Connecting Neutron Star Observations and the Nucleon-Nucleon Interaction with Gravitational Waves

Andrew W. Steiner (INT/U. Washington)

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With: Edward F. Brown (MSU), Farrukh J. Fattoyev (TAMU-Commerce),
Stefano Gandolfi (Los Alamos), James M. Lattimer (Stony Brook),
William G. Newton (TAMU-Commerce) and Madppa Prakash (Ohio)

LIGO!

Outline

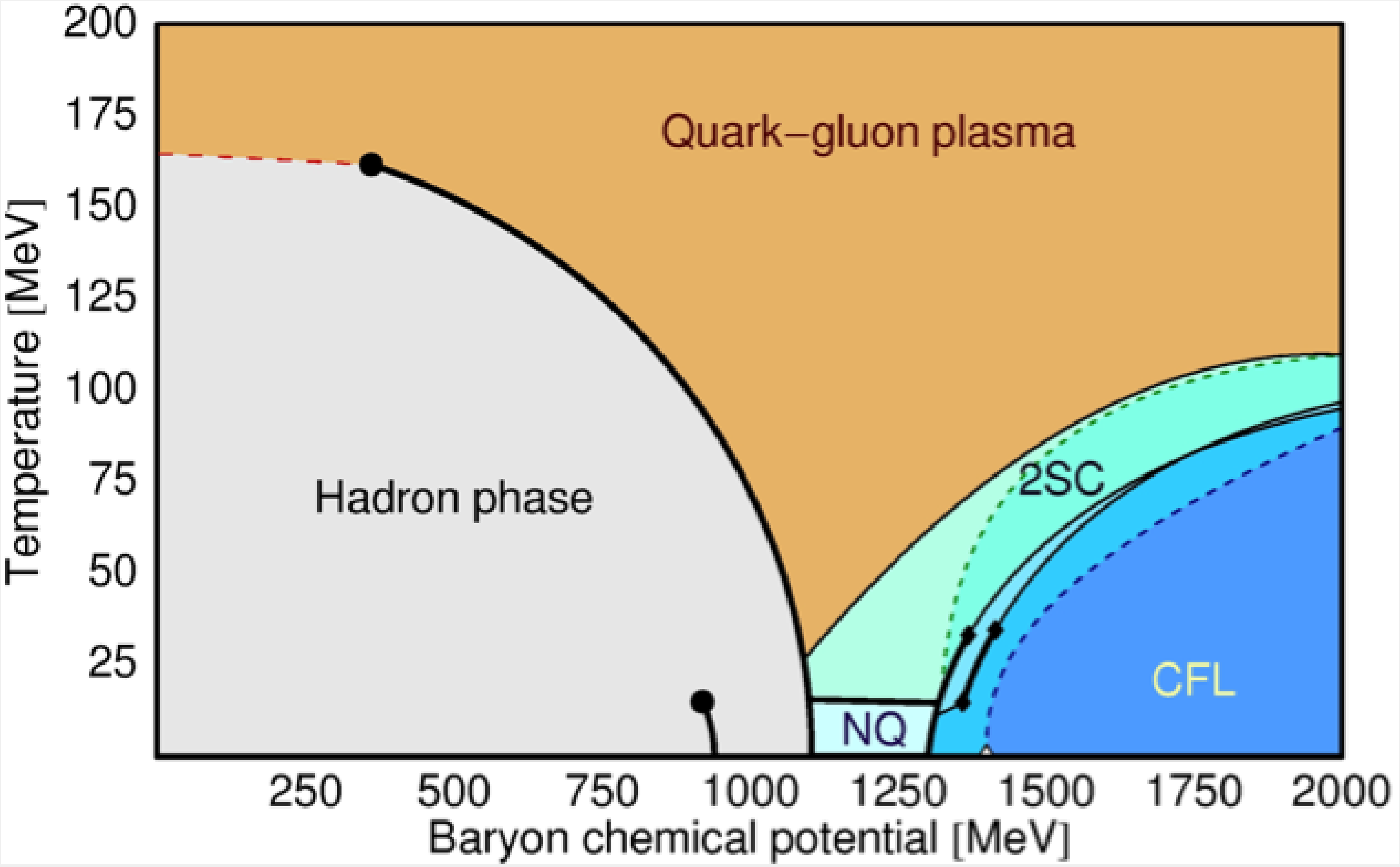
- Neutron star masses and radii and the EOS

- Tidal deformabilities

- Pulsar glitches and moments of inertia

- Neutron drip line

Fundamental Questions



QCD phase diagram, Rüster et al. (2006)

Frontiers of nuclear science (2007):

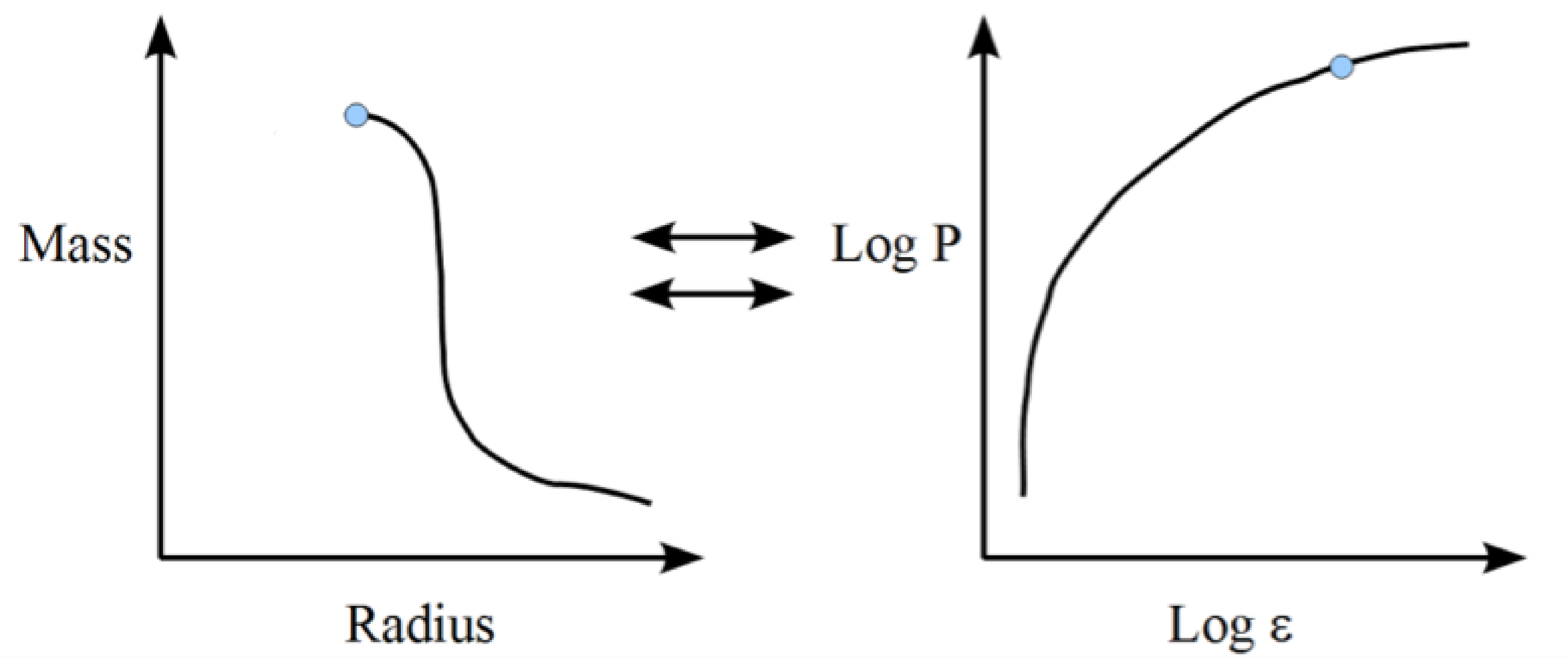
- What is the nature of neutron stars and dense matter?
- What is the nucleon-nucleon interaction?
- What is the origin of the elements?

Also,

- How do neutron stars merge?
- How do mergers generate gravitational waves?

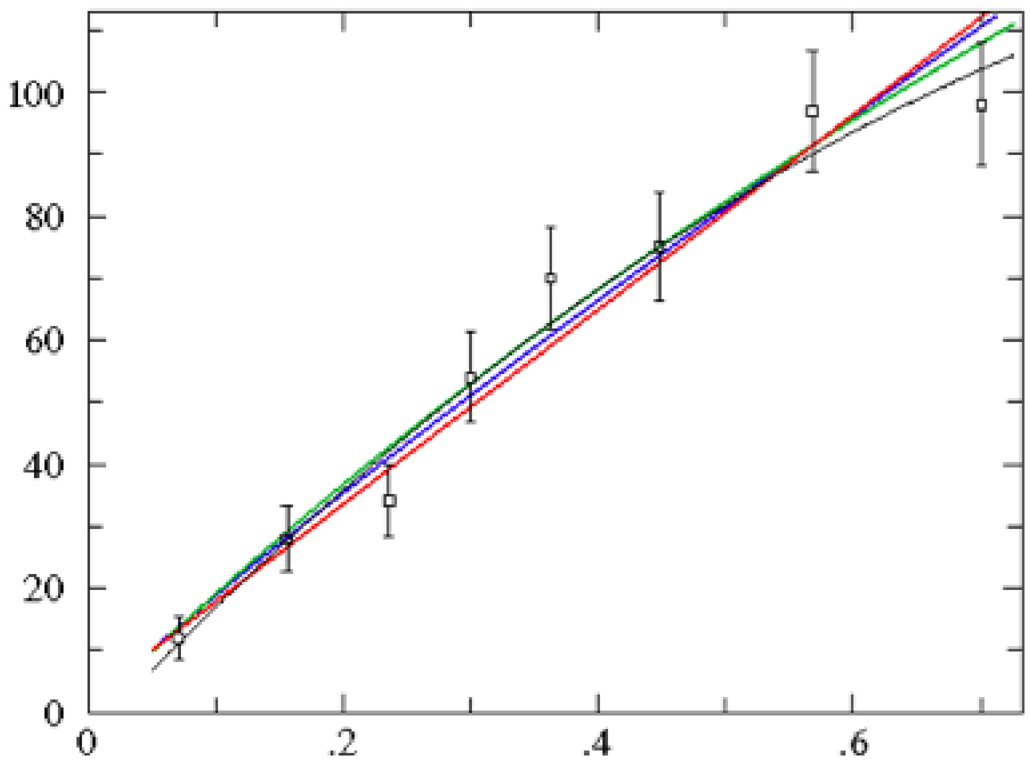
Neutron Star Masses and Radii and the EOS

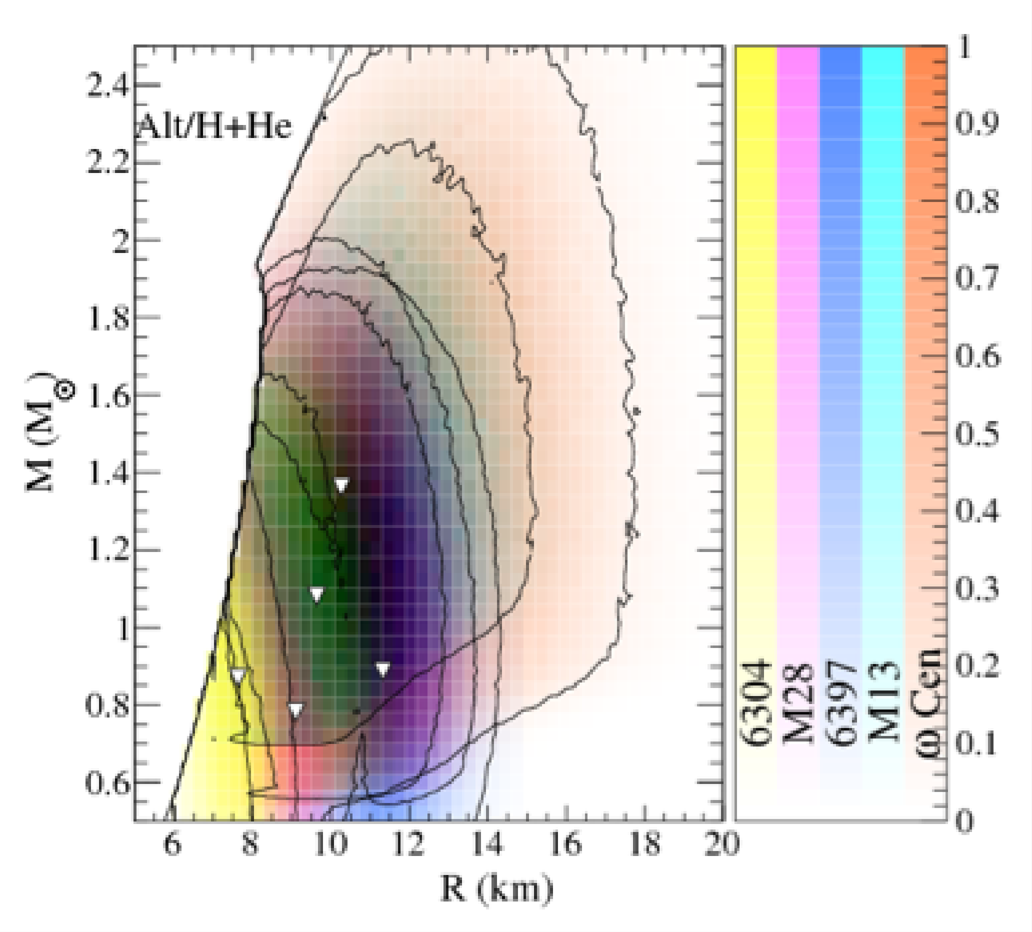
- Neutron stars (to better than 10%) all lie on one universal mass-radius curve
  (Largest correction is rotation - work in progress)
- Recent measurement of two 2 $M_\odot$ neutron stars
  Demorest et al. (2010), Antoniadis et al. (2013)
- As of 2007 neutron star radii constrained to 8-15 km, now 10-13 km
  Lattimer and Prakash (2007); Steiner, Lattimer and Brown (2013)



- Einstein's field equations provide a 1-1 correspondence
- Formally an underconstrained problem, but effectively over constrained if you have enough precise data (we don't yet)

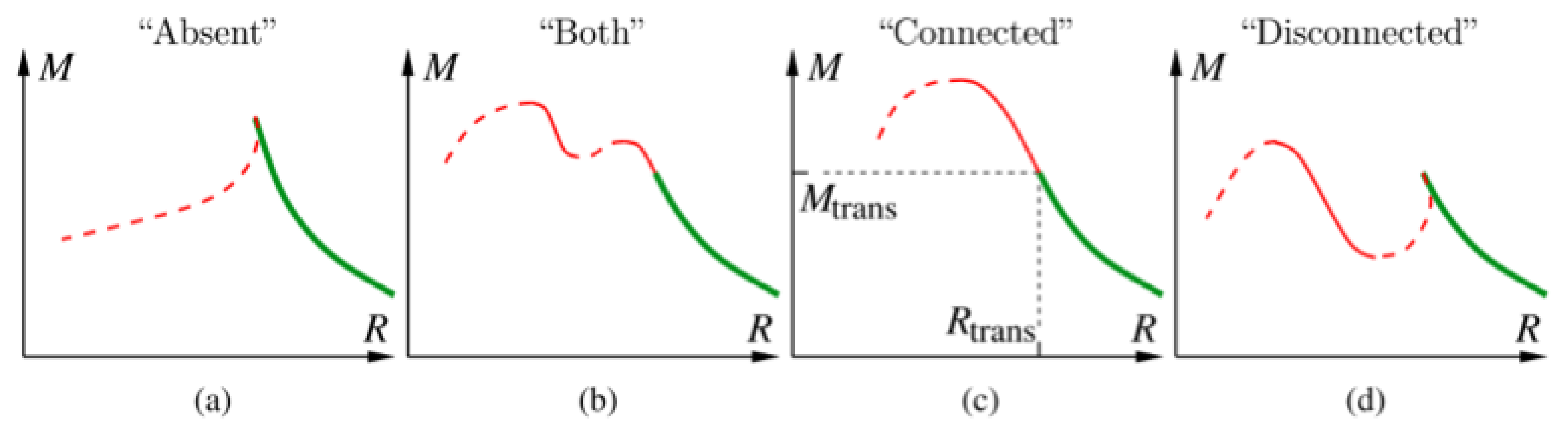
χ^2 fits





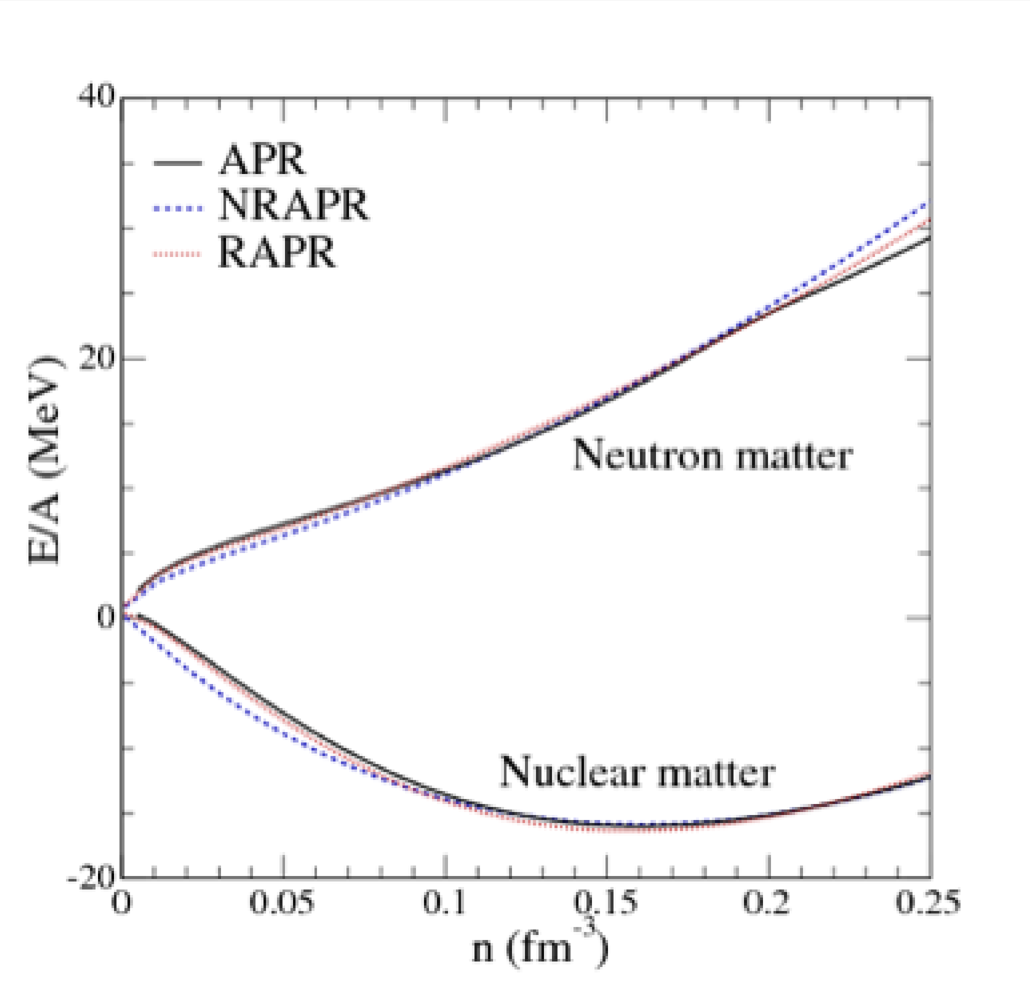
Lattimer and Steiner (2014)

- Straightforward when there's no uncertainty in the horizontal axis
- When there is: e.g. "Deming regression"
- M-R curve is not a function (central pressure is a better "independent" variable)



Alford, Han, and Prakash (2014)

EOS parameterization



Steiner et al. (2005)

Nucleonic matter:

$$\varepsilon = B + \frac{K}{18 n_0^2}(n - n_0)^2$$

$$+(1-2x)^2 (17\ \mathrm{MeV}) \left(\frac{n}{n_0}\right)^{2/3}$$

$$+(1-2x)^2 (S - 17\ \mathrm{MeV}) \left(\frac{n}{n_0}\right)^{\gamma}$$

- Parameters: $B, K, S,$ and γ
- $S(n_B) \equiv E_{\mathrm{neut}}(n_B) - E_{\mathrm{nuc}}(n_B)$
- $S = S(n_0); L = 3 n_0 S'(n_0)$

High densities:

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

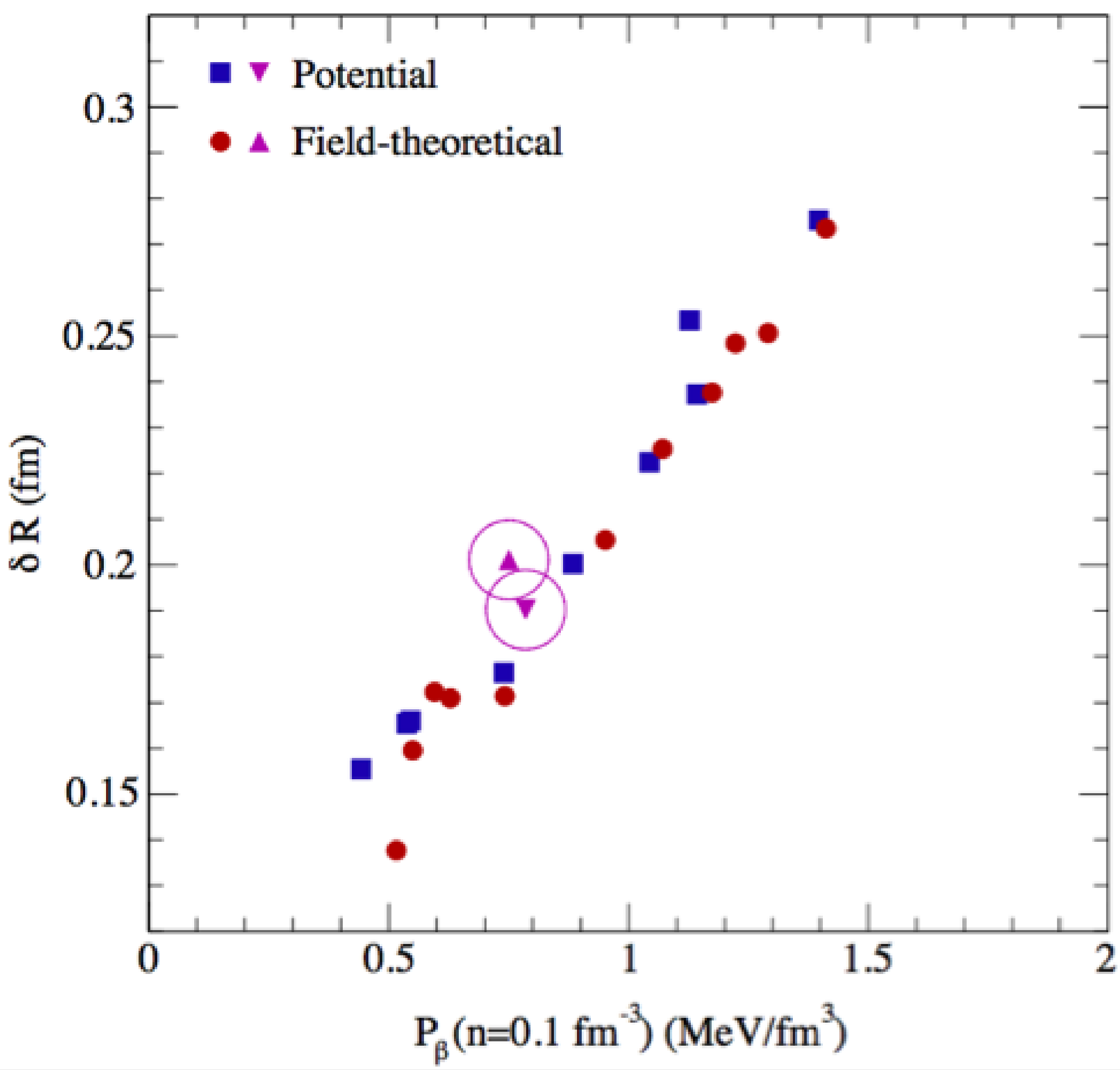
$$\text{crust} \mid \varepsilon_{\text{trans}} \mid \text{nucleons} \mid \varepsilon_1 \mid \text{Polytrope 1} \mid \varepsilon_2 \mid \text{Polytrope 2}$$

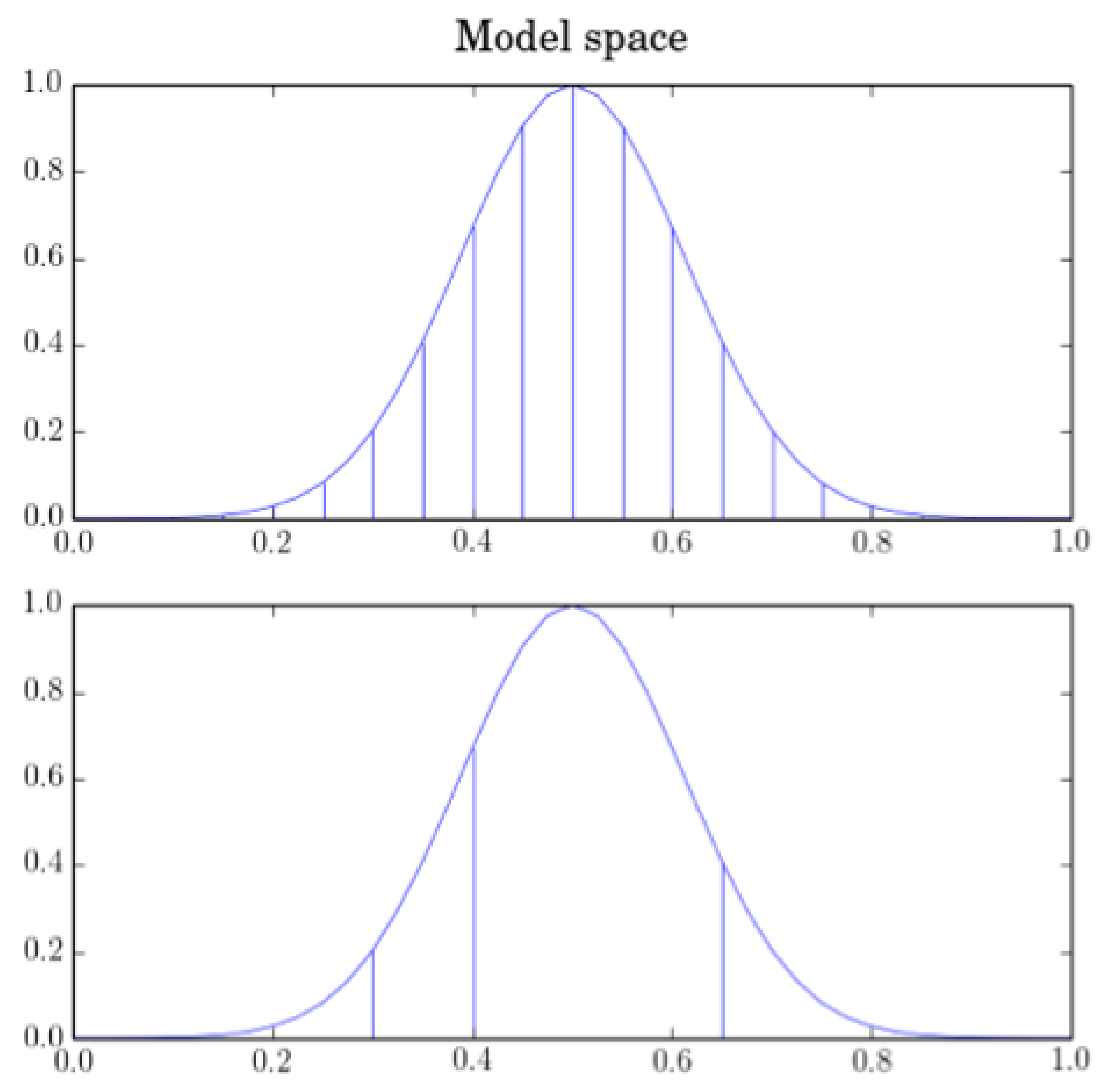
- Lines: $P(\varepsilon) = A_i \varepsilon + P_i$

$$\text{crust} \mid \varepsilon_{\text{trans}} \mid \text{nucleons} \mid \varepsilon_1 \mid \text{line 1} \mid \varepsilon_2 \mid \text{line 2} \mid \ldots$$

Purpose of a Model

- Model comparison
  Model A vs. Model B?
- Parameter estimation
  However, parameters don't always have a clear physical meaning
- Predictions
  Produce a probability distribution
  - Distribution over parameter space and also over model space





Steiner et al. (2005)

Radius Measurements in qLMXBs

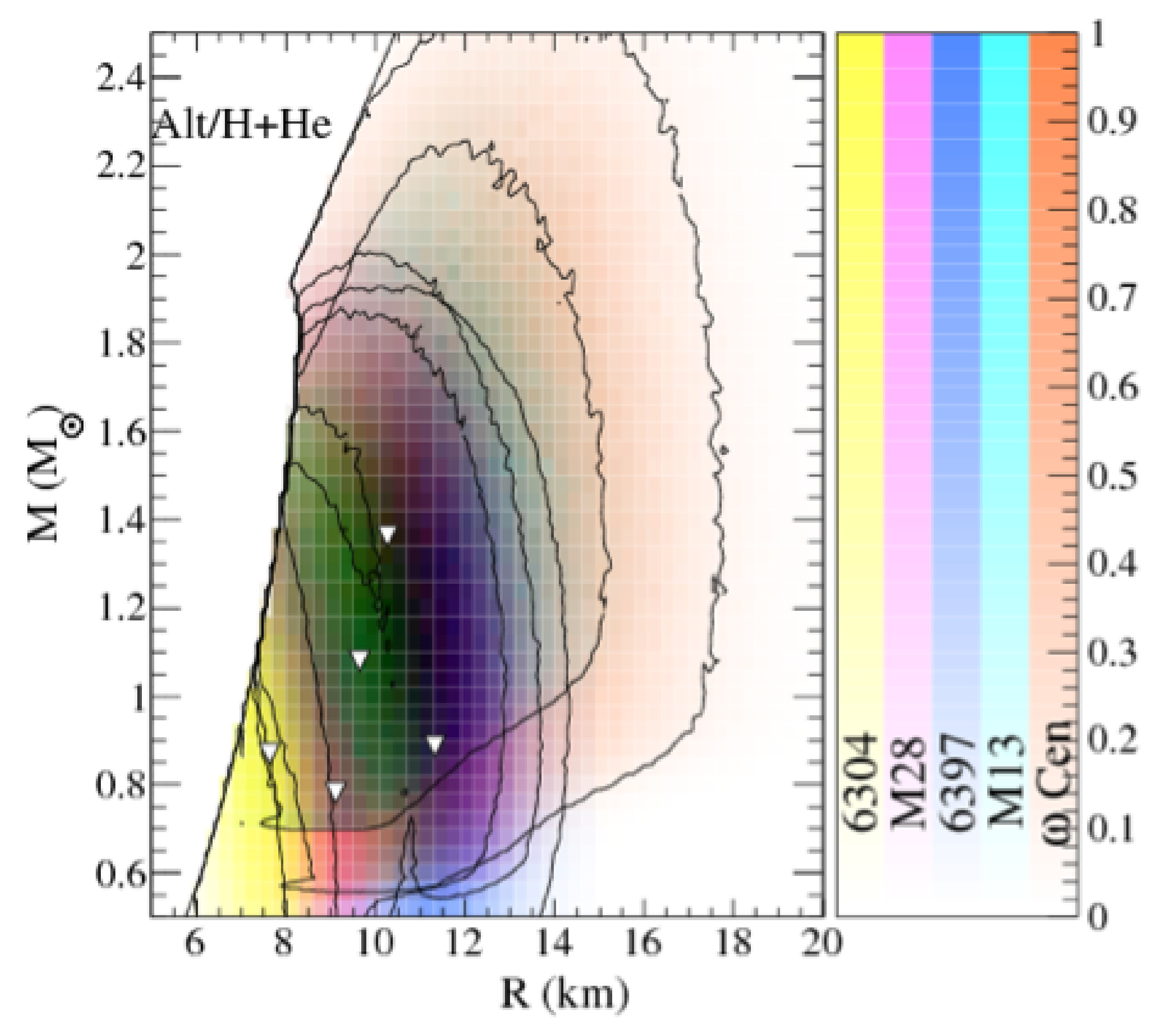
Quiescent LMXBs

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

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

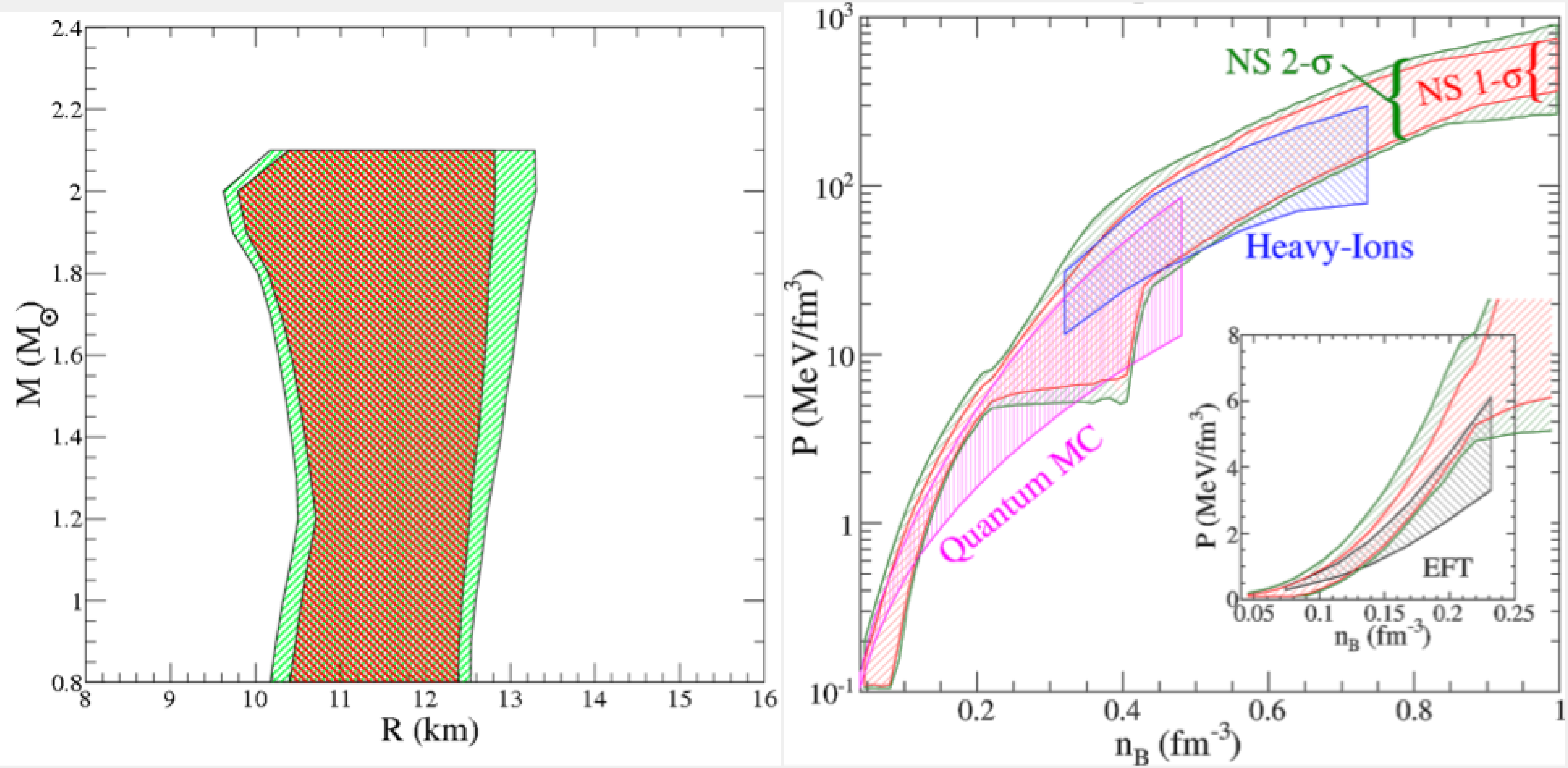
i.e. Rutledge et al. (1999)

- Many important unresolved systematics
- Need to understand X-ray absorption between source and observer
- Need information about the atmosphere, including composition
- Also need X-ray absorption and absolute flux calibration
- Inevitably give small radii for some low-mass stars



Lattimer and Steiner (2014) - Probability distributions for five neutron stars, colors added together

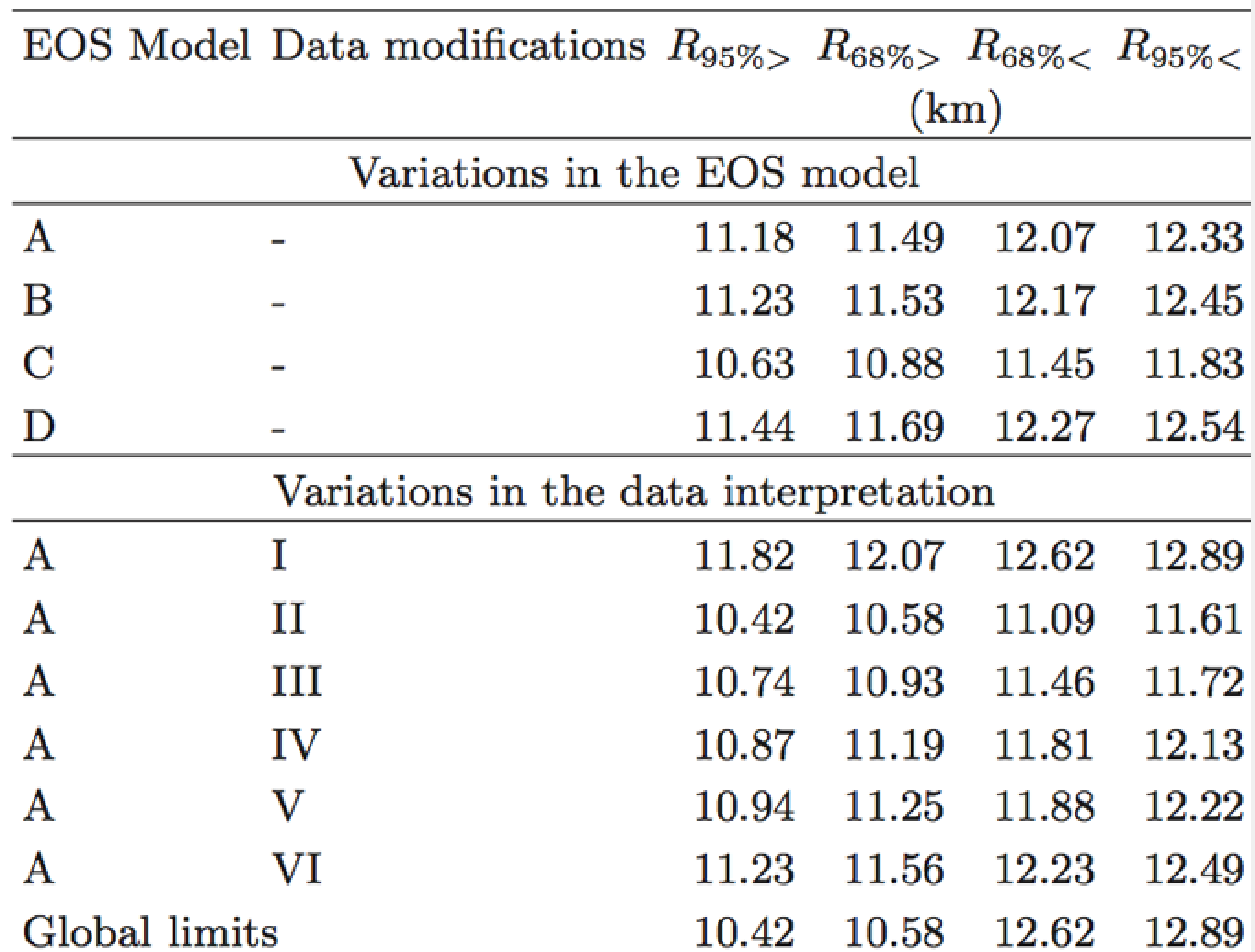
The M-R curve and the EOS of Dense Matter



Steiner, Lattimer, and Brown (2013); red and green outlines 68% and 95% regions

- Full Bayesian MCMC sampling of the likelihood (times prior)
- Radius of a 1.4 solar mass neutron star is 10.4 - 12.9 km
- Note the uncertainty in the EOS at a few times saturation
- These results are limited by strong systematic uncertainties
- No assumption that pressure is correlated between low and high-densities

The M-R curve and the EOS of dense matter

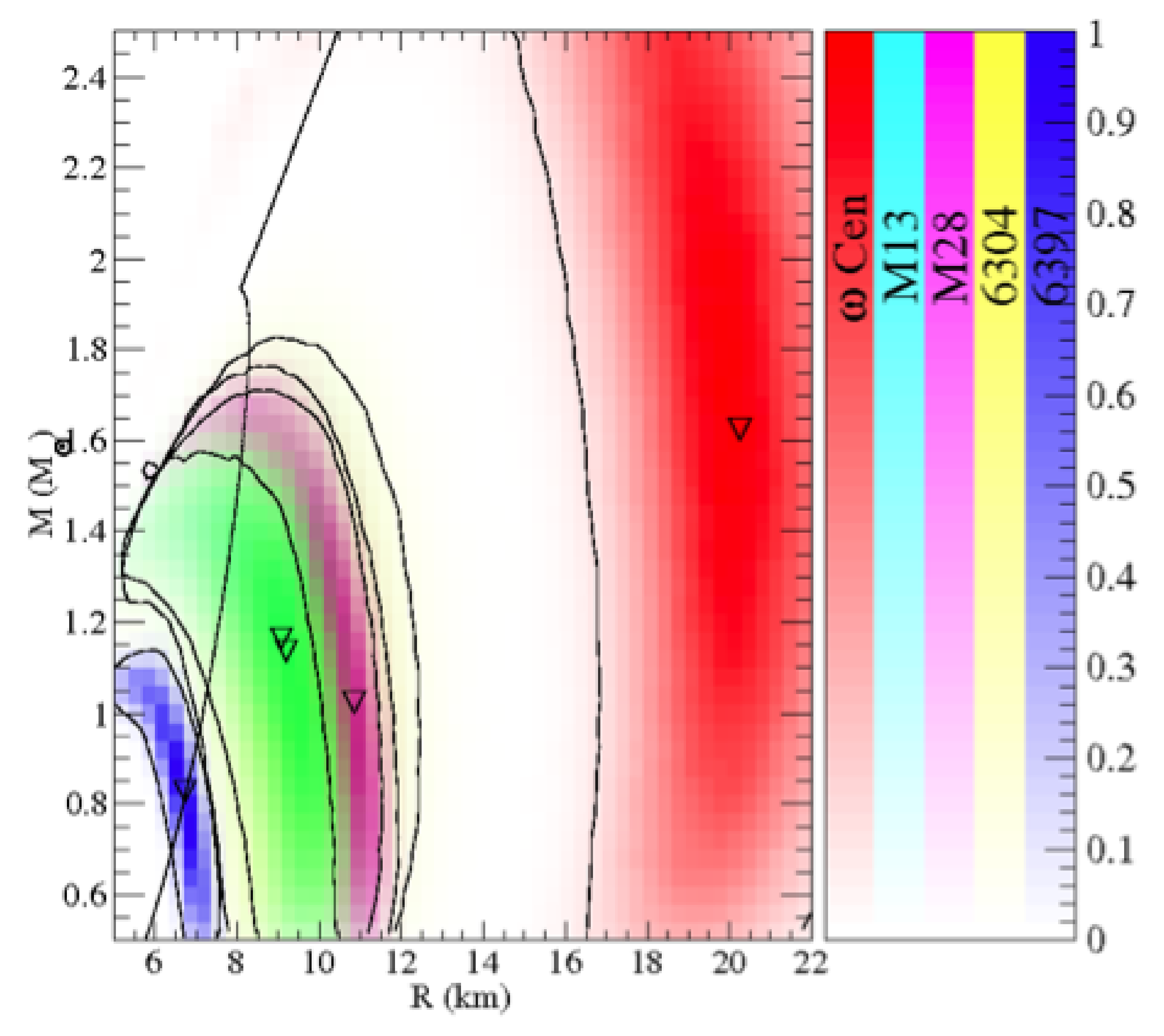


EOS Model	Data modifications	$R_{95\%>}$	$R_{68\%>}$	$R_{68\%<}$	$R_{95\%<}$
			(km)		
Variations in the EOS model					
A	-	11.18	11.49	12.07	12.33
B	-	11.23	11.53	12.17	12.45
C	-	10.63	10.88	11.45	11.83
D	-	11.44	11.69	12.27	12.54
Variations in the data interpretation					
A	I	11.82	12.07	12.62	12.89
A	II	10.42	10.58	11.09	11.61
A	III	10.74	10.93	11.46	11.72
A	IV	10.87	11.19	11.81	12.13
A	V	10.94	11.25	11.88	12.22
A	VI	11.23	11.56	12.23	12.49
Global limits		10.42	10.58	12.62	12.89

