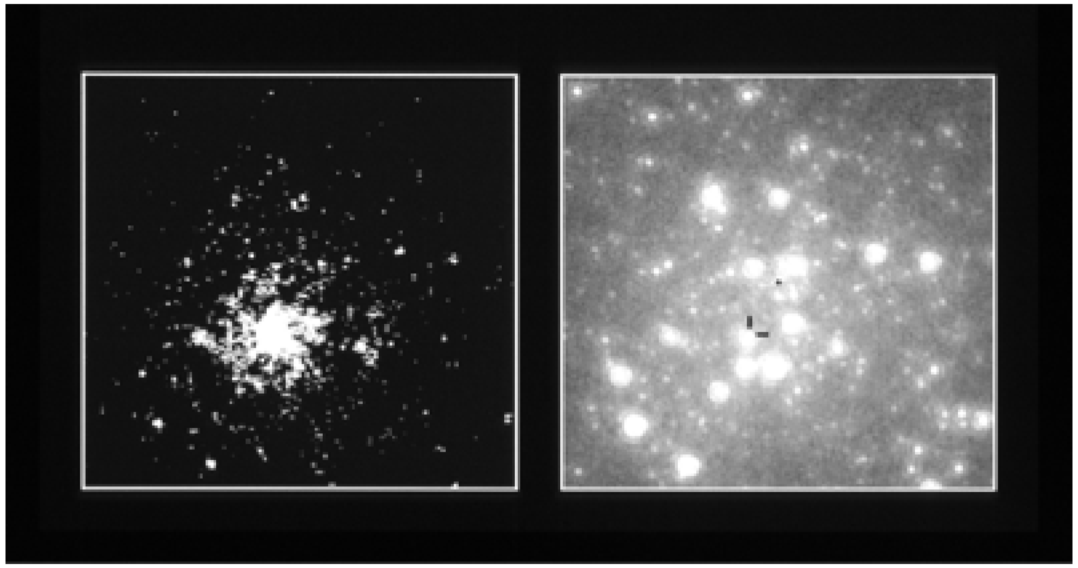
Neutron Stars and the Equation of State of Dense Matter



HST observation of 4U1820

Andrew W. Steiner
Institute for Nuclear Theory
University of Washington (Seattle)

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With: Edward F. Brown (Michigan State Univ.), Tobias Fischer (GSI)
Stefano Gandolfi (Los Alamos), Matthias Hempel (Basel)
James M. Lattimer (Stony Brook Univ.), Dany Page (UNAM),
Madappa Prakash (Ohio Univ.)

Outline

- Fundamental questions about the equation of state of dense matter
  - What is the composition of neutron stars?
  - What is the nature of superfluidity at high densities?
  - What observables can help us determine the nature of dense matter?
- Fundmanetal neutron star questions are connected to fundmamental nuclear physics questions, i.e. *What is the nuclear symmetry energy?*
- Background
- Mass and Radius Measurements
- Neutron Star Cooling
- Core-collapse Supernovae

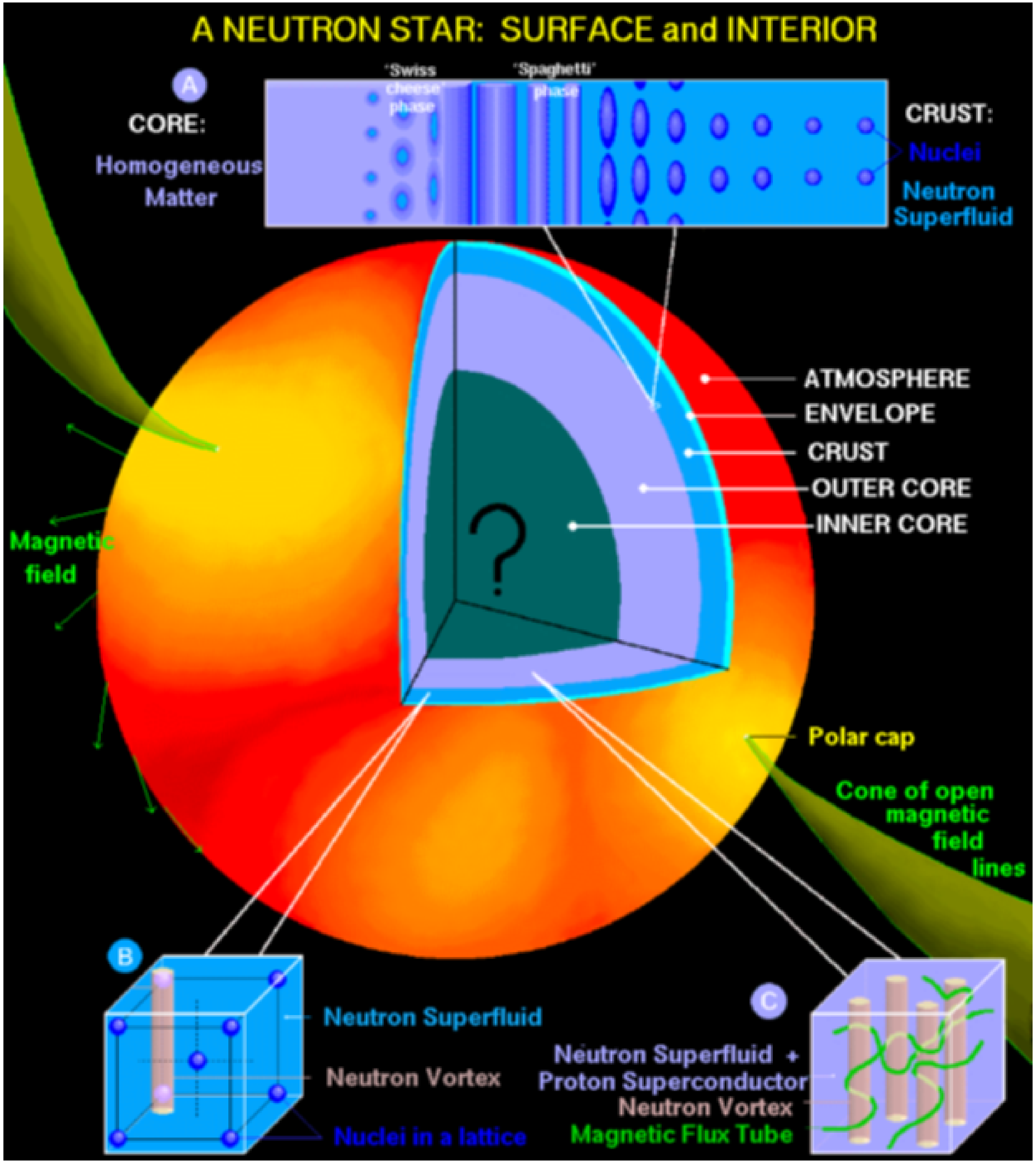


Figure by Dany Page

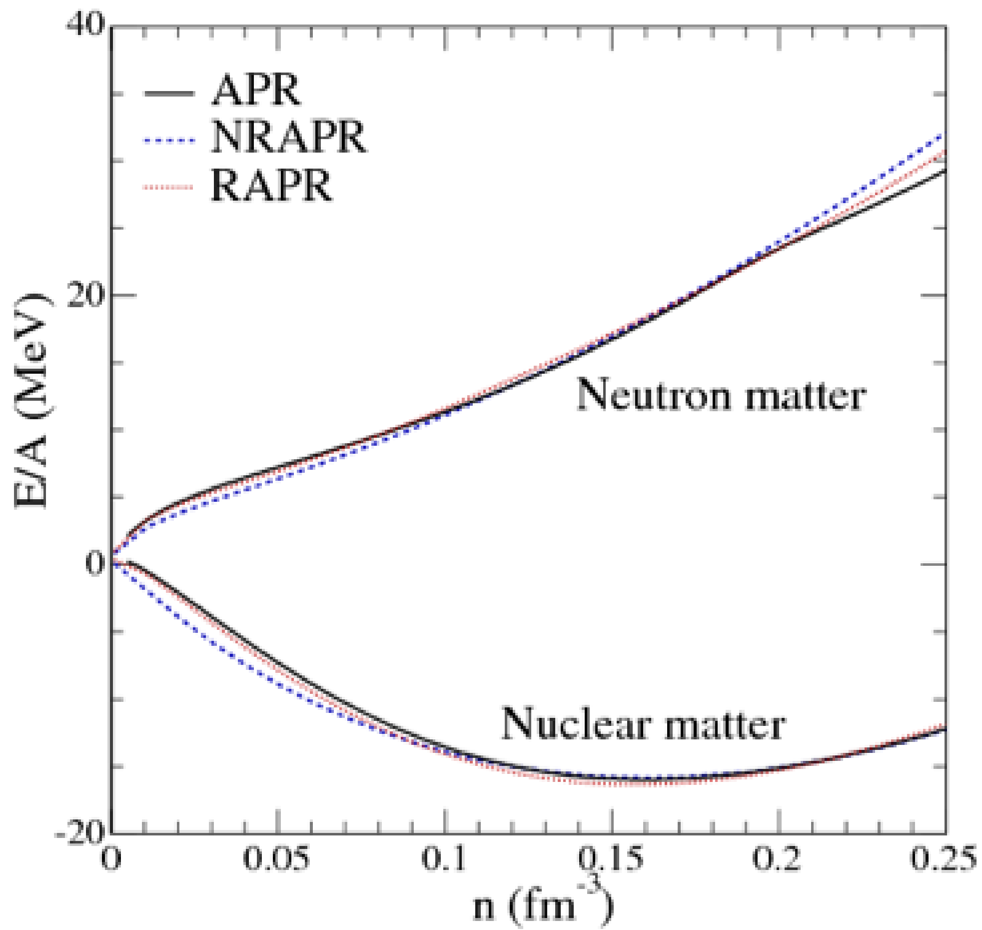
Neutron Star Composition

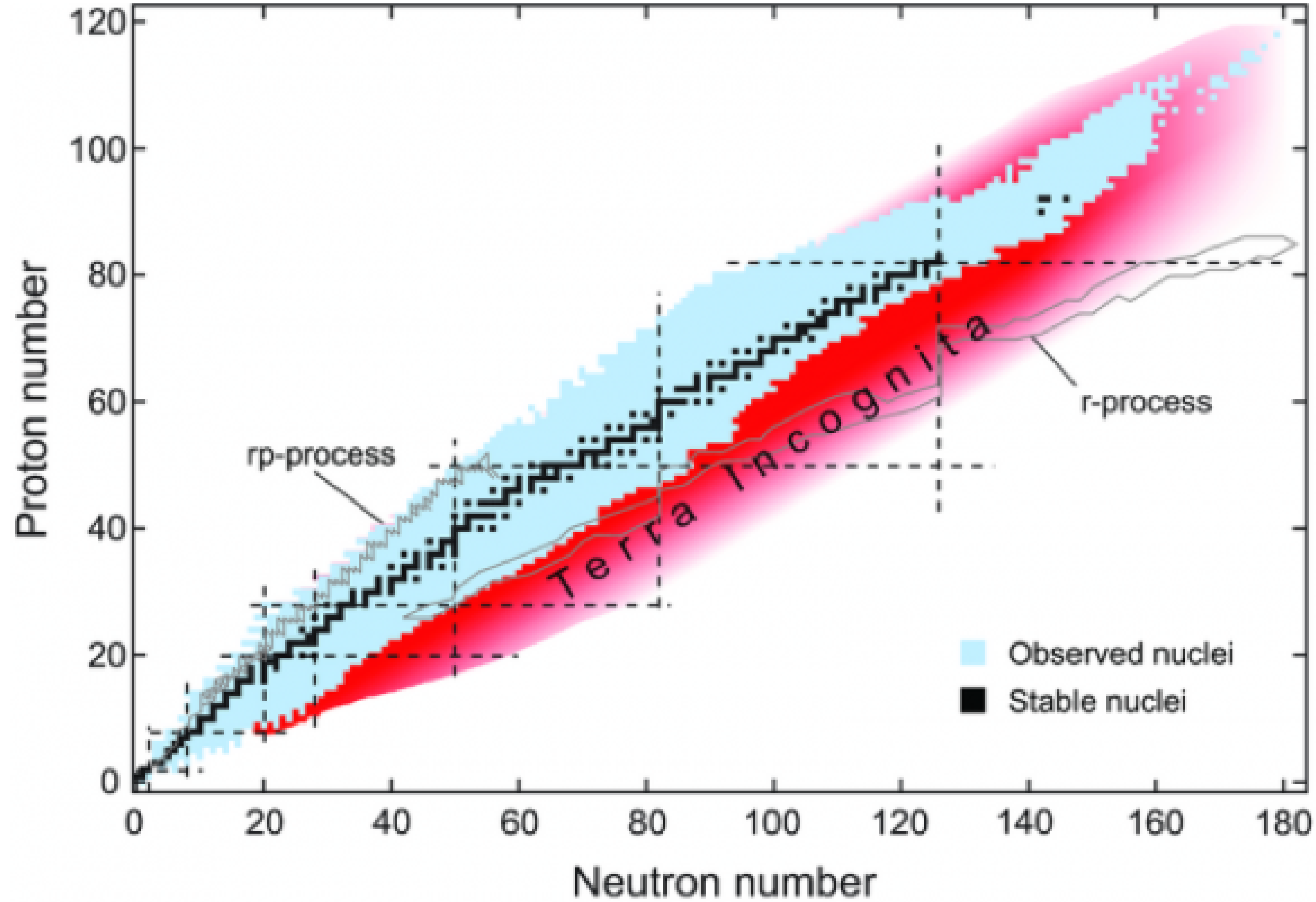
- Crust is a lattice of neutron-rich nuclei
- Composition of the crust different in accreting systems
- Outer core is homogeneous nucleonic matter
- Inner core may contain phase transitions:

