CONSTRAINING THE DENSE MATTER EQUATION OF STATE

WITH ACCRETING NEUTRON STARS

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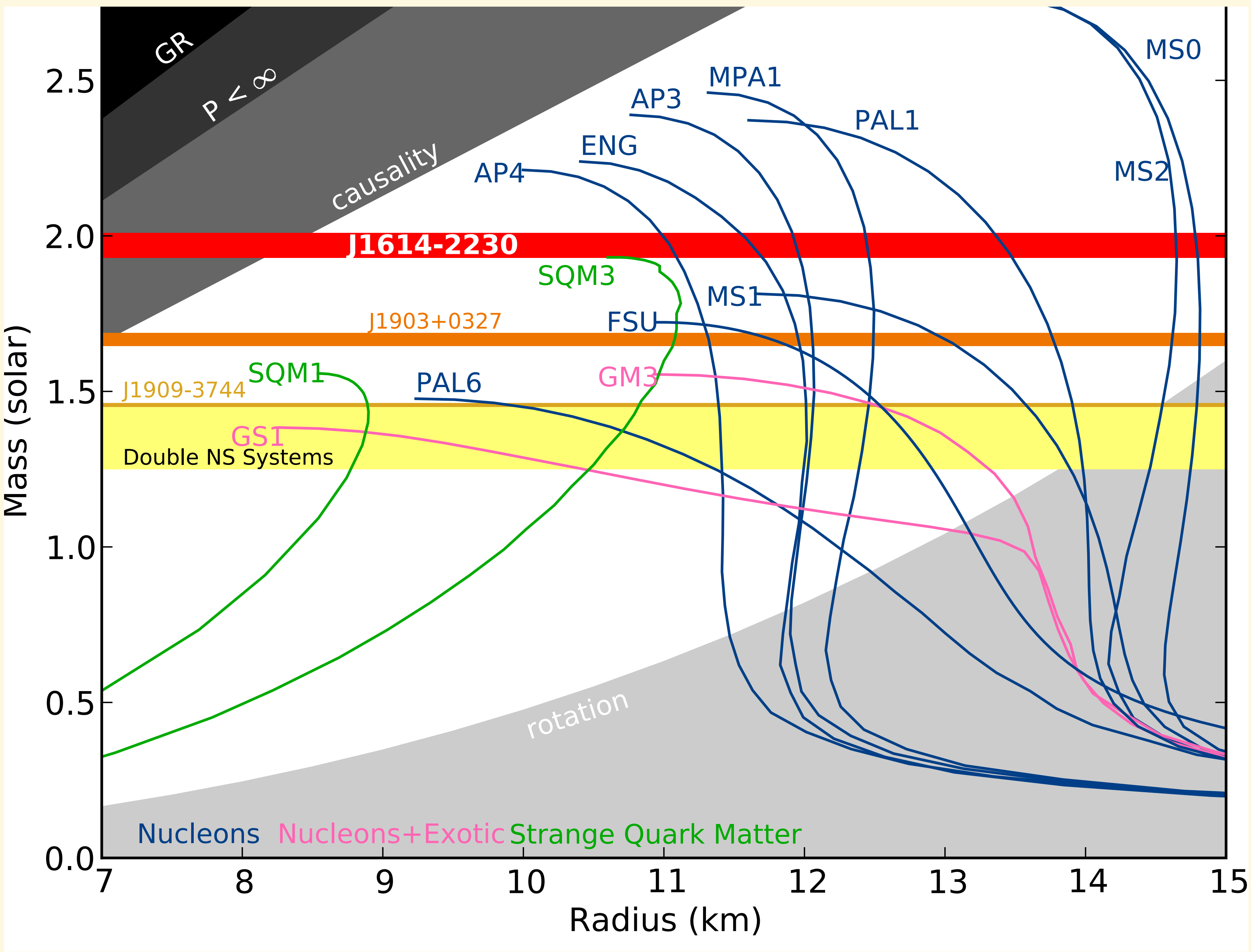
Further reading: 1401.5839, 1510.07515, and references therein

$M_{max} > 2\ M_{sun}$

Demorest et al. 2010, Antoniadis et al. 2013

Demorest et al. 2010



Nuclear interactions are critical for understanding neutron star structure and evolution

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On Massive Neutron Cores

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(Received January 3, 1939)

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

two solutions exist, one stable and quasi-Ne

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

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 (talks this afternoon, Thursday)

Masses, radii of neutron stars from X-ray bursts & implications for the EOS

- Photospheric radius expansion bursts
- Thermal emission from cooling neutron stars

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 $x \ll 1$.)

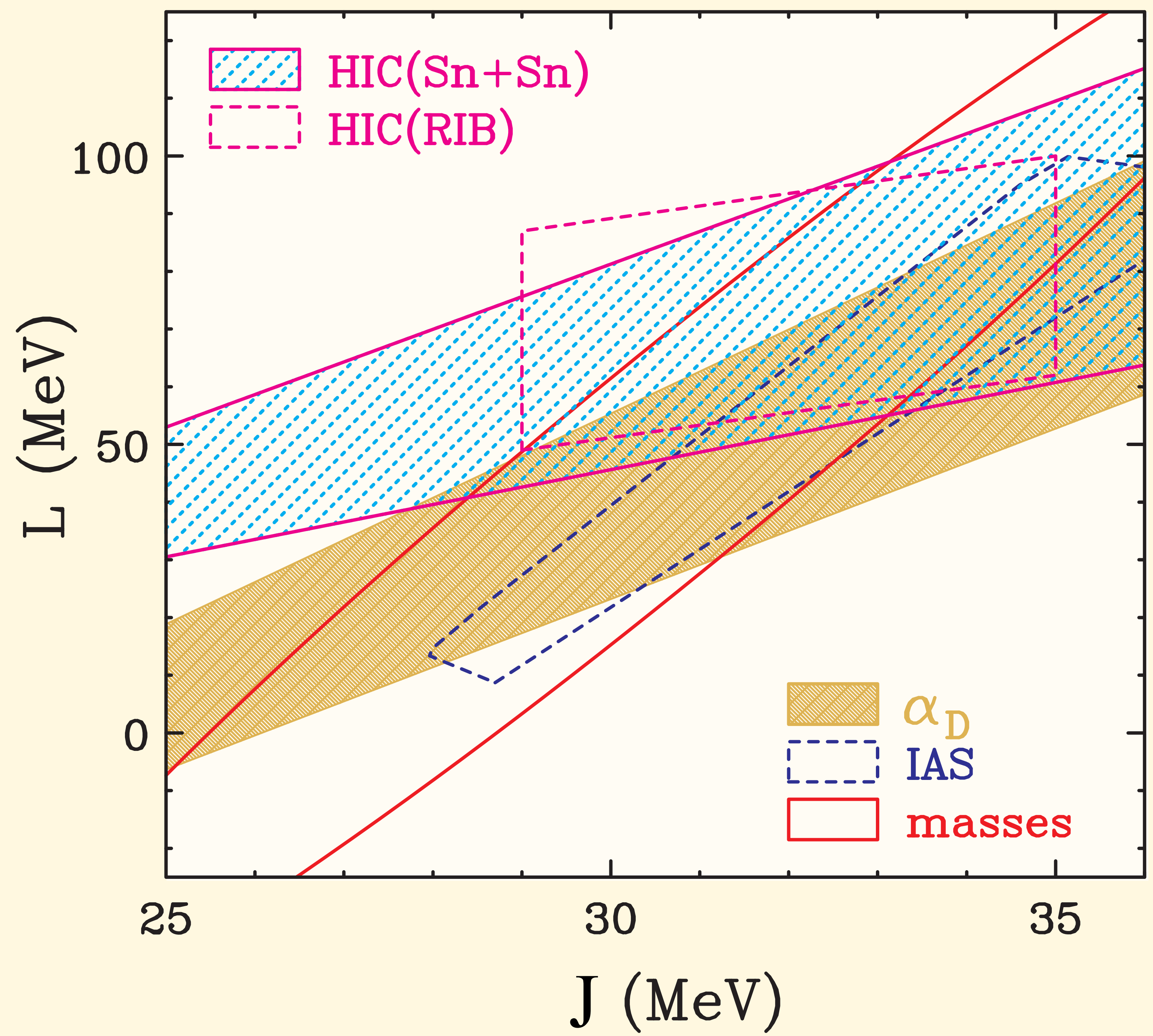
EOS near ρ_0 | experimental constraints

Horowitz et al. (2014)

