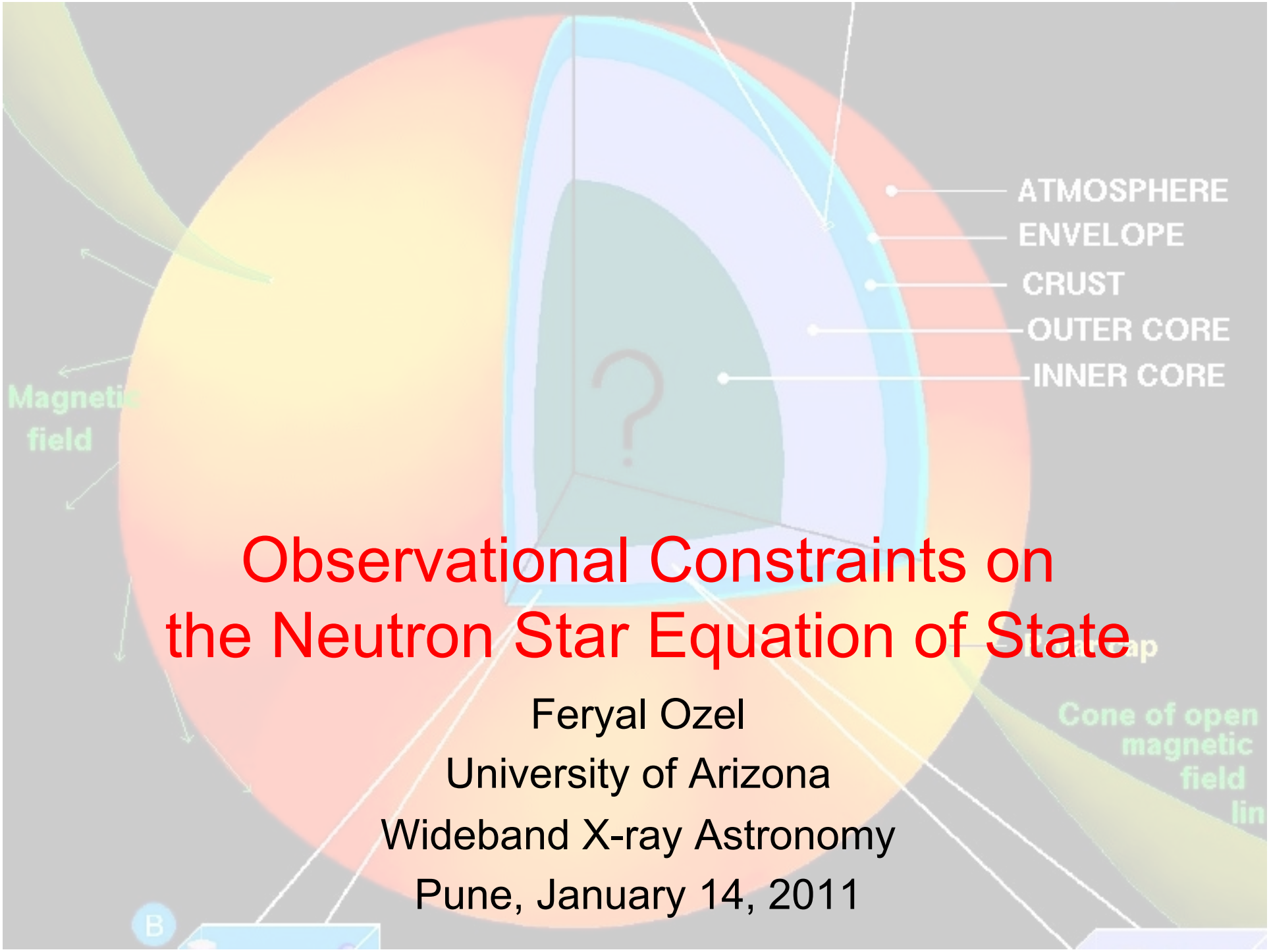


Observational Constraints on the Neutron Star Equation of State

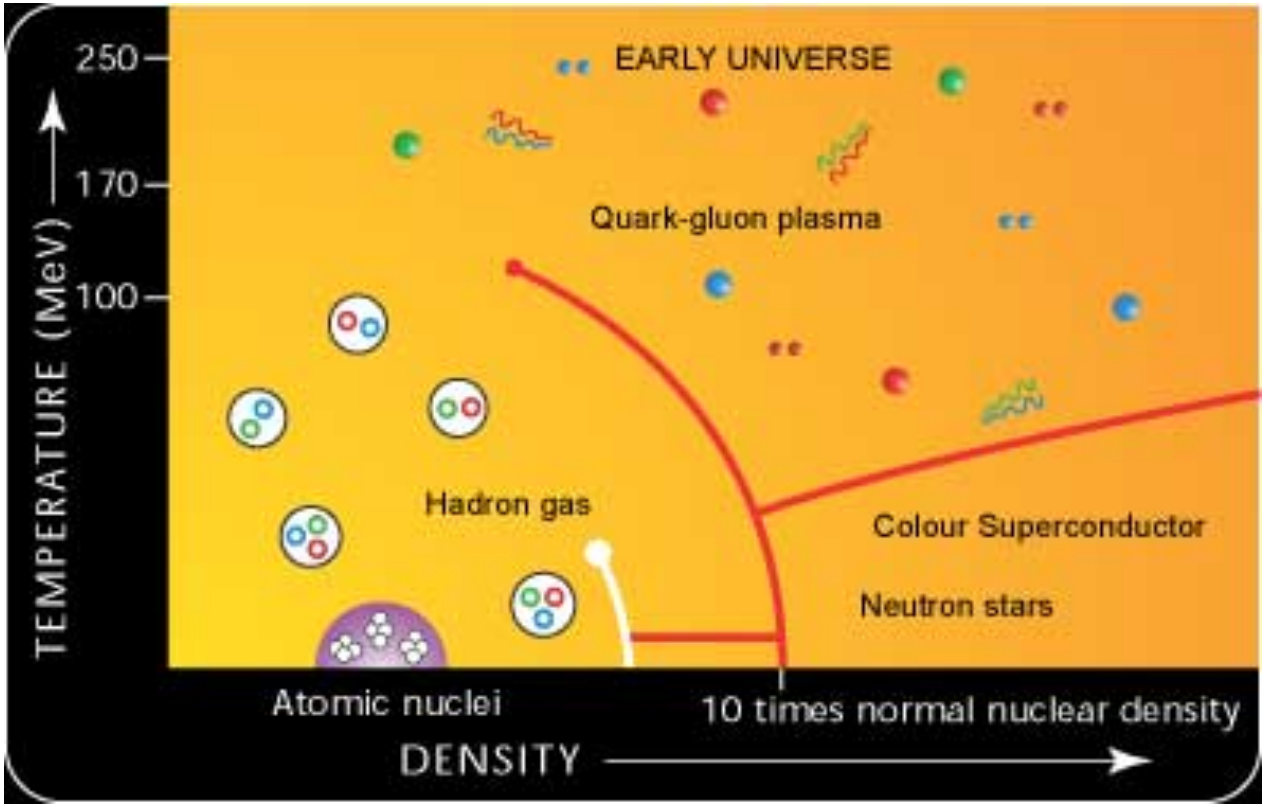
Feryal Ozel

University of Arizona

Wideband X-ray Astronomy

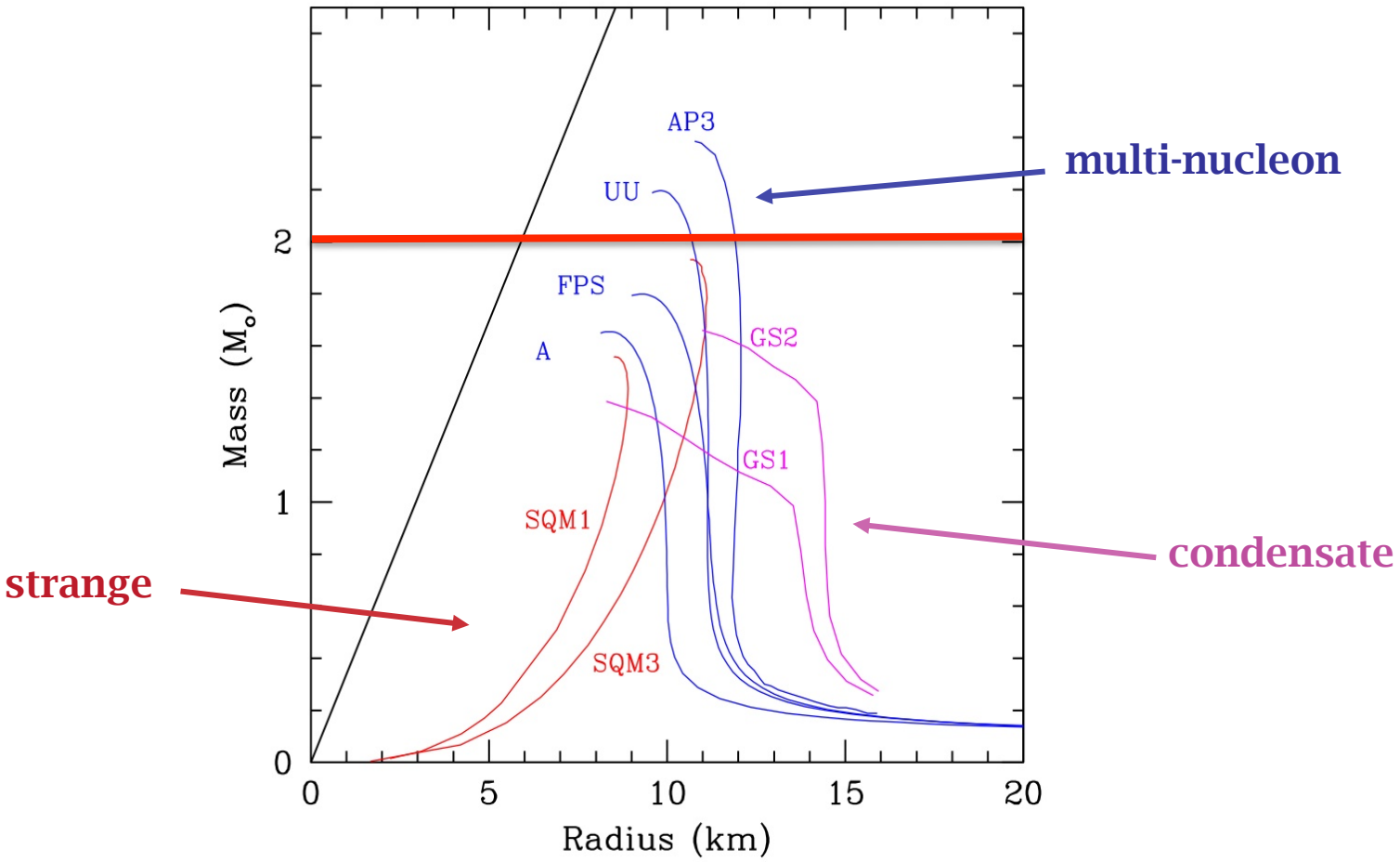
Pune, January 14, 2011

Neutron Stars and Exploring New Physics



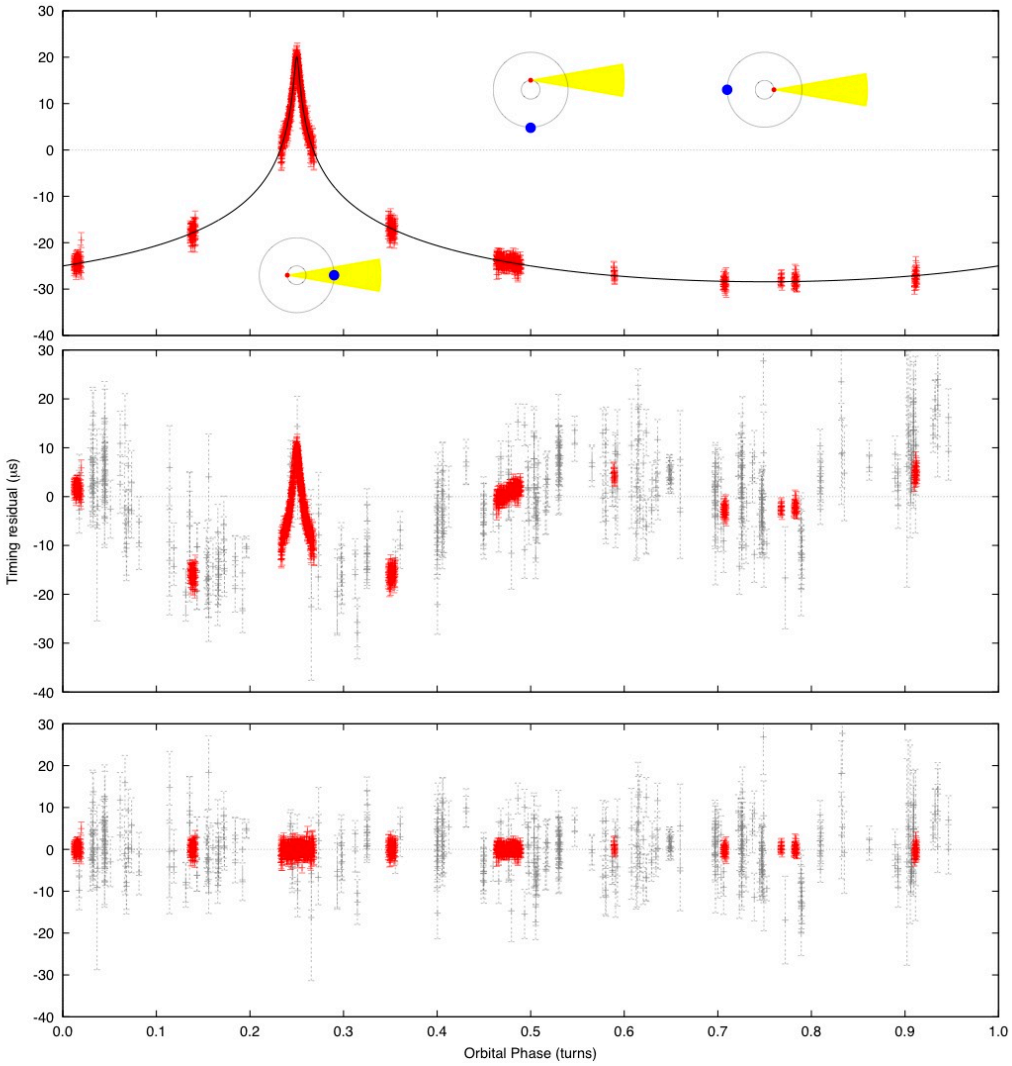
- Neutron stars probe a temperature-density region different than the early universe or hadron colliders
