The Neutron Star Crust and Giant Flares in Magnetars

Andrew W. Steiner

Workshop on the Equation of State in Astrophysics

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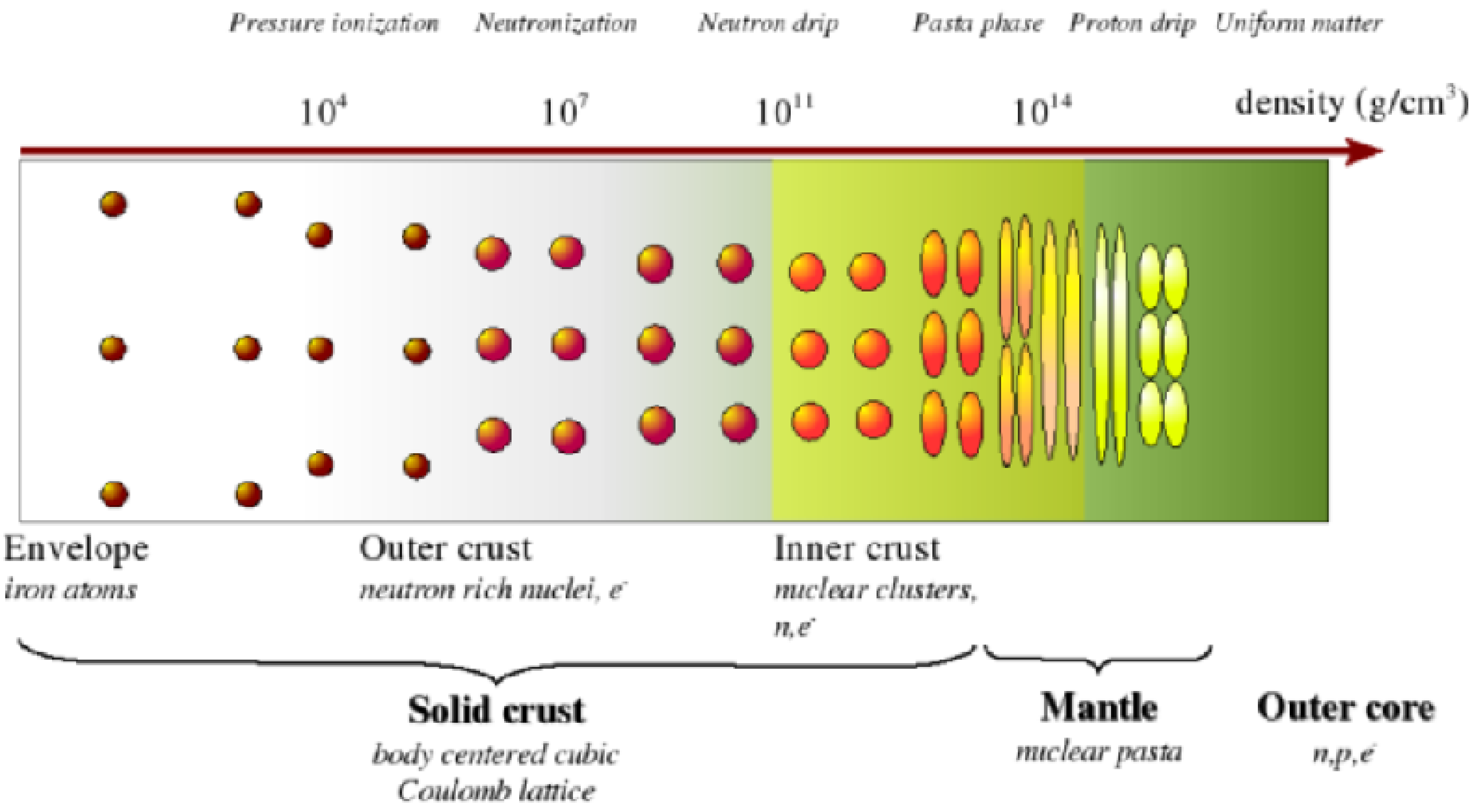
In collaboration with: E. Brown (Mich. State Univ.), R. Donangelo (Federal University, Porto Alegre, Brazil), M. Famiano (Western Mich. Univ.) W.G. Lynch (Mich. State Univ.), S.R. Souza (Federal University, Porto Alegre, Brazil), A. Watts (Univ. of Amsterdam)

Outline

- Model of the Neutron Star Crust
- Low-density Neutron Matter and the Symmetry Energy
- Magnetars and Giant Flares
- New Frequencies?
- Supernova EOS
- Conclusions

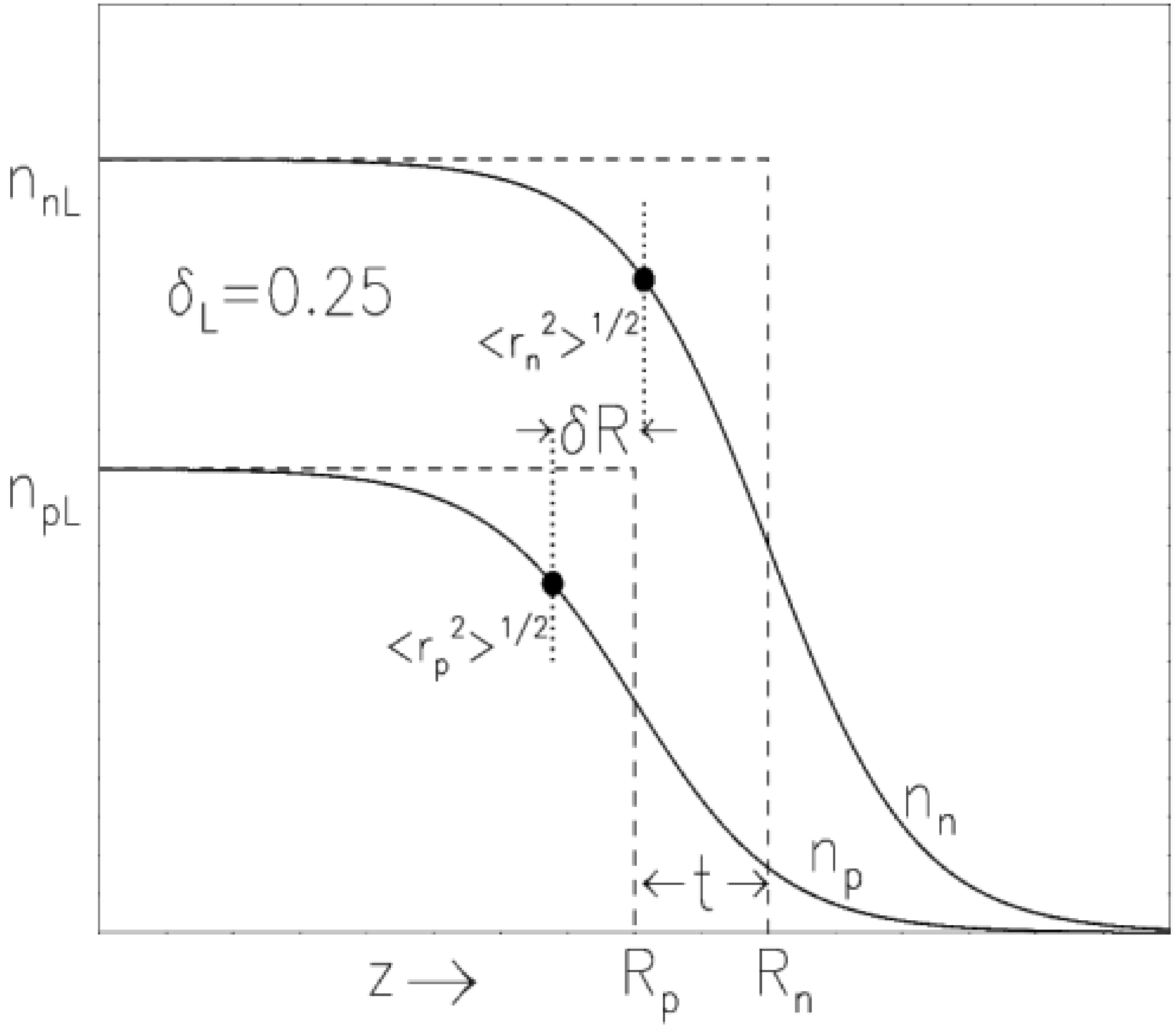
Equilibrium Neutron Star Composition



(Illustration by N. Chamel)

- The crust consists of increasingly exotic nuclei, followed by a transition to nuclear matter, demarcated into "inner" and "outer" by neutron drip density
- ^{56}Fe to ^{118}Kr to $^{200\text{-}400}$(28-50)
- Outer crust ~ 1/3 km, Inner crust ~ 1/2 km, Remainder of star ~ 10km

