Searching for nucleons and quarks in dense matter

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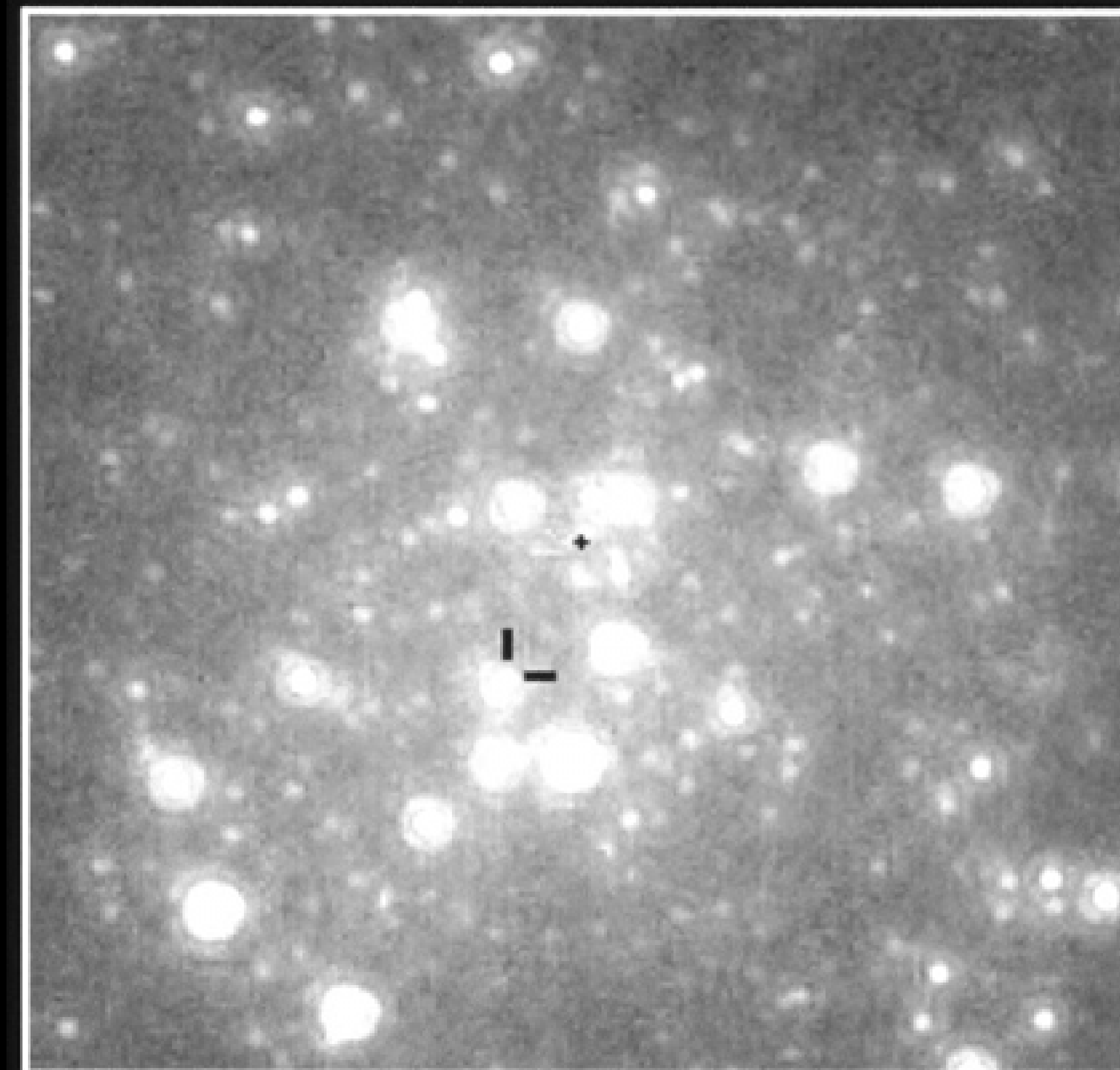


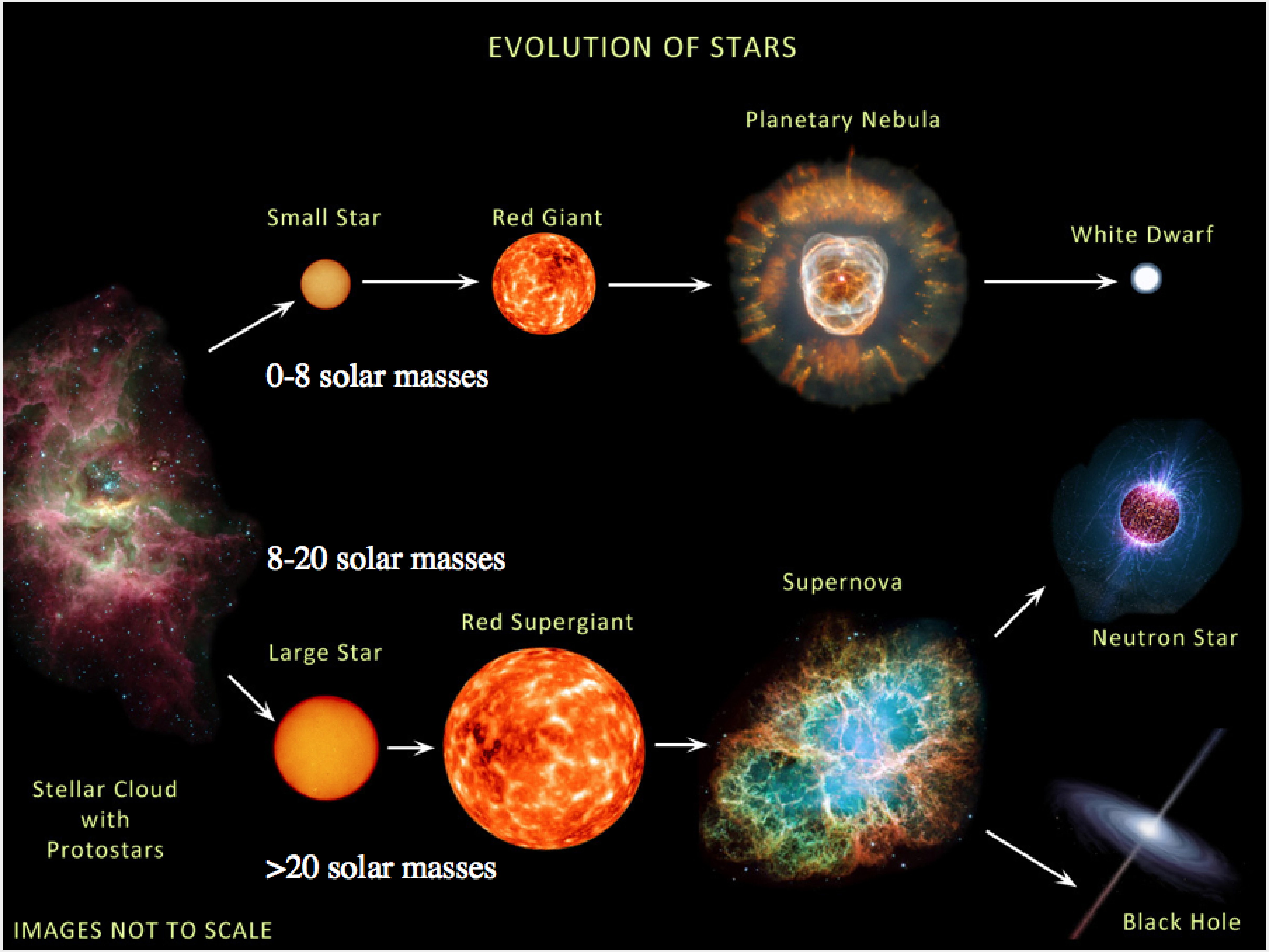
HST observation of 4U 1820-30

With: Edward F. Brown (Michigan State Univ.),
Stefano Gandolfi (Los Alamos), James M. Lattimer (Stony Brook Univ.),
Dany Page (UNAM), Madappa Prakash (Ohio Univ.), and Sanjay Reddy (INT)

Outline

- Neutron structure and the EOS of dense matter
- Neutron star cooling, neutrino emission
- Cassiopeia A

Stellar Evolution and Neutron Stars



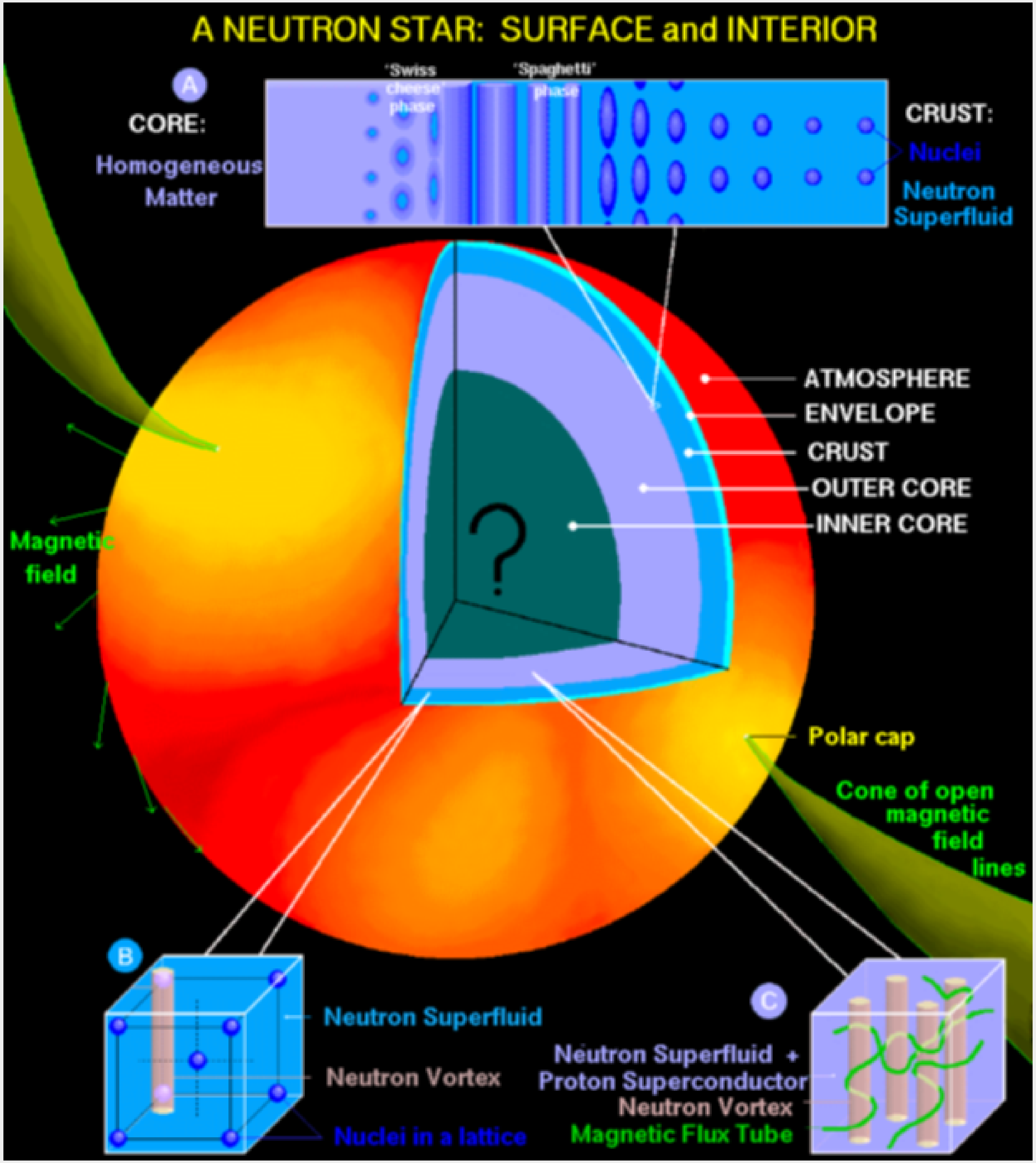
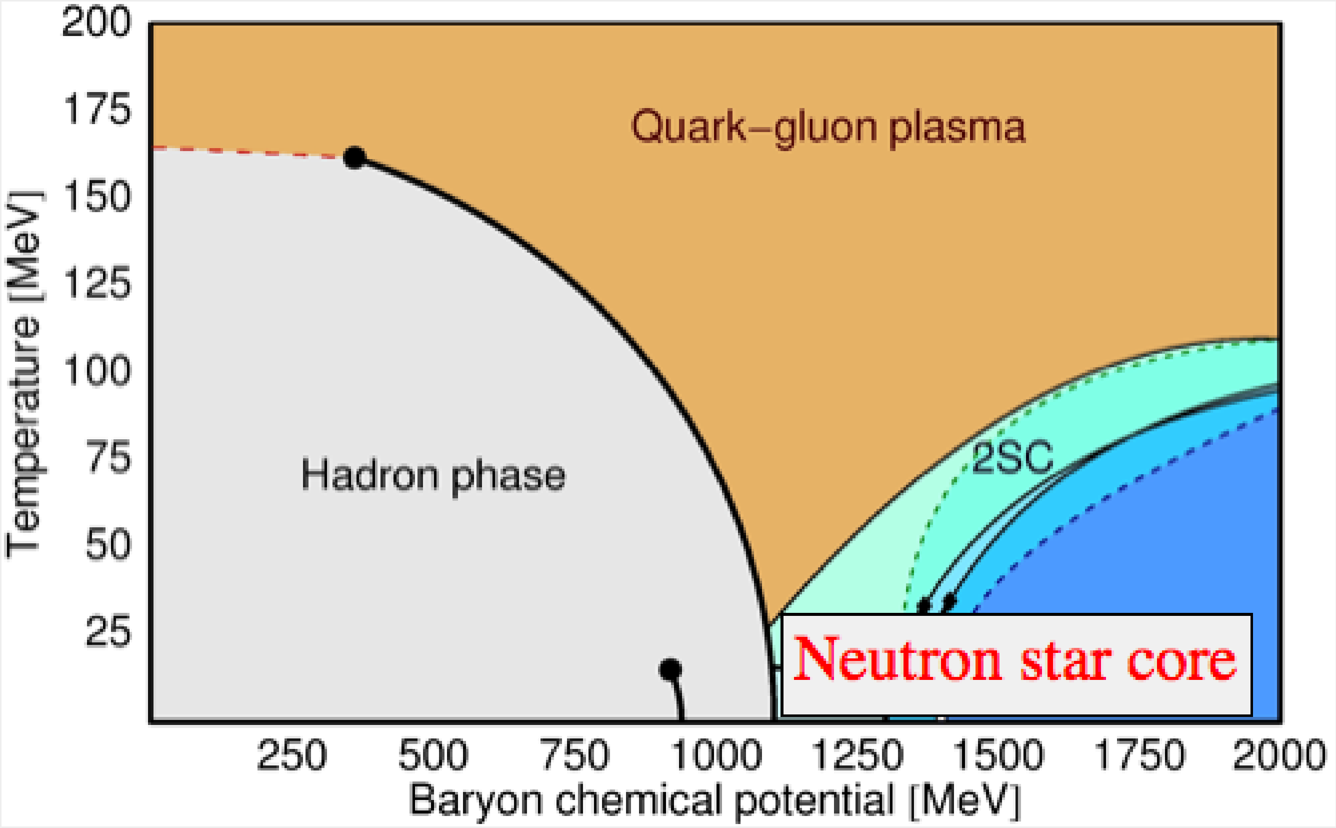


Figure by Dany Page

Neutron Star Composition

- Outer crust is nuclei + degenerate electrons
- Crust is a lattice of neutron-rich nuclei
- Outer core is a fluid with neutrons, protons and electrons
- Inner core is a mystery $\Lambda, \Sigma, \Xi, \pi, K, u, d, s$?

