The influence of accretion on the spectral evolution of X-ray bursting neutron stars

Valery Suleimanov +

Universität Tübingen, Germany
Space Research Institute (IKI), Moscow, Russia
Kazan (Volga region) Federal University, Russia

Burst Environment, Reactions and Numerical Modelling Workshop 2018 (BERN18)

June 11, 2018, Florence

X-ray bursting neutron stars

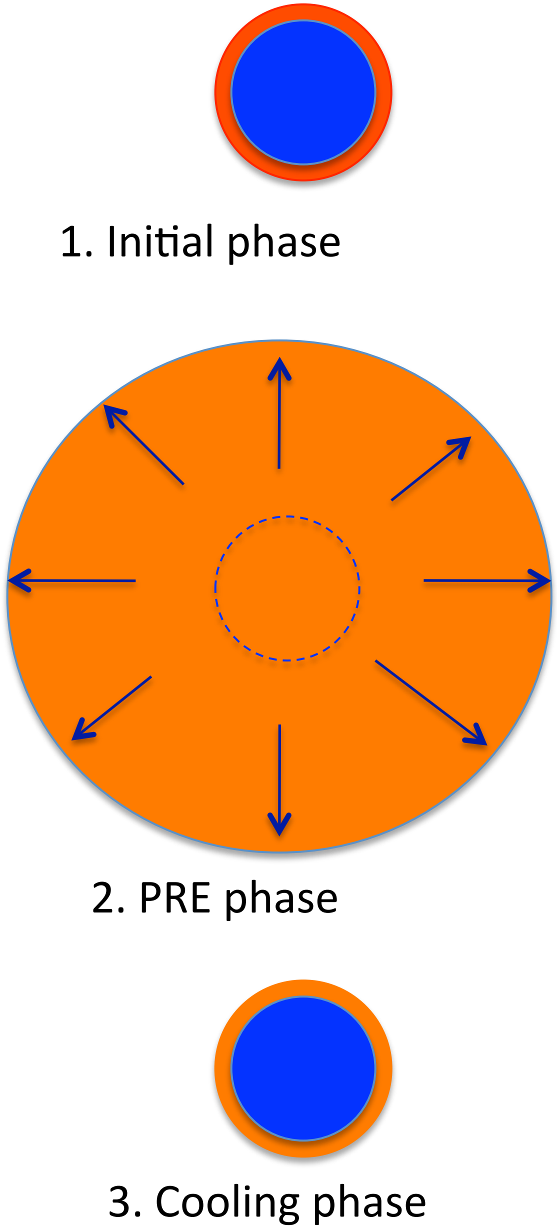
- X-ray bursting NSs – LMXBs with thermonuclear explosions at the neutron star surface

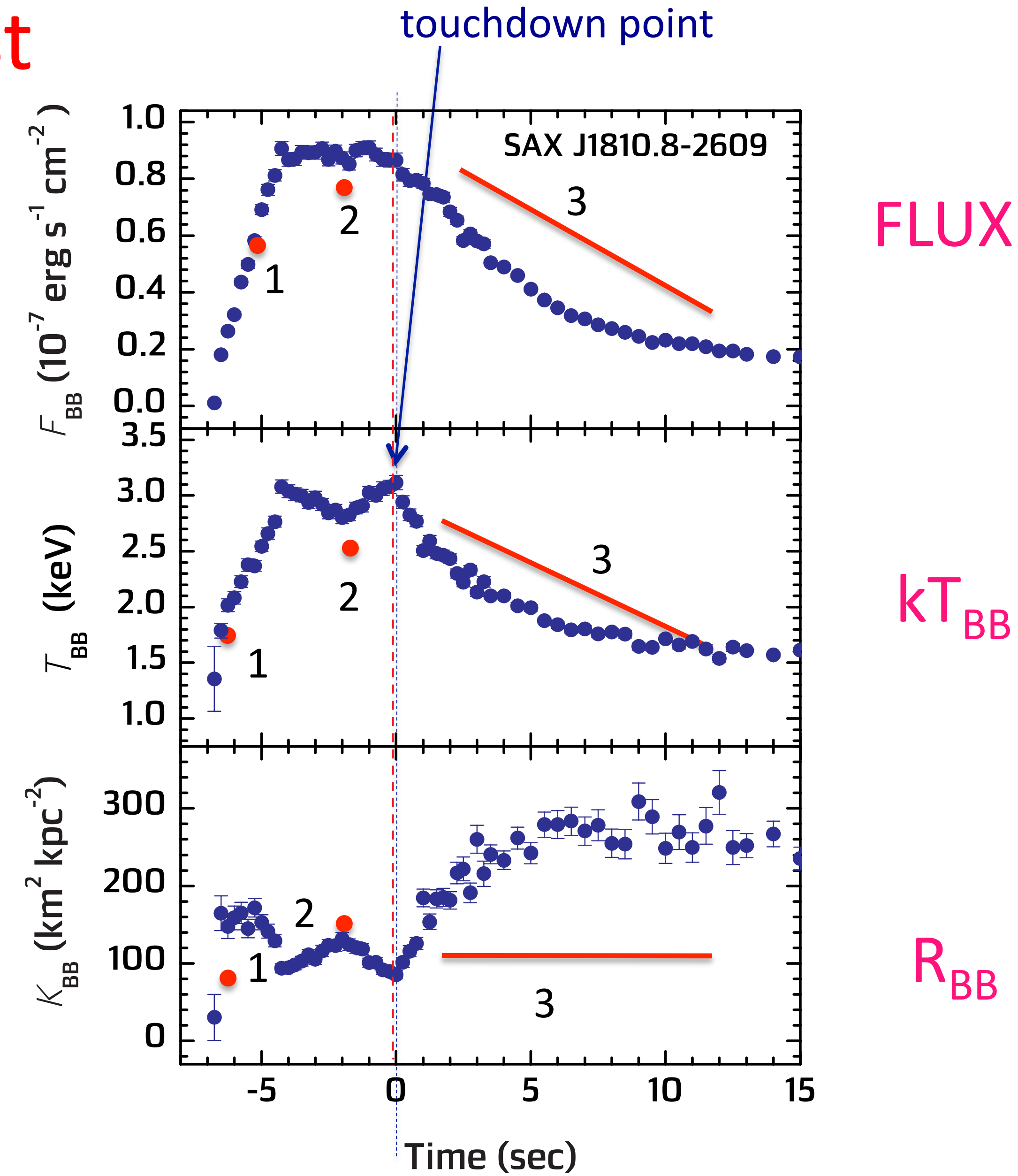
- Sometimes close to the Eddington limit during the burst (photospheric radius expansion (PRE) bursts)

