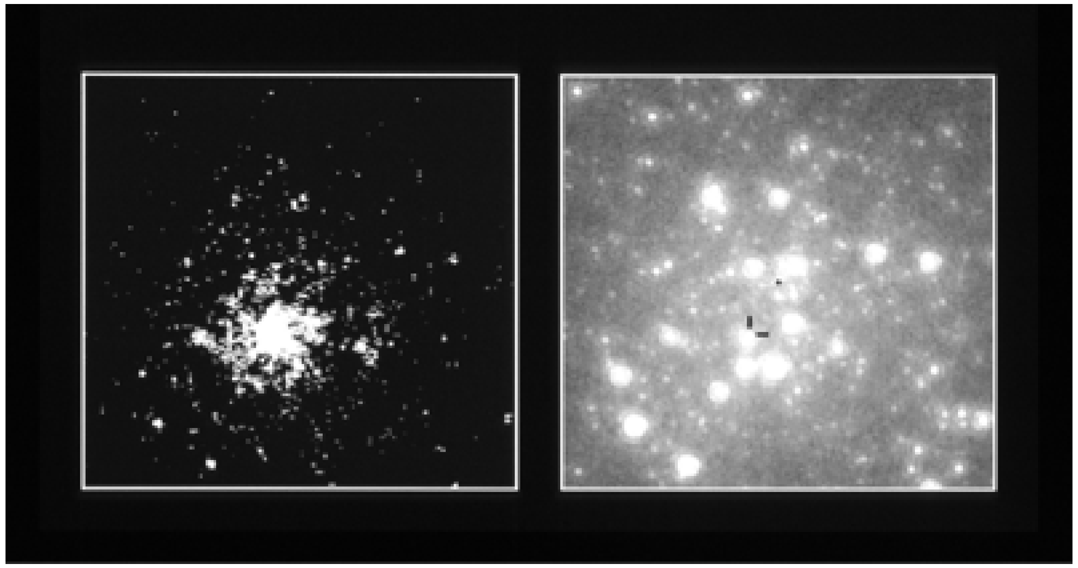
Neutron Stars as a Laboratory for the Nuclear Symmetry Energy



HST observation of 4U1820

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Outline

- Fundamental questions about neutron stars
    - What are their masses and radii?
    - What are they made of?
    - These fundamental neutron star questions are connected to fundamental nuclear physics questions. *What is the nuclear symmetry energy?*

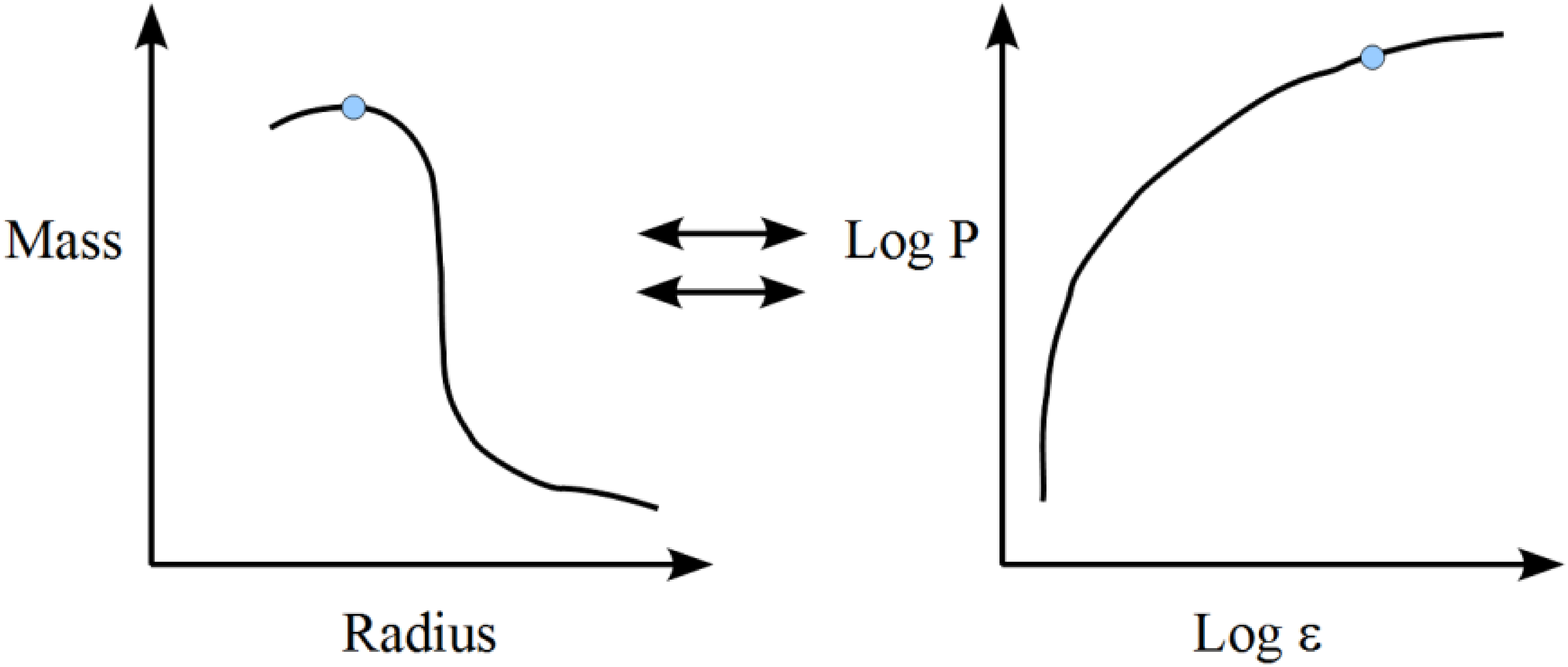
- Mass, radius, and the equation of state
- Neutron star composition and the QCD phase diagram
- Nuclear symmetry energy and lead radii
- Accreting neutron stars and X-ray bursts

- Results on Masses, Radii, and the EOS

- Constraints on the Symmetry Energy from Neutron Stars

- How the Symmetry Energy Affects Deep Crustal Heating

M vs. R and the EOS of Dense Matter



As of 5 years ago:

- Accurate mass measurements from double pulsars (e.g. Hulse-Taylor pulsar)
- Limited radius information for a few sources (e.g. Rutledge et al.)
- A few limited constraints from pulsar spins and pulsar glitches

Now:

- 10-15 percent measurements of M and R for the same object
- A 2 solar mass neutron star (Demorest et al. 2010)

Neutron Star Composition

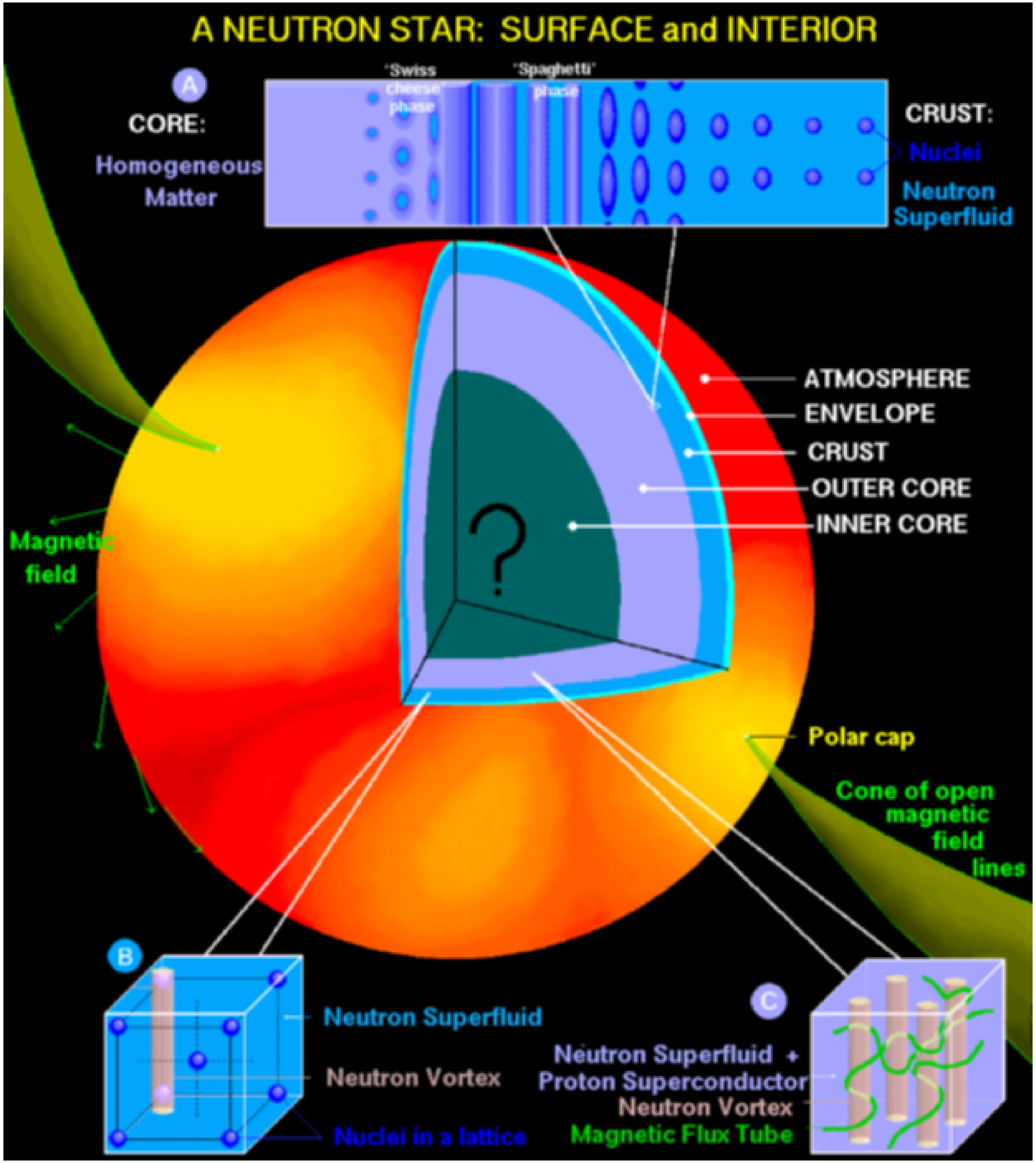
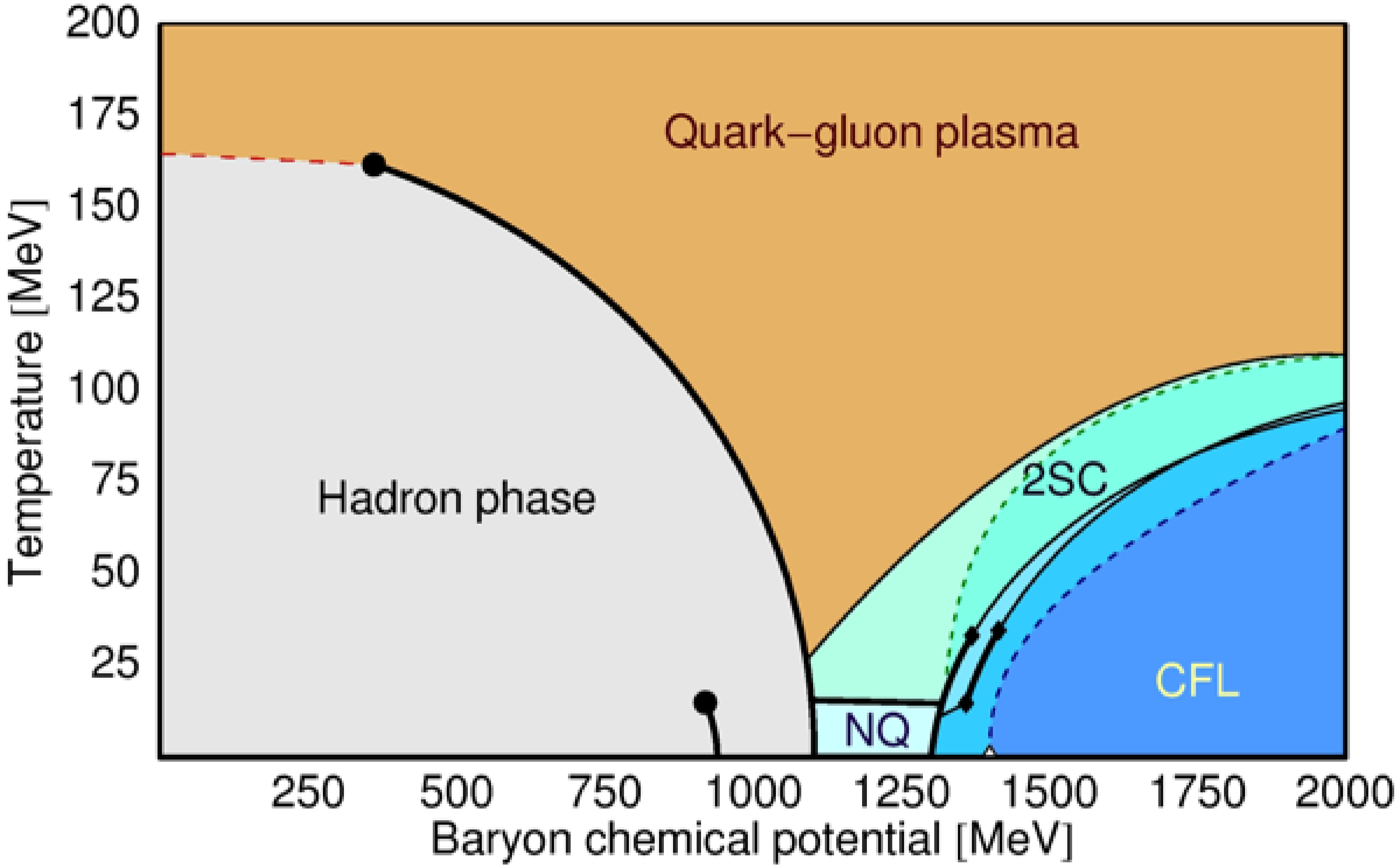


