Constraining neutron star equation of state from cooling stages of X-ray bursts

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Plan

- Advances in the atmosphere models
- PRE X-ray burst spectral evolution
- Theory vs observations
- Results: constraints on accretion geometry; neutron star M, R

Atmosphere models of X-ray bursts
accounting for Compton scattering

- Using Kompaneets equation: London et al. 1984, 1986; Lapidus et al. 1986; Ebisuzaki 1987; Pavlov et al. 1991, Suleimanov et al. 2006, 2011
- Using approximate Compton redistribution function (Guilbert 1981): Madej 1991; Madej et al. 2004; Majczyna et al. 2005
- Using exact relativistic Compton redistribution function (Suleimanov et al. 2012)

Model atmosphere calculations

(Suleimanov, Poutanen, Werner 2011, A&A 527, A139 / 2012, A&A, submitted)

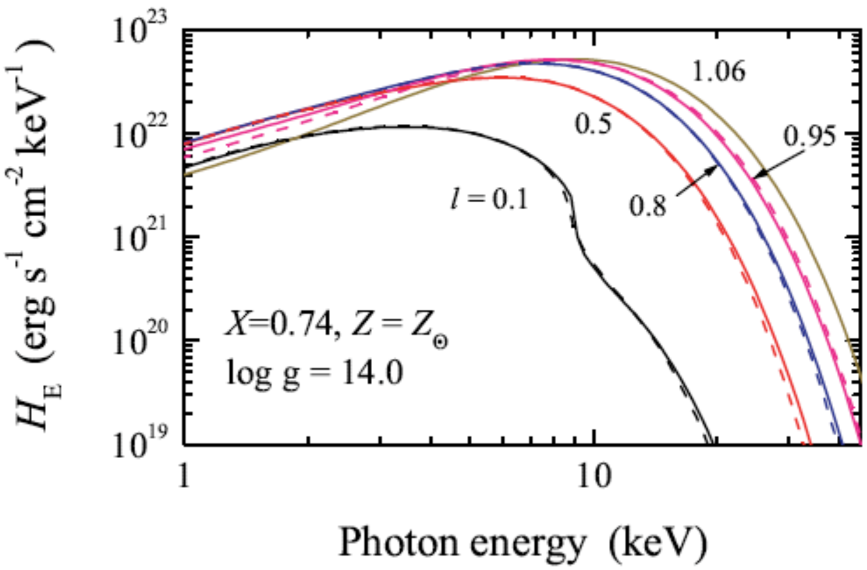
- 6 chemical compositions:
H, He, solar H/He with
Z = 1, 0.3,0.1,0.01 Z_{sun}

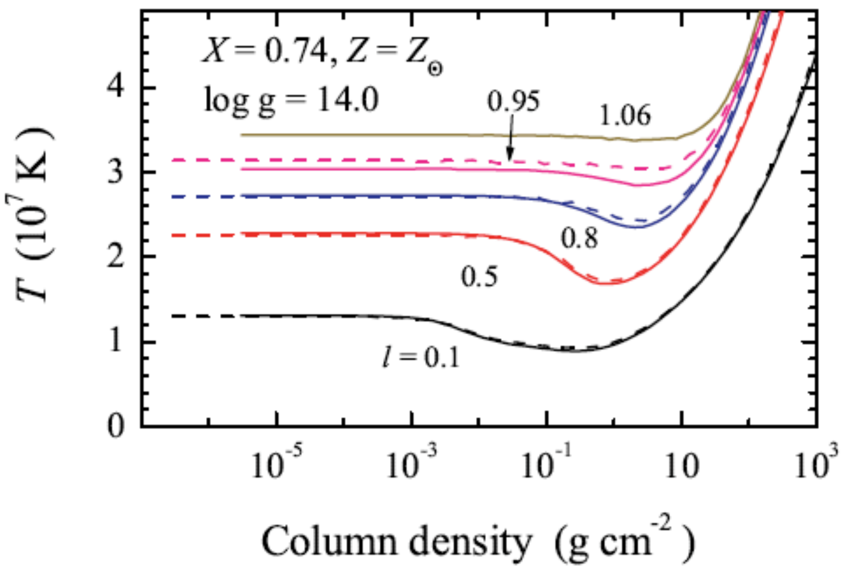
- 3 surface gravities:
log g = 14.0, 14.3 and 14.6

- 28 relative luminosities $l = L / L_{edd}$
from 0.001 to 1.1
(super-Eddington luminosities for Thomson cross-section)

