The EOS of Dense Matter and Symmetry Energy from Neutron Star Mass and Radius Observations

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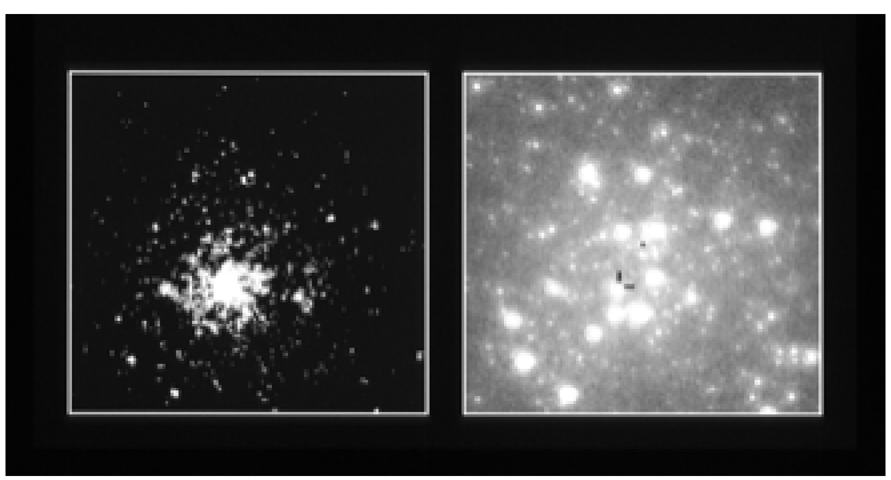

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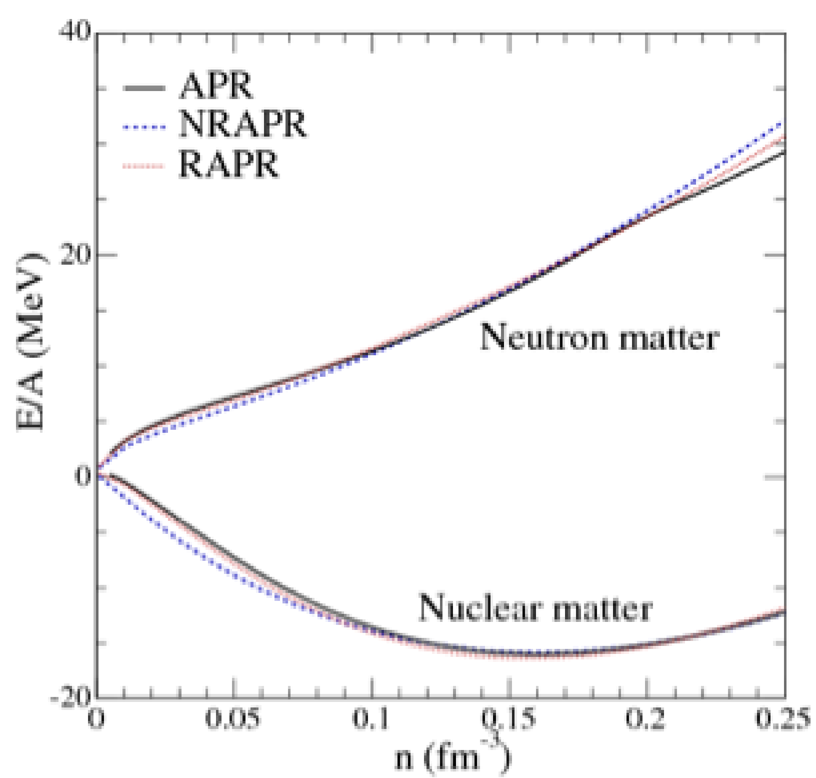
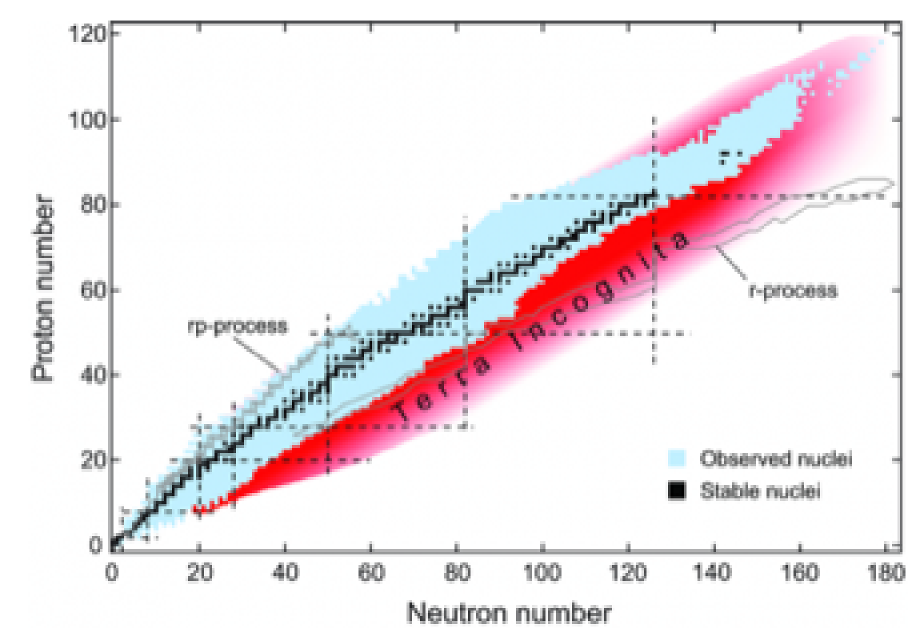




The Physics is in the Data

- How much do neutron star mass and radius measurements tell us neutron star radii?
- How much do neutron star mass and radius measurements tell us about the EOS at large densities? At saturation densities?
- How tightly coupled is the behavior of the EOS at saturation densities to the EOS at higher densities?
- How can we answer these questions, and how can we remove as much of the model dependence as is reasonable?
- The strongest constraints come from quiescent LMXBs with smaller radii.