- At high densities, are stable bosons produced? Do nuclei dissolve into quarks? Does strange matter form?

EoS Determines the Mass-Radius Relation



- One-to-one mapping between EoS and M-R relation
- Mass alone is constraining only if extreme

Highest Mass Neutron Star



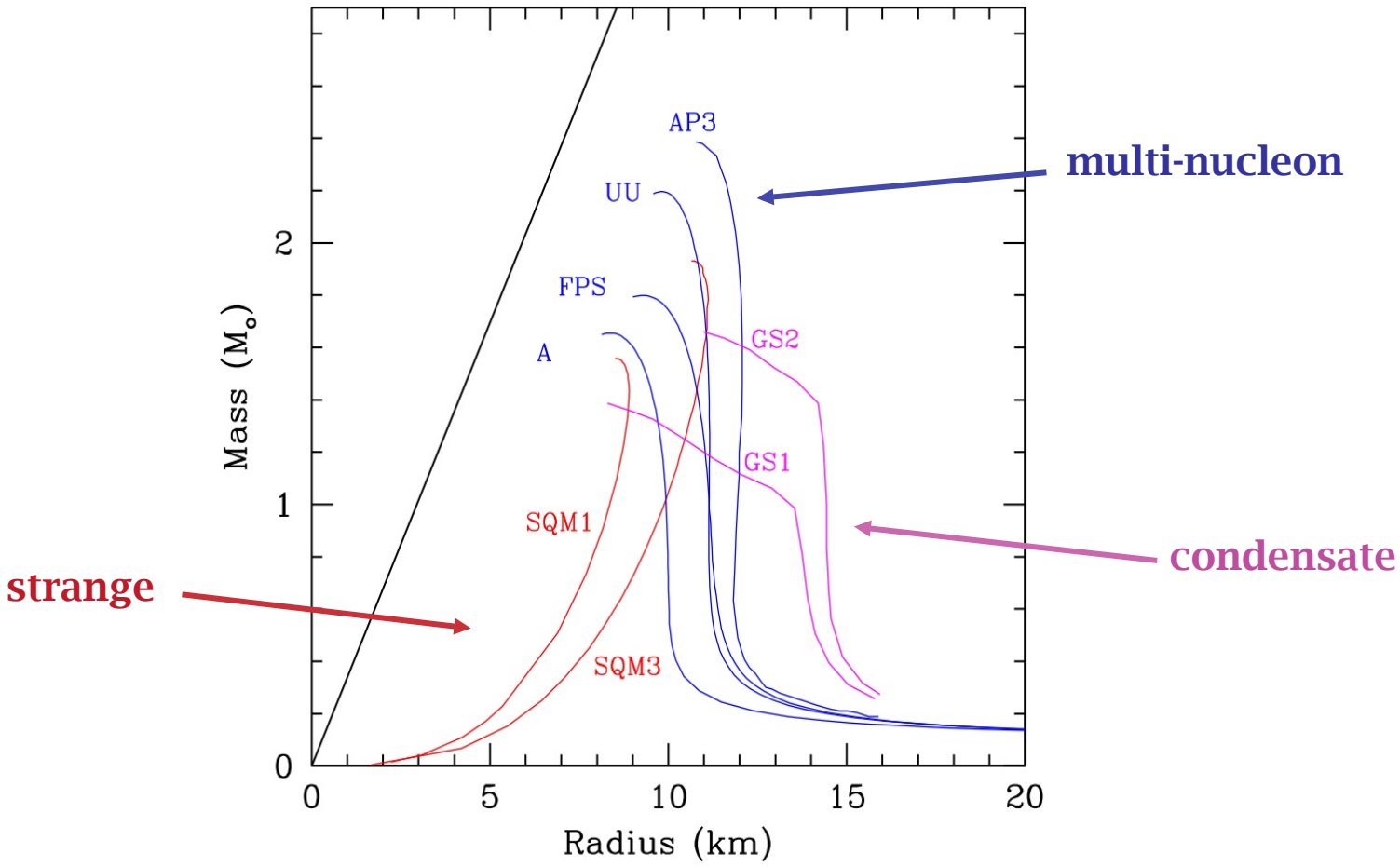
Measurement of the Shapiro delay in PSR J1614-2230 with the GBT

