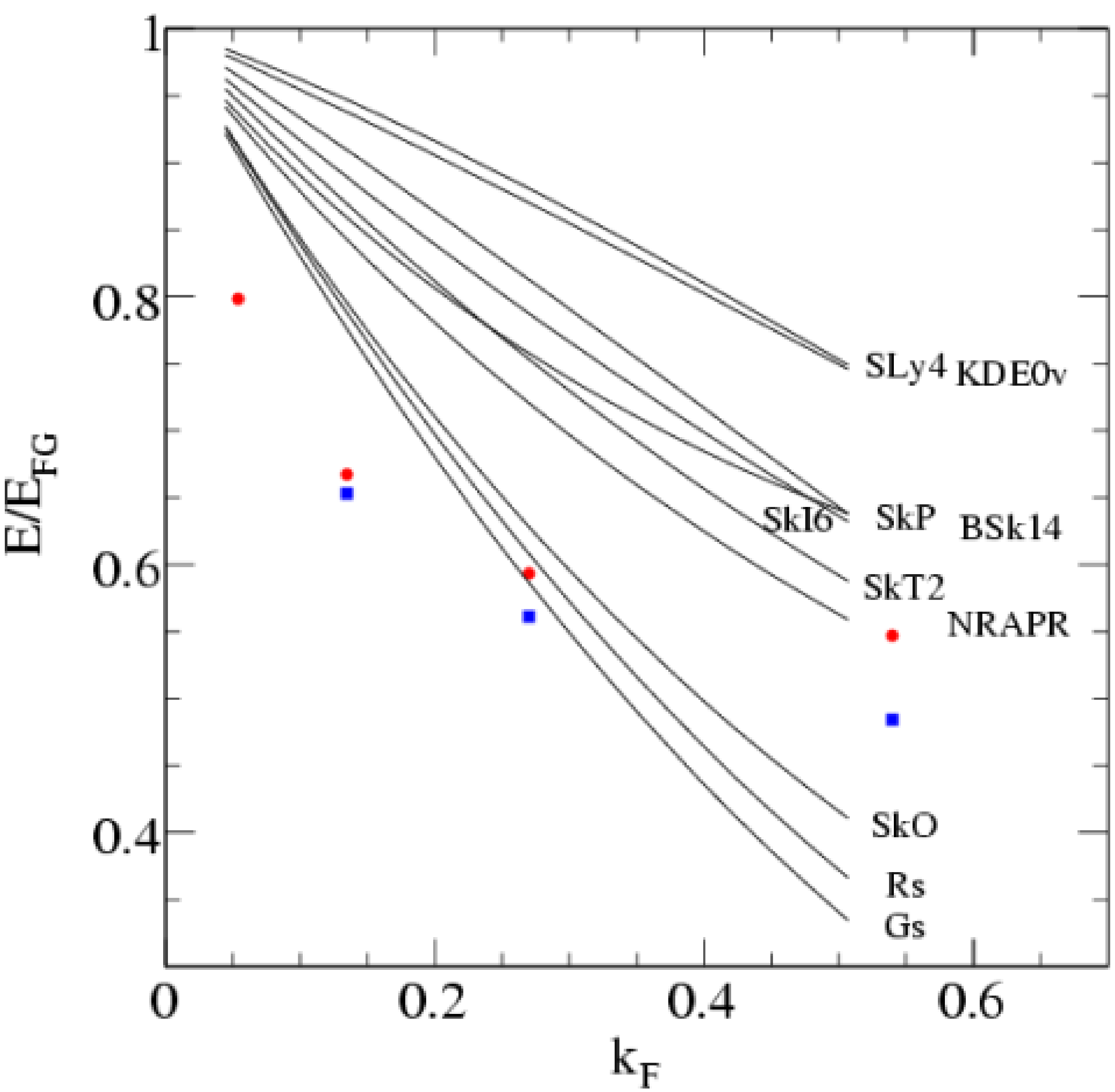




- Place the lead nucleus in medium with $n_n = n_p = 0.02\ \text{fm}^{-3}$ and $R_{\text{ws}} = 30\ \text{fm}$
- Future: examine effect of pasta on shear oscillation frequencies

