Measuring the Masses and Radii of Neutron Stars through X-ray Spectral Observations

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Neutron Stars

- Strongest gravitational field among all objects in the Universe that still have surface,
- Extreme Densities,
- Strongest magnetic fields.

Observations of neutron stars offer unique insight to the behaviour of matter and radiation in these extraordinary conditions.

Equation of State to Mass and Radius

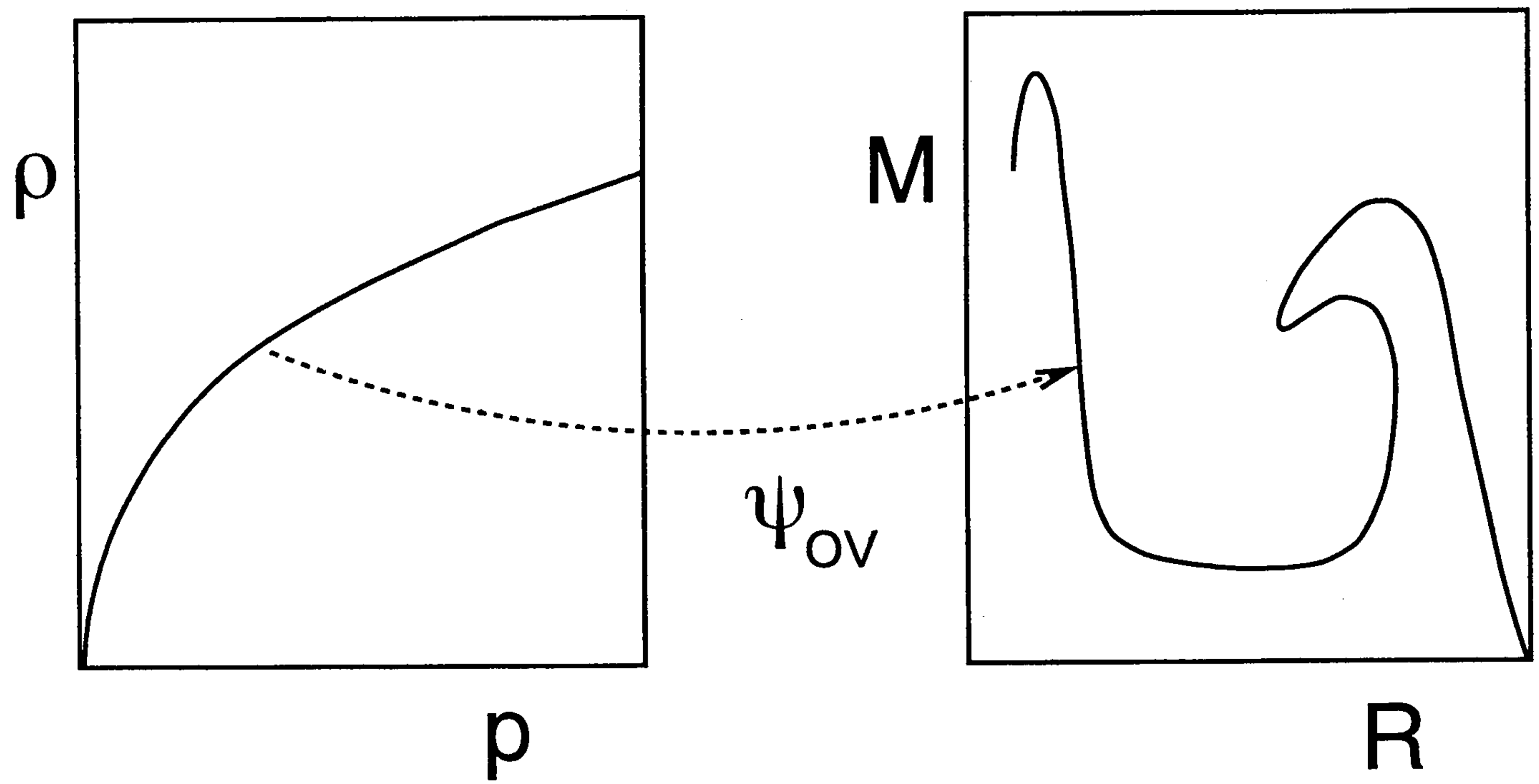


FIG. 1.—A schematic representation of the map—generated by the OV equations—that takes equations of state into mass-radius relationships.

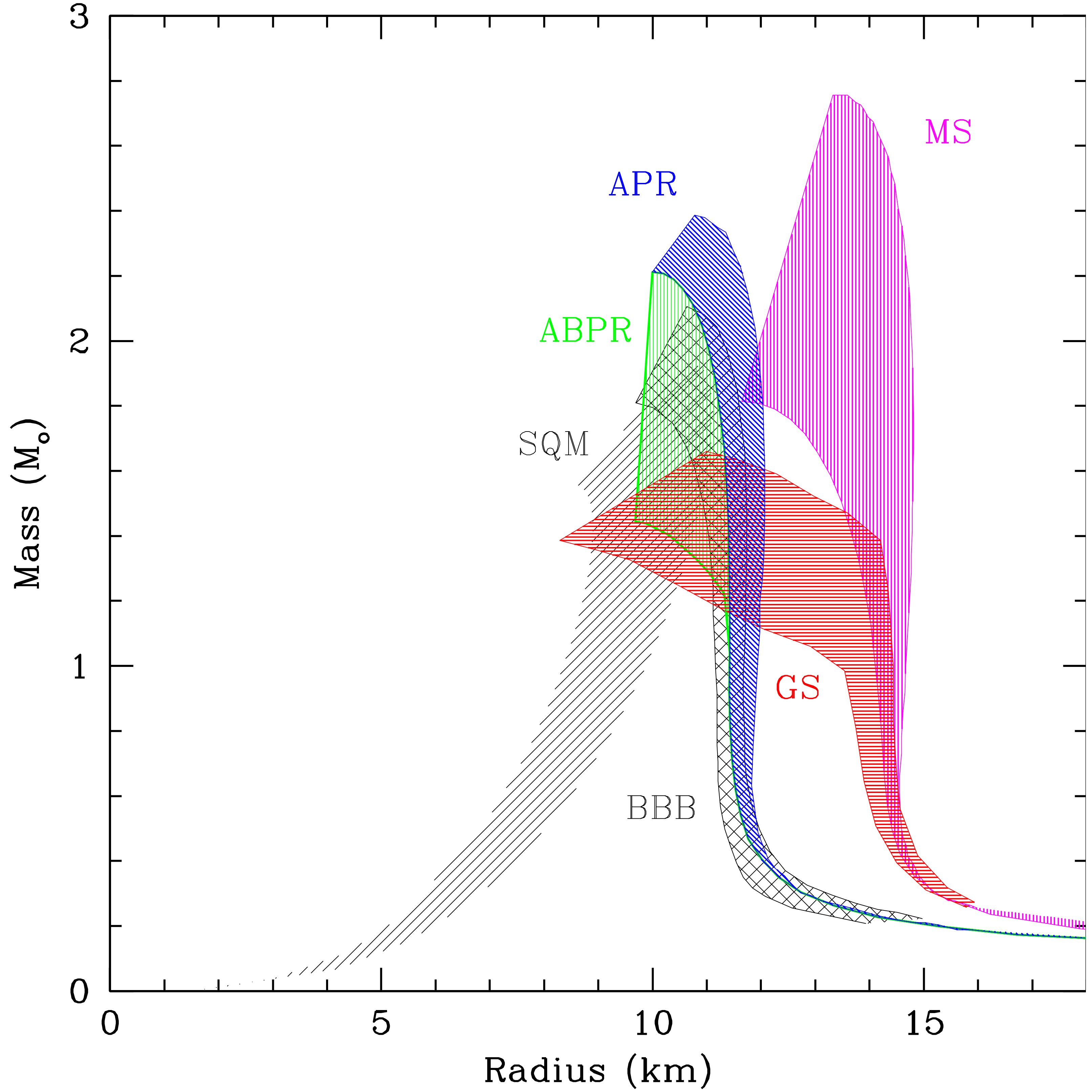
$$\frac{dm}{dr} = 4\pi r^2 \rho \ ,$$

$$\frac{dp}{dr} = -(\rho + p)\,\frac{m + 4\pi r^3 p}{r(r - 2m)} \ ,$$

$$\rho = \rho(p)$$

Lindblom 1992, ApJ, 398, 569

Equation of State to Mass and Radius



Özel, 2013

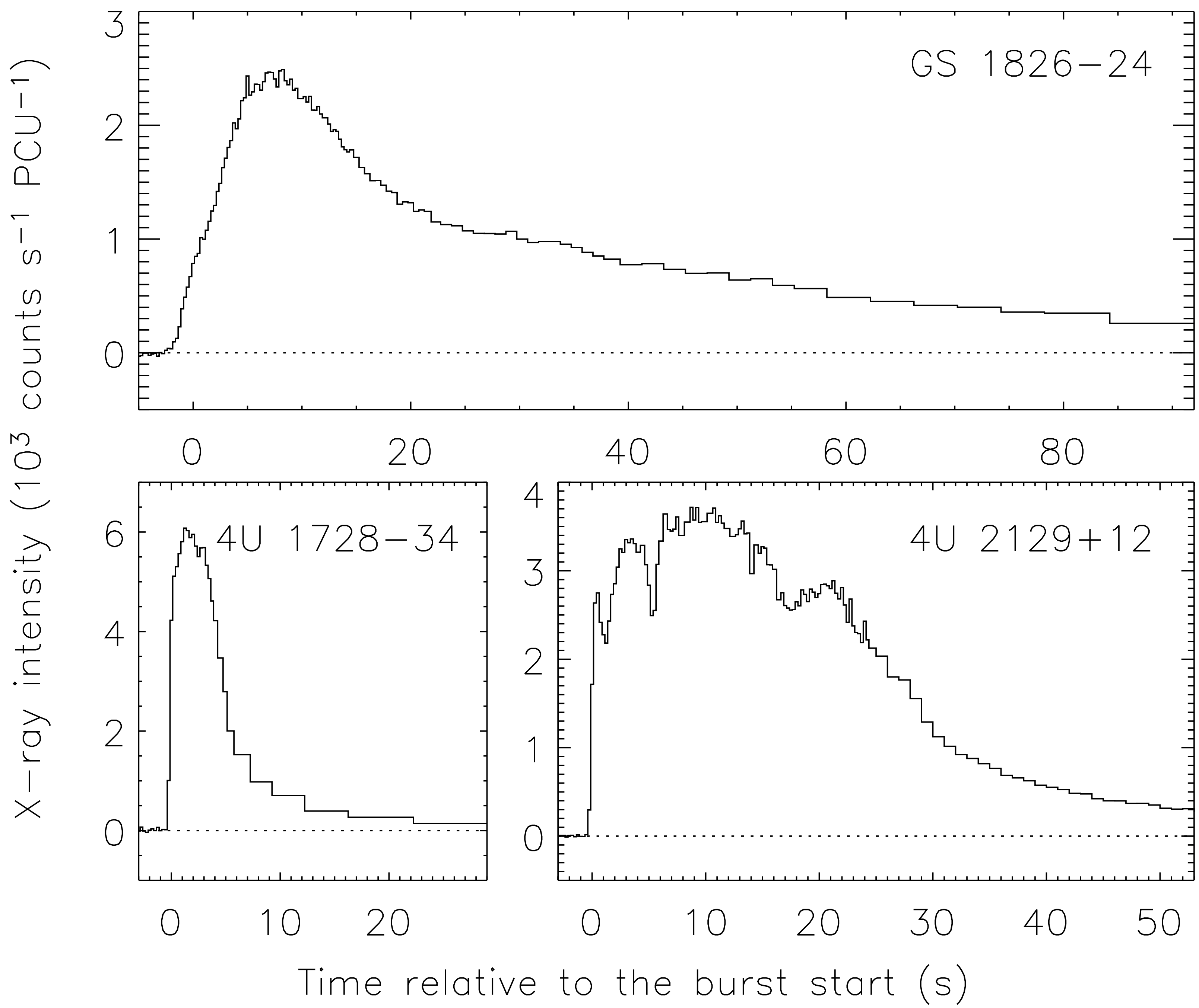
Spectroscopic Measurements

- Time Resolved X-ray Spectroscopic Measurements of Thermonuclear X-ray Bursts from Low Mass X-ray Binaries

