The Neutron Star Crust and Giant Flares in Magnetars

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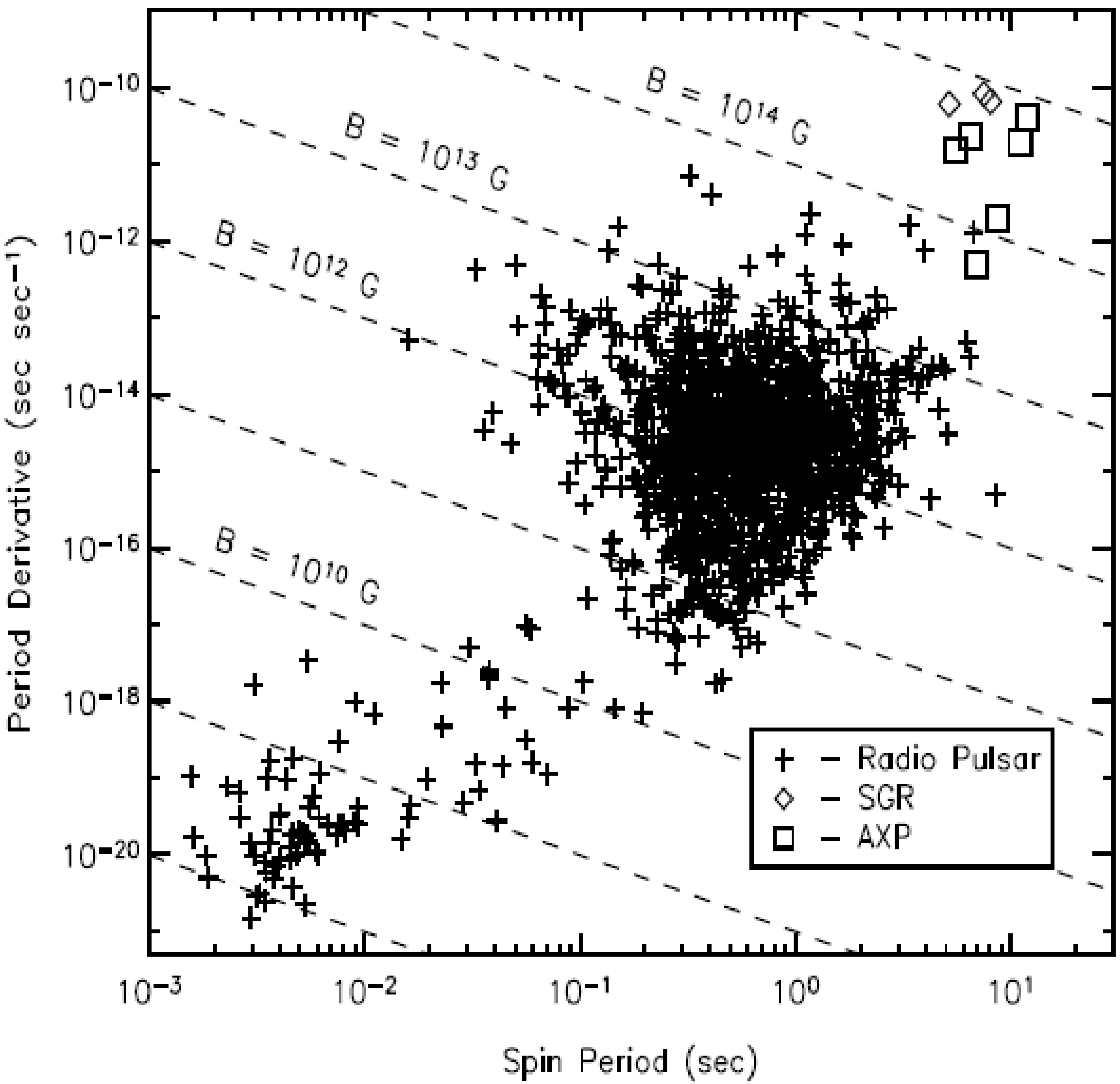
Outline

- Astrophysical constraint on bulk matter: Magnetars
  - One part of a multi-faceted effort to learn about dense matter
  - Example: What is the best *model-independent* constraint on dense matter above the saturation density?
  - Learn about neutron stars: Static properties, Cooling, Evolution, Explosive Phenomena, ...
- Low-density Neutron Matter and the Symmetry Energy
- New Frequencies?
- Conclusions