$$[\Lambda, \Sigma, \Xi], [\pi, K], [u, d, s]$$

- Superfluidity is important

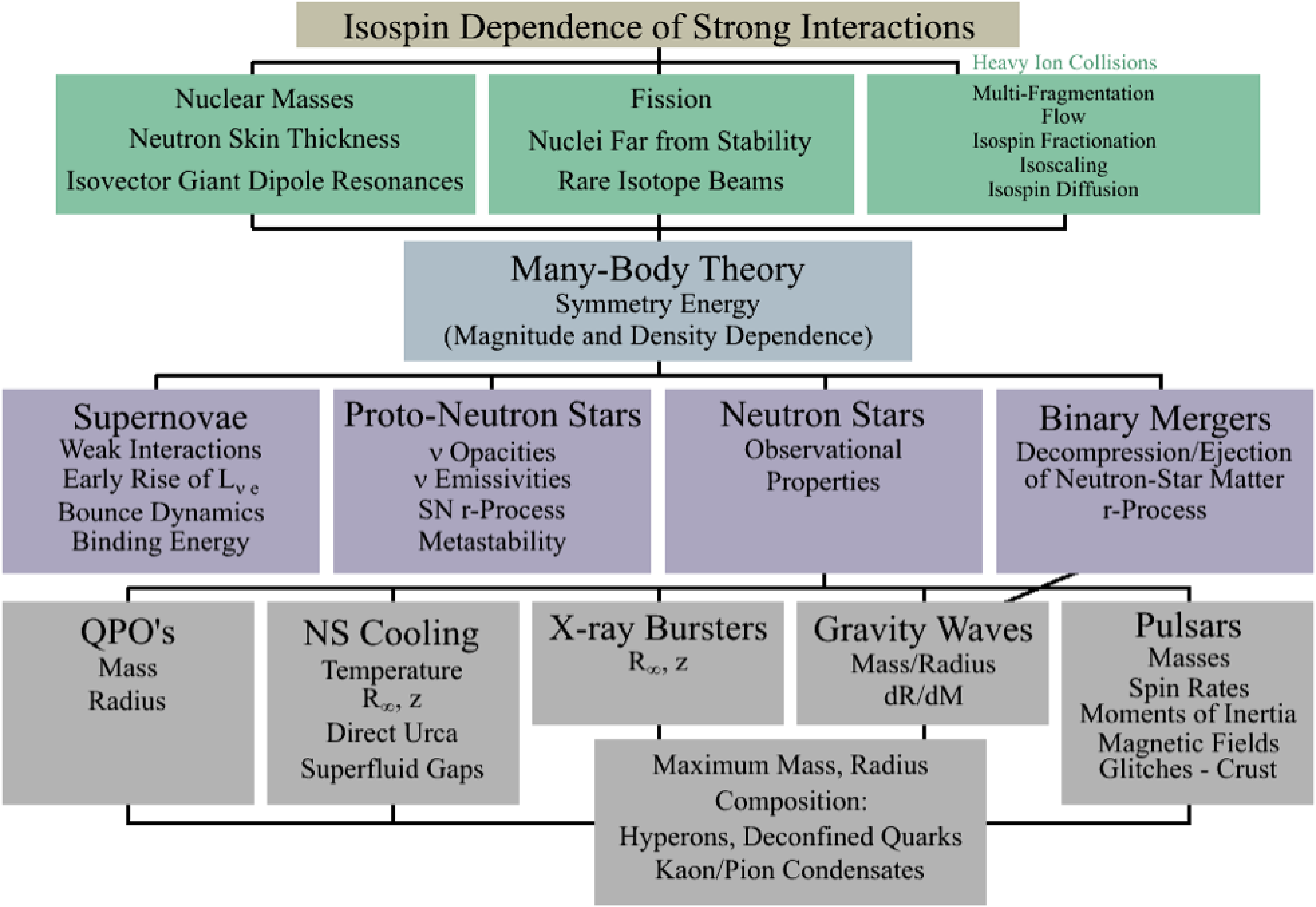
The Nuclear Symmetry Energy



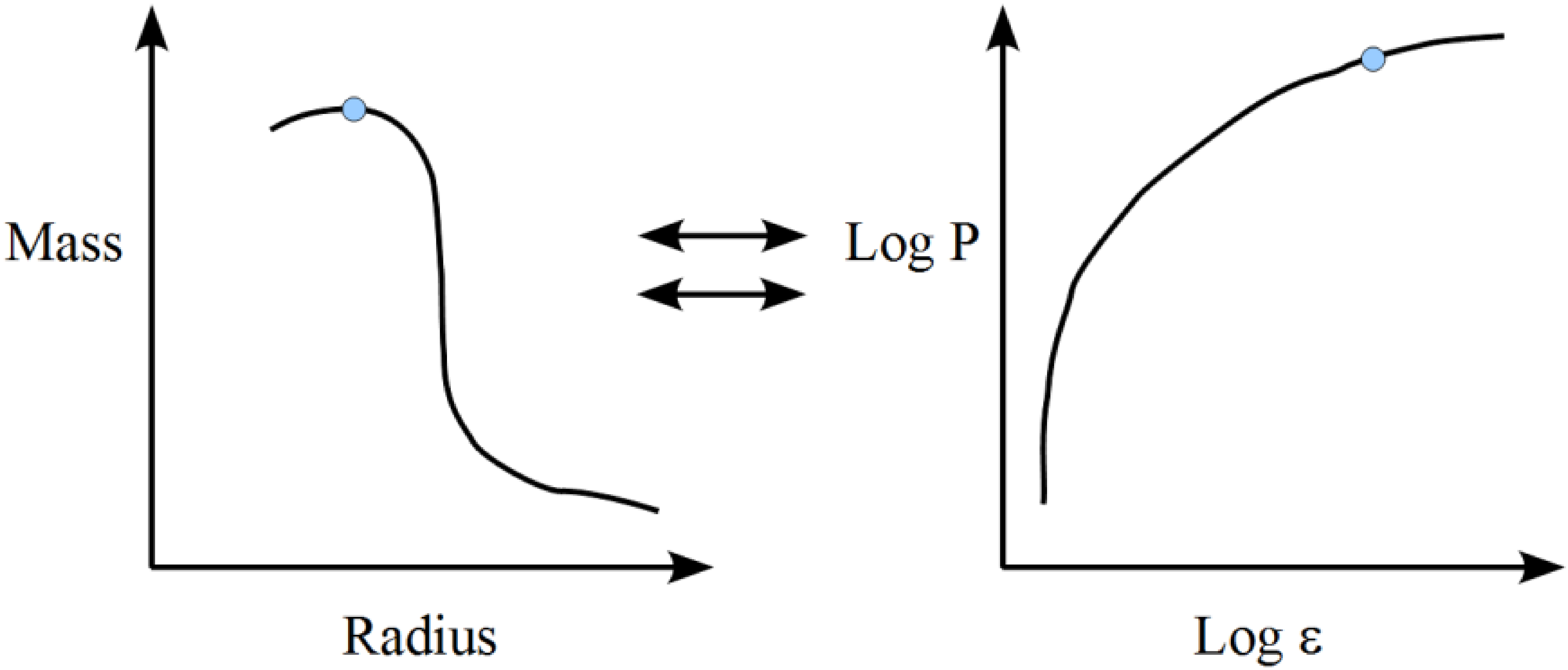


- The symmetry energy is the energy cost to create an isospin asymmetry
- The origin of the 'valley of stability'
- One of the largest uncertainties in the nucleon-nucleon interaction
- S is the value at the nuclear saturation density $S = S(n_0)$
- L is the derivative, $L = 3n_0 S'(n_0)$

Connections to the Symmetry Energy



M vs. R and the EOS of Dense Matter

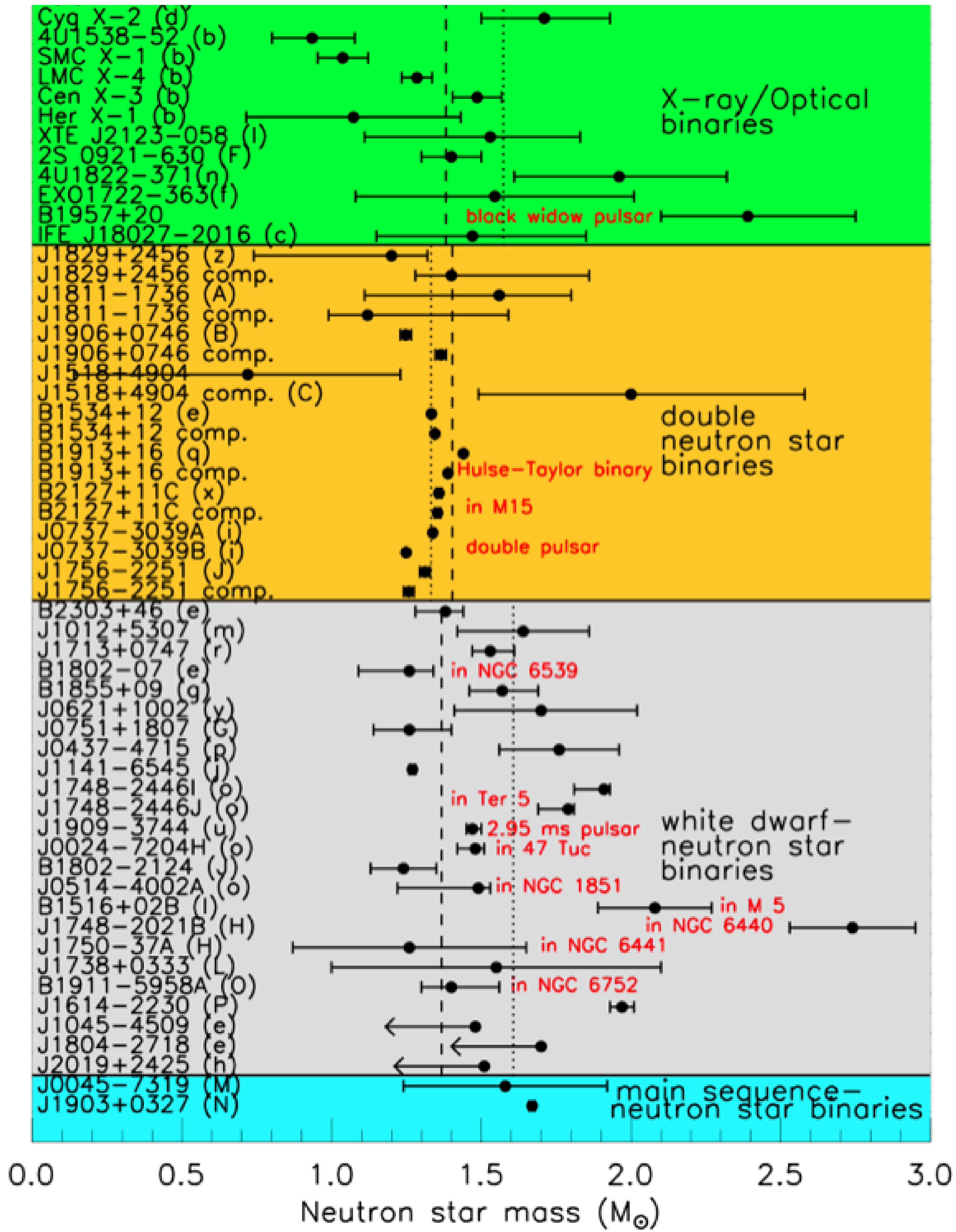


As of 5 years ago:

- Accurate mass measurements from double pulsars (e.g. Hulse-Taylor pulsar)
- Limited radius information for a few sources (e.g. Rutledge et al.)
- A few limited constraints from pulsar spins and pulsar glitches

Now:

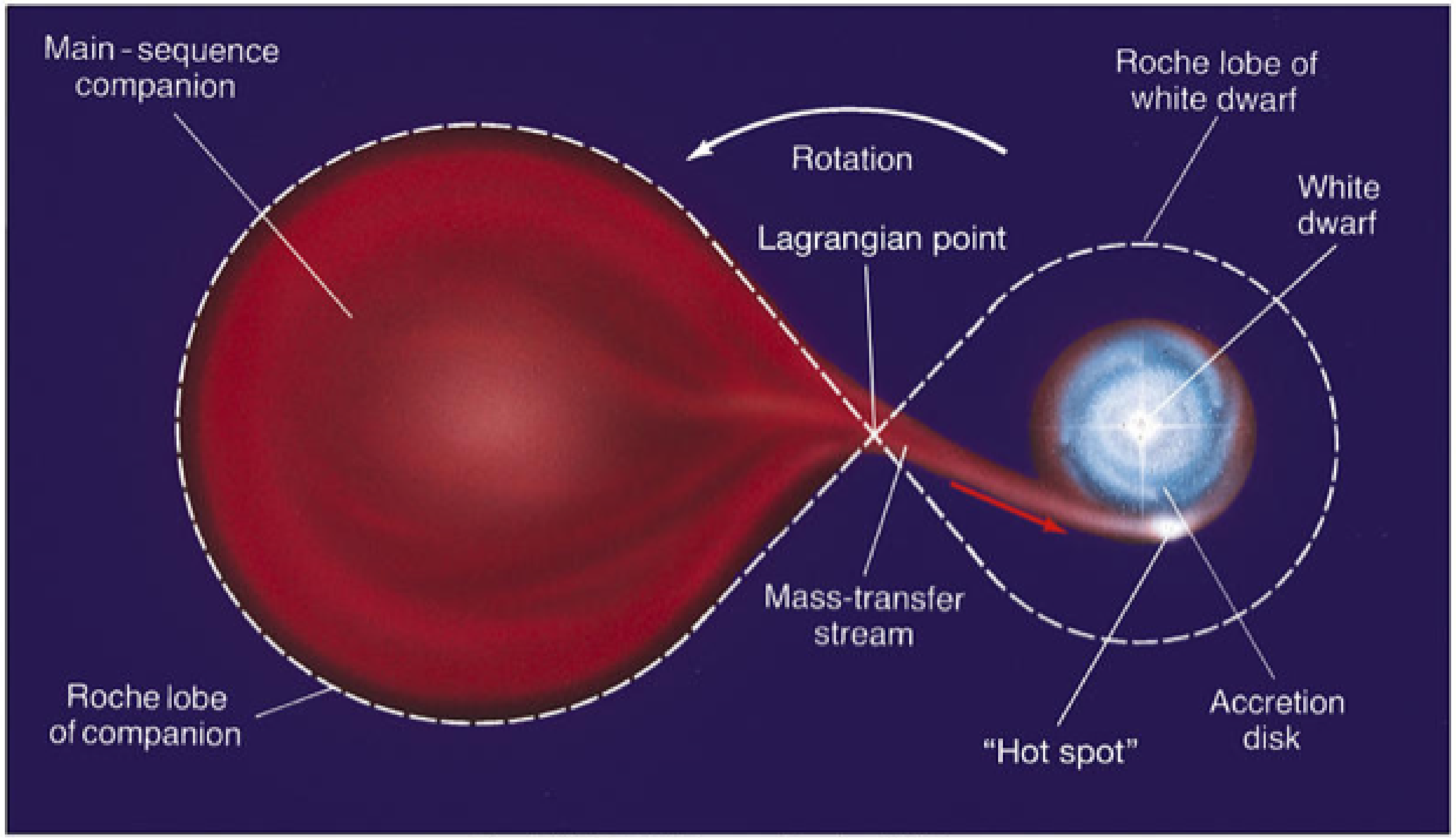
- 10-15 percent measurements of M and R for the same object
- A 2 solar mass neutron star (Demorest et al. 2010)

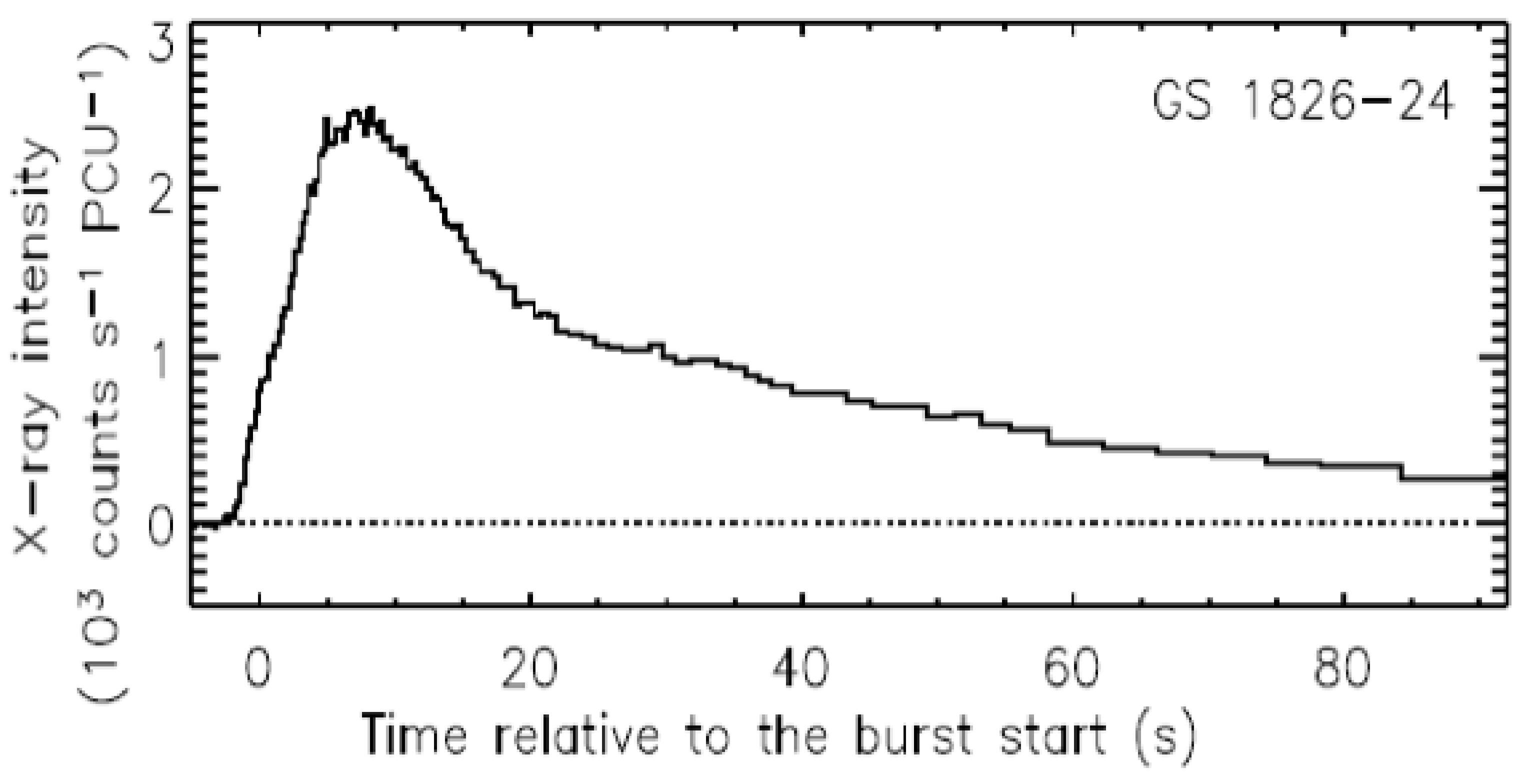


Neutron Star Mass Measurements

- Neutron star mass distribution is an important unknown quantity
- Friere et al. (2008): 2.74 ± 0.21, but depends on assumptions about the inclination angle
- Demorest et al. (2010) measurement: $1.97 \pm 0.04\ M_\odot$

Accreting Neutron Stars: LMXBs





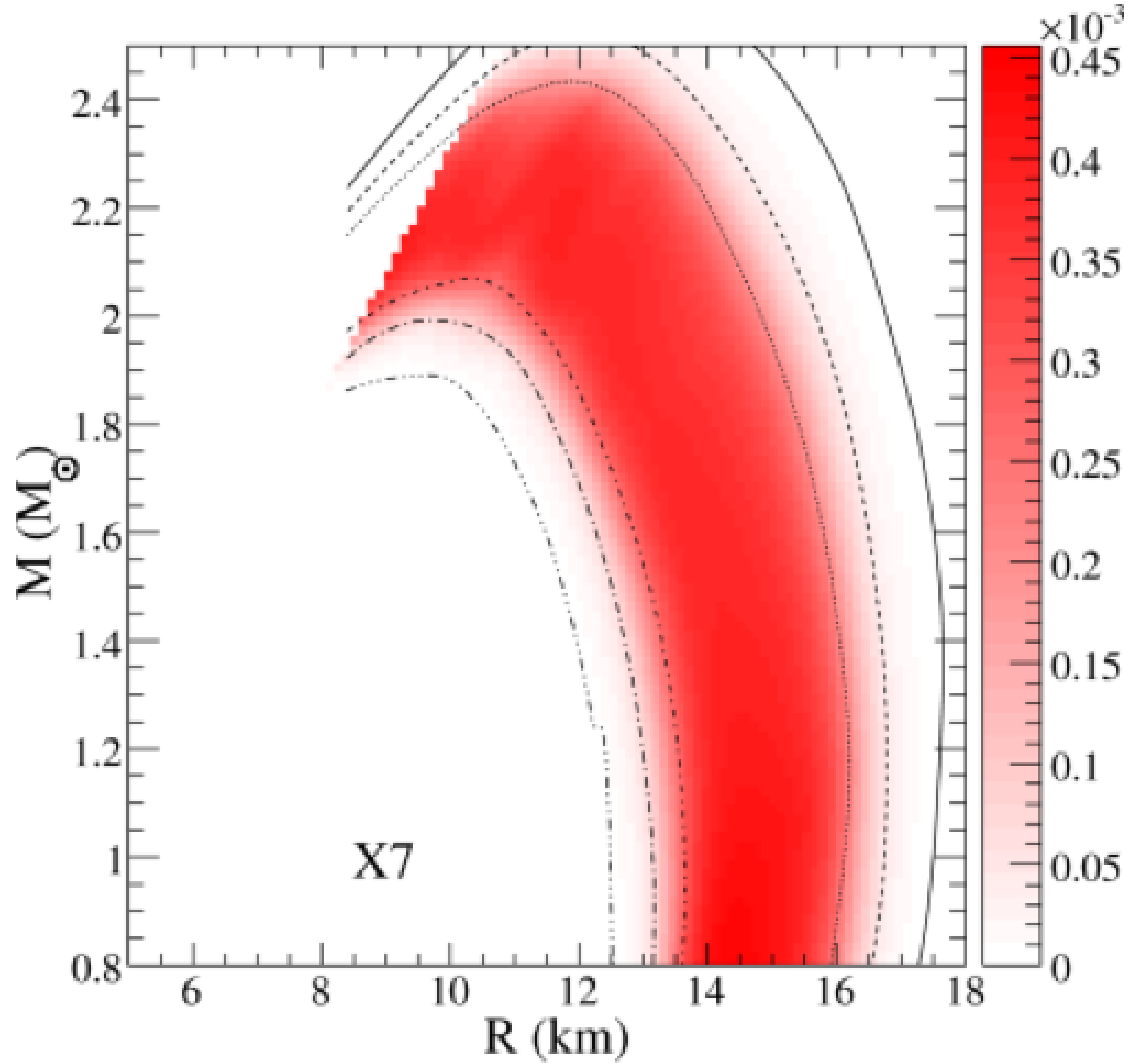
- From a main-sequence (normal) star or a white dwarf
- Overflowing the Roche lobe
- Most often accrete a mix of hydrogen and helium, sometimes heavier elements
- At high enough density, light elements are unstable to thermonuclear explosions

