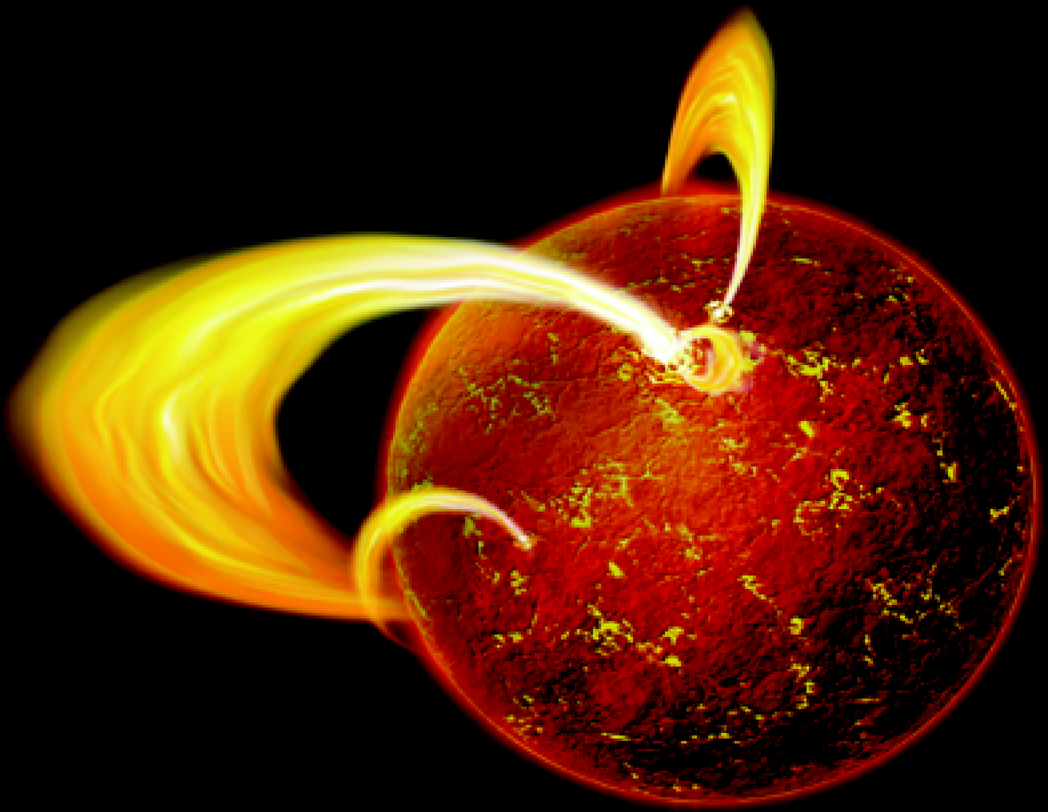
Using Neutron Star Observations to Constrain the Nuclear Symmetry Energy and the Equation of State



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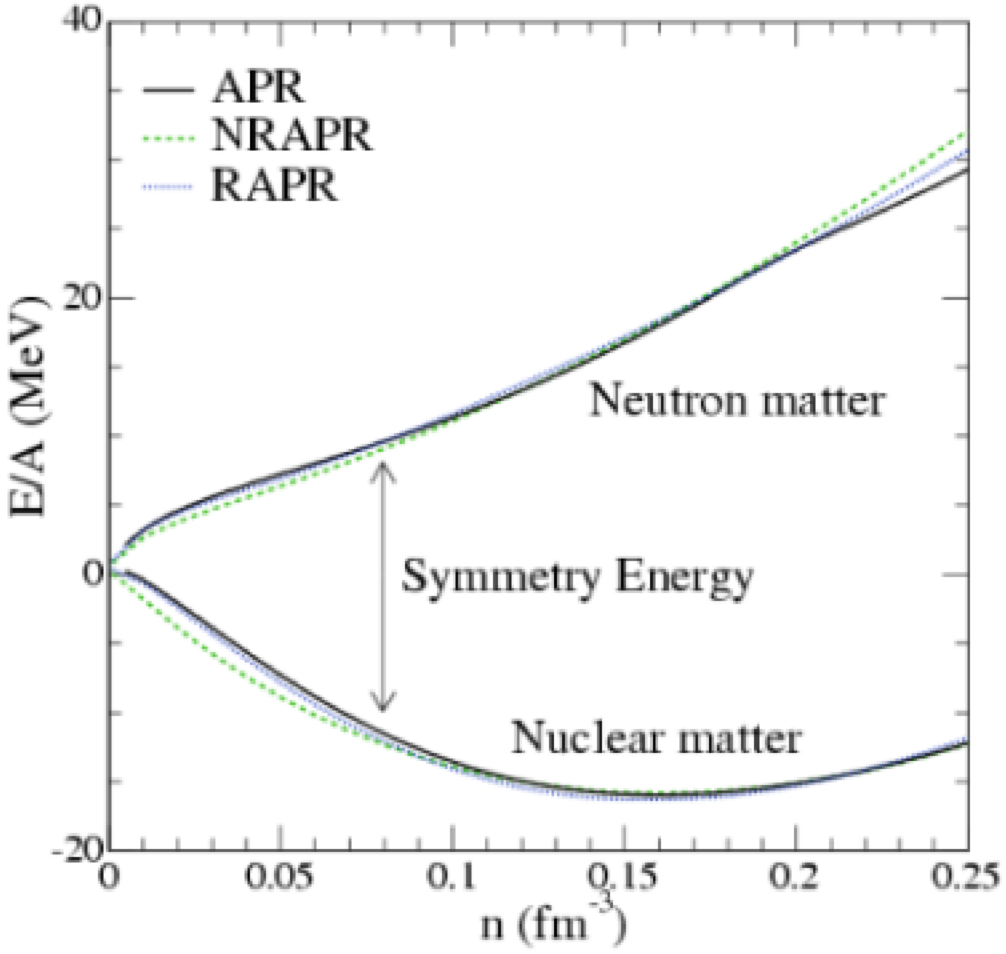
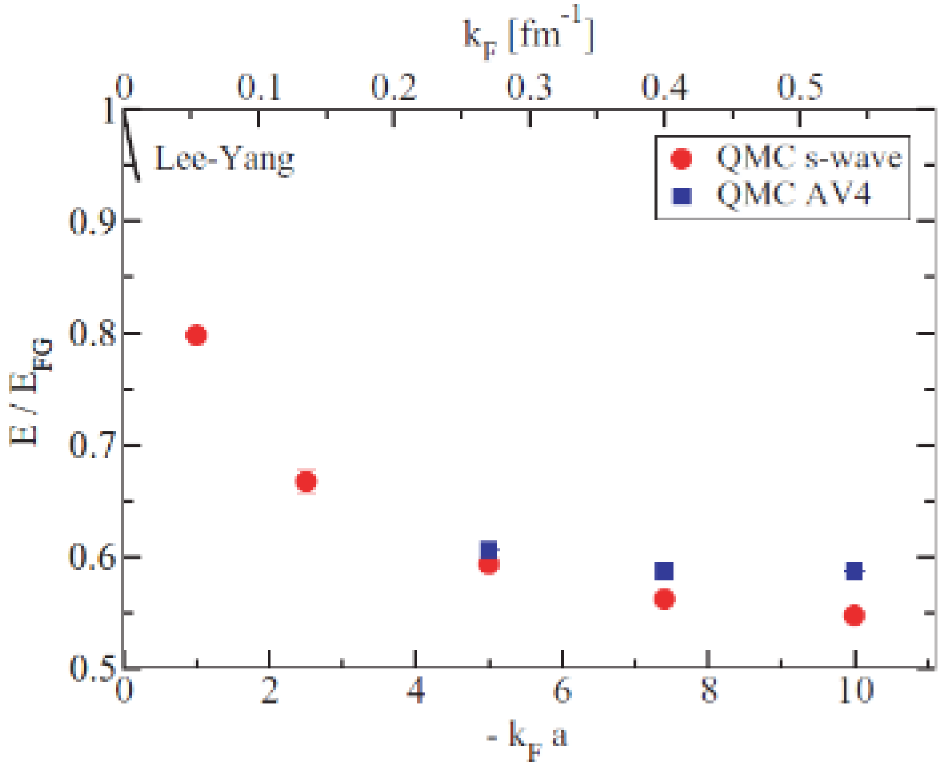
Outline

- Background
    - Definition of the symmetry energy
    - Neutron star structure
    - The EOS of homogeneous nucleonic matter
    - Pressure and neutron star masses radii
    - Exotic matter
- Observations
    - Isolated NS cooling
    - Crust cooling
    - Magnetars
    - Masses and radii
    - Several other alternatives...
- Summary