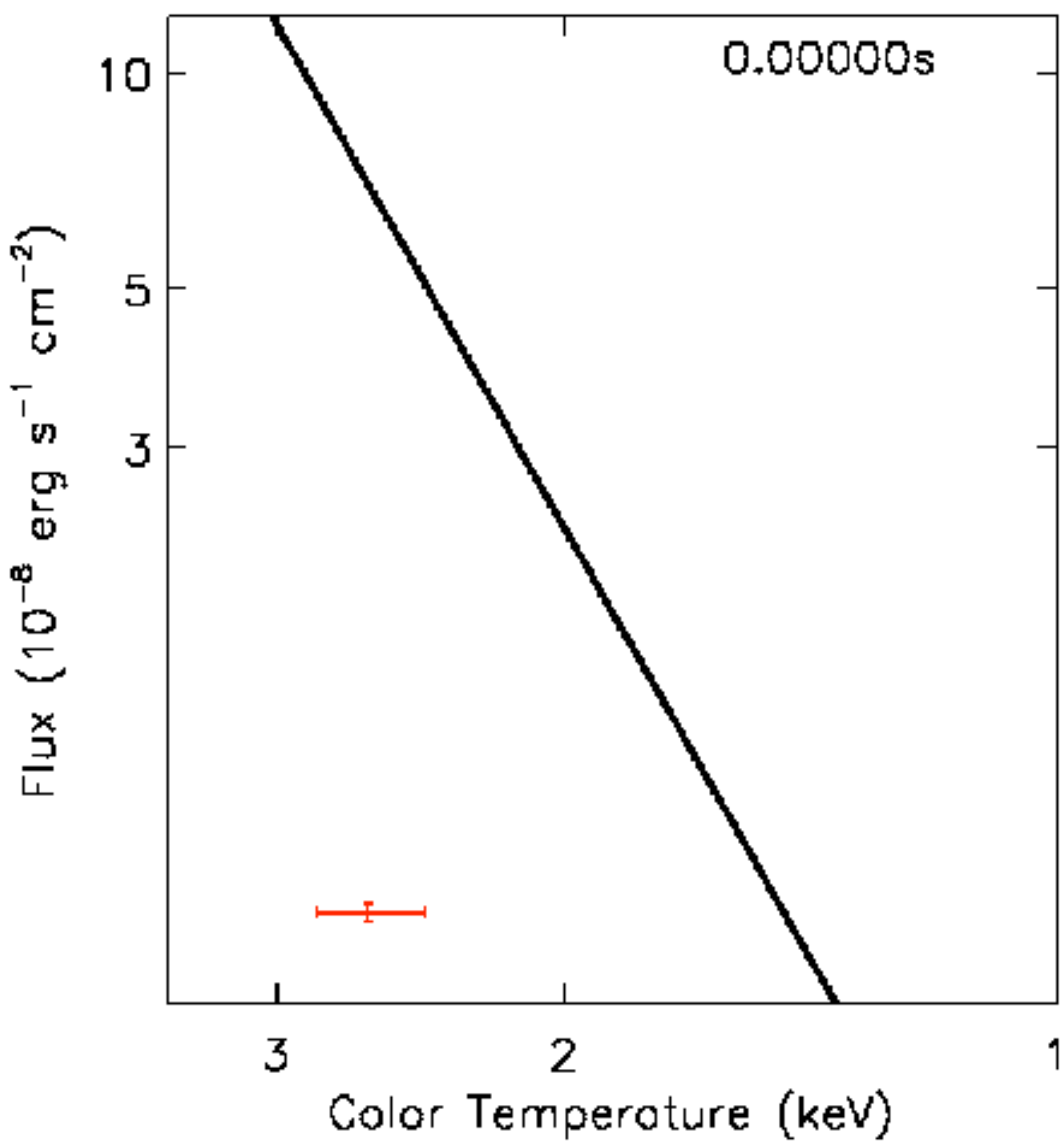
- Cooling Neutron Stars in Quiescent Low Mass X-ray Binaries

Time Resolved X-ray Spectroscopy of X-ray Bursts

Sudden flashes observed in the X-rays that are thought to be caused by thermonuclear burning of the accreted material.



Galloway et al. 2008



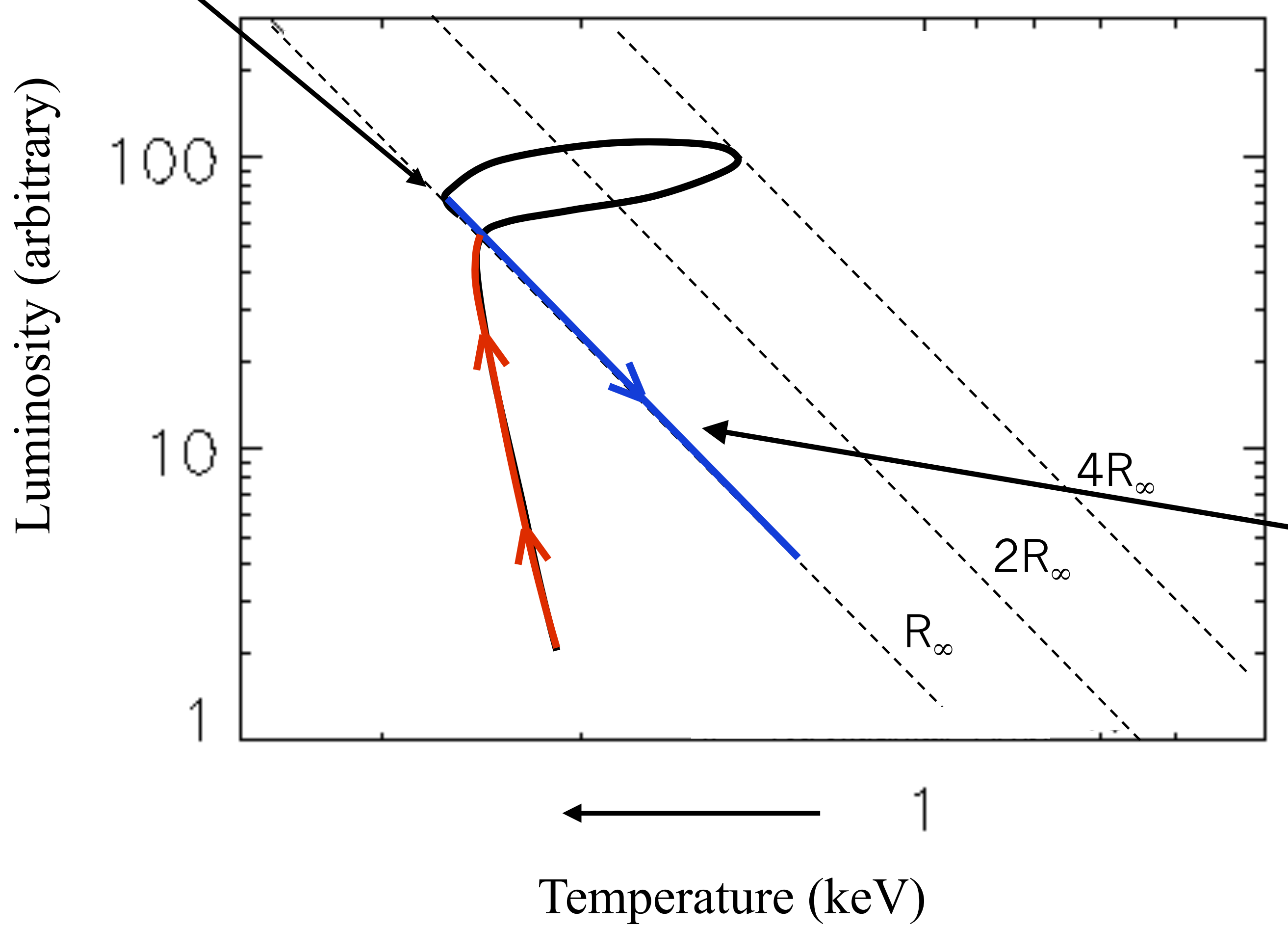
0.00000s
10
5
3
Flux (10^-8 erg s^-1 cm^-2)
3
2
1
Color Temperature (keV)