Liquid Droplet Model

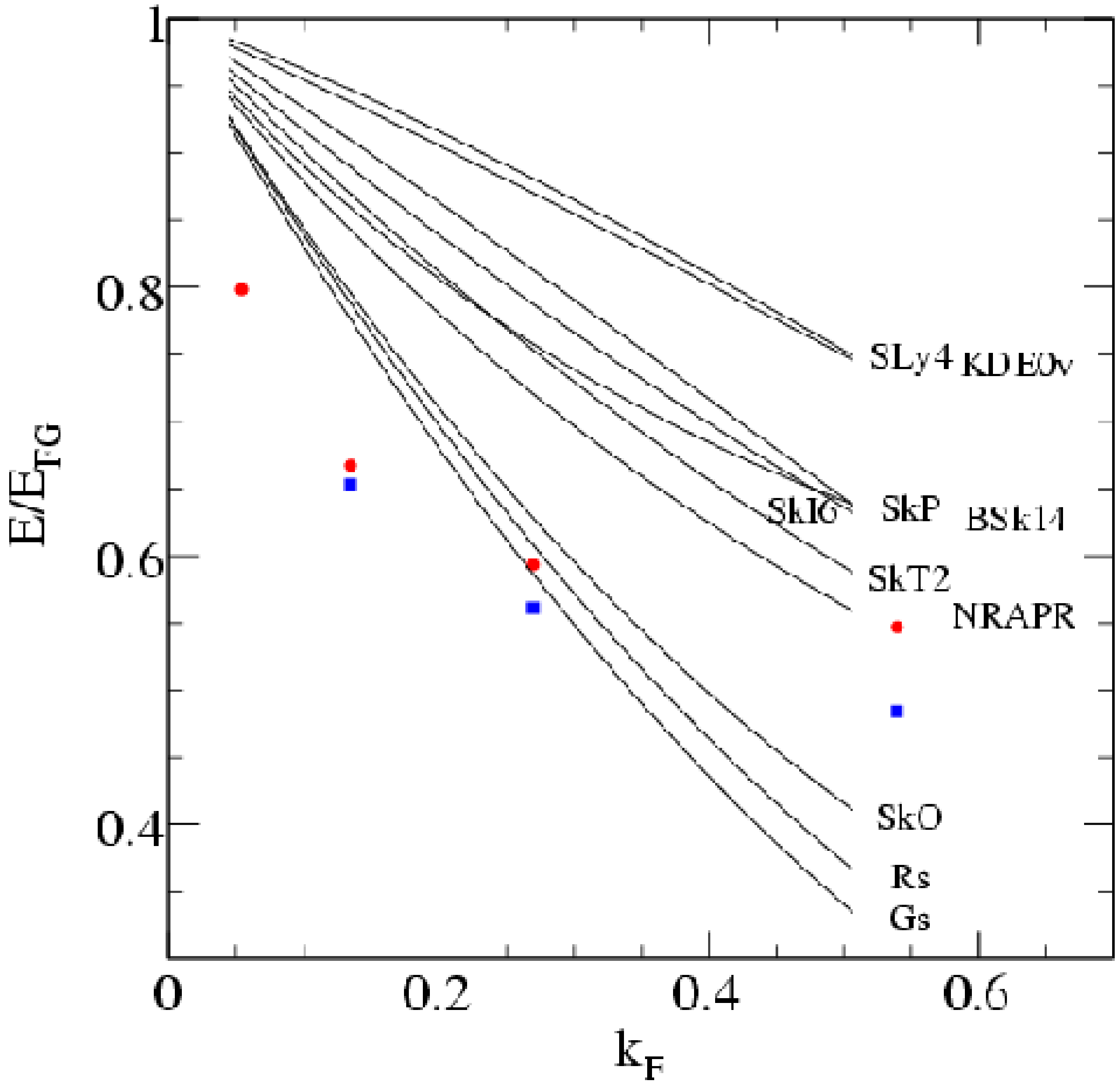


A.W. Steiner, M. Prakash, J.M. Lattimer, P.J. Ellis, Phys. Rep 411 (2005) 325.

- Liquid drop models are important: they help illustrate the basic physical principles
- 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
- Several variables: neutron and proton densities, number of nuclei, Z and A.
- Mass formula ~ 2.5 MeV

Low-density Neutron Matter

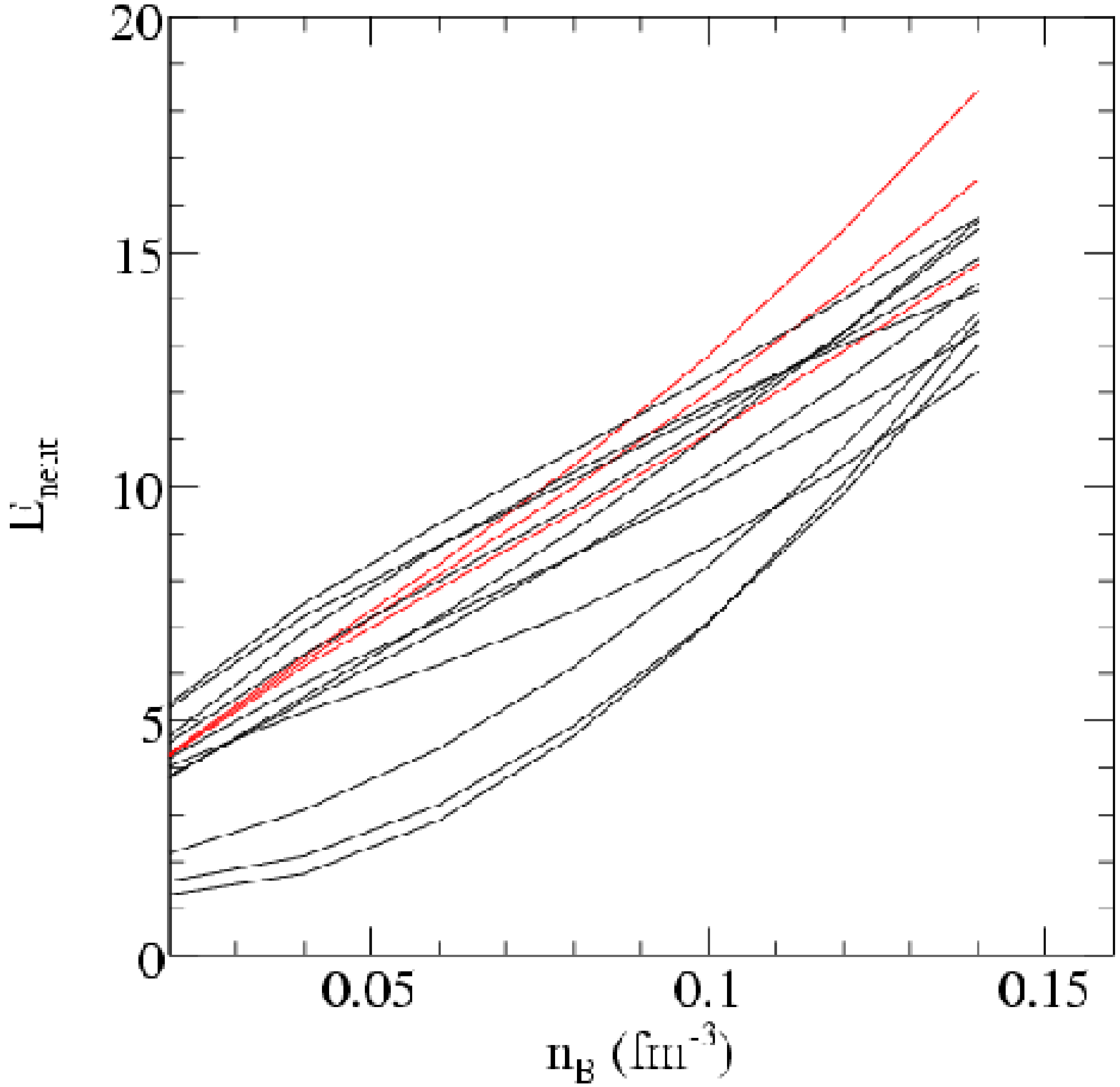
- Neutron matter is well-understood
- Well-described by the effective range expansion, accessible in experiment
- At lower densities three body interactions are small
- $E_{FG} = \frac{k_F^5}{10\pi^2 m^*}$
- In Skyrme models, low-density behavior controlled by t_0, but also by t_3



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

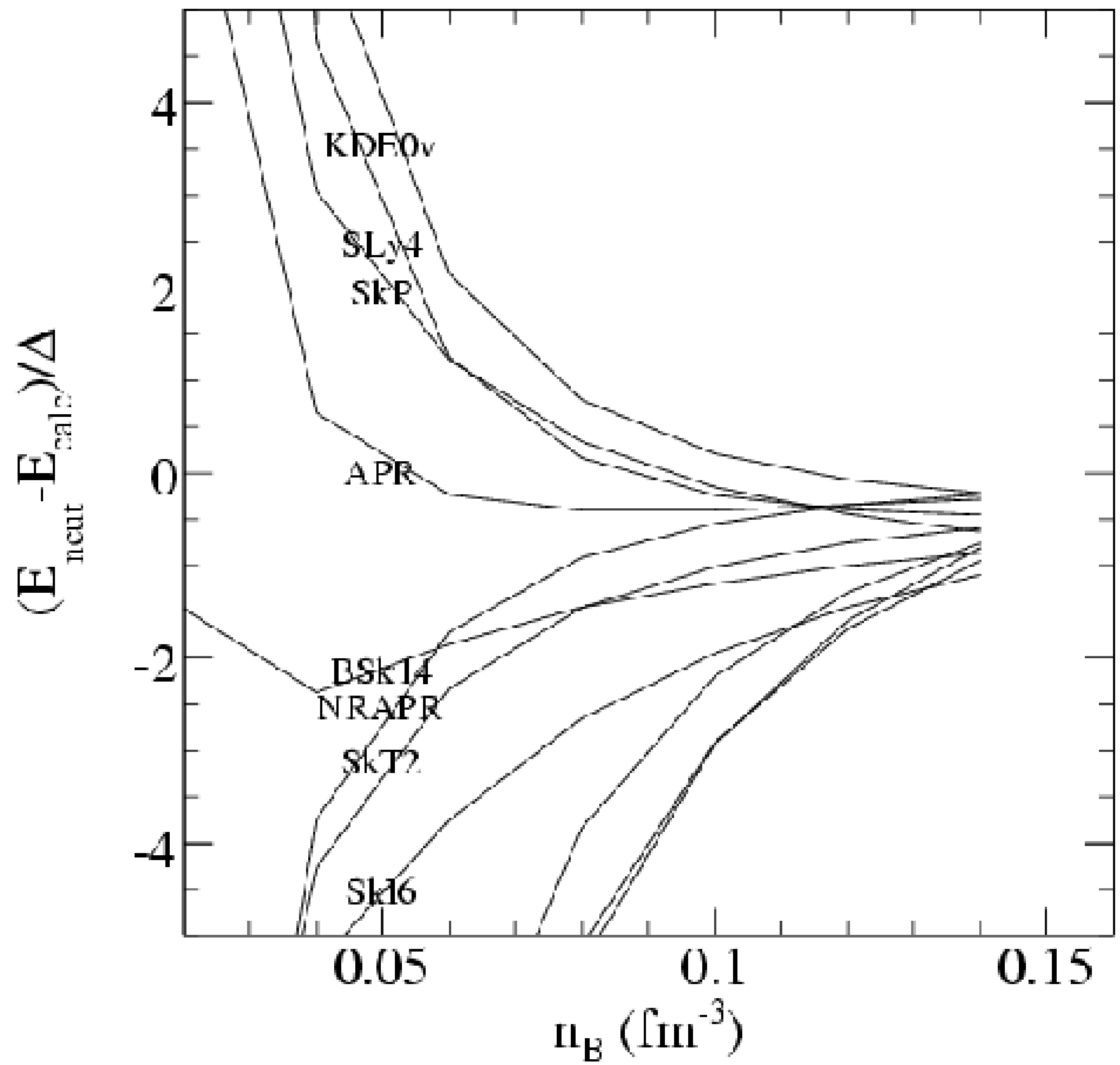
- $E_{neut} = \left[1 - 0.6 k_F^{0.4} + \eta_1 (n/n_0) + \eta_2 (n/n_0)^2\right] E_{FG}$
- This form, however, does not always provide reasonable neutron stars