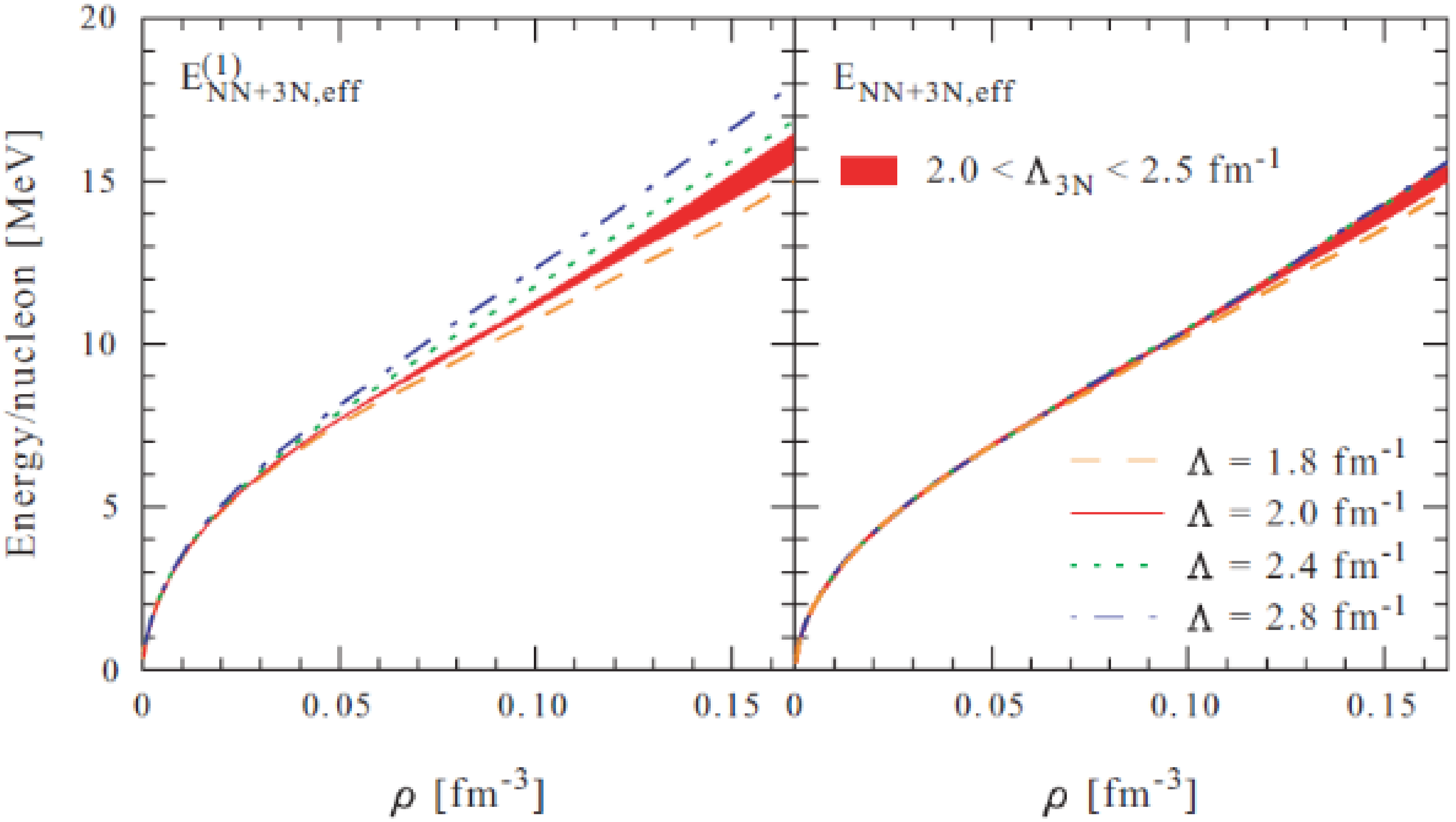
Symmetry Energy

- We *define* the symmetry energy with
  $n \equiv n_n + n_p \qquad \delta \equiv (n_n - n_p)/(n_p + n_n)$
  $E(n,\delta) = E_0(n) + S(n)\delta^2 + \mathcal{O}(\delta^4)$
- $S \approx E(n,1) - E(n,0)$
- Quartic terms can matter for cooling and crust
- In the future, it may be better to fix neutron matter and define nuclear matter from S





Gezerlis and Carlson (2010)



Hebeler and Schwenk (2010)

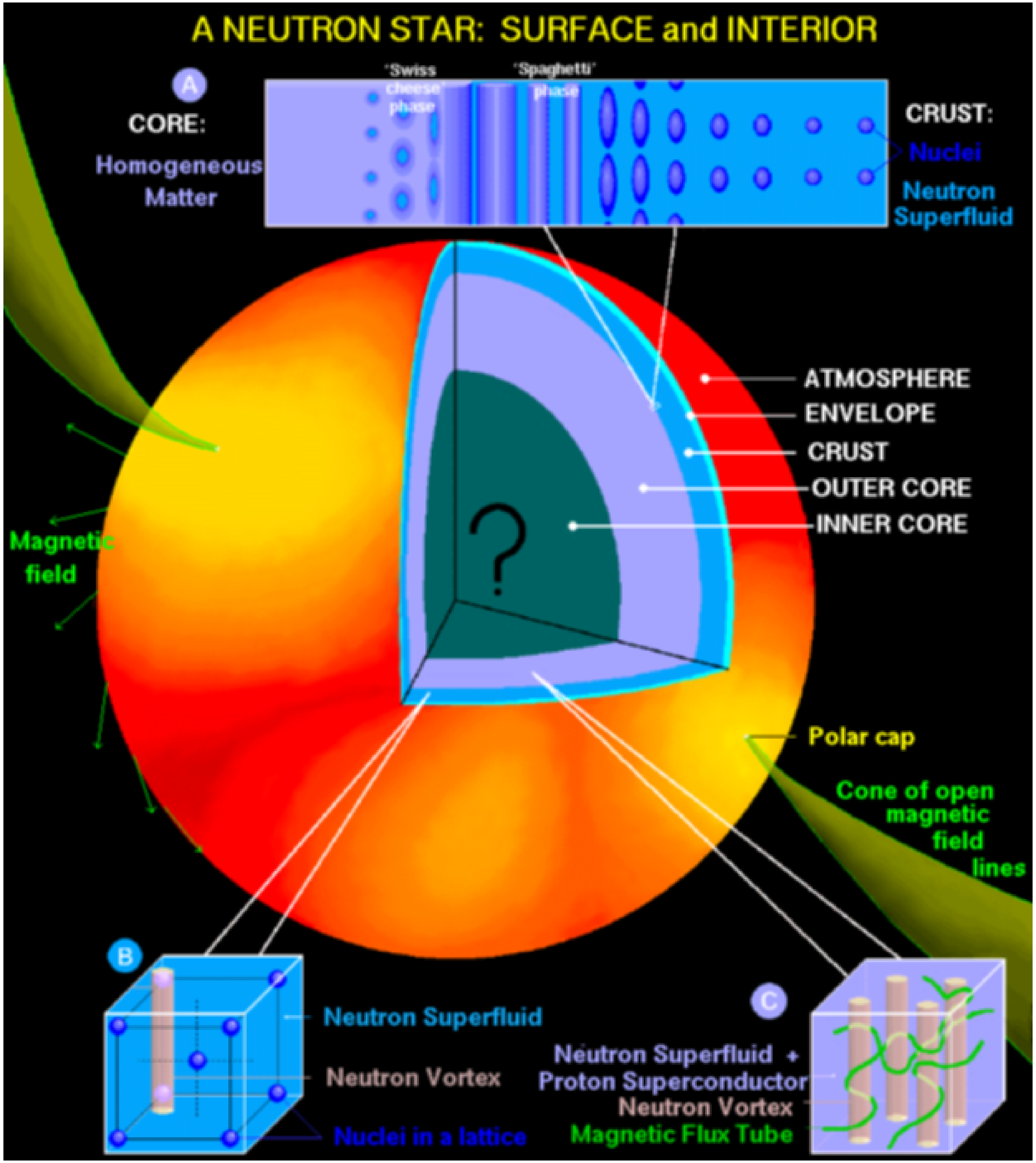


Figure by Dany Page

- Crust is a lattice of neutron-rich nuclei
- Outer core is homogeneous nucleonic matter
- Inner core may contain phase transitions:

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

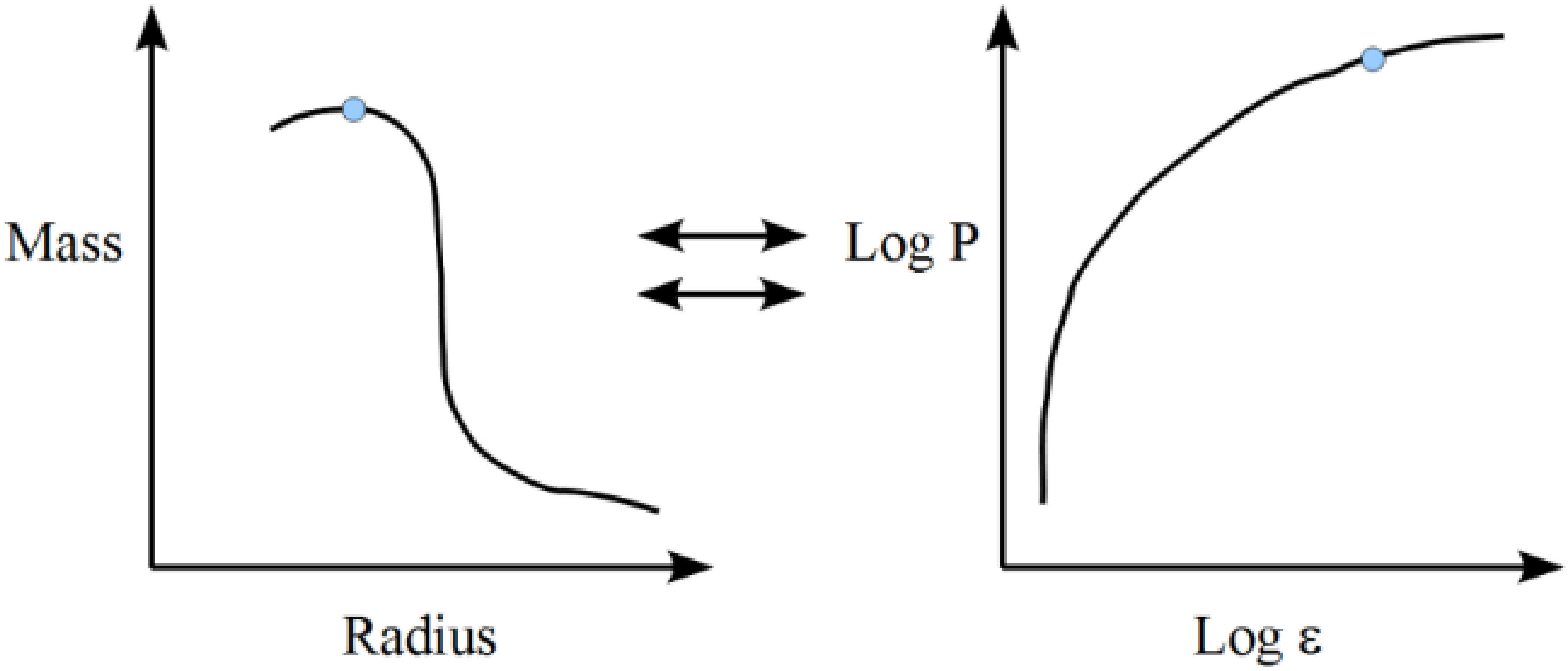
Neutron Star Microphysics

- Near the saturation density:

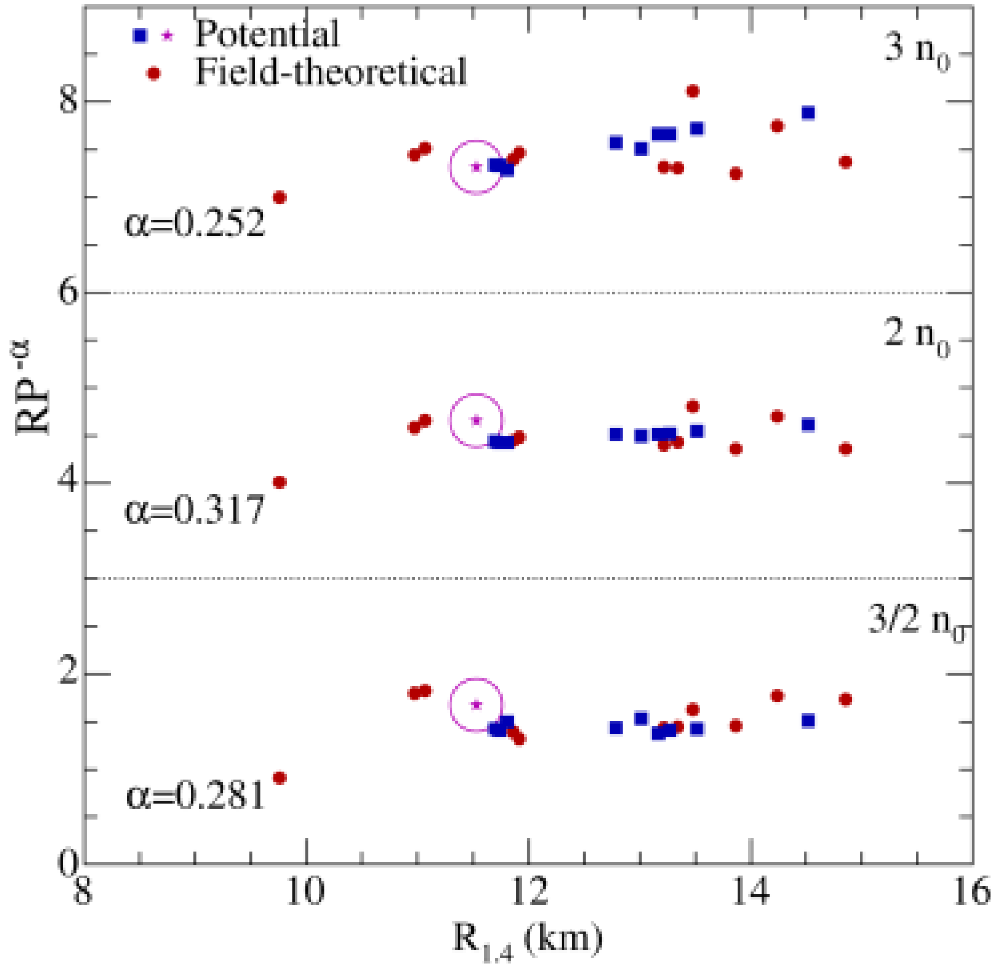
$$\varepsilon = n\left\{m_n n_n + m_p n_p + B + \frac{K}{18n_0^2}(n-n_0)^2 + \frac{K'}{162n_0^3}(n-n_0)^3 + \delta^2 S(n)\right\}$$

