Towards Constraining the Nucleon-Nucleon Interaction from Neutron Star Observations

Andrew W. Steiner (INT/U. Washington)

July 31, 2014

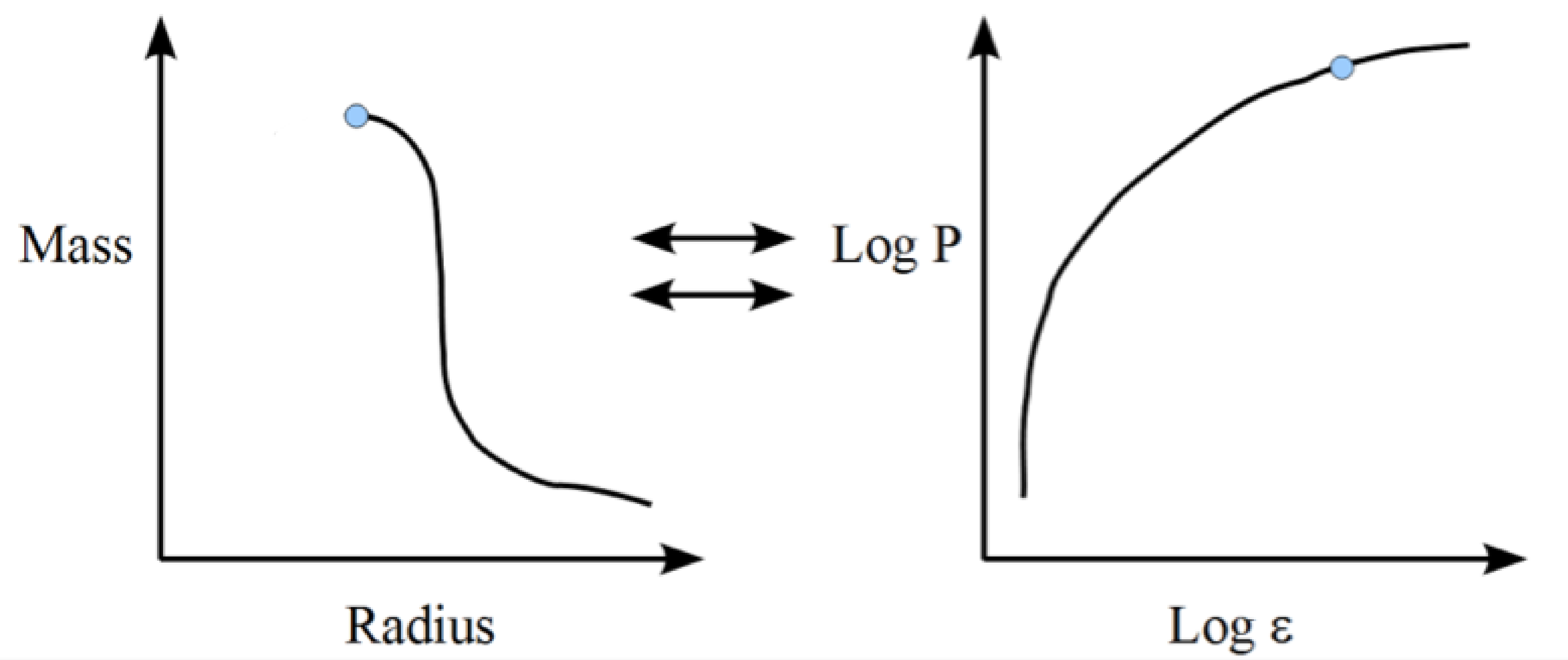
With: Edward F. Brown (MSU), Farrukh J. Fattoyev (TAMU-Commerce), Tobias Fischer (Wroclaw), Stefano Gandolfi (Los Alamos), Matthias Hempel (Basel), James M. Lattimer (Stony Brook), William G. Newton (TAMU-Commerce) and Madappa Prakash (Ohio)

Outline

- Neutron star masses and radii and the EOS
- Nucleon-nucleon interaction and the symmetry energy
- Systematic uncertainties and self-consistency
- Finite-temperature EOS tables
- Tidal deformabilities

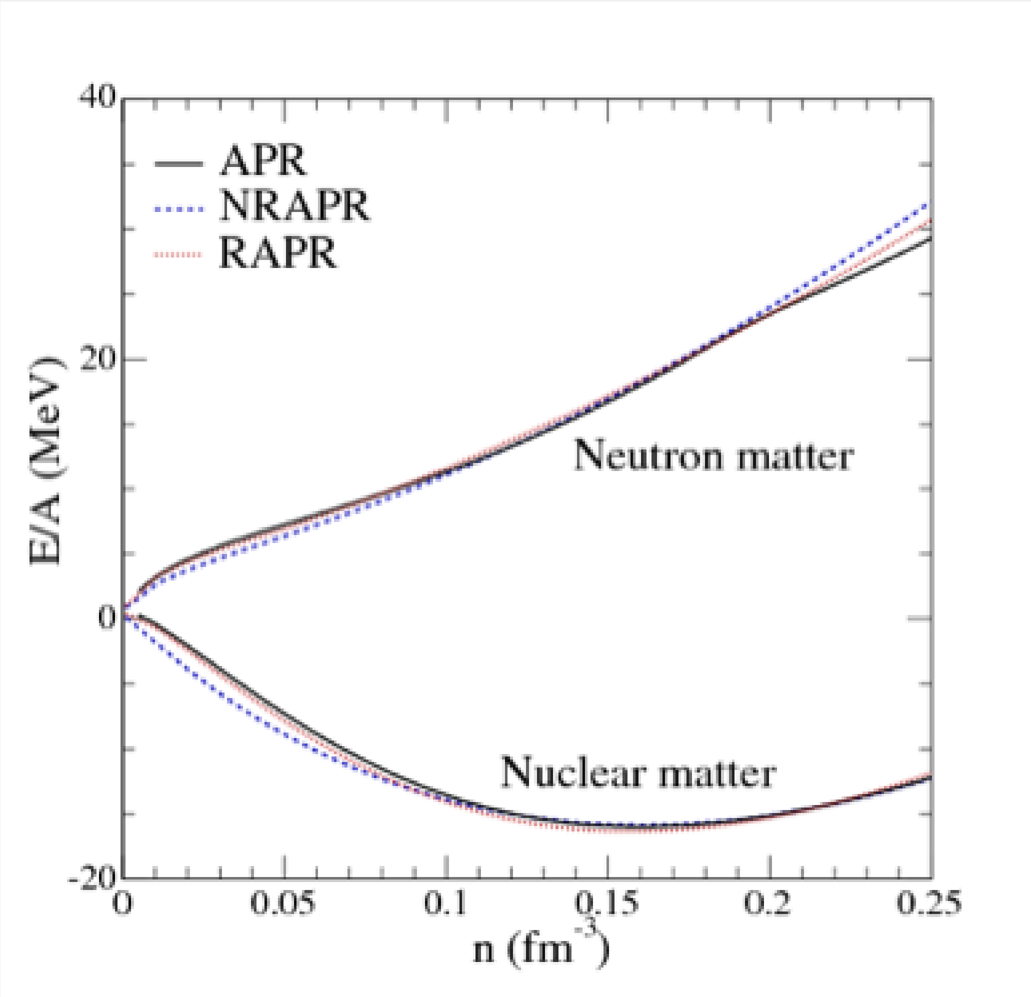
Neutron Star Masses and Radii and the EOS

- 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)

Nucleon-Nucleon Interaction

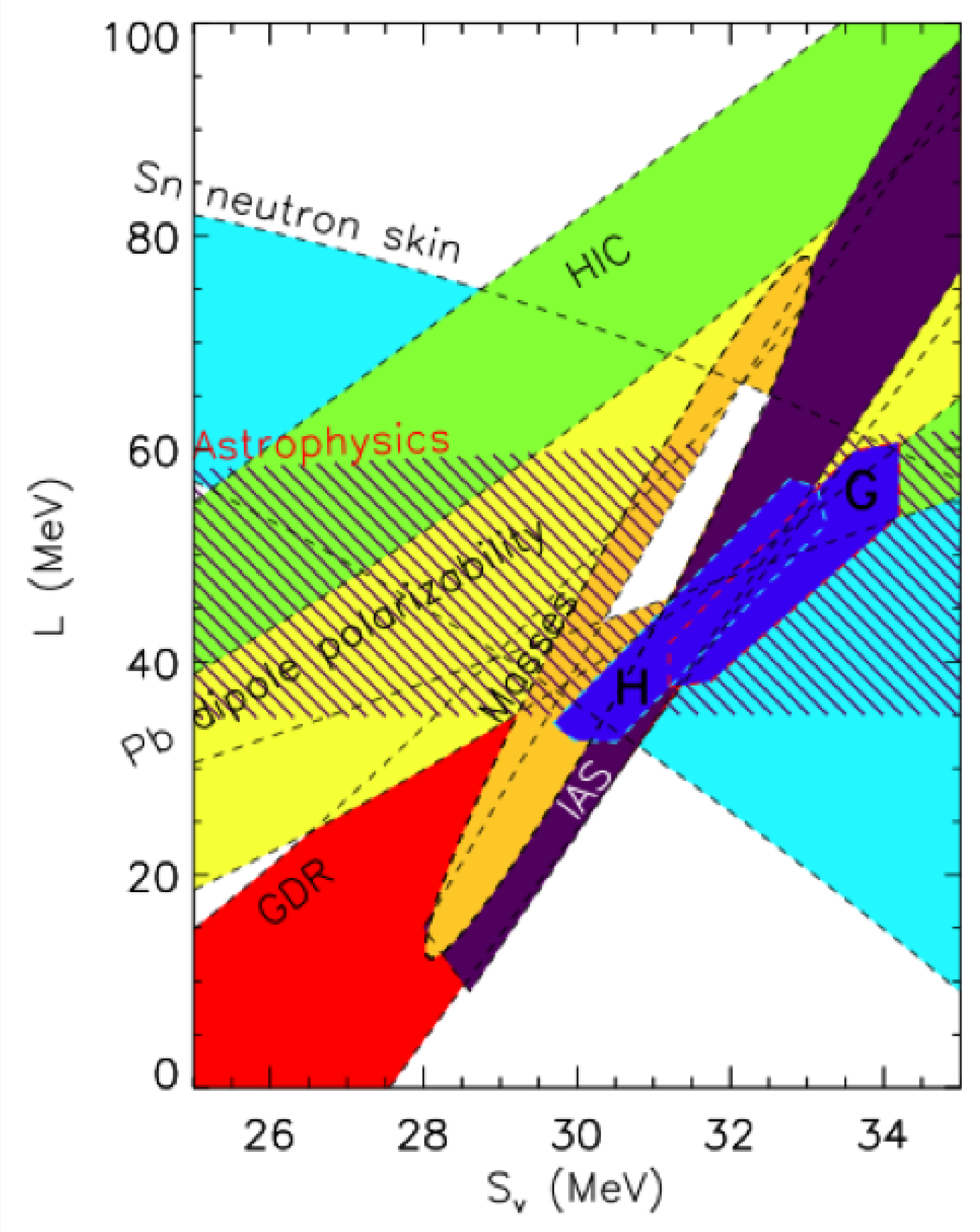


Steiner, Prakash, Lattimer, and Ellis (2005)

Nucleonic matter:

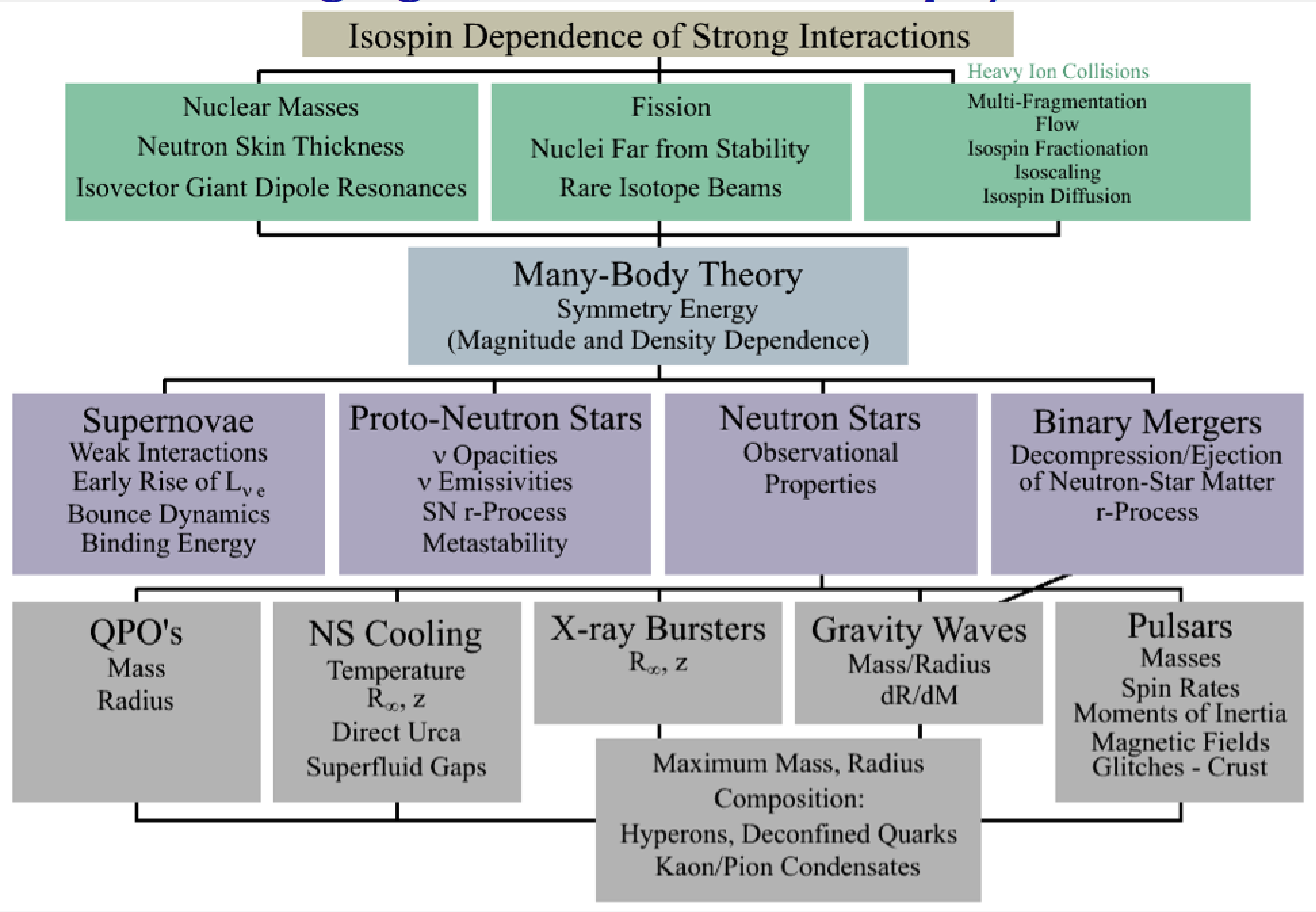
$$\varepsilon = B + \frac{K}{18 n_0^2}(n - n_0)^2 + (1-2x)^2 S(n)$$

- $S(n_B) \equiv E_{\mathrm{neut}}(n_B) - E_{\mathrm{nuc}}(n_B)$
- $S = S(n_0)$; $L = 3 n_0 S'(n_0)$
- Not just EOS: finite-temperature, transport properties, etc.
- Not necessarily applicable at high densities



Lattimer and Steiner (2014)

Bridging Nuclear and Astro-physics



Steiner, Prakash, Lattimer, and Ellis (2005)

Radius Measurements in qLMXBs

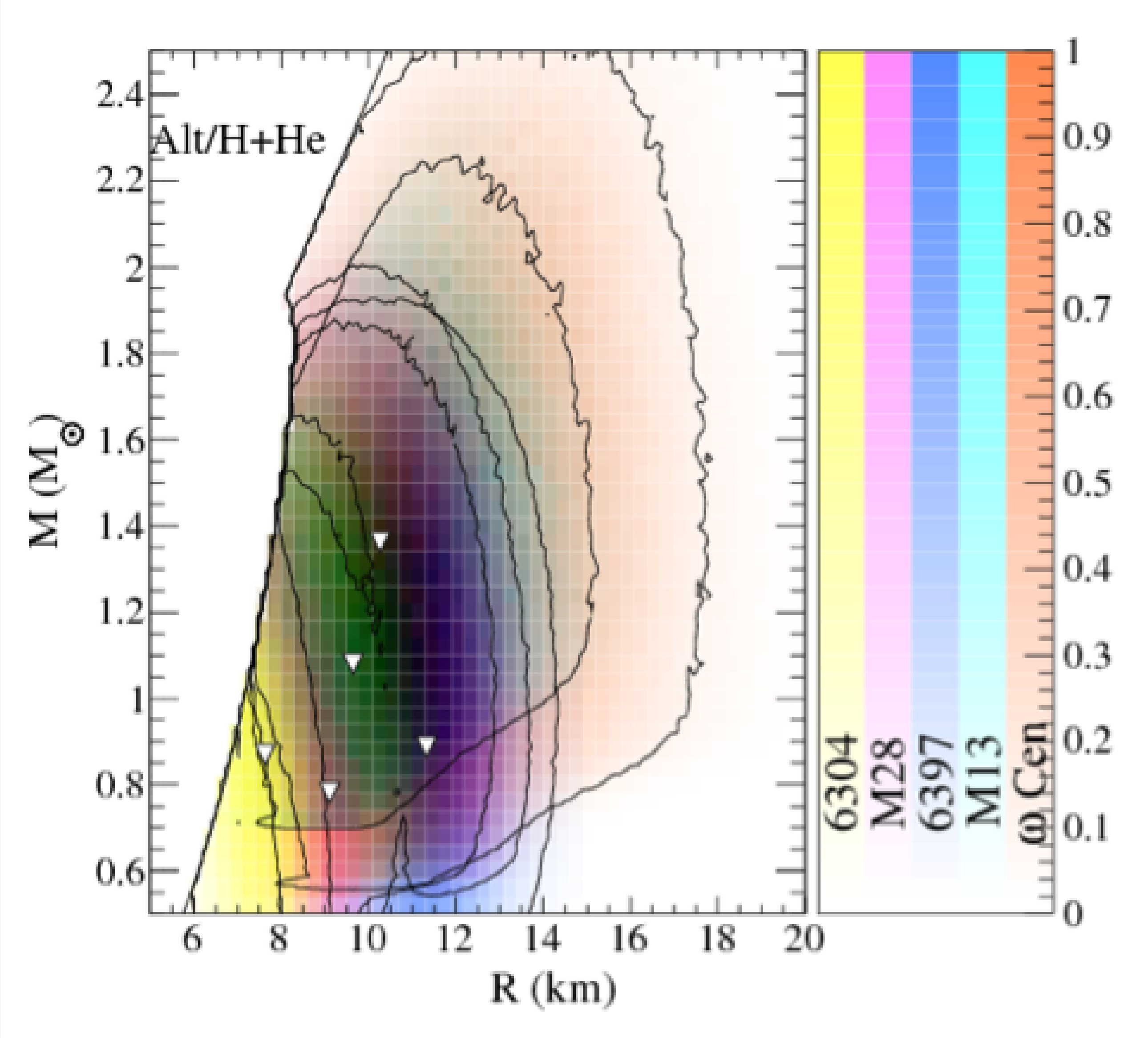
Quiescent LMXBs

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

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

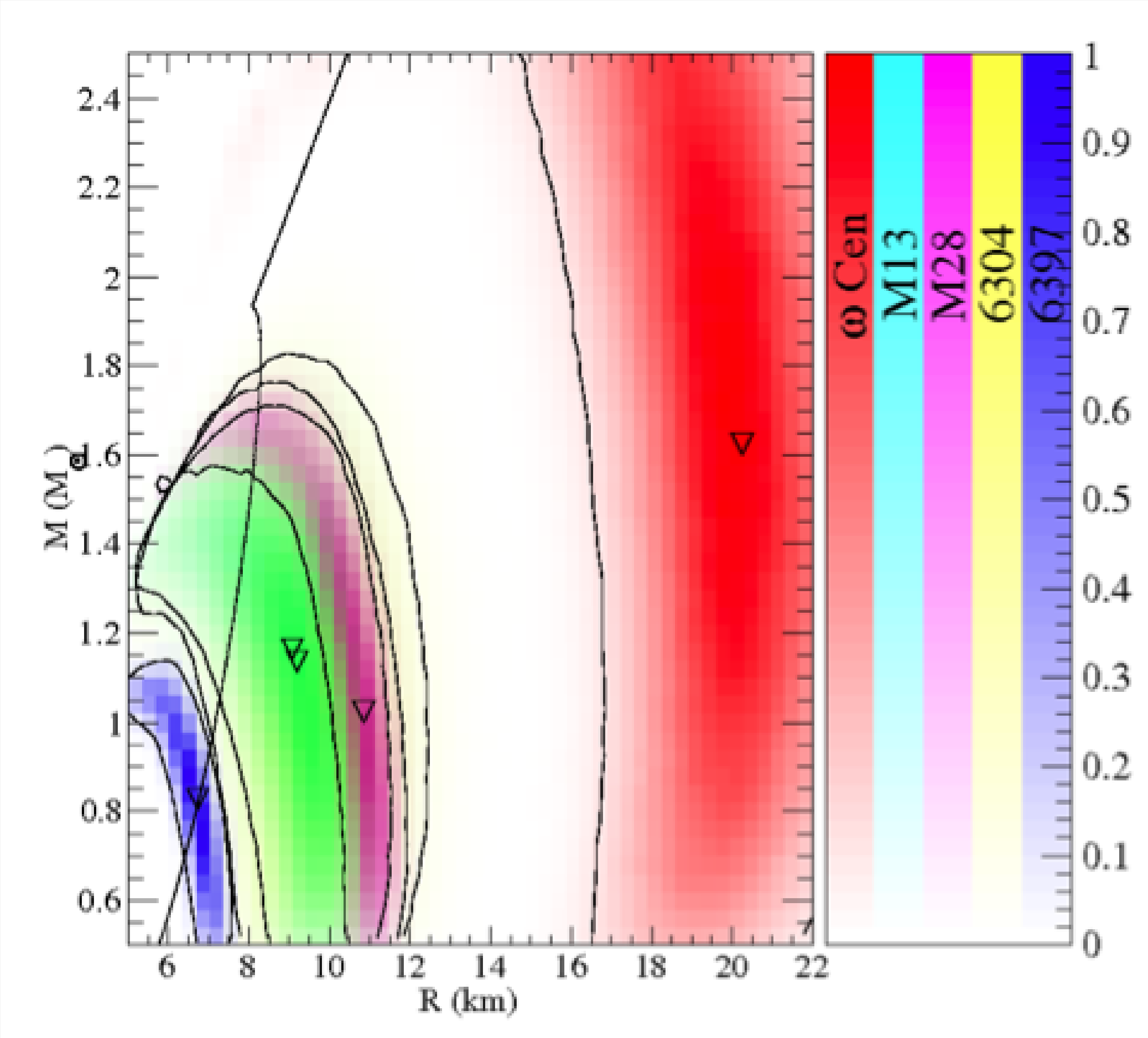
i.e. Rutledge, Bildsten, and Brown (1999)

- 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

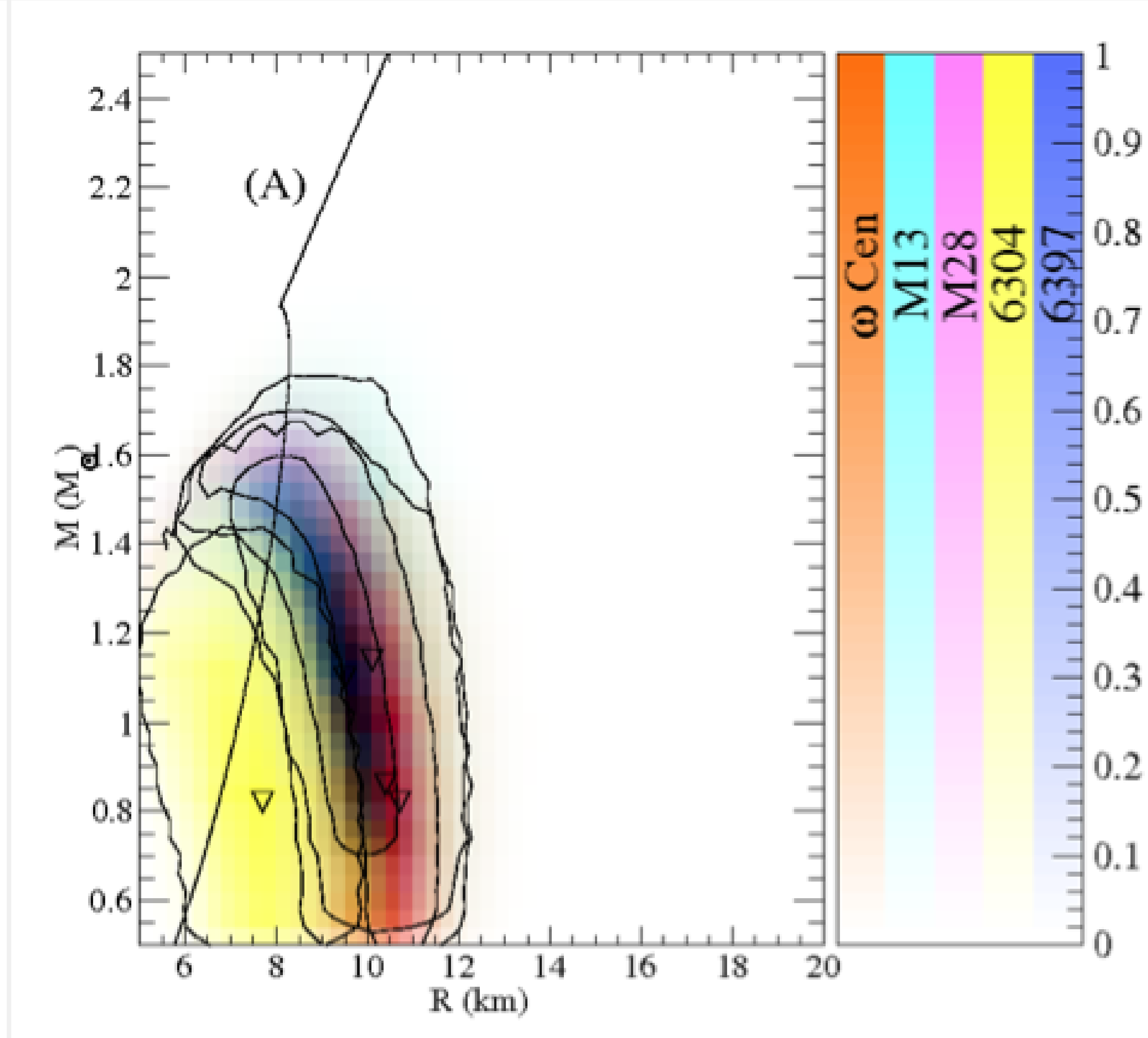


Lattimer and Steiner (2014) - Probability distributions for five neutron stars, colors added together

As of last year...