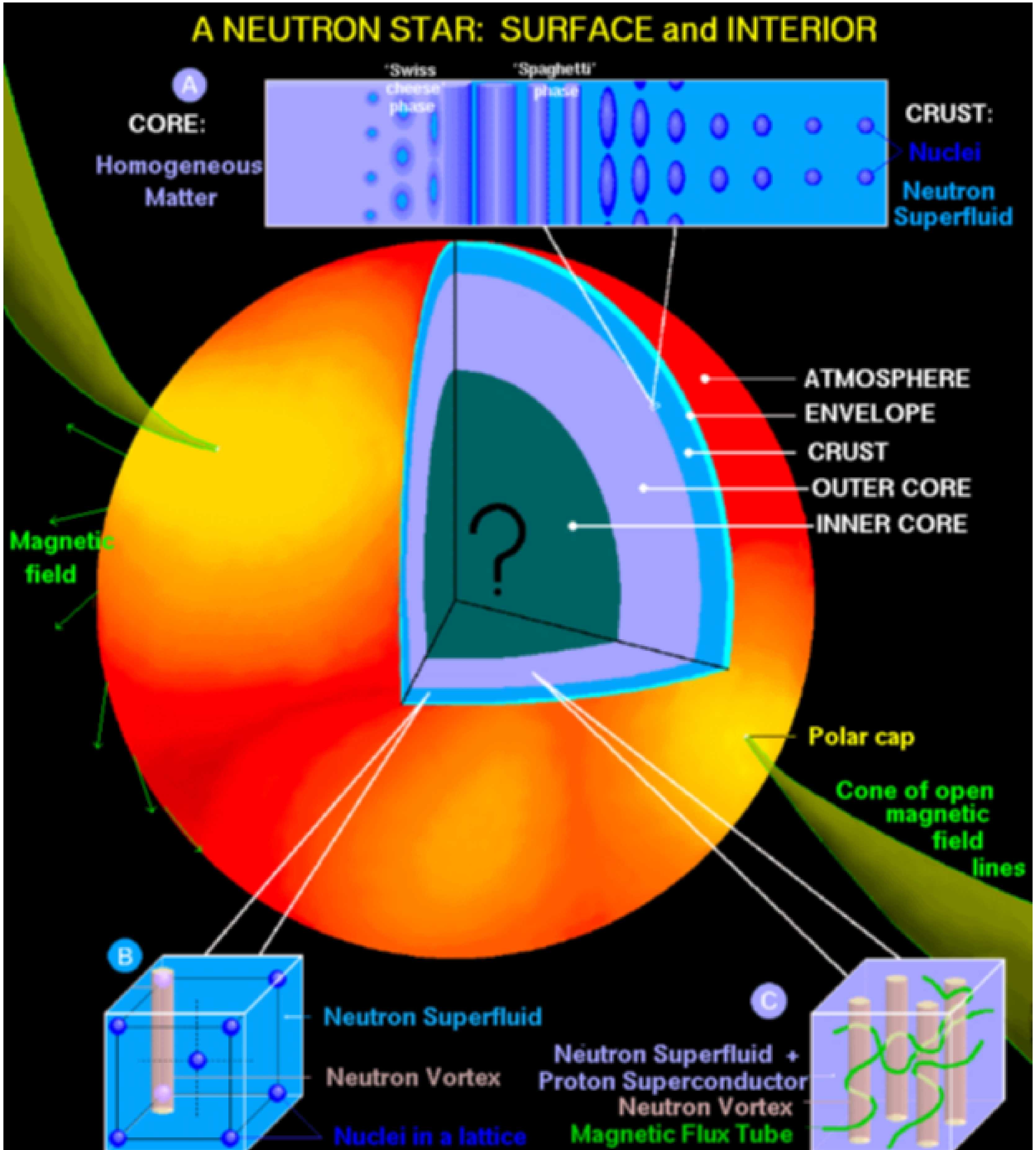


Figure by Dany Page

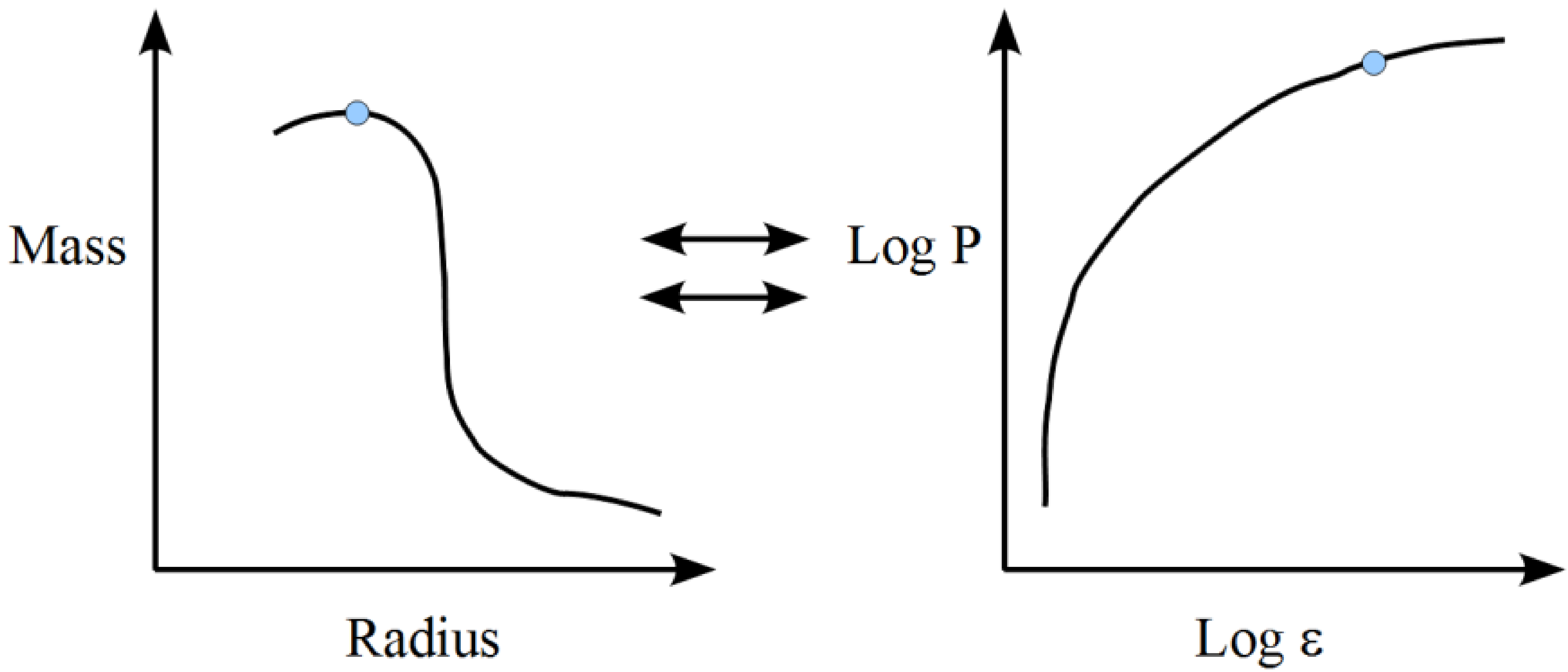
Neutron Star Composition

- Crust is a lattice of neutron-rich nuclei, a ten percent correction to radius
- Outer core is homogeneous nucleonic matter
- Inner core may contain phase transitions:

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

- Current observations are insufficient to deduce the composition of the core, but neutron star cooling may help

M vs. R and the EOS of Dense Matter



- M-R curve is (to a good approximation) universal: *all neutron stars lie on the same M-R curve*

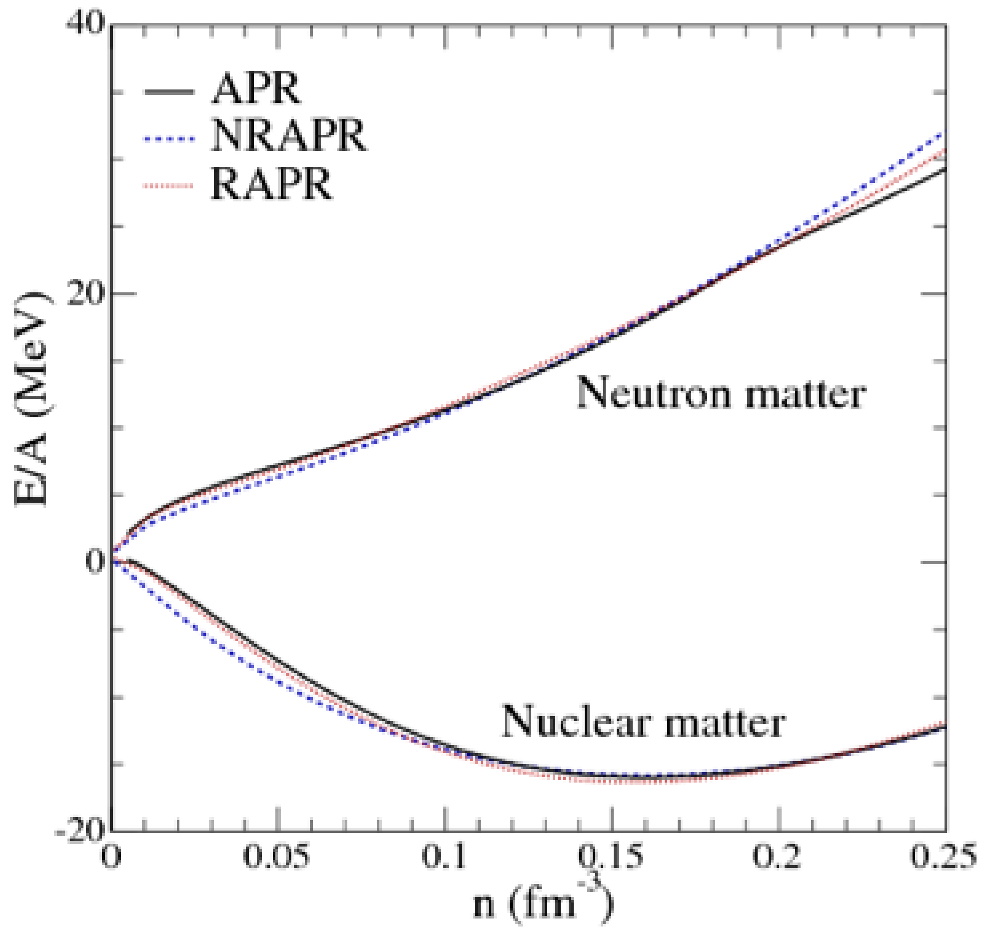
$$\frac{dP}{dr} = -\frac{G\varepsilon(P)m}{r^2}\left[1+\frac{P}{\varepsilon(P)}\right]\left[1+\frac{4\pi P r^3}{m}\right]\left[1-\frac{2Gm}{r}\right]^{-1}$$