Mass Measurements and QLMXBs

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

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

[Rutledge et al. (1999), Heinke et al. 2006, Webb and Barrett (2007), Guillot et al. (2010)]



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"

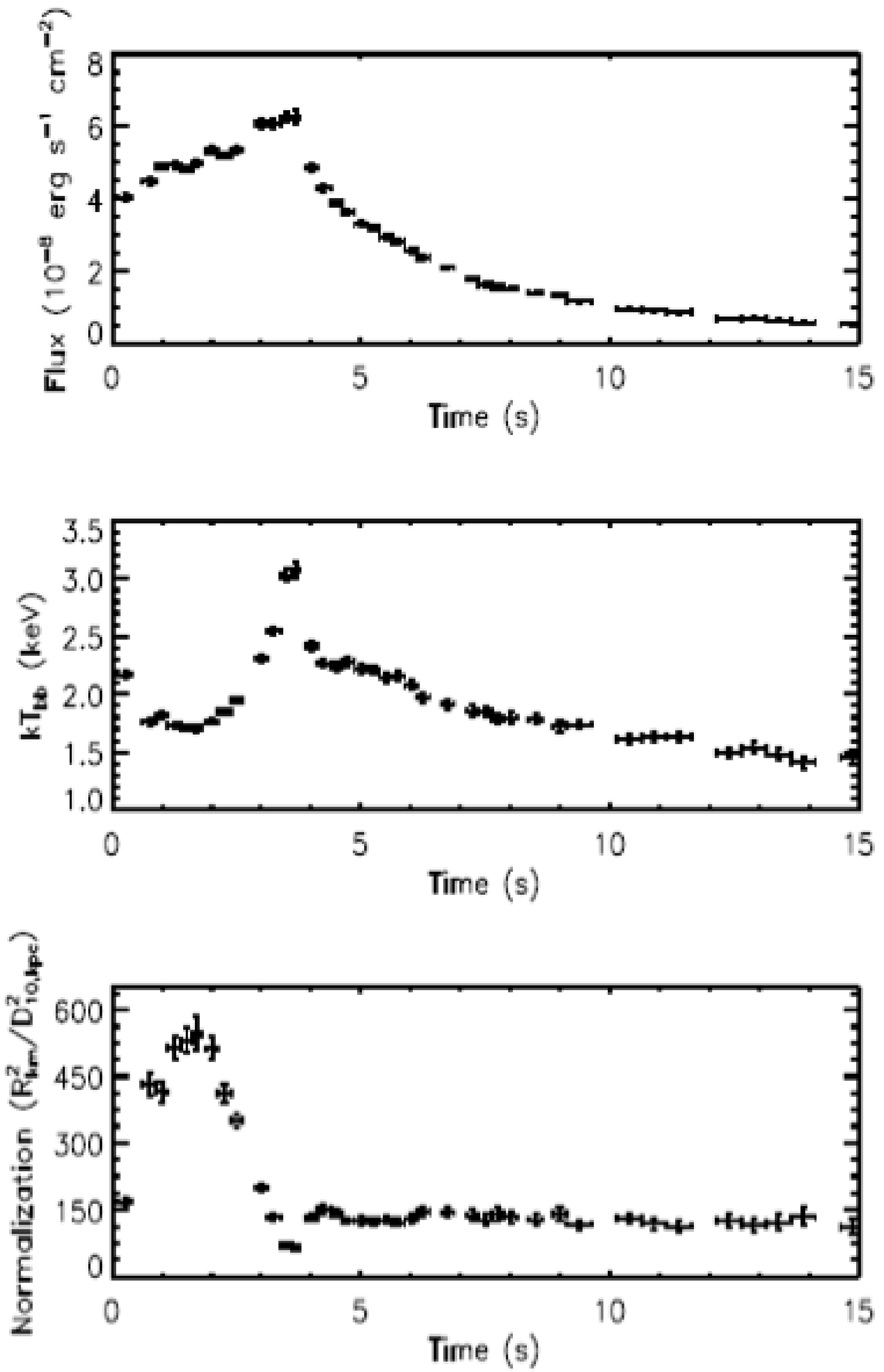
$$F_{TD} = \frac{GMc}{\kappa D^2} \sqrt{1 - 2\beta(r_{ph})}$$

- 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

(Pioneered by van Paradijs et al. 1979 and 1982 and Ebisuzuki et al. 1983)



Ozel et al. (2010)

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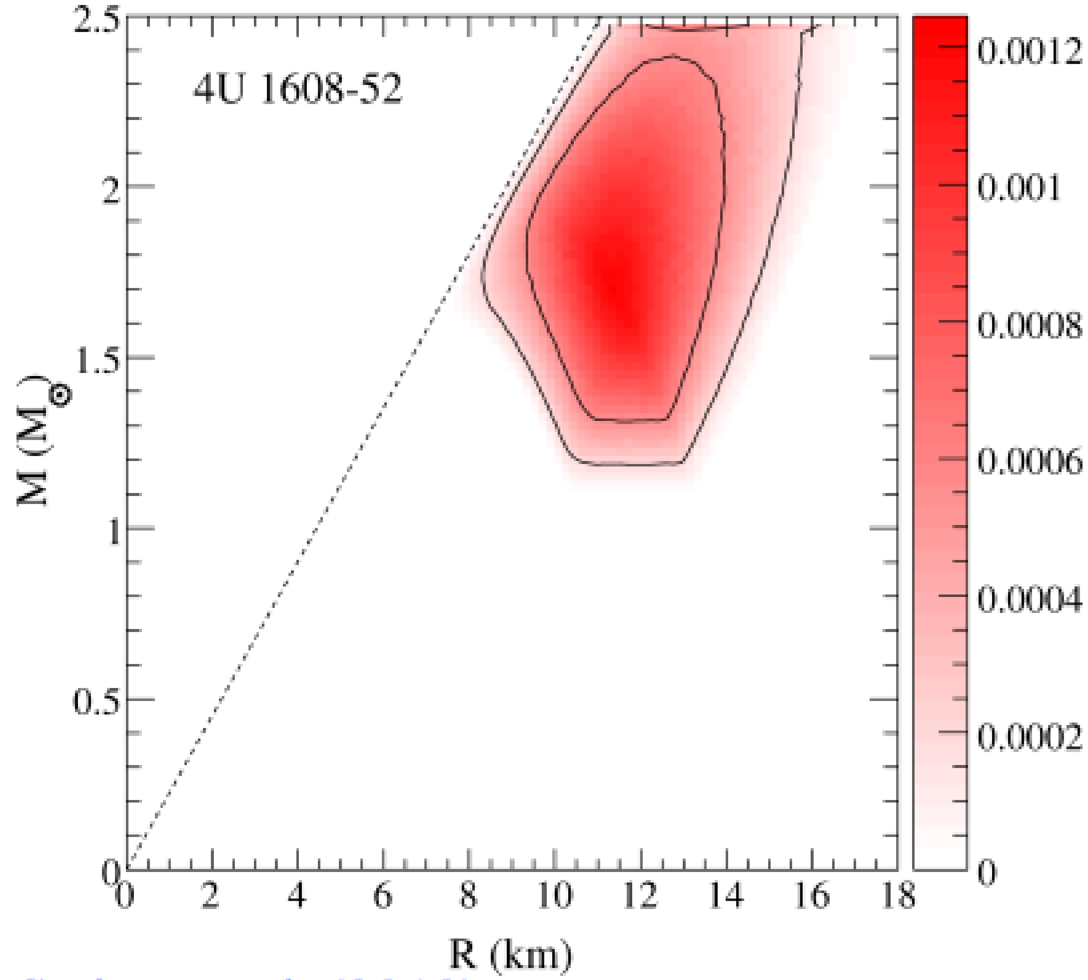
- Dimensionless parameter

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



Steiner et al. (2010)

Statistical Approach

- Well-suited to this underconstrained problem: 7-8 EOS parameters, 7-8 data points

- Bayes theorem:

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

- Different prior distributions produce different results

- Conditional probability is provided by the data

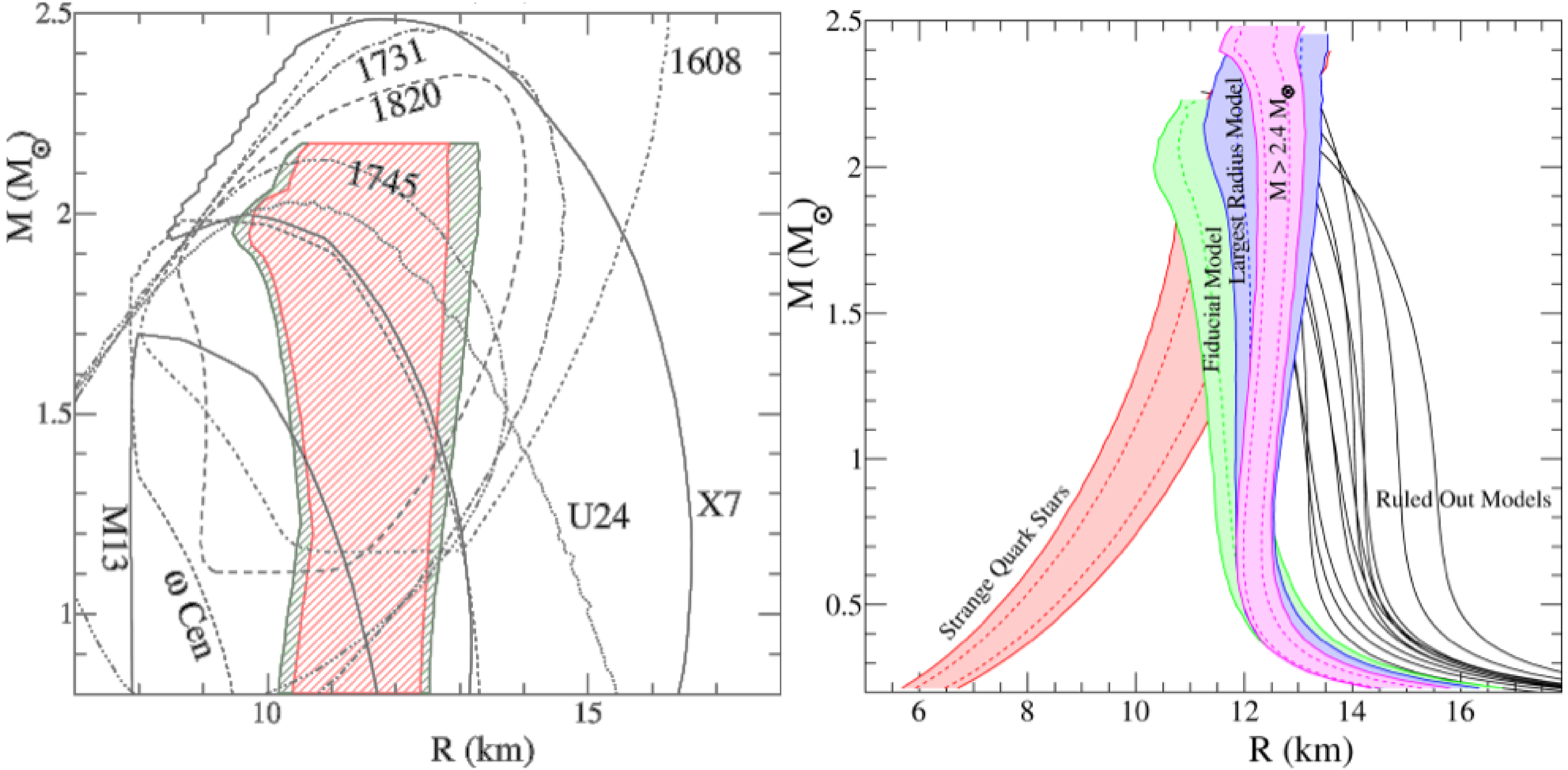
$$P[D|\mathcal{M}] = \prod_{i \in n_{\mathrm{datasets}}} \mathcal{D}_i(M,R)|_{M=M_i, R=R(M_i)}$$

the analog of the likelihood function

- In Bayesian analysis, marginal estimation is often employed:

$$P[p_j|D](p_j) = \frac{1}{V}\int dp_1 \ldots dp_{j-1}\, dp_{j+1} \ldots dp_{N(p)} P[M|D]$$