- Spectra are well fitted by blackbodies

Ideal sources for NS masses and radii measurements

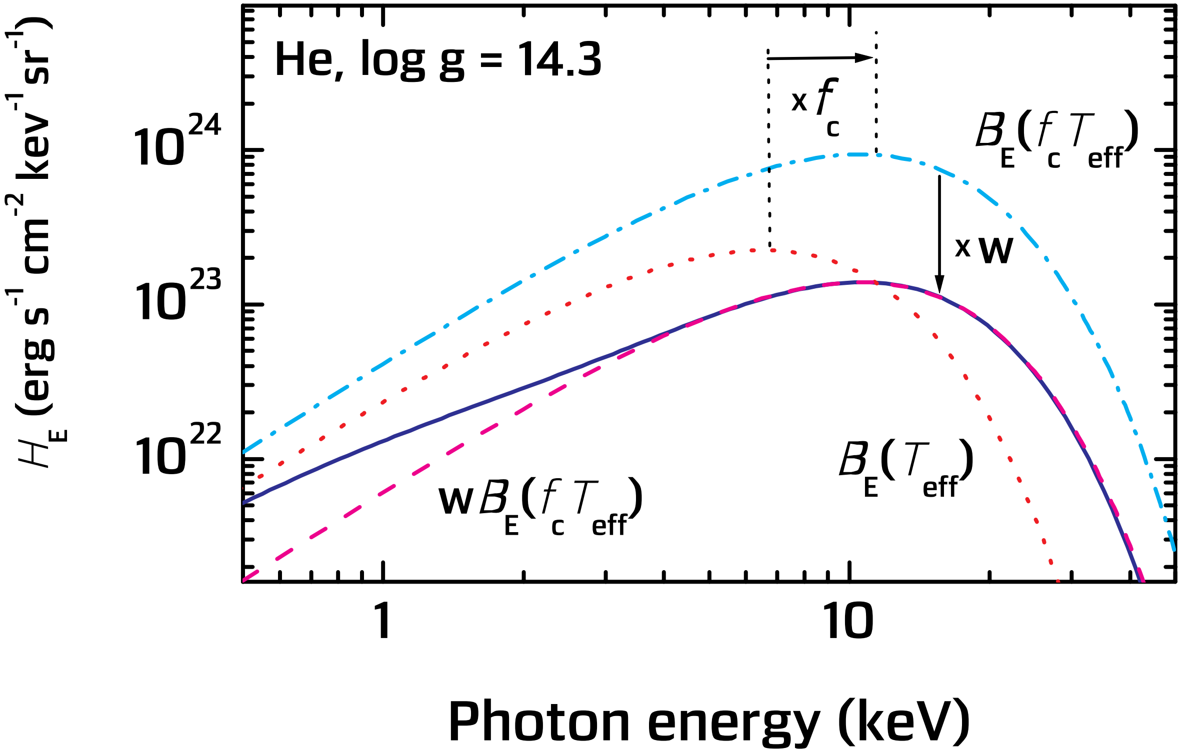
PRE burst


1. Initial phase
2. PRE phase
3. Cooling phase


touchdown point
SAX J1810.8-2609
F_{BB} (10^{-7} erg s^{-1} cm^{-2})
T_{BB} (keV)
K_{BB} (km^2 kpc^{-2})
Time (sec)
1
2
3
FLUX
kT_{BB}
R_{BB}

Spectrum formation of X-ray bursting NSs

Compton scattering is important !!!



