Understanding the Ultradense Matter Equation of State from Radii and Mass Measurements of Neutron Stars

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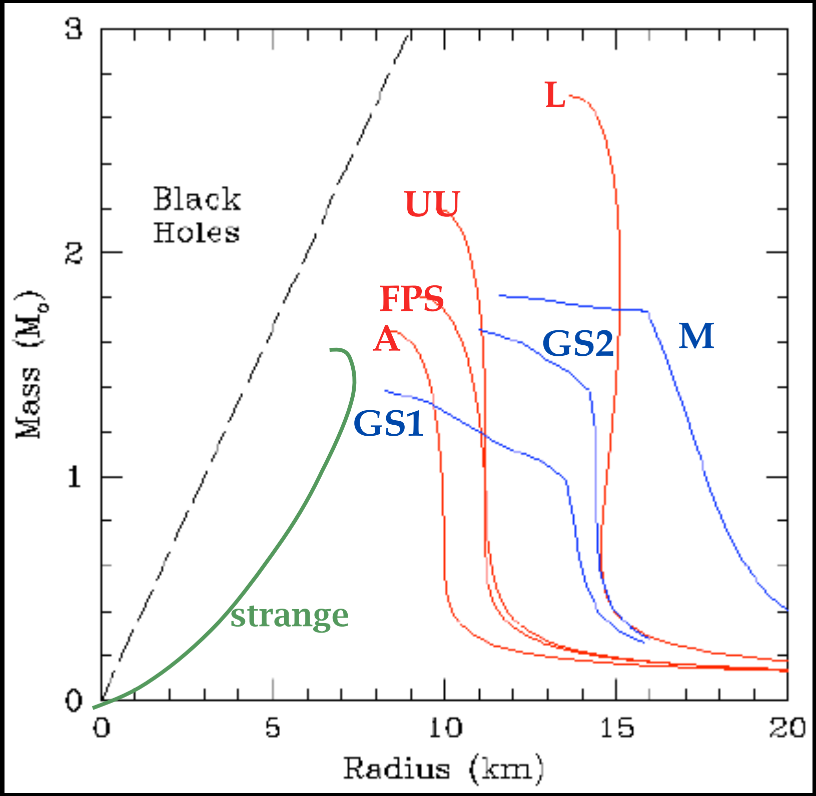
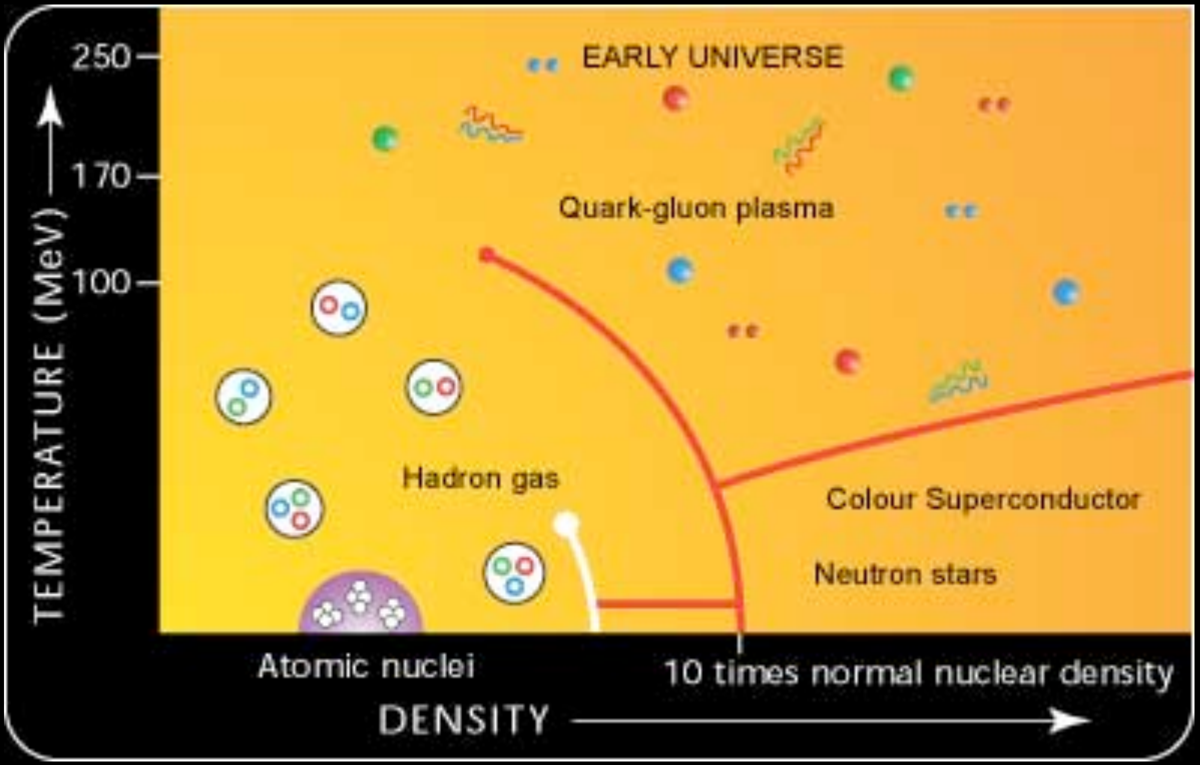


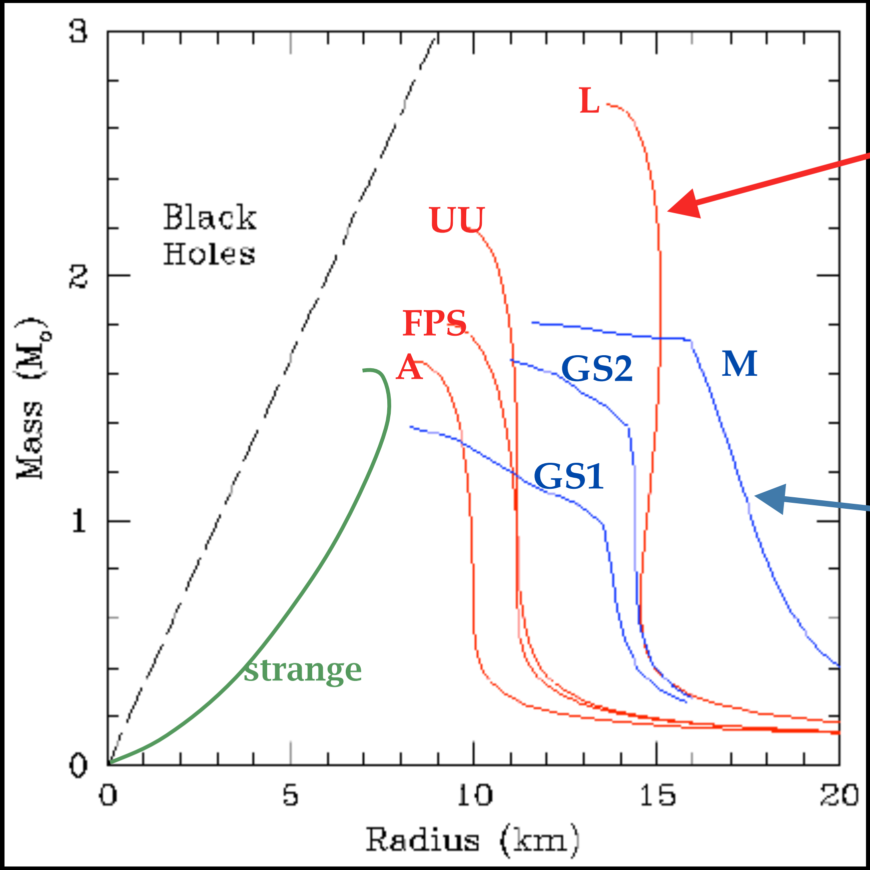
ASU
April 16, 2009

Neutron Stars and QCD Phase Diagram



Neutron stars probe a temperature-density region different than the early universe or hadron colliders