Heavy ion collisions

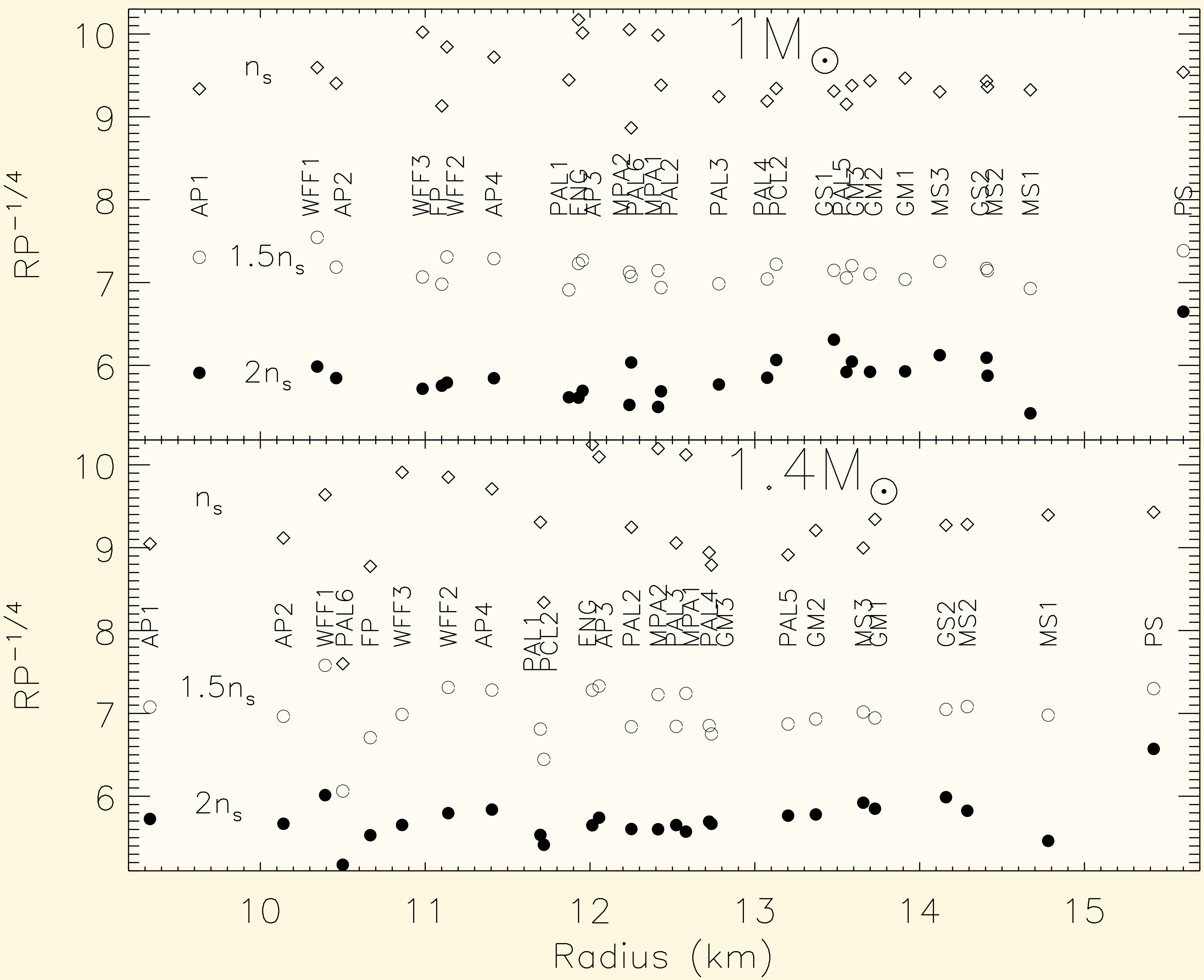
Dipole resonance

Masses



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

Lattimer & Prakash 2001



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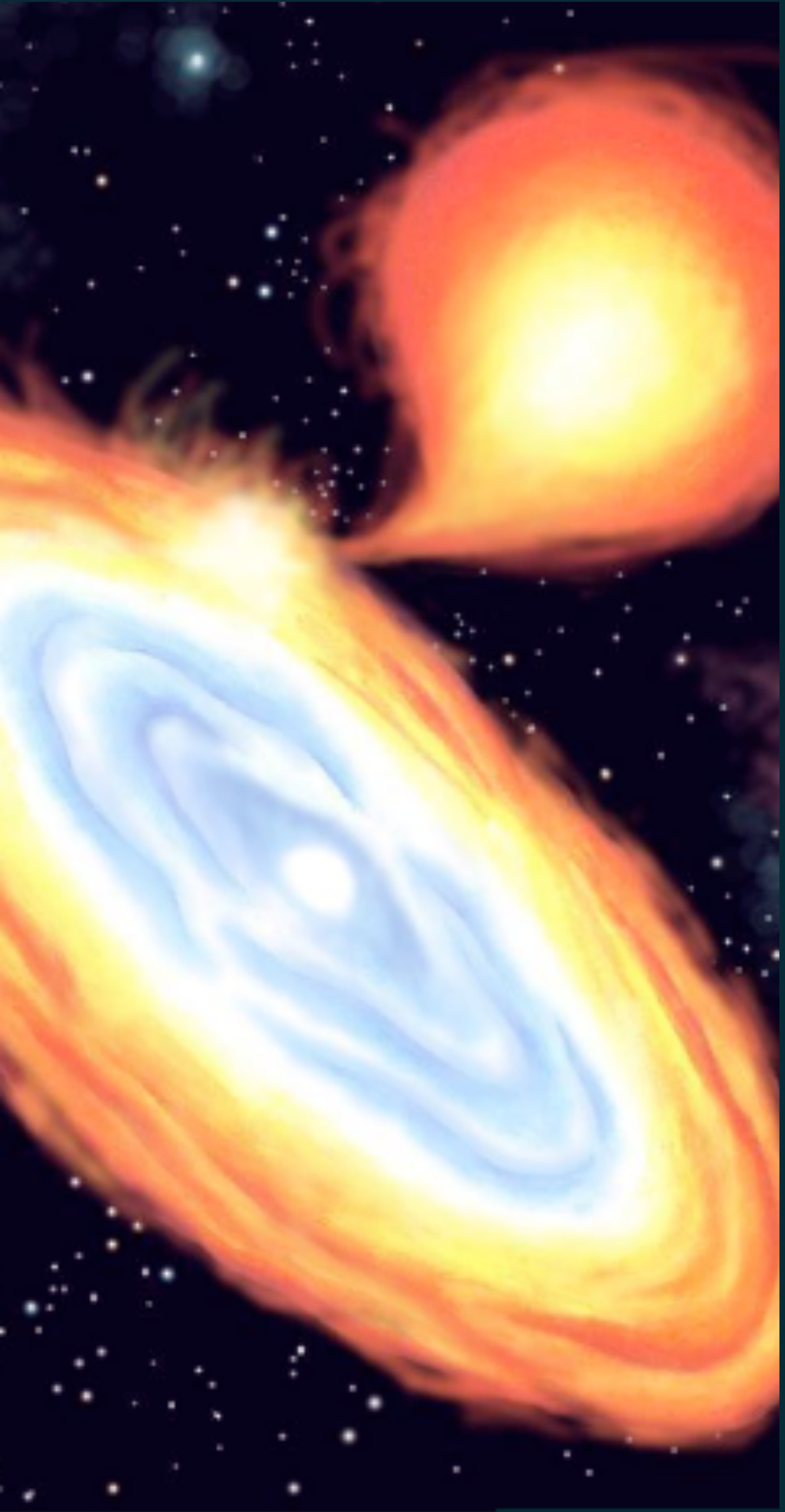


artwork courtesy T. Piro

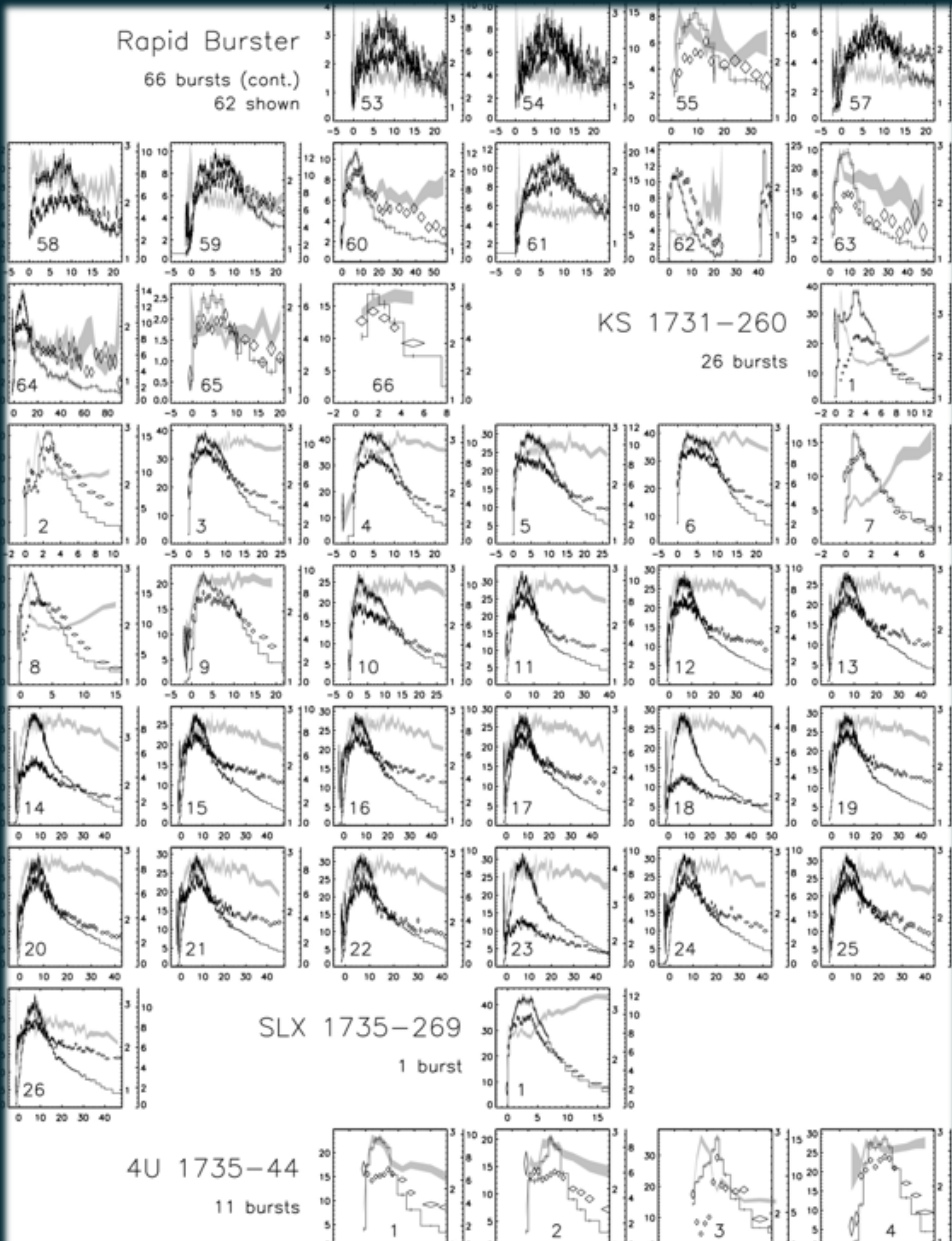
accreting neutron stars

Exhibit thin-shell flashes (analog of classical novae)

$$\frac{E_{\rm grav}}{E_{\rm H\rightarrow He}} \approx \frac{200\ \rm MeV}{7\ \rm MeV}$$

Recurrence timescale is hours–days

Many systems are transients



Galloway et al. 2008

A sample of 4192 X-ray bursts from 48 sources

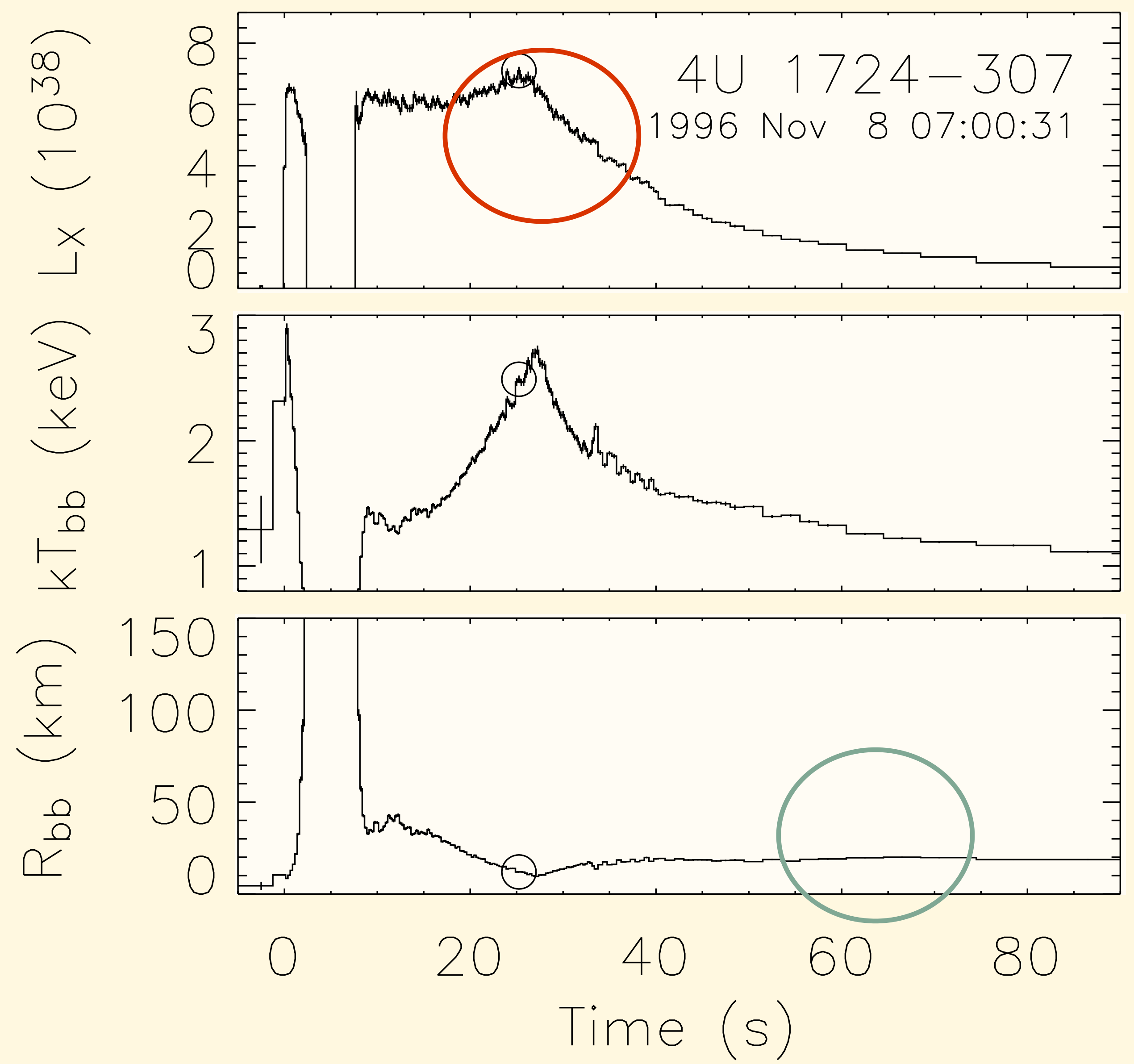
X-ray bursts | photosphere radius expansion (PRE)

van Paradijs '79; Özel '06, '09,...,'15; Steiner et al. '10, '13; Kajava et al. '14, Poutanen et al. '14, Nättilä et al. '15