$$F_\nu \approx w\, B_\nu(f_c T_{eff})$$

$f_c > 1$ color correction factor

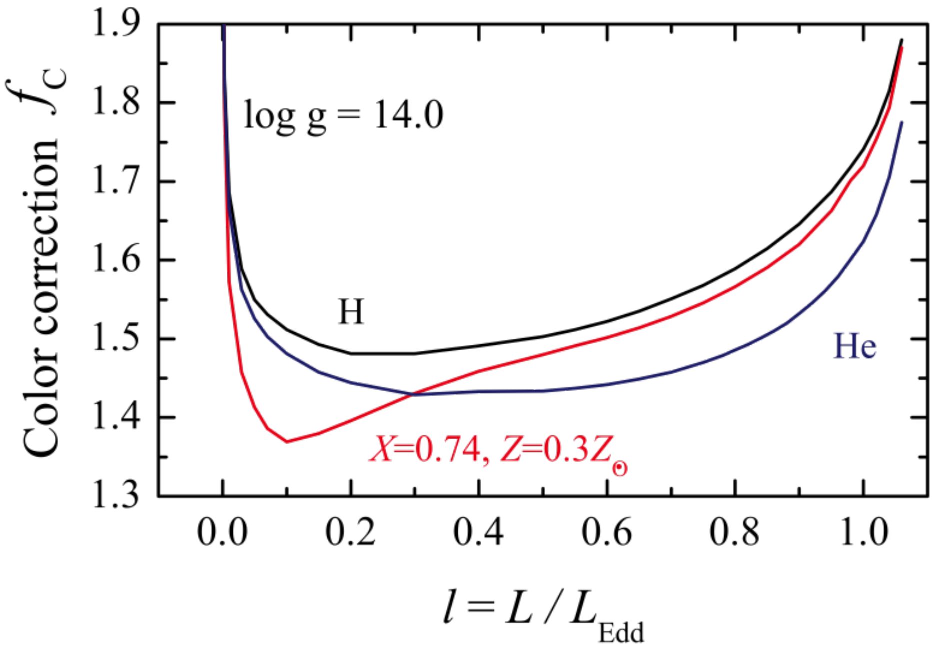
$w \approx f_c^{-4} < 1$ dilution factor

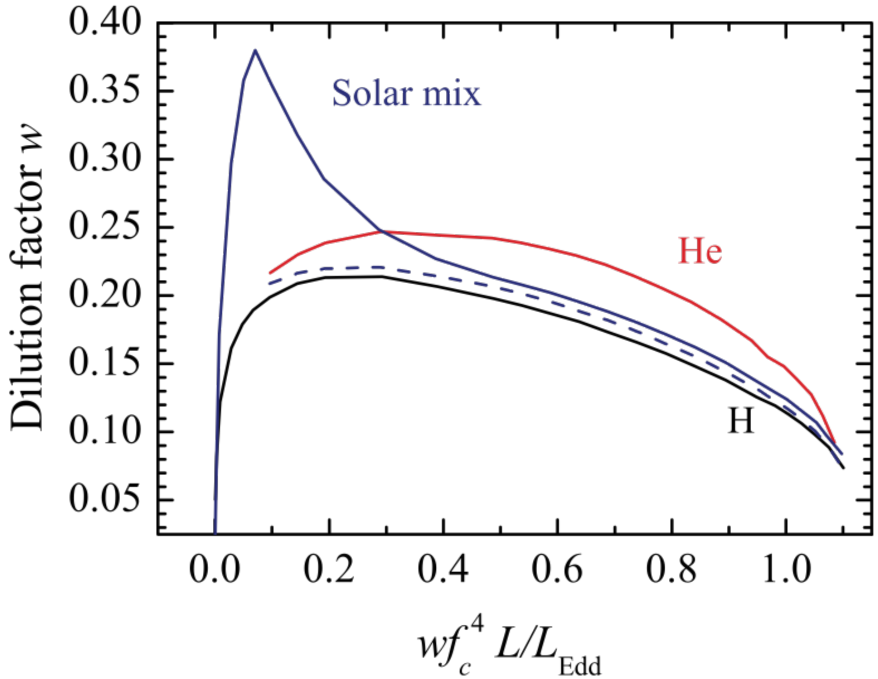
$$\boxed{F_\nu^{obs} \approx B_\nu(T_{BB}) K = B_\nu(T_{BB})\, w\, \frac{R^2(1+z)^2}{D^2}}$$

