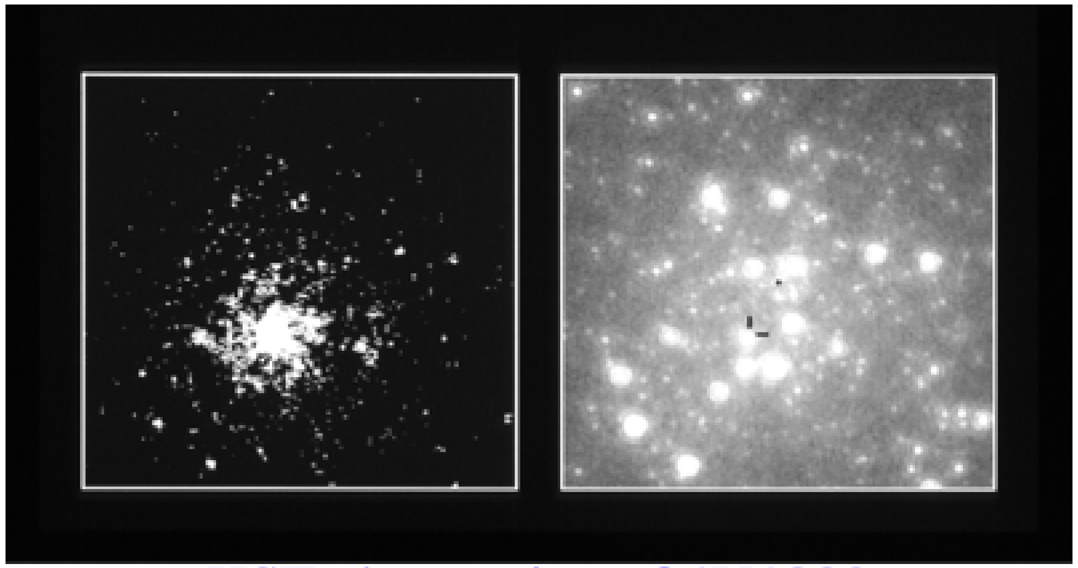
Determining the EOS of Dense Matter from Neutron Star Mass and Radius Observations



HST observation of 4U1820

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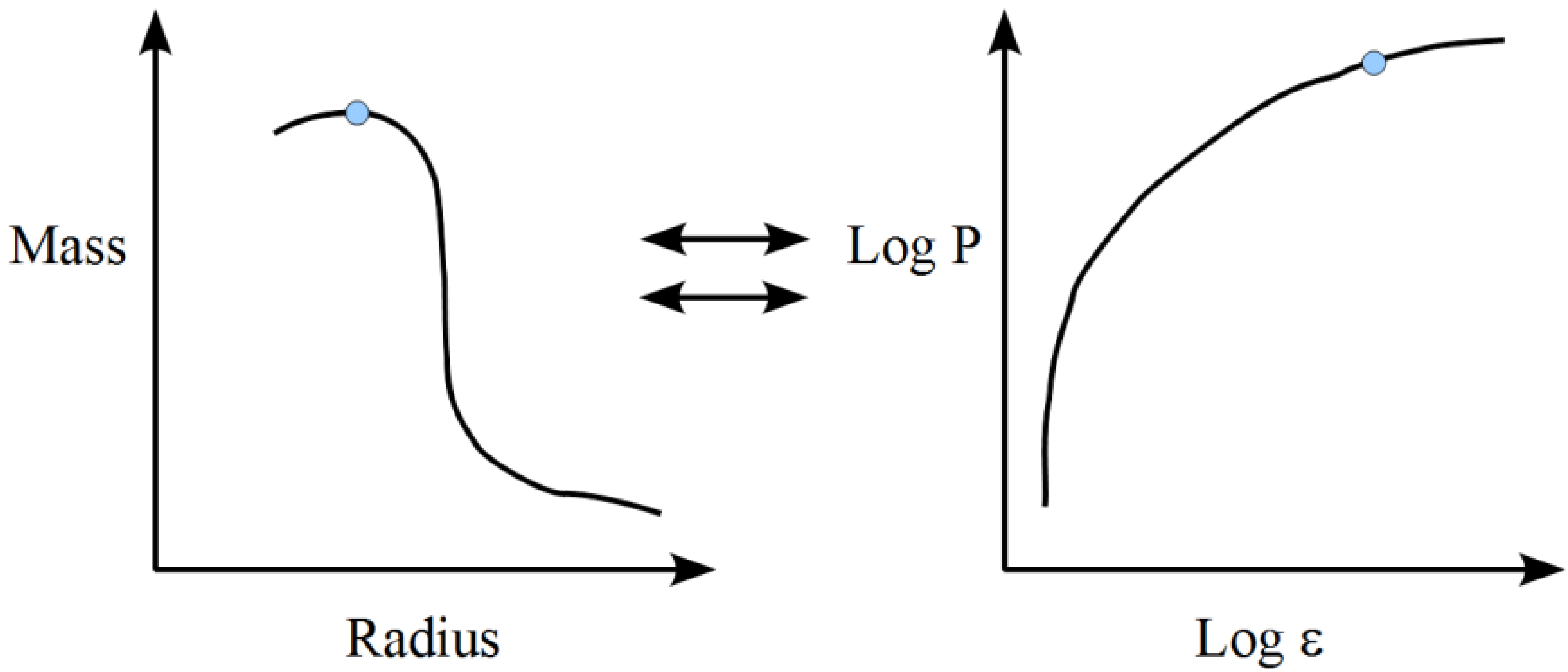
Outline

- The M-R curve and the EOS
- Introduction to the astrophysics and nuclear physics
- Observational data
- Bayesian analysis
- Results: We find interesting and quantitative constraints, e.g. the radius of 1.4 solar mass NSs is between 10.4 and 12.9 km, and many models are ruled out
- Bayesian analysis discussion tomorrow?
  - χ^2 and standard fitting
  - Parameter estimation
  - Model comparison
  - Application to M-R curves and the EOS
  - Anything you else you want

