Recent Neutron Star Observations and the Nature of Matter Near and Above Saturation

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47 TUCANAE:
Probing Extreme Matter Through Observations of Neutron Stars

Neutron stars, the ultra-dense cores left behind after massive stars collapse, contain the densest matter known in the Universe outside of a black hole.
More (6 Mar 13)

With: Edward F. Brown (MSU), Stefano Gandolfi (Los Alamos), and James M. Lattimer (Stony Brook)

Outline

- Masses, Radii, and the EOS
- PRE X-ray bursts
- QLMXBs
- Statistical analysis
- Results: $M-R$ curves, EOS, and L
- As many of the skeletons in my closet that I have time for


HikingArtist.com

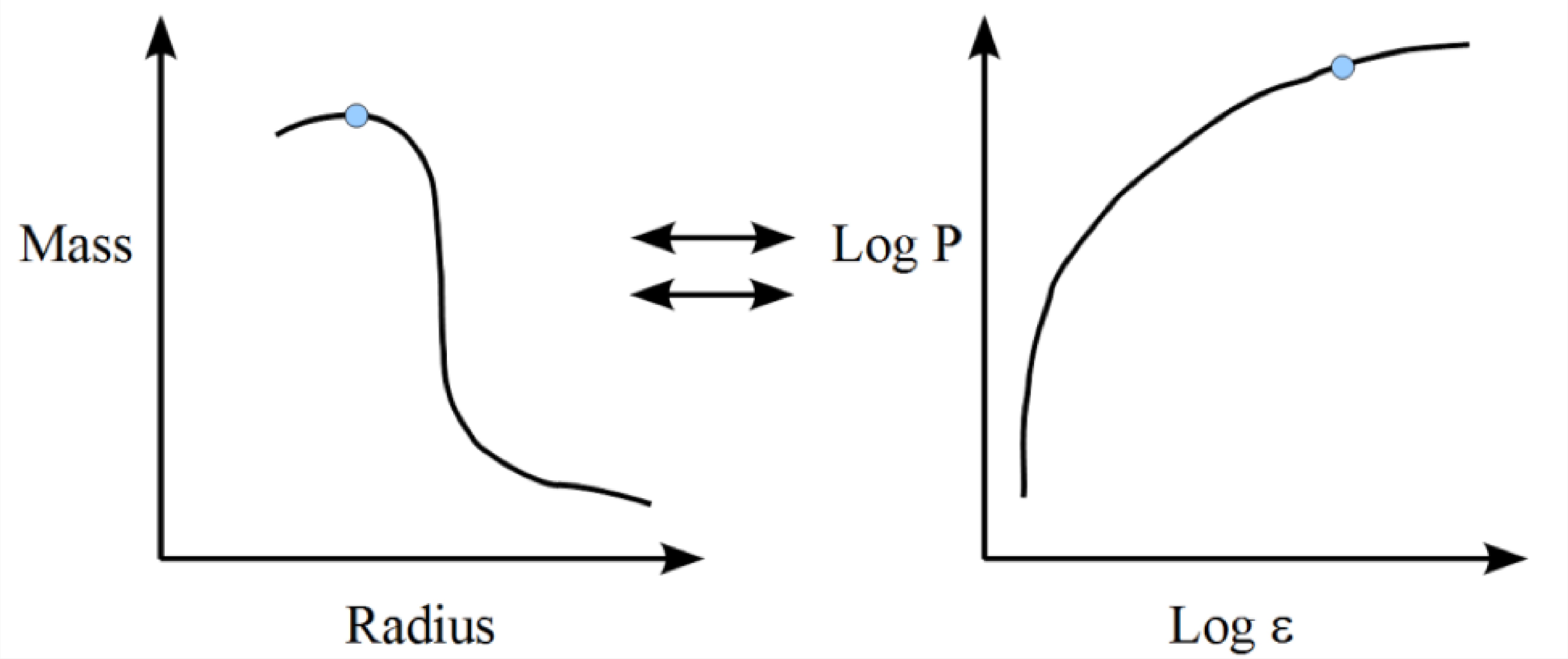
Gateway Quantities to the Symmetry Energy

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

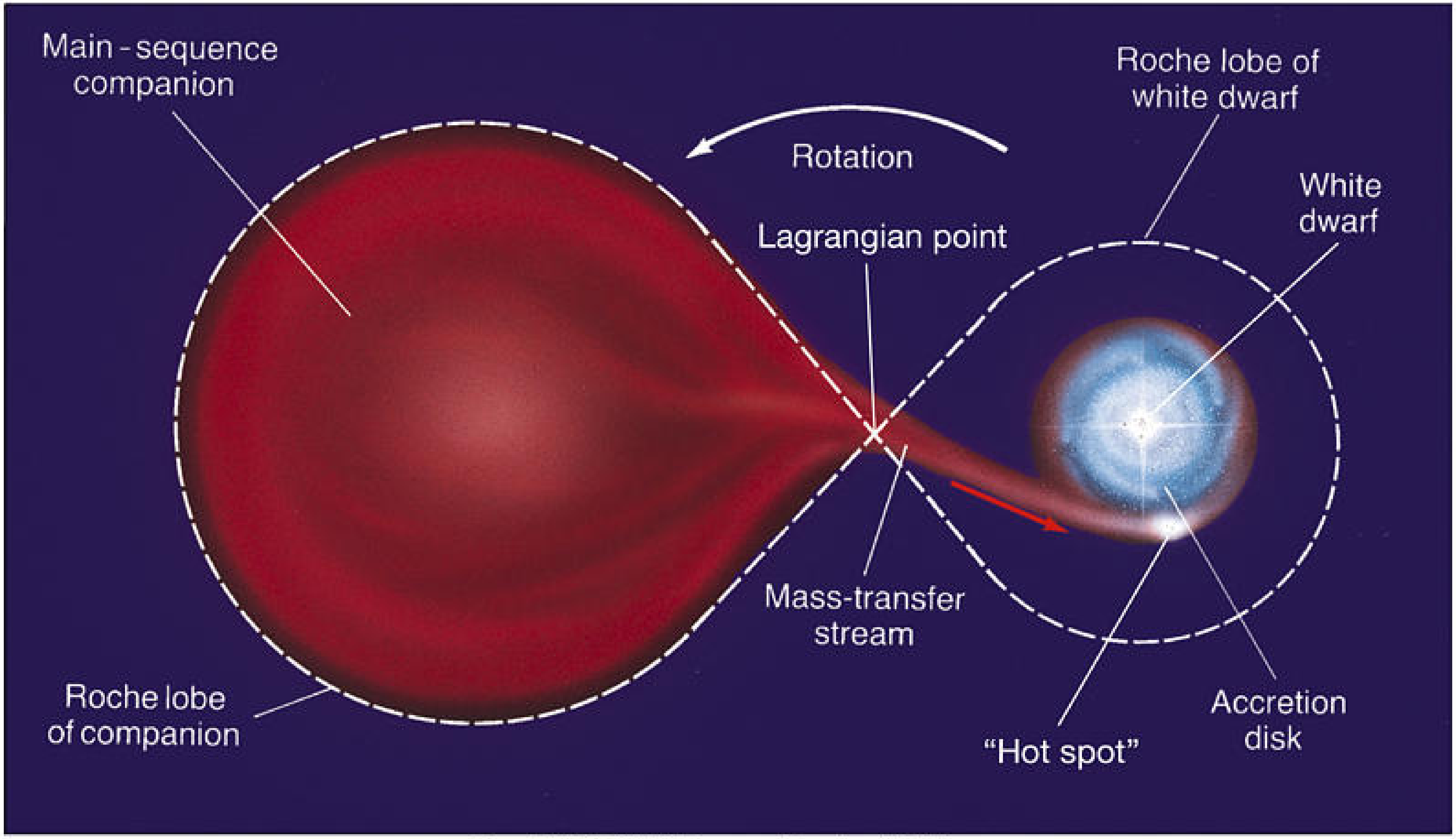
Nevertheless, for now I stick with S and L.

