Neutron Star Crusts: The Symmetry Energy and the Equation of State

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INT Workshop on The Neutron Star Crust and Surface

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- Introduction and the Symmetry Energy
- Size of the crust
- Nuclei in the crust
- Minimal models
- Summary

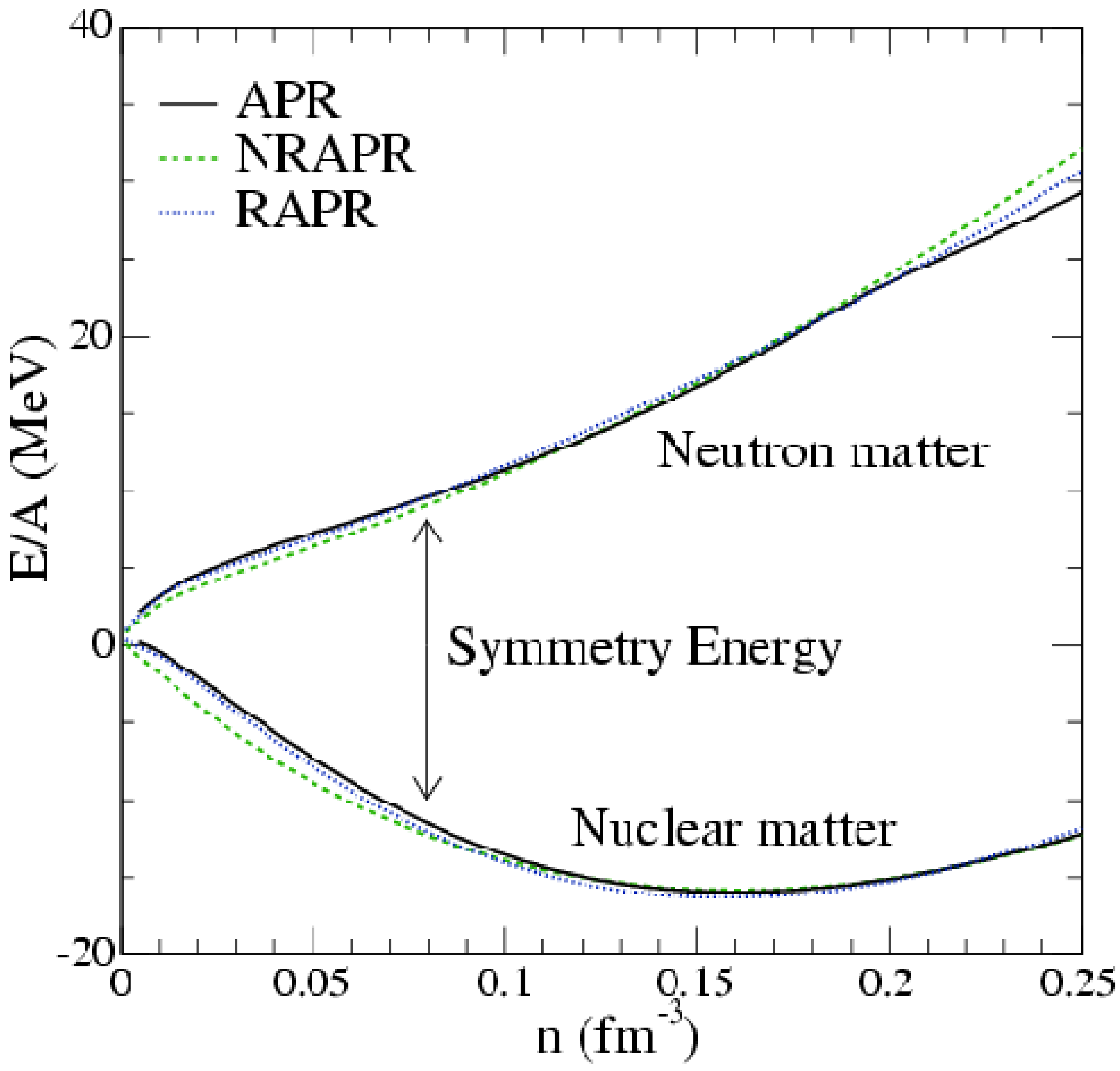
- Energy difference between infinite homogeneous neutron matter and infinite homogeneous nuclear matter
- Alternatively,

$$E_{\rm sym} = \frac{1}{2n}\frac{d^2\varepsilon(n_n,n_p)}{d\delta^2}, \quad \delta = 1 - \frac{2n_p}{n_n+n_p}$$

- These two quantities need not coincide at high density

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

- Crusts: Symmetry energy contributes to the transition density, the properties of nuclei in the crust and the dripped neutron density.