- Nuclear properties relevant for the nuclei in the crust
- Superfluid gap and specific heat
- Transport properties
  - Shear modulus
  - Shear and bulk viscosities
  - Breaking strain
  - Thermal conductivity
  - Neutrino emissivity
- Knowledge of these properties of matter is often required to extract the symmetry energy

Pressure of Matter and Neutron Star Masses and Radii



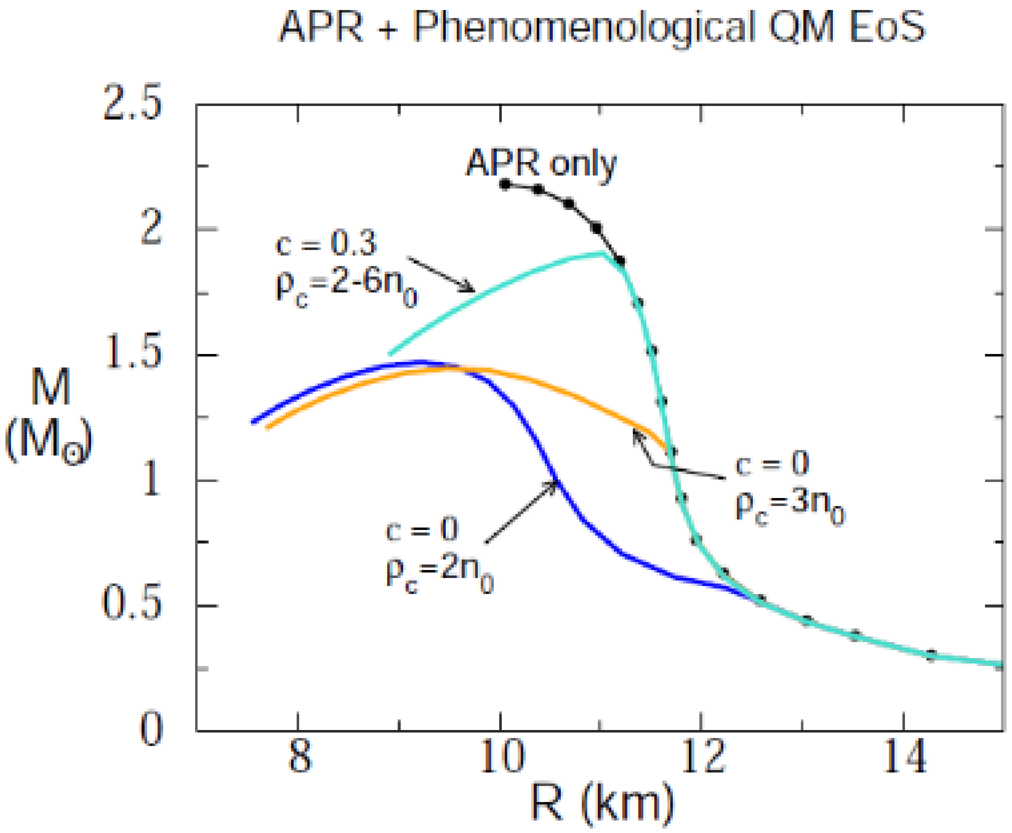
- Larger pressures, i.e. stiffer EOS, imply larger radii for a given mass
- Generally stiff => larger pressure at *a particular* density
- Some physical phenomena have different relevant density regimes, EOSs may vary strongly with density
- Lattimer-Prakash correlation, $P \propto R^{\alpha}$
- Mass and radius observations can constrain the symmetry energy



Steiner, et al (2005)

Exotic Matter

- Quarks, Bose condensates, Hyperons
- Generally reduce the pressure and suggest smaller radii, also suggest lower maximum masses.
- Presence of exotic components often determined in part by the electron chemical potential
- Significant effects to transport properties
- Can be indistinguishable from neutrons and protons.
  "less protons" <-> "more quarks"



Alford, et al. (2005)

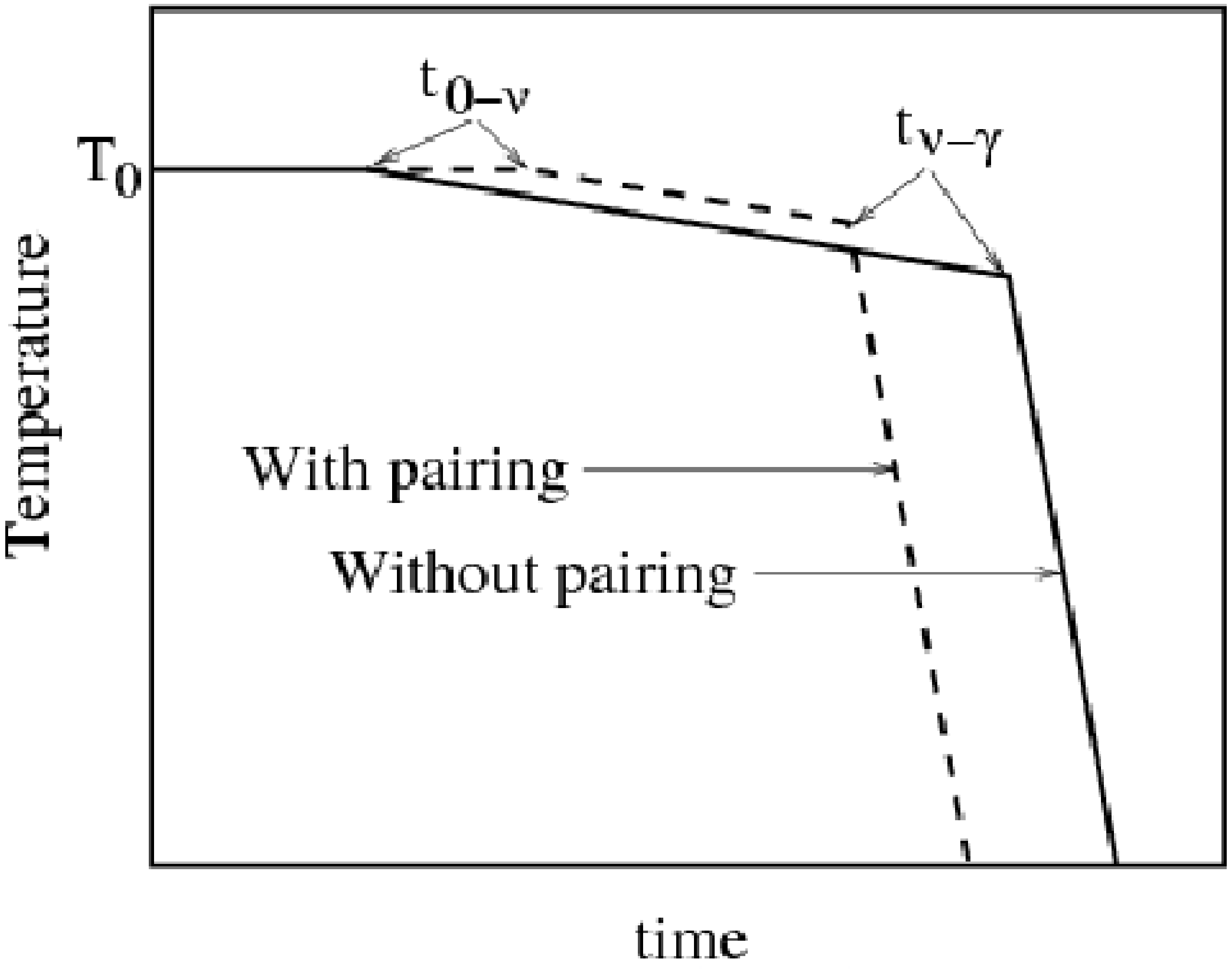
- Scott Ransom is reporting a precise 2 solar mass NS observation!
- Previous largest star was 1.7 from Champion et al. (2008)

Thermal Emission from Isolated Neutron Stars

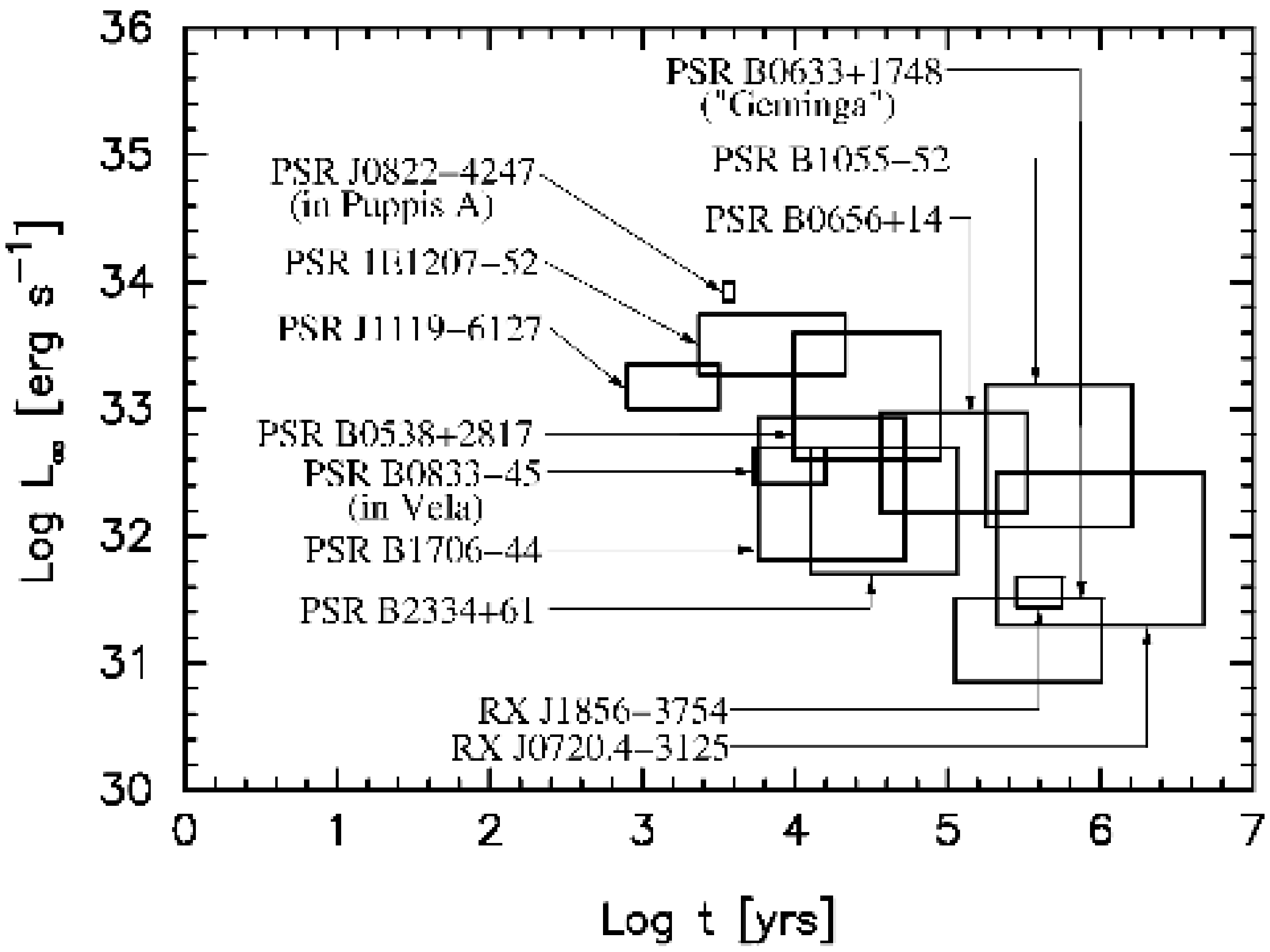
- No distance measurement required
- Requires a model of the NS atmosphere to associate the observed spectrum with a luminosity or temperature

