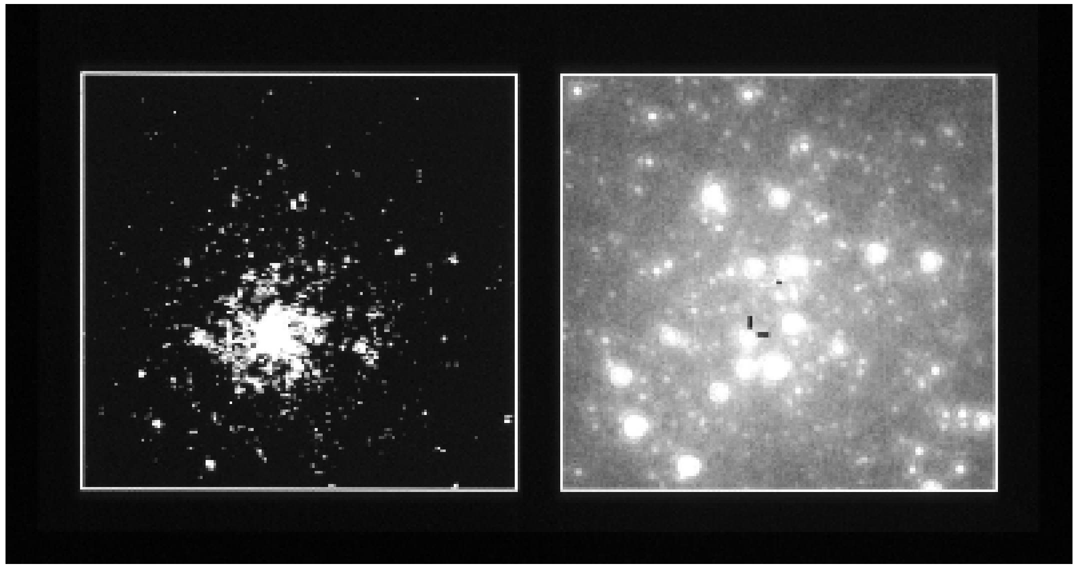
Determining the Nuclear Symmetry Energy from Neutron Star Masses and Radii



HST observation of 4U1820

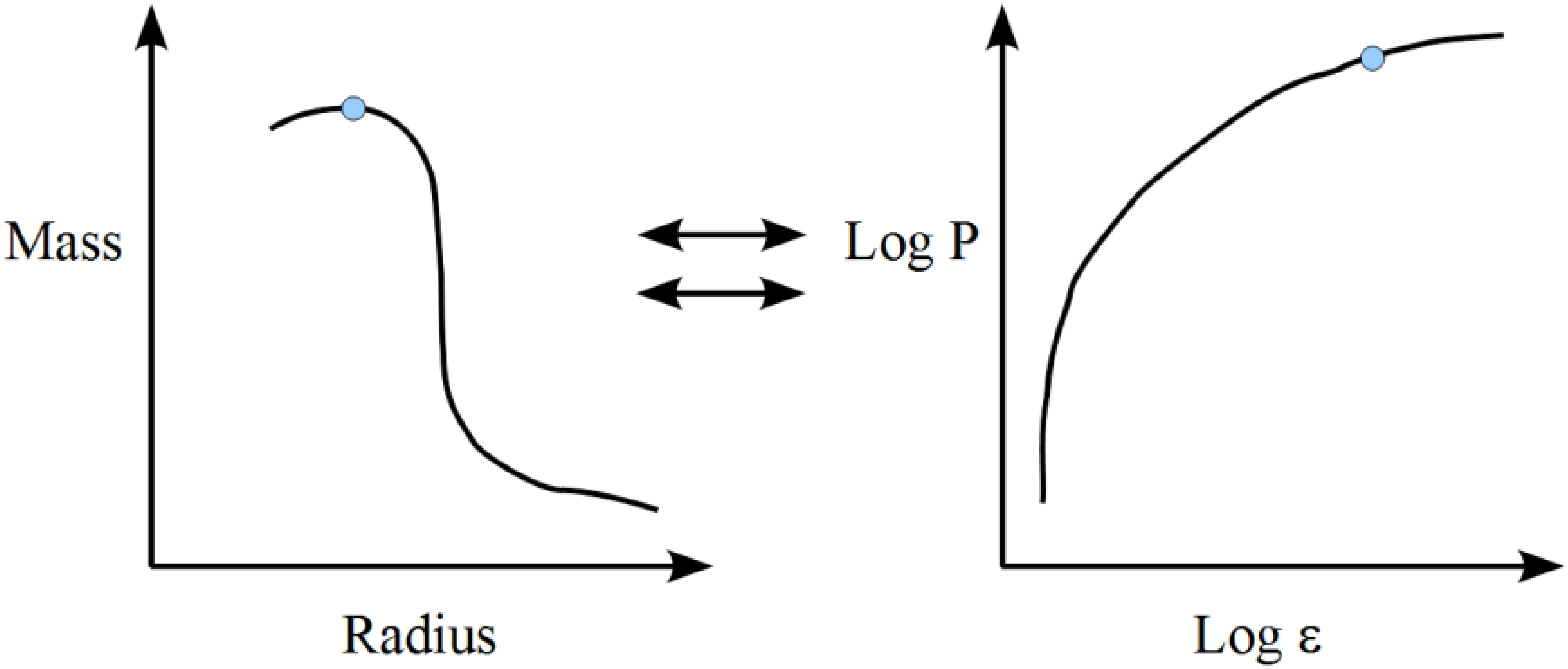
Andrew W. Steiner
Michigan State University