Quantum Chromodynamics Phase Diagram



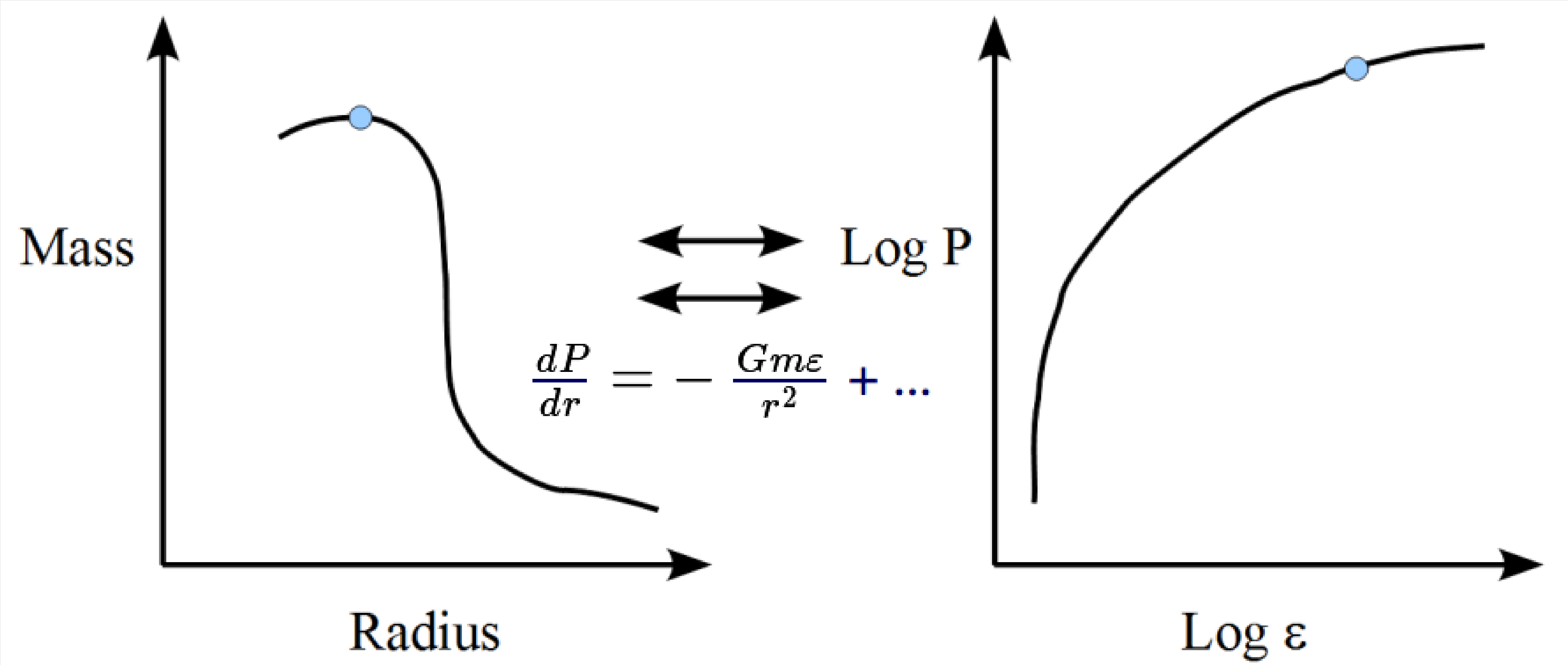
Adapted from Rüster, et al. (2005)

- Dense hadronic matter and dense quark matter have the same underlying symmetries
  Schäfer and Wilczek, "Continuity of Quark and Hadron Matter" (1999)
  Isgur, Jeschonnek, Melnitchouk, Van Orden "Quark-Hadron Duality in Structure Functions" (2001)

- High-density effective theory in quark or hadron degrees of freedom?

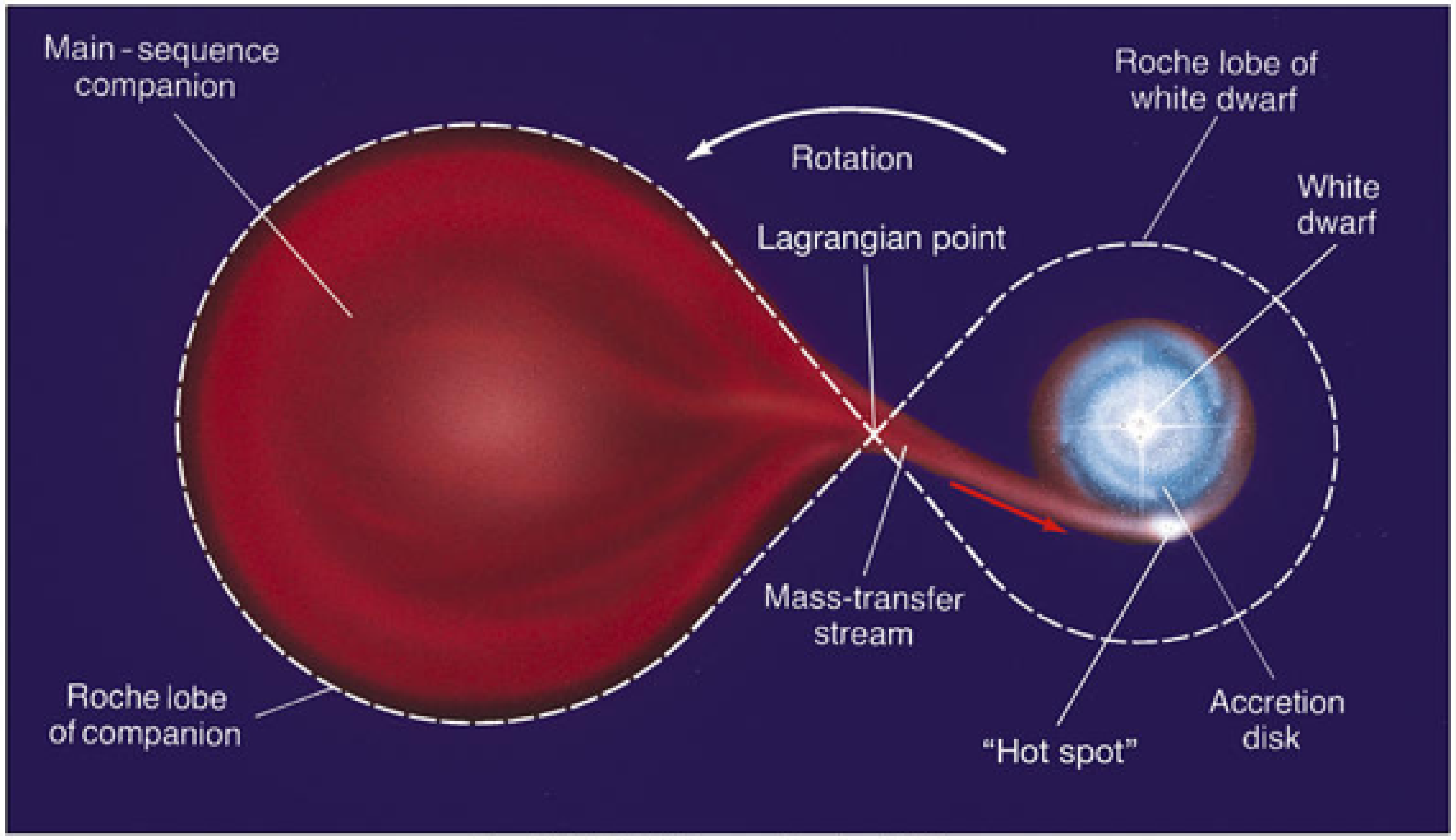
- Neutron stars naturally probe the high-density, low-temperature part of the QCD phase diagram

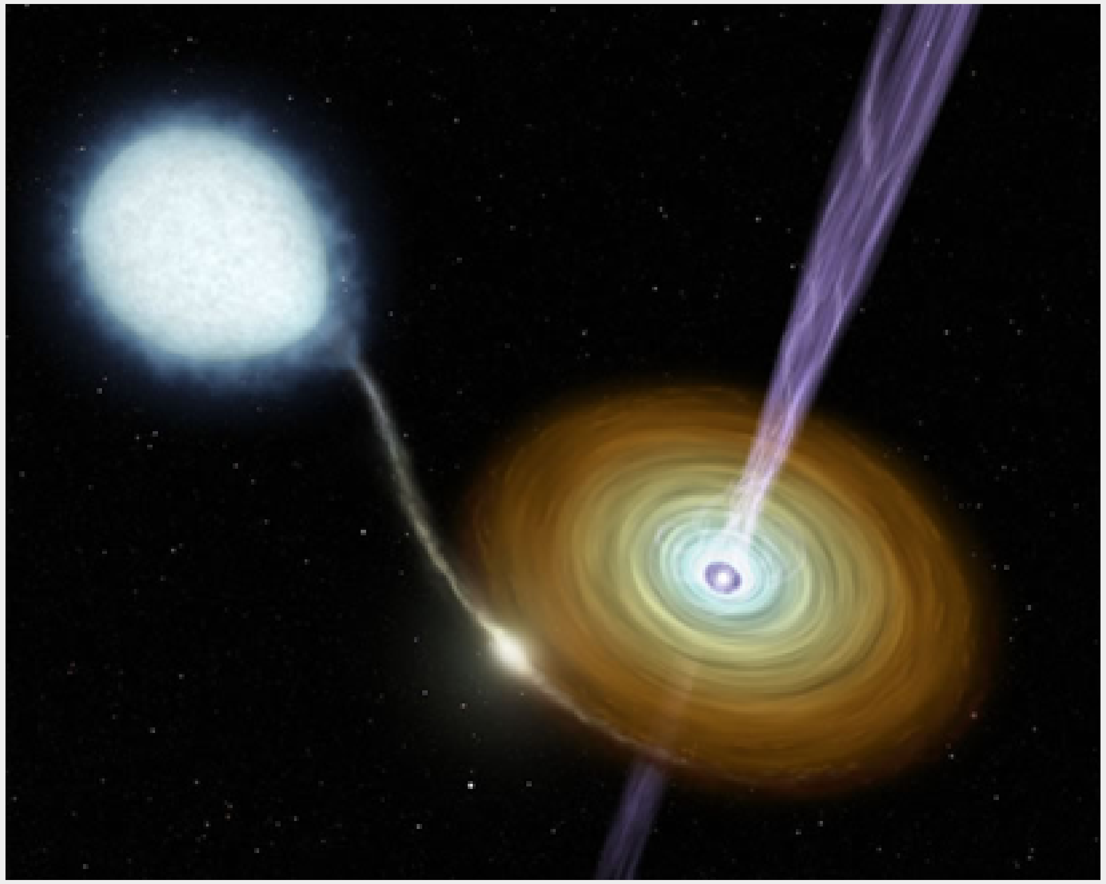
Masses, Radii, and Equations of State



- Unlike planets, neutron stars are uniform
- Neutron stars (to a good approximation) all lie on one *universal* mass-radius curve
- Recent measurement of a two solar mass neutron star
  Demorest et al. (2010)
- Until recently, neutron star radii constrained to 8-15 km

Accreting Neutron Stars: LMXBs





- Most stars have companions: neutron stars can have main-sequence ("normal star") companions
- Stellar matter accretes onto the neutron star surface and heats the crust
- Accretion is episodic