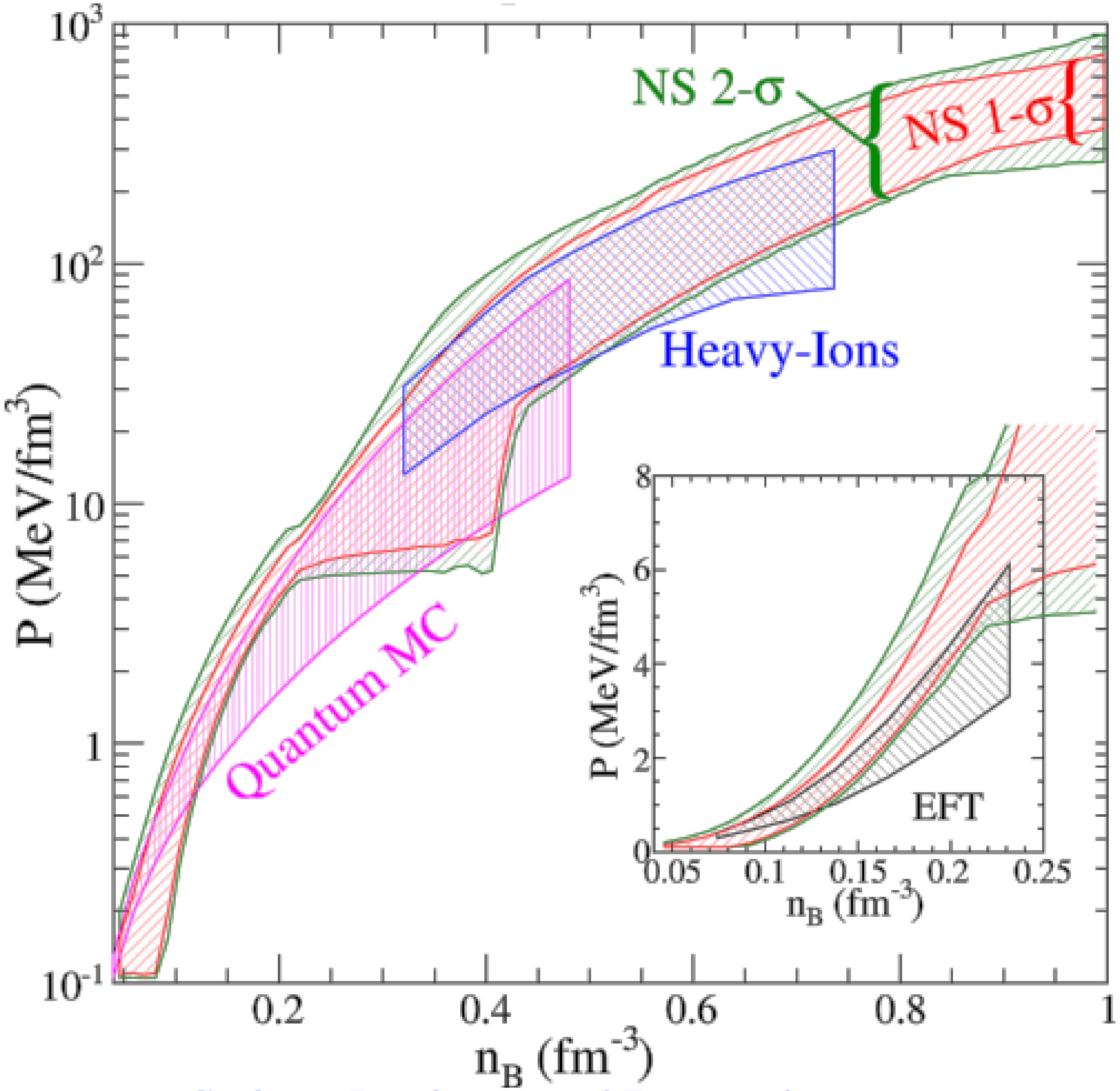
Mass and Radius Results



Steiner, Lattimer, and Brown, in prep.

- Choose the largest range which encloses several choices in model assumptions and prior distributions
- Range of radii for a 1.4 solar mass star: 10.4 and 12.9 km

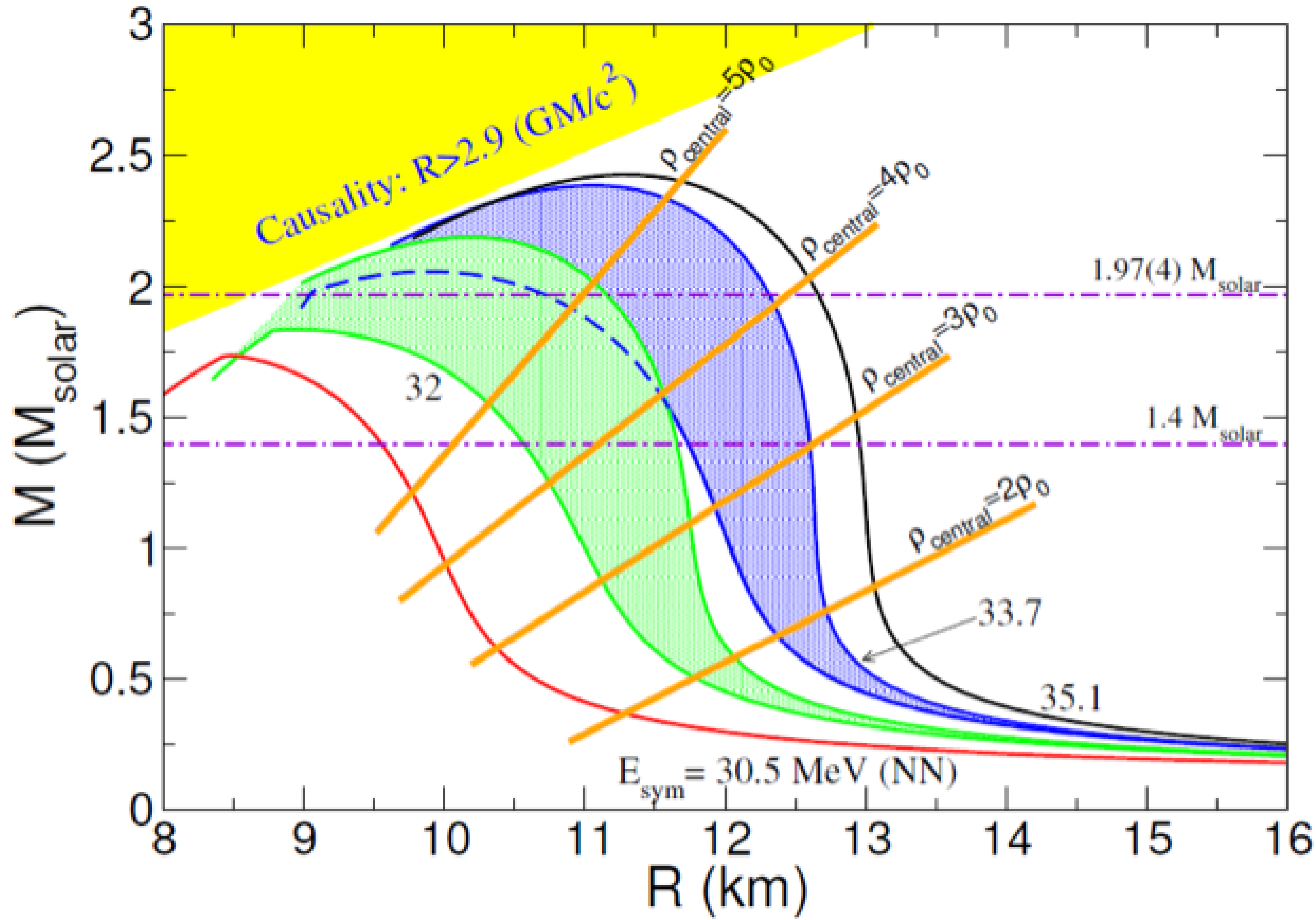
EOS results



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

Connection to nuclear three-body forces

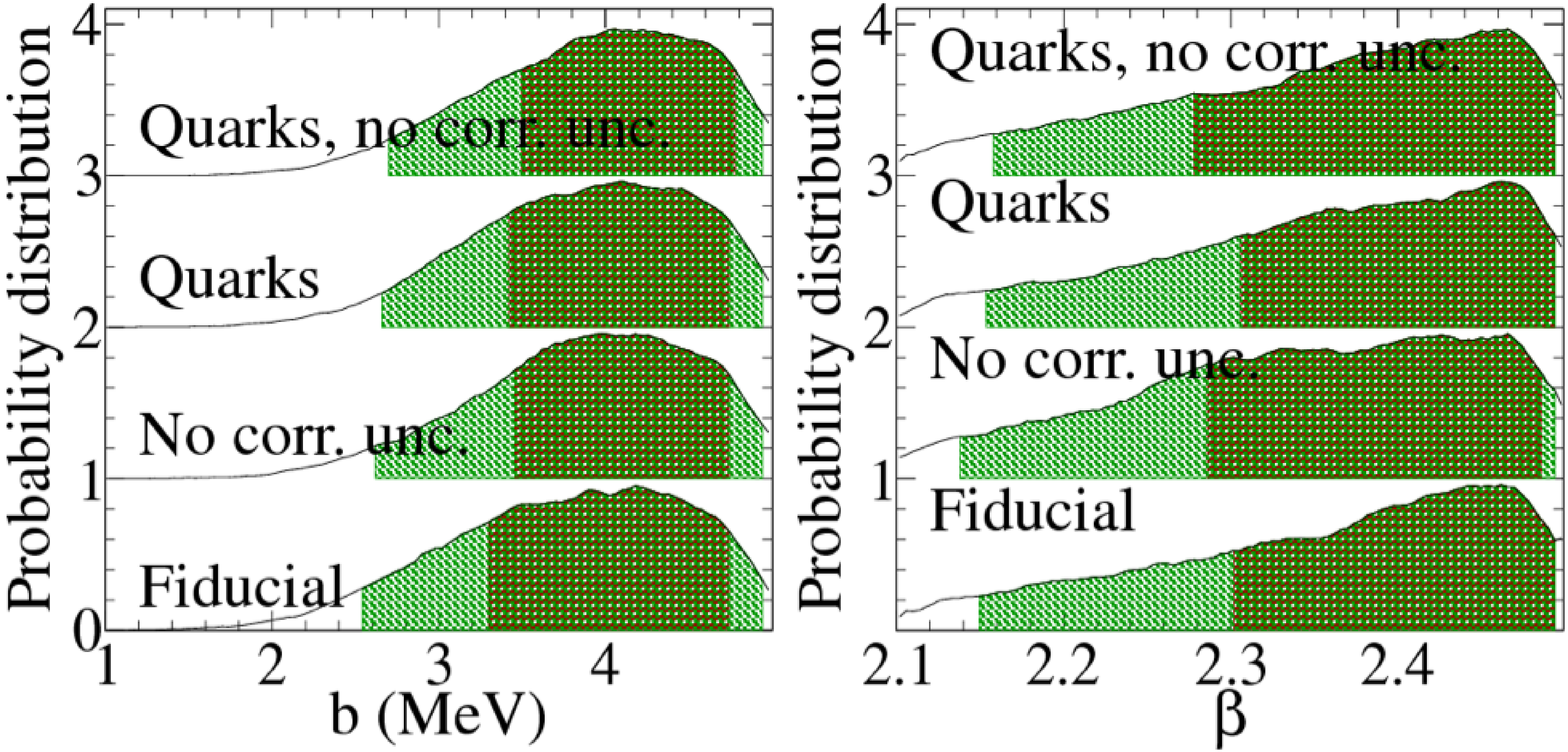


Gandolfi et al. (2012)