Results from Guillot, Servillat, Webb, and Rutledge (2013) slightly adapted for Lattimer and Steiner (2014) before any assumption about the M-R curve

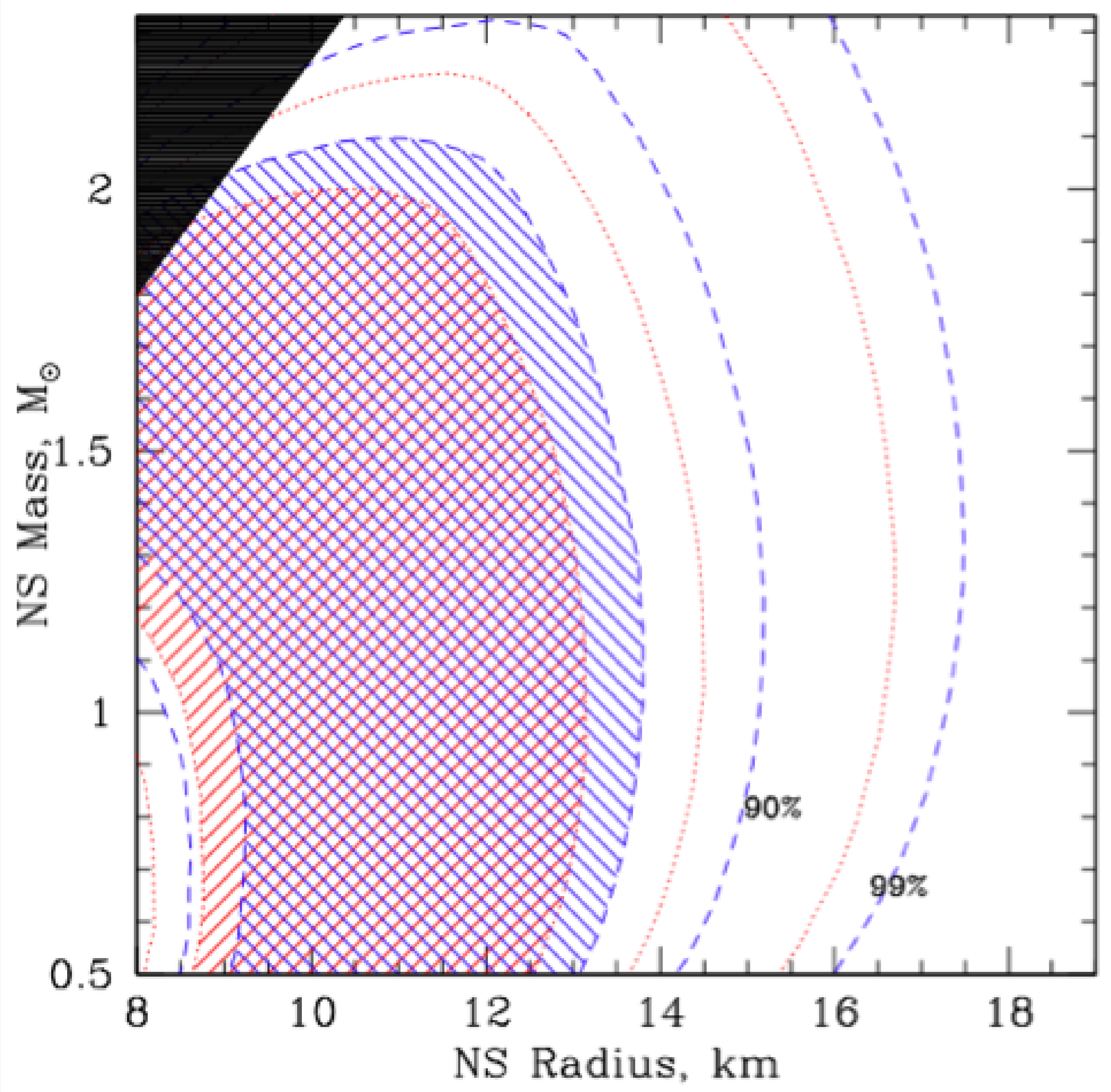


Lattimer and Steiner (2014), relative Bayes factor of 1200

- $R_{\mathrm{NS\ in\ }\omega\mathrm{\ Cen}}$: 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

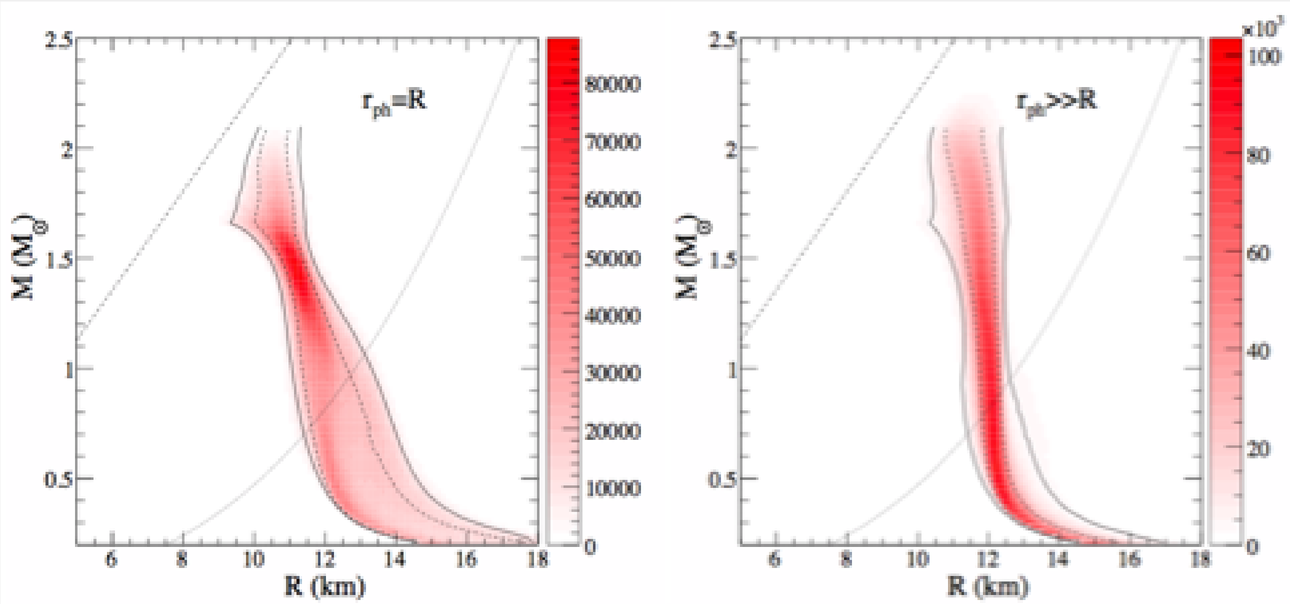
- Smaller N_H values for ω Cen!
- "This is a ~25% change in the best-fit NS radius (or a 20% change in the radius lower limit) due to a change in the ISM model, reinforcing the critical importance of accurate modeling of the ISM"
  Heinke et al. (2014)
- Changed ISM abundances from Anders & Ebihara (1982) to Wilms, Allen & McCray (2000) (XSPEC options)
- Confirmation of expectations from nuclear physics



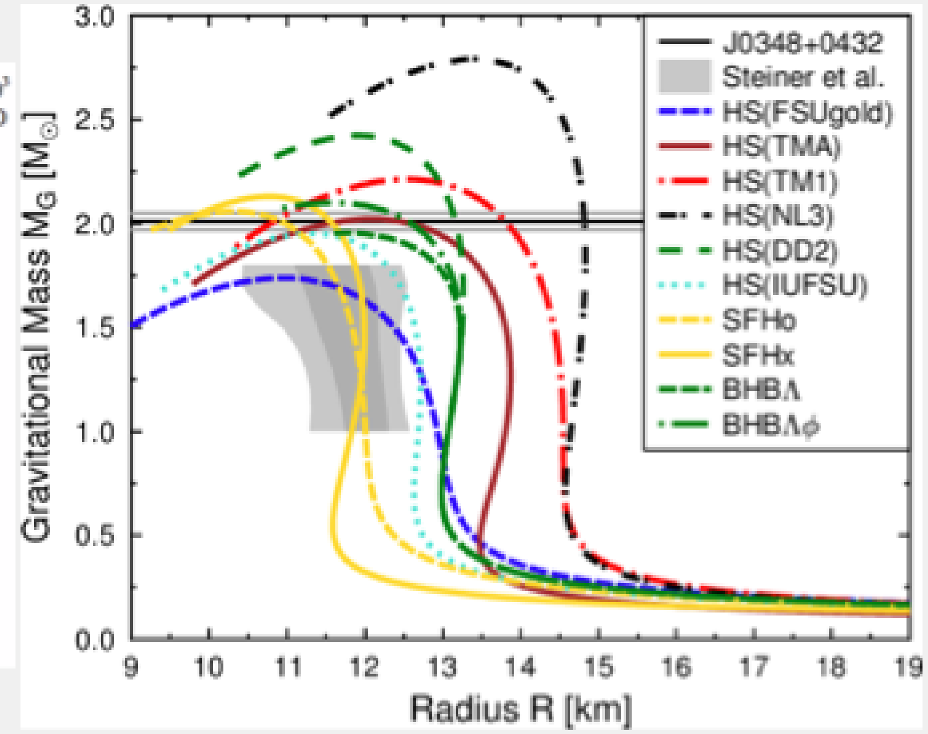
Heinke et al. (2014)

- Radius ranges won't change that much from Steiner, Lattimer, and Brown (2013)

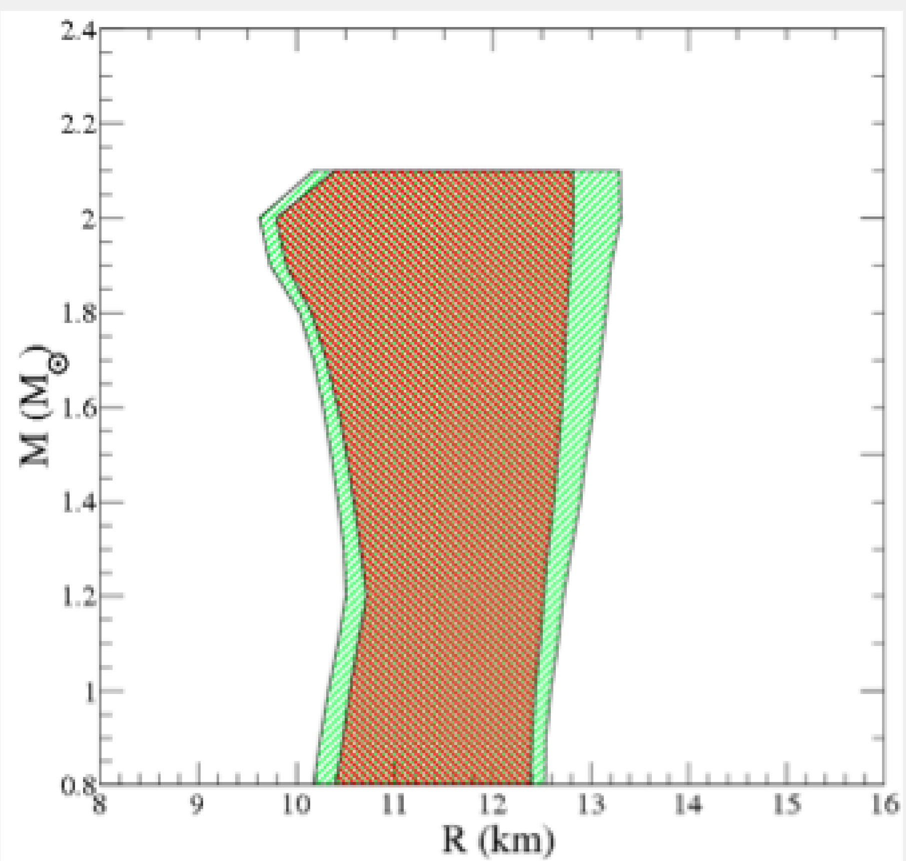
Evolution of Radius Constraints



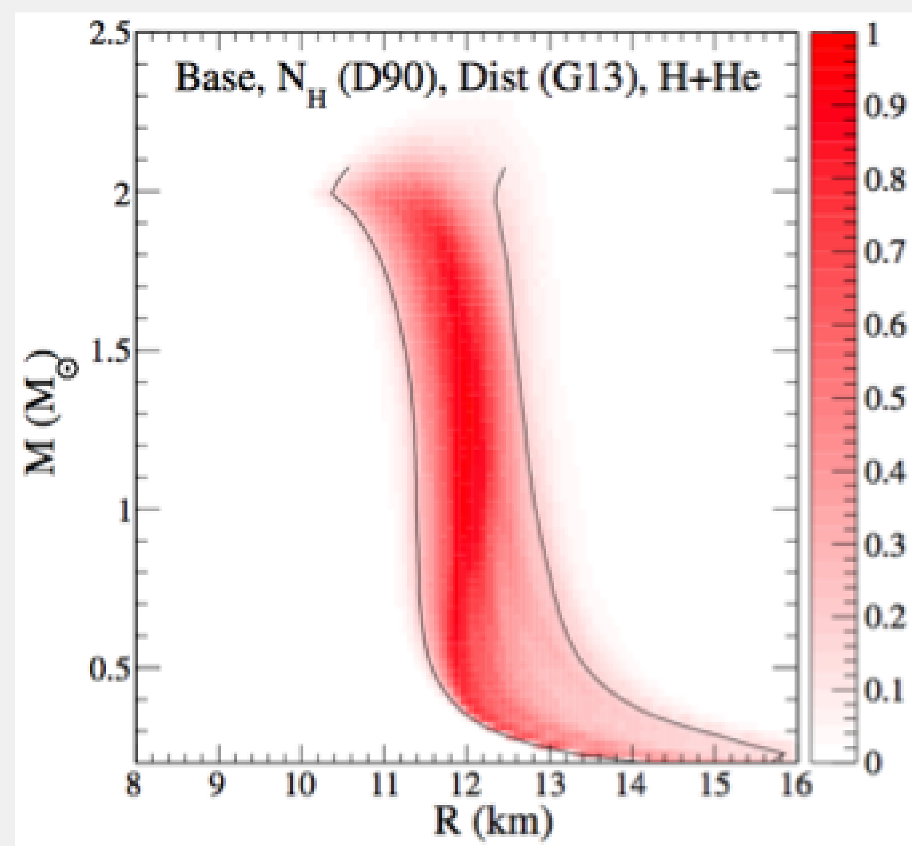
Steiner, Lattimer, and Brown (2010)



Steiner, Hempel and Fischer (2013)



Steiner, Lattimer, and Brown (2013)



Lattimer and Steiner (2014)

Varying Models and Data Assumptions

EOS Model	Data modifications	$R_{95\%>}$	$R_{68\%>}$ (km)	$R_{68\%<}$	$R_{95\%<}$
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)

- Each model represents $10^5 - 10^6$ individual EOSs
- 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

Table 5
Posterior Confidence Ranges and Evidence Integrals

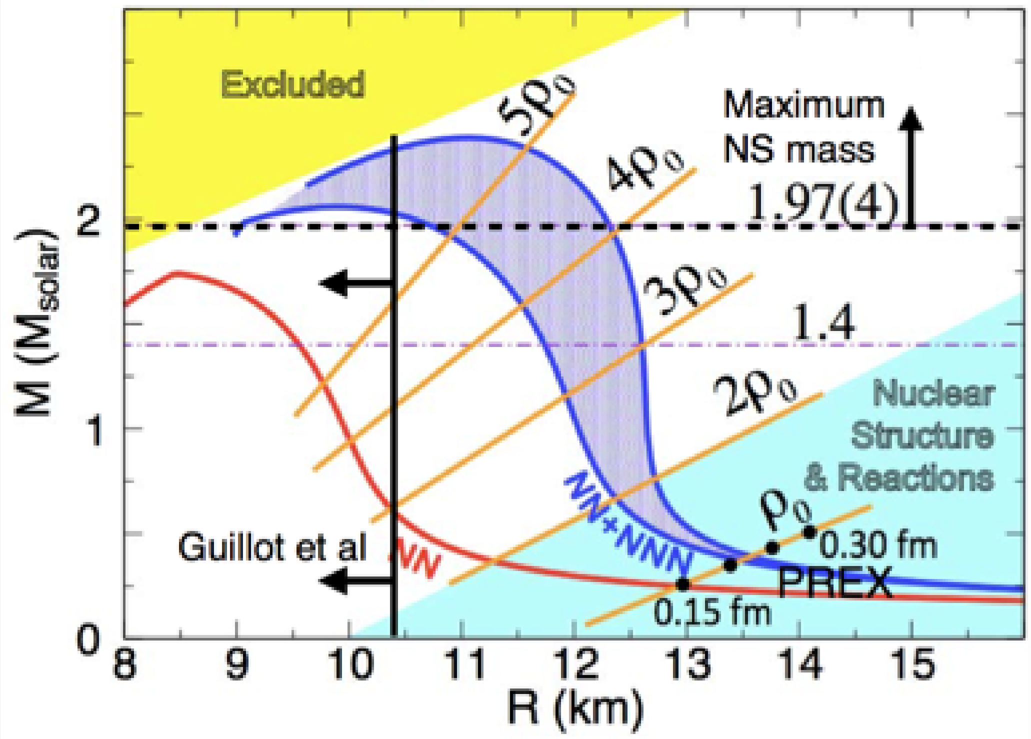
Model	N_H	Dist.	Comp.	$R_{1.4}$ (km)	I
Base	G13	G13	H	11.11–11.88	$(1.77 \pm 0.09) \times 10^{-8}$
Base	G13	G13	H+He	11.36–12.84	$(4.50 \pm 0.21) \times 10^{-3}$
Base	G13	Alt	H	10.73–11.65	$(1.86 \pm 0.18) \times 10^{-6}$
Base	G13	Alt	H+He	11.45–13.32	$(3.71 \pm 0.21) \times 10^{-1}$
Base	G13	H10	H	10.77–11.71	$(1.23 \pm 0.09) \times 10^{-7}$
Base	G13	H10	H+He	11.36–13.44	$(4.28 \pm 0.35) \times 10^{-3}$
Base	D90	G13	H	10.67–11.51	$(4.65 \pm 0.48) \times 10^{-3}$
Base	D90	G13	H+He	11.31–12.64	$(2.14 \pm 0.19) \times 10^{+2}$
Base	D90	Alt	H	10.85–11.79	$(9.40 \pm 1.22) \times 10^{-3}$
Base	D90	Alt	H+He	11.37–12.61	$(4.06 \pm 0.36) \times 10^{+2}$
Base	D90	H10	H	10.78–11.70	$(4.78 \pm 0.73) \times 10^{-3}$
Base	D90	H10	H+He	11.23–12.62	$(1.57 \pm 0.07) \times 10^{+2}$
Base	H10	G13	H	10.87–11.82	$(1.04 \pm 0.08) \times 10^{+0}$
Base	H10	G13	H+He	11.15–12.38	$(1.84 \pm 0.12) \times 10^{+2}$
Base	H10	Alt	H	11.03–12.07	$(1.39 \pm 0.20) \times 10^{+2}$
Base	H10	Alt	H+He	11.04–12.31	$(1.44 \pm 0.10) \times 10^{+2}$
Base	H10	H10	H	10.78–11.95	$(7.52 \pm 0.65) \times 10^{+1}$
Base	H10	H10	H+He	11.31–12.66	$(5.30 \pm 0.22) \times 10^{+2}$
Exo	G13	G13	H	9.15–10.81	$(7.32 \pm 0.63) \times 10^{-6}$
Exo	G13	G13	H+He	10.52–11.77	$(4.46 \pm 0.38) \times 10^{-2}$
Exo	G13	Alt	H	10.42–11.39	$(1.21 \pm 0.19) \times 10^{-3}$
Exo	G13	Alt	H+He	10.88–12.59	$(7.33 \pm 0.78) \times 10^{-1}$
Exo	G13	H10	H	10.61–11.41	$(2.23 \pm 0.48) \times 10^{-5}$
Exo	G13	H10	H+He	10.76–12.38	$(1.67 \pm 0.16) \times 10^{-2}$
Exo	D90	G13	H	9.39–10.97	$(5.46 \pm 1.74) \times 10^{-1}$
Exo	D90	G13	H+He	10.53–12.45	$(2.29 \pm 0.13) \times 10^{+1}$
Exo	D90	Alt	H	9.86–11.44	$(3.04 \pm 0.42) \times 10^{-1}$
Exo	D90	Alt	H+He	10.90–12.31	$(4.46 \pm 0.22) \times 10^{+1}$
Exo	D90	H10	H	9.60–11.38	$(2.27 \pm 0.50) \times 10^{-1}$
Exo	D90	H10	H+He	10.61–12.28	$(2.59 \pm 0.15) \times 10^{+1}$
Exo	H10	G13	H	9.87–11.49	$(5.15 \pm 0.51) \times 10^{+0}$
Exo	H10	G13	H+He	10.60–11.99	$(4.67 \pm 0.46) \times 10^{+1}$
Exo	H10	Alt	H	10.45–11.74	$(5.17 \pm 0.64) \times 10^{+1}$
Exo	H10	Alt	H+He	10.53–11.81	$(7.49 \pm 0.75) \times 10^{+1}$
Exo	H10	H10	H	10.42–11.72	$(2.83 \pm 0.21) \times 10^{+1}$
Exo	H10	H10	H+He	10.74–12.39	$(8.93 \pm 0.47) \times 10^{+1}$