Neutron Star Masses and Radii and the EOS



- Unlike planets, neutron stars form a one-dimensional family
- Neutron stars (to better than 10%) all lie on one universal mass-radius curve
- Recent measurement of two $2\ M_\odot$ neutron stars
  Demorest et al. (2010), Antoniadis et al. (2013)
- Until recently, neutron star radii constrained to 8-15 km
  Lattimer and Prakash (2007)

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

Photospheric Radius Expansion X-ray 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"

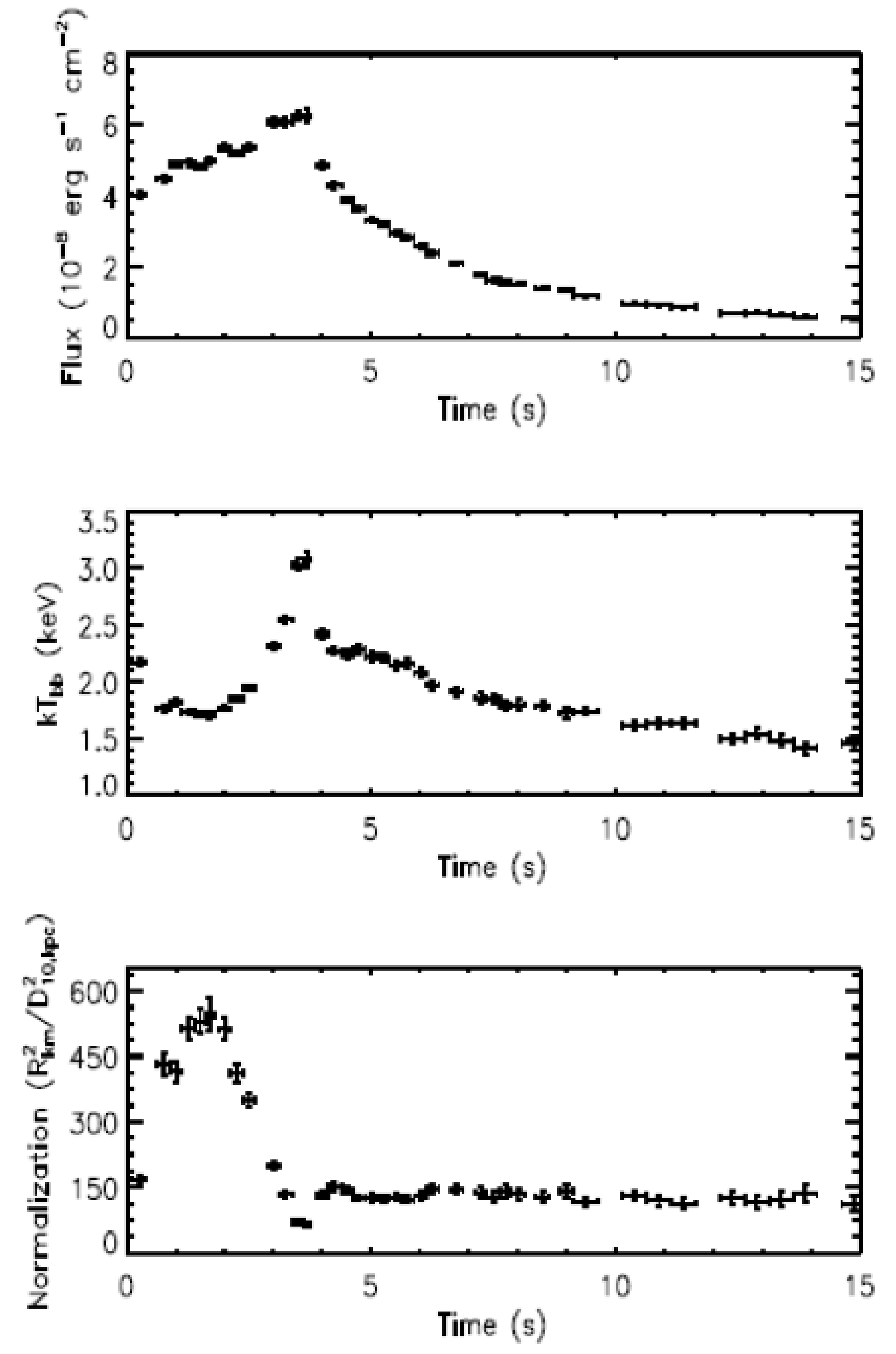
$$F_{TD} = \frac{GMc}{\kappa D^2}\sqrt{1 - 2\beta(r_{ph})}$$

- Normalization during the tail of the burst:

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

- 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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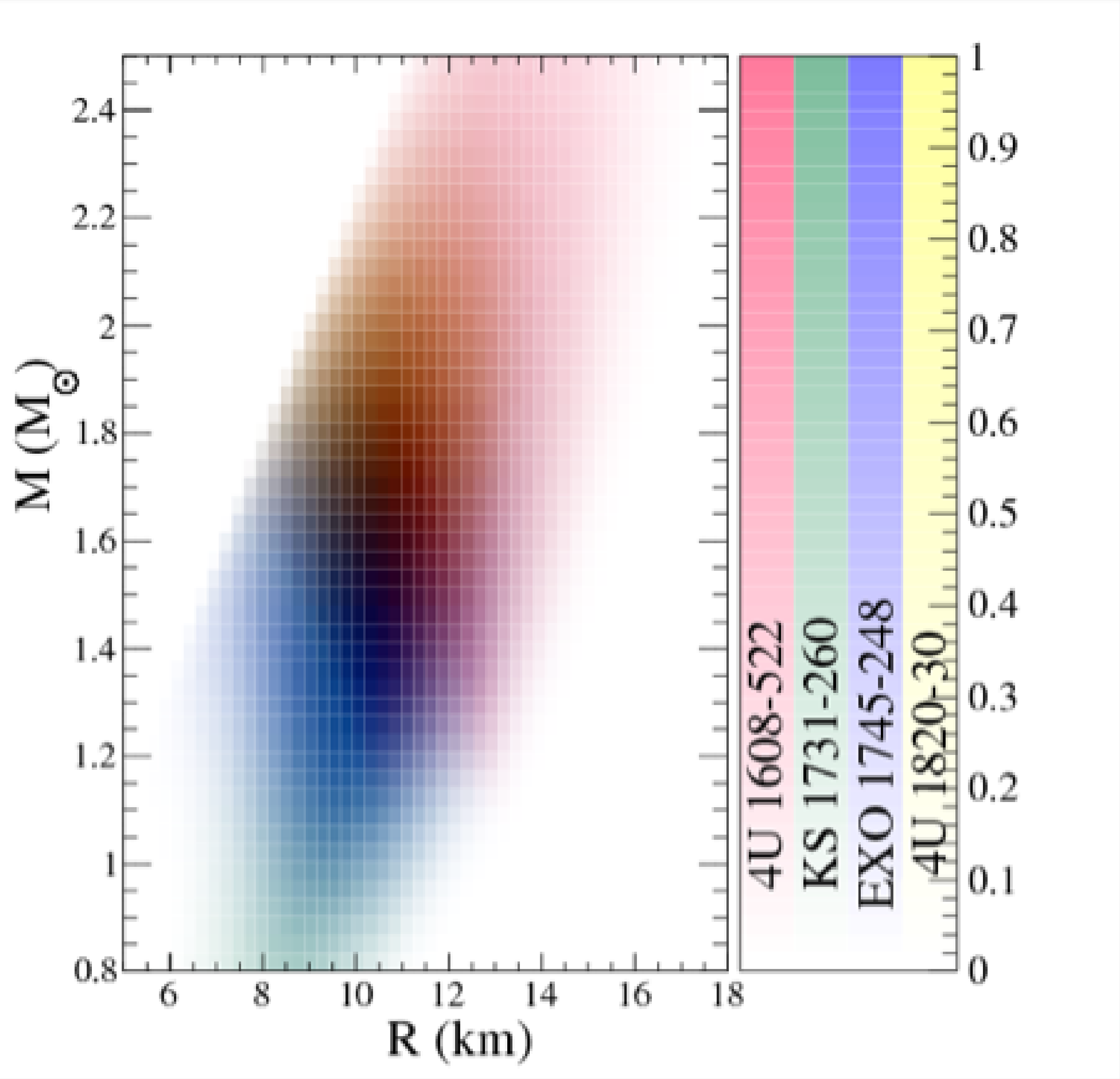