Low-density Neutron Matter

- Neutron matter is well-understood
- Well-described by the effective range expansion, accessible in experiment
- At lower densities three body interactions are small
- $E_{FG} = \dfrac{k_F^5}{10\pi^2 m^*}$
- In Skyrme models, low-density behavior controlled by t_0, but also by t_3
- Relativistic models fit to nuclei also typically have difficulty in this region



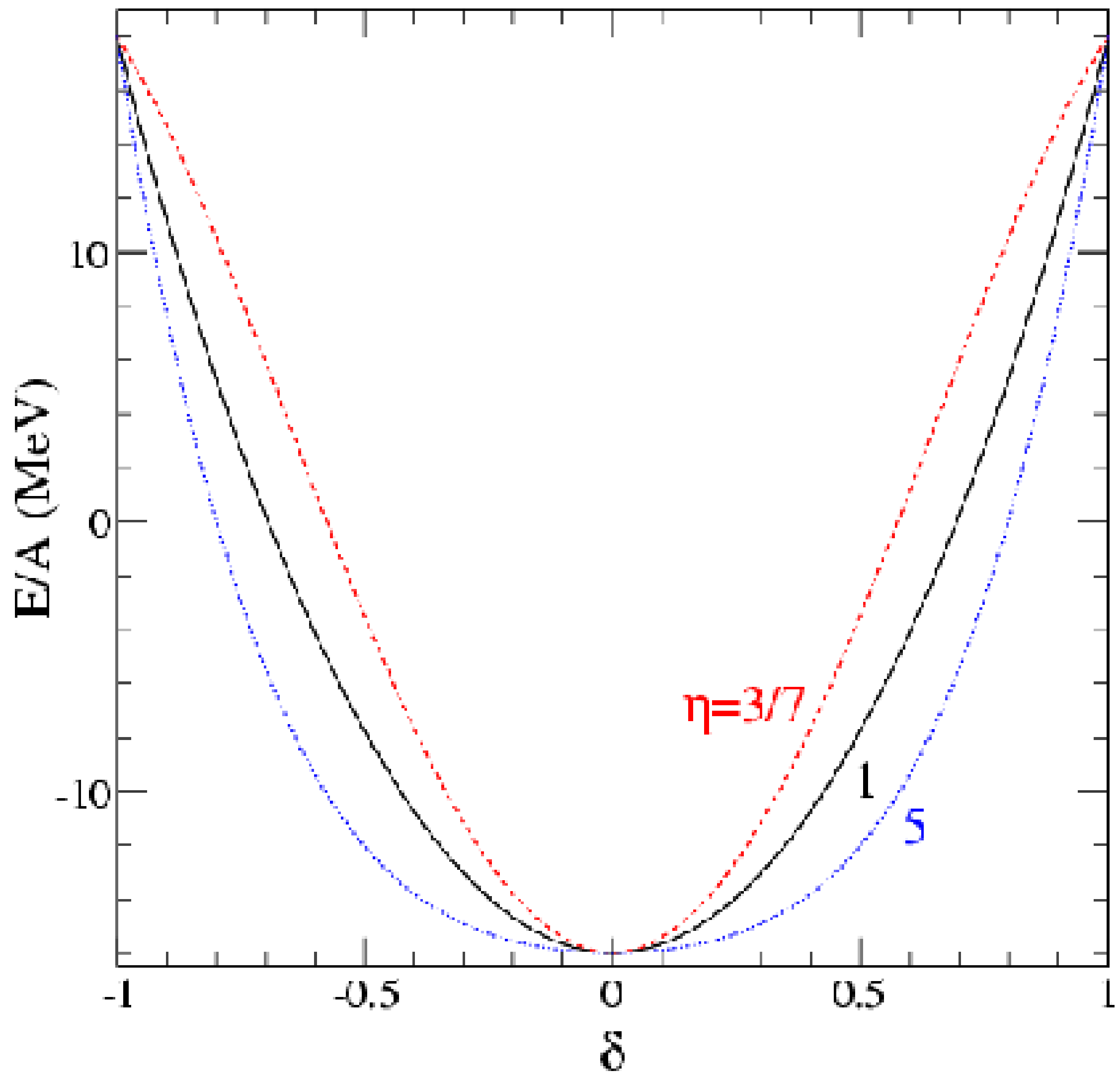
Data from A. Gezerlis and J. Carlson, Phys. Rev C. 77 (2008) 032801(R).