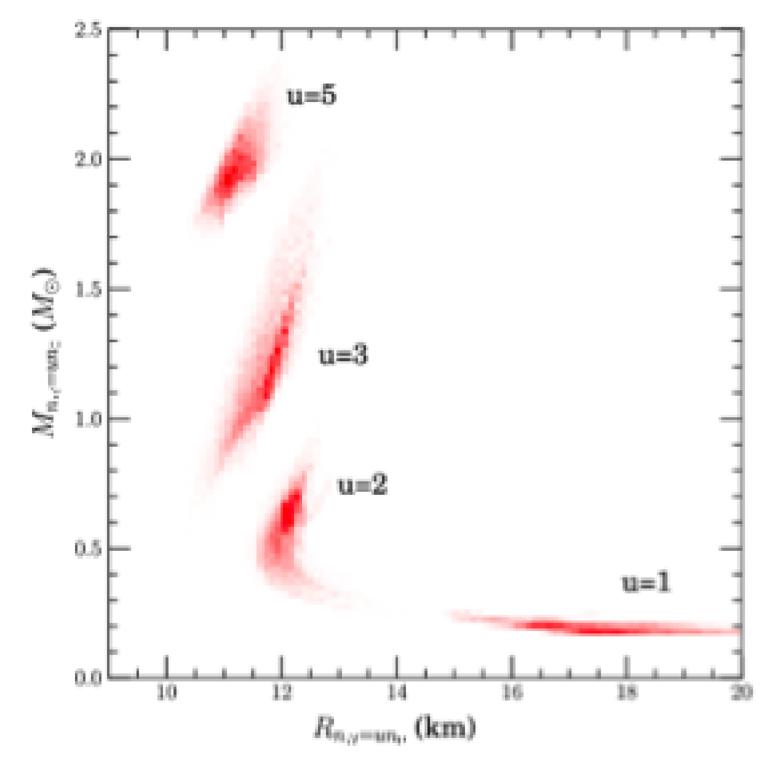
Lattimer and Steiner (2014)

Varying Models and Data Assumptions

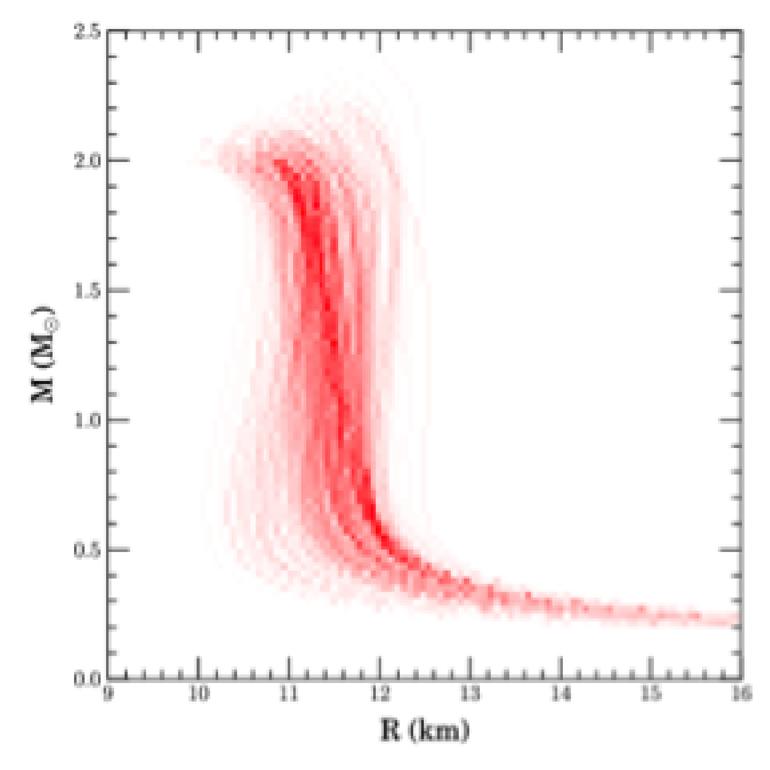
- In this case, 36 separate combinations, each with $10^5 - 10^6$ individual EOSs
- Not all systematic uncertainties are included

A More Detailed Look

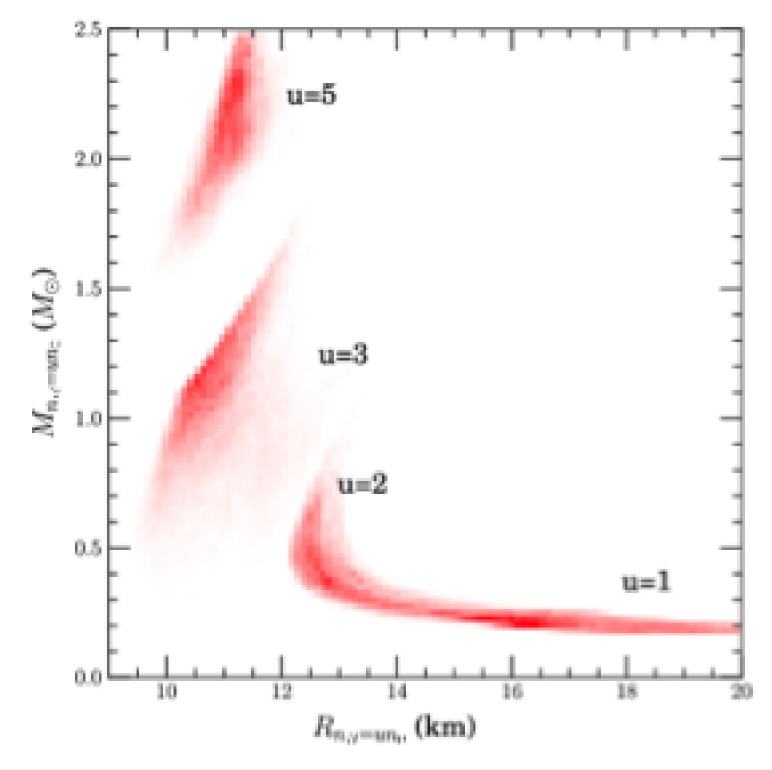




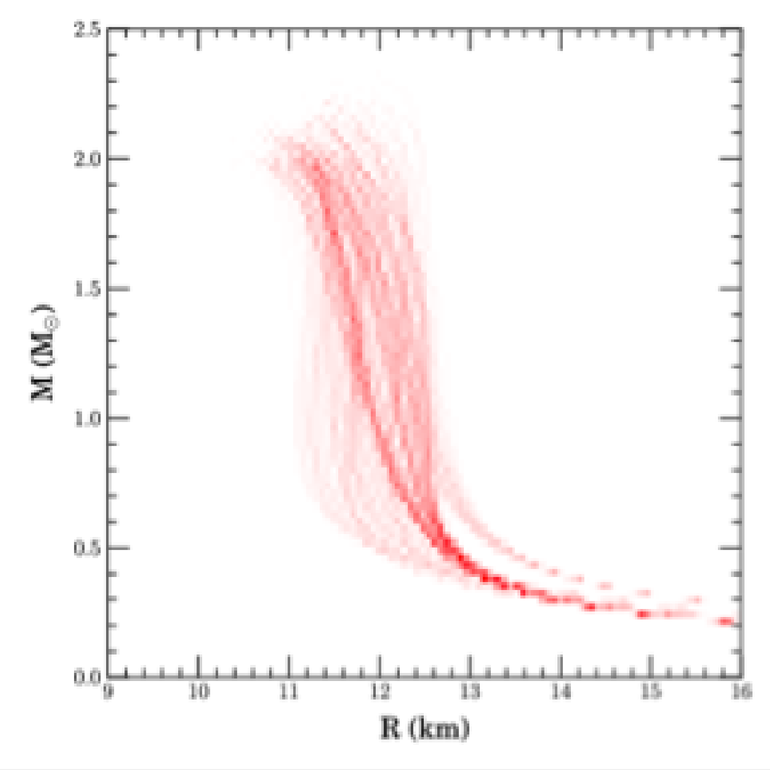
Model A from Steiner, Gandolfi, Fattoyev and Newton (2014)



Model A
$L = 32 \pm 0.6$ MeV

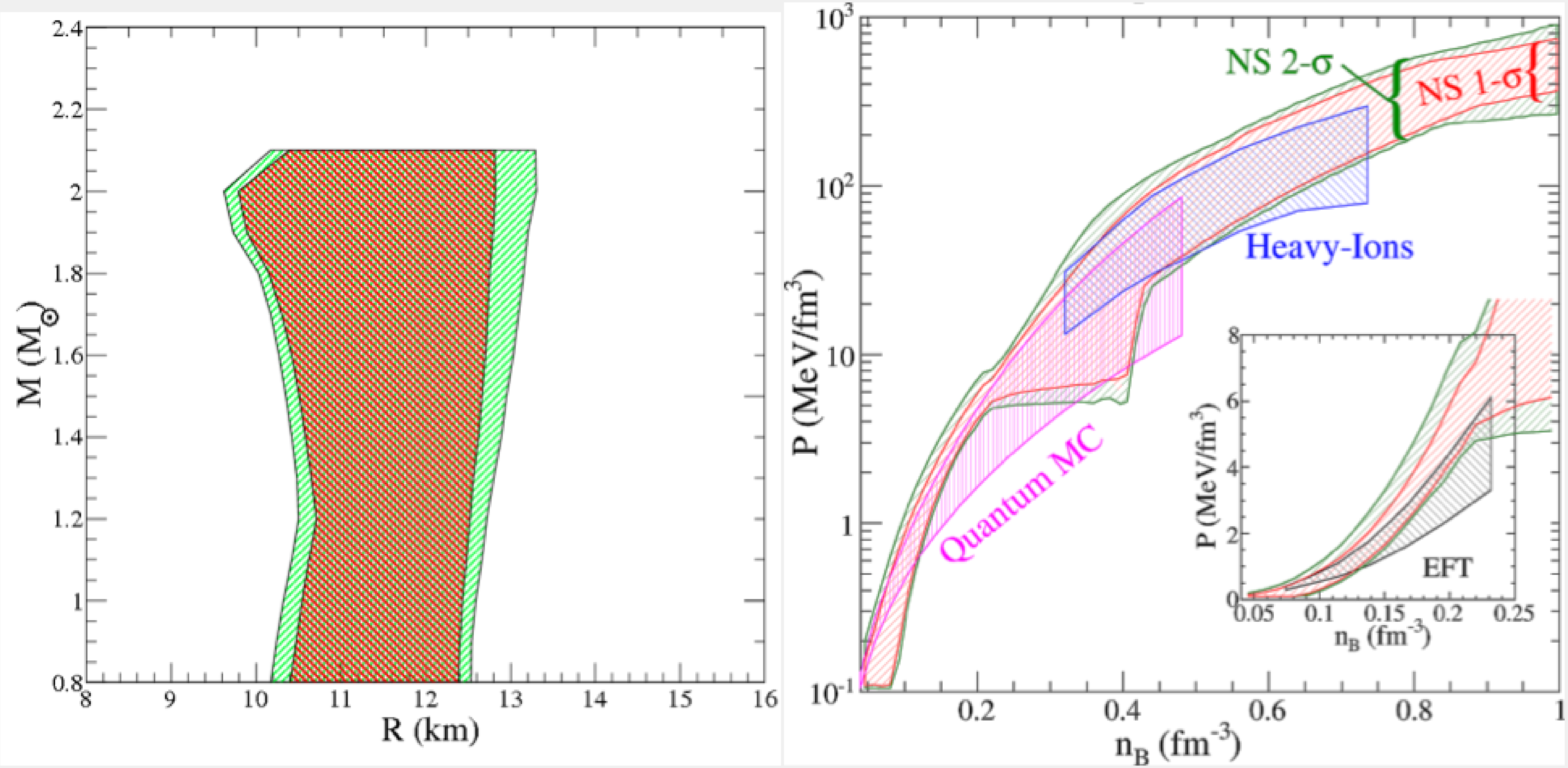


Model C from Steiner, Gandolfi, Fattoyev and Newton (2014)



Model A
$L = 62 \pm 1$ MeV

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
- No assumption that pressure is correlated between low and high-densities
- Some bursts/models give larger radii, inconsistent with QLMXB results Suleimanov et al.

Self-Consistency?!

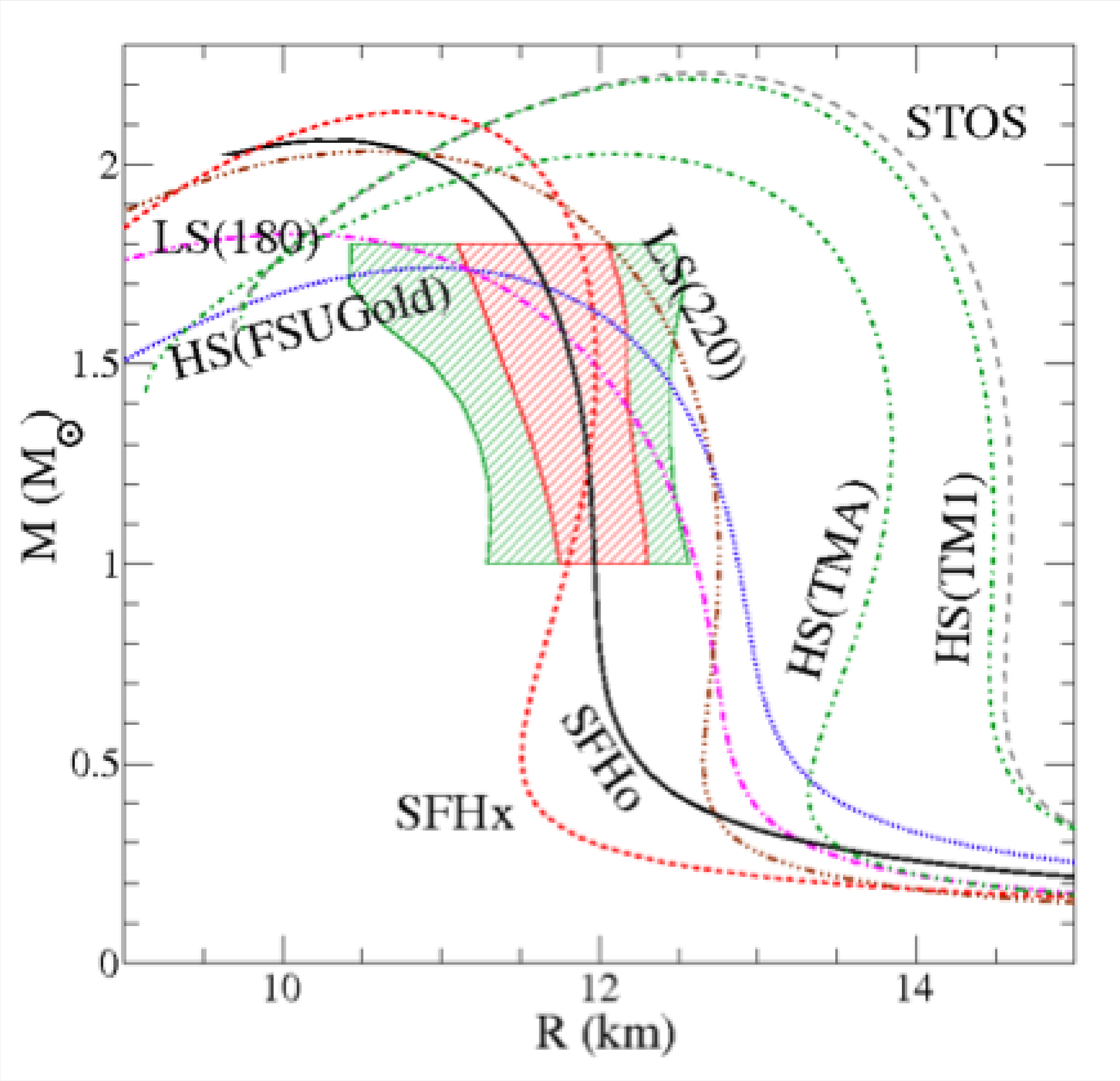
- Take e.g. a model of r-process from NS-NS mergers

- The nucleon-nucleon interaction's impact is extensive
  - The original supernova
  - Neutron star structure
  - Mass ejected in the merger
  - The nuclear masses, beta-decay, and neutron capture rates
  - The neutrino spectra

- More self-consistency can lead to advances

- Until then, we have to be careful about how we choose our models

EOS Tables for Simulations



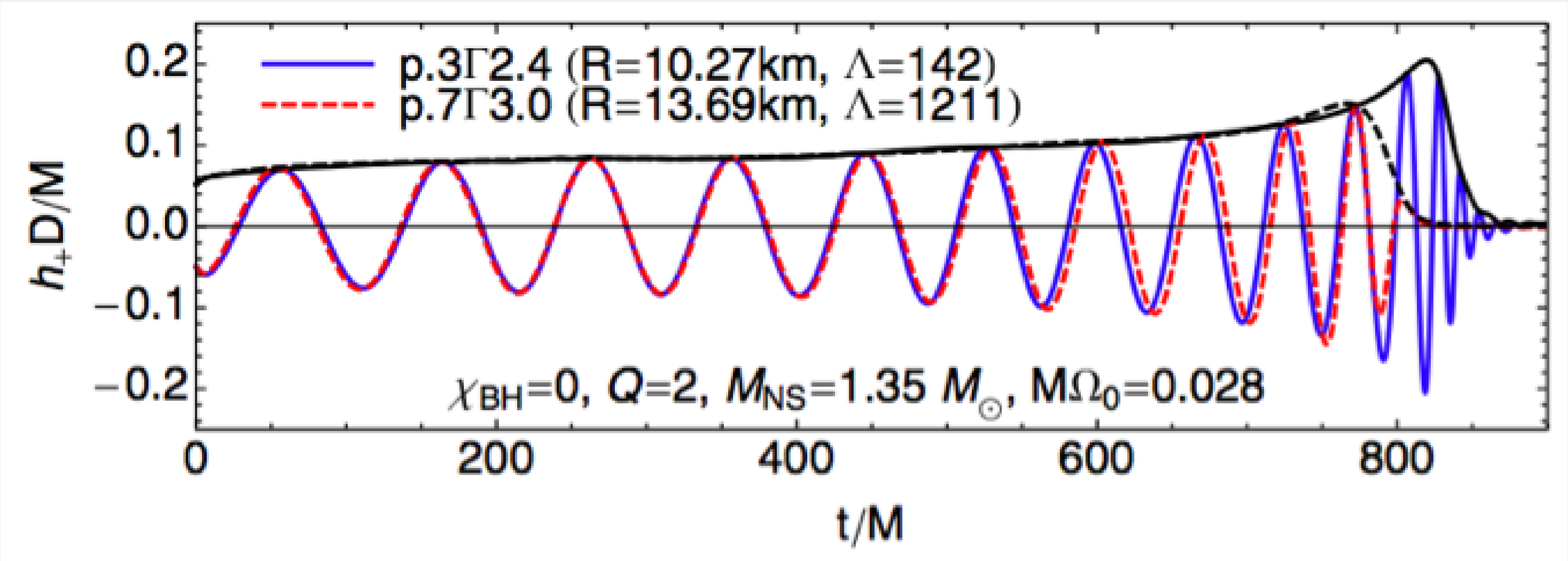
Steiner, Hempel, and Fischer (2013)

$$\mathcal{L} = \bar{\Psi}\left[i\not{\partial} - g_\omega \not{\omega} - \frac{1}{2} g_\rho \vec{\not{\rho}}\cdot\vec{\tau} - M + g_\sigma \sigma - \frac{1}{2} e(1+\tau_3)\not{A} \right]\Psi + \frac{1}{2}(\partial_\mu \sigma)^2 - V(\sigma) - \frac{1}{4} f_{\mu\nu} f^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu - \frac{1}{4} \vec{B}_{\mu\nu}\cdot\vec{B}^{\mu\nu} + \frac{1}{2} m_\rho^2 \vec{\rho}^\mu \cdot \vec{\rho}_\mu - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\zeta}{24} g_\omega^4 (\omega^\mu \omega_\mu)^2 + \frac{\xi}{24} g_\rho^4 (\vec{\rho}^\mu \cdot \vec{\rho}_\mu)^2 + g_\rho^2 f(\sigma, \omega_\mu \omega^\mu) \vec{\rho}^\mu \cdot \vec{\rho}_\mu ,$$

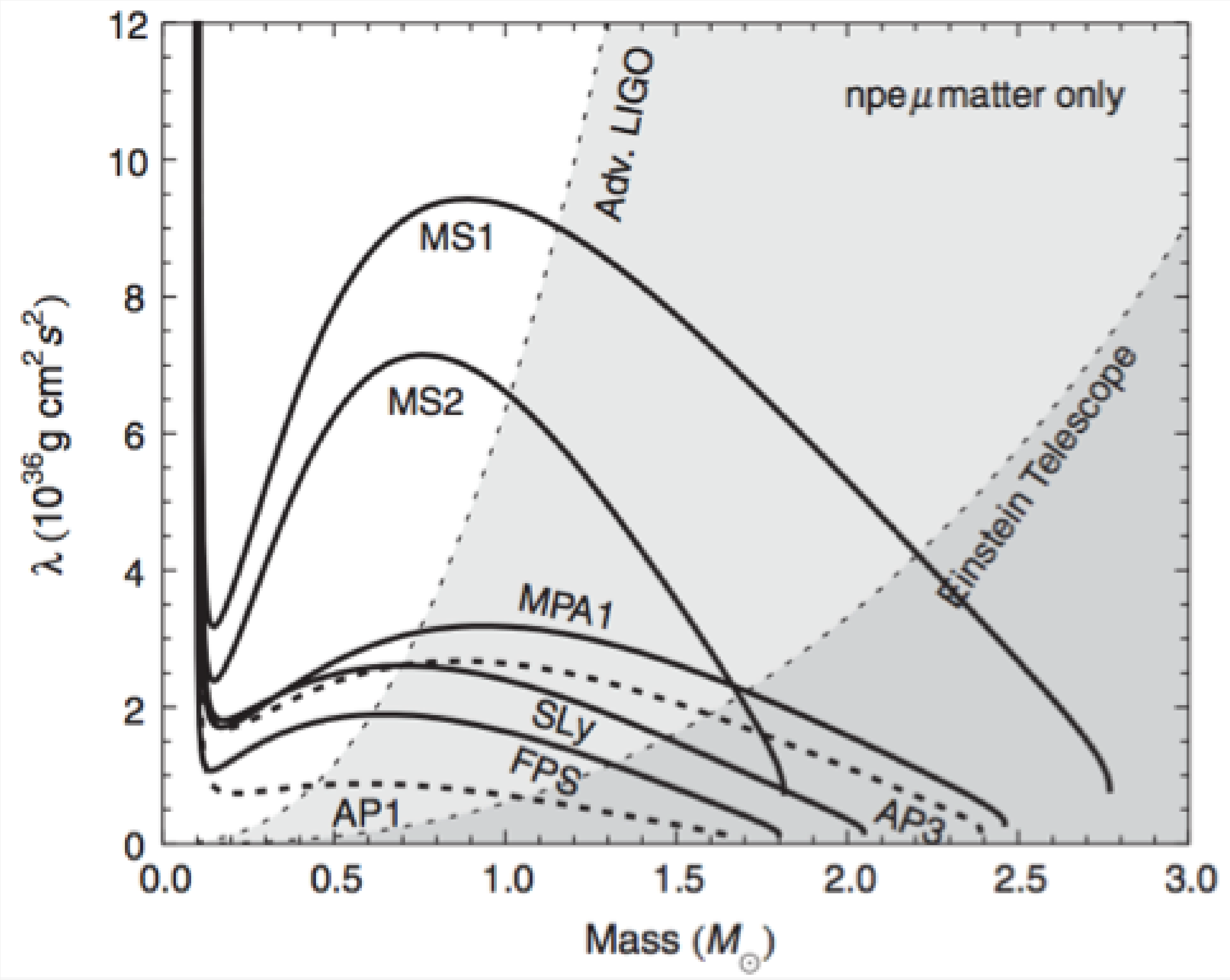
- Binding energies and charge radii of ^{208}Pb and ^{90}Zr within 2% of experiment
- Fix K to 240 $\pm$ 20 MeV
- Match M-R curves from SLB '2010

- Limited number of supernova EOSs which satisfy $M - R$ constraints and nuclear structure constraints
- Smaller radii may increase amount of ejecta
- Maximum mass is also an important parameter
  Does merger nucleosynthesis constrain the maximum mass?