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 $L_{\nu e}$
- 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

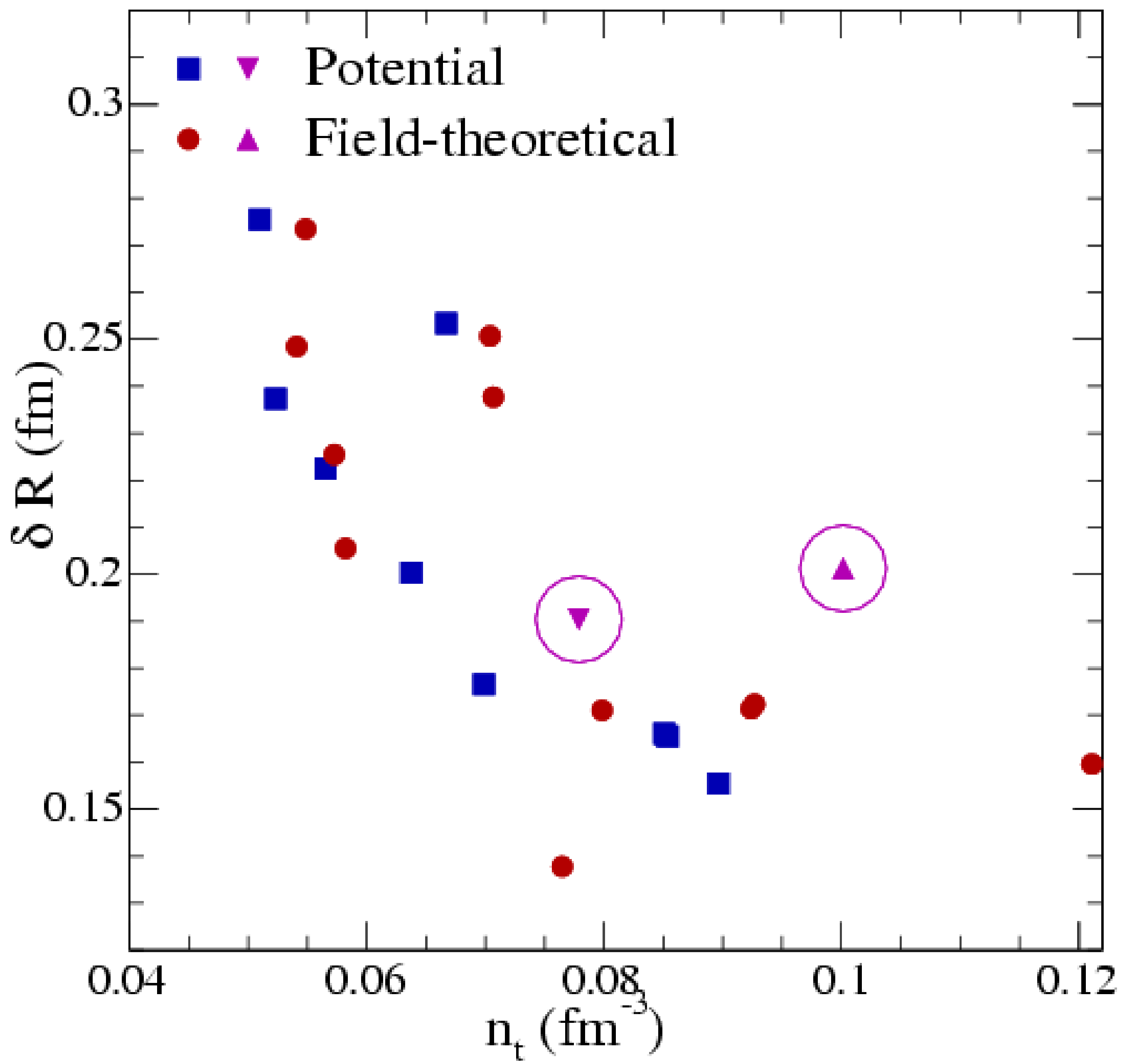
X-ray Bursters
- R_∞, z

Gravity Waves
- Mass/Radius
- dR/dM

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

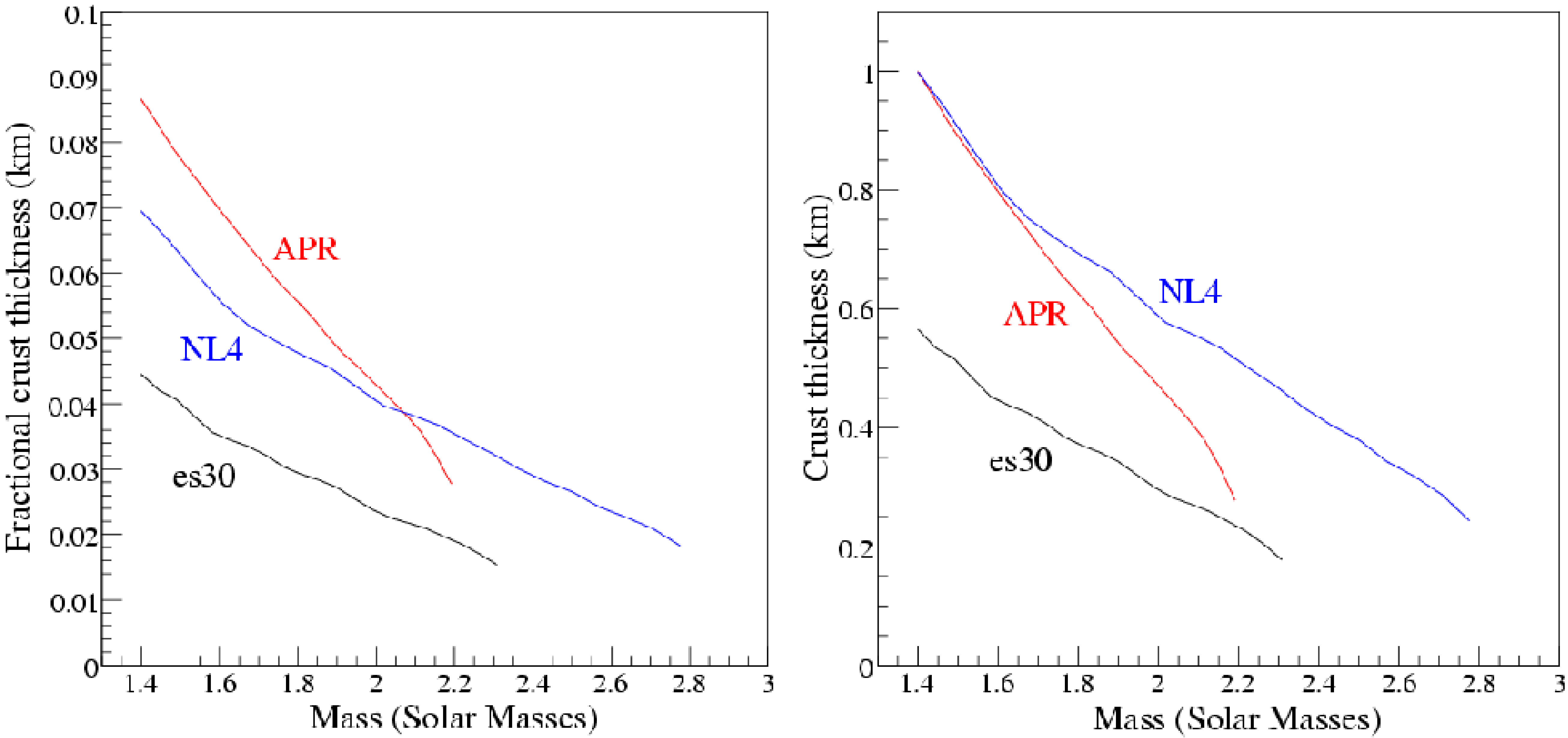
Maximum Mass, Radius
Composition:
Hyperons, Deconfined Quarks
Kaon/Pion Condensates

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



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

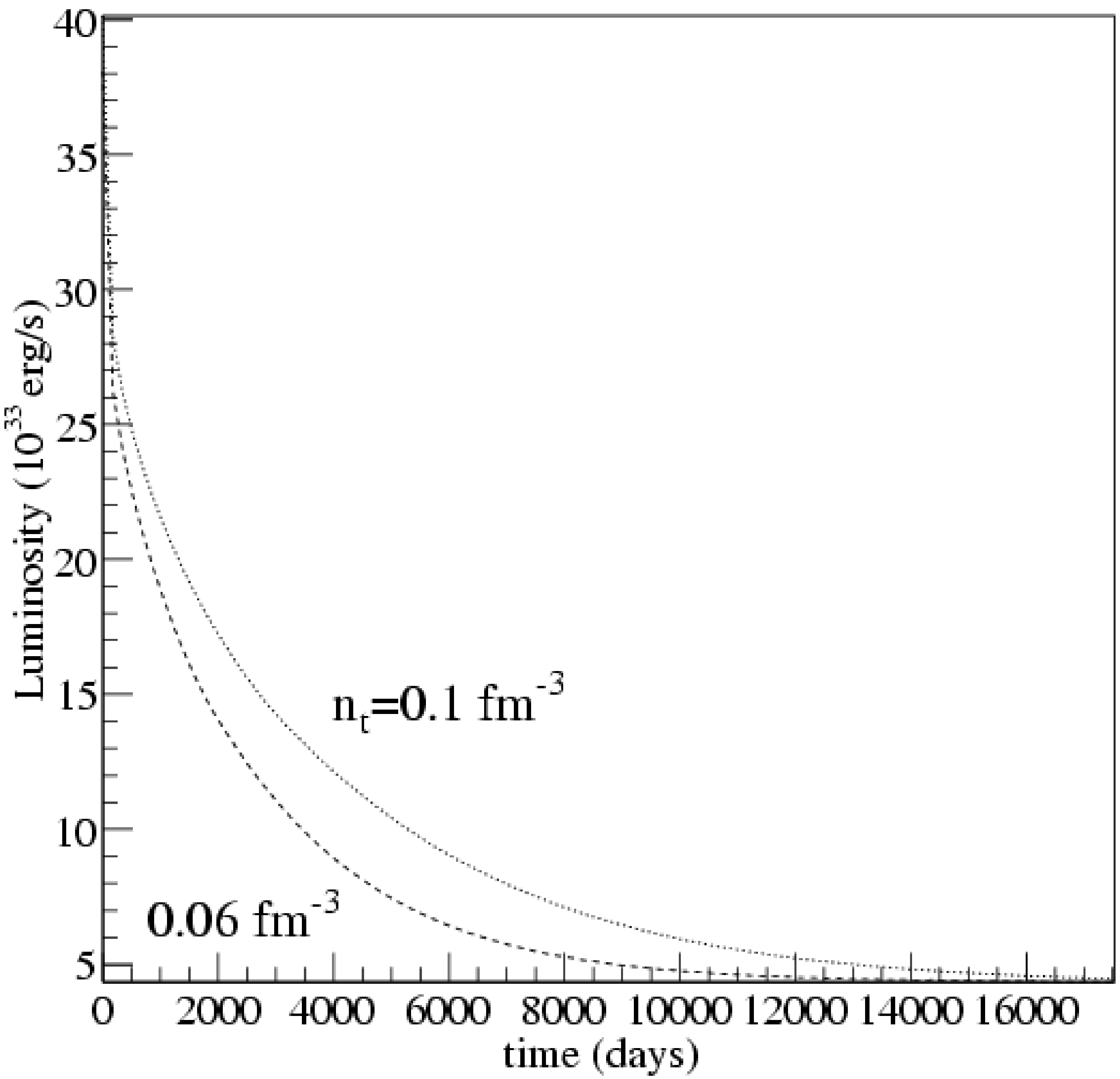
- Transition density is correlated to skin thickness
- Use several models calibrated to laboratory nuclei and saturation properties
- Varies by a factor of 2 (of more)