Constraining Neutron Star Equation of State



multi-nucleon

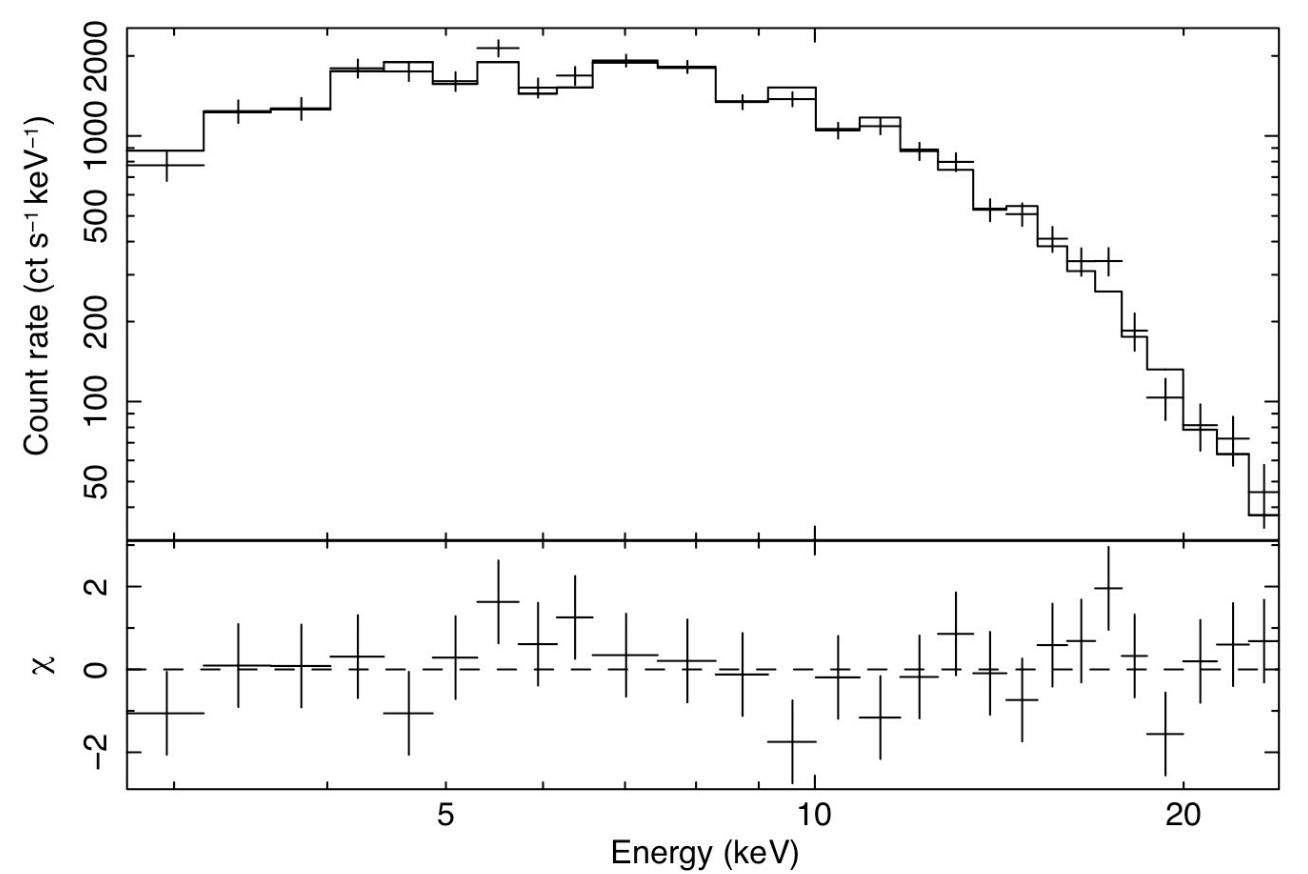
condensate

β-stability, the Strong Force, Isospin Symmetry, Quark Matter or Strange Matter, and the Presence of Bosons, Hyperons, Condensates determine the EoS

Methods to Determine Mass and/or Radius

Radius for a thermally emitting object from continuum spectra:

$$R^2 = \frac{F\,D^2}{\sigma\,T^4}\left(1 - \frac{2M}{R}\right)^{-1}$$

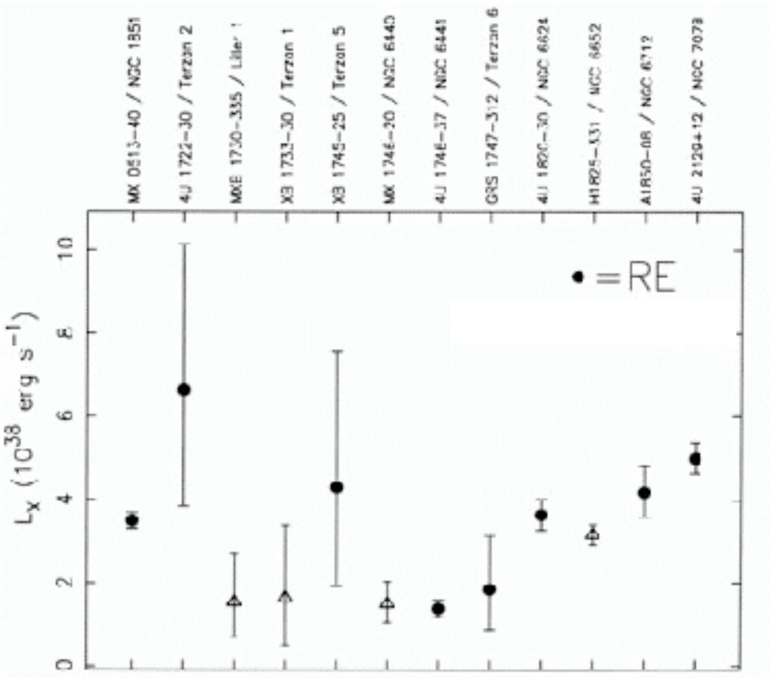


XTE observations of EXO 1745

Methods to Determine Mass and/or Radius

Mass from the Eddington limit:

$$L_{Edd} = \frac{4 \pi G c M}{\sigma \ (1+X)} \left(1 - \frac{2M}{R}\right)^{1/2}$$



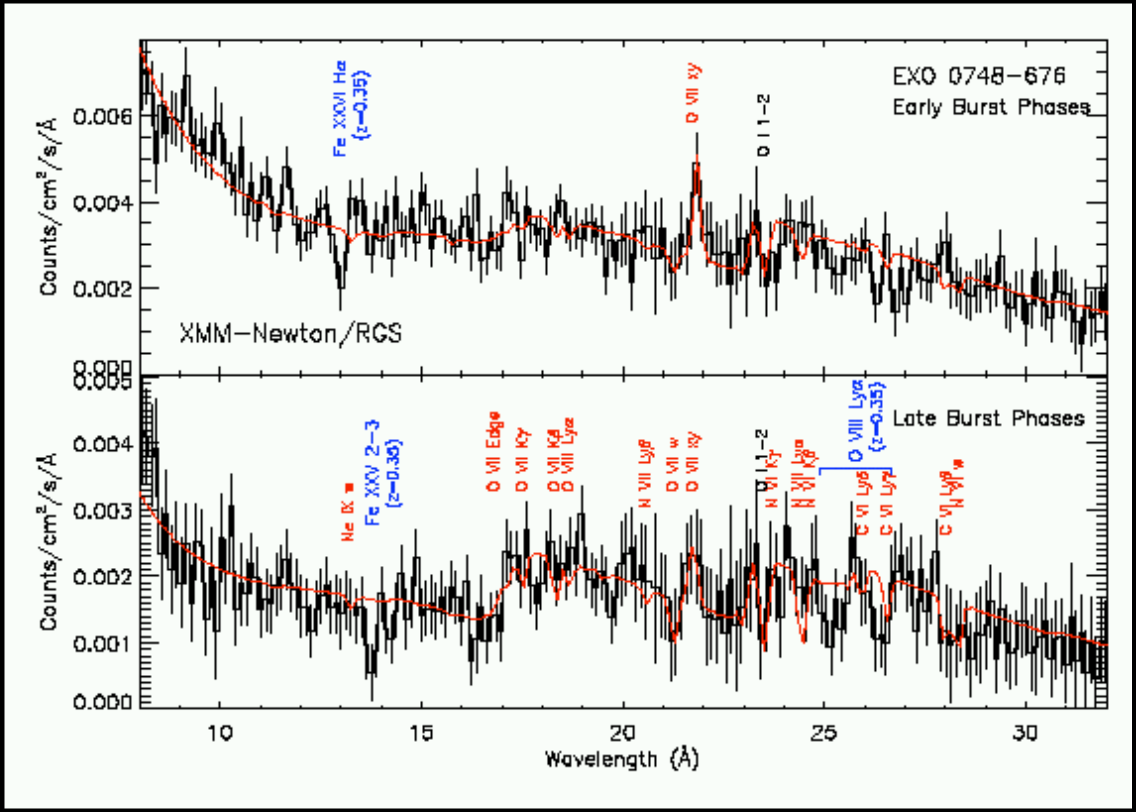
Globular Cluster Burster

Kuulkers et al. 2003

Methods to Determine Mass and/or Radius

M/R from spectral lines:

$$E = E_0\left(1 - \frac{2M}{R}\right)$$



Cottam et al. 2003

Other Methods

- Dynamical mass measurements (very important but mass only)
- Analysis of pulse shapes
- Neutron star cooling (provides --fairly uncertain-- limits)
- Quasi Periodic Oscillations
- Glitches (provides limits)
- Maximum spin measurements