Neutron Star Tidal Deformabilities



Lackey et al. (2014)

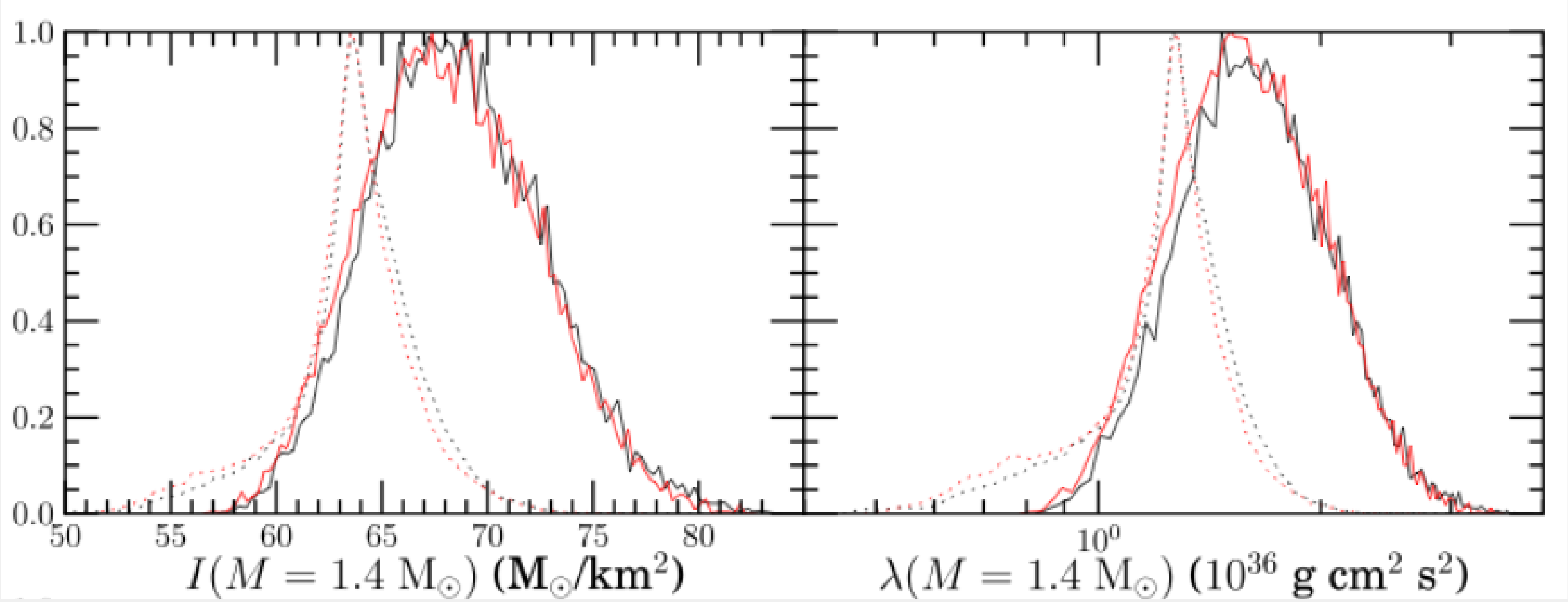


Hinderer, Lackey, Lang, and Read (2010)

- 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



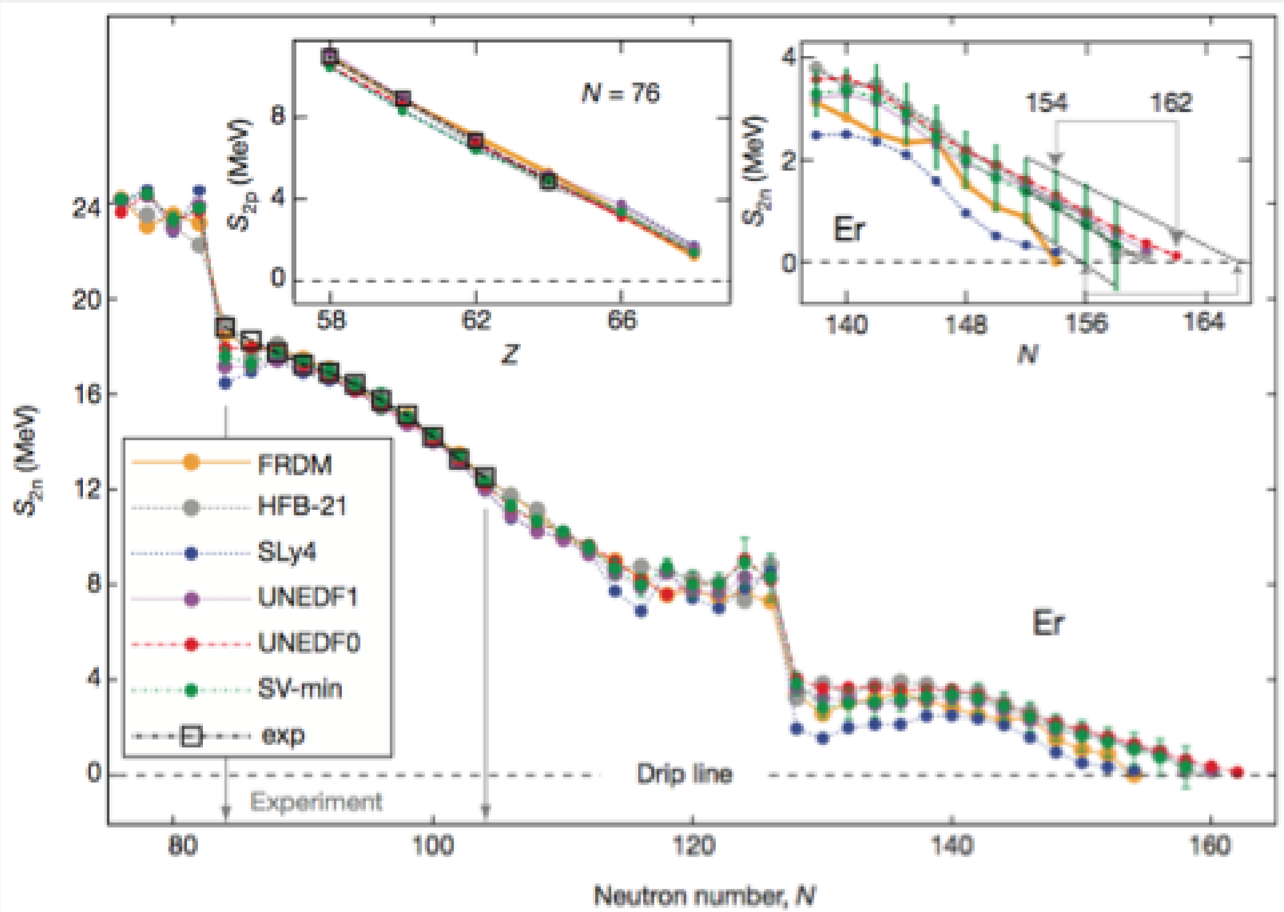
Steiner, Gandlfi, Fattoyev, and Newton (2014)

- LIGO sensitivity improved by
  - multiple measurements
    del Pozzo, et al (2013)
  - and by directly simulating the EOS
    Lackey et al. (2014)
  - Using information beyond 400 Hz
    Hinderer, Lackey, Lang, and Read (2010); Damour, Nagar, and Villain (2012)
- For large enough signal-to-noise, LIGO may have smaller systematics

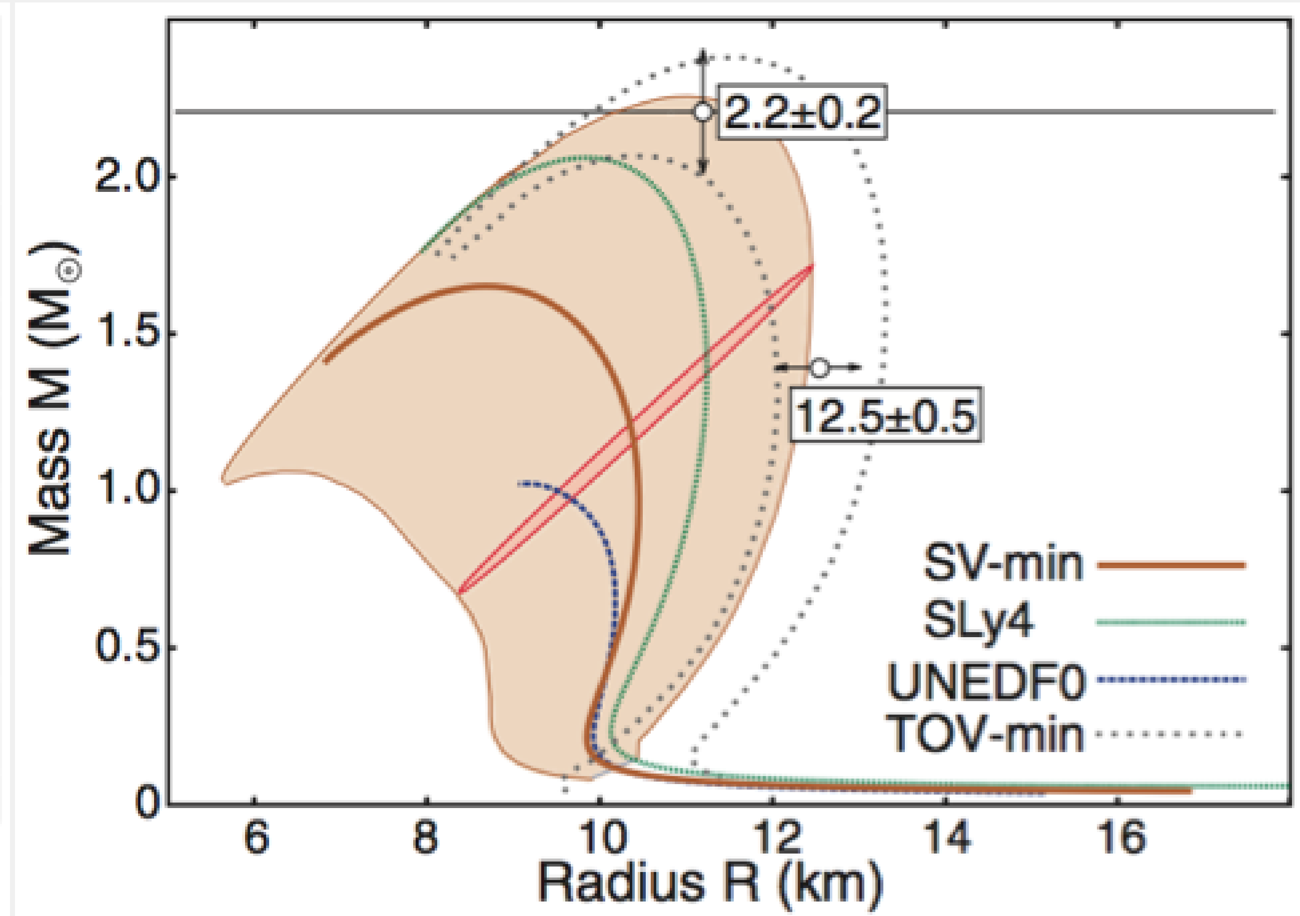
Summary

- 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
    Ranges from 9-15 km are possible, but improbable
  - We now have constraints on the EOS
  - $1 < \lambda < 3 \times 10^{36} g\ \mathrm{cm}^2\ \mathrm{s}^2$
- Constrain the nucleon-nucleon interaction and QCD.
  - (41) 43 MeV $< L <$ 67 (83) MeV
- Published 1000s of EOS parameterizations of cold EOSs
- Need more EOS tables and better nuclear physics input, but where should improvements be focused?
- There is a bright future ahead: LIGO, Chandra, NICER, Athena+, LOFT, and more

Neutron Star Radii and the Neutron Drip Line



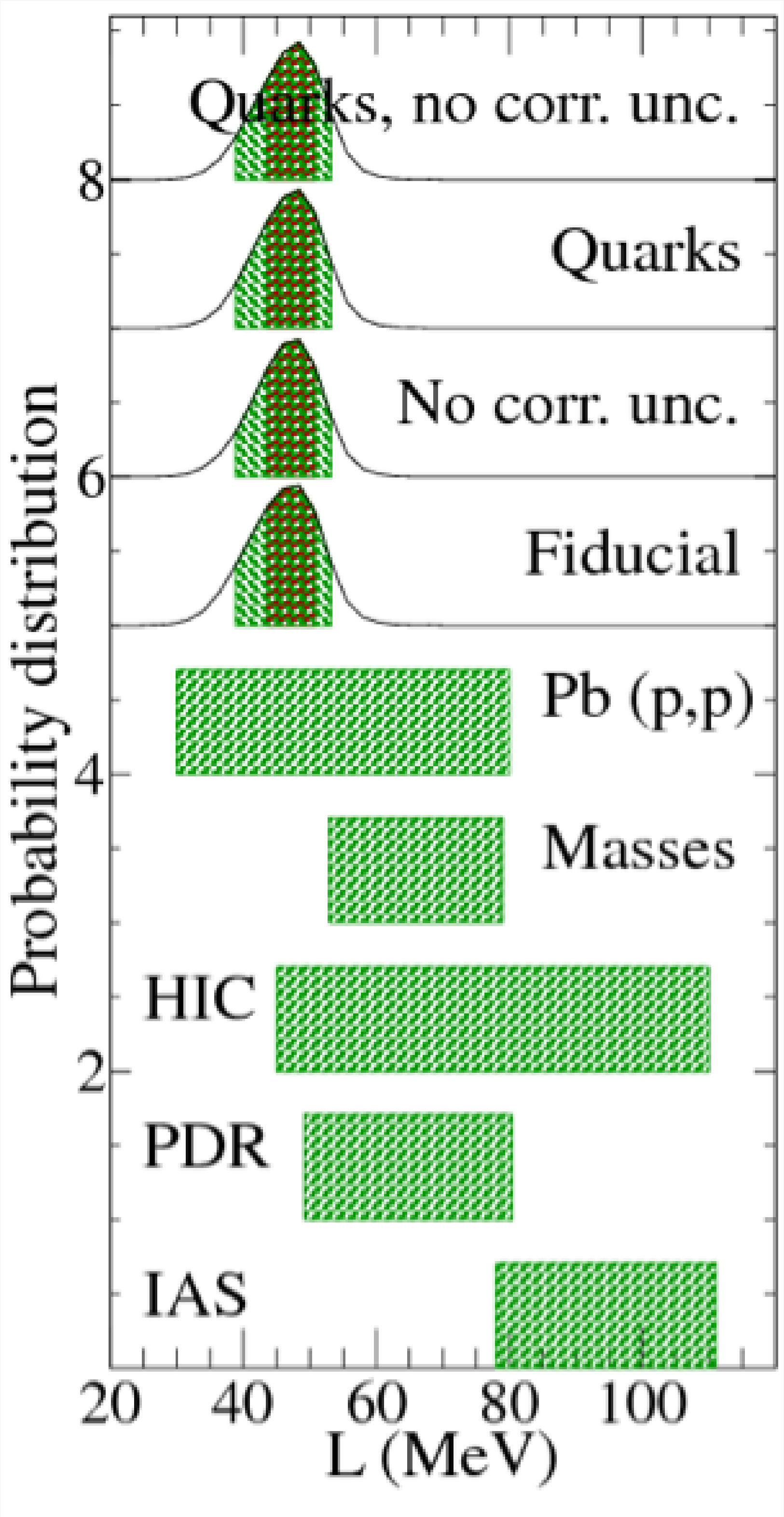
Erler et al. (2012)



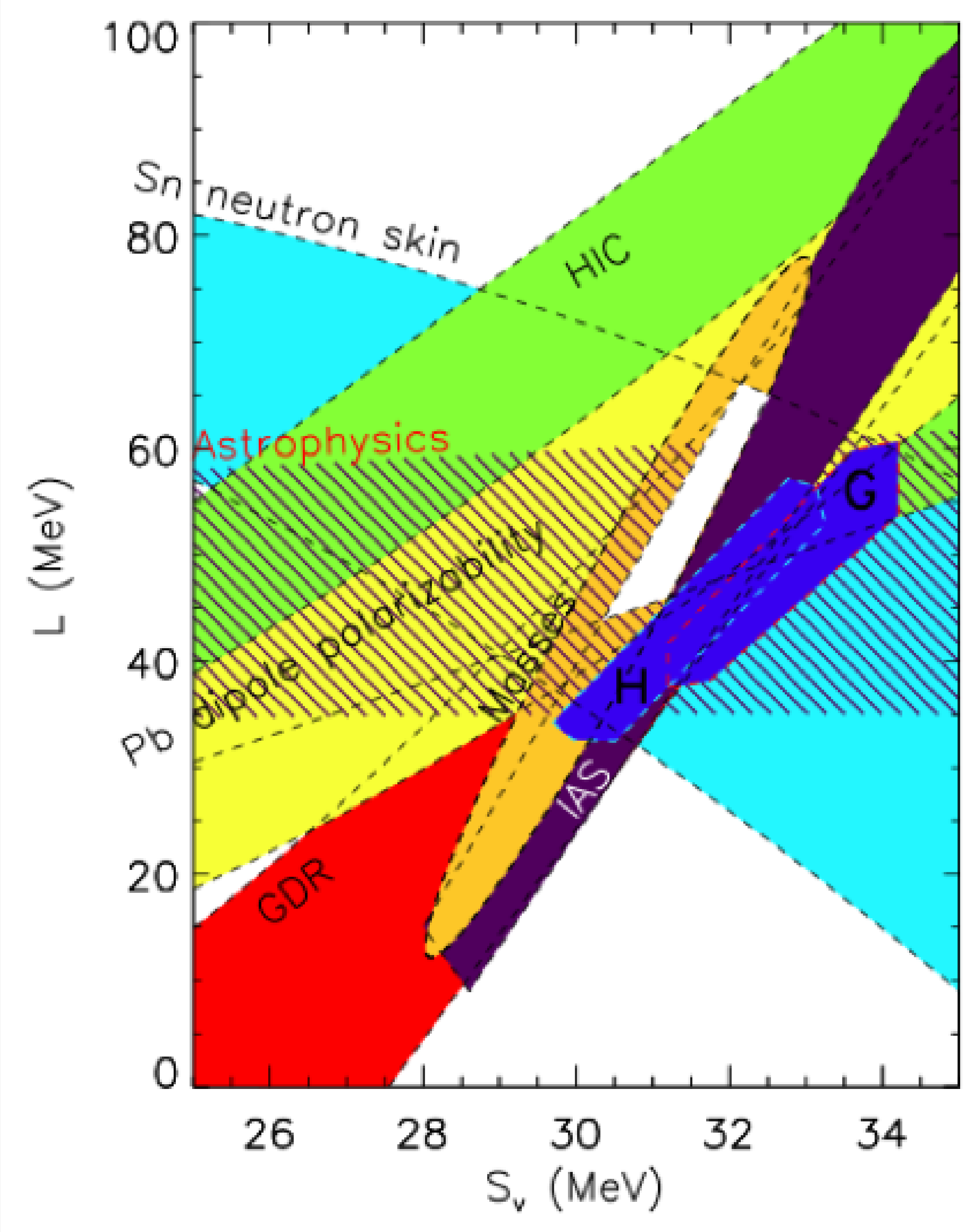
Erler et al. (2013)

- 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

Neutron Star Constraints on L



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

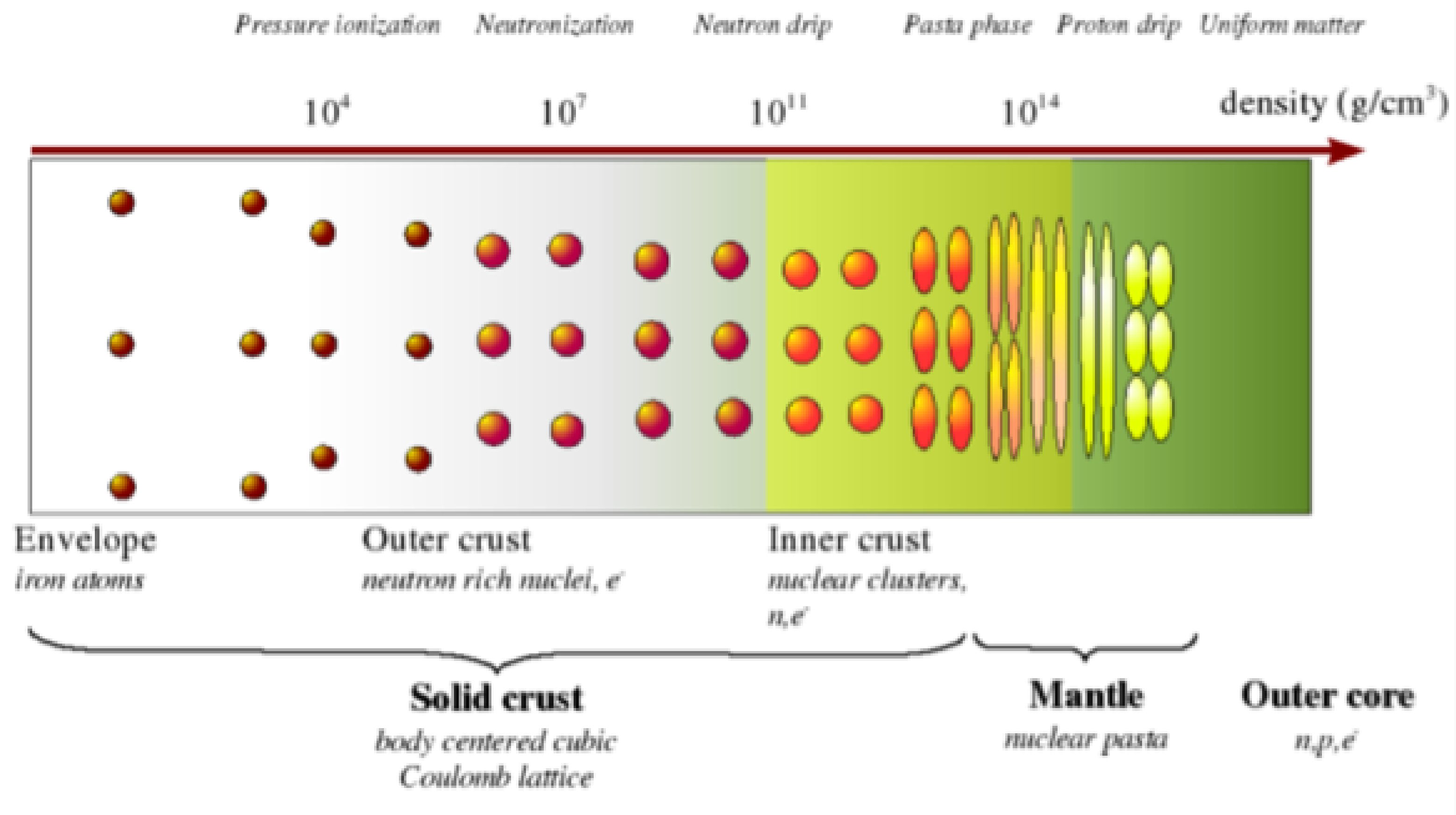


Lattimer and Steiner (2014)