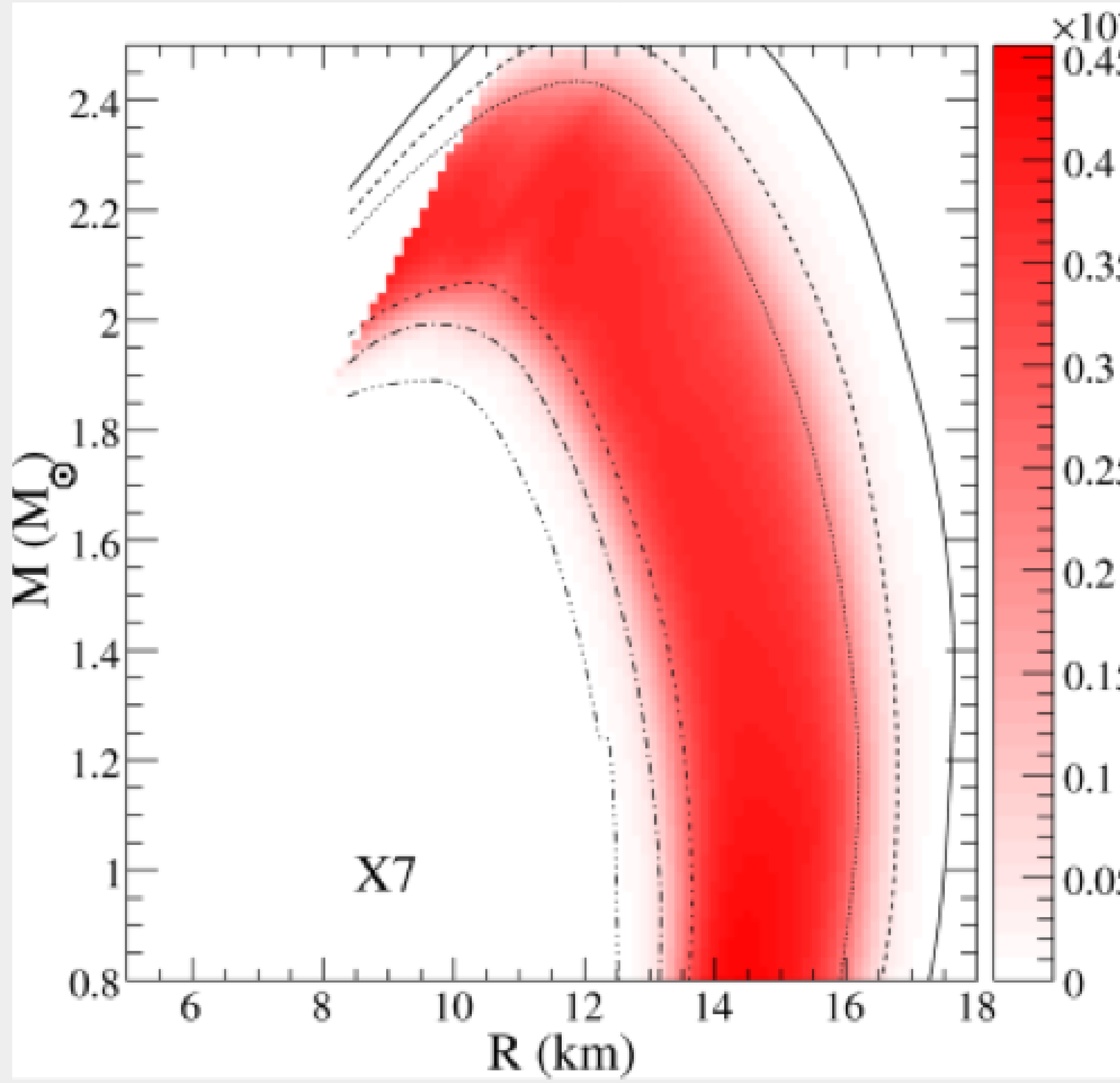
Neutron Star Radius Measurements

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

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

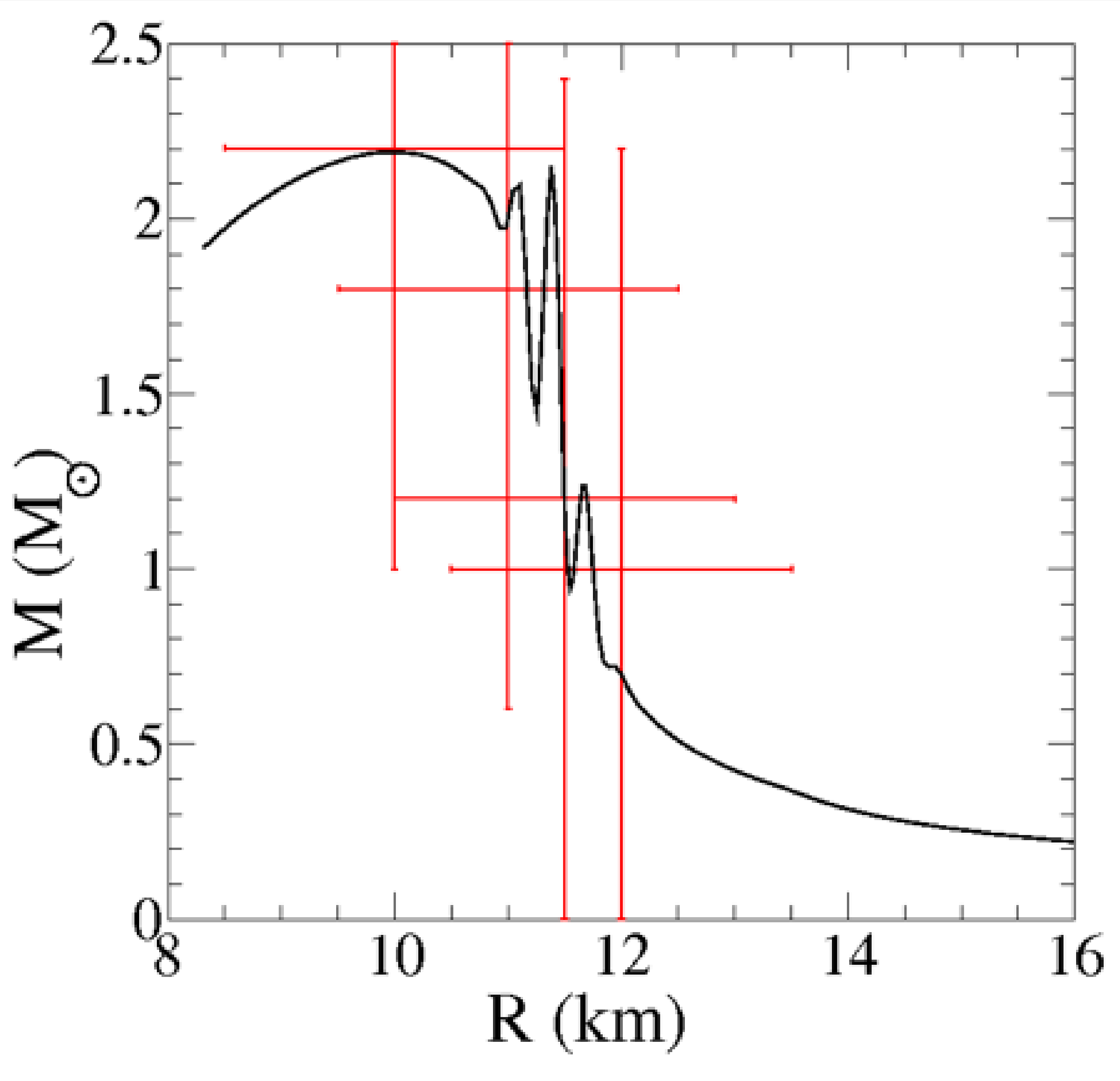
[i.e. Rutledge et al. (1999)]

- ~ 8 objects (more on the way)



Steiner, Lattimer, and Brown (2010)

Data Analysis - Bayesian Methods

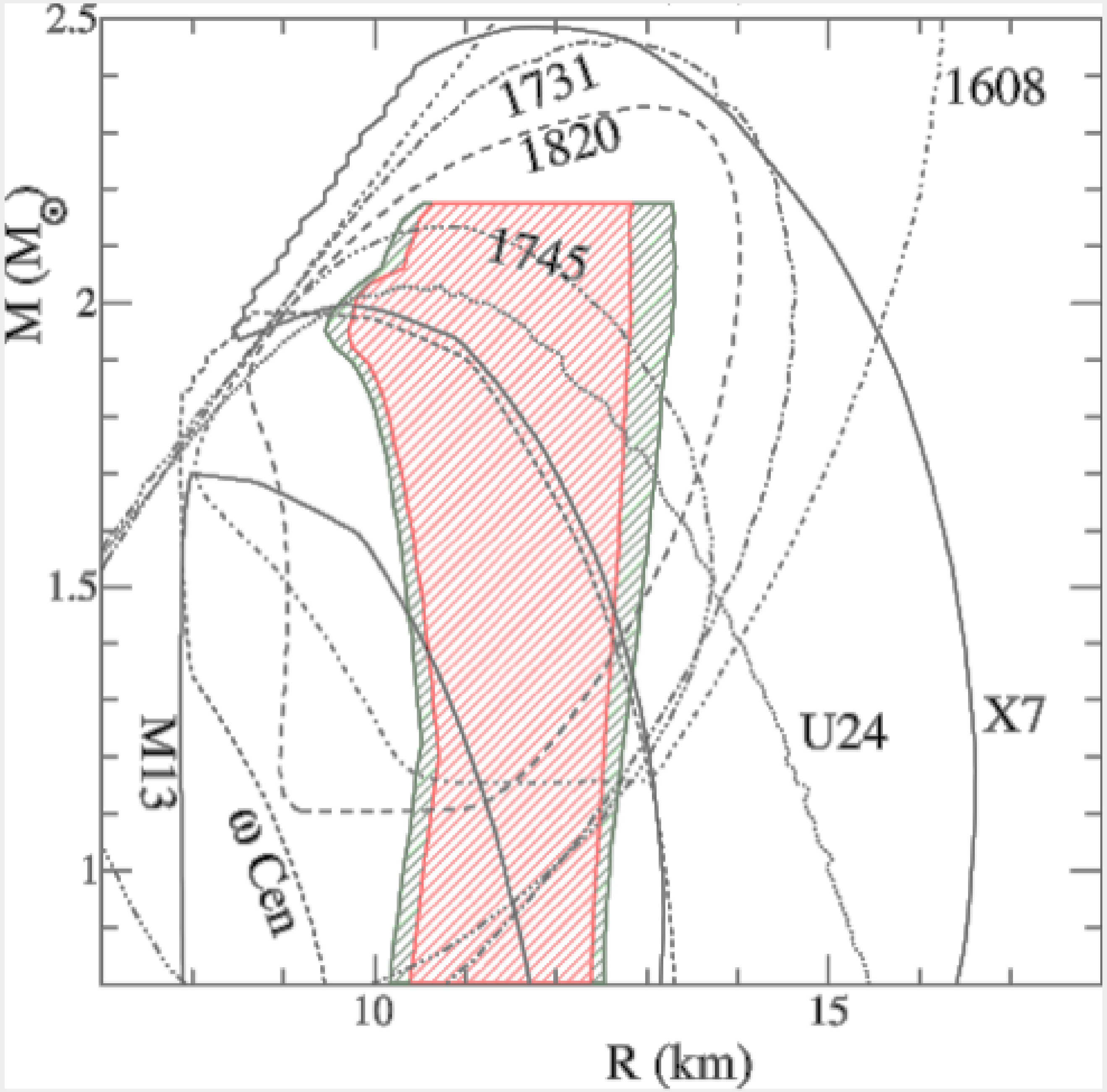


- Underconstrained problem
- Bayes theorem:

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

- Natural way to include theoretical input
- Parameterizations based on known nuclear physics for low densities