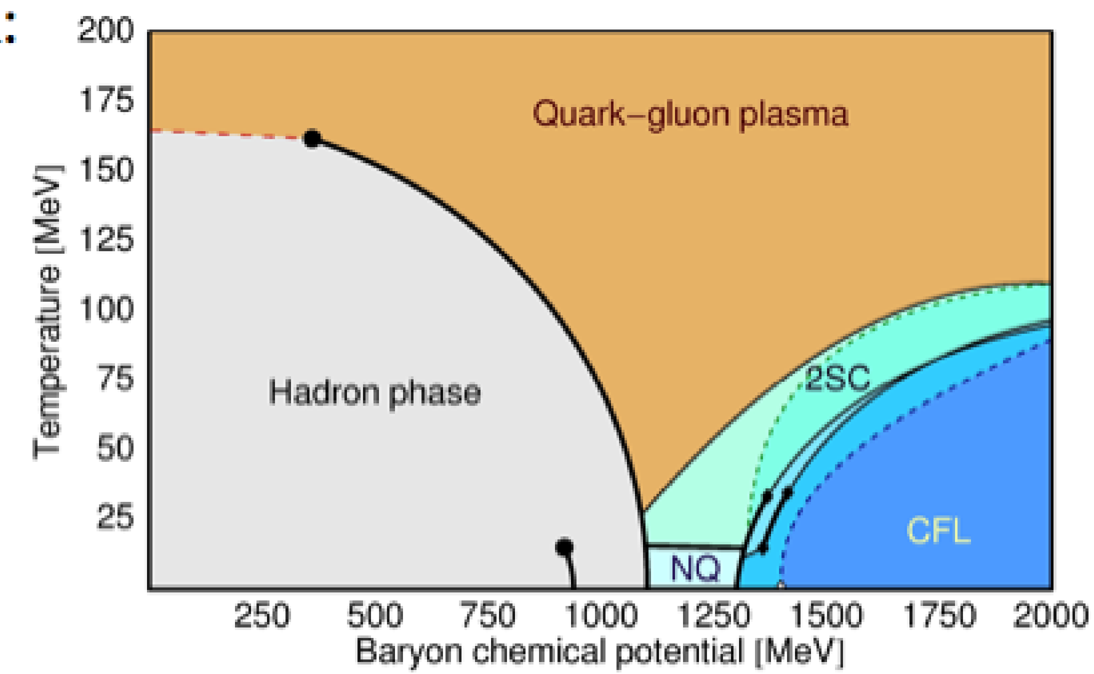
M vs. R and the EOS of Dense Matter



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

- Properties of dense matter:
  - Drive other features of NS evolution
  - Tells us about QCD at high density

- Masses and radii connected to:
  - What is the neutron star mass function?
  - How do neutron stars get their mass?



Rüster, et al. (2005)

Dense Matter in Neutron Stars

- Attraction vs. repulsion

- Lower pressure decreases the radius and lowers the maximum mass

- Phase transitions tend to (but don't always) lower the pressure, smaller radius and smaller maximum mass

- The smaller the radius of a 1.4 solar mass NS, the smaller the maximum mass

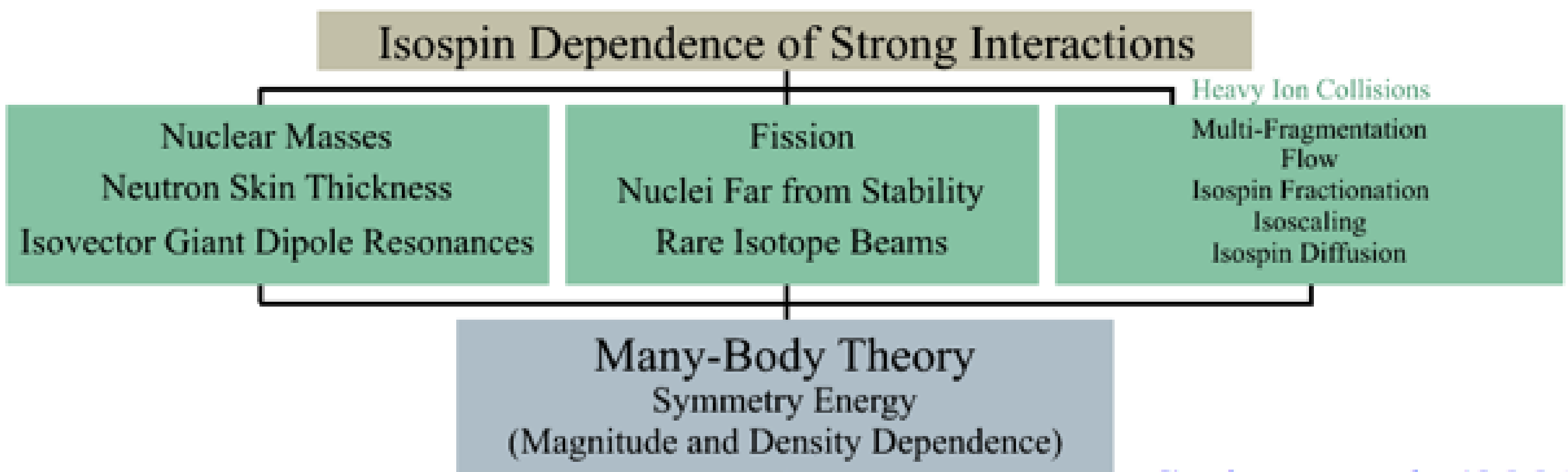
- Neutron star masses and radii are probes of total energy density and pressure only

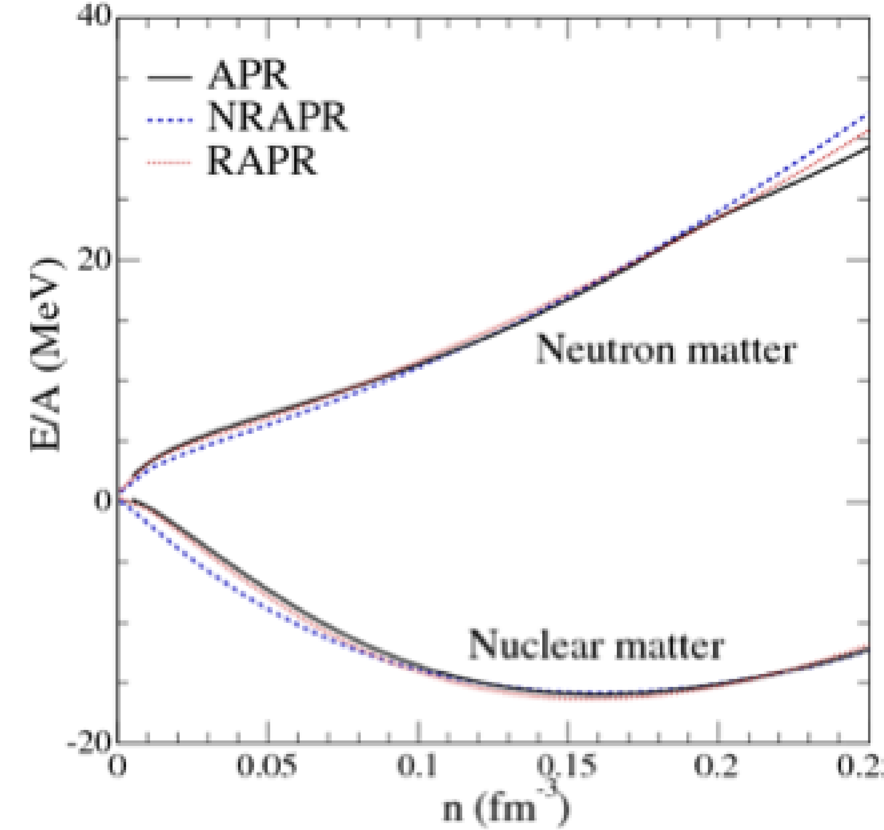
- To get composition, we are going to need multiple observations and/or multiple messengers

- The larger the maximum mass, the smaller the largest (baryon density/energy density/pressure) reached in the maximum mass star