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

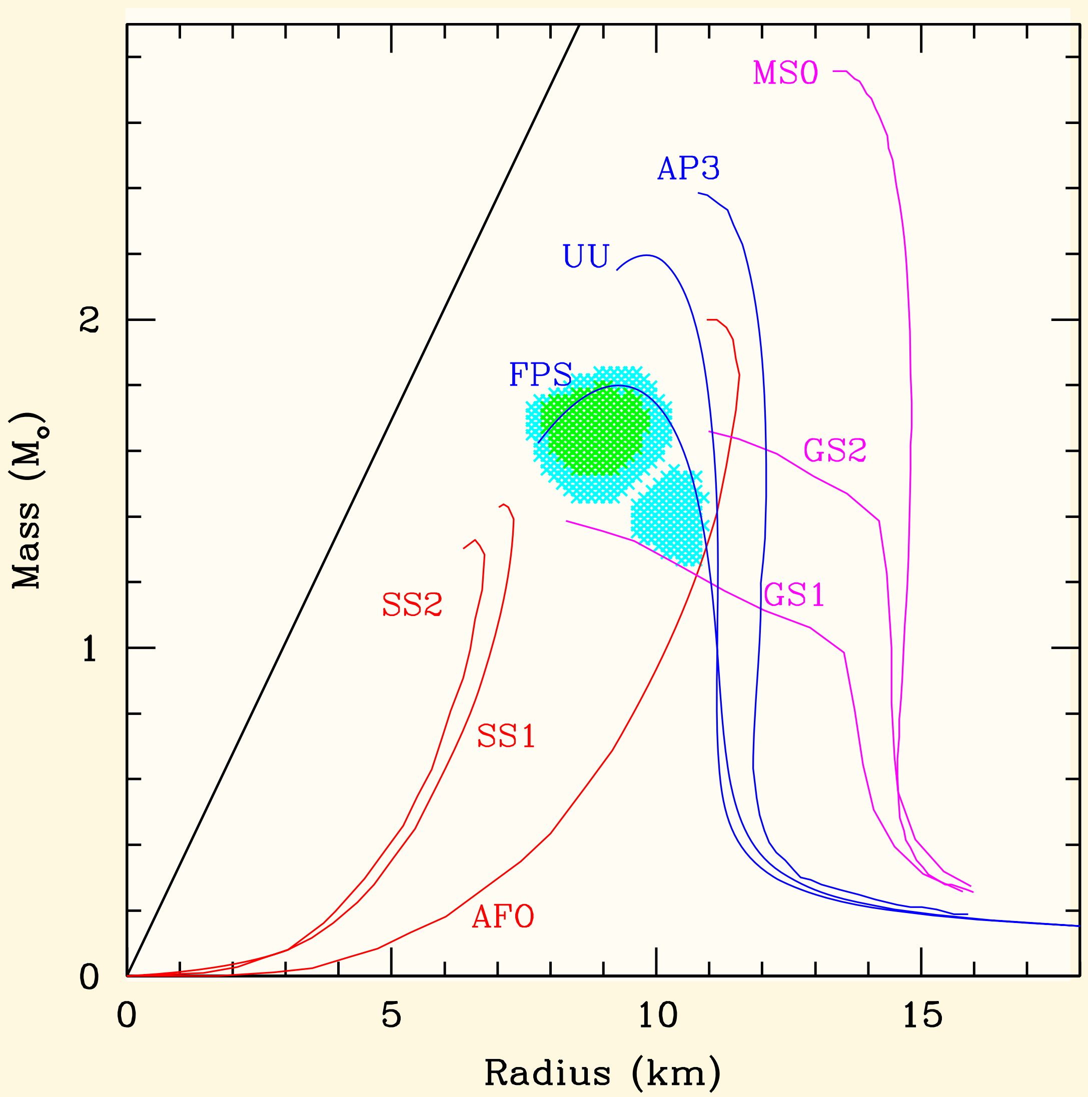
$$\frac{F}{\sigma T_{bb}^4} = f_c^{-4}\left(\frac{R}{D}\right)^2\left(1 - 2\frac{GM}{Rc^2}\right)^{-1}$$

RXTE observations; Galloway et al. '08

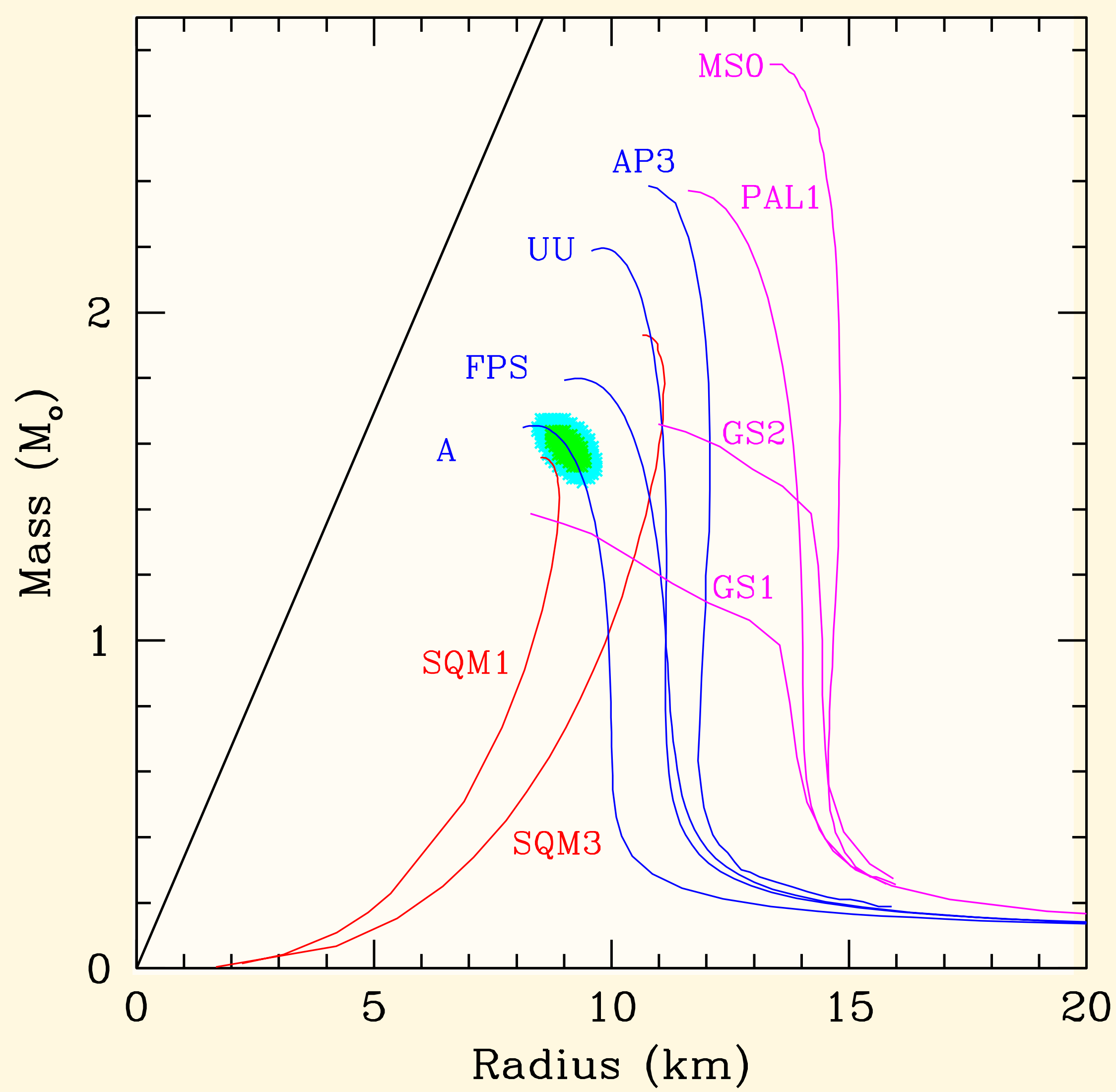


initial efforts had tight constraints on mass, radius

EXO 1745; Özel et al. '09

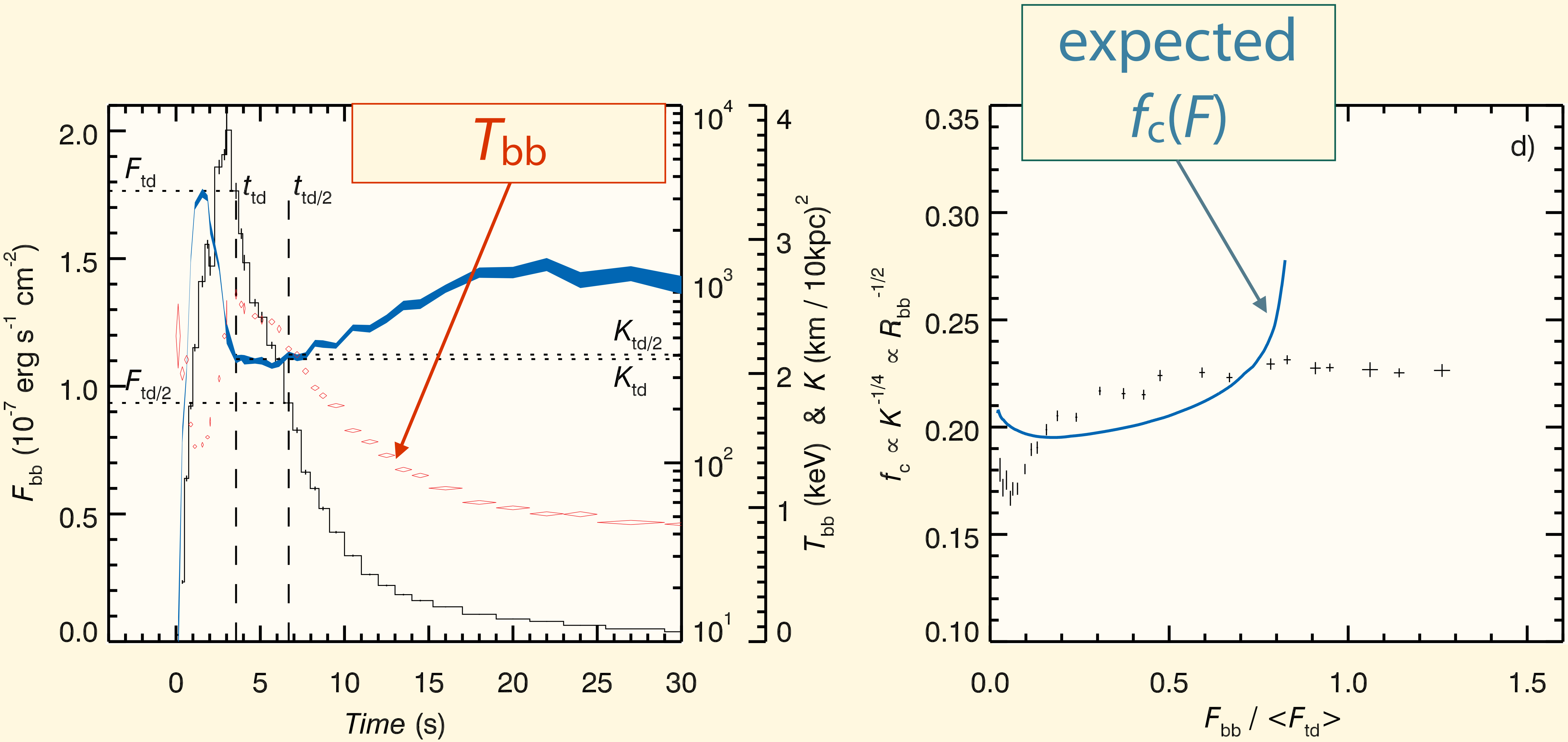


4U 1820; Güver et al. '10



evolution of $f_c = T_{bb}/T_{eff}$ predicted | not observed (Suleimanov et al. ’11, Kajava et al. ‘14)