June 17-20, 2011

With: Edward F. Brown (Michigan State Univ.) and
James M. Lattimer (Stony Brook Univ.)

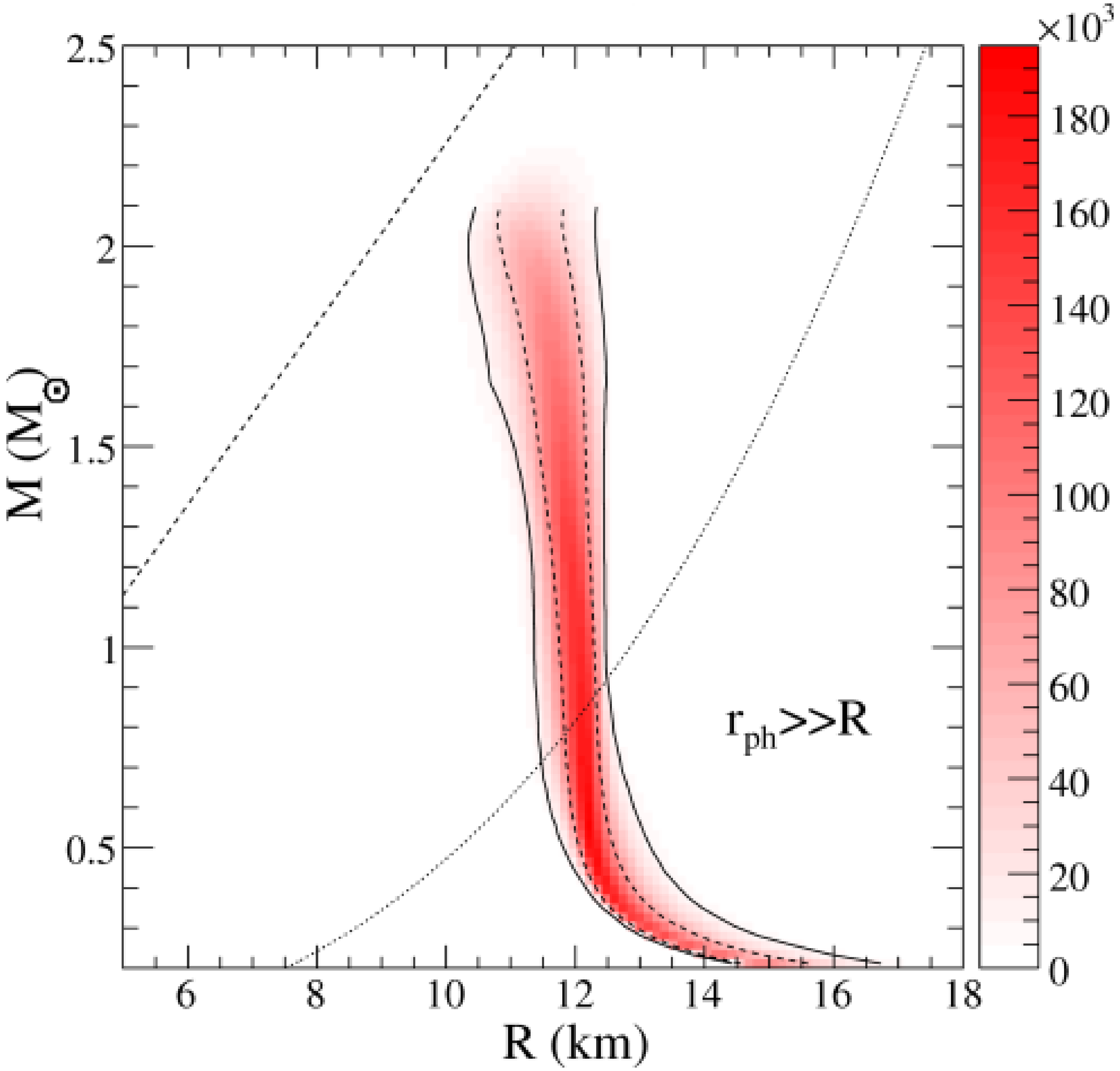
(Moving to the INT at U. Washington as of July 1st)