- $E_{neut} = \left[1 - 0.6 k_F^{0.4} + \eta_1 (n/n_0) + \eta_2 (n/n_0)^2\right] E_{FG}$
- This form, however, does not always provide reasonable neutron stars

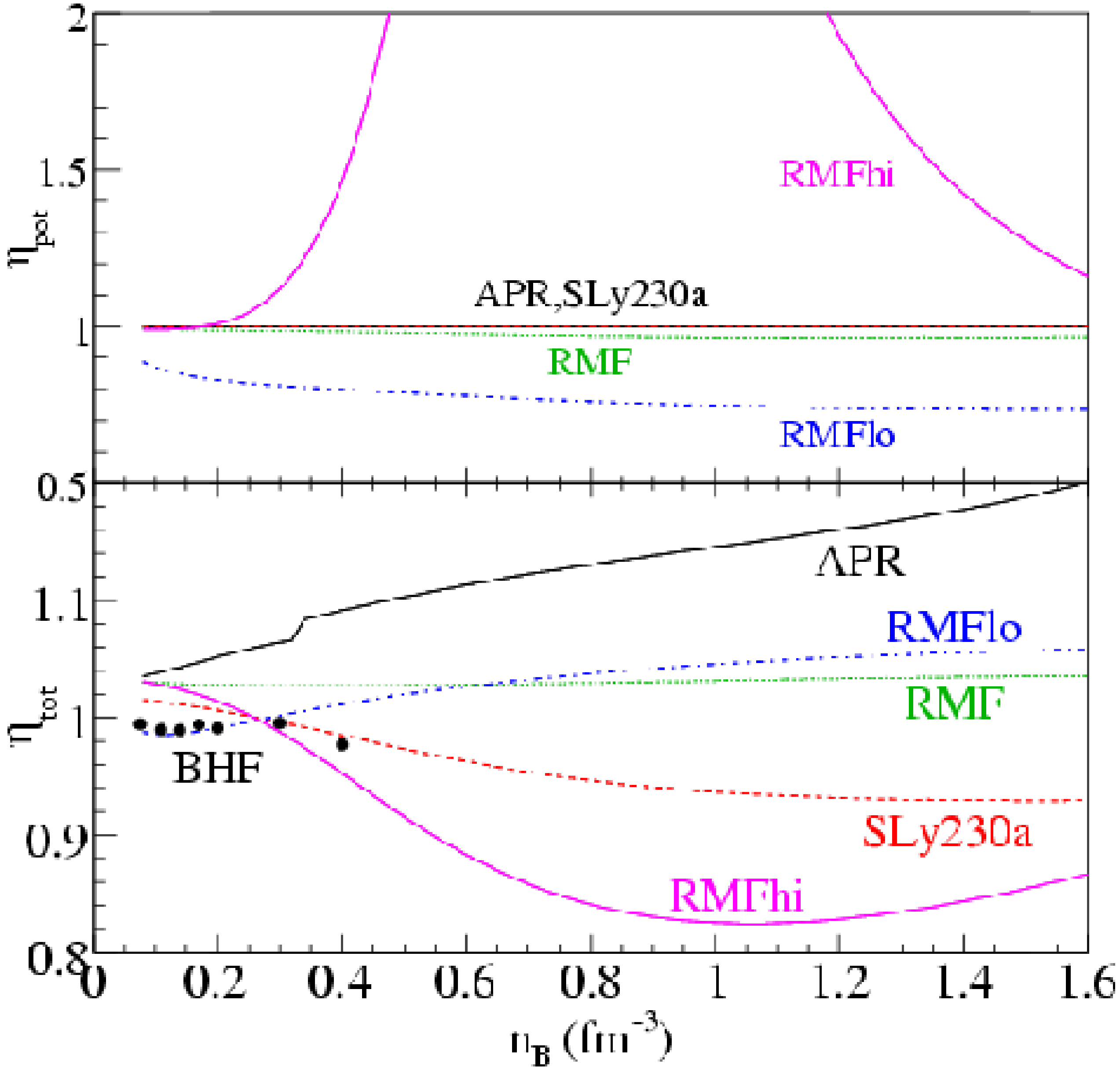
$$E = E_{\rm nuc} + S_{\rm sym}\delta^2 + Q_{\rm sym}\delta^4$$

$$\eta = \frac{E_{\rm neut} - E_{\rm qtr}}{3(E_{\rm qtr} - E_{\rm nuc})} = \frac{4S + 5Q}{4S + Q}$$