Connections to Nuclear Physics

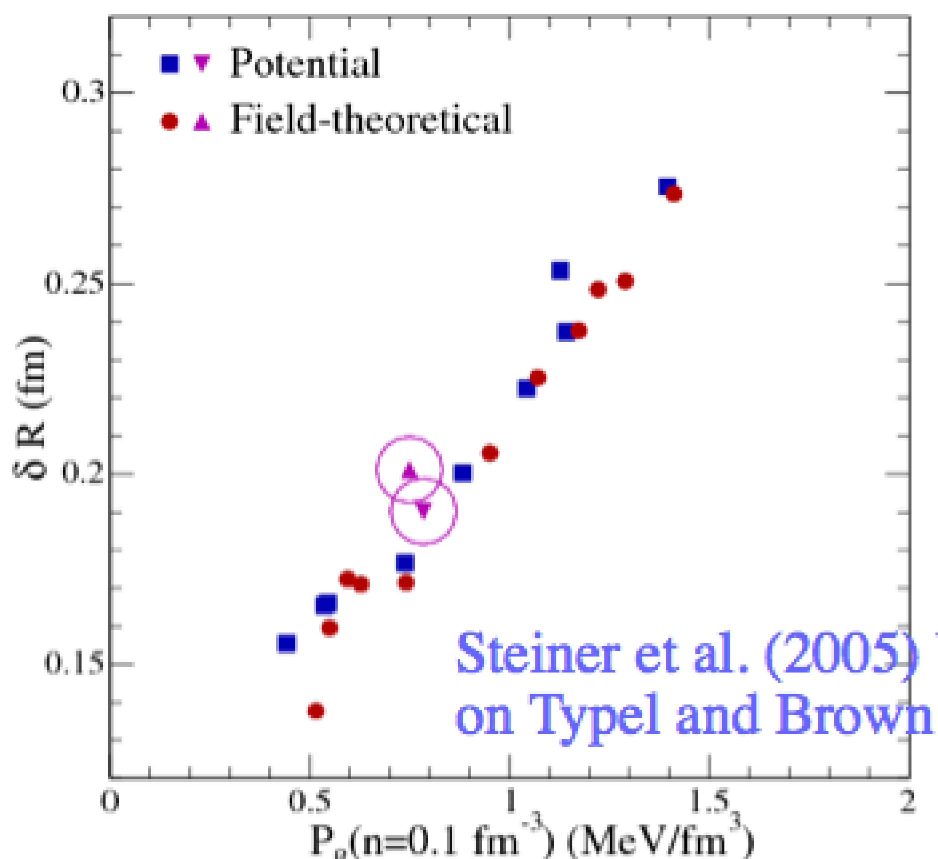
- Nuclear symmetry energy
- Neutron skin thickness in lead
- Three-body force



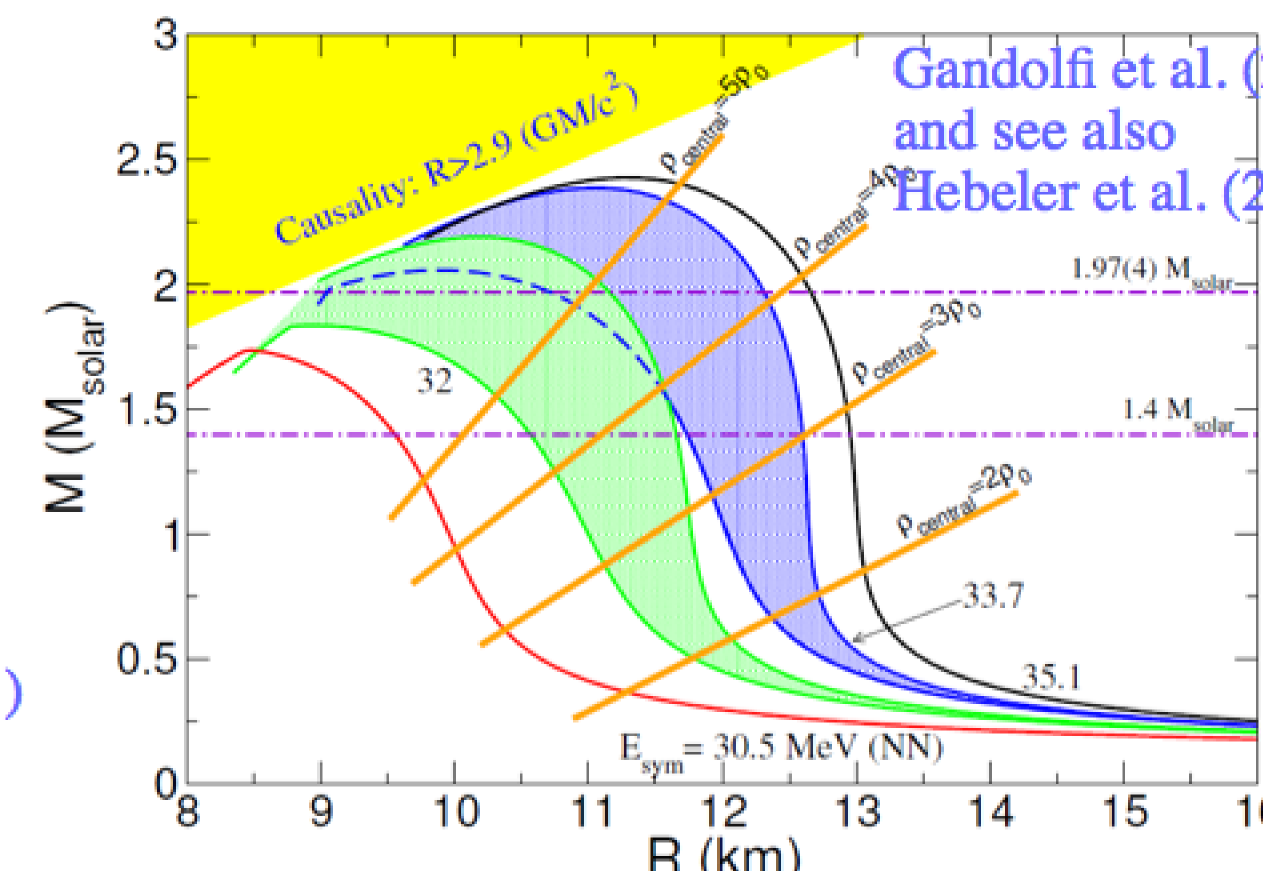


Steiner et al. (2005)

Connection to three-body forces:



Steiner et al. (2005) based on Typel and Brown (2001)



Gandolfi et al. (2010), and see also Hebeler et al. (2010)