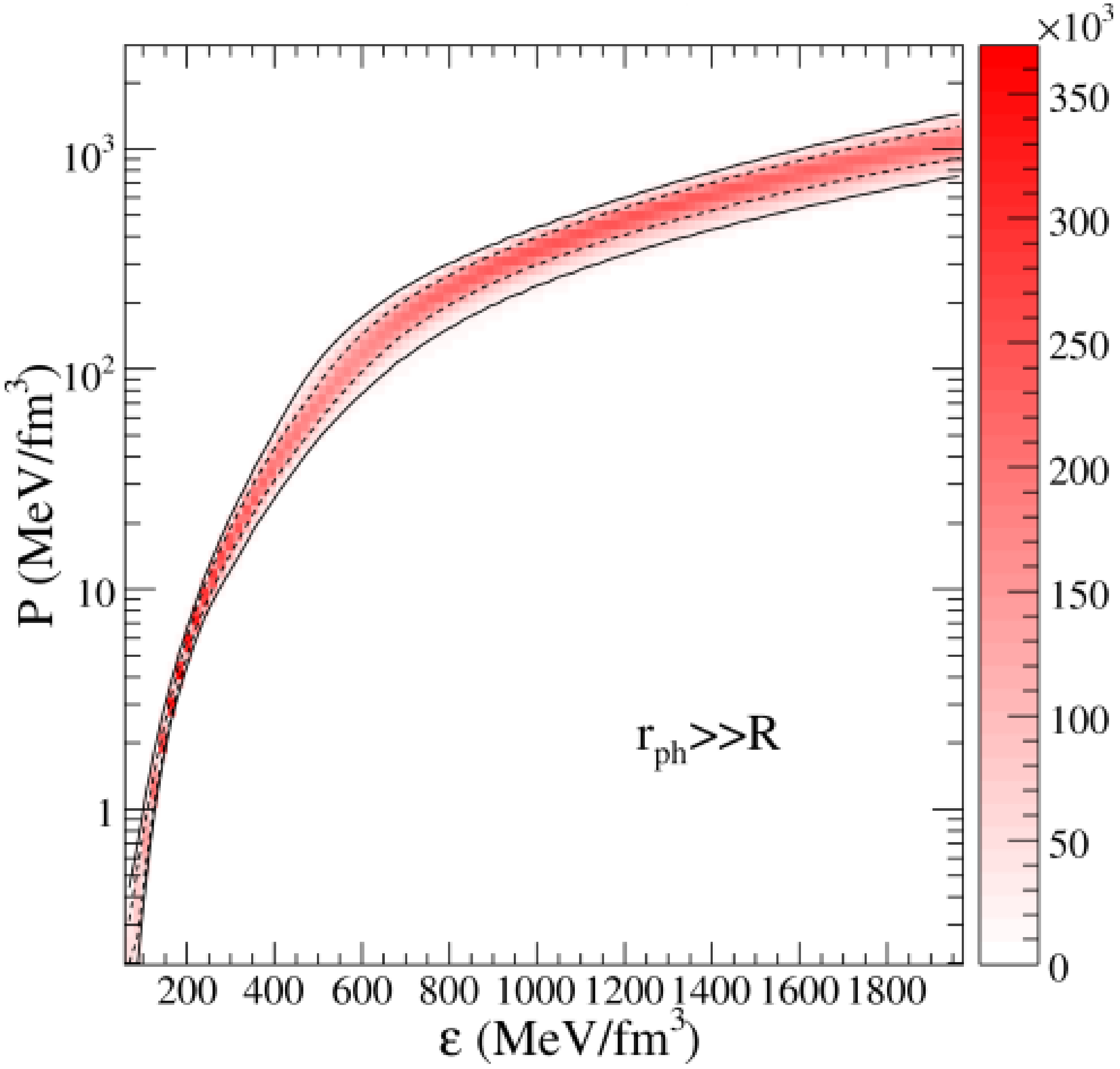
M vs. R and the EOS of Dense Matter



- To a good approximation, all neutron stars lie on one universal mass versus radius curve
- Observations provide points, "connect the dots"
- One-to-one correspondence with the equation of state (EOS)
- *We can determine the EOS directly from data.*