Low-density Neutron Matter II



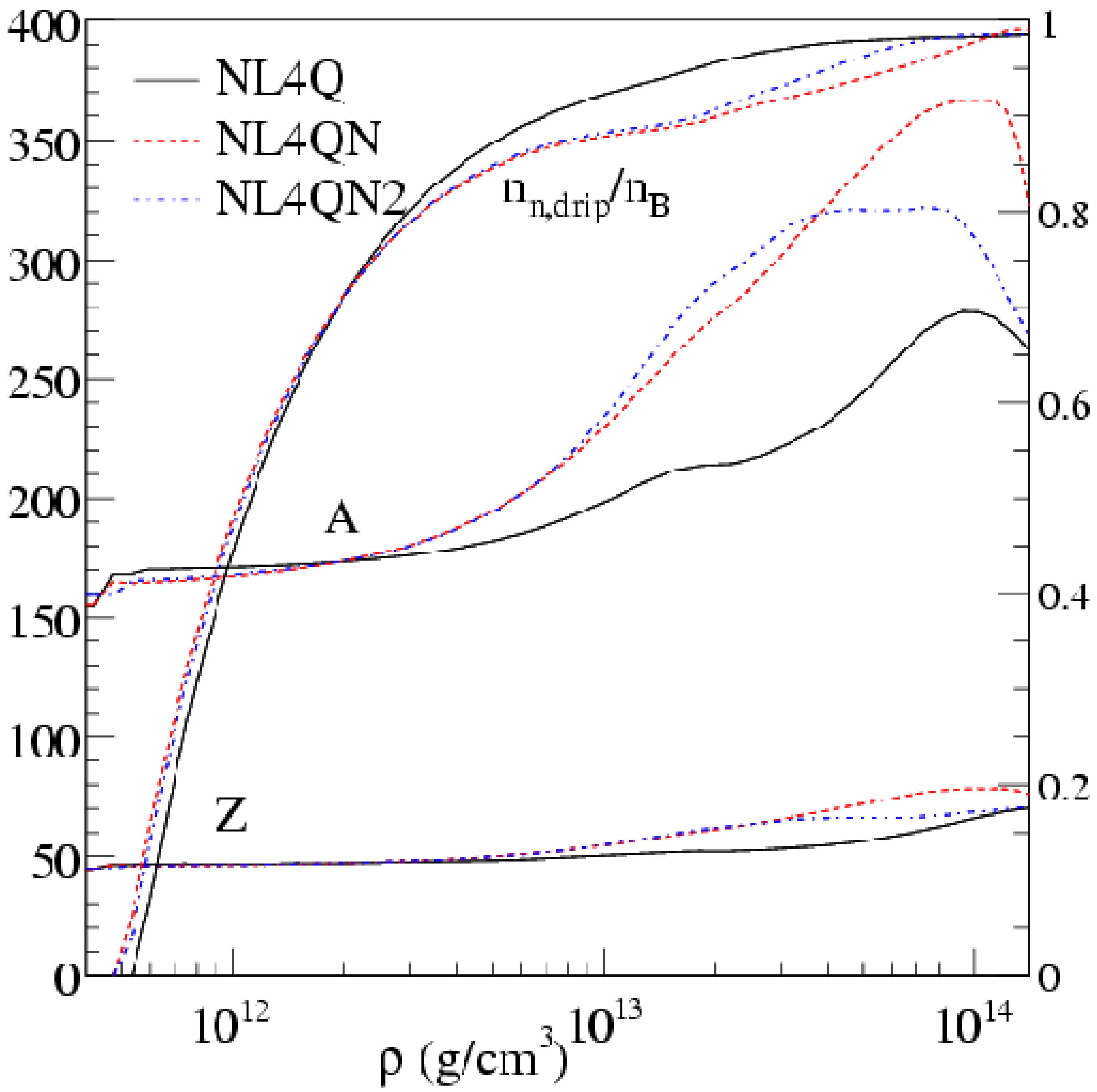
Adapted from

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



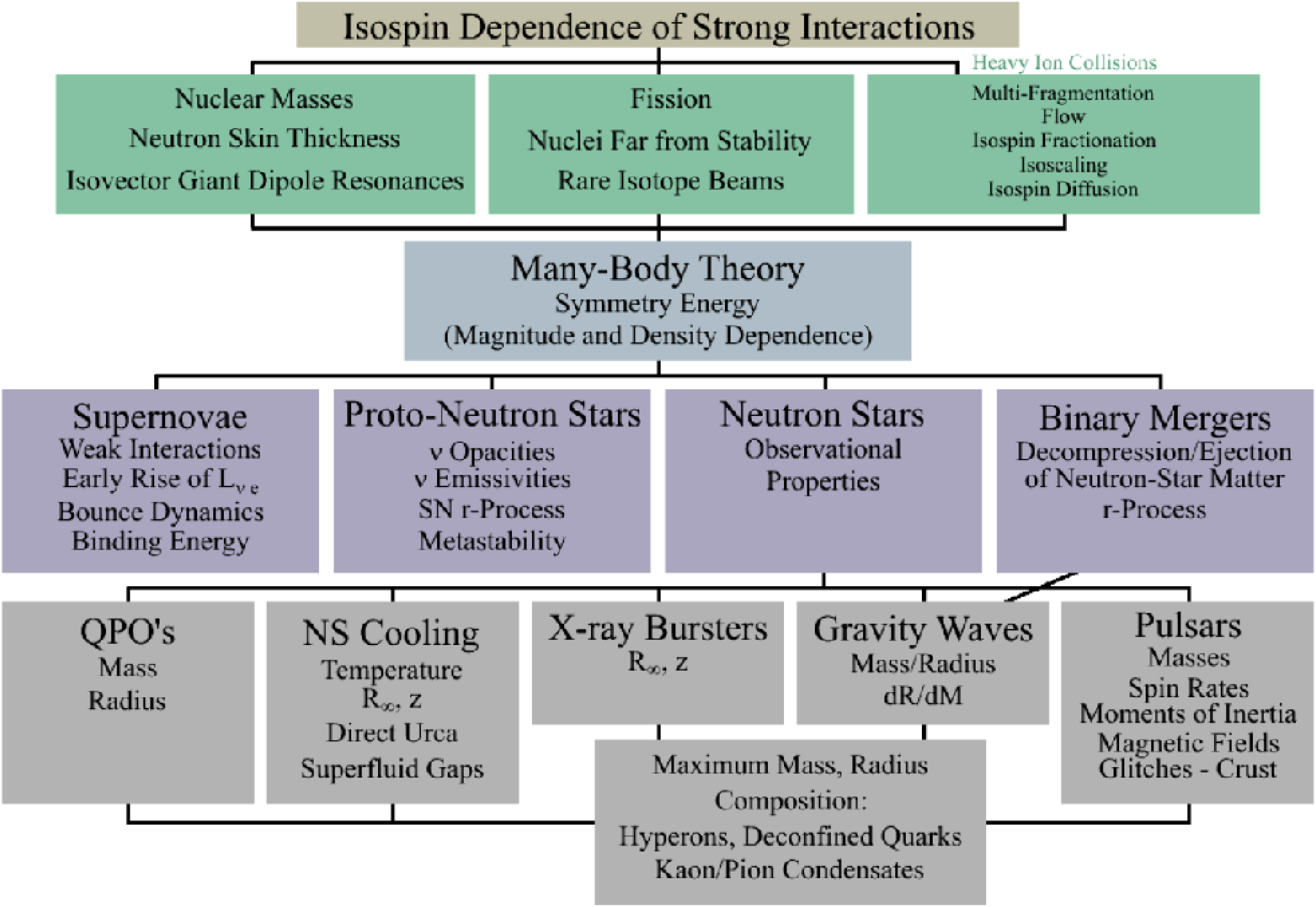
- Even the models which work at low densities have trouble at higher densities

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
- $$E_{\mathrm{neut}}^{\mathrm{NL4QN}} = E_{\mathrm{neut}}^{\mathrm{APR}} + \frac{E_{\mathrm{neut}}^{\mathrm{NL4Q}} - E_{\mathrm{neut}}^{\mathrm{APR}}}{1 + e^{(n_t - n)/\nu}}$$
  $n_t = 0.08\ \mathrm{fm}^{-3}$, $\nu = 0.08\ \mathrm{fm}^{-3}$
- Significant change in the composition
- We care about the composition because it affects the transport properties



Isospin Dependence of Strong Interactions

Nuclear Masses
Neutron Skin Thickness
Isovector Giant Dipole Resonances

Fission
Nuclei Far from Stability
Rare Isotope Beams

Heavy Ion Collisions
Multi-Fragmentation
Flow
Isospin Fractionation
Isoscaling
Isospin Diffusion

Many-Body Theory
Symmetry Energy
(Magnitude and Density Dependence)

Supernovae
Weak Interactions
Early Rise of L_{ν_e}
Bounce Dynamics
Binding Energy