$$C_V \frac{dT}{dt} = L_\nu + L_\gamma \,, \quad L_\gamma \sim T^{2+4\alpha} \,, \quad L_\nu \sim T^8 \text{ (Modified Urca)} \,, \quad \alpha << 1 \,, \quad C_V \sim CT$$

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



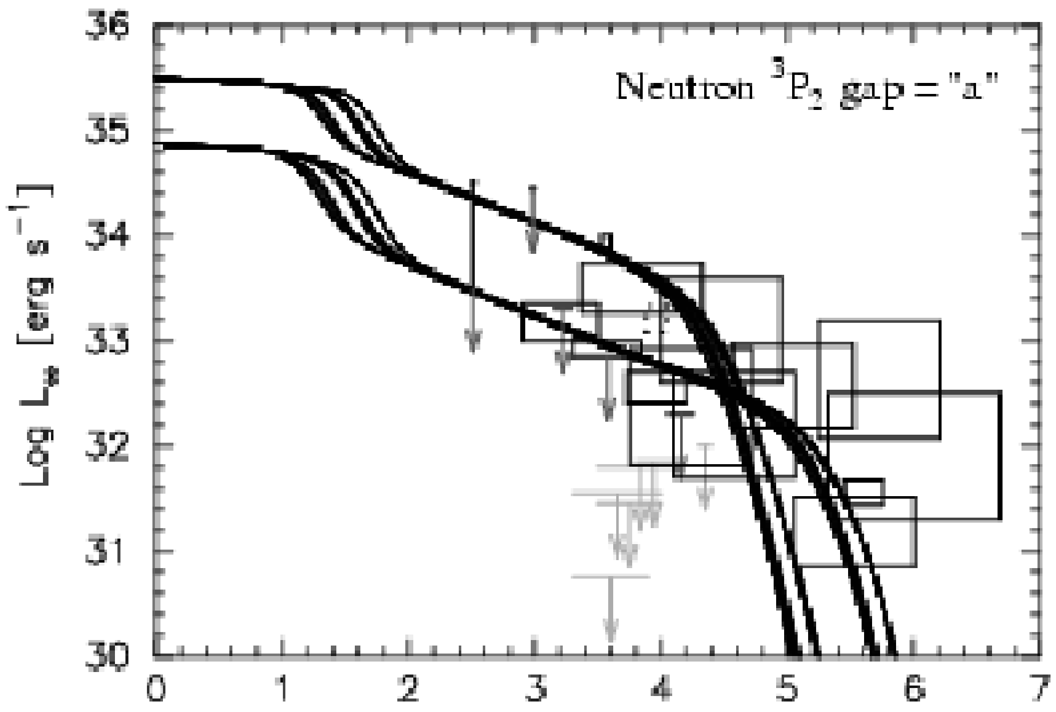
Page, et al (2004)



Page, et al (2009)

Using Thermal Emission to Constrain the EOS

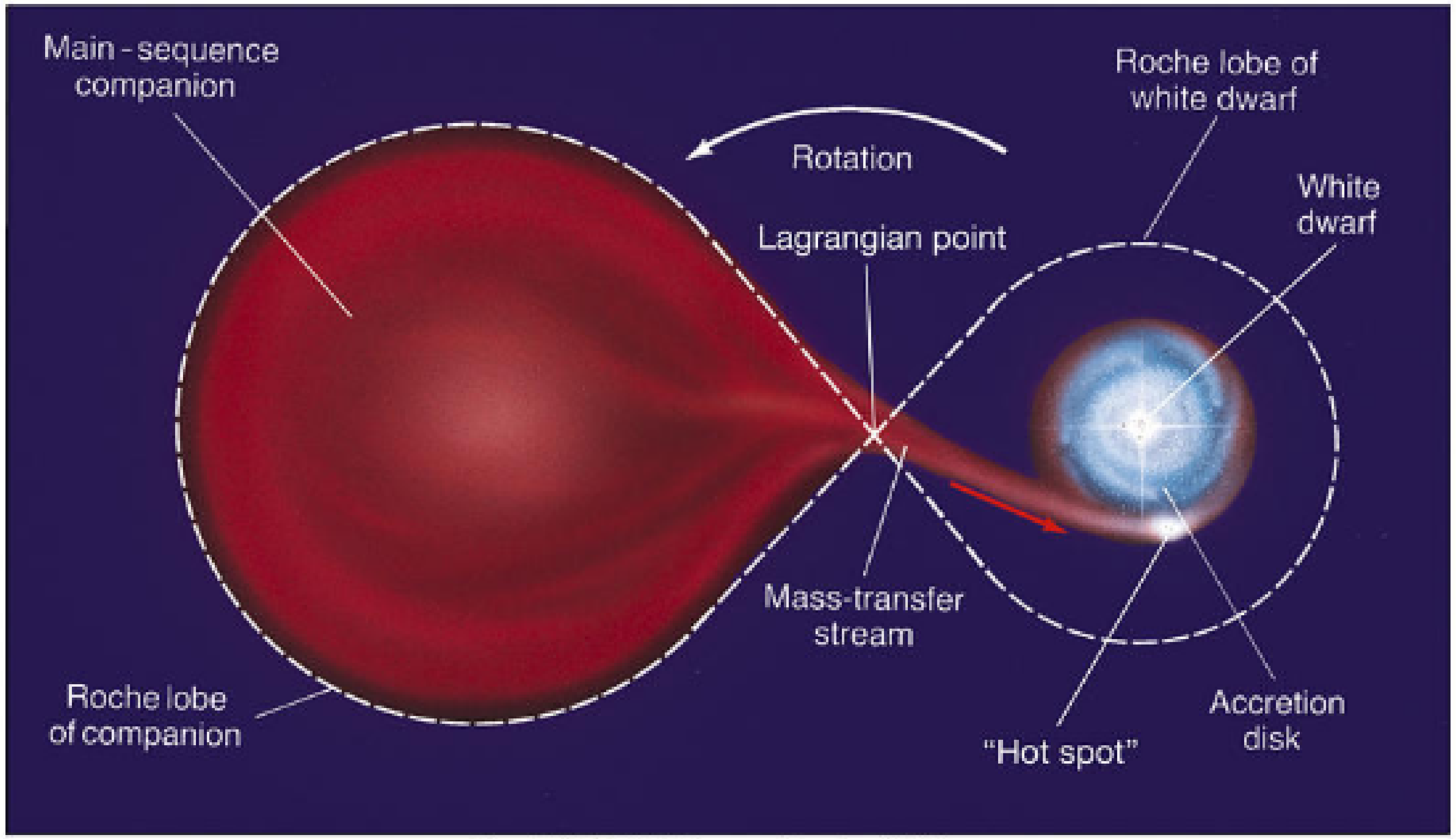
- Direct Urca ($n \to p + e + \bar{\nu}$ and $p + e \to n + \nu$) requires sufficient number of protons
- Symmetry energy controls the proton fraction
- Large S => more protons => faster cooling
- Specific heat depends on extent of superfluidity
- Current research focused on
    - Whether or not direct Urca is allowed, required, or ruled out
    - Presence of exotic matter



Page et al. (2009)

- Minimal model has only neutrons and protons and no direct Urca
- Marginal, but not decisive, evidence for either direct Urca or exotic matter
- Crustal magnetic fields may disguise direct Urca (Aguilera, et al. 2008)

Accreting Systems



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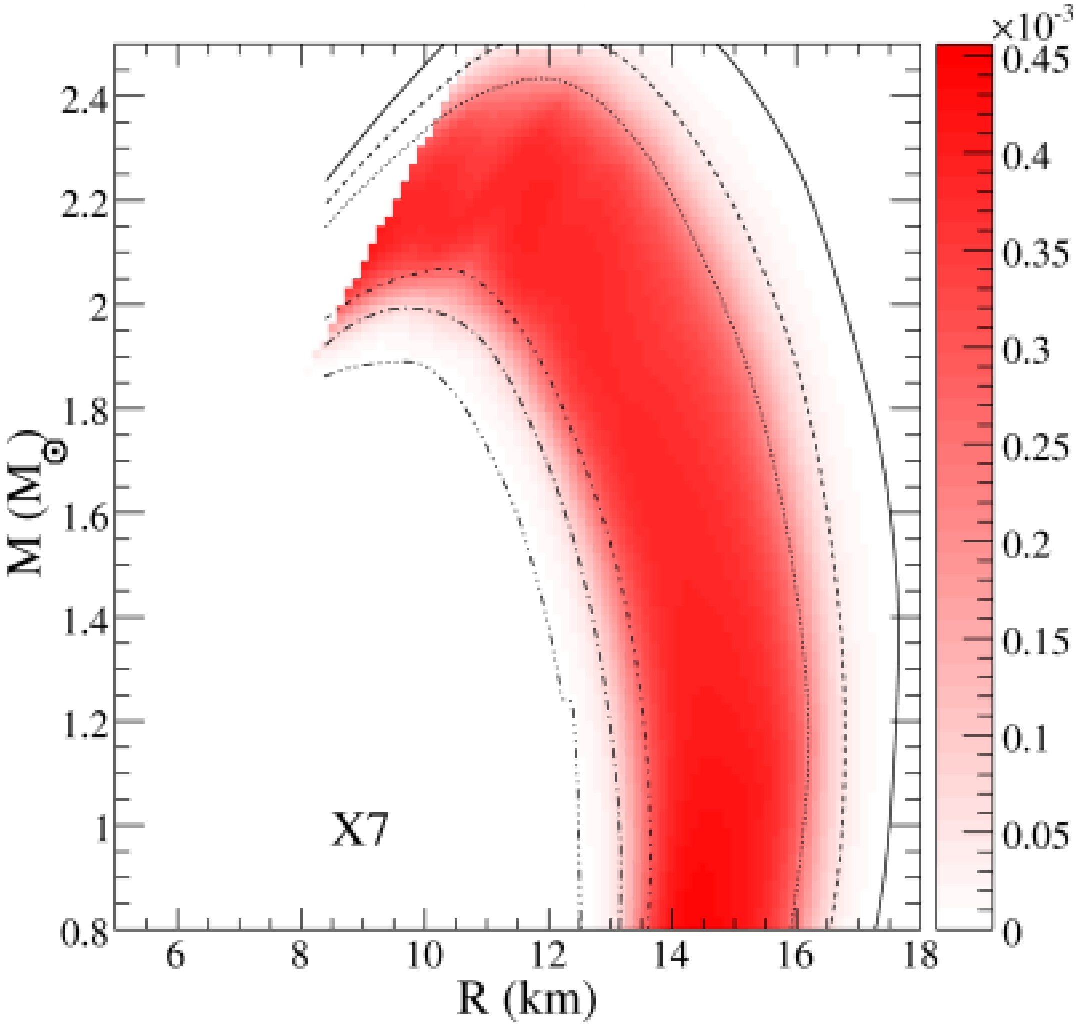