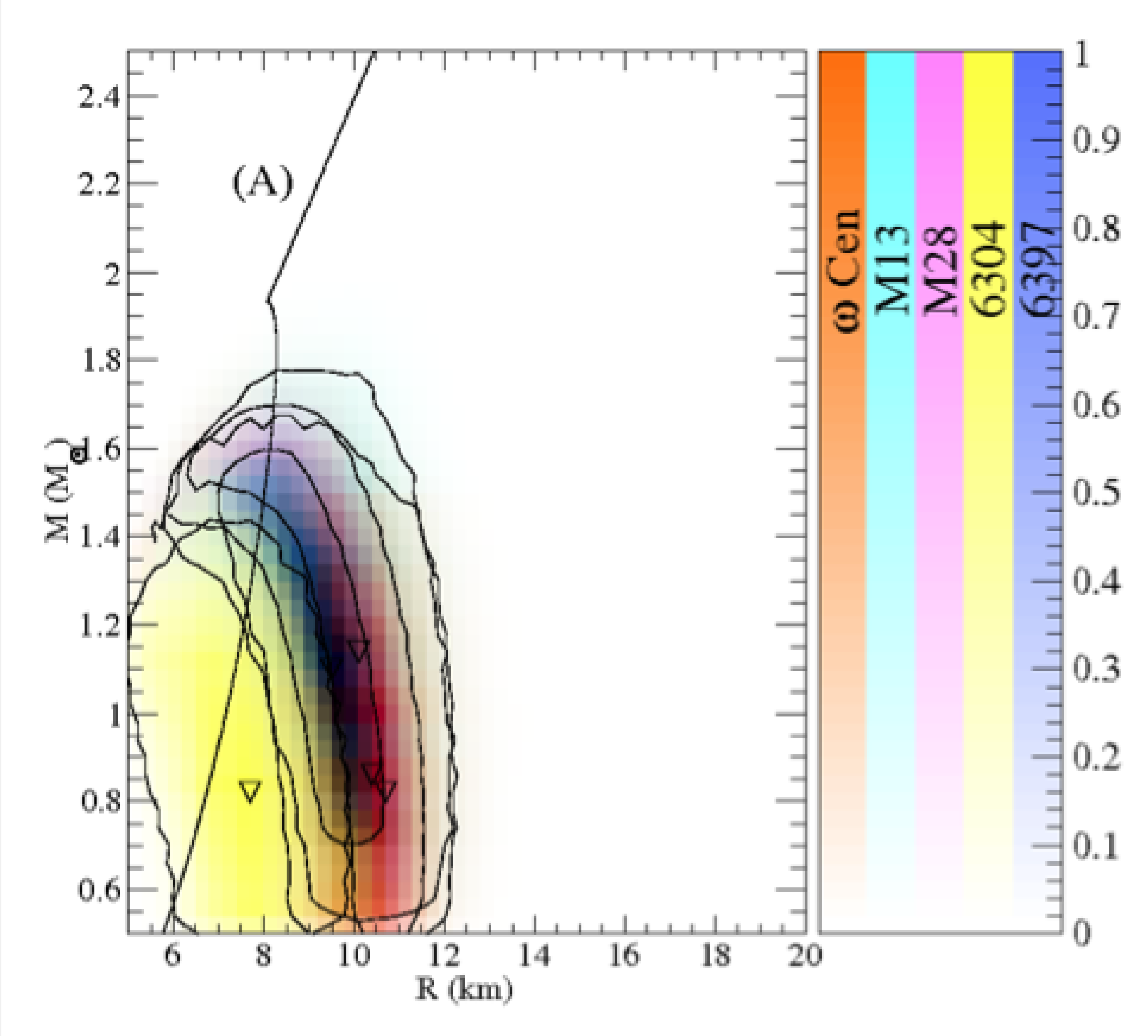
Steiner, Lattimer, and Brown (2013)

- Critical component: trying different EOS parameterizations and different interpretations of the data
- Model C allows for strong phase transitions
- Try several different models to assess systematics

As of last year...



Results from Guillot et al. (2013) slightly adapted for Lattimer and Steiner (2014) before any assumption about the M-R curve

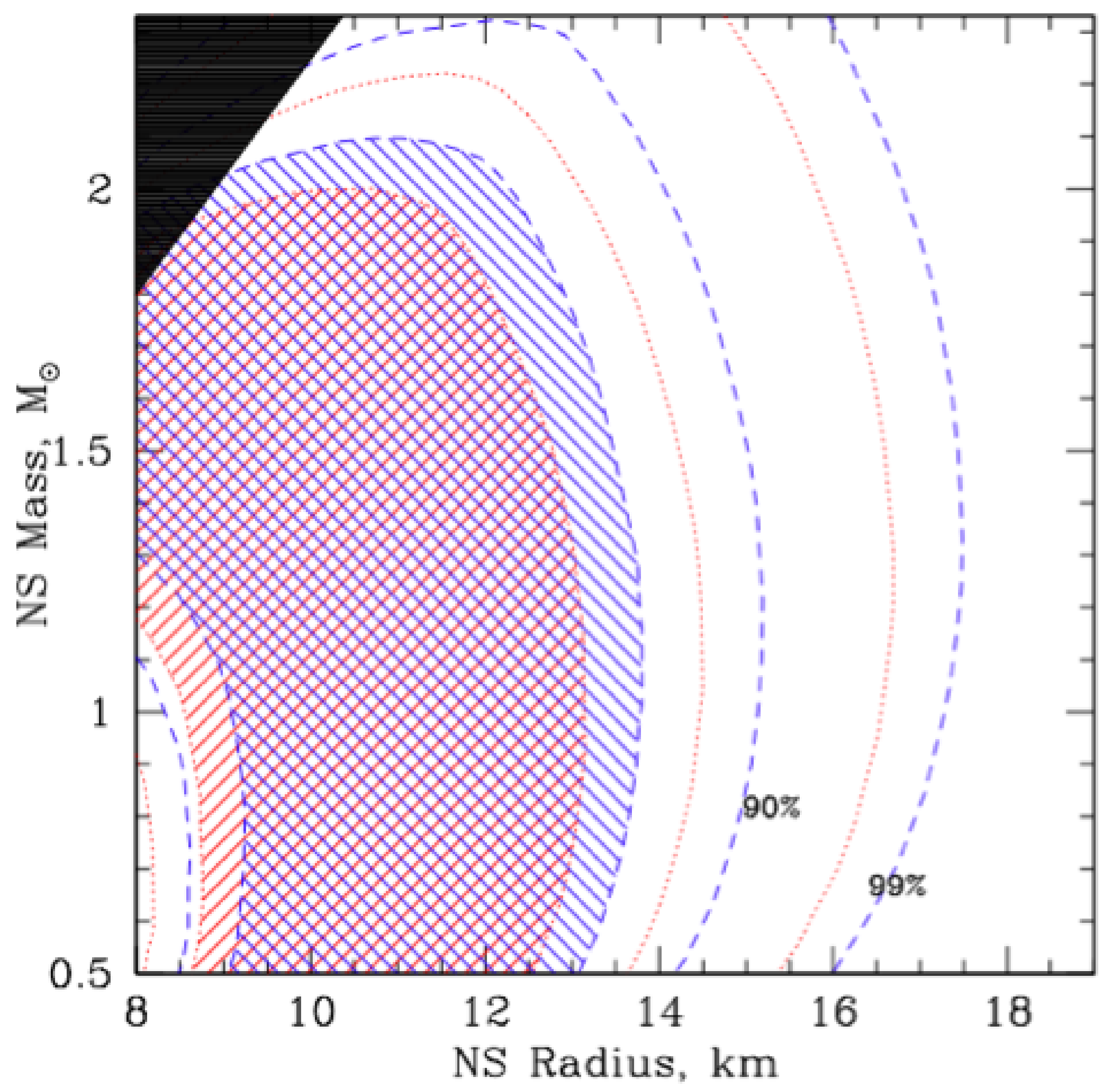


Lattimer and Steiner (2014), relative Bayes factor of 1200

- $R_{\mathrm{NS\ in\ }\omega\mathrm{\ Cen}}$: 11 km or 20 km!
- $R_{\mathrm{NS\ in\ NGC\ 6397}} \sim 7$ km?
- We tried different N_H values, different distances, and Helium atmospheres
- 36 separate models, millions of parameterizations

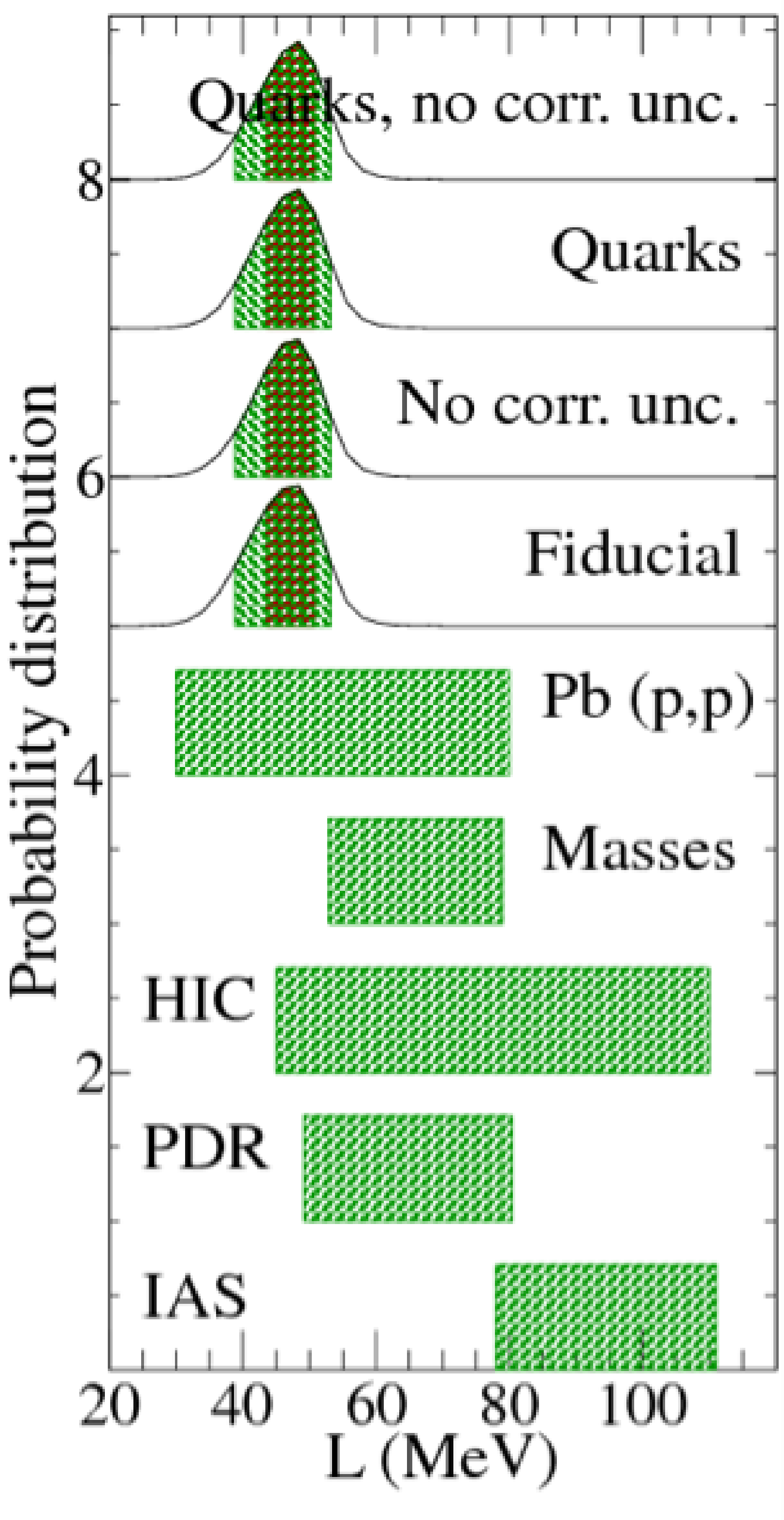
Recent Updates

- Heinke et al. (2014) confirms smaller N_H values for ω Cen with different model for the ISM and new data
- Confirmation of expectations from nuclear physics
- Radius ranges don't change that much from Steiner et al. (2013)

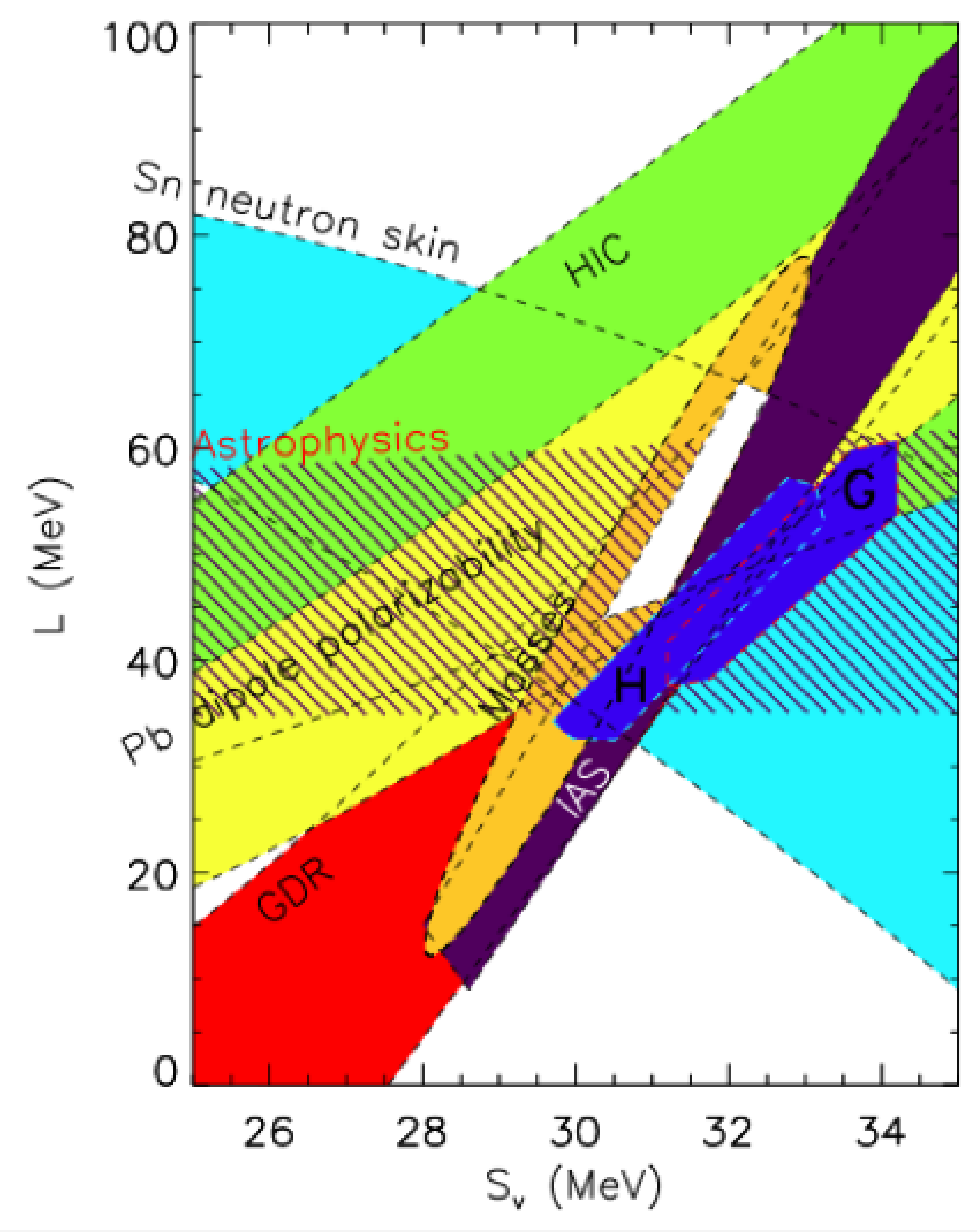


Heinke et al. (2014)

Neutron Star Constraints on L



Steiner and Gandolfi (2012)
(IAS results have since come down)

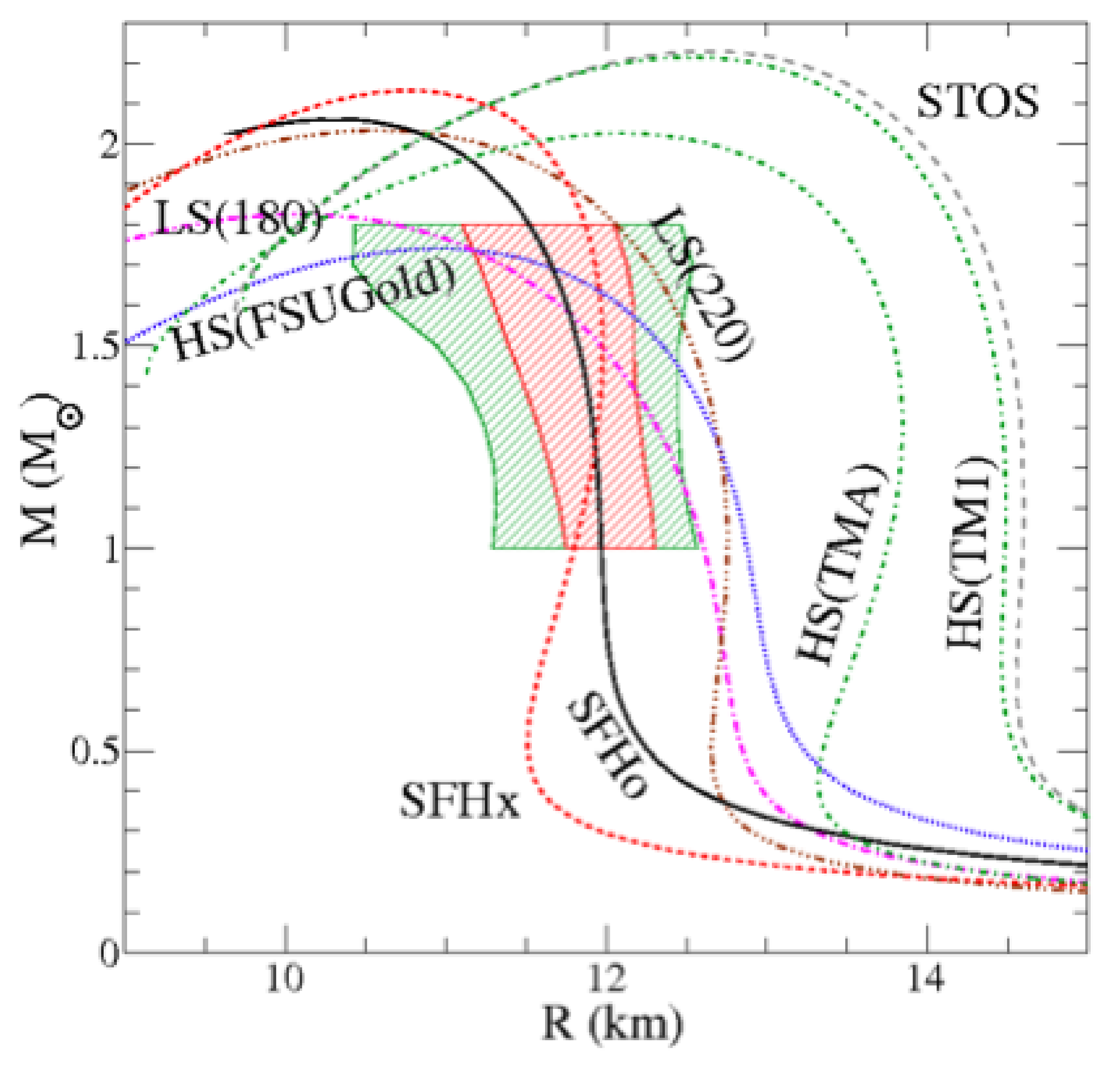


Lattimer and Steiner (2014)