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

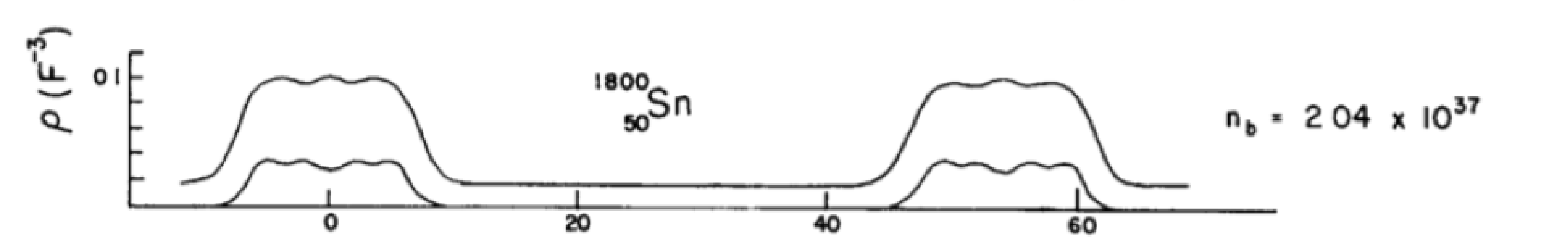
  Confirmed by MAMI data

Structure of Matter in the Neutron Star Crust



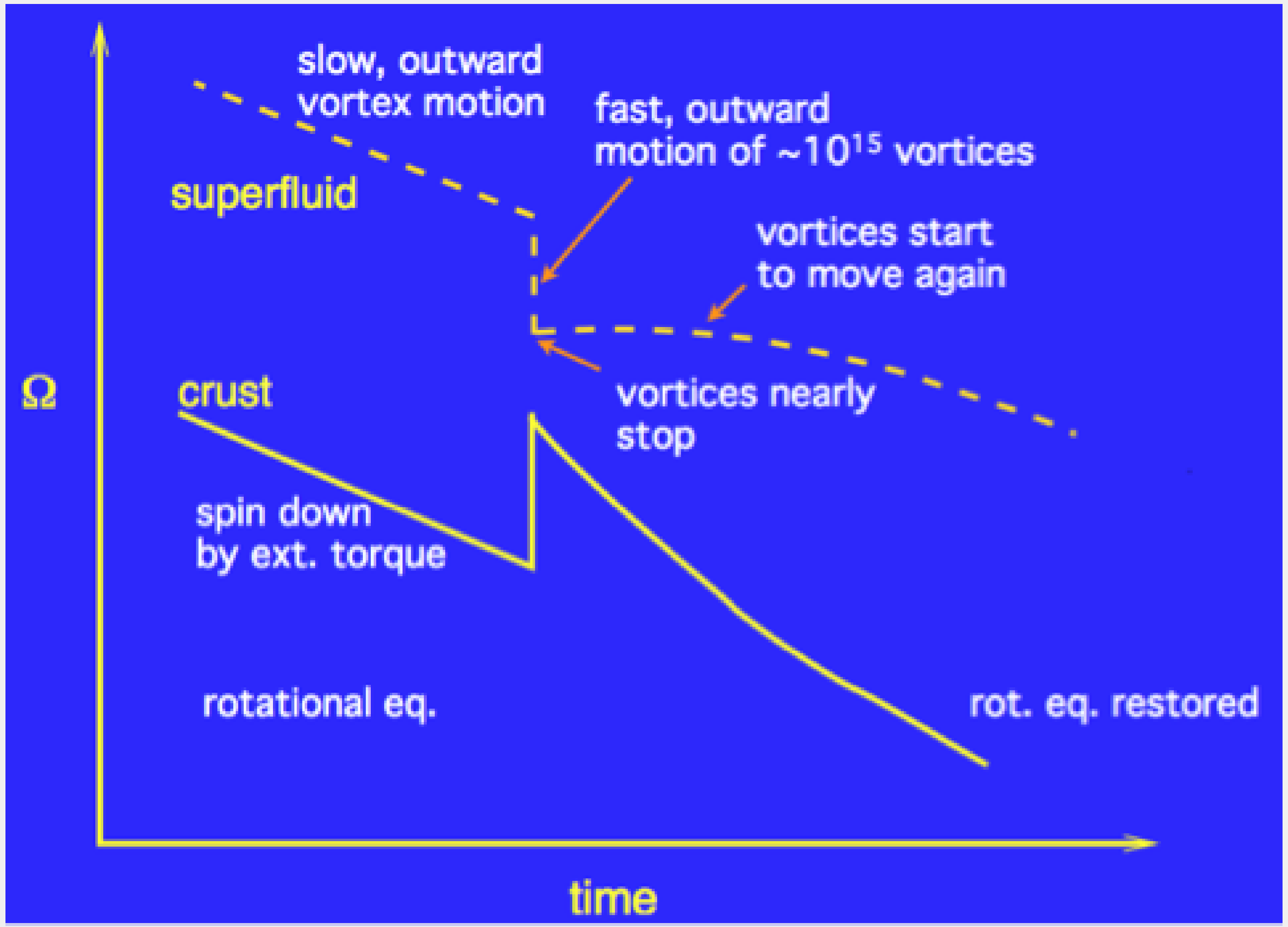
Picture from N. Chamel

- 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

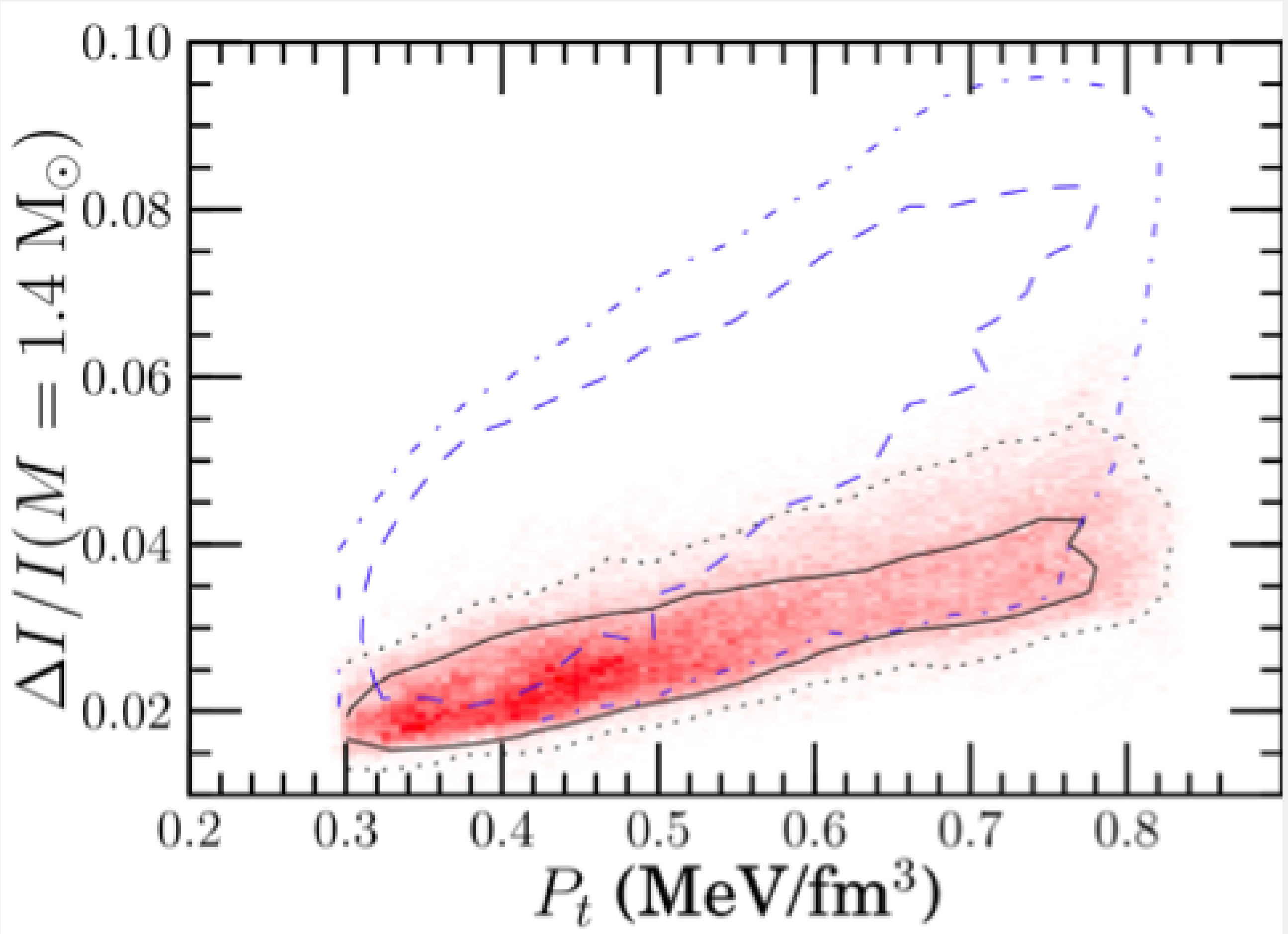
Is There Enough Superfluid in the Crust?

- 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)

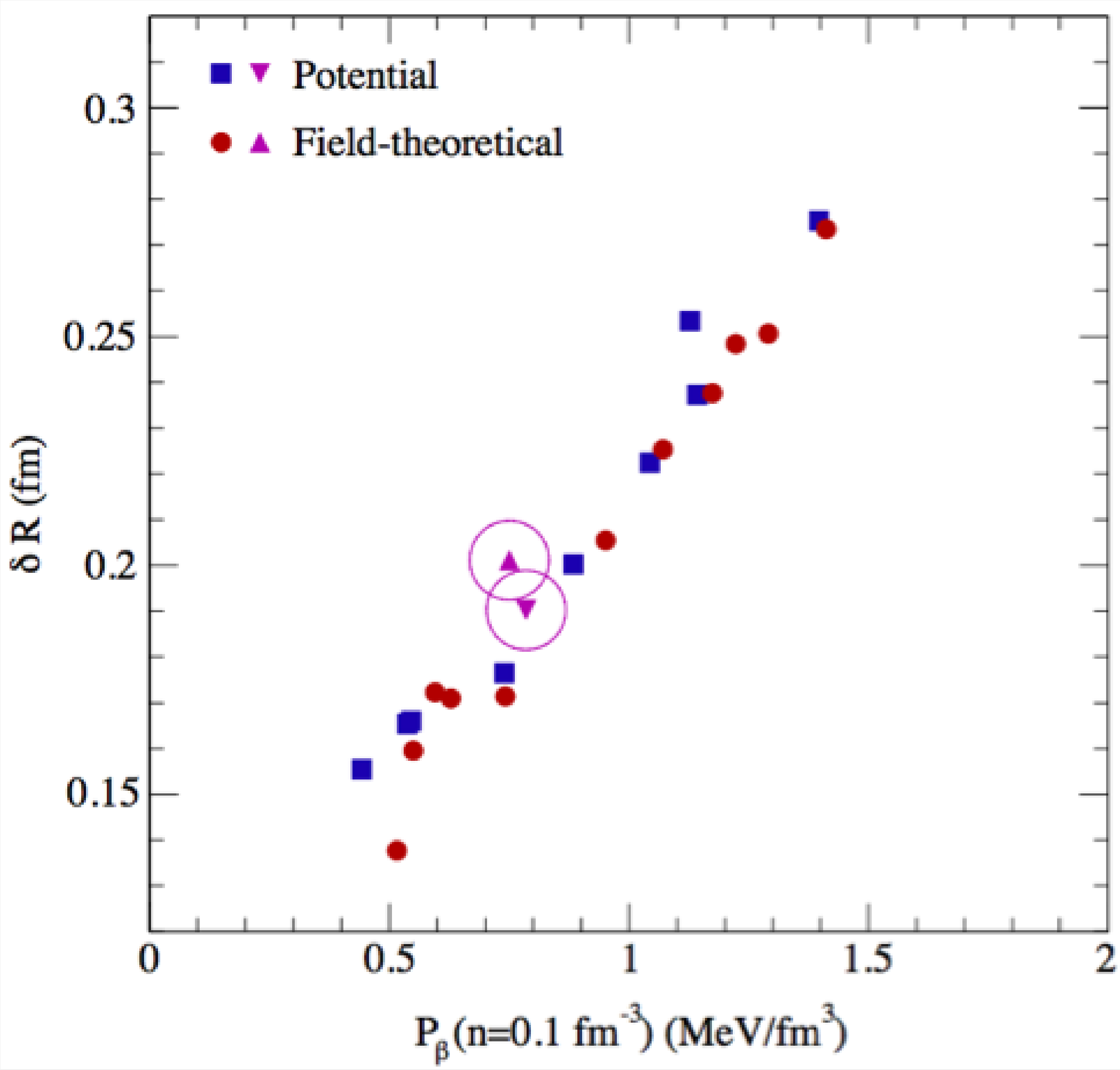
- Unless the systematics force much larger neutron star radii and P_t is large



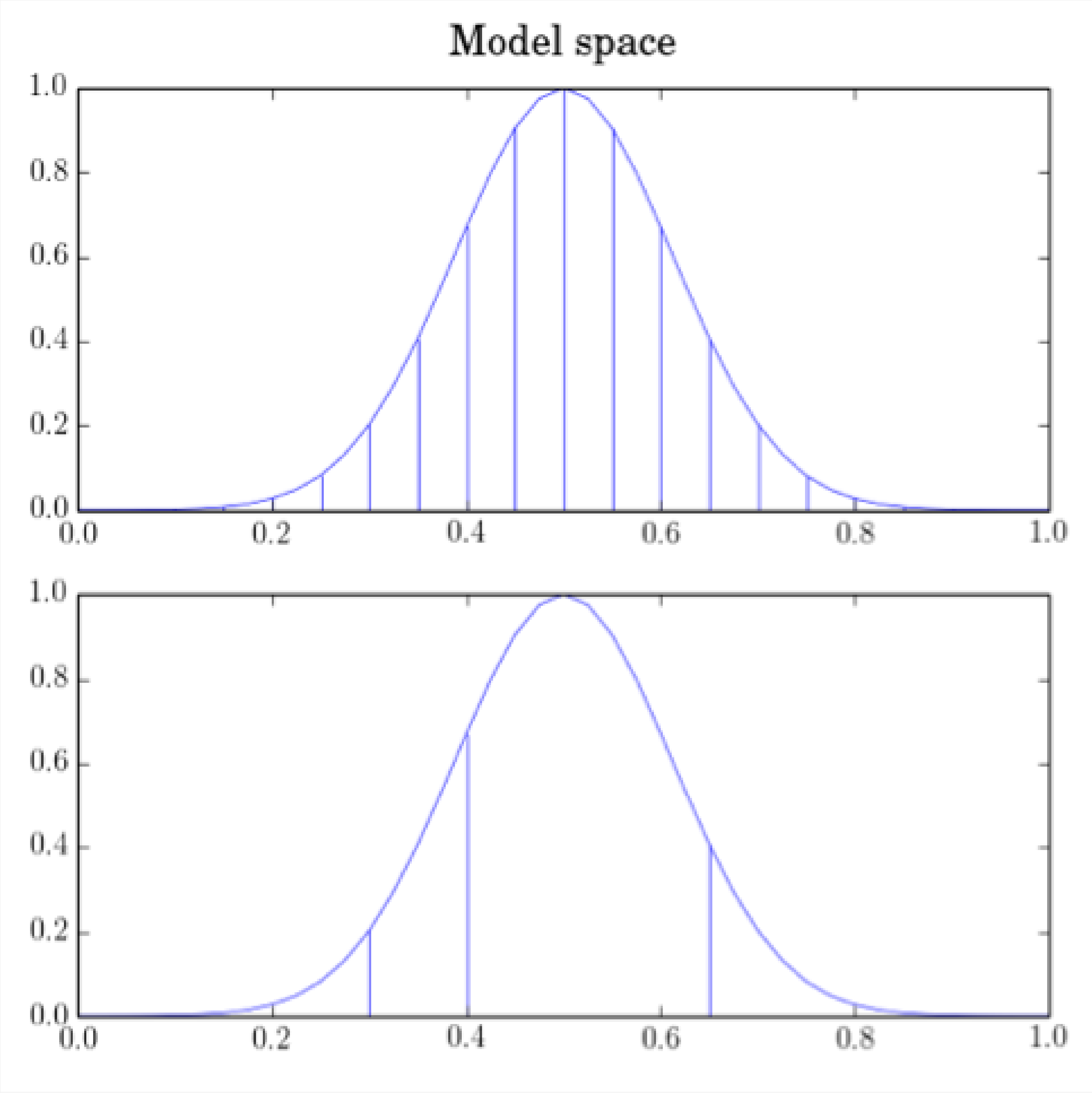
Steiner et al. (2014); black and red are with M & R observations, blue contours are with $I = 70\ \mathrm{M}_\odot\ \mathrm{km}^2$

Purpose of a Model

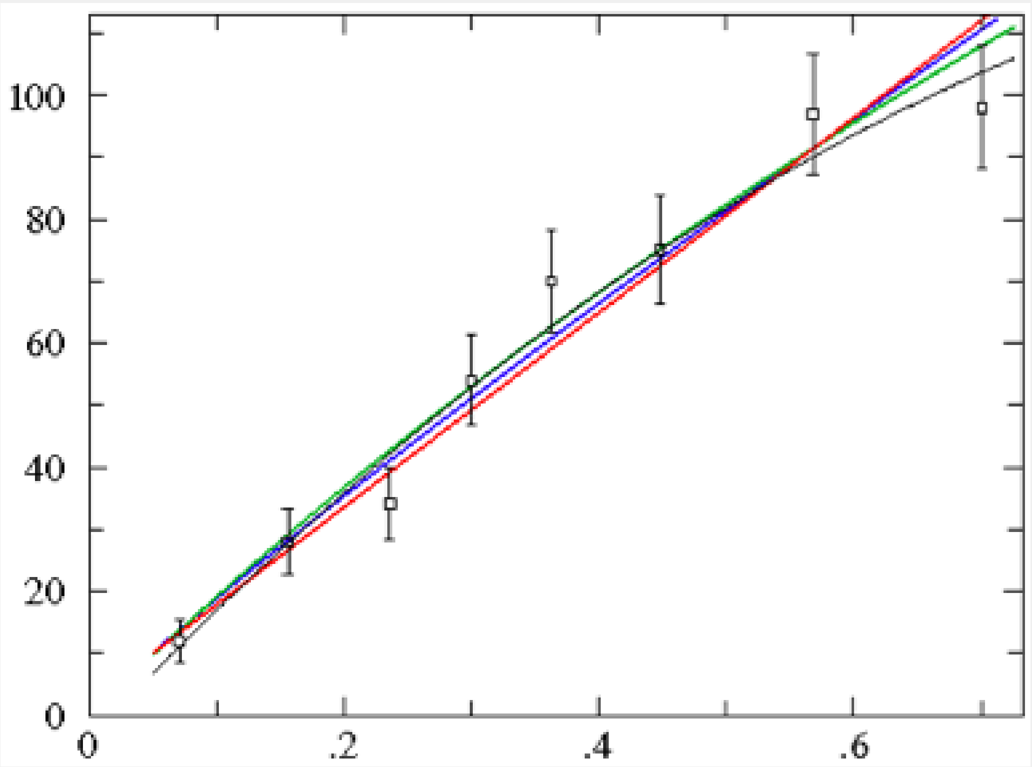
- Model comparison
  Model A vs. Model B?
- Parameter estimation
  However, parameters don't always have a clear physical meaning
- Predictions
  Produce a probability distribution
  - Distribution over parameter space and also over model space

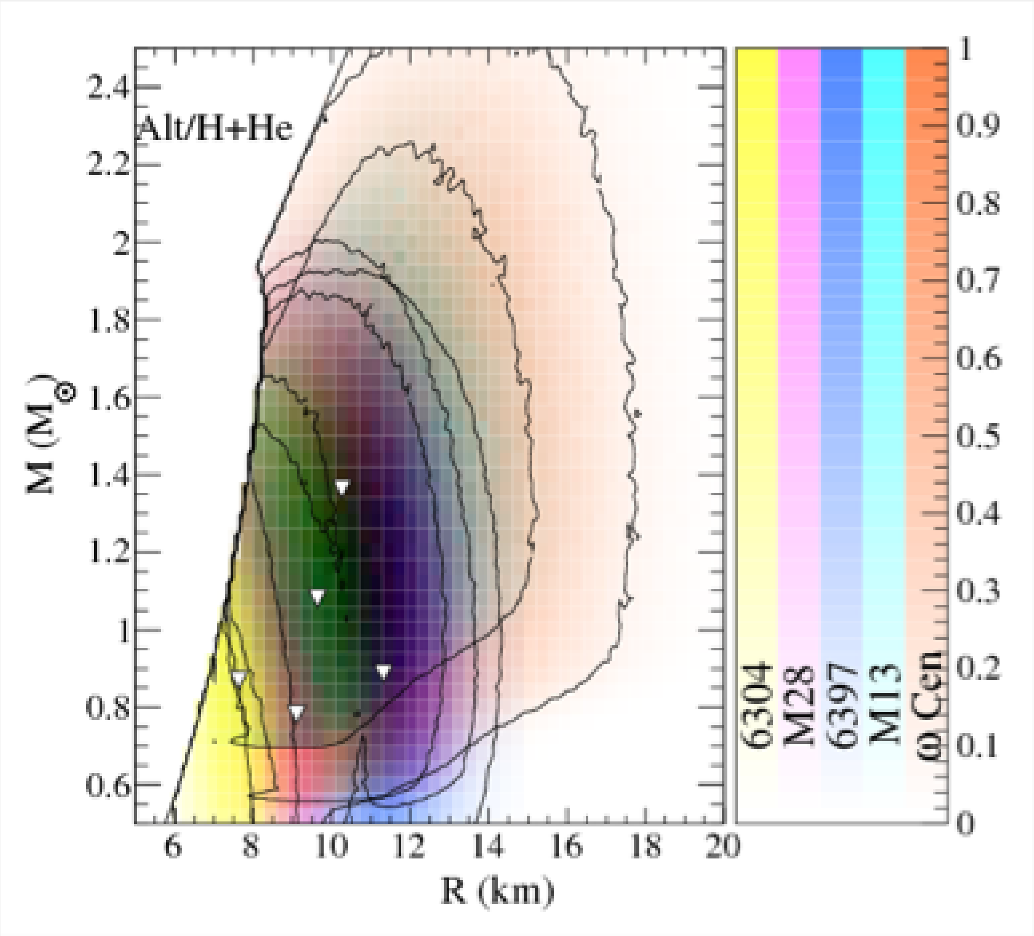


Steiner et al. (2005)