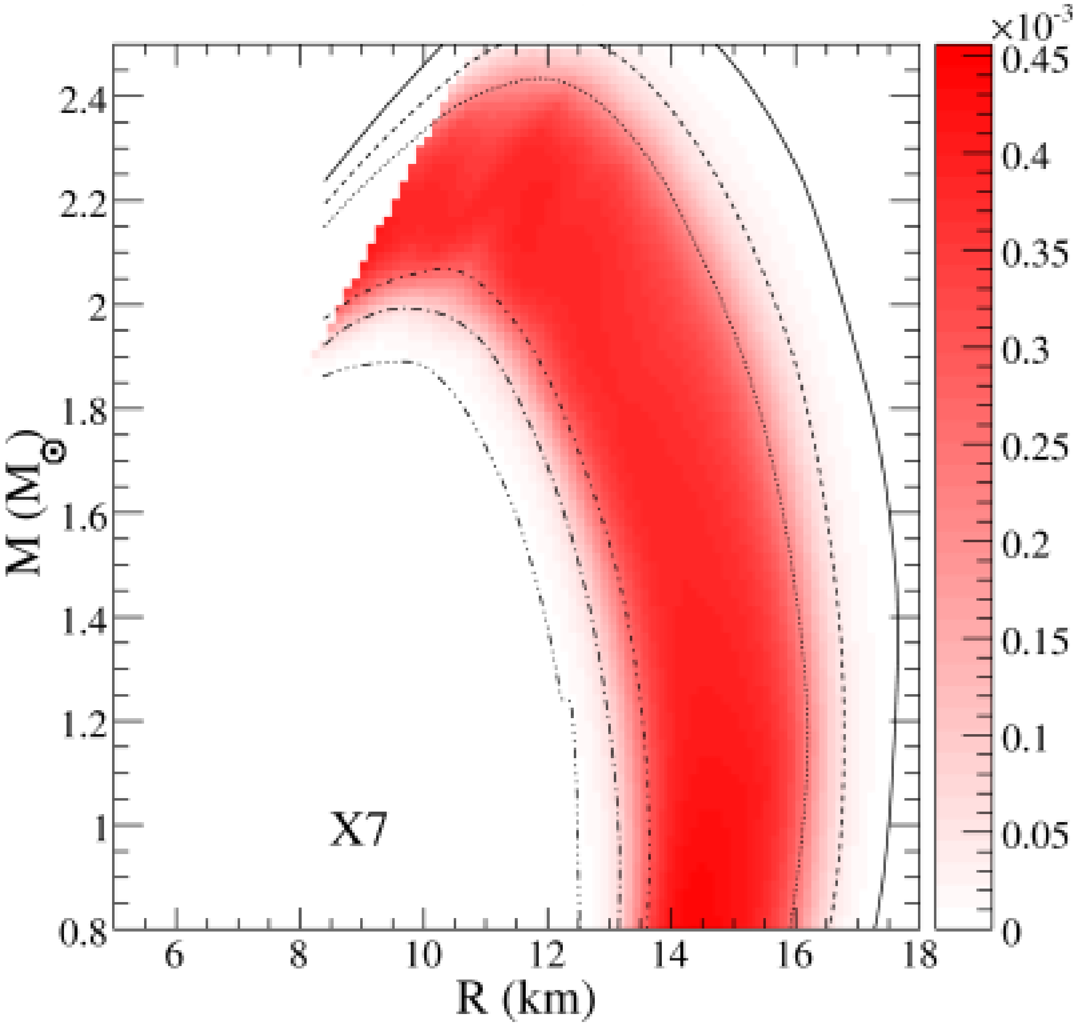
M vs. R and the EOS of Dense Matter



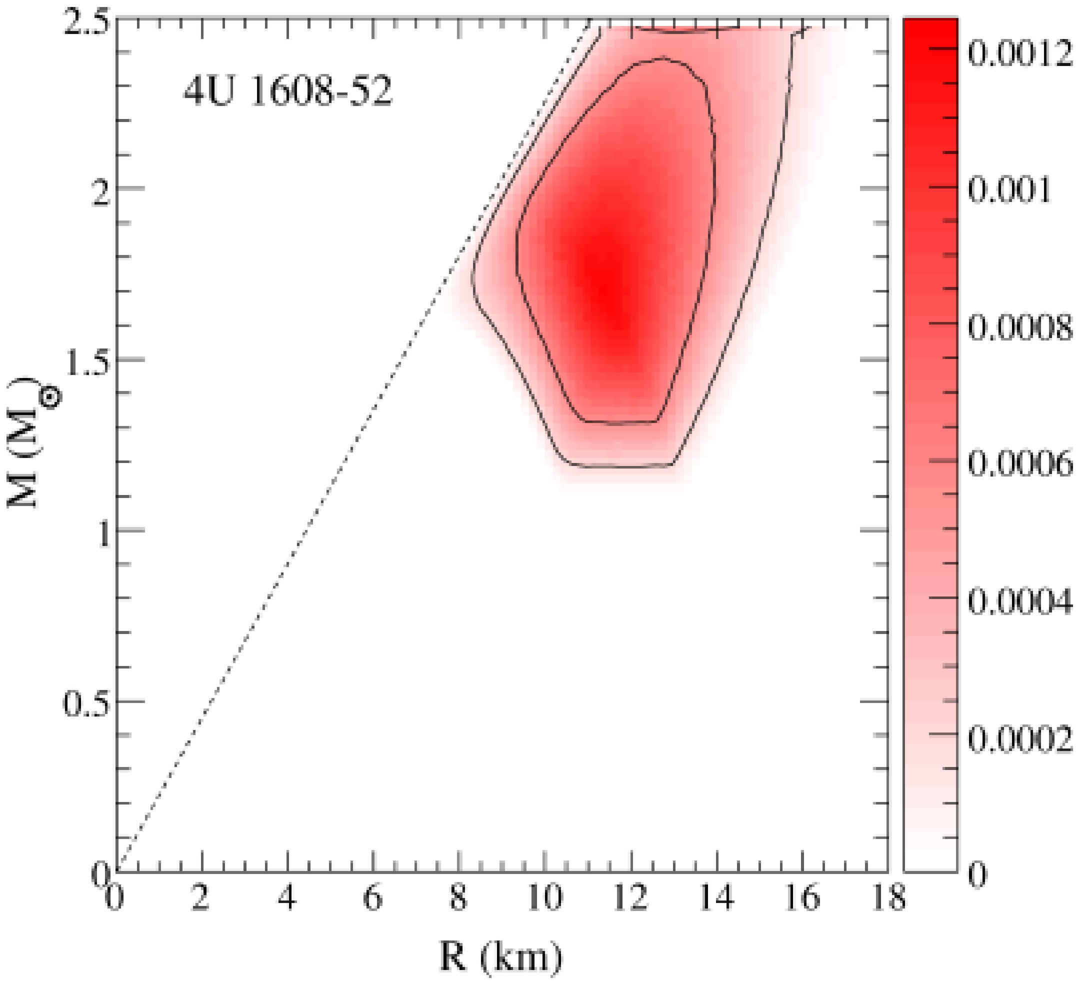


- Update of results from Steiner, Lattimer, and Brown (2010)
- Model dependence, systematic uncertainties, updated data, extra correlations between low- and high-densities
- I will attempt to address *all* of these issues

Mass and Radius Data



- Quiescent low-mass X-ray binaries
- Only GR-corrected radius, less difficulties with systematics



- Photospheric Radius Expansion X-ray Bursts
- Mass and radius simultaneously
- Some difficulties in interpreting the burst data

Statistical Approach

- Well-suited to this underconstrained problem
- Bayes theorem:

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

- 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

EOS parameterization

- Schematic EOS near the saturation density:

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

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

