NEUTRON STARS AND DENSE MATTER:

IMPLICATIONS OF X-RAY BURST OBSERVATIONS

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Nuclear interactions are critical for understanding neutron star structure and evolution

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On Massive Neutron Cores

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It has been suggested that, when the pressure within stellar matter becomes high enough,

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For masses greater than $\frac{3}{4}\odot$ there are no static eq

For masses $\frac{1}{3}\odot < m < \frac{3}{4}\odot$ two solutions exist, one stable and quasi-Newtonian, one more condensed, and unstable. For masses greater than $\frac{3}{4}\odot$ there are no static equilibrium solutions.

Ideal gas: $M_{max} = 0.75\ M_{\odot}$

Outline

- The nuclear equation of state—a quick reminder
- Experimental constraints near saturation density
- Masses, radii from X-ray bursts & implications for the EOS
- Strong neutrino cooling in the neutron star crust

From nuclei to neutron stars

Start with the Bethe-Weizäcker formula:

$$B(A,Z) = \underbrace{a_V A}_{\text{vol.}} \underbrace{-a_S A^{2/3}}_{\text{surf.}} \underbrace{-a_C \frac{Z^2}{A^{1/3}}}_{\text{Coul.}} \underbrace{-a_A \frac{(A-2Z)^2}{A}}_{\text{asym.}} + \ldots$$

Then take the limit $A \to \infty$, with $x = Z/A$, for B/A:

$$\varepsilon(x) = -\frac{B}{A} = -a_V + a_A(1-2x)^2.$$

From nuclei to neutron stars | thermodynamics

Symmetric nuclear matter saturates at $\rho = 0.16\,\mathrm{fm}^{-3}$ with $B/A \approx 16\,\mathrm{MeV}$; expanding our simple formula,

$$\varepsilon(\rho, x) \approx \varepsilon_0 + \left[J + \frac{L}{3}\left(\frac{\rho}{\rho_0} - 1\right)\right](1 - 2x)^2 + \ldots$$

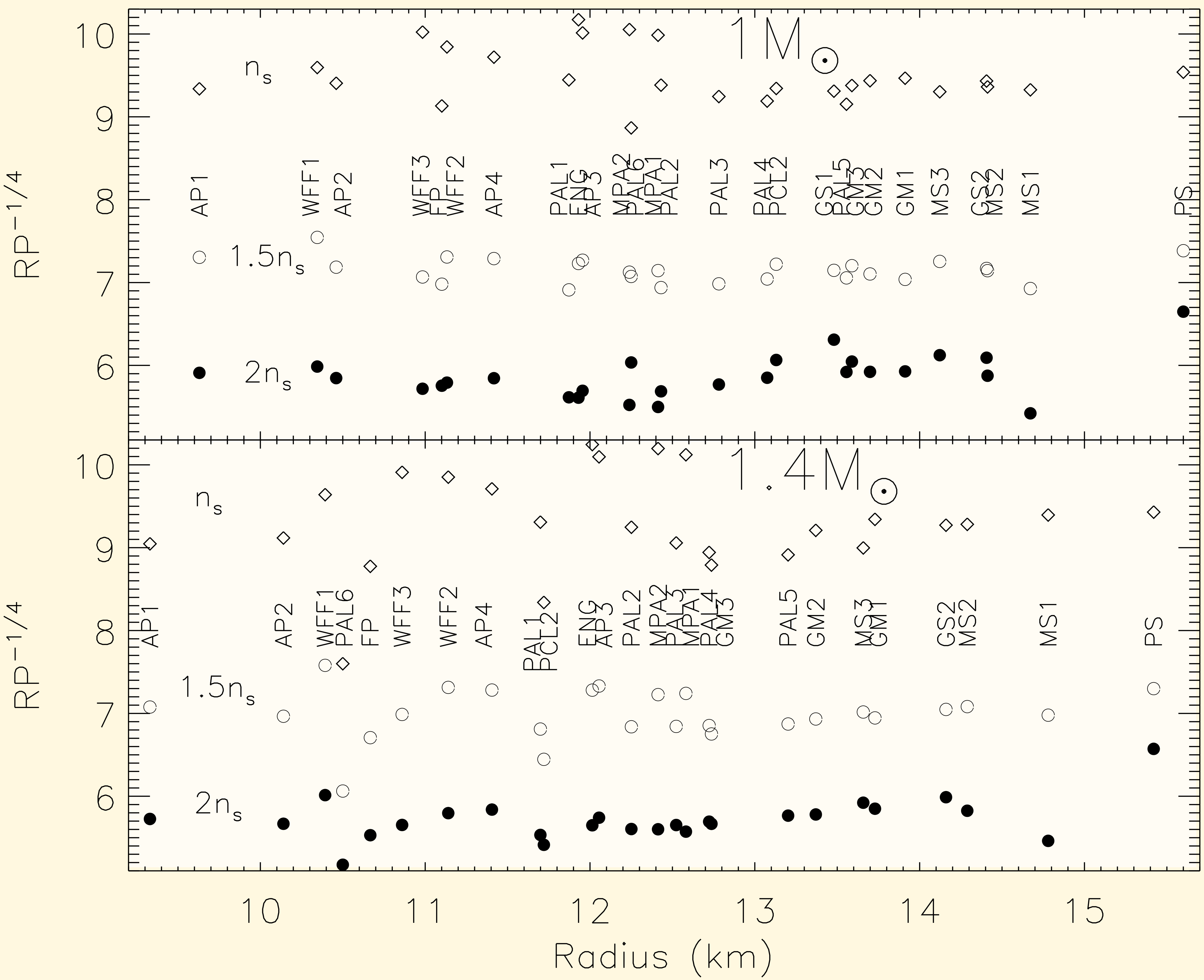
The pressure is $\rho^2 \partial\varepsilon/\partial\rho$, so at $\rho \approx \rho_0, x \ll 1$,

$$P \approx \frac{L}{3\rho_0}\rho^2.$$

(Charge neutrality and β-equilibrium imply that $x \ll 1$.)

The NS radius is correlated with pressure at near-saturation densities

Lattimer & Prakash 2001



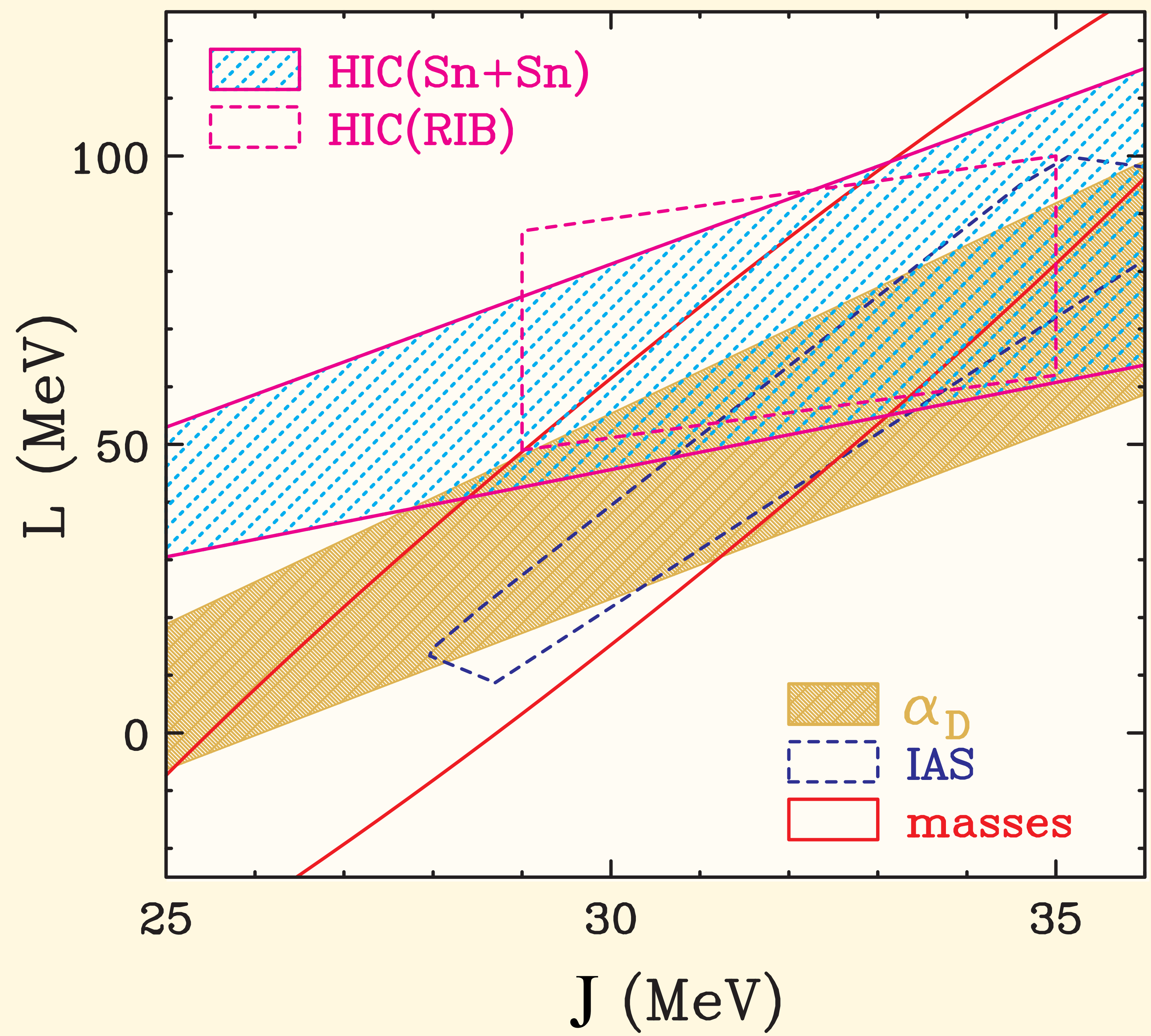
EOS near ρ_0 | experimental constraints

Horowitz et al. (2014)