- Crust thickness varies by as much as a factor of five
- Of relevance for the cooling of quiescent LMXB's after outburst

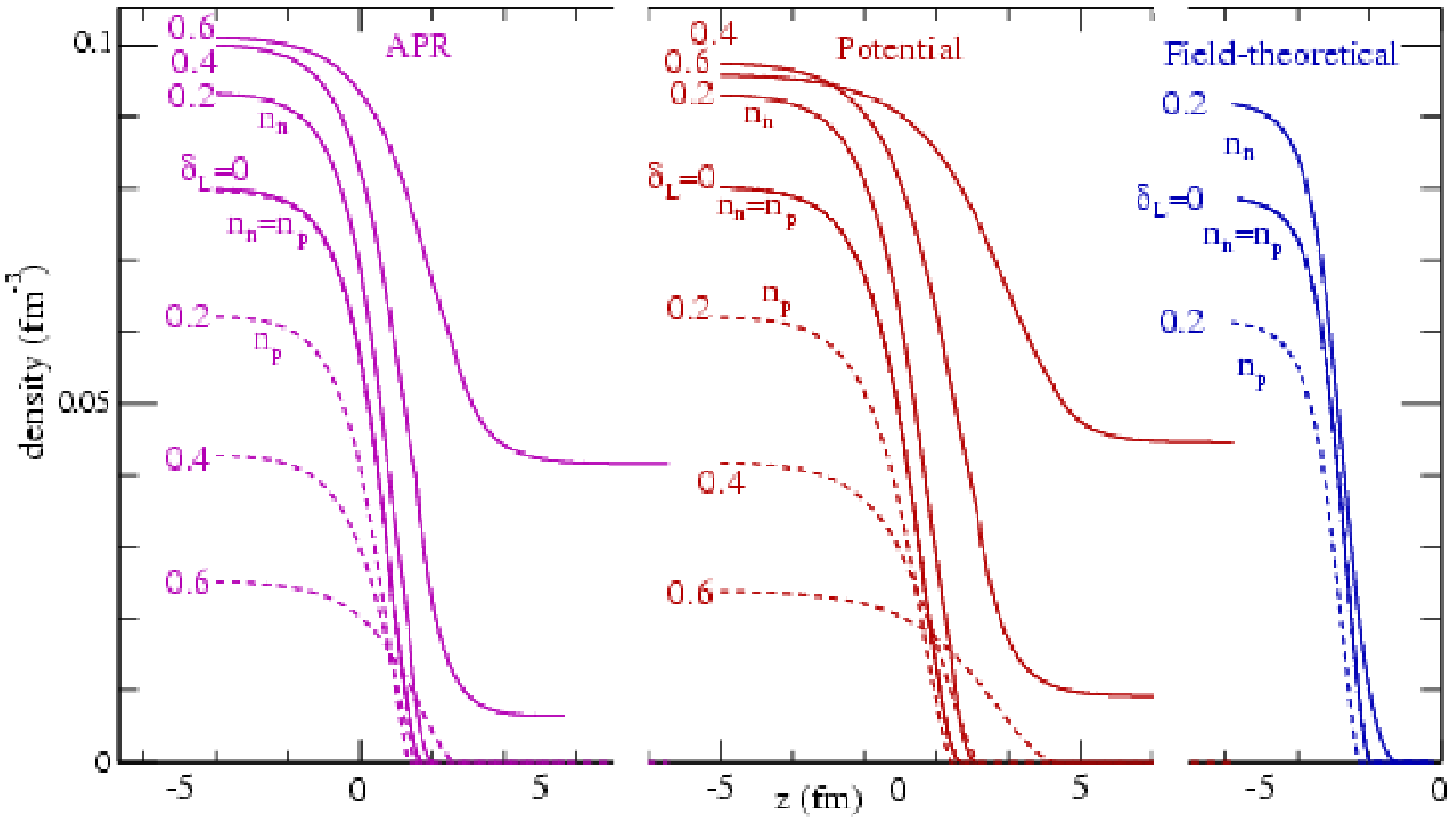
$$t_{cool} \sim R_{crust}^2 (1 - 2GM/R)^{-3/2}$$