$M = 1.97 \pm 0.04\ M_{\odot}$

Demorest et al. 2010
Ozel et al. 2010

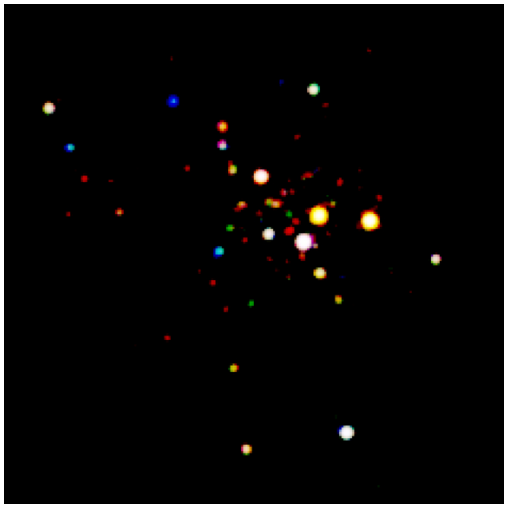
Already rules out most condensate, hyperon, quark models

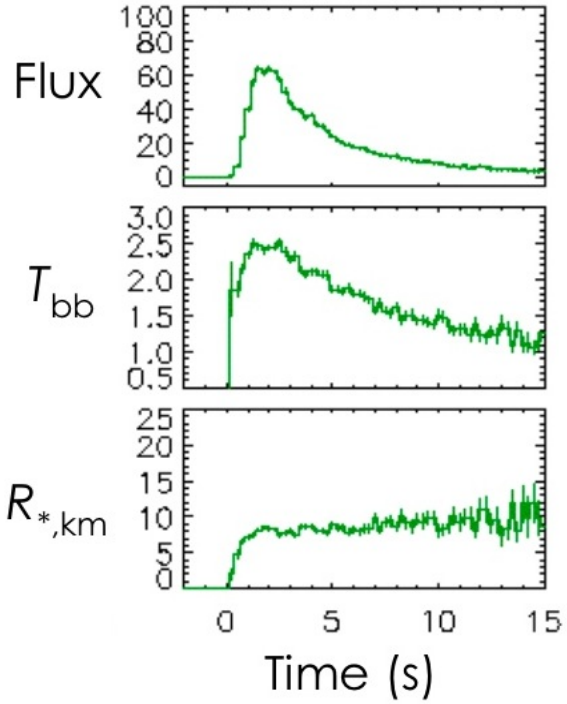
EoS Determines the Mass-Radius Relation



- Radii carry valuable information on EoS
- Tracing M-R relation even better

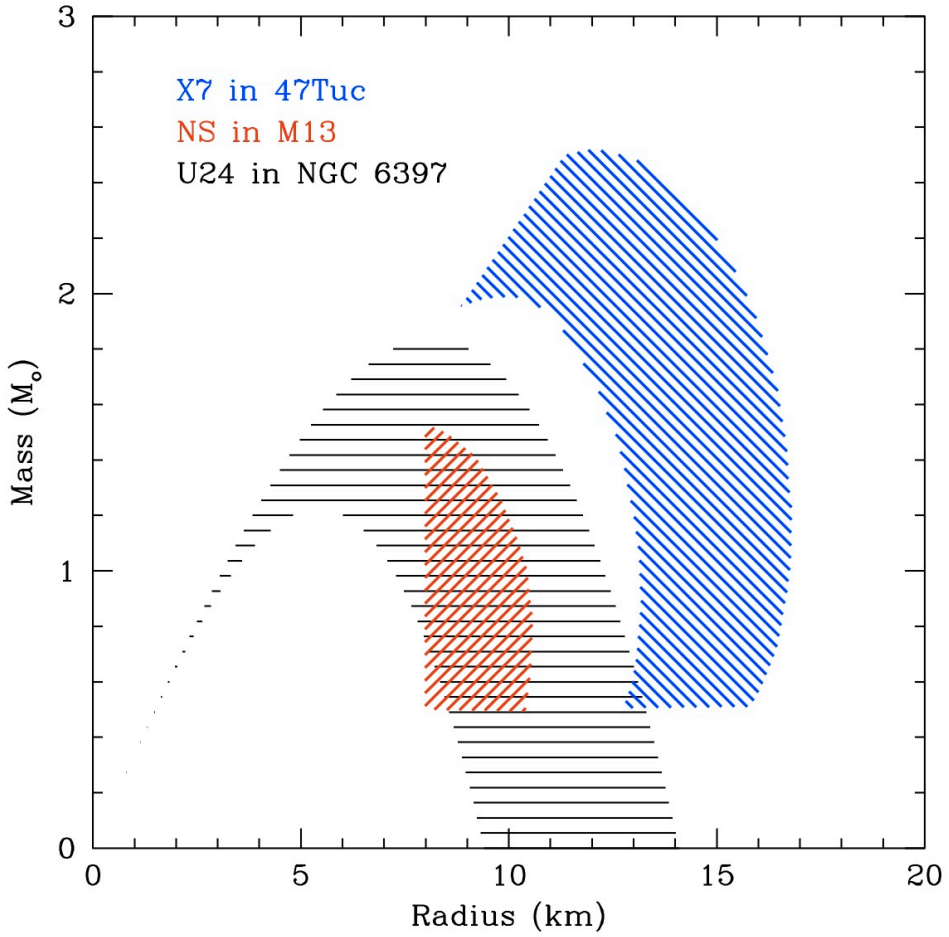
Low-Mass X-ray Binaries Offer Advantages





- Indication of low, dynamically unimportant magnetic fields
  ($B < 10^9$ G)
- Thermonuclear bursts are the brightest emission ever produced at NS surface (sometimes reaching the Eddington limit)
- Ongoing accretion → metallicity → spectral features
  search for lines in these sources
- Expectation for uniform emission in quiescence and during bursts
- The realm of ASTROSAT science