Dashed lines – Kompaneets approximation

Solid lines – exact Compton scattering kernel

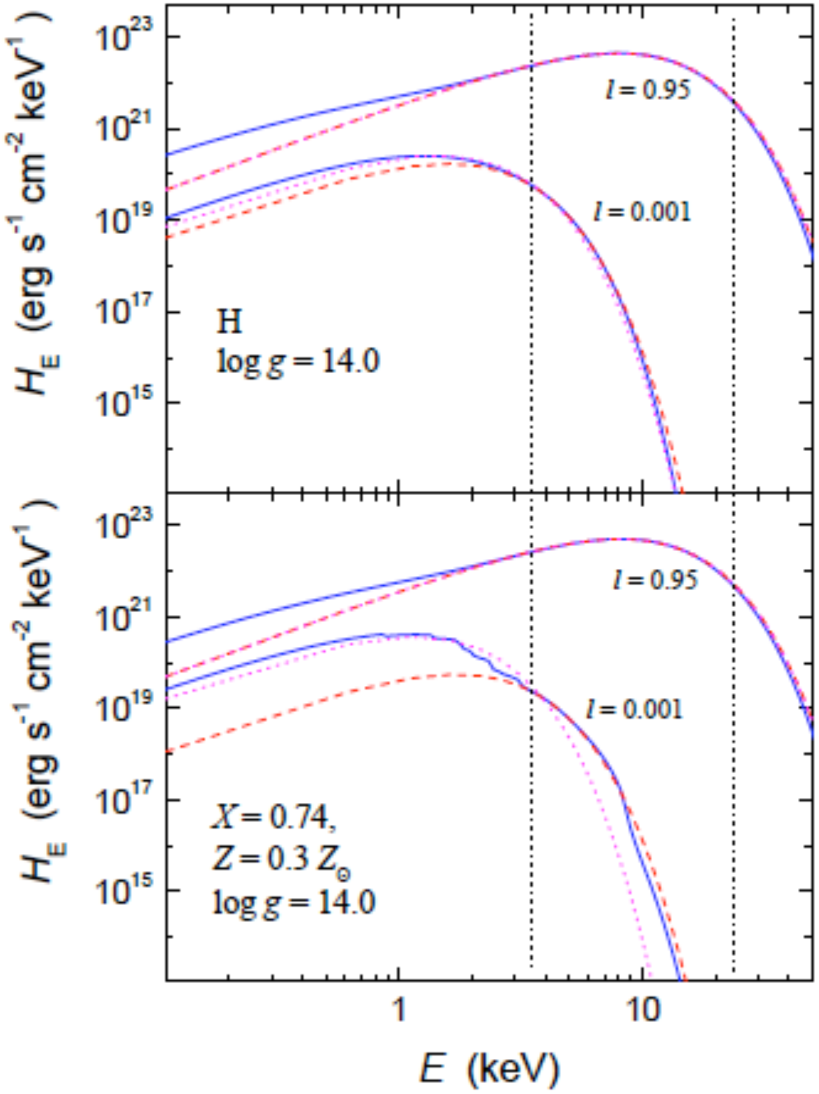




Color correction f_c calculations

Calculated spectra are redshifted and fitted by diluted blackbody (one- and two-parameters functions) (assuming M = 1.4 M_{sun}) in the *PCA/ RXTE* energy band (3-20) keV