- Red = no three-body
- Blue, Green = adjusted three-body interactions
- Black = Urbana IX
- Strong correlation between S and L

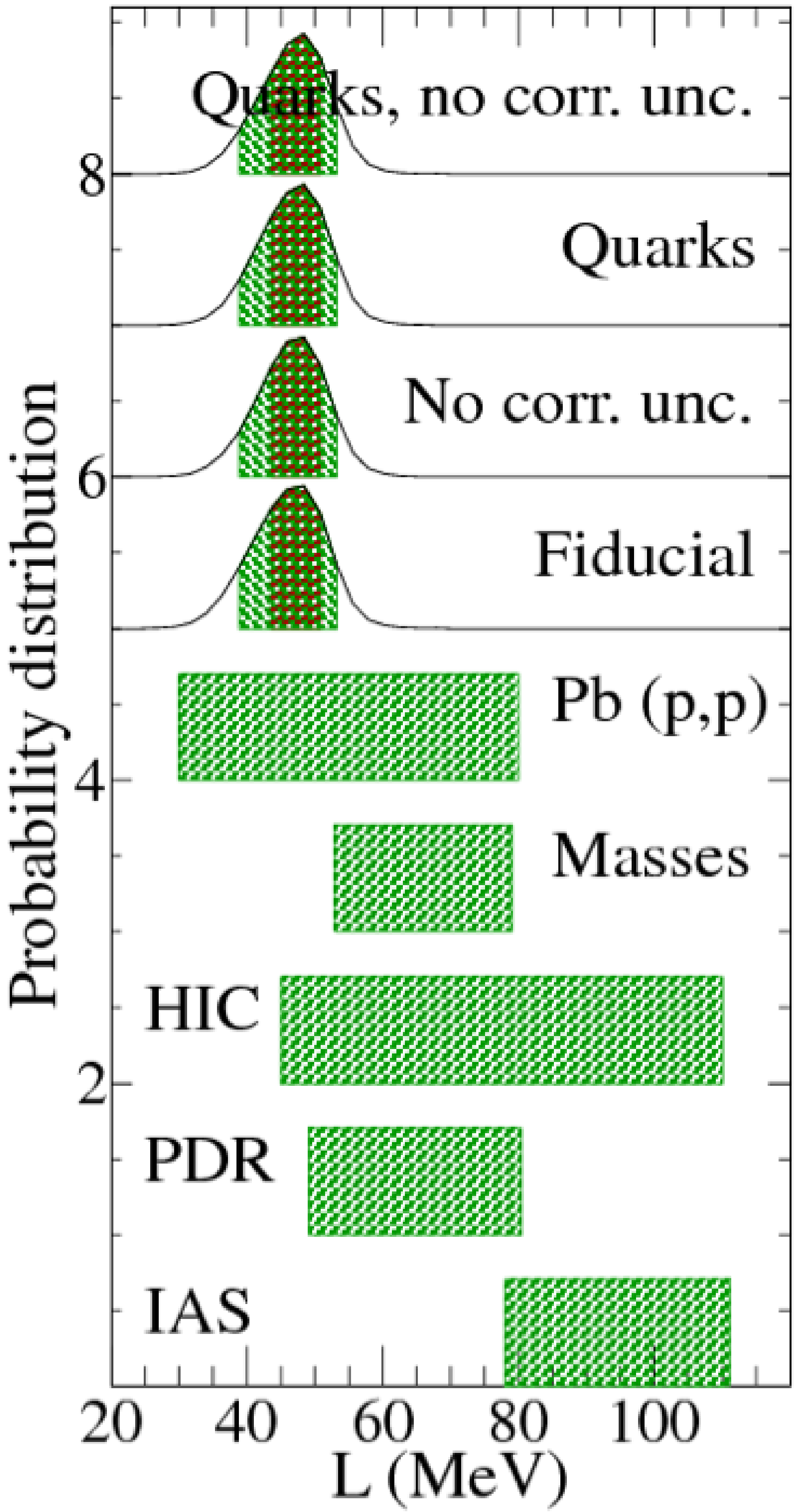
- Build up a many-body system from effective two- and three-body nucleon-nucleon interactions
- Three-body forces are also related to neutron star radii
- $E = a\left(\frac{n}{n_0}\right)^{\alpha} + b\left(\frac{n}{n_0}\right)^{\beta}$ is a convenient parameterization

Constraints on three-body force parameters



Steiner and Gandolfi (2012)

- Values of a and α are unconstrained, but constraints on b and β
- This means that neutron star radii are constraining nuclear three-body forces



Steiner and Gandolfi (2012)

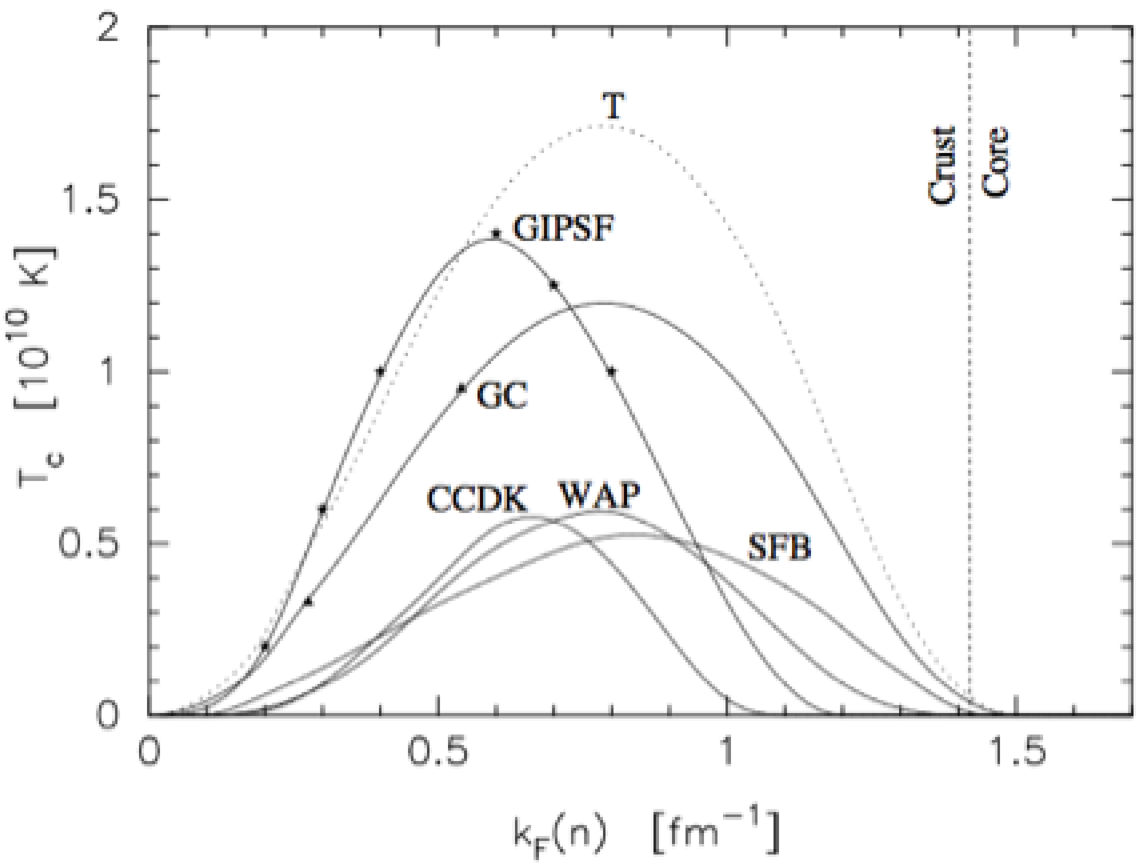
Symmetry Energy Results

- Strong constraints on the derivative of the symmetry energy
- Almost no constraint on S
- Implications for neutron star cooling through the direct Urca process

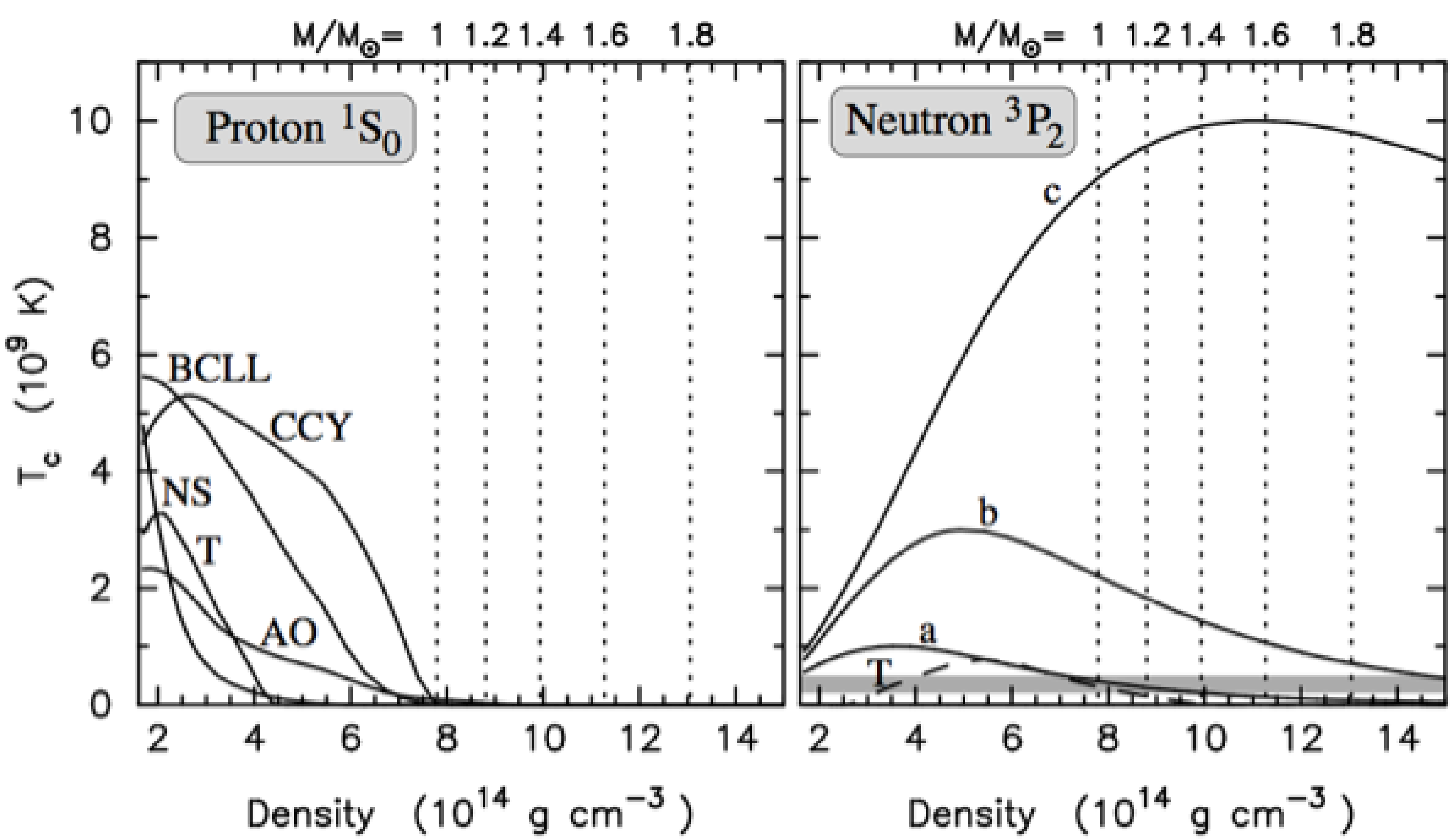
The direct Urca process

- Neutron Star cooling processes
  - Modified Urca cooling: $n + n \to n + p + e + \bar{\nu}$,
    $Q \sim T^8$
  - Cooper pair breaking emissivity $n + n \to n + n + \nu + \bar{\nu}$,
    $Q \sim T^7 \log T$
  - Direct Urca: $n \to p + e + \bar{\nu}$,
    $Q \sim T^6$
- Direct Urca requires a large enough proton Fermi momentum
- Thus also connected to the symmetry energy
- Also quark and hyperon direct Urca processes