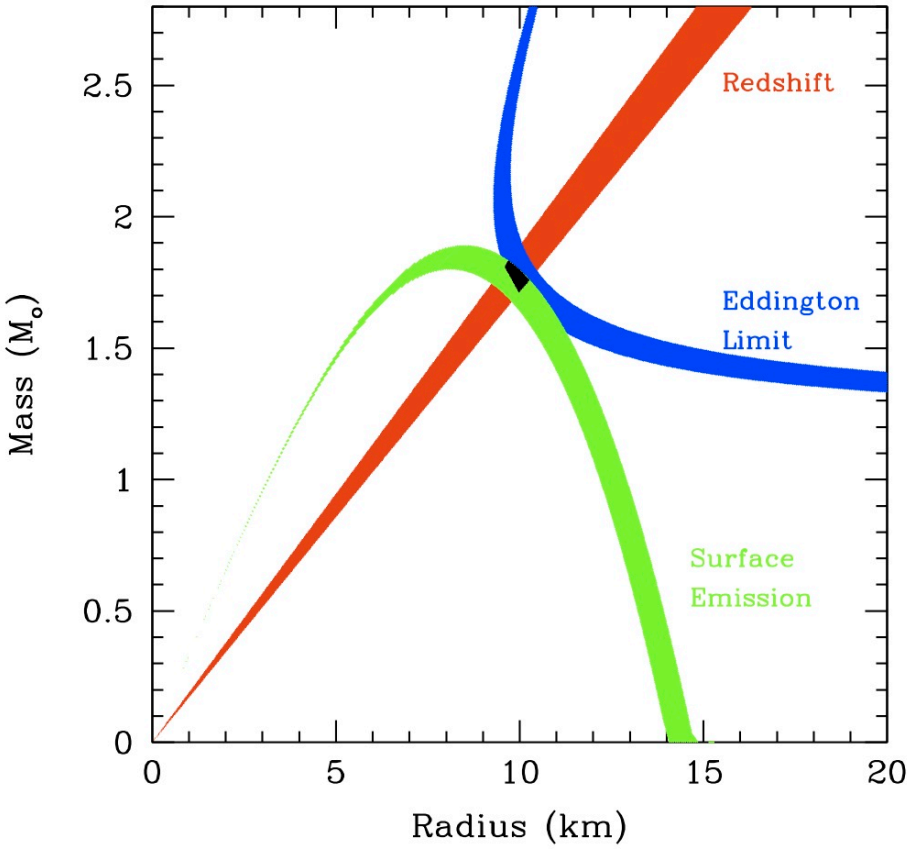
Quiescent LMXBs in Globular Clusters



Heinke et al. 2006
Webb & Barret 2007
Guillot et al. 2010

Correlated mass-radius measurements in several sources

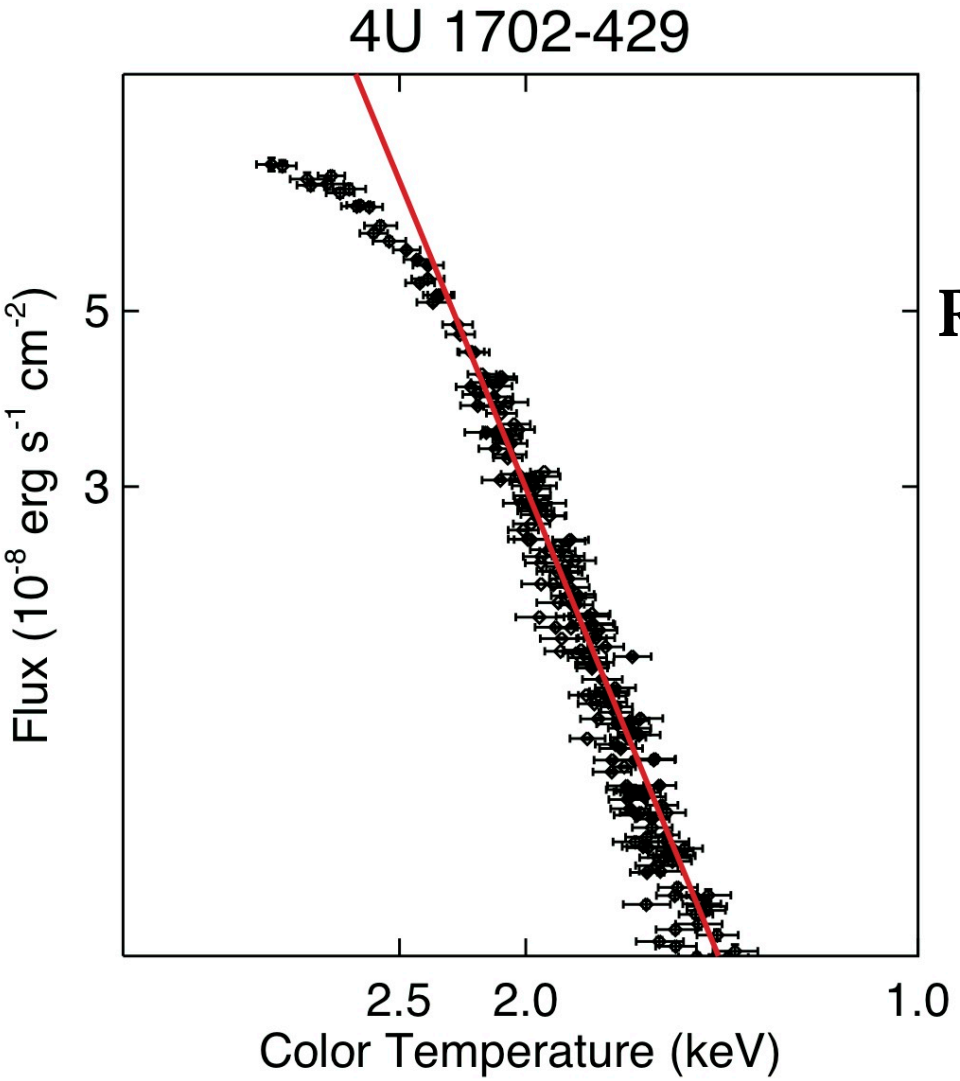
Bursters Have Indeed Been Fruitful



Özel 2006, Nature, 441, 1115

Use 1. emitting area during bursts and
2. the Eddington limit
to measure mass and radius

Apparent Area During Burst Cooling



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

- $F \sim T^4$
- Reproducible
- Atmosphere models take into account spectral distortions

Neutron Star Surface Emission

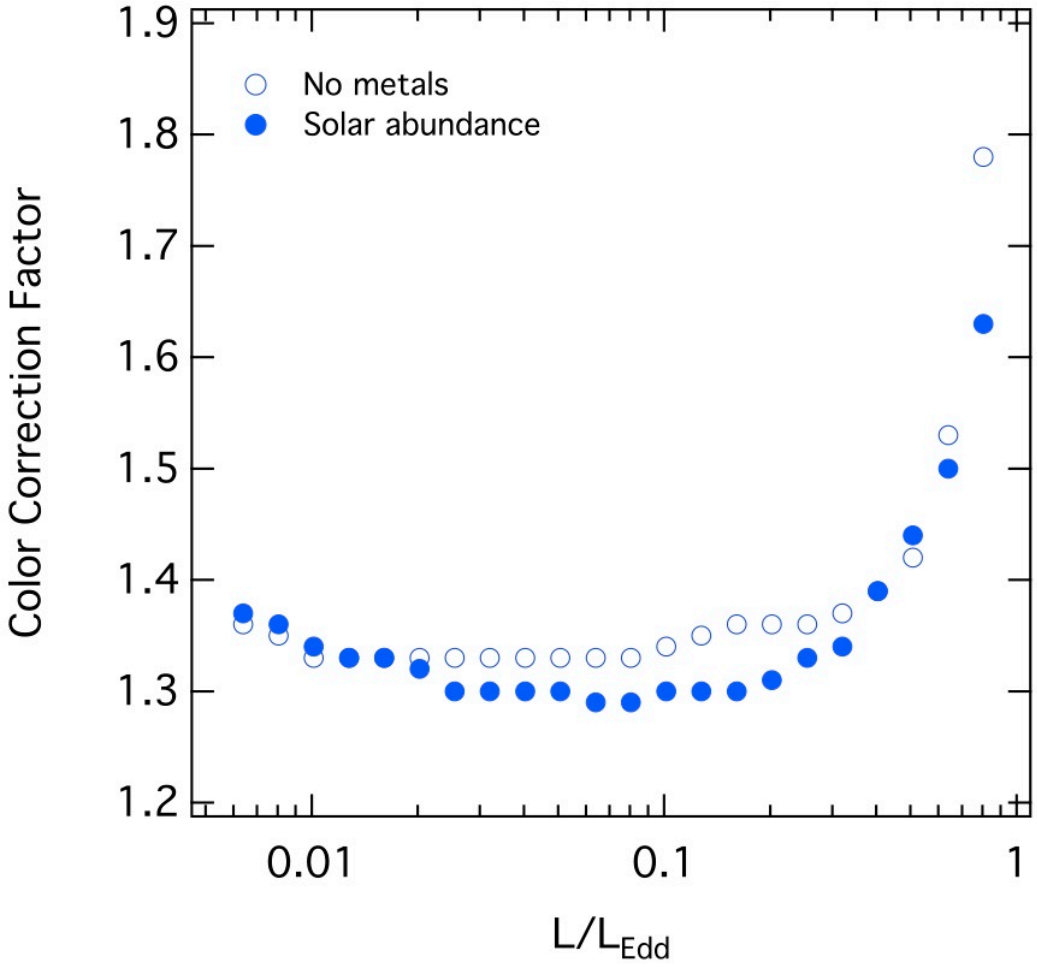


- **Low magnetic fields**
- **Plane parallel atmospheres**
- **Radiative equilibrium**

