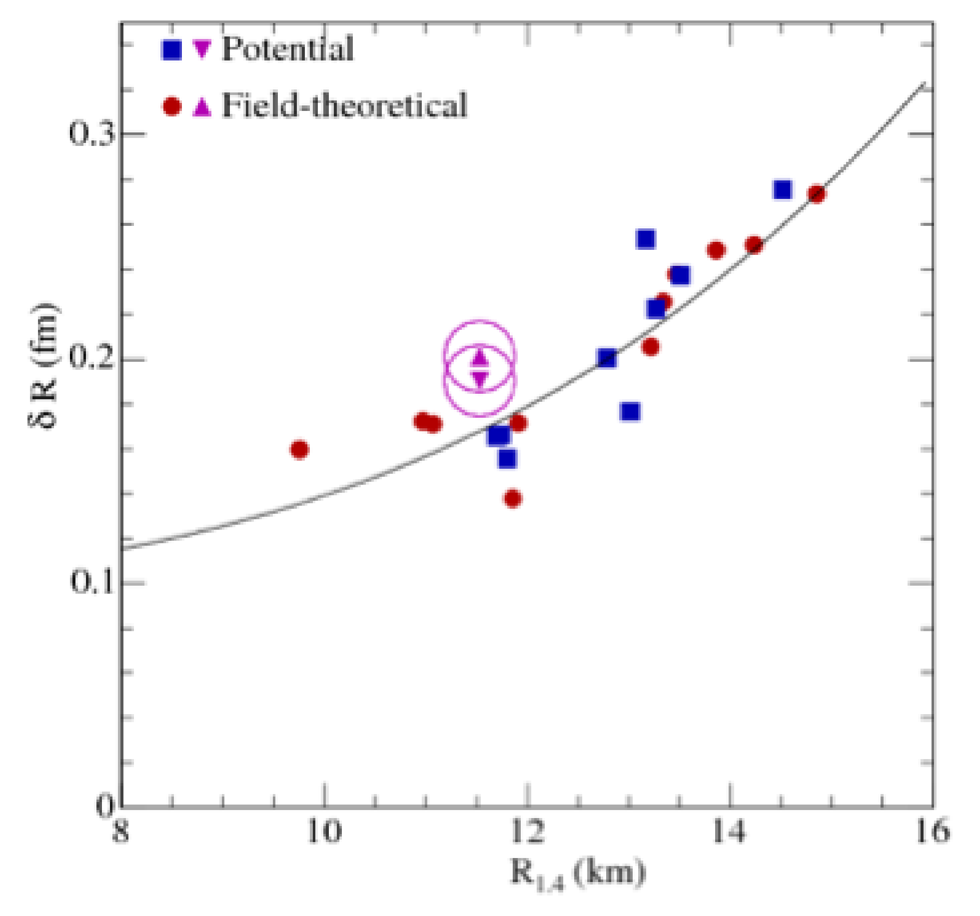
Observations and the Nuclear Symmetry Energy

Andrew W. Steiner (INT/U. Washington)



Steiner et al. (2005), adapted from Horowitz and Piekarewicz (2001)

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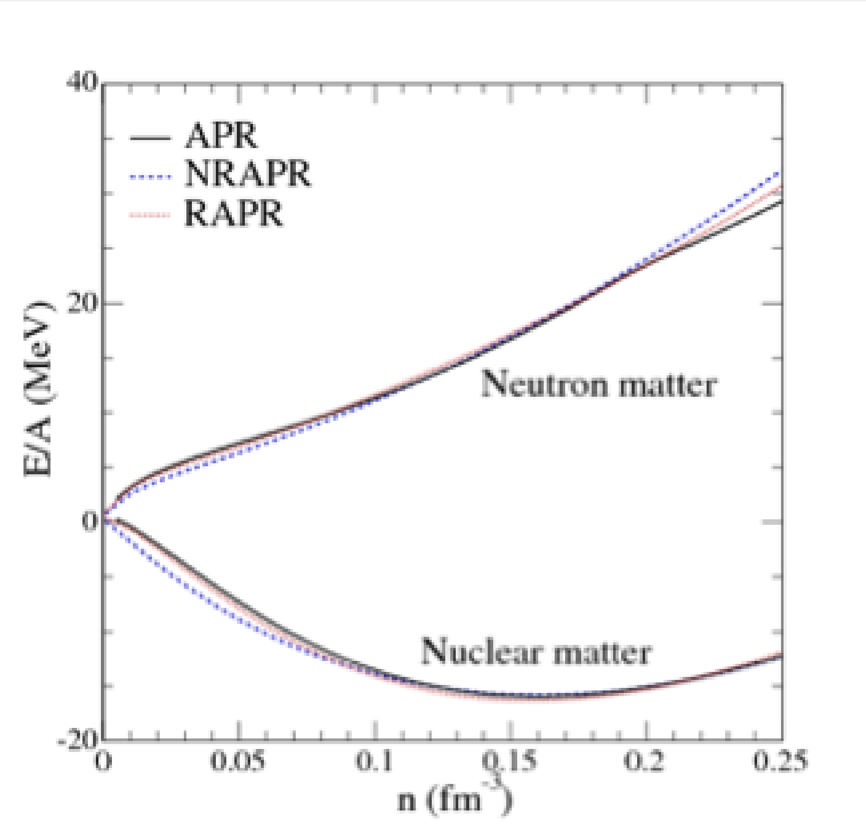
Outline

- Definitions and Diversions
- Neutron Star Basics

- Cooling and Direct Urca
- Radii
- Magnetar Flares
- Supernova EOS
- Deep Crustal Heating
- Other Observables

The Nuclear Symmetry Energy



Steiner et al. (2005)

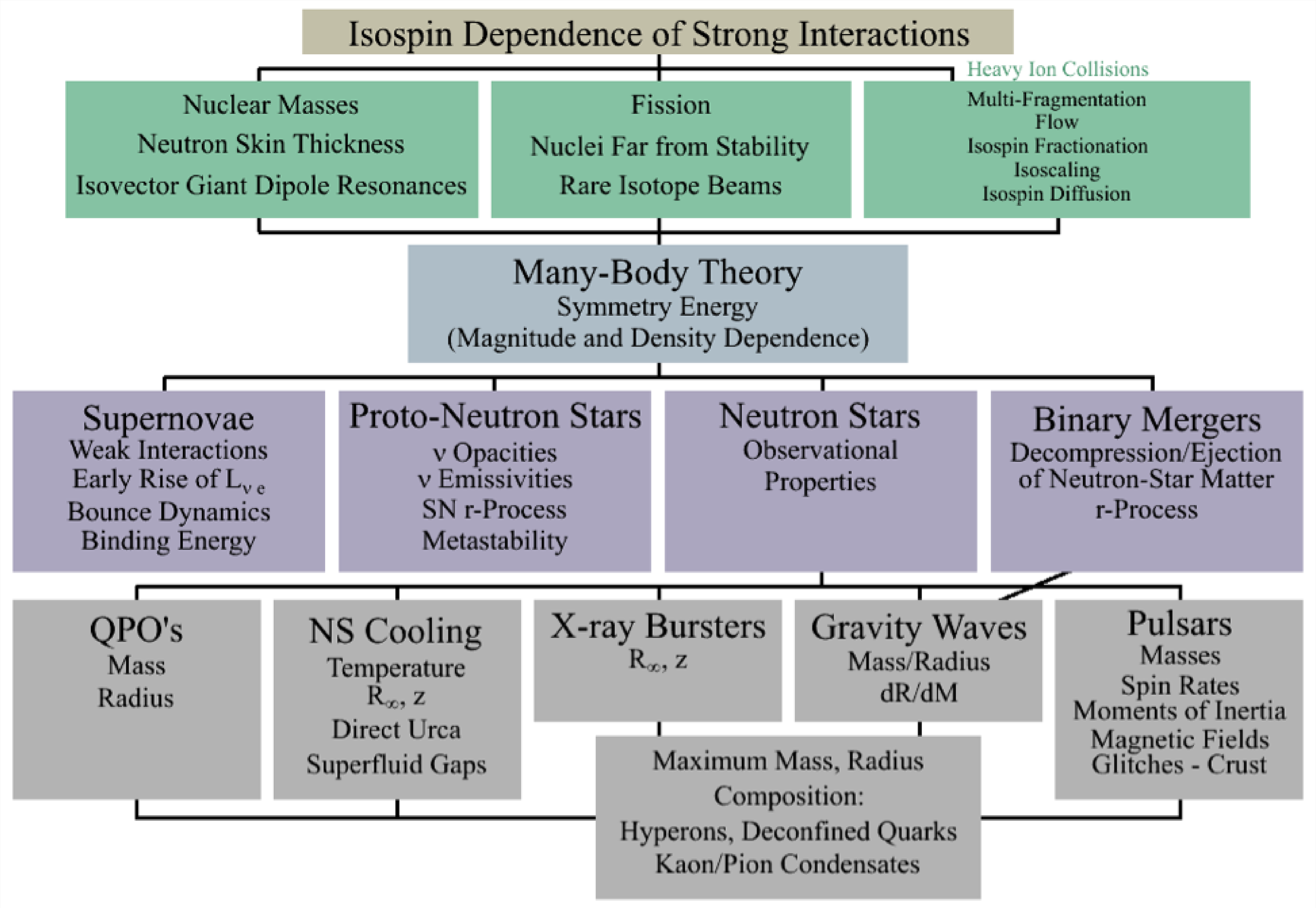
- Define $\alpha \equiv (n_n - n_p)/n$

$$S(n) = \frac{1}{2n}\left(\frac{\partial(nE/A)}{\partial\alpha}\right)_{\alpha=0}$$

- $\tilde{S}(n) = (E/A)_{\mathrm{neut}}(n) - (E/A)_{\mathrm{nuc}}(n)$
- If E/A is quadratic in α, $S(n) = \tilde{S}(n)$
- $S \equiv S(n_0)$
- L is the derivative, $L \equiv 3n_0 S'(n_0)$

- I define S and L entirely from homogeneous matter
- At low-densities one can include clusters
- In either case, I prefer to be consistent
- $4S(n) = \partial_\alpha \left[\mu_n(n,\alpha) - \mu_p(n,\alpha)\right]$
- Useful definition because there are so many connections...