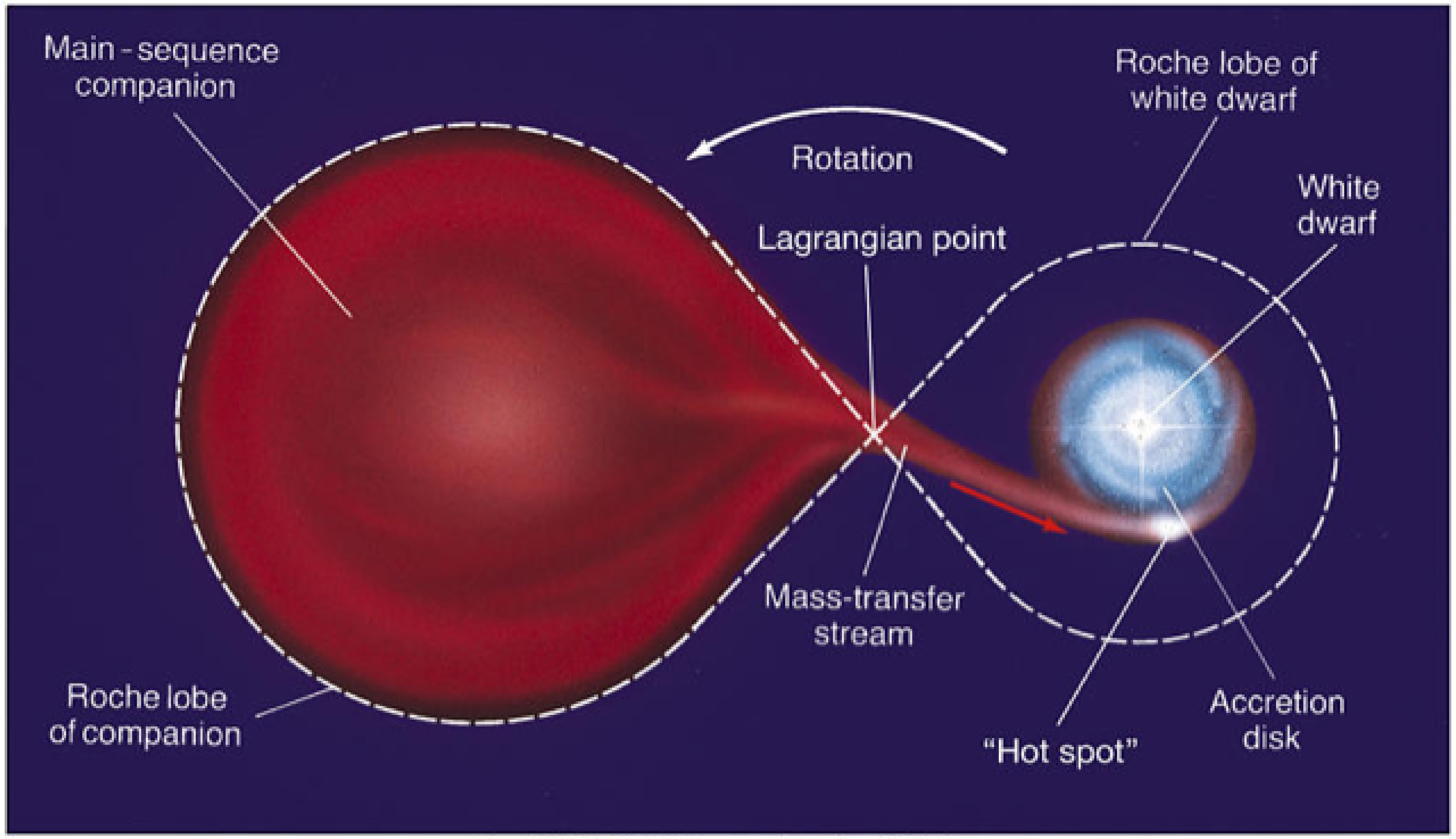
Connecting M-R and the EOS with Observations

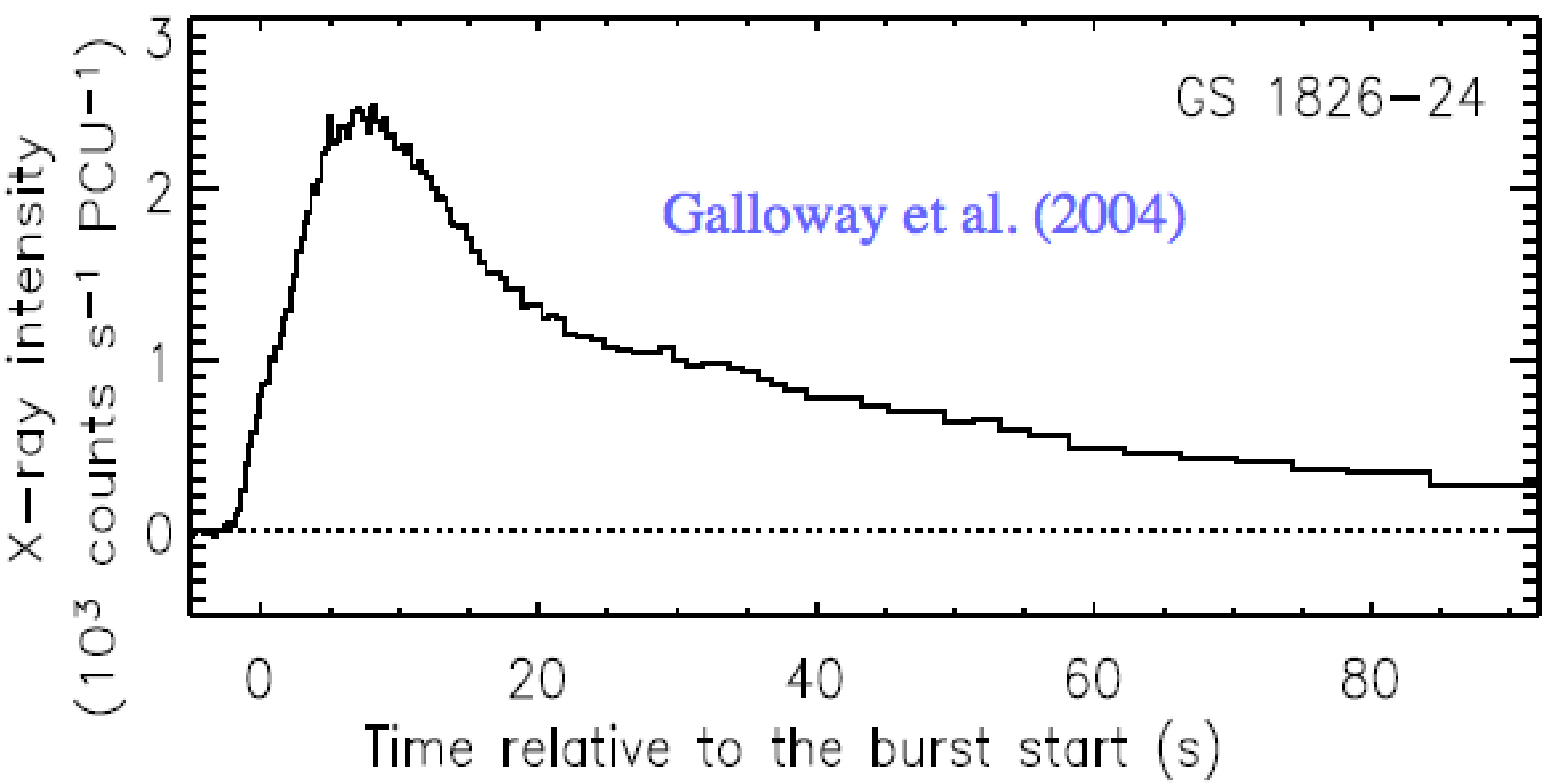
- Do our models match the data? If not, why not?

- What are the statistical and systematic uncertainties and how do we account for them?
  - Take model alternatives and pick the smallest range which encloses all of them
  - Is there is some reasonable alternative model which is possible to implement and not yet included?