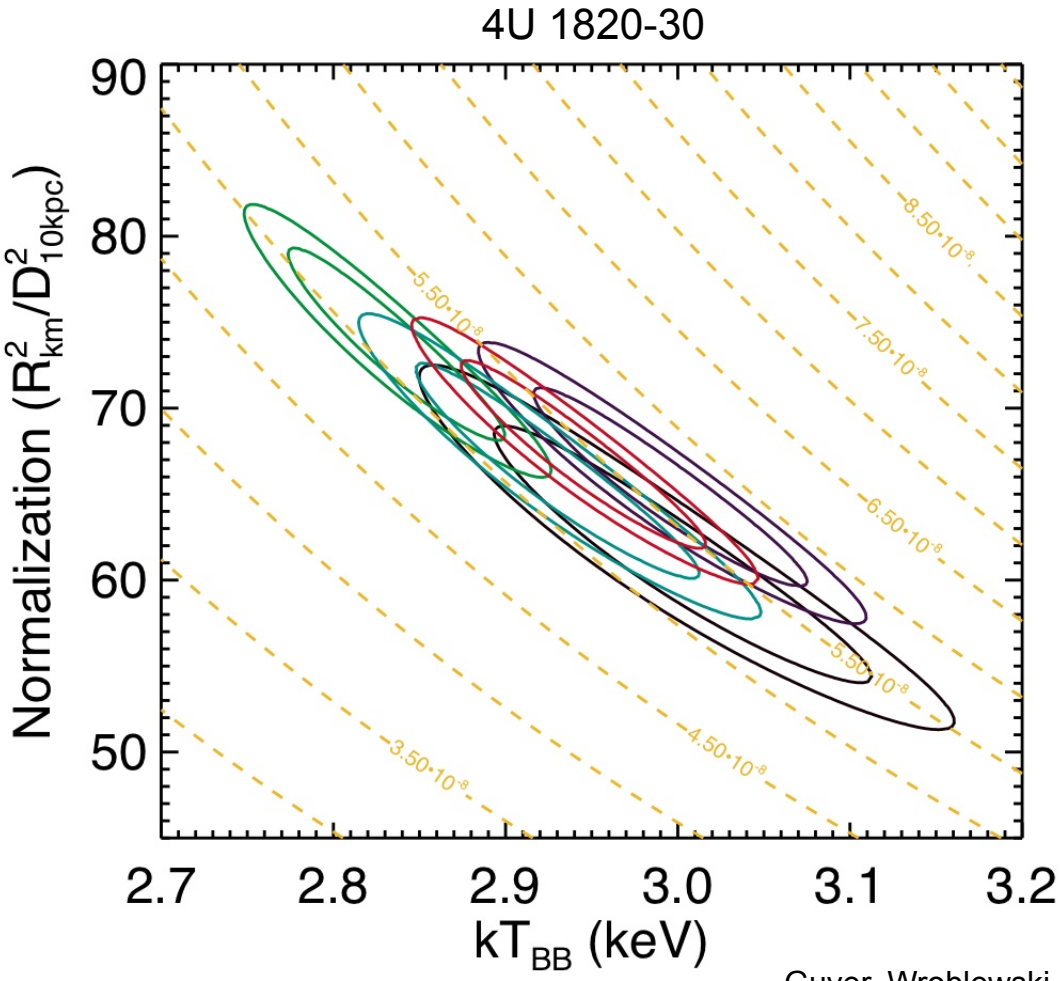


- **Non-coherent scattering**

from Madej et al. 2004,
Majczyna et al 2005, Ozel et al. 2009



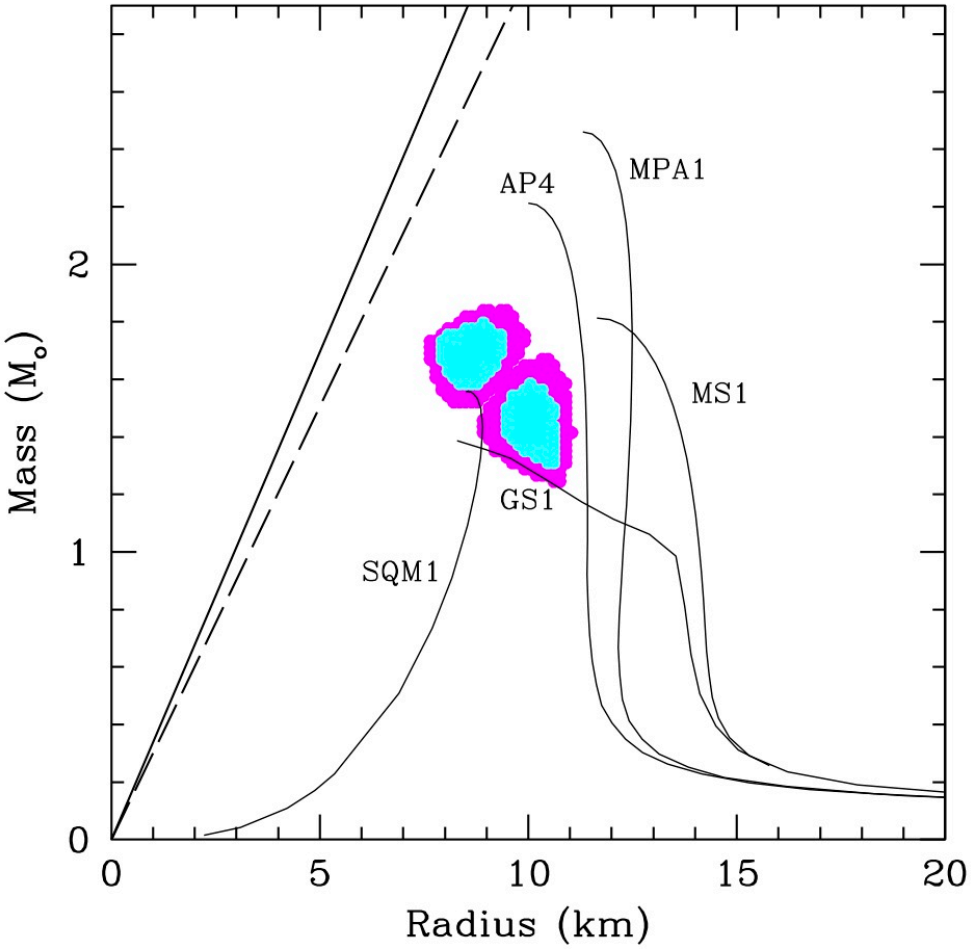
Measuring the Eddington Flux



Guver, Wroblewski, Camarota, & Ozel 2010

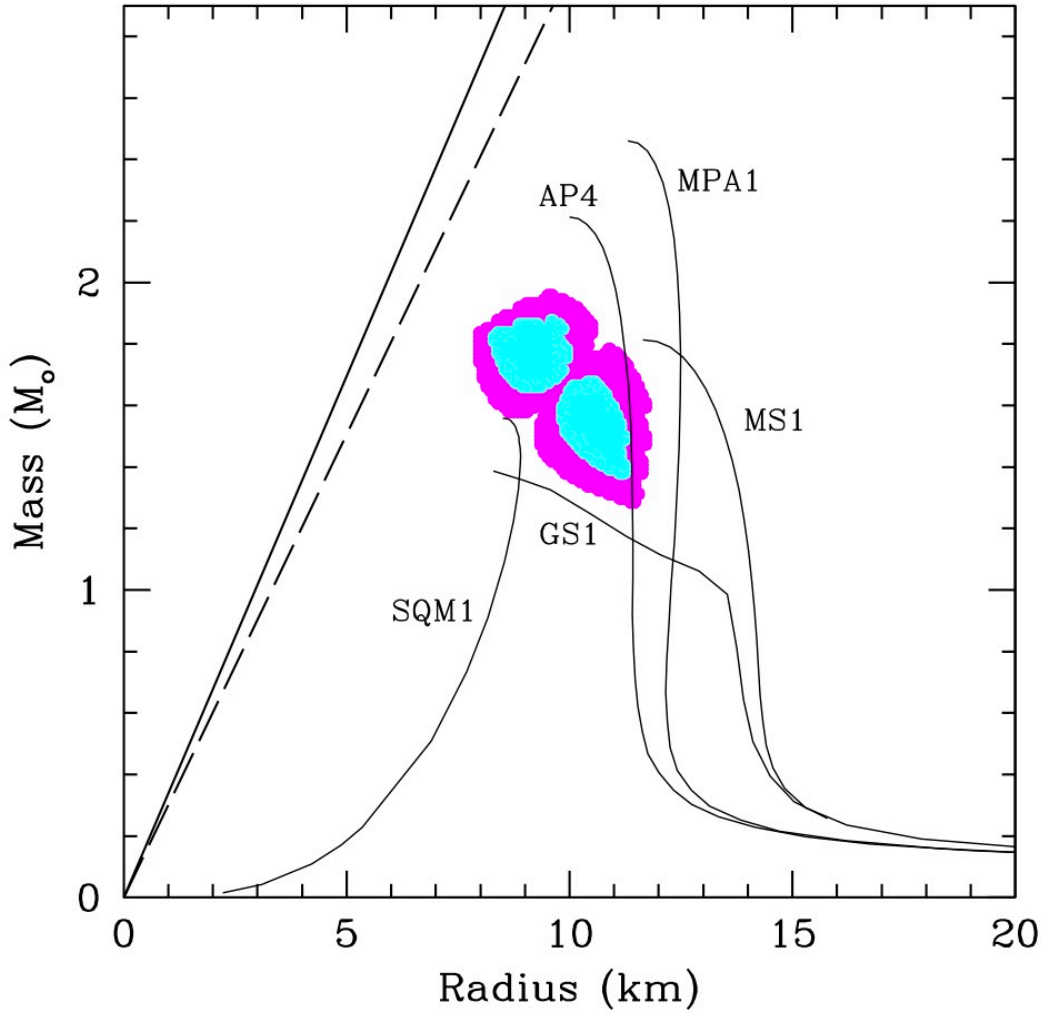
Mass and Radius of EXO 1745-248