$$T_{BB} = f_c T_{eff} (1+z)^{-1}$$

Model dependences for f_C and w

Computed using models of hot NS atmospheres



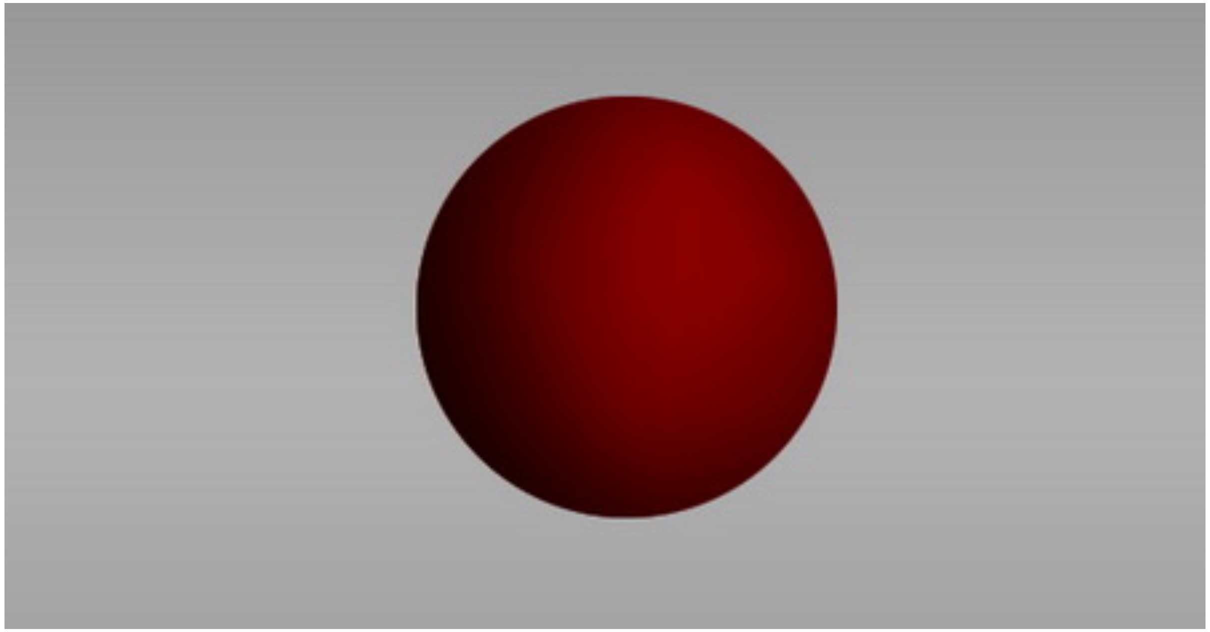


Suleimanov et al. 2011

Suleimanov et al. 2017

Spectral fitting

Problem

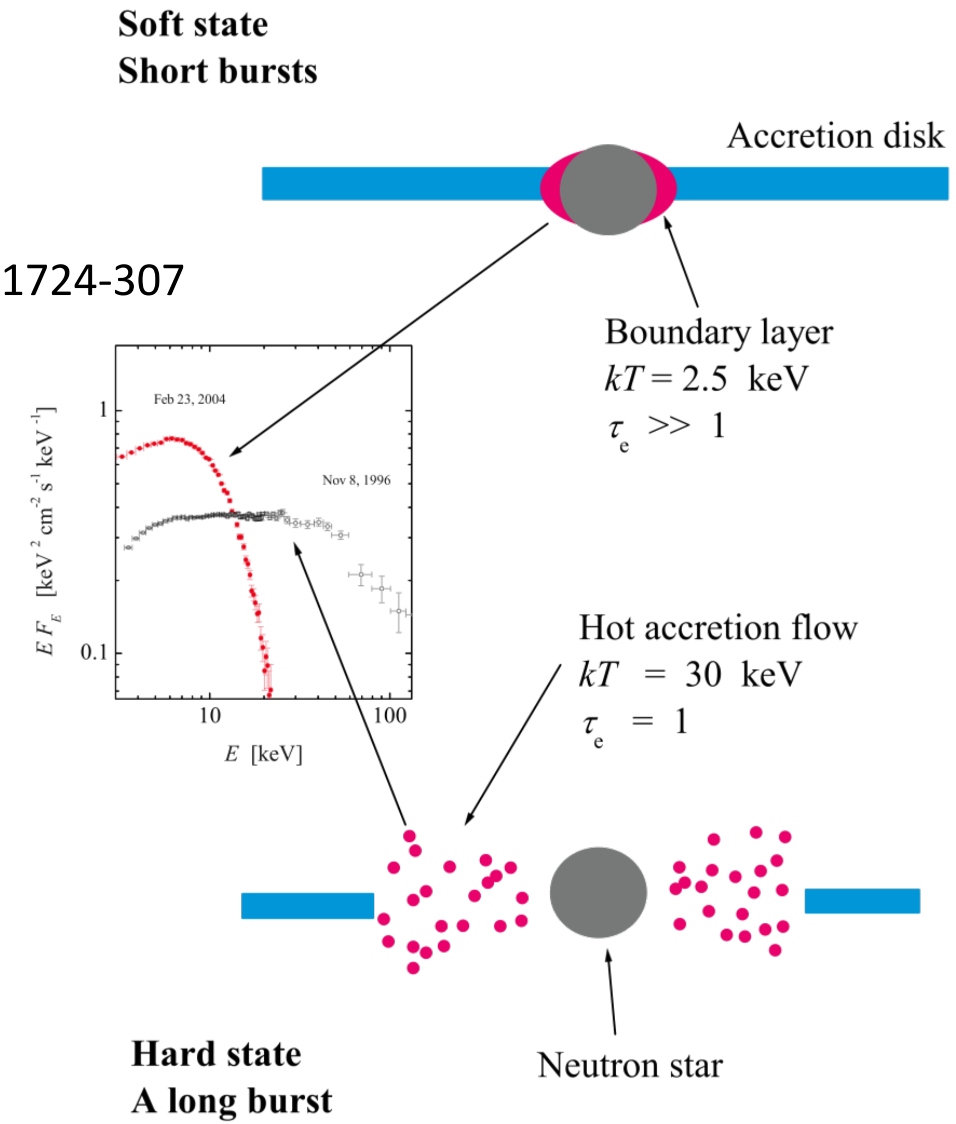


$$f_E = F_E K = F_E \frac{R^2 (1+z)^2}{d^2}$$

This Equation is correct for an isolated homogeneuos NS only ! Without any surrounding matter.