Thermonuclear X-ray Bursts as tools for mass-radius measurements

Touchdown point

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

An "H-R" diagram for a burst

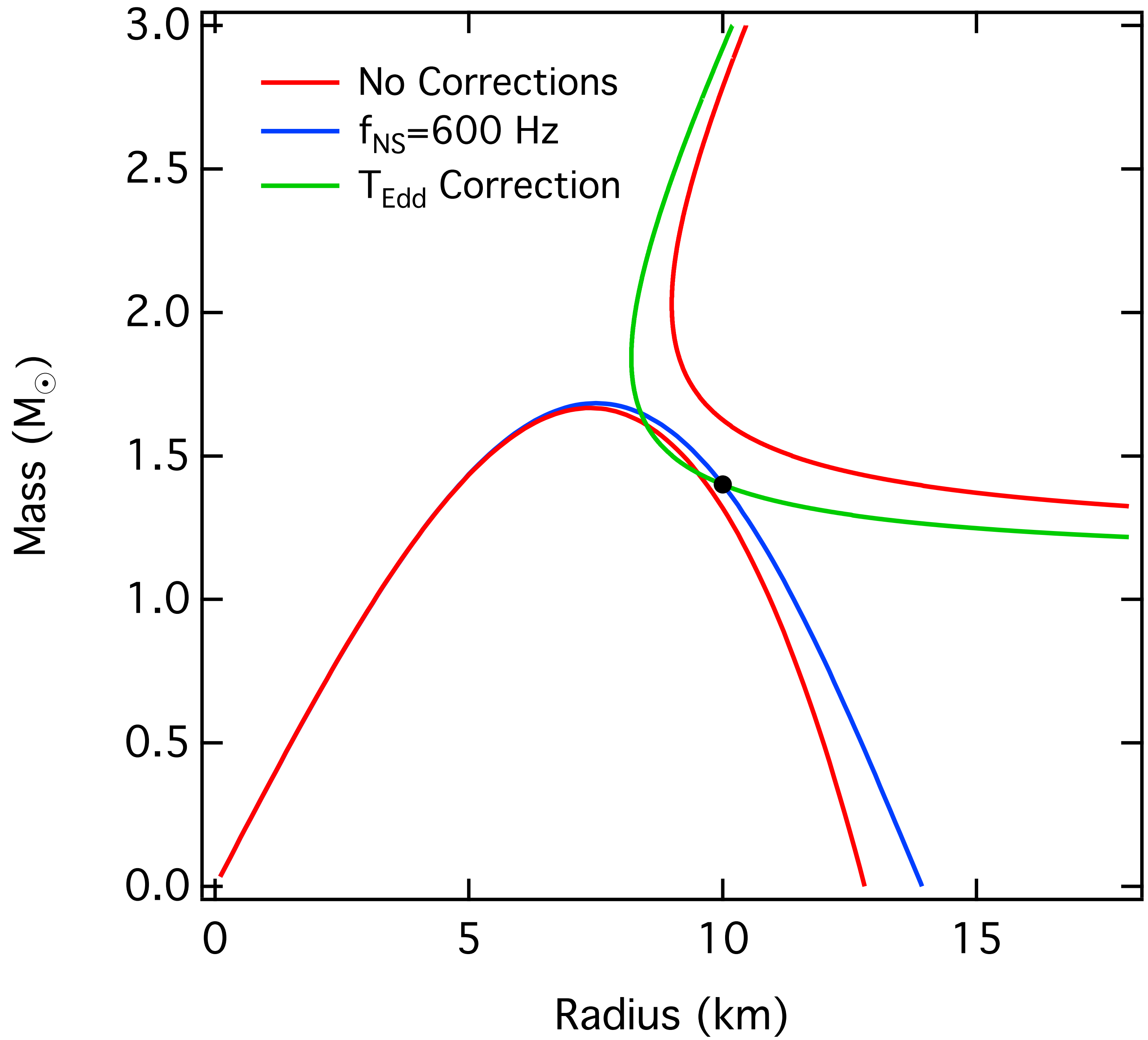


$$A = \frac{R^2}{D^2 f_{\rm c}^4}\left(1 - \frac{2GM}{Rc^2}\right)^{-1}$$

$$f_{\rm c} \equiv T_{\rm c}/T_{\rm eff}$$

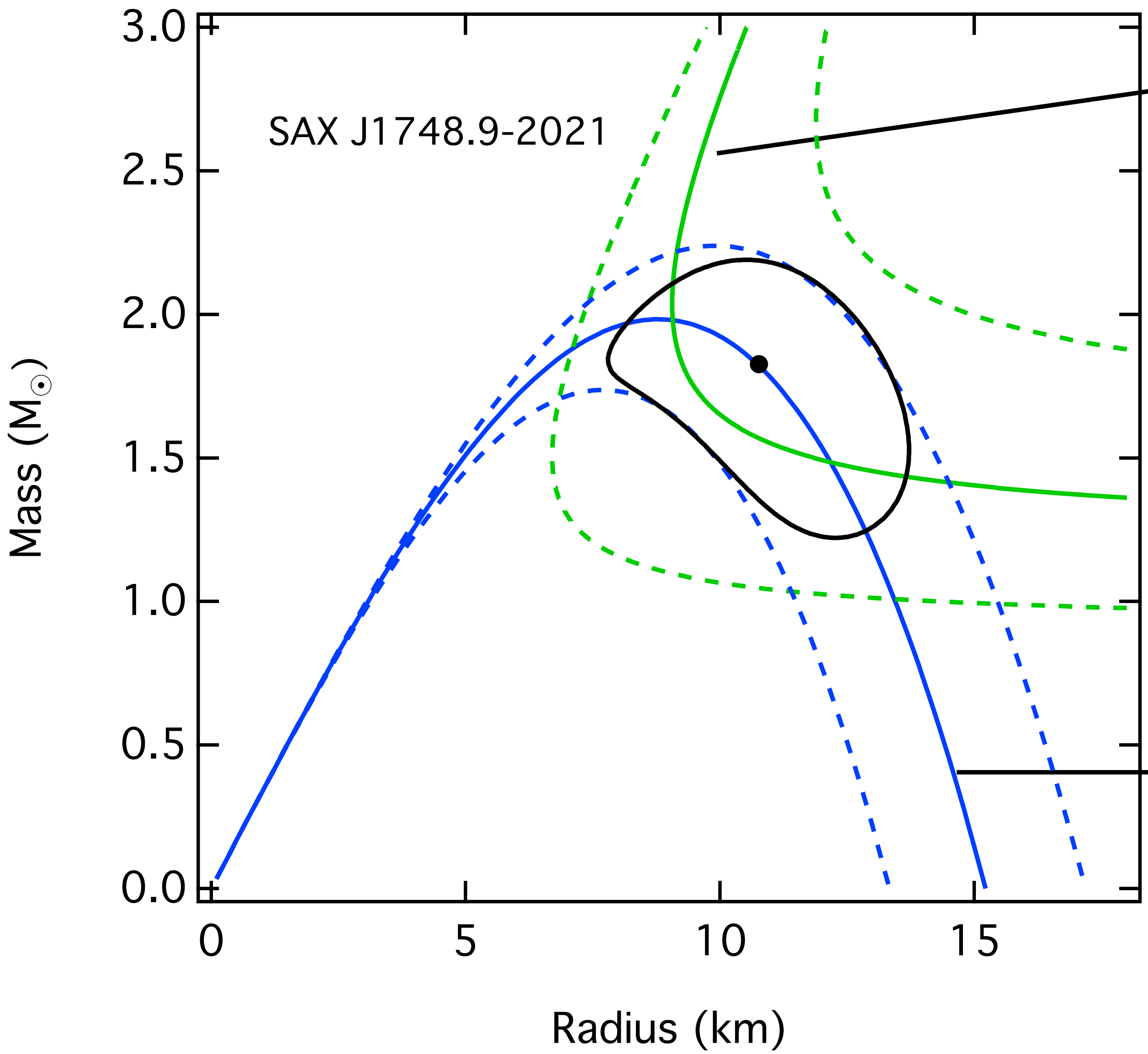
Özel et al. 2016

Effects of Rotation and Temperature Correction to Eddington Limit



Özel et al. 2016

Thermonuclear X-ray Bursts as tools for mass-radius measurements



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

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

$$f_c \equiv T_c / T_{\rm eff}$$

Güver & Özel 2013

Possible Sources of Uncertainties

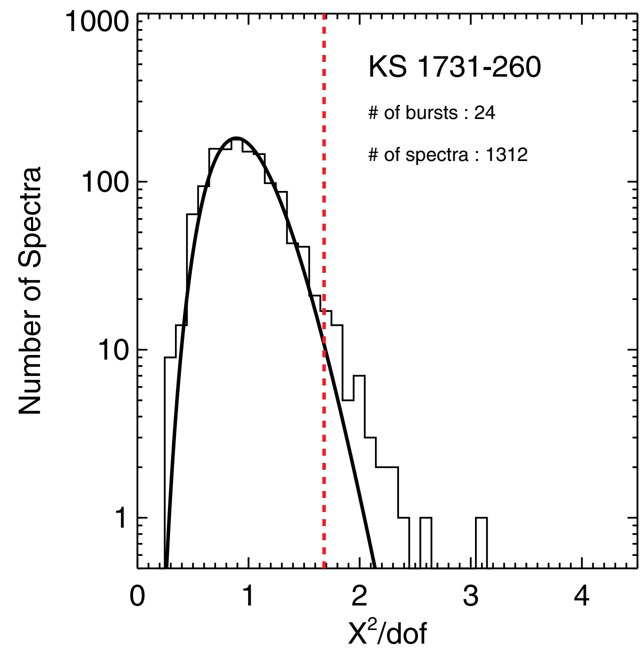
- **Is it really statistically appropriate to fit the X-ray spectra during burst decay with Planckian functions ? (Güver et al. 2012a)**

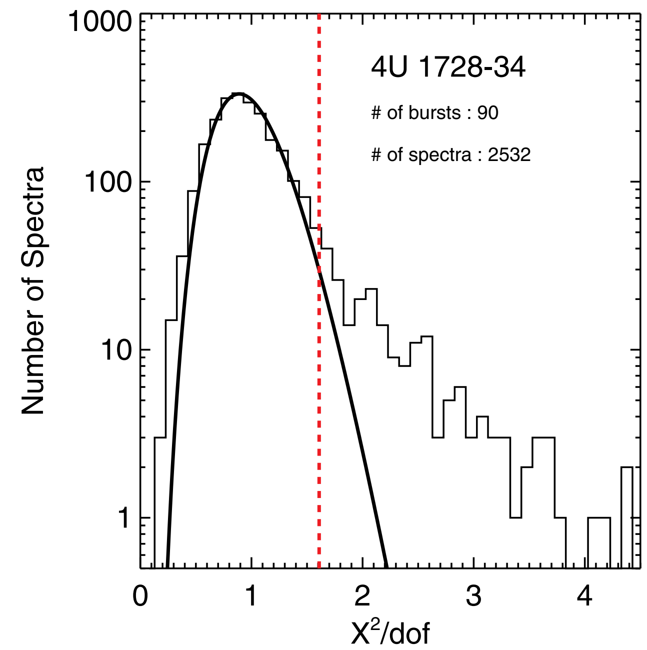
- **Do we observe the whole neutron-star surface during the decay of an X-ray burst? (Güver et al. 2012a)**

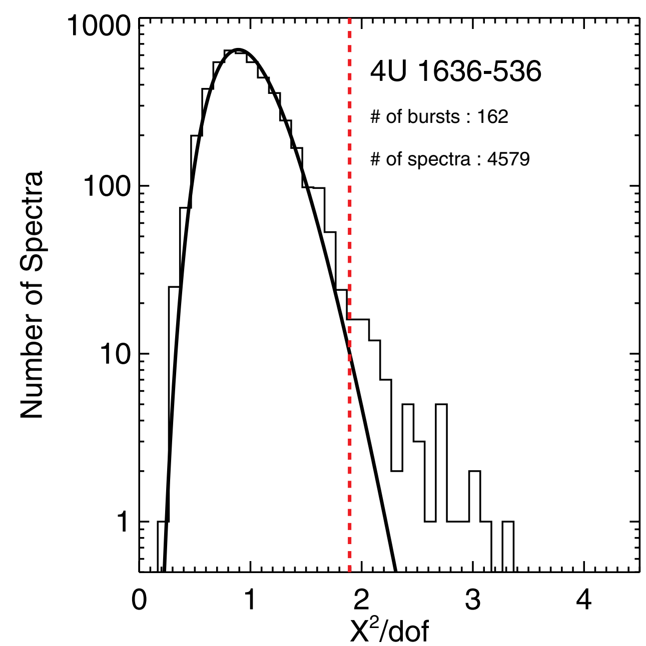
- **How are the maximum fluxes of X-ray bursts related to the Eddington Limit ? (Güver et al. 2012b)**

- **Are the flux measurements absolutely correct (Güver et al. 2016)**

How good are the blackbody fits ?





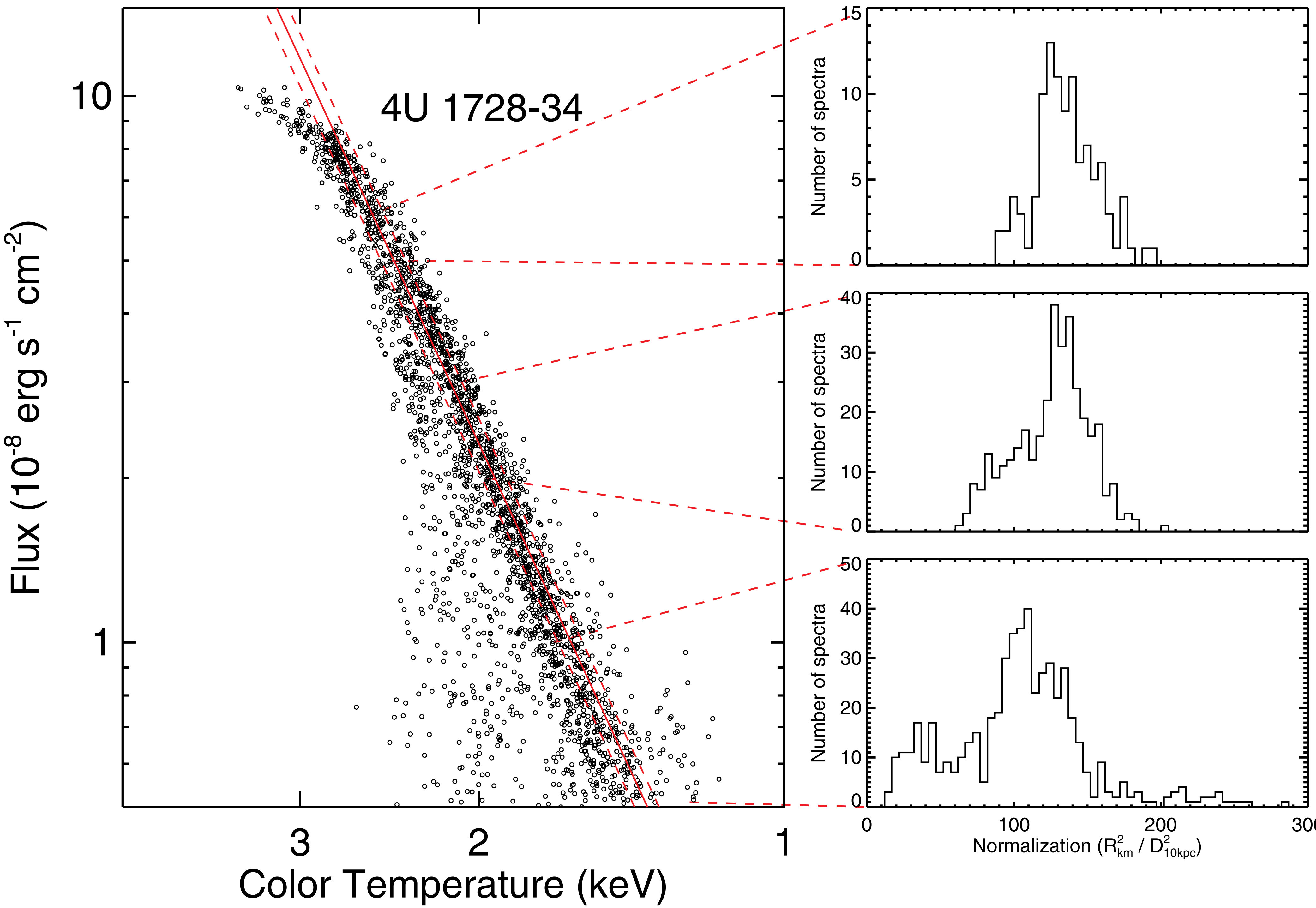


The systematic uncertainty required to render the observed spectra as a blackbody is ~3-5%

A similar amount (~3-5%) of X-ray spectra are just not consistent with a blackbody function.