Figure by Dany Page

- Crust is a lattice of neutron-rich nuclei
- Composition of the crust depends on the history
- Outer core is homogeneous nucleonic matter
- Inner core may contain phase transitions:

$$[\Lambda, \Sigma, \Xi], [\pi, K], [u, d, s]$$

The QCD Phase Diagram

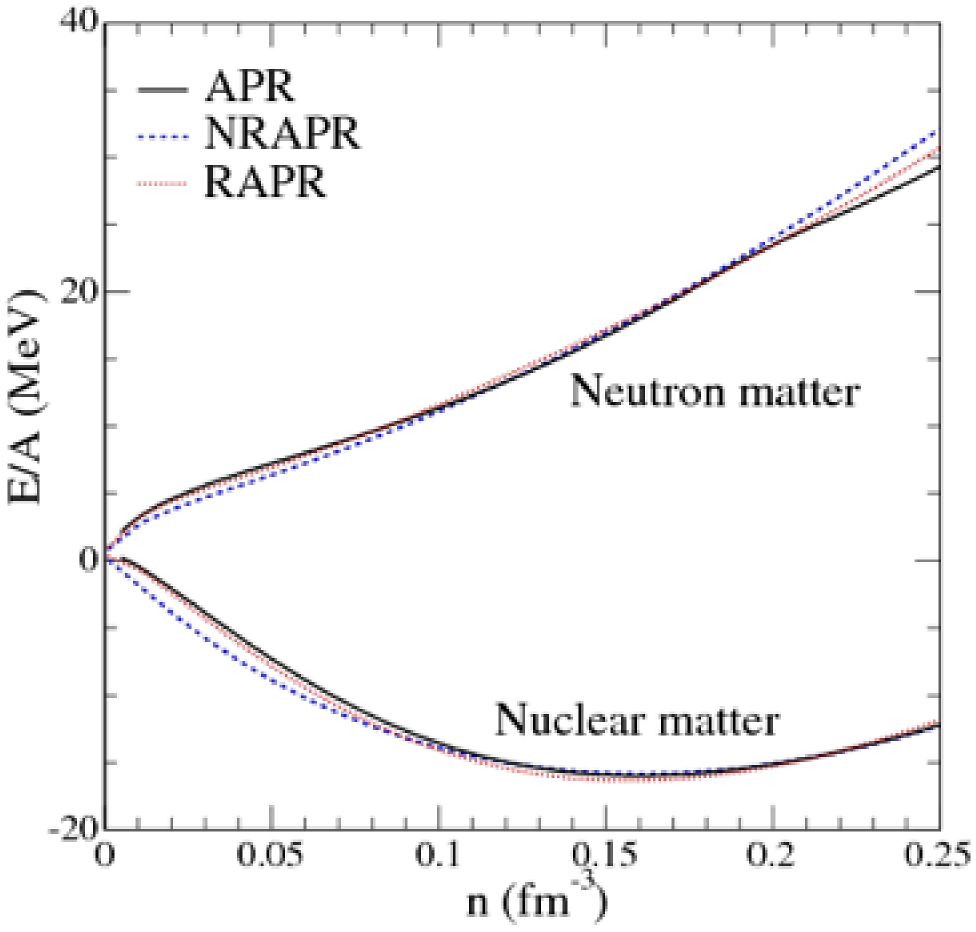


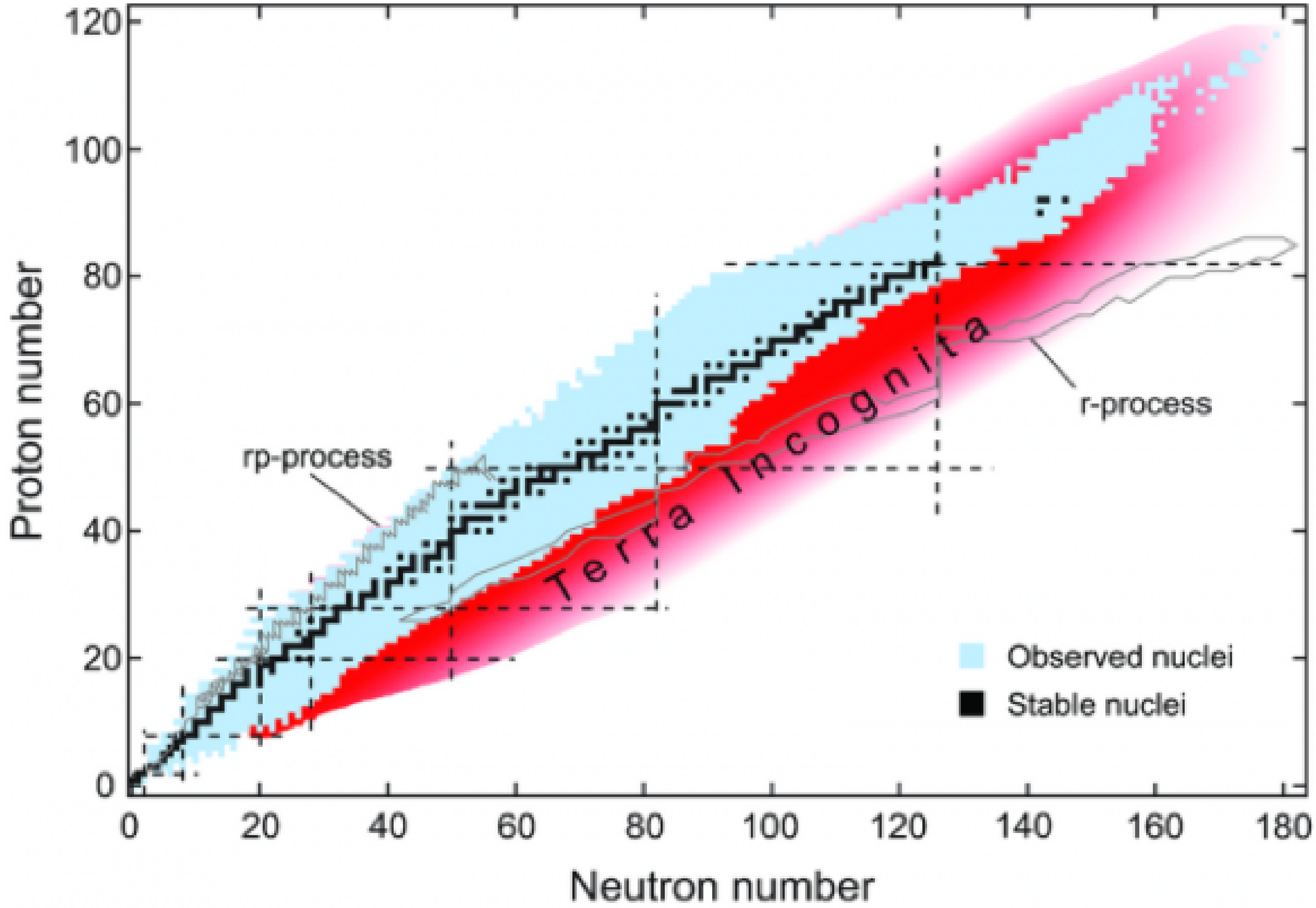
Rüster, et al. (2005)

- Neutron stars probe the high-density, low-temperature part of the QCD phase diagram