There are many correlations...



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

Steiner et al. (2005)

Gateway Quantities to the Symmetry Energy

Are S and L really the quantities of interest?

- Pressure of neutron matter near and above saturation
  - Easier to compute theoretically
  - Related to neutron stars
- Isovector dependence of the nucleon optical potential
  - Input for heavy-ion collisions
  - Relevant for transport in dense matter
- Isovector response of the ground state of a nucleus
  - Modification of the single particle energies
  - and the density distributions
- Isovector effective mass

Nevertheless, for now I stick with S and L.

Neutron Star Composition

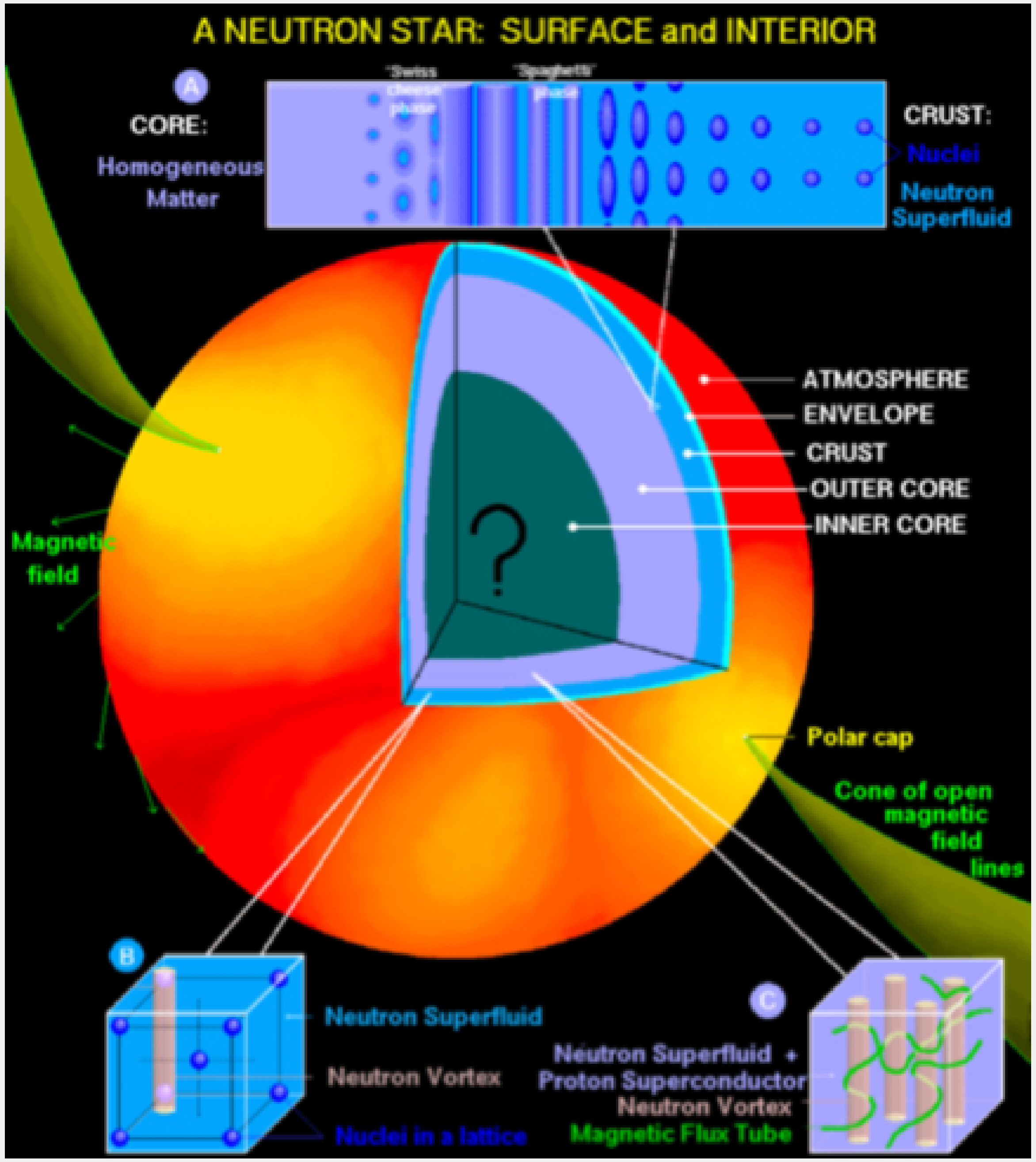


Figure by Dany Page

- In outer crust, μ_e increases faster than $\mu_{n,p}$, higher densities more neutron-rich
- In inner crust, S determines EOS of neutron matter as well as properties of nuclei
- As one proceeds into the core $\mu_{n,p}$ increase faster, tend to restore isospin symmetry
- High μ_e can favor phase transitions, i.e. $\mu_{\pi^-} = \mu_e$
- Relationship with hyperons more complicated
- When strange quarks appear, there is a hypercharge asymmetry energy

Thermal Emission from Isolated Neutron Stars

$$C_V \frac{dT}{dt} = L_\nu + L_\gamma\,, \quad L_\gamma \sim T^{2+4\alpha}\,, \quad L_\nu \sim T^{6-8}\,, \quad C_V \sim CT$$

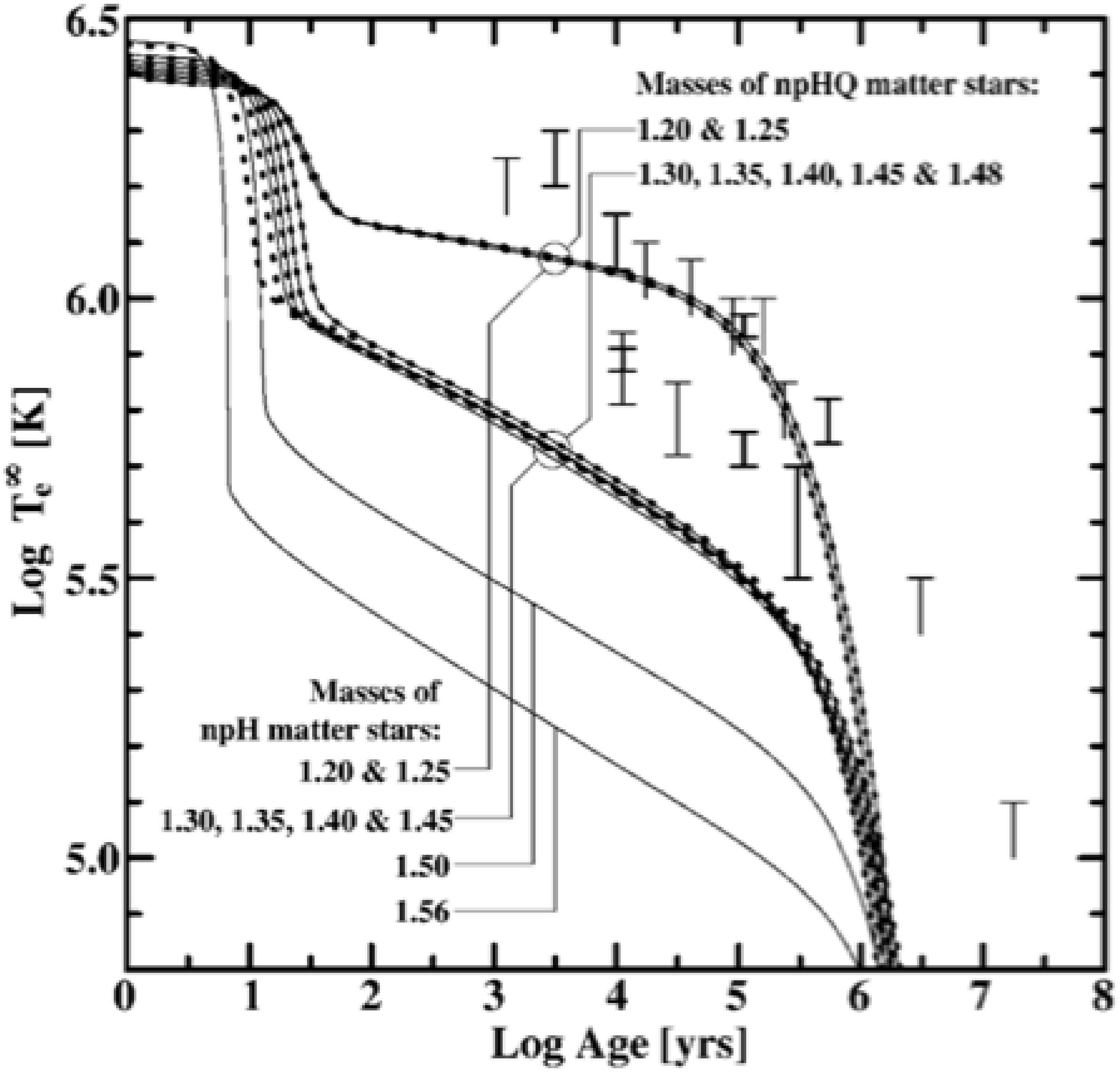


FIG. 3. Cooling of stars with *npH* (continuous lines) and *npHQ* matter (dotted lines) for various stellar masses (in $M_\odot$). $n\ ^3P_2$ gaps are from case [c] while quark gaps, when present, are from model [C] of Fig. 1.