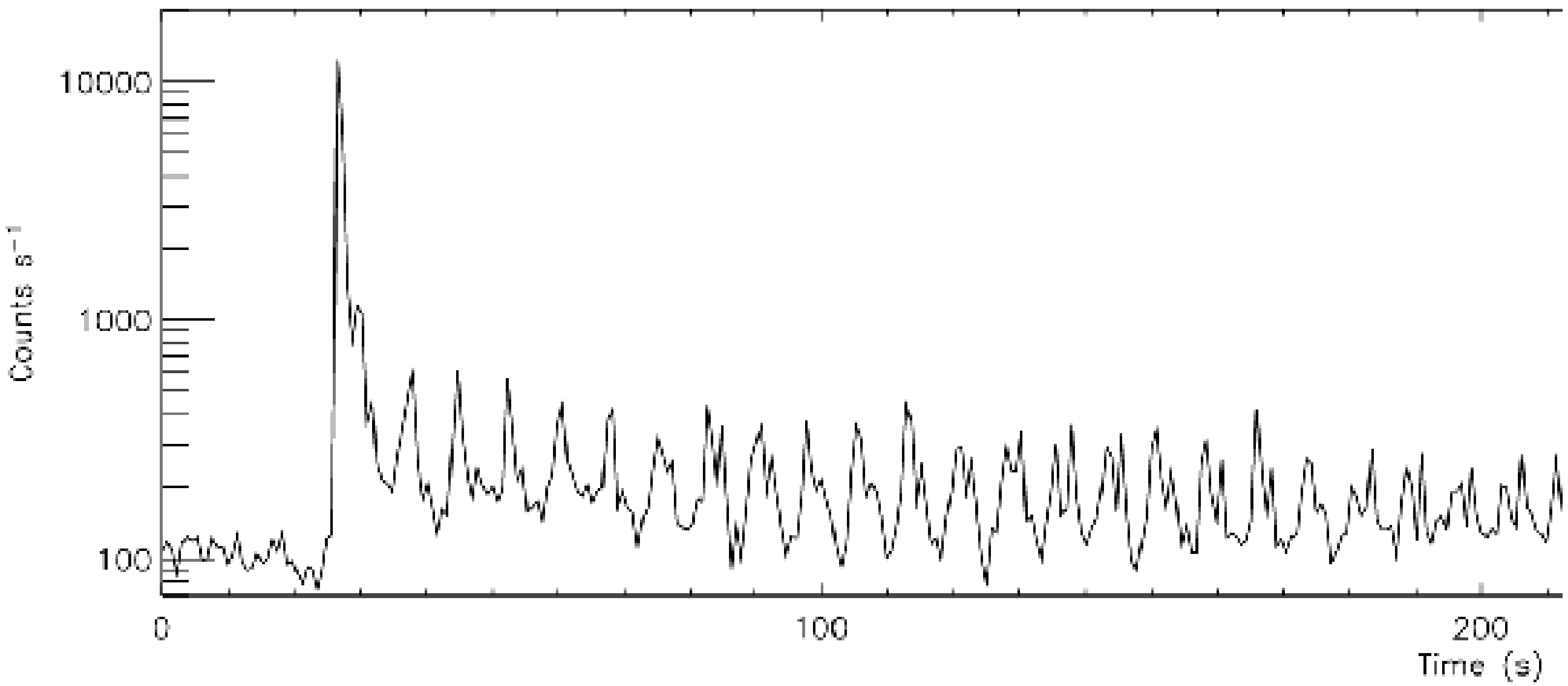
Magnetars - SGRs and AXPs



Woods and Thompson, astro-ph/0406133

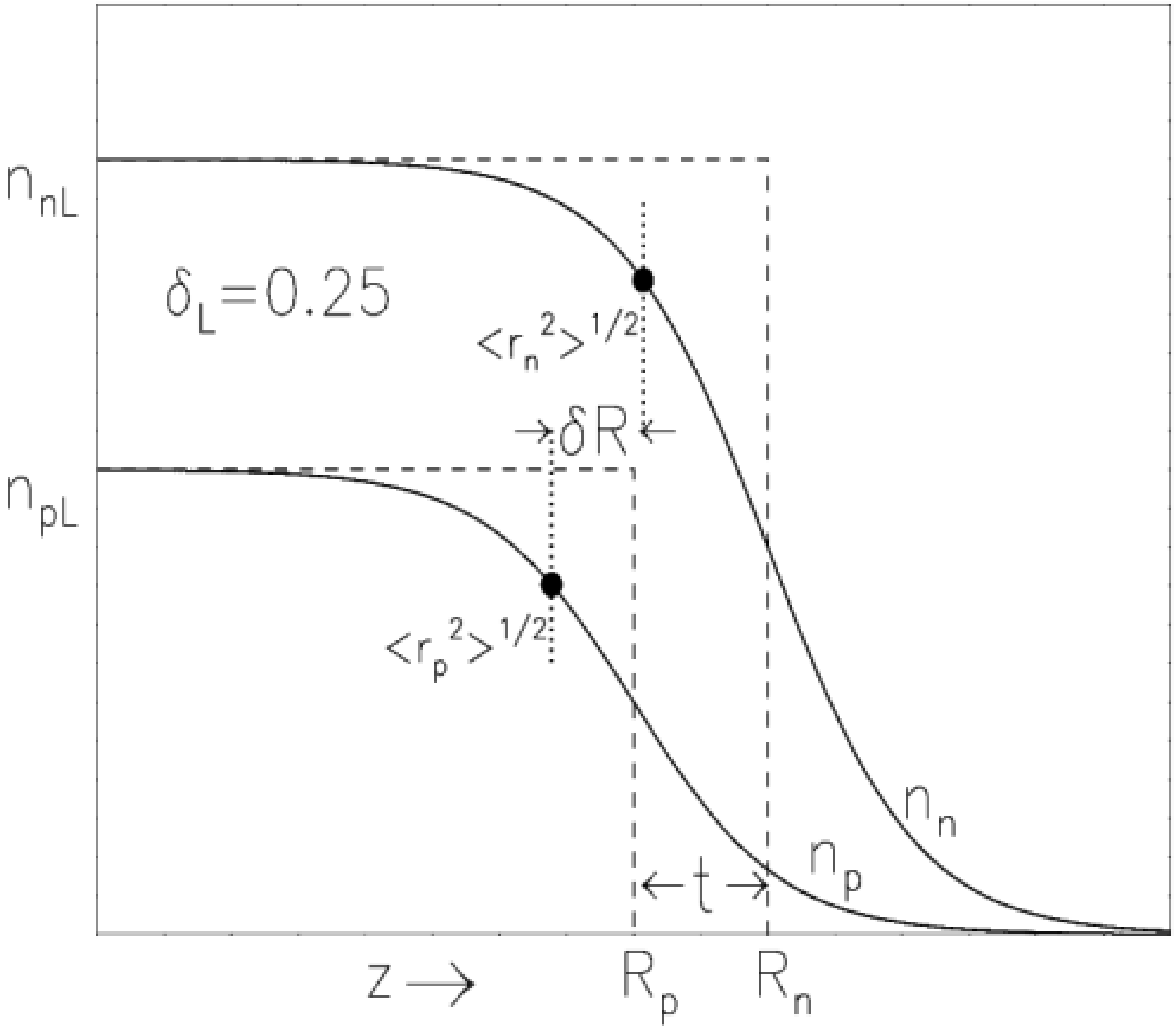
- Soft Gamma-ray Repeaters (SGRs) - emit flares of gamma-rays, originally thought to be short-soft GRBs
- But they repeat!
- Anomalous X-ray Pulsars (AXPs) - Pulsations from LMXB-like X-ray sources, but X-rays softer than usual.
- But young, and associated with SNRs
- Pulsations in SGR flares and gamma-ray flares from AXPs
- Magnetars - neutron stars with $B > 10^{14}$G

Periodic Oscillations in Giant Flares



- These flares are driven by a catastrophic reconfiguration of a highly magnetized neutron star crust
- Inside the flare, quasi-periodic oscillations
- They excite normal modes in the crust
- 30 Hz - n=0, l=2
- 626 Hz - n=1, l=2
- Also in 1806 is an 18 Hz mode, possibly a magnetospheric mode in the core