- Three- and higher-body interactions can induce non-trivial value for η
- RMF models already contain such terms

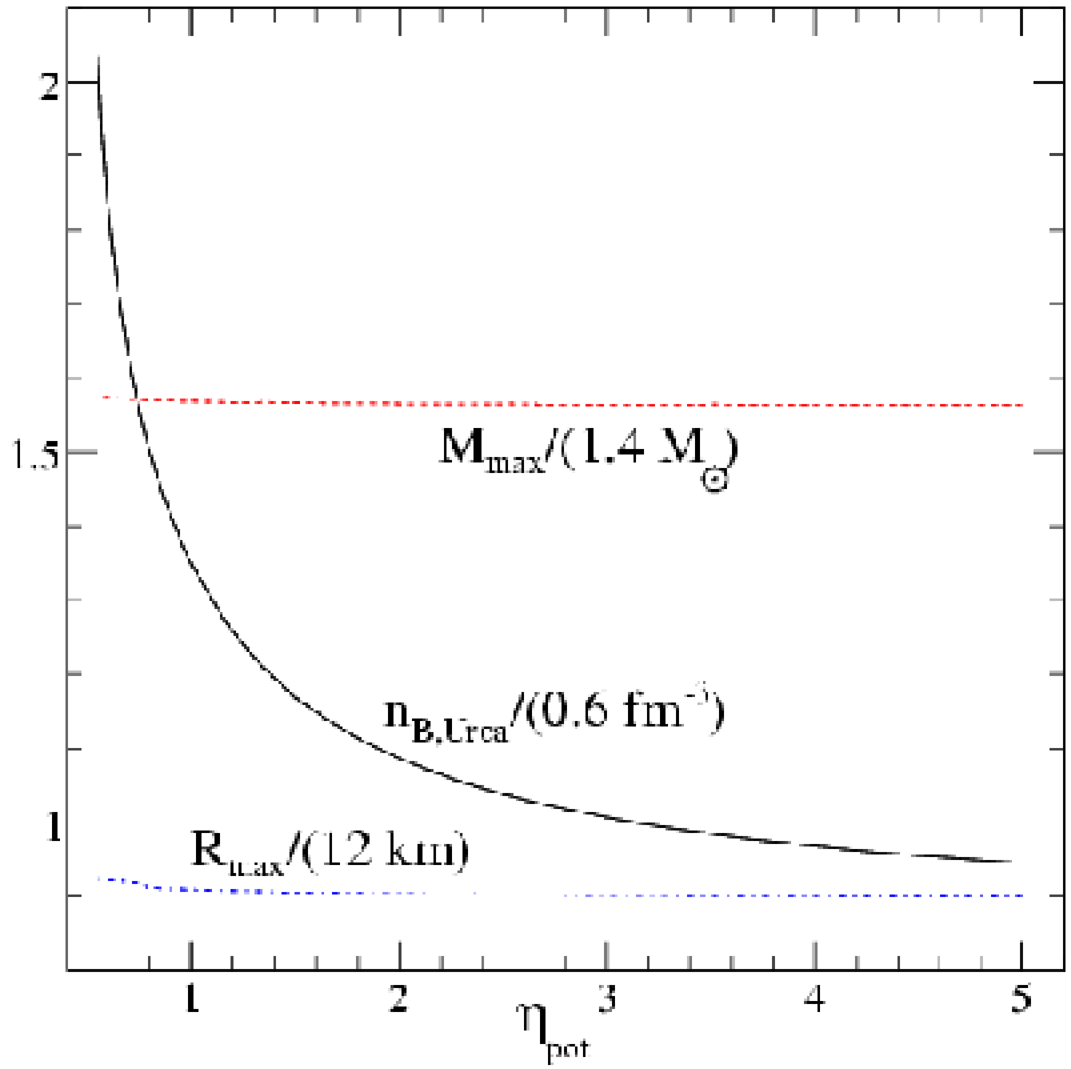


A.S. PRC 74 (2006) 045808.