Heavy ion collisions

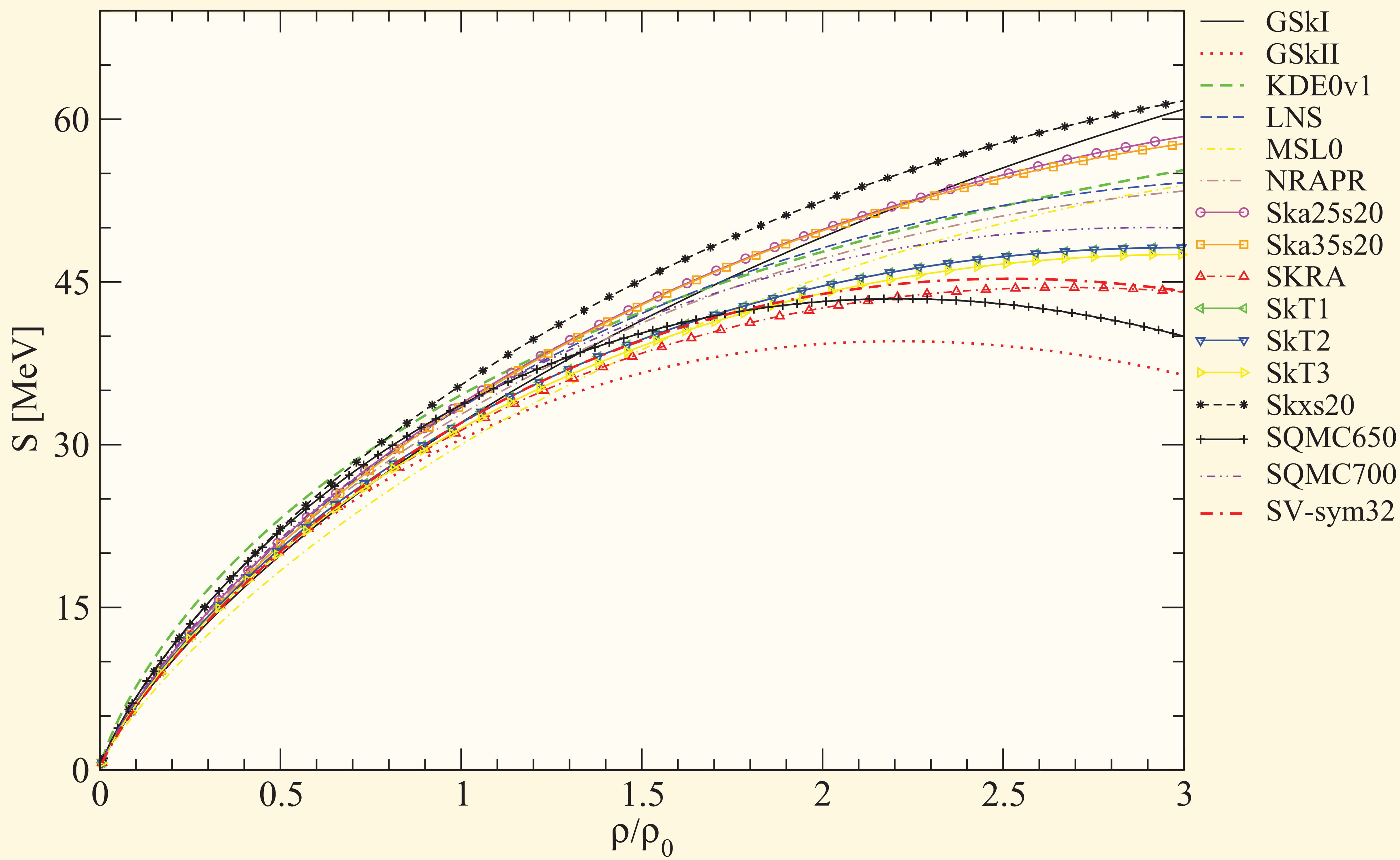
Dipole resonance

Masses



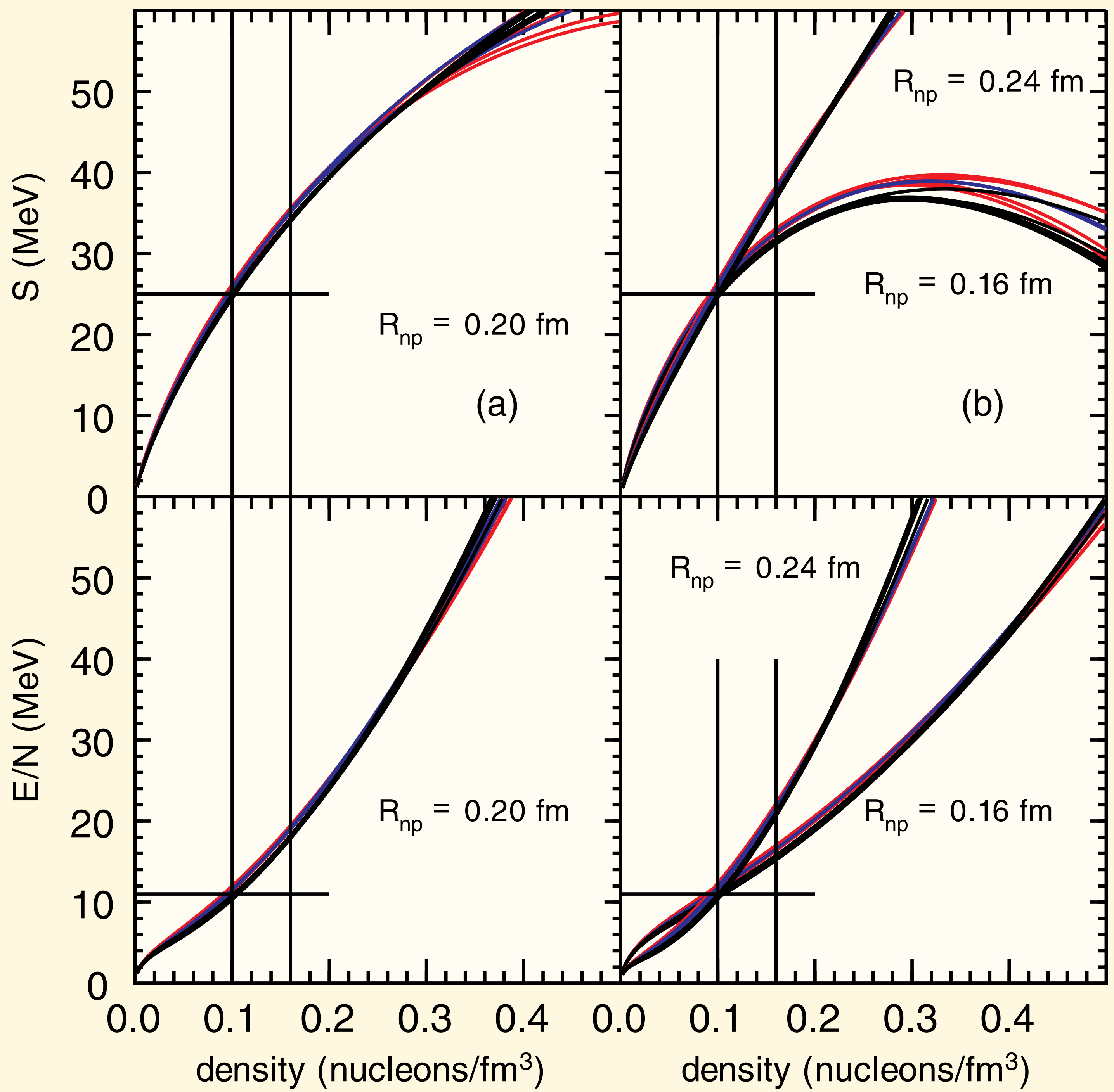
Skyrme models satisfying constraints | symmetry energy

Dutra et al. 2012



Skyrme models | fits to properties of doubly magic nuclei

B A Brown 2013; B A Brown & Schwenk 2014



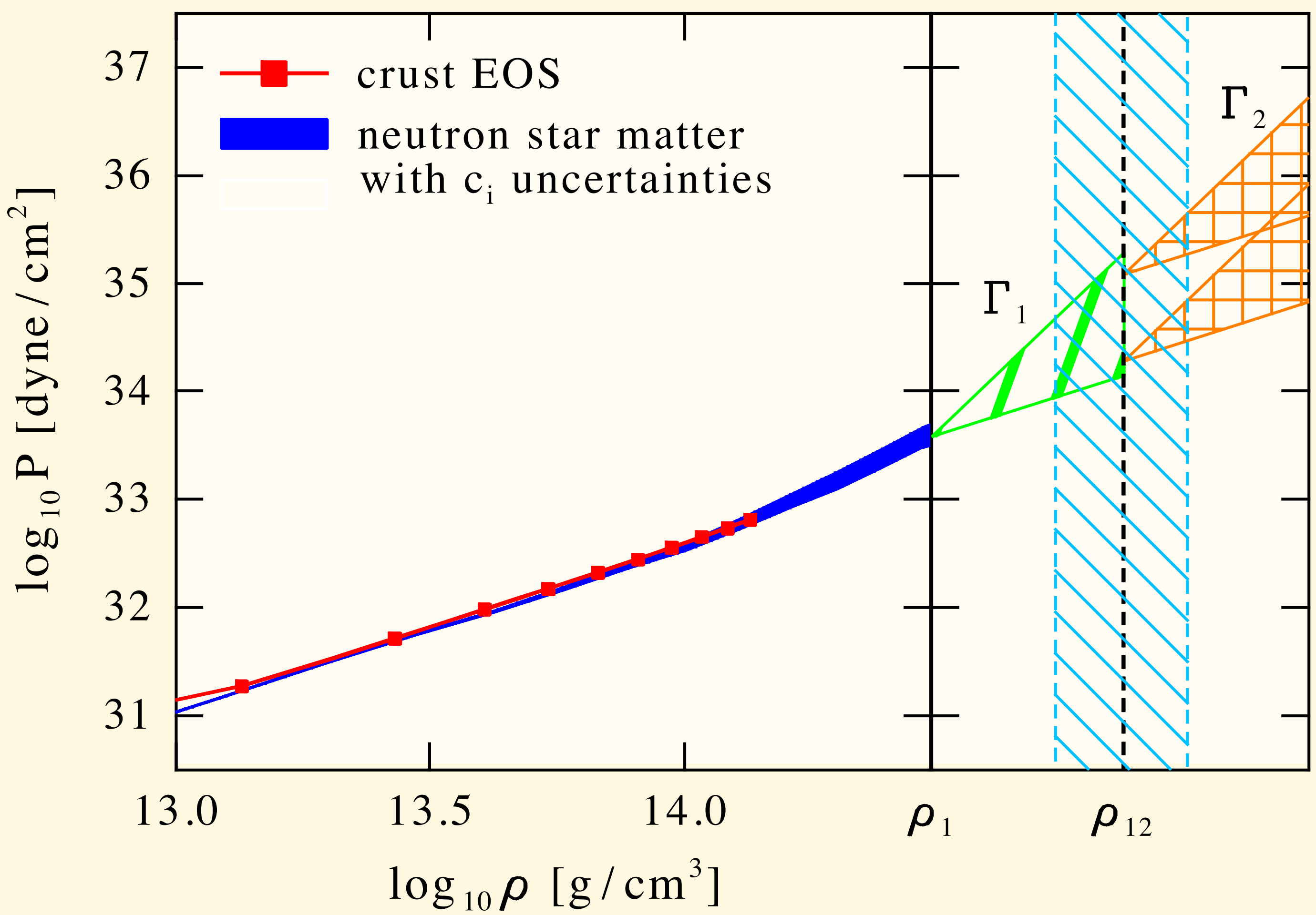
NB. $R_{np} = R_n - R_p$ for ^{208}Pb;
$R_{np} = 0.33^{+0.16}_{-0.18}$ fm
(Abrahamyan et al. '12)

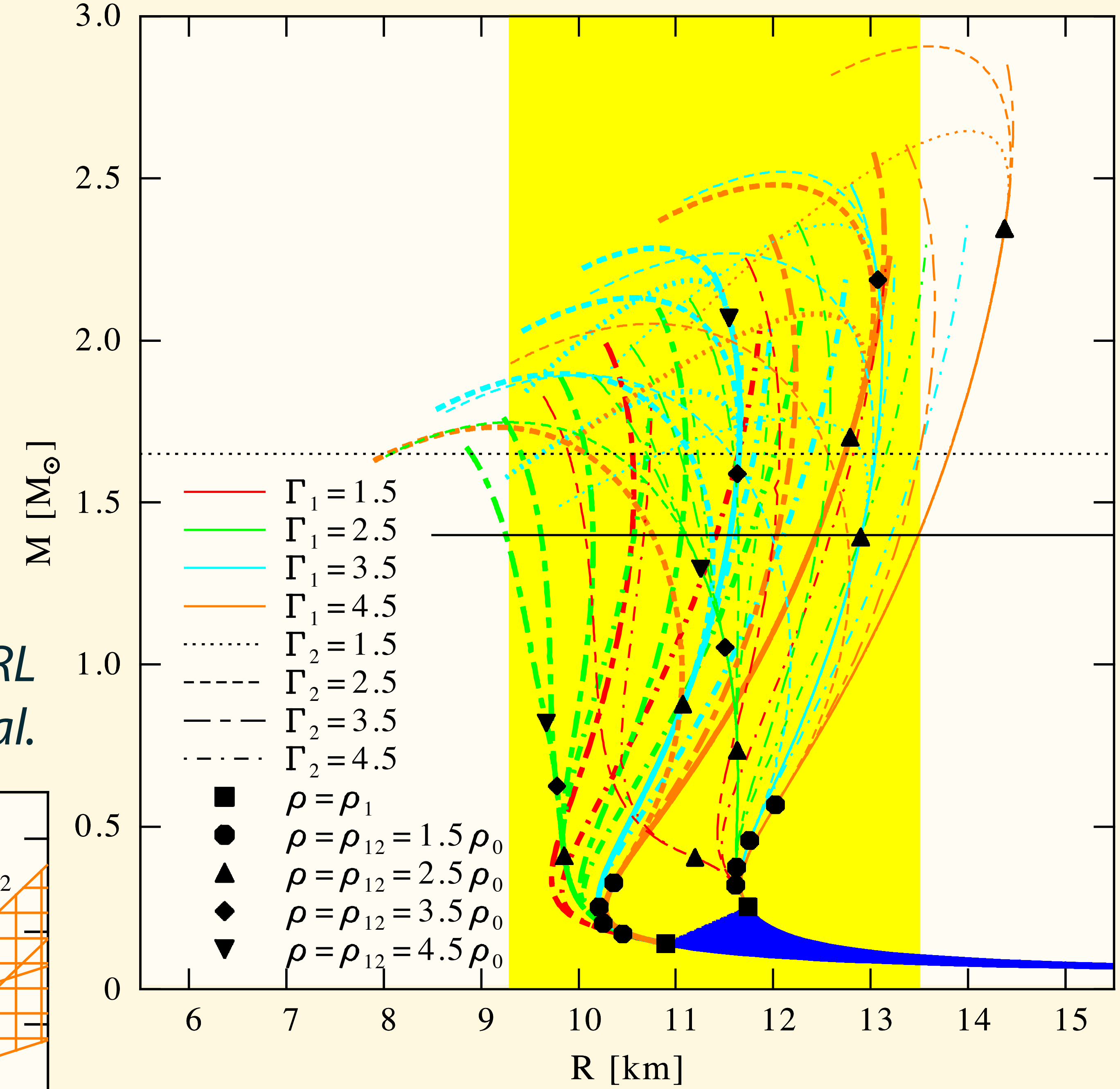
R_{np} is correlated with $P(\rho \approx 2/3\ \rho_0)$

PREx-II approved; will measure R_{np} to 0.05 fm

M, *R* from just nuclear physics…

Hebeler et al. (2010), PRL
EOS similar to results from QMC—Gandolfi et al.





NB. Predicts $R_{np} = 0.17 \pm 0.03$ fm

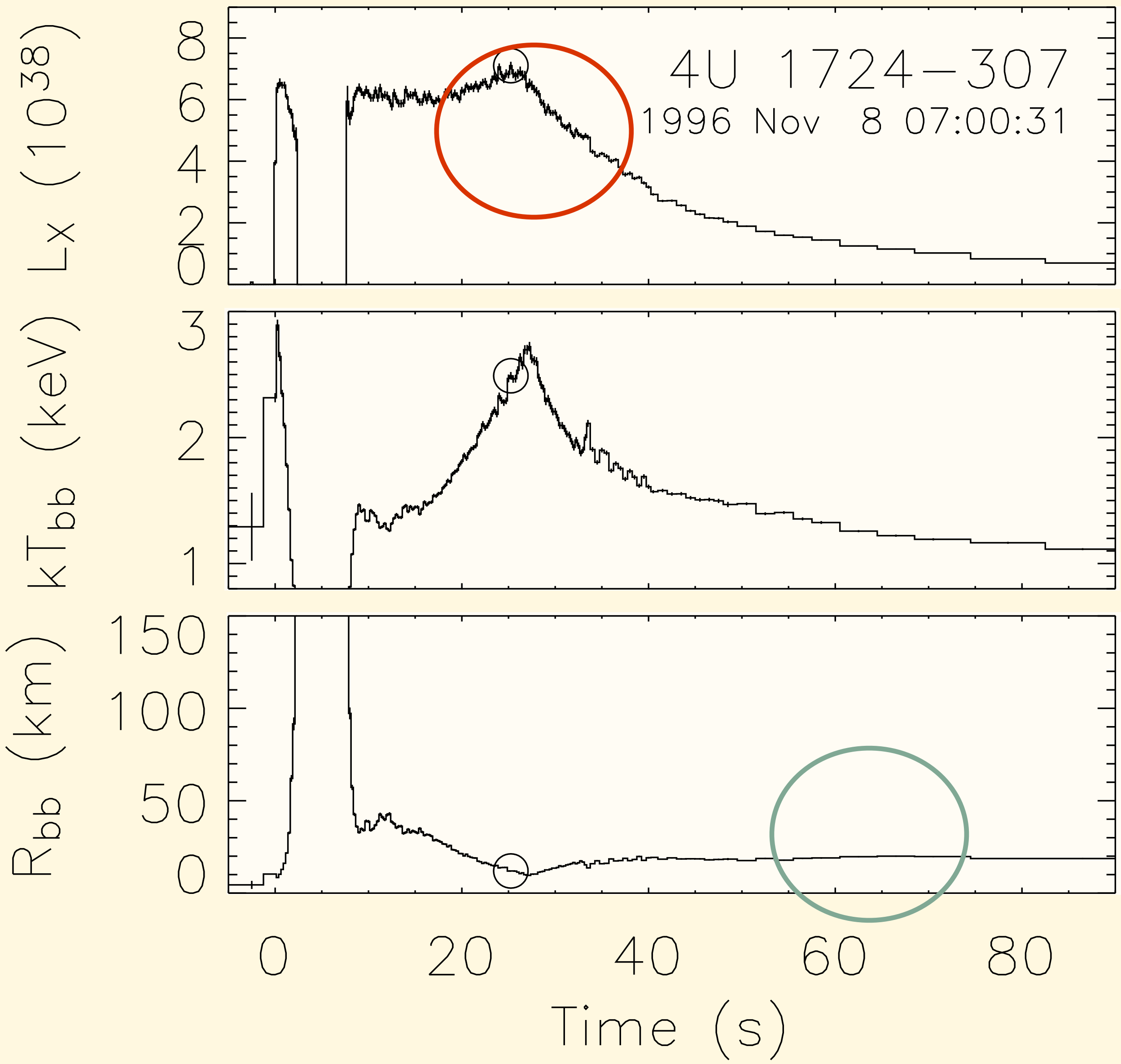
X-ray bursts | photosphere radius expansion (PRE)

van Paradijs '79; Özel '06, '09 and following; Steiner et al. '10, '13; cf. talk by Güver