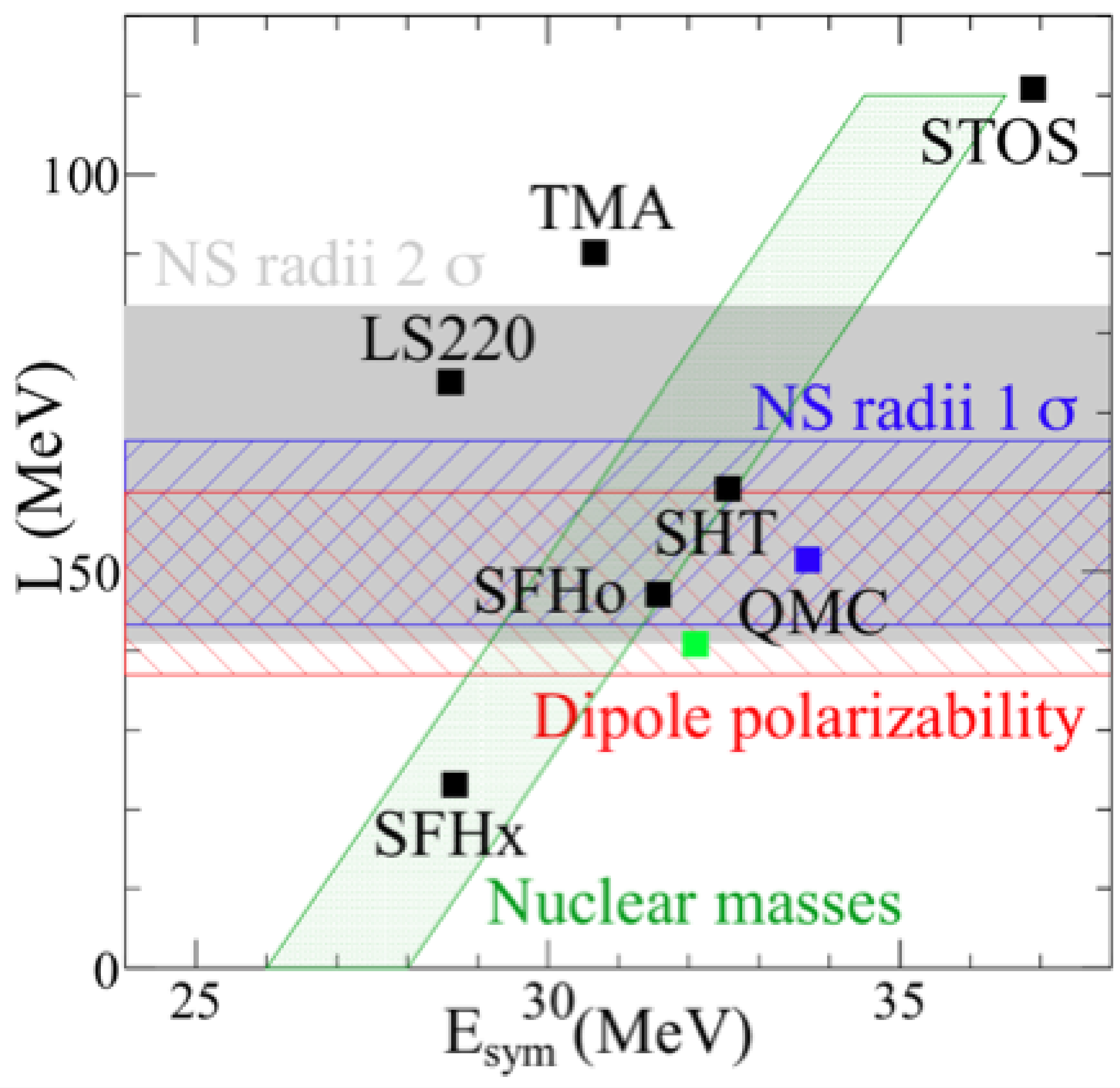
- Neutron stars strongly constrain L
- We also found $R_n - R_p < 0.2$ fm

Confirmed by MAMI data

Supernova EOS and the Symmetry Energy



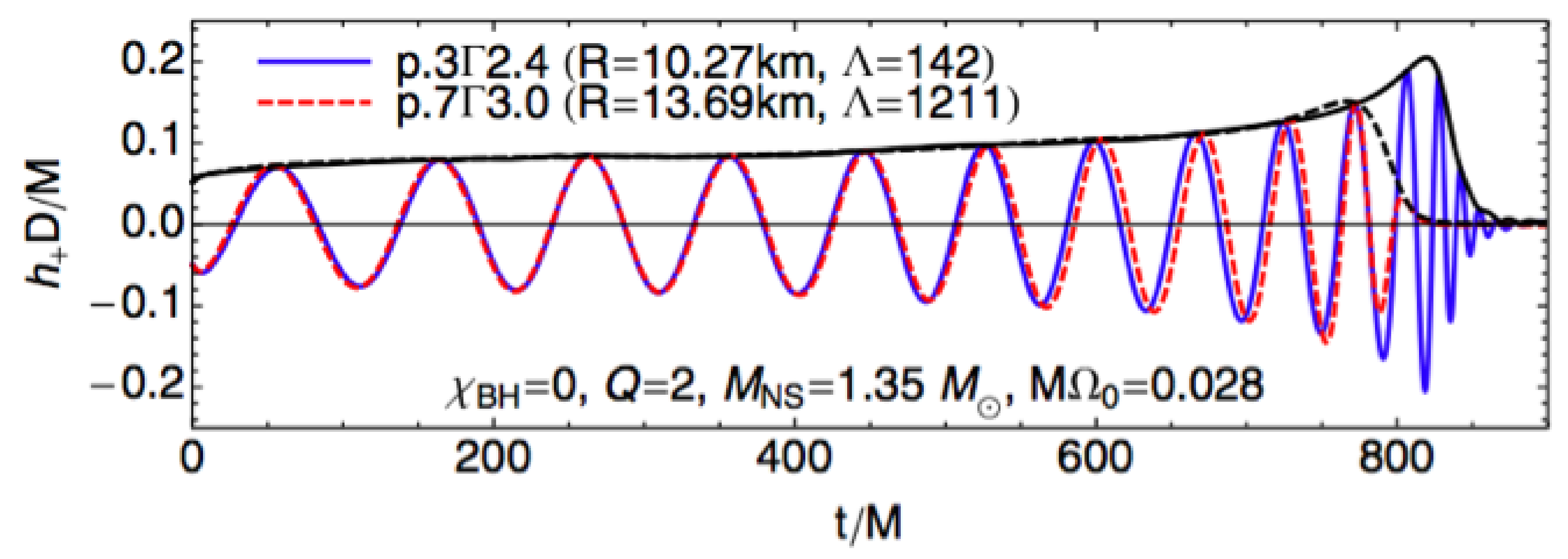
Steiner, Hempel, and Fischer (2013)



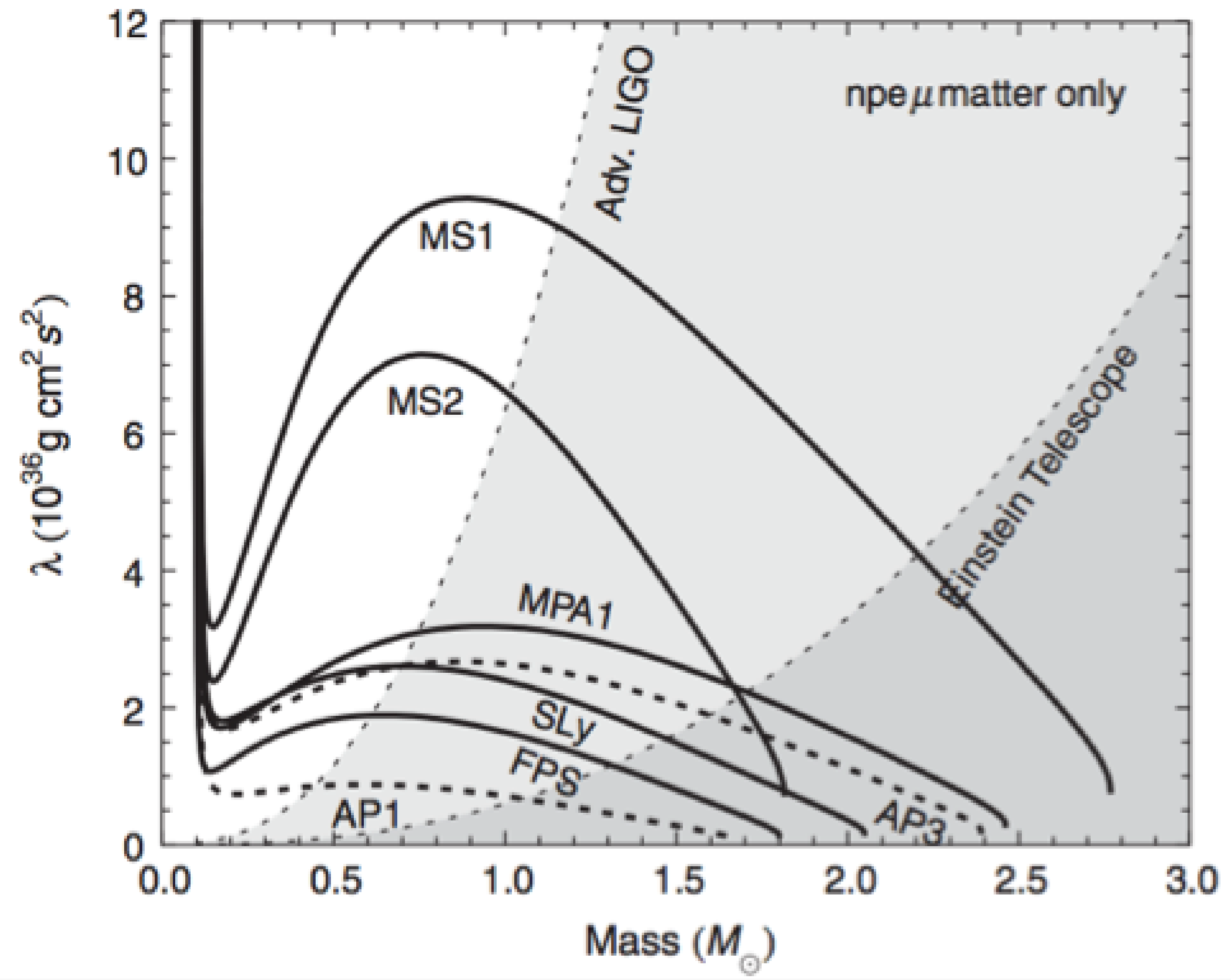
Based on Steiner, Hempel, and Fischer (2013)

- Limited number of supernova EOSs which satisfy $M - R$ constraints and the $S - L$ correlation
- Current EOS uncertainties too small to explain explosion
- Many simulation properties are weakly correlated with the symmetry energy

Neutron Star Tidal Deformabilities



Lackey et al. (2014)

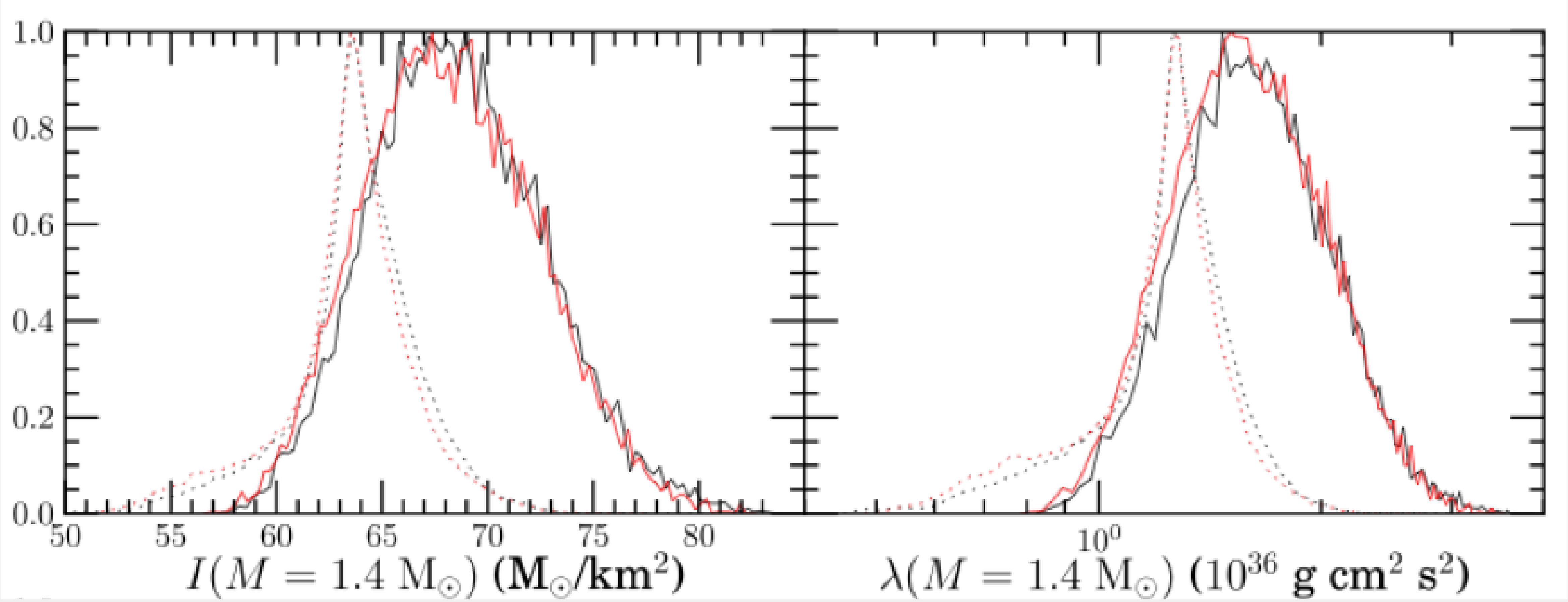


Hinderer et al. (2010)

- Gravitational wave signal from an NS merger measures tidal deformability λ
- Point masses early on; deformation near 400 Hz
- Easier to detect larger tidal deformations

Tidal Deformabilities

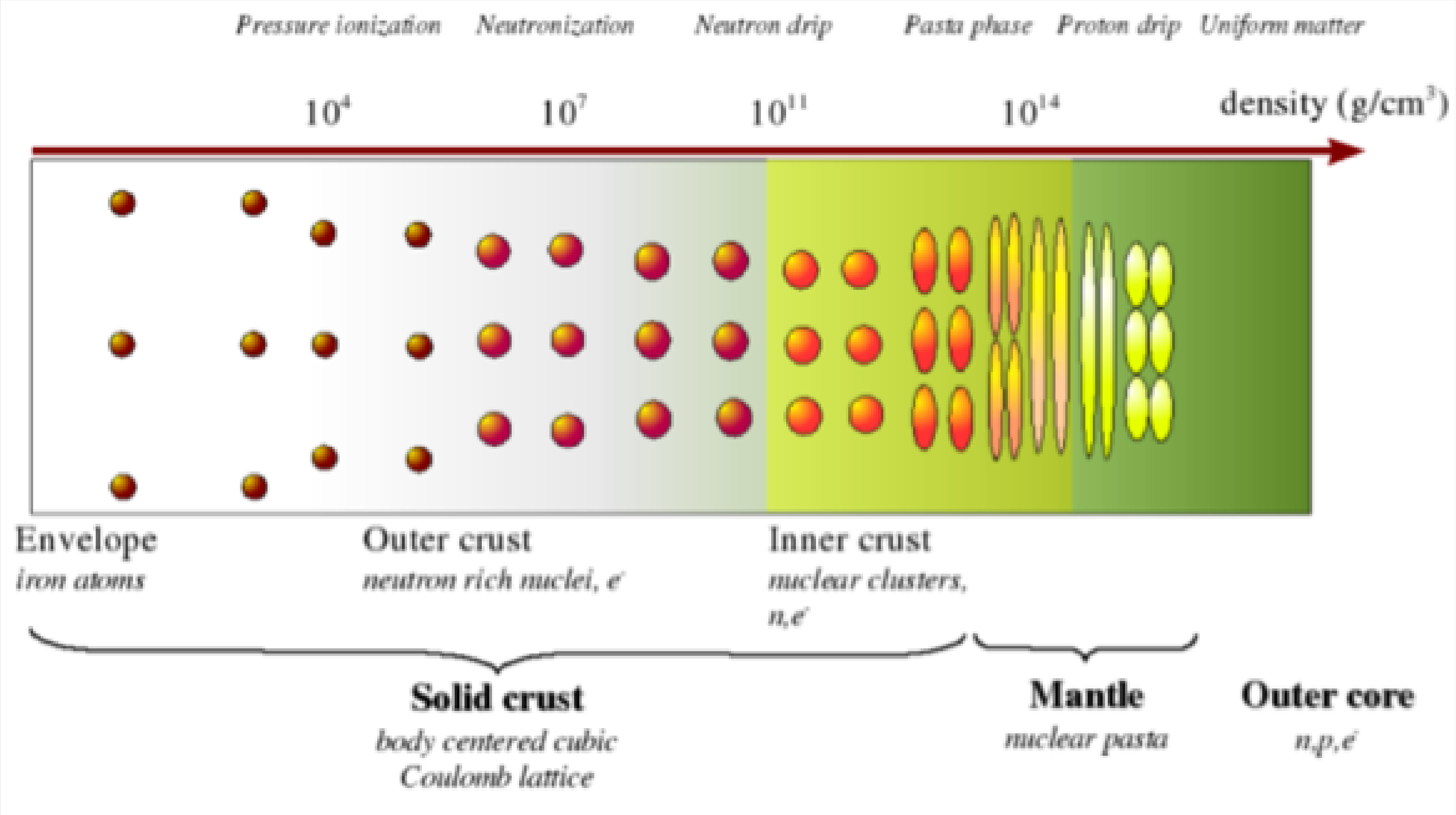
- Current neutron star mass and radius observations suggest tidal deformabilities are small



Steiner, et al. (2014)

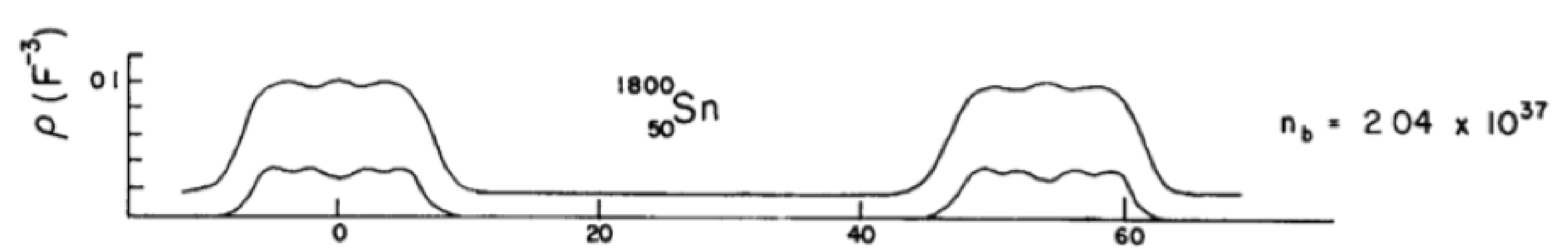
- LIGO sensitivity improved by
  - multiple measurements
    del Pozzo, et al.
  - and by directly simulating the EOS
    Lackey et al.
  - Using information beyond 400 Hz
    Damour and Nagar
- For large enough signal-to-noise, LIGO may have smaller systematics

Structure of Matter in the Neutron Star Crust



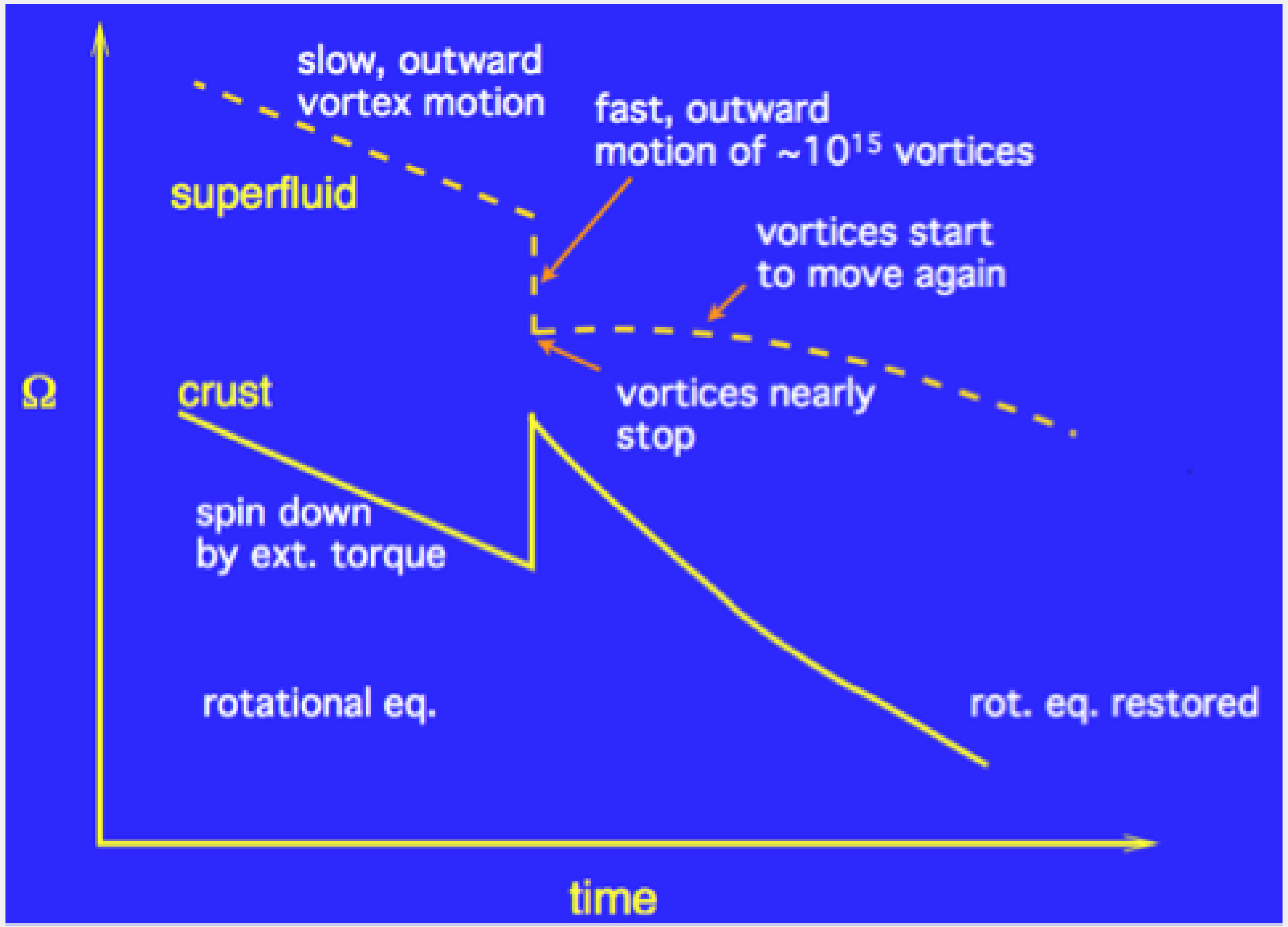
Picture from N. Chamel

- Neutron-rich nuclei
- Sea of superfluid neutrons
- Crust-core transition



Negele and Vautherin (1973!)