Adapted from Heinke et al. (2006)

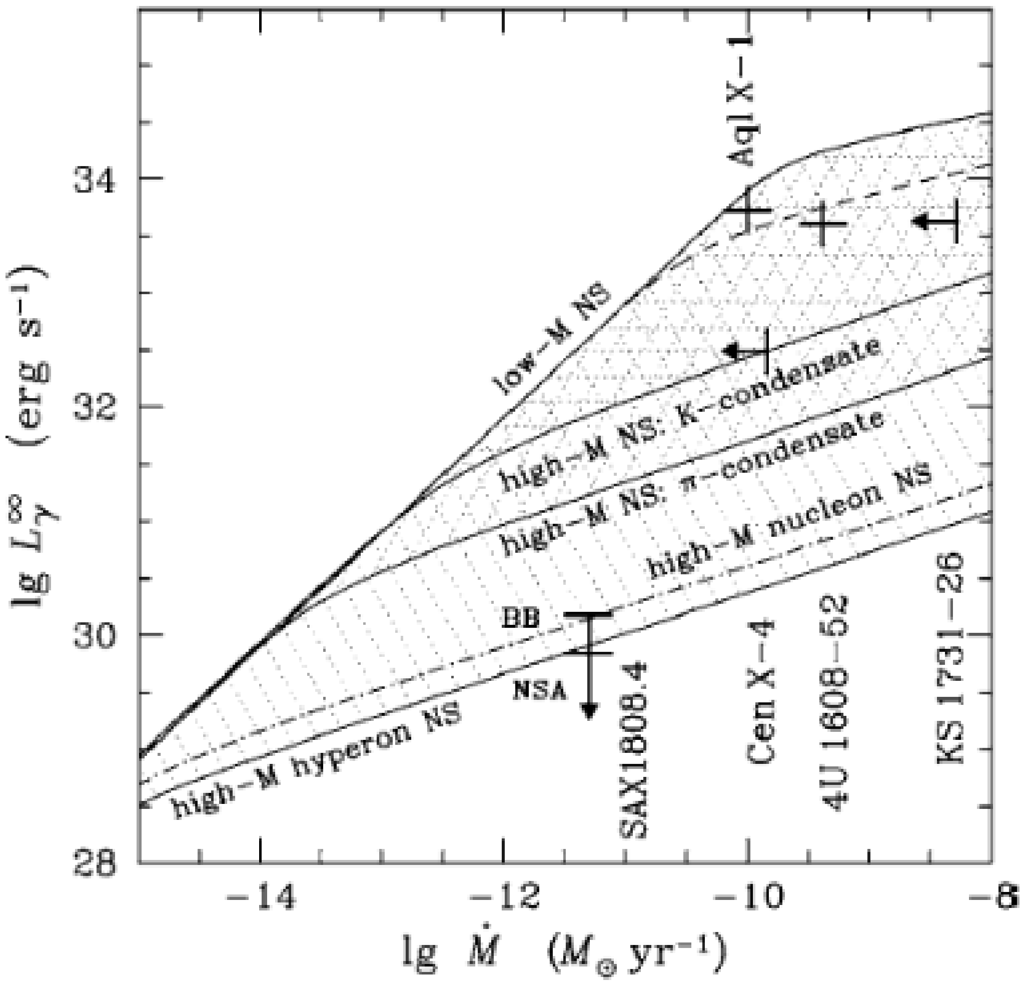
- Low magnetic fields, well-known composition
- In quiescent systems, if distance is known, can estimate radius

$$L_\infty \propto \left(\frac{R_\infty}{D}\right)^2 T_\infty^4 \quad ; \quad R_\infty = R/\sqrt{1-2GM/R}$$

- Recent observations: Heinke et al. (2006), Webb and Barrett (2007), Ho et al. (2009), and Guillot et al. (2010)

Crust Cooling

- When accretion shuts off, watch the crust cool
- Deep crustal heating
- Estimate time-averaged mass accretion rate from outburst history
- Residual accretion may be an issue in some sources

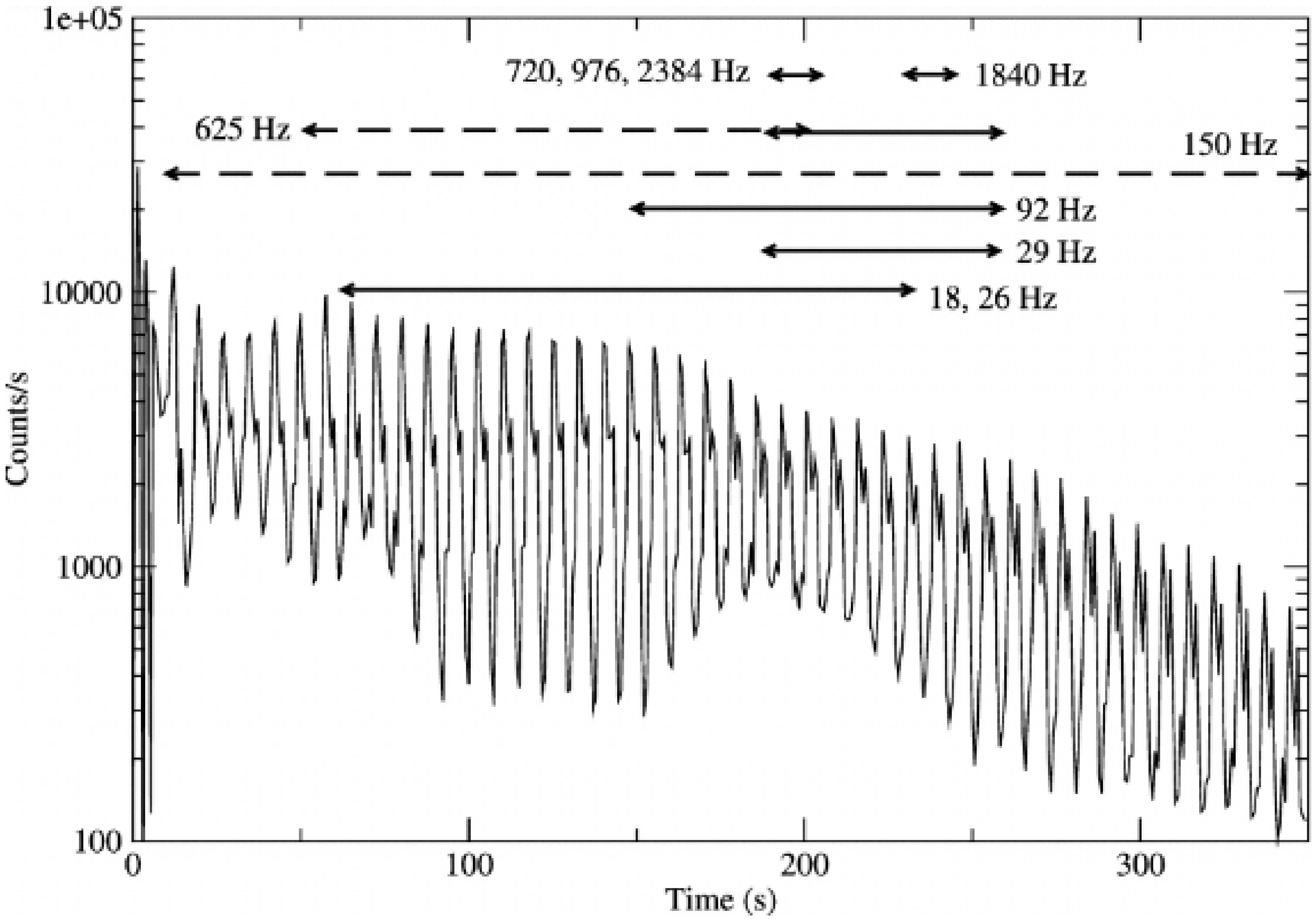


Yakovlev and Pethick (2004)

- Some, but not all, systems are very cold
- Implies direct Urca process
- Strong cooling: SAX J1808 (Heinke et al. 2007) and 1H 1900 (Jonker et al. 2007)
- Marginally enhanced cooling, MXB 1659 and KS 1731 (Cackett et al. 2008)
- Still some model dependence which is not fully explored

Magnetar Flares

- Emit (up to 10^{46} ergs) flares of hard X-rays/gamma rays
- Seismic energy contained in the crust is sufficient to drive the flares
- Flares originate in reconfigurations of a magnetized crust
- Quasi-periodic oscillations are embedded in the giant flares
- Some of the oscillation frequencies are thought to be shear modes of the crust
- Can pure crustal shear modes really exist? (van Hoven and Levin, 2010)