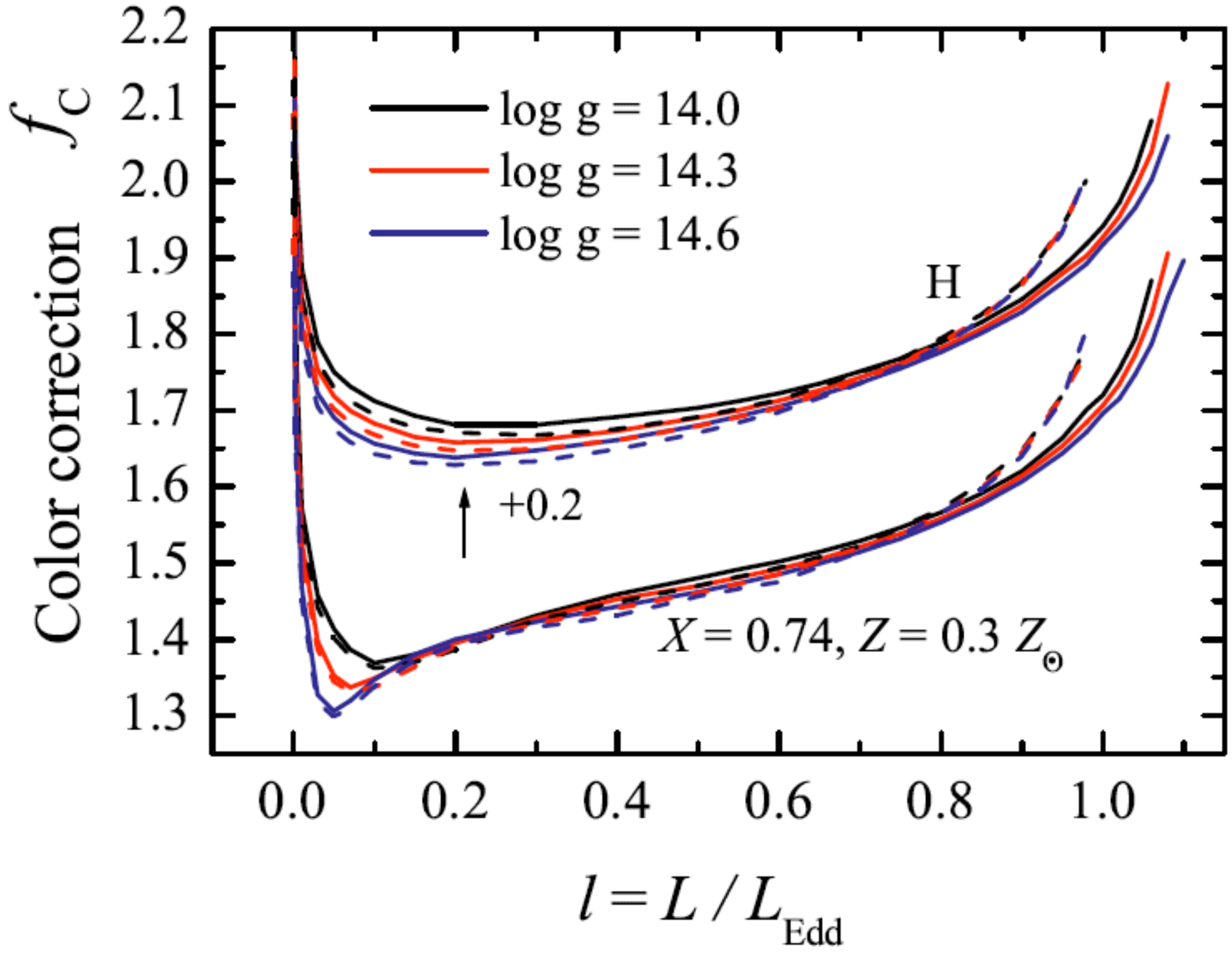
$$F_E = wB_E(f_c T_{eff})$$



Minimizing deviations in photon number flux

$$\sum_{n=1}^{N} \frac{(F_{E_n} - w_2 B_{E_n}(f_{c,2} T_{\rm eff}))^2}{E_n^2}$$

Color correction f_c calculations



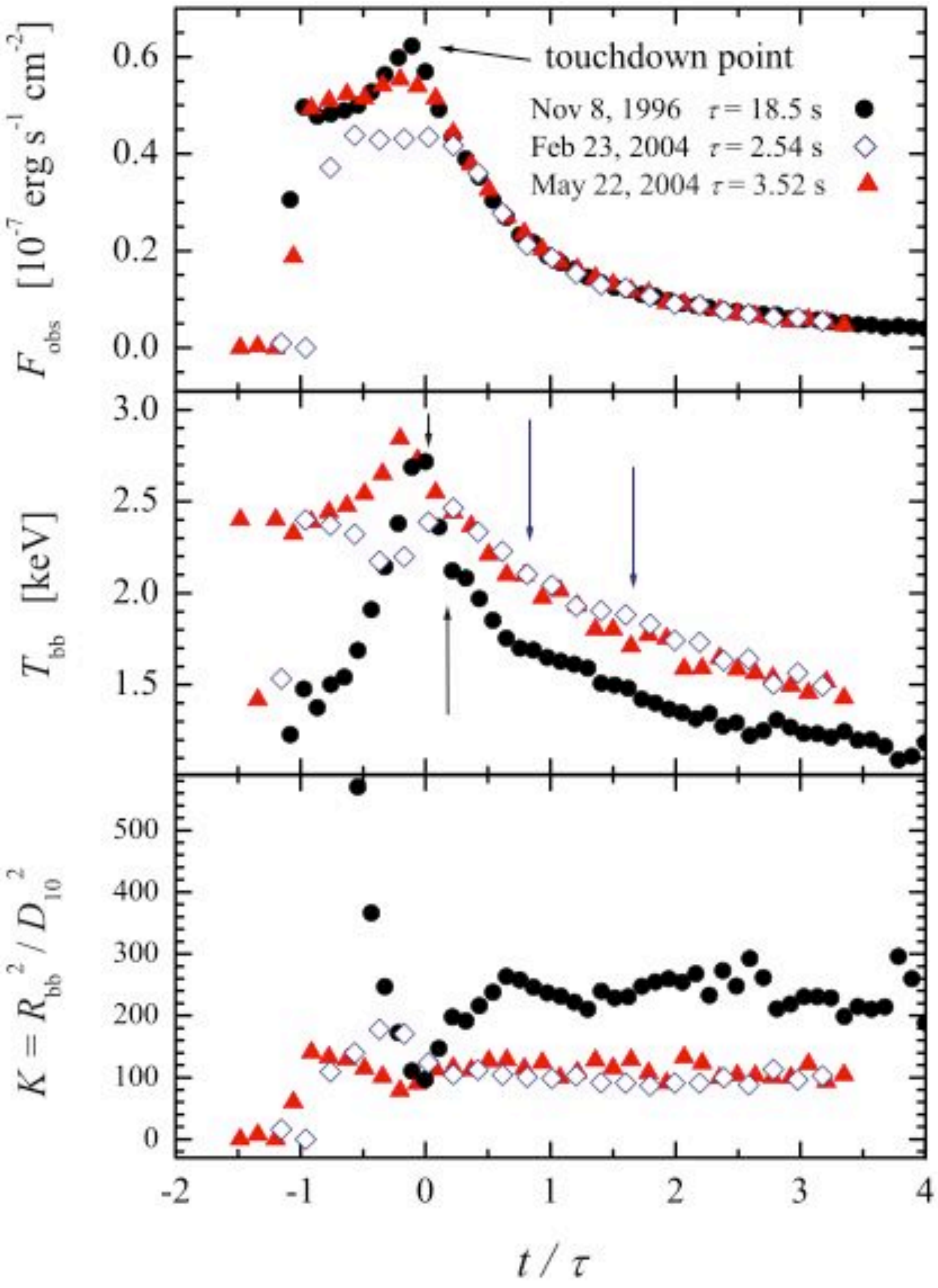
Dashed lines – Kompaneets approximation

differences are small at $L/L_{edd} < 0.8$

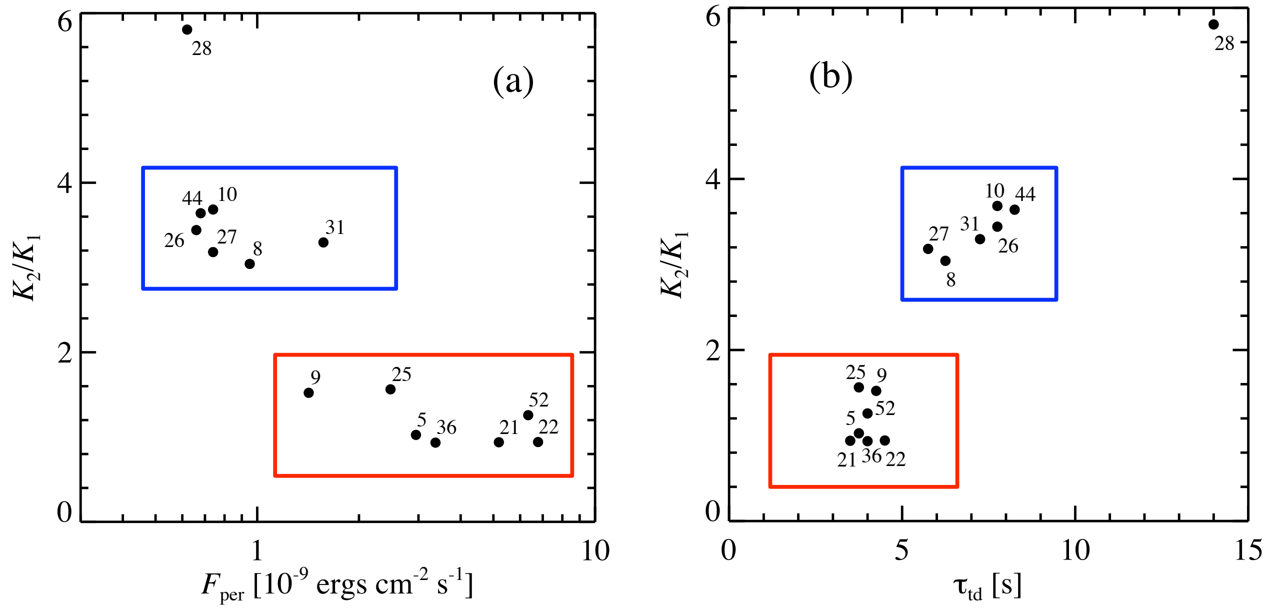
Solid lines – exact Compton scattering kernel