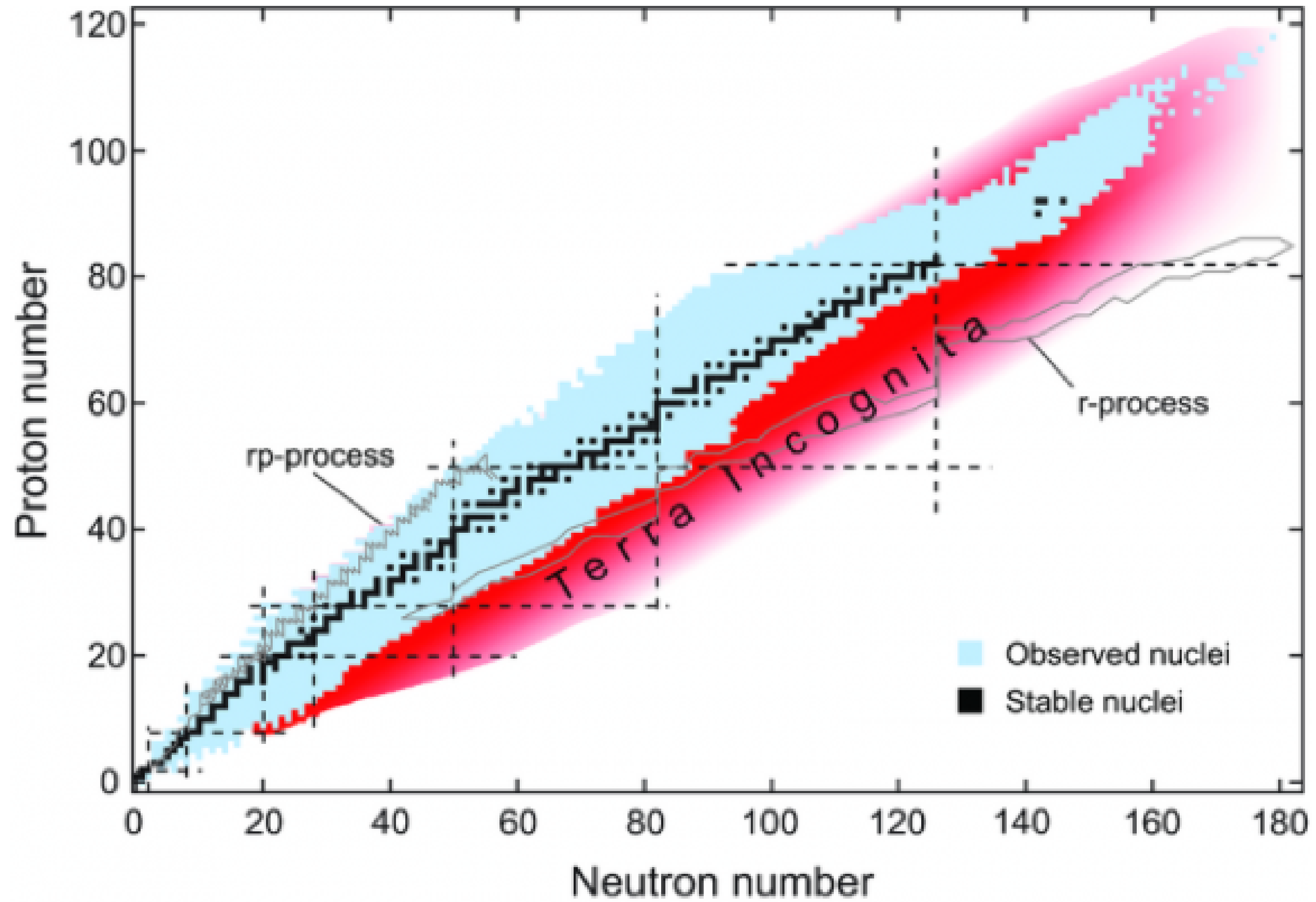
- Corrections from magnetic fields and rotation

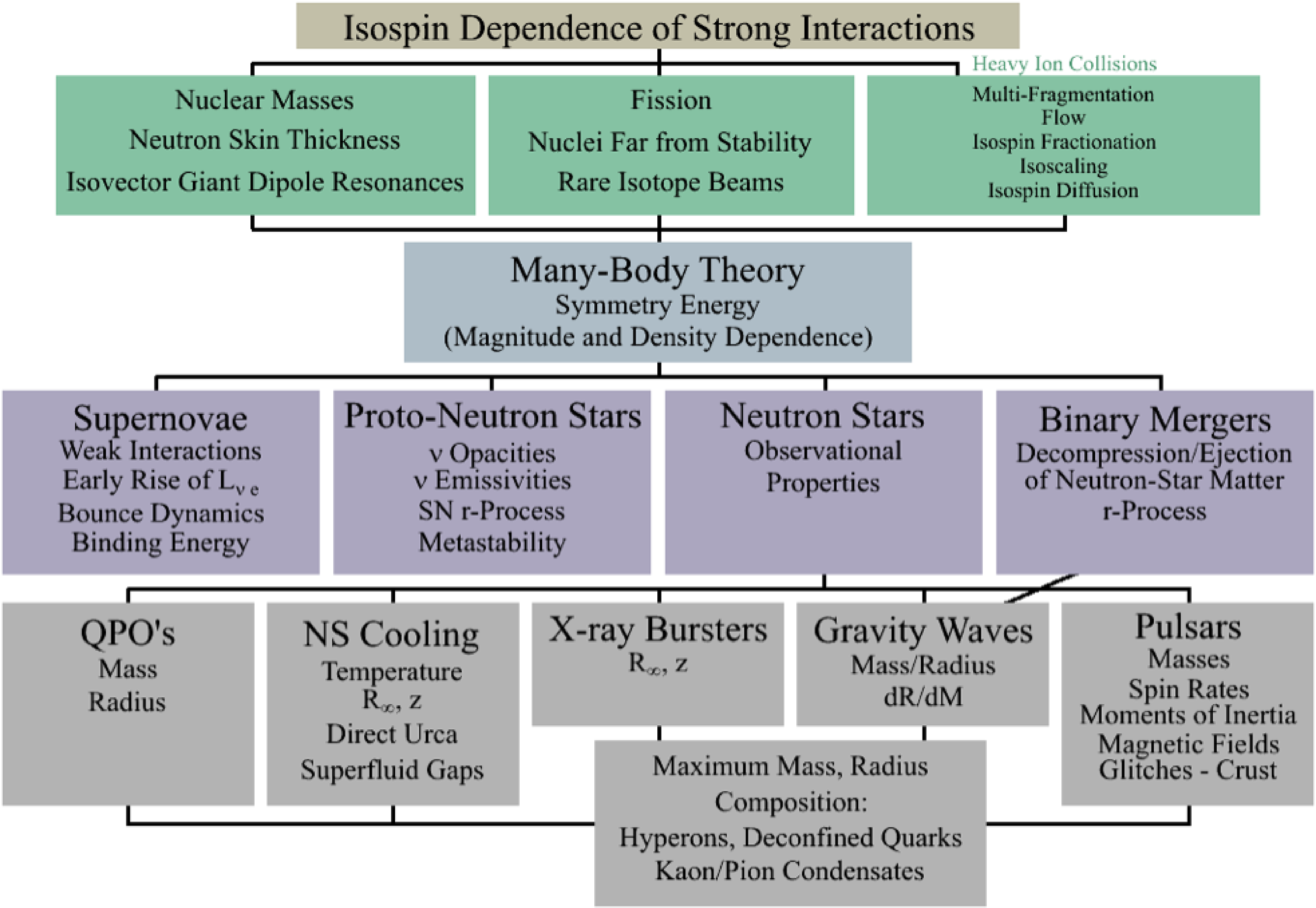
- As of a few years ago, radius of a 1.4 solar mass neutron star was between 8 and 16 km