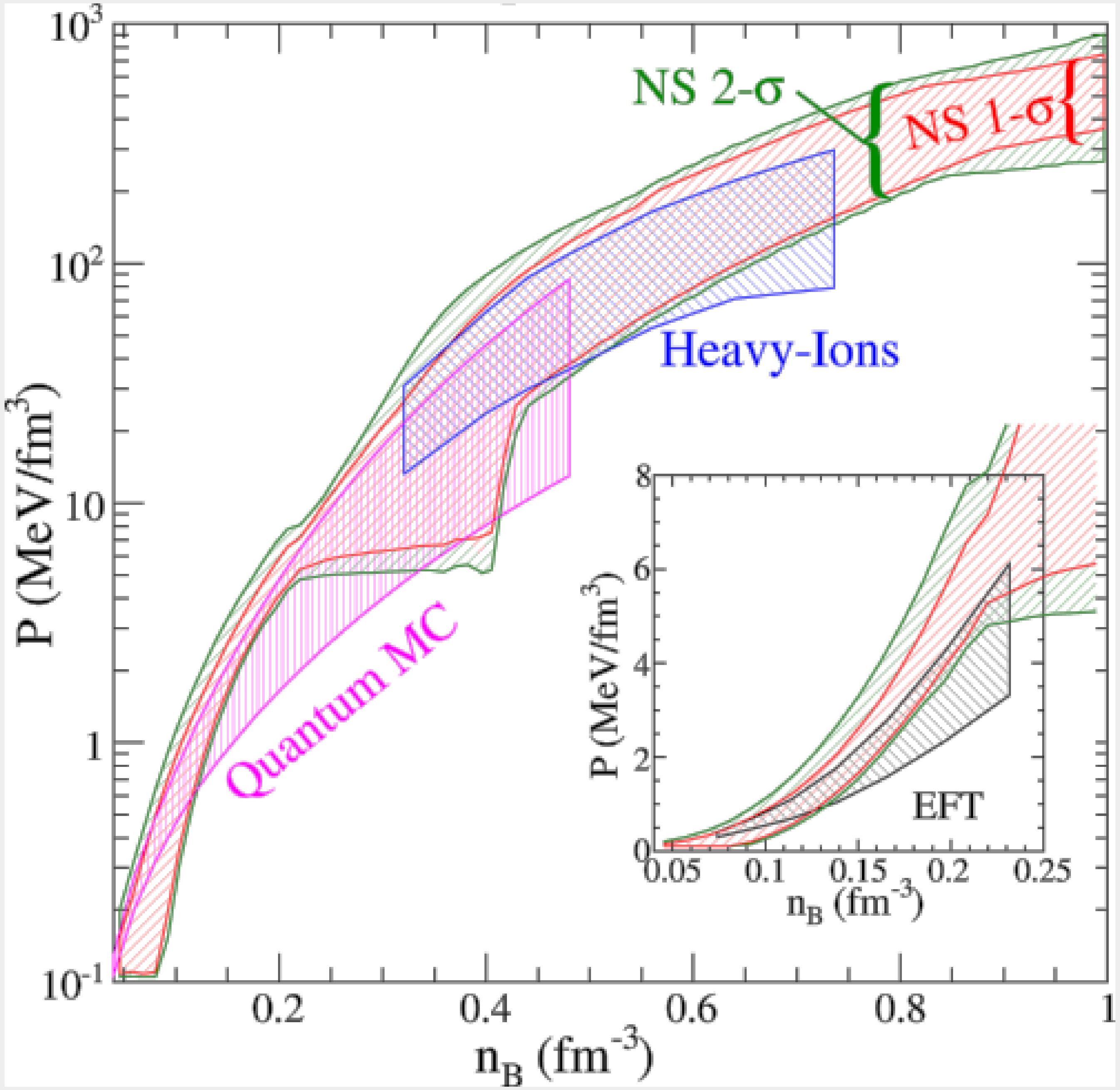
Mass and Radius Results

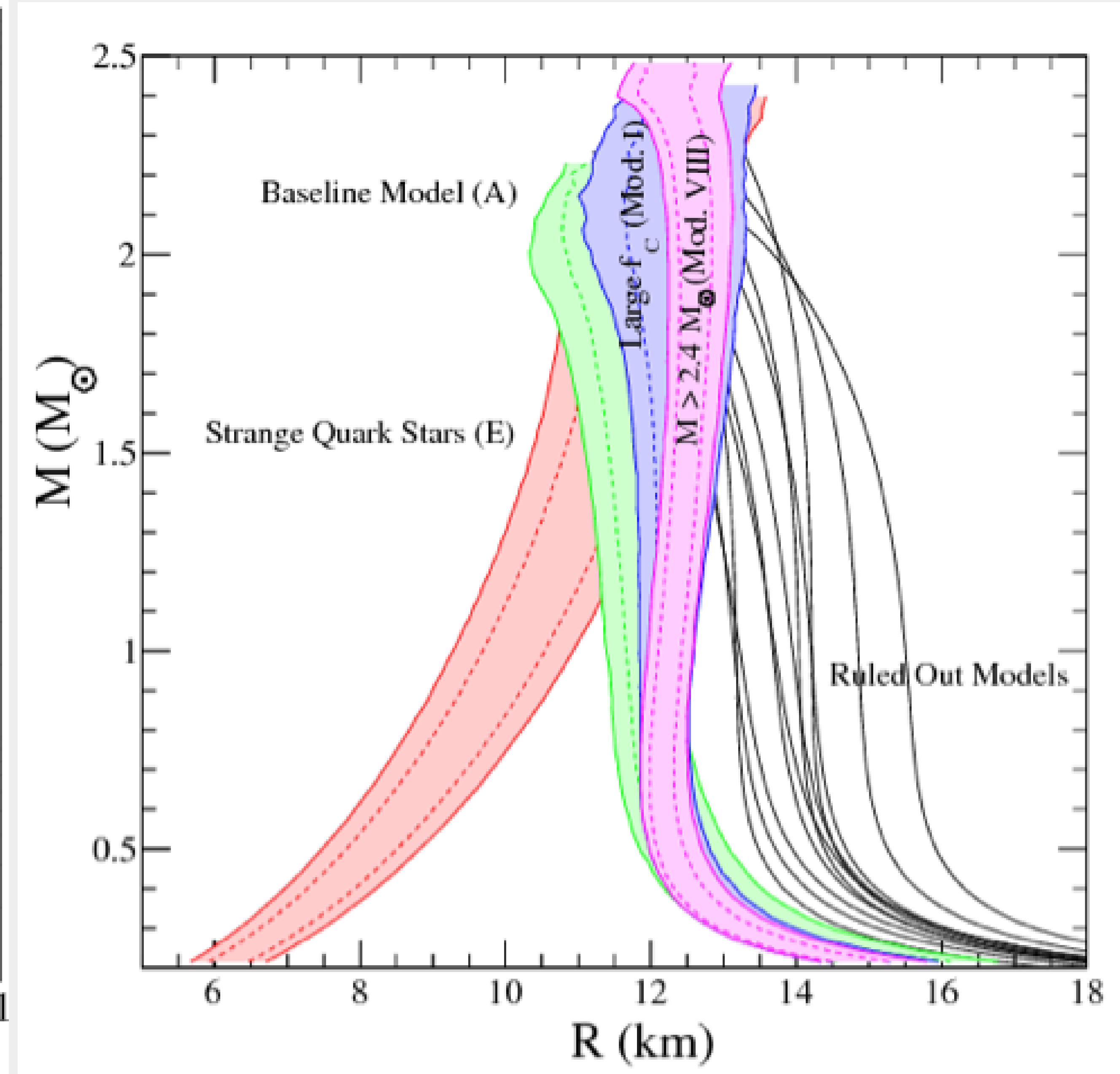


Steiner, Lattimer, and Brown (2013)

- 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

Constraining the EOS of dense matter

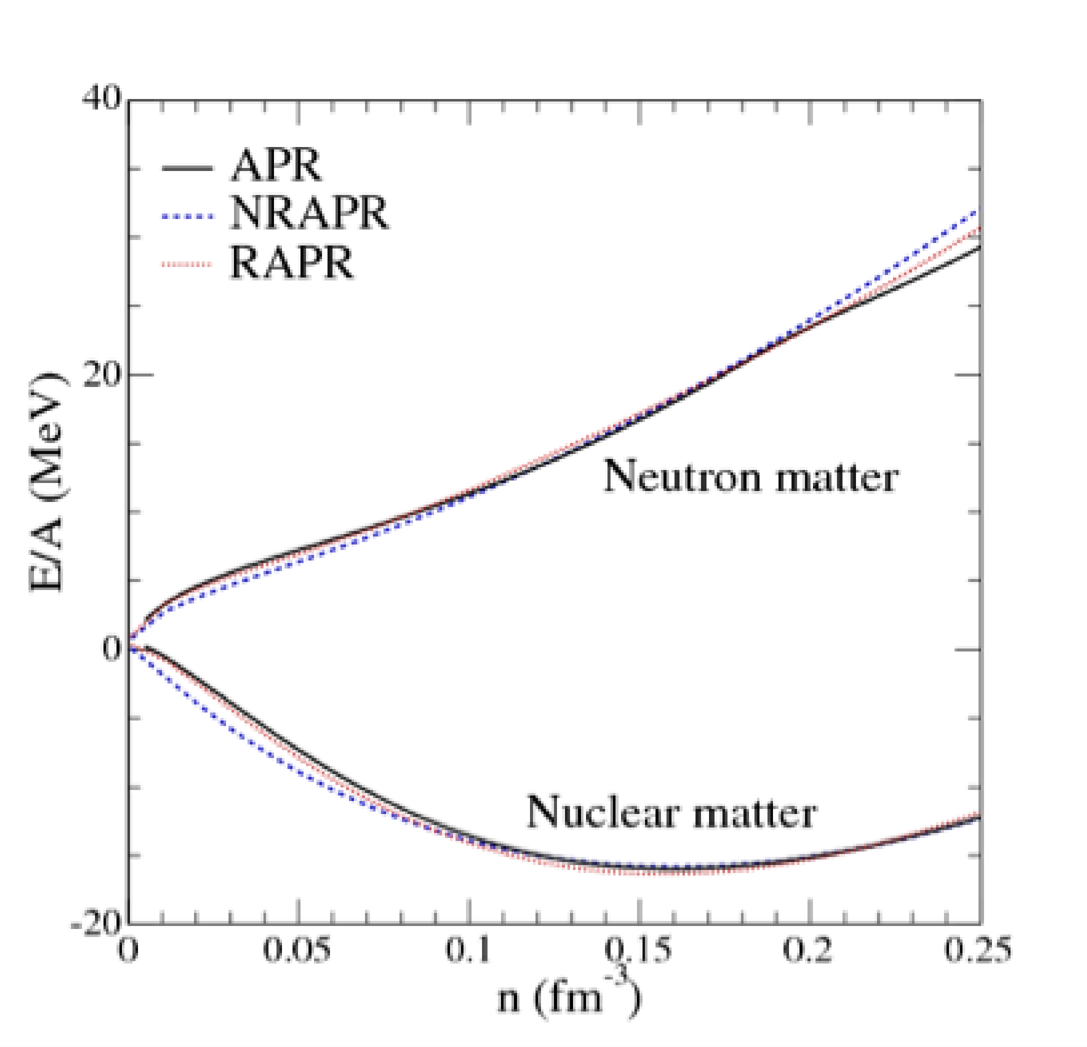


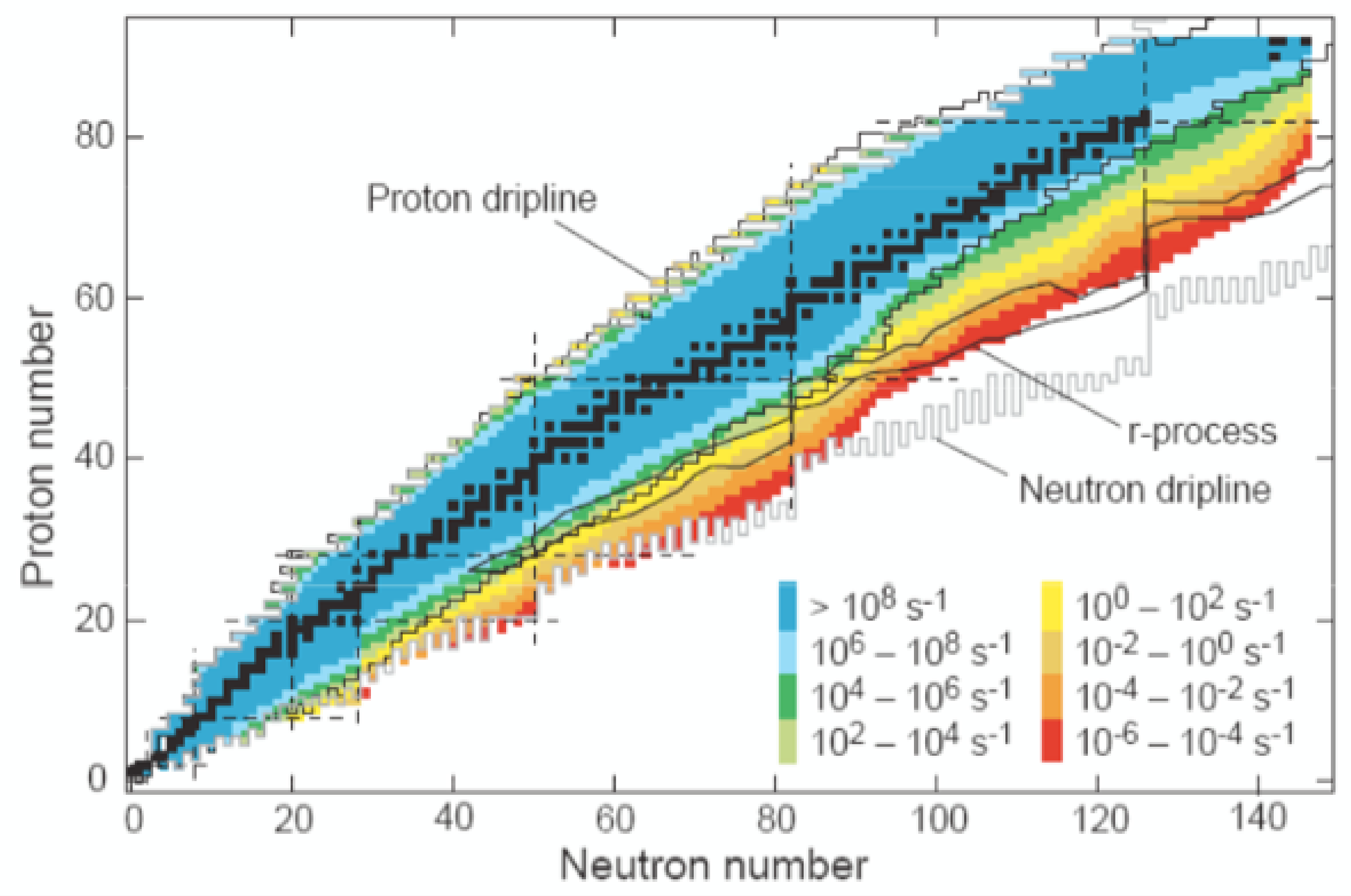


Steiner, Lattimer, and Brown (2013)

- $P(\varepsilon)$ determined to within about 60%
- Probe densities inaccessible to experiment and to perturbation theory in QCD
- We cannot yet determine the composition of the core