- In globular cluster Terzan 5, D = 6.3±0.6 kpc from HST NICMOS observations



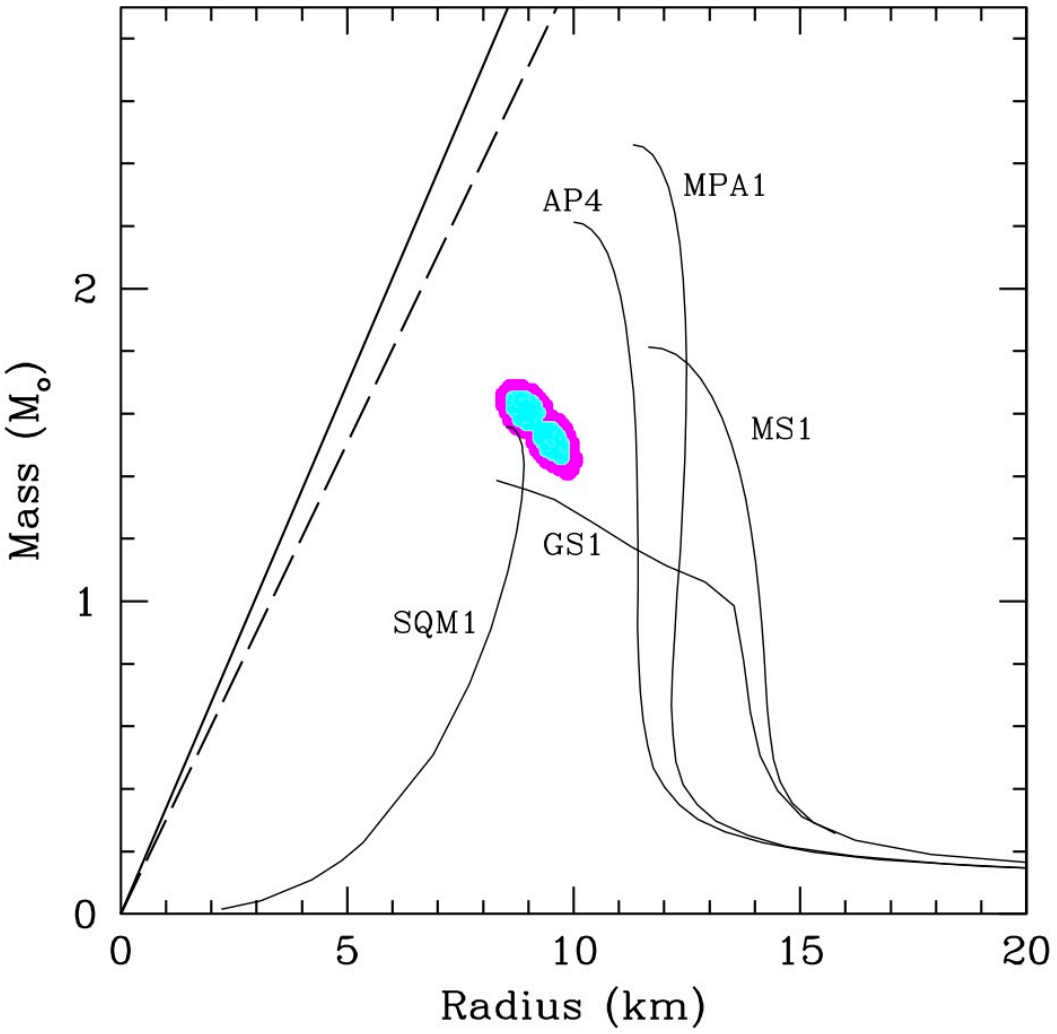
Ozel et al. 2009, ApJ, 693, 1775

Mass and Radius of 4U 1608-52



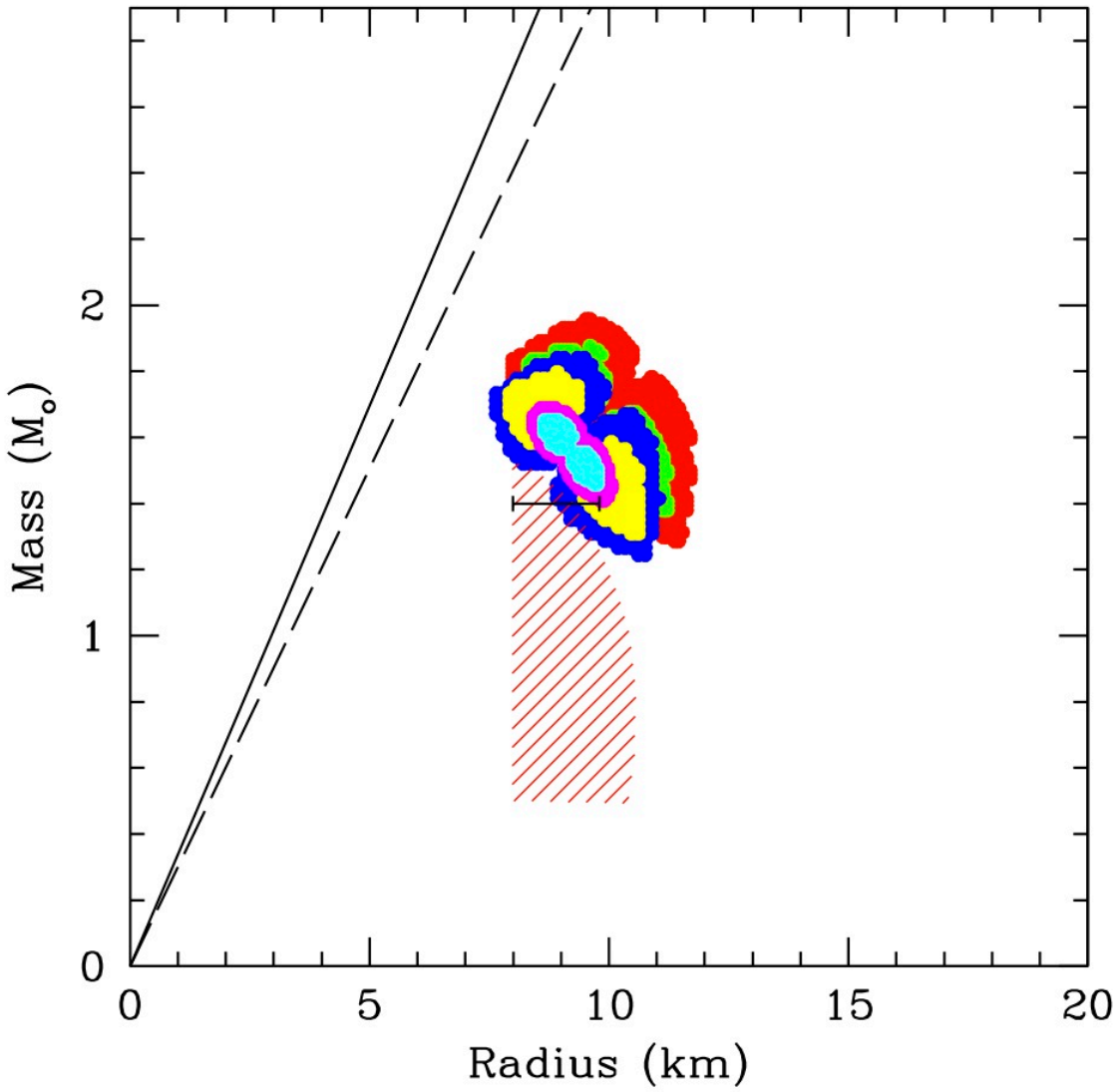
Mass and Radius of 4U 1820-30

- In globular cluster NGC 6624, D = 6.8 - 9.6 kpc (Kuulkers et al. 2003, Valenti et al. 2007)