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, $L = 3n_0 S'(n_0)$

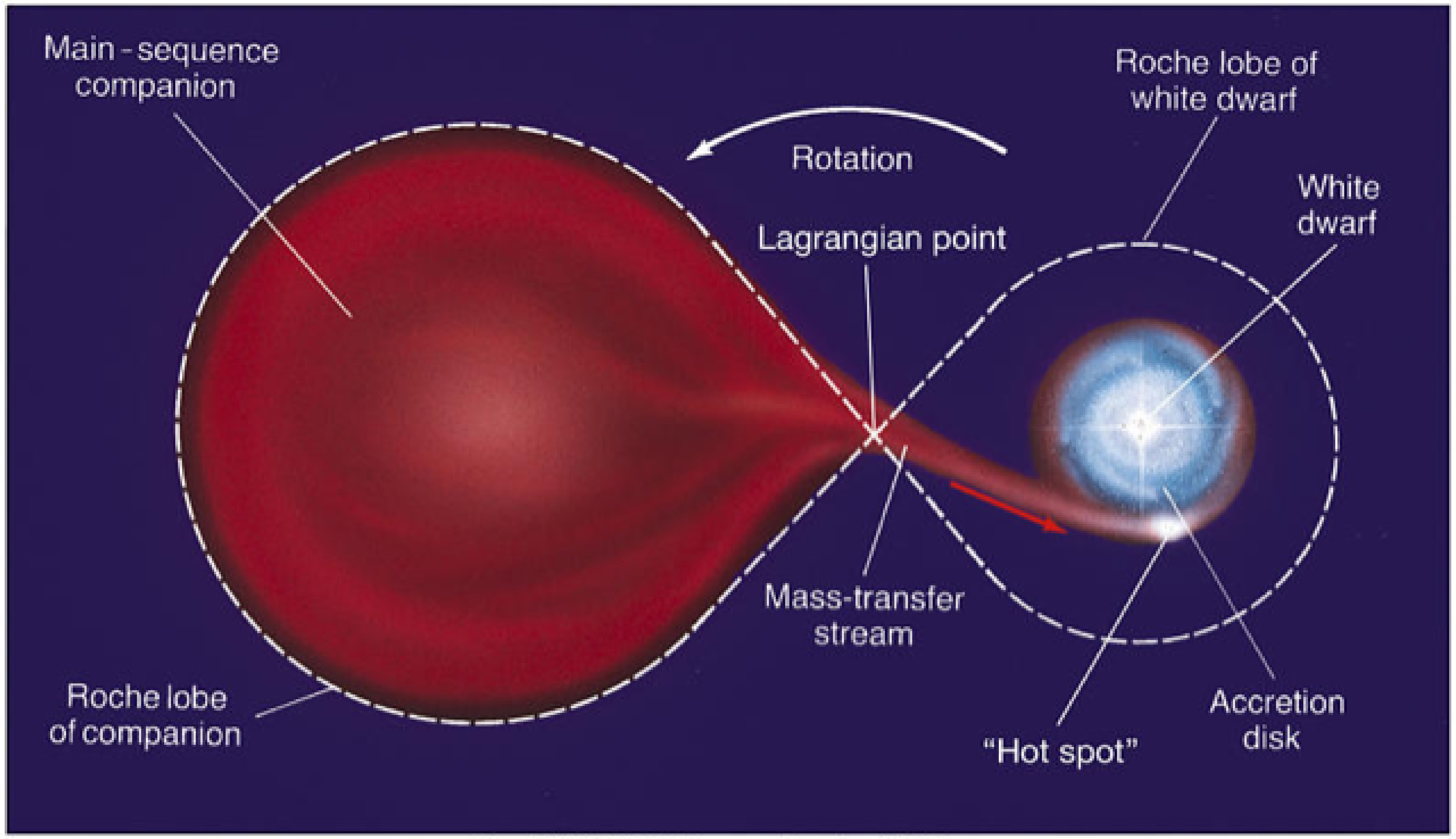


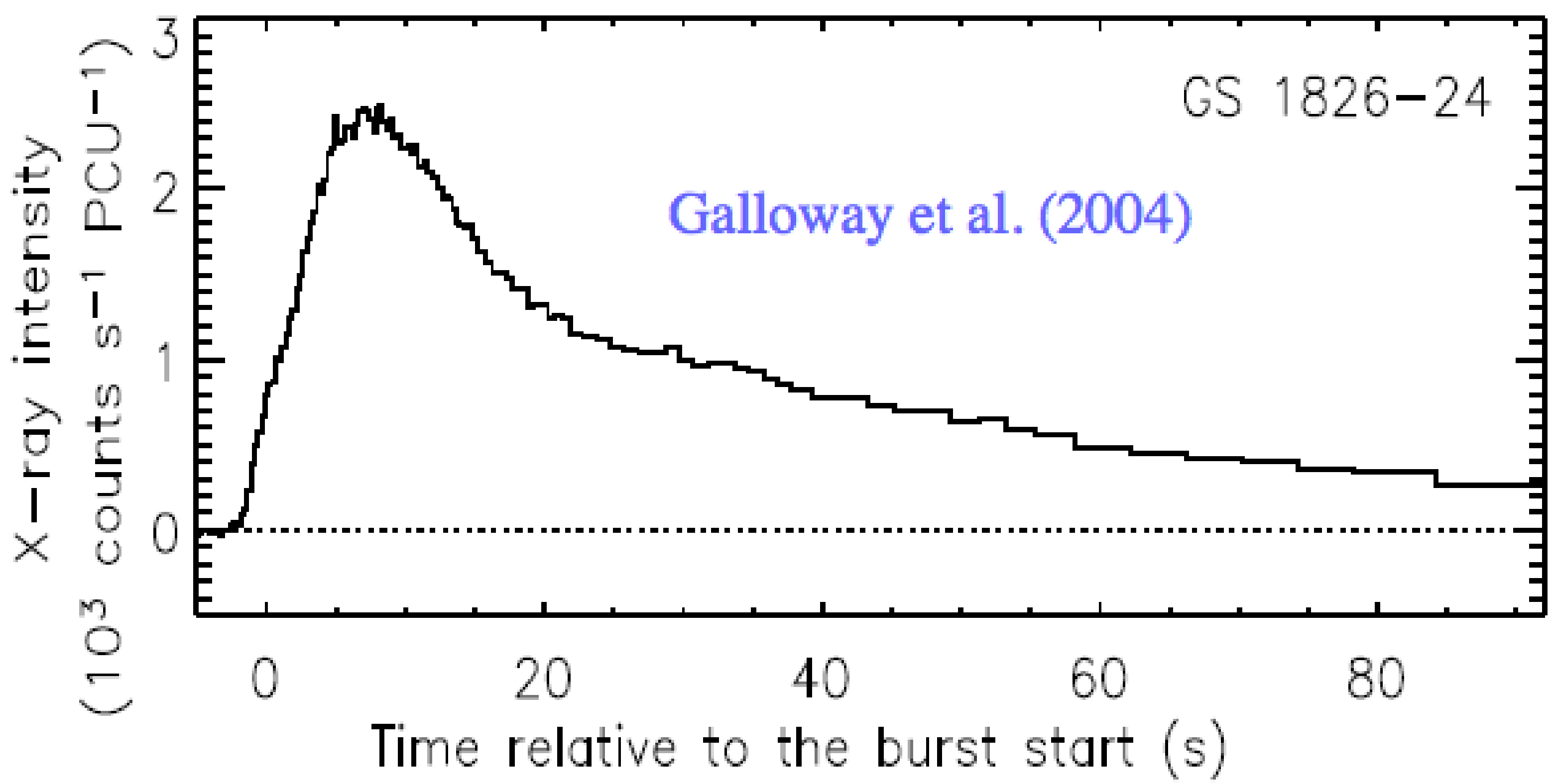




Steiner, et al. (2005)

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
- Accretion luminosity dominates over emission from the NS surface
- At high enough density, light elements are unstable to thermonuclear explosions

Mass Measurements and QLMXBs

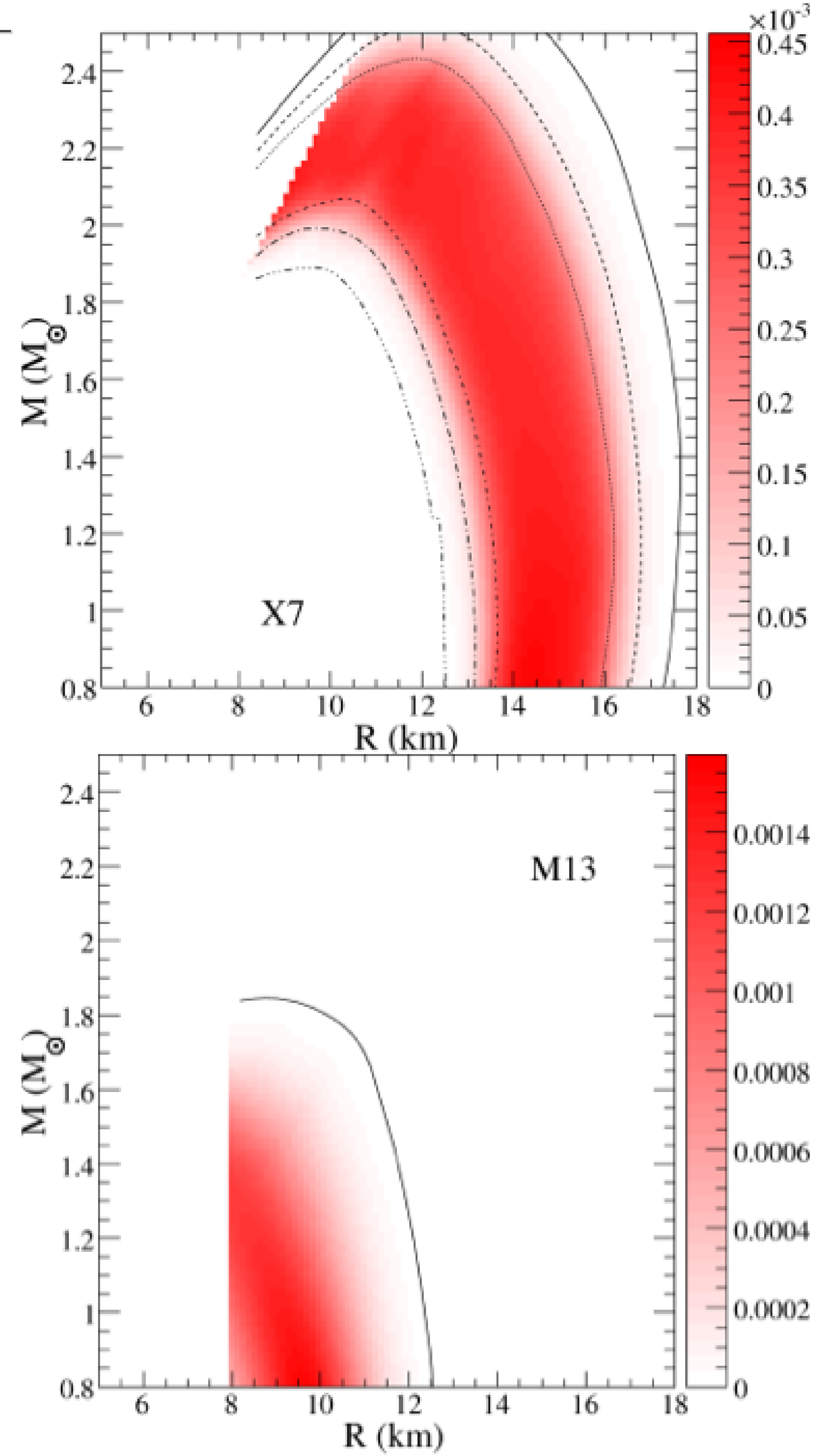
- *Quiescent LMXBs in globular clusters:*
  - H atmosphere
  - Known distance
  - Small magnetic field
  - Measure radius:

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

[Rutledge et al. (1999), Heinke et al. 2006, Webb and Barrett (2007), Guillot et al. (2010)]

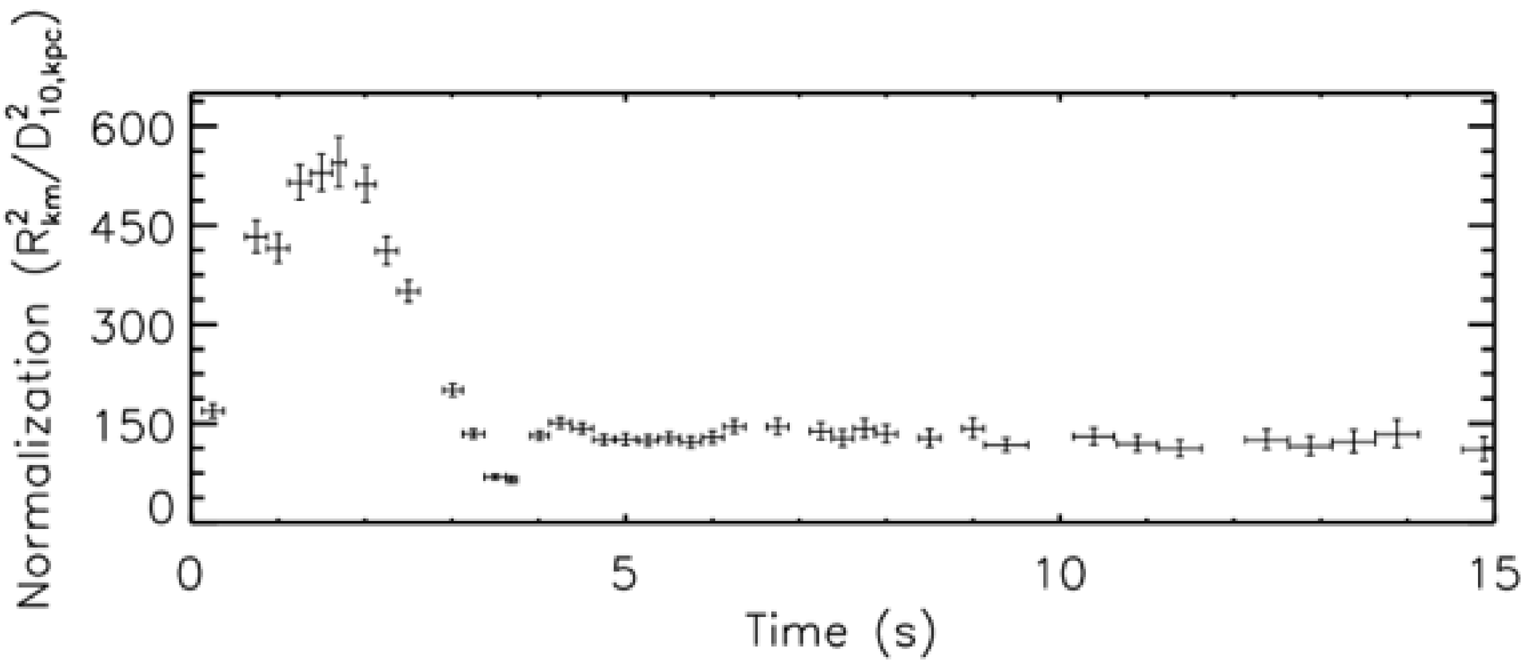
- More than one temperature?
  - No evidence for pulsations

- Accretion?
  - Power law is typically a small fraction of thermal component



Steiner et al. (2010)

Photospheric Radius Expansion Bursts



Ozel et al. (2010)

- 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:

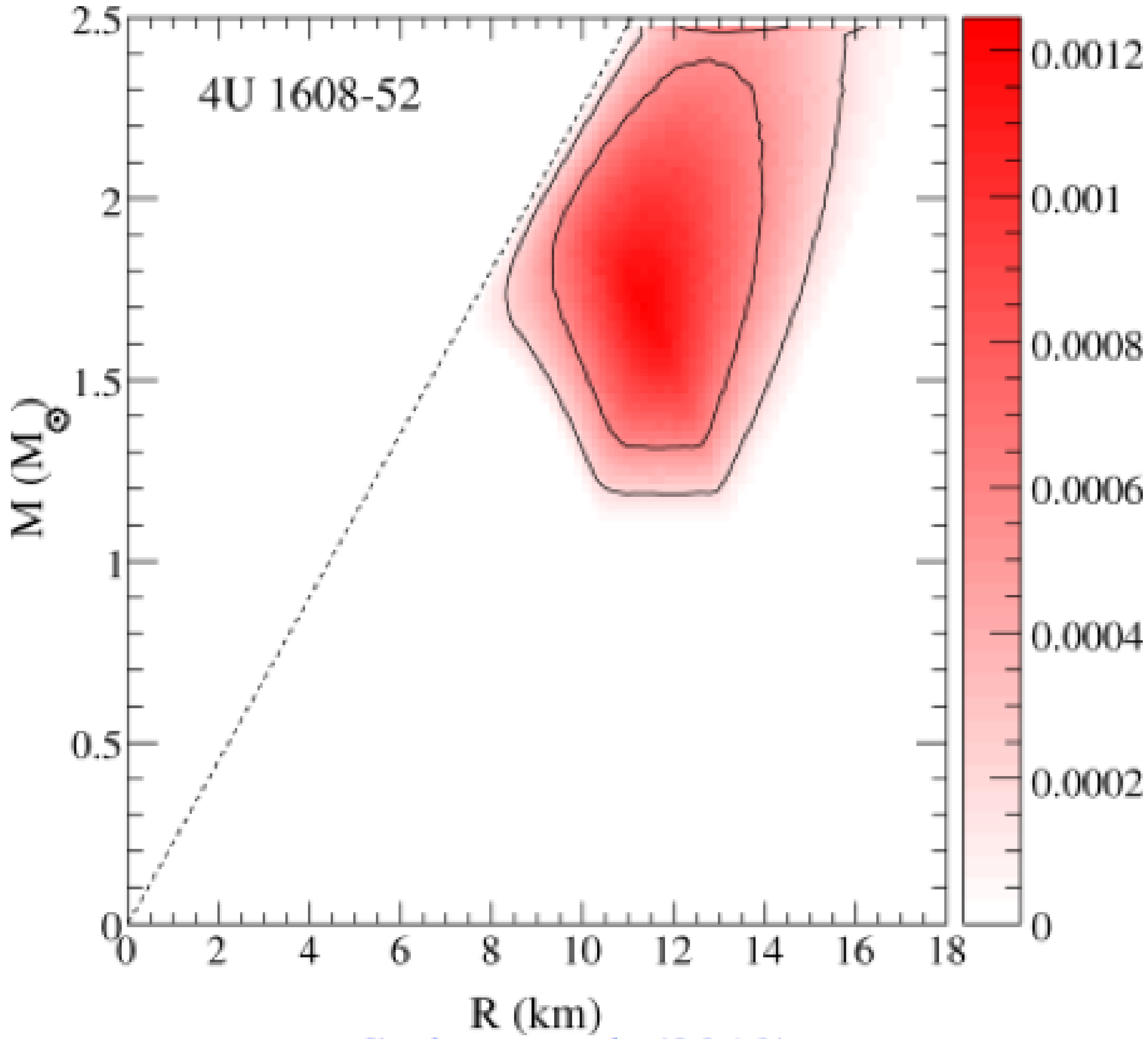
$$A \equiv \frac{F_\infty}{\sigma T^4_{bb,\infty}} = f_c^{-4}\left(\frac{R}{D}\right)^2 (1-2\beta)^{-1}$$

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

Photospheric Radius Expansion Bursts II

- Four objects in total
- Serious systematic uncertainties, we'll try to respect them
  - Color correction factors
  - Radius of the photophere
  - Spectrum at touchdown
  - Accretion
- Dimensionless parameter

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



Steiner et al. (2010)

Statistical Approach

- Bayes theorem:

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

- Well-suited to this underconstrained problem

- Conditional probability is provided by the data

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

- In Bayesian analysis, marginal estimation is often employed:

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

- Different EOS parameterization is degenerate with different prior distribution

- Choosing only one parameterization does not lead to a model-independent result

EOS parameterization (low density)