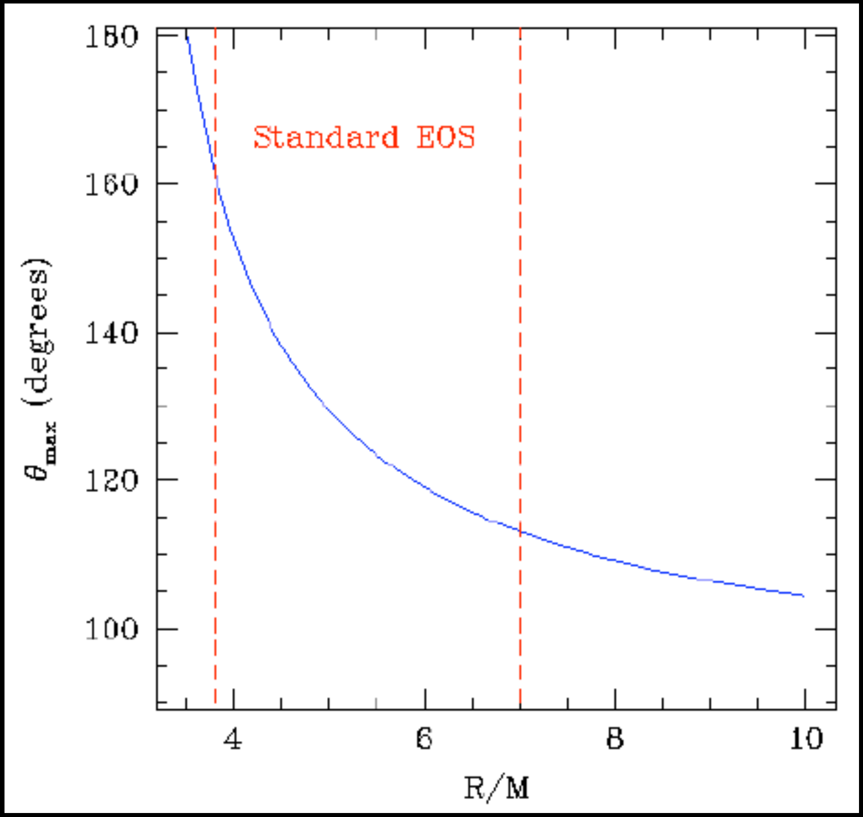
Disentangling Radius and Mass

M and R are *always coupled* because of neutron star gravity.

The Schwarzschild metric:

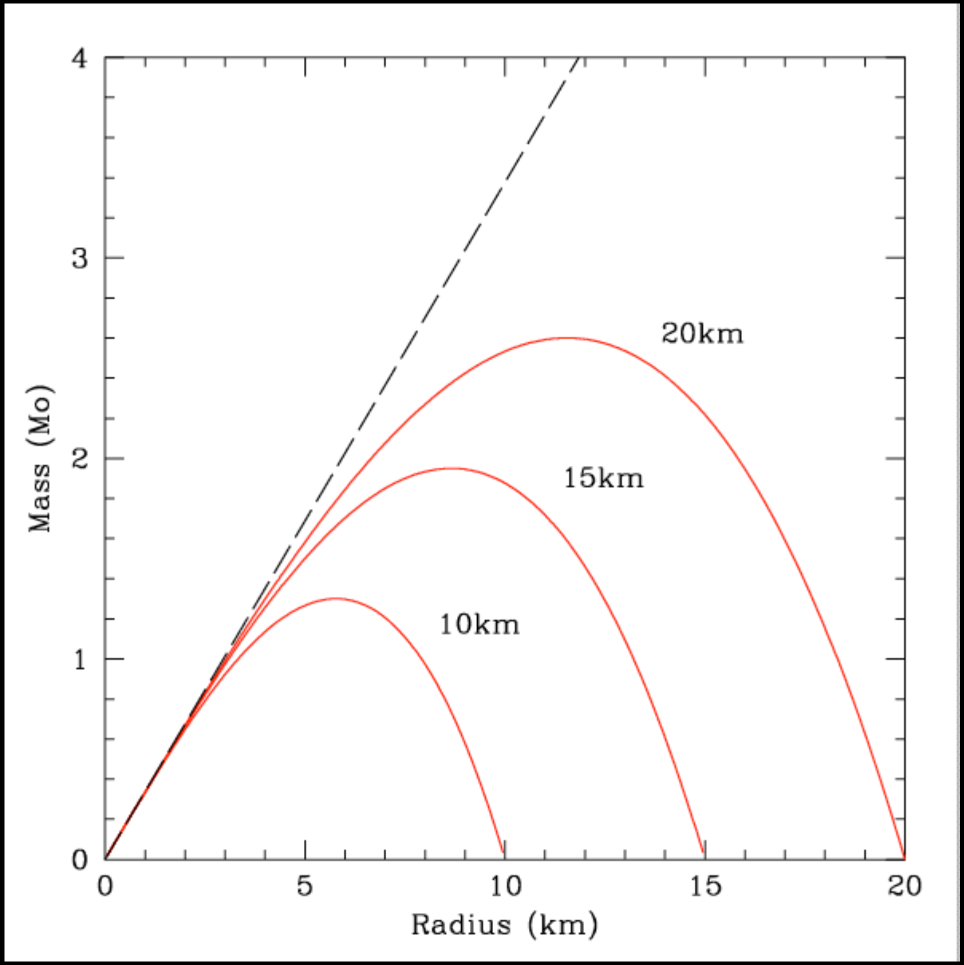
$$ds^2 = dt^2\left(1-\frac{2M}{R}\right) - dr^2\left(1-\frac{2M}{R}\right)^{-1} - r^2\, d\Omega$$

θ_{max}= 90^0+deflection angle



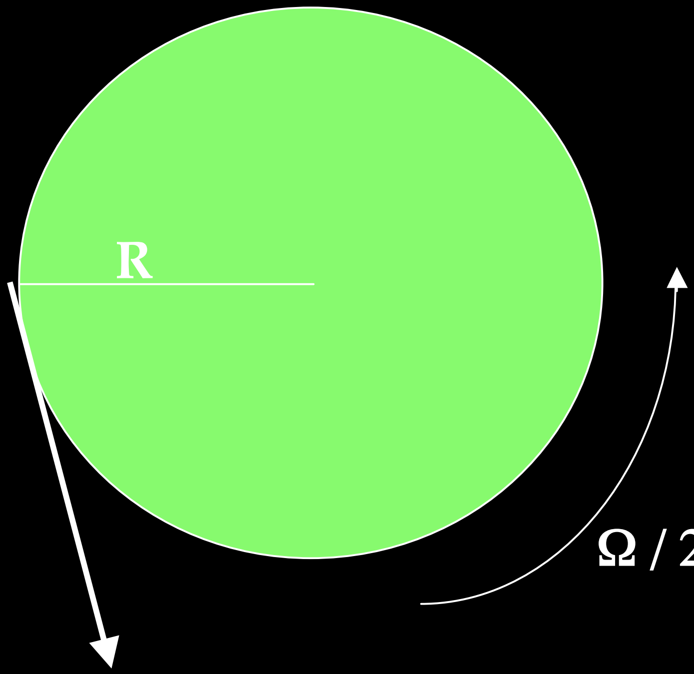
Effects of Strong Gravity

Modifications to the Inferred Radius



$$R_{app} = R(1 - 2\frac{M}{R})^{-1/2}$$

What if the Neutron Star is rotating rapidly?



R

$\Omega / 2\pi \sim 600$ Hz

v --> 0.1 c

$$\boxed{E_\infty = E_0 \gamma (1+\Omega R/c)}$$

Doppler Boosts

$$\boxed{\delta t = \pi/\Omega \sim \pi R/c}$$

Time delays

Other effects:

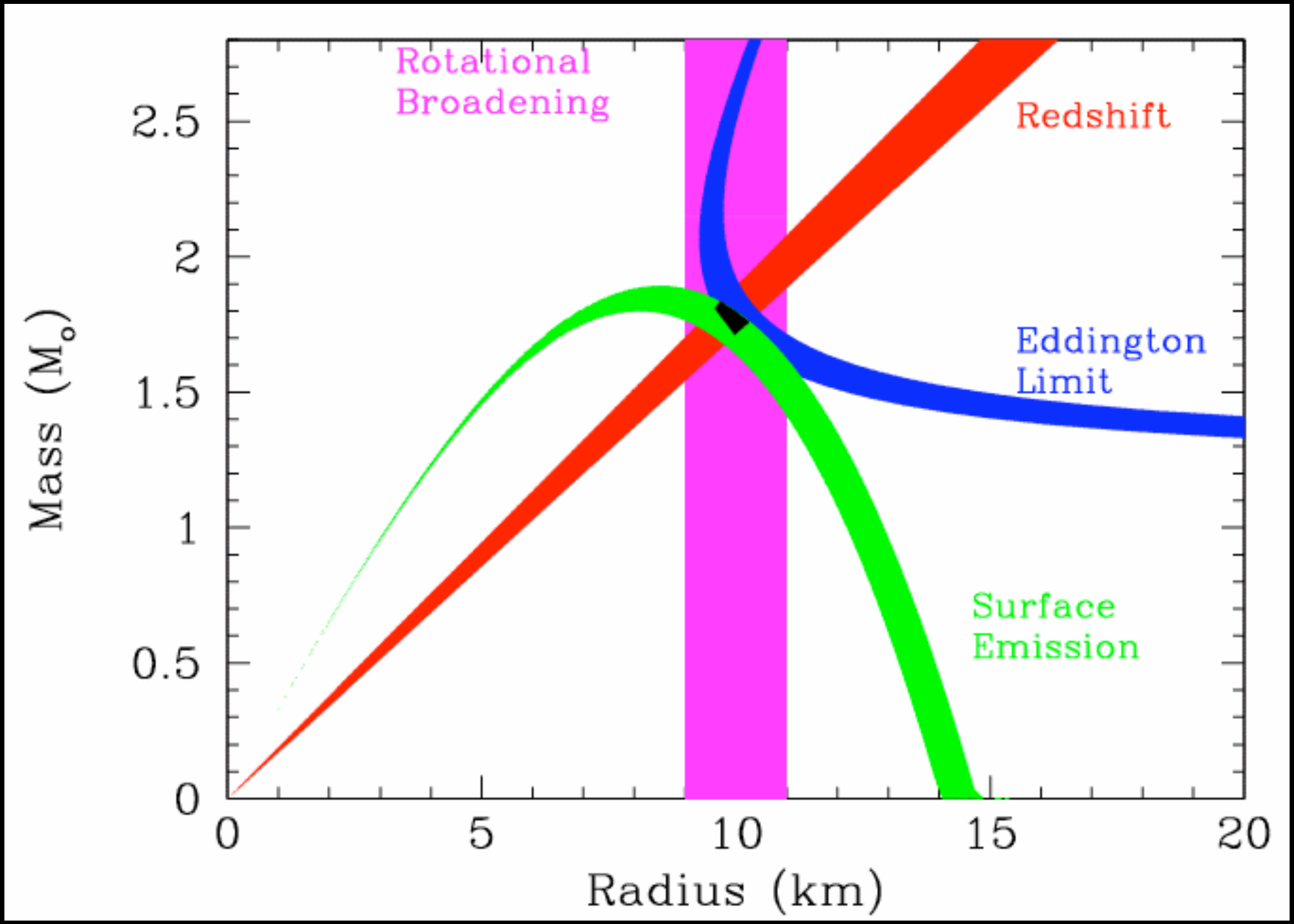
Frame dragging

Oblateness

Equation of State

(Stergioulas, Morsink, Cook)

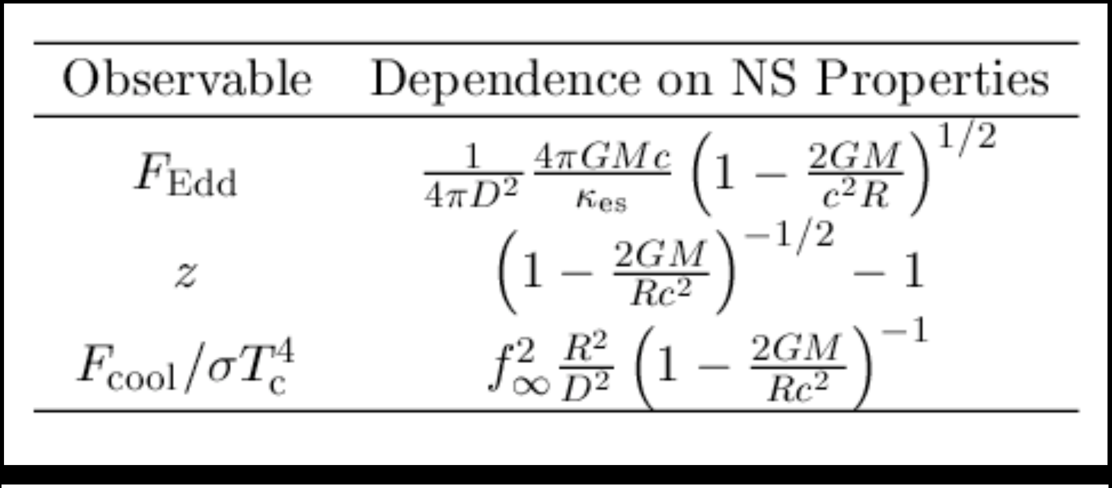
Determining Mass and Radius



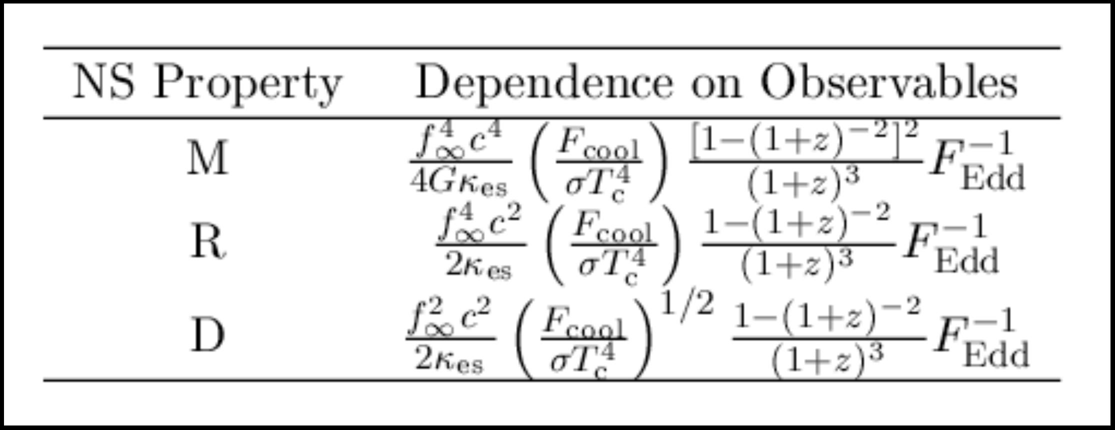
Özel 2006

Radius and mass can be independently determined by making multiple, complementary measurements

A Unique Solution for Neutron Star Mass and Radius



Observable	Dependence on NS Properties
$F_{\rm Edd}$	$\frac{1}{4\pi D^2}\frac{4\pi GMc}{\kappa_{\rm es}}\left(1-\frac{2GM}{c^2R}\right)^{1/2}$
z	$\left(1-\frac{2GM}{Rc^2}\right)^{-1/2}-1$
$F_{\rm cool}/\sigma T_{\rm c}^4$	$f_\infty^2\frac{R^2}{D^2}\left(1-\frac{2GM}{Rc^2}\right)^{-1}$



NS Property	Dependence on Observables
M	$\frac{f_\infty^4 c^4}{4G\kappa_{\rm es}}\left(\frac{F_{\rm cool}}{\sigma T_{\rm c}^4}\right)\frac{[1-(1+z)^{-2}]^2}{(1+z)^3}F_{\rm Edd}^{-1}$
R	$\frac{f_\infty^4 c^2}{2\kappa_{\rm es}}\left(\frac{F_{\rm cool}}{\sigma T_{\rm c}^4}\right)\frac{1-(1+z)^{-2}}{(1+z)^3}F_{\rm Edd}^{-1}$
D	$\frac{f_\infty^2 c^2}{2\kappa_{\rm es}}\left(\frac{F_{\rm cool}}{\sigma T_{\rm c}^4}\right)^{1/2}\frac{1-(1+z)^{-2}}{(1+z)^3}F_{\rm Edd}^{-1}$

M and R not affected by source inclination because they involve flux ratios

Obtaining Sufficient Observational Constraints

Alternatively, if the distance to the source is measured,

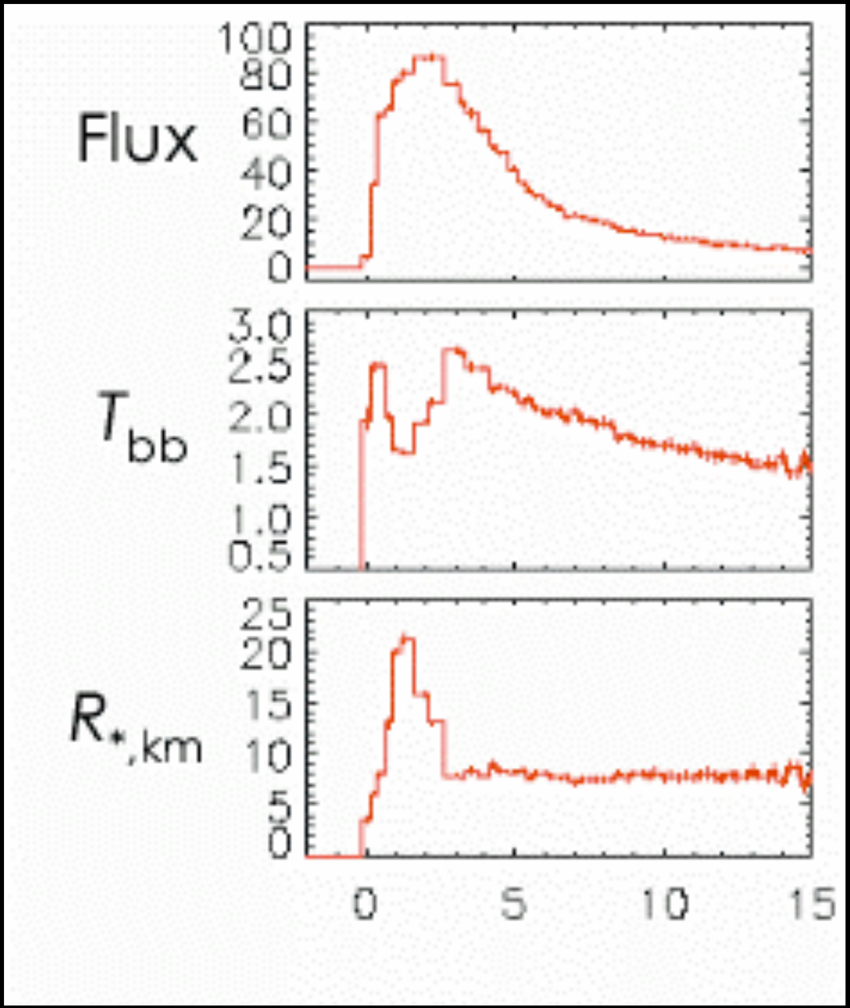
F_{edd}, F_{cool}, and D can be used to solve for M and R