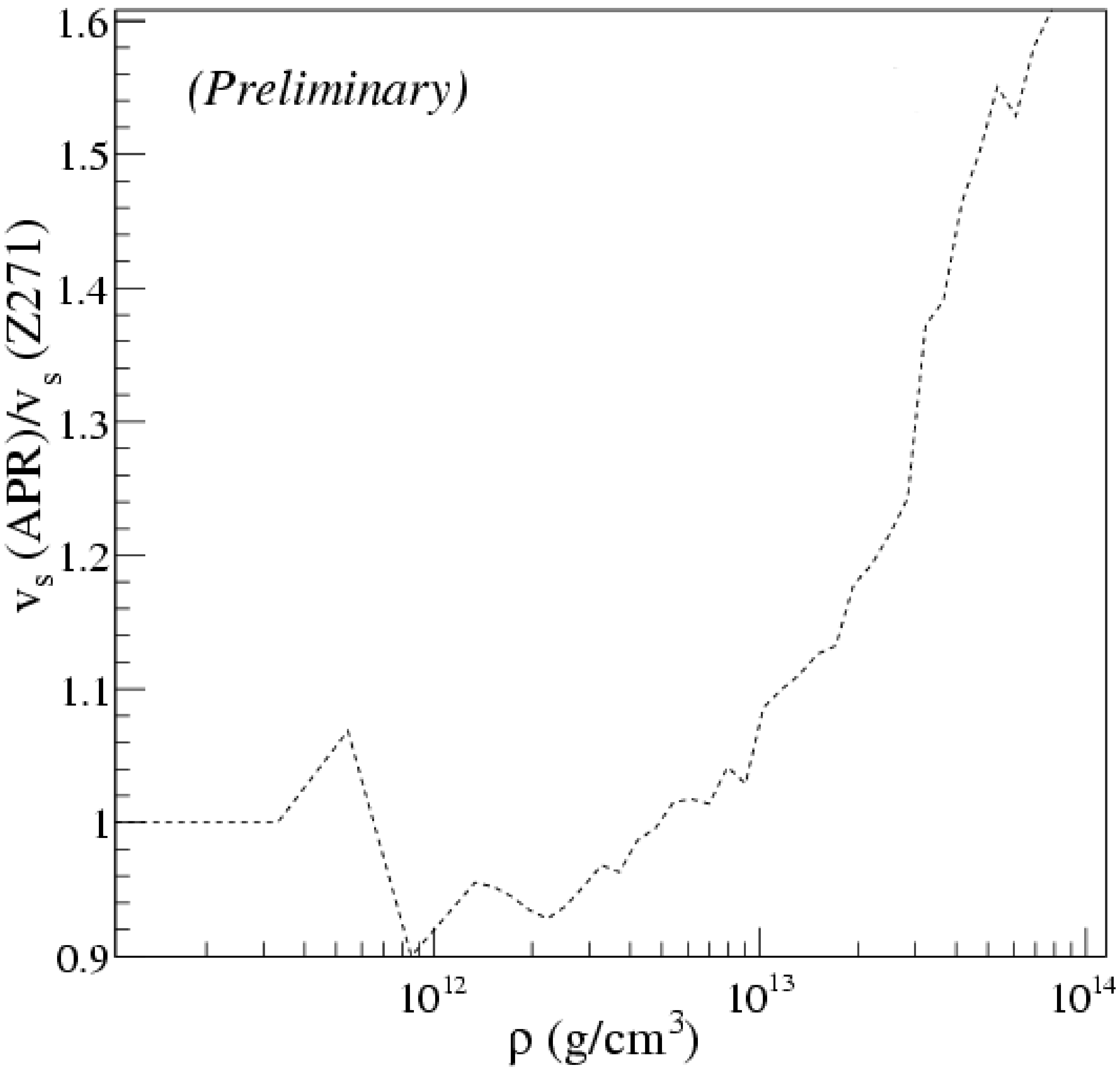
J.M. Lattimer, K.A. van Riper, M. Prakash, and M. Prakash, Ap. J 425 (1994) 802.