Liquid Droplet Model



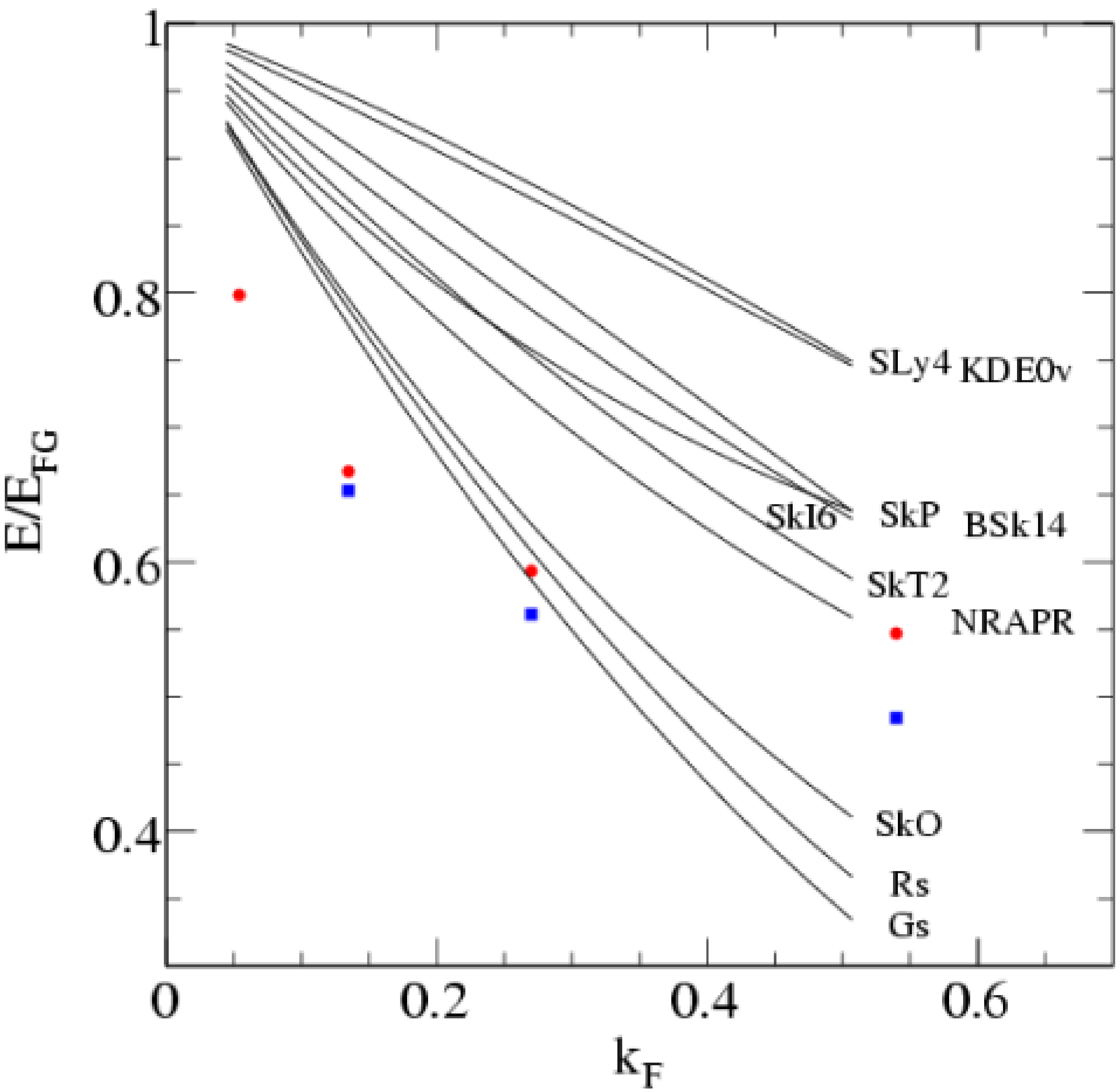
A.W. Steiner, M. Prakash, J.M. Lattimer, P.J. Ellis, Phys. Rep 411 (2005) 325.

- Liquid drop models are important: they help illustrate the basic physical principles
- More microscopic is not necessarily more accurate
- Speed
- Nucleonic matter EOS, e.g. APR
- Bulk energy
- Surface energy: energy density is surface tension divided by radius.
- Coulomb energy: Spherical droplet in a Wigner-Seitz cell
- No pairing or shell effects at the moment