- *Either all neutron stars are as we predict them to be, or there is something fundamental about them that we're wrong about, or we're really really unlucky.*

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

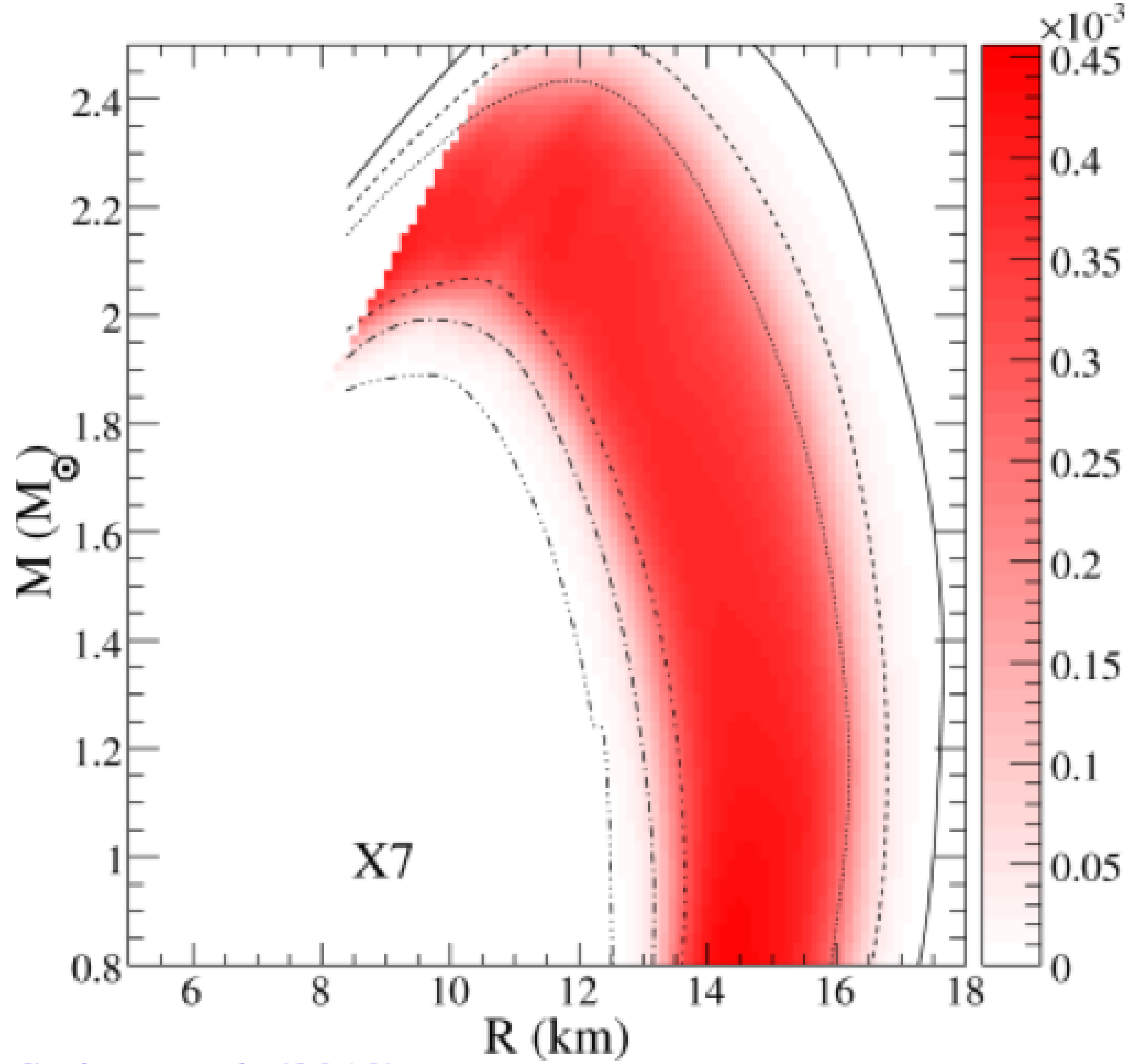
Mass Measurements and QLMXBs

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

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

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

[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"

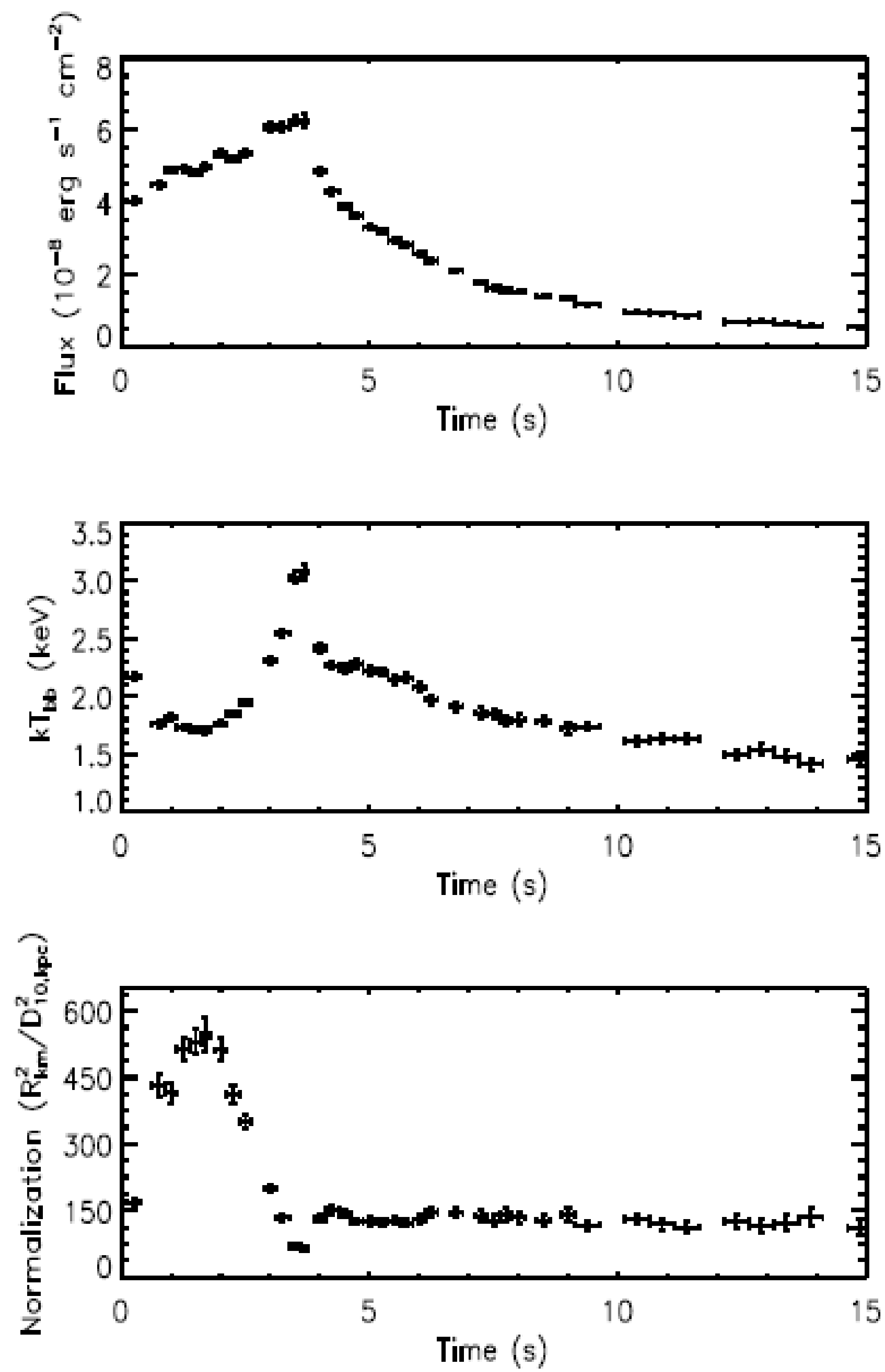
$$F_{TD} = \frac{GMc}{\kappa D^2}\sqrt{1 - 2\beta(r_{ph})}$$