- Schematic EOS near the saturation density:

$$E = m_n n_n + m_p n_p + B + \frac{K}{18 n_0^2}(n - n_0)^2 + \frac{K'}{162 n_0^3}(n - n_0)^3 +$$

$$(1-2x)^2 \left[S_k \left(\frac{n}{n_0} \right)^{2/3} + S_p \left(\frac{n}{n_0} \right)^{\gamma} \right]$$

- γ plays the role of L

- Correlation between S and L

EOS parameterizations (high density)

- High density

$$P(\varepsilon) = K\varepsilon^{\Gamma} \text{ with } \Gamma \equiv 1 + \frac{1}{n}$$

High-density parameters:

$$n_1, n_2, \varepsilon_1 \text{ and } \varepsilon_2 \quad \text{or} \quad \Gamma_1, \Gamma_2, \varepsilon_1 \text{ and } \varepsilon_2$$

or

$$P\left(400\ \mathrm{MeV}/\mathrm{fm}^3\right),\ P(600),\ P(1000),\ P(1400)$$

- The second parameterization tends to have stronger phase transitions
- Quark matter

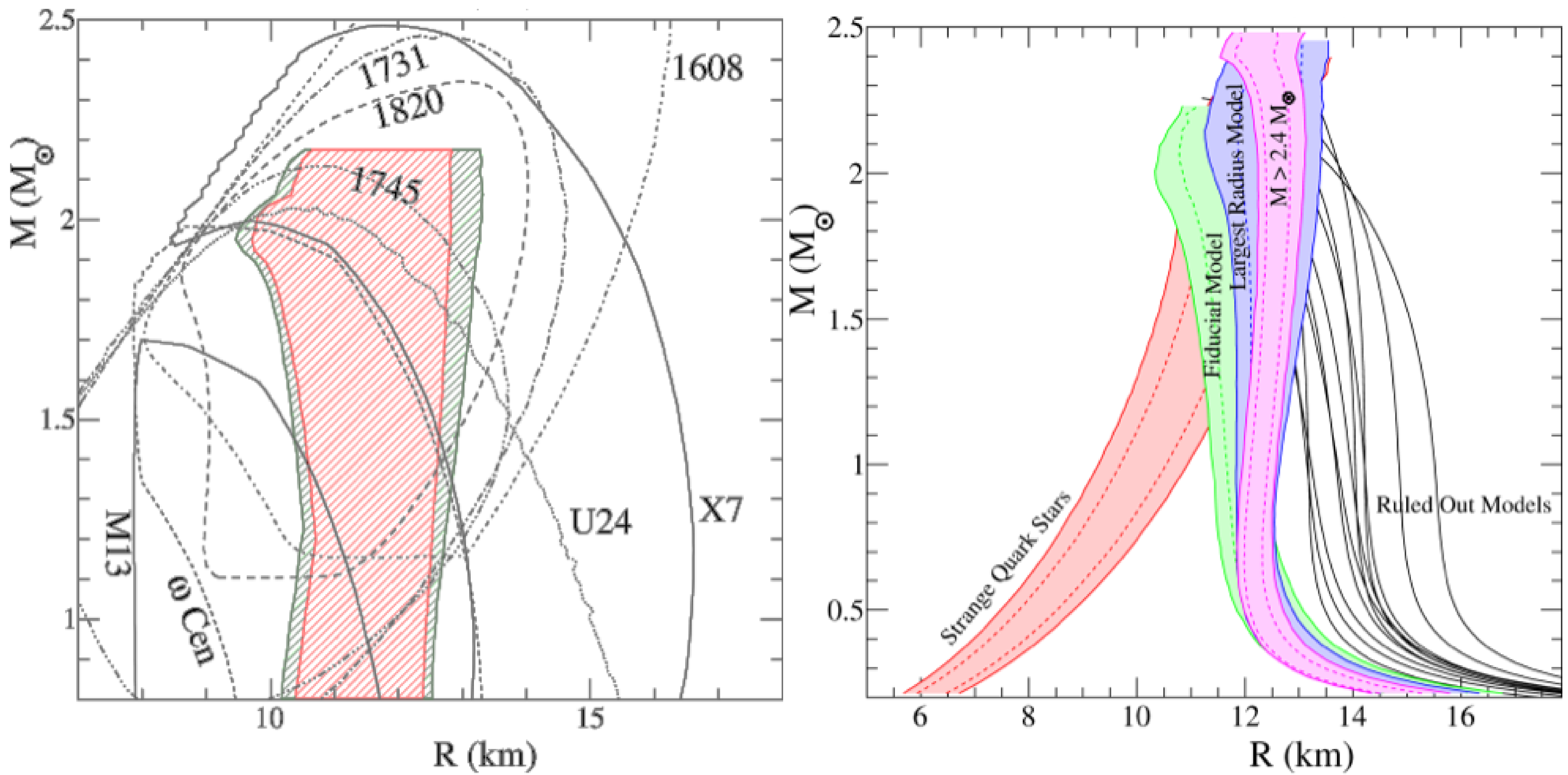
$$P = \frac{3(1-c)}{4\pi^2}\mu^4 - \frac{3\left(m_s^2 - 4\Delta^2\right)}{4\pi^2}\mu^2 - B$$

- Mixed phase modeled by an additional polytrope
- Hybrid or "strange quark stars"

Limits on Radius of a 1.4 Solar Mass Neutron Star

Model	-2σ	-1σ	$+1\sigma$	$+2\sigma$
Indices	11.18	11.49	12.07	12.33
Exponents	11.23	11.53	12.17	12.45
Grid	10.63	10.88	11.45	11.83
Quarks	11.44	11.69	12.27	12.54
Redshifted photosphere	10.74	10.93	11.46	11.72
Without X7	10.87	11.19	11.81	12.13
Without M13	10.94	11.25	11.88	12.22
No PREs	11.23	11.56	12.23	12.49
$1.0 < f_C < 1.33$	10.42	10.58	11.09	11.61
$1.47 < f_C < 1.8$	11.82	12.07	12.62	12.89
For all models	10.42	10.58	12.62	12.89
More speculative models				
$1.0 < f_C < 1.33$, Grid	9.17	9.34	9.78	10.07
$M_{\rm max} \geq 2.4$	12.14	12.29	12.63	12.81
Strange quark stars	10.19	10.64	11.57	12.01
Long-bursts only	12.35	12.83	13.61	13.92

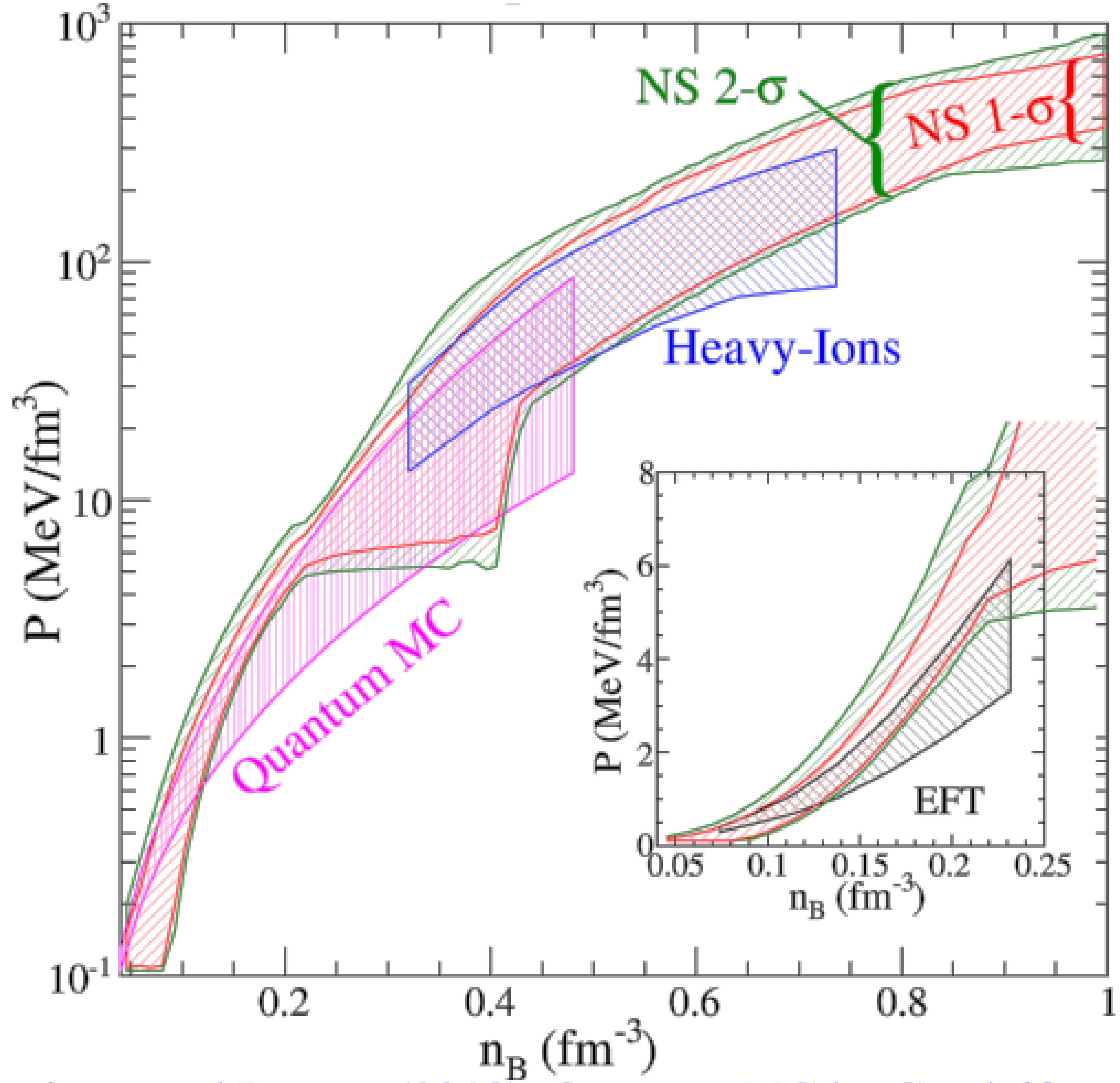
Mass and Radius Results



Steiner, Lattimer, and Brown (2012)