Page, et al. (2000)

- Fastest cooling from $n \rightarrow p + e + \bar{\nu}_e$
- Only possible if enough protons are around

$$2s \equiv p_{Fn} + p_{Fp} + p_{Fe}$$

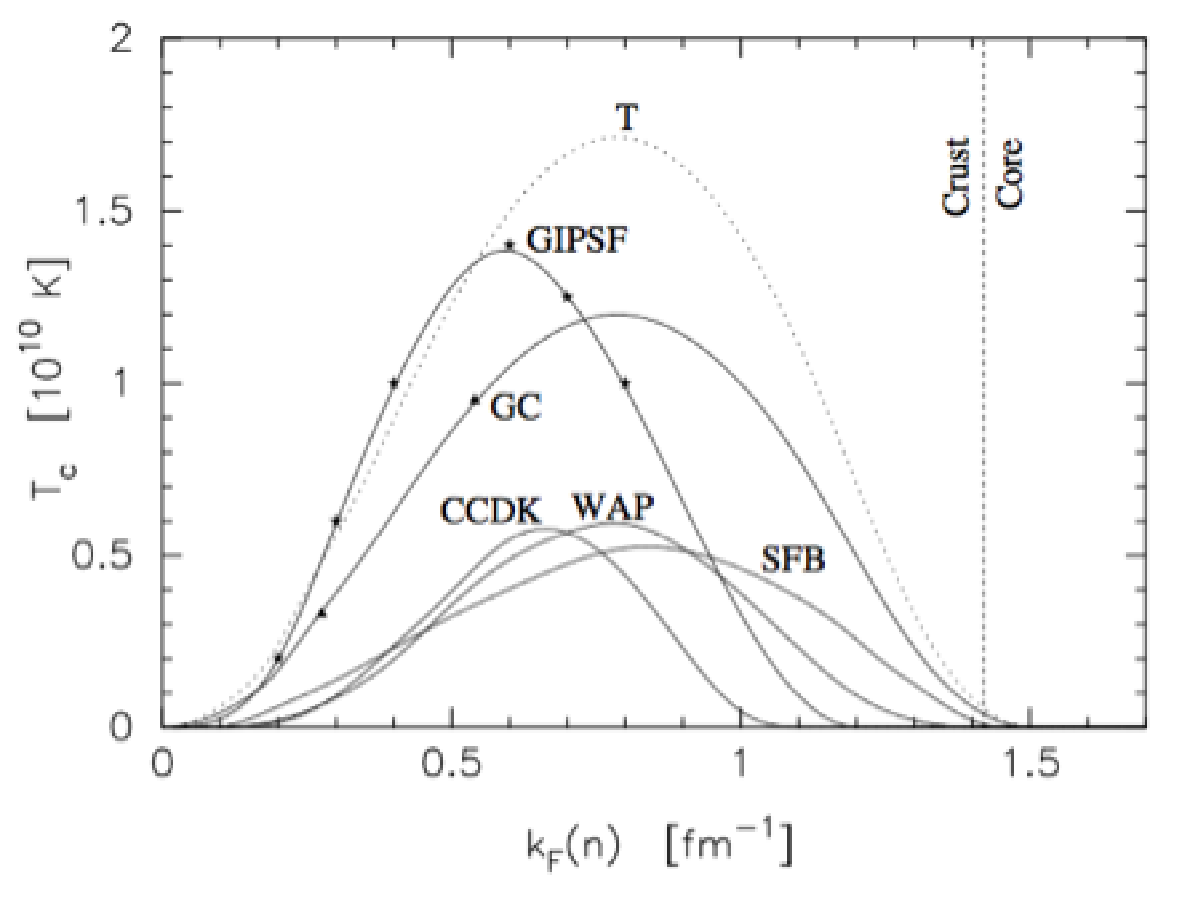
Condition for direct Urca is:

$$s(s - p_{Fn})(s - p_{Fp})(s - p_{Fe}) \geq 0$$

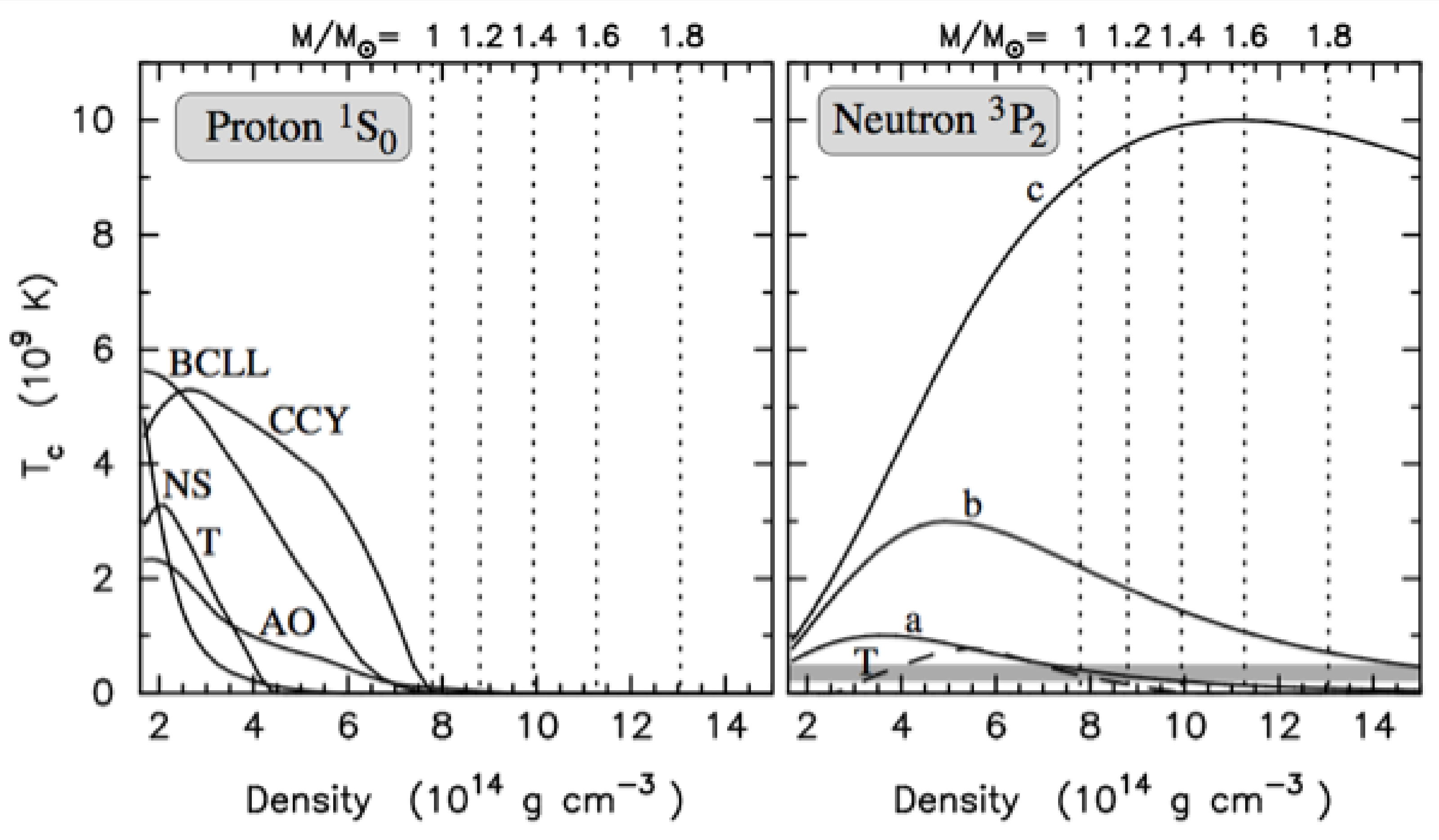
Steiner (2006)

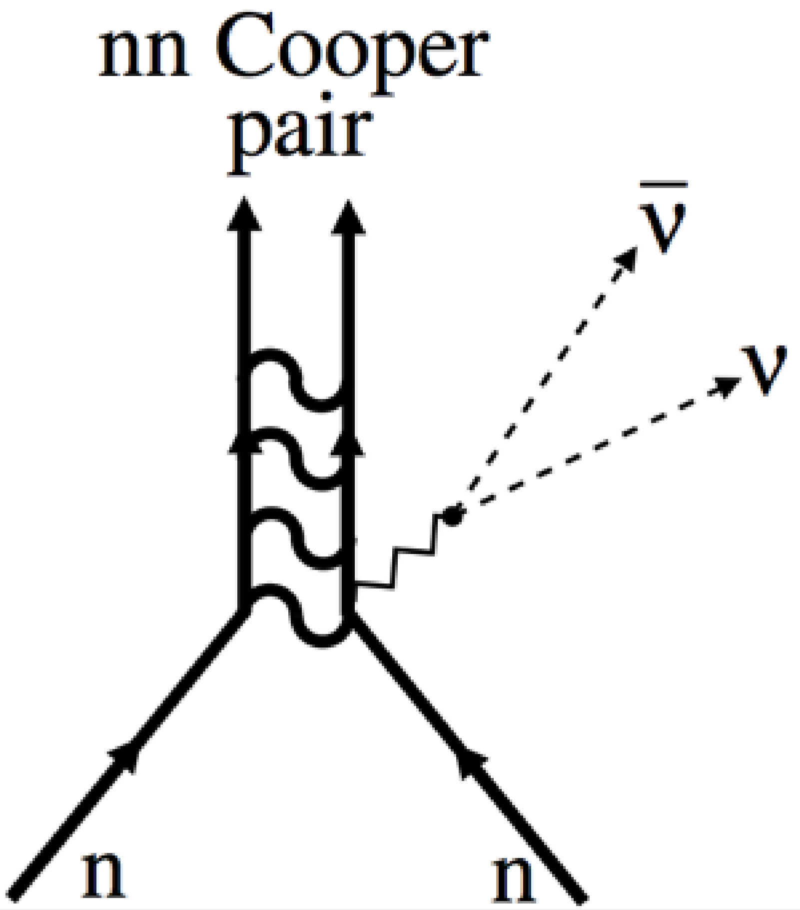
- Alternative: $n + n \rightarrow n + p + e + \bar{\nu}_e$