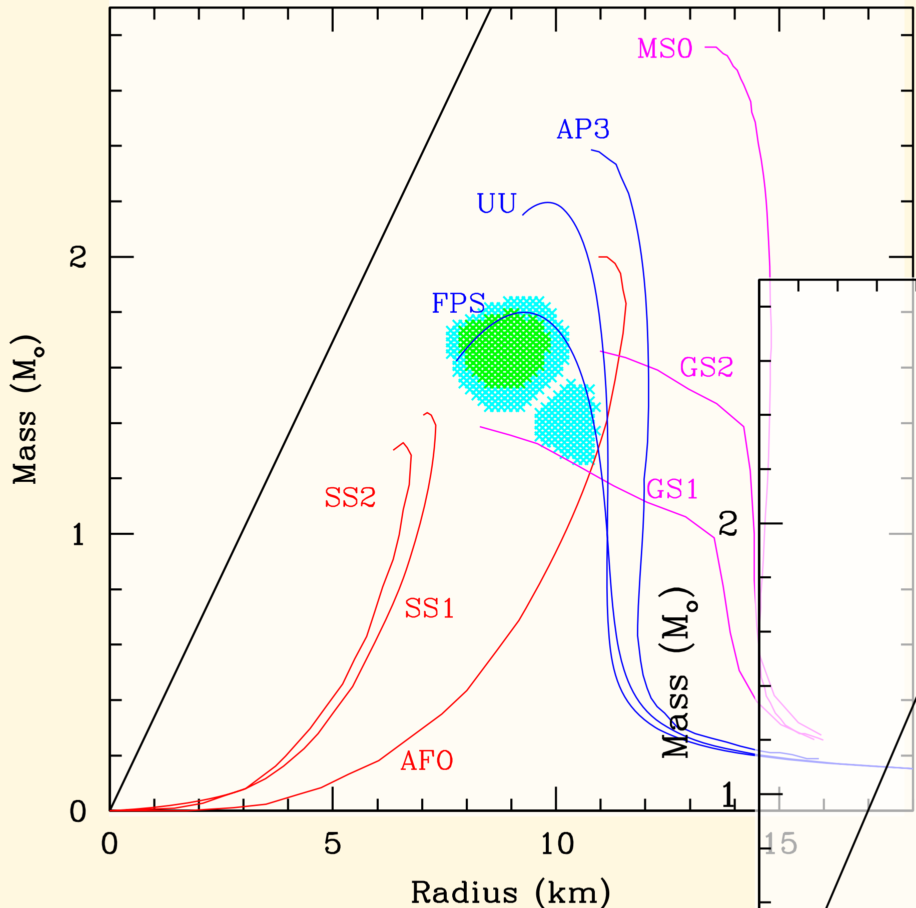
$$F_{\mathrm{TD}} = F_{\mathrm{Edd}} = \frac{GMc}{\kappa D^2}\left(1 - 2\frac{GM}{Rc^2}\right)^{1/2}$$

$$\frac{F}{\sigma T_{\mathrm{bb}}^4} = f_c^{-4}\left(\frac{R}{D}\right)^2\left(1 - 2\frac{GM}{Rc^2}\right)^{-1}$$