- Range of radii for a 1.4 solar mass star: 10.4 and 12.9 km
- 1/3 of Skyrme models ruled out

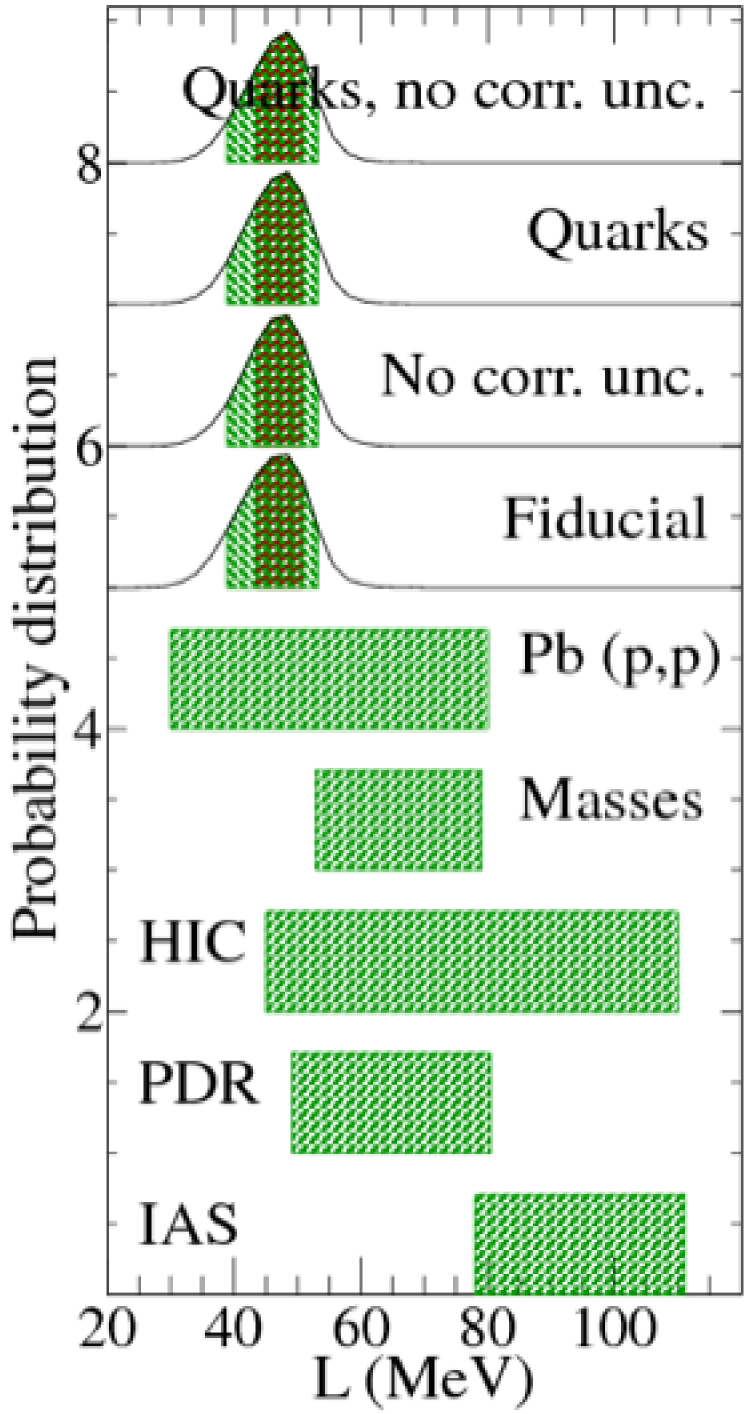
EOS results



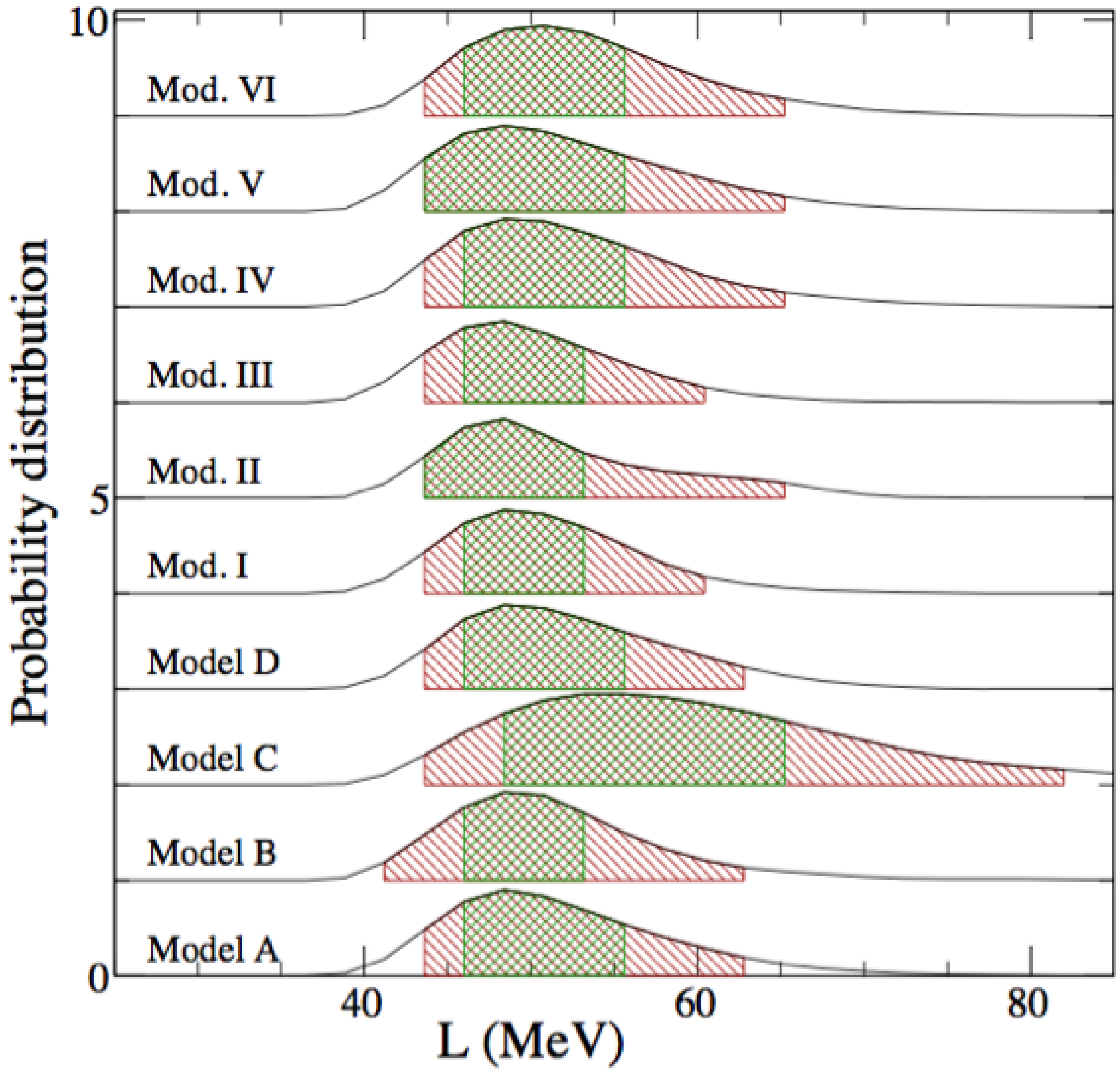
Steiner, Lattimer, and Brown, (2012); Quantum MC by Gandolfi et al. (2012), Heavy-Ions by Danielewicz et al. (2002), and EFT by Hebeler et al. (2010)