Two limit quiescent spectral states of LMXBs

4U 1724-307



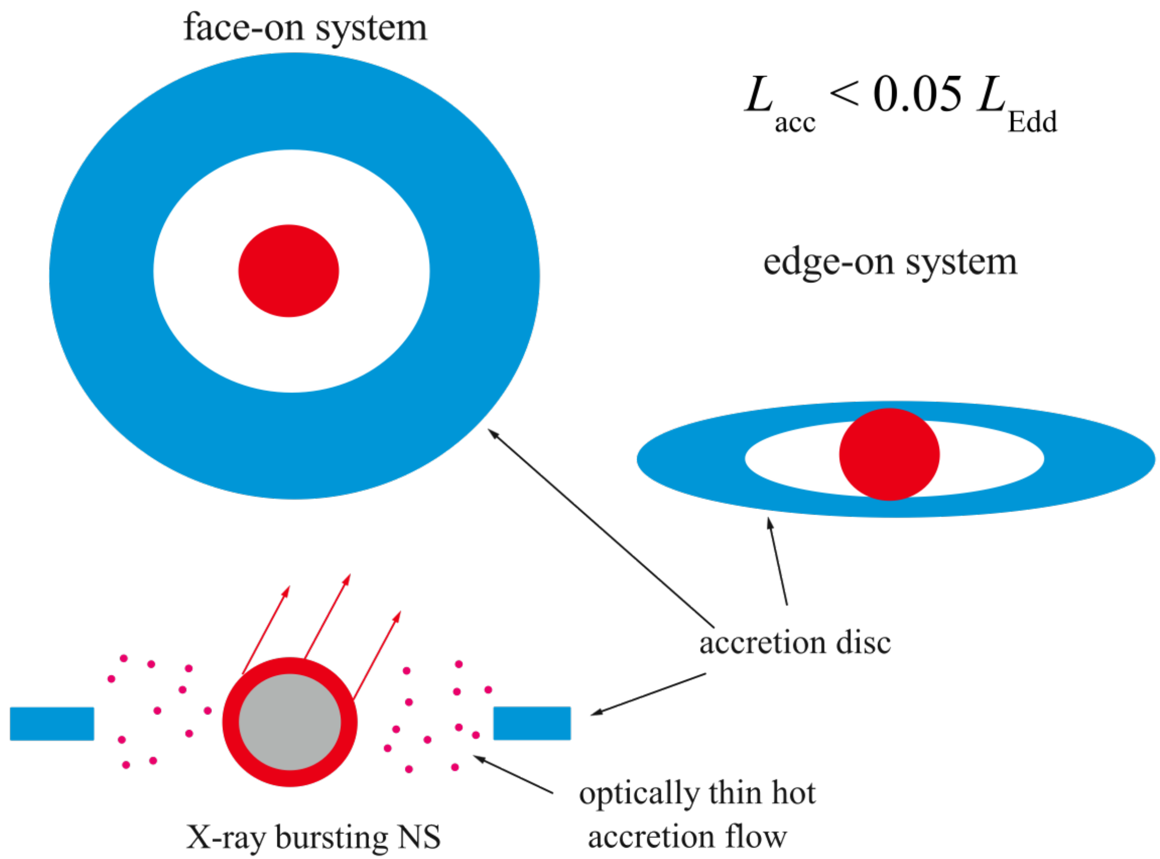
Soft

$L_{acc} > 0.1\ L_{Edd}$

Hard

$L_{acc} < 0.05\ L_{Edd}$

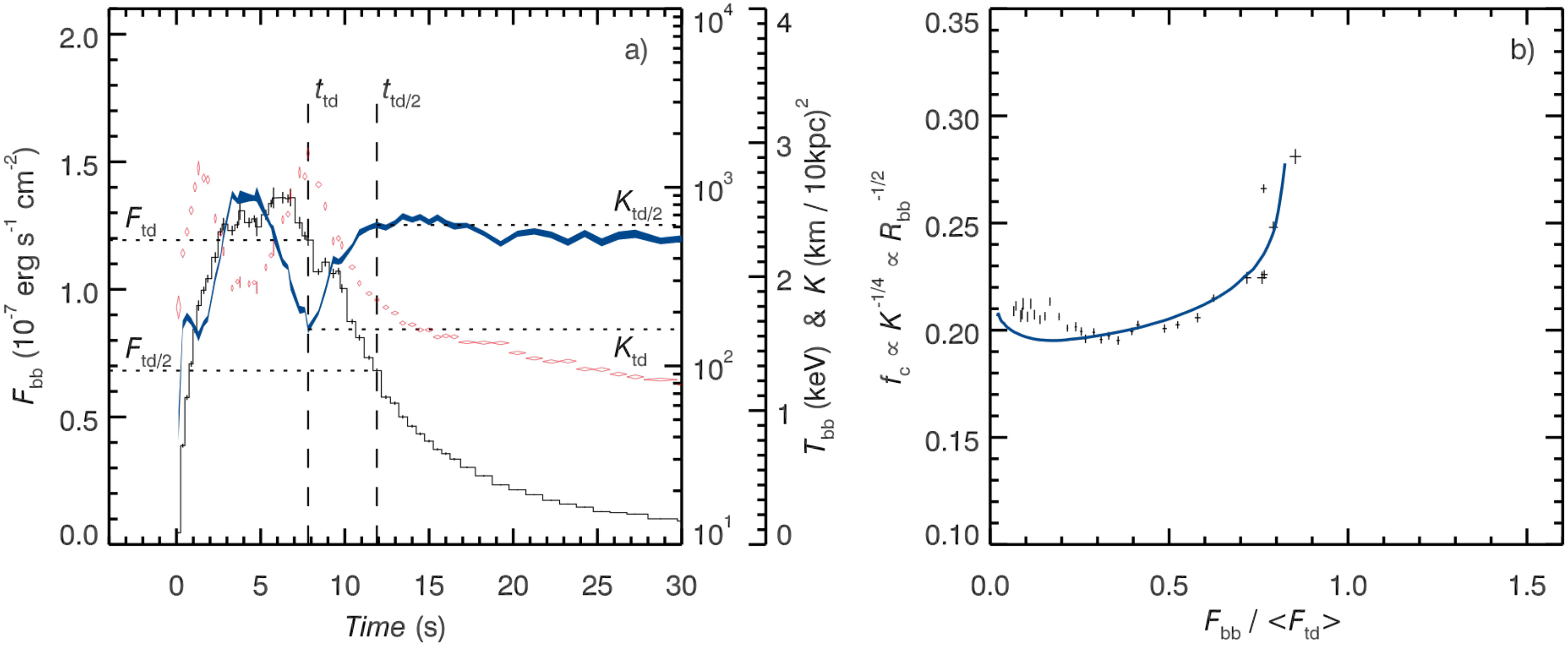