Pulsar Glitch Mechanism



Picture from B. Link

- Superfluid component, decoupled from rotation at the surface
- Natural to associate the superfluid component with the superfluid neutrons in the crust
- What is the mechanism for the sudden change?

- Superfluid vortices pinned to the lattice
- Neutron star spins down, vortices bend creating tension, eventually they must shift lattice sites
- Quasi-free neutrons are entrained with the lattice
  Chamel 2012, Chamel et al. 2013

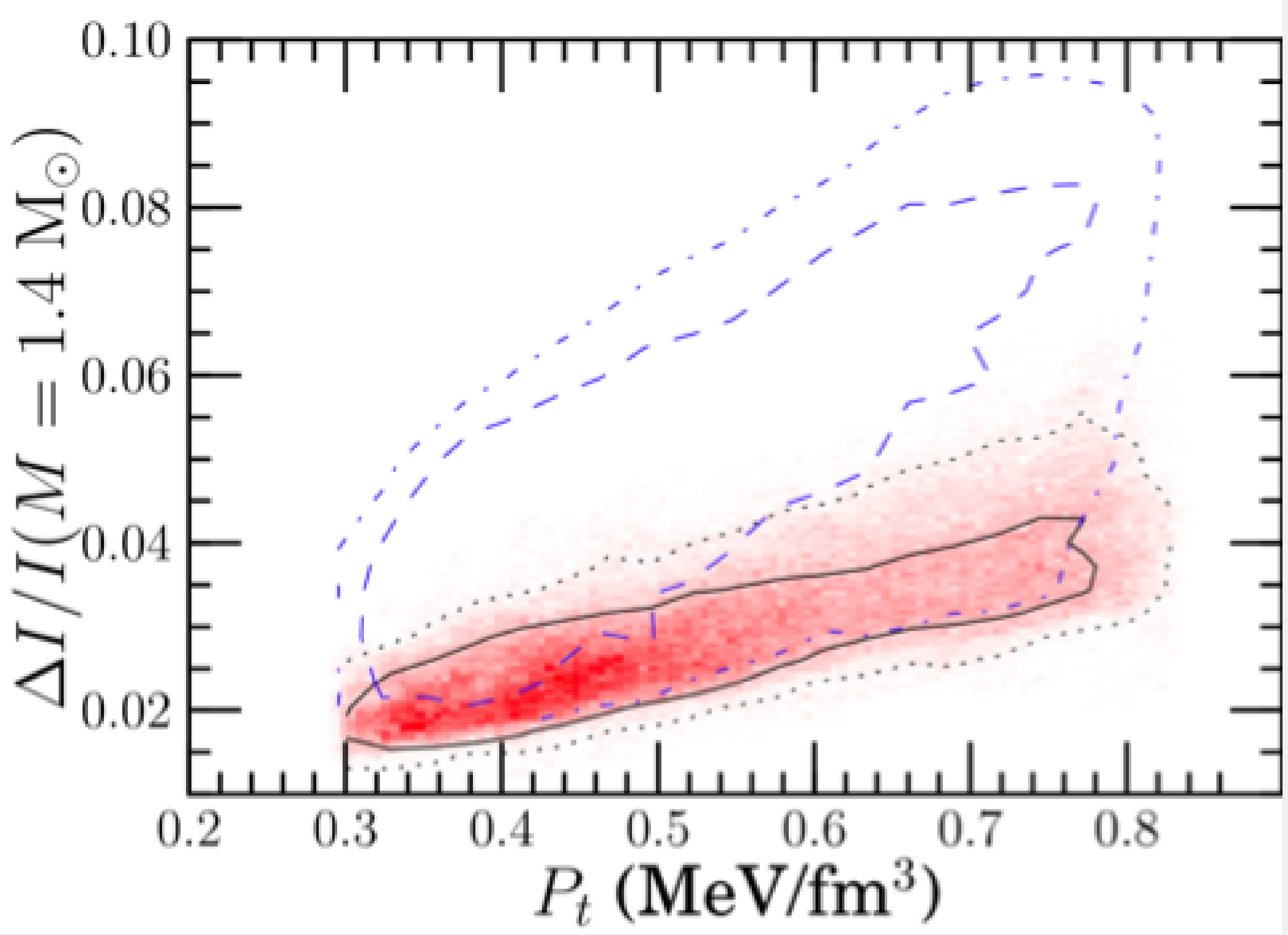
Is There Enough Superfluid in the Crust?

- We require 1.6% of I to explain glitches in Vela
  Link, Epstein, and Lattimer (1999)

- Entrainment: 75-85% of otherwise superfluid neutrons 'connected' to the lattice
  N. Chamel (2012)

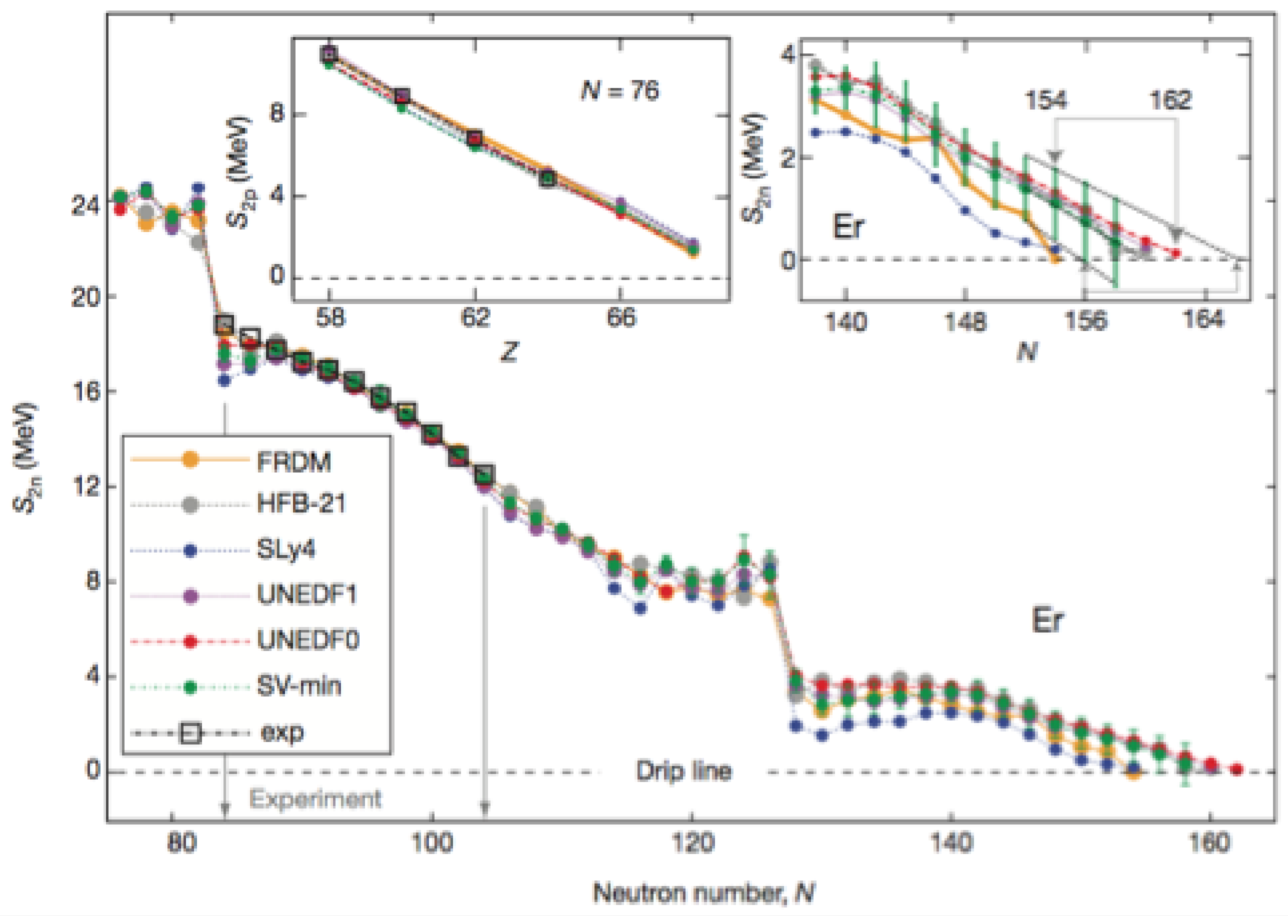
- Current M and R observations suggest there is not enough I in the crust
  See Andersson et al. (2012)

- Unless the systematics force much larger neutron star radii and P_t is large

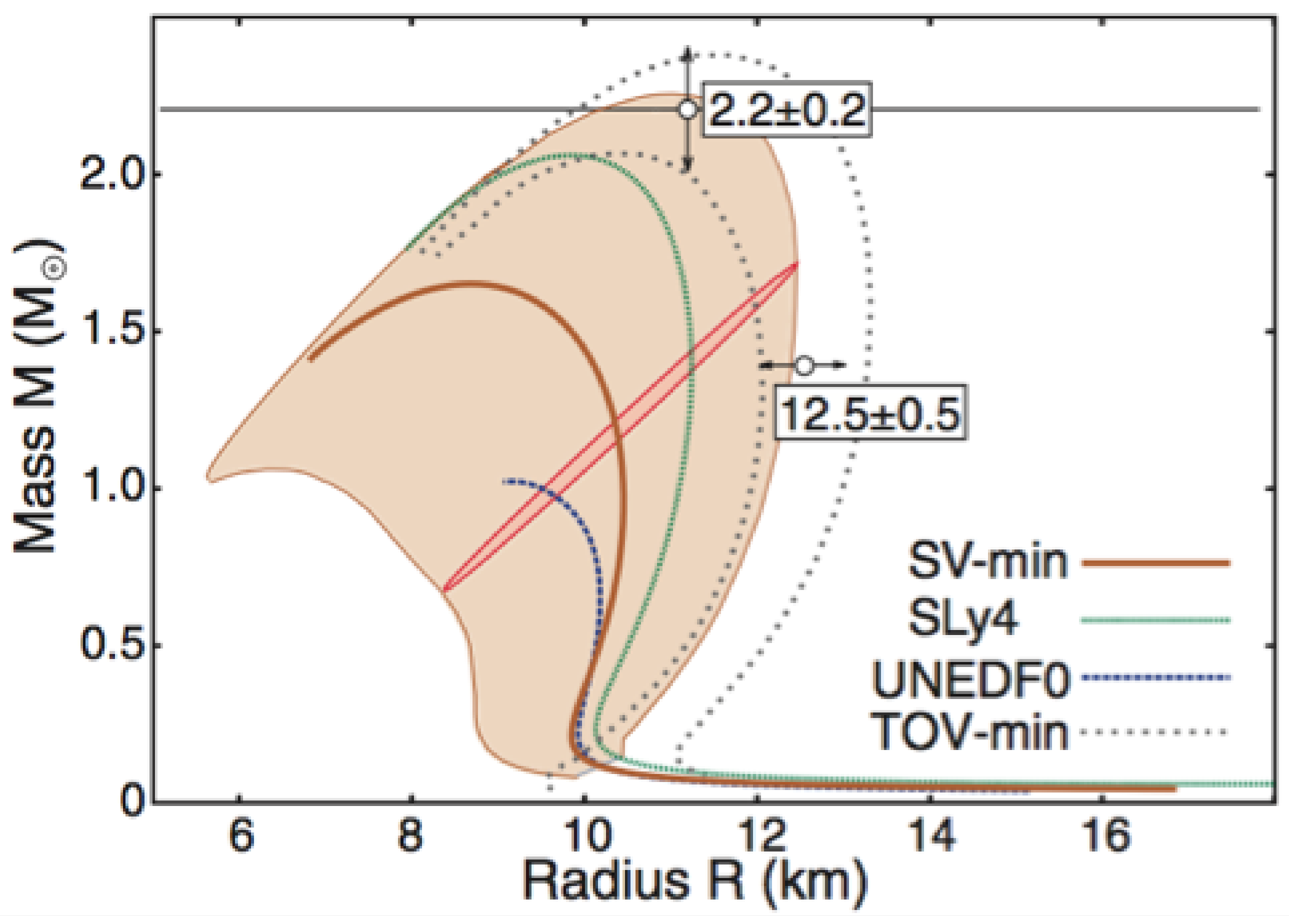


Steiner et al. (2014); black and red are with M & R observations, blue contours are with $I = 70\ \mathrm{M}_\odot\ \mathrm{km}^2$

Neutron Star Radii and the Neutron Drip Line



Erler et al. (2012)



Erler et al. (2013)

- It might be possible to constrain the neutron drip line from neutron radii
- But the connection between these observables has not been fully explored
- In particular:
    - The isovector part of the Skyrme functional is incomplete
      Sheikh et al. (2014)
    - Current work assumes low- and high-density matter are correlated

Summary

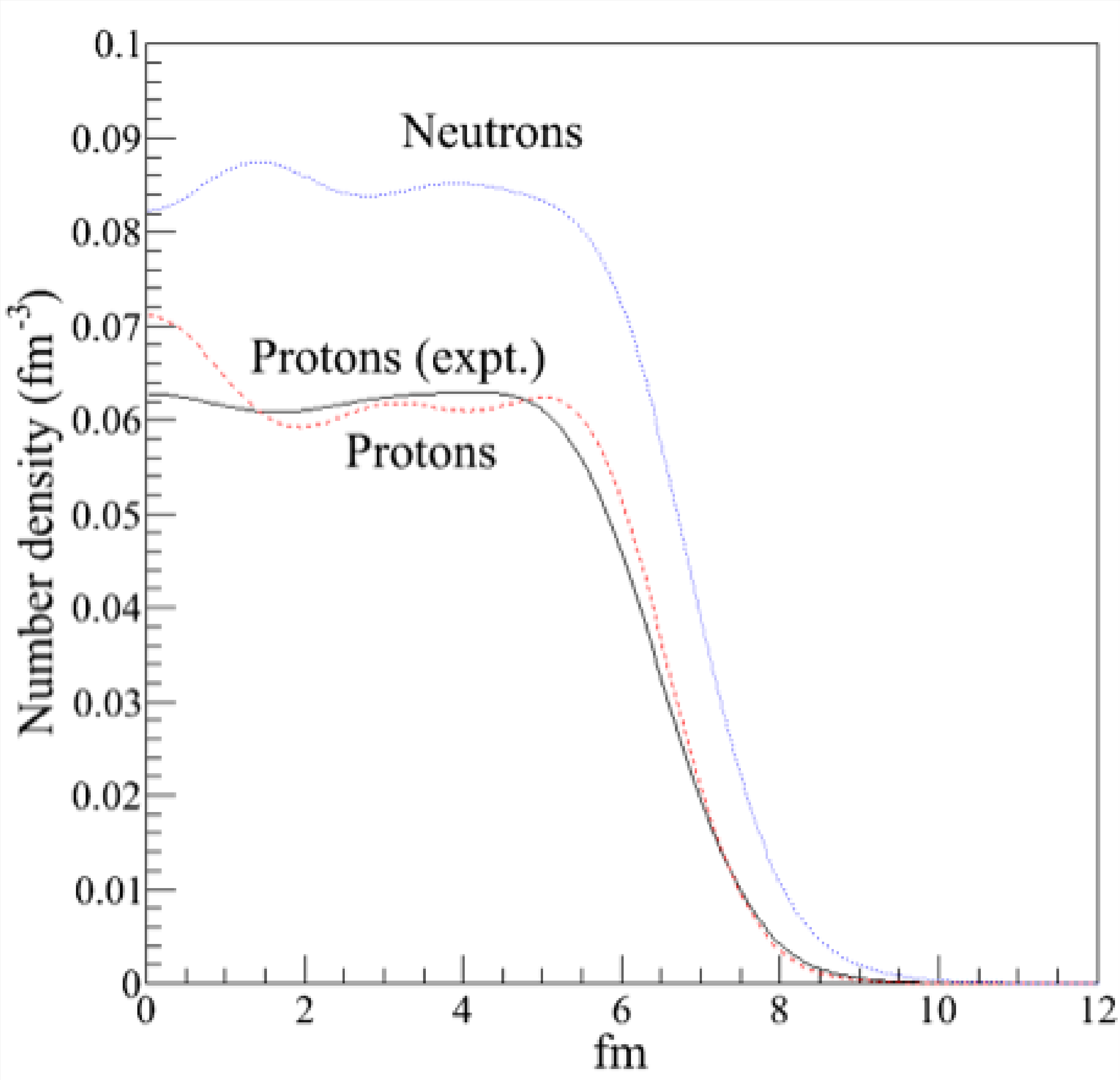
- Currently available neutron star mass and radius observations constrain the universal neutron star $M - R$ curve
  - Neutron star radii are likely between 10.4 and 12.9 km
  - We now have constraints on the EOS
  - $60 < I < 75\ M_\odot\ \mathrm{km}^2$
  - $1 < \lambda < 3 \times 10^{36} g\ \mathrm{cm}^2\ \mathrm{s}^2$

- Constrain the nucleon-nucleon interaction and QCD.
  - (41) 43 MeV $< L <$ 67 (83) MeV
- Current observations imply there is not enough I to explain glitches

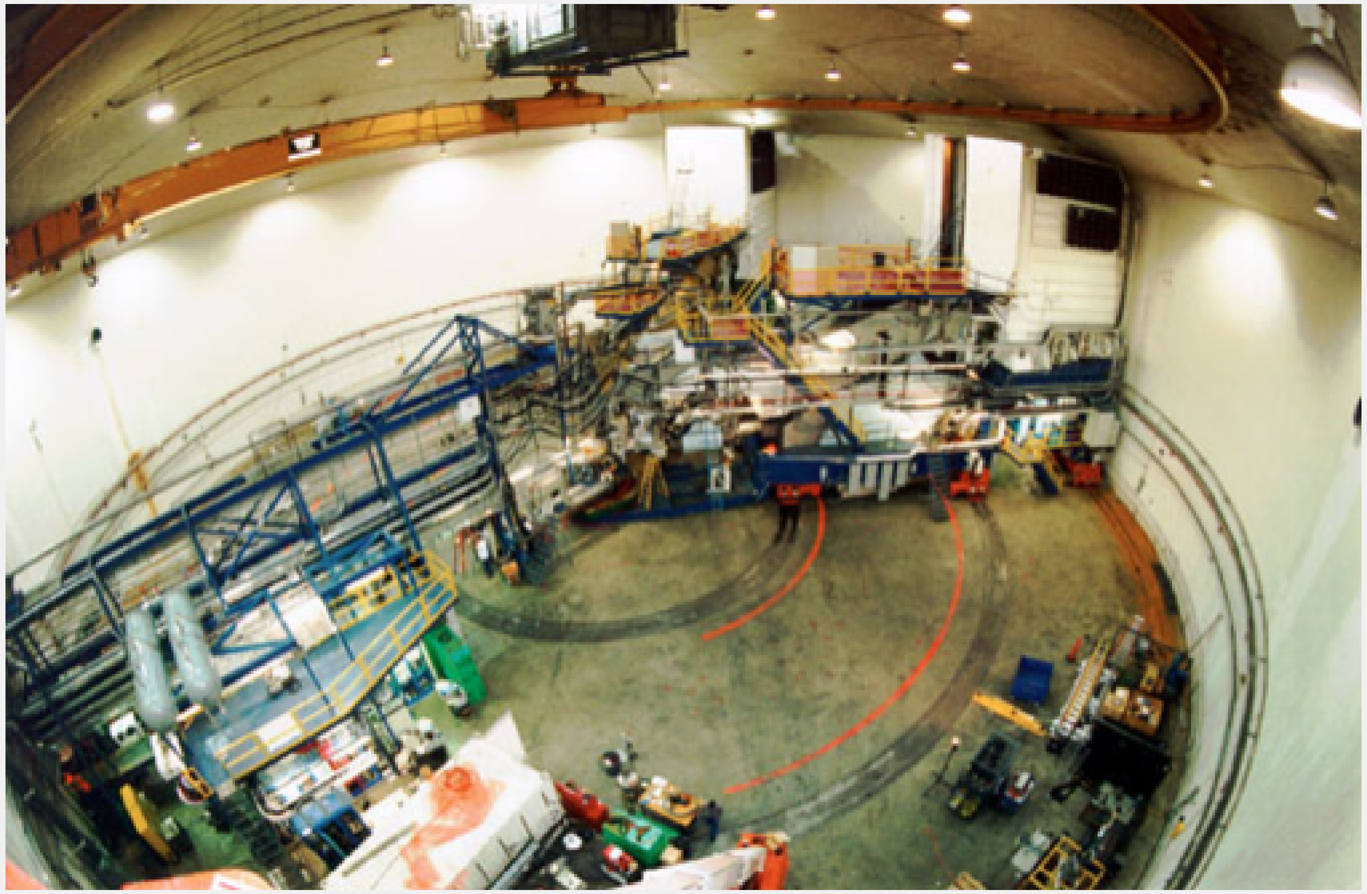
- Potential for further connections and new observations

The Neutron Skin Thickness of Lead

- Lead-208: 82 protons, 126 neutrons
  $R_n^2 \equiv \int r^2 n_n(r)\, d^3 r \qquad R_p^2 \equiv \int r^2 n_p(r)\, d^3 r$
- Neutron radii are hard to measure, use parity-violating electron scattering
- Weak charge of neutron ≫ weak charge of proton, i.e.
  $|-1| \gg 1 - 4\ \sin^2 \theta_W$