- This region is otherwise inaccessible from theory or experiment

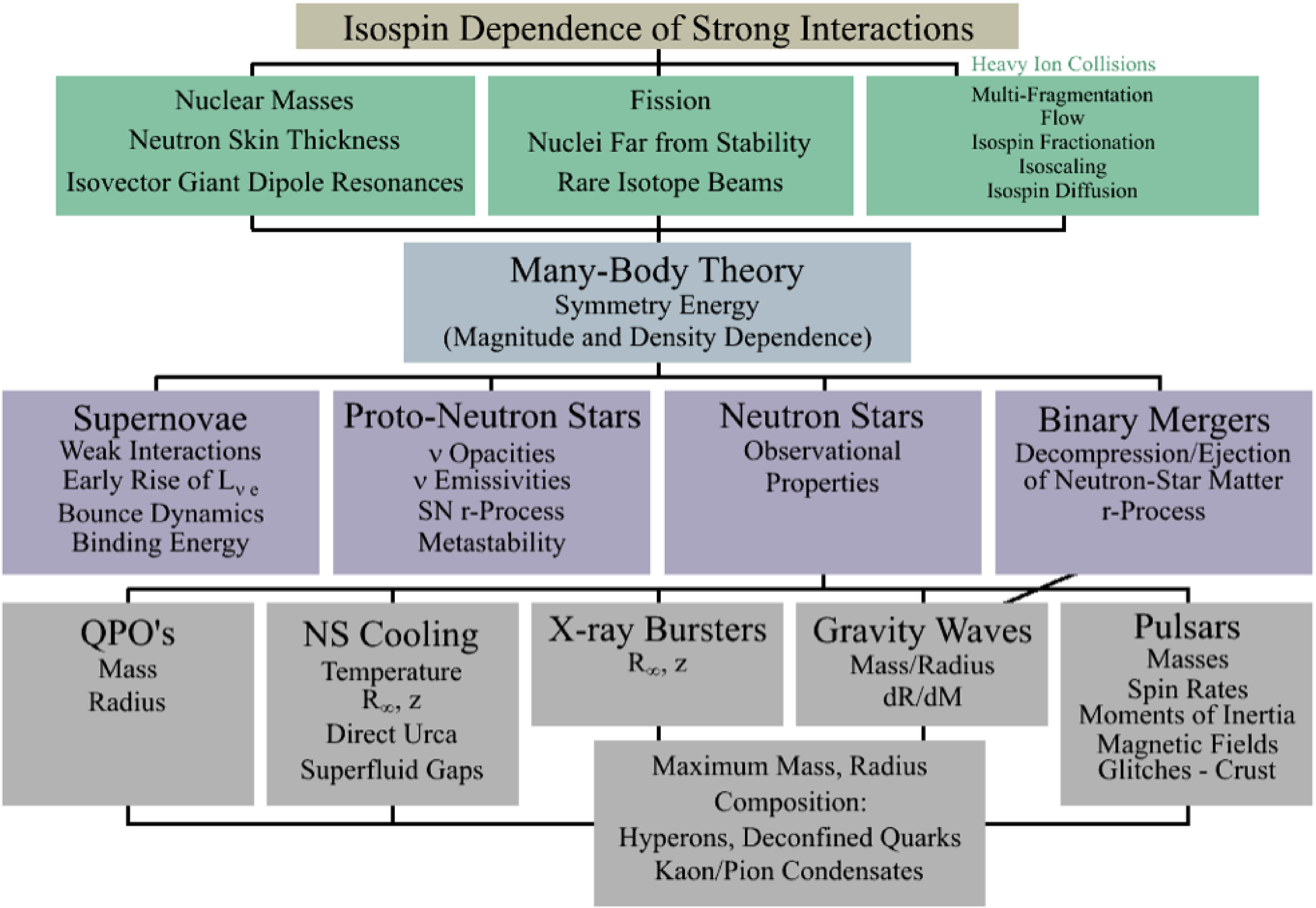
The Nuclear Symmetry Energy





- The symmetry energy is the energy cost to create an isospin asymmetry
- The origin of the 'valley of stability'
- One of the largest uncertainties in the nucleon-nucleon interaction
- S is the value at the nuclear saturation density $S = S(n_0)$
- L is the derivative, $L = 3n_0 S'(n_0)$

Connections to the Symmetry Energy



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

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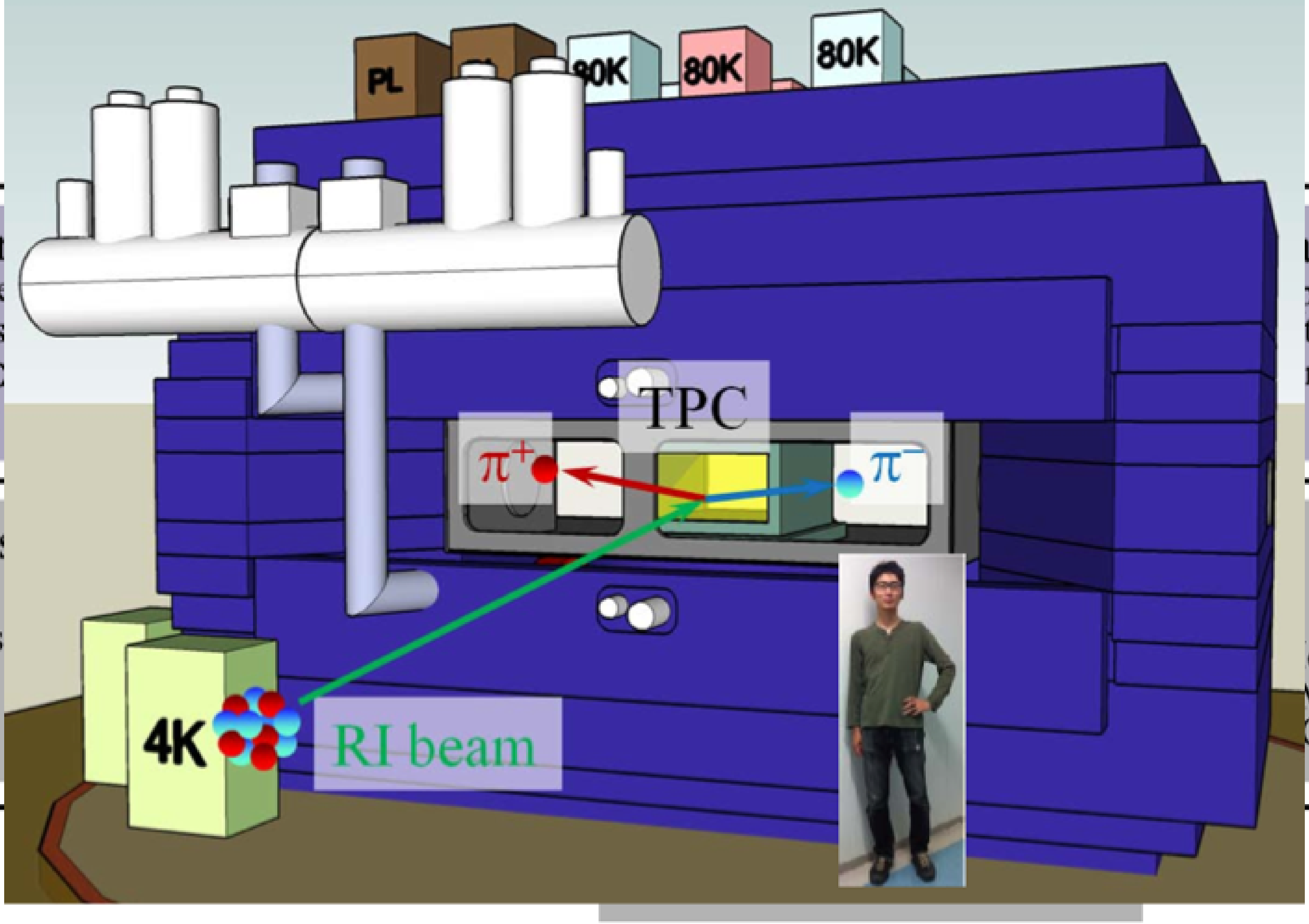

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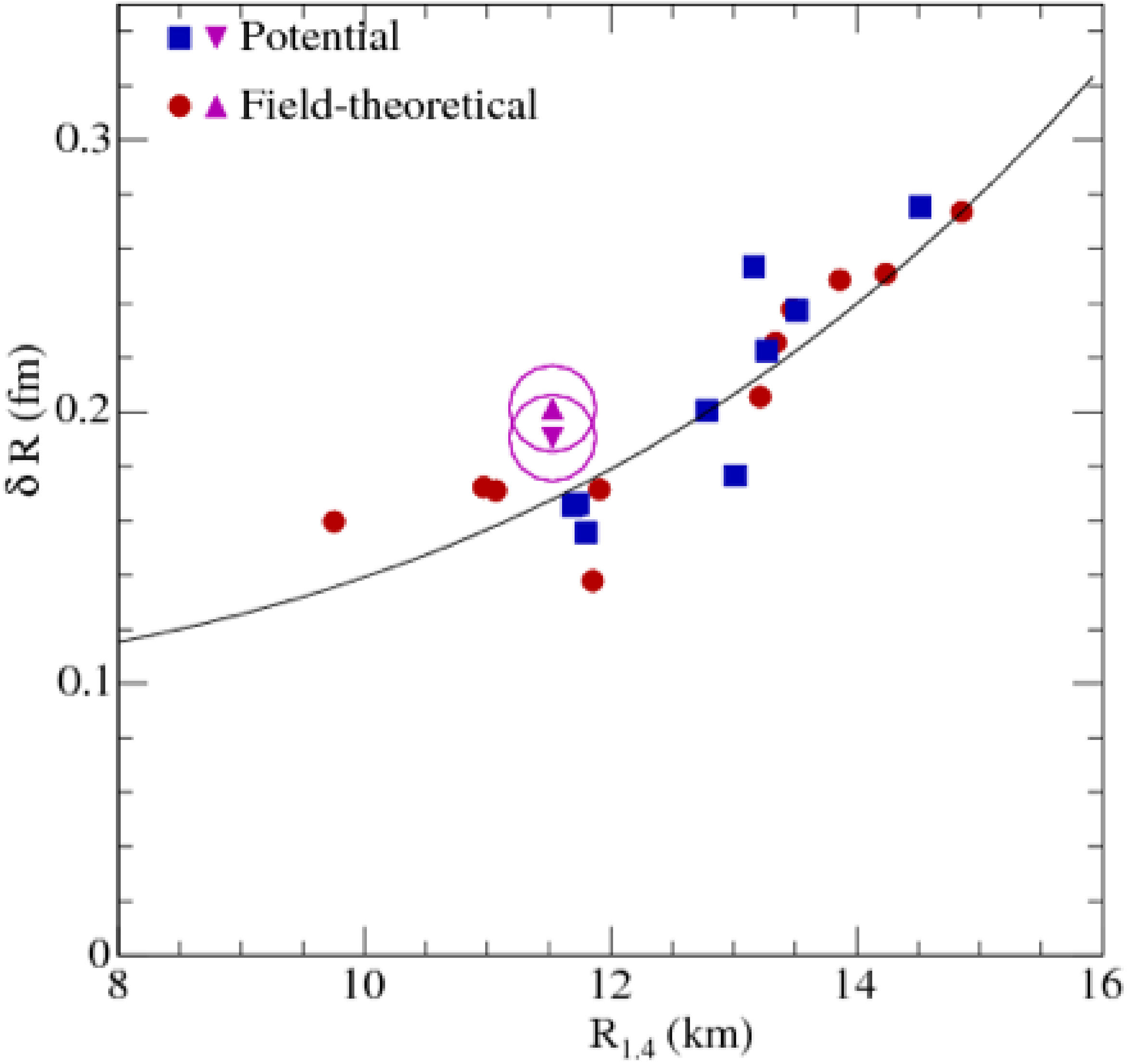
Symmetry Energy in Intermediate-Energy Heavy Ion Collisions