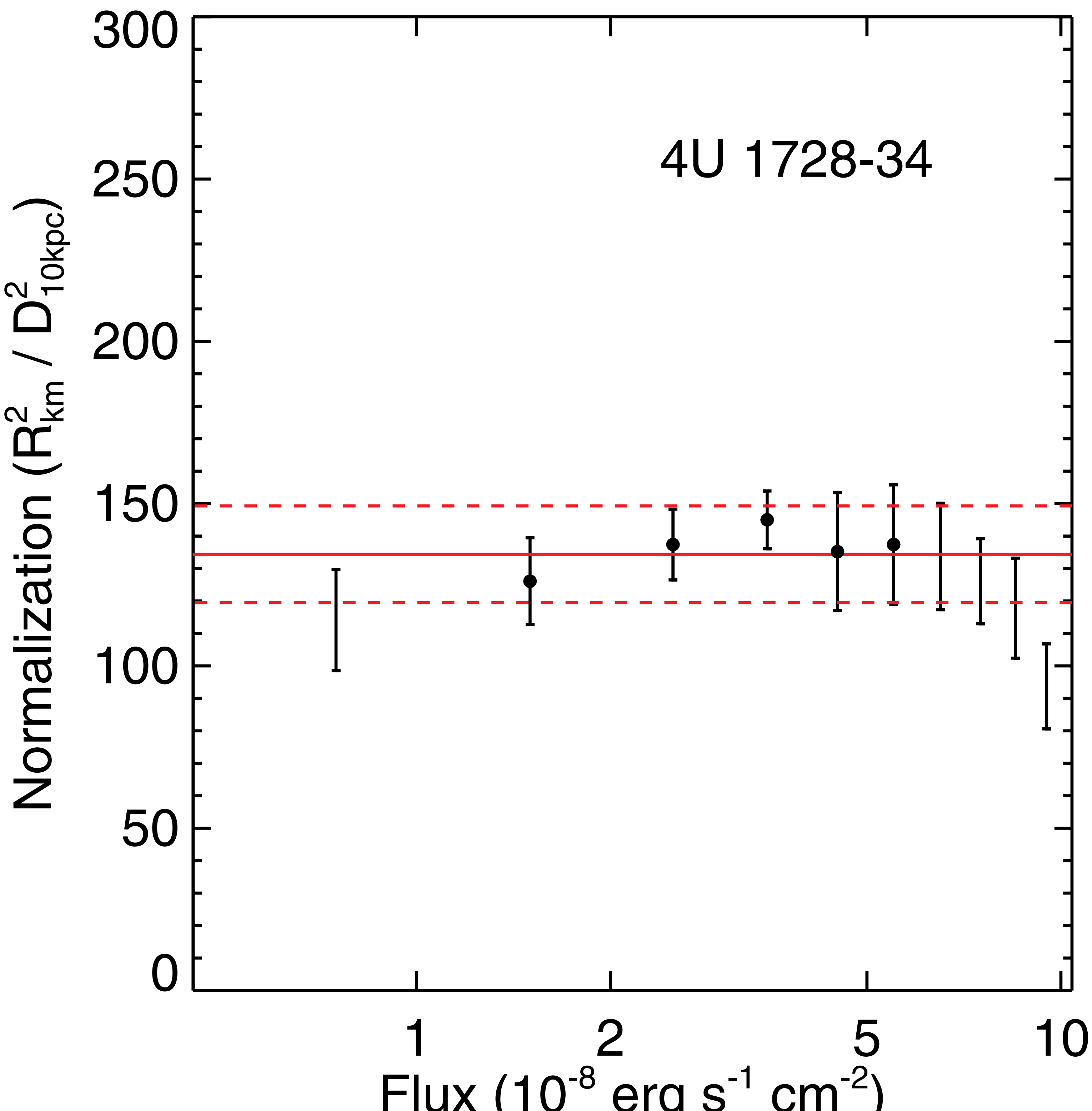
Güver et al. 2012a

How reproducible are the cooling tails ?



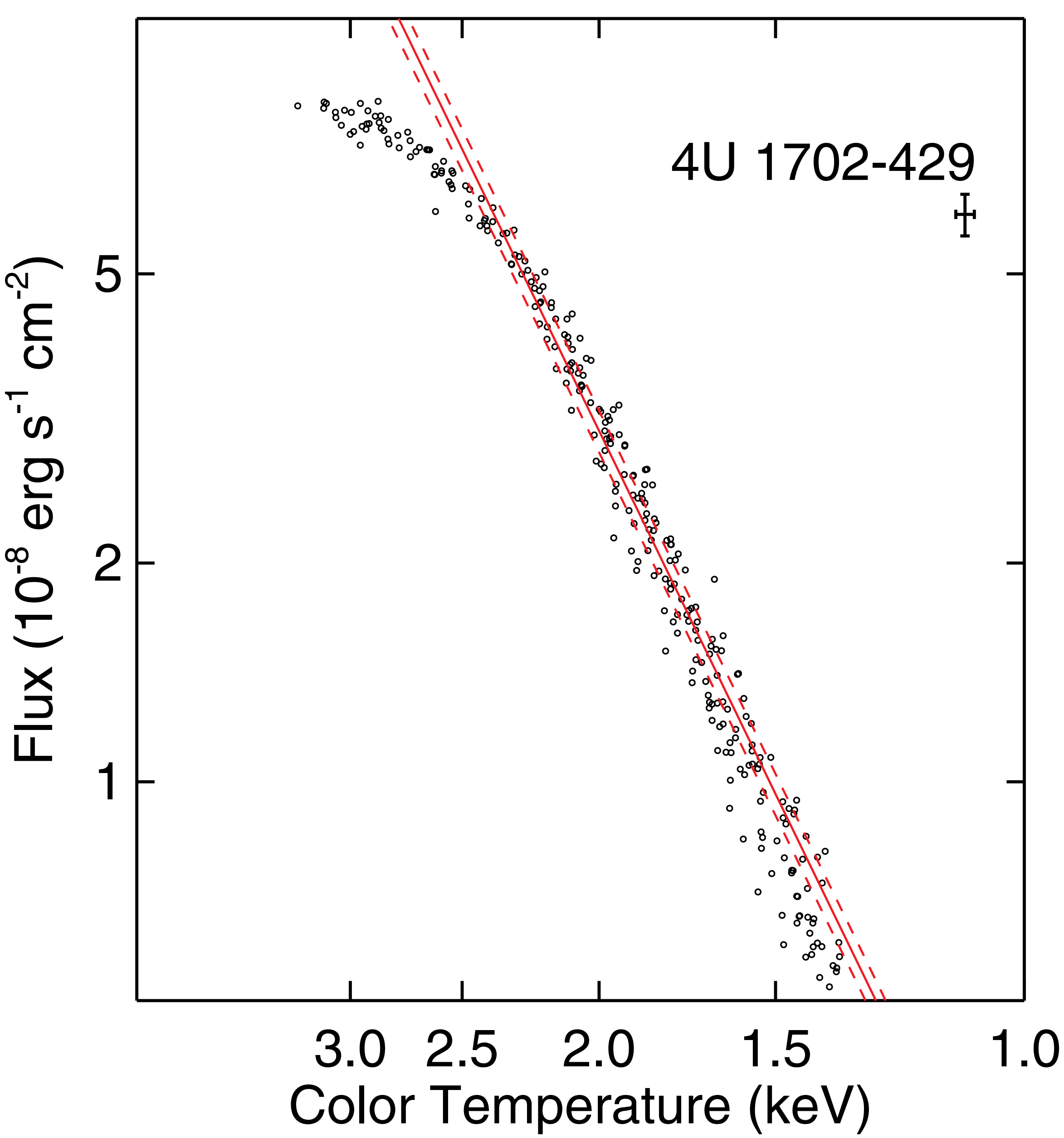
Güver et al. 2012a

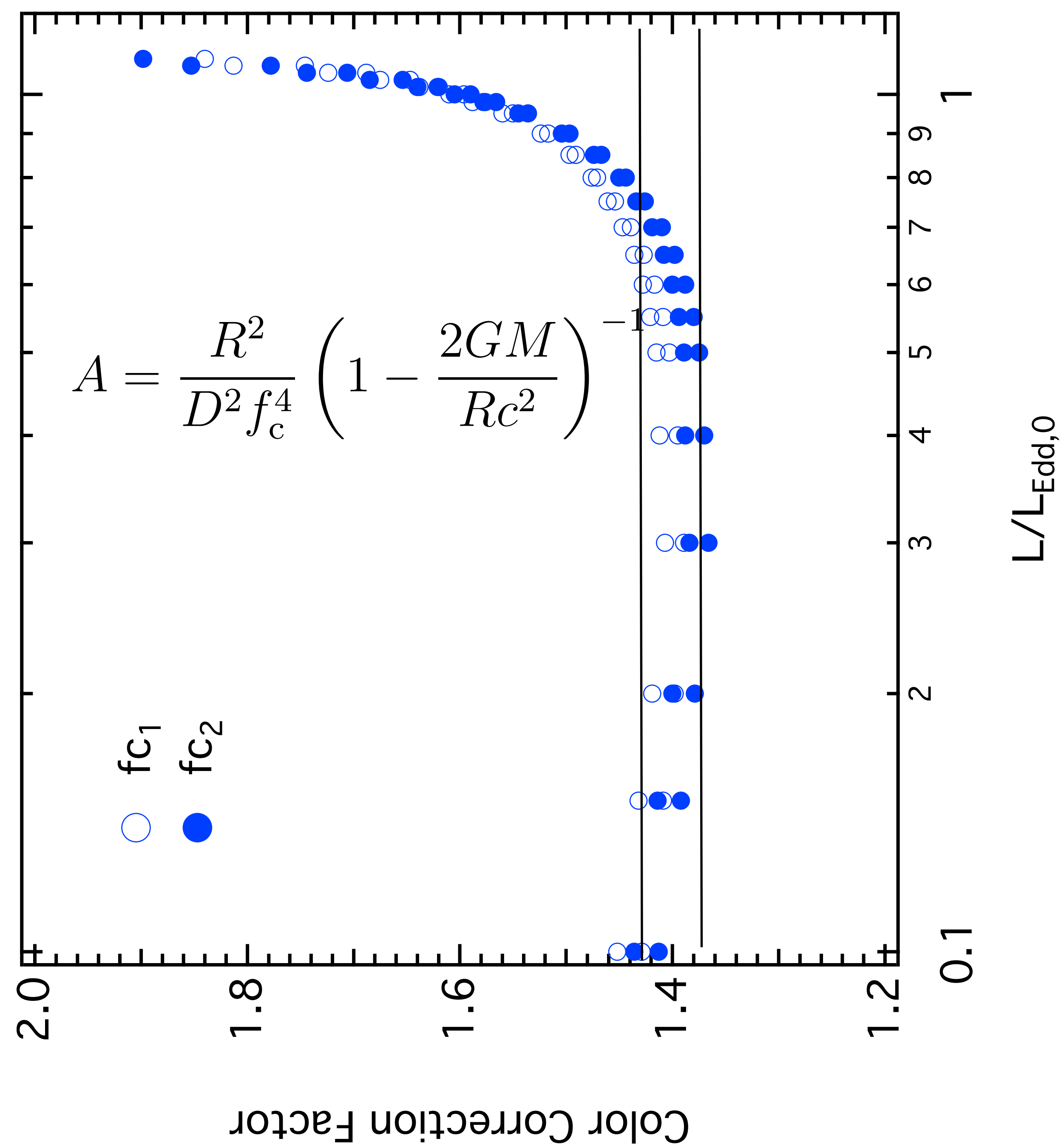
How reproducible are the cooling tails ?