- 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

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

EOS parameterization

- Quark matter

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

- Mixed phase modeled by an additional polytrope
- Hybrid or "strange quark stars"
- May be a correlation between low and high-densities
- Repar this by fixing a transition density and adding a new polytrope

Radius of a 1.4 Solar Mass Neutron Star

Model A	11.18	11.49	12.07	12.33
Model B	11.23	11.53	12.17	12.45
Model C	10.63	10.88	11.45	11.83
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Processing Math: 100%

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$M_{\max} \geq 2.4$	12.14	12.29	12.63	12.81
No X7 or M13, Model D	11.36	11.65	12.41	12.83
No M13 and $1.47 < f_C < 1.8$, Model B	11.84	12.12	12.70	12.98
No X7 and $1.0 < f_C < 1.33$, Model C	9.17	9.34	9.78	10.07

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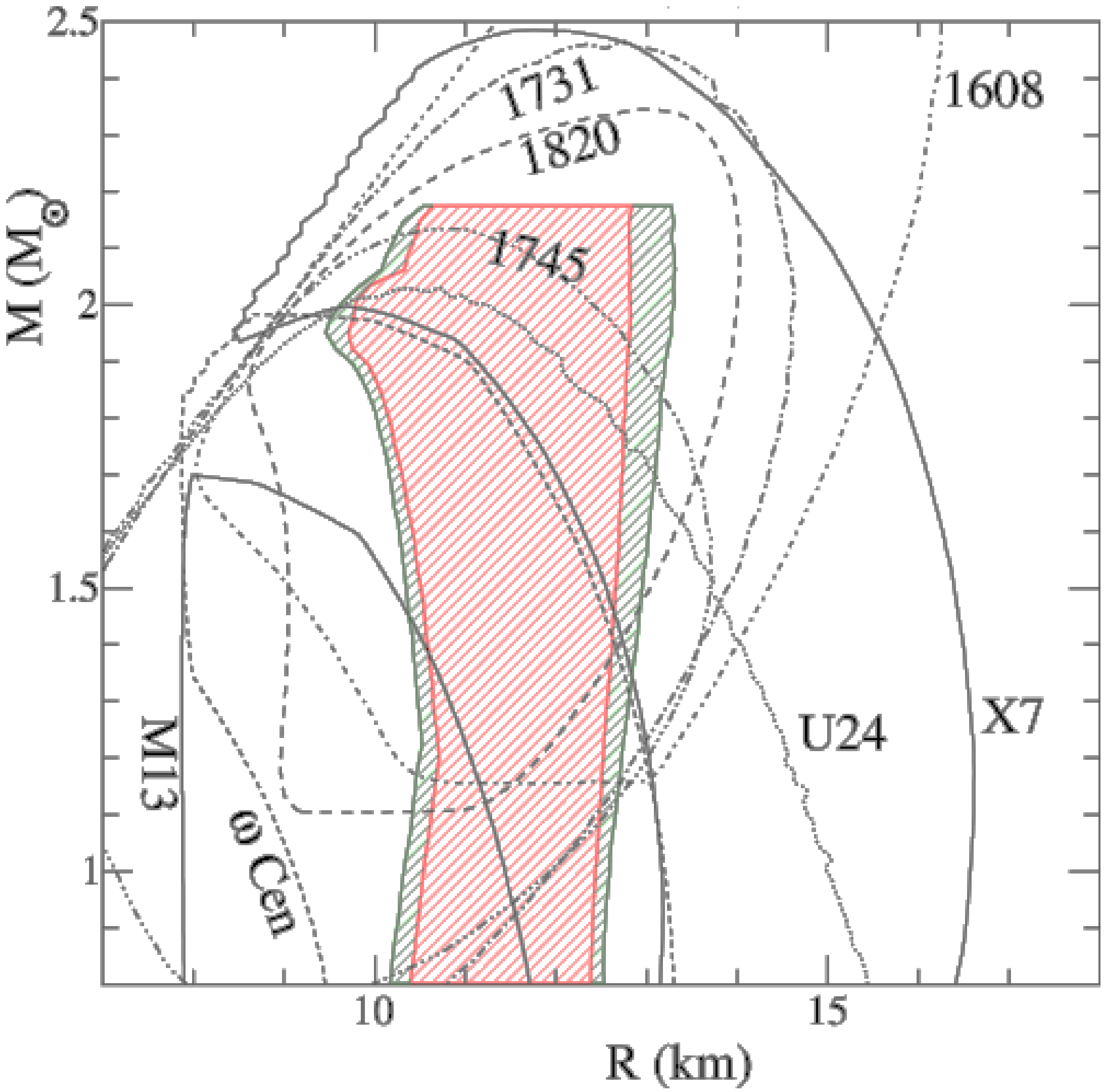
Strange quark stars	10.19	10.64	11.57	12.01