(PRE) X-ray burst spectral evolution

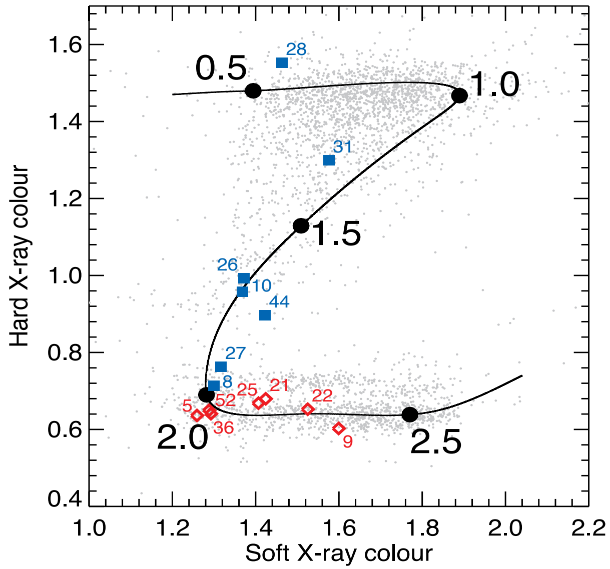
PRE bursts


touchdown point
Nov 8, 1996 τ = 18.5 s
Feb 23, 2004 τ = 2.54 s
May 22, 2004 τ = 3.52 s
F_{obs} [10^{-7} erg s^{-1} cm^{-2}]
T_{bb} [keV]
$K = R_{bb}^2 / D_{10}^2$
t / τ
0.6
0.4
0.2
0.0
3.0
2.5
2.0
1.5
500
400
300
200
100
0
-2
-1
0
1
2
3
4