- Determinations of the symmetry energy in heavy-ion collisions have shown much promise
- Much work is focused on determining the derivative, L
- Growing evidence that L is small, but some results suggest otherwise
- One of the principal difficulties seems to lie in the understanding of the systematic uncertainties in the models which connect observables to L

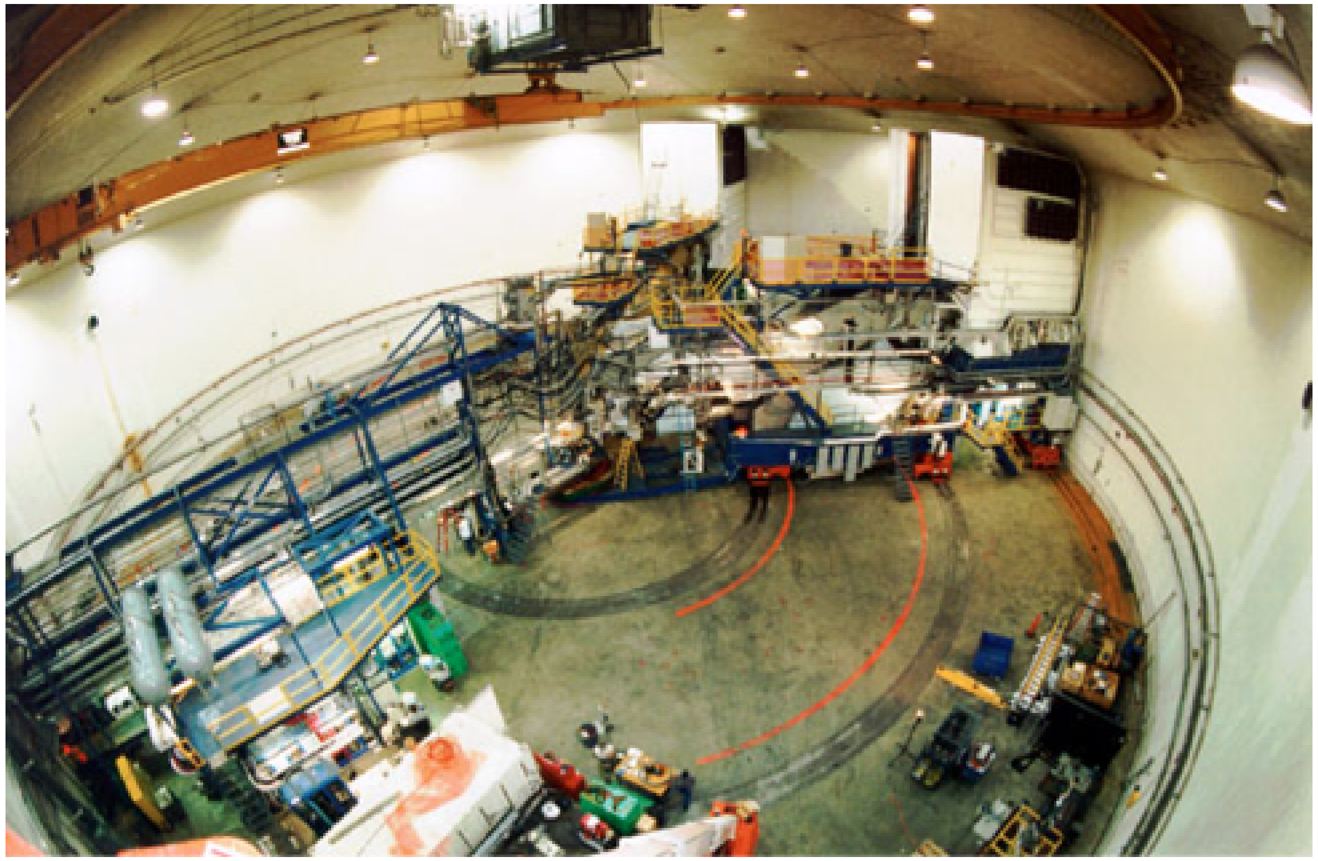
- Frontiers(?)
  - Observables which are easier to interpret
  - Probe higher density, where there is more uncertainty
  - Calibrating current models (chiral effective theory?!)
  - Syntheses of data from heavy-ion collisions, low-temperature observables, and astrophysical observables

The Neutron Skin Thickness of Lead

- Nuclei like Pb have $N > Z$, and thus $R_n > R_p$
- The quantity $R_n - R_p$ is related to L as are neutron star radii
- PREX measured $R_n - R_p$

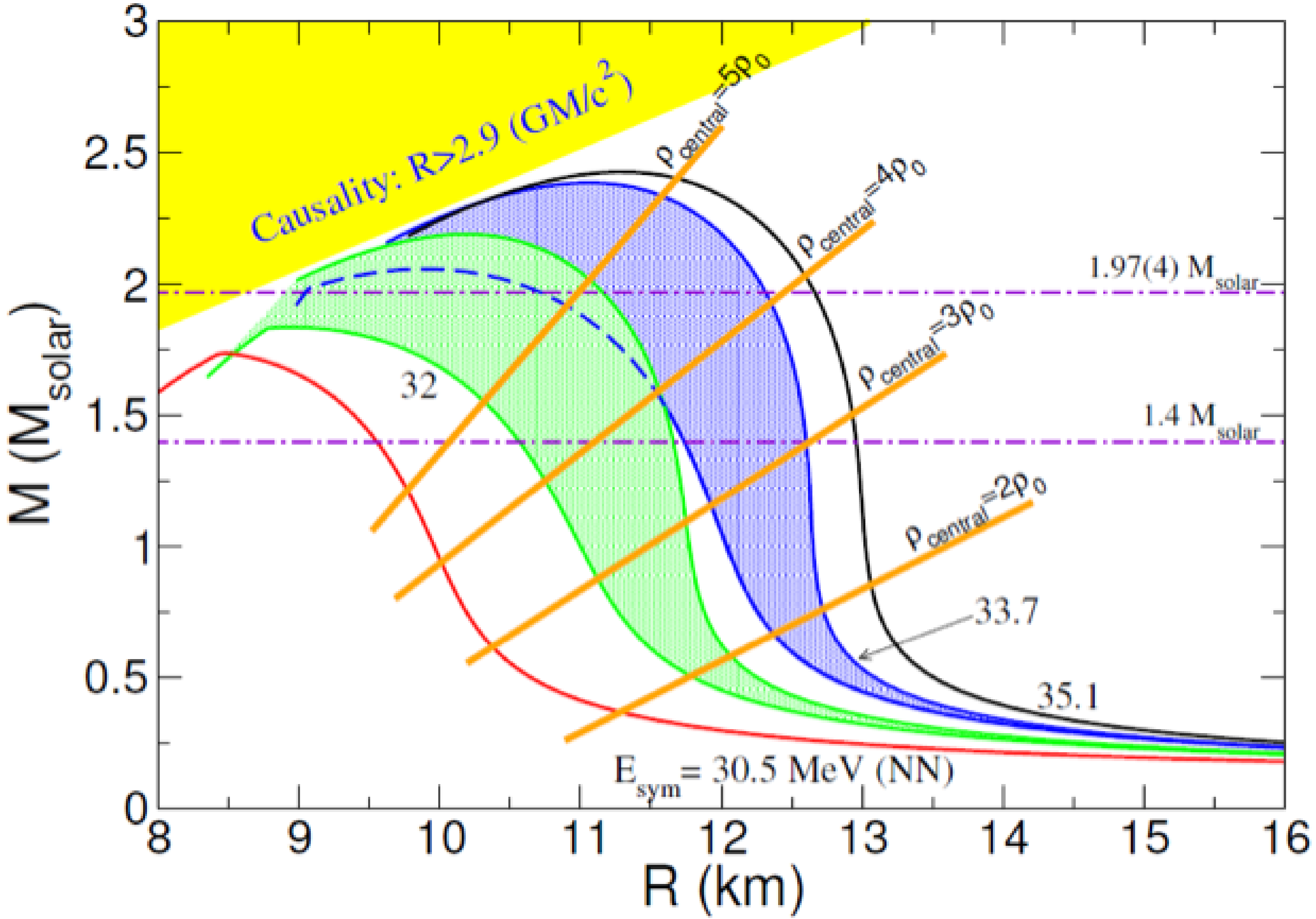


Steiner et al. (2005), based on Horowitz and Piekarewicz (2001)