Hard spectral states of LMXBs



Influence of optically thin accretion flow is insignificant ?

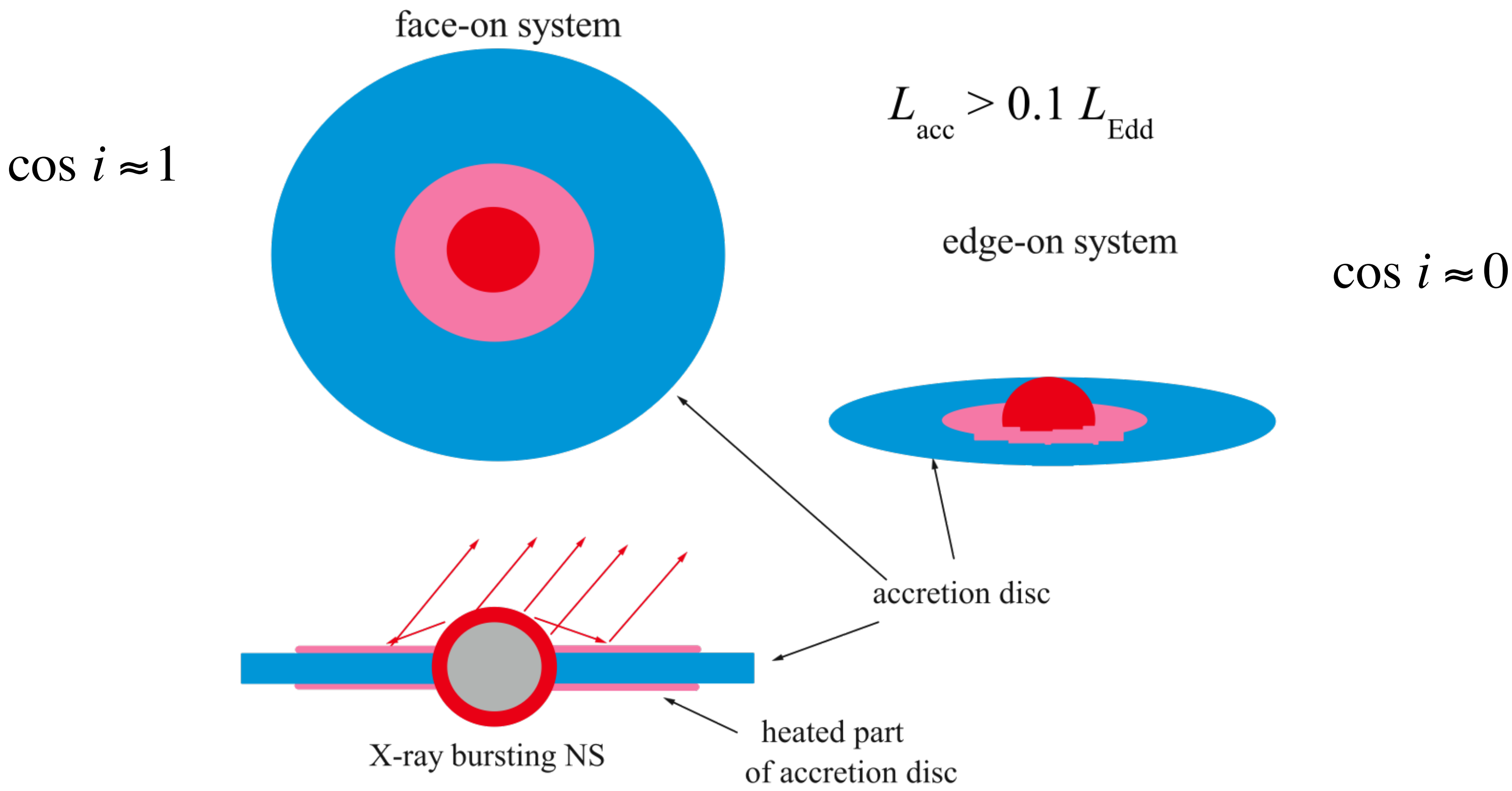
X-ray burst at hard quiescent spectral state