bb normalizations ratio at =1/2 touchdown flux to the touchdown

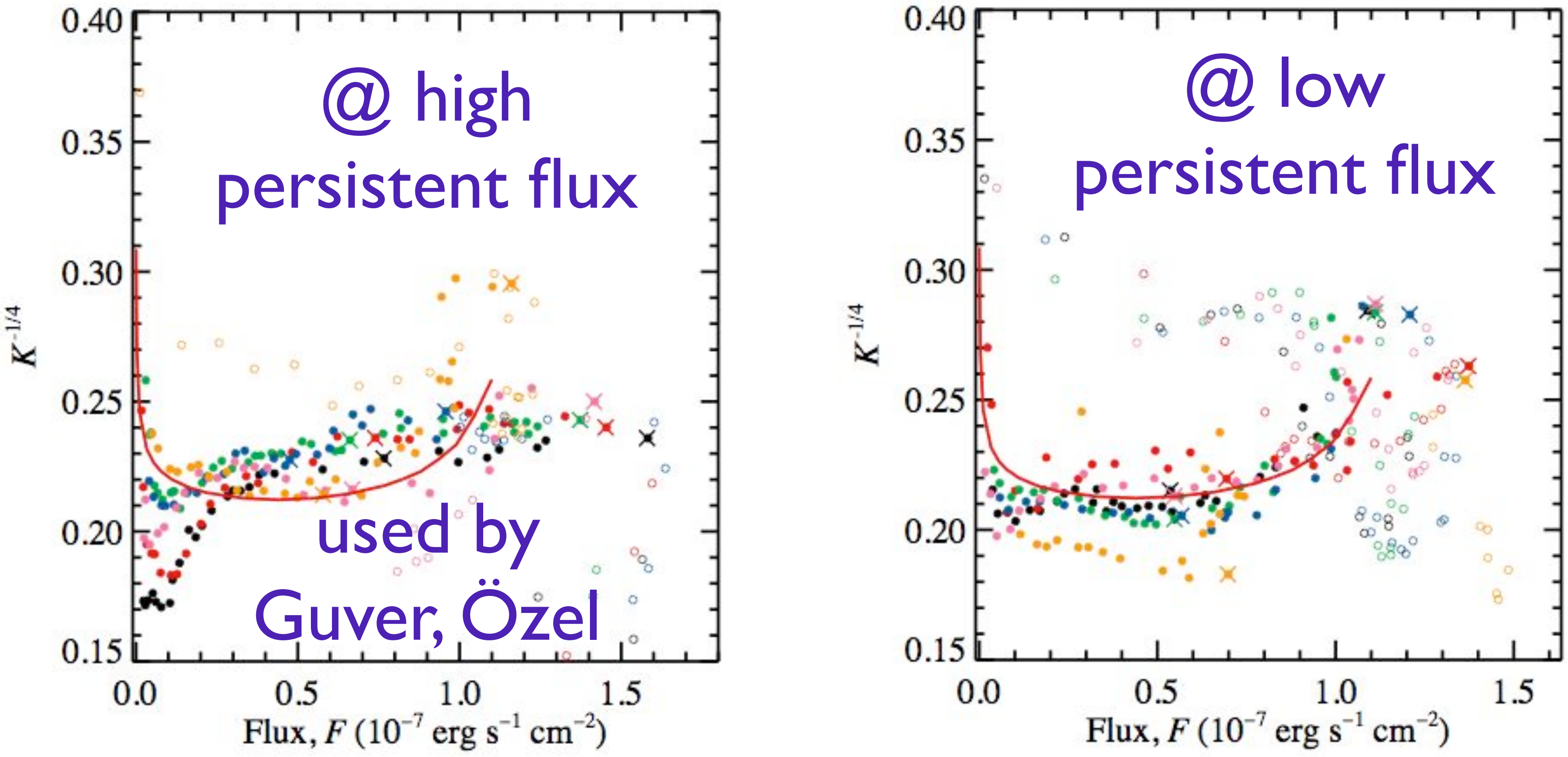


Evolution of blackbody normalization depends strongly on persistent flux, time until touchdown, and position on a color-color diagram



4U 1608-52

Bursts from 4U 1608-52 at different accretion rates



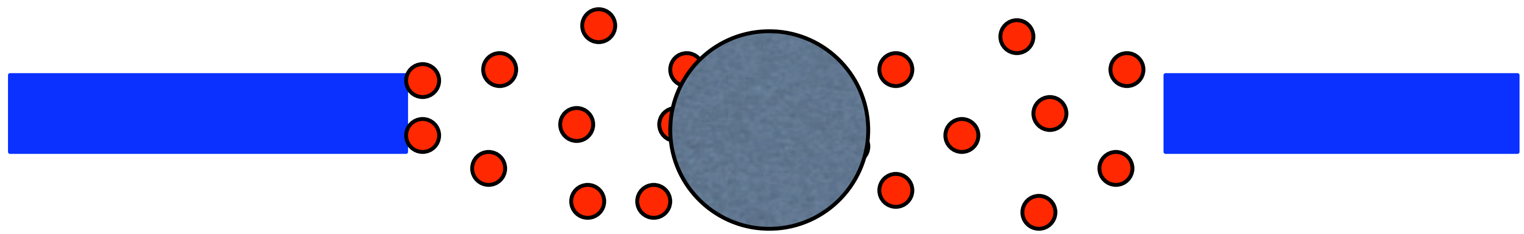
Poutanen et al. (2012, in preparation)

Why the apparent area is different in different bursts?

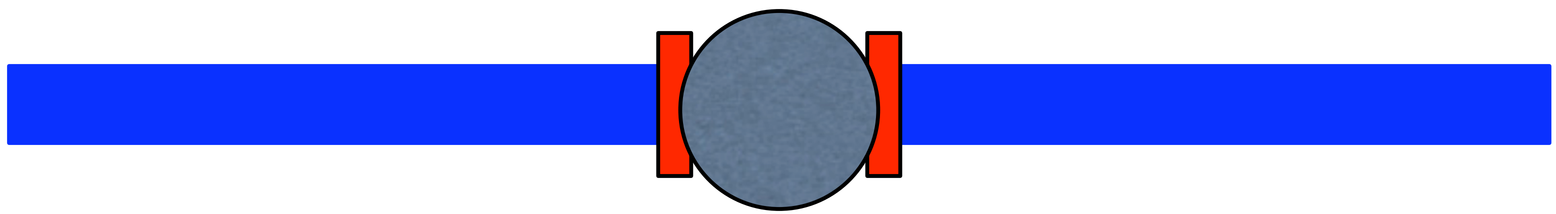
Influence of accretion on the burst apparent area and the spectra

Accretion geometry

Hard state - hot flow / hot optically thin boundary layer



Soft state - optically thick boundary layer



Measuring neutron star parameters from PRE bursts using the “cooling tail” method

Cooling tail method

The observed evolution of $K^{-1/4}$ vs. F should look similar to the theoretical relation f_c vs. $F/F_{\rm Edd}$

$$K = \left(\frac{R_{bb}}{D_{10}}\right)^2 = \frac{1}{f_c^4}\left(\frac{R_\infty}{D_{10}}\right)^2 \longrightarrow K^{-1/4} = A\, f_c(F/F_{\rm Edd})$$

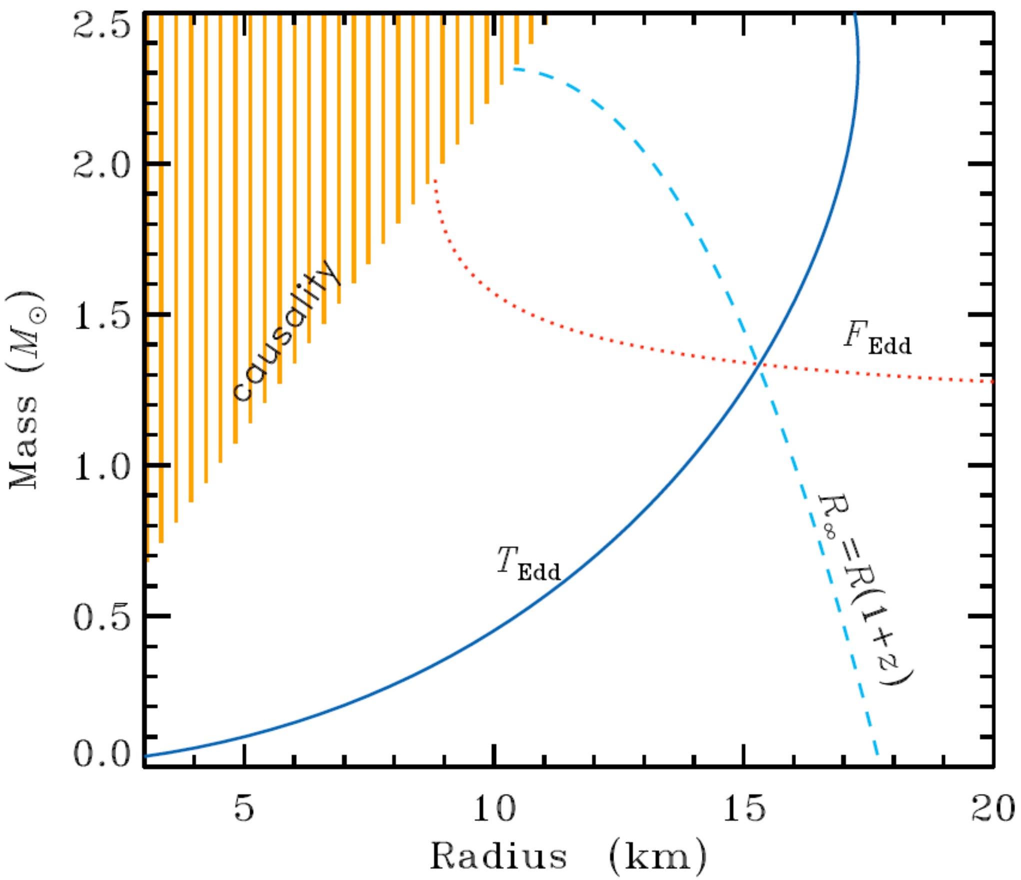
$$A = (R_\infty[\mathrm{km}]/D_{10})^{-1/2}$$