Superfluidity and NS Cooling



- Superfluidity can block the direct Urca process
- ...but it opens up new cooling processes
- Superfluidity also implicitly dependent on S(n)





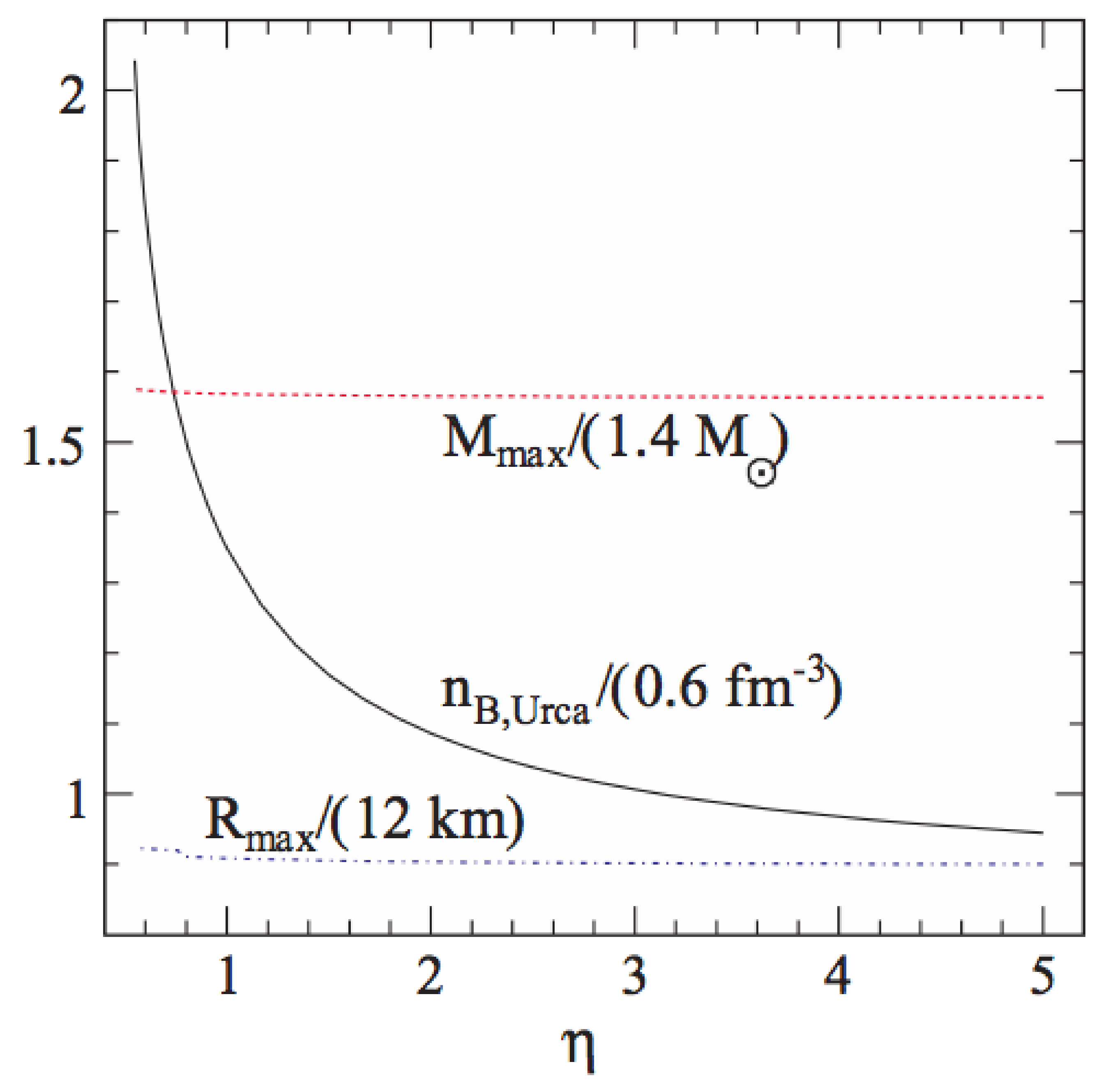
Quartic Terms and the Direct Urca Process

$$(E/A)(n,\alpha) = (E/A)_{\mathrm{nuc}}(n,\alpha) + \alpha^2 S(n) + \alpha^4 Q(n)$$

- Below saturation, quartic terms are likely "small", above saturation densities, they may be important

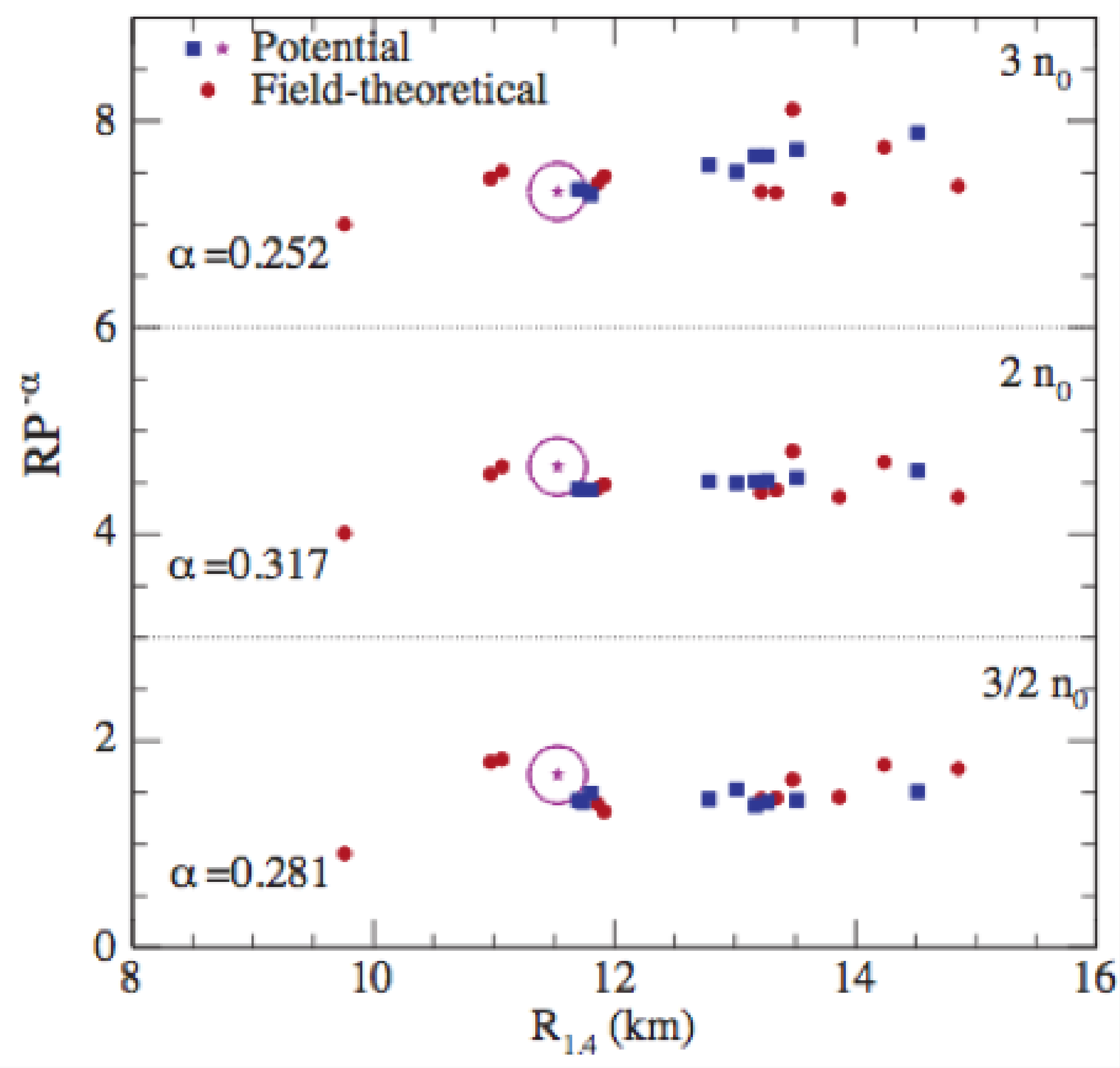
$$\eta(n) \equiv \frac{4S(n)+5Q(n)}{4S(n)+Q(n)}$$

- $3/7 < \eta(n) < 5$
- Complicates connection between symmetry energy and direct Urca
- Superfluidity also very important, and depends on L