- Assume a 1.4 solar mass star with an 11 km radius
- Observations imply cooling timescale of 300 days
- Symmetry energy alone cannot account for observations
- Implies higher mass (and thus smaller crust) or higher thermal conductivity
- 1629 cools slower, but this could just mean it has a smaller mass

- Standard liquid drop model: Bulk + Surface + Coulomb
- Bulk energy determined by the equation of state
- Treat neutron and proton surfaces independently: two surface energies
- No shell effects or pairing yet...
- Some surface and Coulomb parameters fixed by matching to Moller's FRDM





- Determine effect of symmetry energy on the shear velocity $v_s = (\mu/\rho)^{1/2}$
  T. Stromayer et al., Ap J 375 (1991) 679, T. Piro Ap. J Lett. 634 (2005) 153, L. Samuelsson and N. Andersson, MNRAS 374 (2007) 256, J.M. Lattimer and M. Prakash, astro-ph/0612440 (2006)
- Shear modulus determined under the assumption of a simple one-component crystal
- Shell effects and pairing may be smaller for more neutron-rich and heavier systems?

What is a simple model for the content and mass of neutron stars and the nature of the crust which can account for a large class of observations?

For now, ignore magnetic fields, magnetars, and pulsar mechanism.

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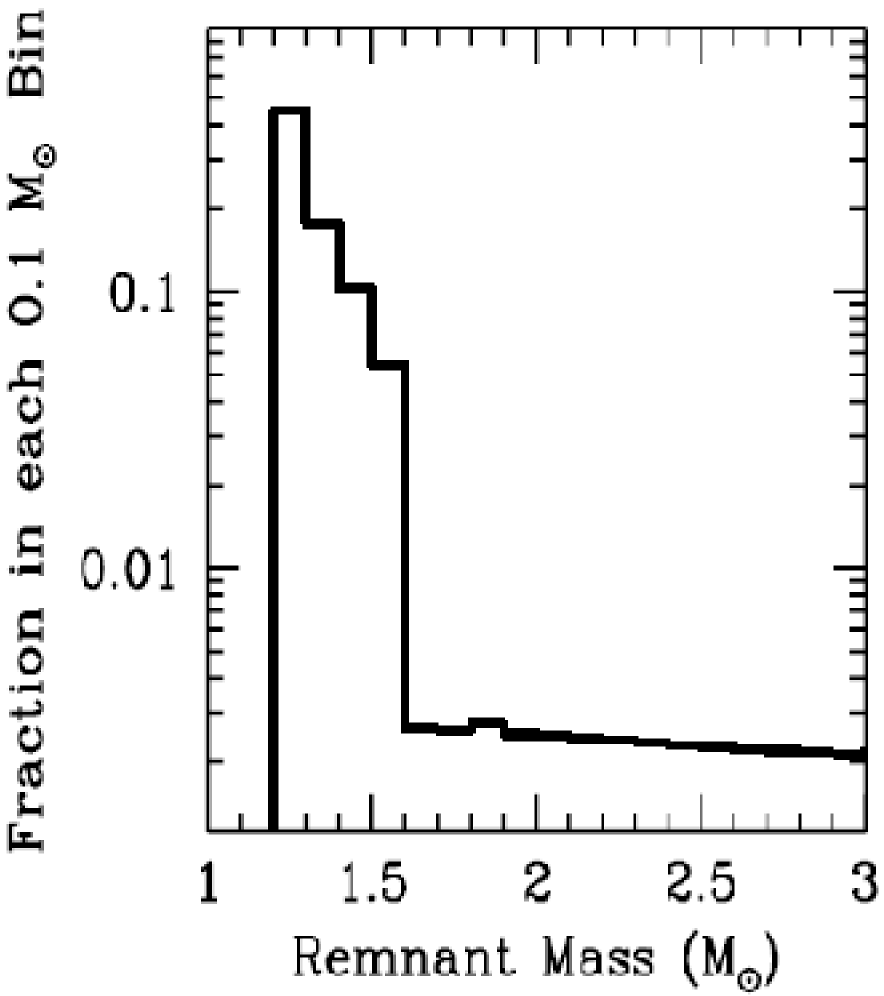
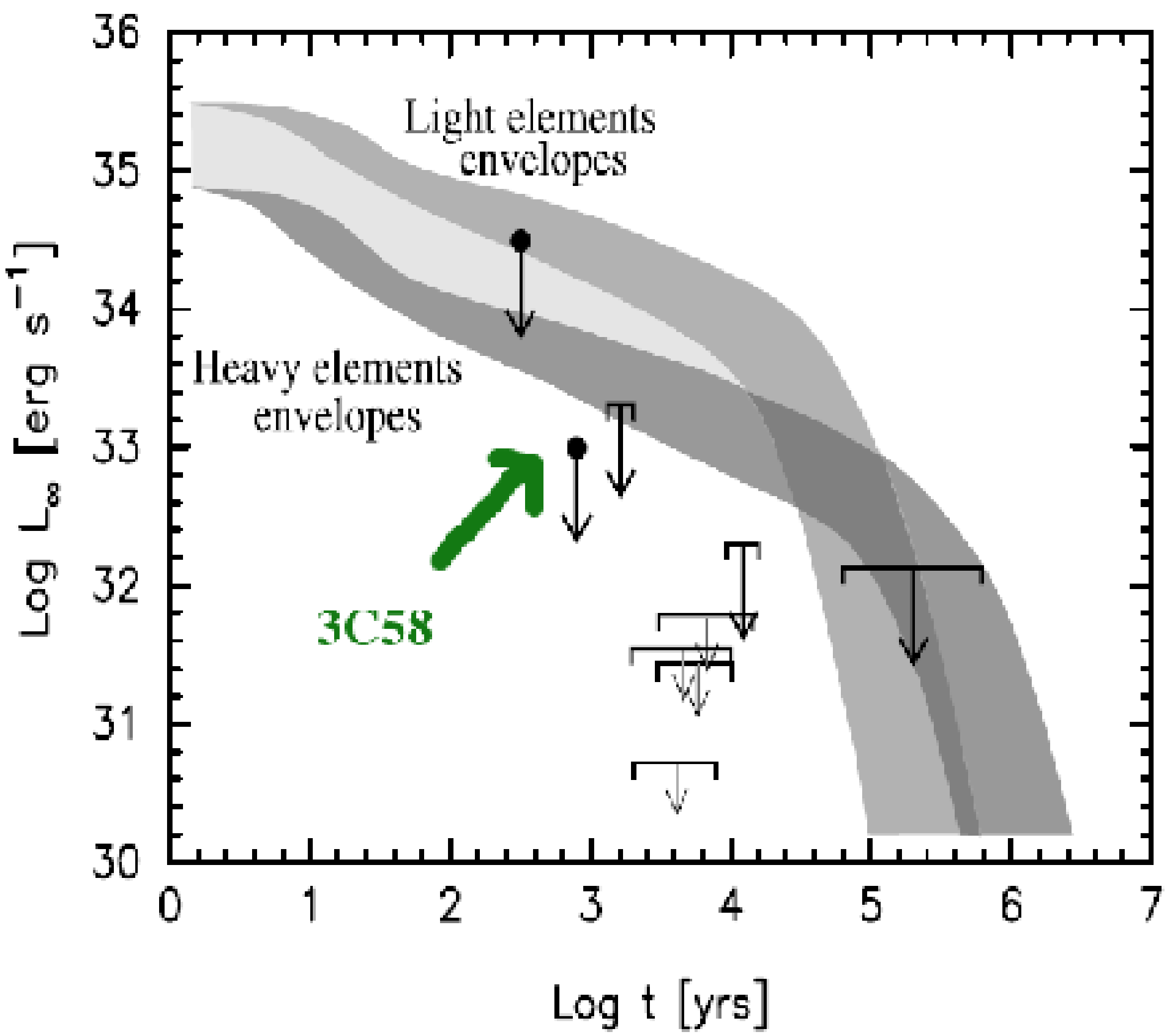
- The minimal cooling paradigm
  - No exotic matter
  - No direct Urca cooling
  - Include the full variation in pairing, envelope composition, neutrino emission from Cooper pair breaking and reformation
  - Then, compare with data