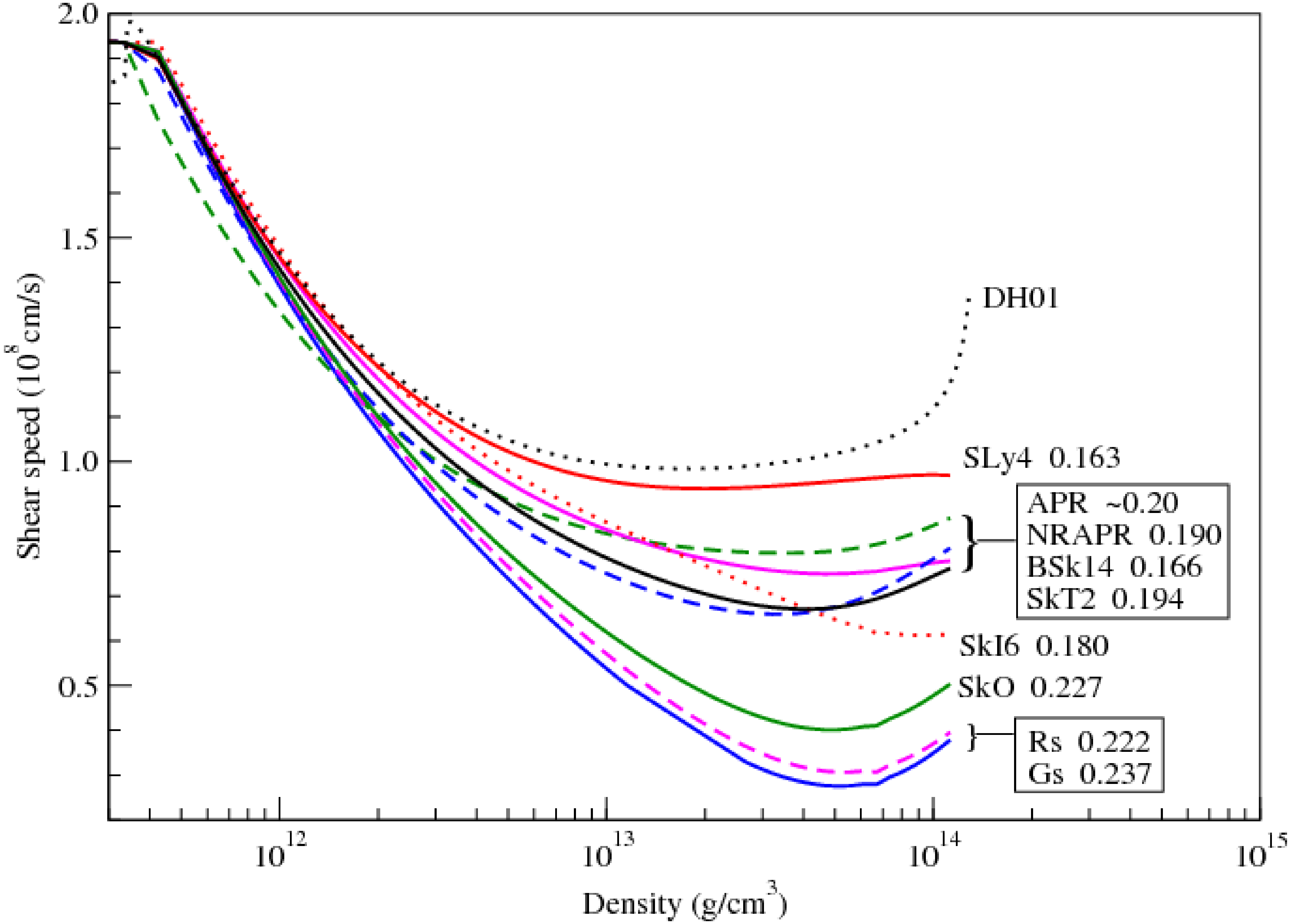


Strohmayer and Watts (2006)

Shear moduli and shear speeds

The shear modulus is $\mu = \frac{0.12}{1+0.6(173/\Gamma)^2} \frac{n(Ze)^2}{a}$; $v_s = (\mu/\rho)^{1/2}$

T. Stromayer et al., Ap J 375 (1991) 679, T. Piro Ap. J Lett. 634 (2005) 153,

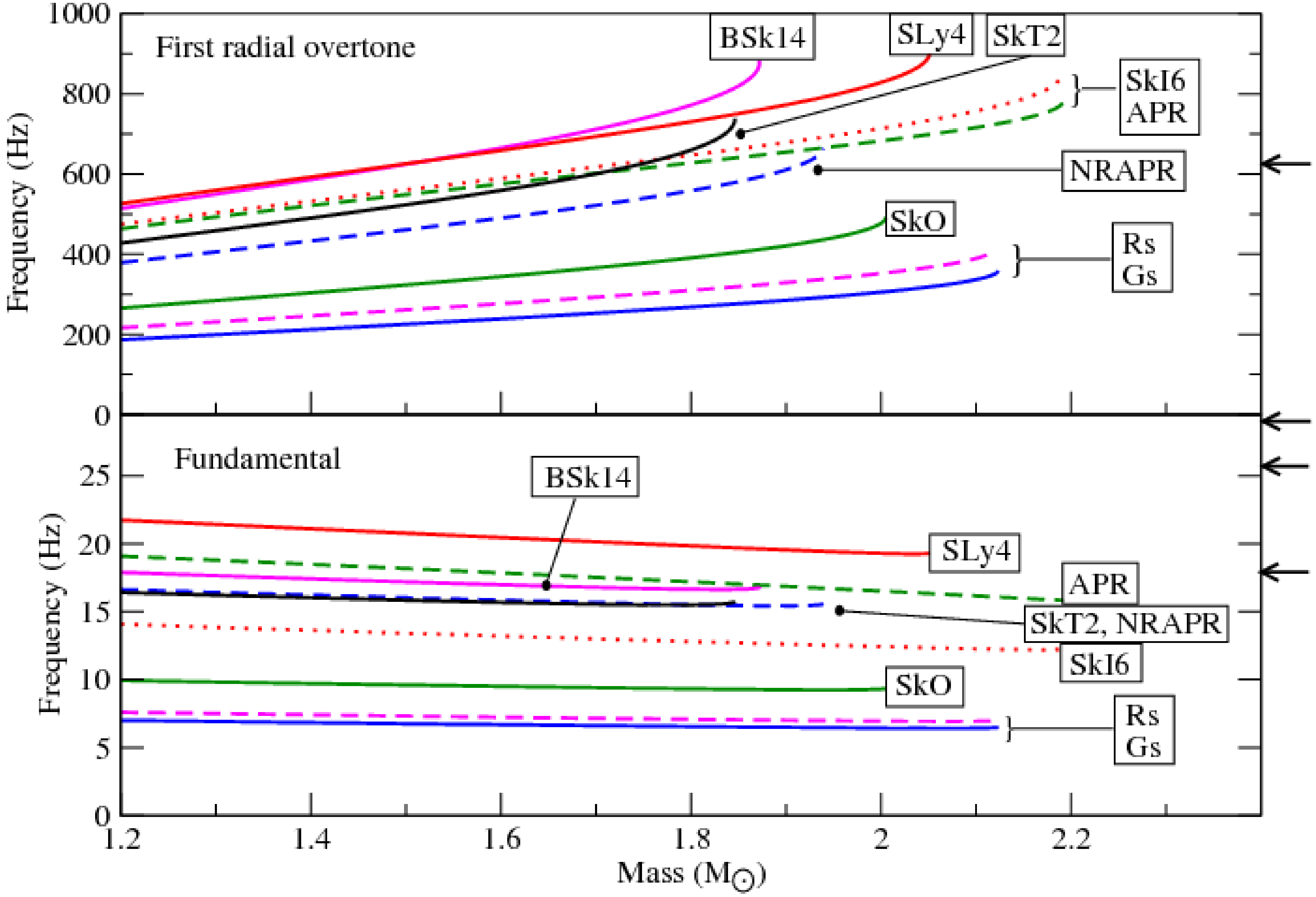


Steiner and Watts (2009)

- Monte Carlo calculations of a Coulomb solid
- Ignore the neutrons, superfluidity
- Shear modulus varies with the symmetry energy

Matching the Observed Frequencies

- Only models with symmetry energies which depend weakly on density ("soft") match the data



Steiner and Watts (2009)

- Shear modulus not well understood
- Shell effects not considered yet
- Non-trivial coupling to core

Other Connections to the Symmetry Energy

- Crustal fraction of the moment of inertia for Vela (Link et al. 1999)
- Neutron star radii from gravitational wave emission (Ferrari et al. 2010)
- X-ray Pulse profile analysis (Leahy, 2009, and Morsink and Leahy, 2009)
- Double pulsar PSR 0737
    - Posiadlowski et al. (2005): electron capture supernovae, but see Willems et al. (2006)
    - Moment of inertia measurement (Lattimer and Schutz 2005), but see Iorio (2008).
- Constraints from rotation (Hessels et al. 2006) - not very constraining, except for light neutron stars
- Supernovae? Neutronization peak sensitive to neutron-proton ratio
- r-process? Neutron to proton ratio helps determine the ratio of electron neutrinos to electron anti-neutrinos and then also the composition of the wind
- kHz QPOs? No longer vogue, some serious modeling issues
- RXJ 1856 - Radius information plus a distance measurement, but serious difficulties with a possible magnetic field

Photospheric Radius Expansion Bursts

- X-ray bursts sufficiently strong to blow off the outer layers - radiate at the Eddington limit

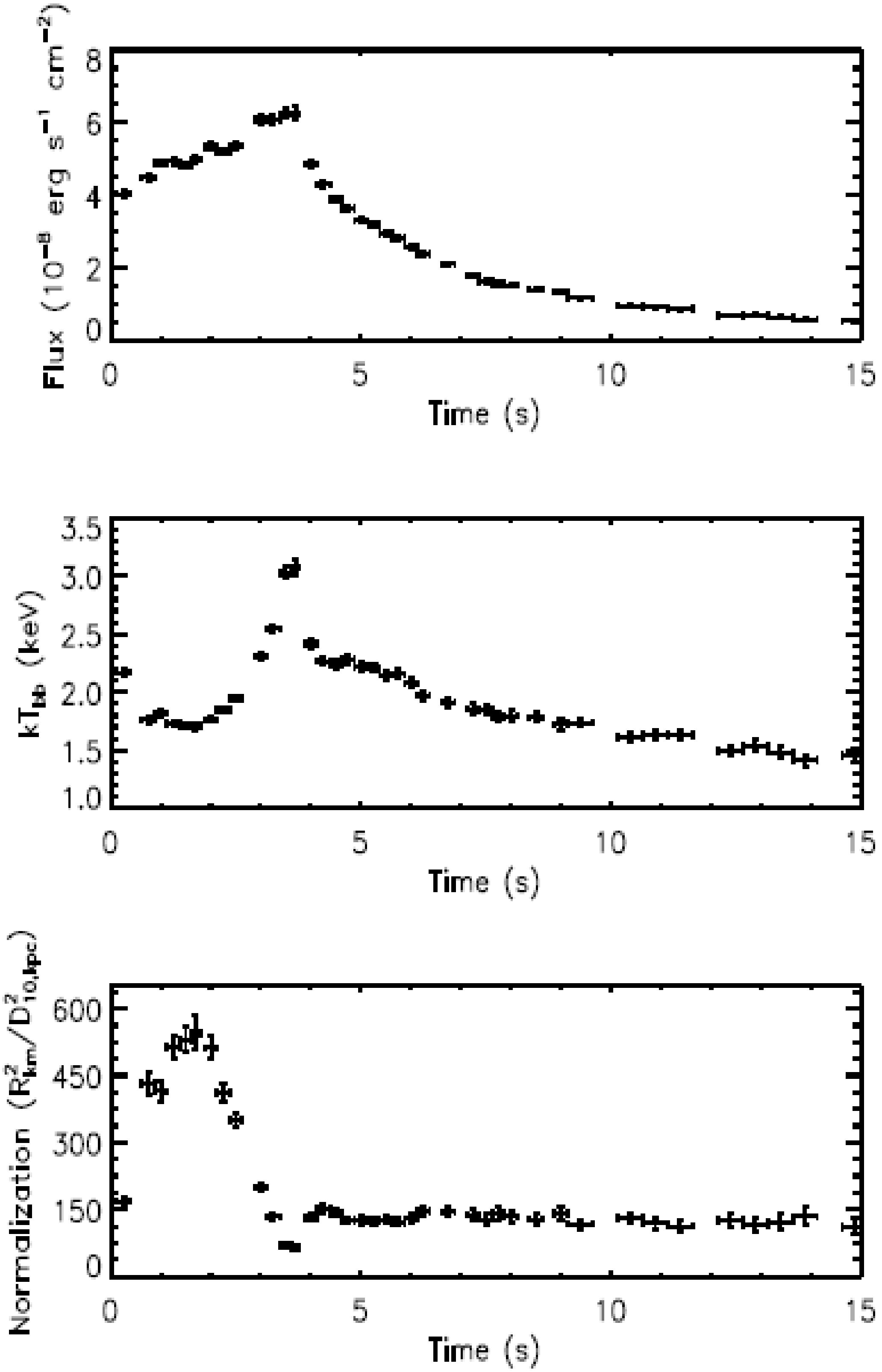
- Flux peaks, then temperature reaches a maximum, "touchdown"