- Mass formula ~ 2.5 MeV

Low-density Neutron Matter

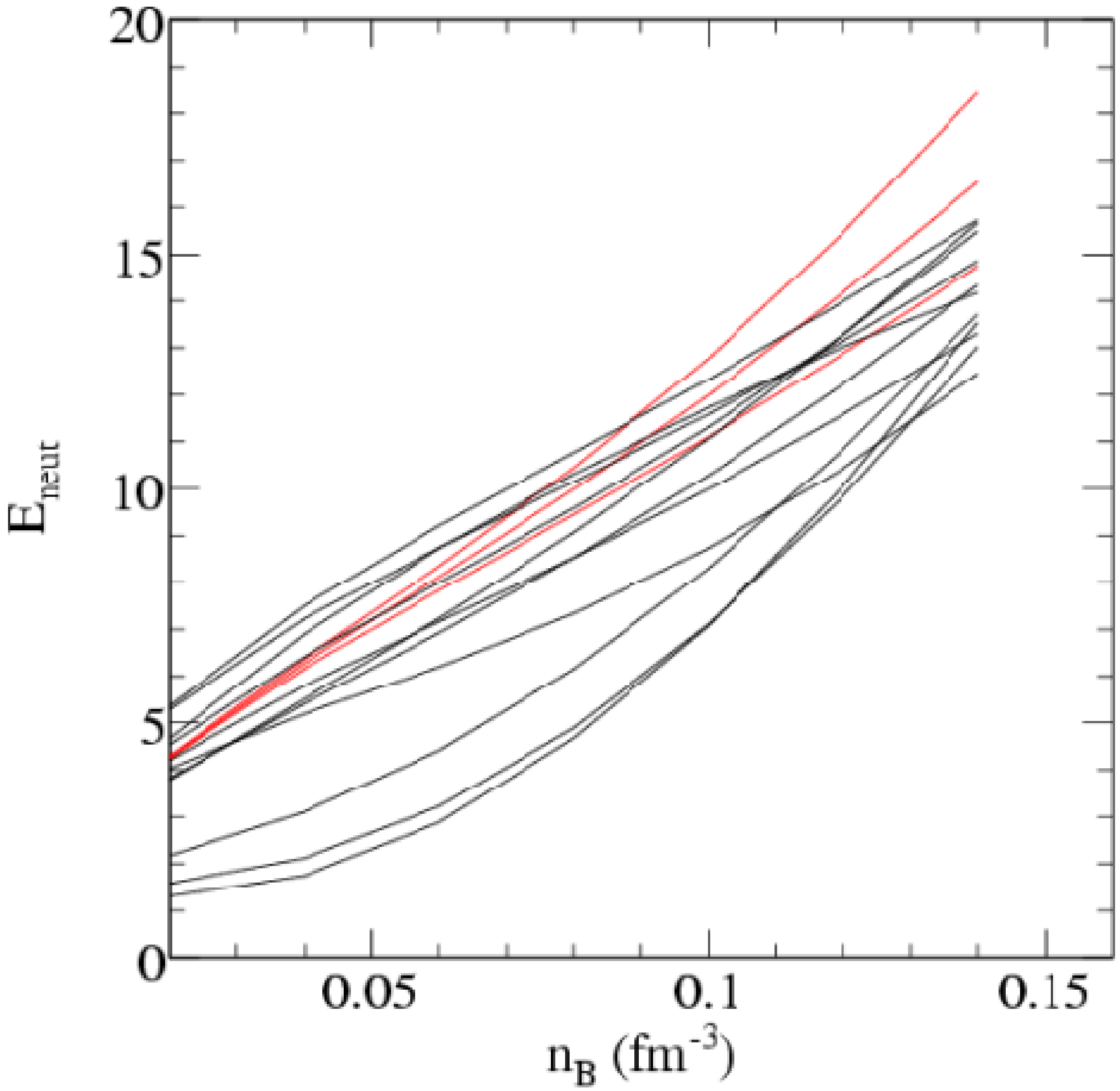
- Neutron matter is well-understood
- Well-described by the effective range expansion, accessible in experiment
- At lower densities three body interactions are small
- $E_{FG} = \frac{k_F^5}{10\pi^2 m^*}$
- In Skyrme models, low-density behavior controlled by t_0, but also by t_3
- Relativistic models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



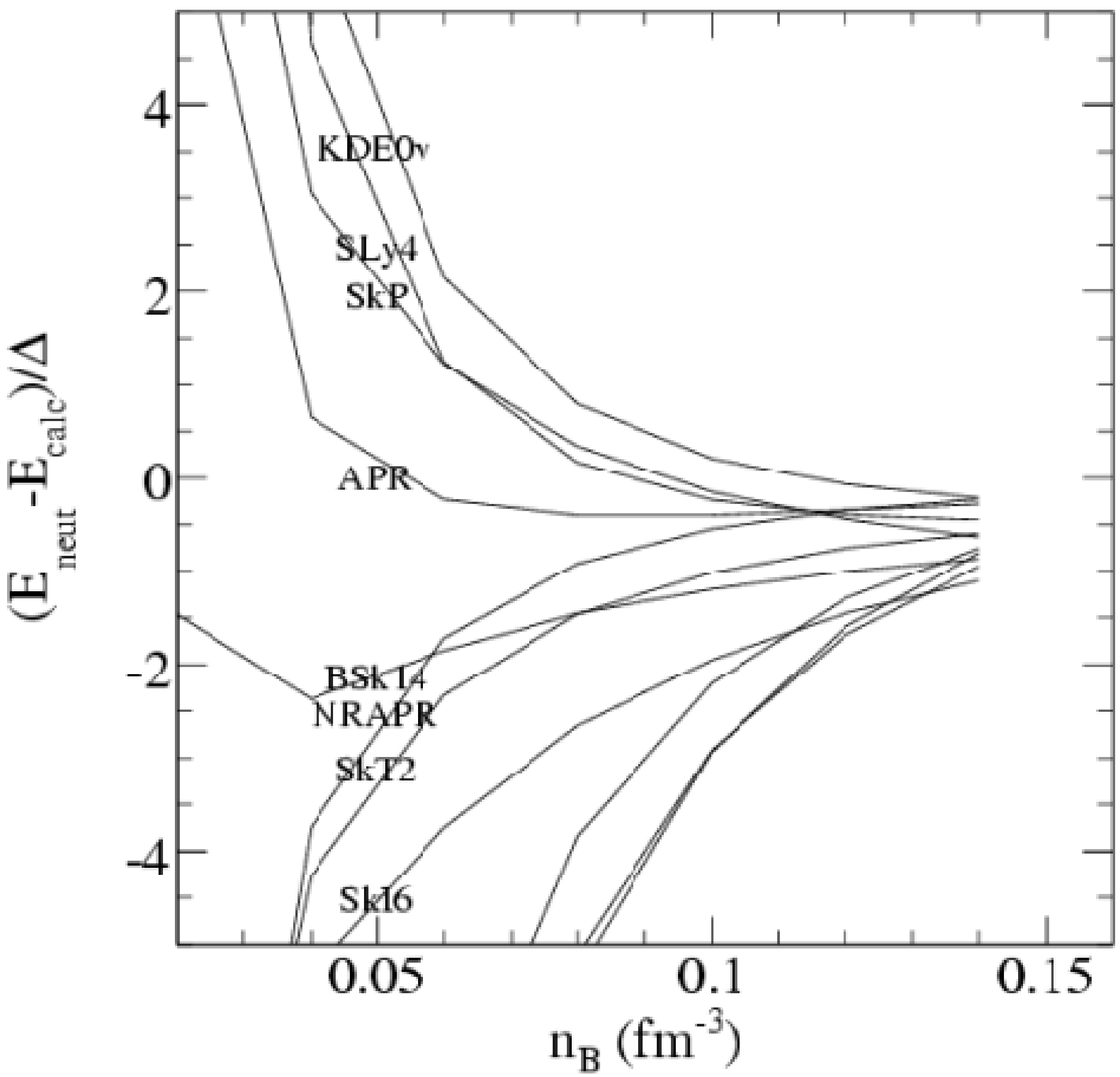
Data from A. Gezerlis and J. Carlson, Phys. Rev C. 77 (2008) 032801(R).