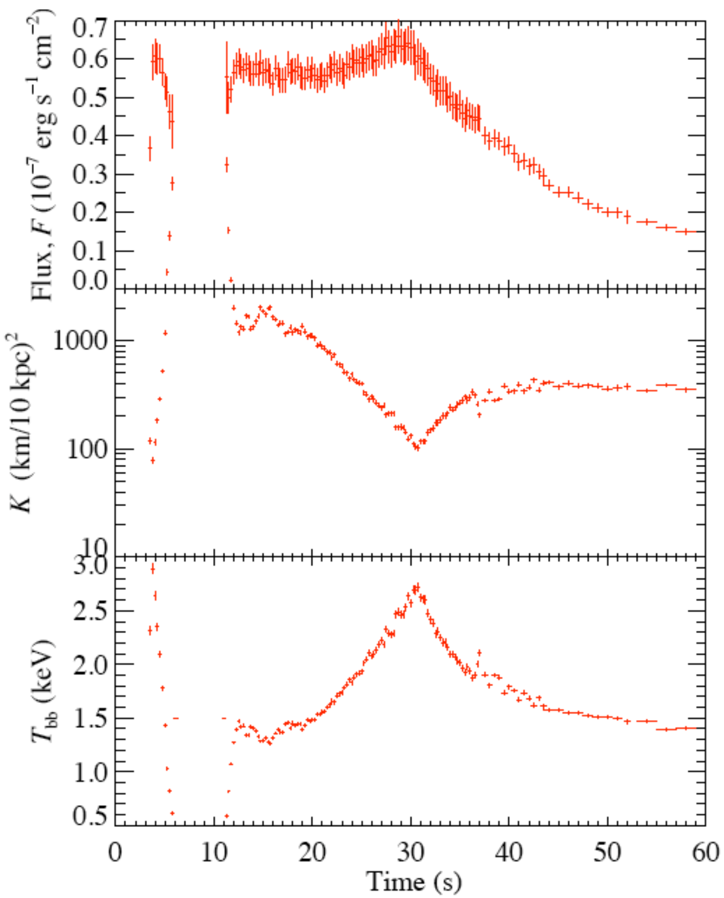
From the fits a more reliable estimate of the Eddington flux and apparent radius can be obtained.

Two free parameters: A and $F_{\rm Edd}$.