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

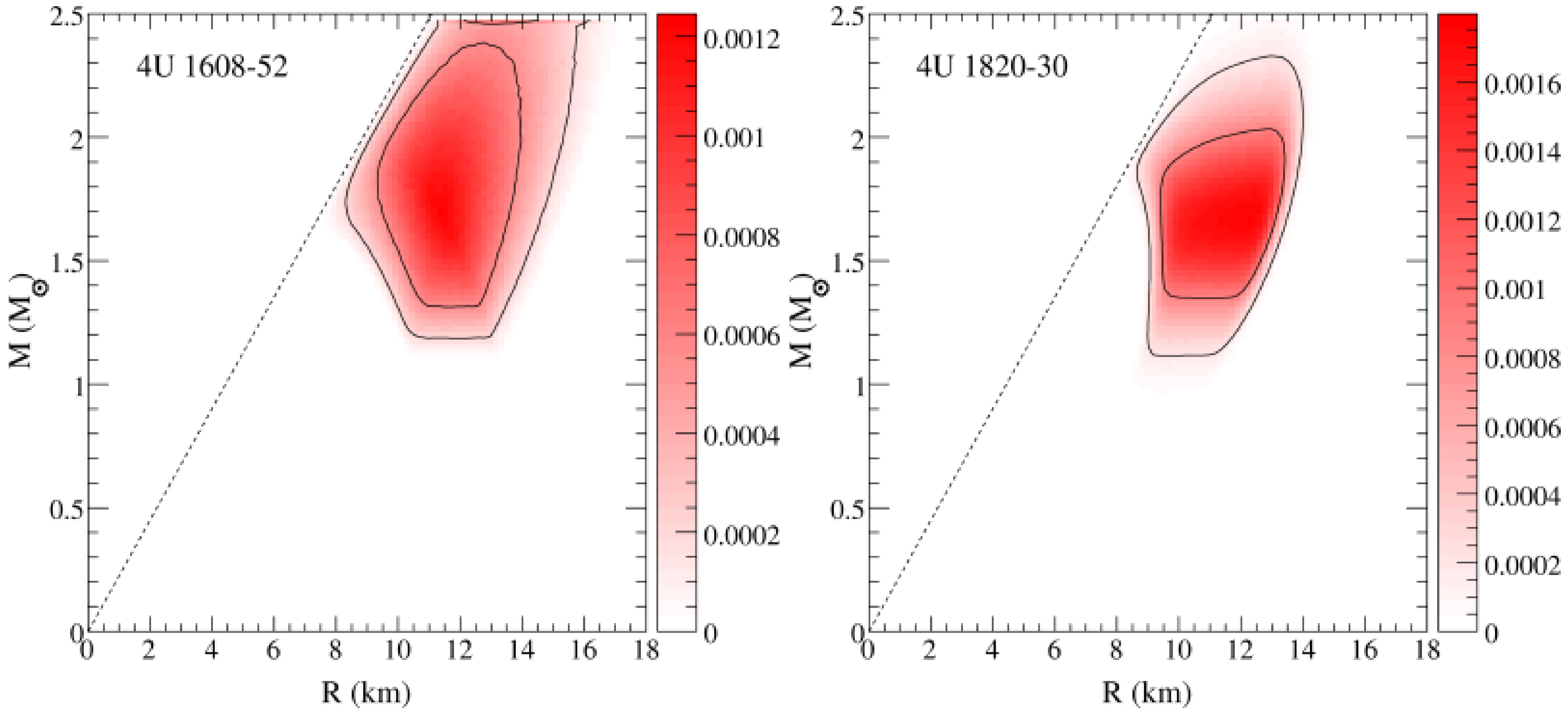
- Normalization during the tail of the burst: $A \equiv \frac{F_\infty}{\sigma T_{bb,\infty}^4} = f_c^{-4}\left(\frac{R}{D}\right)^2 (1-2\beta)^{-1}$

- If we have the distance, two constraints for mass and radius

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



Typical M and R constraints from PRE Bursts



Steiner et al. (2010)

- Technique applied to 4U 1608, EXO 1745, and 4U 1820 by Ozel and collaborators
- Also for 4U 1724 by Suleimanov et al. (2010)
- Can we put together information on masses and radii to constrain the EOS?

EOS parameterization

- Tabulated crust model

- Schematic EOS near the saturation density:

$$\varepsilon = n\left\{m_n n_n + m_p n_p + B + \frac{K}{18n_0^2}(n-n_0)^2 + \frac{K'}{162n_0^3}(n-n_0)^3 + \delta^2 S(n)\right\}$$
$$+(1-2x)^2\left[S_k\left(\frac{n}{n_0}\right)^{2/3} + S_p\left(\frac{n}{n_0}\right)^{\gamma}\right]\Bigg\}$$

  Four parameters: $K, K', S_p + S_k, \text{ and } \gamma$

- Polytropes at high density

  $P(\varepsilon) = C\varepsilon^{\Gamma} \text{ with } \Gamma \equiv 1 + \frac{1}{n}$

  Four high-density parameters: $n_1, n_2, \varepsilon_1 \text{ and } \varepsilon_2$

- Ensure reasonable boundaries for the parameters

  $150 \text{ MeV/fm}^3 < \varepsilon_1 < \varepsilon_2 < 1600 \text{ MeV/fm}^3$

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

Bayesian Analysis

- Each data set is a probability, the product of these gives the likelihood function
- Bayes theorem: $P[\mathcal{M}_i|D] = \frac{P[D|\mathcal{M}_i]P[M_i]}{\sum_j P[D|\mathcal{M}_j]P[\mathcal{M}_j]}$
- 8 EOS parameters, 7 neutron stars = 15-dimensional space
- Choice of priors allows choice of input physics, trivial priors for now

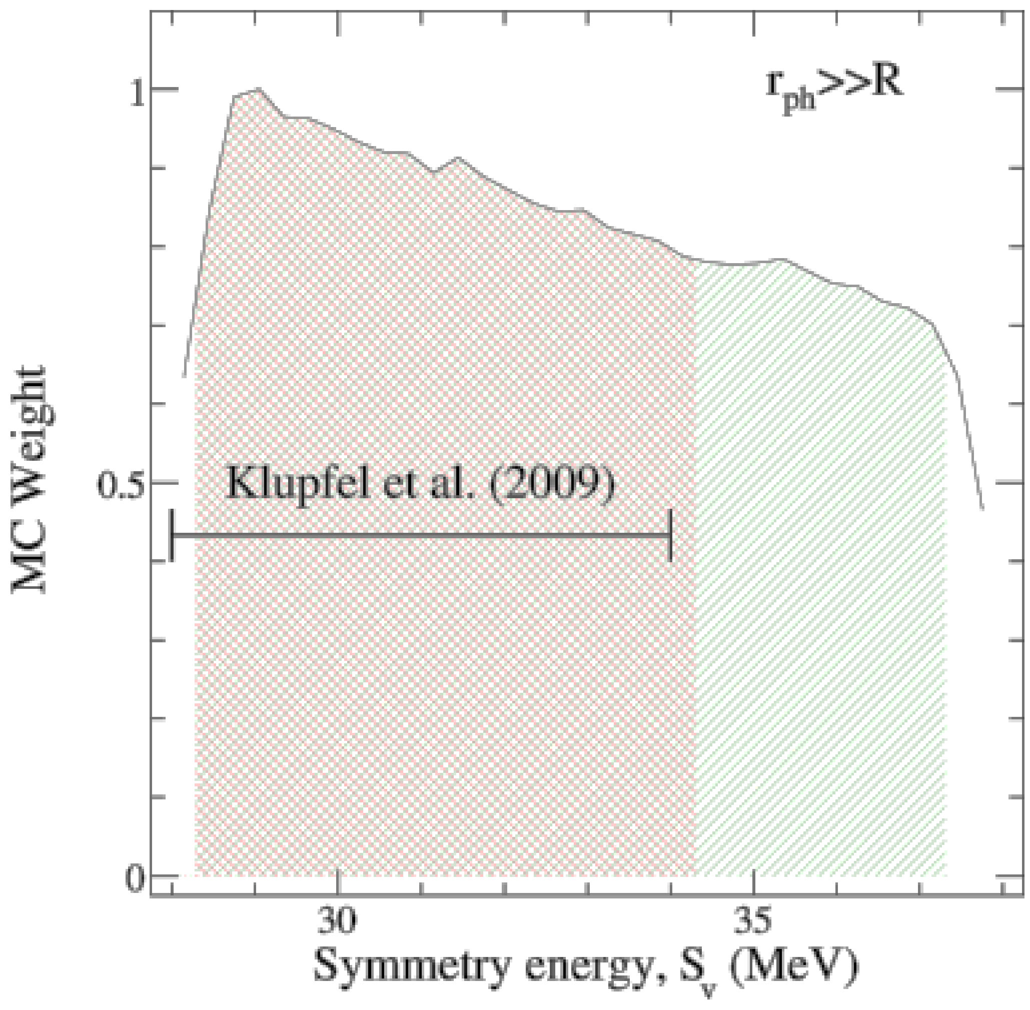
$$P[D|\mathcal{M}] = \prod_{i \in n_{\mathrm{datasets}}} \mathcal{D}_i(M, R)|_{M=M_i, R=R(M_i)}$$