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

Low-density Neutron Matter II

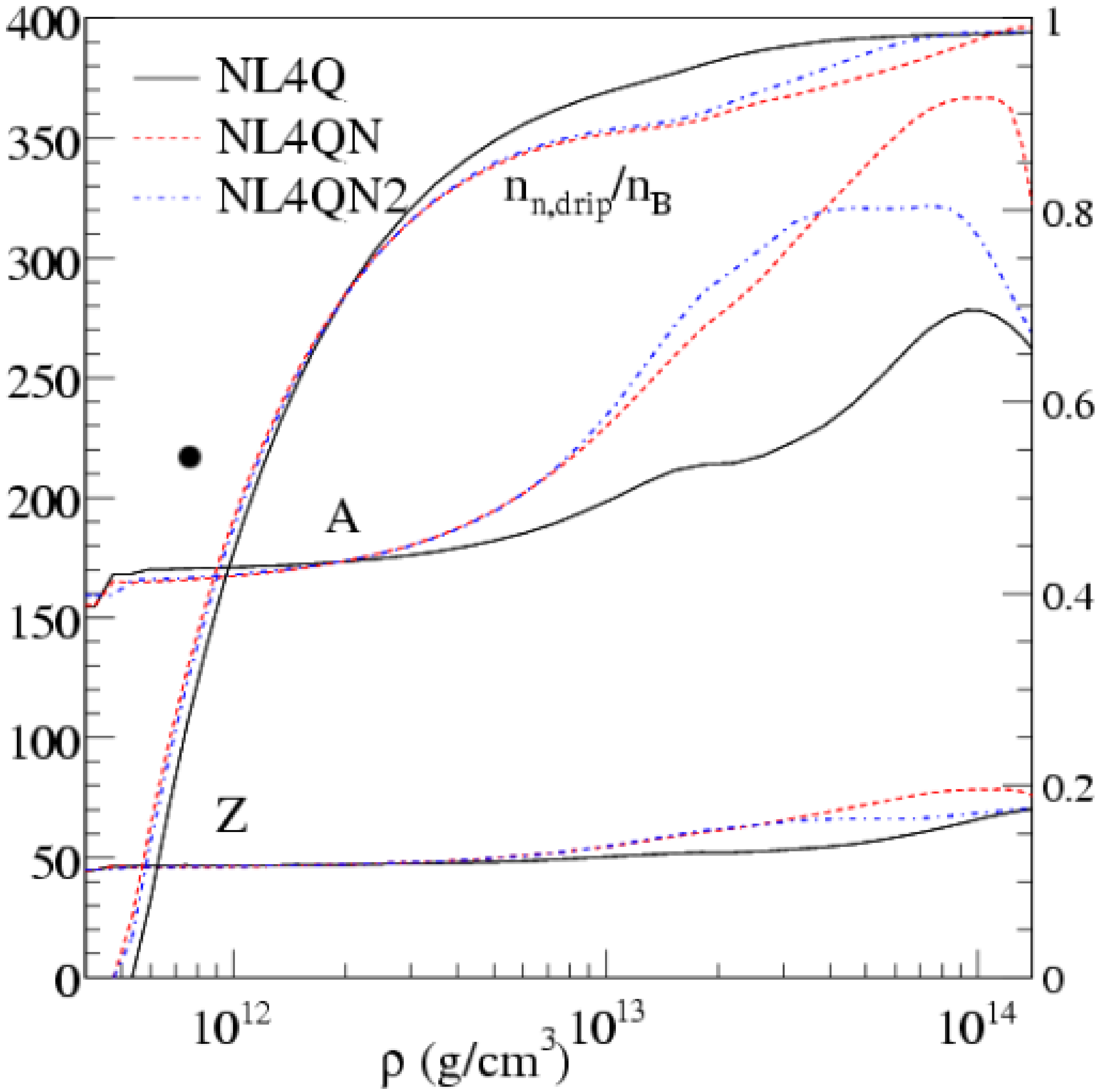


Adapted from
L. Tolos, B. Friman, and A. Schwenk (2007)