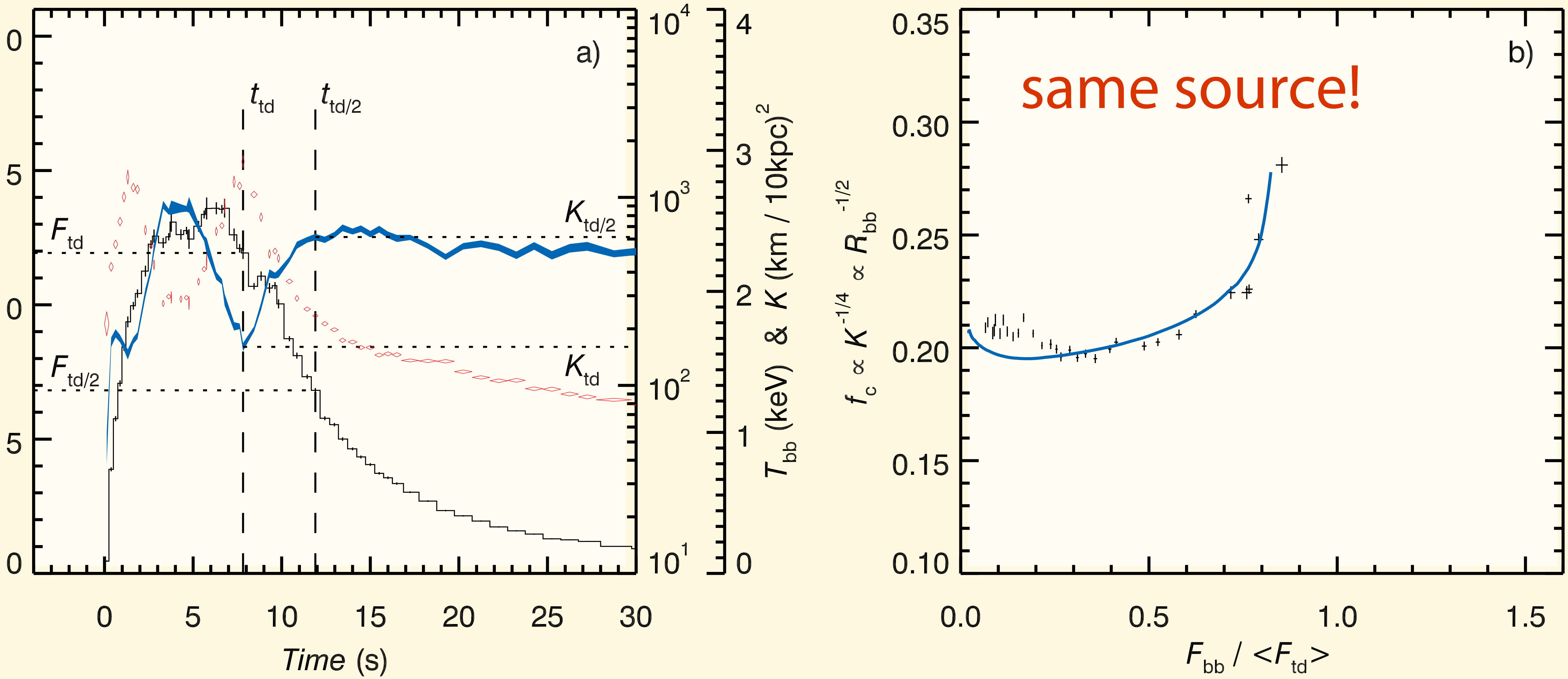
accretion during tail of burst important?



Kajava et al. 14

spectral models do agree with some bursts

Kajava et al. '14



Central values of f_c, D, X_H do not produce solutions for M, R

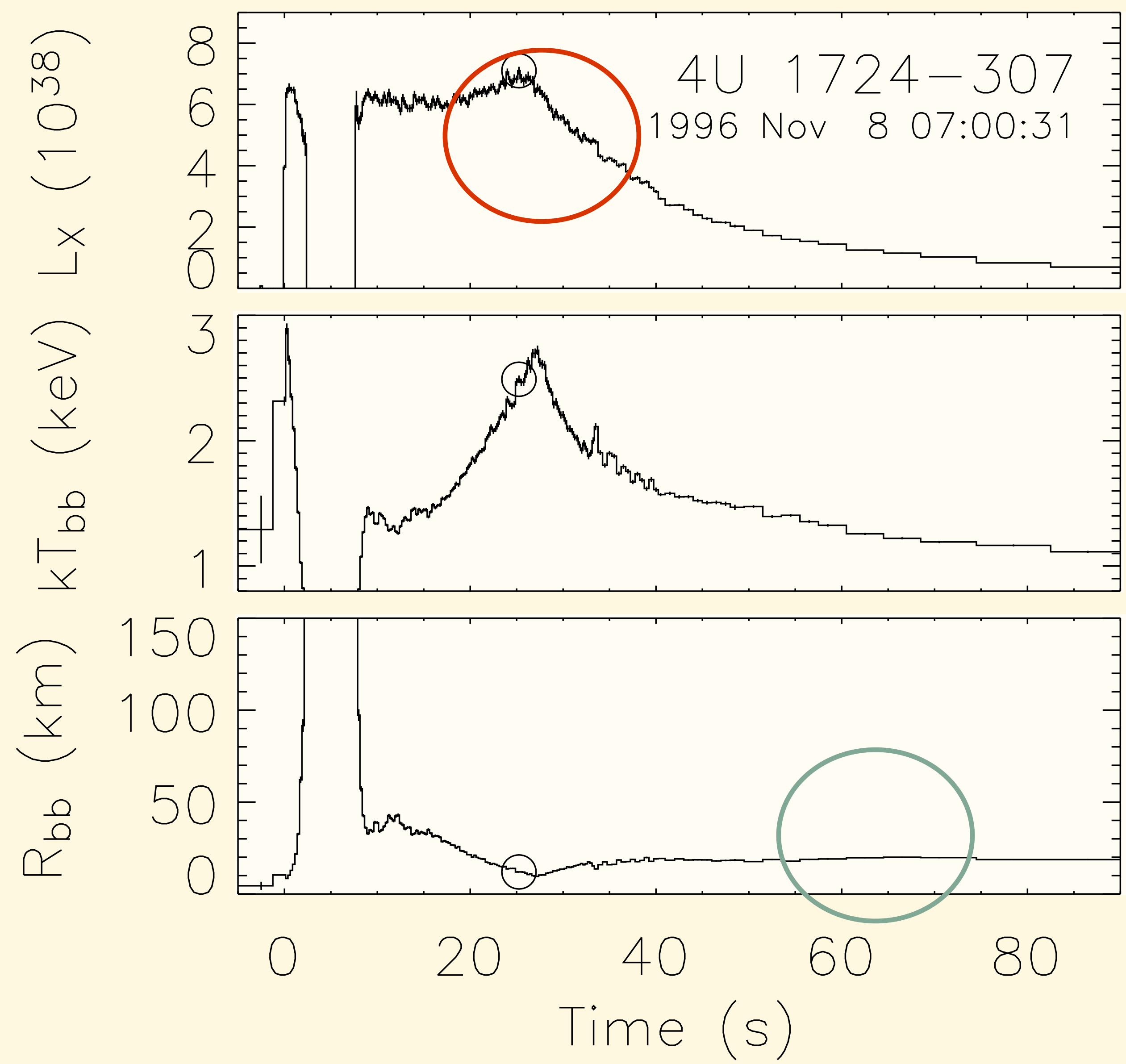
$$F_{TD} = F_{Edd} = \frac{GMc}{\kappa D^2}\left(1 - 2\frac{GM}{Rc^2}\right)^{1/2}$$

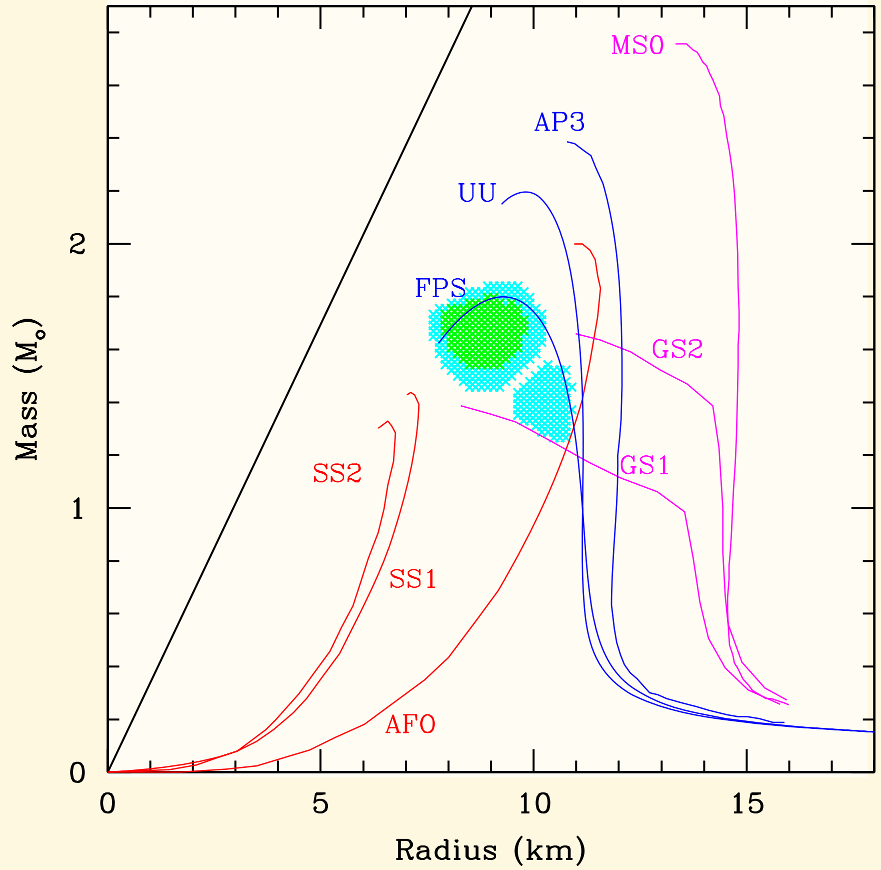
$$\frac{F}{\sigma T_{bb}^4} = f_c^{-4}\left(\frac{R}{D}\right)^2\left(1 - 2\frac{GM}{Rc^2}\right)^{-1}$$

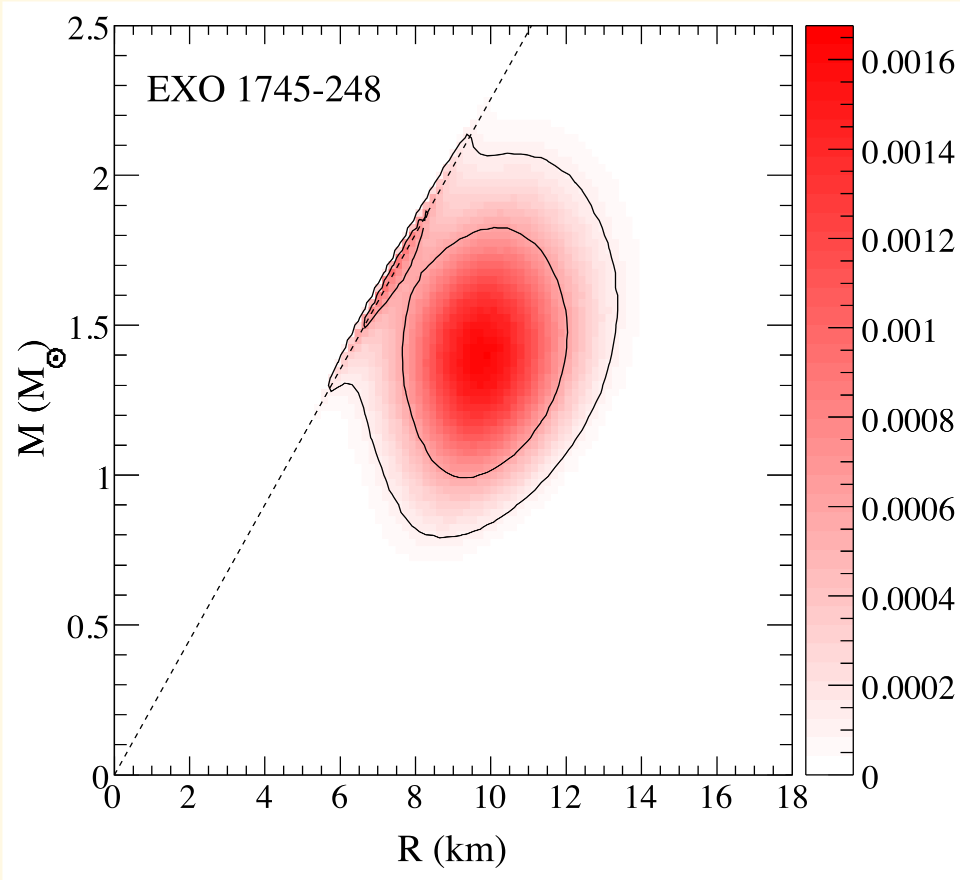
$$\frac{GM}{Rc^2} = \frac{1}{4} \pm \frac{1}{4}\sqrt{1 - 8\alpha}$$

$$\alpha = \frac{F_{TD,\infty}}{\kappa D} c^3 f_c^2 \sqrt{\frac{\sigma T_{bb}^4}{F_{tail}}}$$