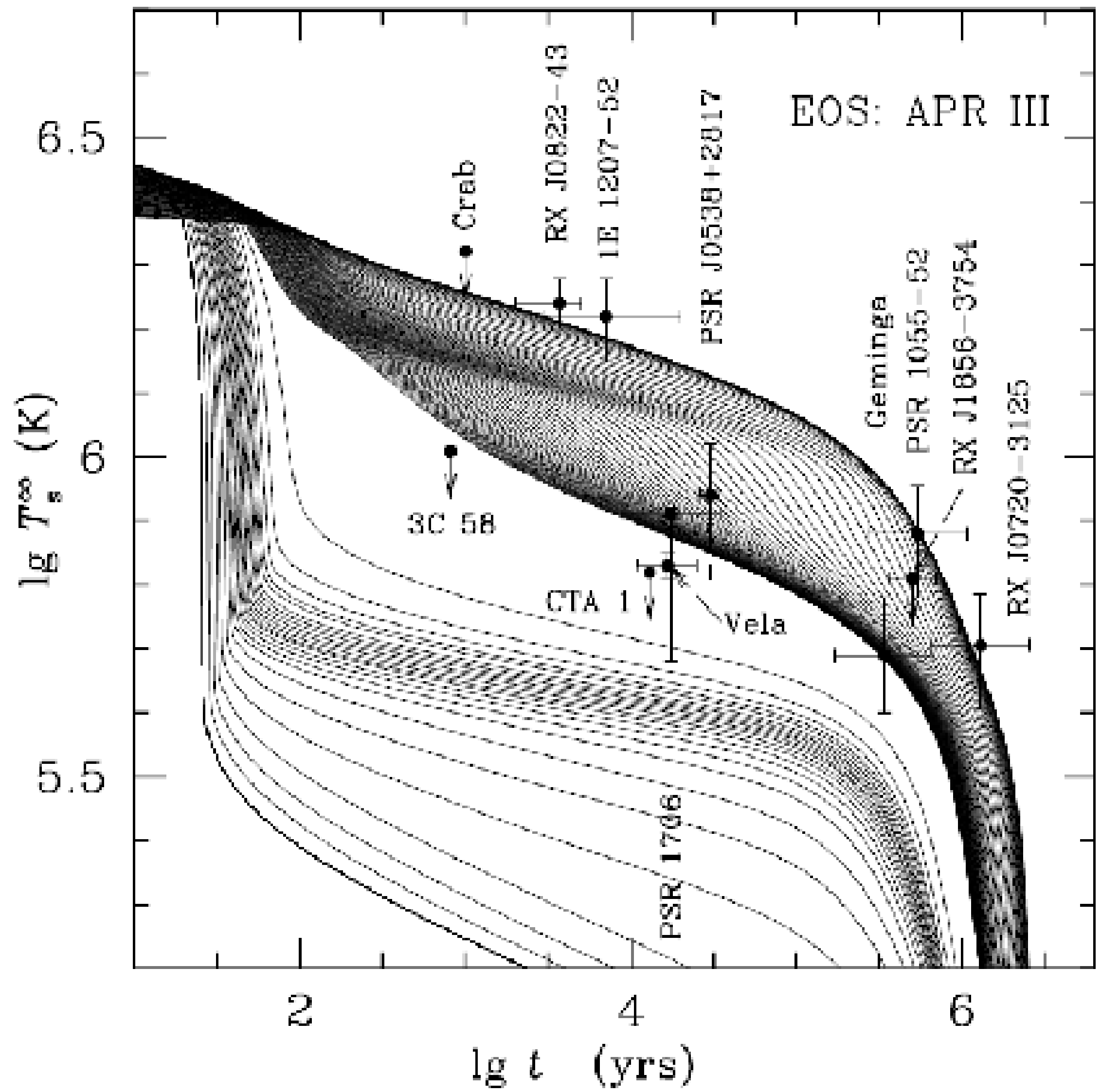
A.S. PRC 74 (2006) 045808.

- A small modification in the isospin dependence of the symmetry energy results in a large change of the critical density for direct Urca



A.S., PRC 74 (2006) 045808.

- This might alleviate difficulties with the presence of the direct Urca process in neutron star cooling calculations



M.E. Gusakov, A.D. Kaminker, D.G. Yakovlev, O.Y. Gnedin, MNRAS 363 (2005) 563.