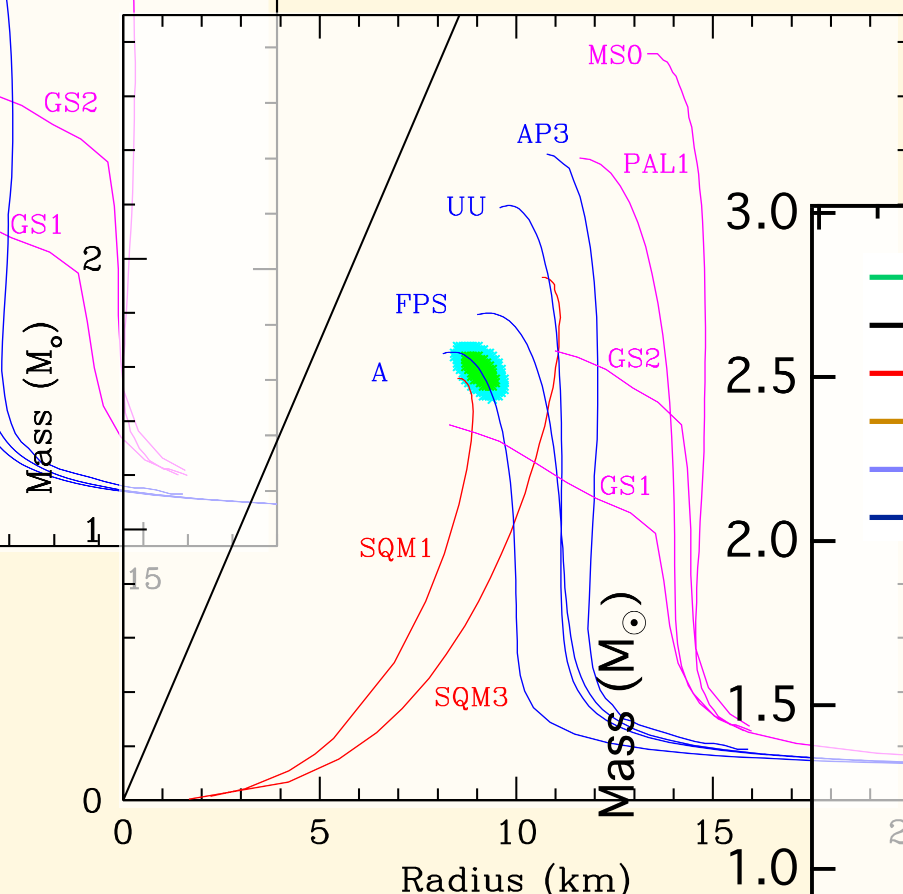
RXTE observations; Galloway et al. '08



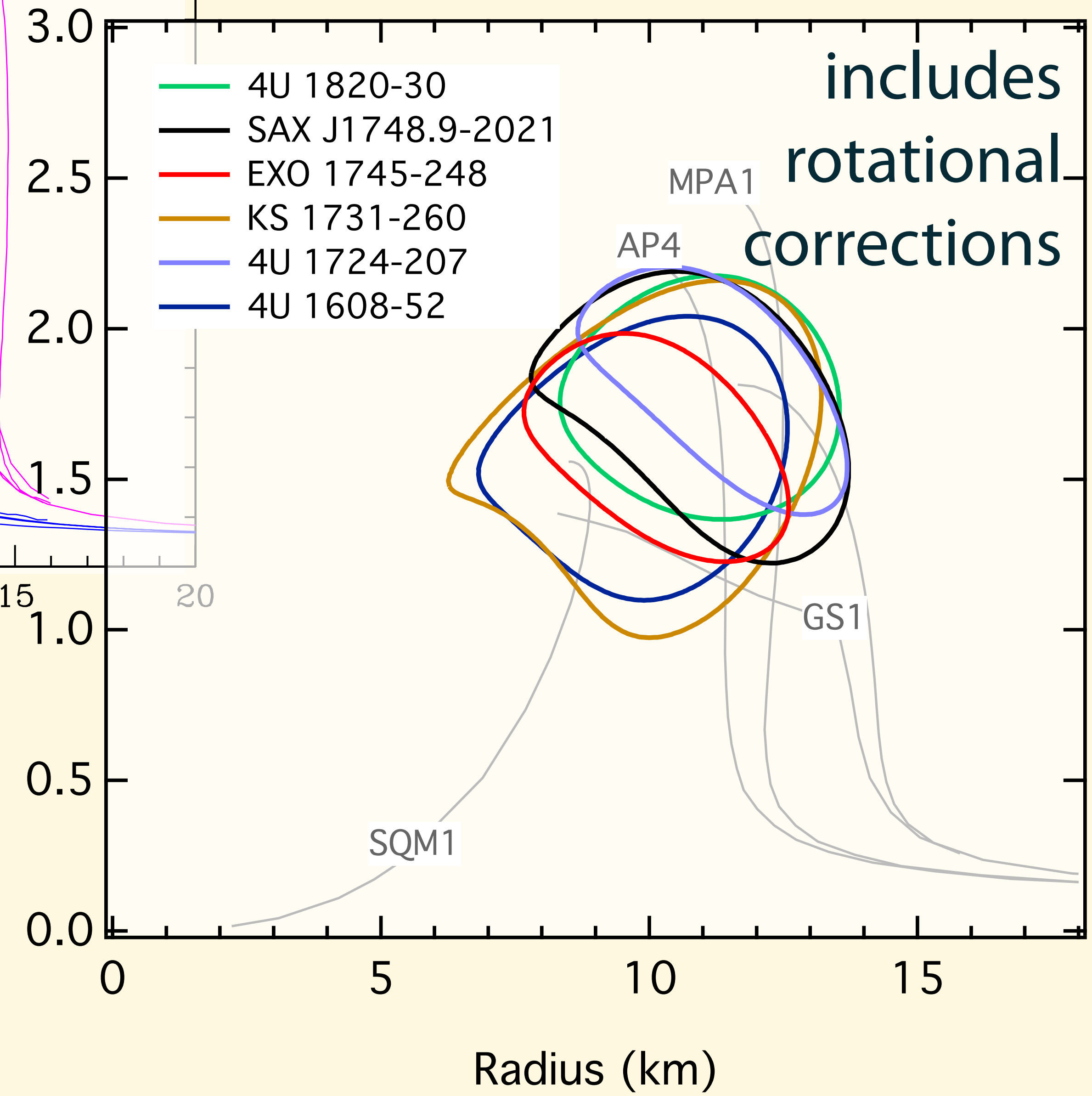
EXO 1745; Özel et al. '09



4U 1820; Güver et al. '10

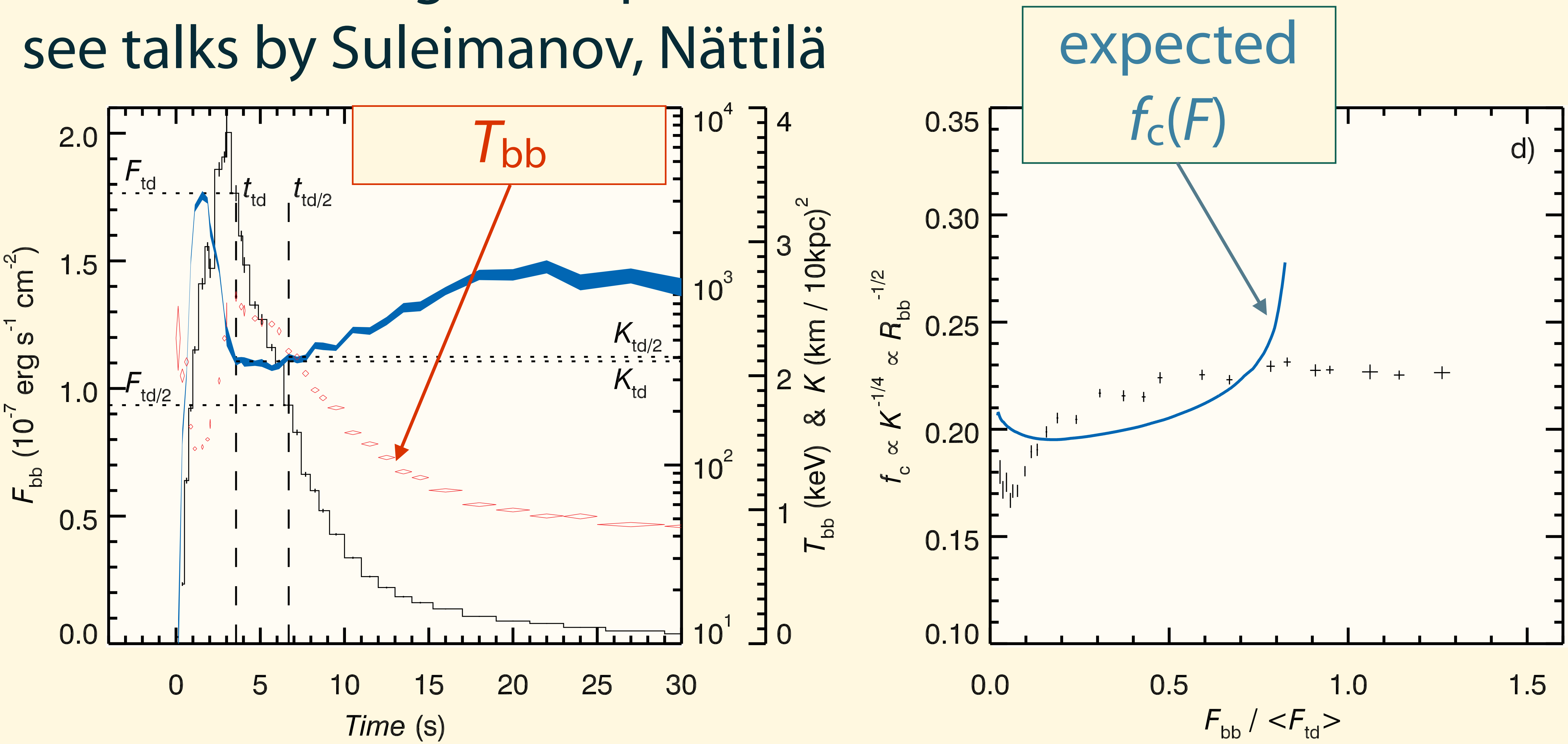


Özel et al. '15



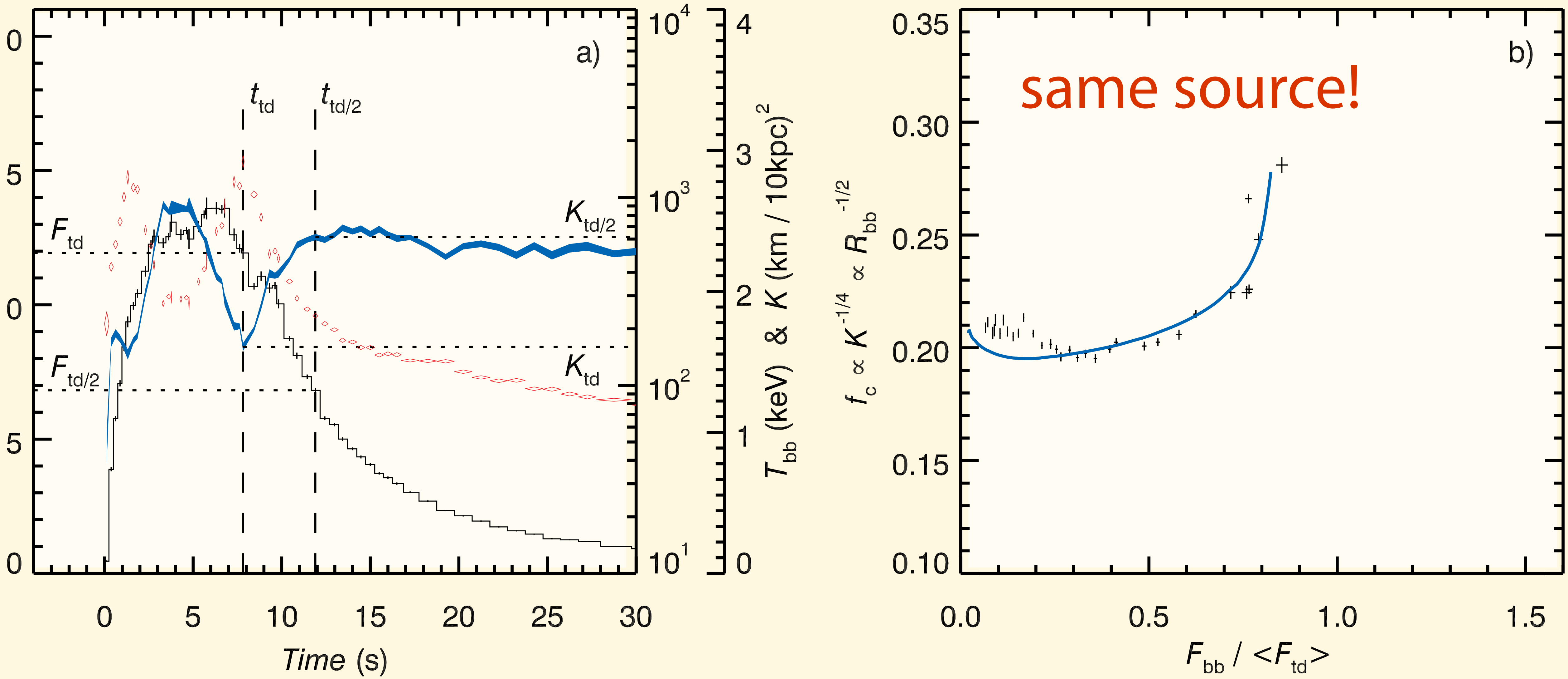
Systematics | Evolution of T_{bb}/T_{eff}