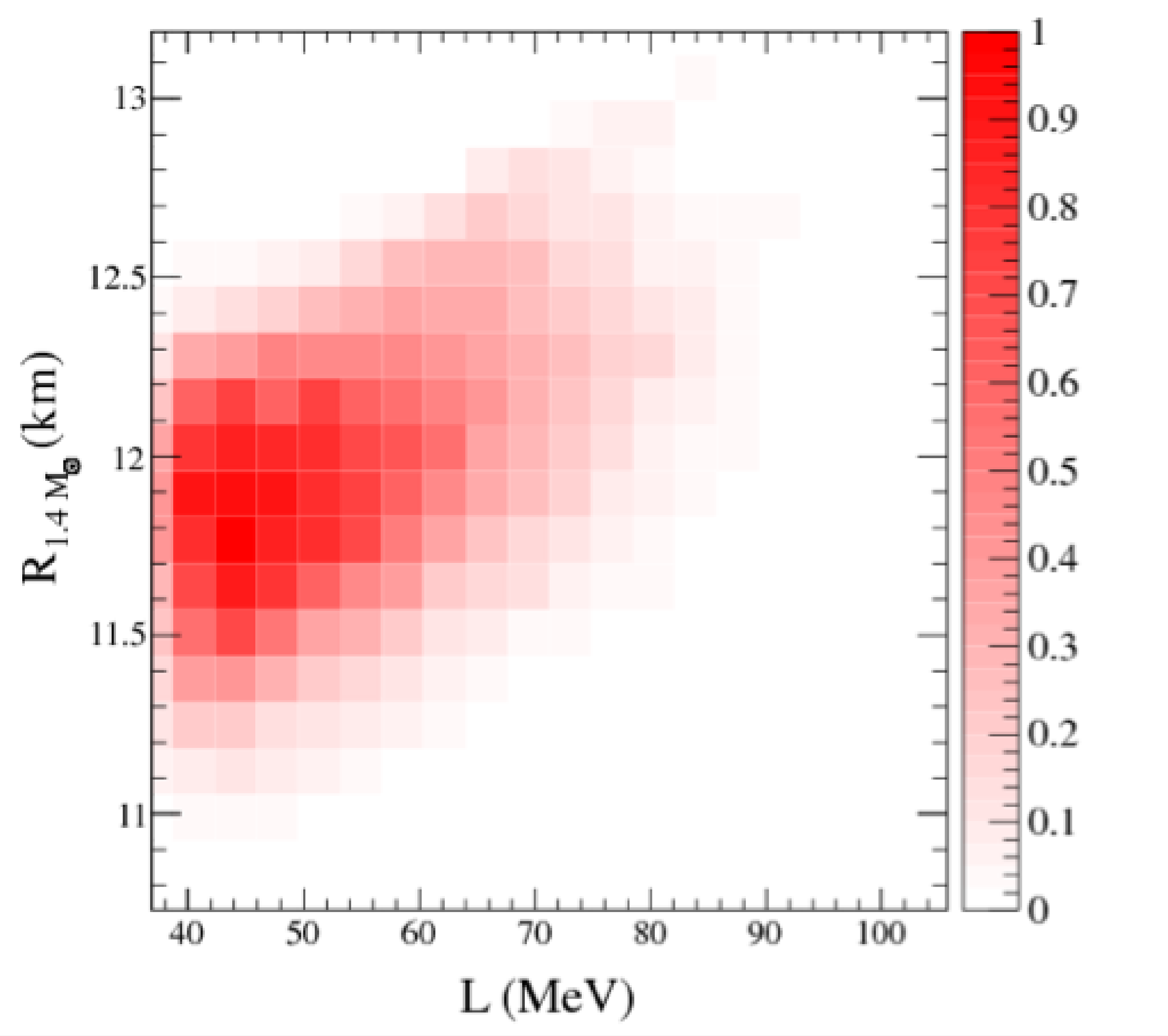


Steiner (2006)

Connection to Neutron Star Radii



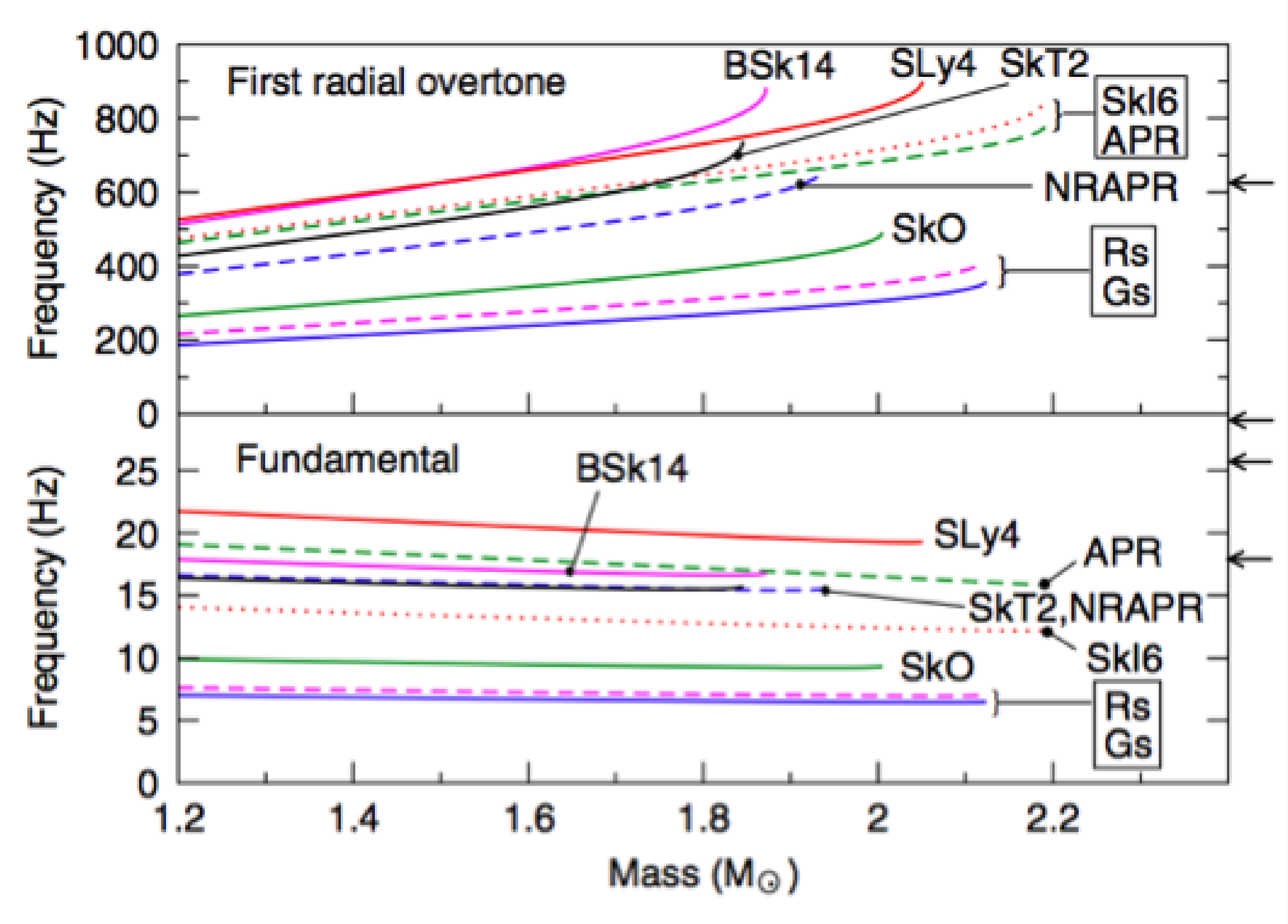
Steiner et al. (2005) based on Lattimer and Prakash (2001)