Jefferson Lab's Hall A

Connection to nuclear three-body forces

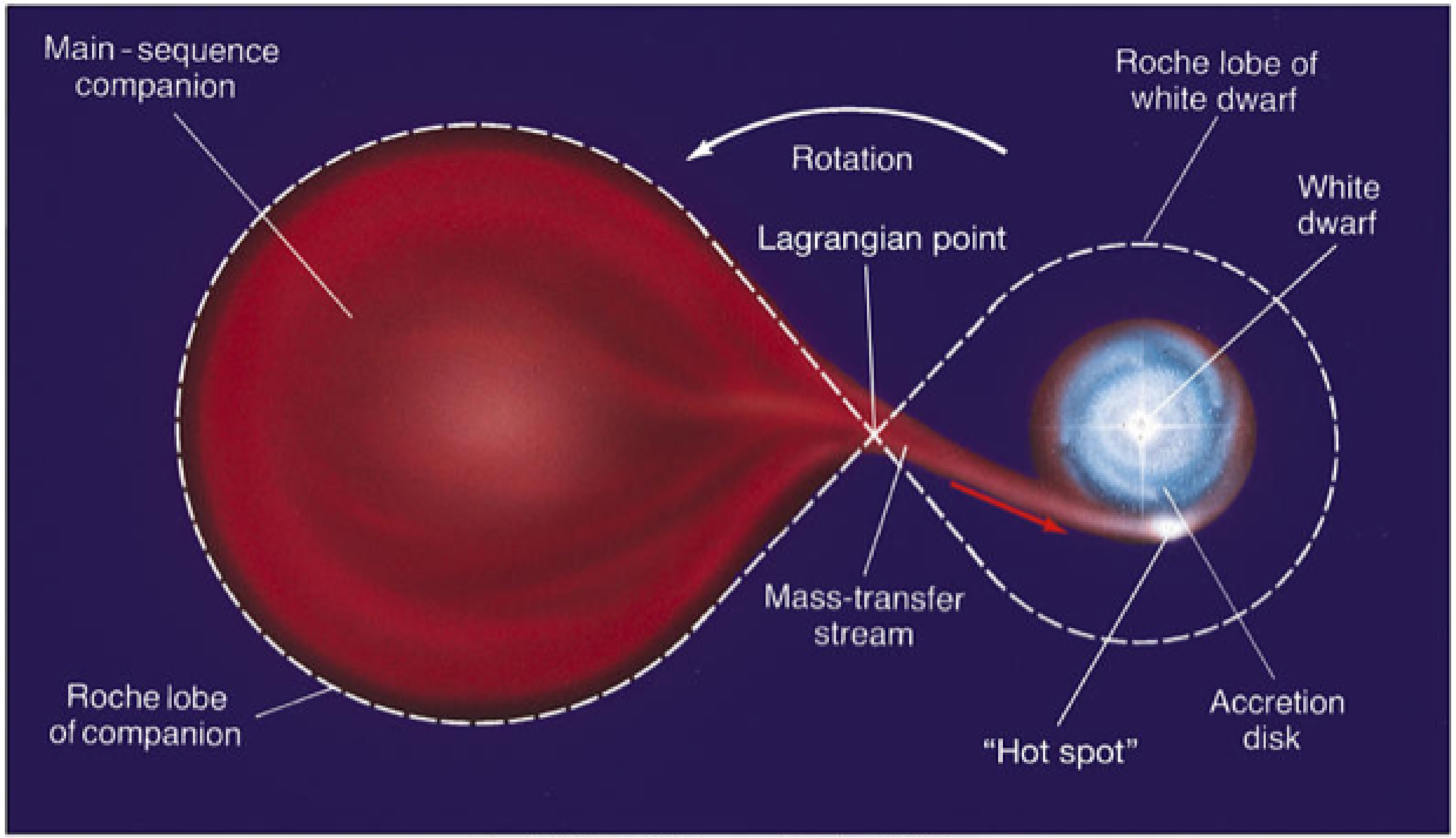


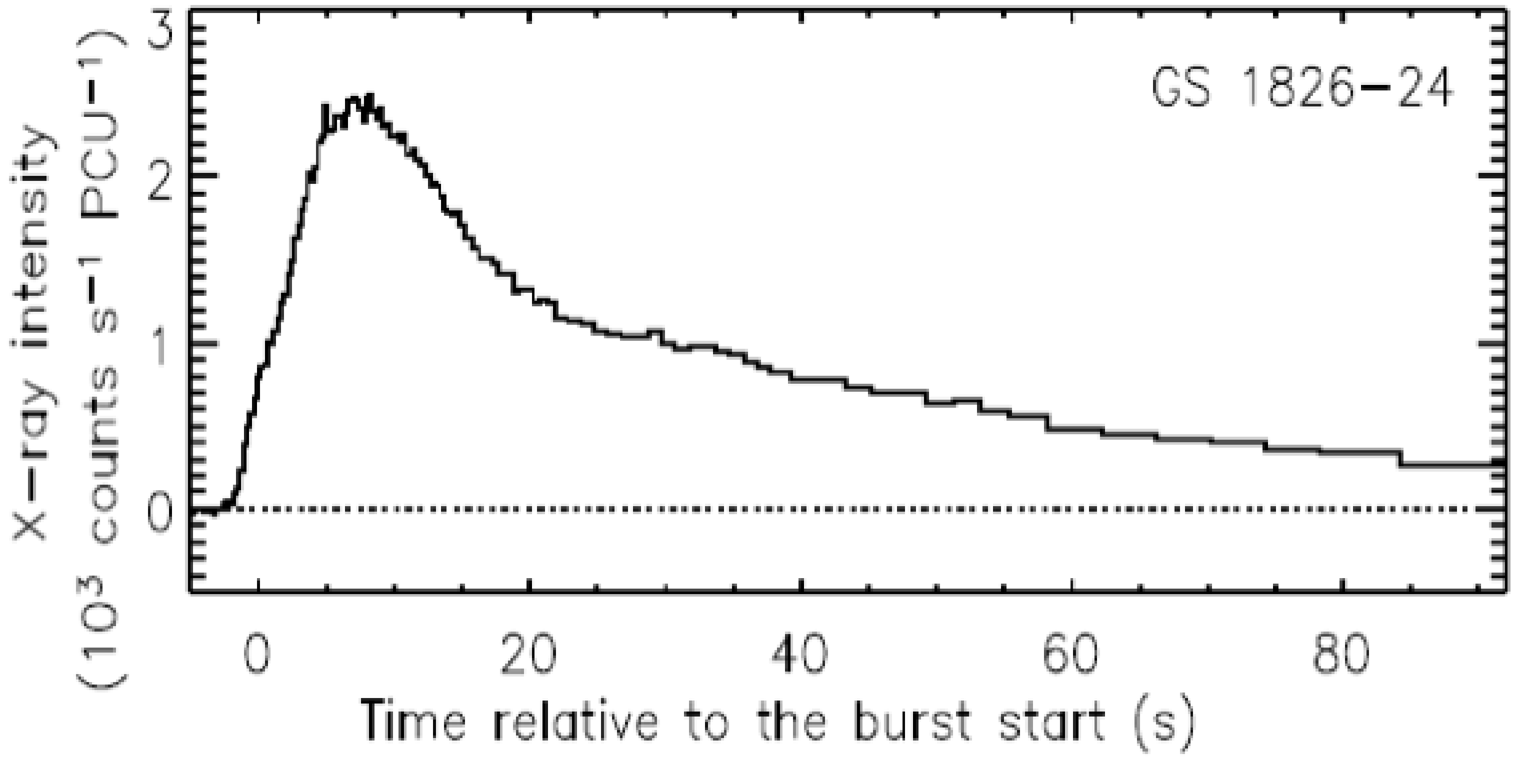
Gandolfi et al. (2012)

- Red = no three-body
- Blue, Green = adjusted three-body interactions
- Black = Urbana IX
- Strong correlation between S and L

- Build up a many-body system from effective two- and three-body nucleon-nucleon interactions
- Three-body forces are also related to neutron star radii
- $E = a\left(\frac{n}{n_0}\right)^{\alpha} + b\left(\frac{n}{n_0}\right)^{\beta}$ is a convenient parameterization

Accreting Neutron Stars: LMXBs





- From a main-sequence (normal) star or a white dwarf
- Overflowing the Roche lobe
- Most often accrete a mix of hydrogen and helium, sometimes heavier elements
- At high enough density, light elements are unstable to thermonuclear explosions

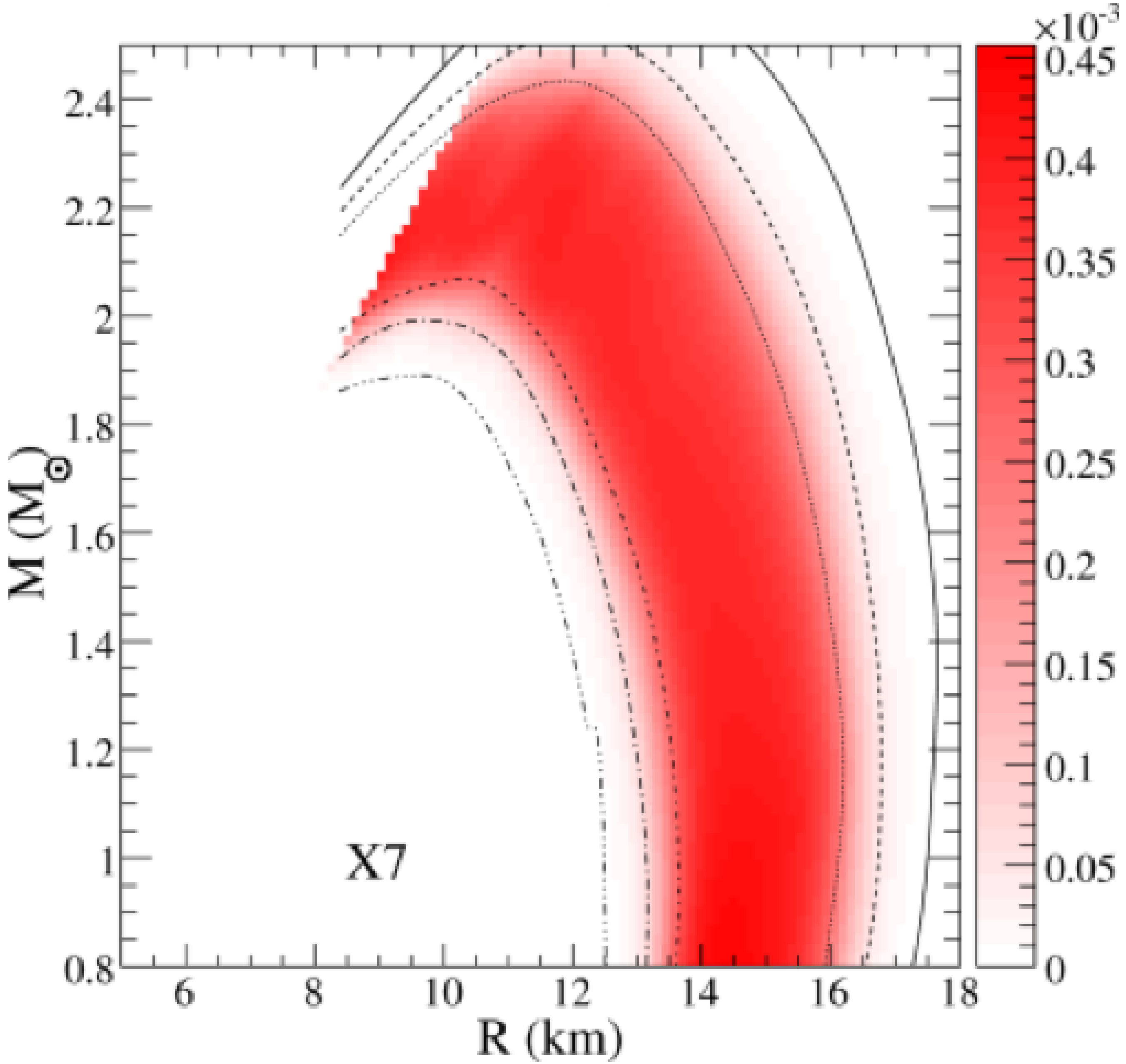
Mass Measurements and QLMXBs

- *Mass measurements:*
  Demorest et al. (2010) find a neutron stars with mass $1.97 \pm 0.04\ \mathrm{M}_\odot$

- *Quiescent LMXBs in globular clusters:*
  - H atmosphere
  - Known distance
  - Small magnetic field
  - Measure radius:

$$F \propto T_{\mathrm{eff}}^4 \left(\frac{R_\infty}{D} \right)^2$$

[i.e. Rutledge et al. (1999)]



Steiner et al. (2010)

Photospheric Radius Expansion Bursts

- X-ray bursts sufficiently strong to blow off the outer layers - radiate at the Eddington limit
- Flux peaks, then temperature reaches a maximum, "touchdown"