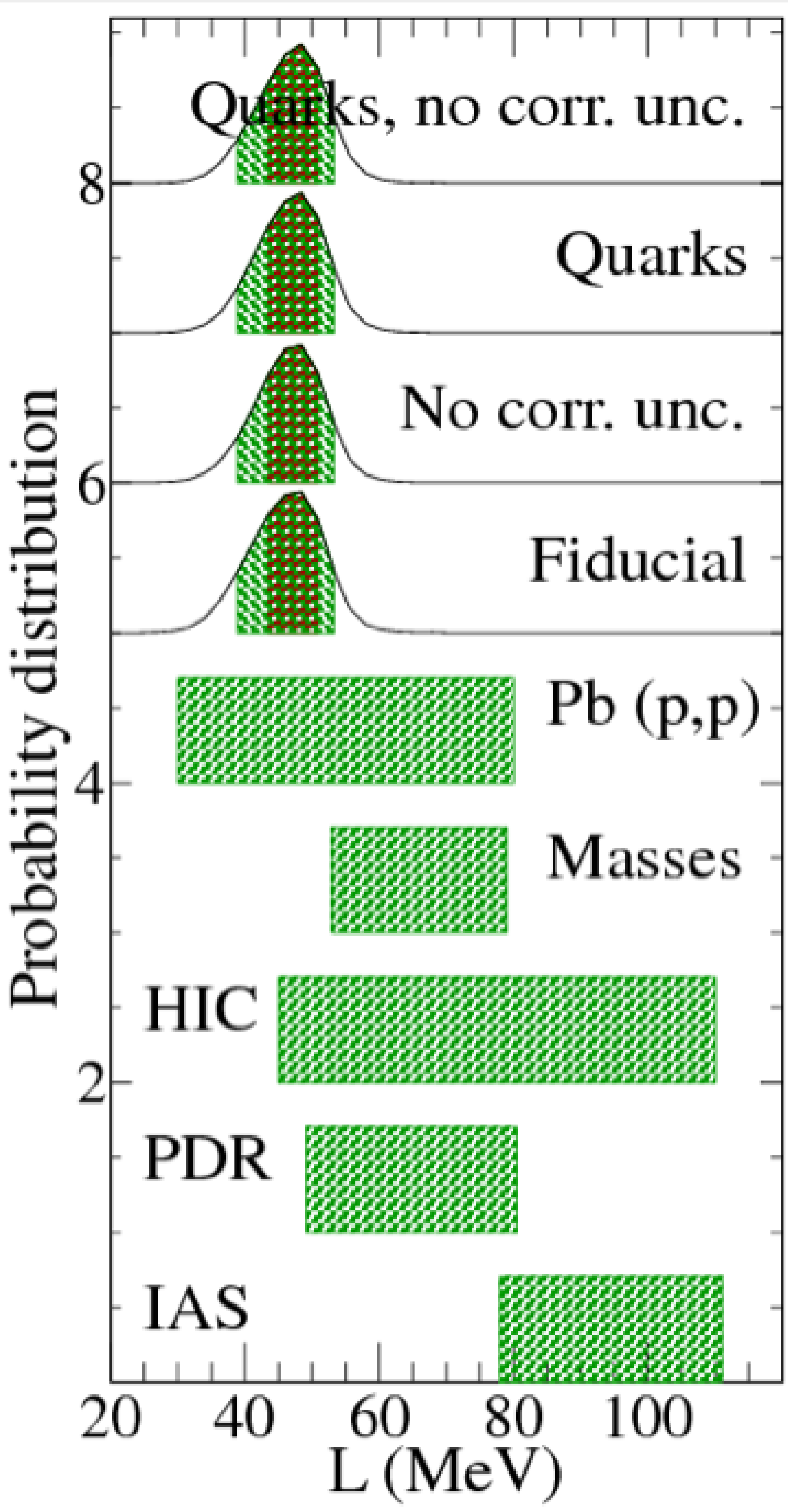
Chart of Nuclei and the Nuclear Symmetry Energy





- QCD prefers equal numbers of neutrons and protons
- The symmetry energy is the energy cost to a system with more neutrons than protons
- The origin of the 'valley of stability'
- S is the value at the nuclear saturation density $S = S(n_0)$
- L is the derivative, $L = 3n_0 S'(n_0)$

Constraints on the Symmetry Energy



Anti-protonic atoms

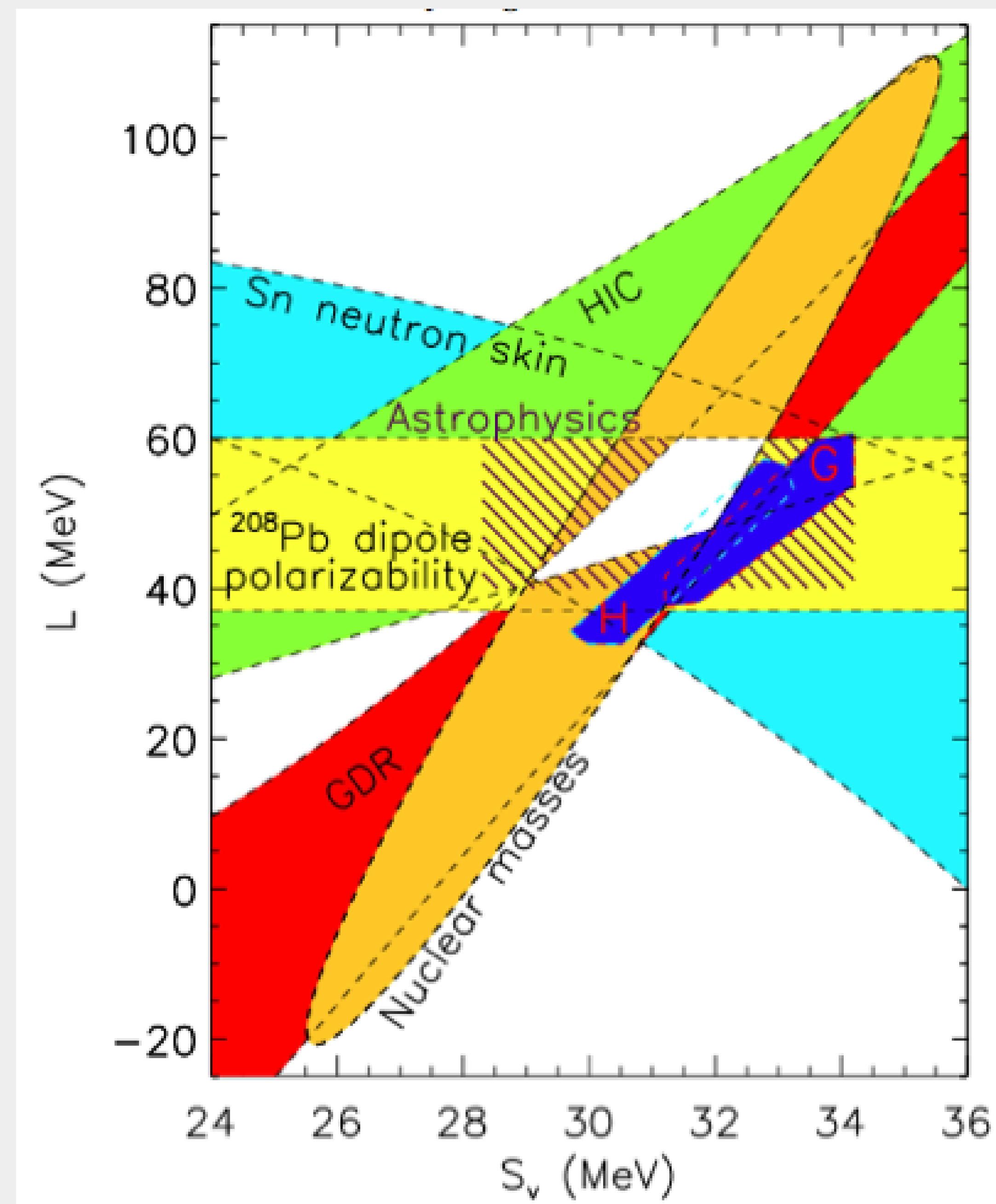
Nuclear masses

Heavy-ion collisions

Pygmy dipole resonances

Isobaric analog states

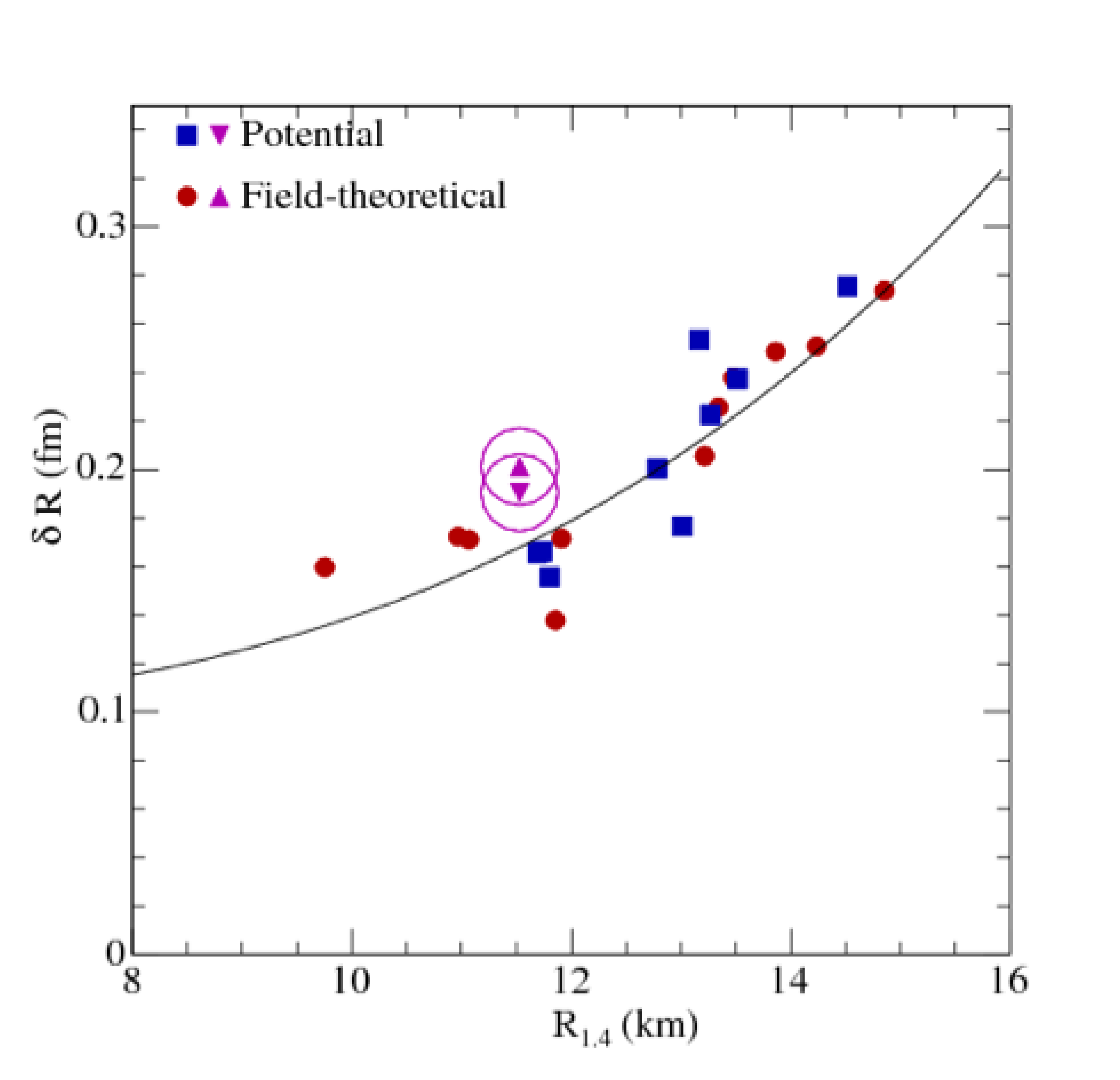
Steiner and Gandolfi (2012)



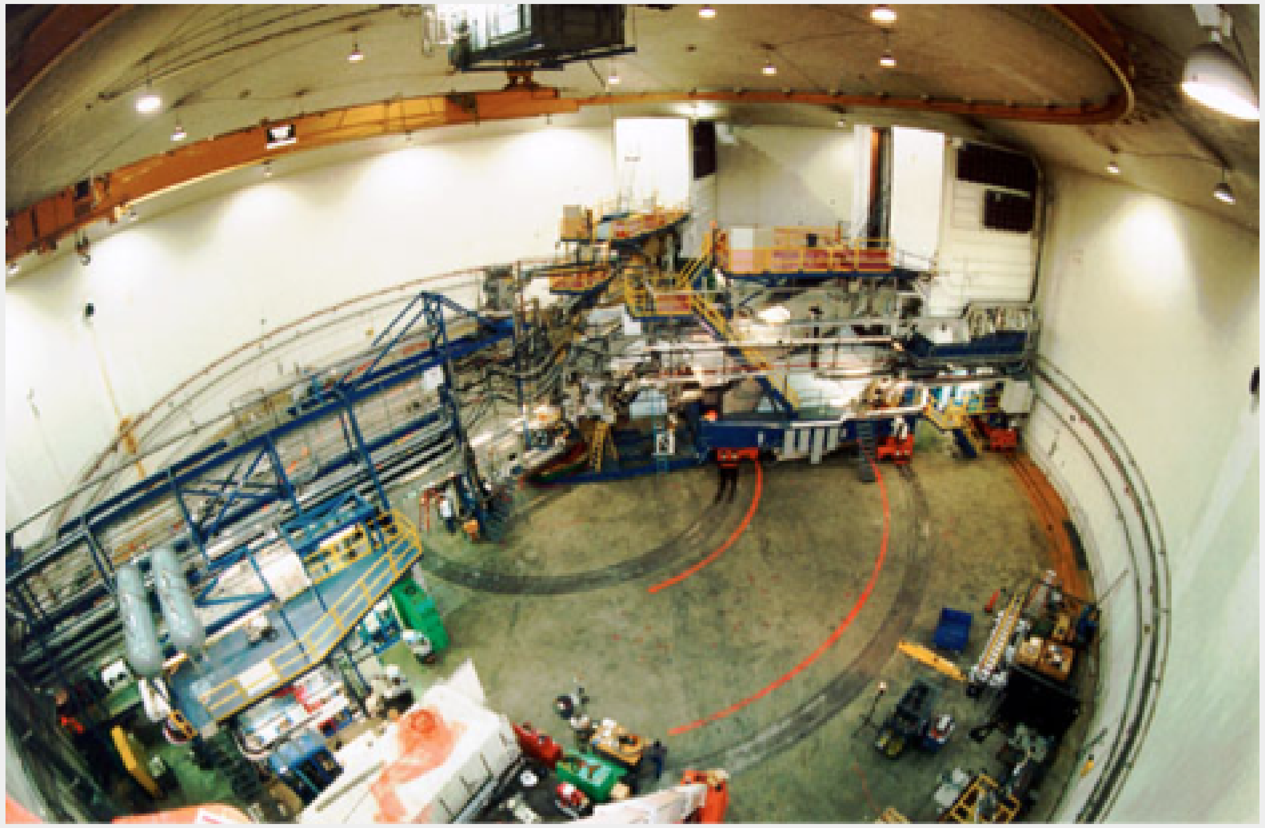
Lattimer and Lim (2012)