Neutron Star Superfluidity



- Superfluidity can block the direct Urca process
- Also blocks quark direct Urca process

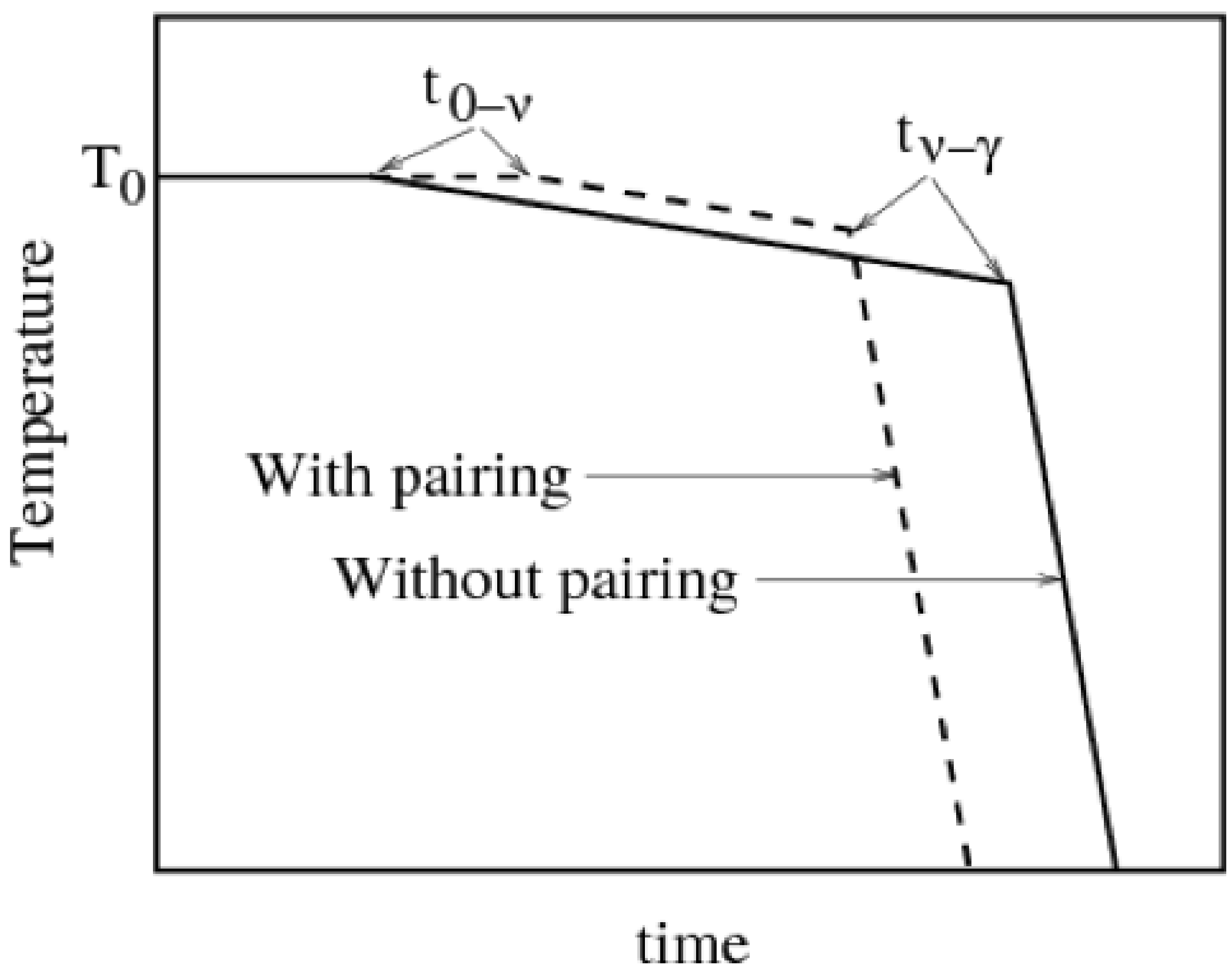


Thermal Emission from Isolated Neutron Stars

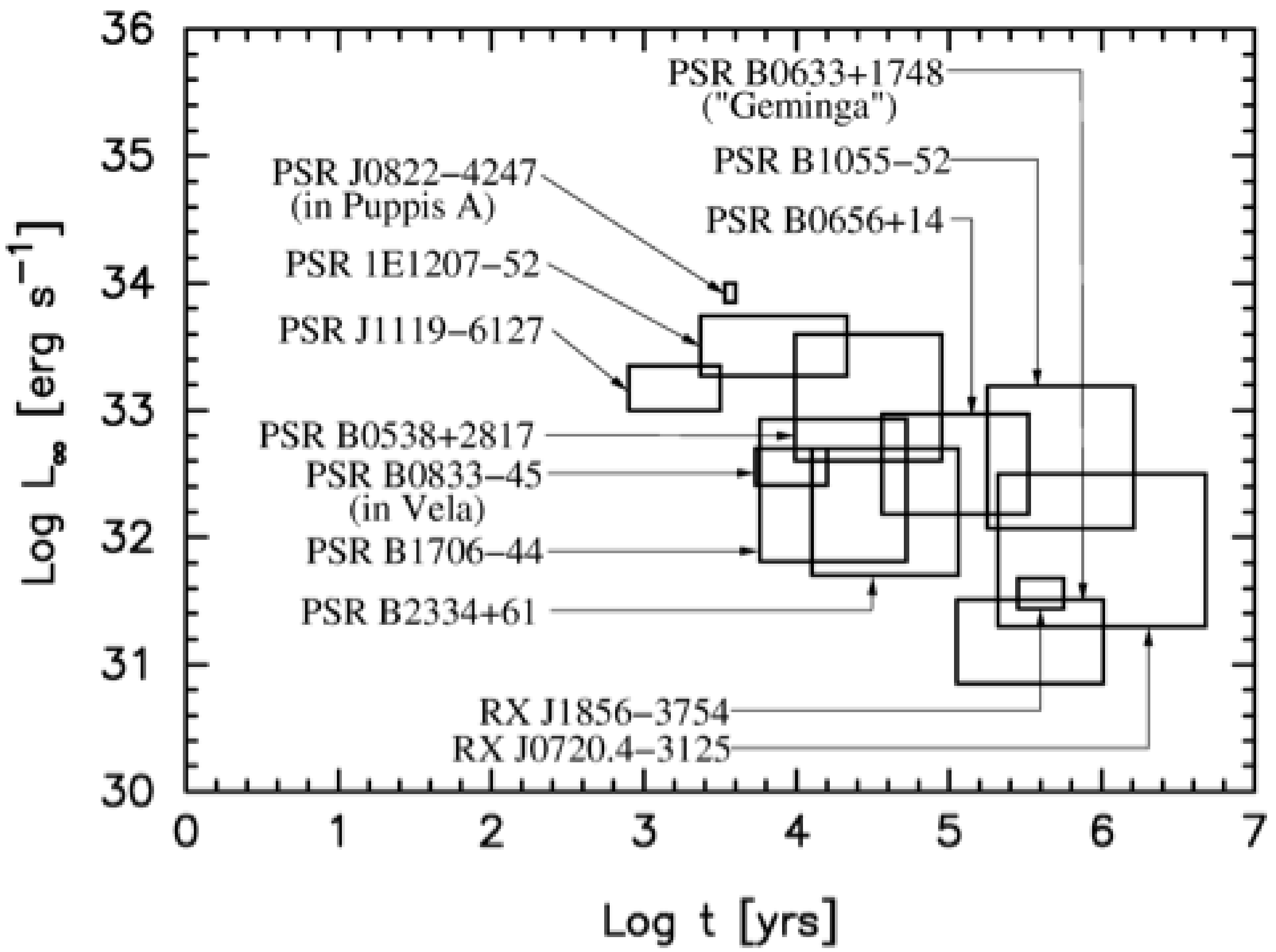
- No distance measurement required
- Requires a model of the NS atmosphere to associate the observed spectrum with a luminosity or temperature

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

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



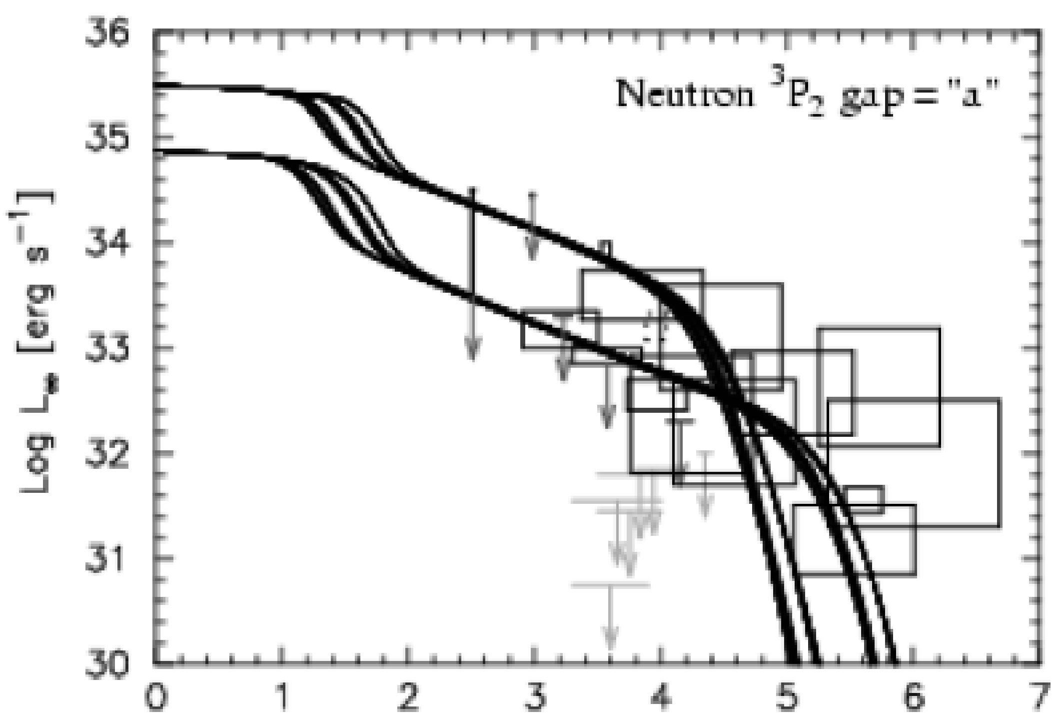
Page, et al (2004)