and we use now our theoretical dependences

f_c vs. $F/F_{\rm Edd}$





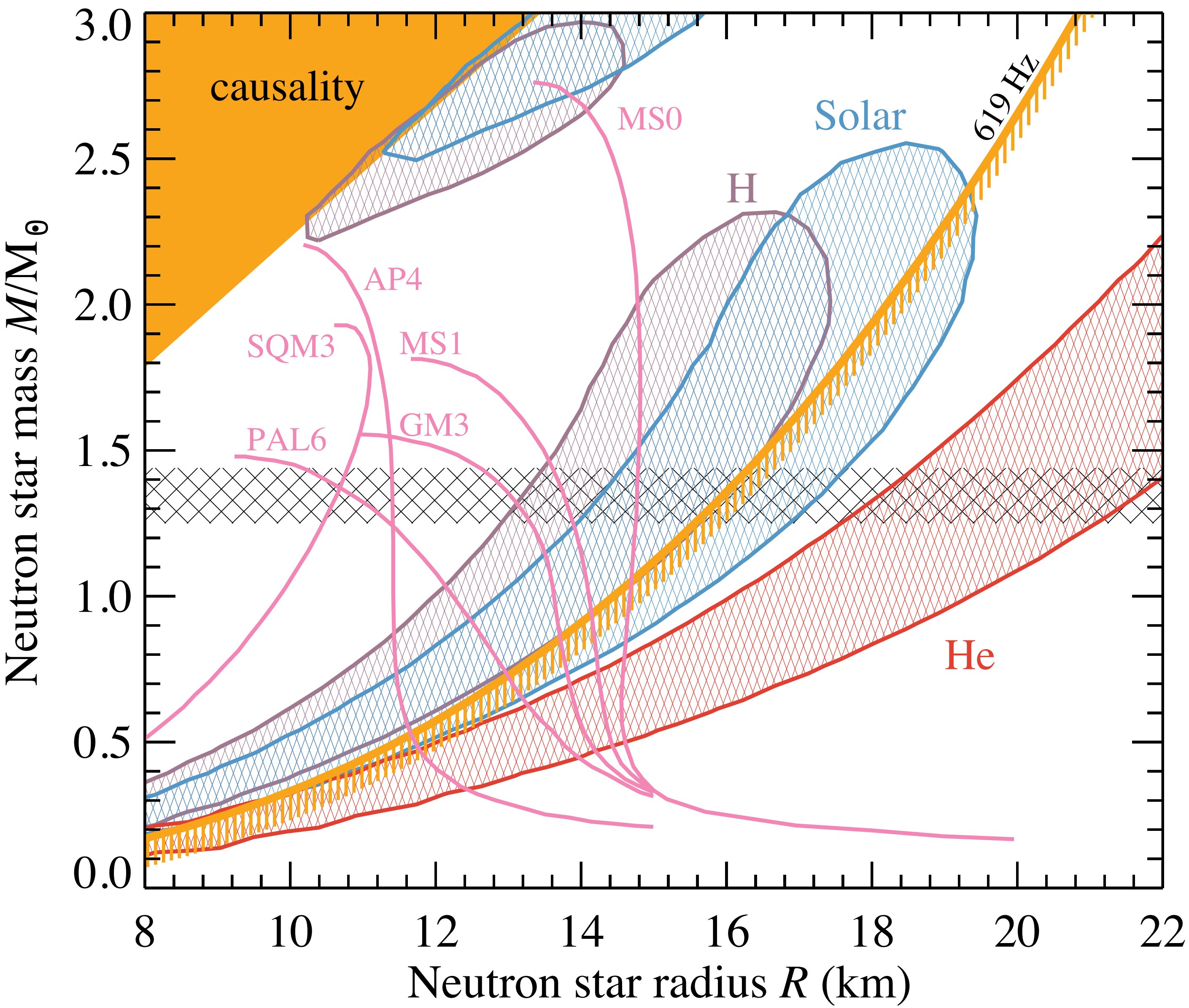
$$F_{\rm Edd} = \frac{L_{\rm Edd}}{4\pi D^2} = \frac{GMc}{D^2 \kappa_{\rm e}(1+z)} \rightarrow R = 14.138 \text{ km } \frac{(1+X) D_{10}^2 F_{-7}}{u\sqrt{1-u}}$$

$$R_\infty = R_{bb} f_c^2 = D_{10}\sqrt{K} f_c^2 \rightarrow R = D_{10}\sqrt{K} f_c^2 \sqrt{1-u}$$

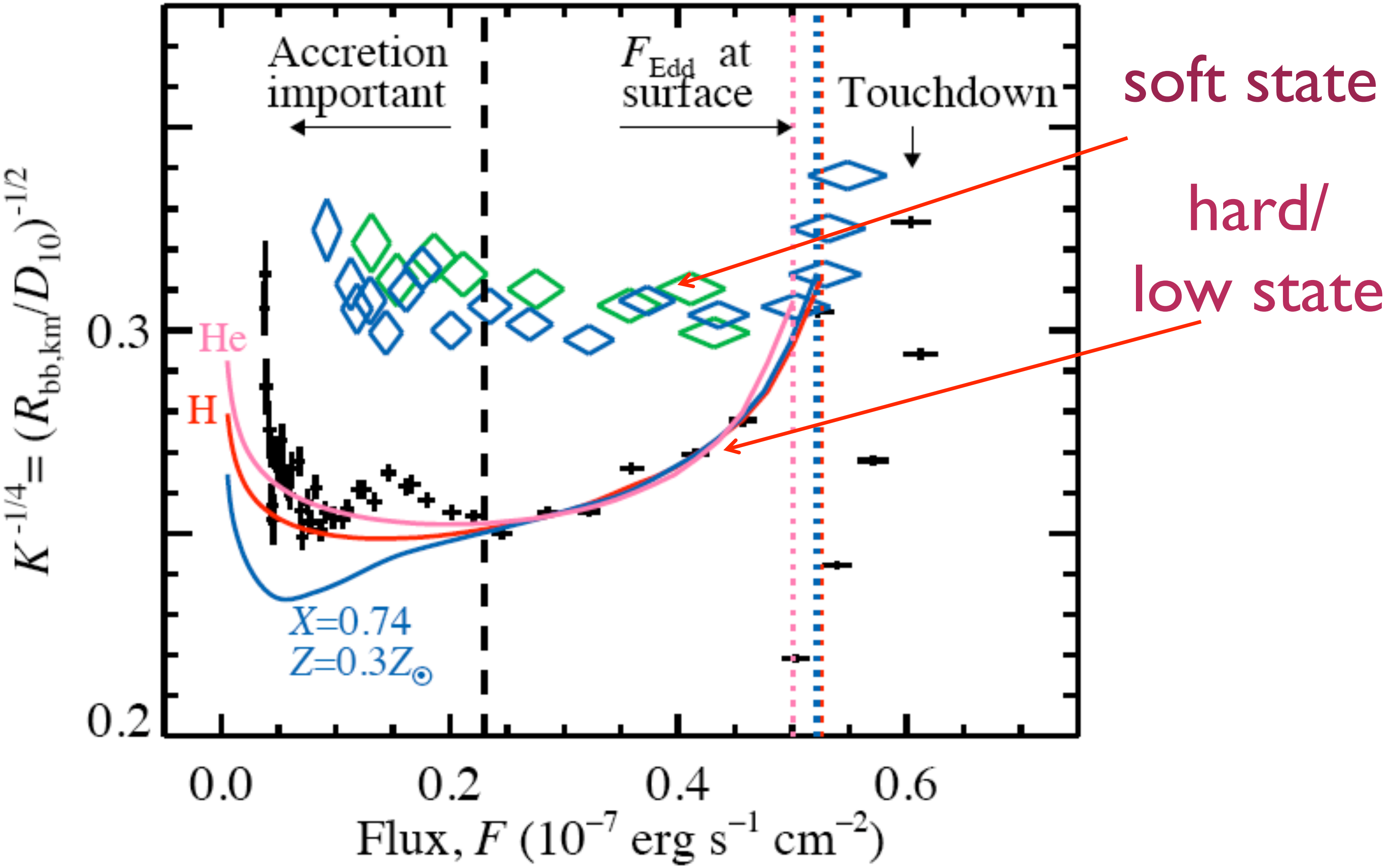
$$T_{\rm Edd,\infty} = \left(\frac{gc}{\sigma_{\rm SB}\kappa_{\rm e}}\right)^{1/4} \frac{1}{1+z} = 6.4 \times 10^9 \, A \, F_{\rm Edd}^{1/4} \text{ K}$$