- $P(\varepsilon)$ 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

Symmetry Energy Results



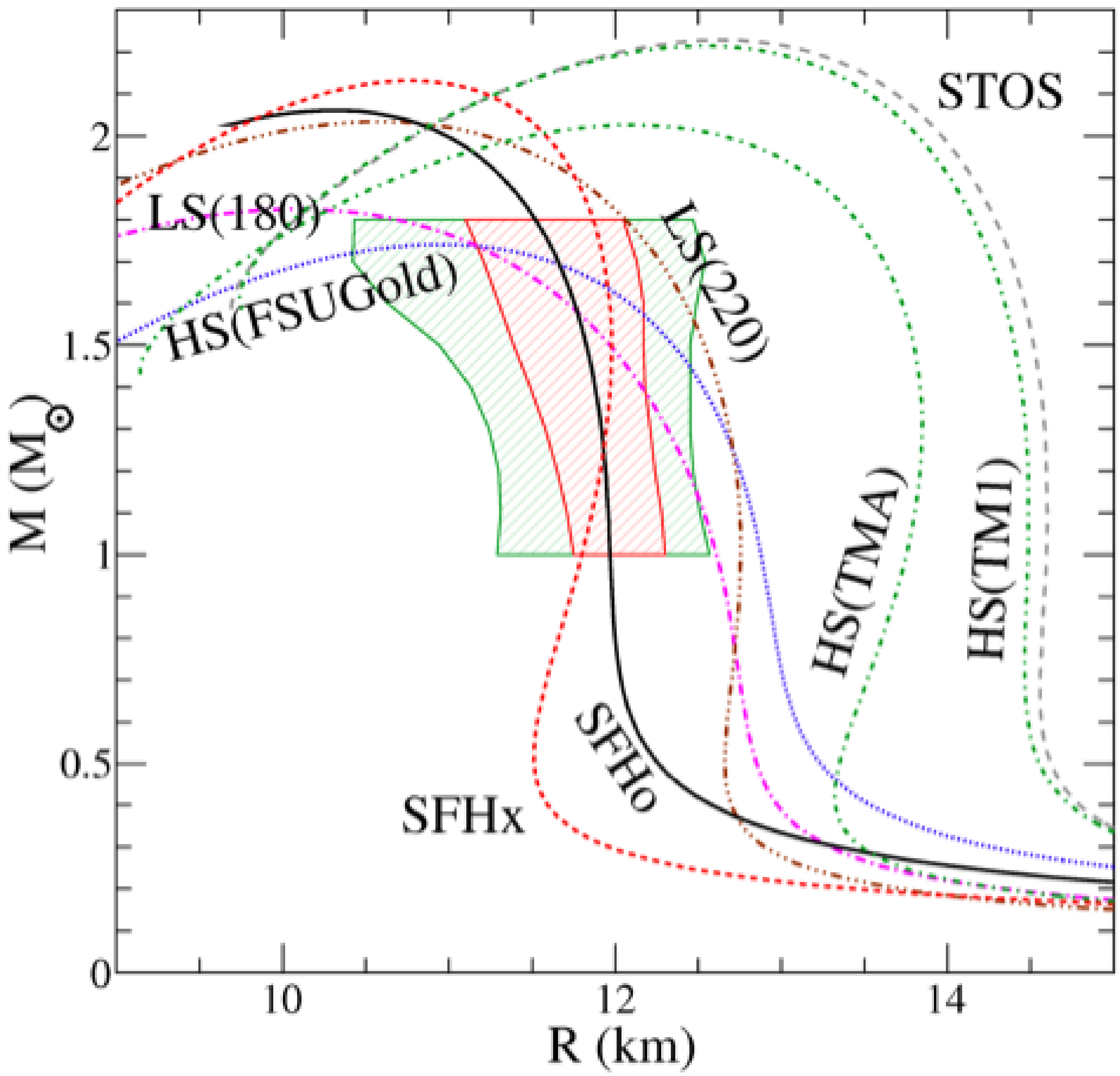
Steiner and Gandolfi (2012)

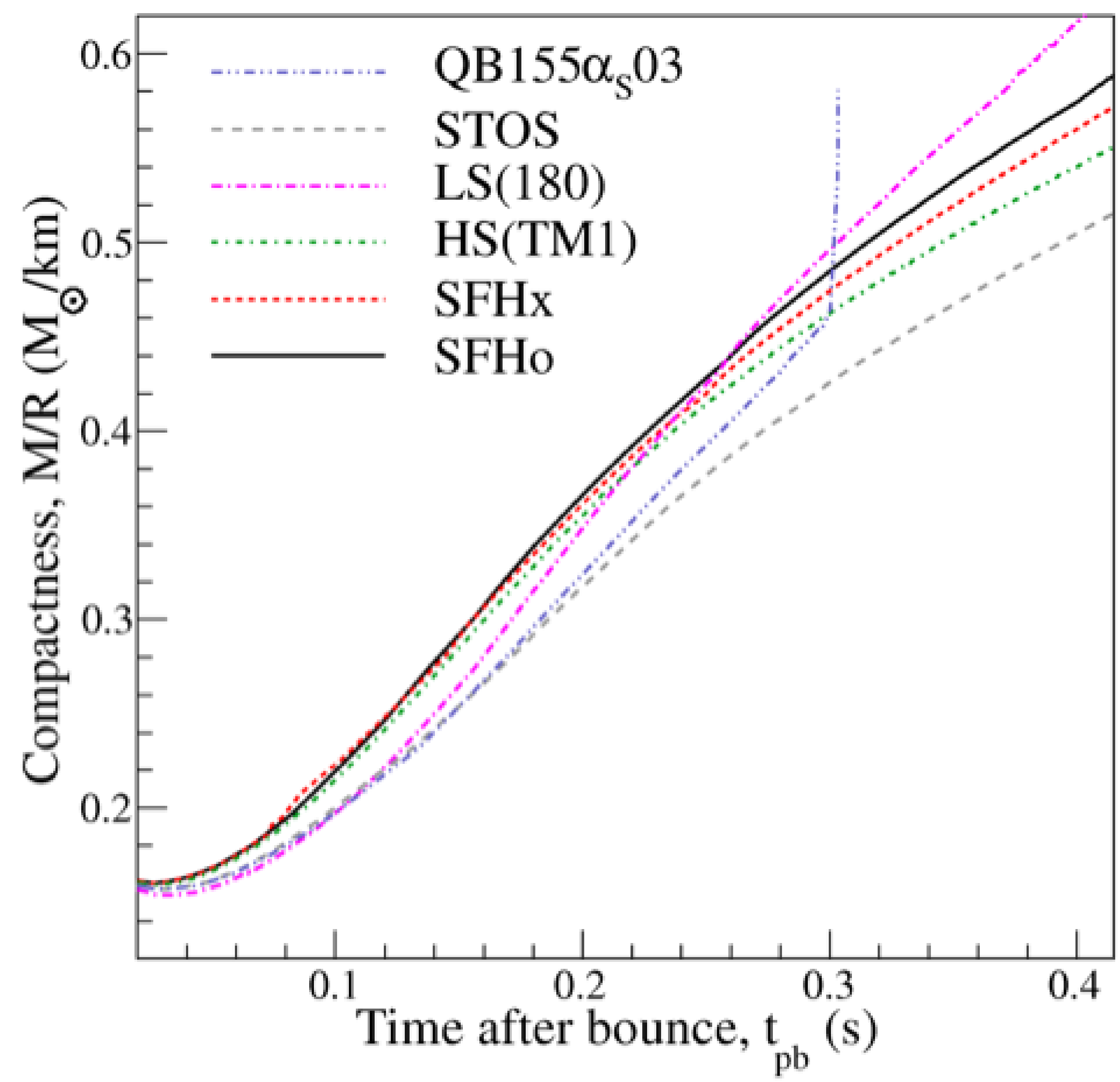


Steiner, Lattimer, and Brown (2012)

- Strong constraints on L
- Almost no constraint on S

New Supernova EOSs





- Match binding energies and charge radii of doubly-magic nuclei
- Properties of matter at saturation match currently accepted ranges
- Match neutron star mass and radius observations
- Probe smaller L
- Not necessarily relevant for the explosion mechanism, but relevant for the detectable neutrino signal

Summary

- How much do neutron star mass and radius measurements tell us neutron star radii?
    - Neutron star radii are most likely between 10.4 and 12.9 km
- How much do neutron star mass and radius measurements tell us about the EOS?
    - EOS determined to 30-50%
    - 40 MeV < L < 80 MeV, $R_n - R_p$ < 0.2 fm
- How tightly coupled is the behavior at saturation densities to higher densities?
    - Coupling limited by possibility of a strong phase transition (e.g. hyperons) just above n_0
- How can we remove as much of the model dependence as is reasonable?
    - By explicitly trying more than one parameterization
- The strongest constraints come from quiescent LMXBs with smaller radii.
- Several currently used EOSs are ruled out, including many EOSs used in modeling core-collapse supernovae
- Neutron star composition is still not well understood
- More data is coming...