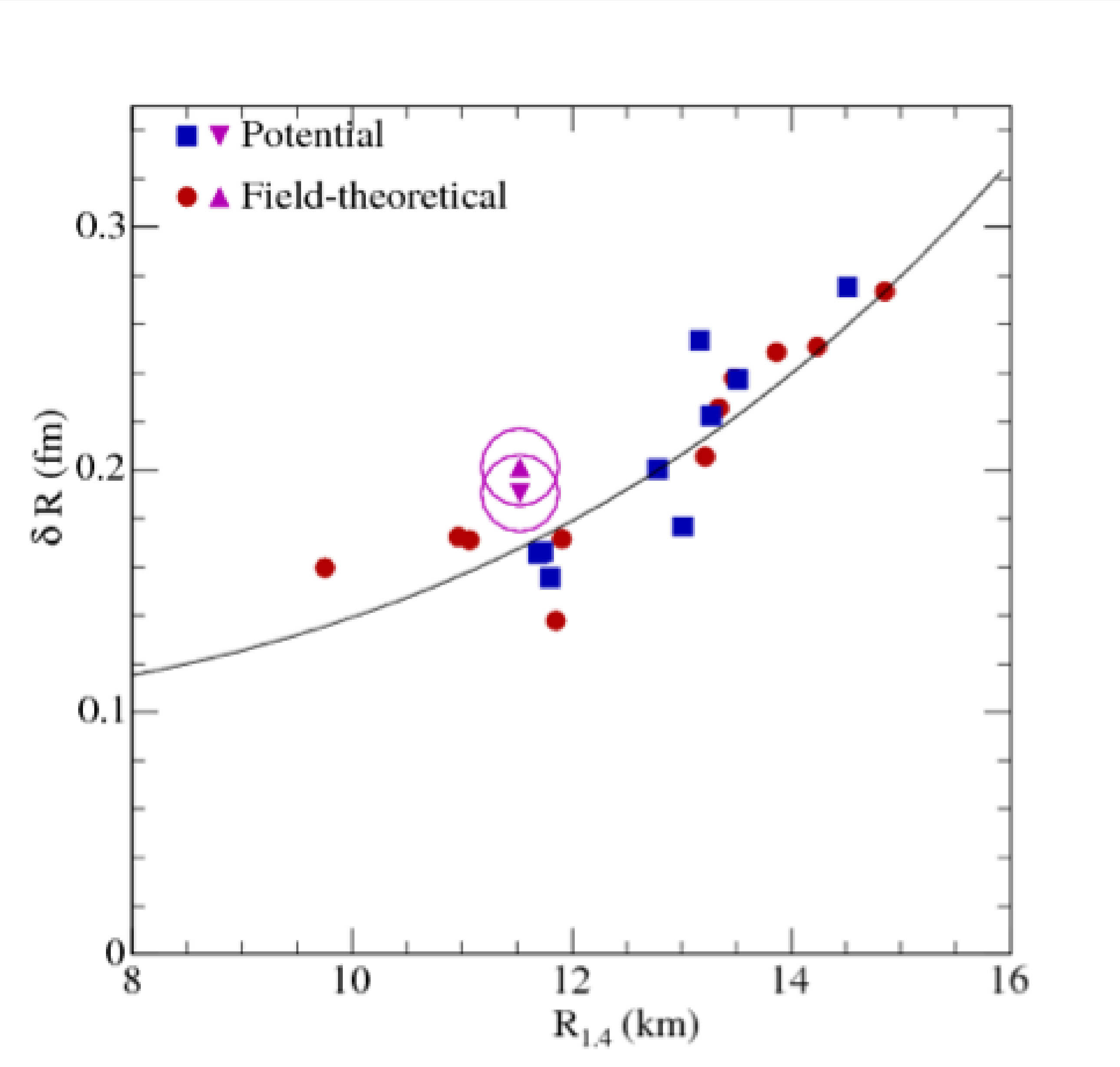
Steiner, Prakash, Lattimer and Ellis (2005)

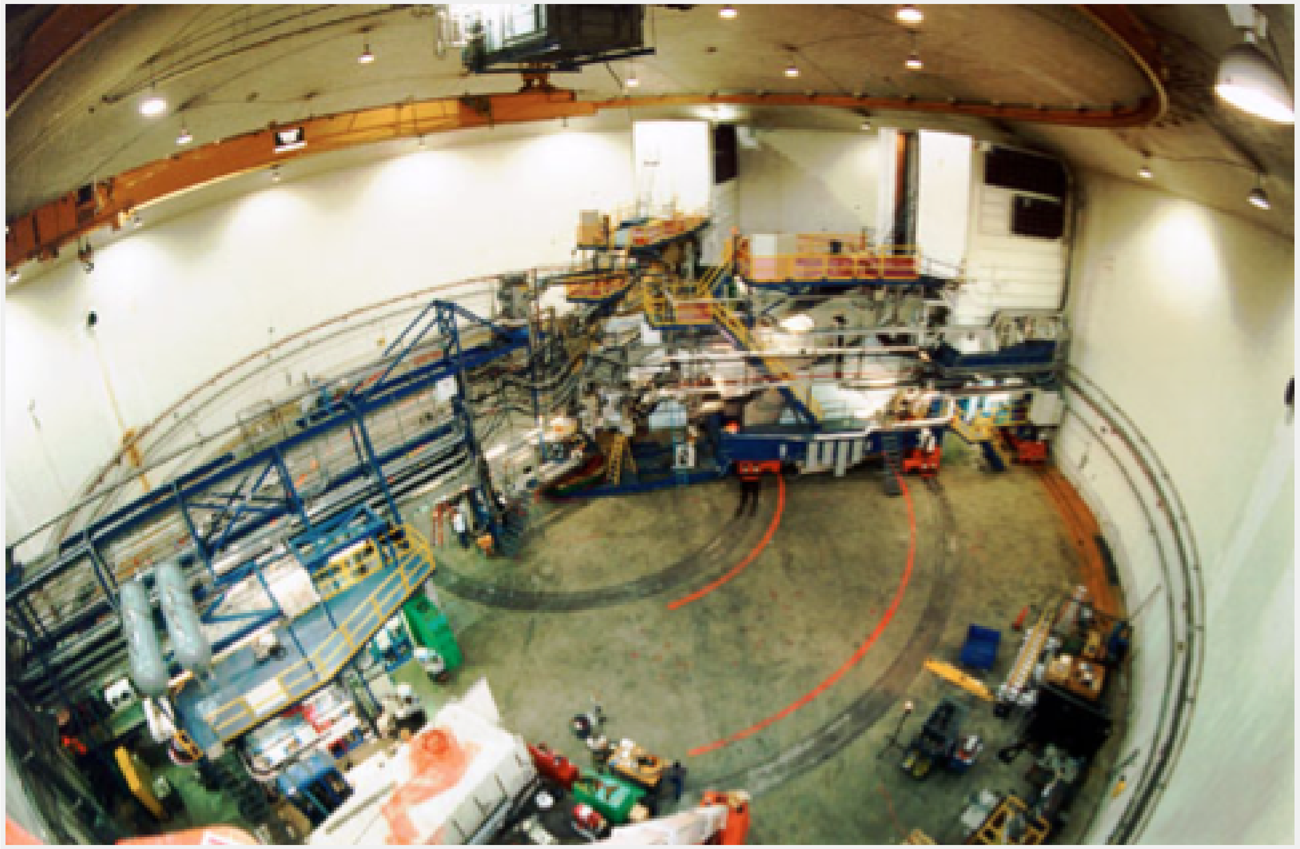


Jefferson Lab's Hall A
Measured $R_n - R_p = 0.33 \pm 0.16$ fm

The Neutron Skin Thickness of Lead

- The quantity $\delta R \equiv R_n - R_p$ is related to L as are neutron star radii





Jefferson Lab's Hall A: Measuring R_n

Steiner, Prakash, Lattimer, and Ellis (2005),
based on Horowitz and Piekarewicz (2001)

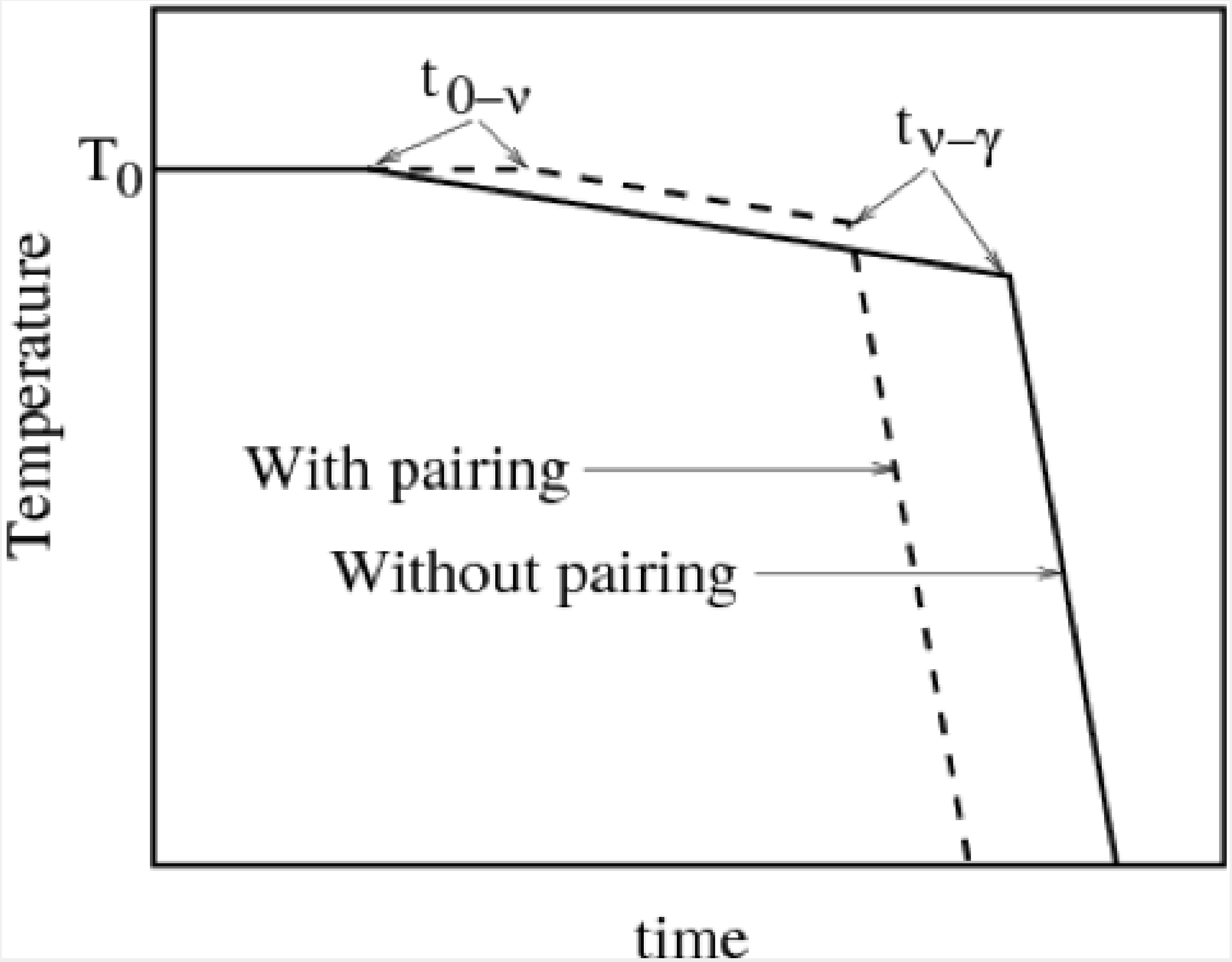
- We find $\delta R < 0.2$ fm (68%) from neutron star observations

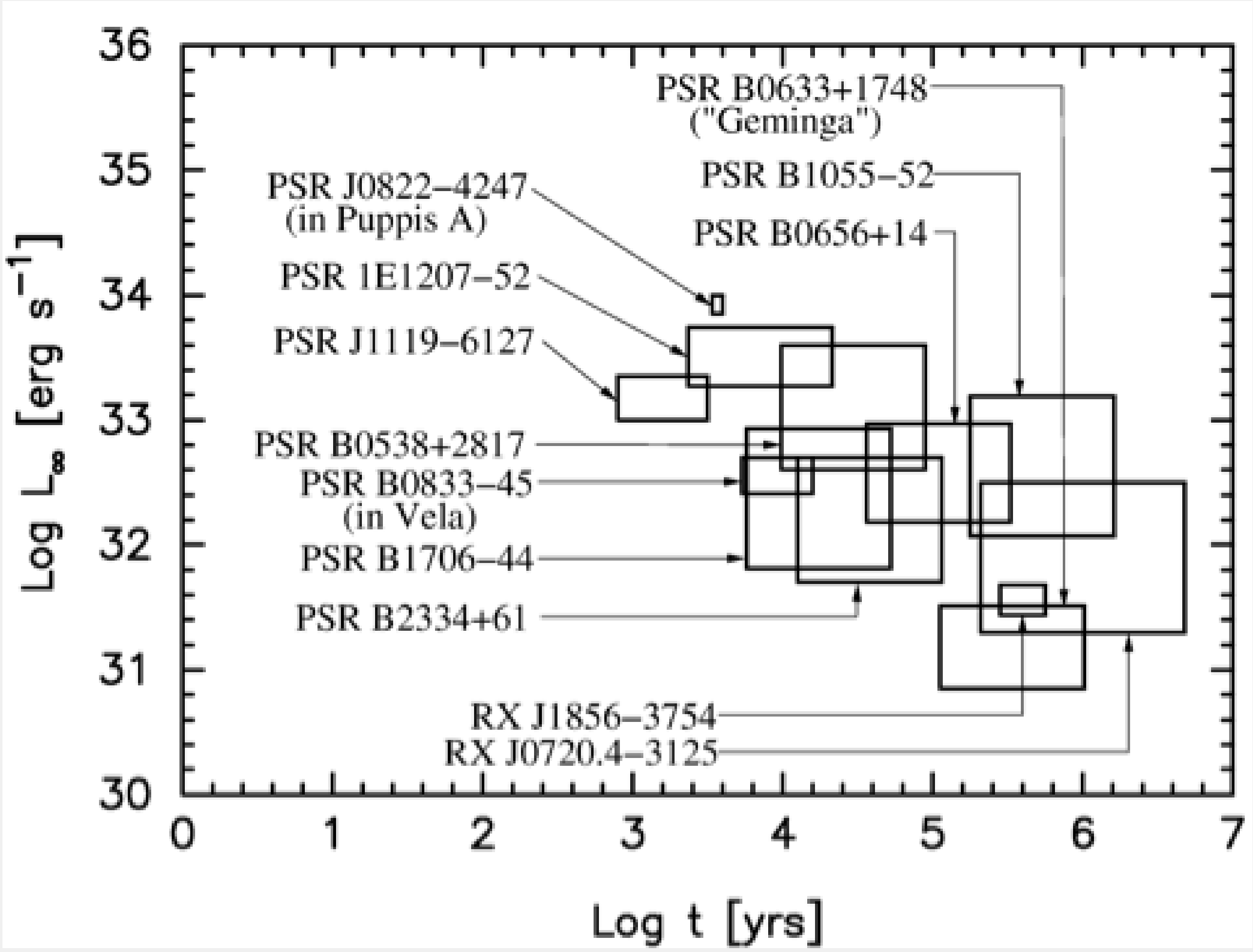
Thermal Emission from Isolated Neutron Stars

- After ~ 10 years, the star is isothermal ⇒ one temperature = T

$$C_V \frac{dT}{dt} = L_\nu + L_\gamma\,, \quad L_\gamma \sim T^{2+4\alpha}\,, \quad L_\nu \sim T^8 \text{ (Modified Urca)}\,, \quad C_V \sim CT$$

- Age assumed from spin-down age or associated with a supernova remnant



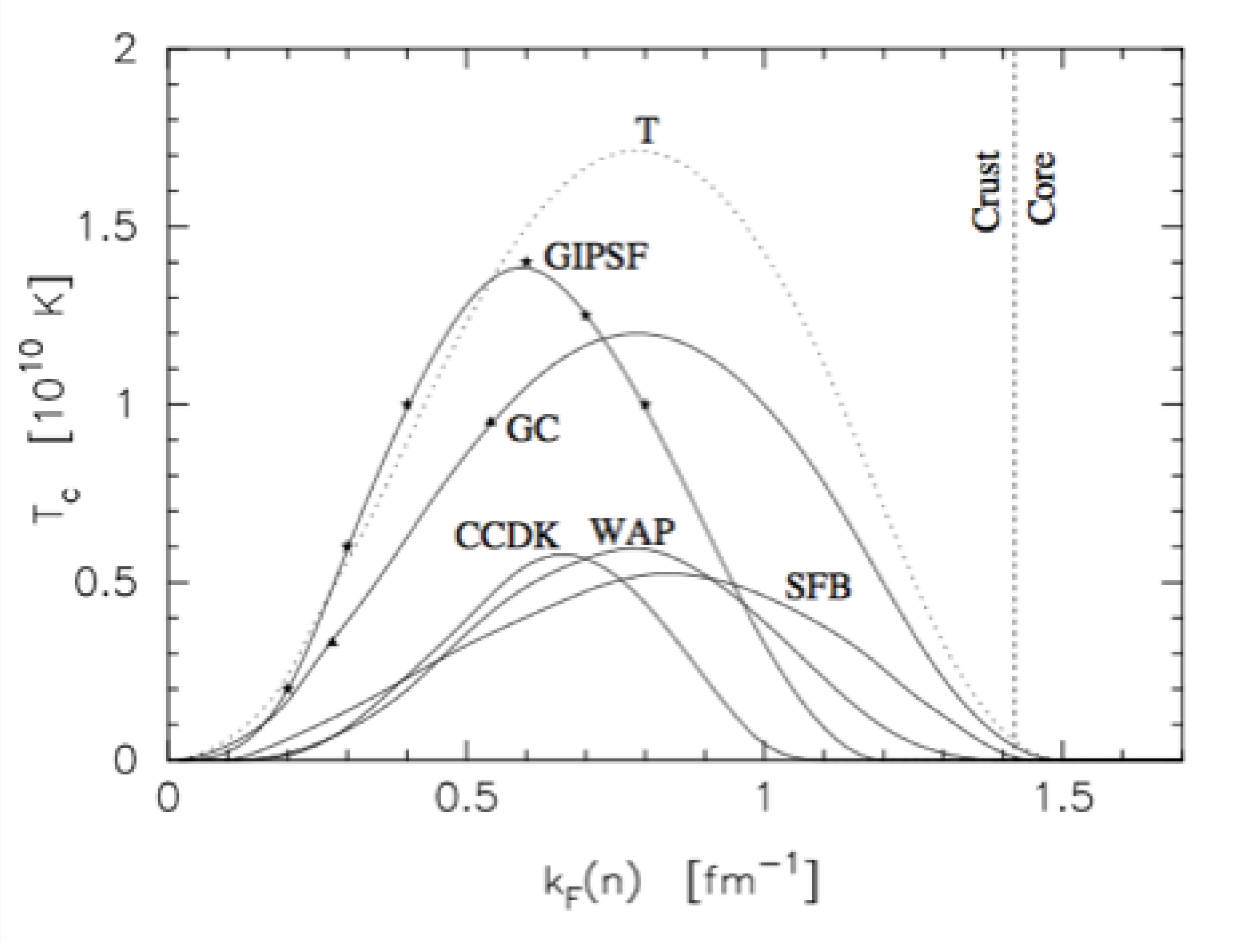


Page, et al (2004)

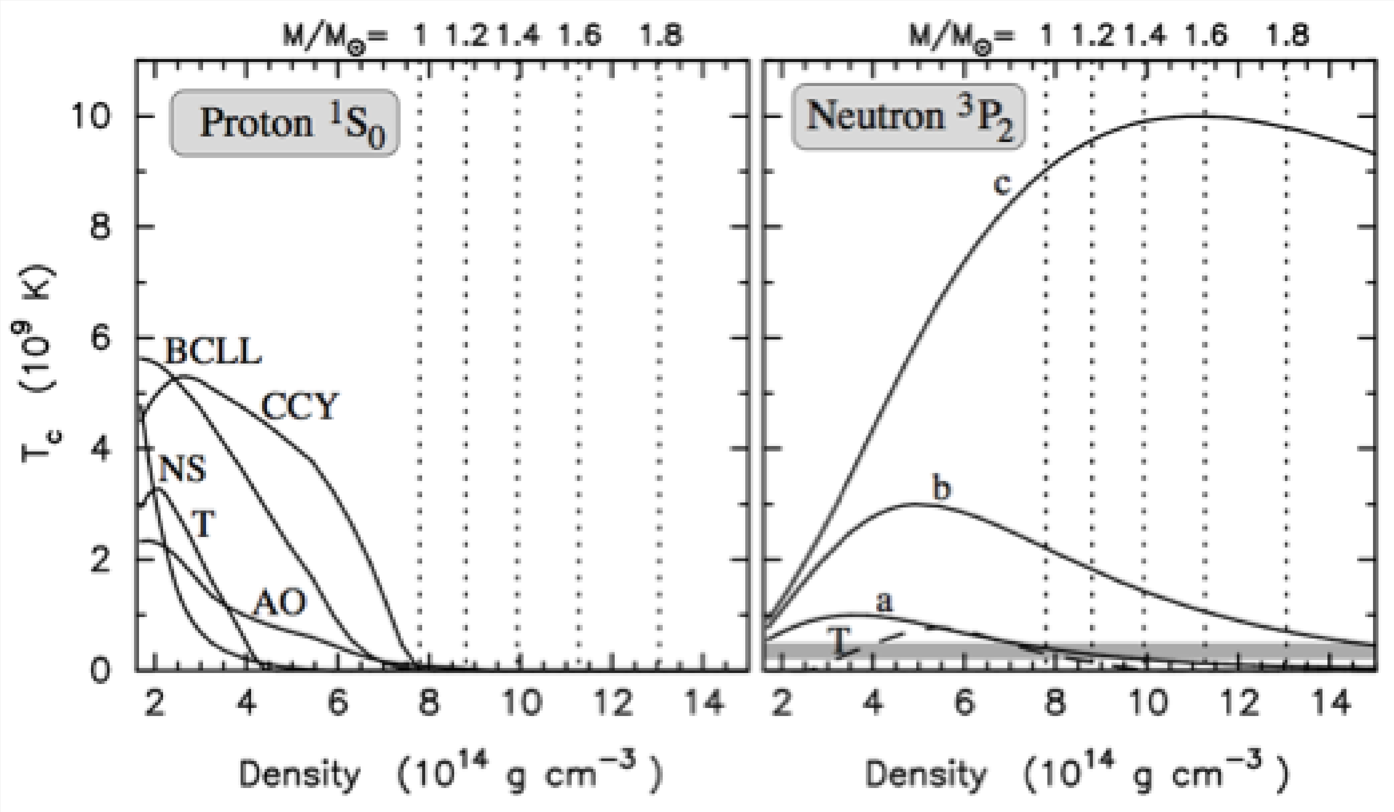
Page, et al (2009)