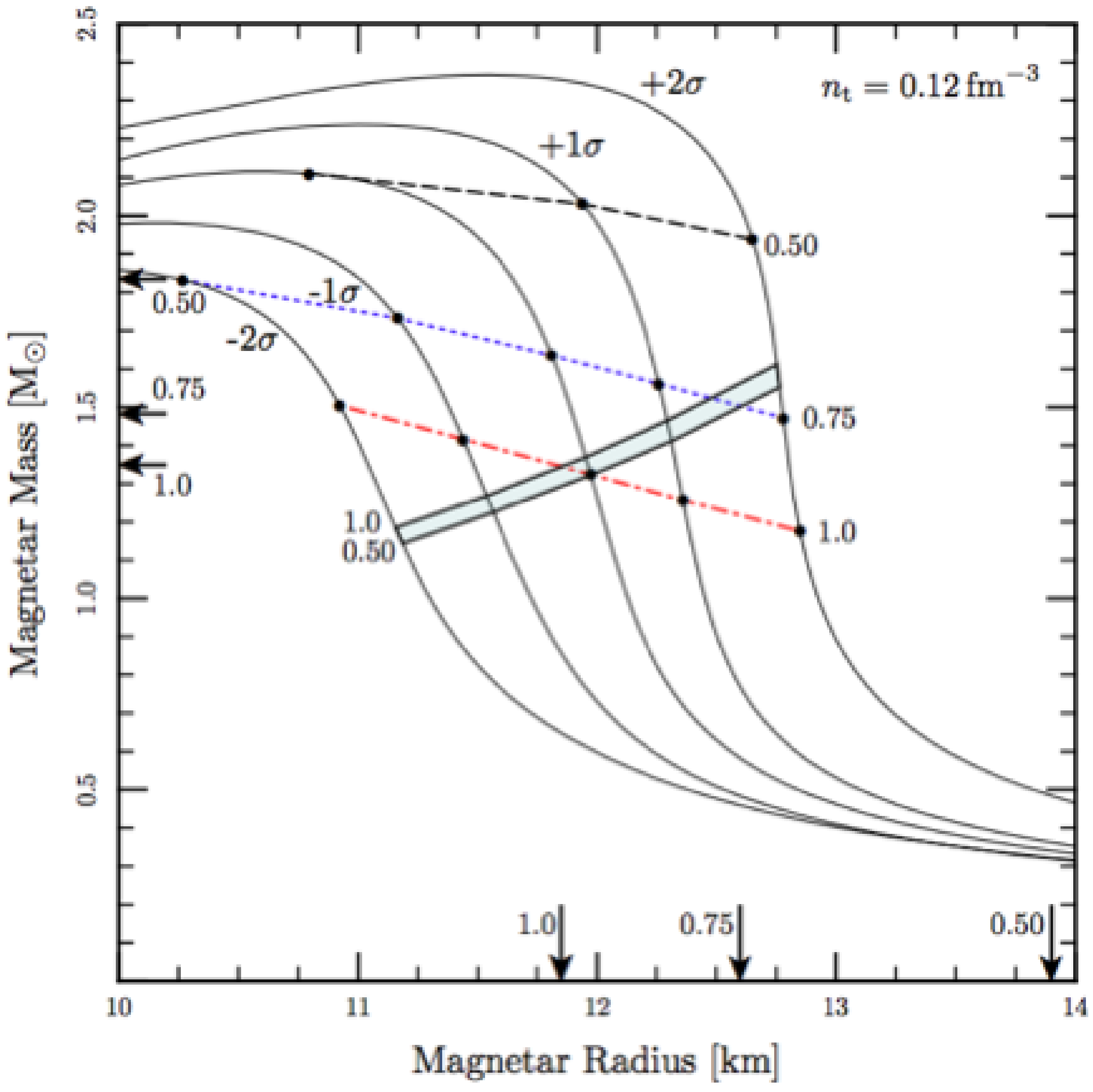
Based on Steiner et al. (2010)

- L correlated with R for 1.4 $M_\odot$
- Unless there is a strong phase transition at low density
- L not correlated with R for 2.0 $M_\odot$
- More about this next week...

Magnetar Flares and the Symmetry Energy



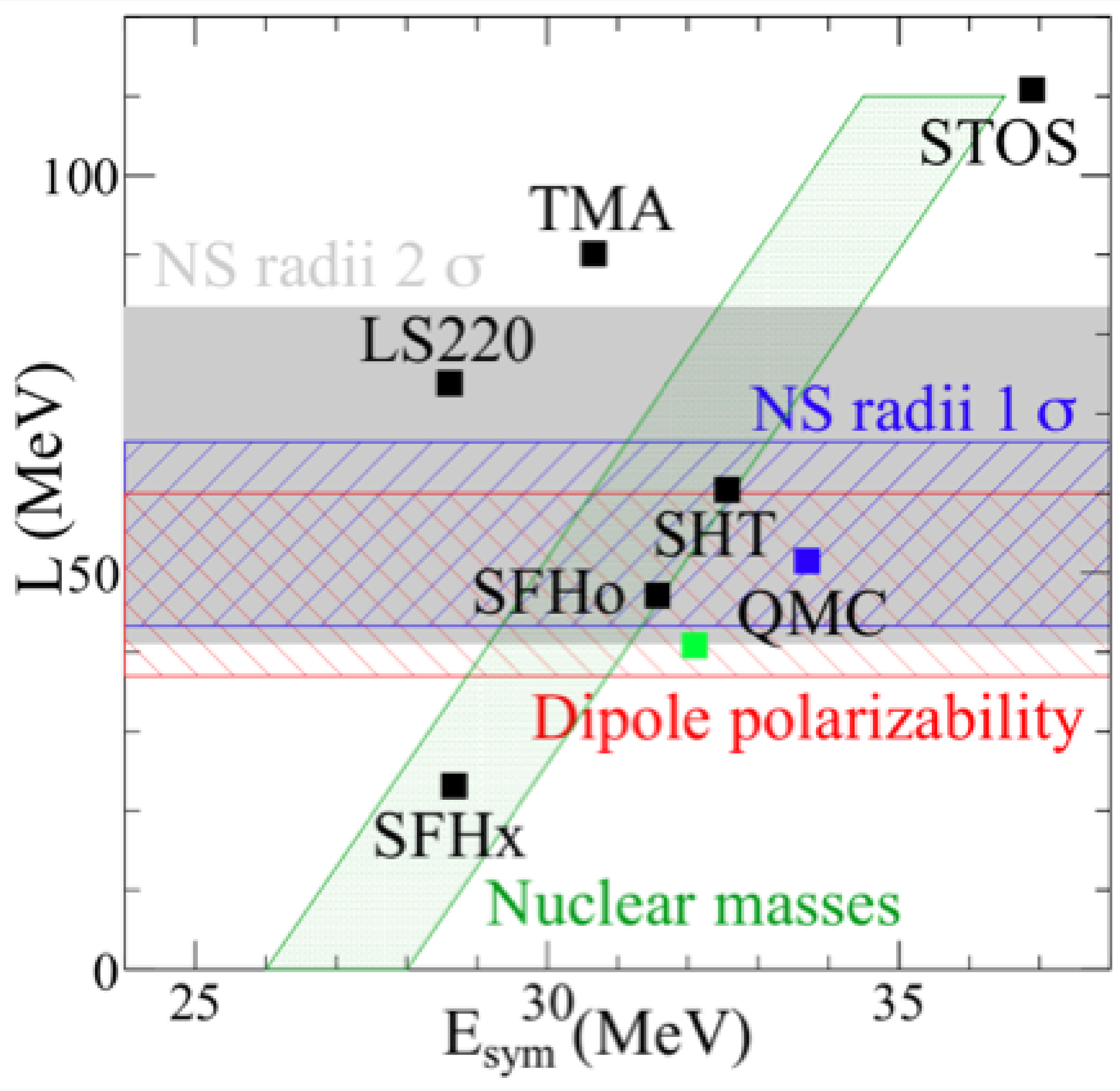
Steiner and Watts (2009), see talks by Iida and Sotani

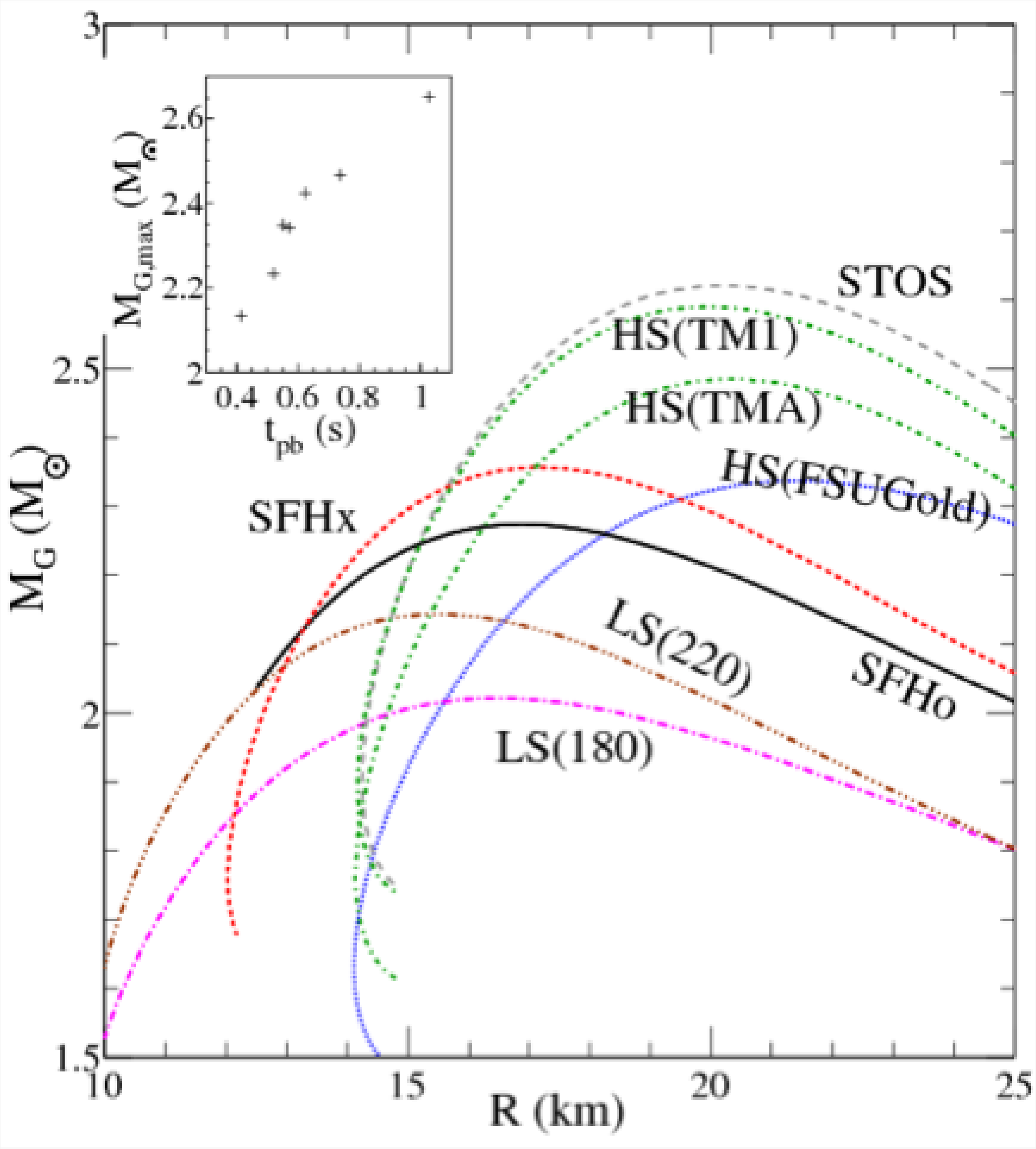


Deibel et al. (2013)

- Seismic events excite torsional modes ← shear modulus ← composition composition ← $S,\ L$
- Unknown mechanism for X-ray generation in magnetosphere
- May come from core modes (these may depend on R and thus L anyway)
- Entrainment is important - How does entrainment depend on L?