Güver et al. 2012a

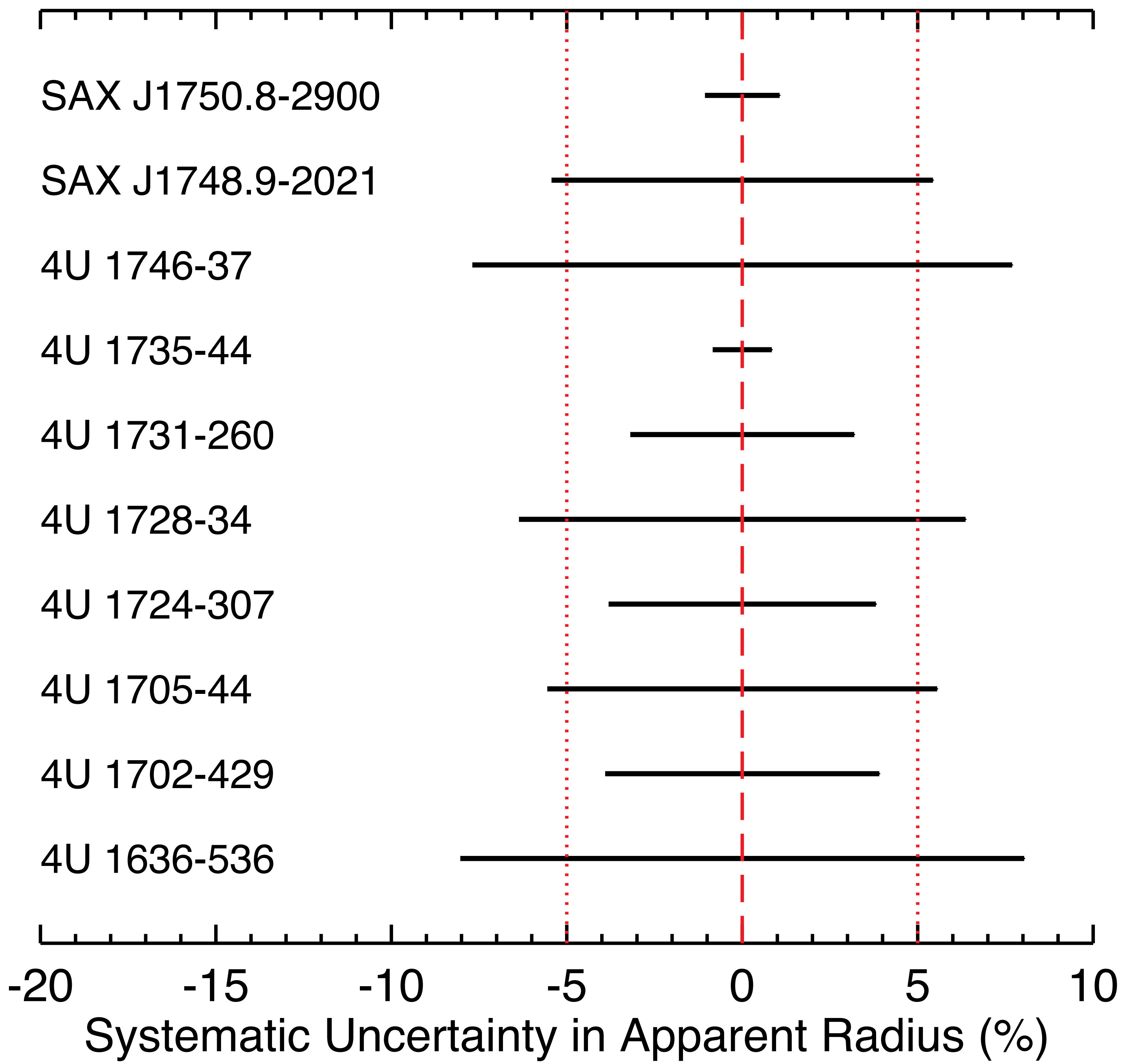
Evolution During the Cooling Tails





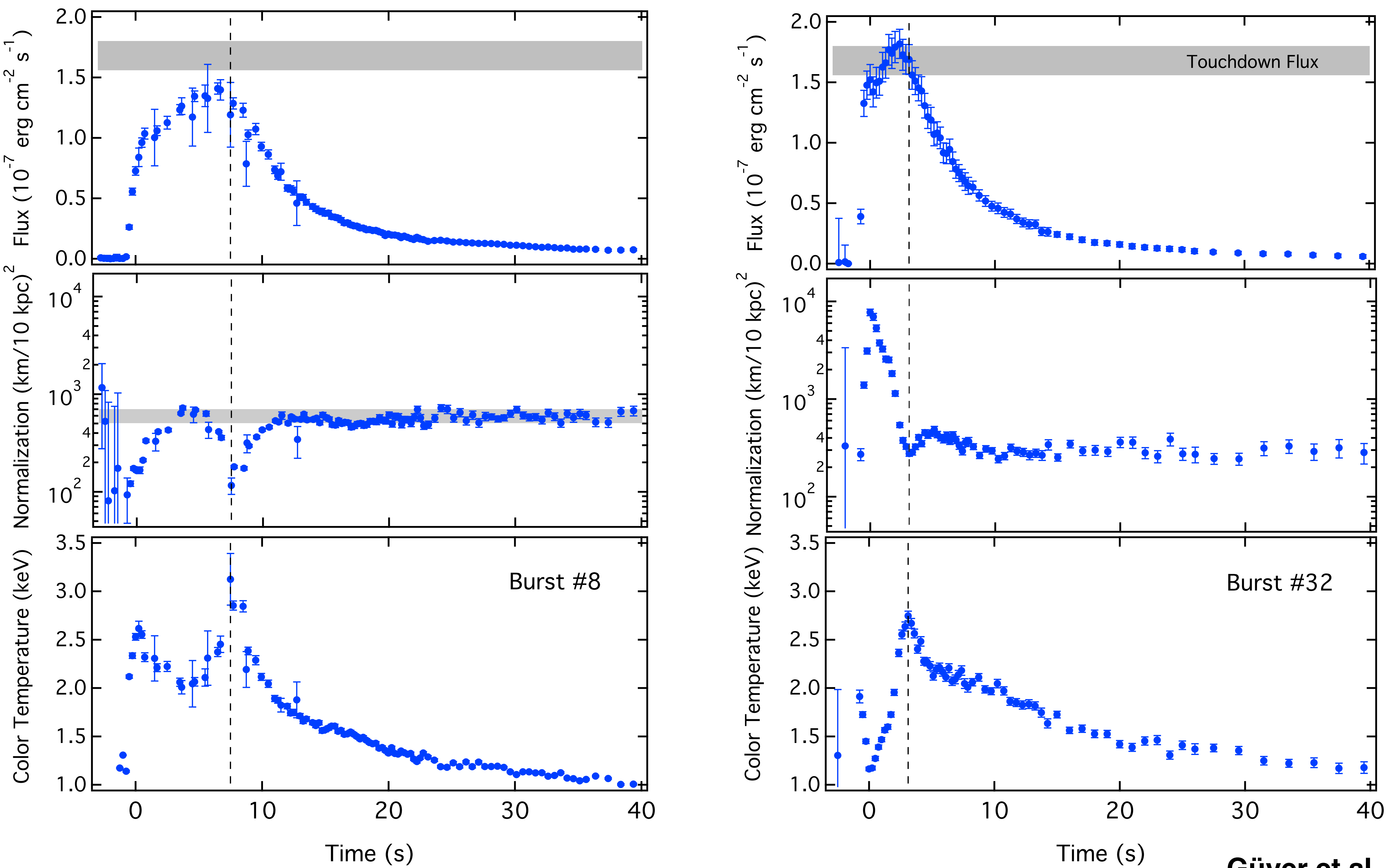
Güver+ 2012, Özel+ 2015
theoretical data from Suleimanov+ 2012