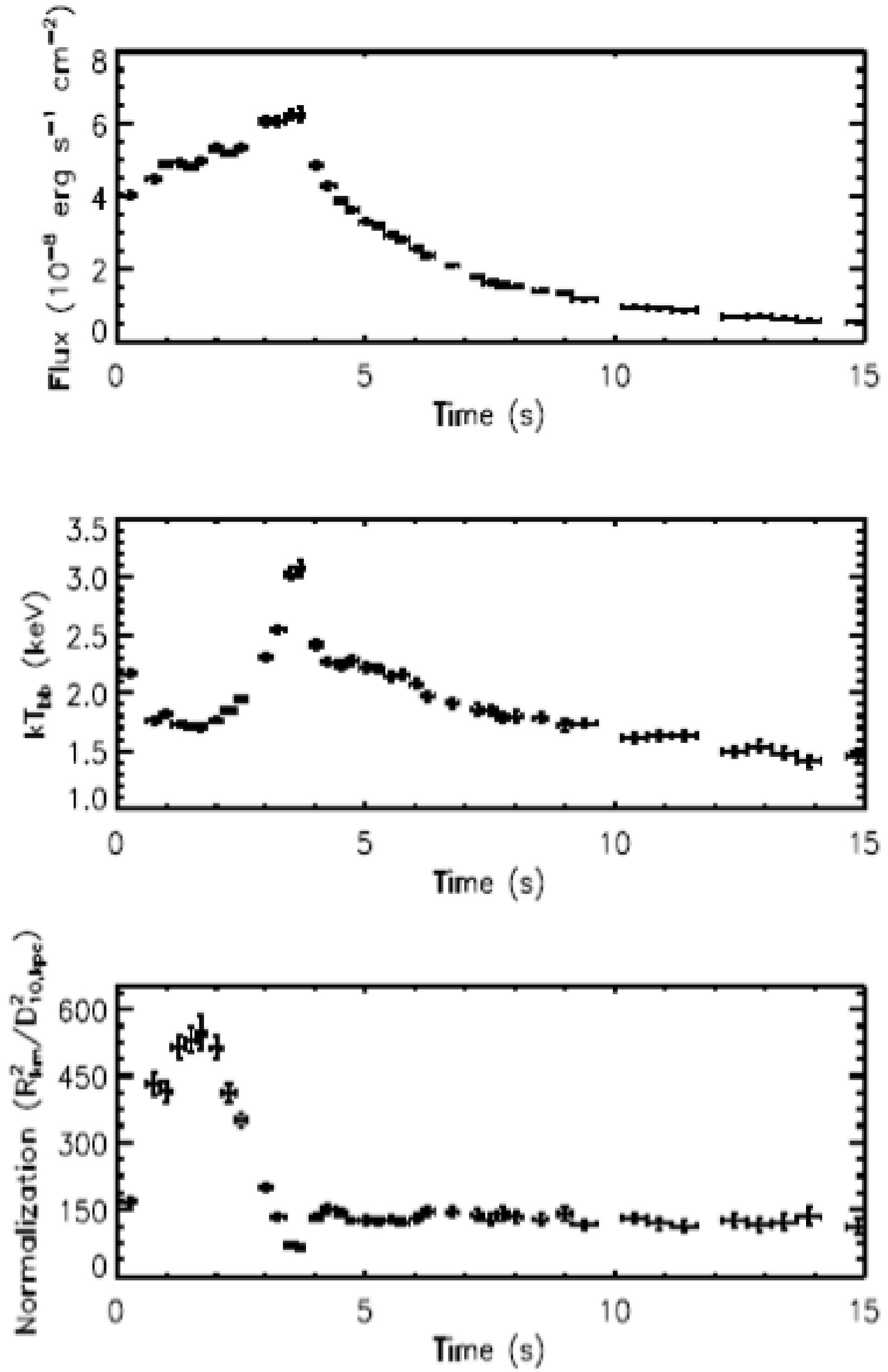
$$F_{TD} = \frac{GMc}{\kappa D^2}\sqrt{1-2\beta(r_{ph})}$$

- Normalization during the tail of the burst:

$$A \equiv \frac{F_\infty}{\sigma T^4_{bb,\infty}} = f_c^{-4}\left(\frac{R}{D}\right)^2 (1-2\beta)^{-1}$$

- If we have the distance, two constraints for mass and radius
- Dimensionless parameter

$$\alpha \equiv \frac{F_{TD}\kappa D}{\sqrt{A}\, c^3 f_c^2}$$



Ozel et al. (2010)

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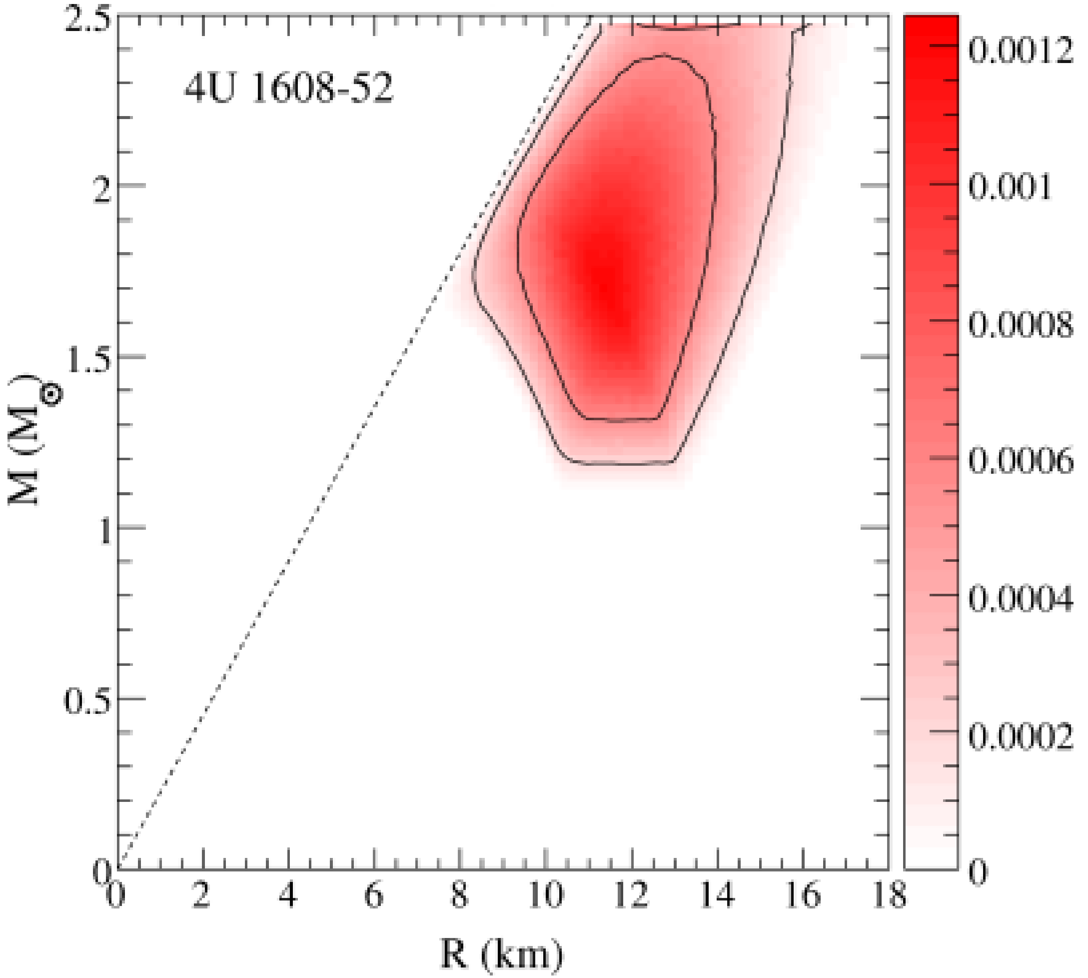


Steiner et al. (2010)

Statistical Approach

- Well-suited to this underconstrained problem: 7-8 EOS parameters, 7-8 data points

- Bayes theorem:

$$P[\mathcal{M}_i|D] = \frac{P[D|\mathcal{M}_i]P[M_i]}{\sum_j P[D|\mathcal{M}_j]P[\mathcal{M}_j]}$$

- Different prior distributions produce different results

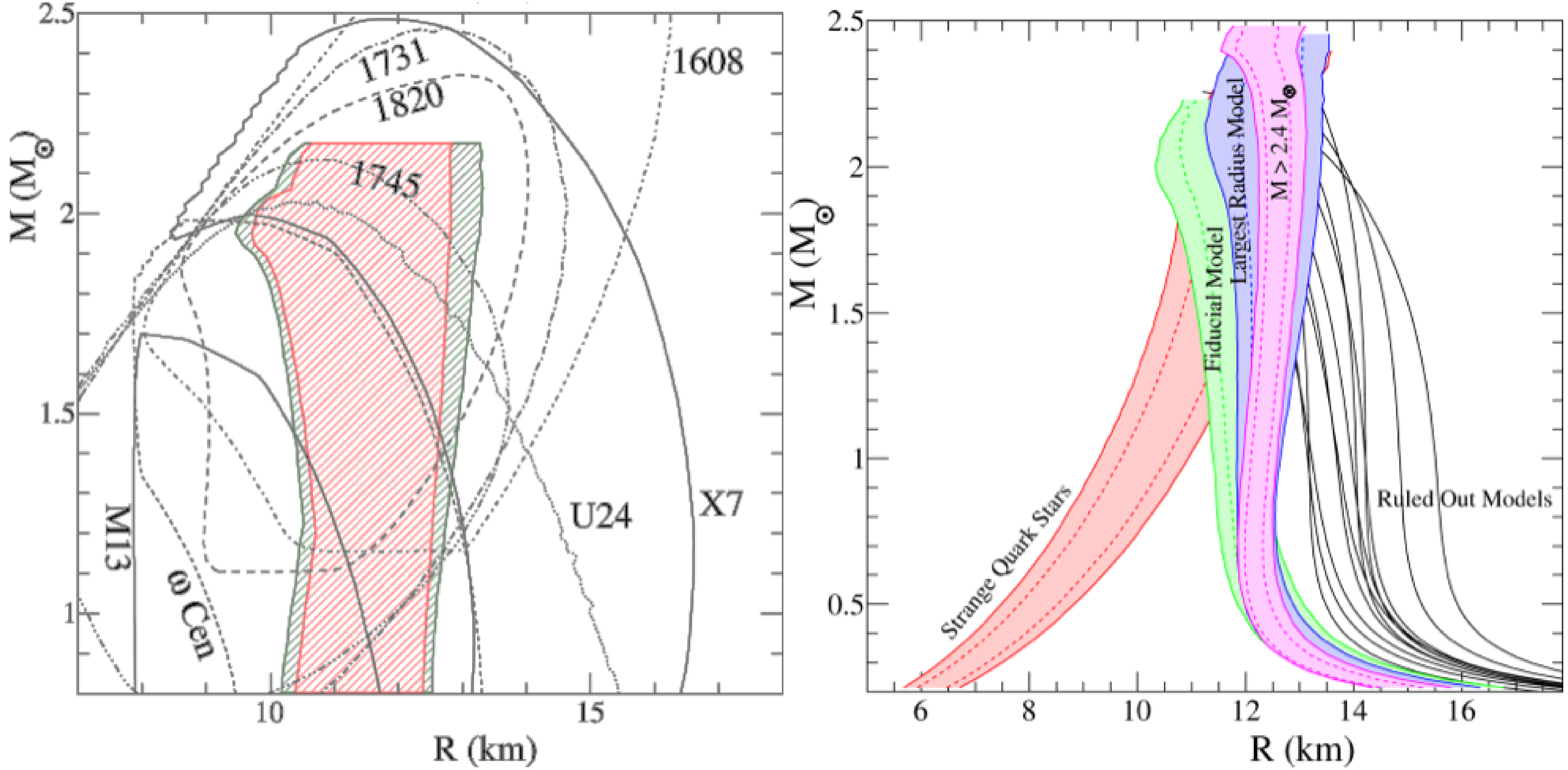
- Conditional probability is provided by the data

$$P[D|\mathcal{M}] = \prod_{i \in n_{\rm datasets}} \mathcal{D}_i(M,R)|_{M=M_i,R=R(M_i)}$$

  the analog of the likelihood function
- In Bayesian analysis, marginal estimation is often employed:

$$P[p_j|D](p_j) = \frac{1}{V}\int dp_1 \, \ldots \, dp_{j-1} \, dp_{j+1} \, \ldots \, dp_{N(p)} P[M|D]$$