- 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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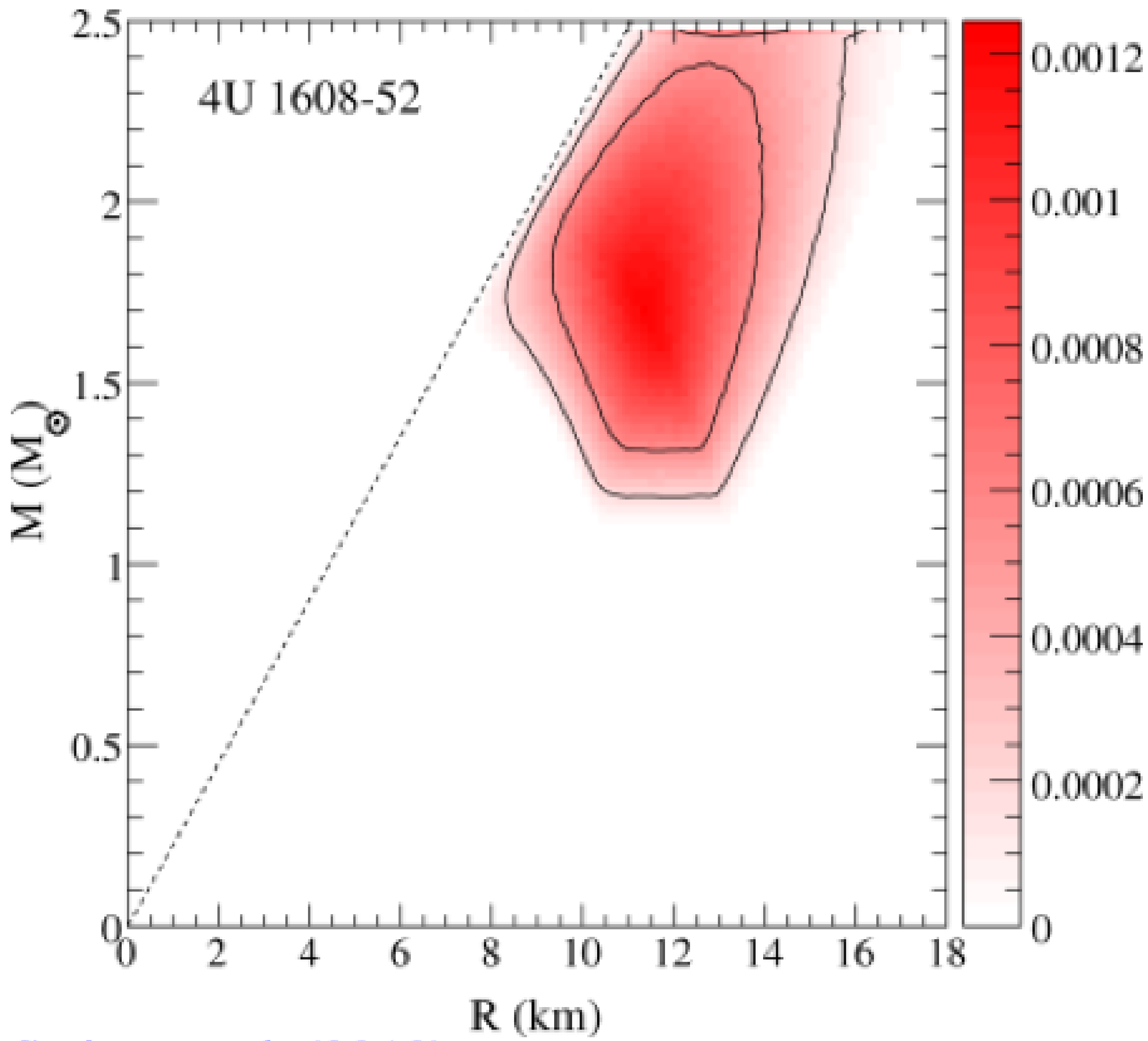


Steiner et al. (2010)

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

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

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"
- Scale invariance:

$$P = -\varepsilon + n\,\frac{\partial\varepsilon}{\partial n}$$

$$\frac{dn}{n} = \frac{d\varepsilon}{P(\varepsilon) + \varepsilon}$$

- We cannot determine baryon densities very precisely

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

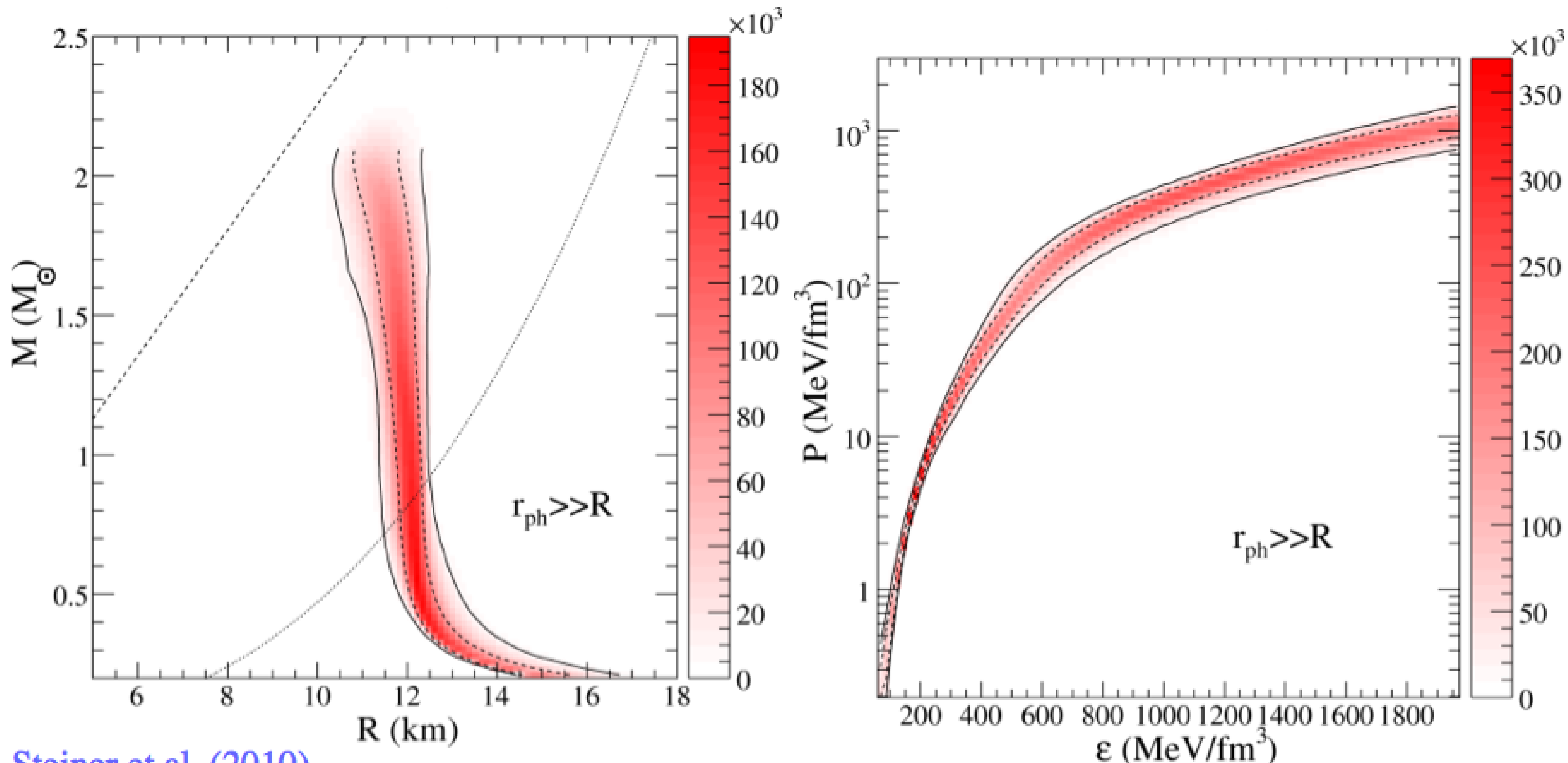
$$P[D|\mathcal{M}] = \prod_{i \in n_{\mathrm{datasets}}} \mathcal{D}_i(M,R)|_{M=M_i, R=R(M_i)}$$