The Neutron Skin Thickness of Lead

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



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



Jefferson Lab's Hall A: Measuring R_n

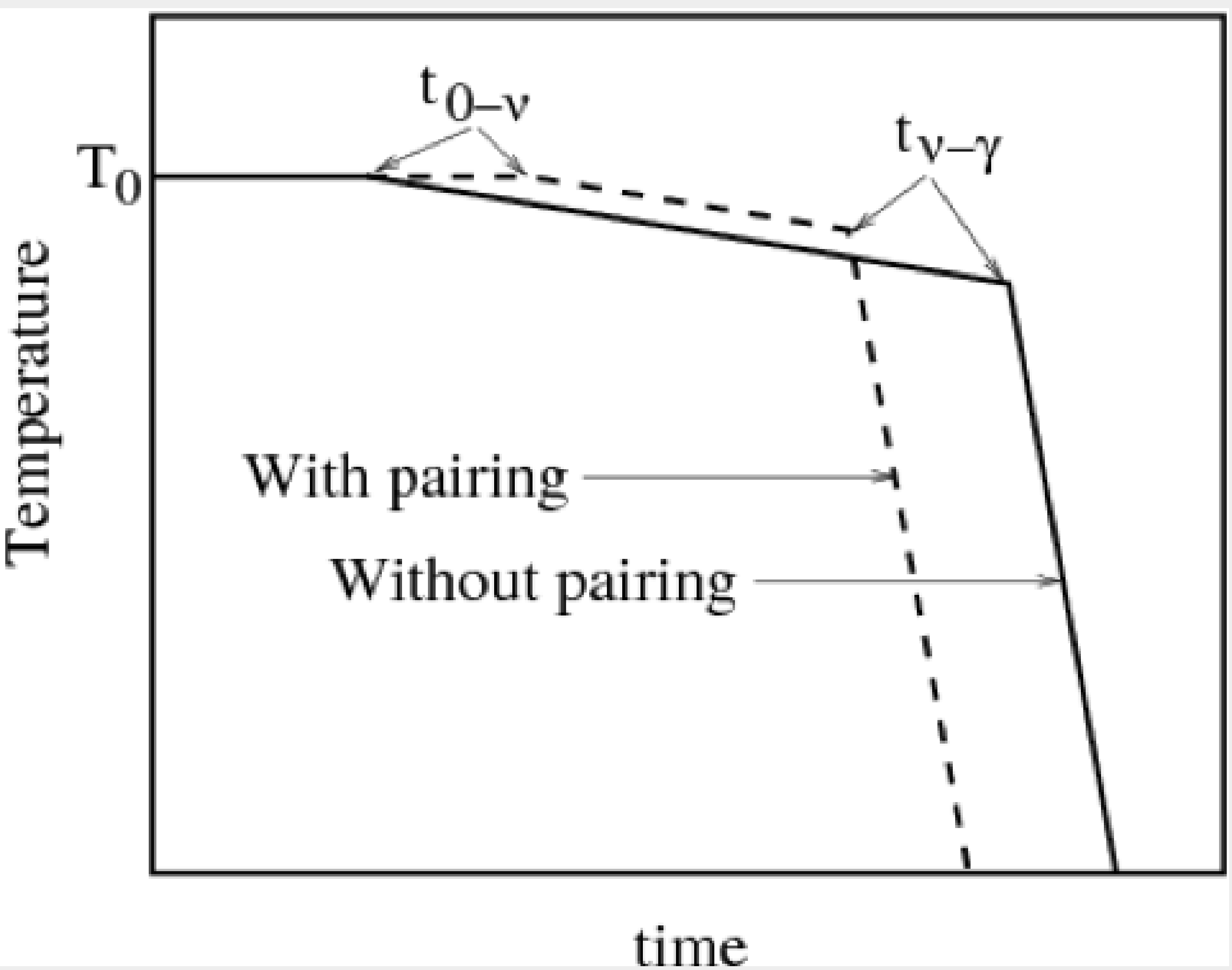
- We find $\delta R < 0.2$ fm from neutron star observations

Thermal Emission from Isolated Neutron Stars

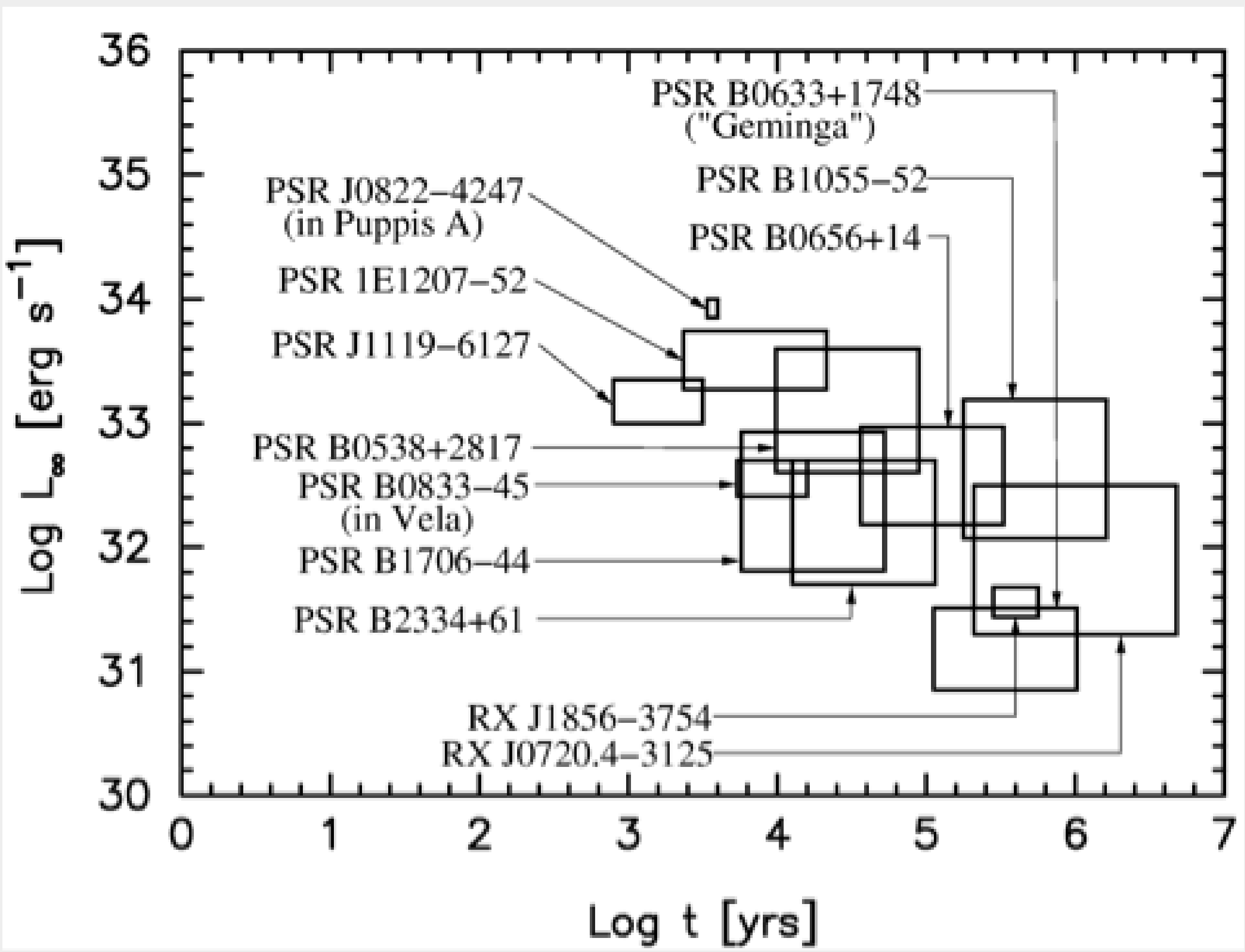
- No distance measurement required
- Requires a model of the NS atmosphere to associate the observed spectrum with a luminosity or temperature

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

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



Page, et al (2004)



Page, et al (2009)

The direct Urca process

- Neutron Star cooling processes

  - Direct Urca: $n \to p + e + \bar{\nu}$,
    $Q \sim T^6$

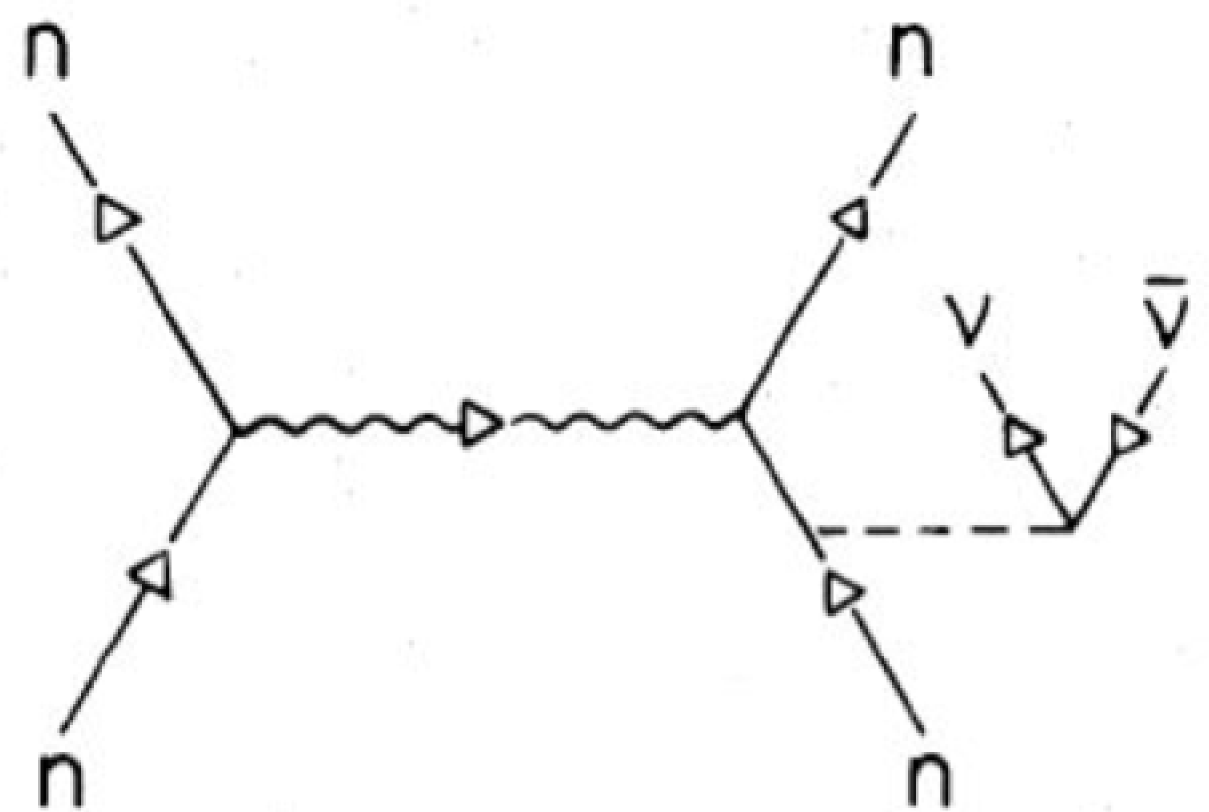
  - Modified Urca cooling: $n + n \to n + p + e + \bar{\nu}$,
    $Q \sim T^8$

- Direct Urca requires a large enough proton Fermi momentum

- Thus also connected to the symmetry energy

- Also quark and hyperon direct Urca processes

Neutrino emission in the dense medium



Friman & Maxwell (1979)

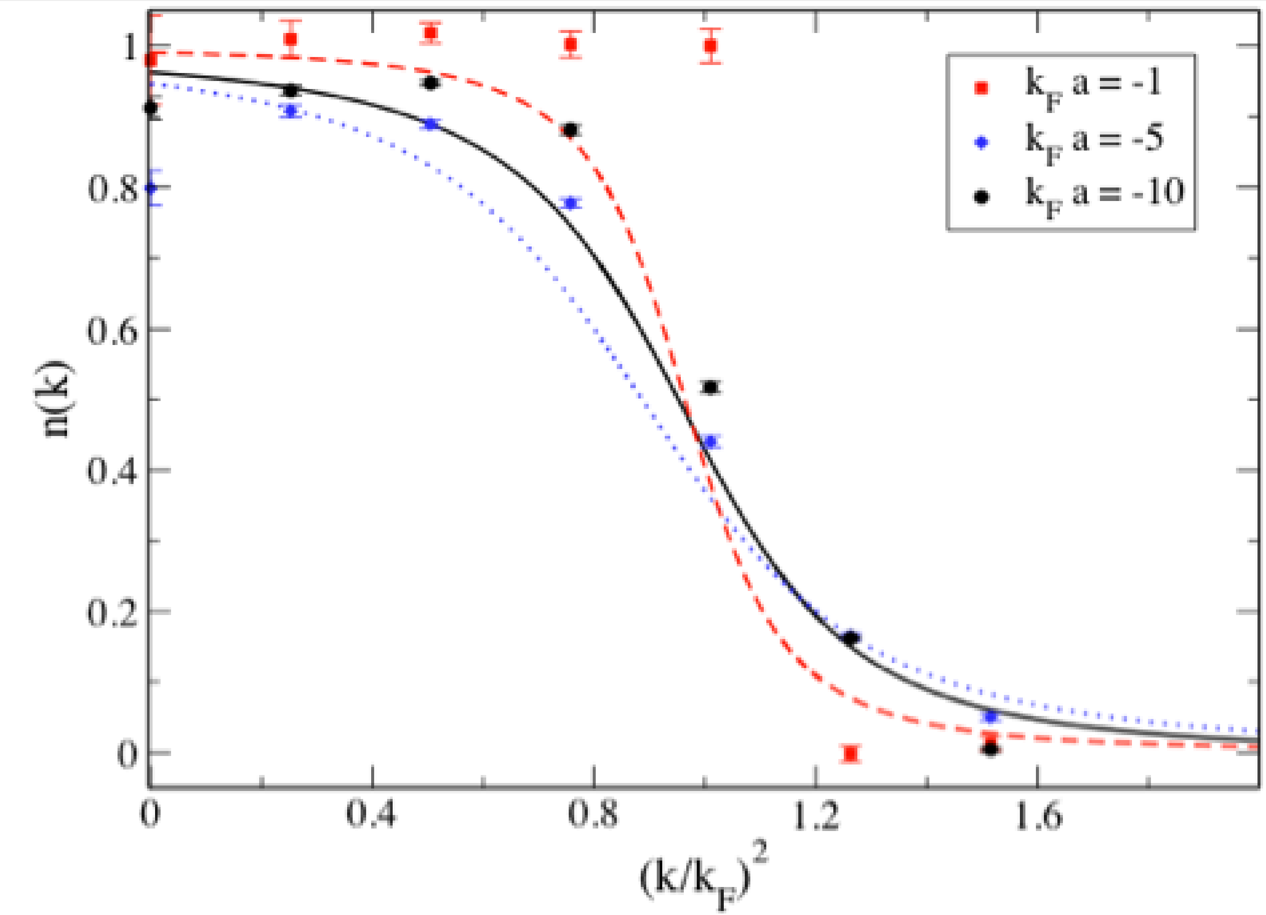


FIG. 8: (color online) The neutron-matter momentum distribution in QMC versus $(k/k_F)^2$ at $k_F a = -1$ (squares), $k_F a = -5$ (diamonds), and $k_F a = -10$ (circles). Also shown are the continuum BCS results at $k_F a = -1$ (dashed line), $k_F a = -5$ (dotted line), and $k_F a = -10$ (solid line).