Proto-Neutron Stars
ν Opacities
ν Emissivities
SN r-Process
Metastability

Neutron Stars
Observational
Properties

Binary Mergers
Decompression/Ejection
of Neutron-Star Matter
r-Process

QPO's
Mass
Radius

NS Cooling
Temperature
R_∞, z
Direct Urca
Superfluid Gaps

X-ray Bursters
R_∞, z

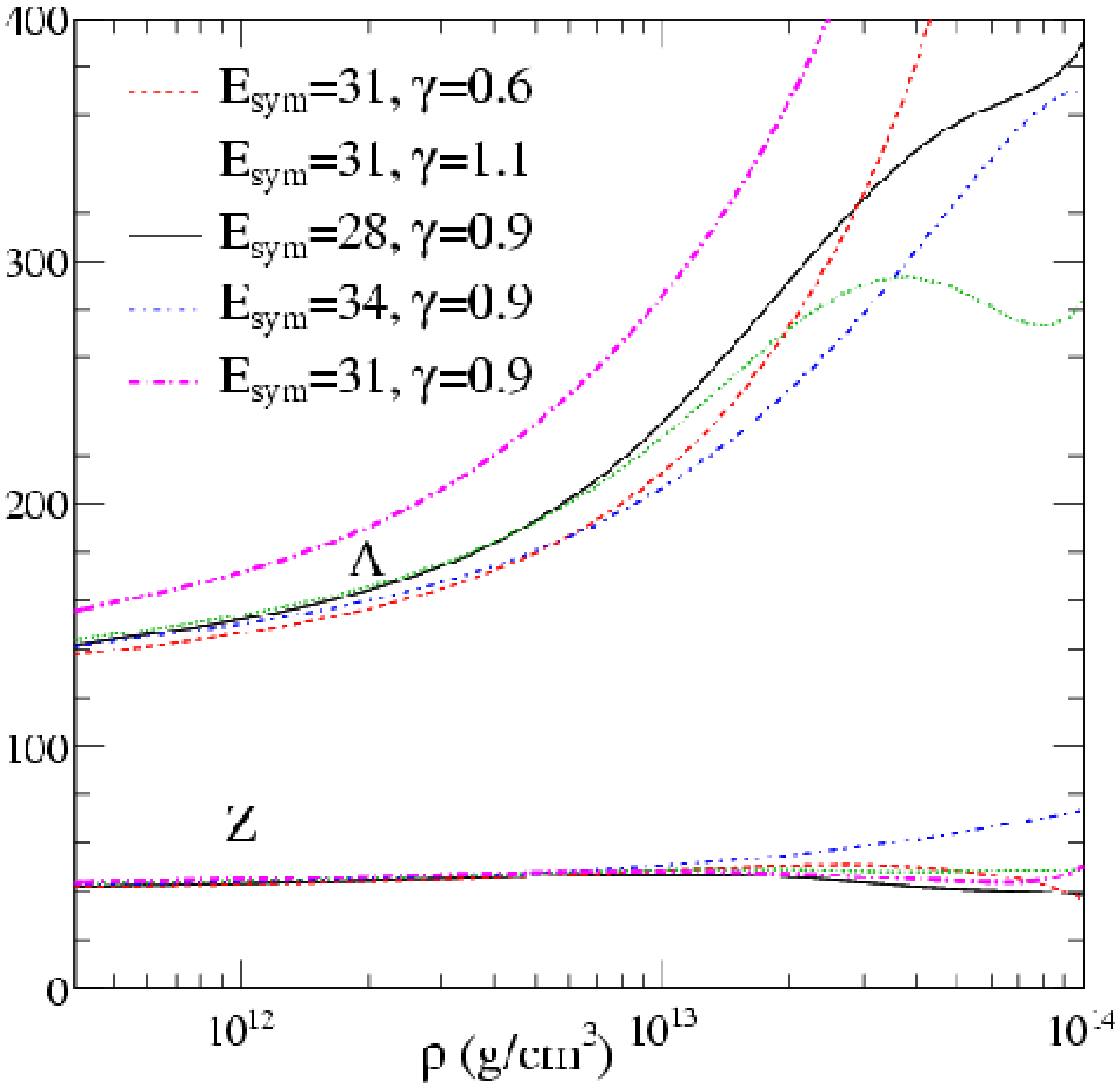
Gravity Waves
Mass/Radius
dR/dM

Pulsars
Masses
Spin Rates
Moments of Inertia
Magnetic Fields
Glitches - Crust

Maximum Mass, Radius
Composition:
Hyperons, Deconfined Quarks
Kaon/Pion Condensates

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

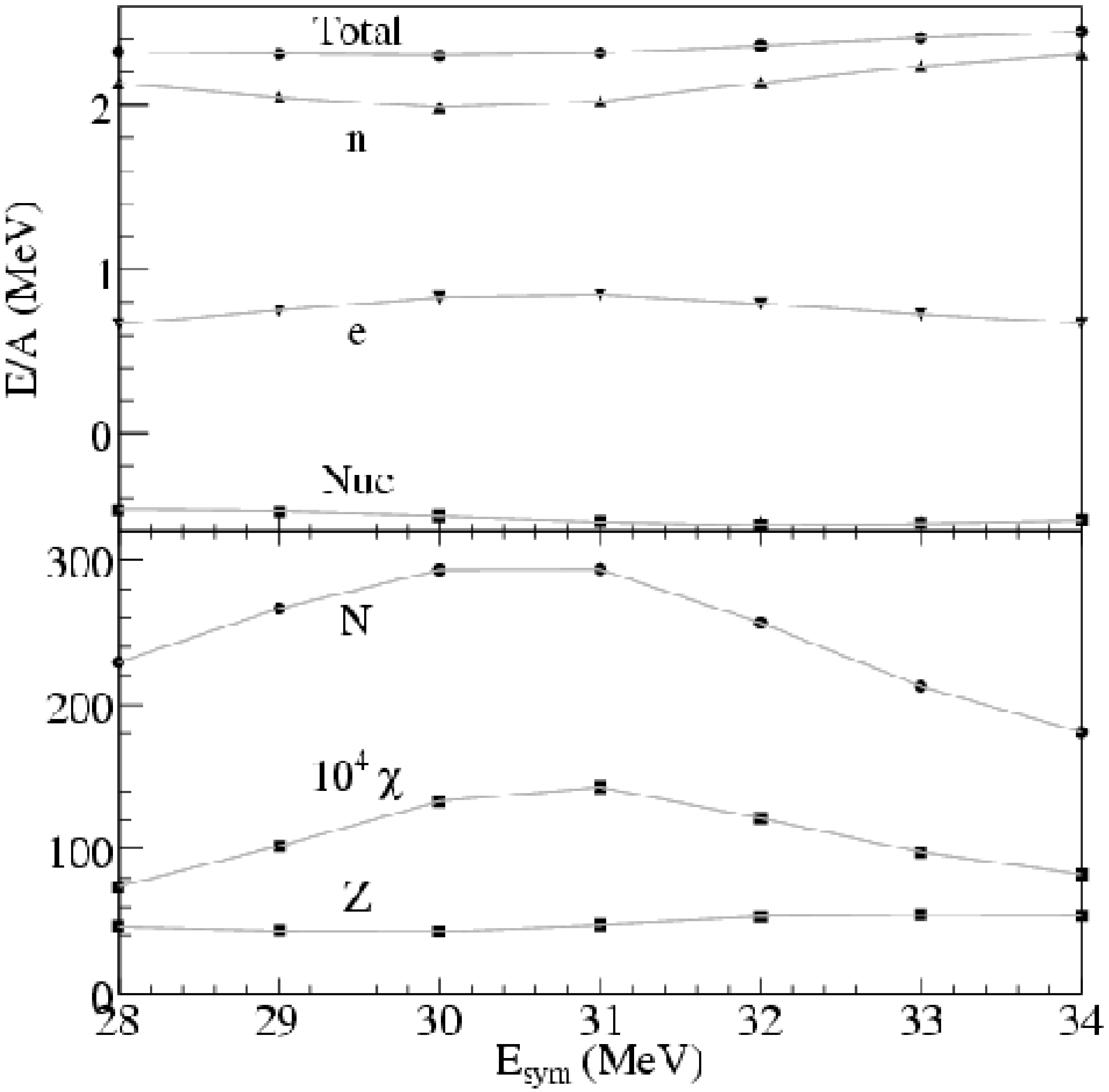
Symmetry Energy and the Crust



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

- $E_{sym} = A(n/n_0)^{2/3} + B(n/n_0)^{\gamma}$
- Fix 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