Gandolfi et al. (2013)

Radius Measurements in QLMXBs

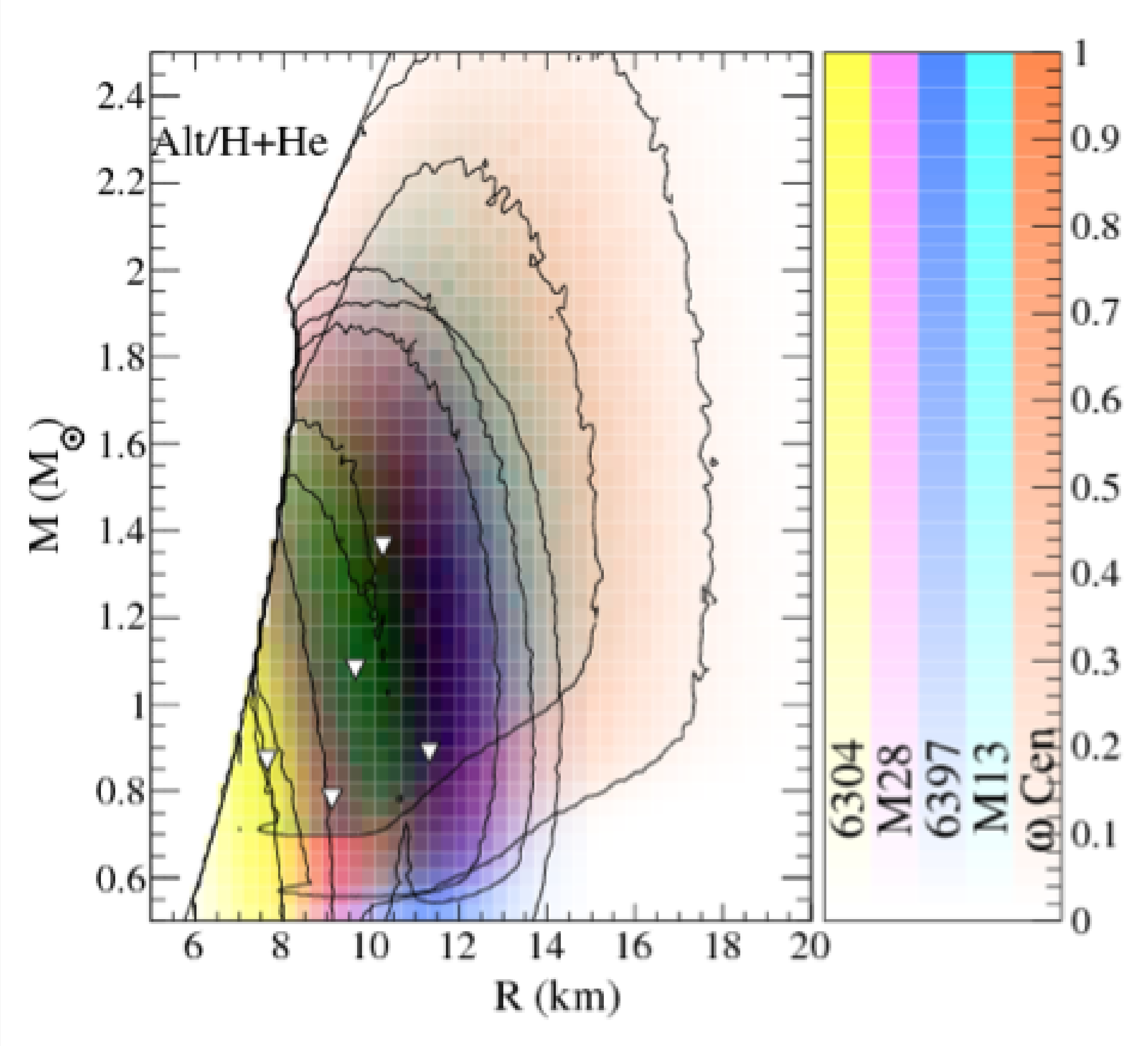
Quiescent LMXBs

- Measure flux of photons and their energy distribution
- Know distance if in a globular cluster
- Implies radius measurement