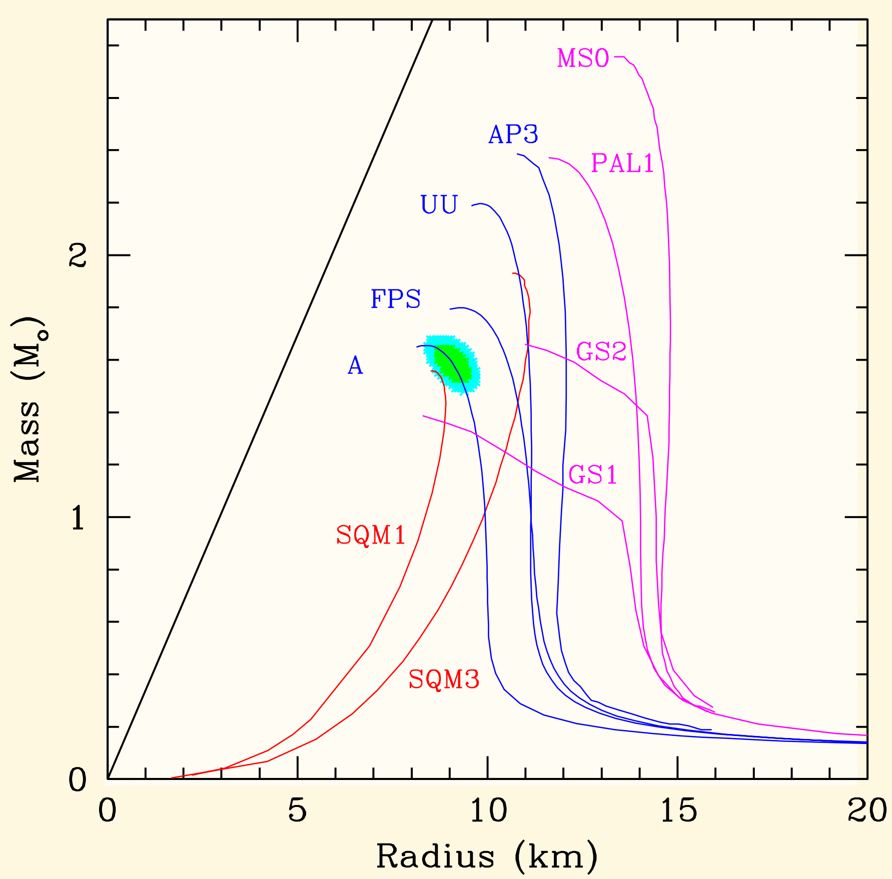
RXTE observations; Galloway et al. '08

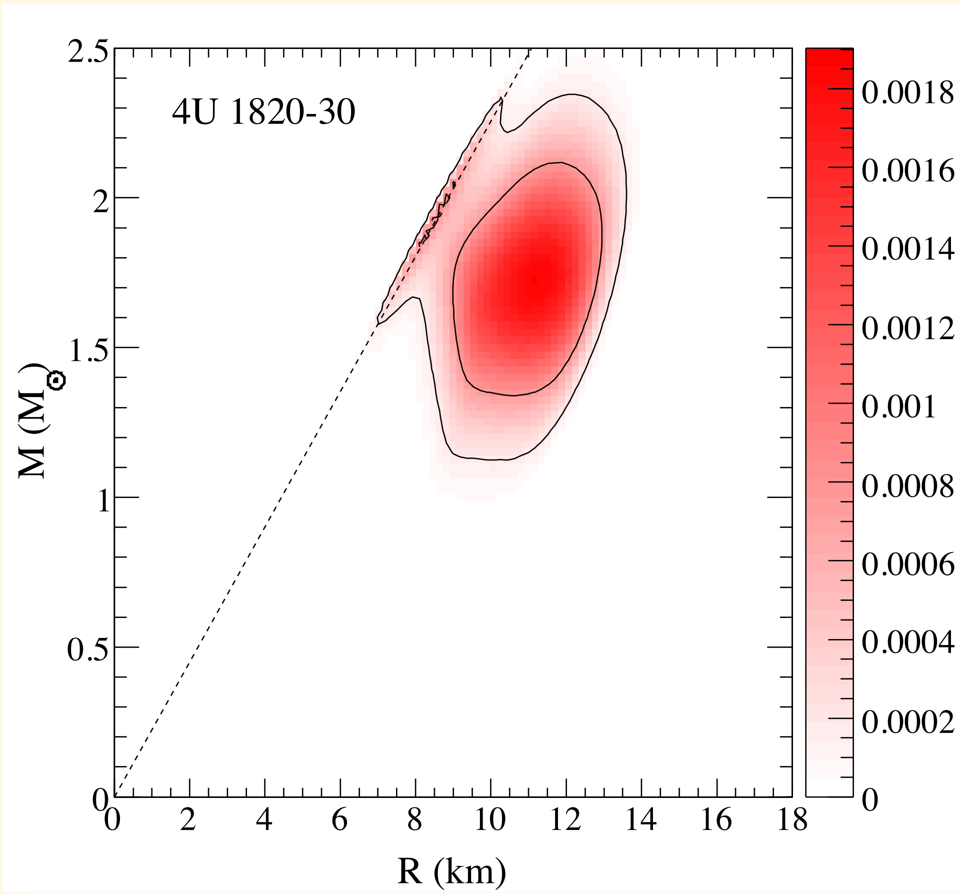






Steiner et al. '10





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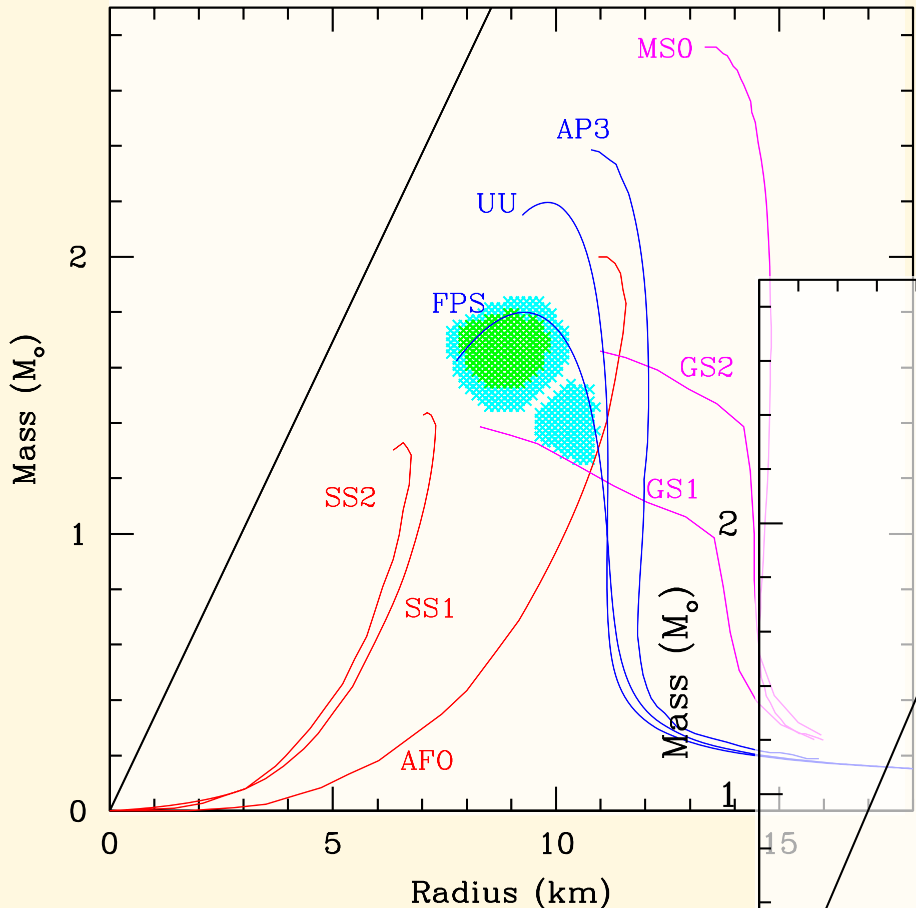