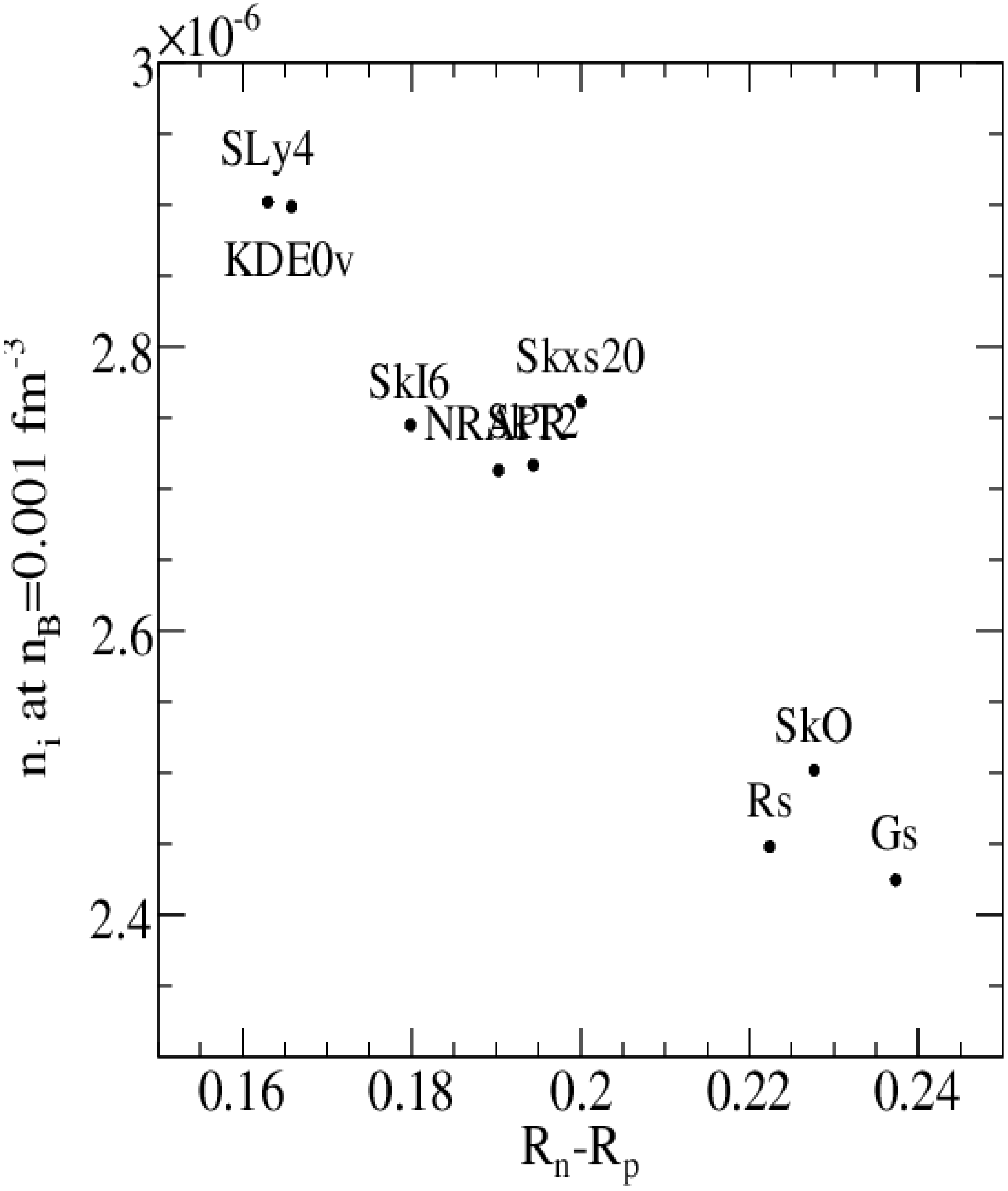
Symmetry Energy and the Crust



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

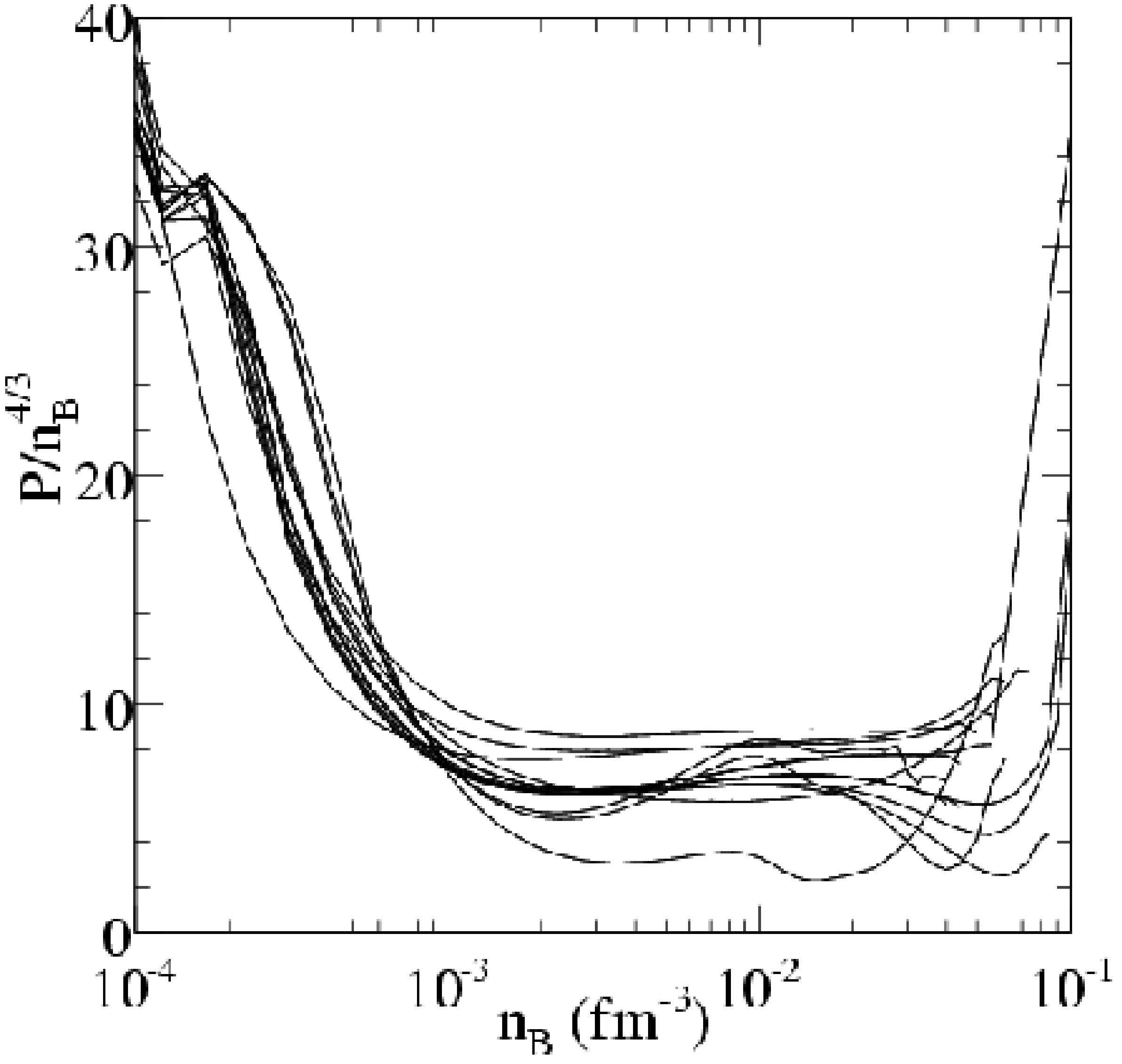
- At sufficiently high densities, the composition is strongly dependent on the symmetry energy
- A larger symmetry energy can imply more asymmetric nuclei

PREX correlation

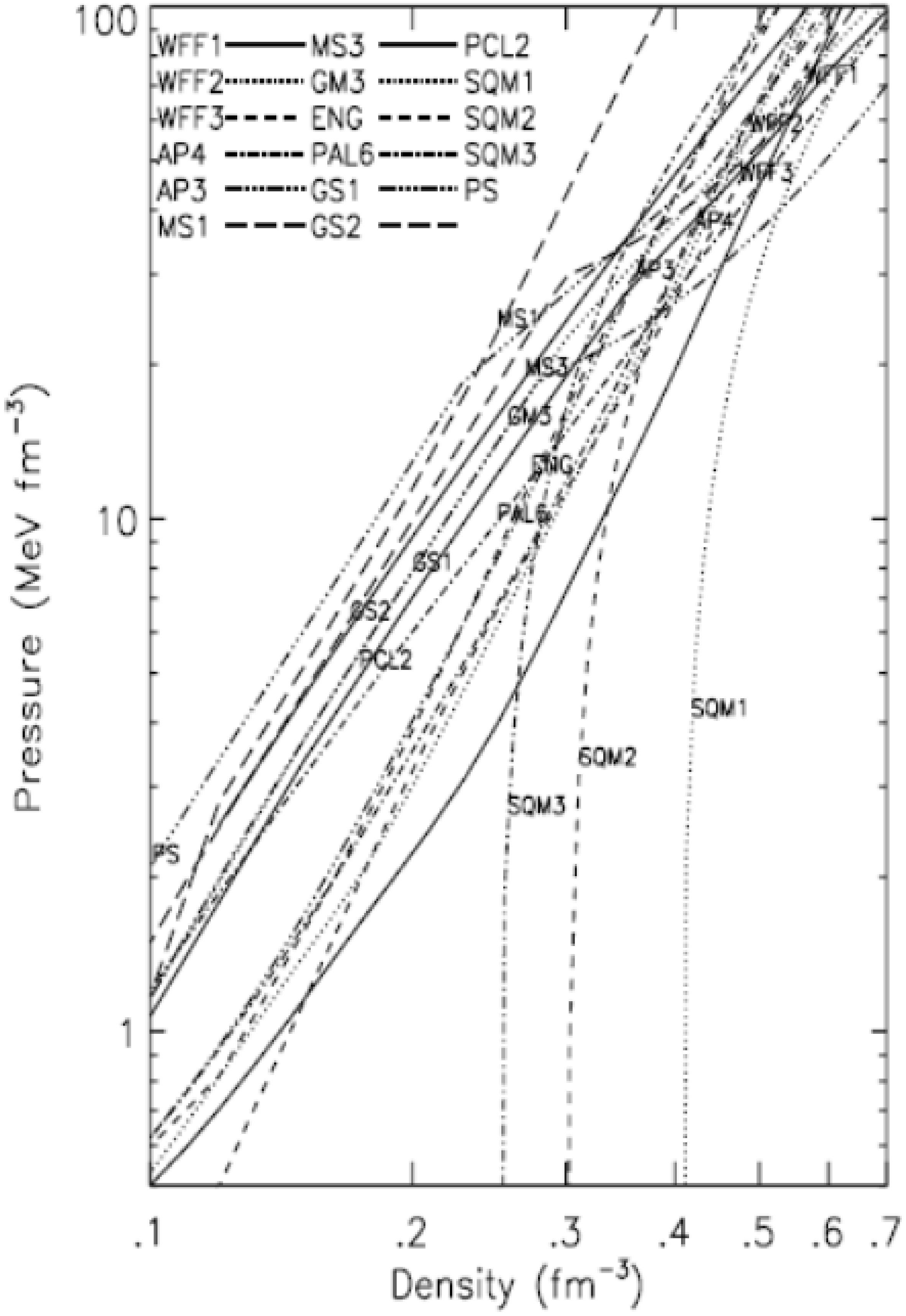


- PREX will measure the neutron radius in lead
- It will also provide a constraint on the composition of the crust