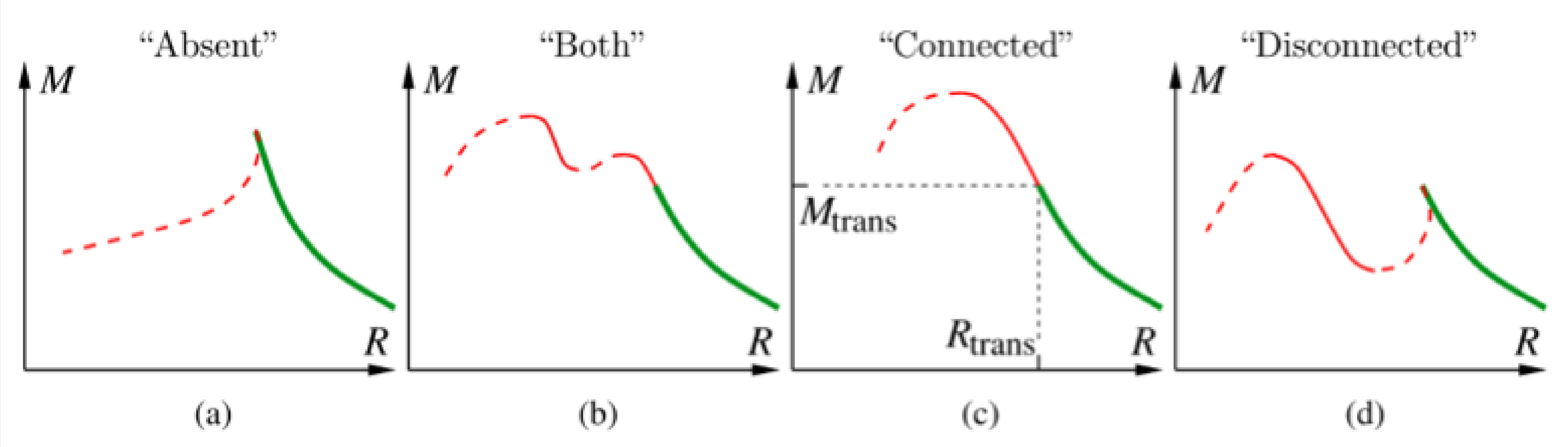
χ^2 fits





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)



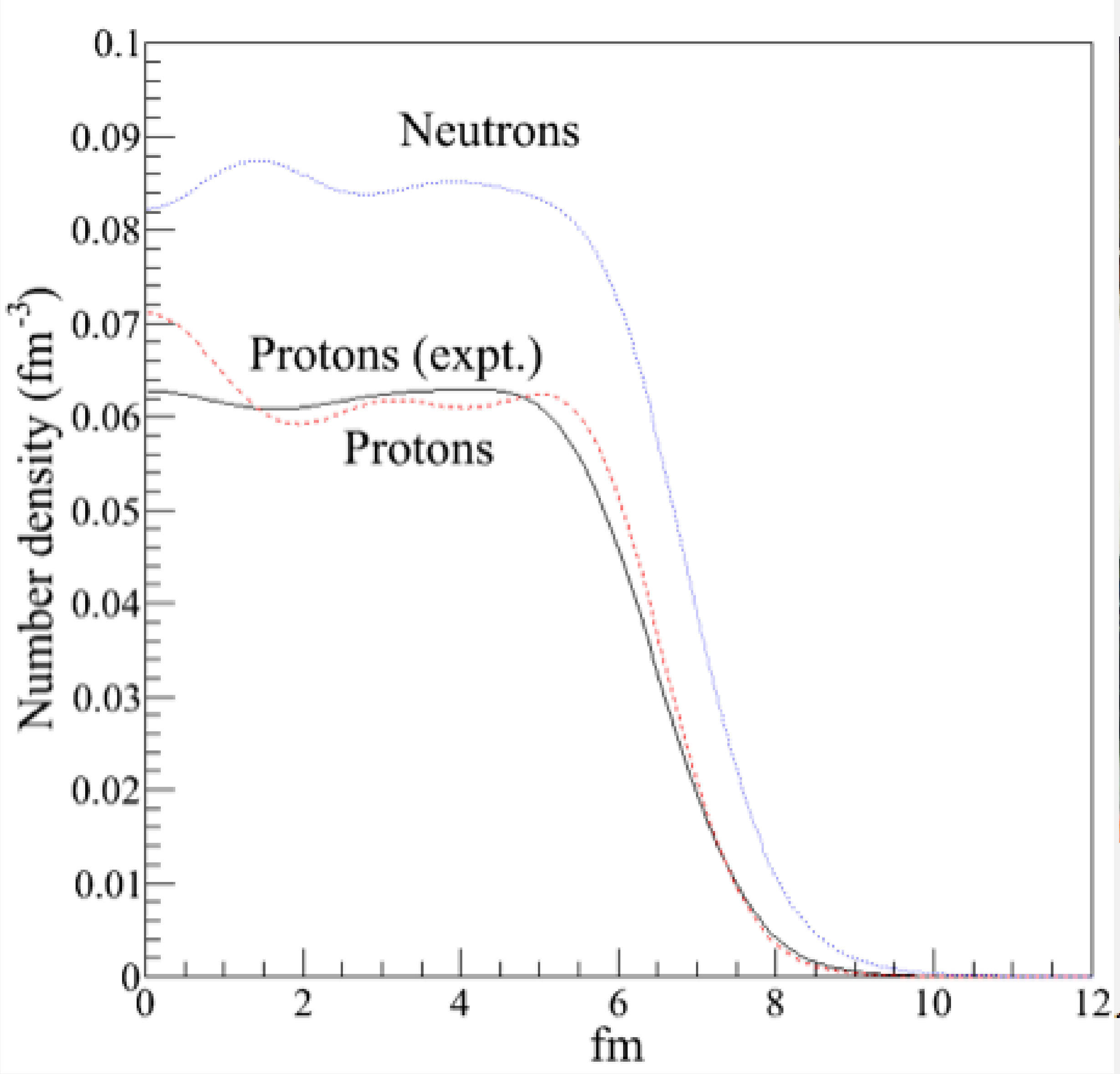
Alford, Han, and Prakash (2014)

The Neutron Skin Thickness of Lead

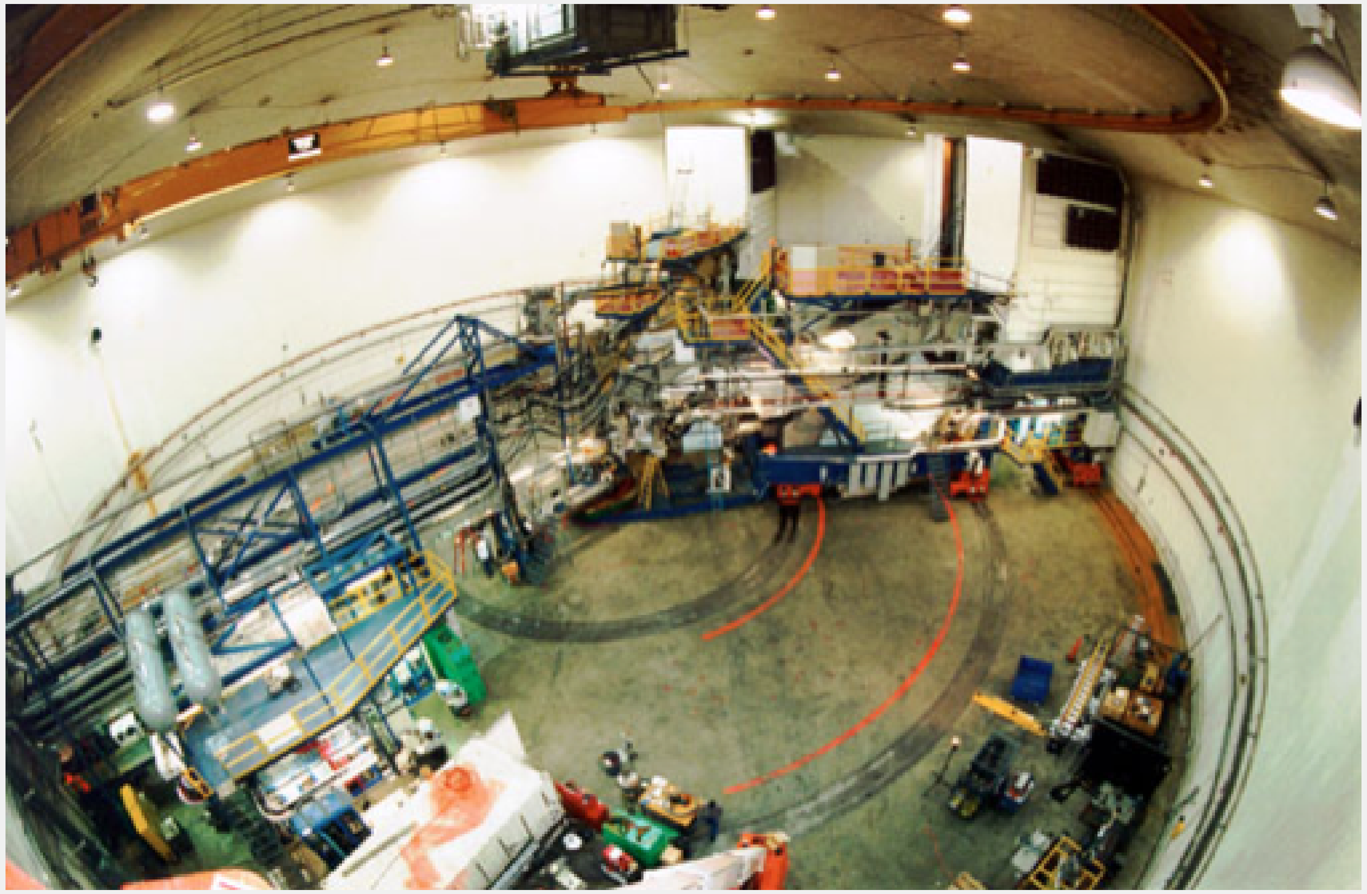
- Lead-208: 82 protons, 126 neutrons

  $R_n^2 \equiv \int r^2 n_n(r)\, d^3 r \qquad R_p^2 \equiv \int r^2 n_p(r)\, d^3 r$
- Neutron radii are hard to measure, use parity-violating electron scattering
- Weak charge of neutron $\gg$ weak charge of proton, i.e.

  $|-1| \gg 1 - 4 \sin^2 \theta_W$



Steiner, Prakash, Lattimer and Ellis (2005)

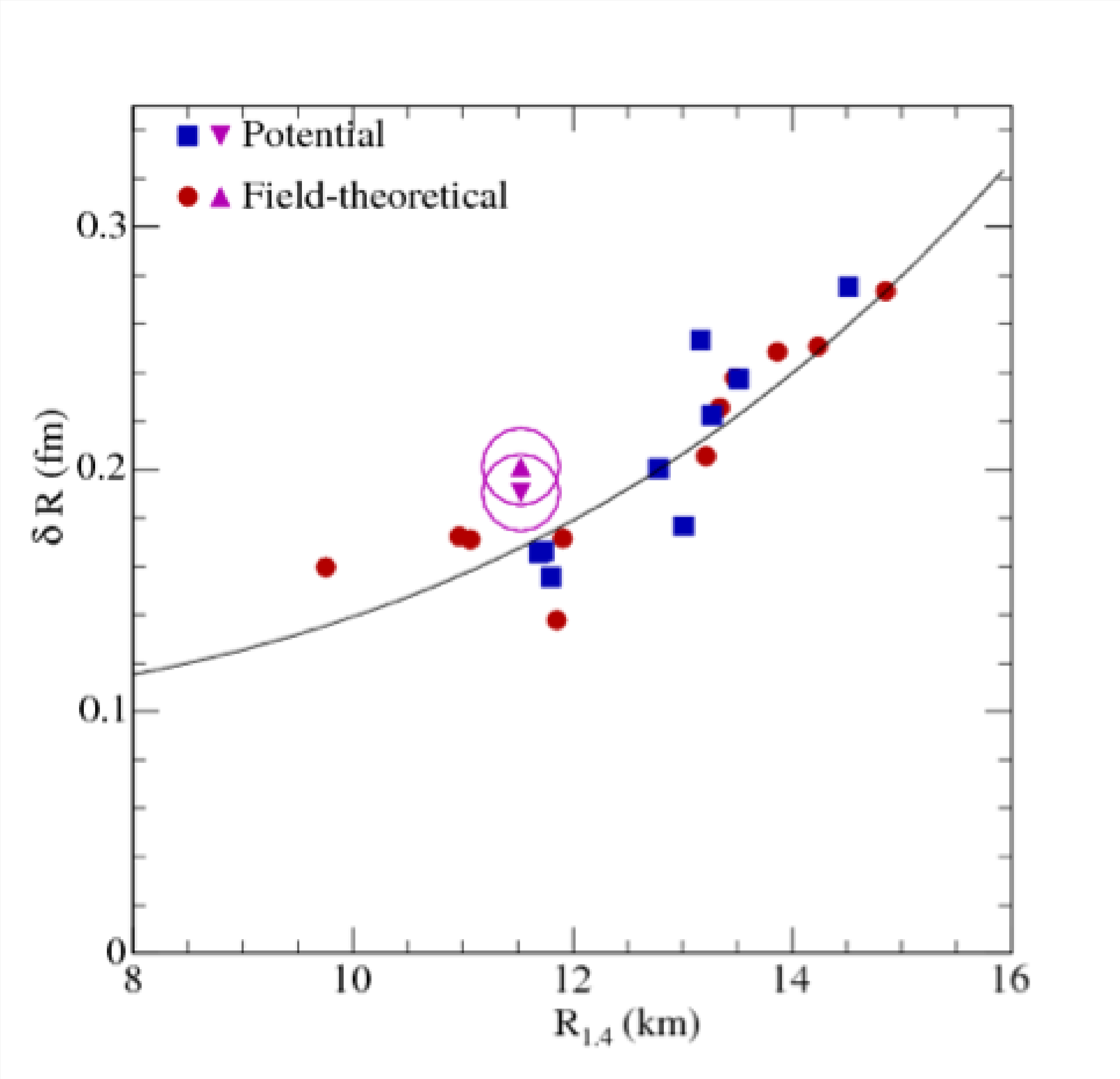


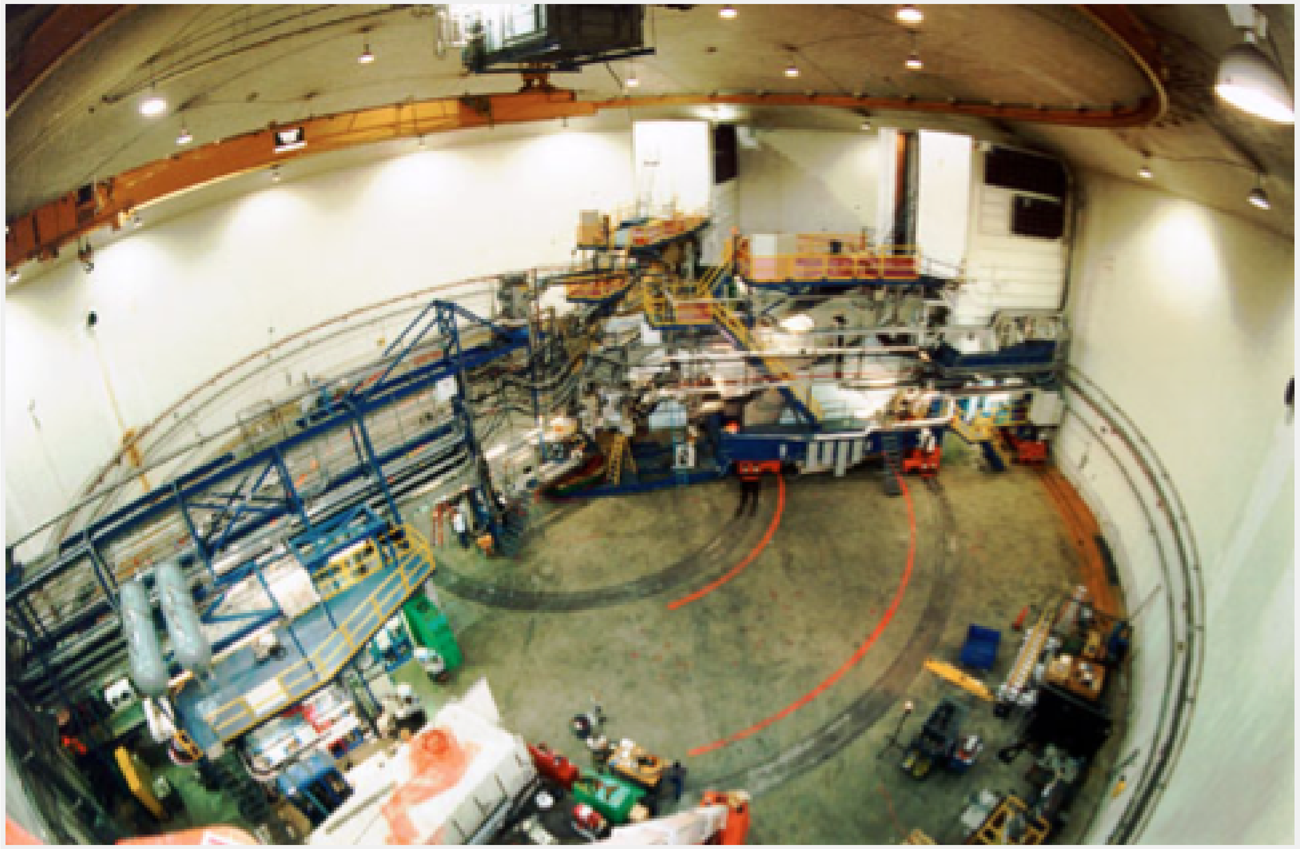
Jefferson Lab's Hall A

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)

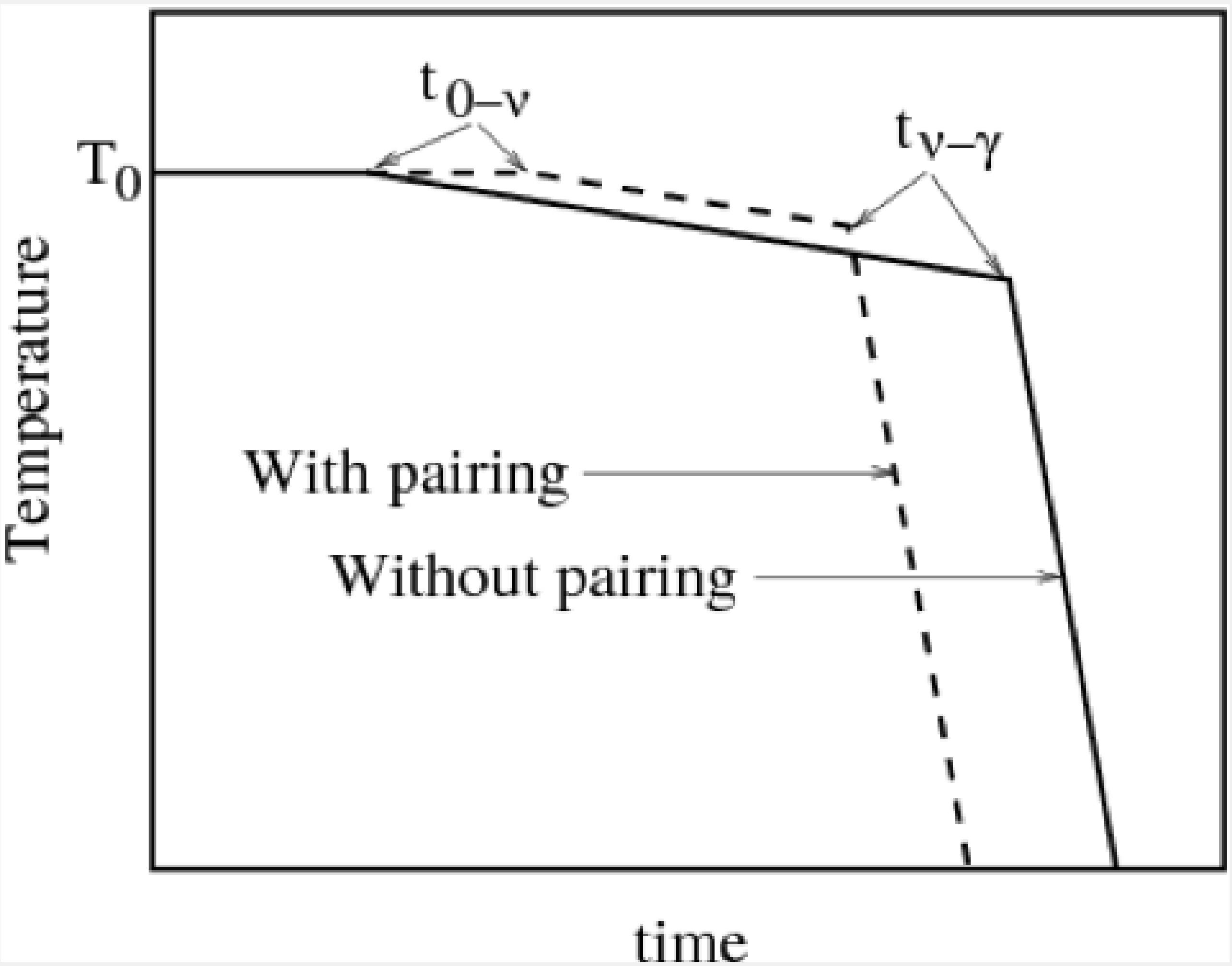
- We find $\delta R < 0.2$ fm (68%) from neutron star observations

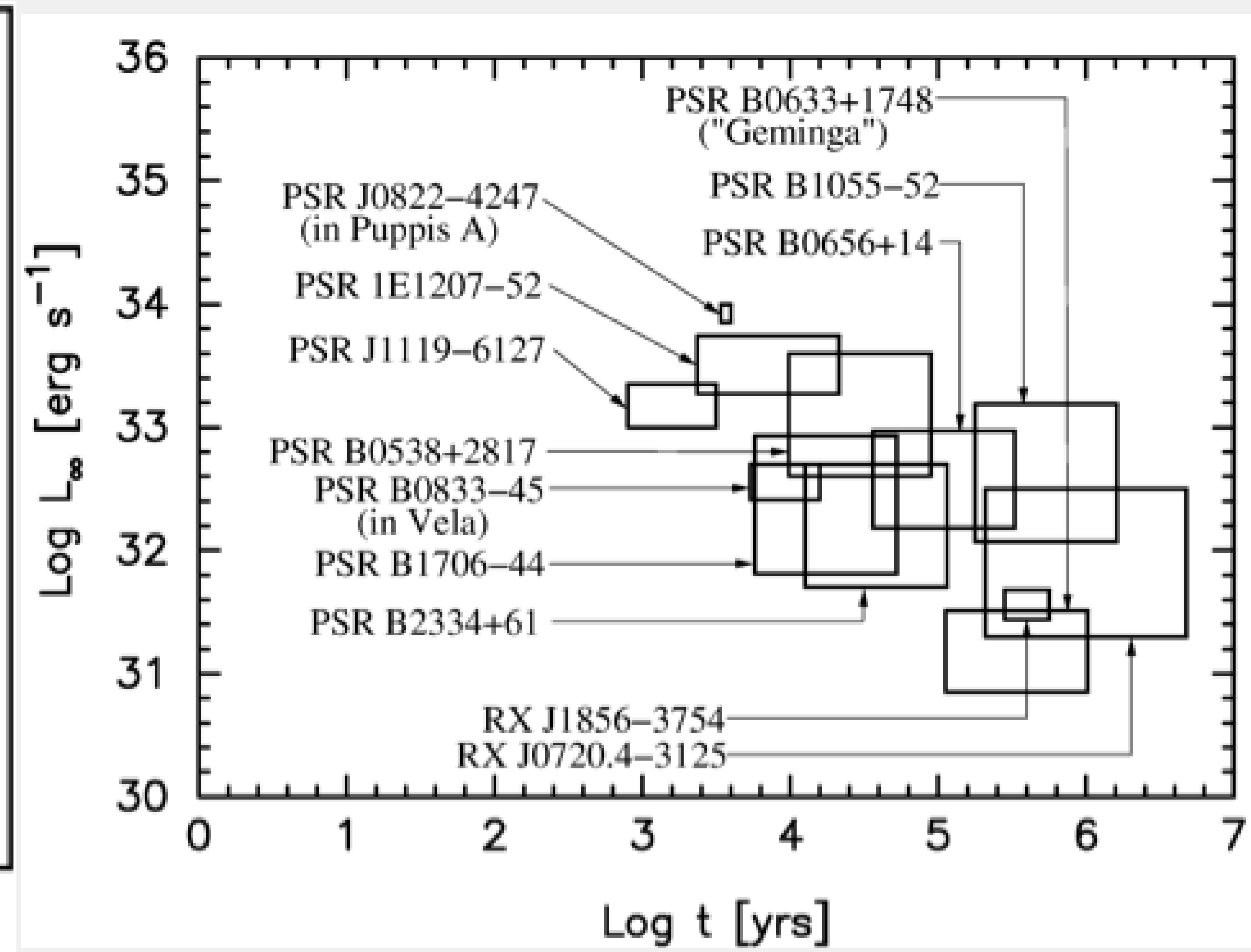
Thermal Emission from Isolated Neutron Stars