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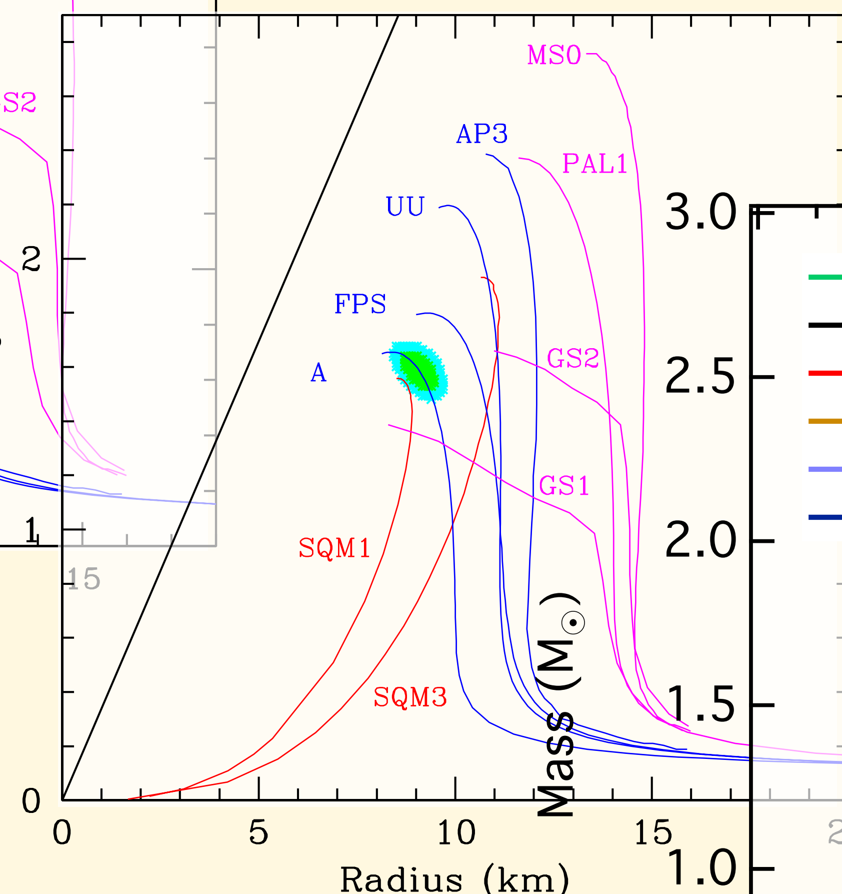
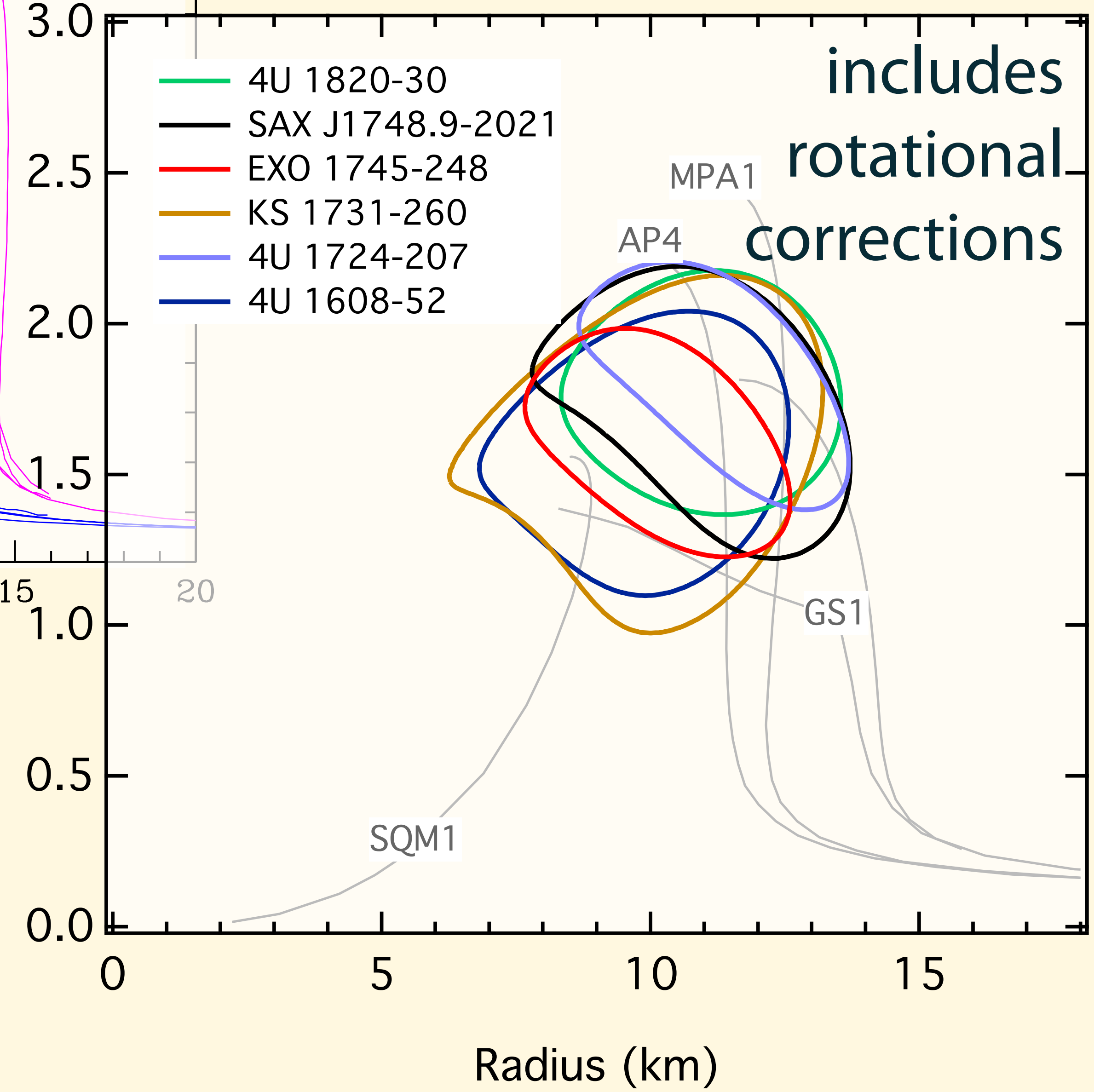
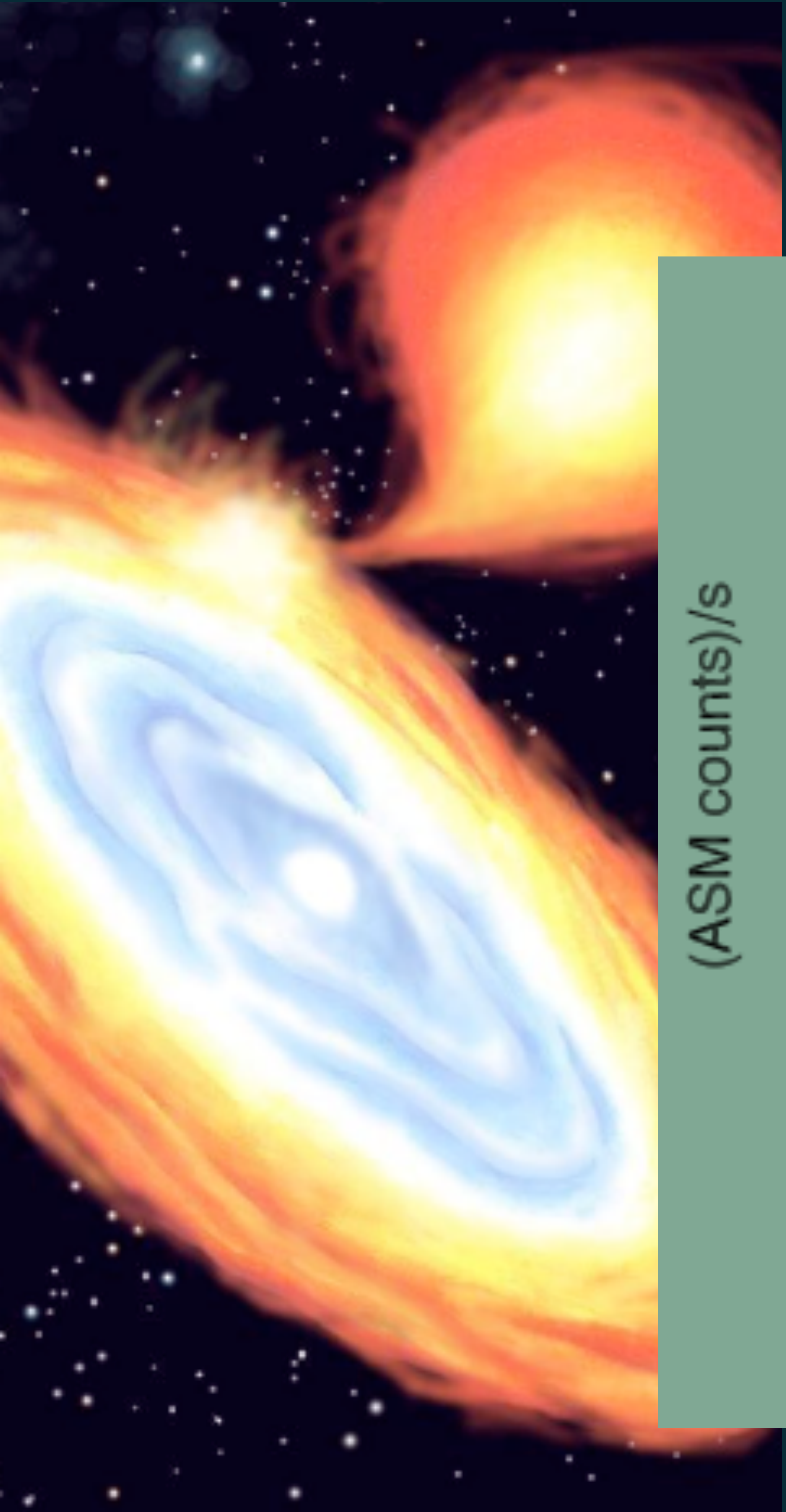
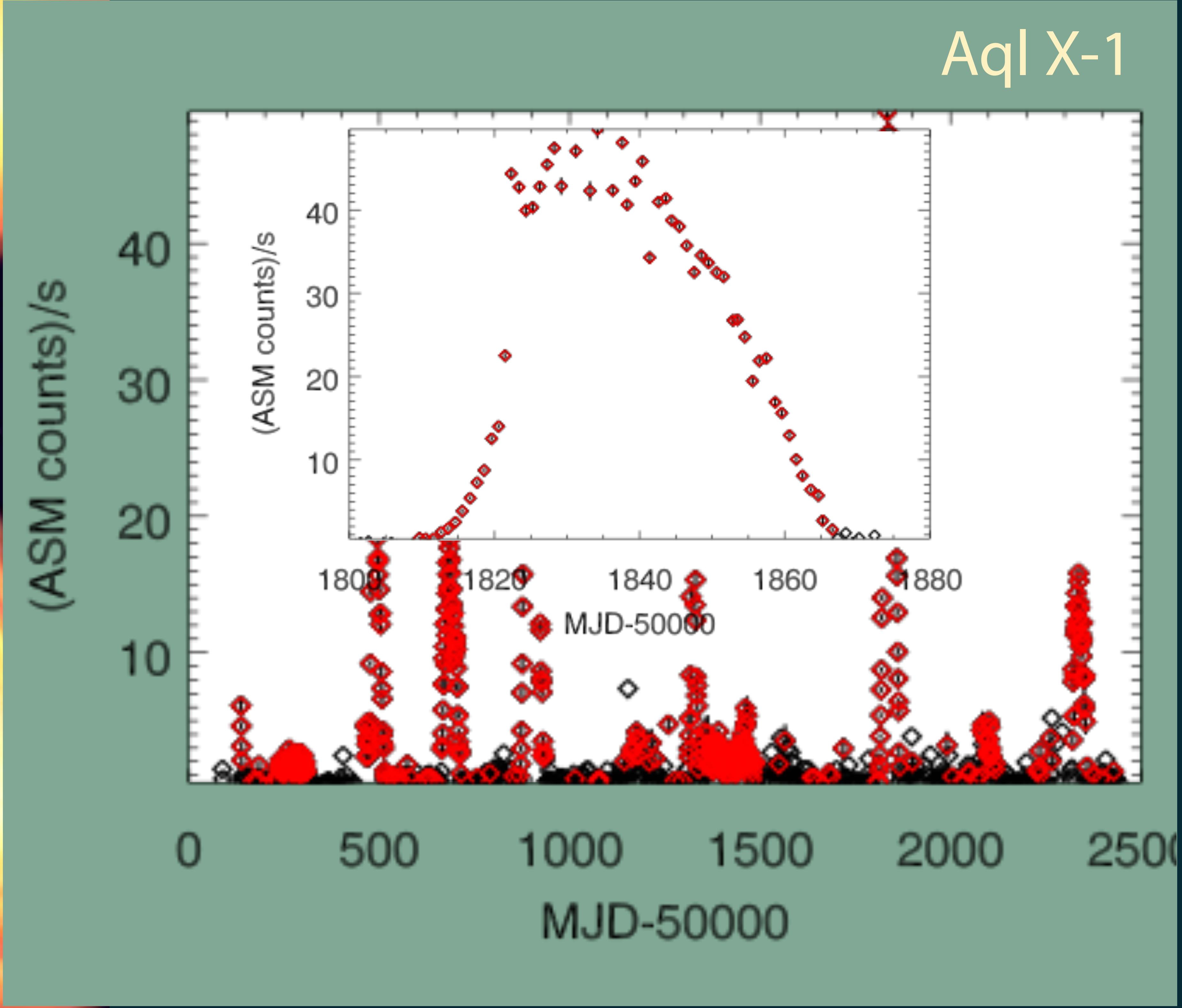