Pressure

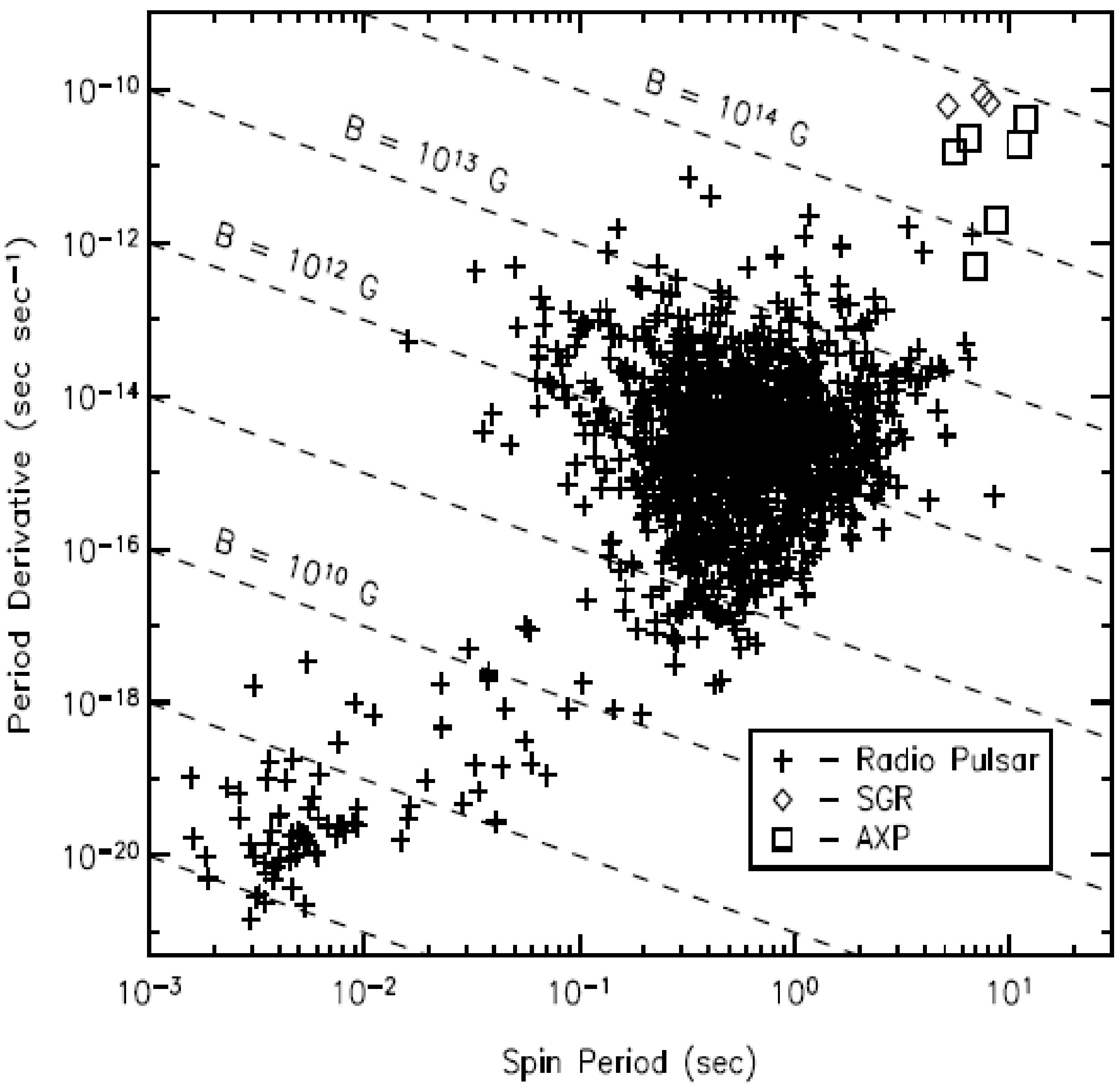


- Pressure of matter in beta-equilibrium does vary by a factor of 2
- Neutron matter beyond the allowed range produces a larger than necessary variation



J.M. Lattimer and M. Prakash, ApJ 550 (2001) 426.

SGRs and AXPs

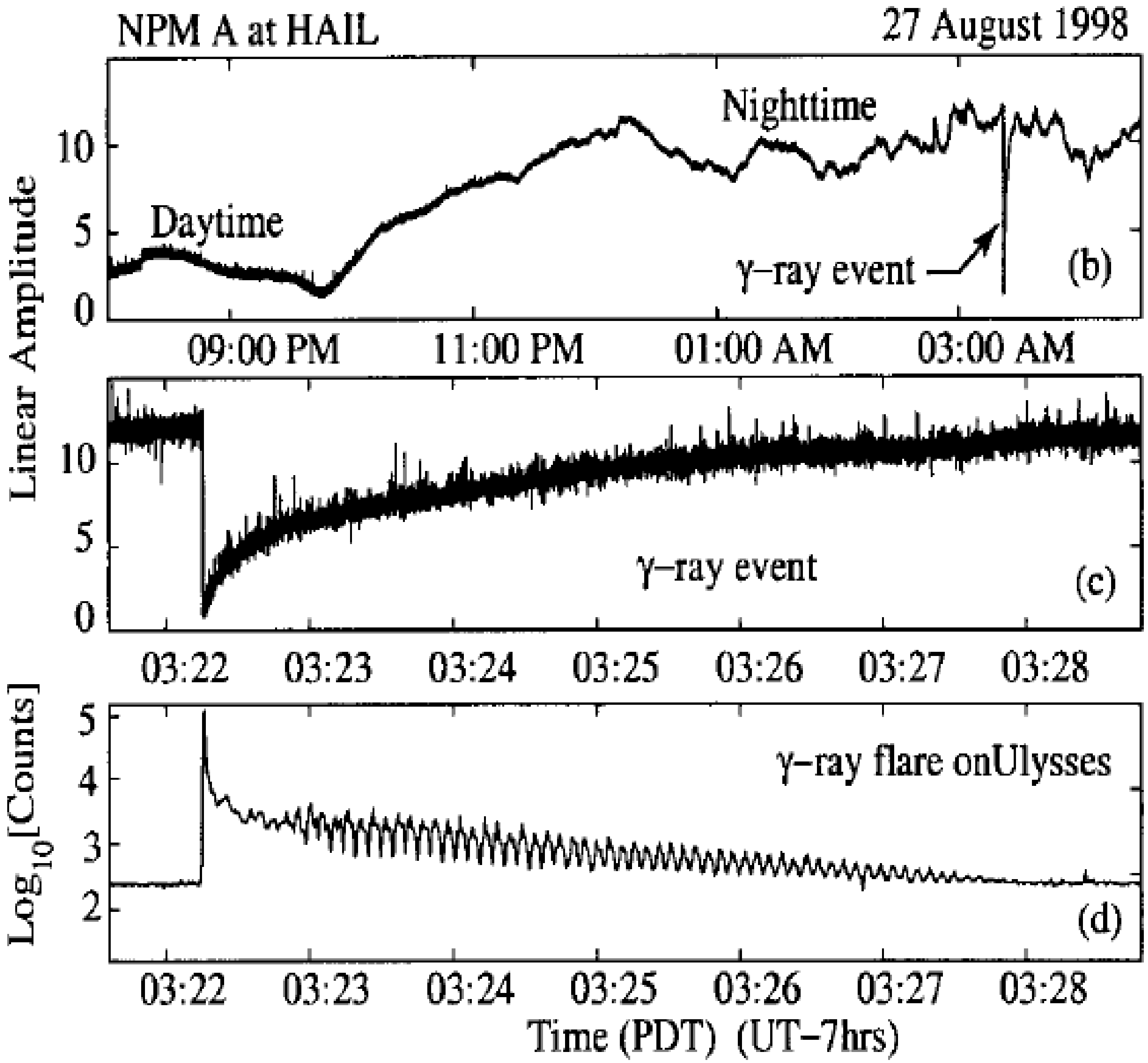


Woods and Thompson, astro-ph/0406133

- 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

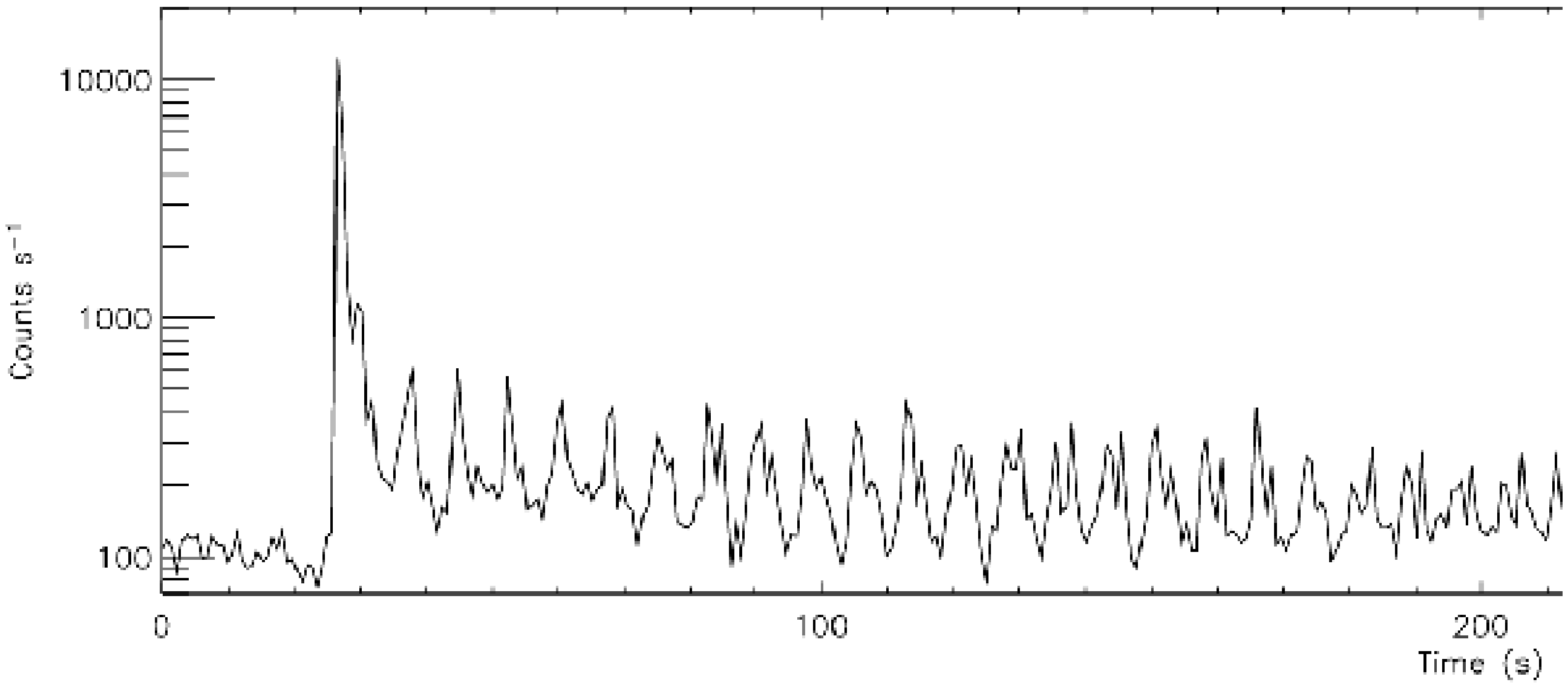
Magnetars and Giant Flares

- Some gamma-ray flares are big
- Ionosphere: ionization depends on sunlight
- Ionized the ionosphere sufficiently to make night into day



Inan et al. Geophys. Res. Lett. 26 (1999) 3357.