Uncertainties in the apparent radii of neutron stars



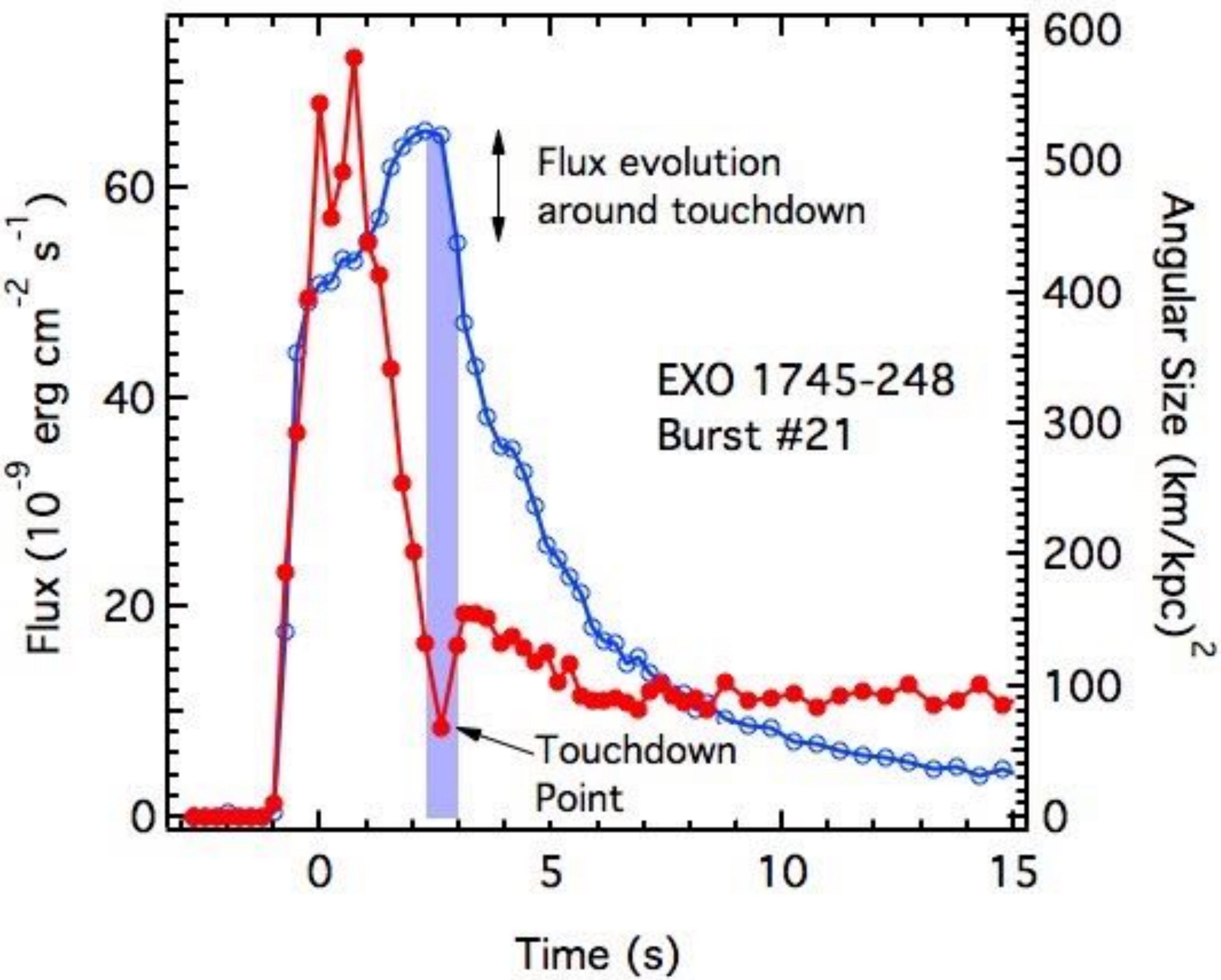
Güver et al. 2012a

Photospheric Radius Expansion Events



Güver et al. 2012b

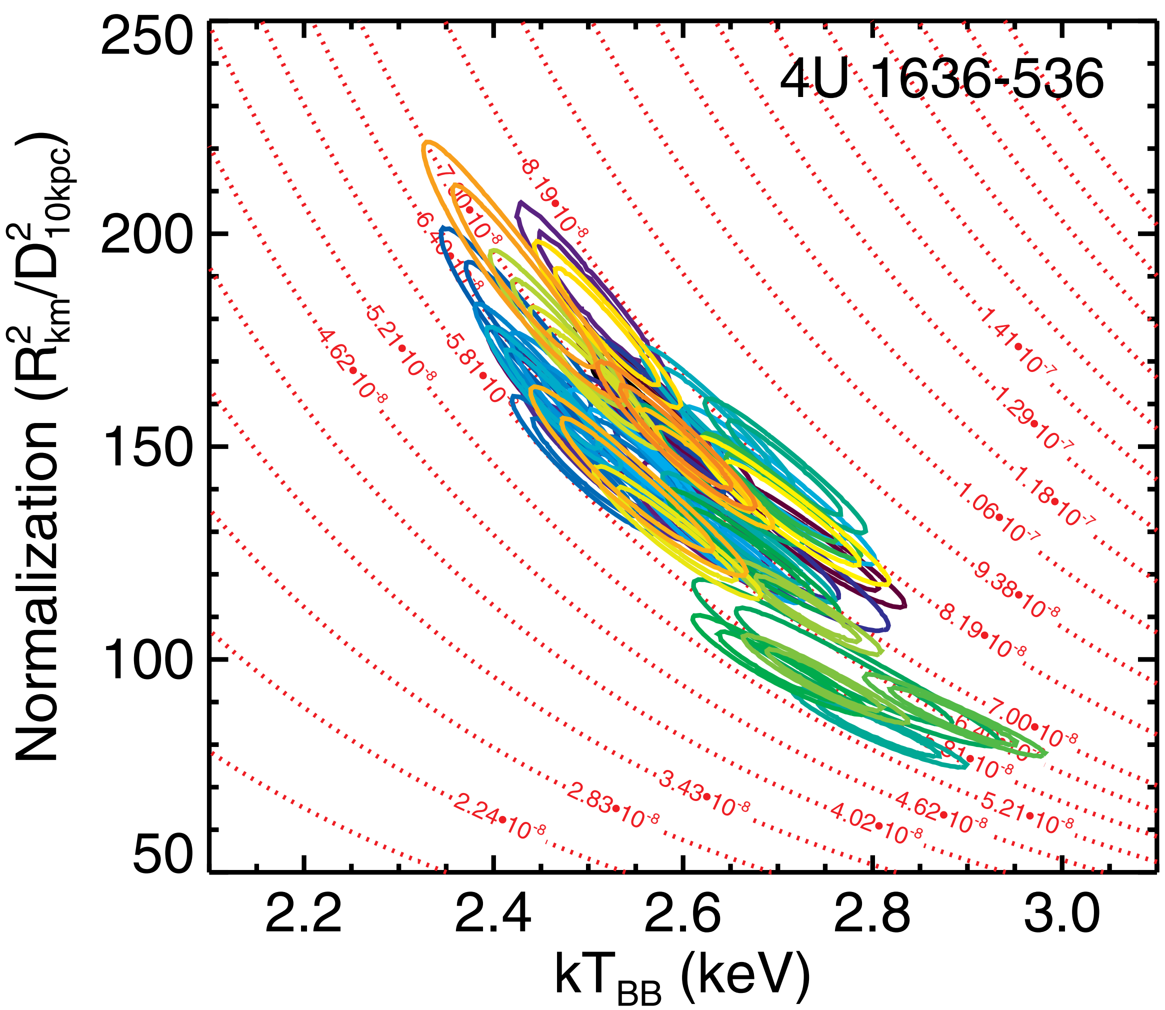
Touchdown Moment

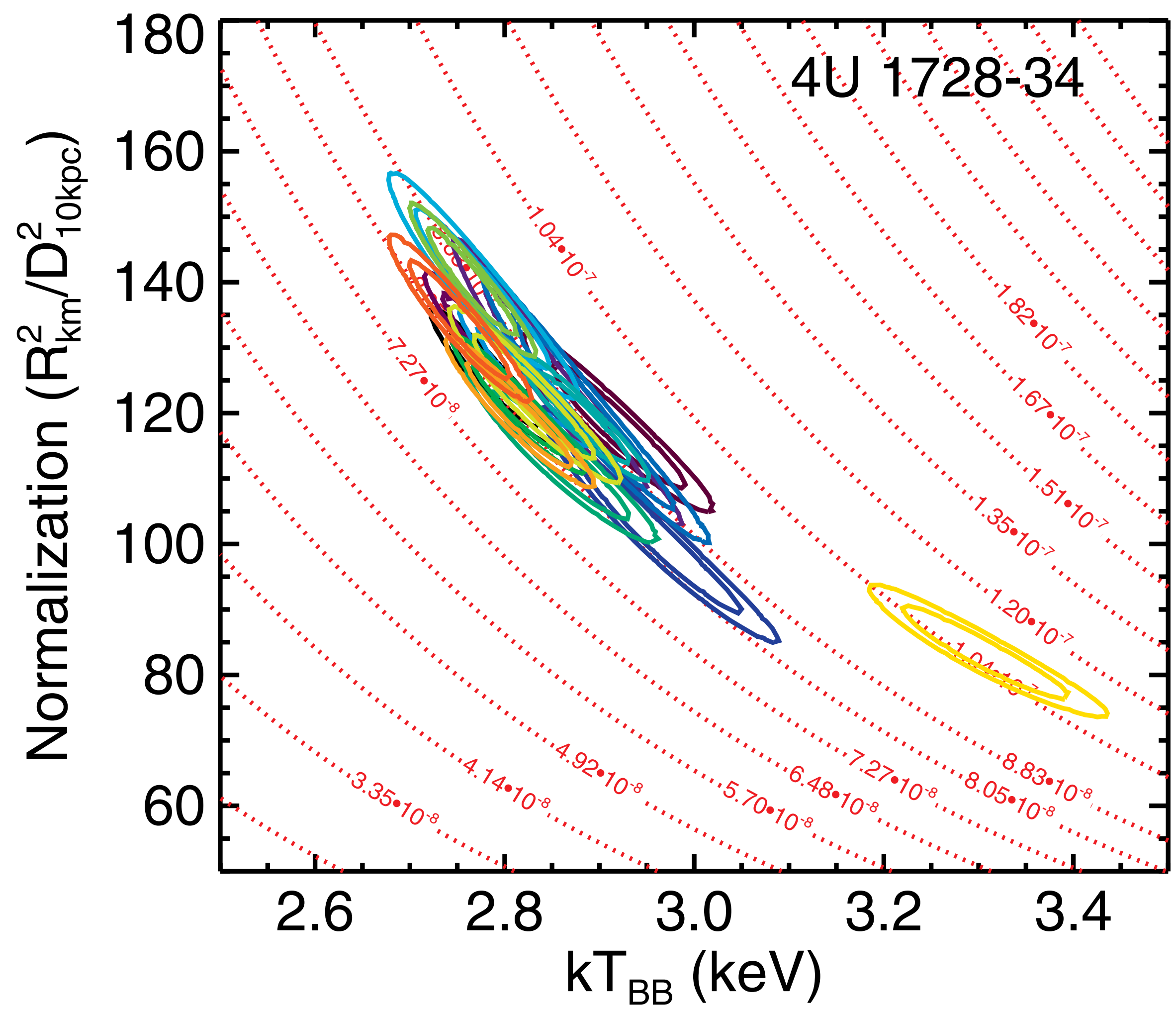


It is impossible to resolve the rapid change of the color correction factor around touchdown