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

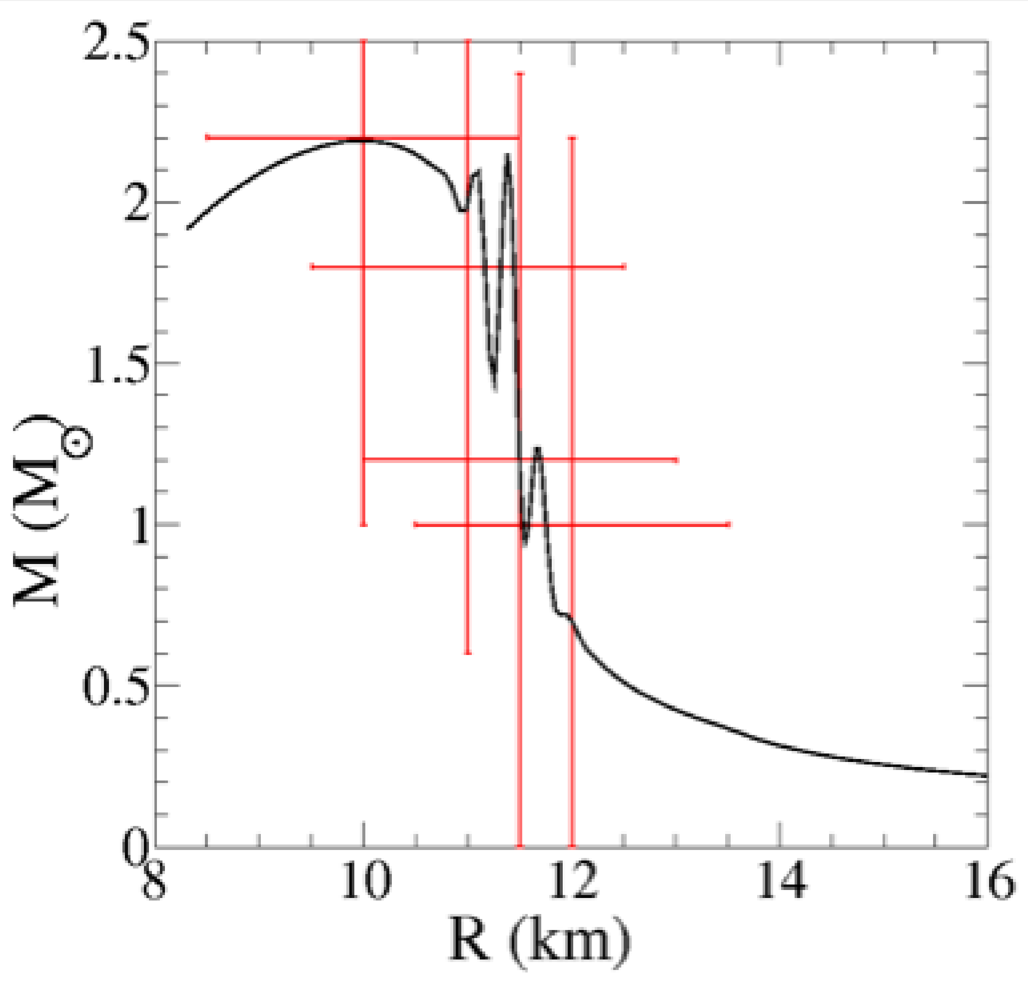
i.e. Rutledge et al. (1999)

Also information from PRE X-ray bursts, ~ 8-12 objects (more on the way)



Lattimer and Steiner (2013)

Bayesian Analysis



- Underconstrained problem
- Intuitive way to theoretical input
- Parameterizations based on known nuclear physics for low densities
- Bayes theorem:

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

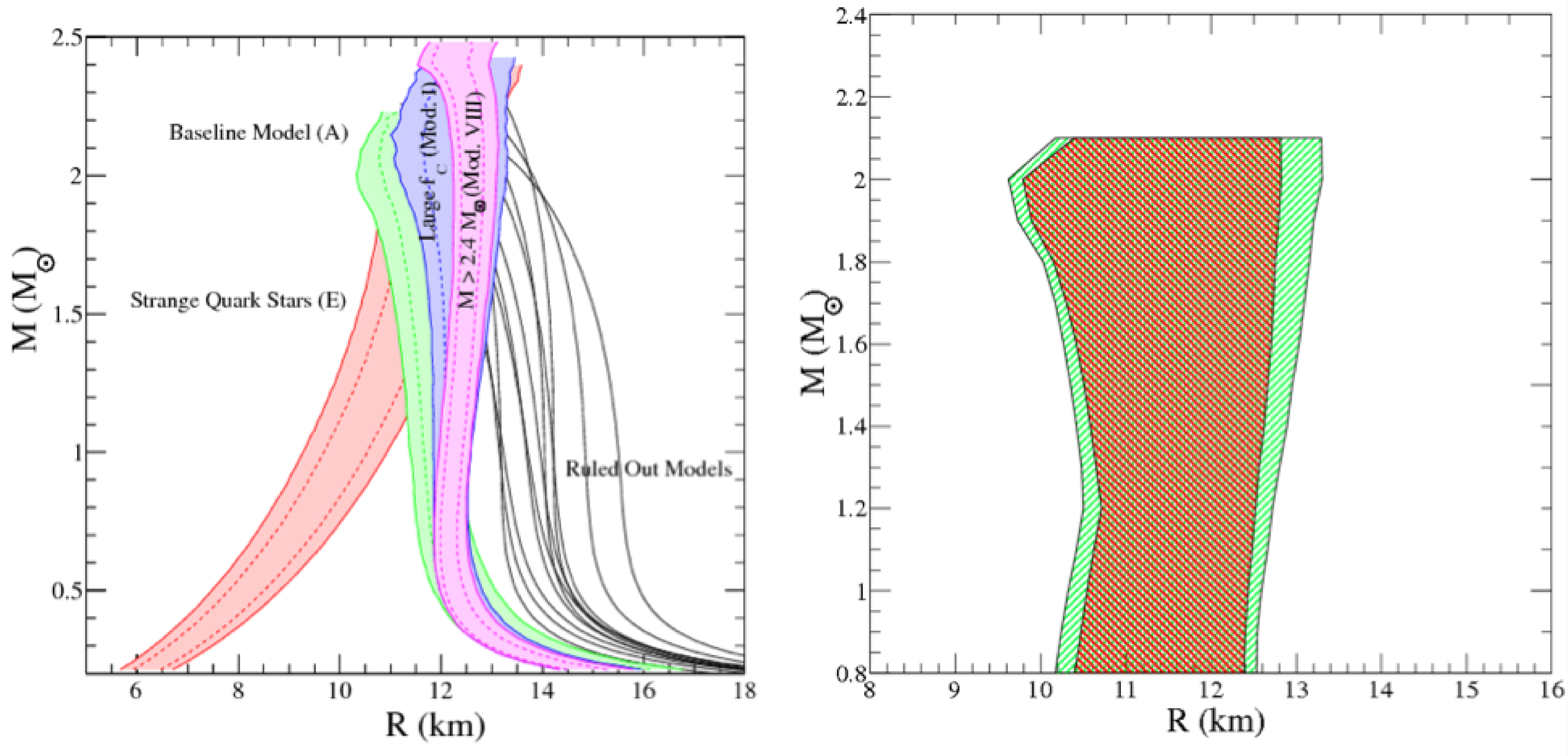
- Prior ⇔ EOS parameterization
- Determine parameters through marginalization, i.e.

$$P(\mathcal{M}_i^0) = \int \delta(\mathcal{M}_i - \mathcal{M}_i^0)P[D|\mathcal{M}_i]P[M]$$