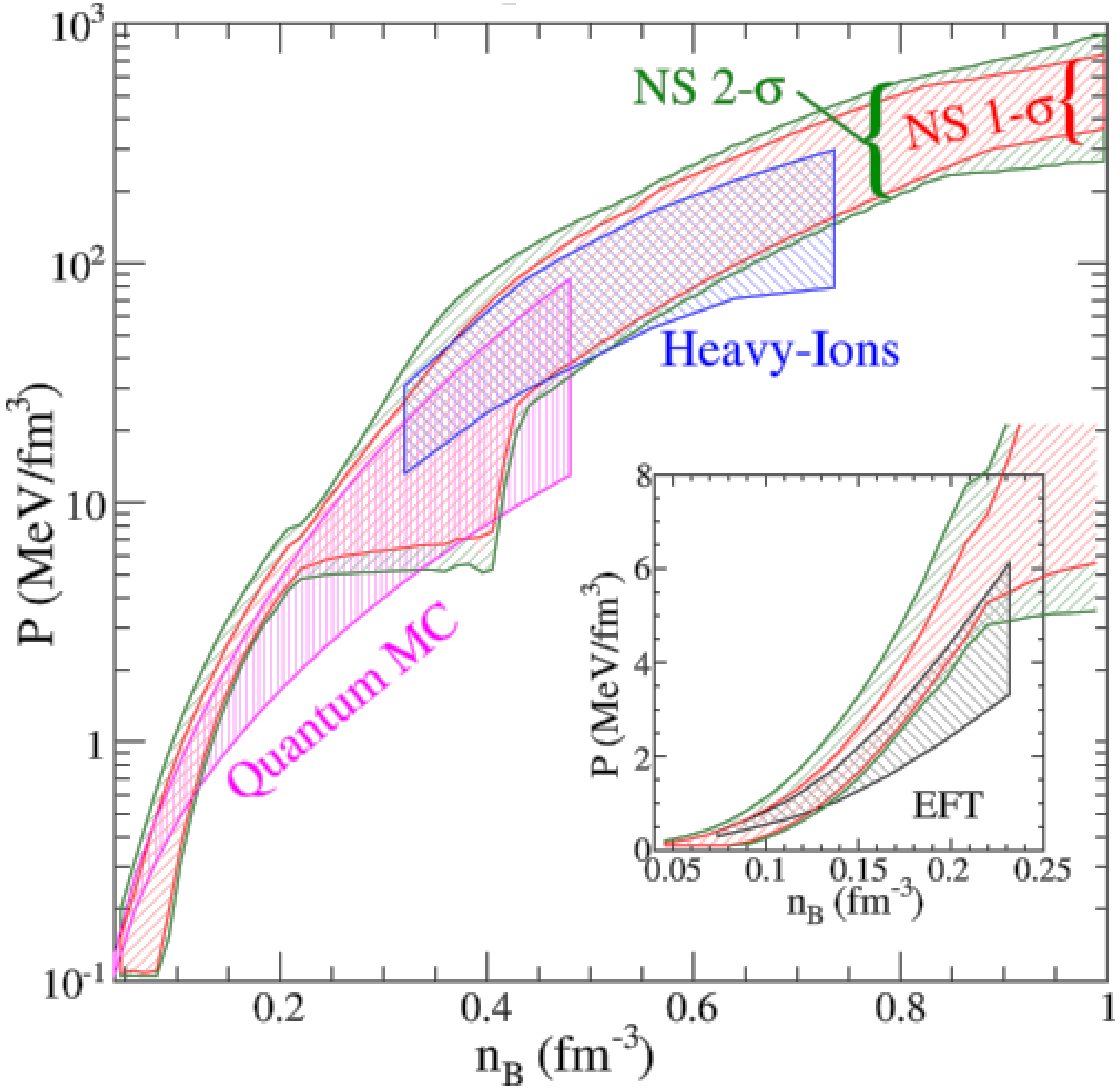
Mass and Radius Results



Steiner, Lattimer, and Brown, in prep.

- Choose the largest range which encloses several choices in model assumptions and prior distributions
- Range of radii for a 1.4 solar mass star: 10.4 and 12.9 km

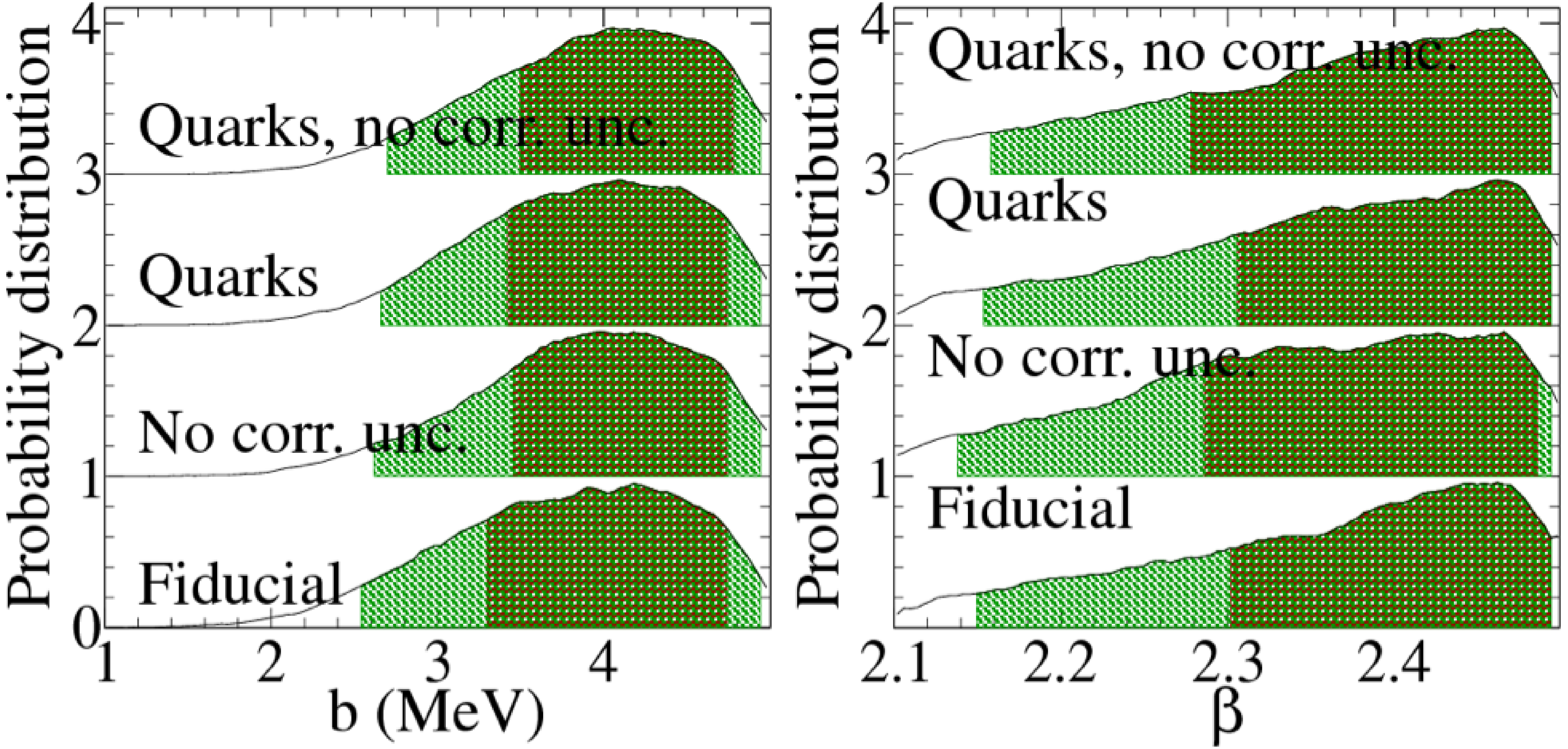
EOS results



Steiner, Lattimer, and Brown, in prep.

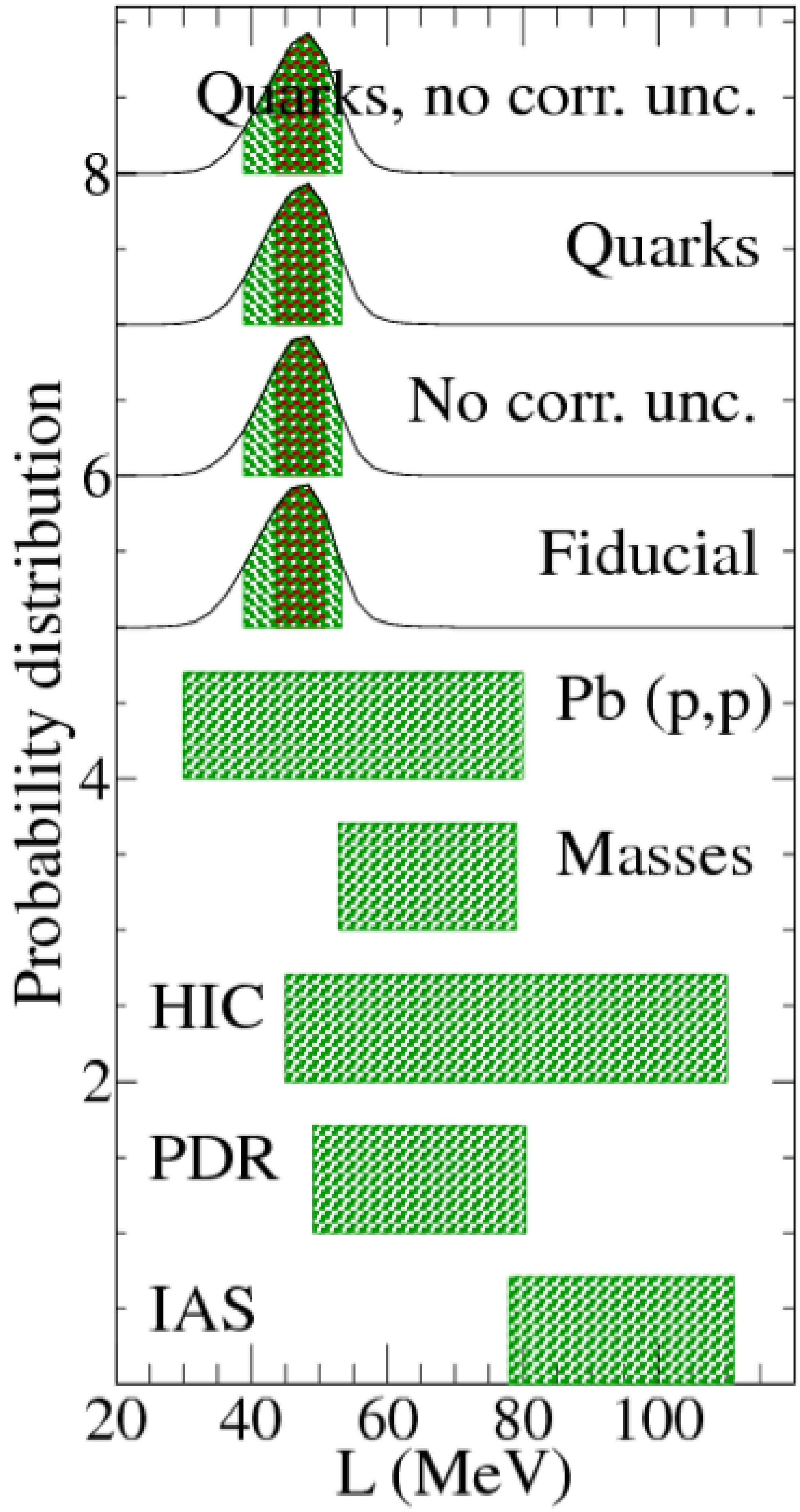
- $P(\varepsilon)$ determined to within 30-50%
- $P(n_B)$ determined to within a factor of 3
- Neutron skin thickness of lead $\delta R < 0.20$ fm