Özel et al. 2015

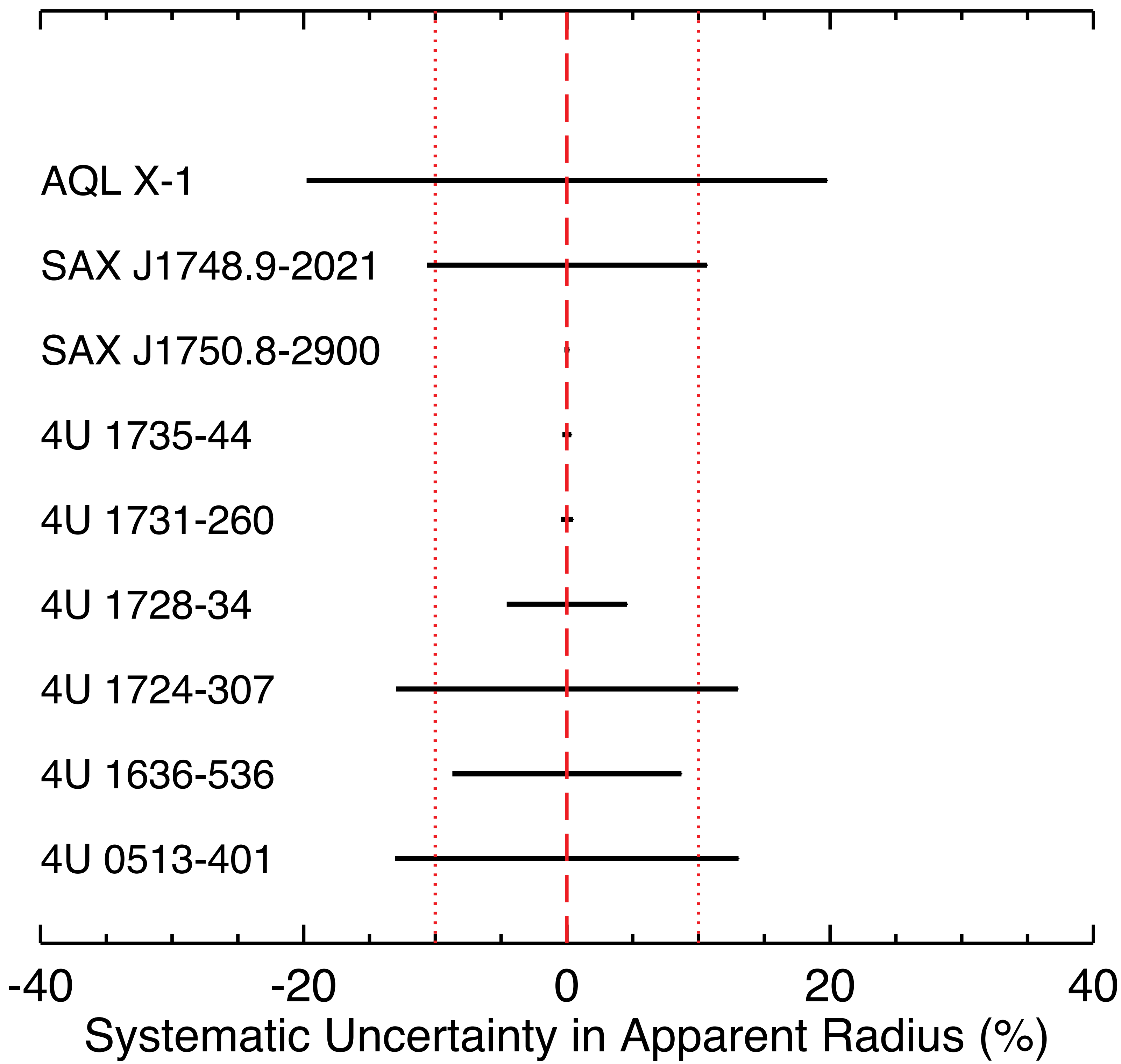
Touchdown Flux Measurements





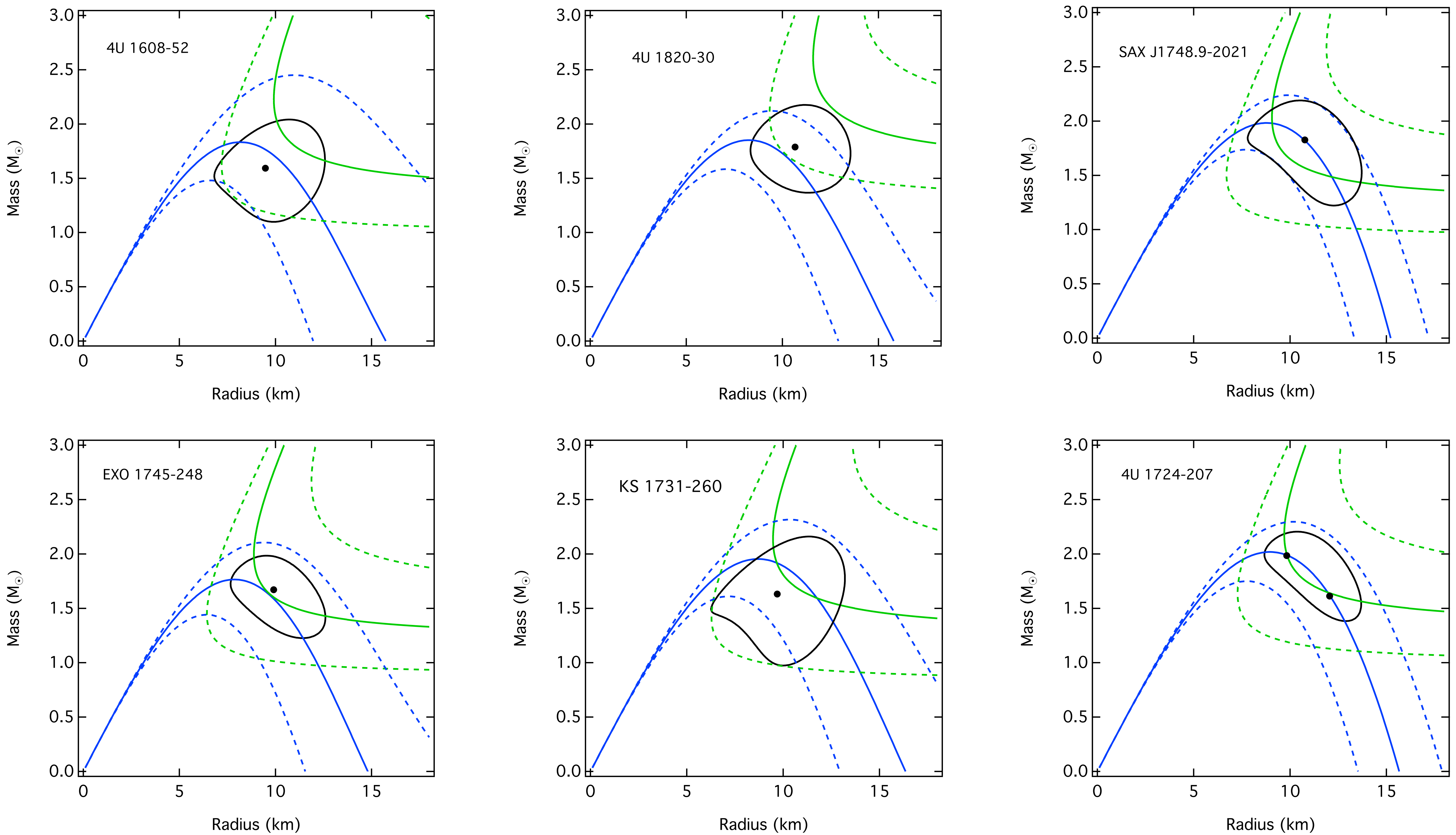
Güver et al. 2012b

Uncertainties in the touchdown flux measurements



Güver et al. 2012b

Recent measurements



Özel et al. 2016

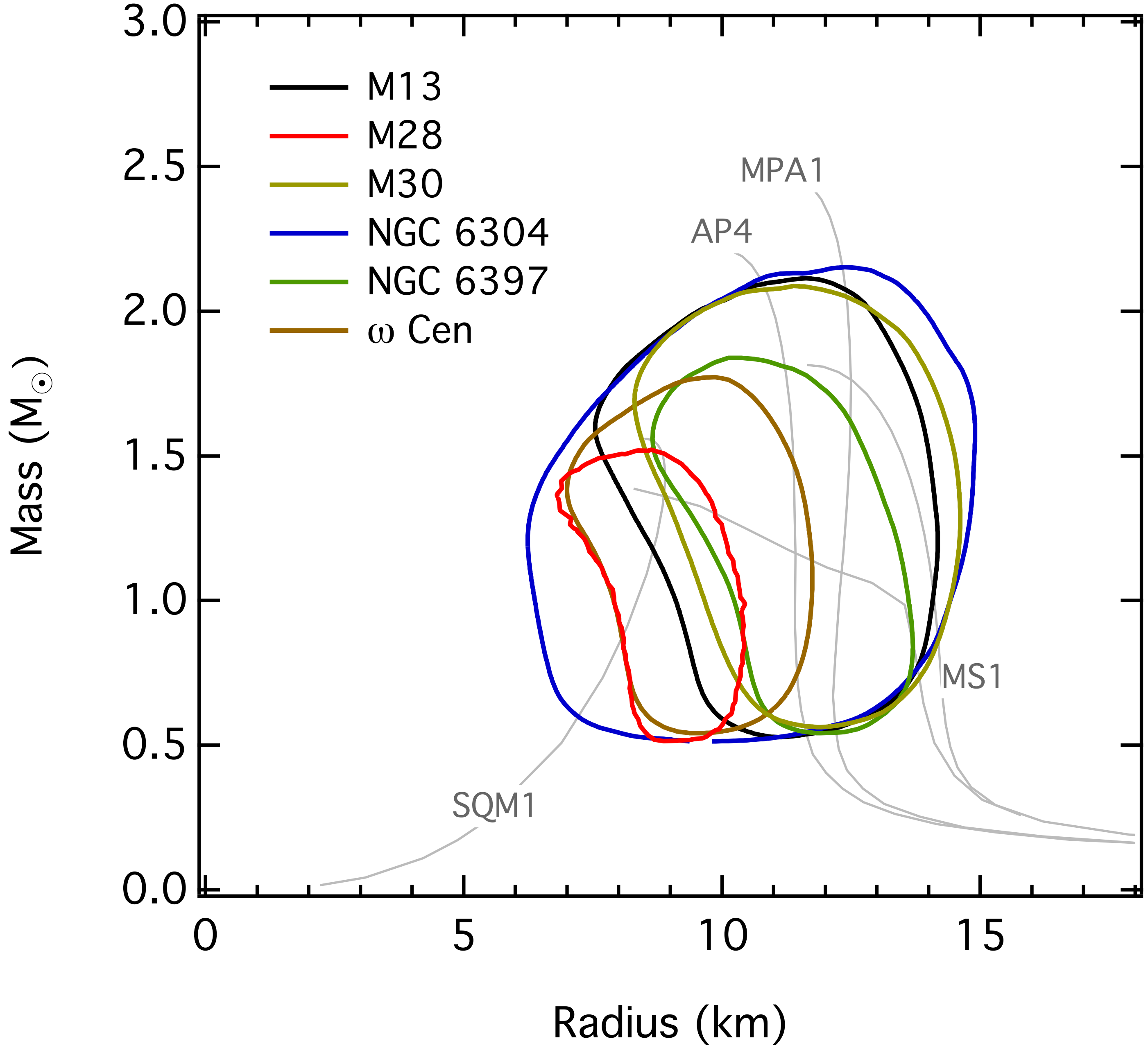
Systematics of Cooling Neutron Star Mass-Radius Measurements

X7 and X5 in 47 Tuc (Heinke et al. 2003, 2006),
U24 in NGC 6397 (Guillot et al. 2011; Heinke et al. 2014),
source 26 in M28 (Becker et al. 2003; Servillat et al. 2012),
NGC 2808 (Webb & Barret 2007; Servillat et al. 2008),
M13 (Gendre et al. 2003a; Webb & Barret 2007; Catuneanu et al. 2013),
ω Centauri (Rutledge et al. 2002; Gendre et al. 2003b; Heinke et al. 2014), and
M30 (Lugger et al. 2007; Guillot & Rutledge 2014).

Possible Sources of Systematic Uncertainties

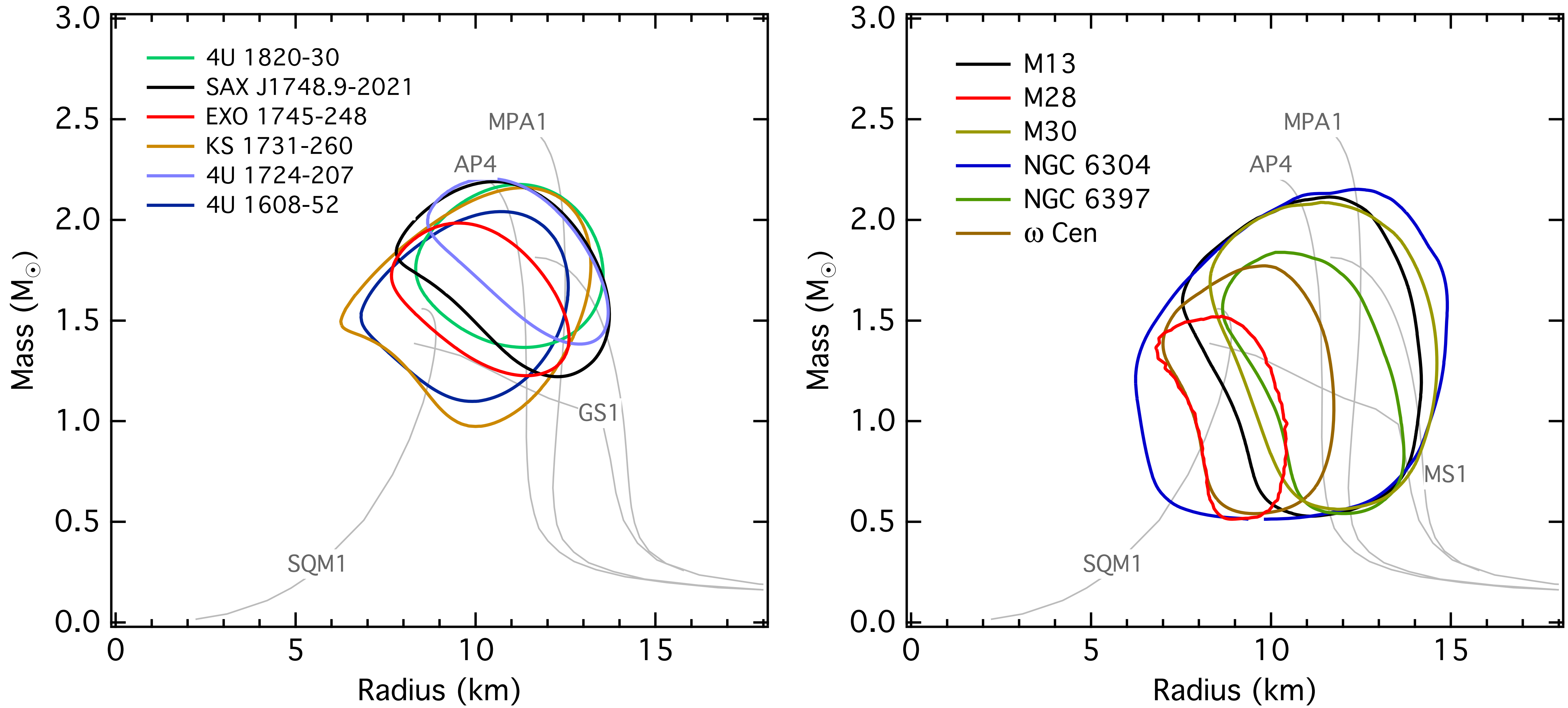
- **Atmospheric Composition**
- **Non-thermal Component**
- **Interstellar Extinction**