Özel et al. '15



accreting neutron stars | transients



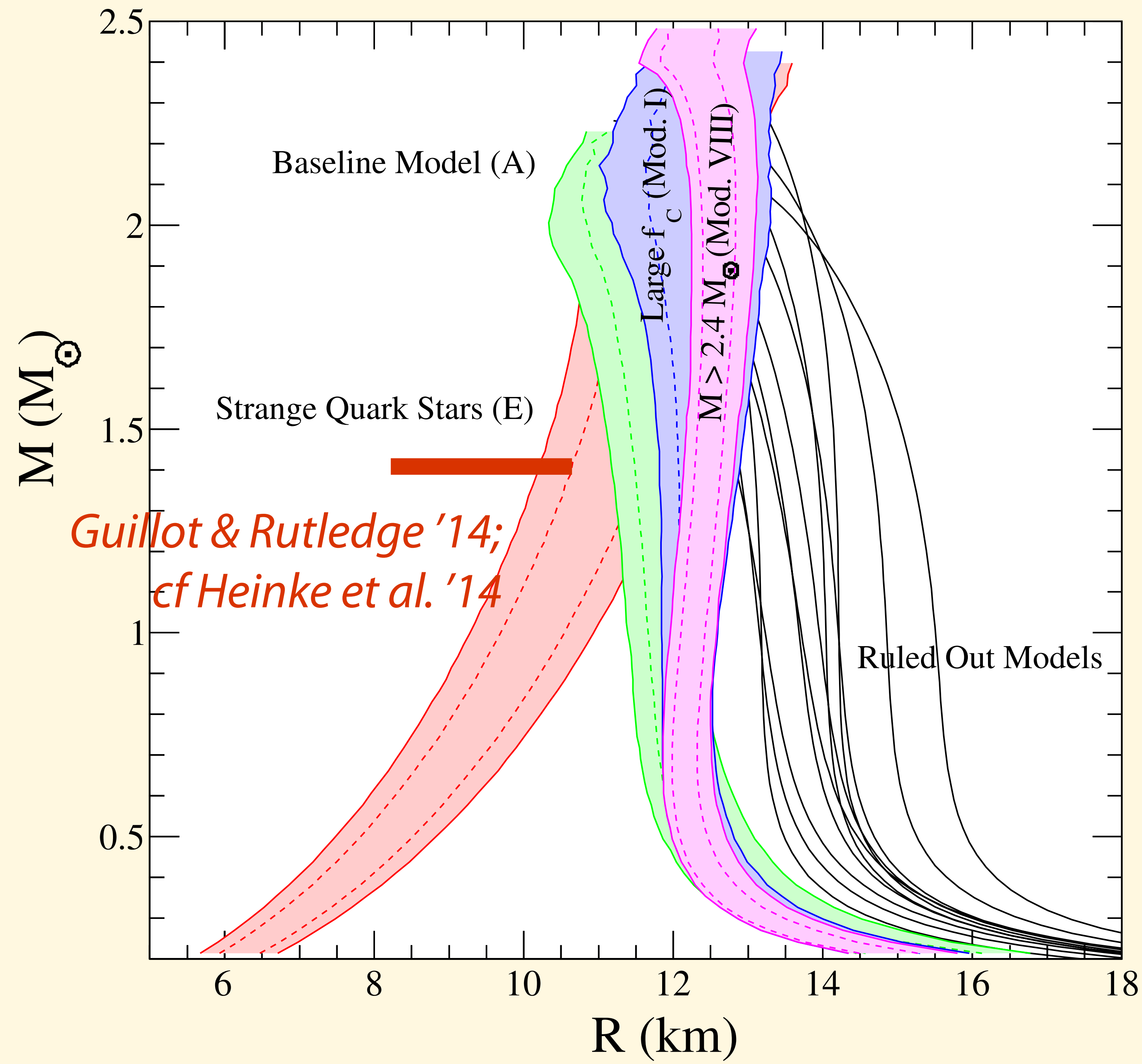


artwork courtesy T. Piro

Parameterization of EOS contributes ≈ ±0.8 km to $R_{1.4}$

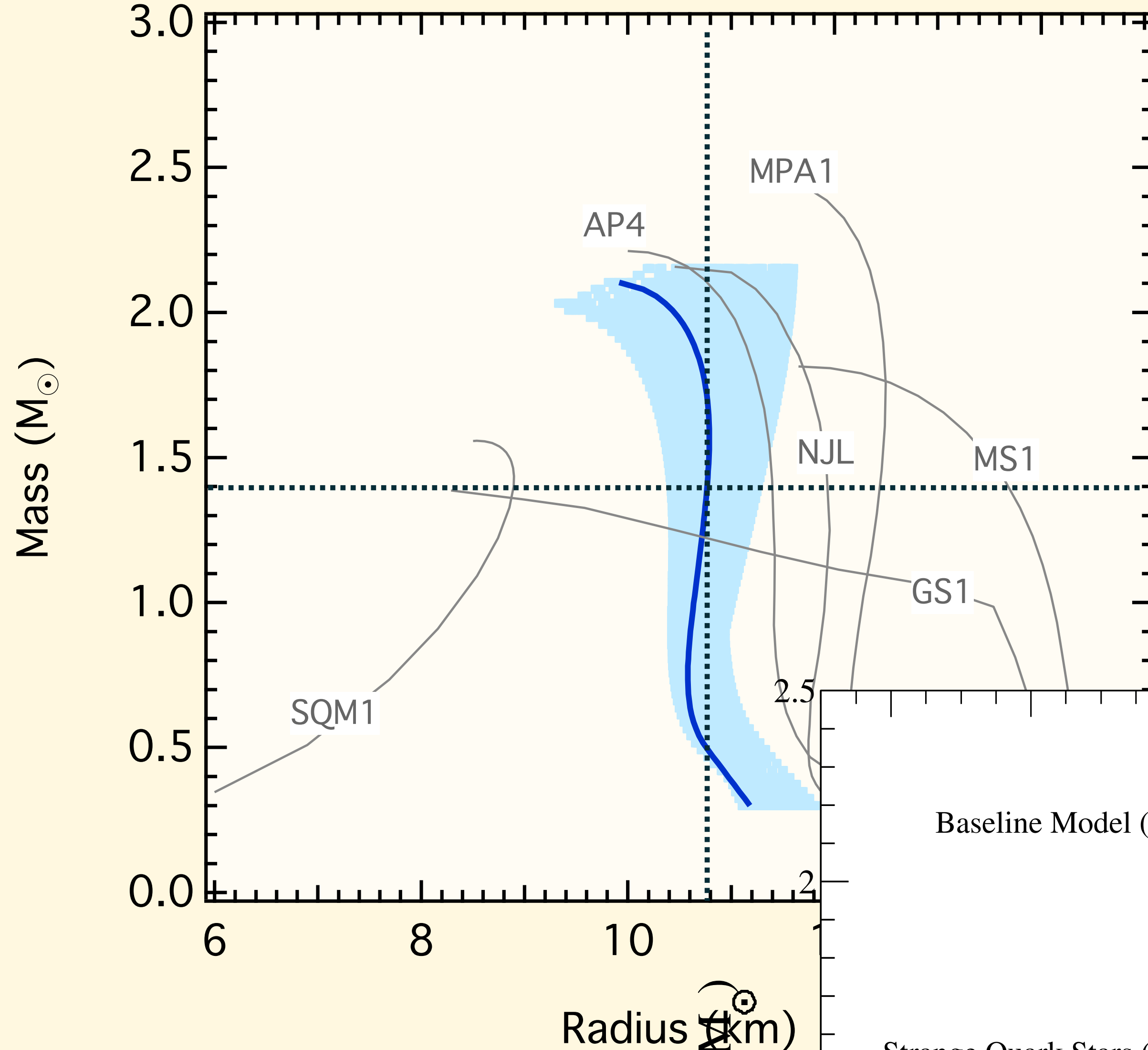
Steiner, Lattimer & Brown ’13; see also Steiner er al. ‘15

Parameterized nuclear EOS at $\rho \approx \rho_s$; 2 piecewise polytropes at higher density (Read et al. ’09)