- 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

Previous Results from the 2010 Paper



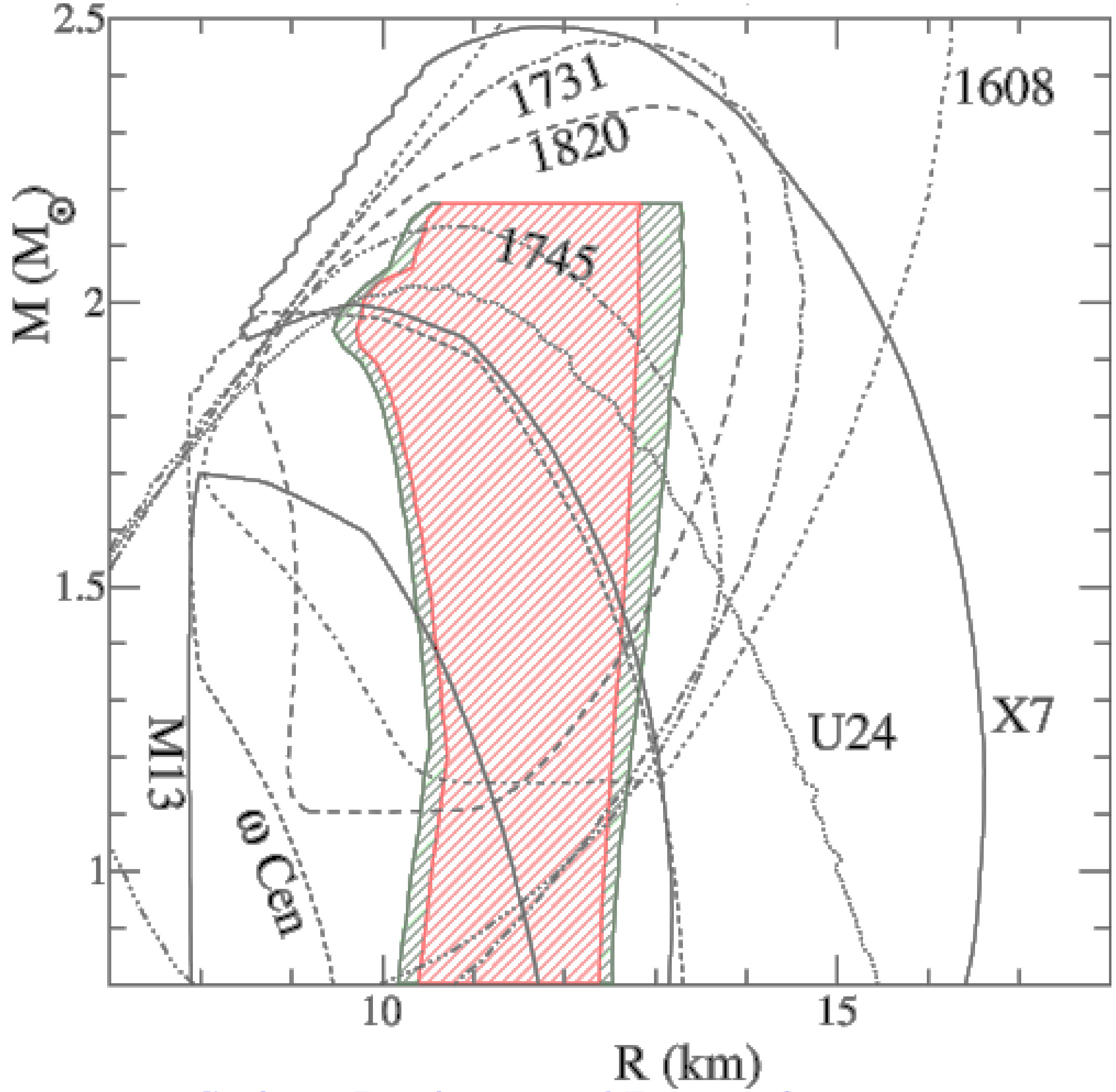
Steiner et al. (2010)

- Not the end of the story:
  - One source removal
  - PRE systematics
  - Prior distributions
  - Correlations between high and low densities
  - Hybrid stars
  - Strange quark stars

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
Model D	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
$1.0 < f_C < 1.33$	10.42	10.58	11.09	11.61
$1.47 < f_C < 1.8$	11.82	12.07	12.62	12.89
No PREs	11.23	11.56	12.23	12.49
For all models	10.42	10.58	12.62	12.89
$M_{\max} \geq 2.4$	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
Strange quark stars	10.19	10.64	11.57	12.01