accretion during tail important;
see talks by Suleimanov, Nättilä



Kajava et al. 14

models do work for some bursts

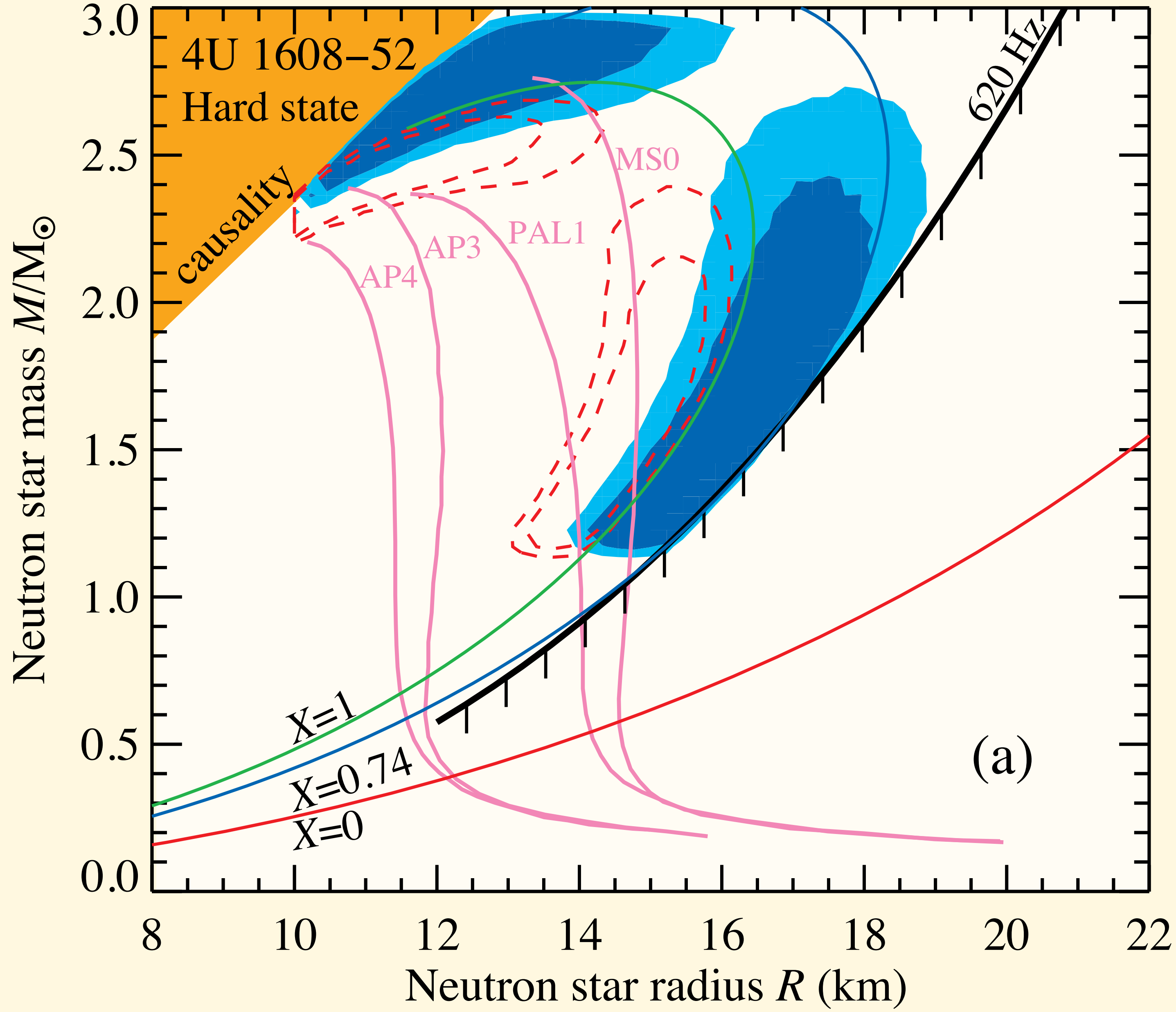


Kajava et al. '14

fits to spectral evolution of the burst

see talk by Nättilä

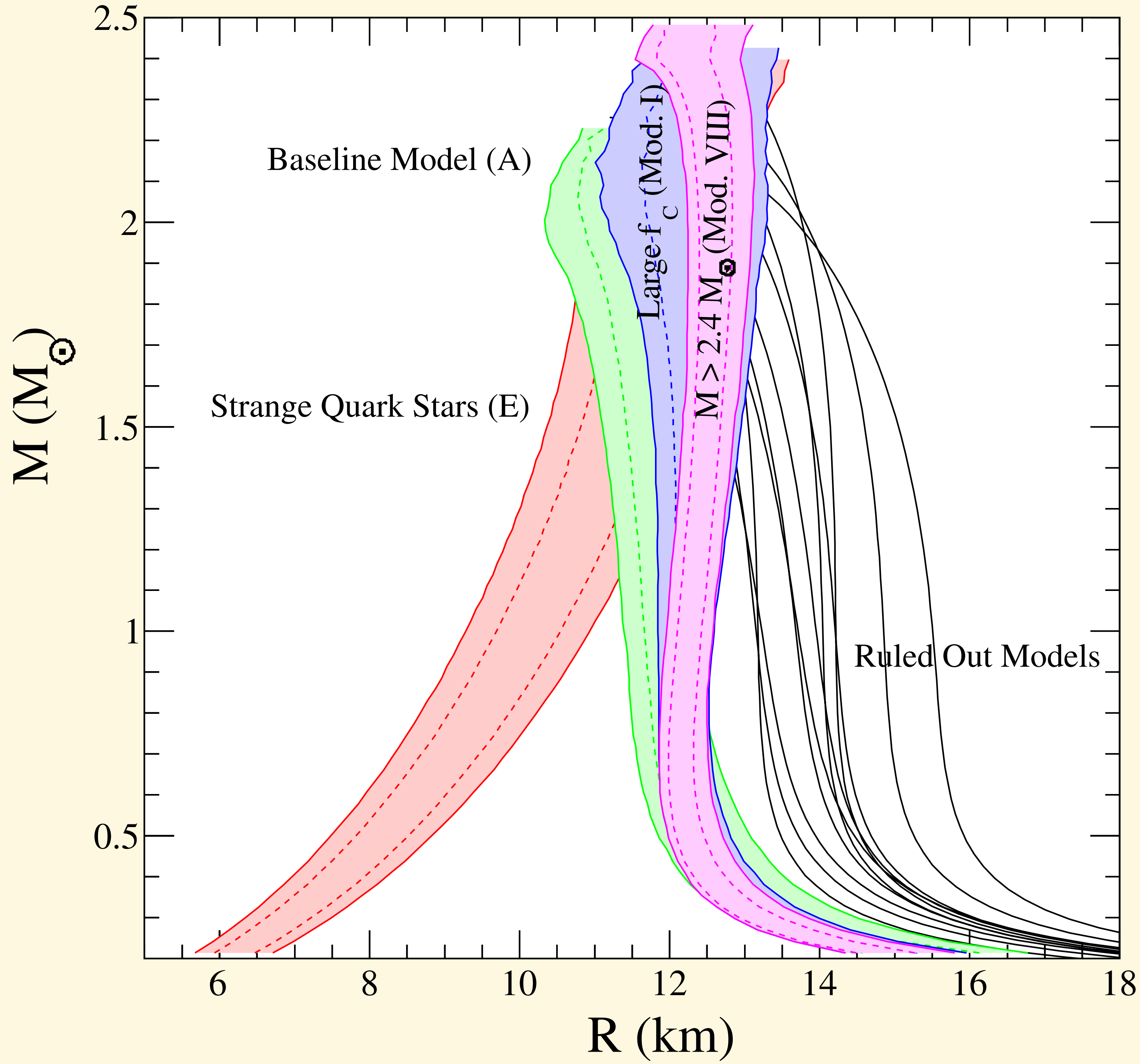
Poutanen et al. '14



Fit over PRE sources, transients

Parameterization of EOS contributes $\approx \pm 0.8$ km to $R_{1.4}$

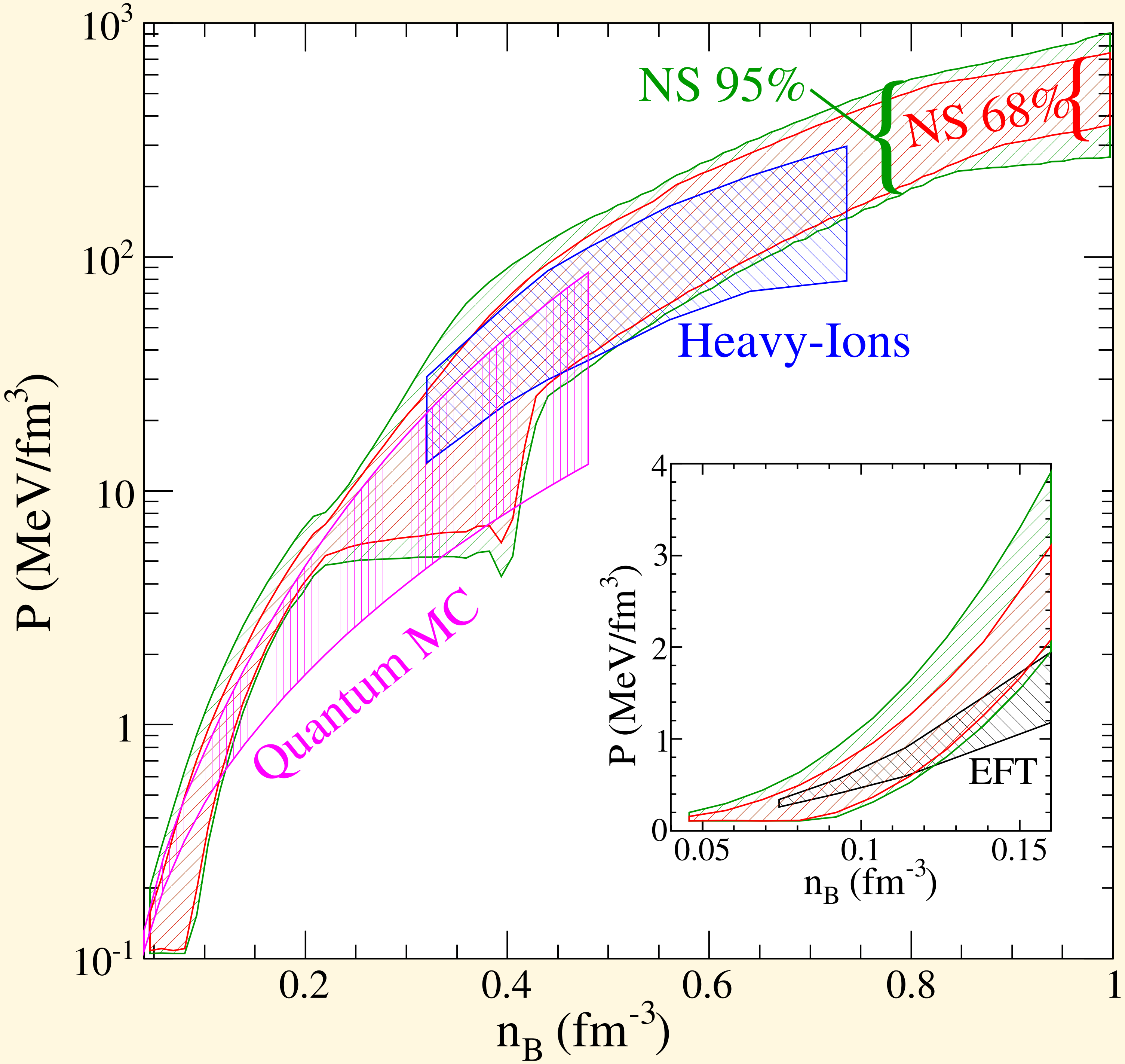
cf. talks by Güver, Mendez



Steiner et al. '13