- Globular clusters
- Standard Candles

Good Candidates: LMXBs Showing Thermonuclear Bursts

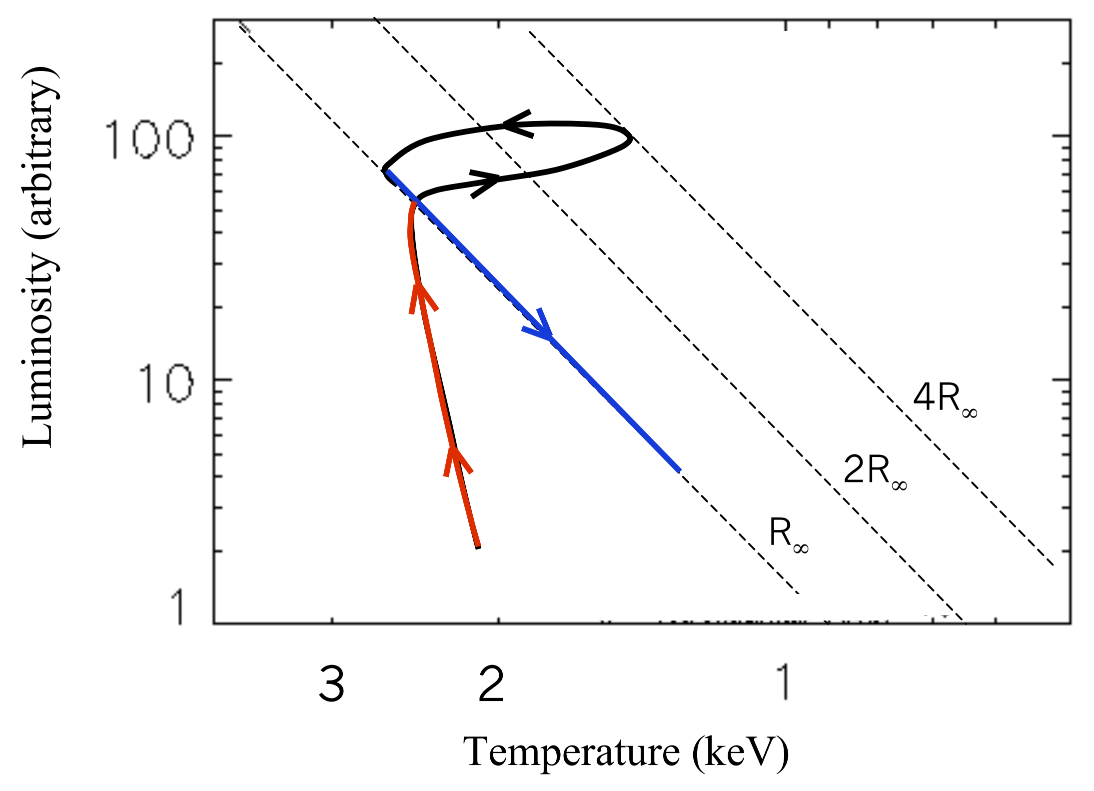
Reasoning

- Brightest emission ever produced at NS surface (reaching the Eddington limit)
- Indication of low magnetic field ($B < 10^9$ G)
  → dynamically unimportant
- Ongoing accretion → metallicity → spectral features
- Numerical simulations indicate the bursts spread quickly over the entire surface



Galloway et al. 2007

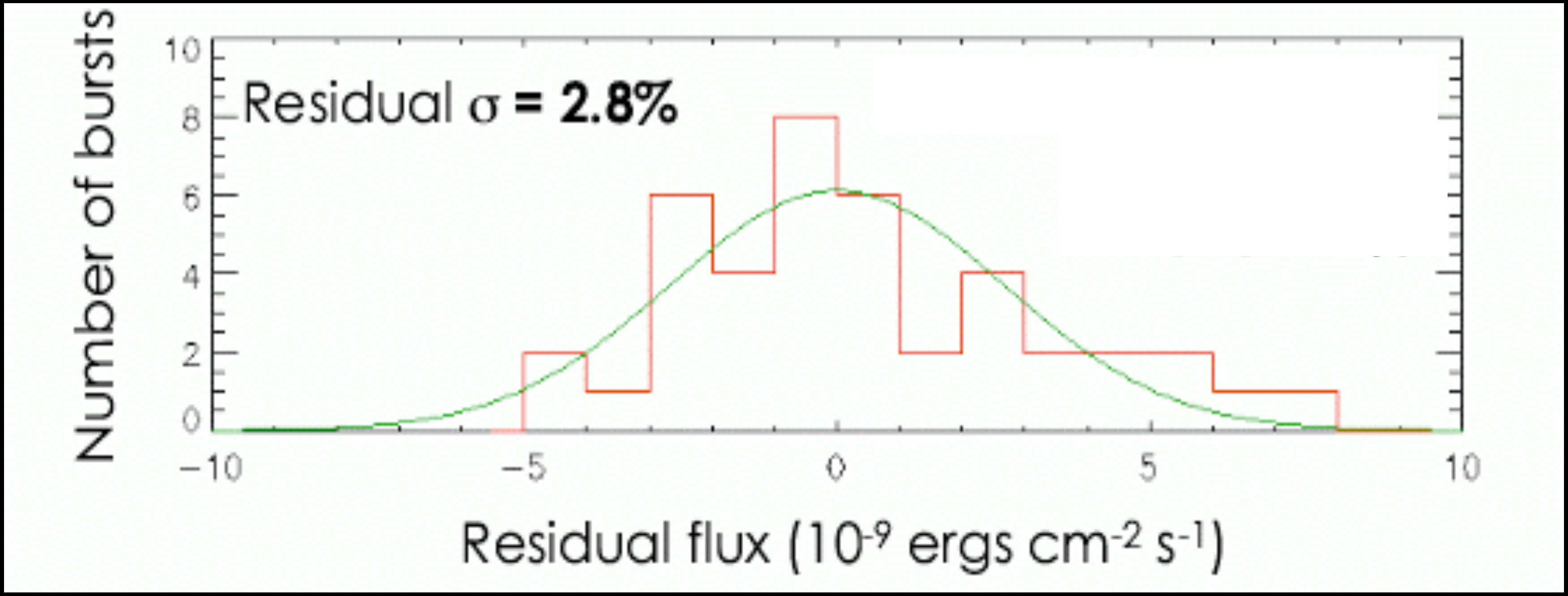
The Evolution of a Burst



An “H-R” diagram for a burst

The Eddington Flux

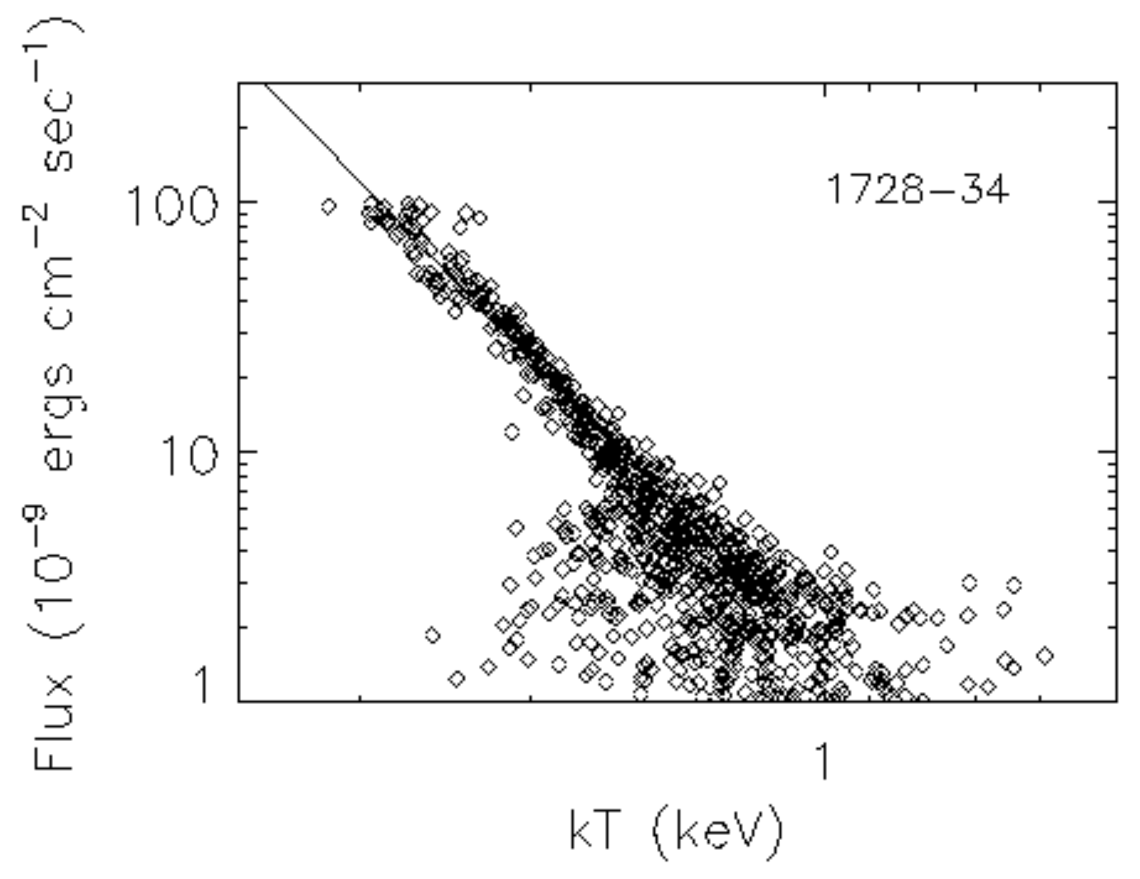
**The peak luminosity is constant to 2.8%
for 70+ bursts of 4U 1728-34**