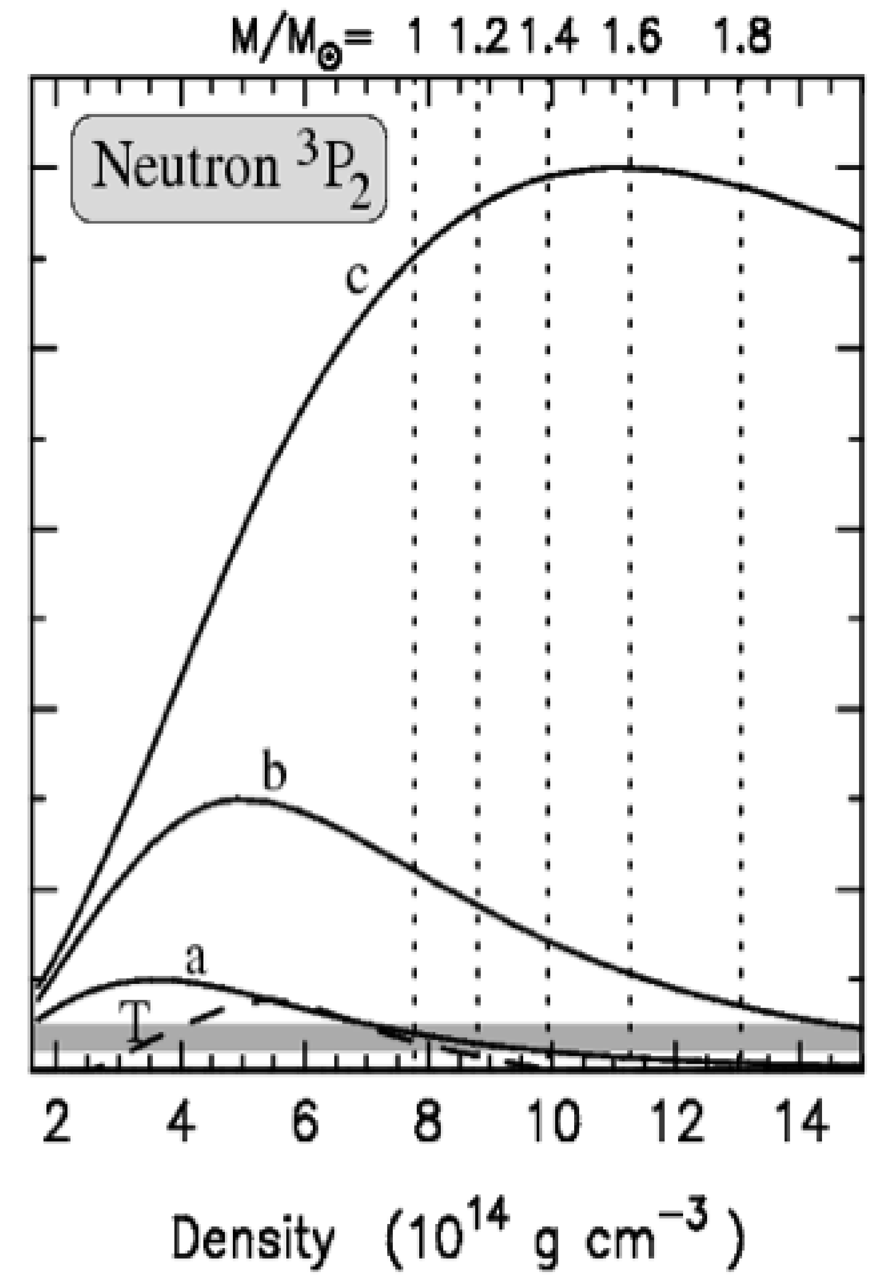
Page, et al (2009)

Using Thermal Emission to Constrain Dense Matter

- Minimal model has only neutrons and protons and no direct Urca, but includes all emissivites for neutrons and protons
- Current observations make very stringent constraints on the neutron $^3P_2$ gap

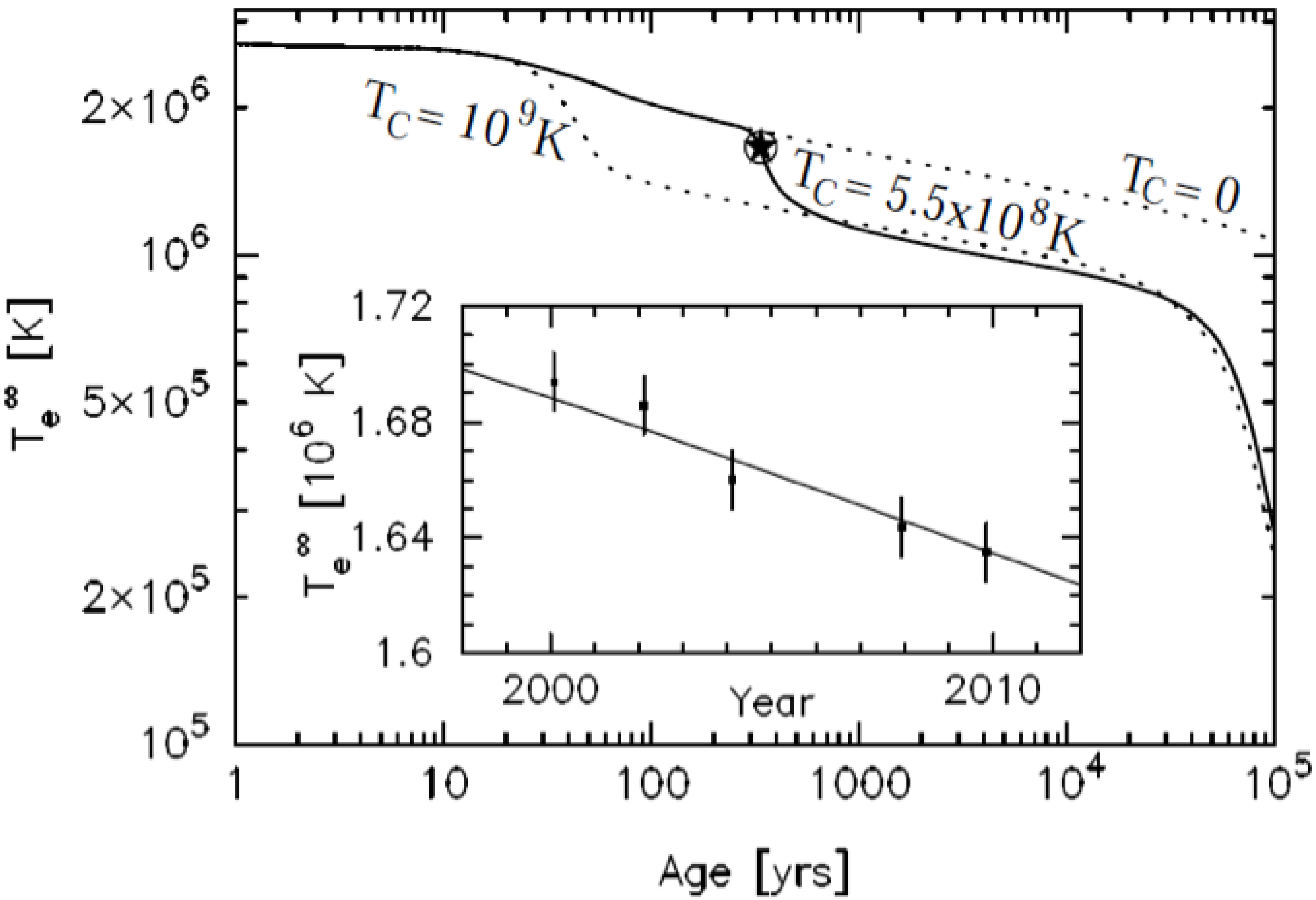


Page et al. (2009), see also Yakovlev et al. and Blaschke et al.



Neutron Star in Cas A

- The large slope is only well reproduced by the neutron triplet superfluid transition and associated PBF emissivity
- Cas A requires a very particular triplet gap

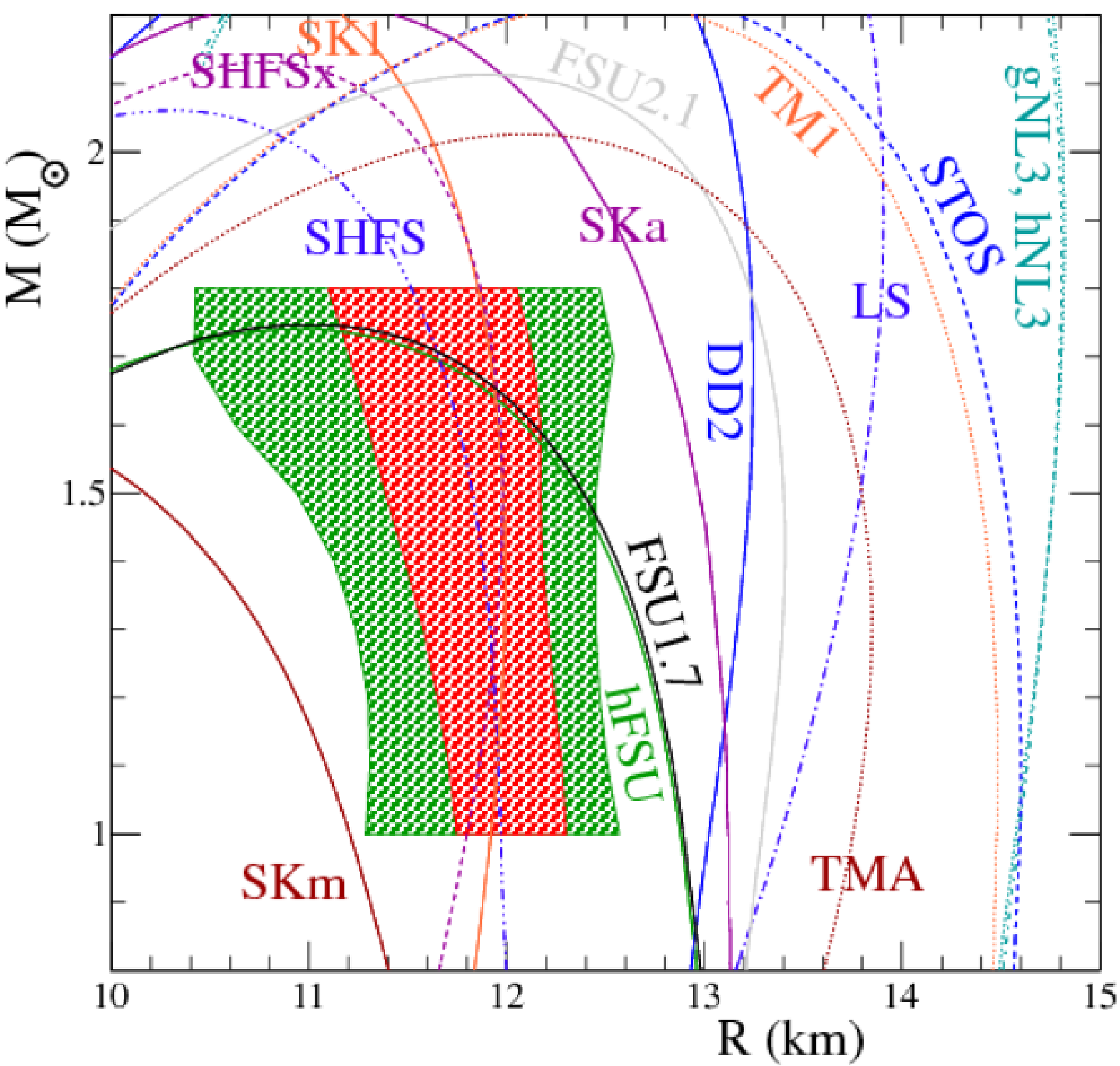


Page, et al. (2011)

Dense Matter from Supernovae

- Historically: EOSs with large compressibilities generated robust explosions!
- Time to black hole formation is a signal of phase transition (Gentile et al. 1993, Nakazato et al. 2008)
- Smaller symmetry energies form more compact NSs, giving larger ν luminosities (Sumiyoshi et al. 1995)
- Protoneutron star metastability (Prakash et al. 1997, Pons et al. 2001): Phase transition gives delayed collapse
- Quark degrees of freedom can impact neutrino signal (Sagert et al. 2009)
- and more!

Masses and Radii Implied by Supernova EOSs



New Supernova EOSs

- Two new supernova EOSs
- RMF mean field model
- Nuclei determined by Hartree calculations for EOS fit

Quantity	Experiment	Baseline	Extreme
K (MeV)	210-250	245	239
n_0 (fm^{-3})	0.155-0.165	0.158	0.160
$-E_B$ (MeV)	15-17	16.2	16.1
$E_{\rm sym}$ (MeV)	28-36?	31.6	28.8
$E_{\rm Pb-208}$ (MeV)	7.87	7.81	7.79
$R_{\rm Pb-208}$ (fm)	5.50	5.44	5.43
$E_{\rm Zr-90}$ (MeV)	8.71	8.64	8.57
$R_{\rm Zr-90}$ (fm)	4.27	4.19	4.20

Status of Matter at High Densities

- Quark matter is neither required nor ruled out
- Neither is absolutely stable quark matter
- Two solar mass neutron star is a problem for hyperons! (see poster by Miyatsu)
- Hyperons + quarks?
- $n - n - \Lambda$ interactions?

Summary

- *Current* mass and radius measurements, modulo some systematic uncertainties, can *quantitatively* constrain the equation of state of dense matter
- Several currently used EOSs are ruled out
- Current results imply all neutron stars have radii between 10.4 and 12.9 km
- Isolated neutron star cooling is giving us information about dense matter
- Supernova EOSs need updating!

The Issue of the Photosphere Radius

- Dimensionless parameter

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