comparison with nuclear physics theory, experiment

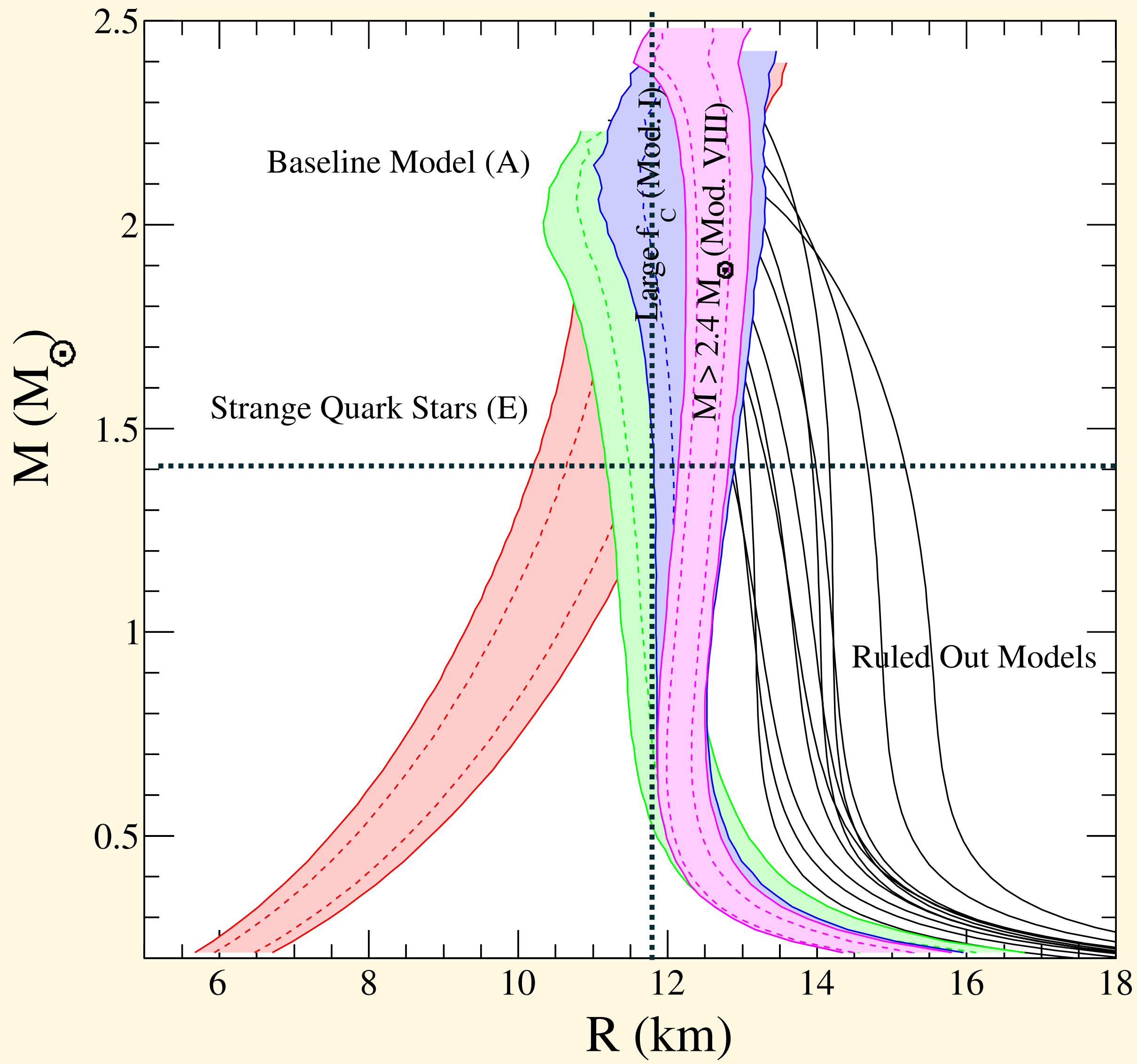
Steiner et al. '13



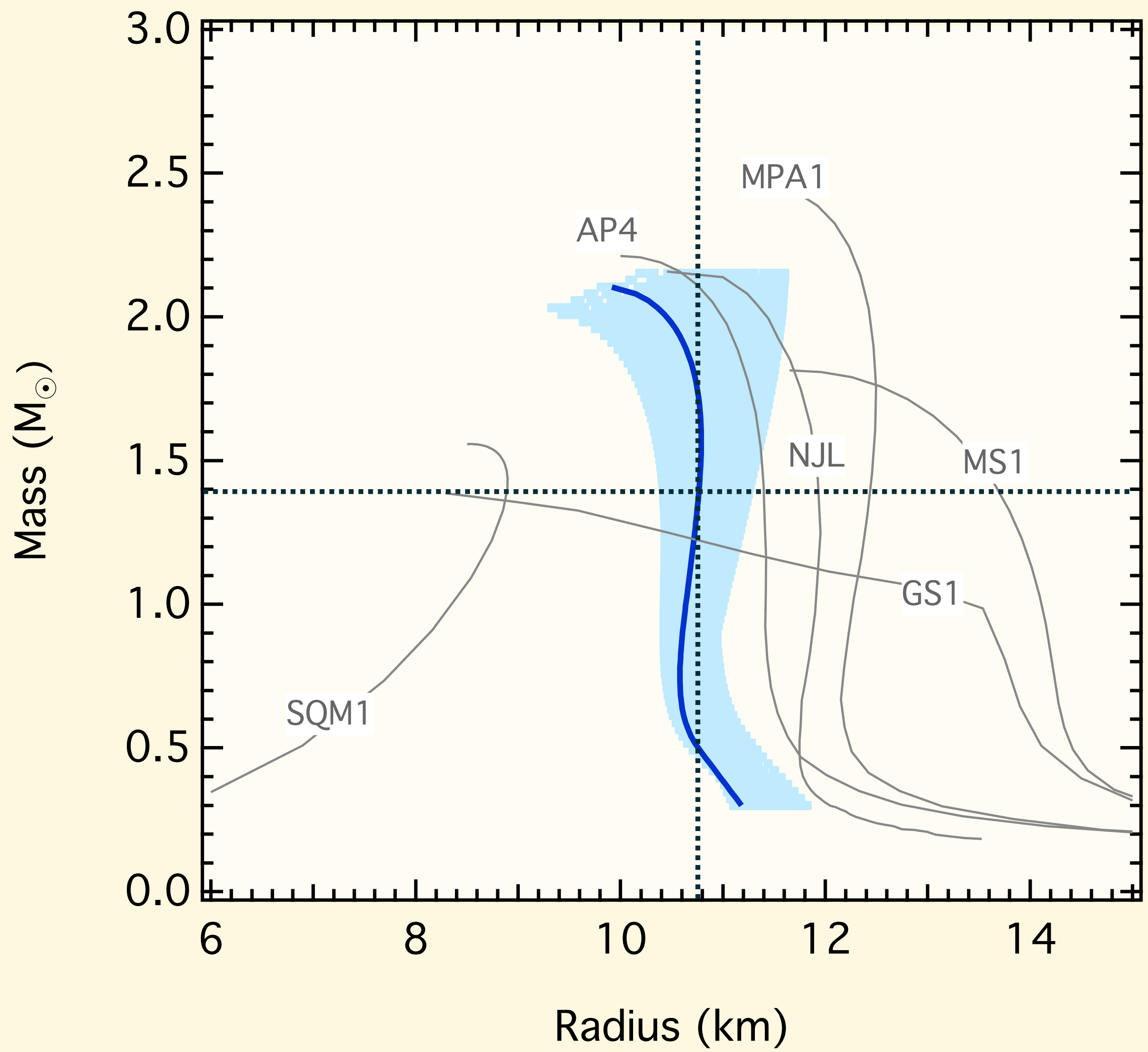
NB. $R_{\rm np} = 0.15 \pm 0.02$ fm

Fit over PRE sources, transients

Steiner et al. '13

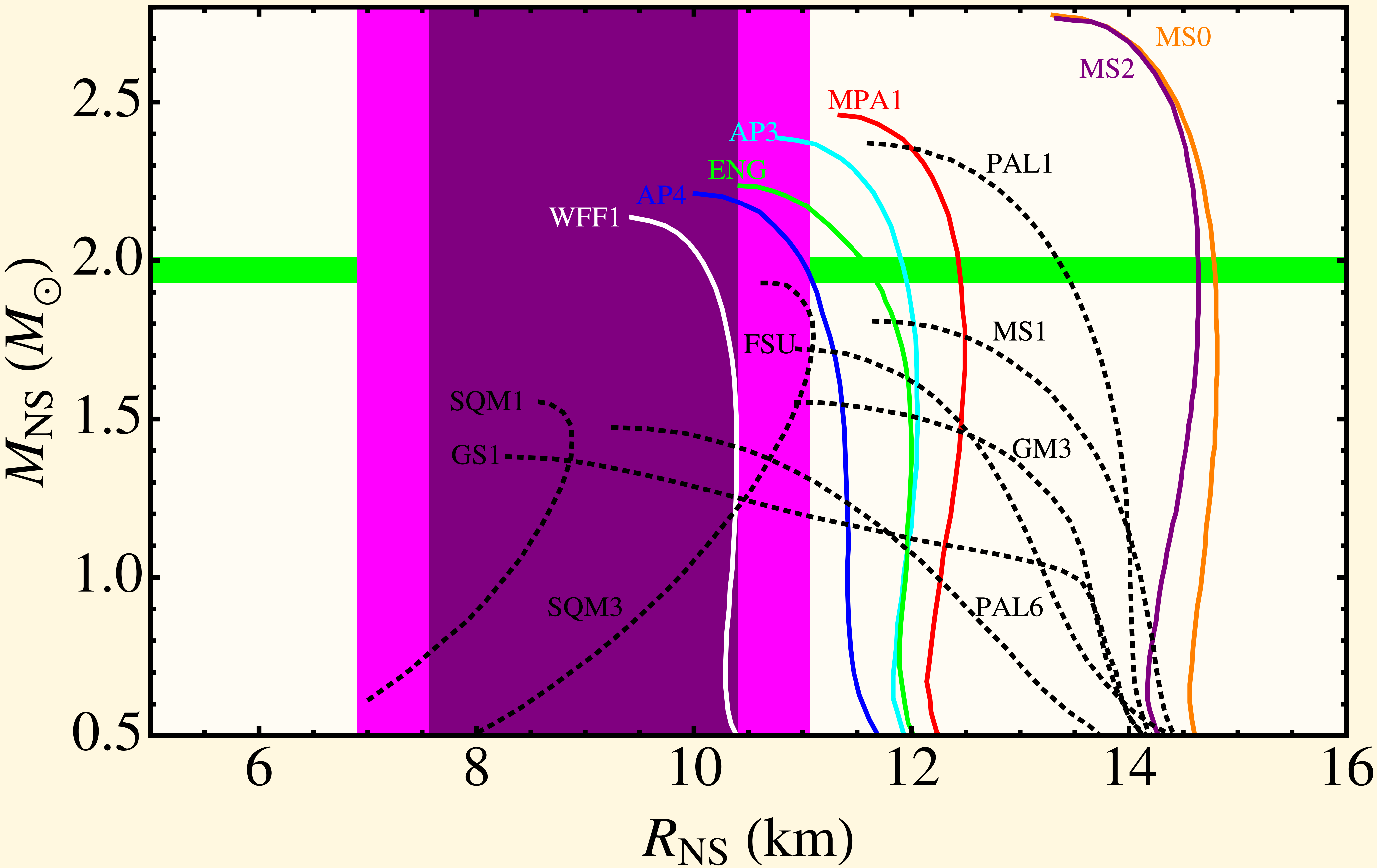


Özel et al. '15

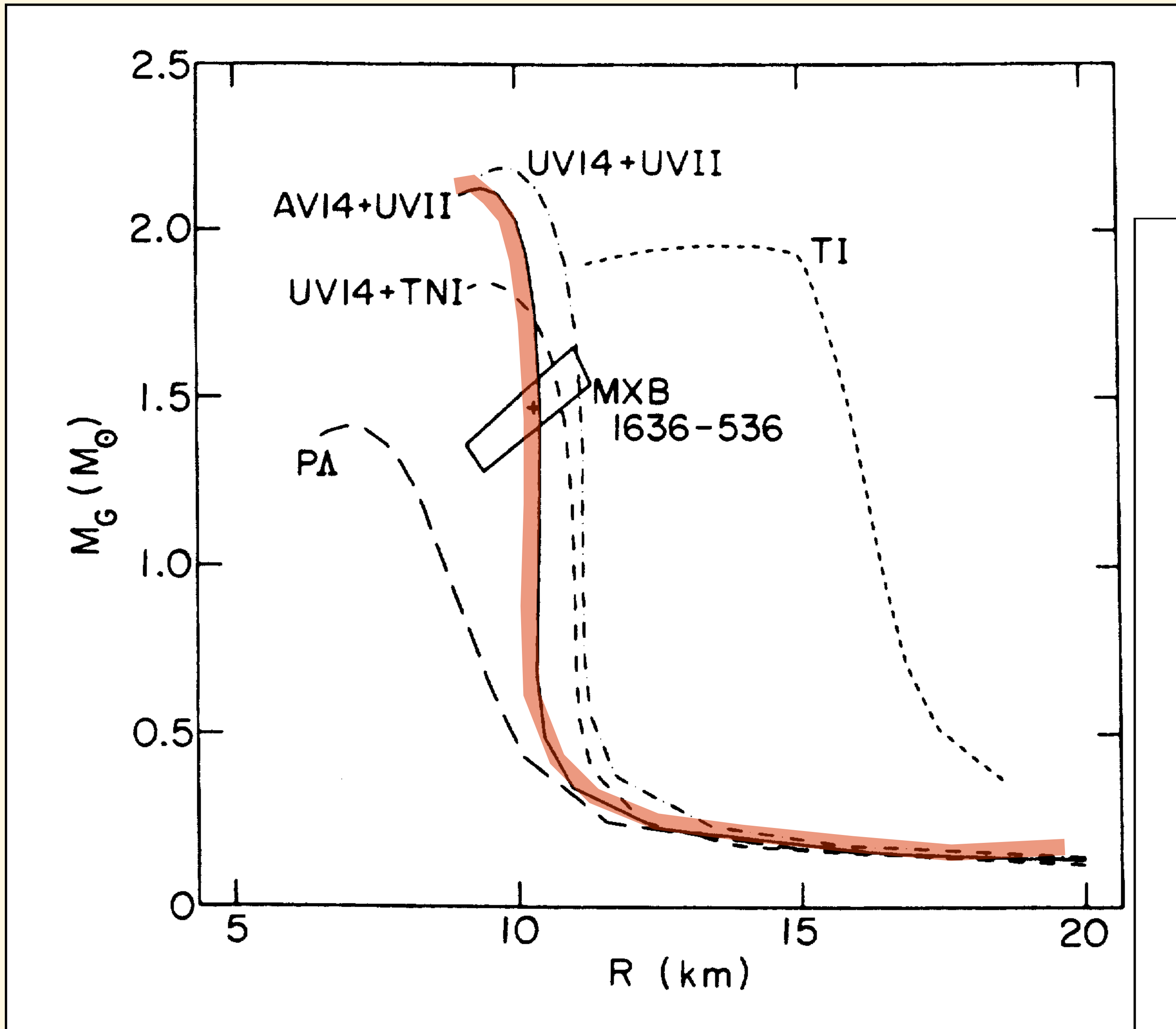


Fit to quiescent transients with *R* held constant | *R* = $9.1^{+1.3}_{-1.5}$ km

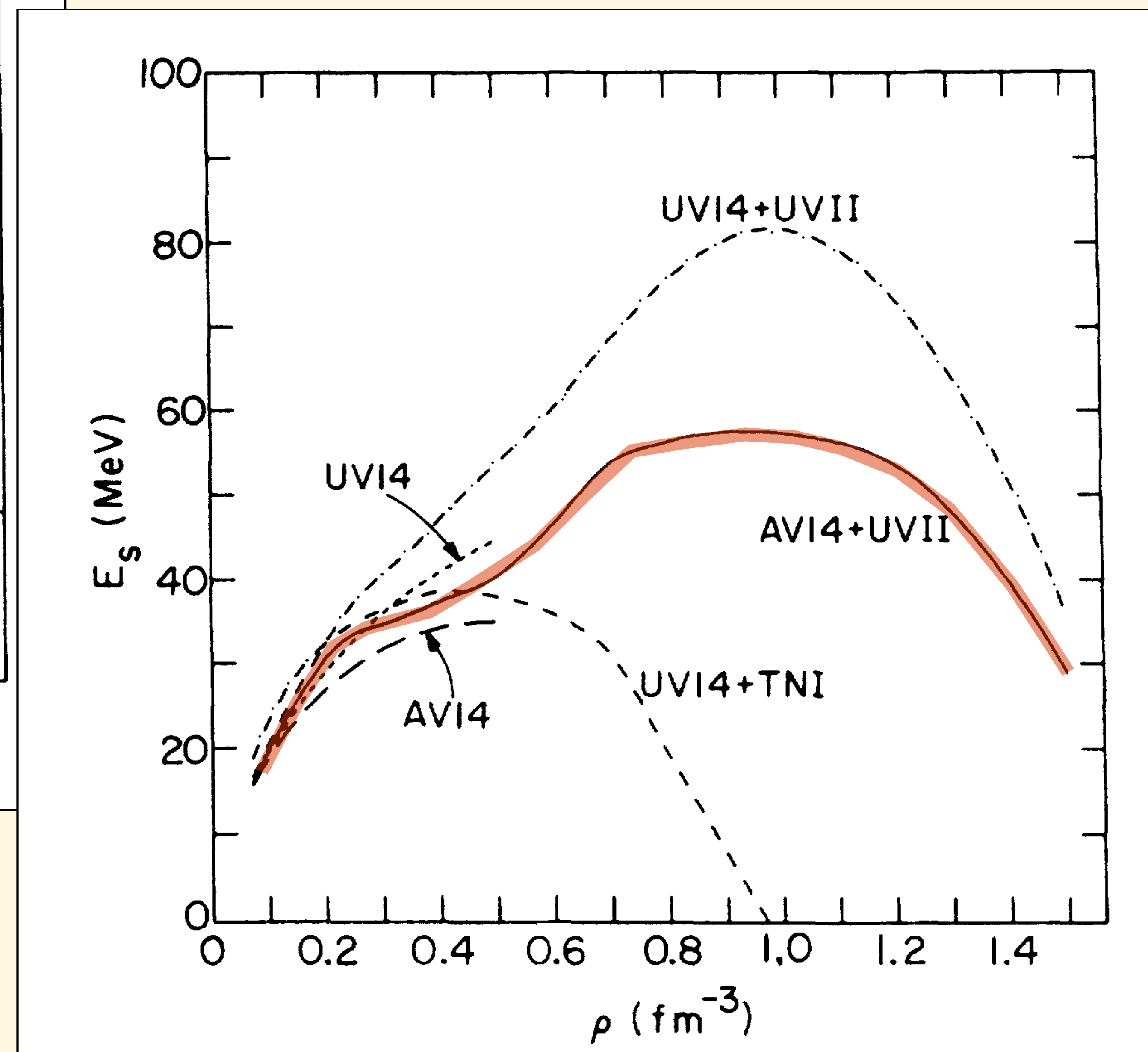
Guillot et al. '13; cf Heinke et al., '14