Periodic Oscillations in Giant Flares



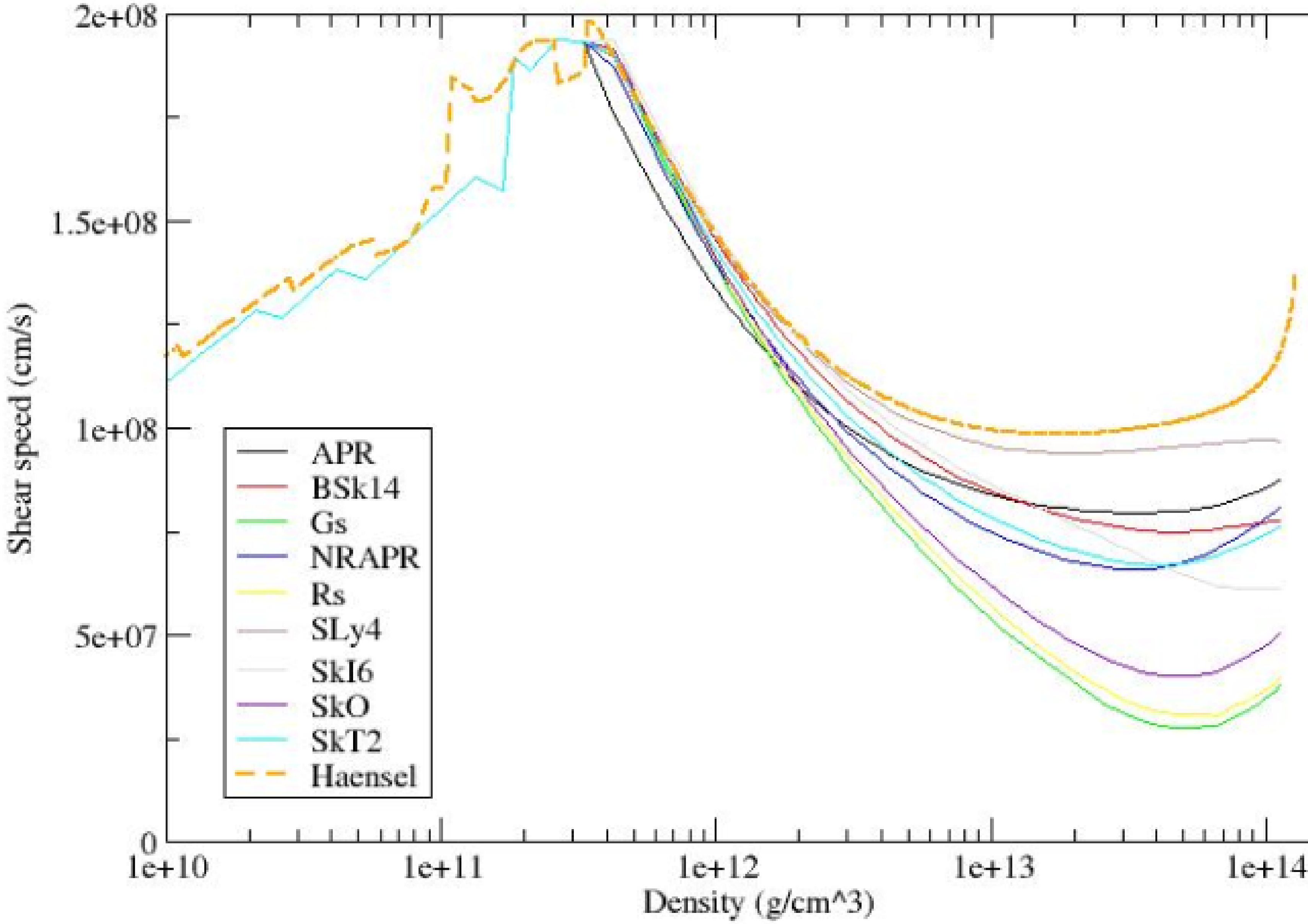
- Inside the flare, quasi-periodic oscillations
- These flares are driven by a catastrophic reconfiguration of a highly magnetized neutron star crust
- They excite normal modes in the crust
- 30 Hz - n=0, l=2
- 626 Hz - n=1, l=2
- Also in 1806 - a 18 Hz mode

Shear properties

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

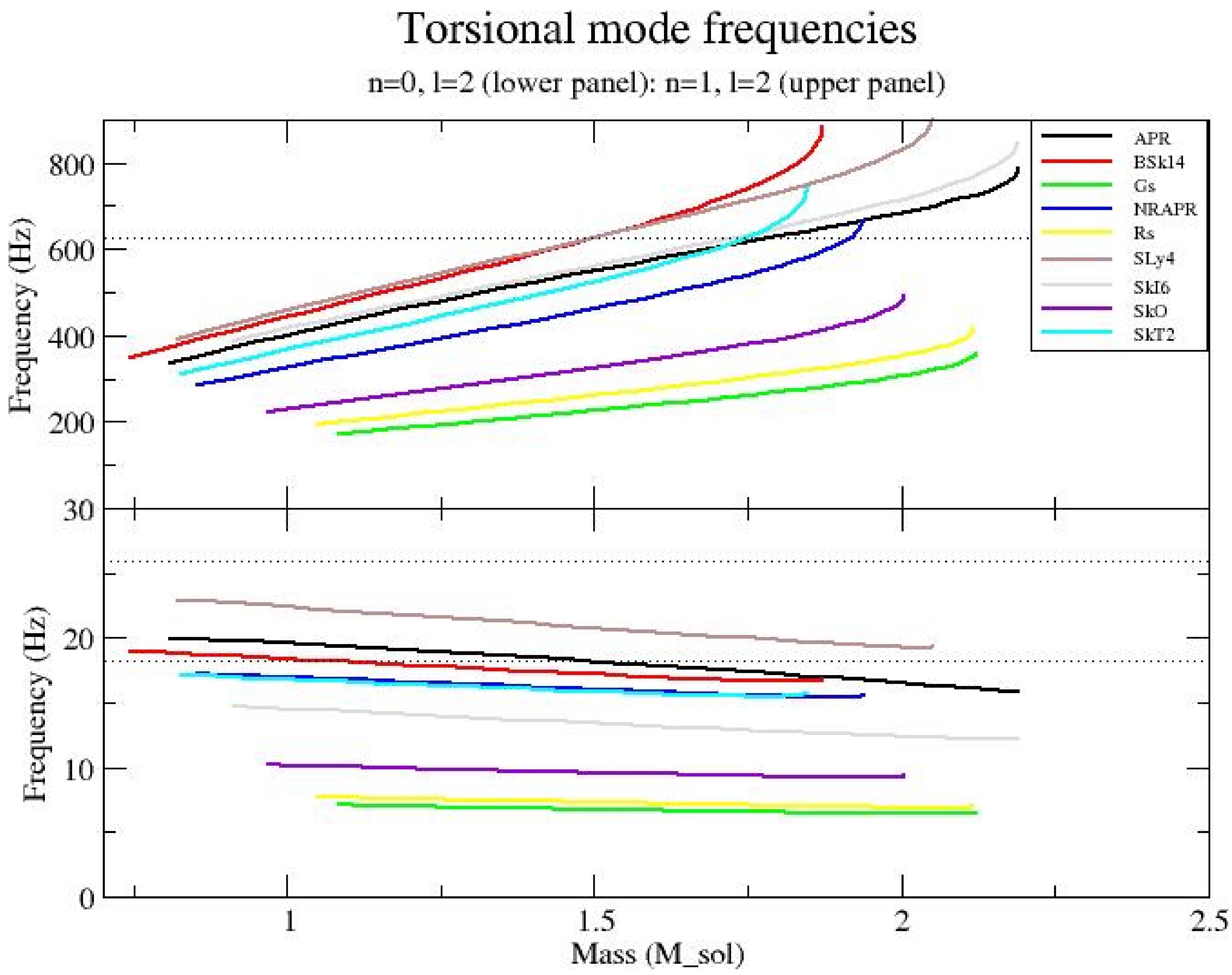
T. Stromayer et al., Ap J 375 (1991) 679, T. Piro Ap. J Lett. 634 (2005) 153,