Supernova EOS and the Symmetry Energy

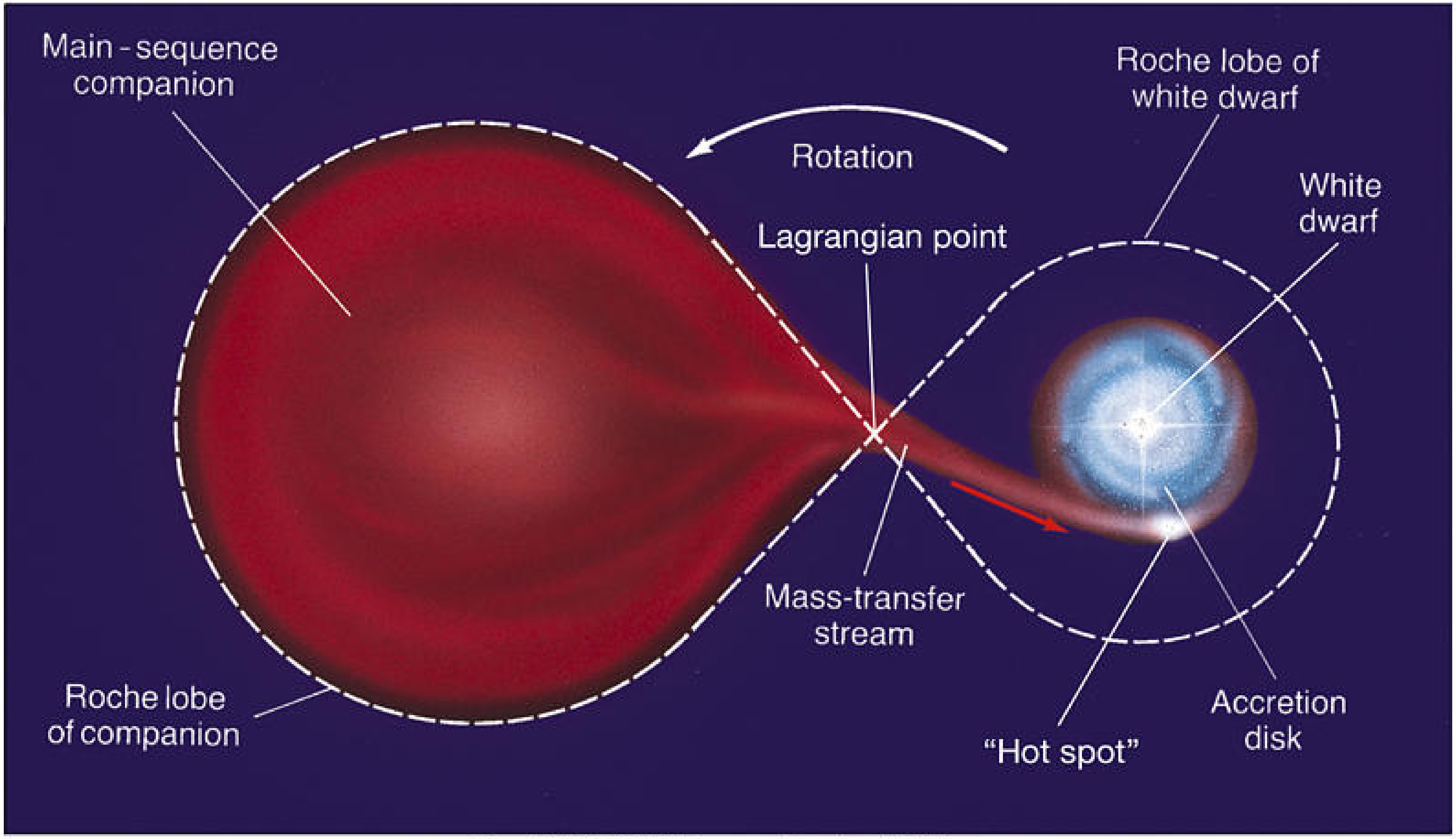




Steiner, Hempel, and Fischer (2013)

- Limited number of supernova EOSs which satisfy $S-L$ correlation
- Current EOS uncertainties too small to explain explosion
- Some correlations with the symmetry energy

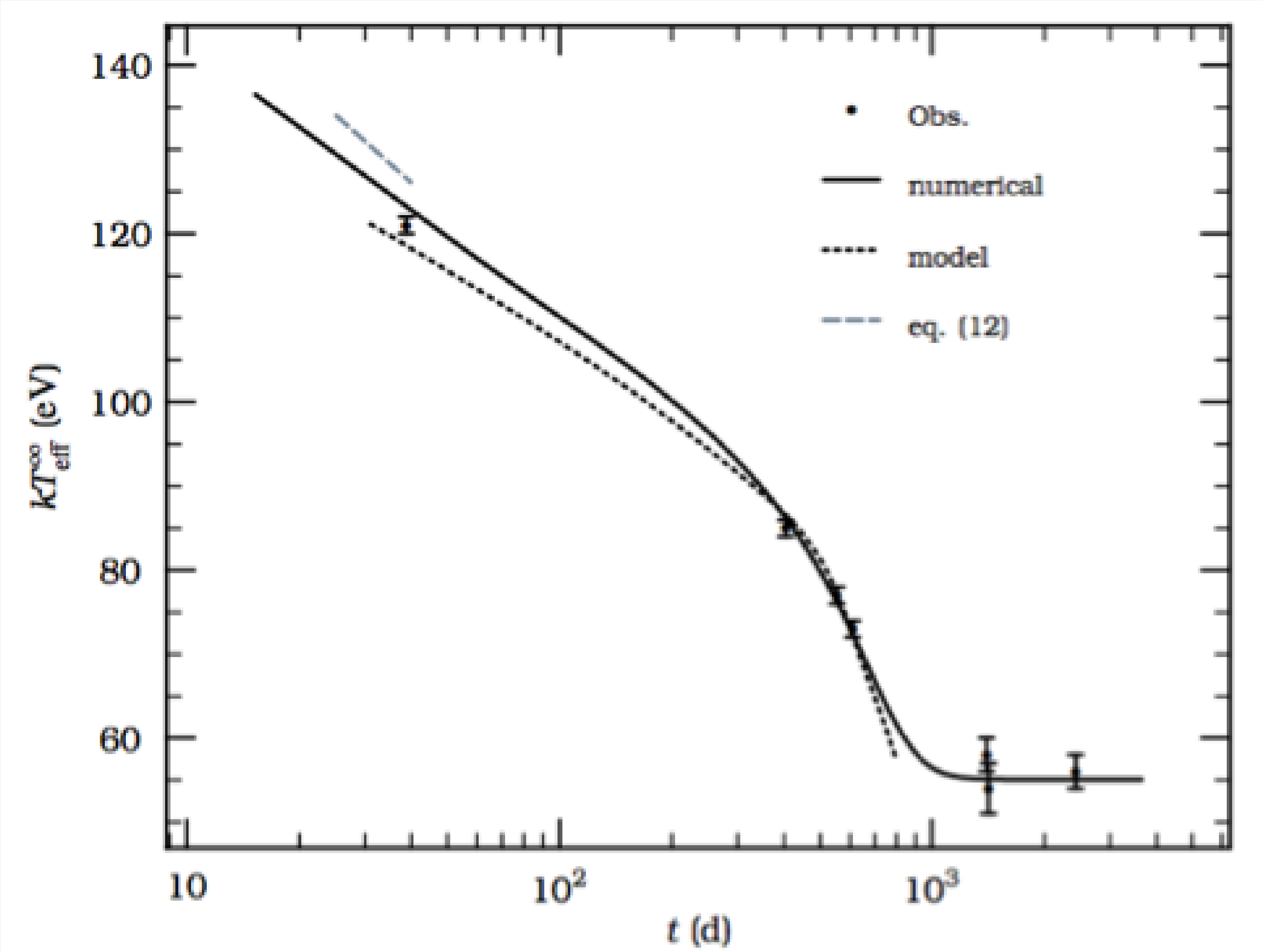
Accreting Neutron Stars: LMXBs



- Most stars have companions: neutron stars can have main-sequence companions
- Accretion heats the crust and is episodic
- At high enough density, H and He are unstable to thermonuclear explosions