Implication of small *R* | AV14+UVII

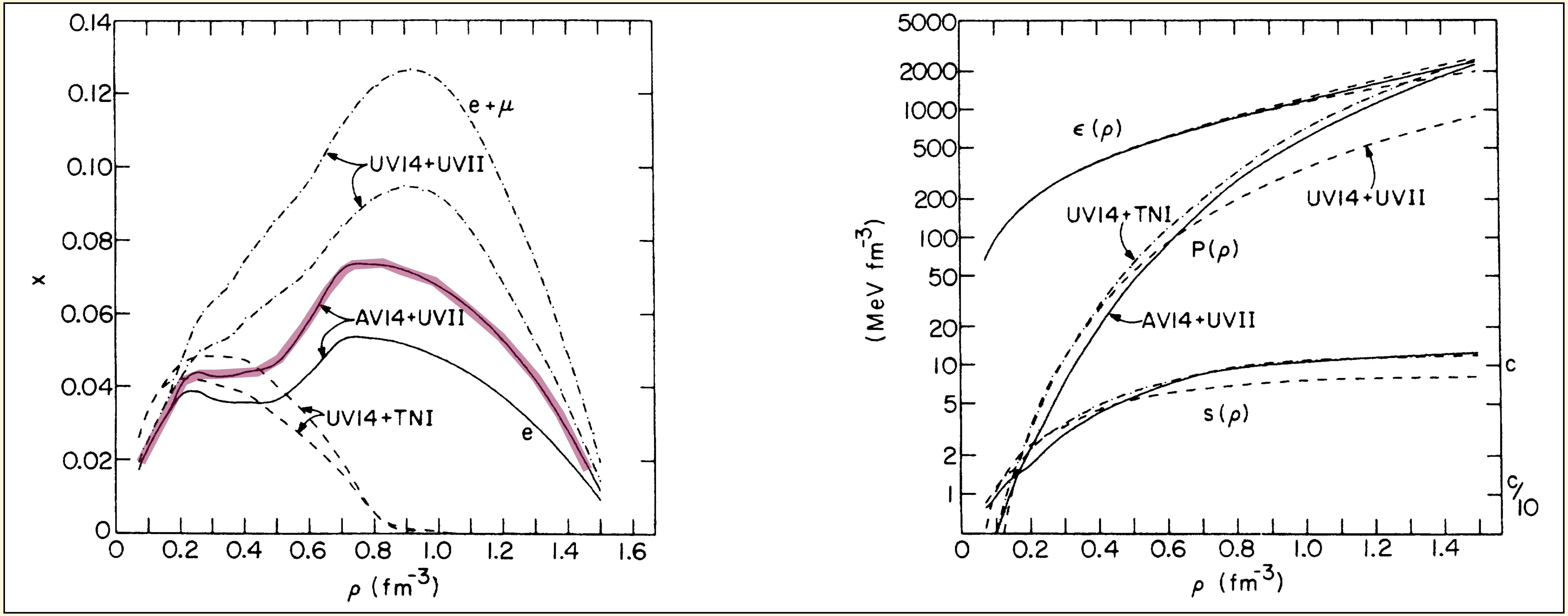


Wiringa, Fiks, & Fabrocini 1988



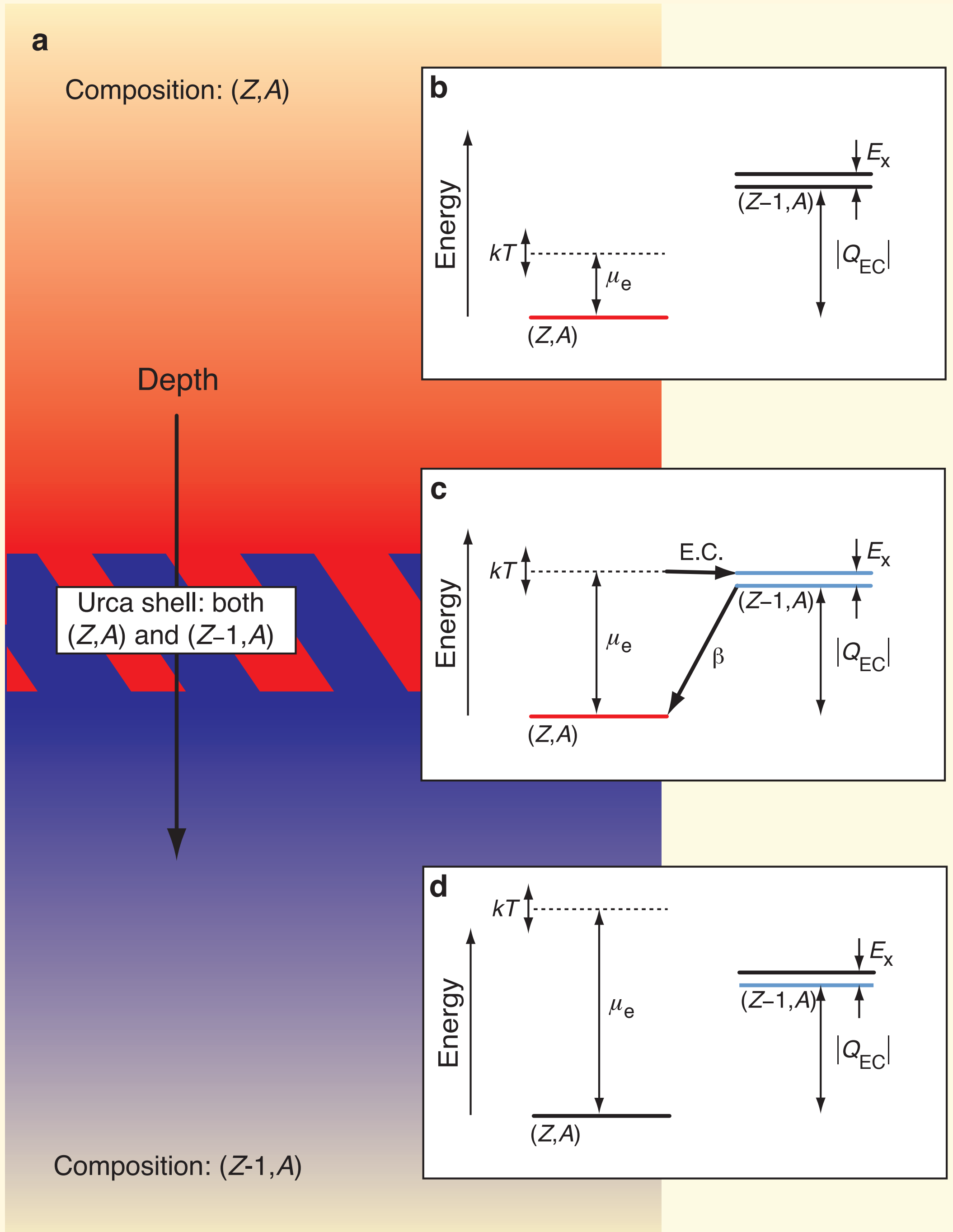
AV14+UVII | proton fraction

Wiringa, Fiks, & Fabrocini 1988

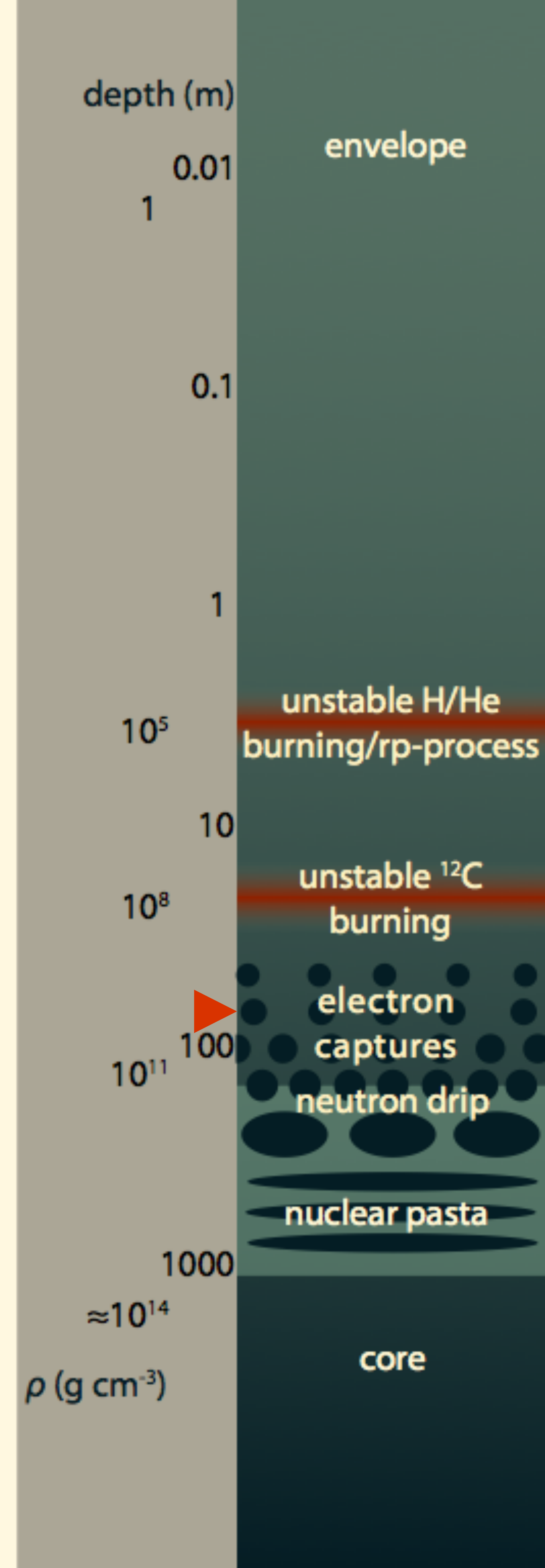


$x > 0.11$ allows rapid neutrino cooling

Electron capture/β– decay cycles cool the crust



Schatz et al., '14, Nature



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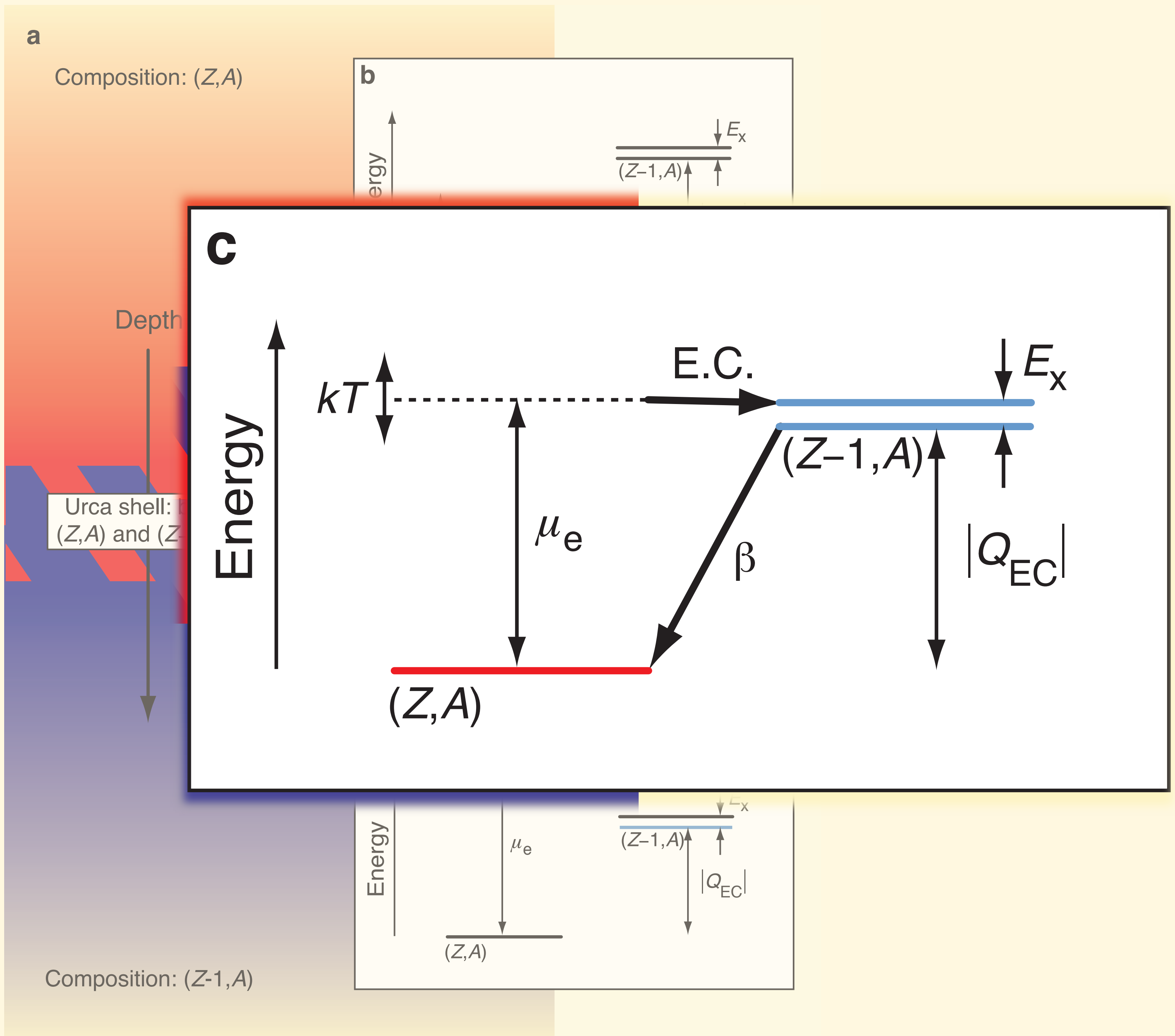
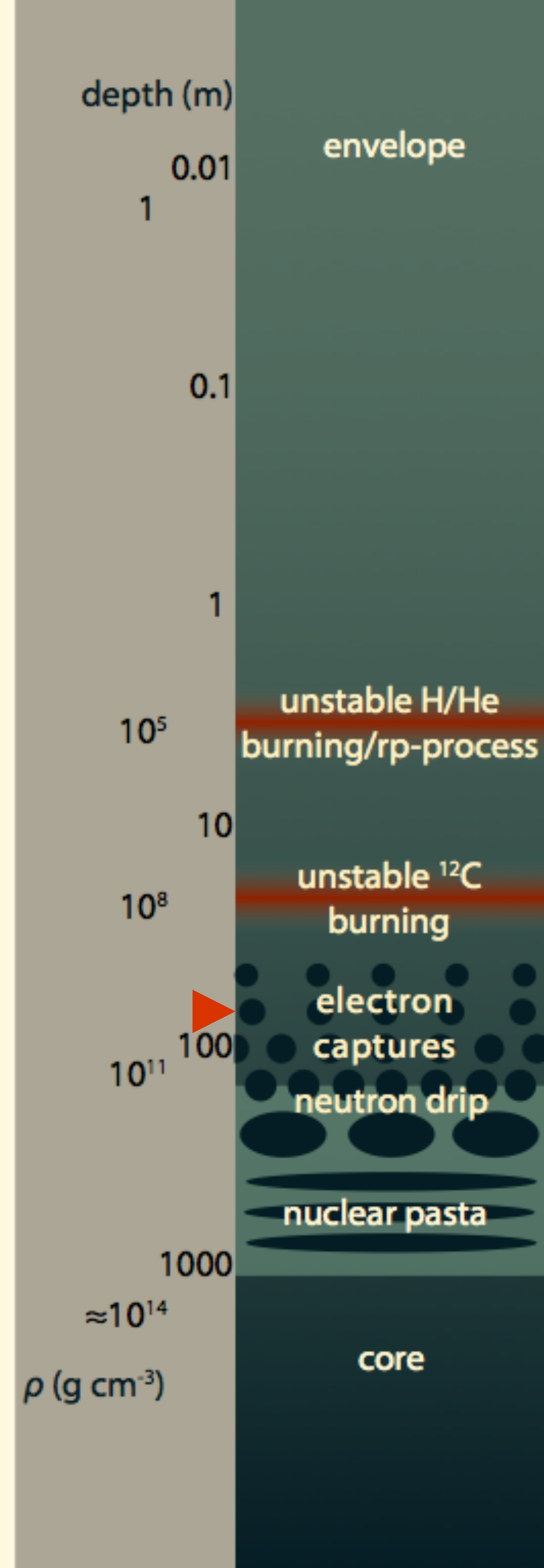
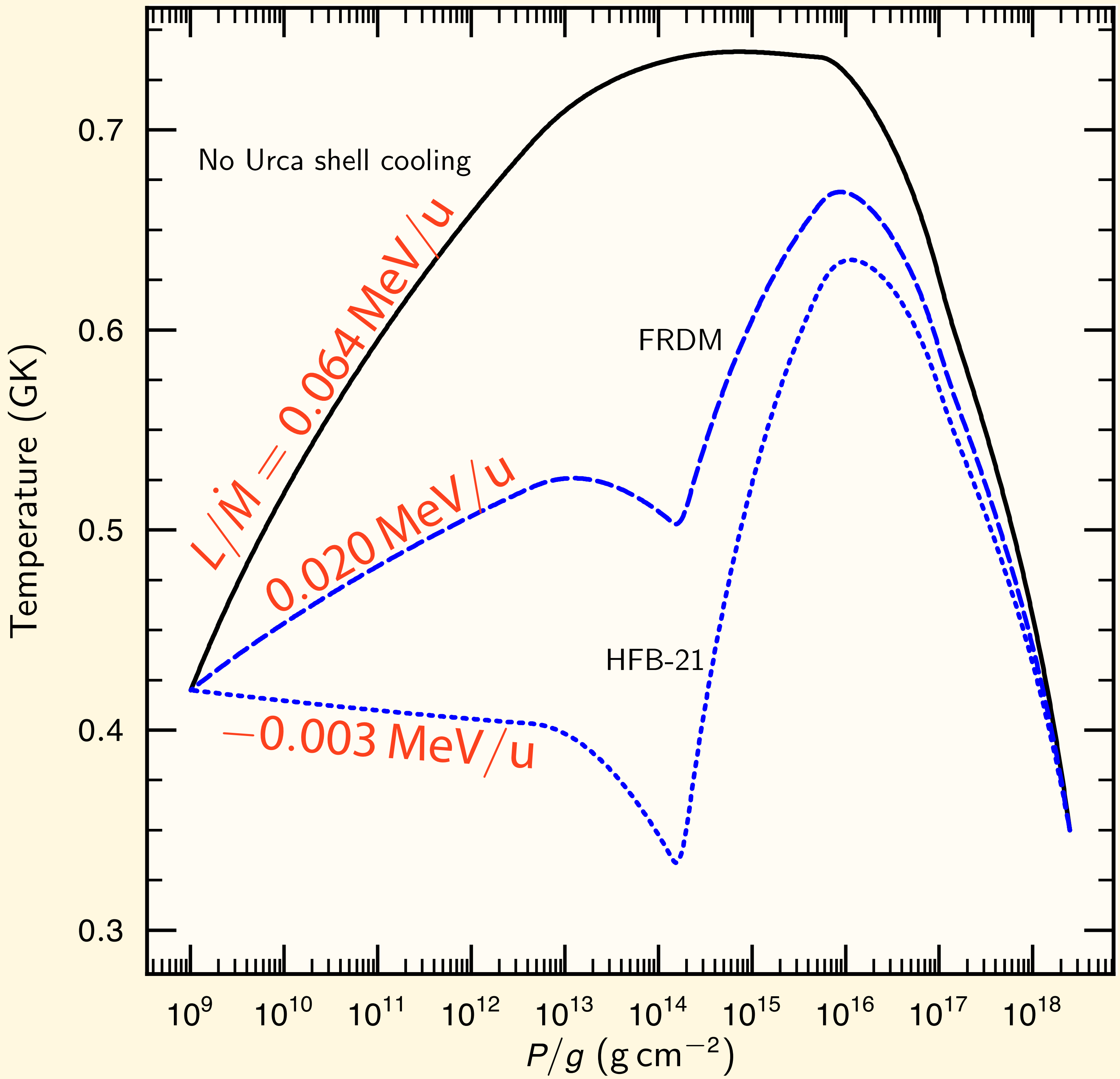