Constraints on three-body force parameters



Steiner and Gandolfi (2012)

- Values of a and α are unconstrained, but constraints on b and β
- This means that neutron star radii are constraining nuclear three-body forces



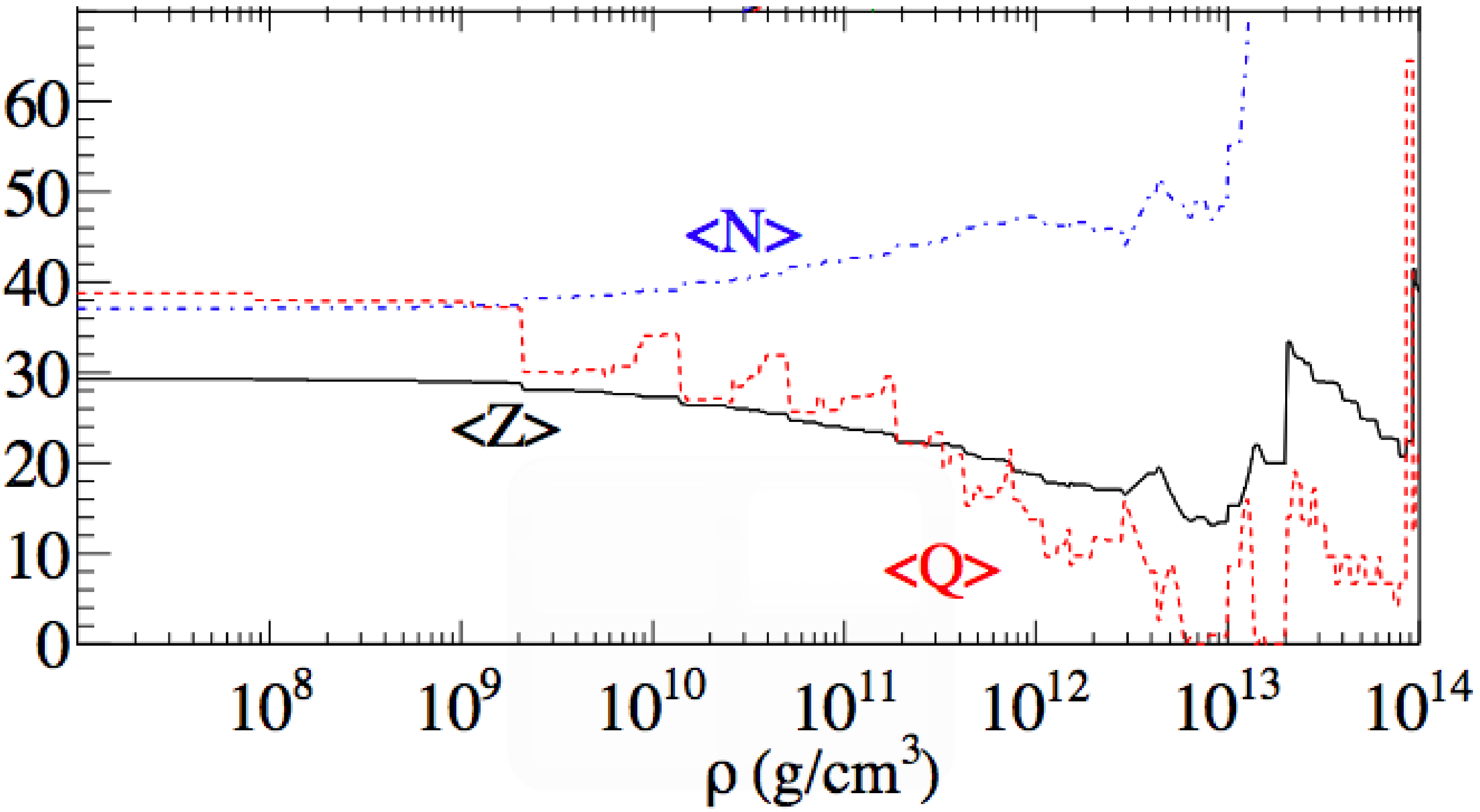
Steiner and Gandolfi (2012)

Symmetry Energy Results

- Strong constraints on the derivative of the symmetry energy
- Almost no constraint on S

Accreted Neutron Star Crusts

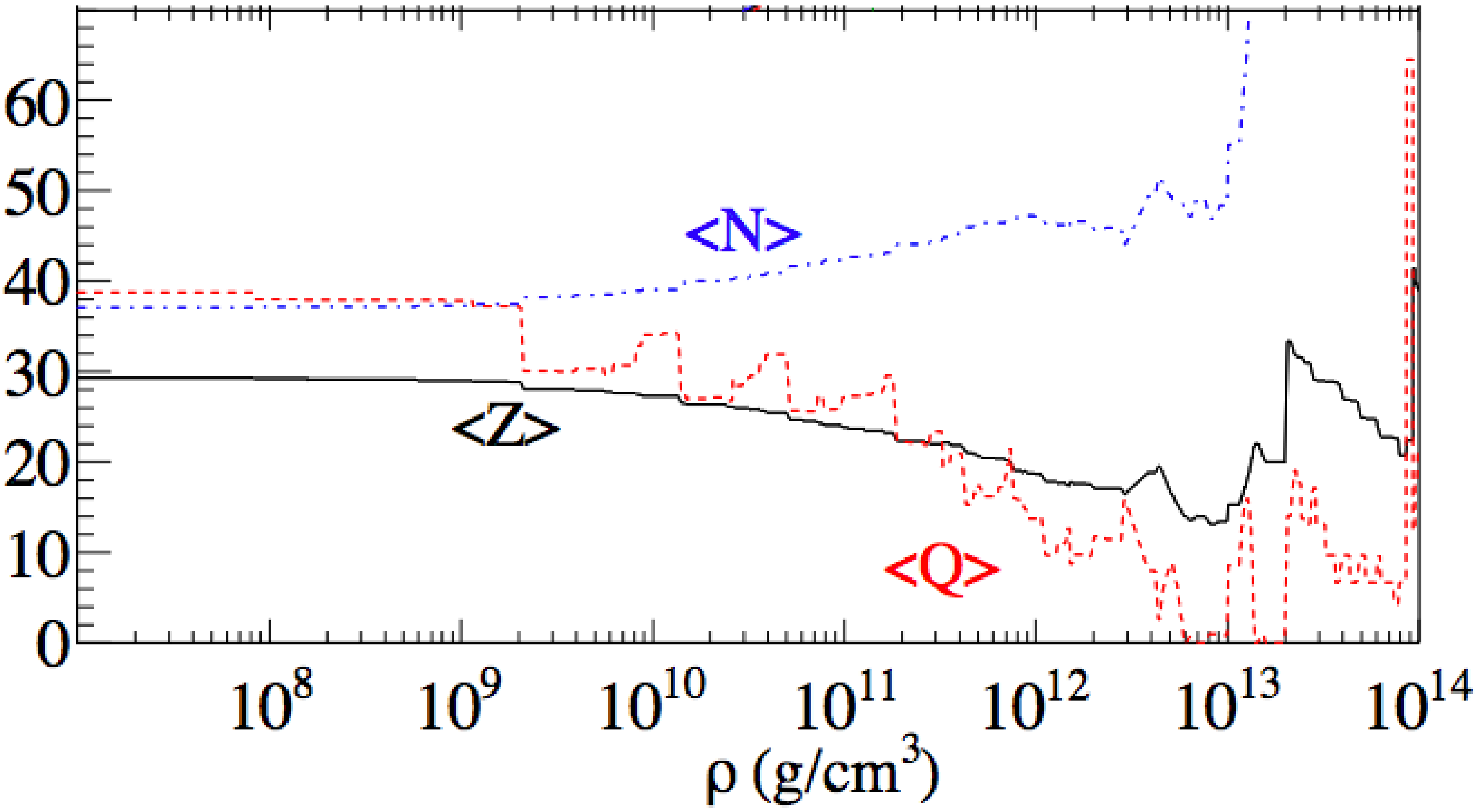
- In a cold neutron star, surface is usually taken to be ~ ^{56}Fe
- Nuclei become larger and more neutron rich with increasing density
- Accretion luminosity (~ 200 MeV) outshines nuclear processes
- H and He is accreted and becomes unstable - X-ray burst
- X-ray burst ashes undergo nuclear reactions as they are driven towards higher densities: deep crustal heating



Steiner (2012)

Nuclear Reactions and a Multicomponent model

- Electron captures, neutron emissions, and pycnonuclear fusions
- Electron capture is often immediately followed by neutron emission
- Steiner (2012) is the first multi-component model of the accreted crust
- 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
- 2 ^{40}Mg nuclei - 2 ^{22}C nuclei and 36 neutrons -
  1 ^{44}Mg nucleus and 36 neutrons - 1 ^{44}Mg nucleus and 40 neutrons



Steiner (2012)

Symmetry Energy and Deep Crustal Heating

- Nuclear symmetry energy is important in determining the amount of deep crustal heating!
- Nuclear masses of neutron rich nuclei are determined by the symmetry energy
- Use a liquid droplet model matches experimental masses within 1.2 MeV yet based on nucleon-nucleon interactions with different symmetry energies
- Skyrme models SLy4 and Gs
- 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

Summary

- *Current* mass and radius measurements, modulo some systematic uncertainties, can *quantitatively* constrain the equation of state
- Several currently used EOSs are ruled out
- Current results imply all neutron stars have radii between 10.4 and 12.9 km
- That the neutron skin thickness of lead is less than 0.2 fm and that L is 45-55 MeV
- Symmetry energy can also affect the amount of heating in accreting neutron star crusts

Other Things to Ask Me About

- How the Carbon fusion rate can be modified to explain X-ray superbursts on accreting neutron stars
- How Bayesian MCMC can be applied to fitting nuclear structure data
- How magnetars (highly magnetized neutron stars) are giving us more information about neutron star crusts