4U 1608-52



Kajava et al. 2014

X-ray burst at soft quiescent spectral state



$$F_{obs} = \xi_b^{-1} \frac{L}{4\pi d^2} \qquad \xi_b^{-1} \approx \frac{1}{2} + \cos i$$

- anisotropy factor

(Lapidus & Sunyaev 1985)

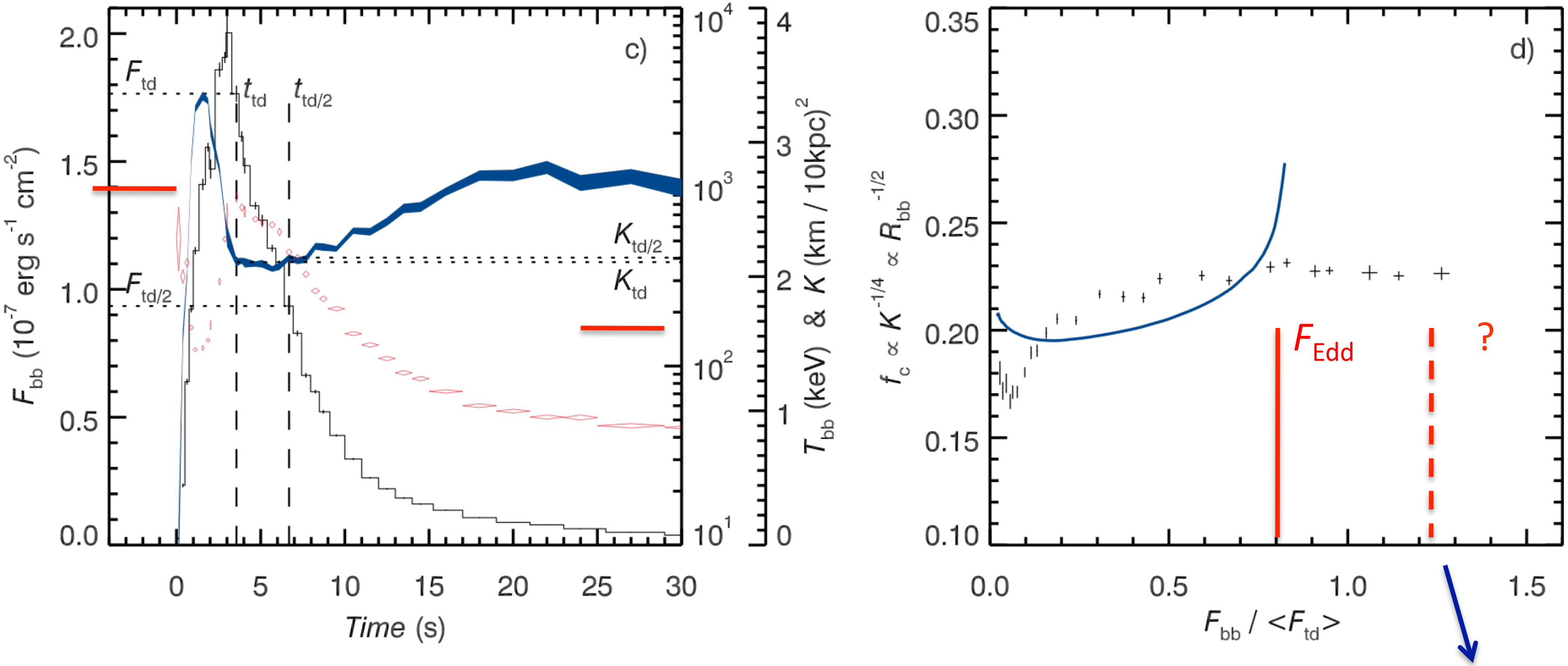
Input of accretion disc reflection is significant for face-on systems

Accretion disc blocks a part of NS in edge-on systems

X-ray burst at soft quiescent spectral state

4U 1608-52

Probably, face-on system



Kajava et al. 2014

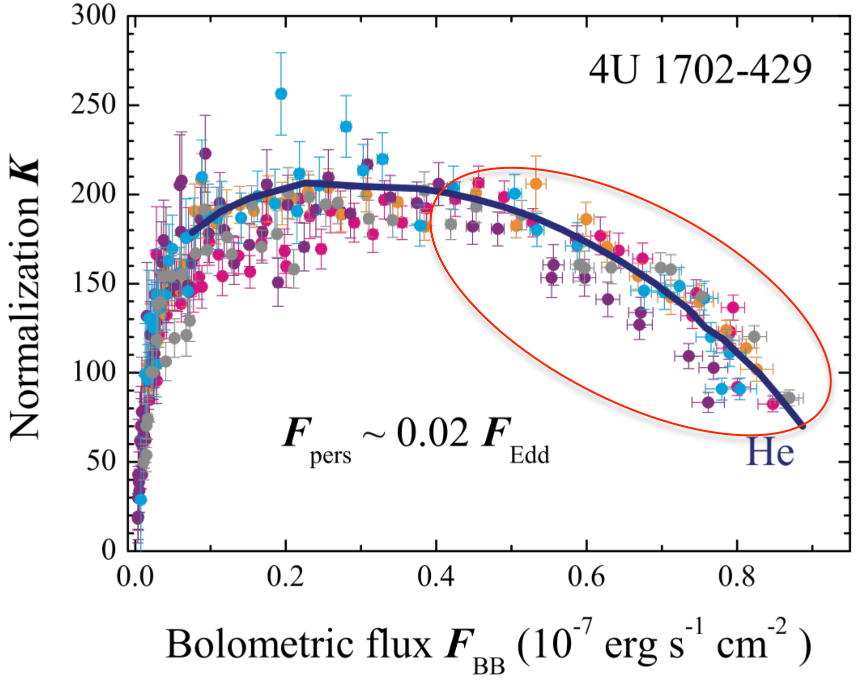
$$L_{Edd} = \frac{4\pi GMc}{0.2(1+X)}(1+z)$$