Accreted Neutron Star Crusts

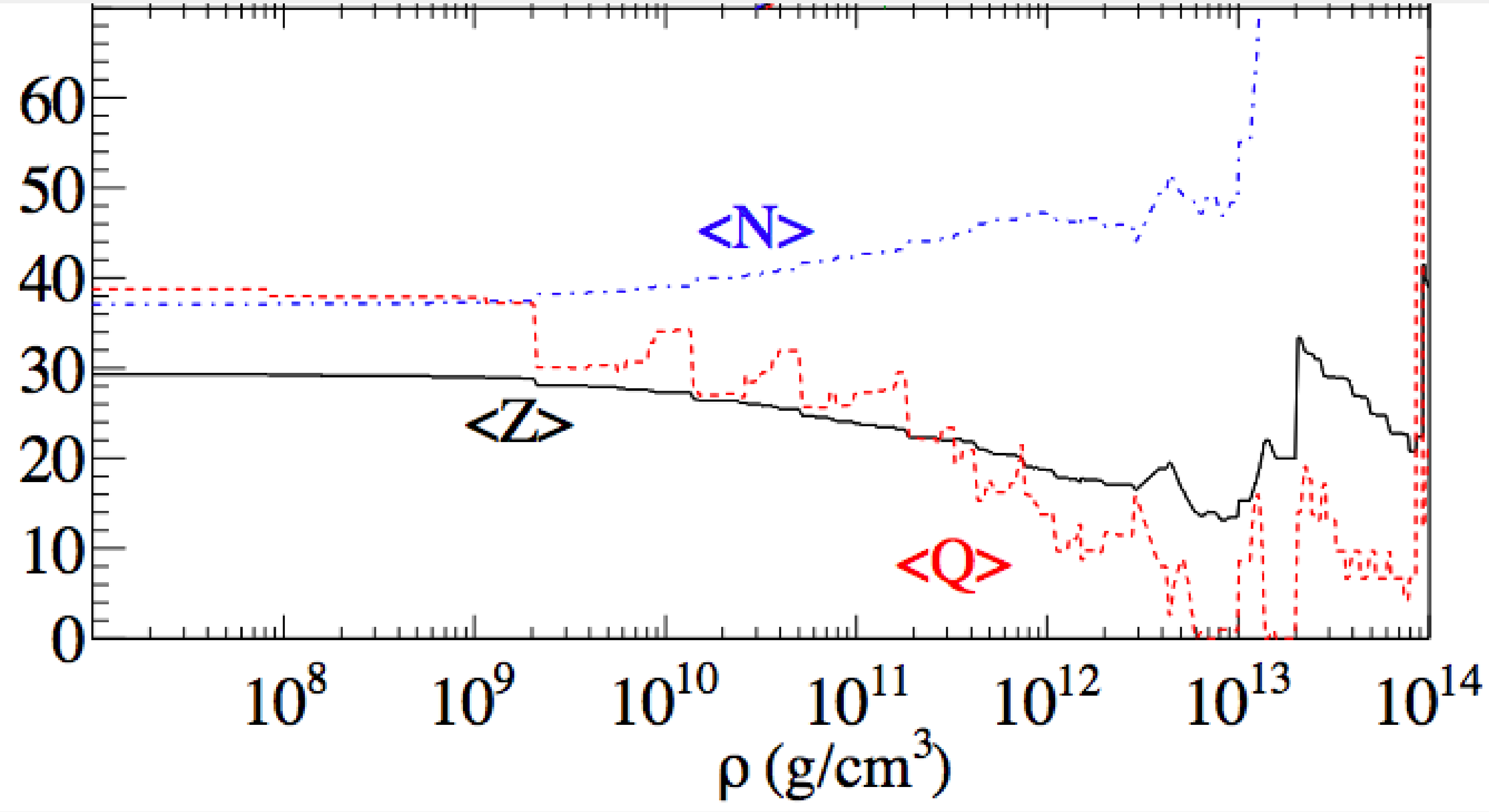
- In a cold neutron star, surface is usually taken to be ~ ^{56}Fe
- Nuclei become larger and more neutron rich with increasing density
- The surface of accreting neutron stars is H and He
- H and He is accreted and becomes unstable - X-ray burst
- X-ray burst ashes undergo electron captures, neutron emissions, and pycnonuclear fusions
- Deep crustal heating



Brown et al. 2009, Page et al. 2012

A Multicomponent Model of the Deep Crust

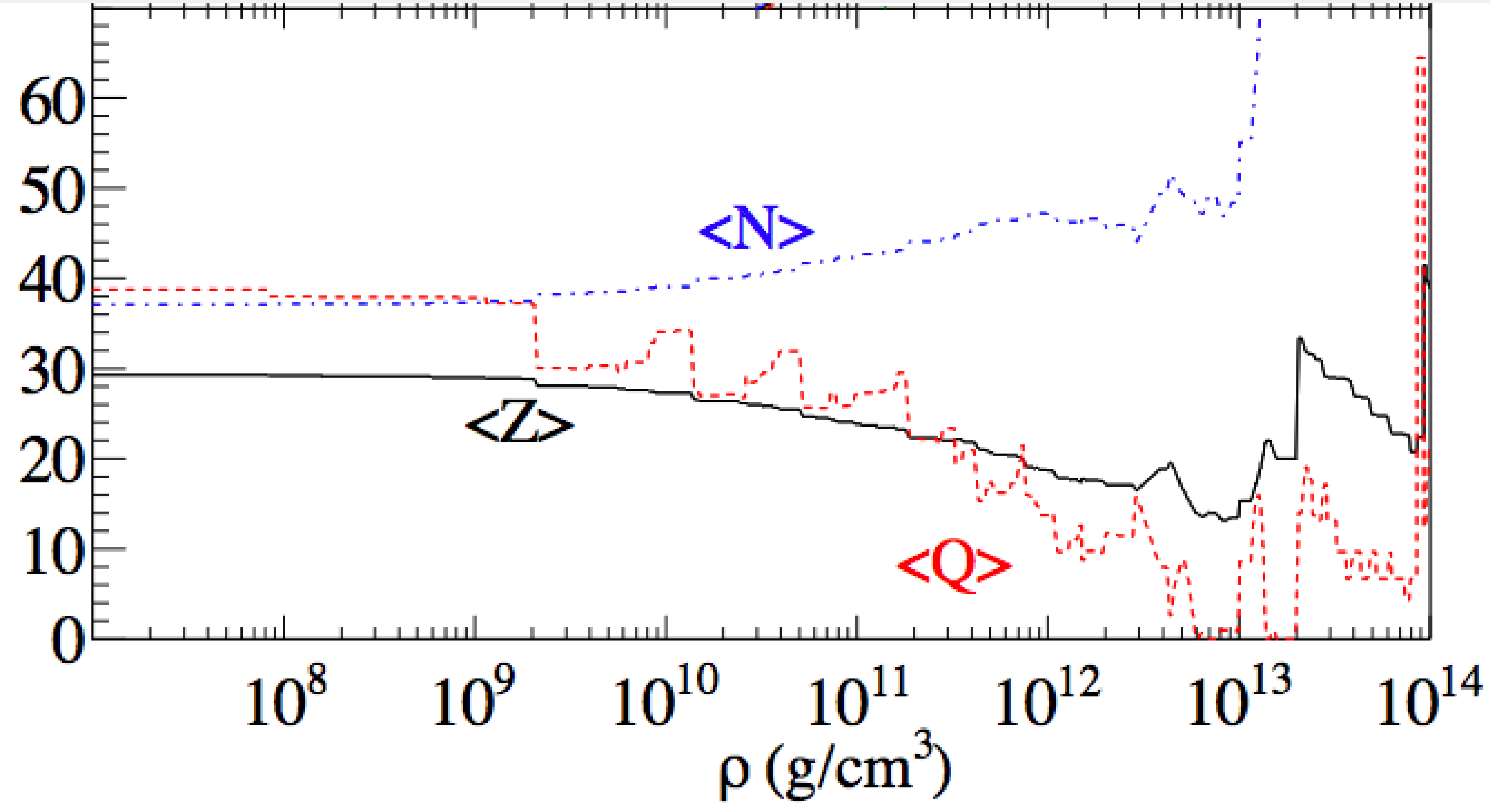
- Steiner (2012) is the first multi-component model of the accreted crust beyond neutron drip
- Employ a liquid-droplet model with an RMS deviation of 1.1 MeV
- Use quasi-statistical equilibrium instead of a full reaction network
- The multi-component model is important because it resolves reaction pathways that are impossible in single-component model



Steiner (2012)

Symmetry Energy and Deep Crustal Heating

- Vary masses based on nucleon-nucleon interactions with different symmetry energies
- Skyrme models: SLy4 (L ~ 45 MeV) and Gs (L ~ 90 MeV)
- Begin with an initial composition of X-ray burst ashes
- Find that SLy4 gives 2.4 MeV per nucleon while Gs gives 4.8 MeV per nucleon



Steiner (2012)

Other Connections to the Symmetry Energy

- Moment of inertia, $I \sim MR^2$ (Talks by Newton and Fattoyev)
  - ○ Potential for measurement in double pulsar J0737
  - ○ Also L is correlated with I_{crust}/I
  - ○ Glitches: magnetic torques spin down lattice
  - ○ Glitch happens when neutron superfluid catches up with crust
  - ○ I_{sfluid} must be large enough to explain glitches
    Link, Epstein, and Lattimer (1999)
  - ○ Entrainment lowers I_{sfluid}
    Chamel
- Tidal deformability, λ
  - ○ Measured by LIGO in NS-NS merger at ~ 400 Hz
- I/M^3 correlated with λ/M^5 (Yagi and Yunes 2013)
- r-process nucleosynthesis (Talks by Shen and Roberts)
  - ○ Determines neutrino spectra in the wind
  - ○ Determines proton fraction in ejected material in NS-NS merger
  - ○ Drip-line may be important in fission cycling

Summary

Symmetry energy is important for both nuclear physics and astrophysics

- There are gateway quantities that we may want to consider carefully
- Be careful with direct Urca, $S(n)$, and $Q(n)$
- L important for NS radii - Lots of fun next week on that
- Maybe important for flares, but this is a bit messy
- Never a bad time to use good microphysics in astrophysical simulations
- Deep crustal heating sensitive to L