- 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



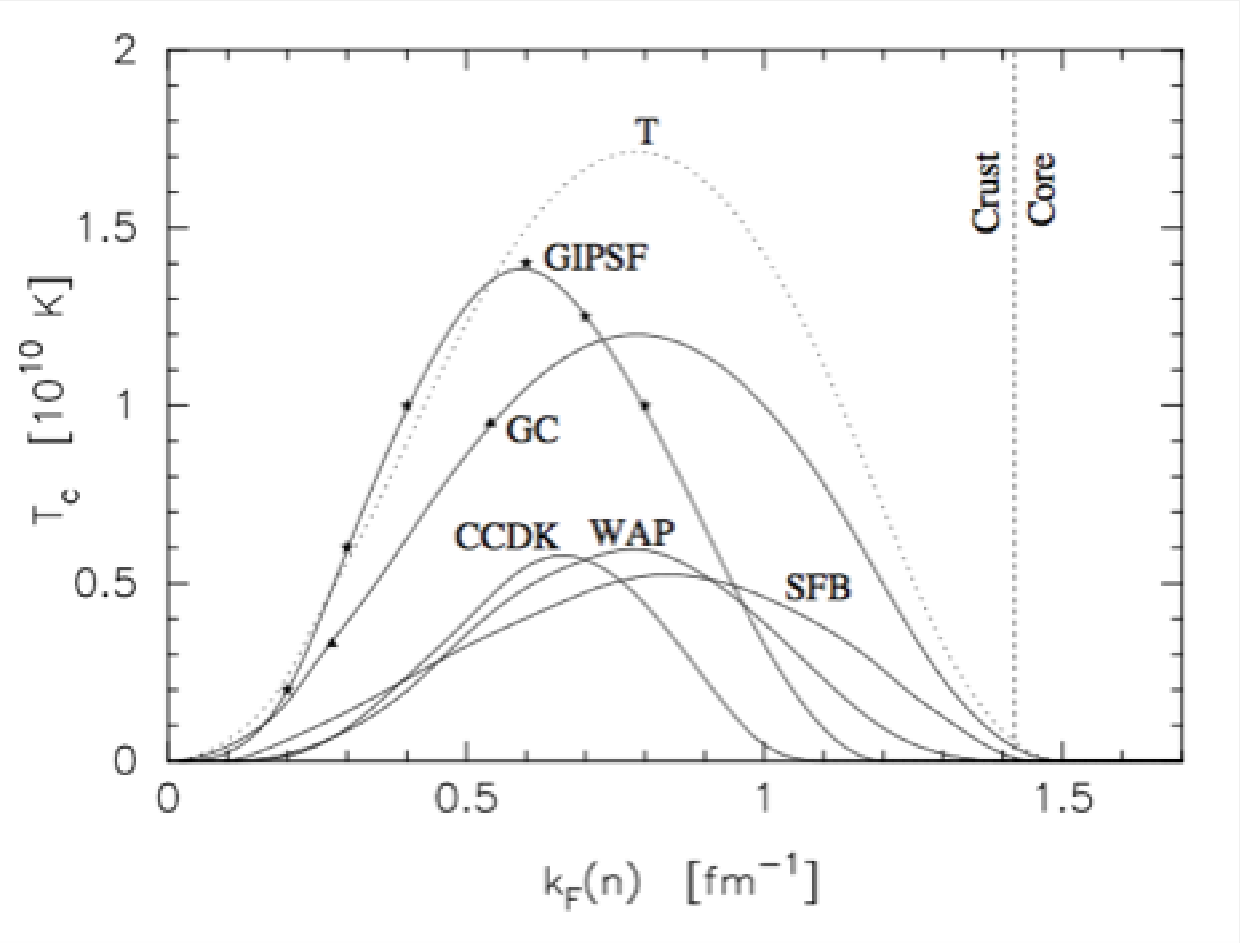


Page, et al (2004)

Page, et al (2009)

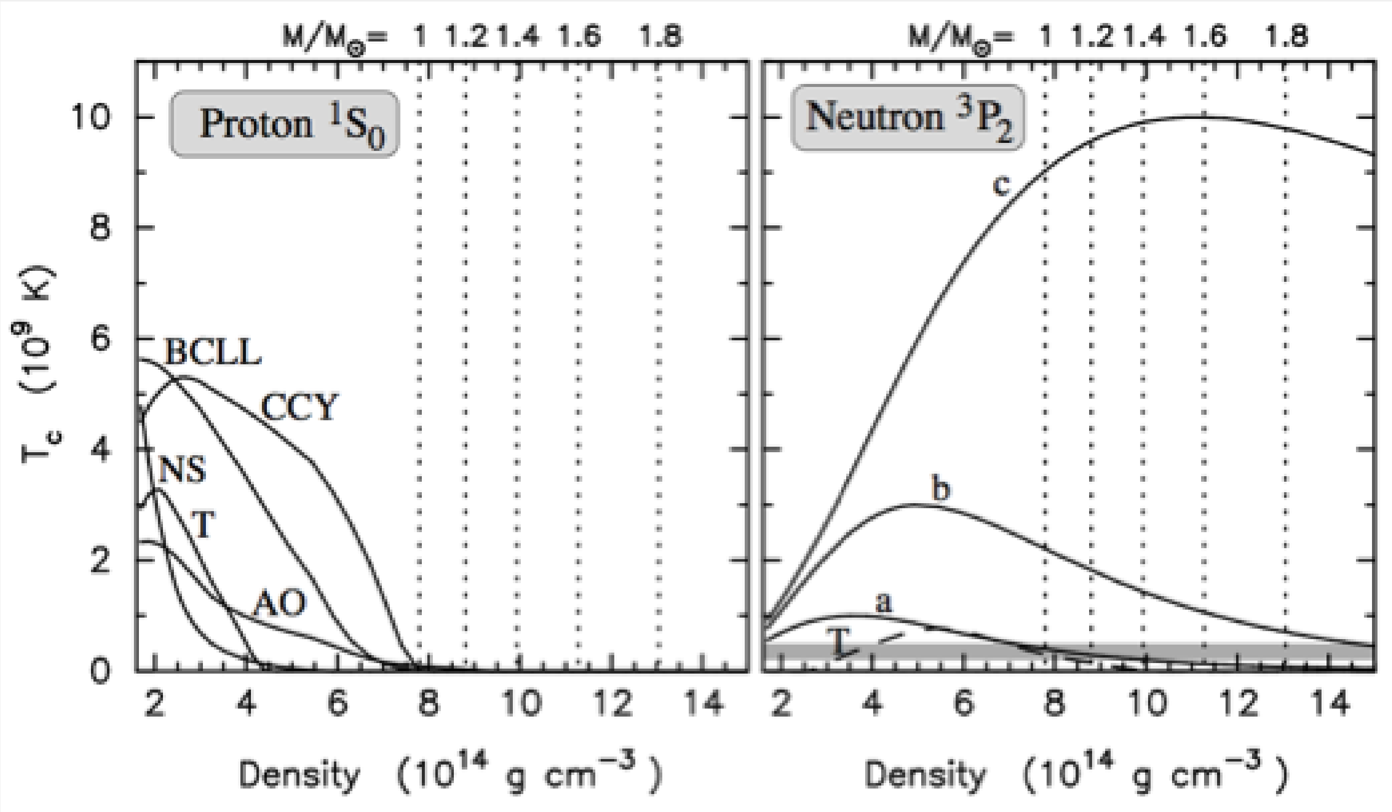
Neutron Star Superfluidity

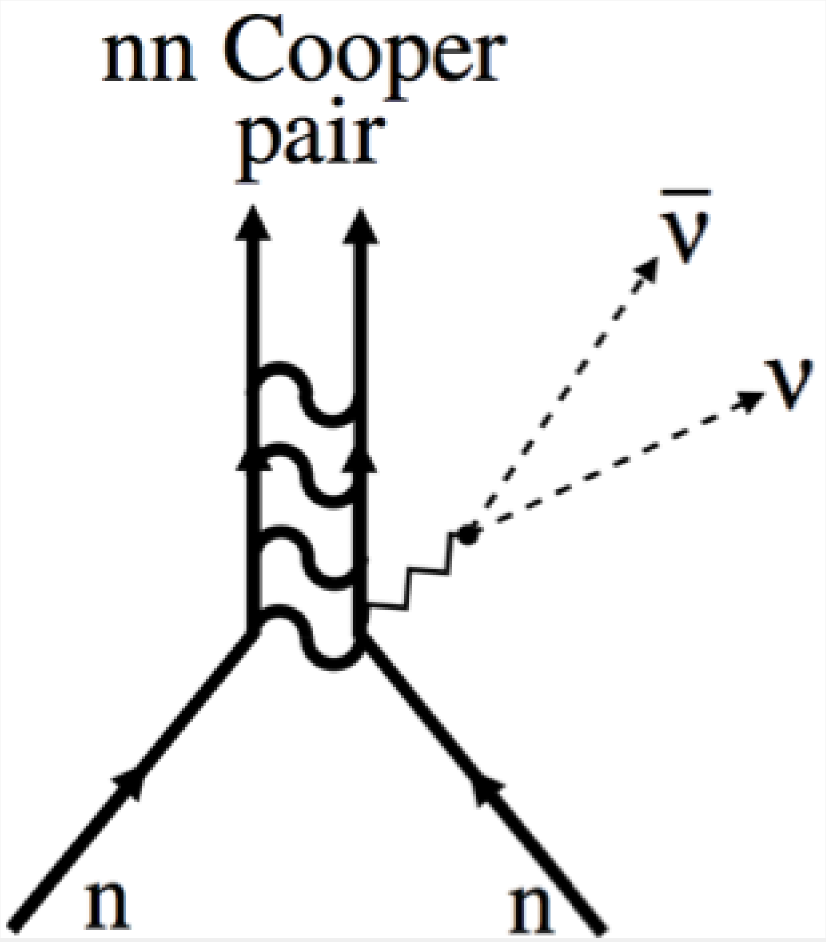
(See our review at 1302.6626)



- $^1S_0$ 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

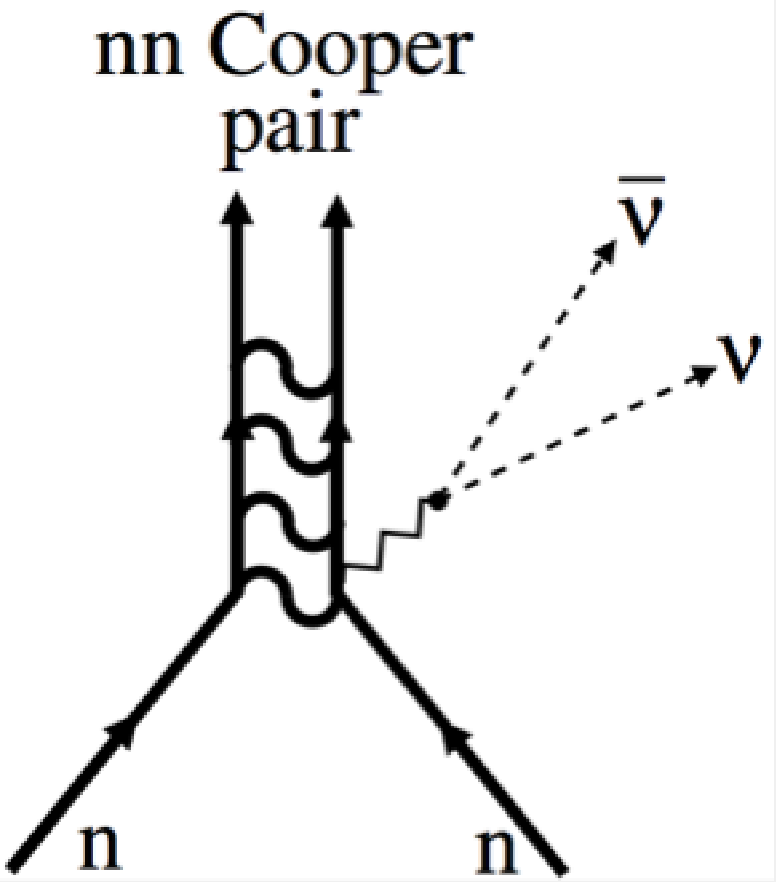
Steiner and Reddy (2009)

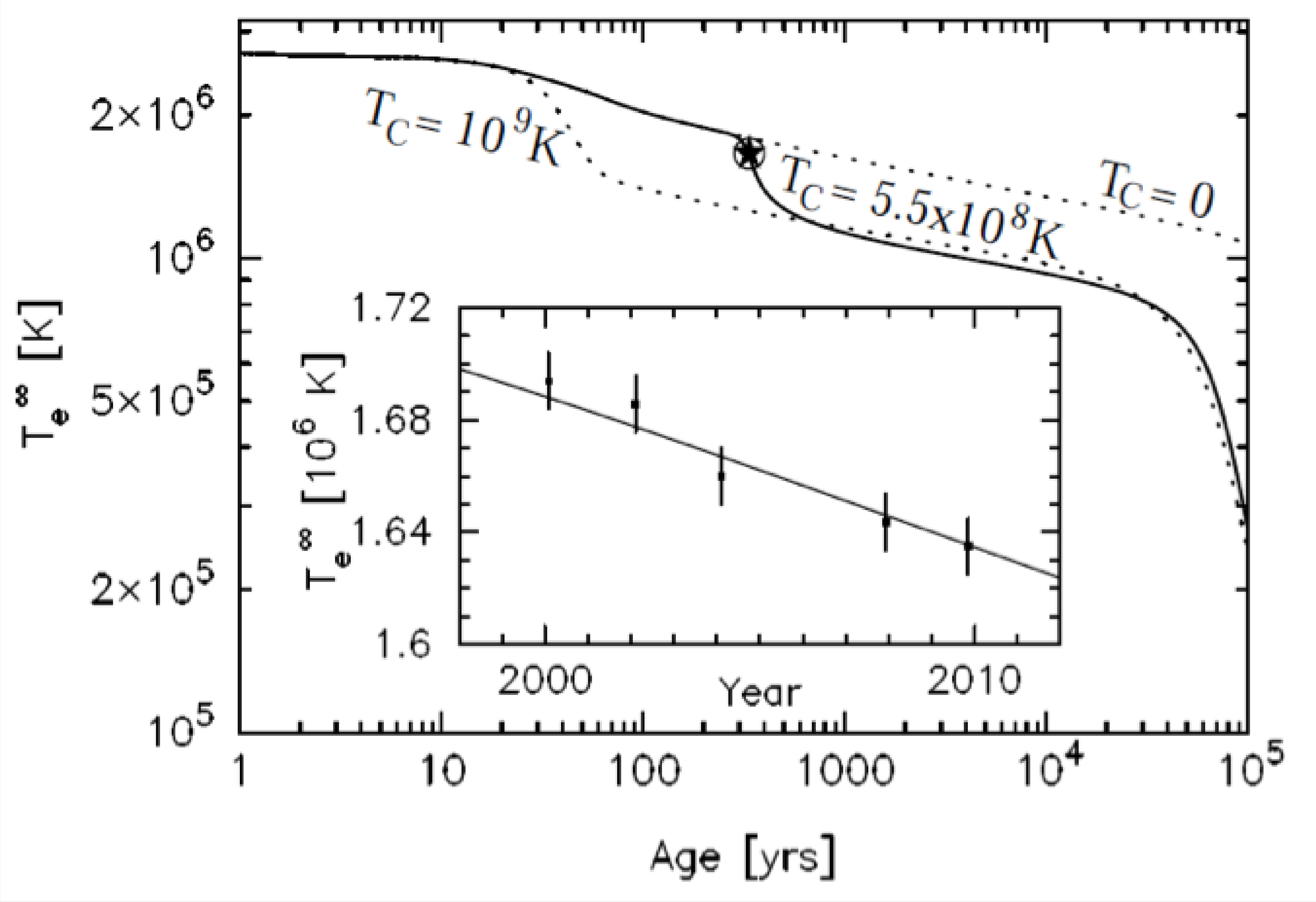




Detecting Neutron Star Superfluidity

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





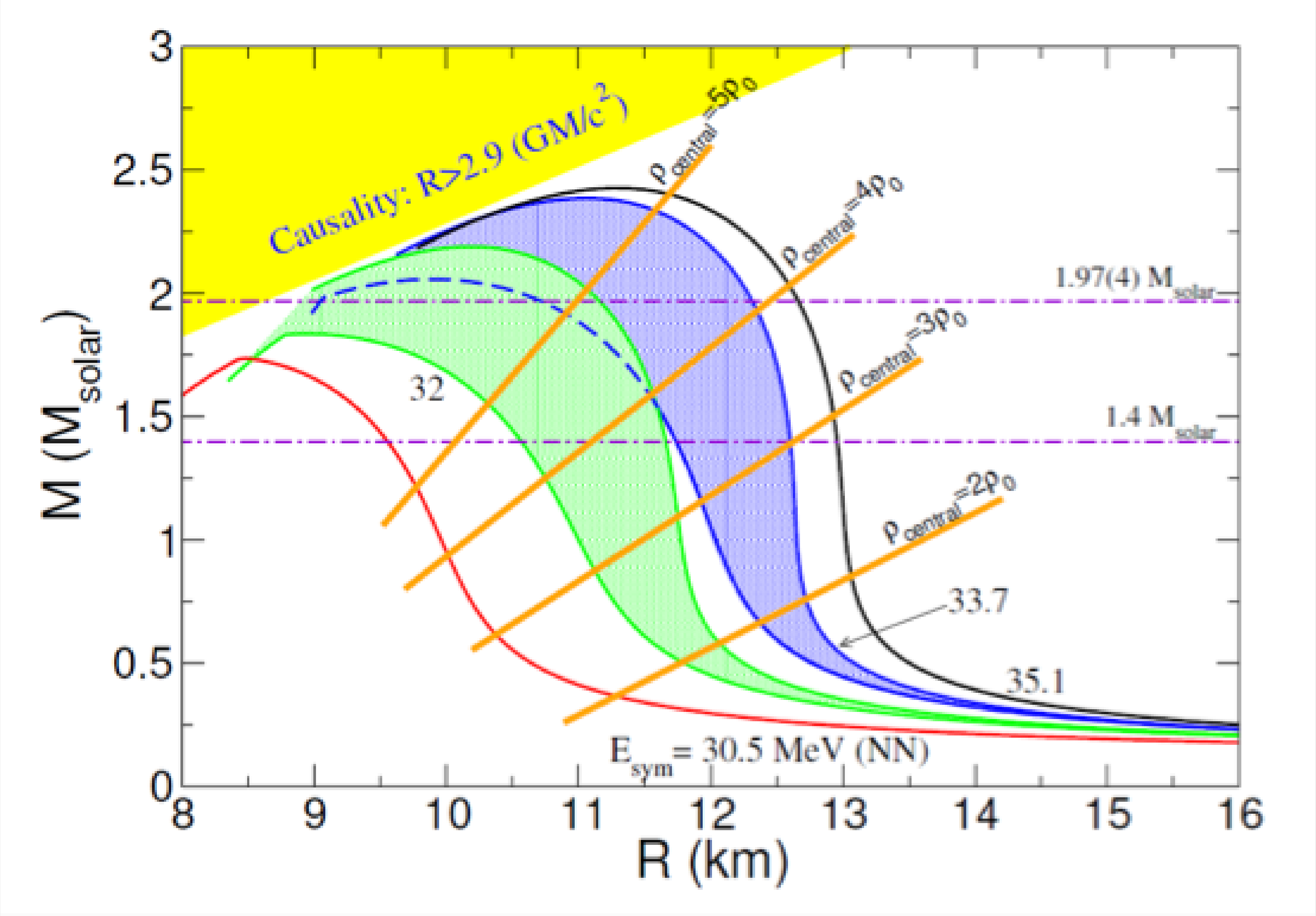
- If you form a Cooper pair, you gain energy

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



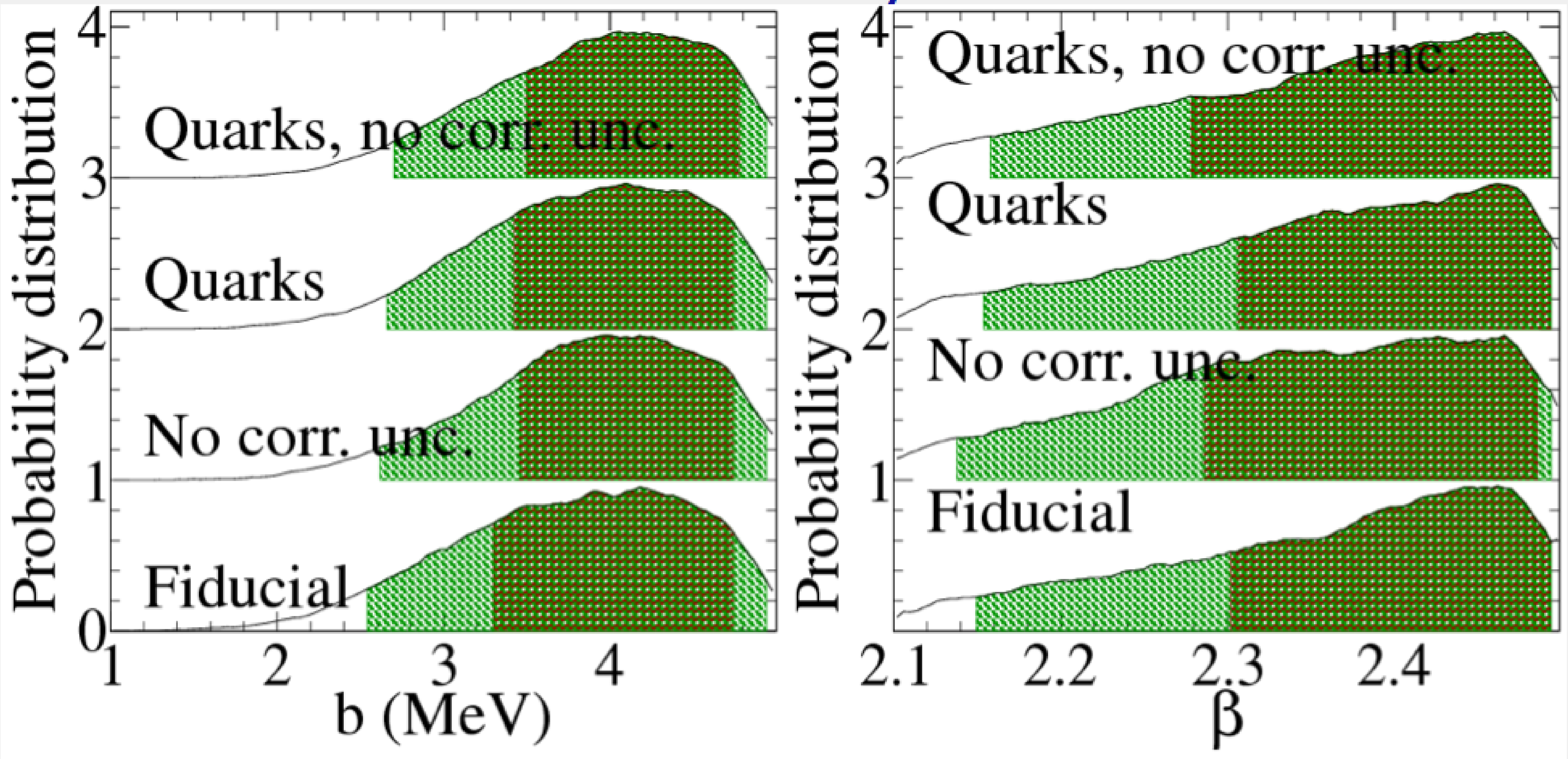
Colored regions denote different three-body forces

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

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?