- Bayes factor for model comparison

$$B_{12} = \frac{\int P[D|\mathcal{M}_1]P[M_1]}{\int P[D|\mathcal{M}_2]P[M_2]}$$

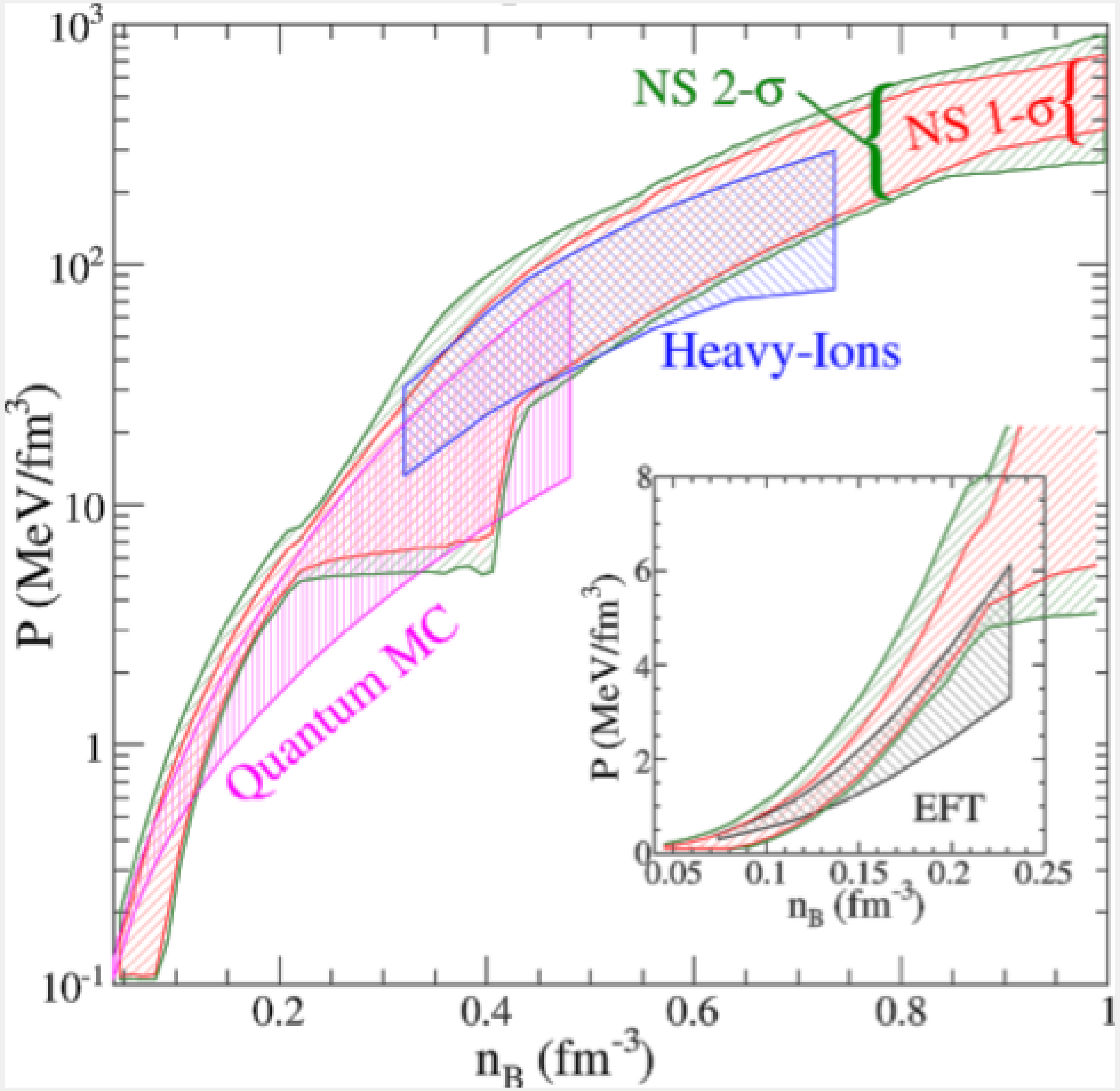
Mass and Radius Results



Steiner, Lattimer, and Brown (2013)

- Vary priors through different EOS parameterizations, choose smallest region enclosing all results
- Range of radii for a 1.4 solar mass star: 10.4 and 12.9 km (95% conf.)
- All neutron stars have nearly the same radius
- Several models are ruled out

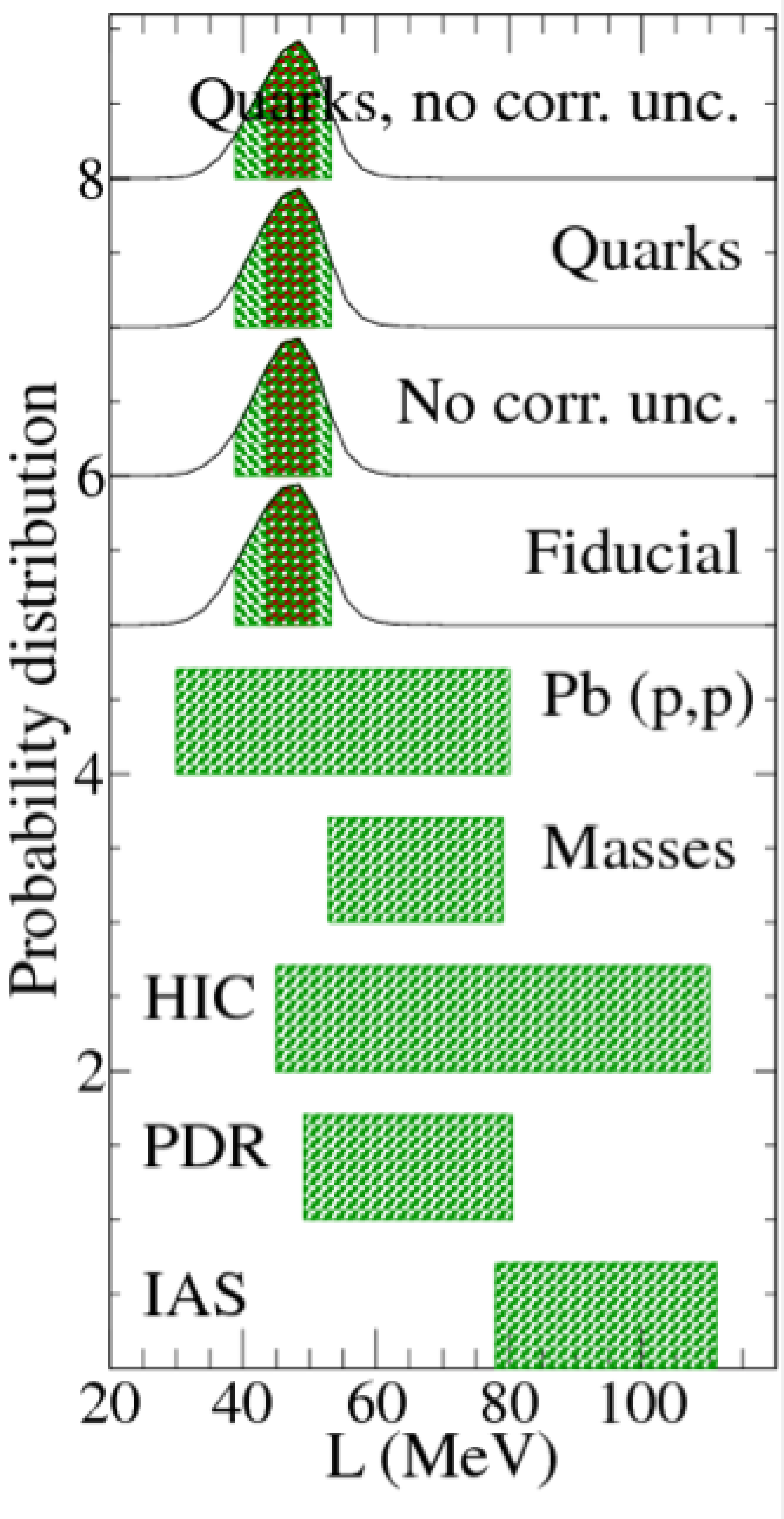
Constraining the EOS of dense matter



Steiner, Lattimer, and Brown (2013)