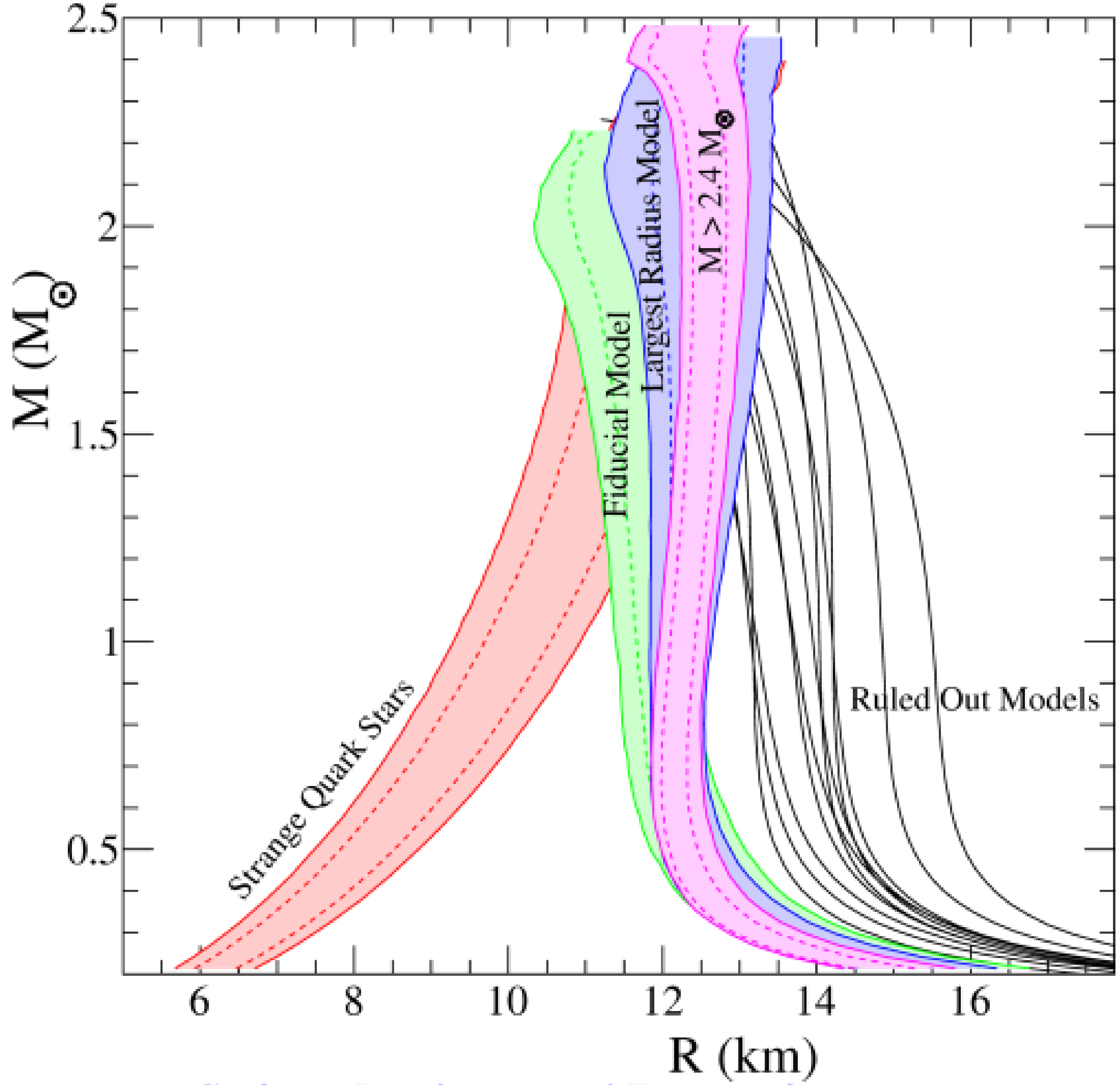
Mass and Radius Results



Steiner, Lattimer, and Brown, in prep.

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

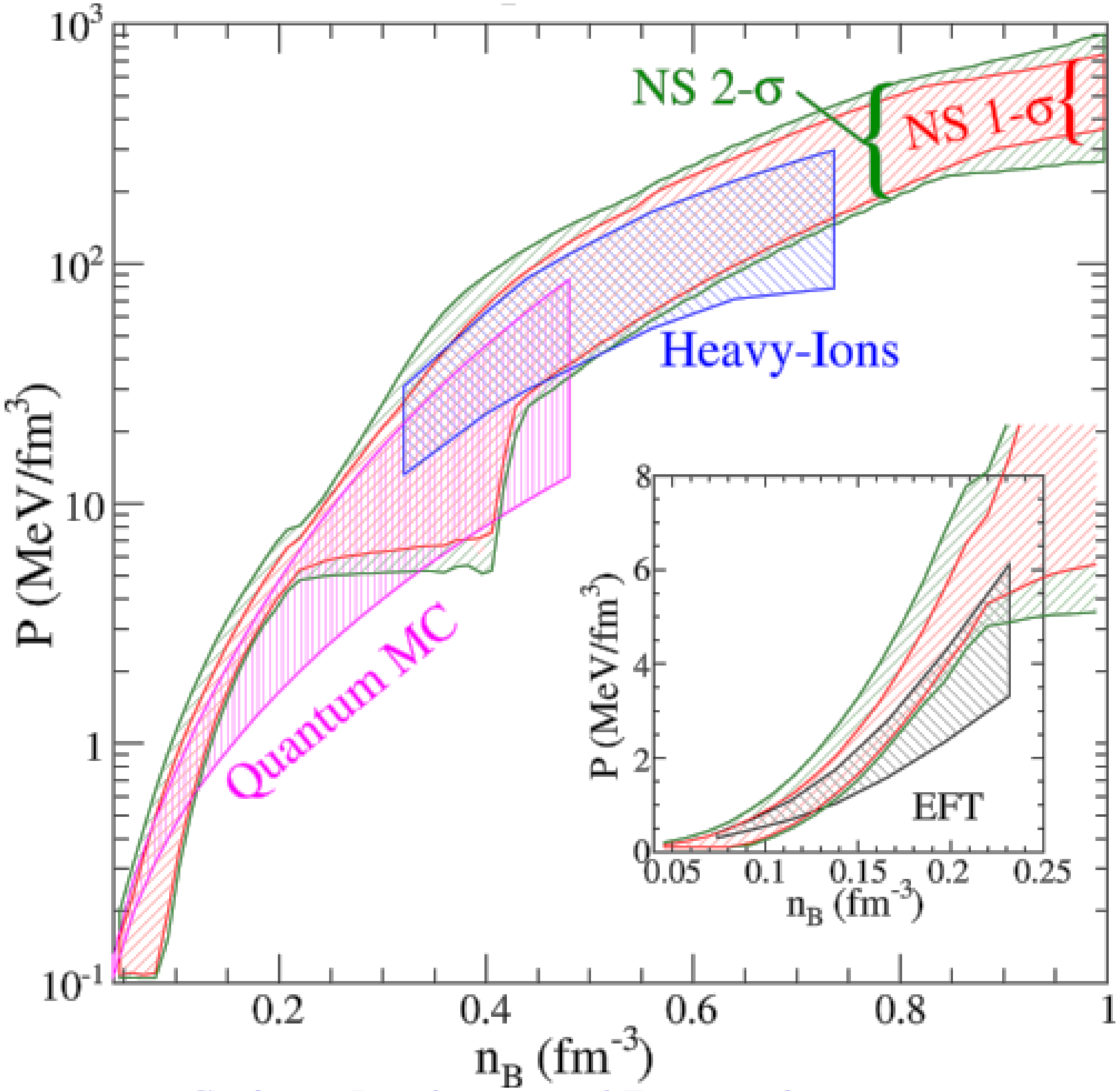
Mass and Radius Results



Steiner, Lattimer, and Brown, in prep.

- Compatible with strange quark stars
- Still rule out 1/3 of Stone's Skyrme models
- Rule out almost all supernova EOSs

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

Summary

- After examining:
  - One source removal
  - PRE systematics
  - 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

- Exciting future work in making connections to the three-body force (Gandolfi) and in direct constraints to the M-R curve without an EOS parameterization (Postnikov, Prakash, Lattimer)