Current Mass-Radius Measurements



Özel et al. 2016

Comparison with Quiescent LMXBs



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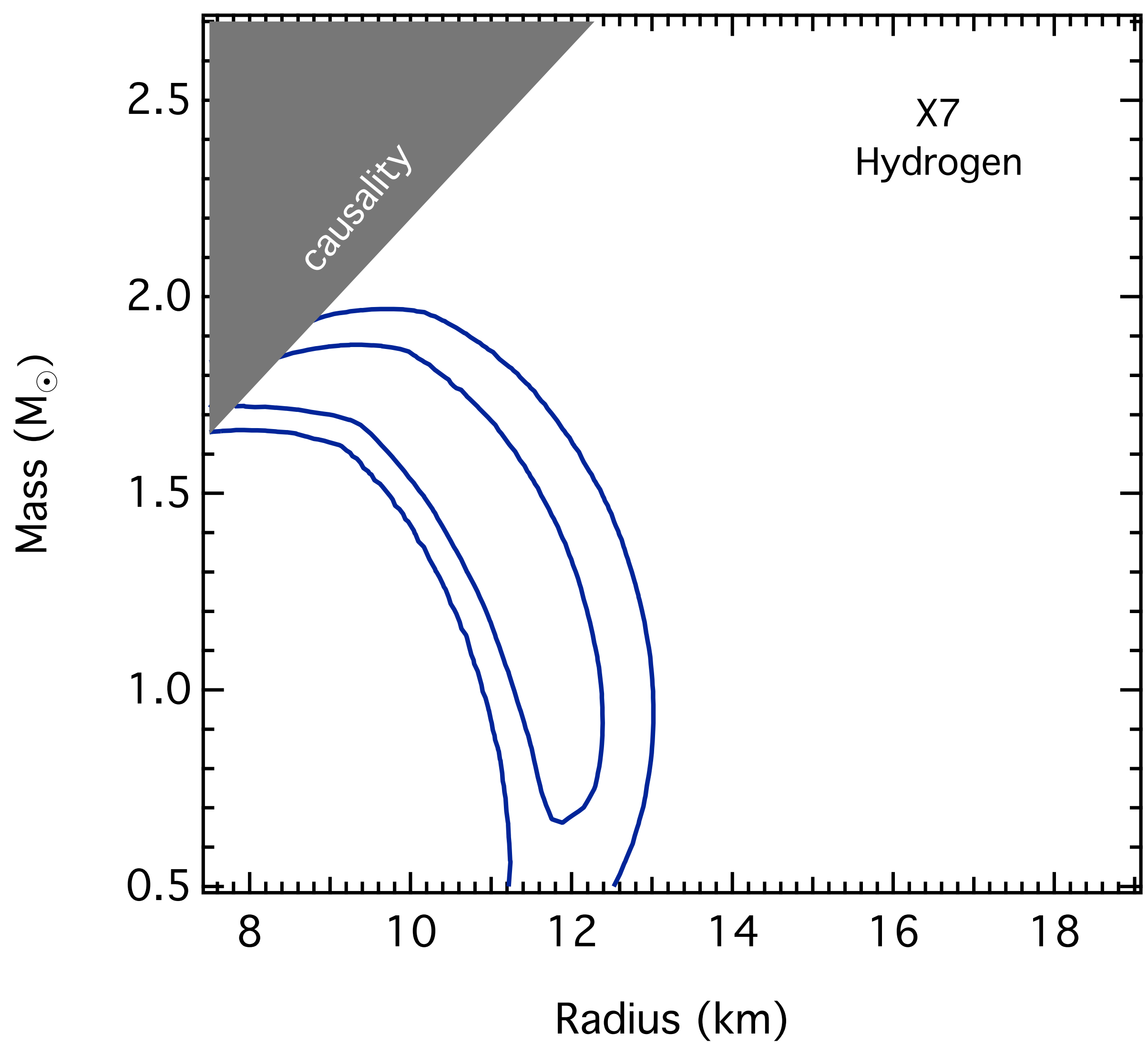
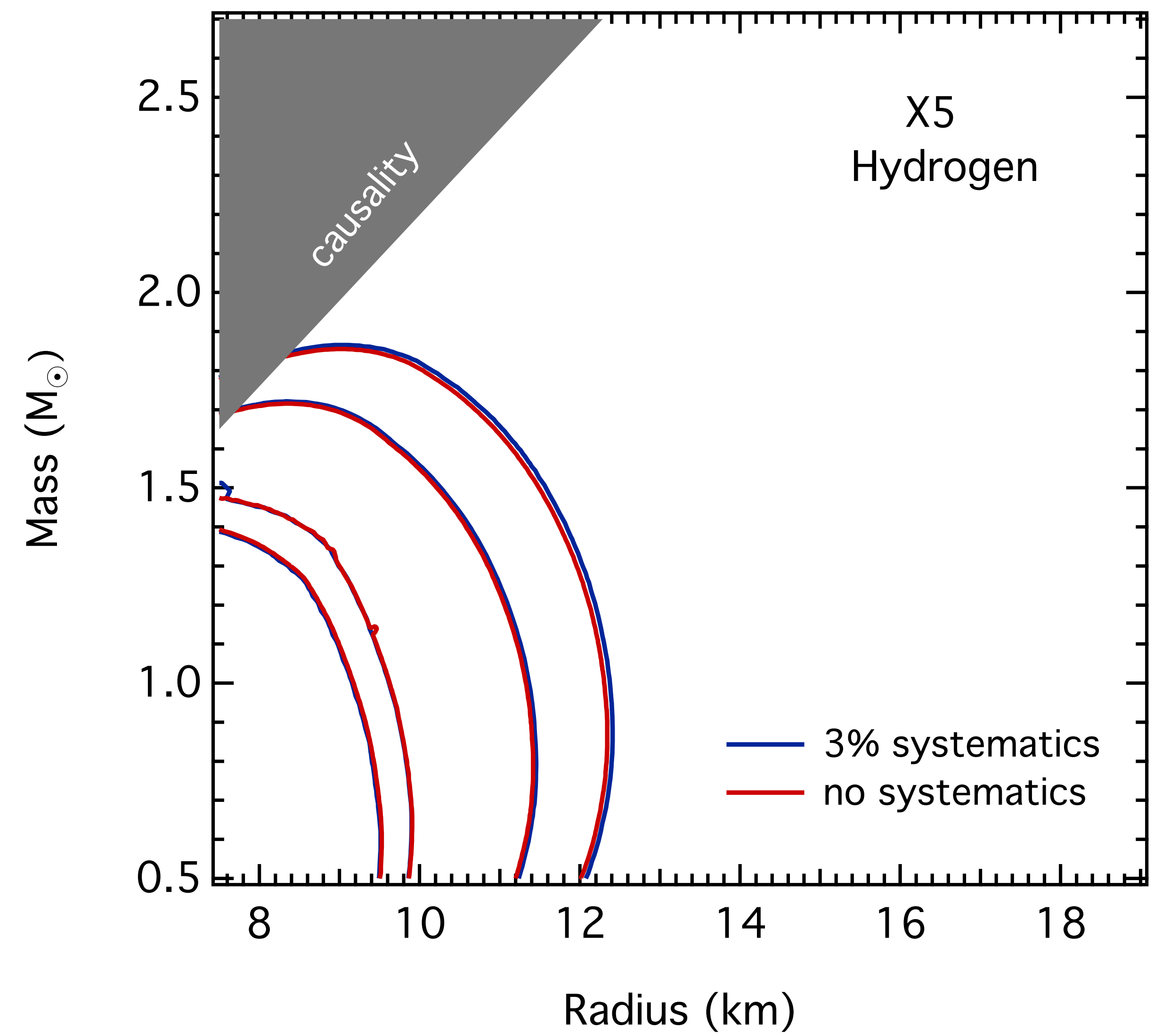
X7 - X5 in 47 Tuc



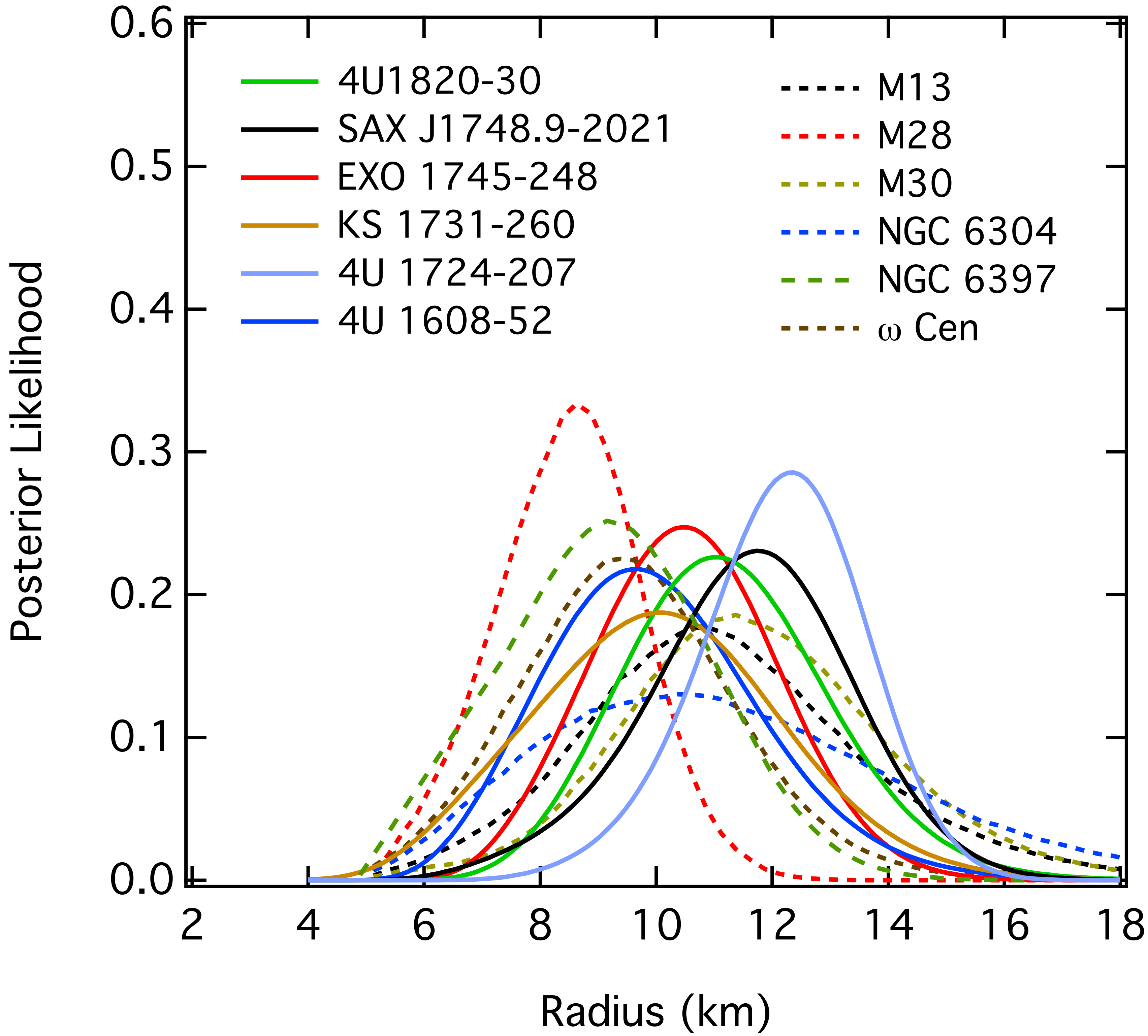
$11.1^{+0.8}_{-0.7}$ km @ 1.4 $M_\odot$



$9.6^{+0.9}_{-1.1}$ km @ 1.4 $M_\odot$

Bogdanov et al. 2016

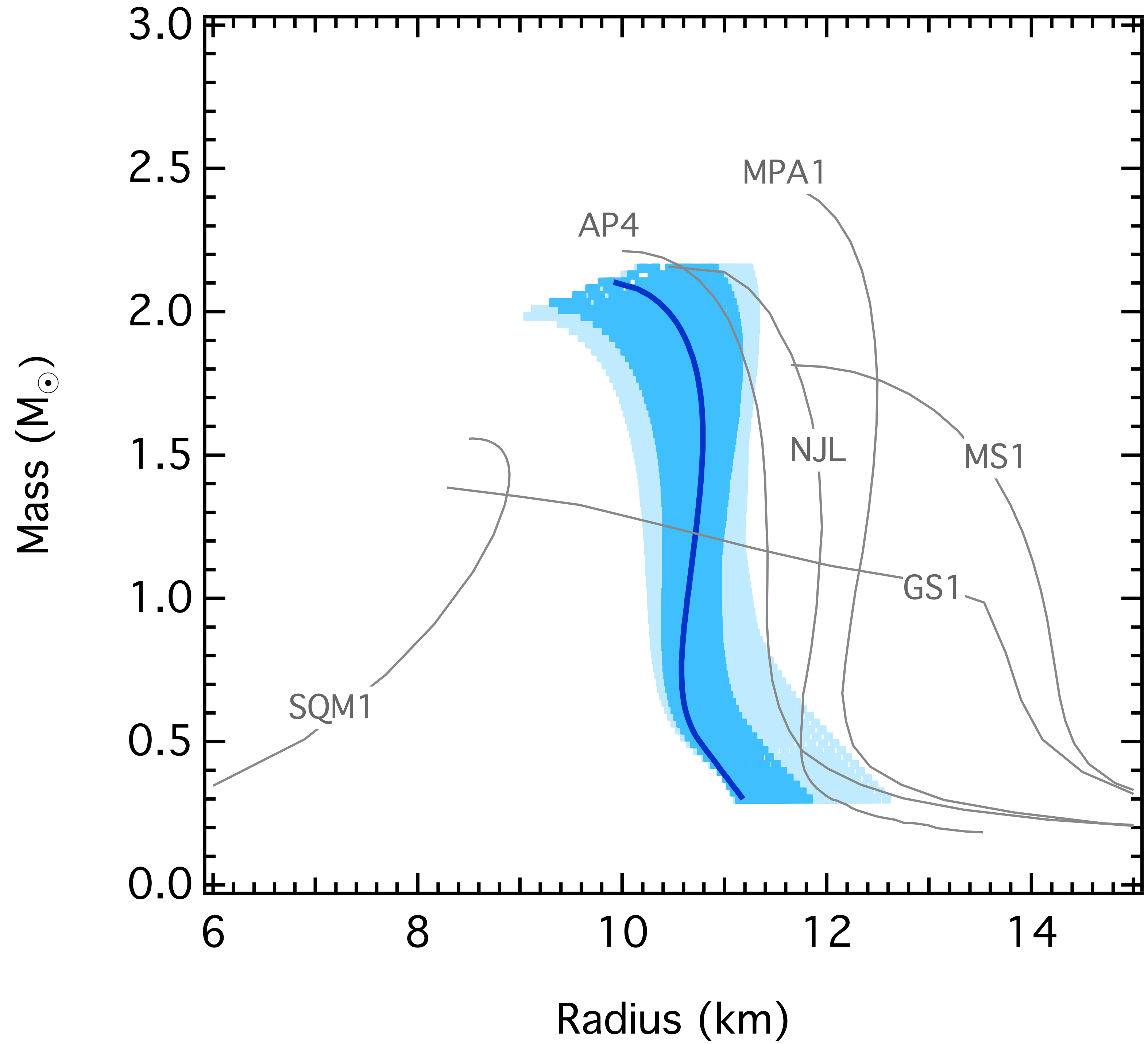
Radius measurements assuming a mass distribution



Özel et al. 2016

Resulting Observational EoS

14 measurements lead to a neutron star of 9.9 - 11.2 km @ M = 1.5 $M_\odot$



Bogdanov et al. 2016

Conclusions & Future

We have a better understanding on the systematic effects in the measurements of masses and radii of neutron stars but our measurements still rely on several assumptions. Independent measurements are necessary to confirm these results.

NICER mission will allow us to both continue these measurements but also allow for measurement using pulse profiles, providing an independent estimate.

Better estimates on the distances from GAIA

More and deeper observations with Chandra are needed to obtain high signal to noise ratio data of LMXBs in quiescence.

Further observations especially in the 0.5 - 25 keV range should be performed and an archive like the RXTE/PCA has should be established.