- $P(\varepsilon)$ determined to within about 60%
- We find concordance between nuclear physics data and astronomical observations
- Probe densities inaccessible to experiment and to perturbation theory in QCD

Constraints on the Nuclear Symmetry Energy



Steiner and Gandolfi (2012)

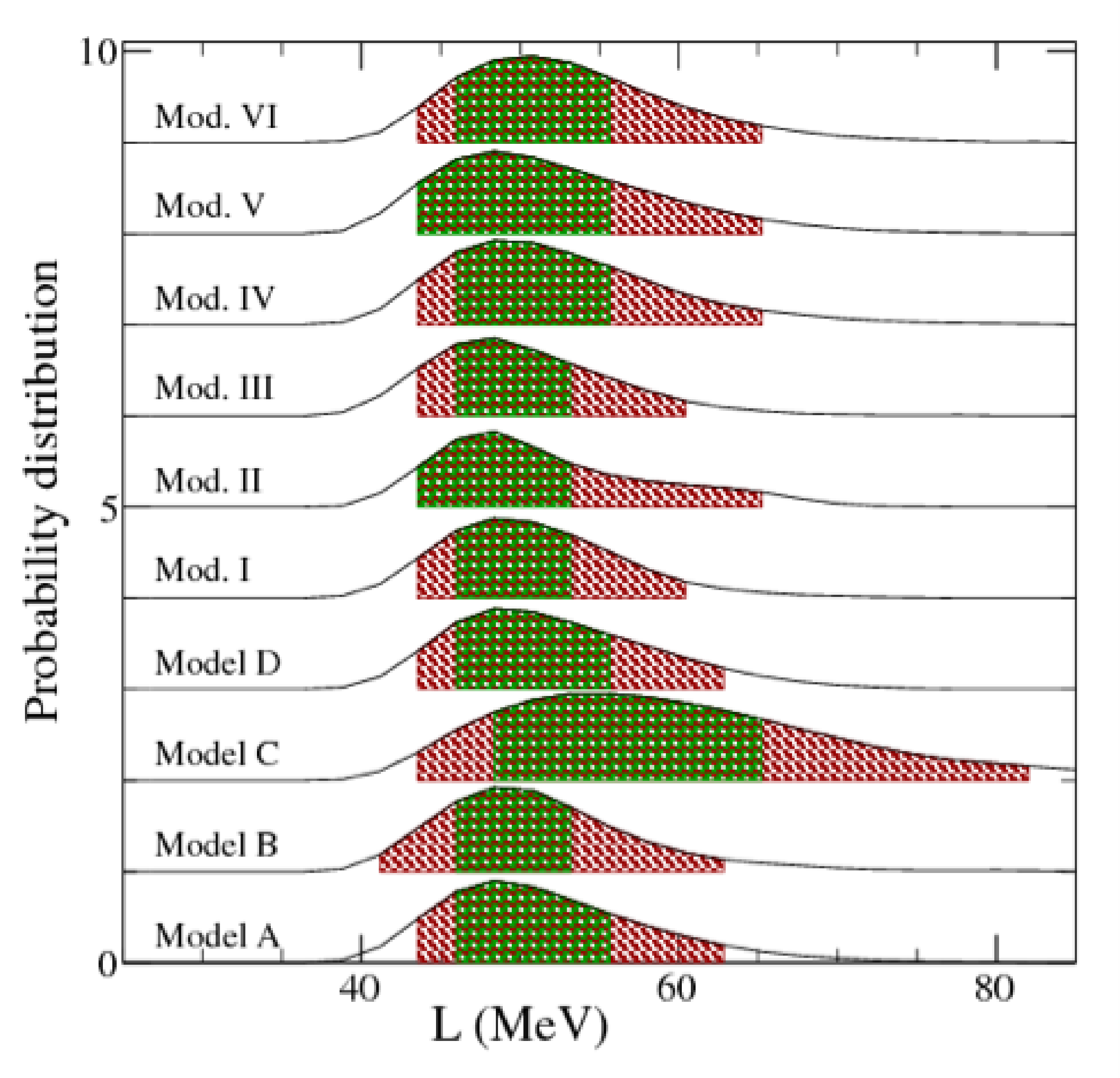
- Found 43 < L < 52 MeV to 68%

  (Steiner and Gandolfi 2012)

- Found 43.3 < L < 66.5 MeV to 68% and 41.1 < L < 83.4 MeV to 95%

  (Steiner et al. 2013)

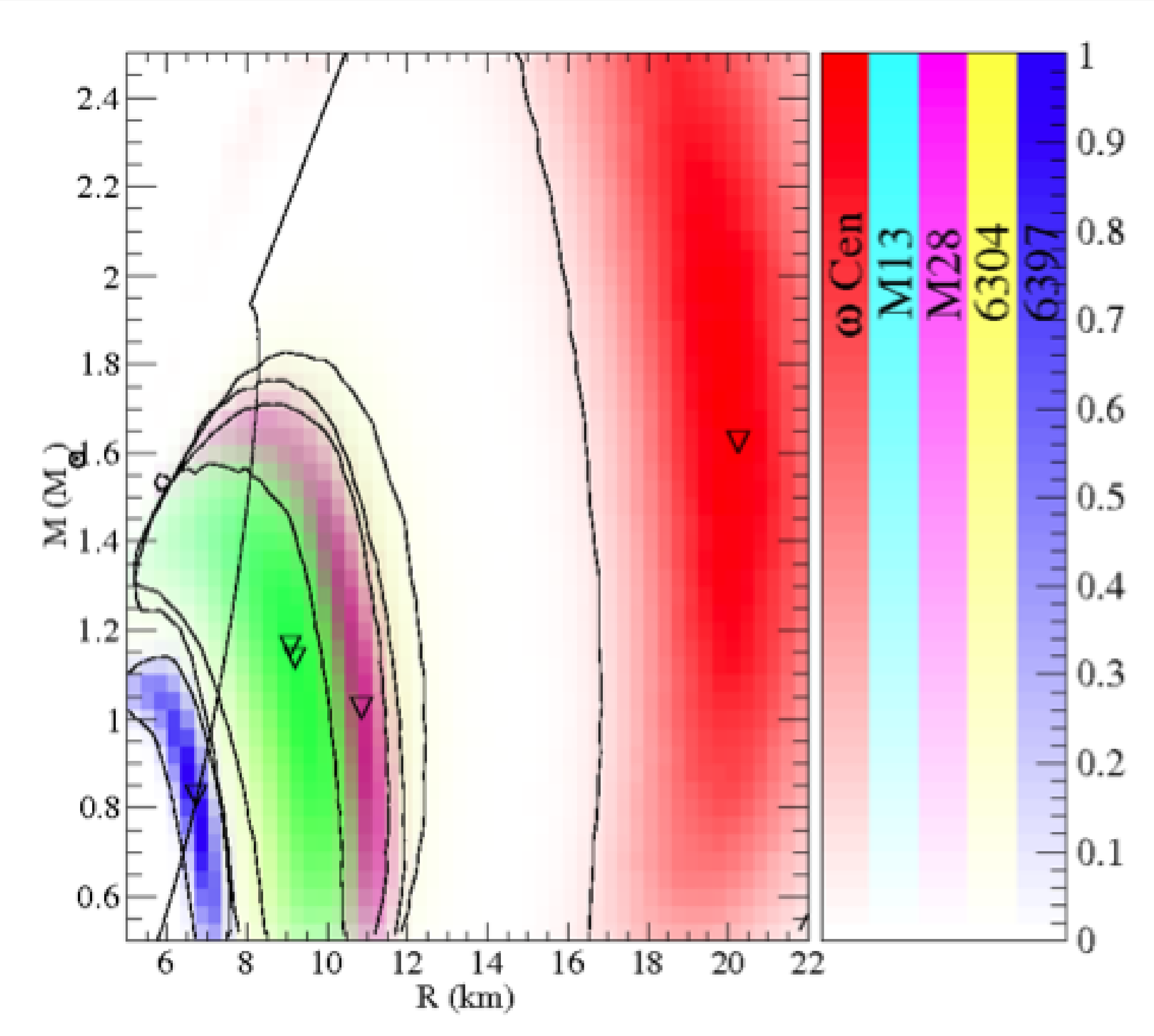
- Model C: Strong phase transitions just above the saturation density