- $\frac{1}{V}\frac{d^3\sigma}{d^2\Omega dE_3} = -\frac{G_F^2}{32\pi^2}\frac{E_3}{E_1}\left[1-\exp\left(\frac{-q_0}{T}\right)\right]^{-1}\left[1-f_3(E_3)\right]\mathrm{Im}\left(L^{\alpha\beta}\Pi^{\mathrm{RPA}}_{\alpha\beta}\right)$
- Short-range correlations in the distribution can be handled with RPA + finite lifetime?
  Lykasov et al. (2005) and Roberts et al. (2012)
- We need density and spin response of dense matter

Quartic Terms in Nuclear Symmetry Energy

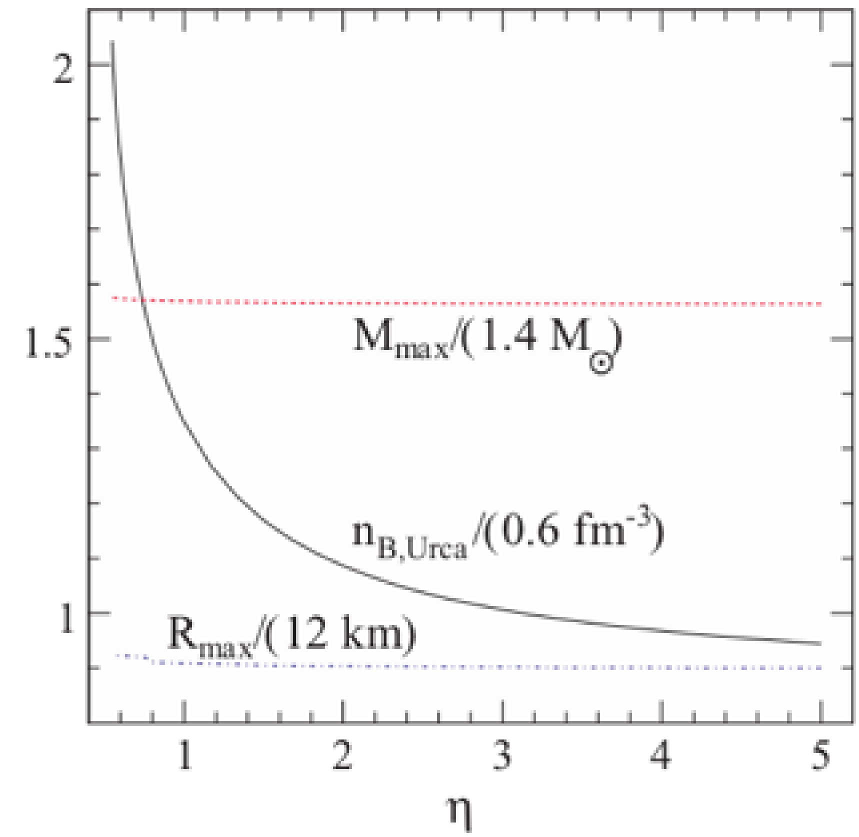
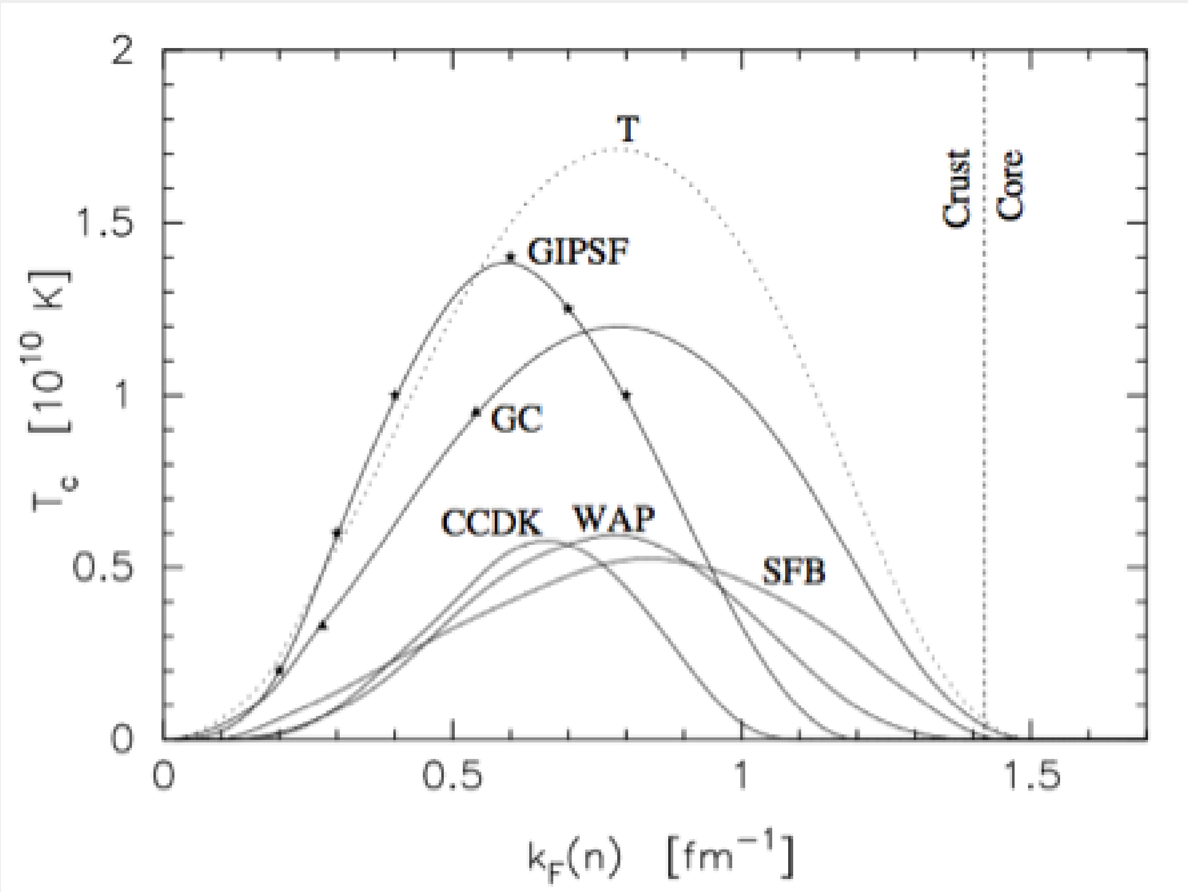


FIG. 3. (Color online) The critical density for the direct Urca process for the APR EOS as a function of η_{pot}. Points with $\eta_{pot} < 1/2$ were not plotted because the Urca process is not allowed at any density for this range of η.

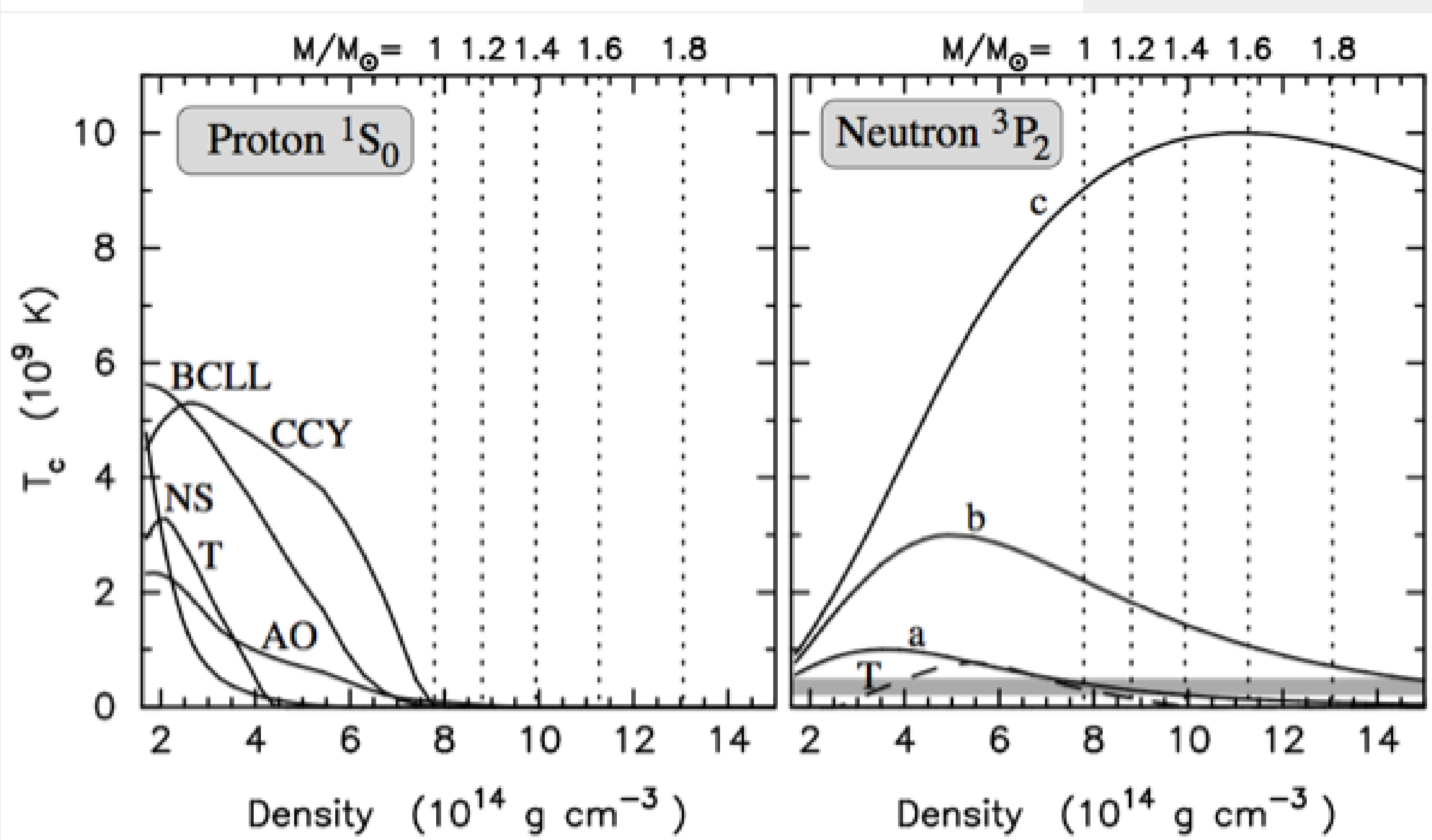
Steiner (2006)

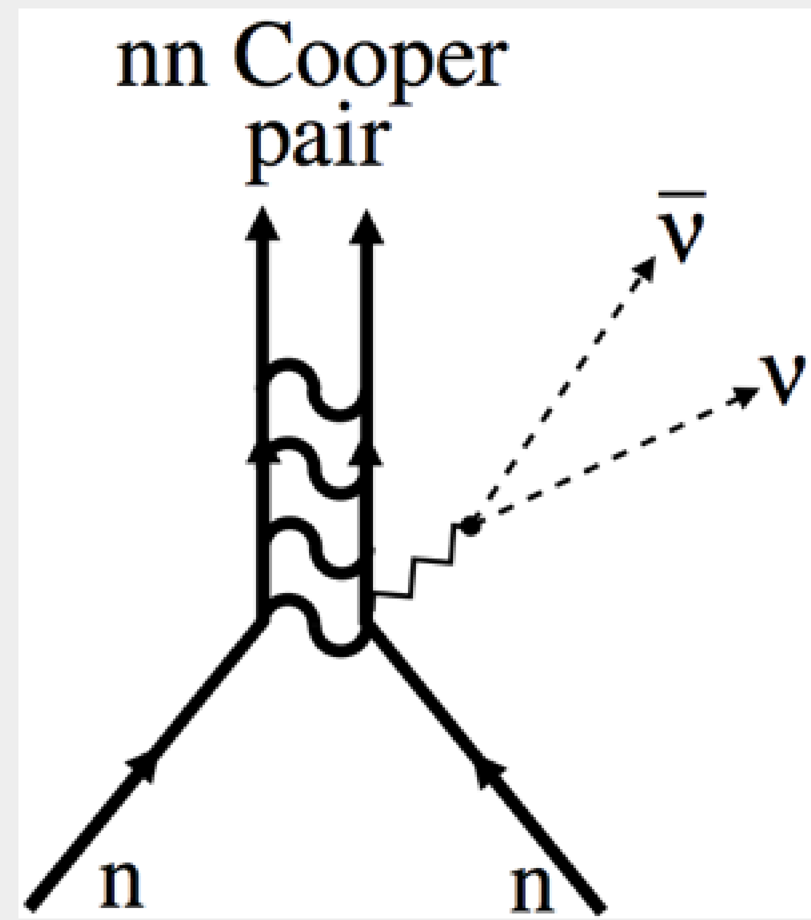
- Typically one assumes $E(n,x) = E_{\rm nuc}(n) + (1-2x)^2 S(n)$
- This works well at low density, but at high density: all bets are off
  $E(n,x) = E_{\rm nuc}(n) + (1-2x)^2 S(n) + S_4(n)(1-2x)^4$
- η related to strength of $S_4(n)$
- Can push around threshold for direct Urca