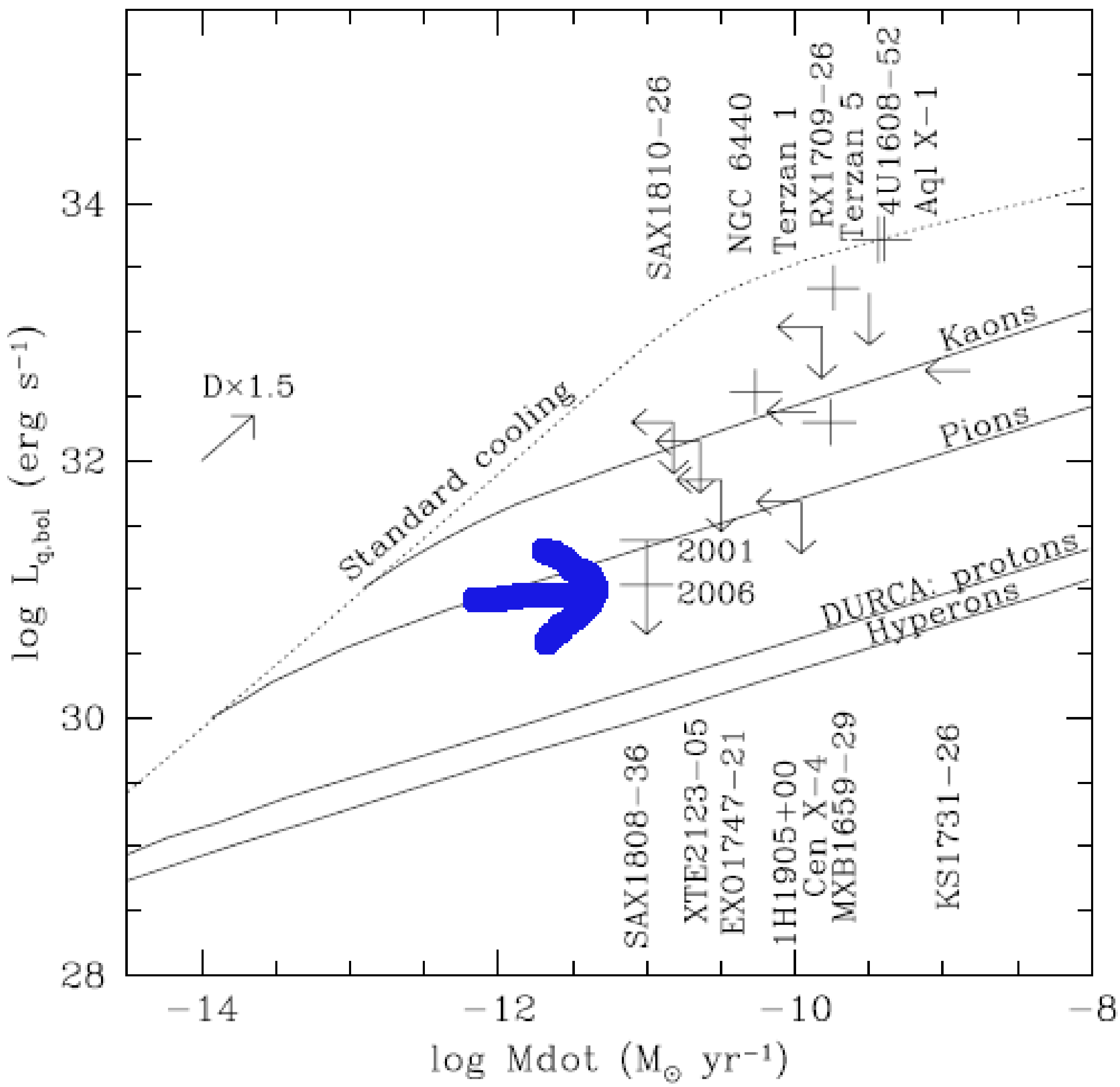


Fryer and Kalogera Ap. J 554 (2001) 548.



D. Page, J.M. Lattimer, M. Prakash and A.S., ApJS 155 (2004) 623.

- The neutron star in 3C58 might suggest "enhanced cooling", but isolated neutron stars are very consistent with "minimal cooling".
- Smaller mass for isolated NSs, with little exotic cooling



From C.O. Heinke, P.G. Jonker, R. Wijnands, and R.E. Taam, Ap. J 660 (2007) 1424, and Yakovlev and Pethick ARA&A 42 (2004) 169.

- Low mass X-ray binaries cool after an accretion outburst
- This cooling is sensitive to the physics of the core
- Enhanced cooling may be required to explain SAX J1808
- LMXB's can have significant accretion, driving them to larger mass

- KS 1731 cooled very fast after going into quiescence, implies temperature near saturation density is 10^8K

- KS 1731 also exhibited a superburst, meaning that the temperature at lower densities was larger 5×10^8K

E.F. Brown, Ap. J Lett. 614 (2004) 57

- This cannot be explained with our simple model unless...
  - Require that the Cooper pair breaking emissivity is suppressed (by a factor of 100)
  - Require that the crust has low thermal conductivity, either because its amorphous or impure.
  - Uncertainties in Carbon fusion cross section don't work
  - Other sources of heating might also work

A. Cumming, J. Macbeth, J.J.M in 't Zand, and D. Page, Ap. J 646 (2006) 429

- Not necessarily incompatible with enhanced cooling in (at least some) LMXBs

- Isolated NSs are born with smaller masses, but that accretion can significantly change that value. What about magnetar masses?

- Enhanced cooling is required at large mass, but not for many cooling isolated NSs (note that this conclusion depended on our knowlege of the NS crust)

- Superbursts and KS 1731 require lowering of the Cooper pair emissivity and some way to lower the crusts thermal conductivity

Summary

- Symmetry energy is important for determining the size of the NS crust, but it's not enough. LMXB's are probably not low mass objects.
- Symmetry energy is important for and the nuclei present inside the NS crust, the shear velocity may have significant uncertainties.
- There is now strong evidence for cooling beyond the "standard model".
- There is likely a minimal model which explains a large number of observations. Are there more possibilities? Which observations can we not explain?

Future

- The physics of neutron star crusts is very thorny, the theorists have much work to do, yet we are a vibrant community which is making progress! Keep the observations coming, contact us with questions or concerns anytime. Don't give in to dark energy!