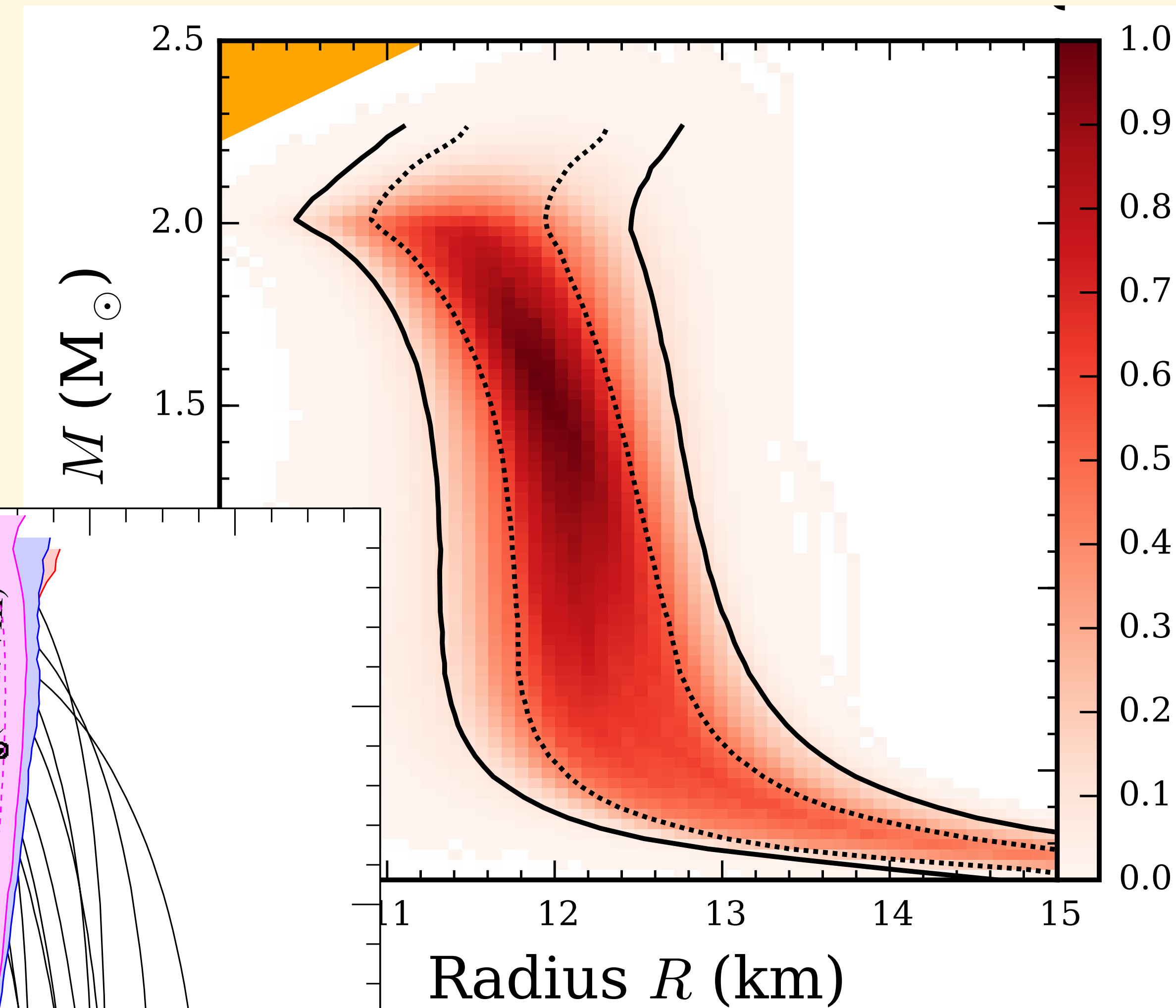


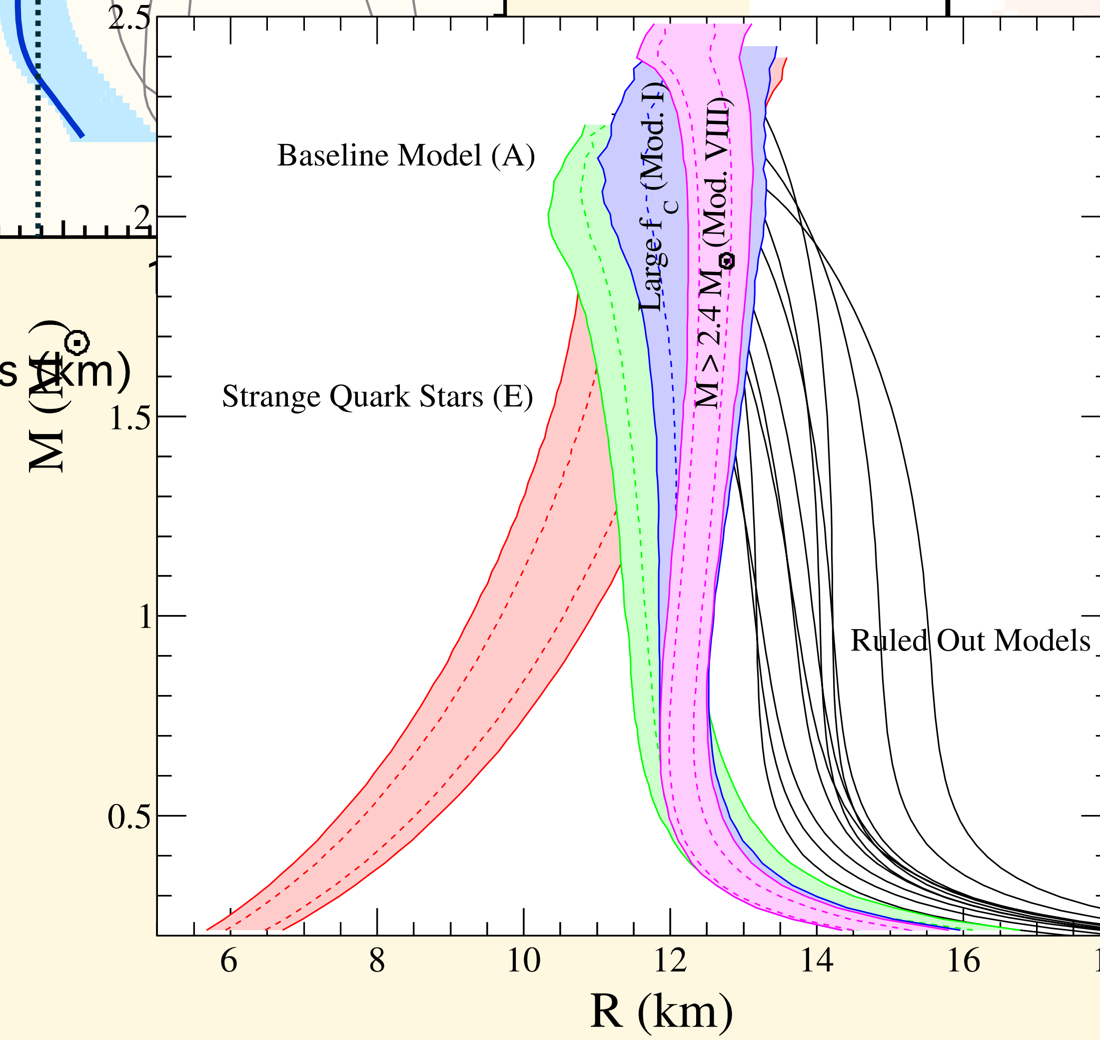
Steiner et al. ‘13

Özel et al. '15



Nättilä et al. '15

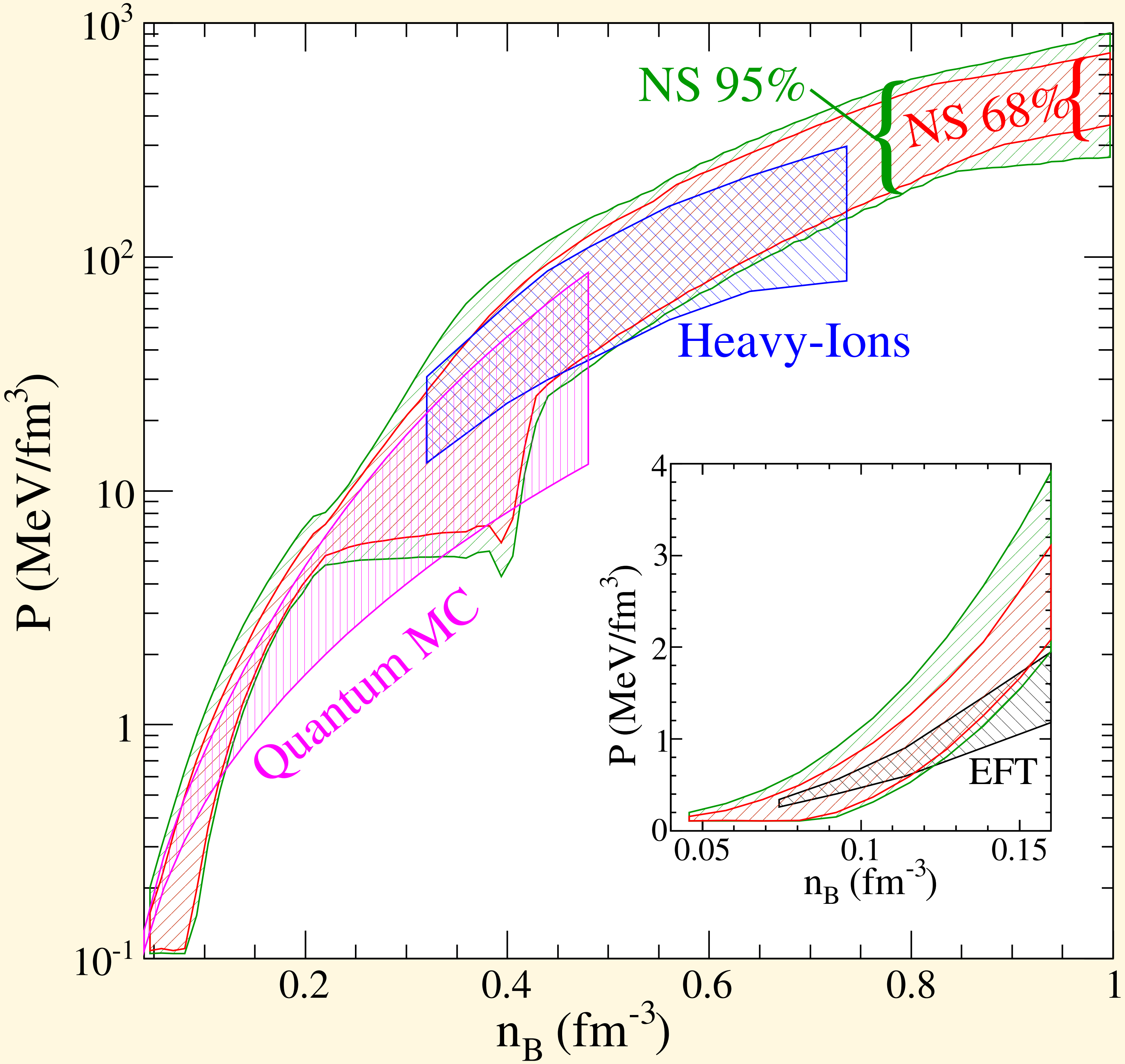




Steiner et al. '13

comparison with nuclear physics theory, experiment

Steiner et al. '13



NB. neutron skin thickness of ^{208}Pb (measurable with PREx) is $R_{np} = 0.15 \pm 0.02$ fm

Facility for Rare Isotope Beams

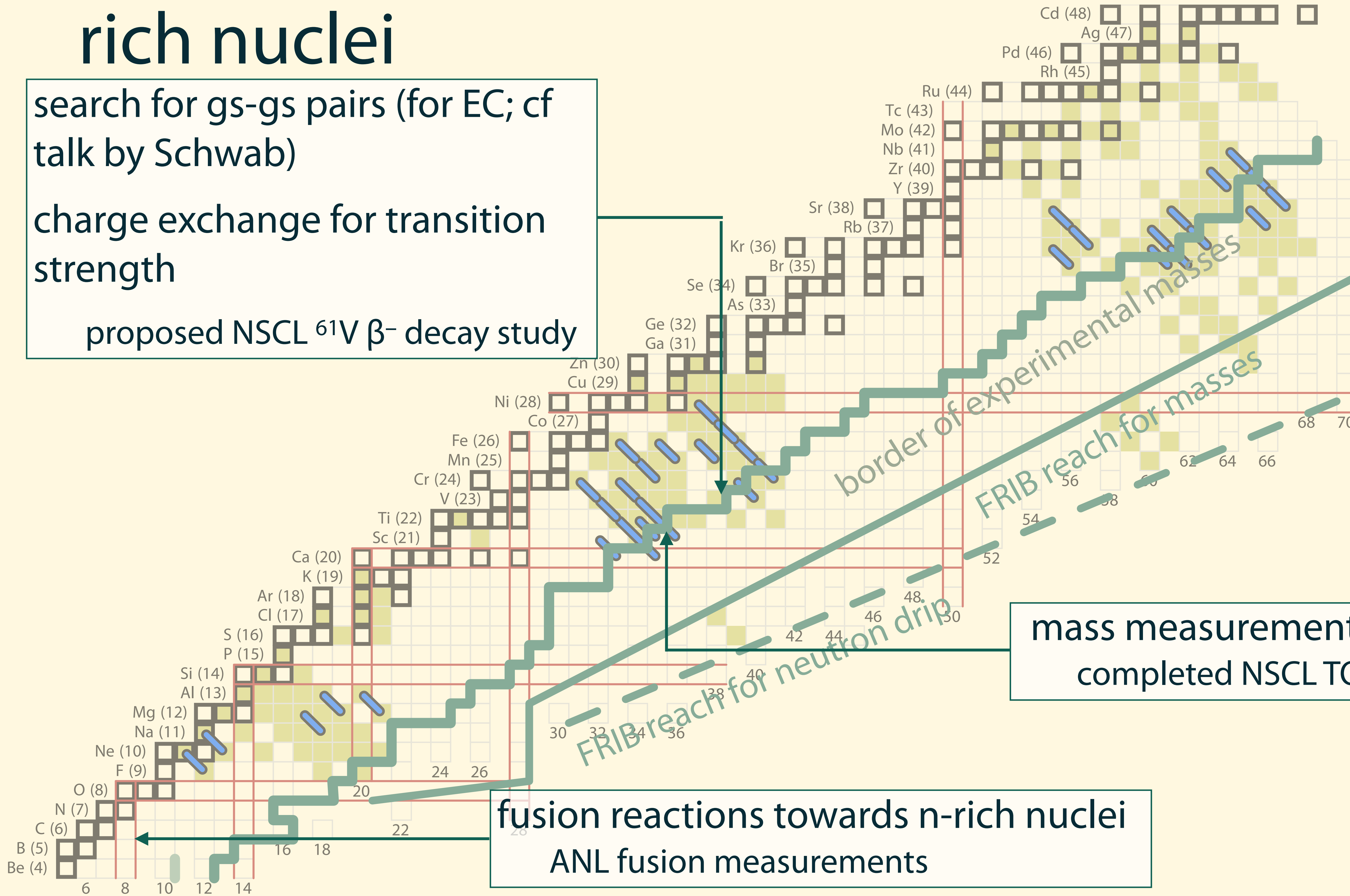
Michigan State University

JINA/JINA-CEE experiments on neutron-rich nuclei

search for gs-gs pairs (for EC; cf talk by Schwab)

charge exchange for transition strength

proposed NSCL ^{61}V β^- decay study



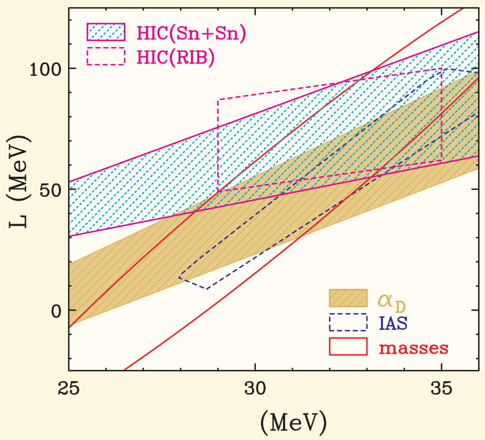
mass measurements

completed NSCL TOF

fusion reactions towards n-rich nuclei

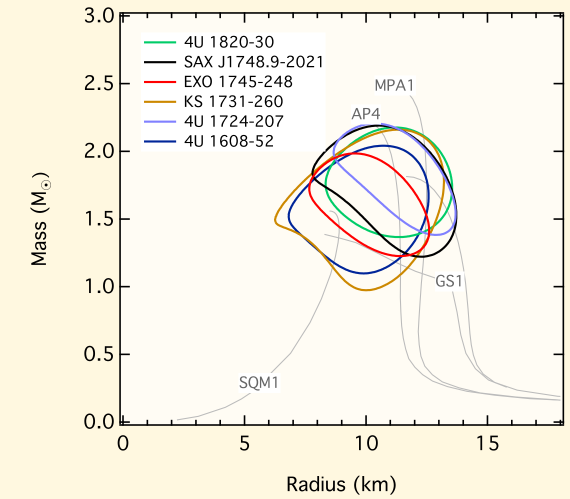
ANL fusion measurements

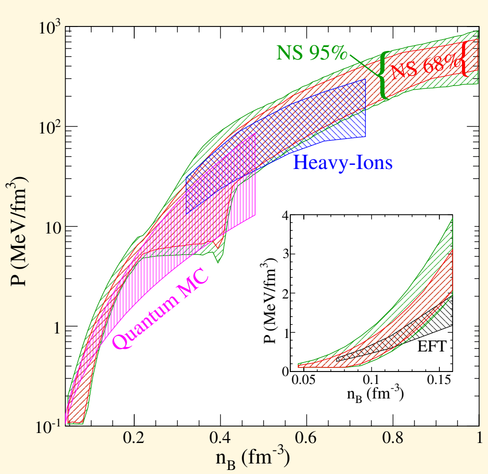
In summary—



Experimental & theoretical constraints on the low-density EOS; plus

M, *R* measurements from PRE bursts and transients, and *M* from pulsars (also future lightcurve fits with *NICER*!)





determine the EOS at several times nuclear density.

New facilities, such as FRIB, will explore properties of neutron-rich nuclei and further constrain the EOS.