- Even the models which work at low densities have trouble at higher densities

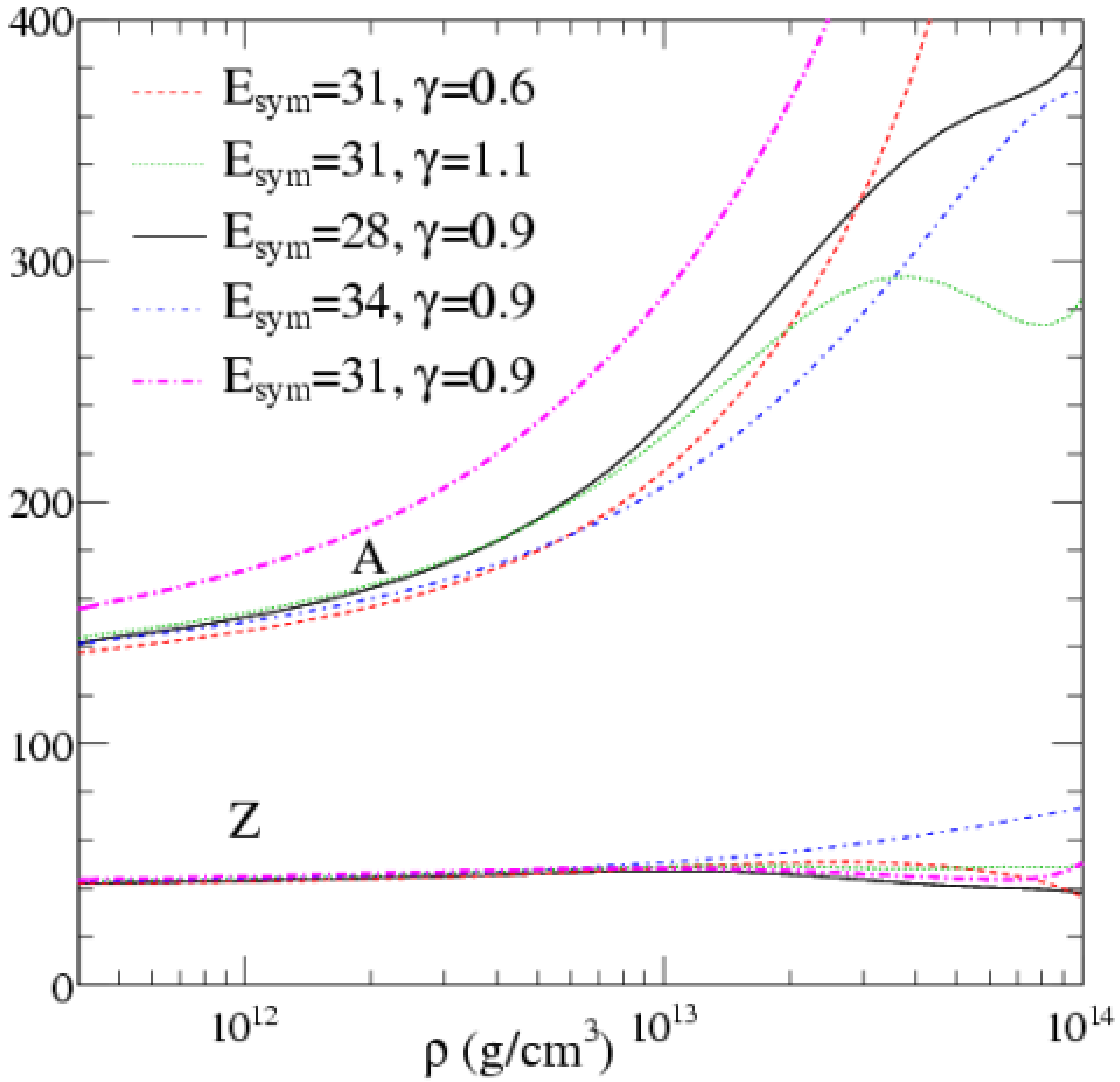
Low-density Neutron Matter III



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

- Very few models have reasonable neutron matter
- Change the low-density neutron EOS for a relativistic model NL4
- $$E_{\rm neut}^{\rm NL4QN} = E_{\rm neut}^{\rm APR} + \frac{E_{\rm neut}^{\rm NL4Q} - E_{\rm neut}^{\rm APR}}{1 + e^{(n_t - n)/\nu}}$$
  $n_t = 0.08~{\rm fm}^{-3}, \nu = 0.08~{\rm fm}^{-3}$
- Significant change in the composition
- We care about the composition because it affects the transport properties

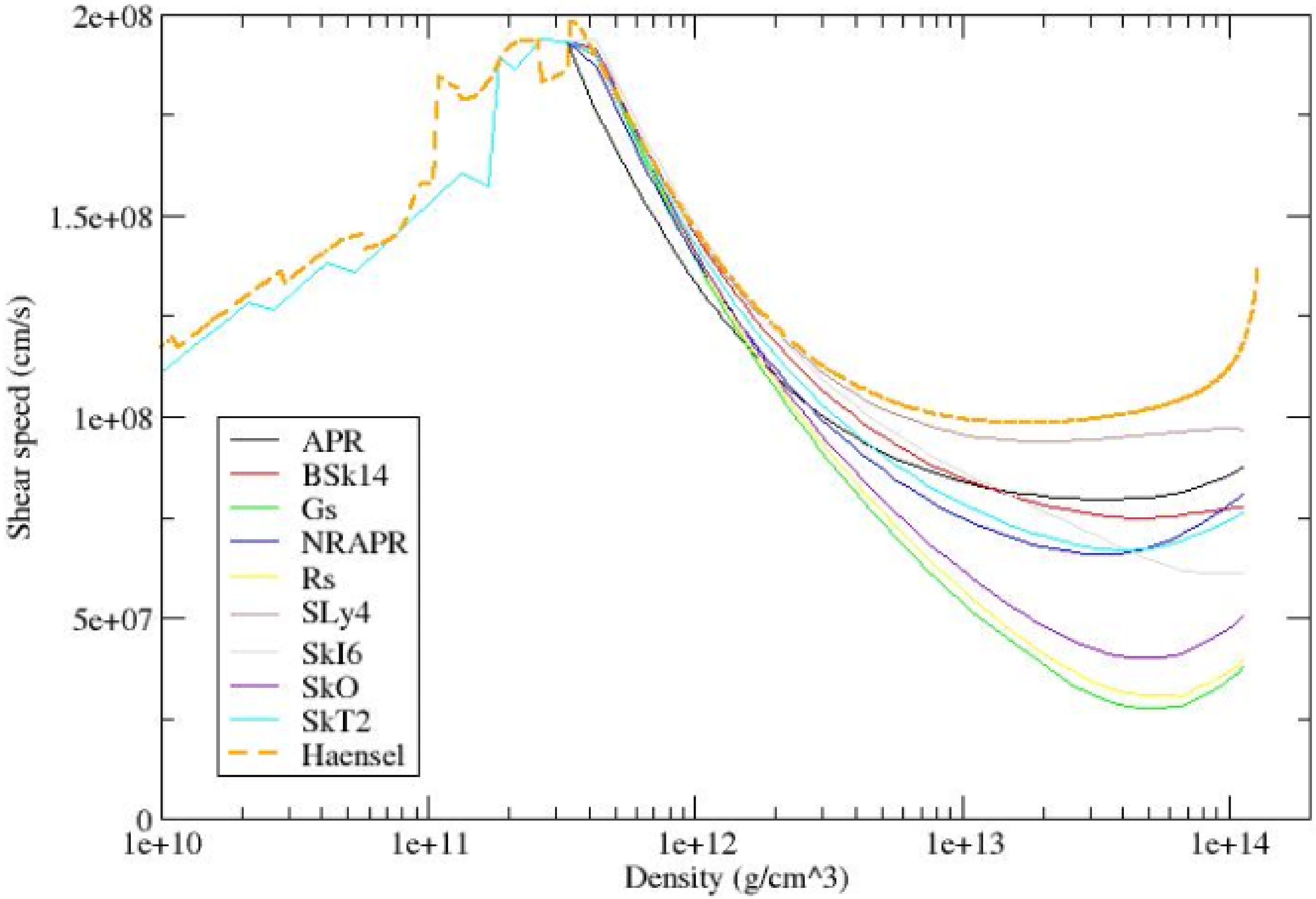
Symmetry Energy and the Crust



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

- $E_{sym} = A(n/n_0)^{2/3} + B(n/n_0)^{\gamma}$
- Fix neutron matter to the Monte Carlo results
- Then, arrange A=17, A+B=E_{sym}, and γ.
- The density dependence of the symmetry energy is the *largest* uncertainty in the composition of the crust
- Compressibility is unimportant
- One model is not correct - a range of models gives a range of predictions

Shear properties



A.W. Steiner and A. Watts (in prep)