Shear speeds for models from 8_7



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

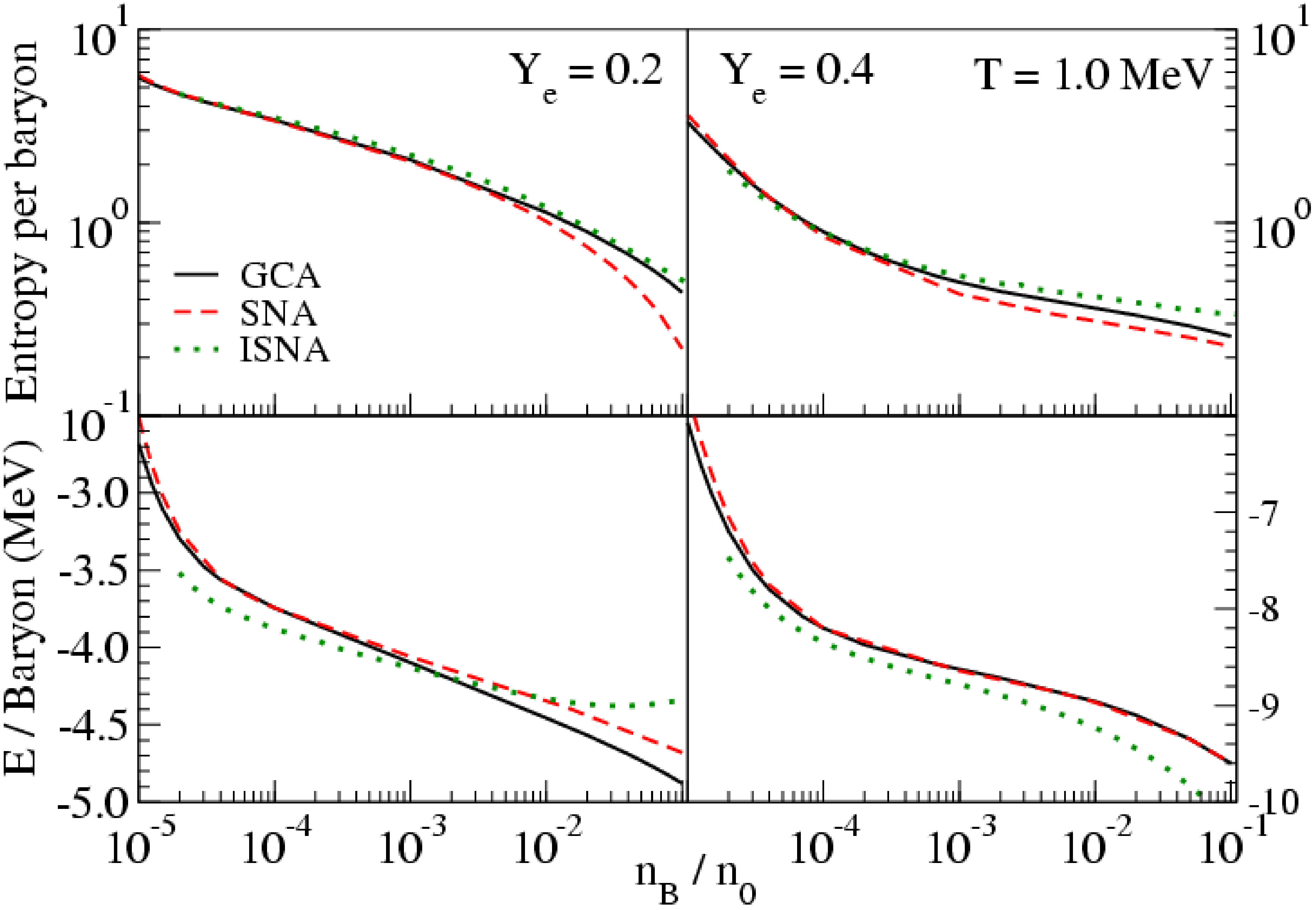
Frequencies



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

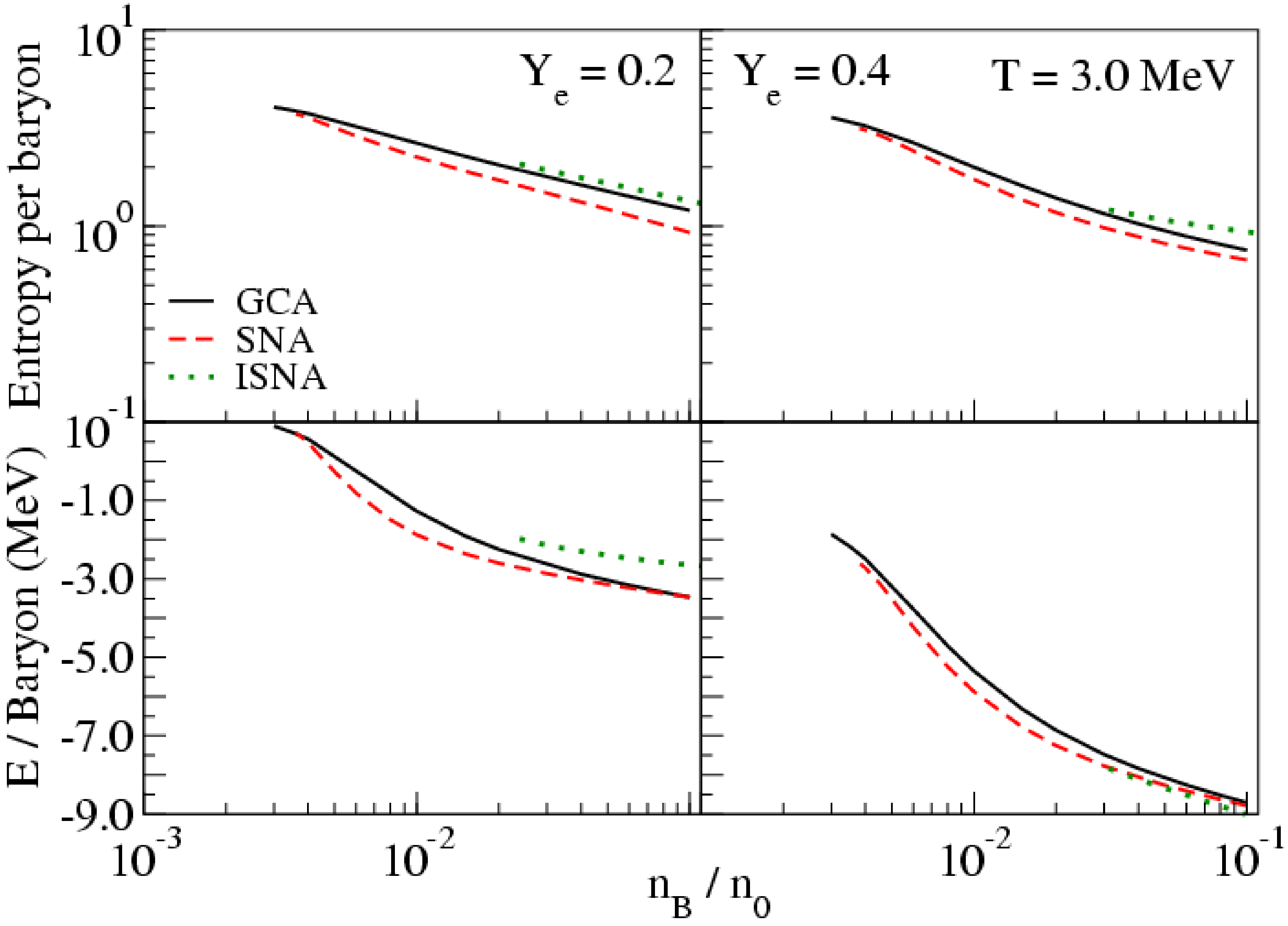
EOS for Supernovae



Souza, et al. (in prep)

- Just add finite temperature
- Compare to a mostly classical model with a distribution non-interacting nuclei
- Low density, Y_e=0.4 works well - few percent level
- High density, Y_e=0.2 doesn't work as well, but still about 10 percent

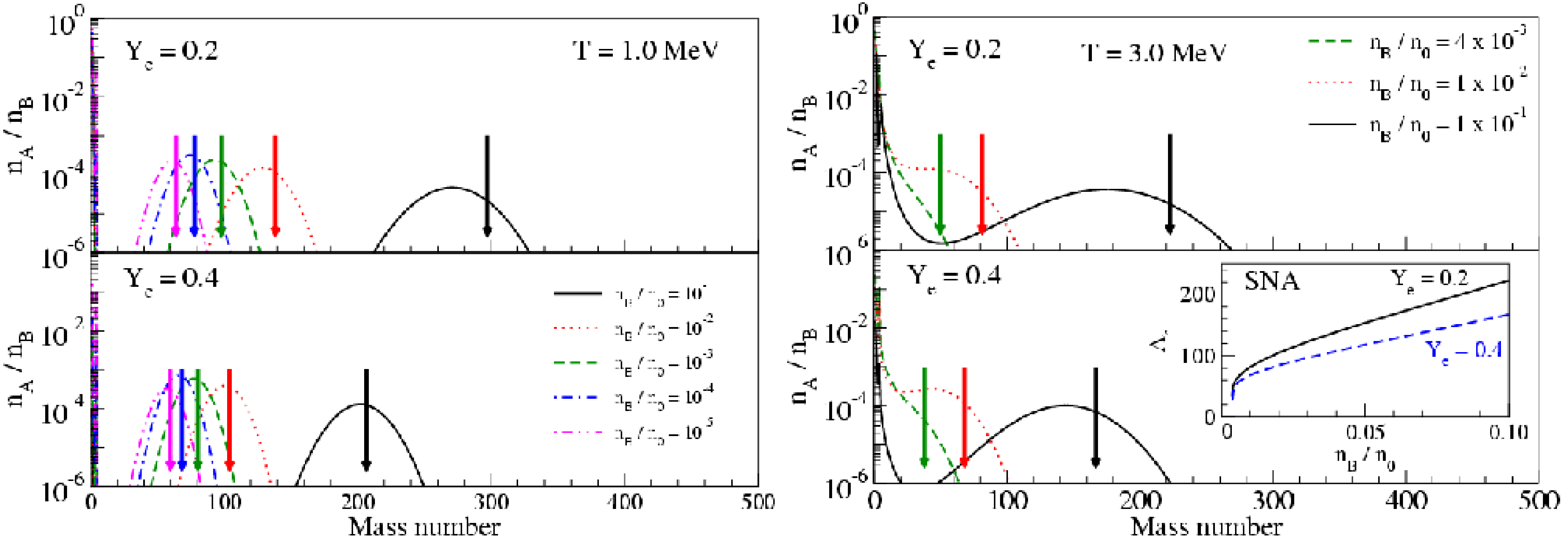
EOS for Supernovae II



Souza, et al. (in prep)

- Transition to nuclear matter very sensitive to input physics

EOS for Supernovae III



Souza, et al. (in prep)

- Single nucleus approximation systematically overpredicts the nuclear size, and underestimates the presence of light fragments
- It seems relatively accurate to replace a single nucleus table with a distribution, so long as the atomic mass varies

Summary

- Skyrme models fail miserably at describing neutron star crusts
- Neutron star crusts demand accurate models of neutron matter and the symmetry energy
- PREX will be important in determining the composition
- The 30 Hz mode in giant flares may not be the fundamental
- The single-nucleus approximation over-predicts the nuclear size
- For many supernova observables, it is possible to replace a single nucleus approximation with a distribution straightforwardly.