PRE X-ray bursts

- van Paradijs et al. pioneer the idea, it's rarely used until Özel writes several papers starting in 2007ish, getting small radii
- We demonstrate that photosphere radii are large at touchdown, add QLMXB data, use some nuclear physics, and get ~ 11 km radii. (Steiner et al. 2010)
- Suleimanov gets larger radii (14 km) for a long burst in XTE J1701, and claims other PRE X-ray data is poisoned by accretion (Suleimanov et al. 2011)
- Yet the larger radius is somewhat inconsistent with QLMXB radii (Steiner et al. 2013)
- There are several systematic issues: absolute flux calibration, atmosphere uncertainties, time evolution of f_C, spherical asymmetry, funny features in A, different A's for different bursts (spherical asymmetry addressed Zamfir et al. 2012, they find small radii)
- Becomes clear that there may be (at least) two types of PRE X-ray bursts, which have different properties. May help explain some phenomenology. (Work by G. Zhang)
- Güver et al. do a systematic analysis of several sources and show that the fit of XTE J1701 is poor, but good for other sources (Güver et al. 2012a and 2012b)
- Work with Suleimanov finds XTE J1701 is complicated by a boundary layer (possibly explaining the poor fit?) (Retvinsev et al. 2013)
- Status: Larger (~14 km) radii are not preferred and result in poorer fits, unless you presume something has gone terribly wrong in QLMXBs. Nevertheless, PRE X-ray bursts are not well-understood. Need time-dependent models and better explanation of observed diversity.

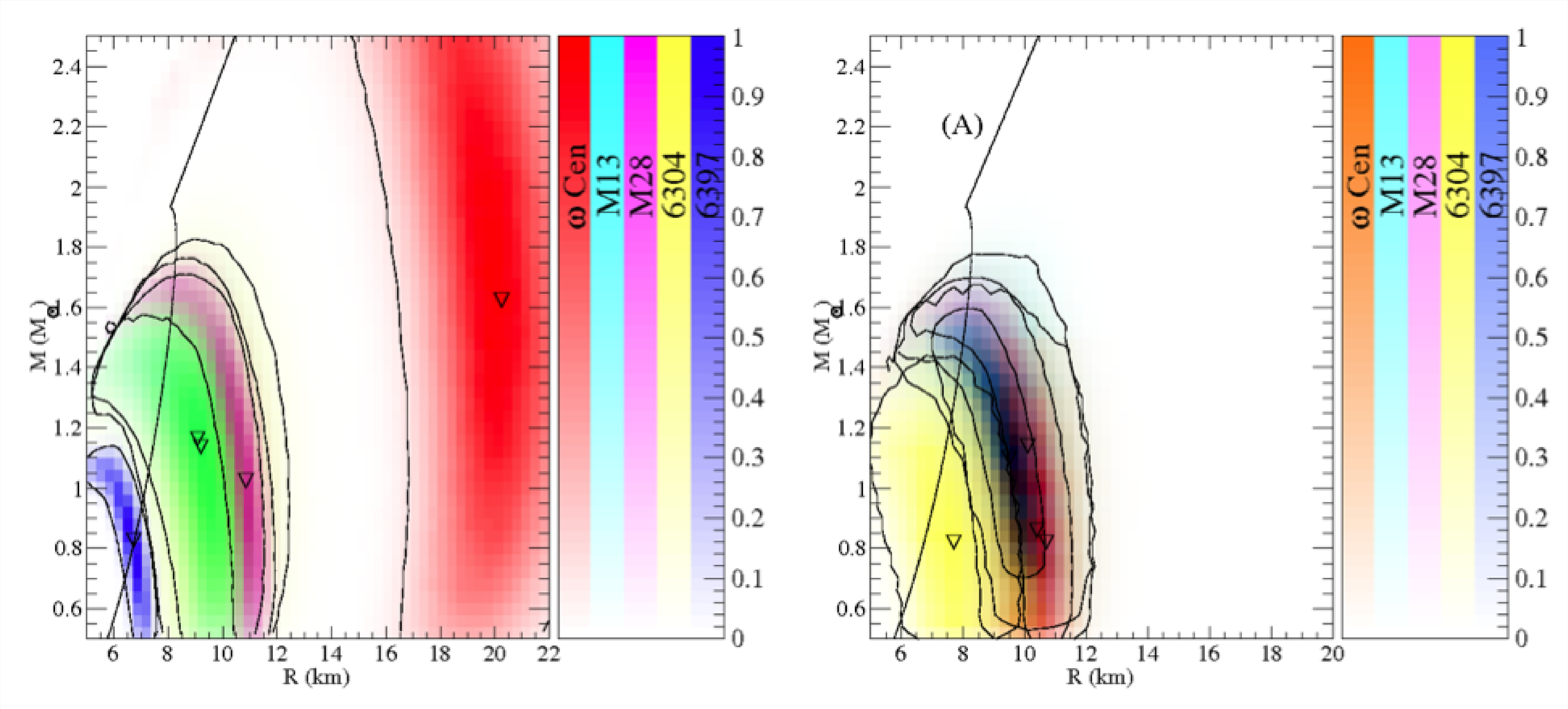
QLMXB Complications



Lattimer and Steiner (2013) and adapted from Guillot et al. (2013)