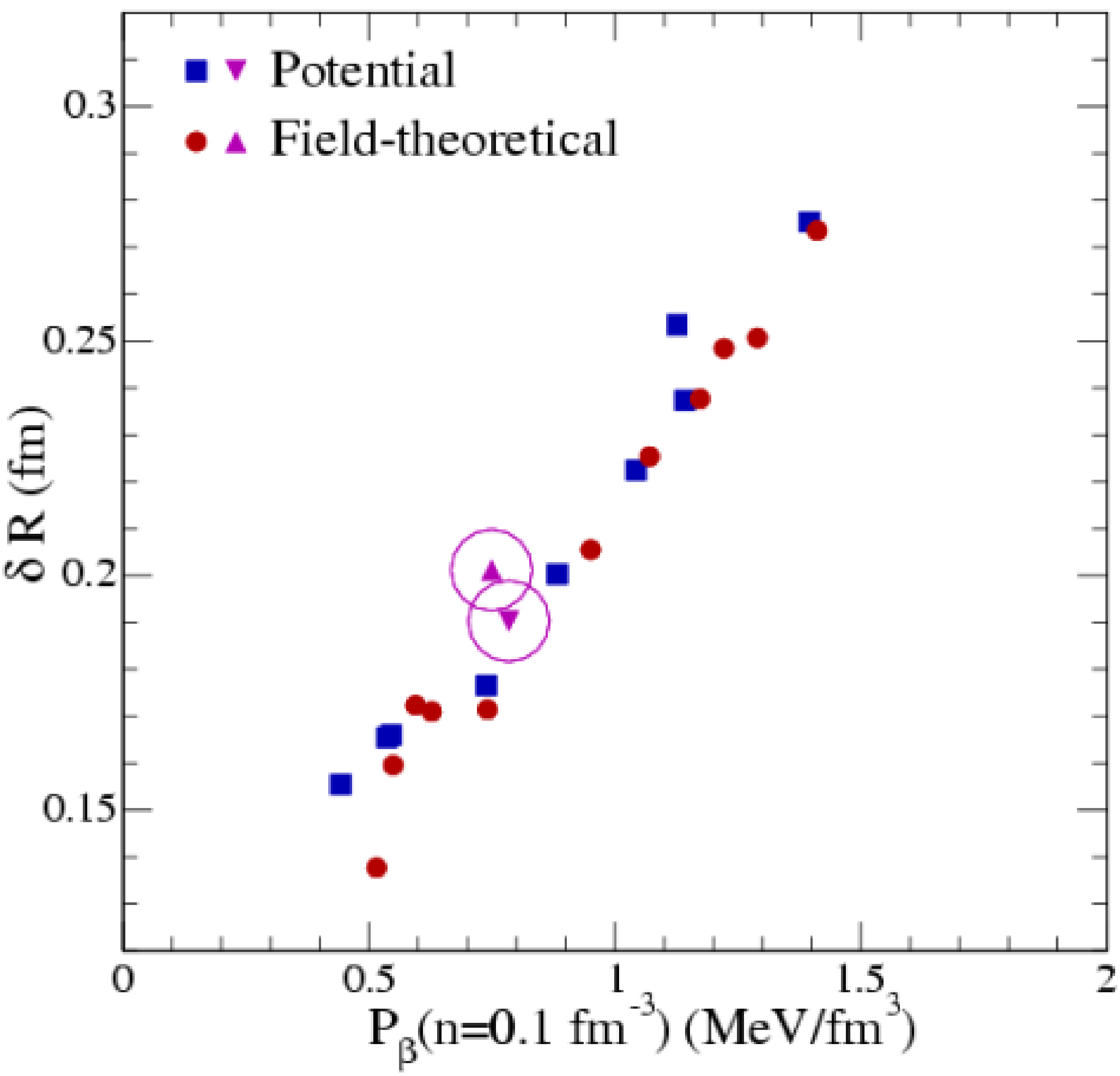
- Still have to make neutron stars - Skyrme model
- Factor of 5 variation in the shear speed

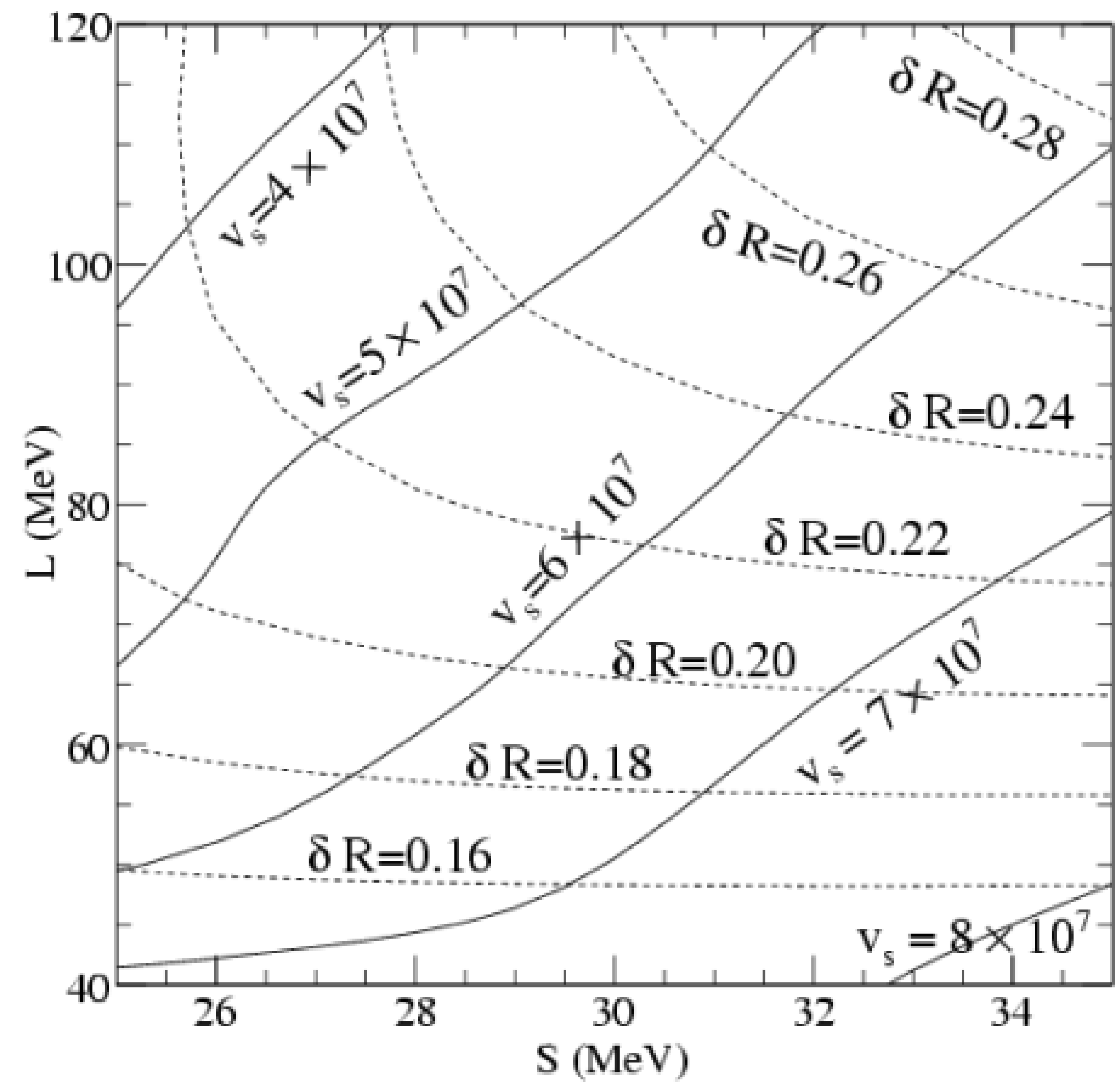
$$\mu = \frac{0.12}{1+0.6(173/\Gamma)^2}\frac{n(Ze)^2}{a} \quad v_s = (\mu/\rho)^{1/2}$$