Neutron Star Superfluidity



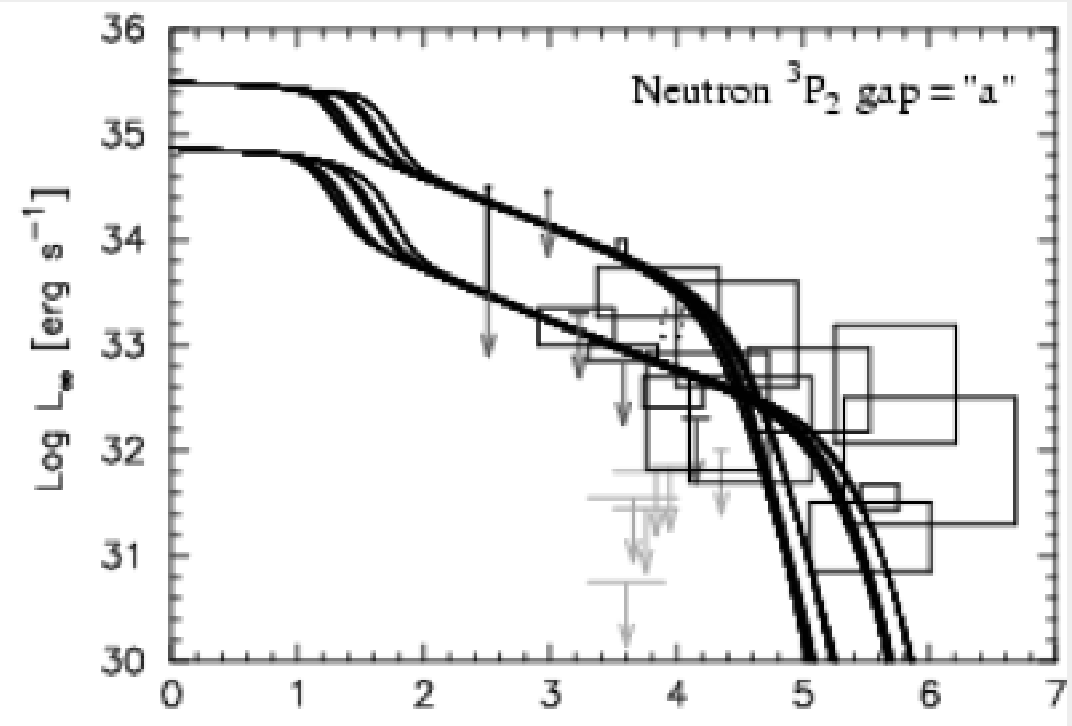
- Superfluidity can block the direct Urca process
- ...but it opens up new cooling processes



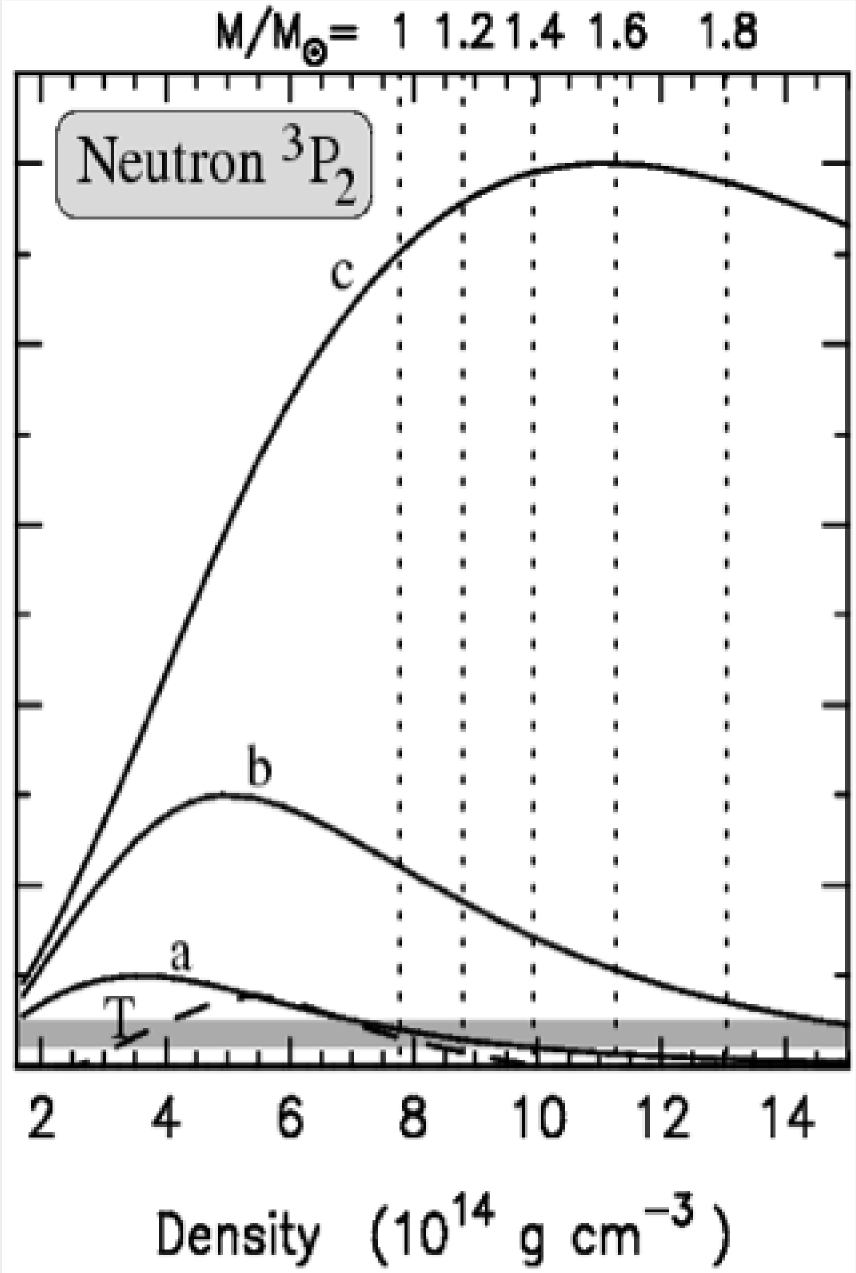


Using Thermal Emission to Constrain Dense Matter

- 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

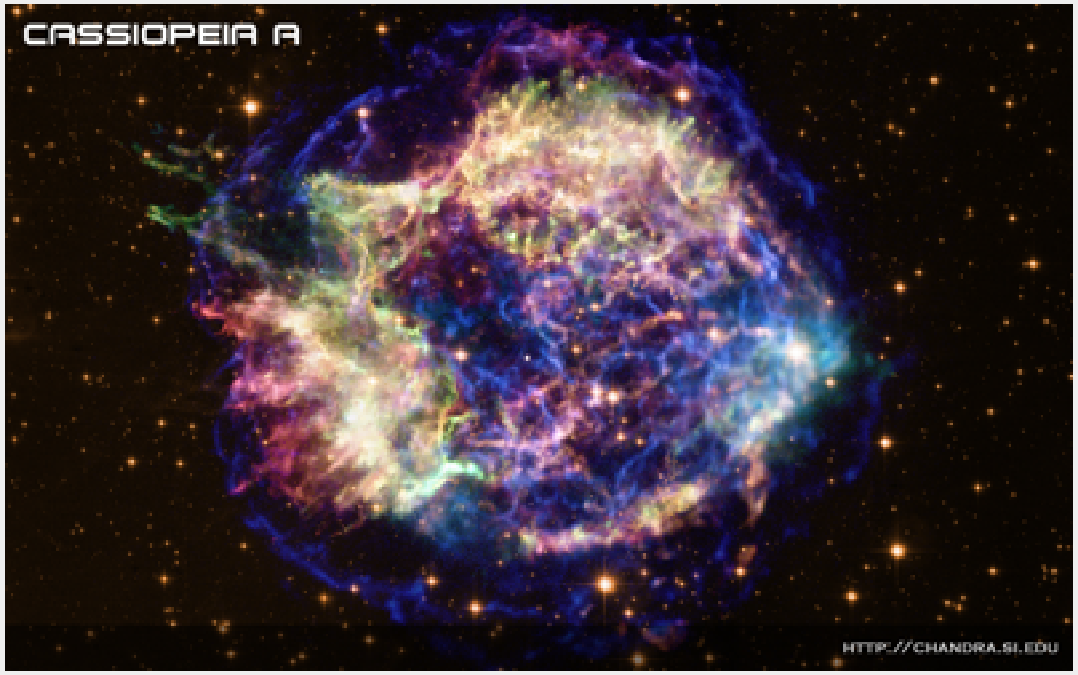


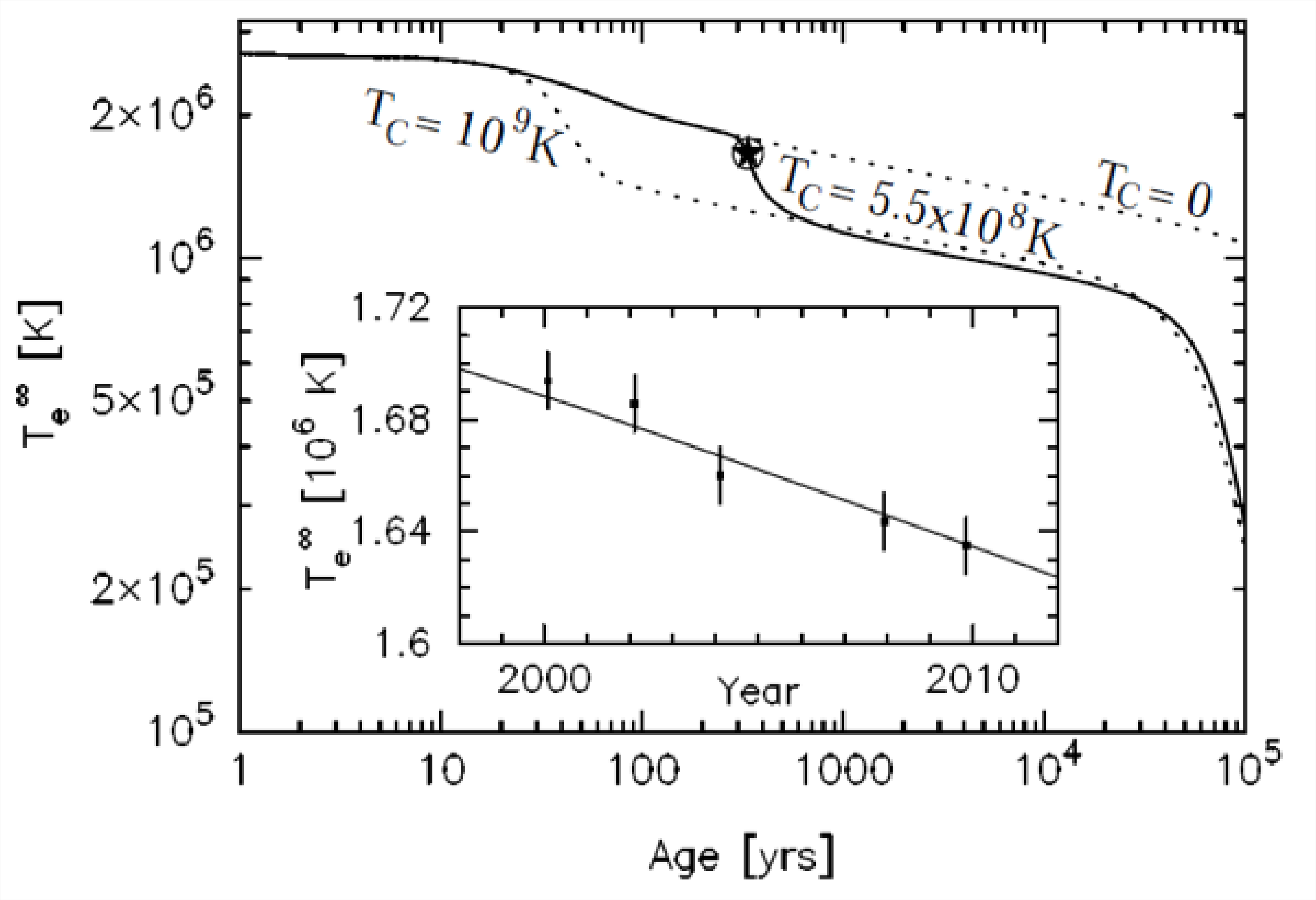
Page et al. (2009)



Detecting Neutron Star Superfluidity

- 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)

Summary

- All neutron star radii are between 10.4 and 12.9 km
- Novel constraints on the EOS and the nuclear symmetry energy
- Don't know the composition yet
- Data seems to require a particular triplet gap
- But may be more systematic uncertainties in dense matter?