Guver et al. 2010, ApJ

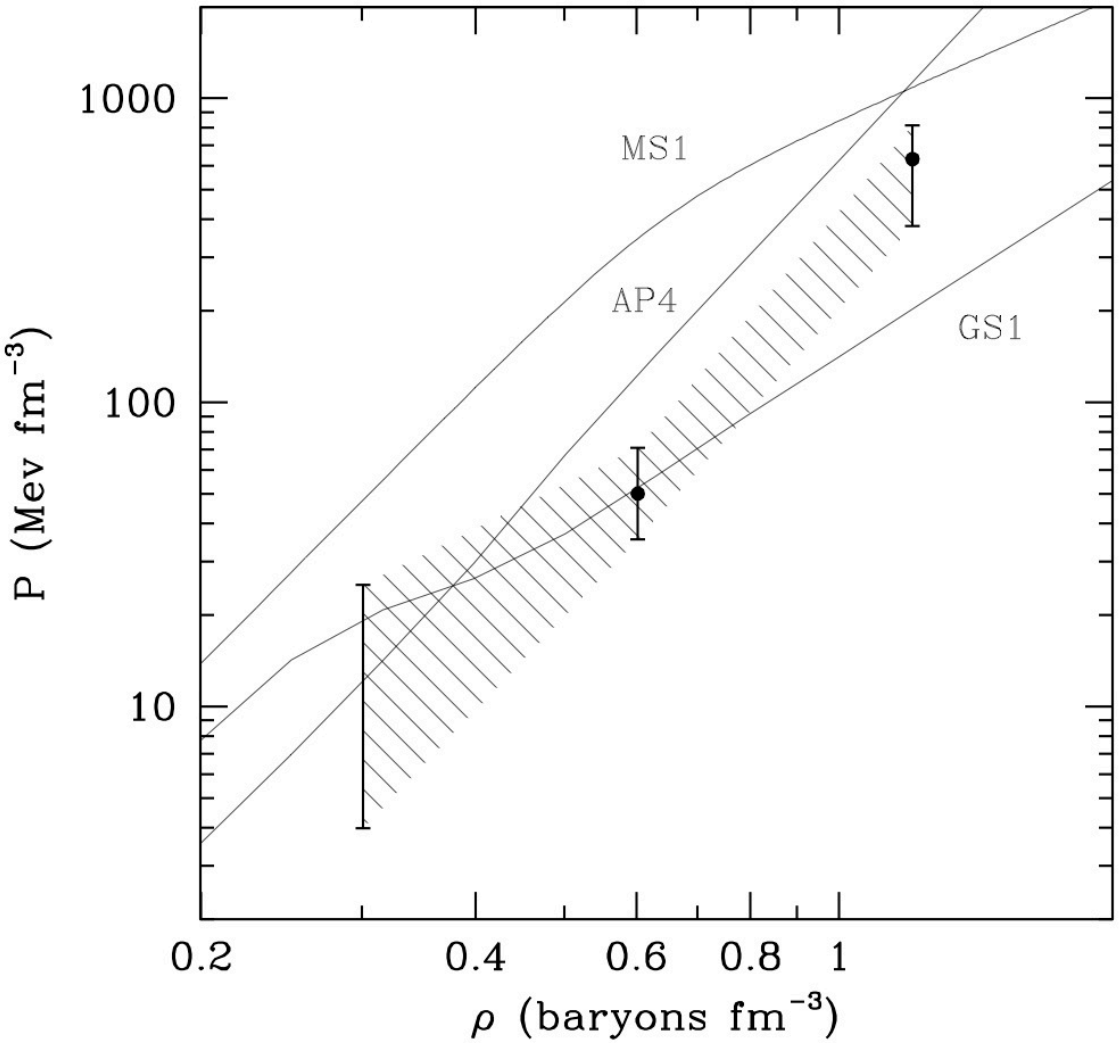
Mass and Radius Measurements



Remarkable agreement in radii between Burst Sources + Thermally Emitting Globular Cluster Sources

M13: Webb & Barret 2007
U24 in NGC6397:
Guillot et al. 2010
(projected in mass)

The Pressure of Cold, Ultradense Matter



Ozel, Baym, & Guver 2010, Phys. Rev.

Address Systematic Uncertainties

Source Selection:

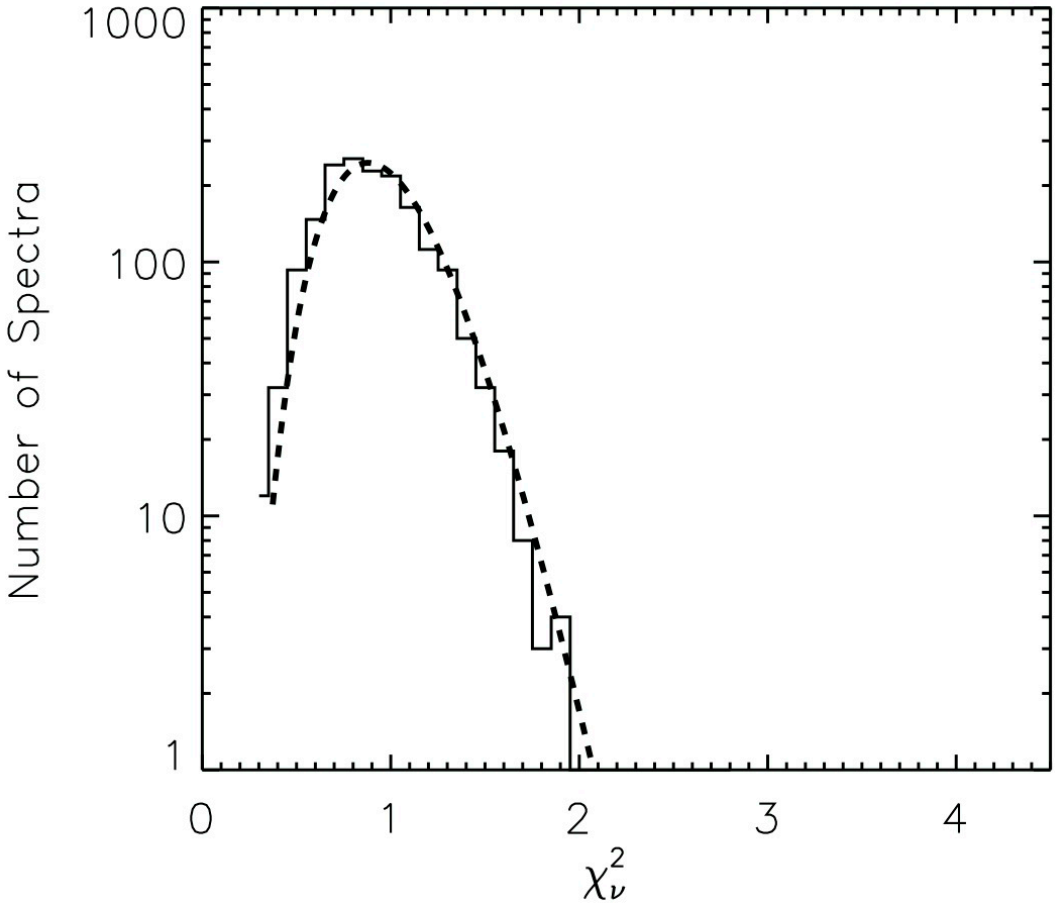
- $L_{pers} < 0.1\ L_{peak}$
- exclude dippers, high inclination sources
- exclude Type II bursts
- Focus on sources that also show Eddington-limited bursts

Measurement Uncertainties Per Source:

- How good are spectral fits?
- Are all data consistent with a single measurement?