T. Stromayer et al., Ap J 375 (1991) 679,

T. Piro Ap. J Lett. 634 (2005) 153,

Parity violating electron scattering

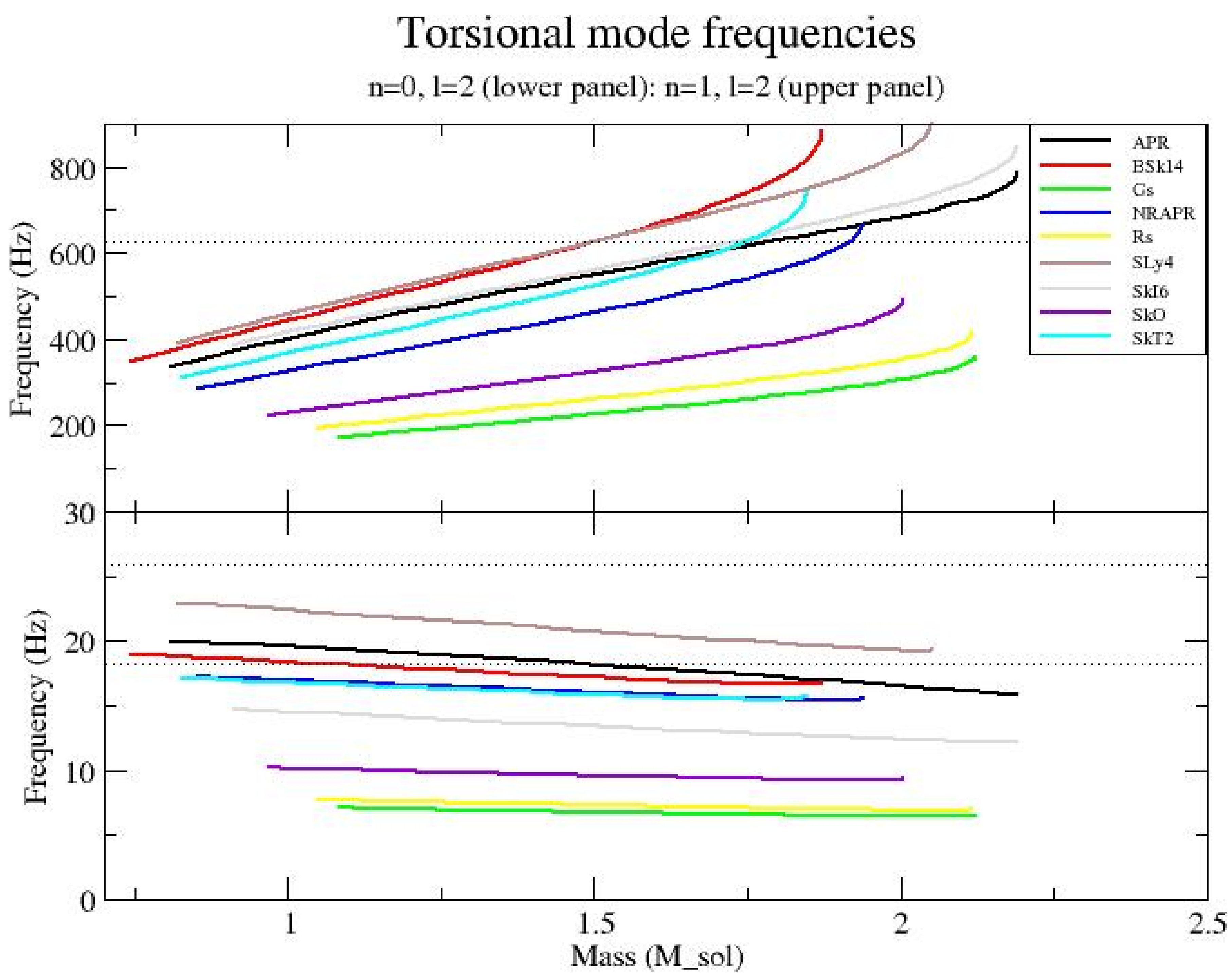




- PREX will measure the neutron radius in lead

- It will also provide a constraint on the composition of the crust

Frequencies



A.W. Steiner and A. Watts (in prep)

- It turns out to be very difficult to generate a 30 Hz fundamental, unless the neutron skin thickness is small
- We have checked that GR and the crust-core transition density don't have a significant effect on the fundamental mode

Summary and Discussion

- Neutron star crusts demand accurate models of neutron matter and the symmetry energy
- Of the traditional Skyrme or mean-field models, how many are usable to describe the crust?
- What is most useful is a model with a range, which describes the uncertainty given a fit to a particular data set. In fact, not just a range, but a multi-dimensional contour!
- I don't have a "best" crust model - this is a good thing!
- How to fix the DFT?
- PREX will be important in determining the composition
- The 30 Hz mode in giant flares may not be the fundamental

- Oscillations in giants flares can potentially offer *quantitative* constraints on the symmetry energy