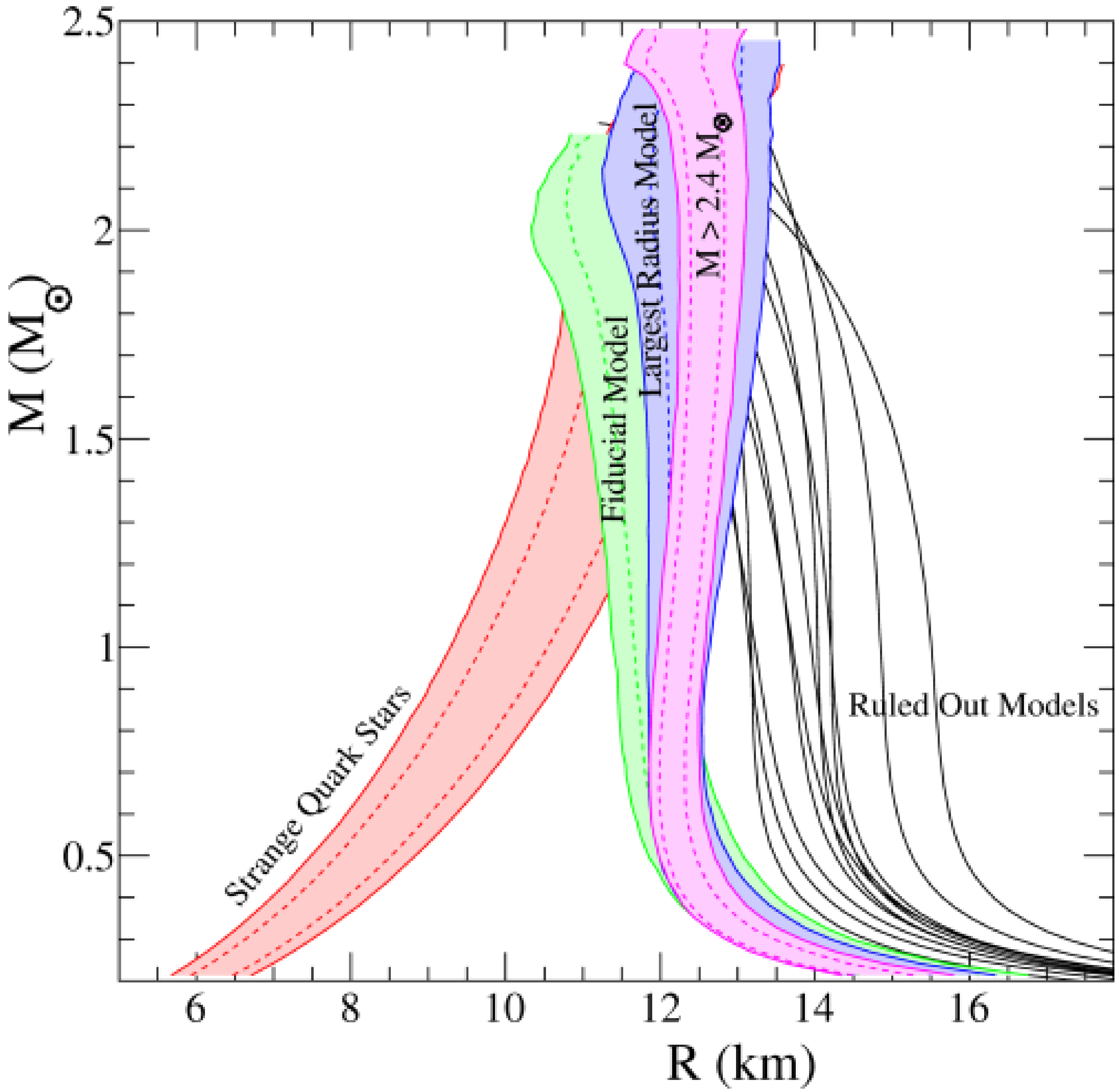
Mass and Radius Results



Steiner, Lattimer, and Brown, in prep.