$$A = (R_\infty / D_{10})^{-1/2} = K^{-1/4}/f_c$$

M-R relation - 4U 1608-52



Cooling tails of PRE bursts from 4U 1724-307

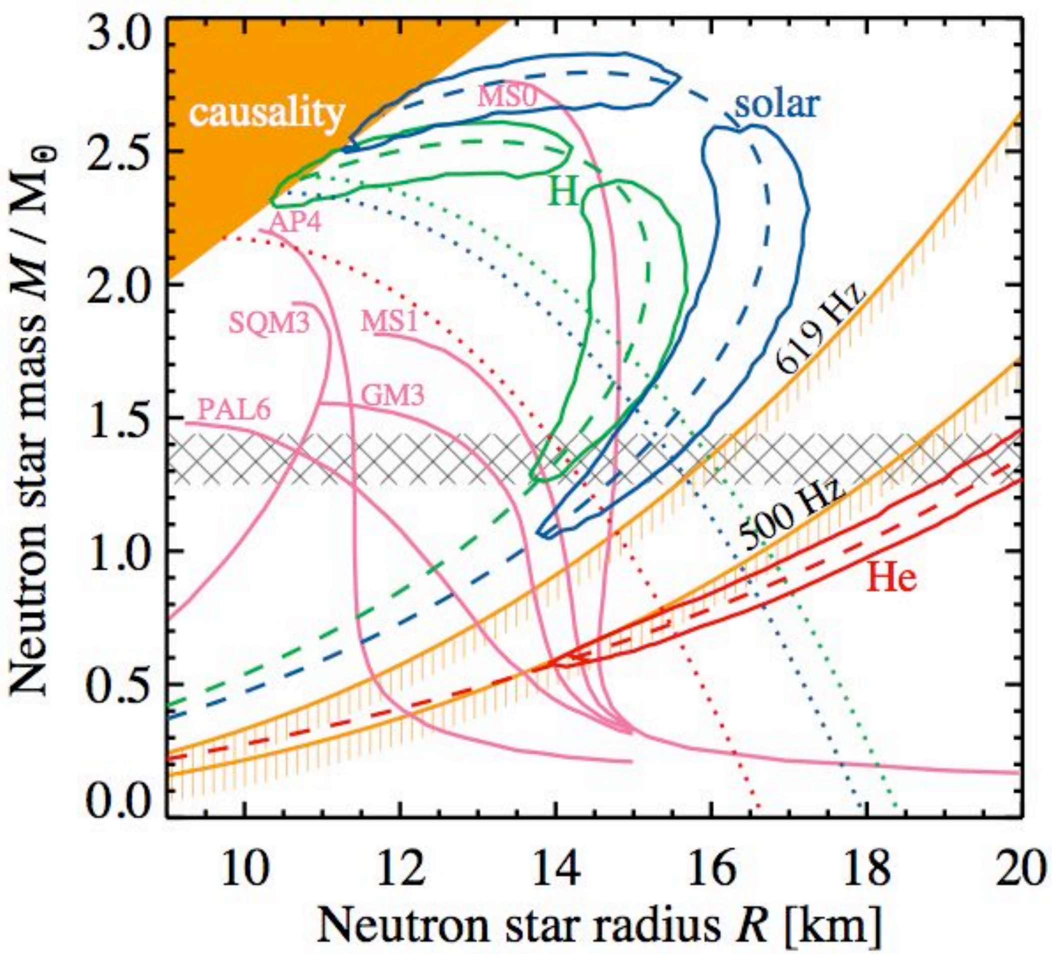


Suleimanov et al. (2011)

M-R relation - 4U 1724-307

Distance = 5.3-7.7 kpc with gaussian tails).

1. Radius > 13.5 km at 90% confidence for any solar composition for M<2.3 solar.
2. Hydrogen-rich atmosphere is preferred.
3. Stiff EoS is preferred.



Contours are elongated along $T_{\rm Edd}$=const track

$$T_{\rm Edd,\infty} = \left(\frac{gc}{\sigma_{\rm SB}\kappa_{\rm e}}\right)^{1/4} \frac{1}{1+z} = 6.4\times 10^9\, A\, F_{\rm Edd}^{1/4}\ {\rm K}$$

Conclusions

1. An extended set of accurate model atmospheres for X-ray bursts covering large range of luminosities, various log g and chemical composition is computed.
2. Evolution of blackbody normalization with flux $K^{-1/4}$ vs. F in "hard state" bursts is well described by the theory. "Soft state" PRE bursts from 4U1724-307 and 4U1608-52 do not show the evolution of $K^{-1/4}$ vs. F predicted for a passively cooling neutron star, therefore they should not be used for M/R determination.
3. Burst properties depend on persistent flux. Optically thick accretion disk blocks nearly 1/2 of the star and possibly affects the short burst (soft state) spectra. In the hard state bursts, accretion is not important (optically thin).
4. Neutron star radii are constrained at R>13.5 km favoring stiff equation of state (consistent with existence of the $2M_\odot$ pulsar).