Schatz et al., '14, Nature

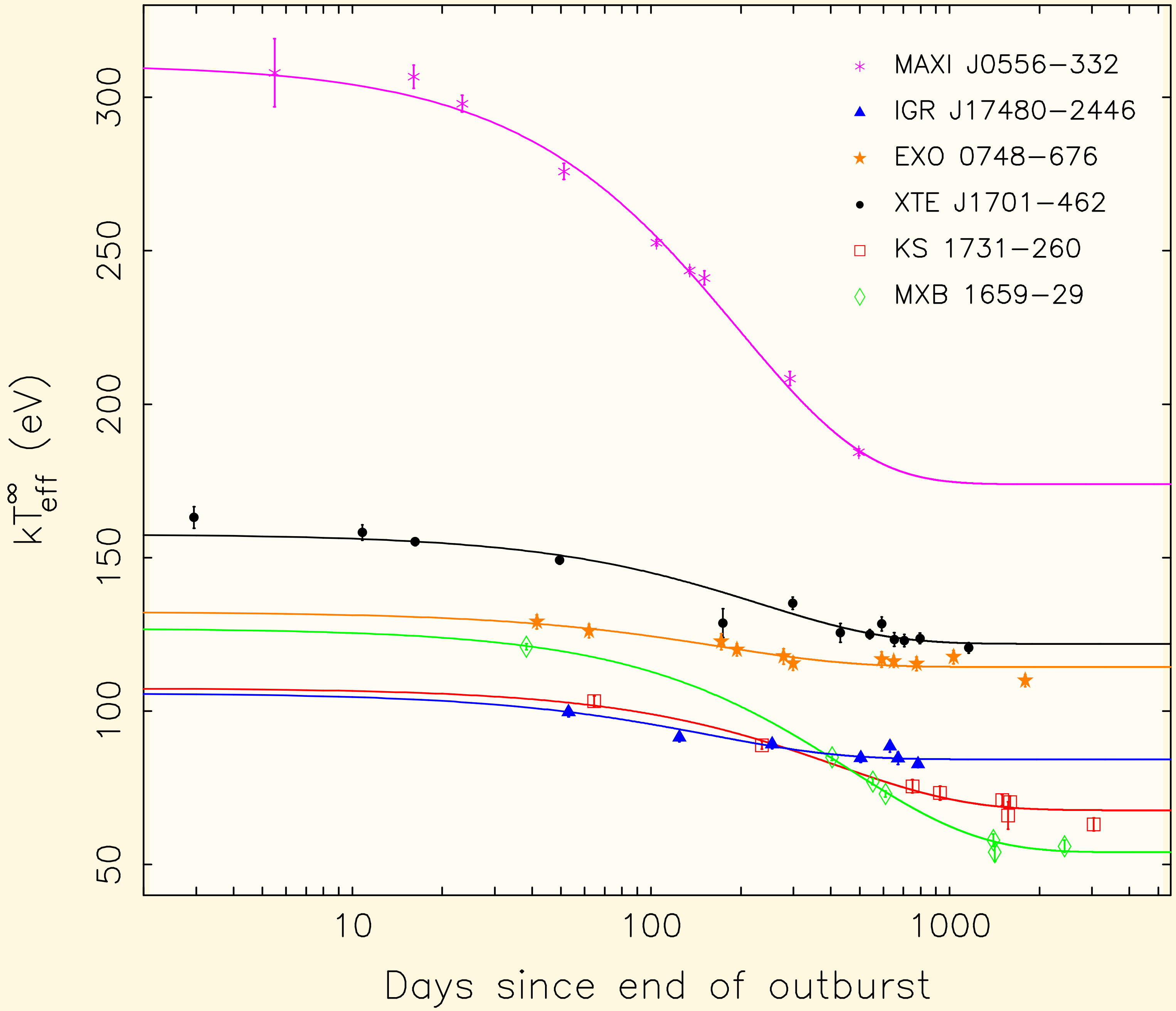


Neutrino emission thermally decouples atmosphere from crust



MAXI J0556-332: A rapidly accreting hot transient

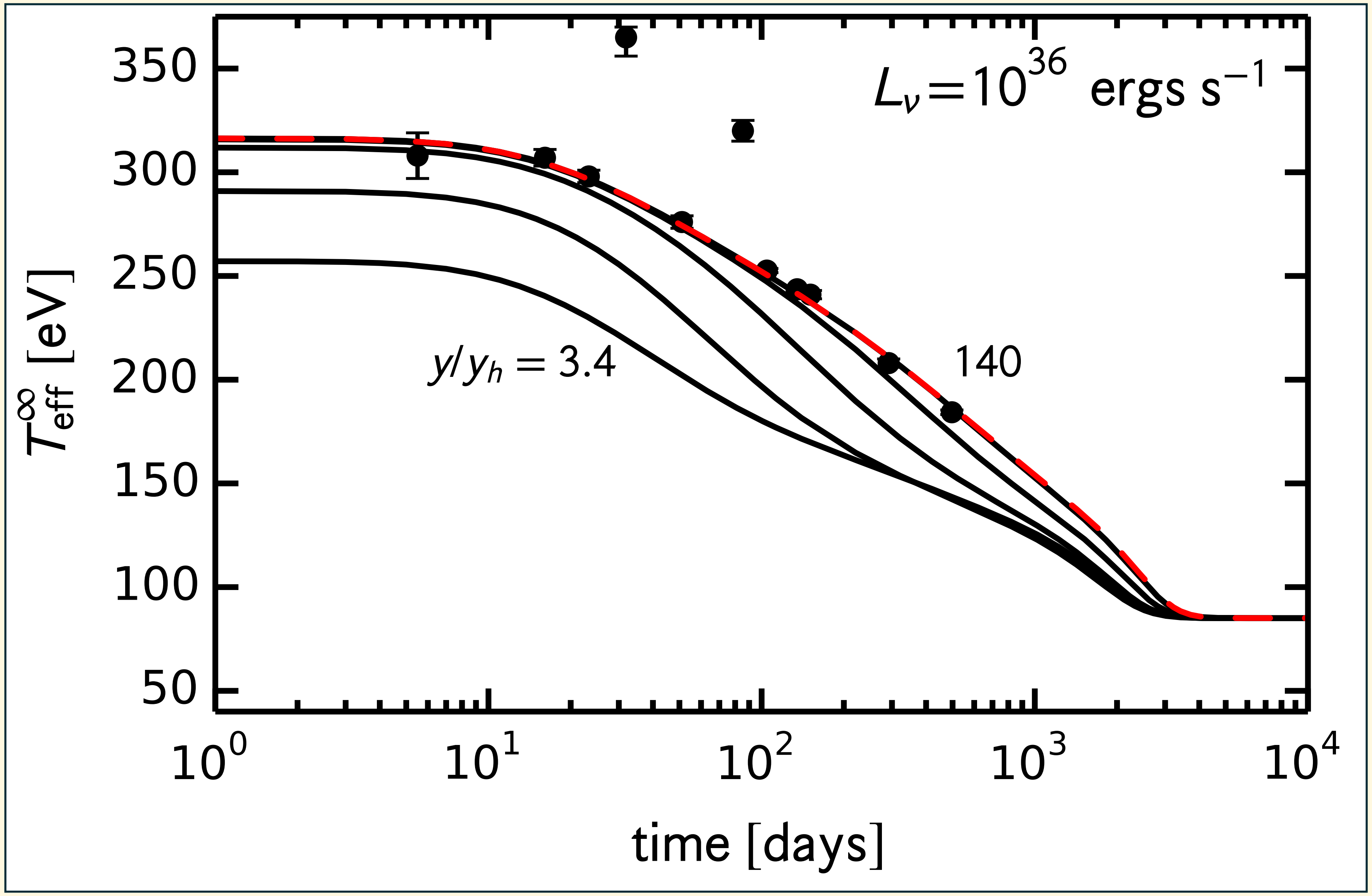
Homan et al. '14



cf. talk by Wijnands

Electron capture/β– decay cycles are not required to fit light curve

Deibel et al., 2014



Consistent with recent measurements of $A = 56$ masses; Meisel & Schatz

lightcurves computed with open-source code
https://github.com/nworbde/dStar

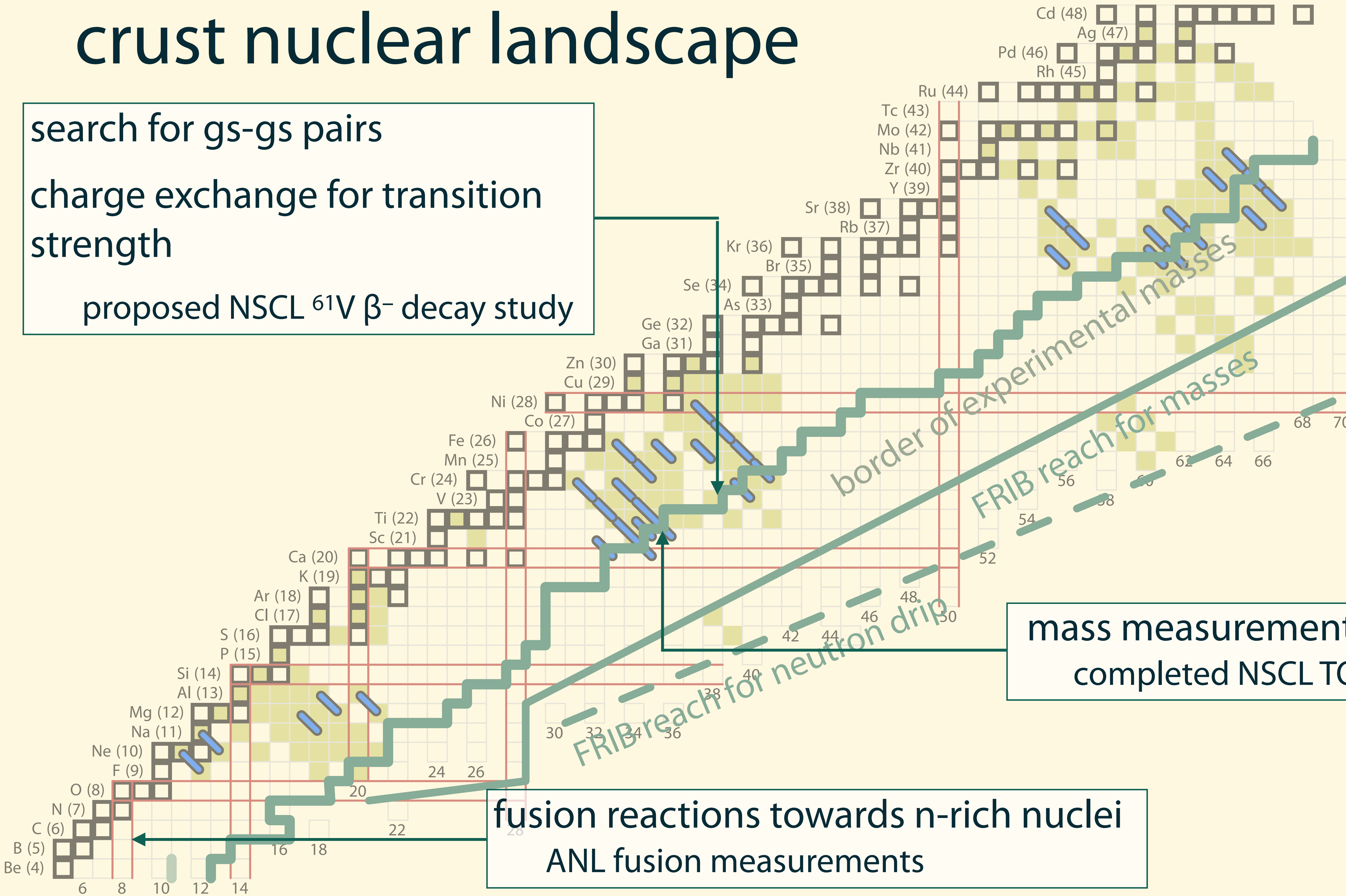
Facility for Rare Isotope Beams

JINA/JINA-CEE experiments across the crust nuclear landscape

search for gs-gs pairs

charge exchange for transition strength

proposed NSCL ^{61}V β^- decay study



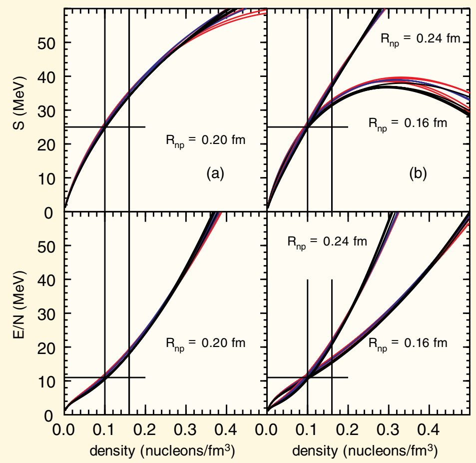
mass measurements

completed NSCL TOF

fusion reactions towards n-rich nuclei

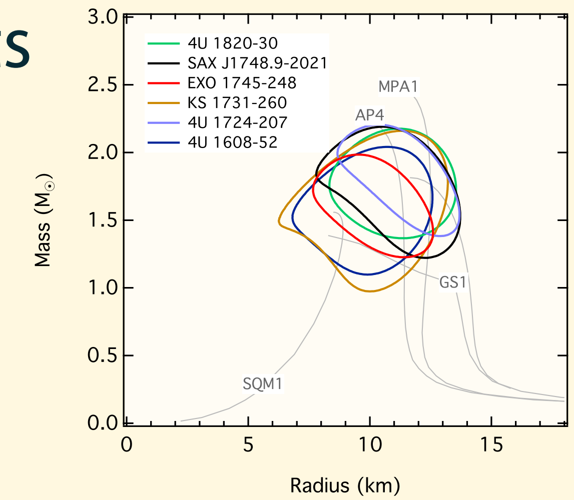
ANL fusion measurements

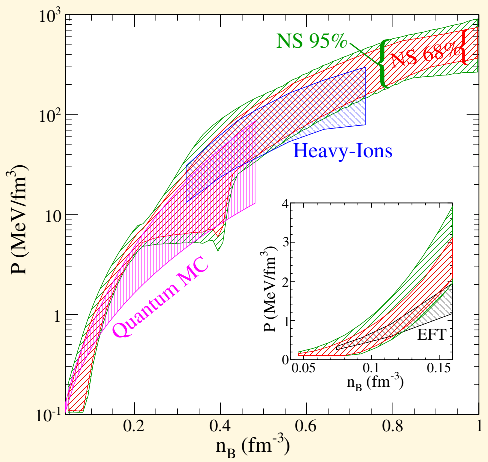
In summary—



Experimental & theoretical constraints on low-density EOS; plus

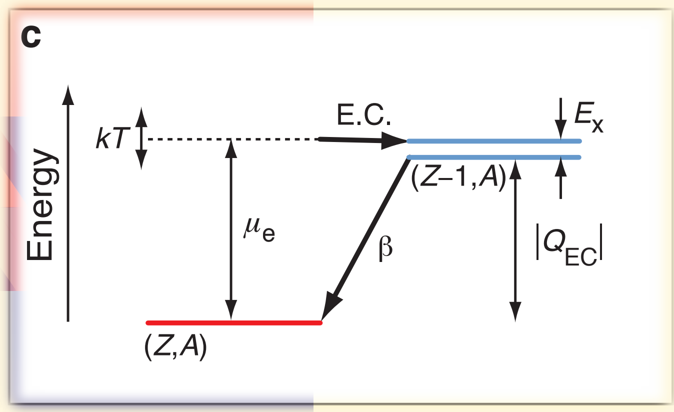
M, *R* measurements from PRE bursts and transients





determine the EOS at several times nuclear density.

Electron capture/β– decay cycles can thermally decouple the burst layer from the interior;



new facilities, such as FRIB, will explore properties of neutron-rich nuclei found in crust.