- Slightly larger range of radii for a 1.4 solar mass star: 10.4 and 12.9 km

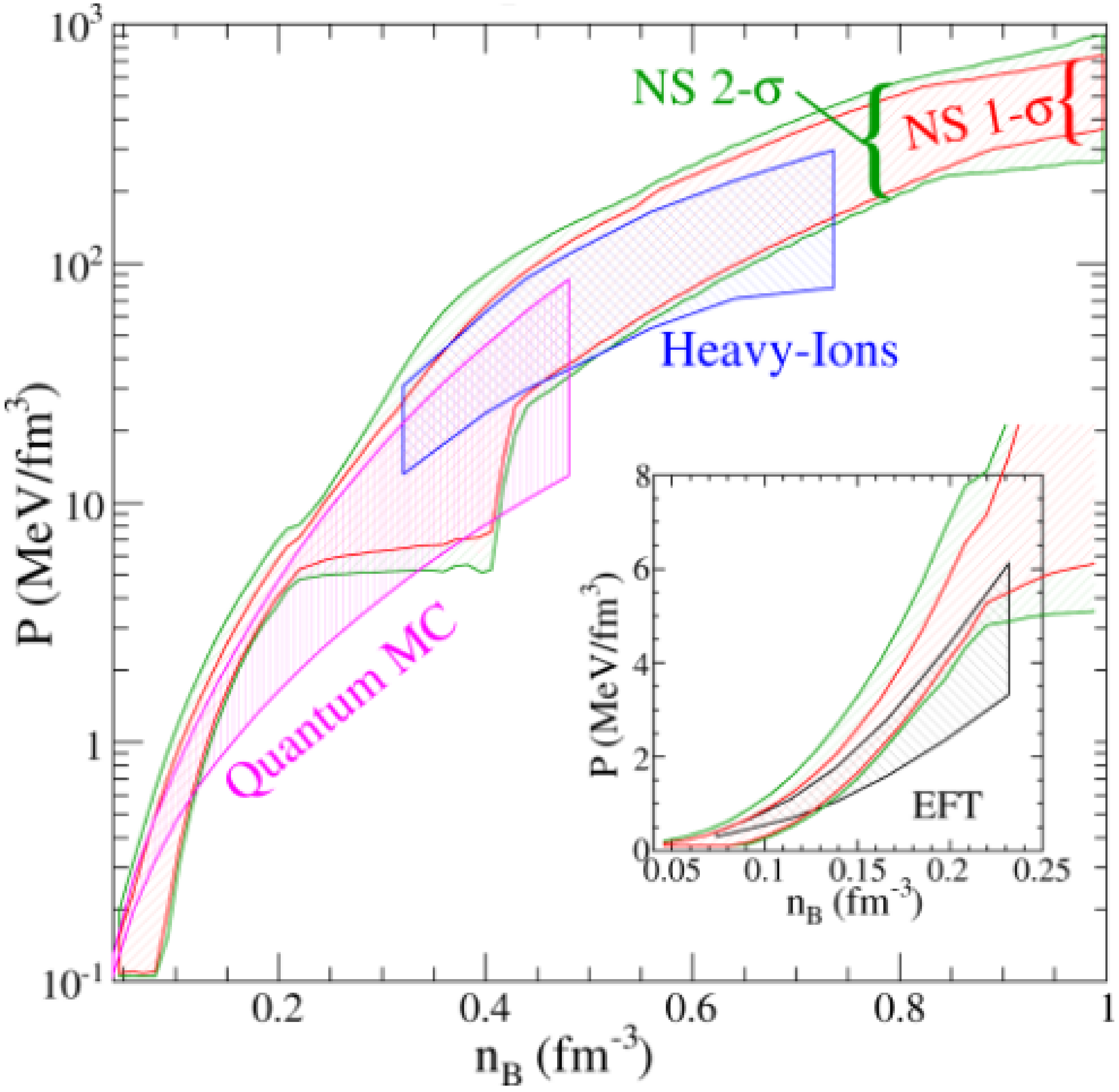
Mass and Radius Results

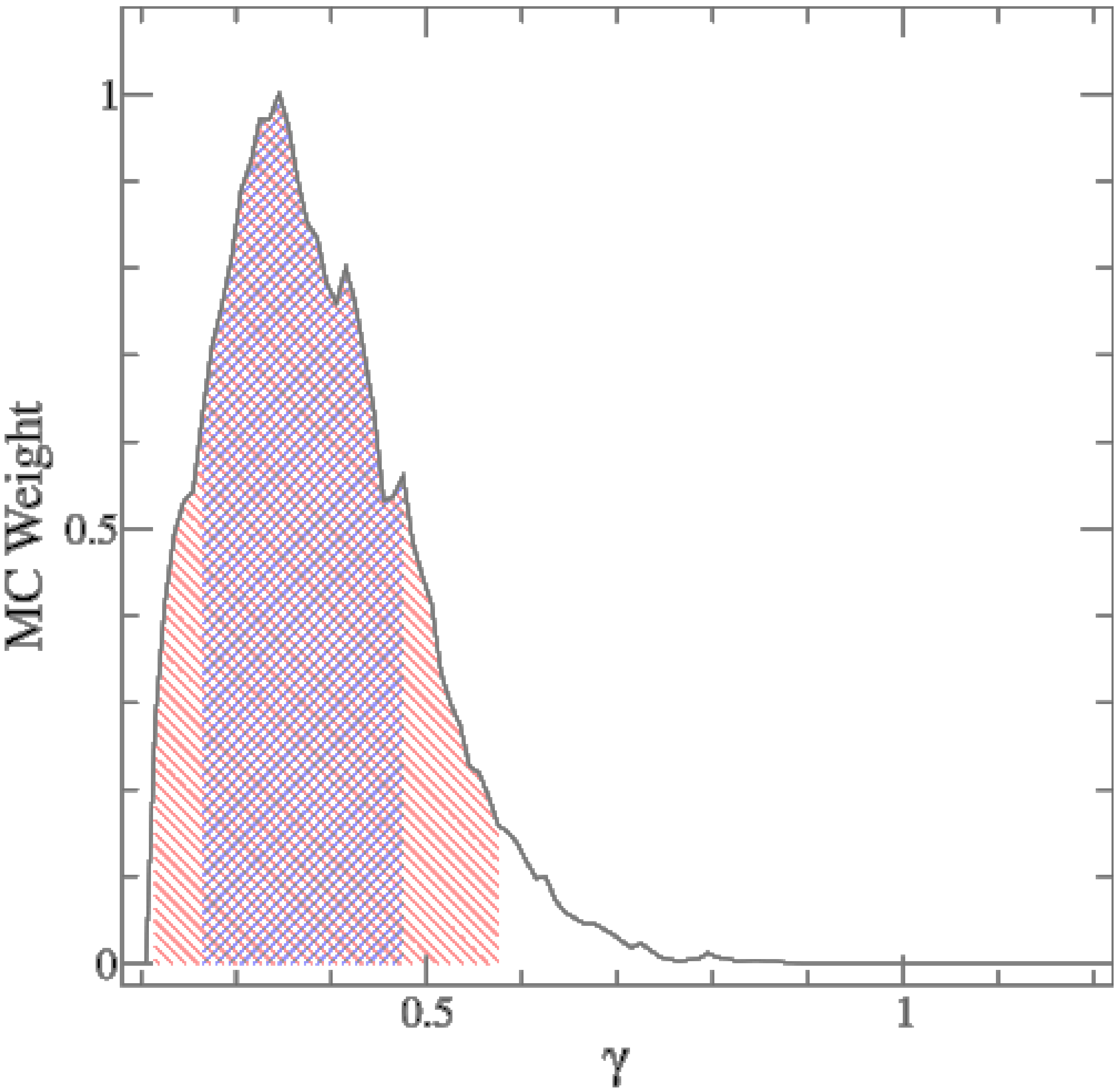


Steiner, Lattimer, and Brown, in prep.

- Compatible with strange quark stars
- Still rule out 1/3 of Stone's Skyrme models

EOS and the Symmetry Energy





Steiner, Lattimer, and Brown, in prep.

- $P(\varepsilon)$ determined to within 30-50%
- $P(n_B)$ determined to within a factor of 3
- $\gamma < 0.6$
- Neutron skin thickness now $\delta R < 0.20$ fm

Summary

- After examining:
    - One source removal
    - PRE problems
    - Prior distributions
    - Correlations between high and low densities
    - Hybrid stars
    - Strange quark stars

  We find neutron stars have radii between 10.4 and 12.9 km

- Or something even more exciting is going on!

- Several currently used EOSs are ruled out

- "Soft" symmetry energy near saturation density is implied

- Also, using Quantum Monte Carlo to design parameterizations of dense matter (S. Gandolfi).

- Dimensionless parameter

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