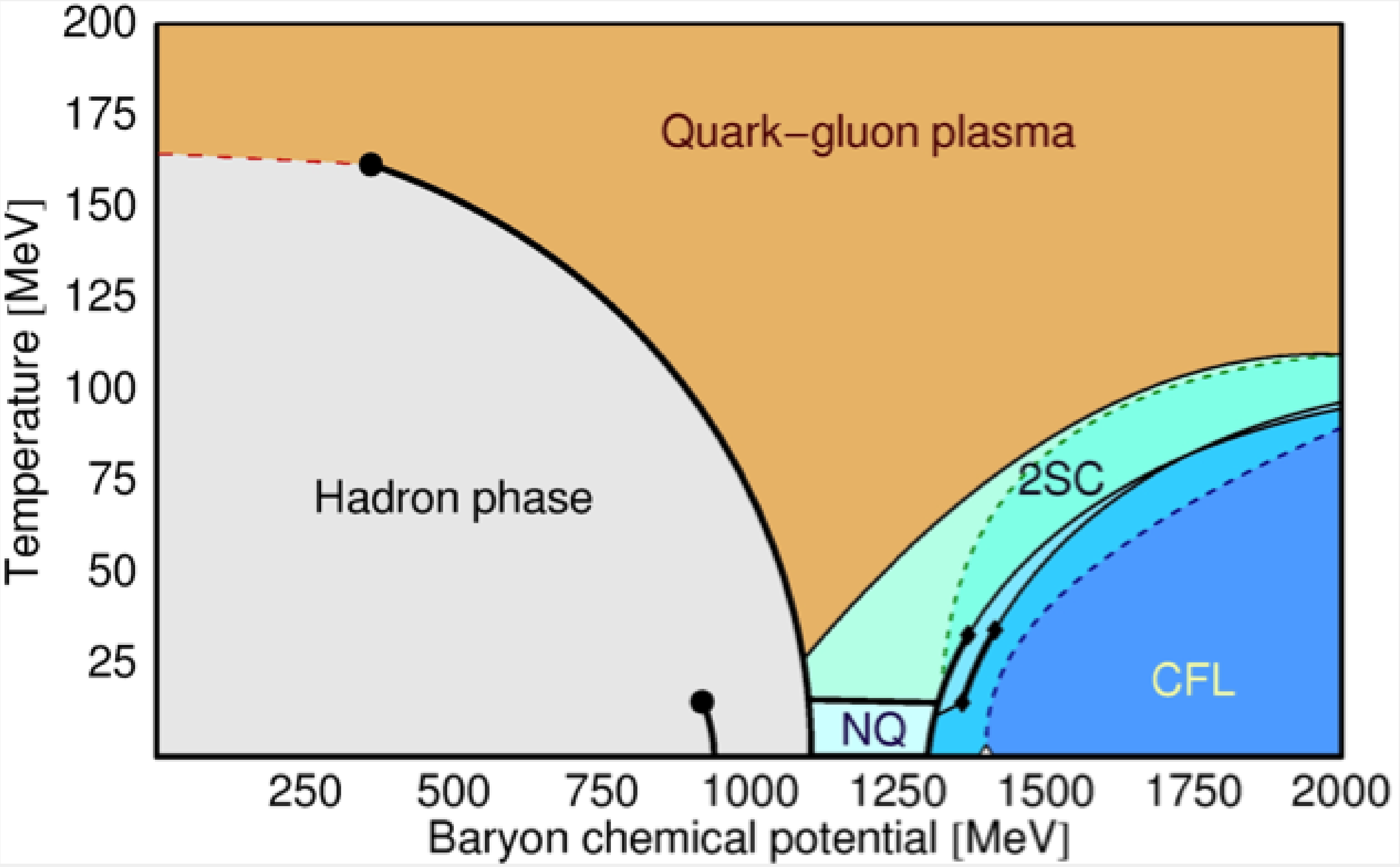
Constraints on Three-Body Force Parameters



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

Fundamental Questions



QCD phase diagram, Rüster et al. (2006)

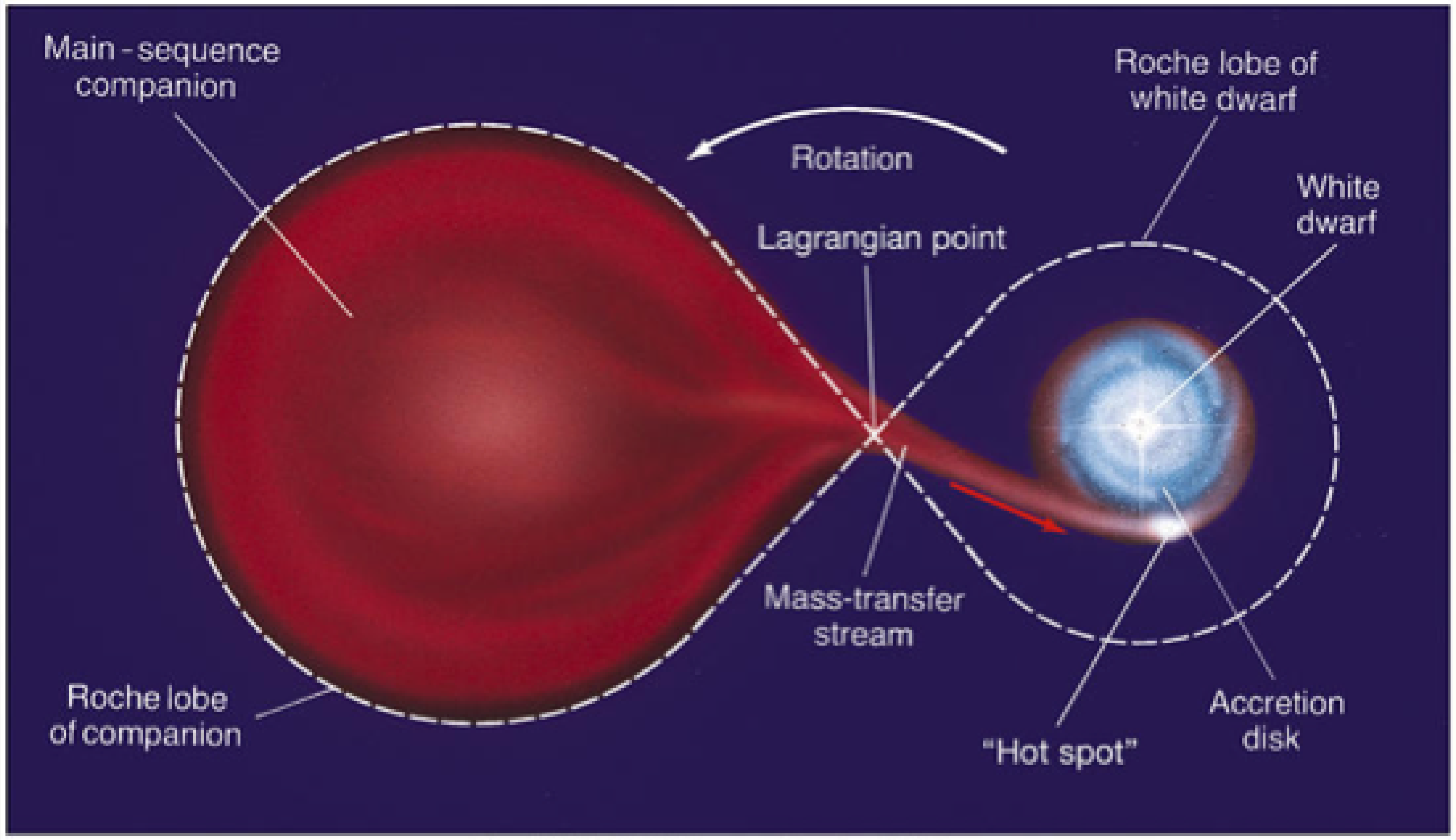
Frontiers of nuclear science (2007):

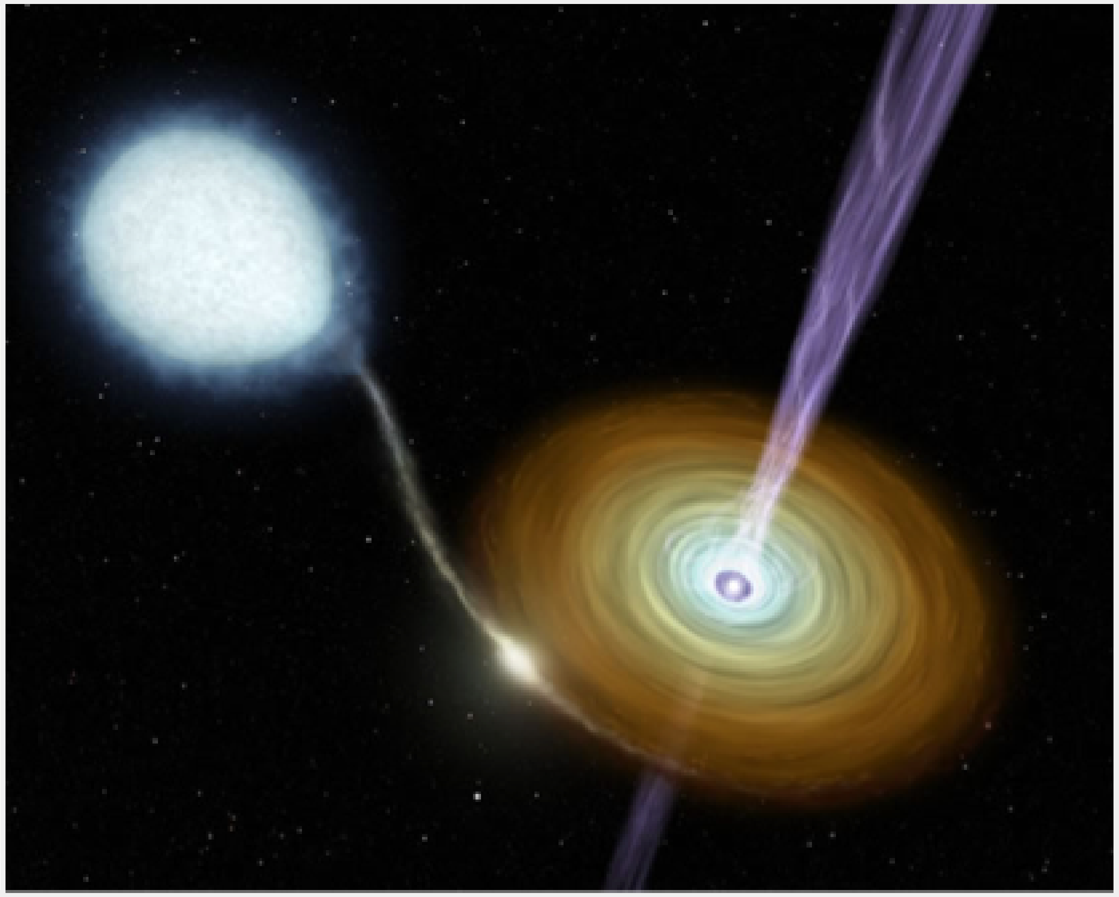
- What is the nature of neutron stars and dense matter?
- What is the nucleon-nucleon interaction?
- What is the origin of the elements?

Also,

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

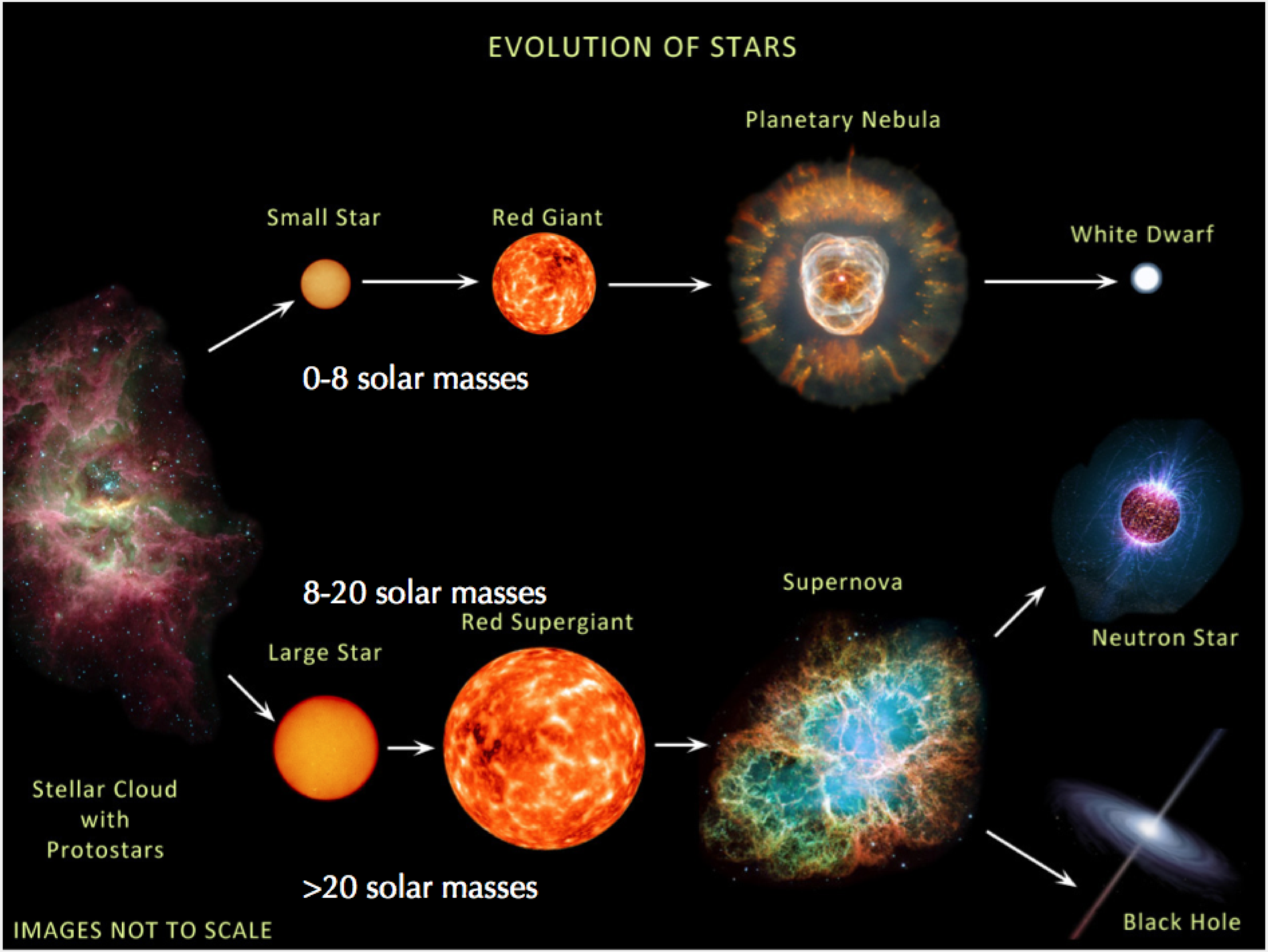
Accreting Neutron Stars: LMXBs





- 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

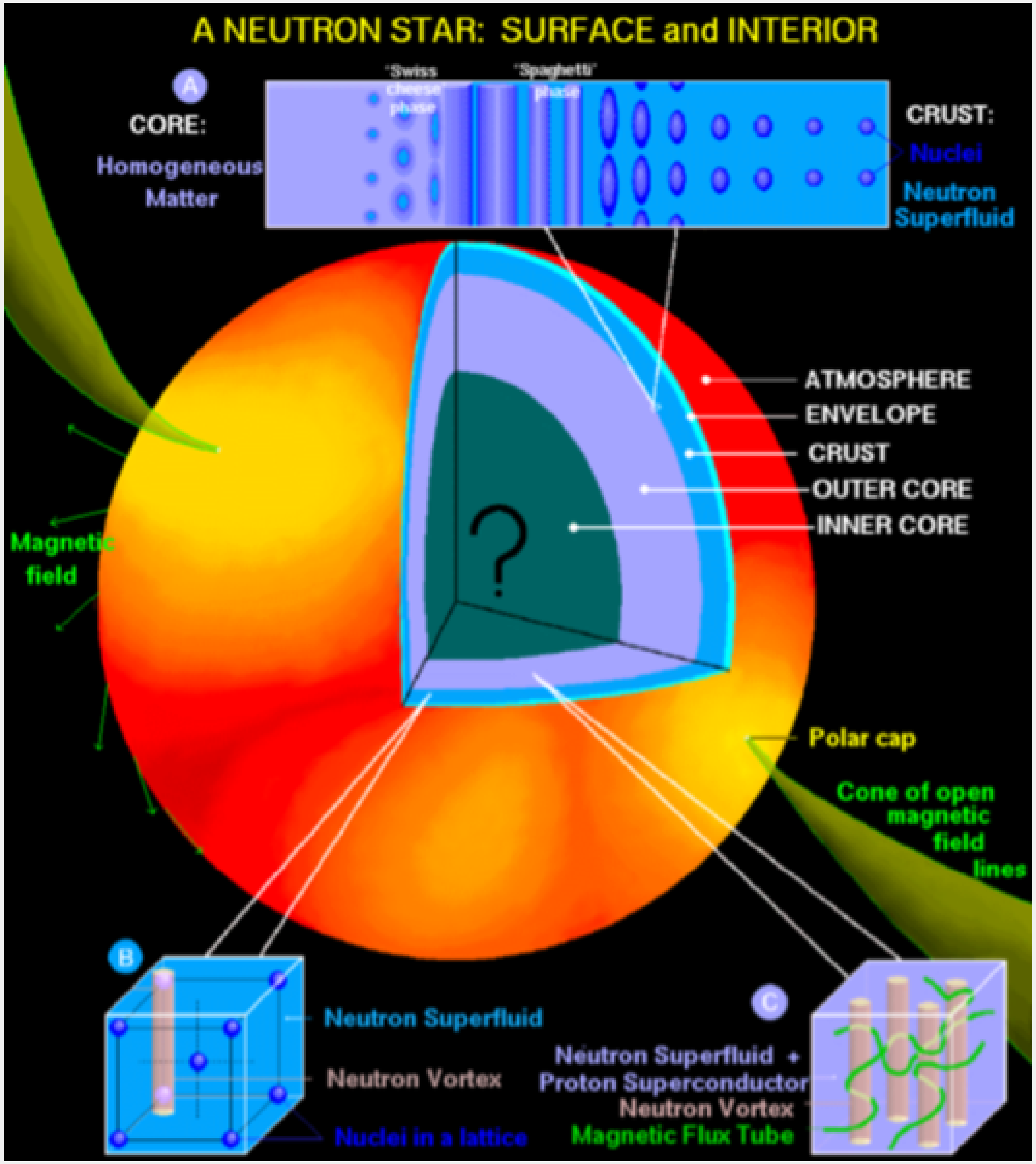
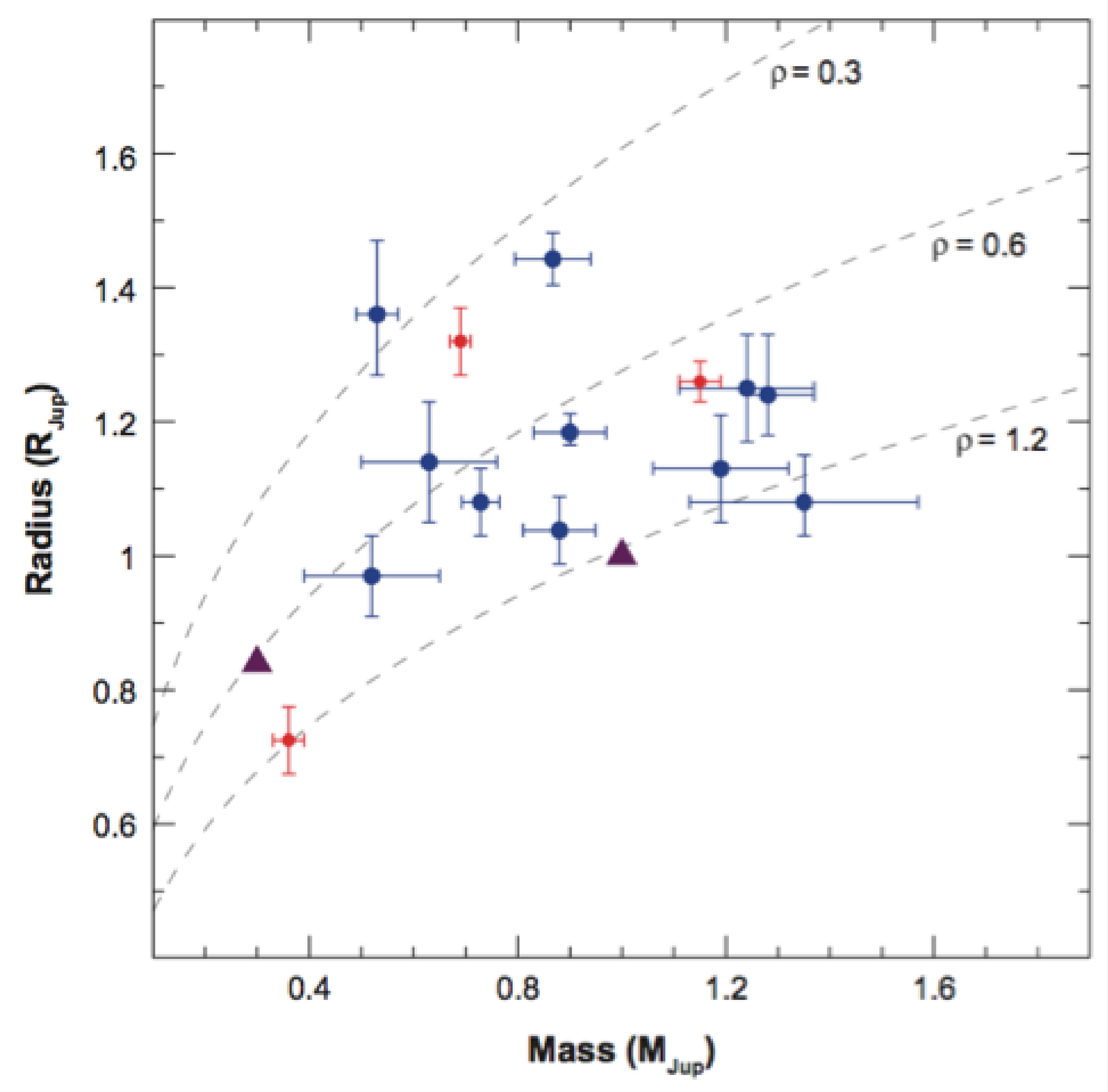


Figure by Dany Page

- 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?**

Planetary Diversity



Udry et al. (2007)

- Varying composition, thus varying radius for a fixed mass