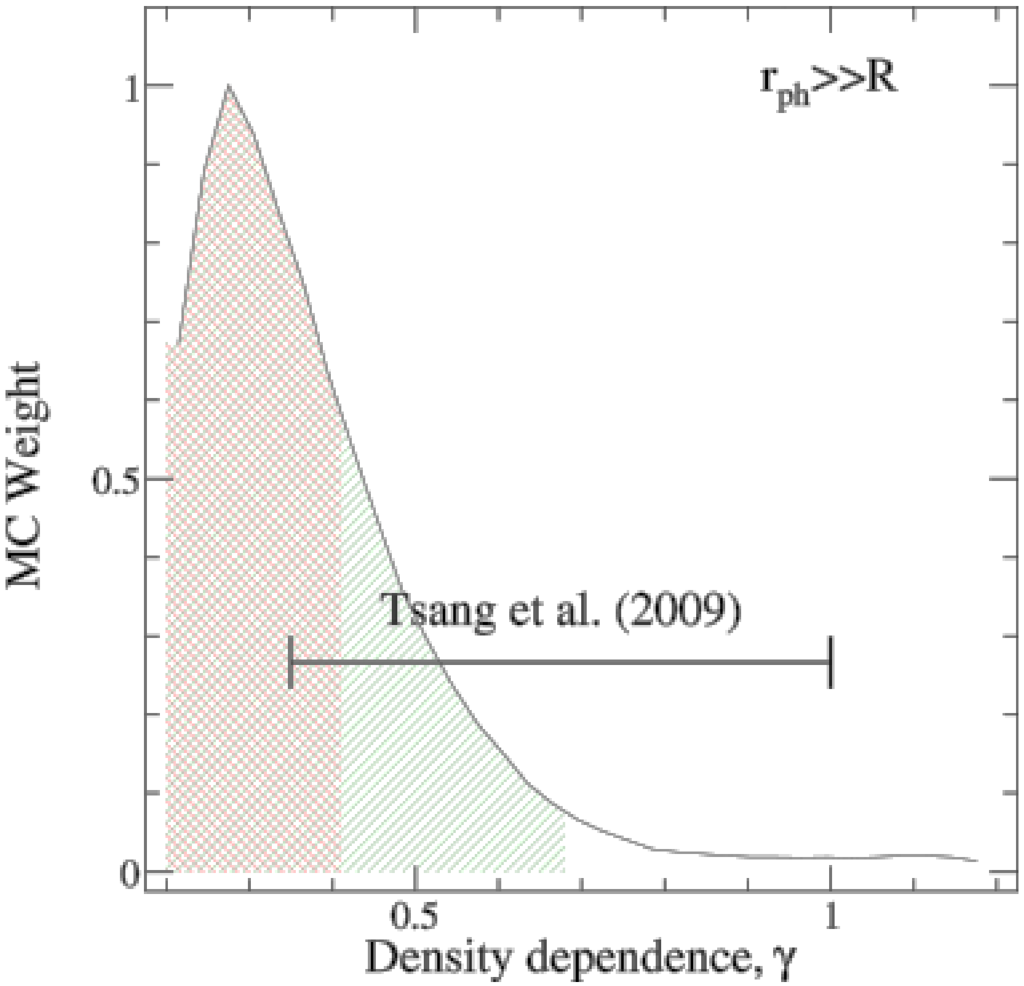
- In Bayesian analysis, marginal estimation is often employed:

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

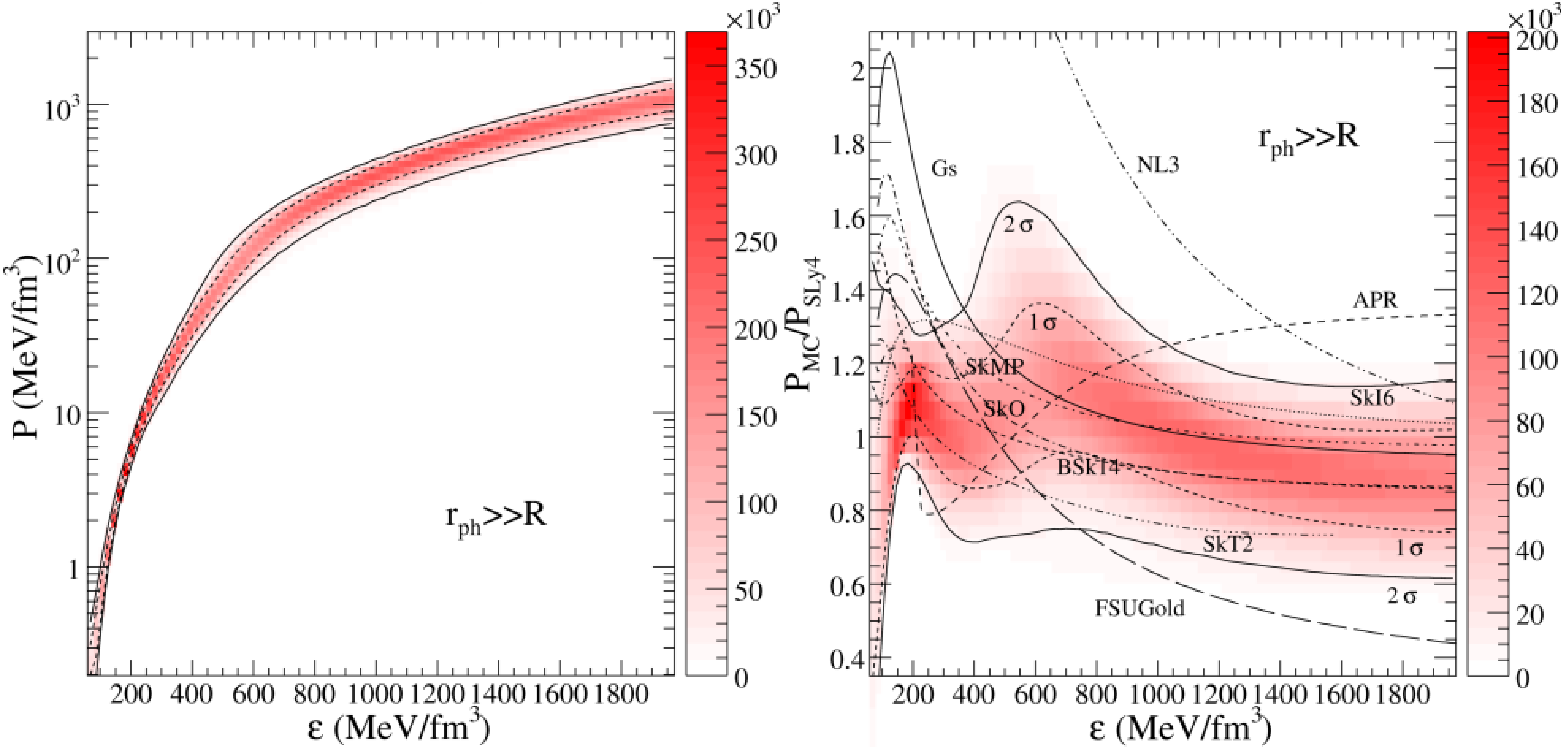
- Not the same as a best fit!
- Determining the EOS is a matter of computing many multi-dimensional integrals, where each point requires a solution of the TOV equations

Resulting Constraints on the Symmetry Energy



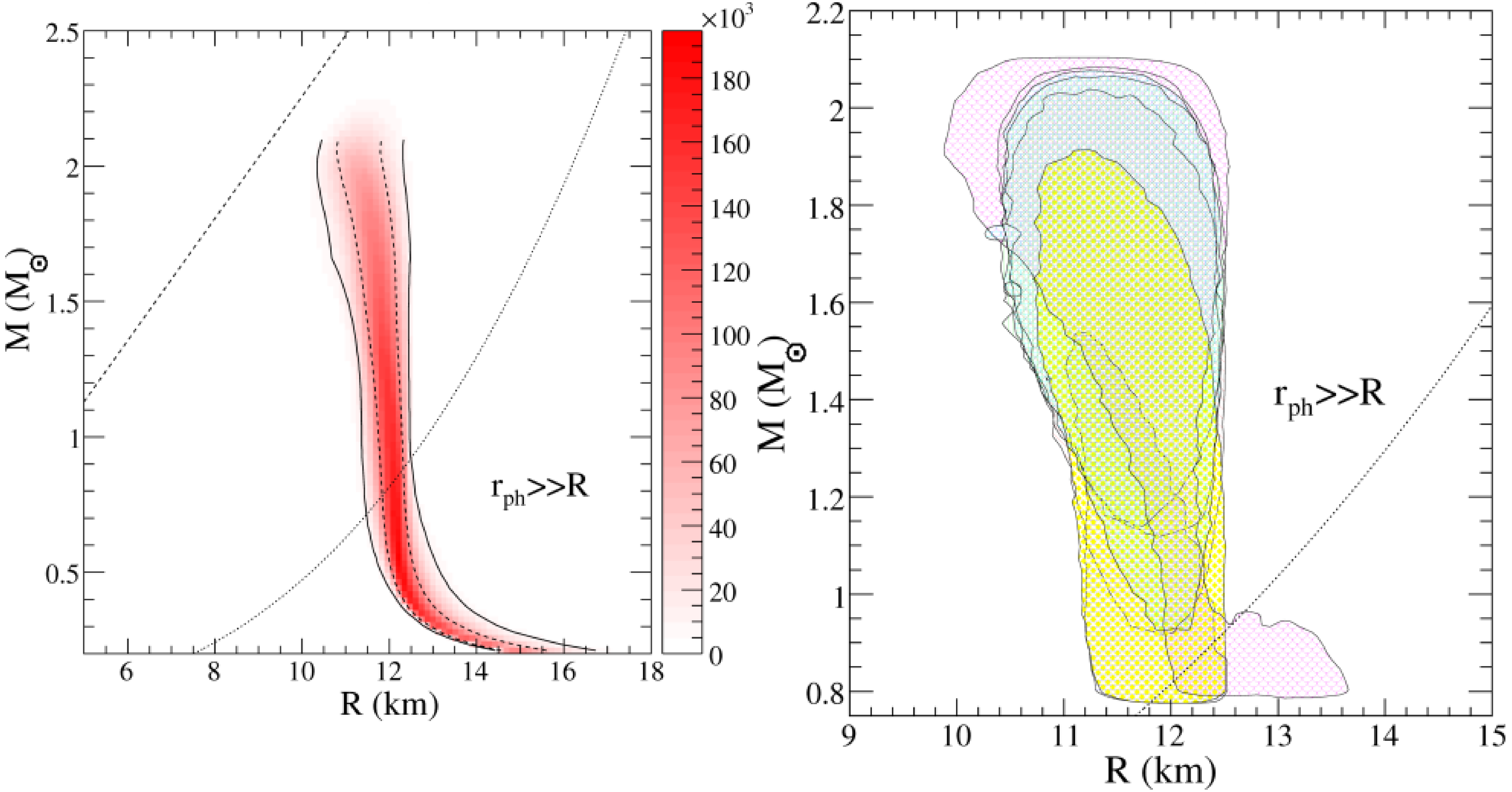


Equation of State Results



- EOS is overall somewhat soft
- Many equations of state appear to be ruled out, including APR, FSUGold, NL3, and a few Skyrme models have problems at low densities

Mass and Radius Results



- Radius of most stars lie between 11 and 12.5 km
- The mass and radius constraints provided by observations are much smaller when taking into account the fact that all objects must lie on the same curve

Summary

- Neutron stars are a rich laboratory for symmetry energy

- There is a lot of opportunity to connect modern theoretical models with recent and upcoming experimental results

- Cooling suggests that the "minimal" model is insufficient, direct Urca may be required to explain observations

- Magnetars may prove to be interesting probes of the symmetry energy

- *Current* mass and radius measurements, modulo some systematic uncertainties, can *quantitatively* constrain the equation of state

- A critical question: How can we observe the crust?