Galloway et al. 2003

Reliability of the Inferred "Radius"

Constant inferred radius from $$\frac{F_{cool}}{\sigma T_c^4}$$

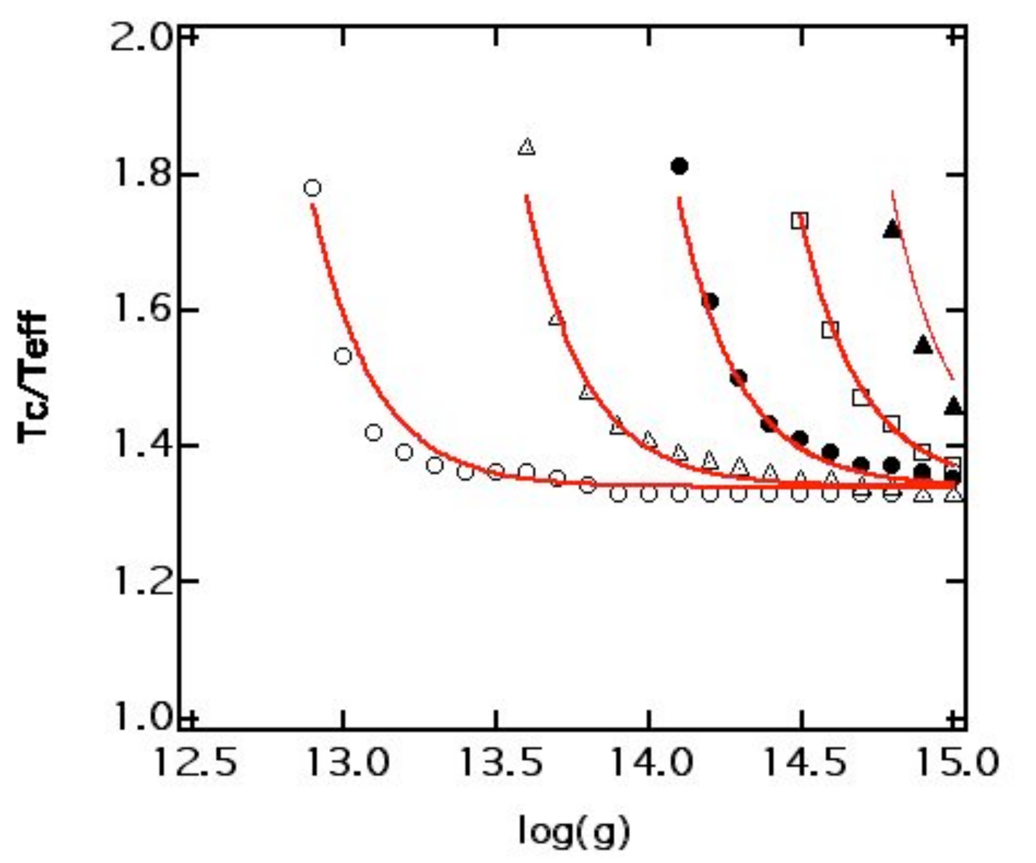


Savov et al. 2001

Spectral Calculations

- Low magnetic fields
- Plane parallel atmospheres

- Non-coherent scattering
- Heavy elements
- Not fully ionized



From Madej et al. 2004, Majczyna et al 2005

EXO 0748-676

Redshifted lines with XMM:

$z=0.35$

Cottam, Paerels, & Mendez 2003

Four Eddington-limited bursts with EXOSAT and RXTE:

$$F_{cool}/\sigma T_c^4 = 1.14 \pm 0.10 \text{ (km/kpc)}^2$$

$$F_{Edd} = 2.25 \pm 0.23 \times 10^{-8}\, erg\, cm^{-2} s^{-1}$$

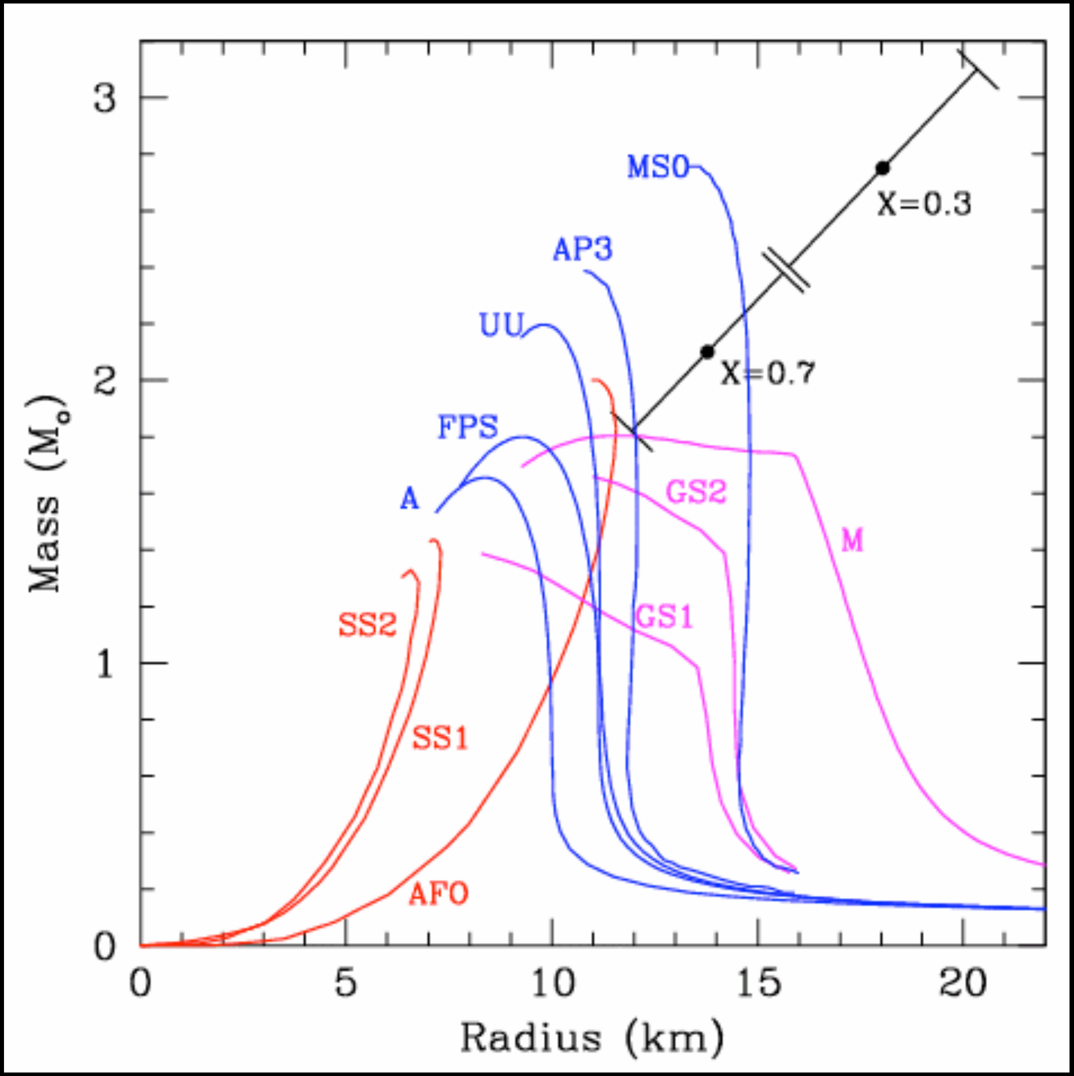
Gottwald et al. 1986, Wolff et al. 2005

Slow rotation

$\nu_0 = 44.7 \text{ Hz}$

Villareal & Strohmayer 2004

Mass and Radius of EXO 0748-676



Özel 2006

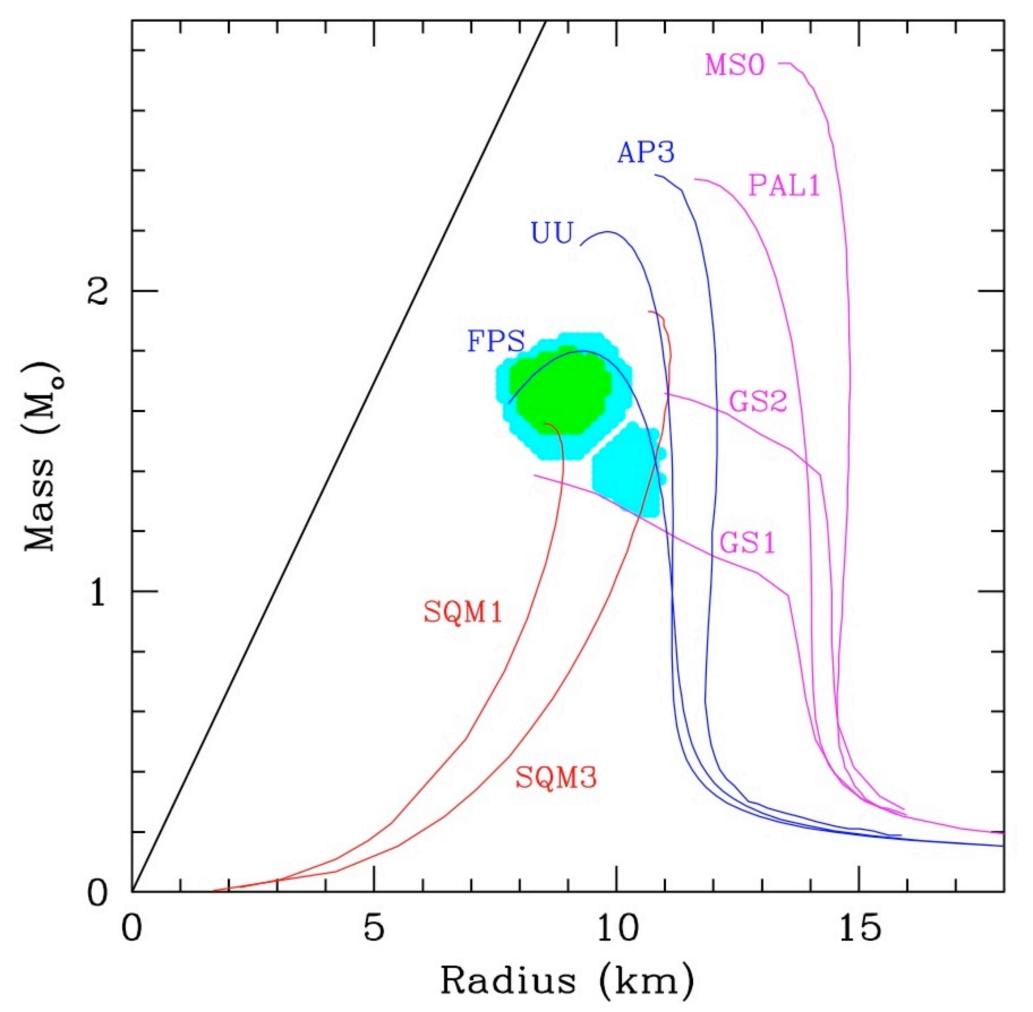
M-R limits:

M = 2.10 ± 0.28 $M_\odot$

R = 13.8 ± 1.8 km

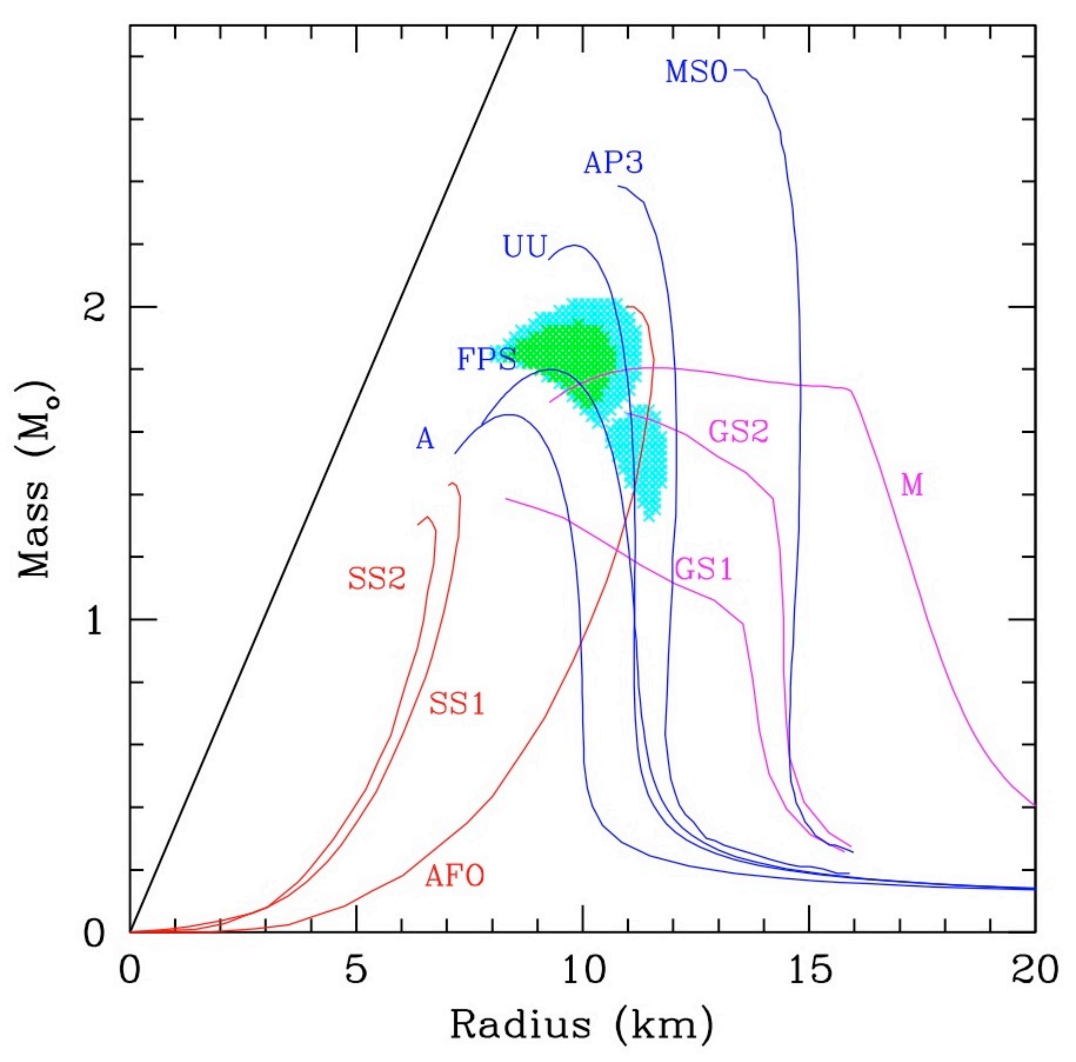
Measurements Using Distances to Sources

EXO 1745-248 in Globular Cluster Terzan 5 (D = 6.5 kpc from HST NICMOS)