Assess Measurement Biases

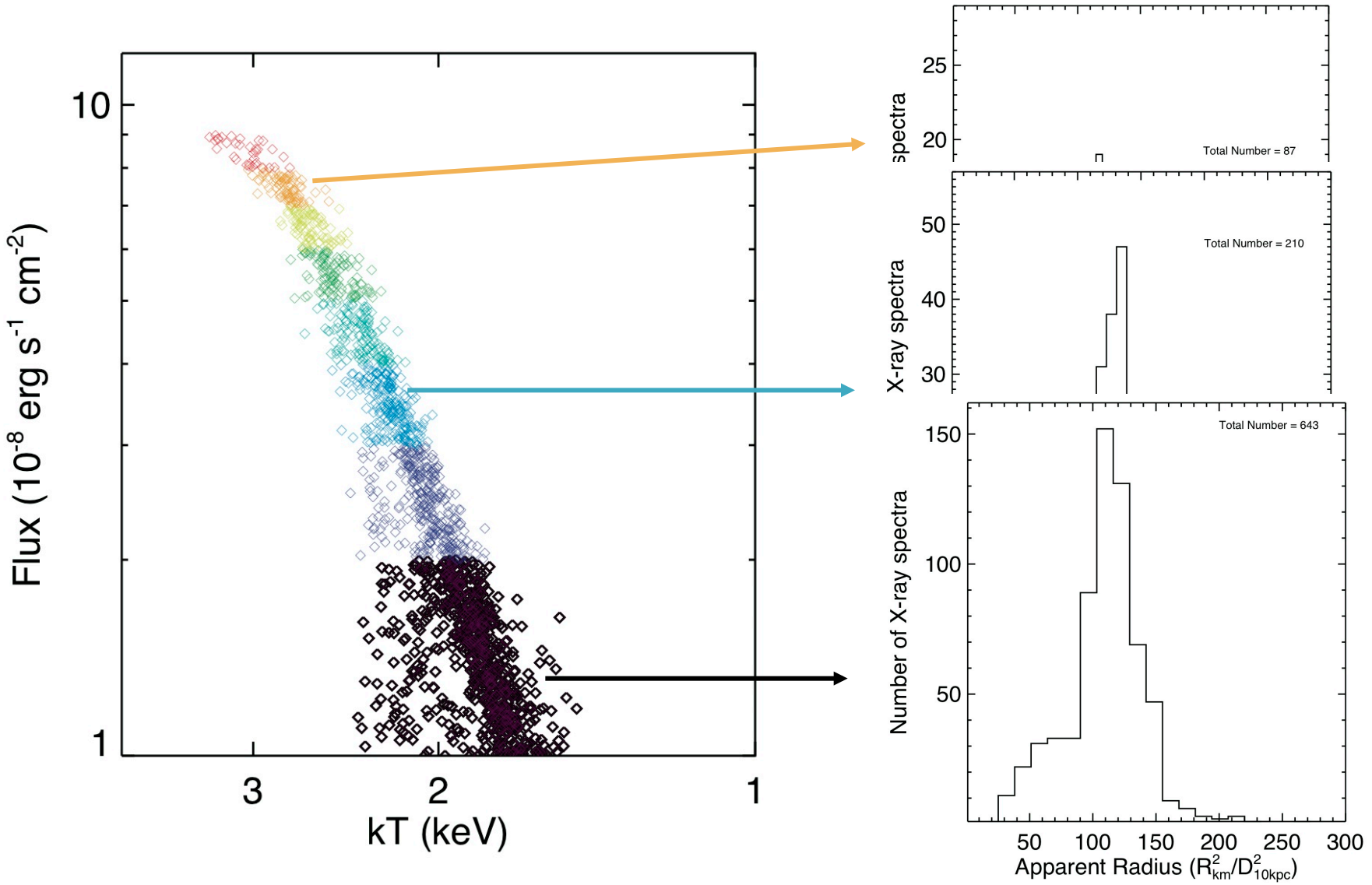
Analysis of the Burst Spectra



4U 1636-536
26 d.o.f.
1712 spectra

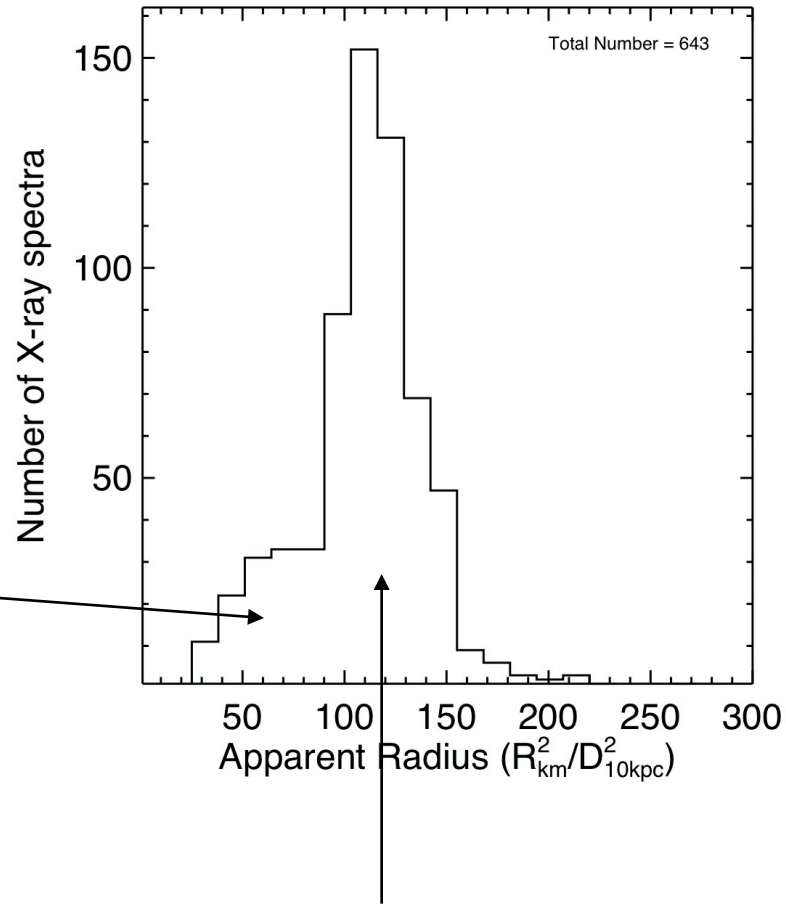
Spectra are well-described by
Comptonized atmosphere models

Apparent Area During Burst Cooling



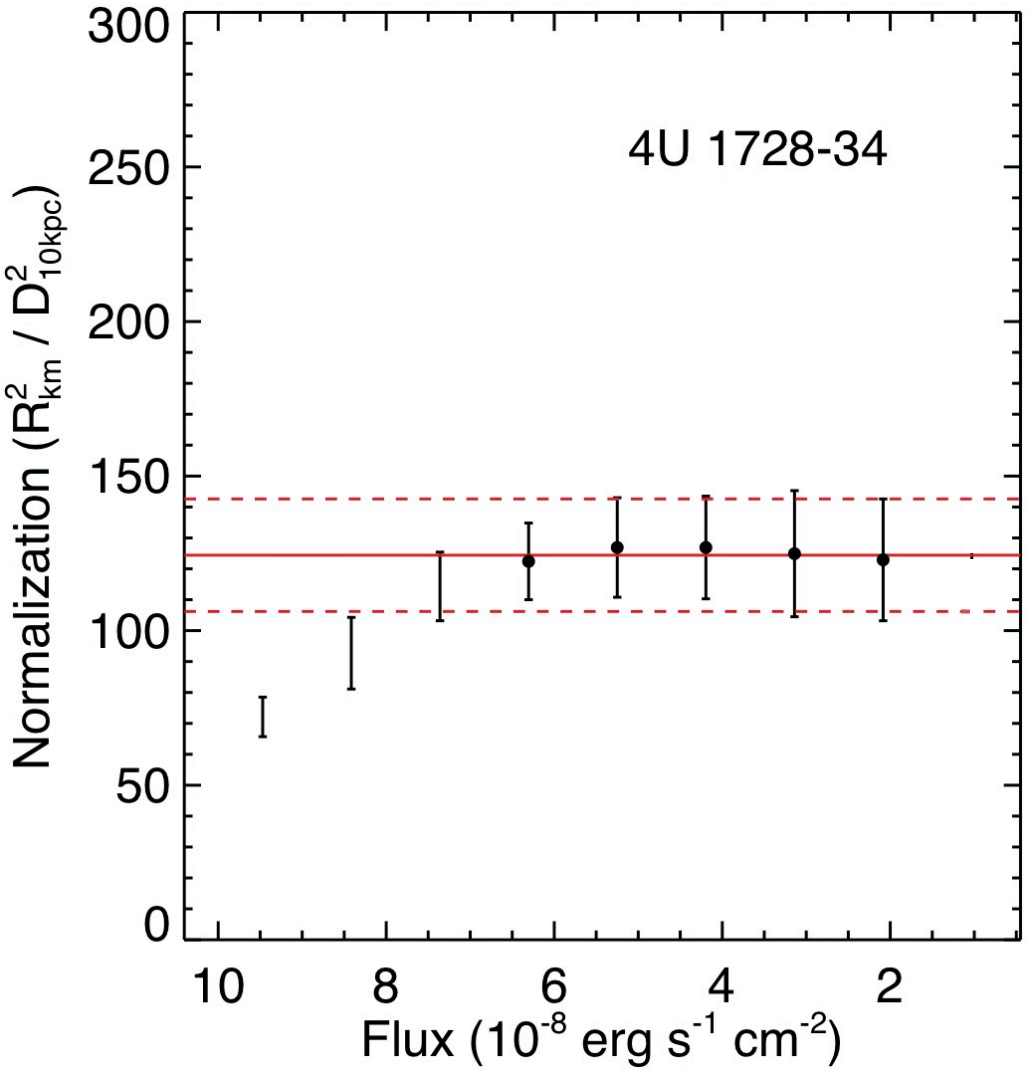
Quantifying Systematic Uncertainties

Use Bayesian Gaussian-mixture outlier detection technique



Determine the width of the underlying distribution

Quantifying Systematic Uncertainties



Determine systematic errors ~11% in area, ~6% in radius

ASTROSAT Era

- Increase sample for sources with few bursts or few Eddington-limited bursts
- Address absolute calibration uncertainties
- Biases in Eddington limit

The Equation of State: Current and Future

- Combination of theoretical effort and high quality data is enabling the first measurements of the NS equation of state
- Nuclear EoS that fit low-density data too stiff at high densities
- Strong indication for new degrees of freedom
- A parametrized EoS can already be incorporated into coalescing neutron star calculations
- Maximum mass of neutron stars ~ 2 $M_{\odot}$
- Expect independent confirmation through gravitational waves, absorption lines, fast oscillations, dynamical NS/BH mass measurements, or cooling