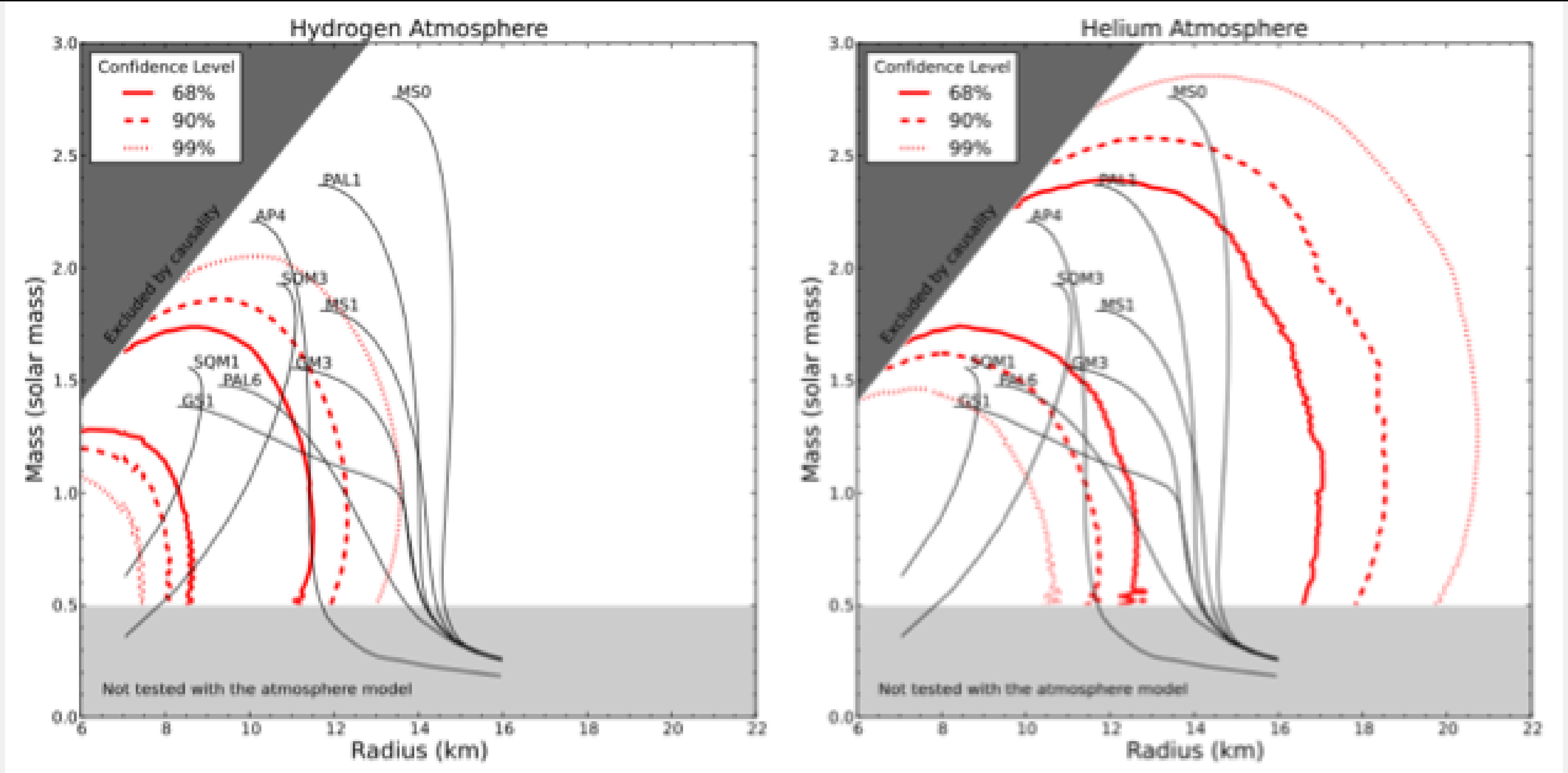
- Observations difficult to reconcile with traditional nuclear physics interpretations

QLMXB Complications

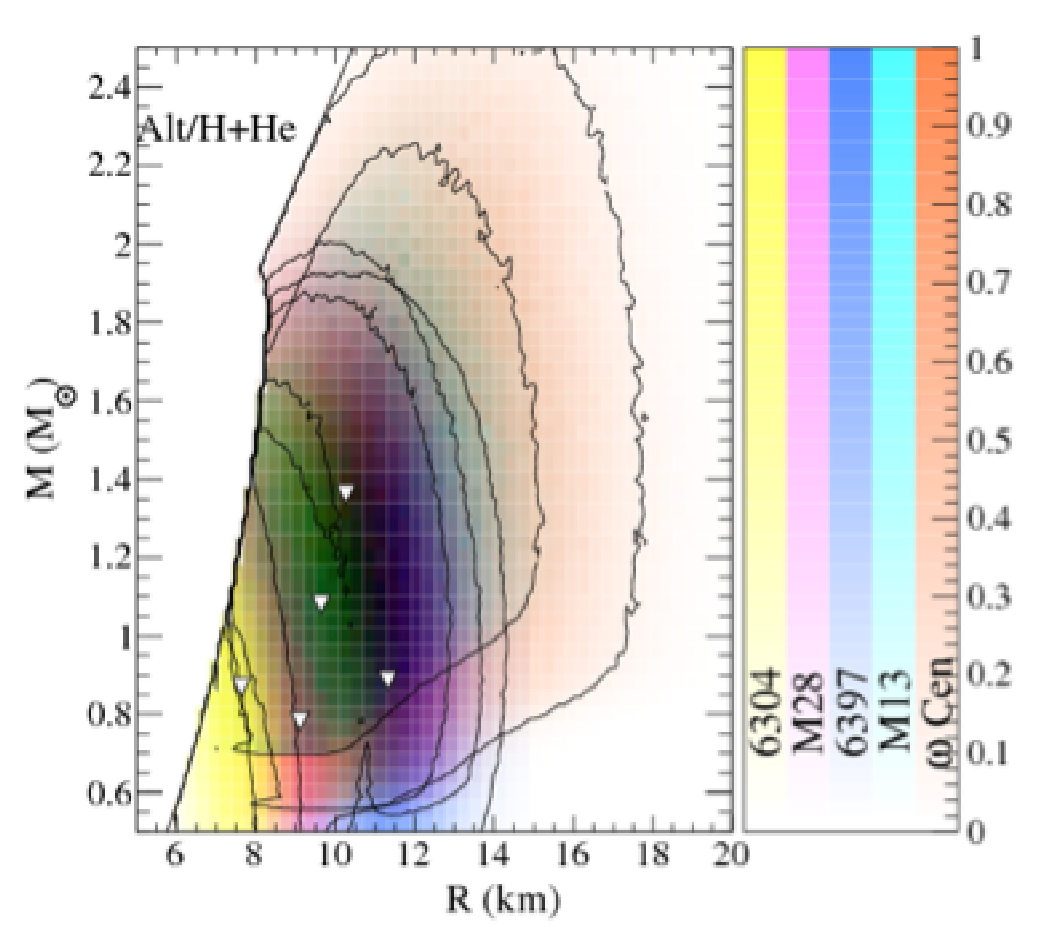


Lattimer and Steiner (2013) and adapted from Guillot et al. (2013)

- We propose treating X-ray absorption differently, infer from optical measurements instead of from X-ray fitting
- We find larger Bayes factors for neutron stars with nuclear crusts



Servillat et al. 2012



Lattimer and Steiner (2013), adapted from Guillot et al. (2013)

QLMXB Complications

- We consider He atmospheres as well
- Generally increases radii and improves Bayes factors for neutron stars with nuclear crusts

Summary

Neutron stars are providing novel constraints on L

- There are gateway quantities that may be helpful
- $10.4\ \text{km} < R_{1.4} < 12.9\ \text{km}$
- $41.1\ \text{MeV} < L < 83.4\ \text{MeV}$
- Lot of work left to do...

- Multitude of interactions with observations and experiment continue to be fruitful

- FRIB in particular will help constrain S, L, the crust, and the EOS above the saturation density