Neutron Star Superfluidity

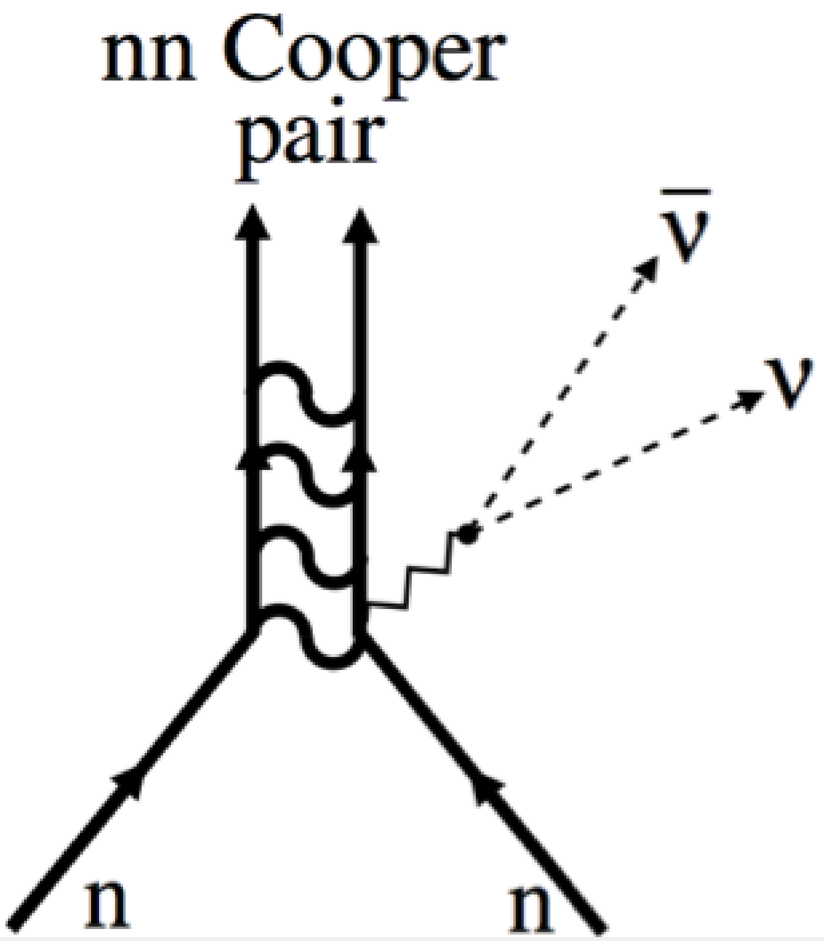
(See our review at 1302.6626)



- $^1S_0$ gap increases with increasing density, but drops off at higher densities because of n-n repulsion
- Superfluidity can block cooling processes
- ...but it opens up new ways of cooling

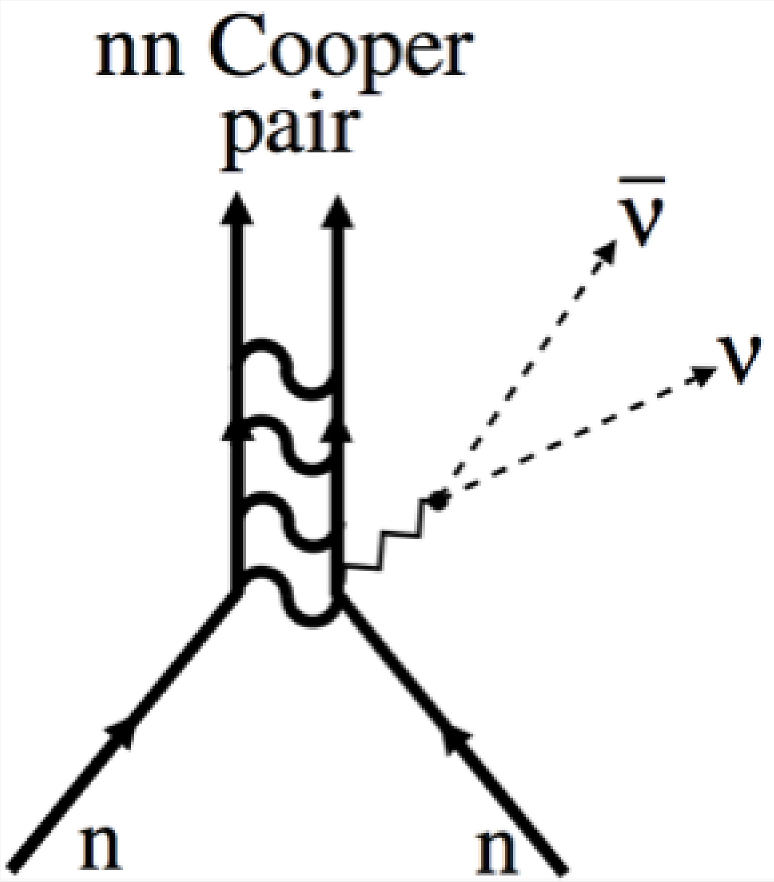


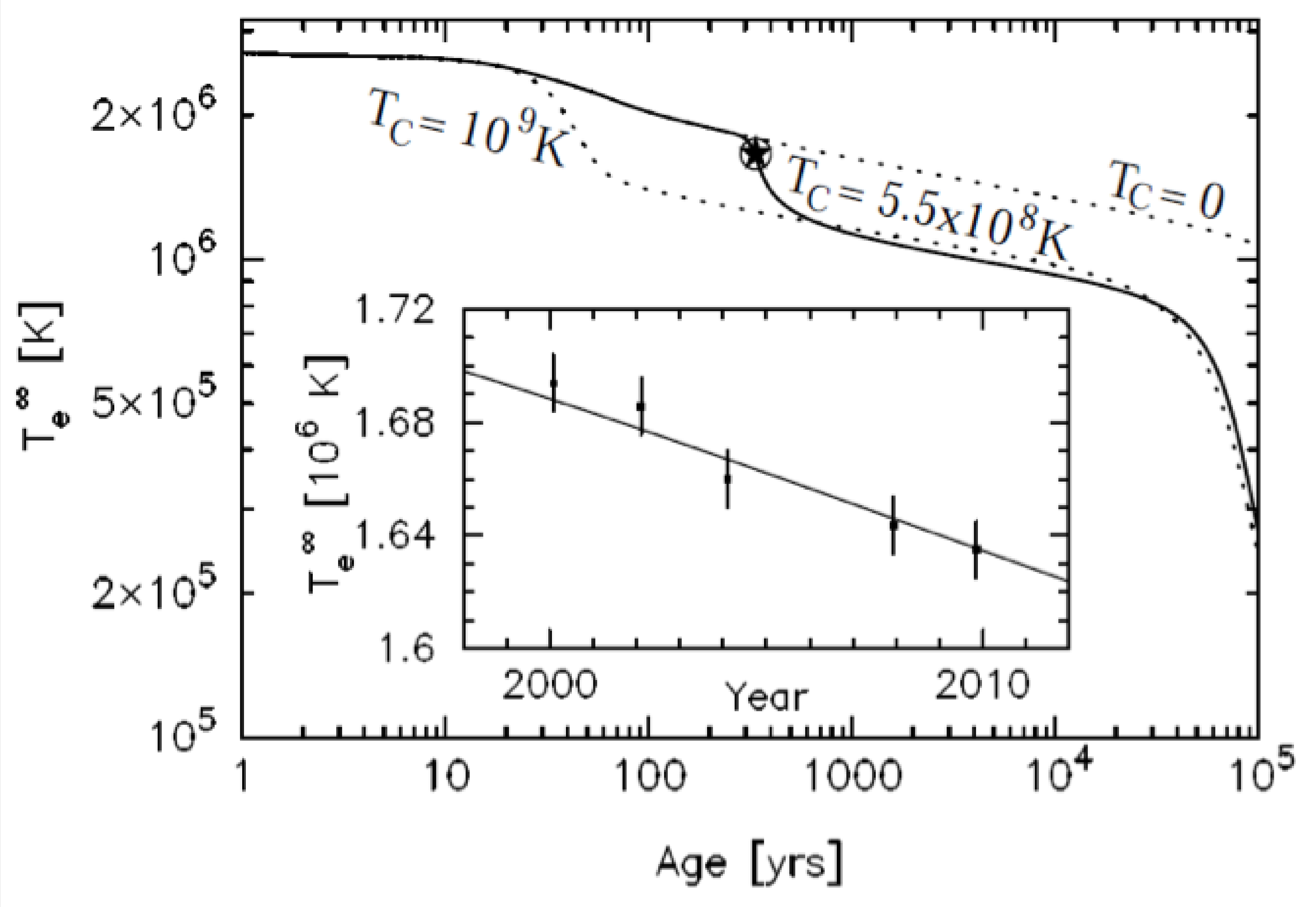
Steiner and Reddy (2009)



Detecting Neutron Star Superfluidity

- The large slope is only well reproduced by the neutron triplet superfluid transition and associated emissivity
- Cas A requires a very particular triplet gap $\Delta(T = 0) \propto T_C$





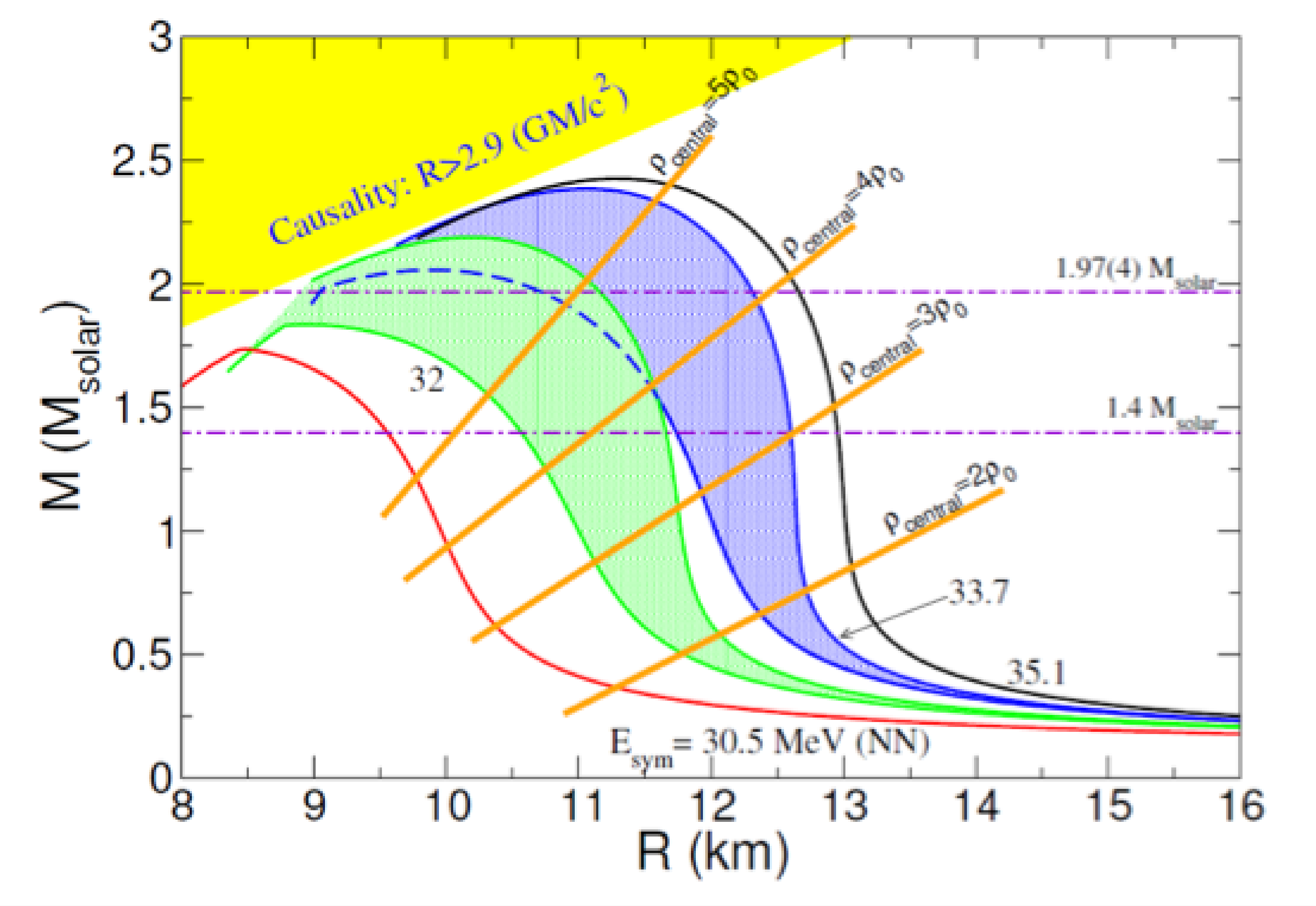
- If you form a Cooper pair, you gain energy

Page, et al. (2011)

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.
- 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. 2012)
- Becomes clear that there may be (at least) two types of PRE X-ray bursts, which have different properties. Also some variation in normalization between bursts. (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)
- Guillot et al. revisit qLMXB measurements, still find small radii (Guillot et al. 2013)
- Lattimer and I re-revisit them, still finding smaller radii, but larger uncertainties (Lattimer et al. 2013)
- 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 and much work remains.

Connection to Nuclear Three-Body Forces



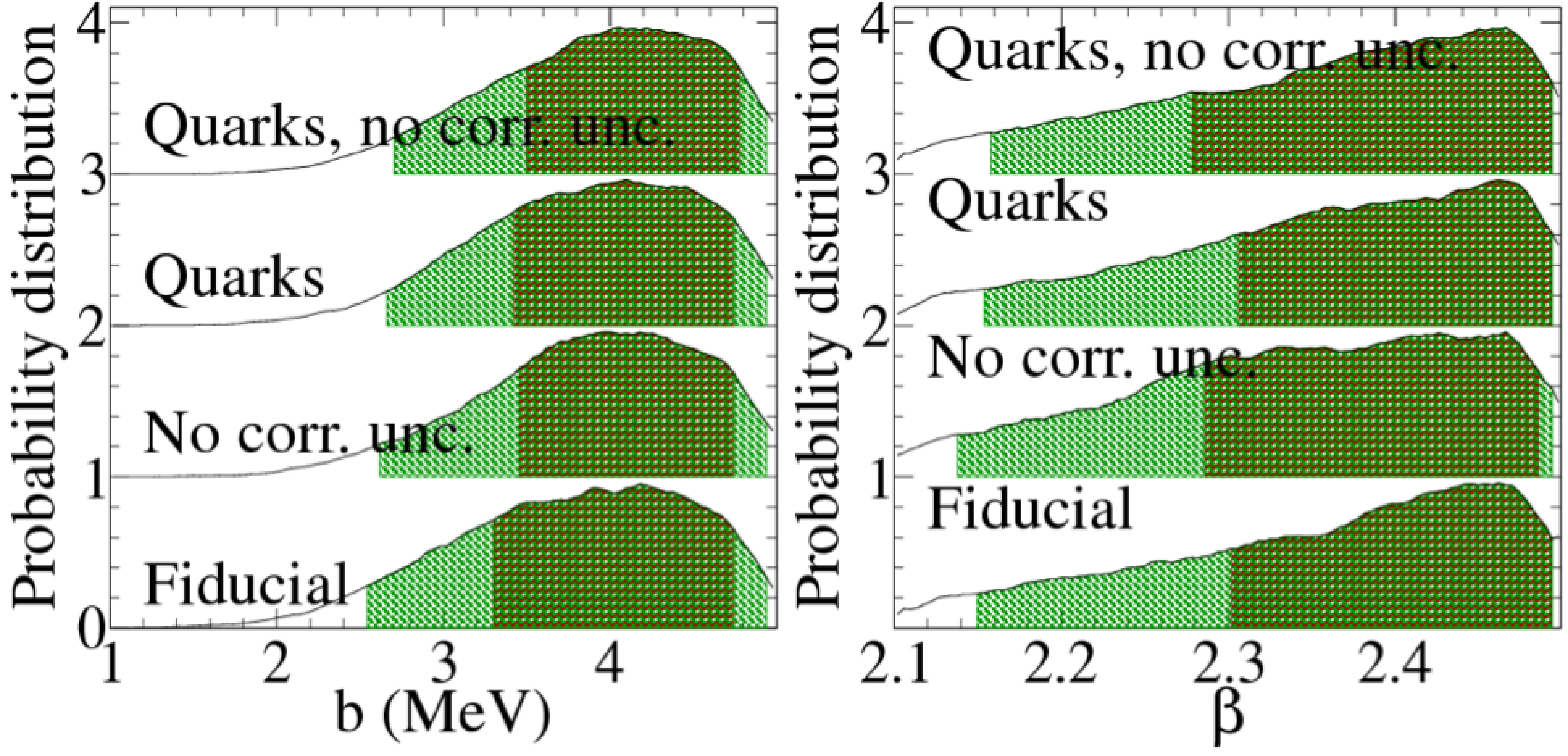
Colored regions denote different three-body forces

$$E_{\text{neut}} = a\left(\frac{n}{n_0}\right)^{\alpha} + b\left(\frac{n}{n_0}\right)^{\beta}$$

Gandolfi, Carlson, and Reddy (2012)

- Three-nucleon interactions are important for nuclei and neutron star radii
- Quantum Monte Carlo (AFDMC) + Stellar structure
- How do neutron star observations constrain b and β?

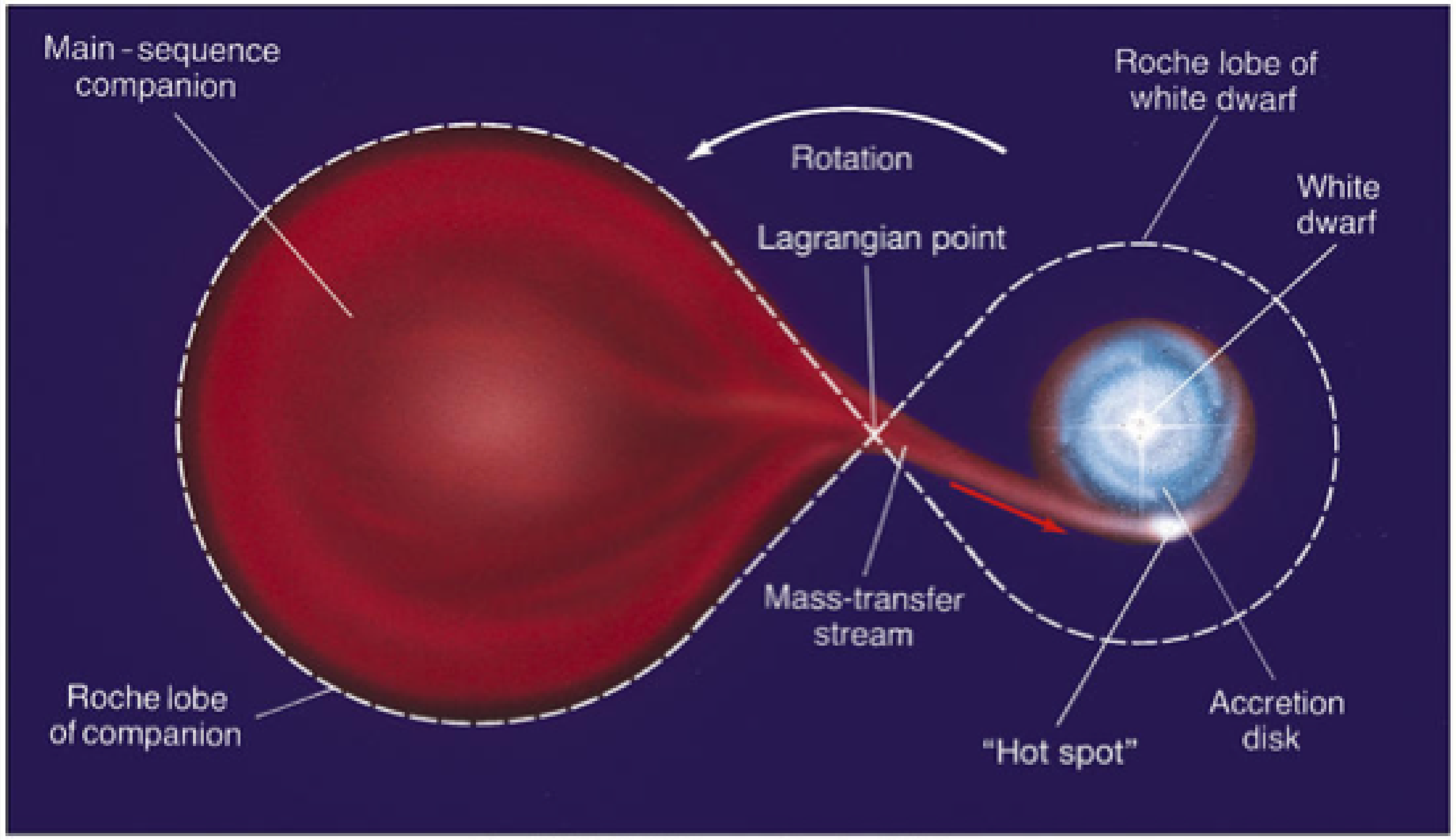
Constraints on Three-Body Force Parameters



Steiner and Gandolfi (2012)

- Values of a and α are unconstrained, but constraints on b and β
- Left and right plot boundaries exhaust expected range
- Neutron star radii are indirectly constraining nuclear three-body forces
- Limitation: if hyperons (or other strong phase transition) happens at a sufficiently low density, then results are modified