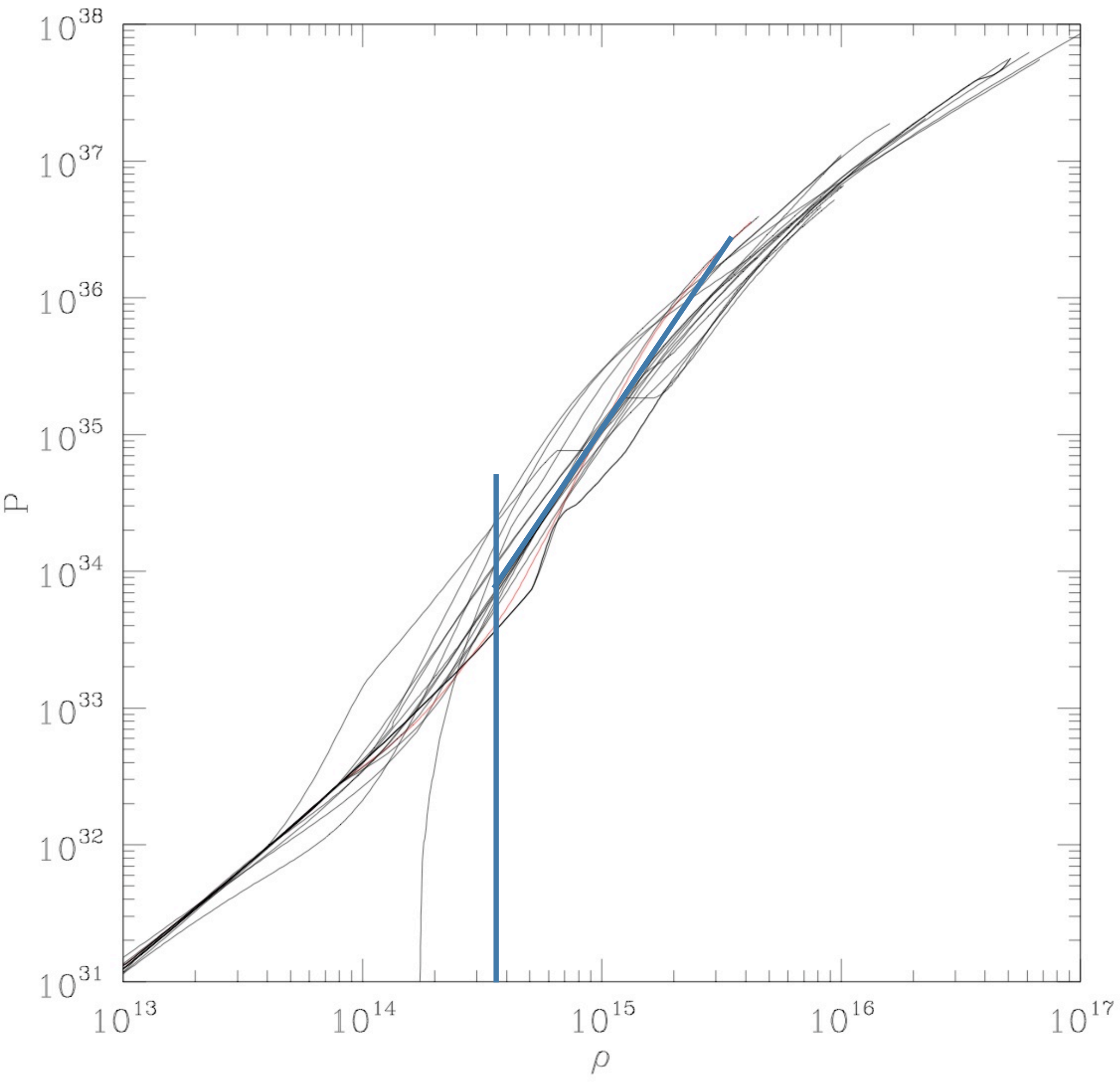


Özel et al. 2008

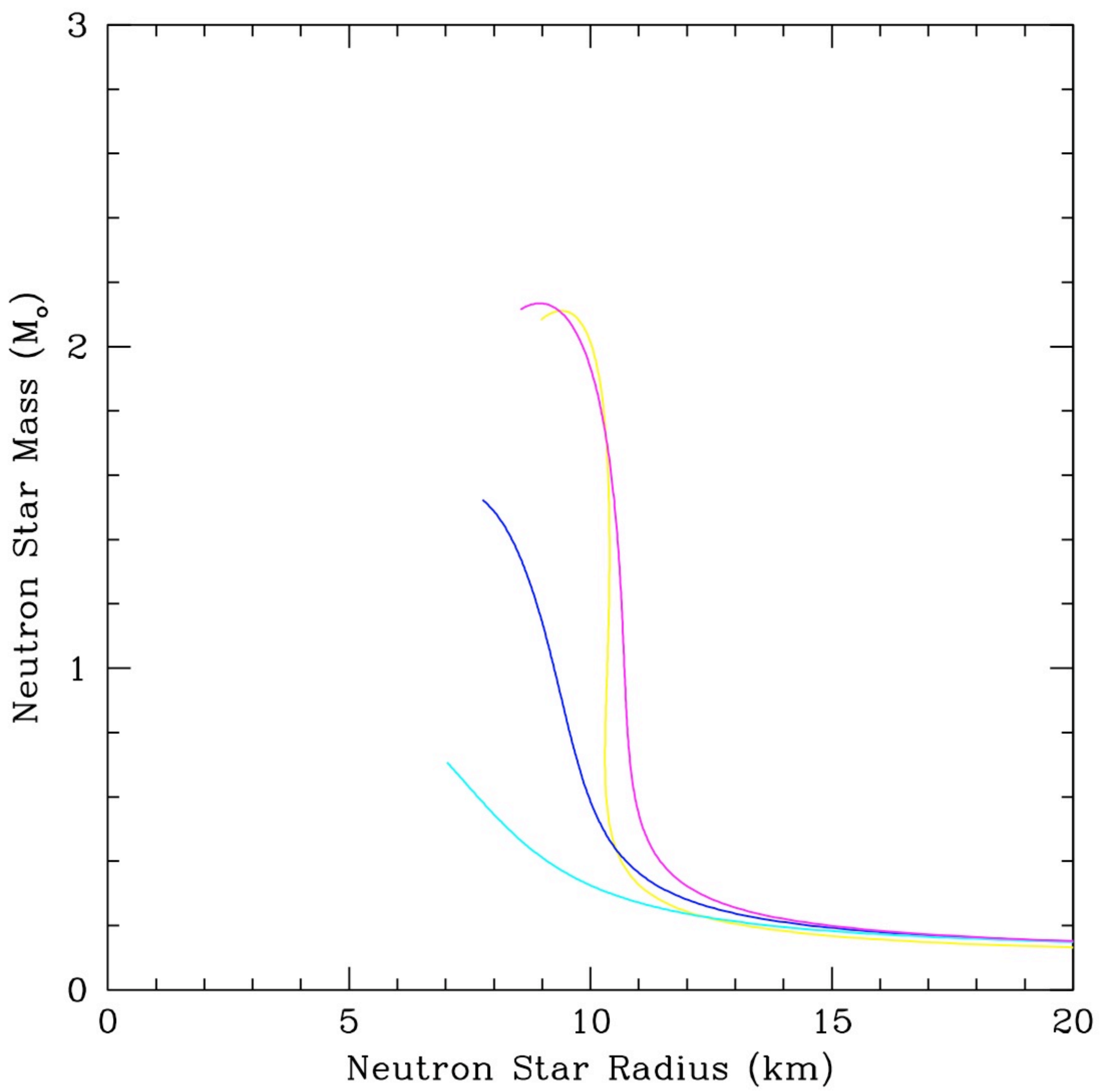
The Mass and Radius of 4U 1608-52



Parametrizing P(ρ)

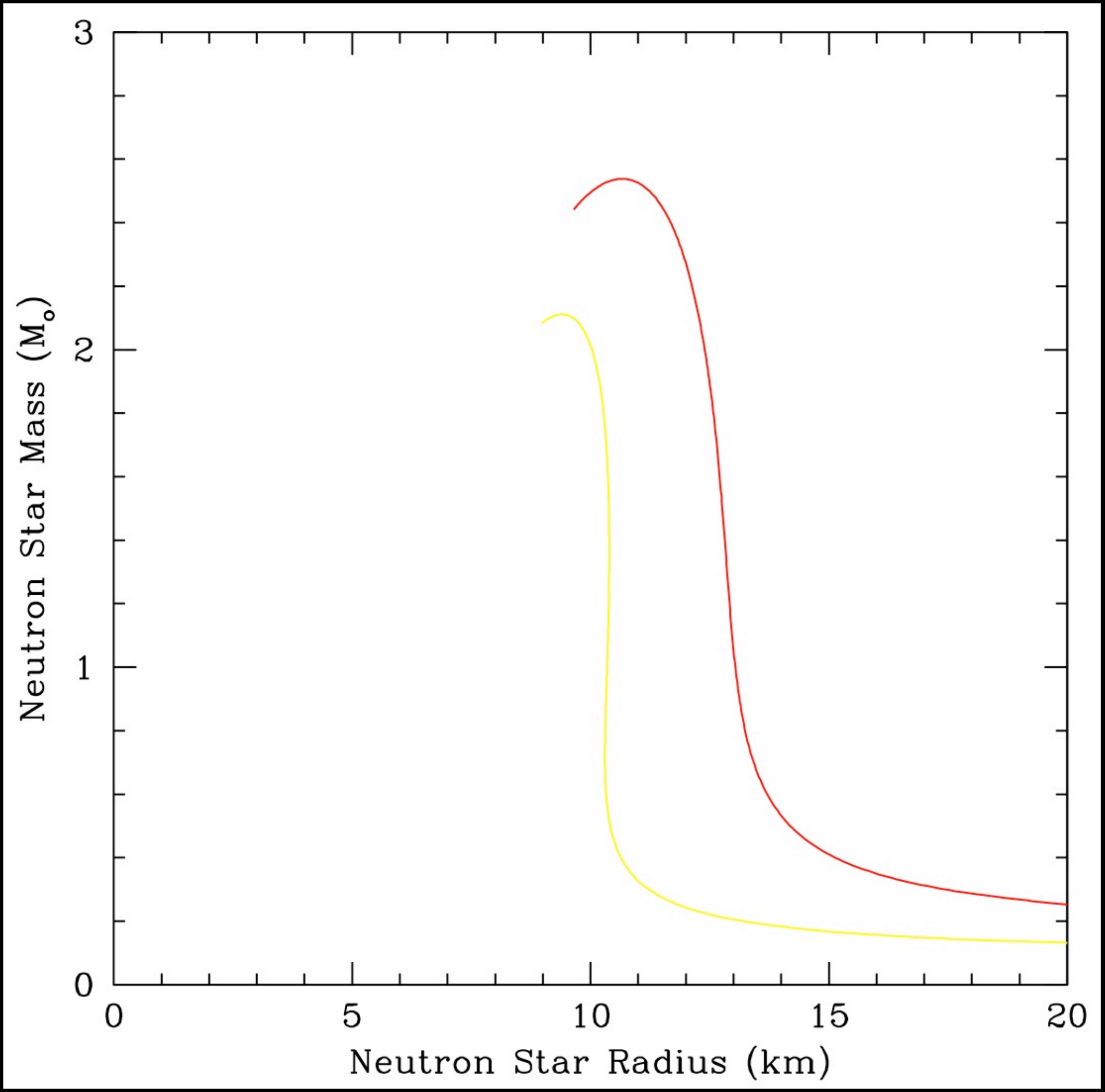


Mapping P(ρ) -- M-R



A single power-law beyond nuclear saturation density

Mapping P(ρ) -- M-R



Pressure at the nuclear saturation density

Conclusions

- We have achieved the first independent mass and radius measurements for a number of neutron stars
- We have undertaken an IR observation campaign with Magellan to find the distances to ~10 more NS binaries
- We are carrying out radiation-hydrodynamical simulations of Eddington-limited bursts to identify any theoretical systematics
- Redshifted absorption line measurements always welcome