Accreting Neutron Stars: LMXBs



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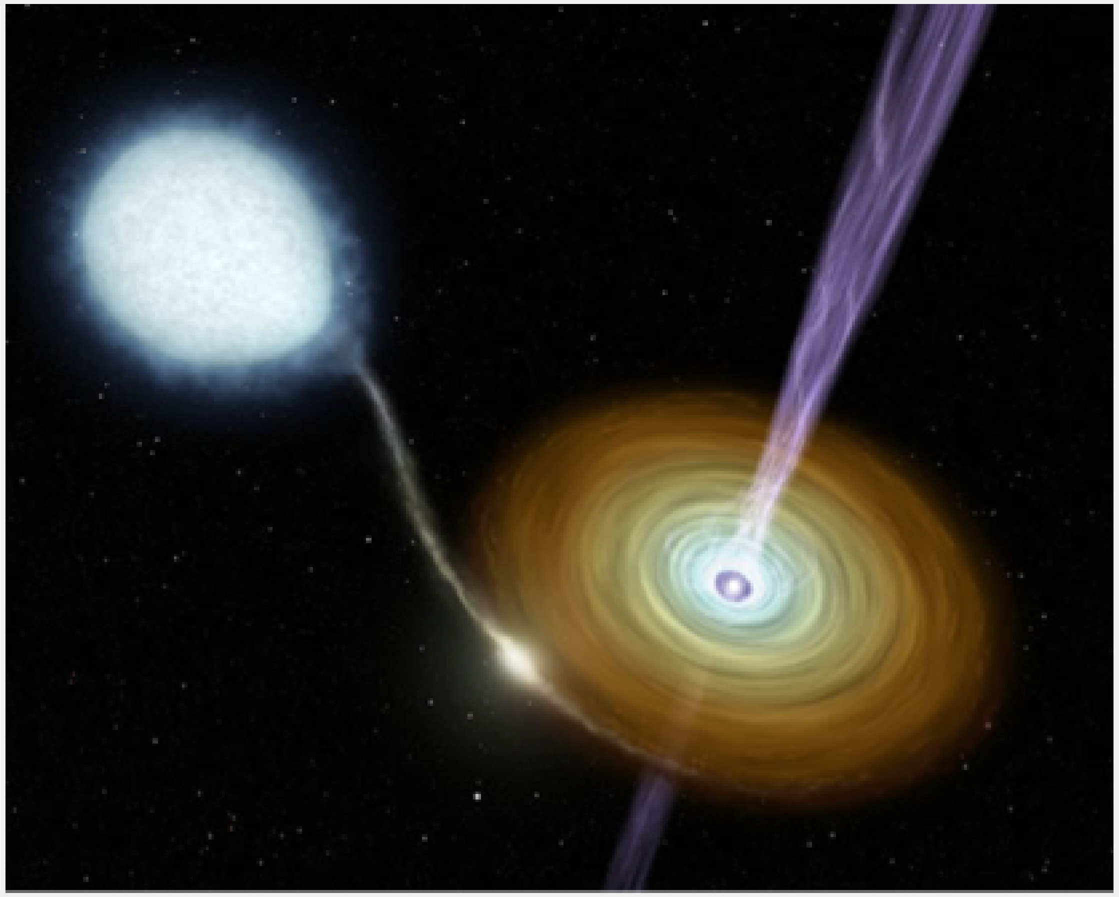
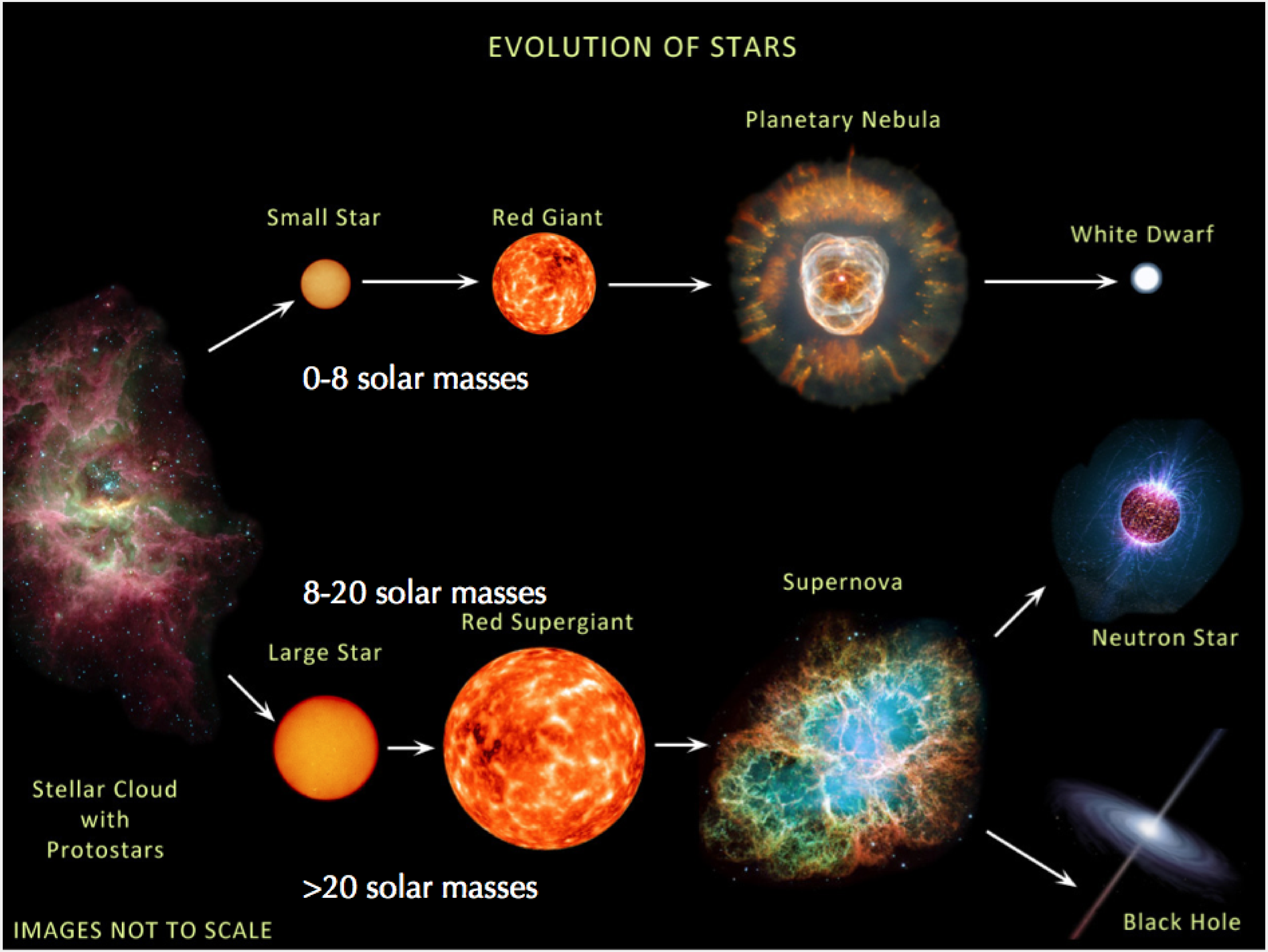


- Most stars have companions: neutron stars can have main-sequence, "normal star", companions
- Accretion heats the crust and is episodic
- At high enough density, H and He are unstable to thermonuclear explosions, i.e. X-ray bursts

Stellar Evolution



Neutron Star Composition

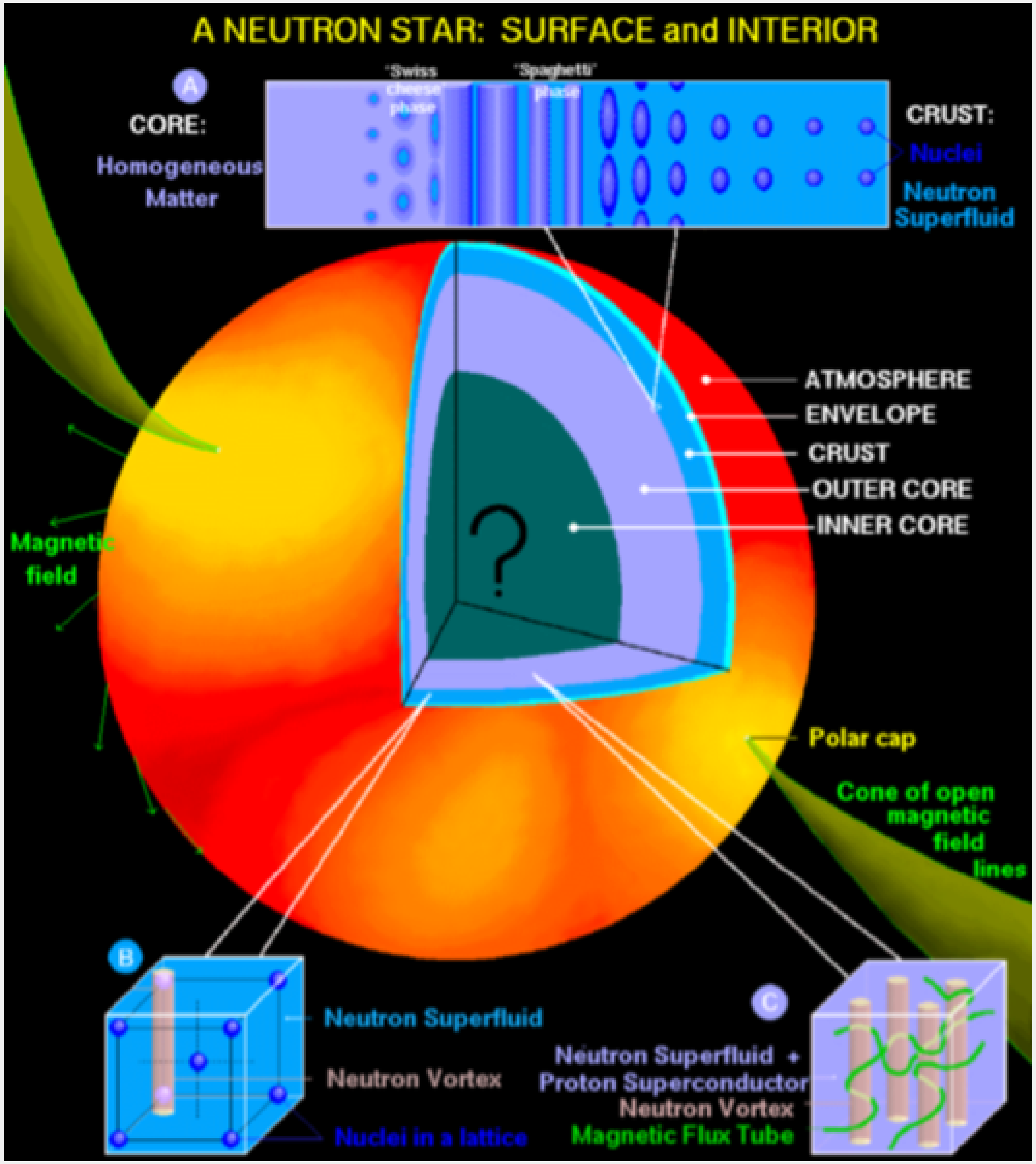
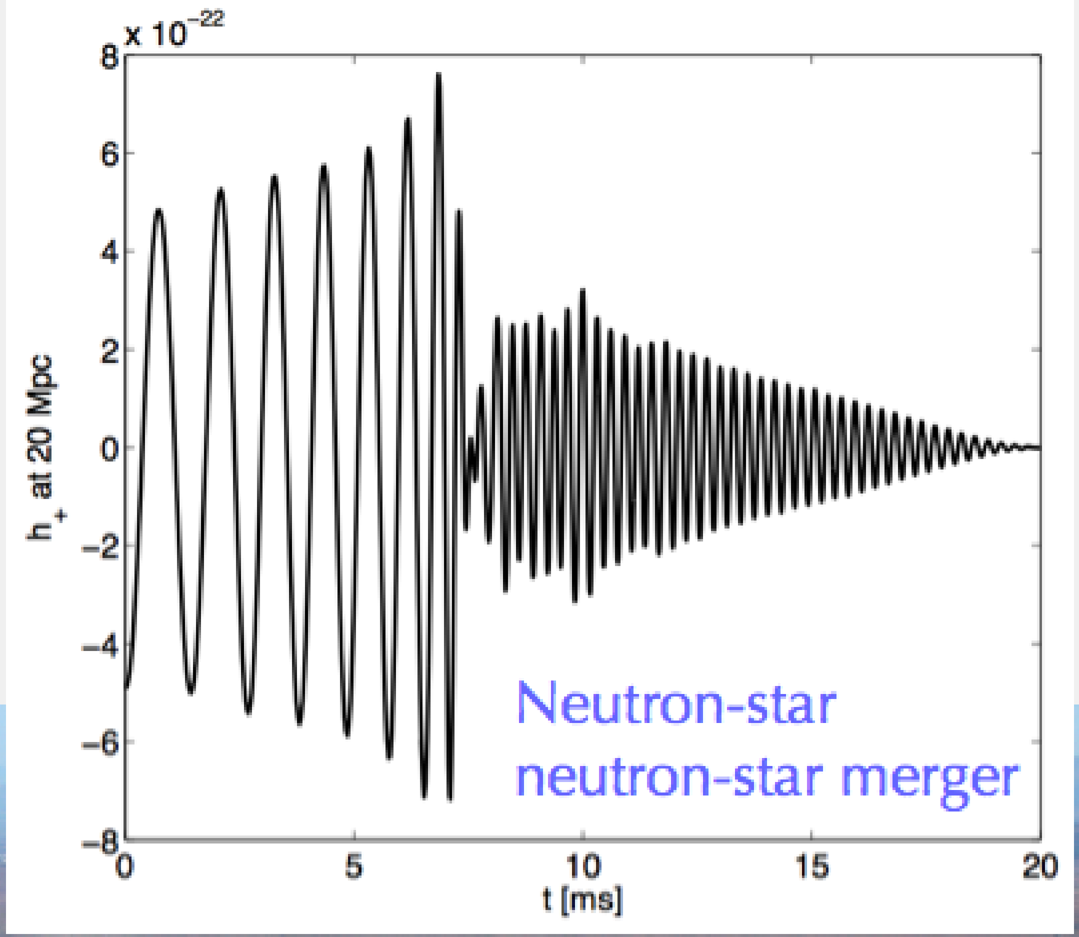


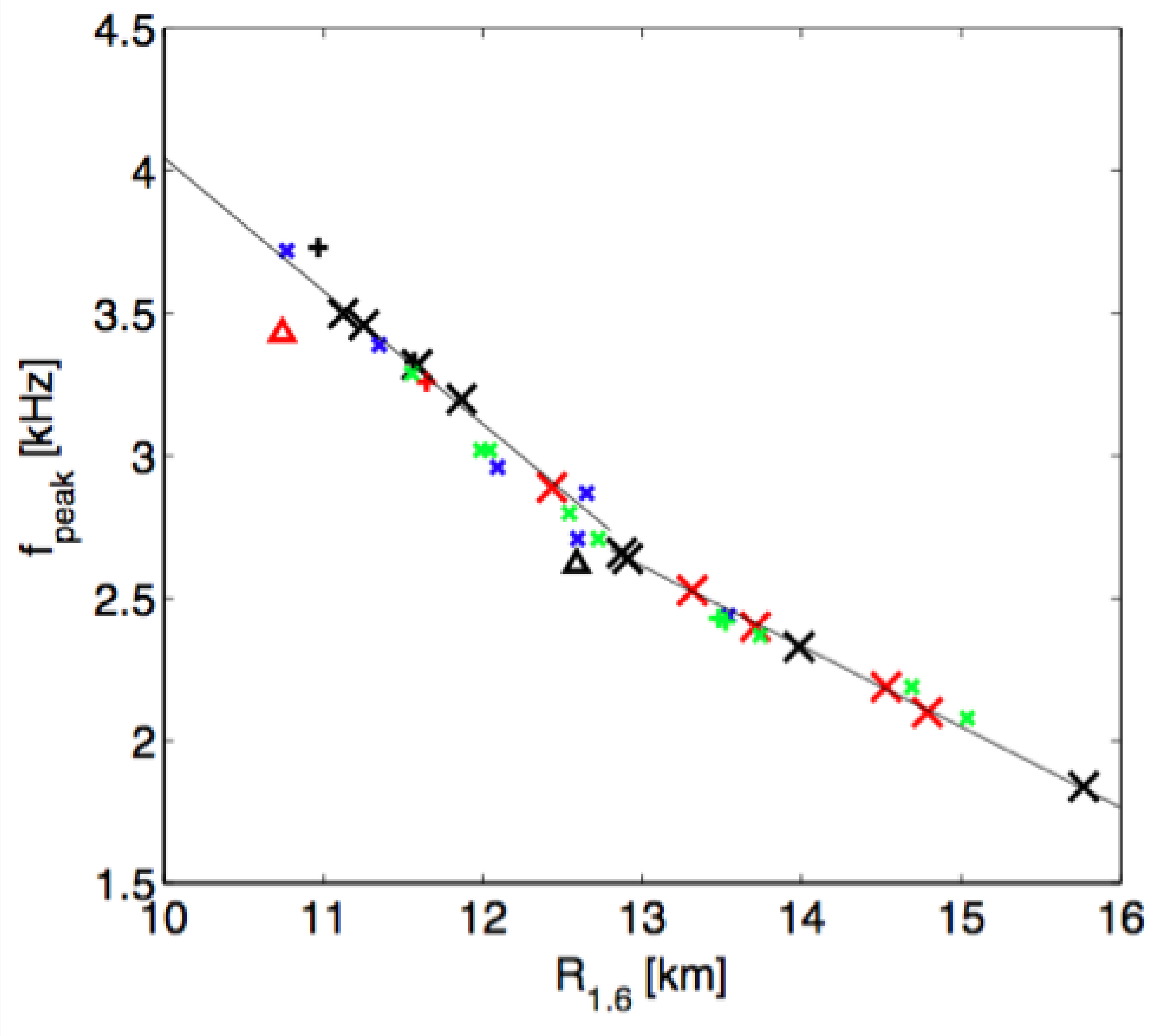
Figure by Dany Page

- Outer crust: of neutron-rich nuclei
- Inner crust: neutron-rich nuclei embedded in a sea of quasi-free superfluid neutrons
- Outer core: fluid of neutrons, protons, and electrons
- Inner core: hyperons, Bose condensates, deconfined quark matter
- **What are the correct degrees of freedom for the effective field theory which describes dense matter?**

Neutron Star Radii and LIGO Observations



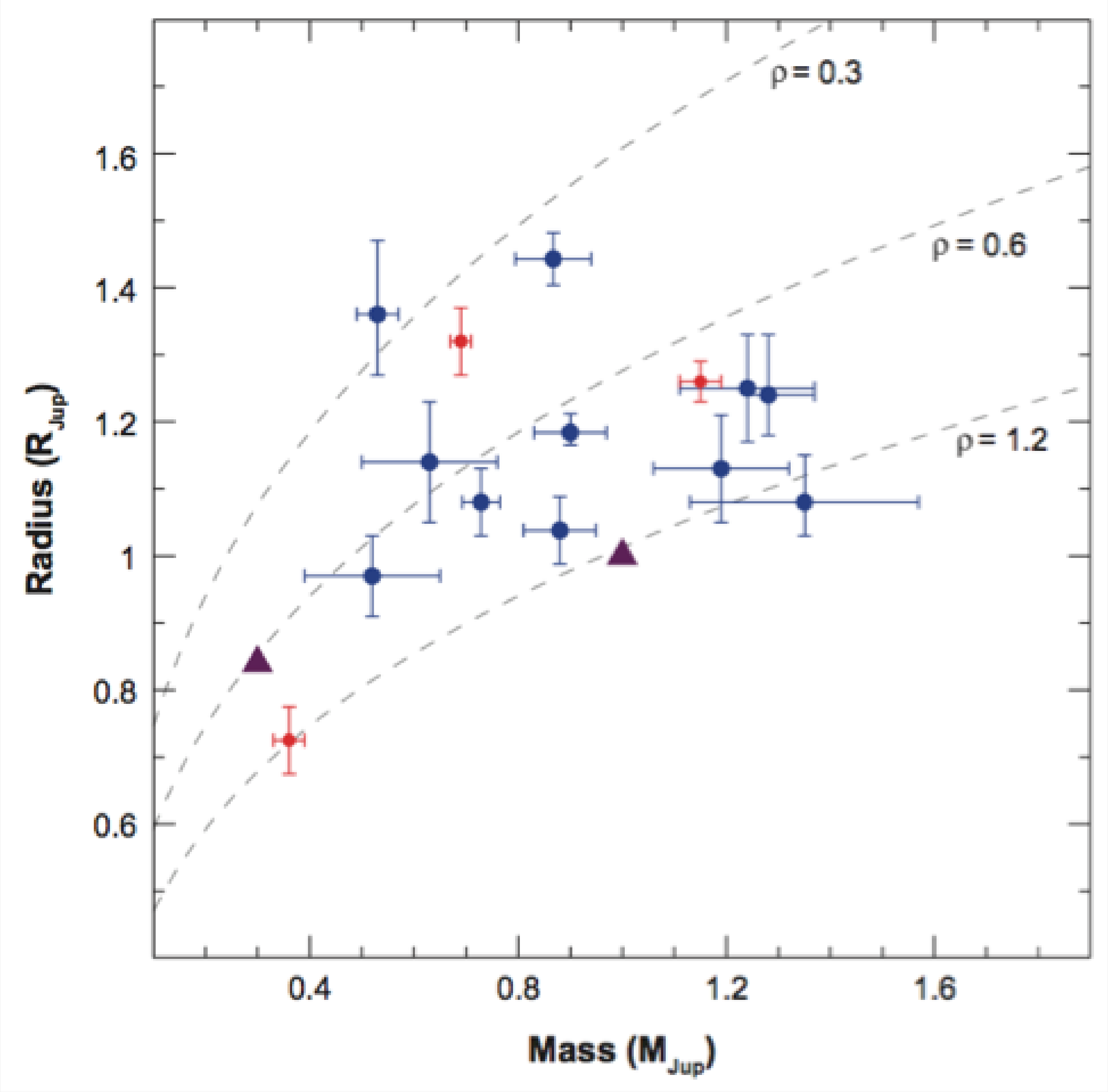
Laser Interferometer Gravitational Wave Observatory Hanford



Bauswein, Janka, Hebeler, and Schwenk (2012)

- h_+ is the GW amplitude
- First detection in ~ 2-3 years
- Neutron star radii determine f_{peak}

Planetary Diversity



Udry et al. (2007)

- Varying composition, thus varying radius for a fixed mass