$$\xi_b^{-1} \approx \frac{1}{2} + \cos i$$

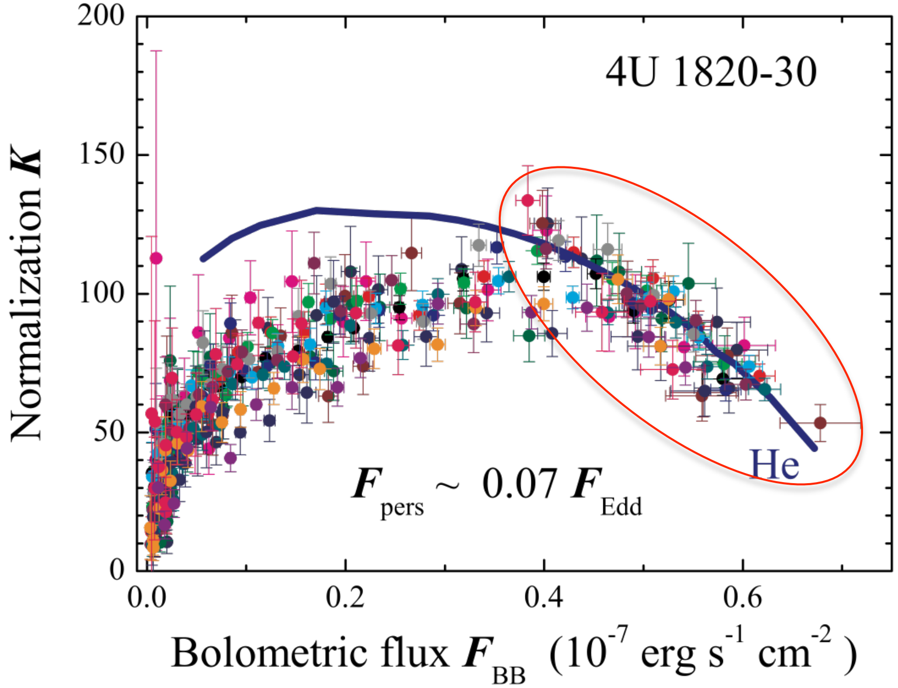
Comparison with observations

Cooling tail method – we can estimate NS masses and radii by fitting the observed curves $K - F_{BB}$ $(K^{-1/4} - F_{BB})$ with the model curves $w - wf_C^4 L/L_{Edd}$ $(f_C - L/L_{Edd})$

Fitting parameters are F_{Edd} and $\Omega = R^2(1+z)^2/D^2$ $(A = \Omega^{-1/4})$



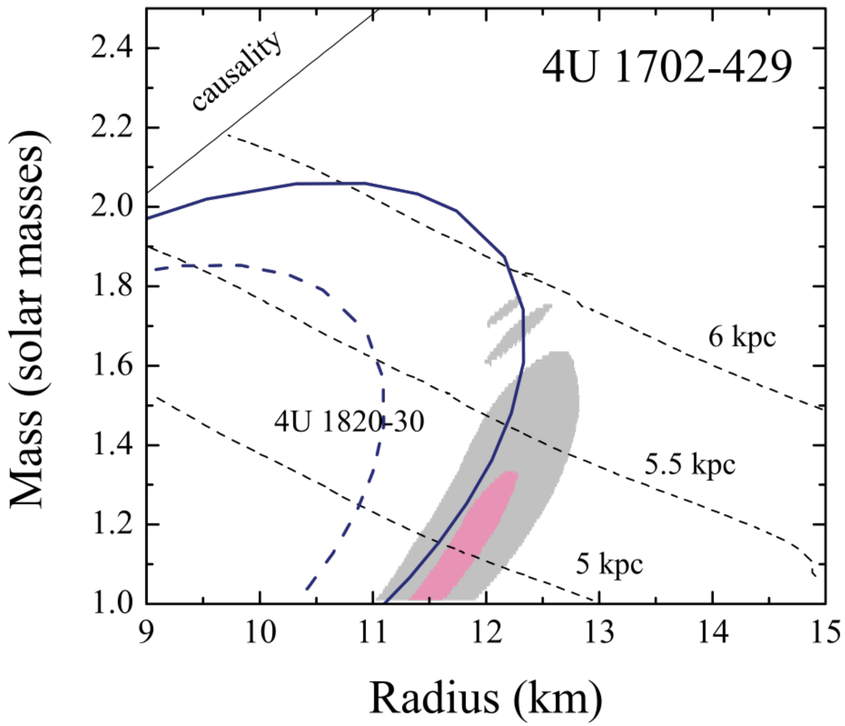
Low persistent flux

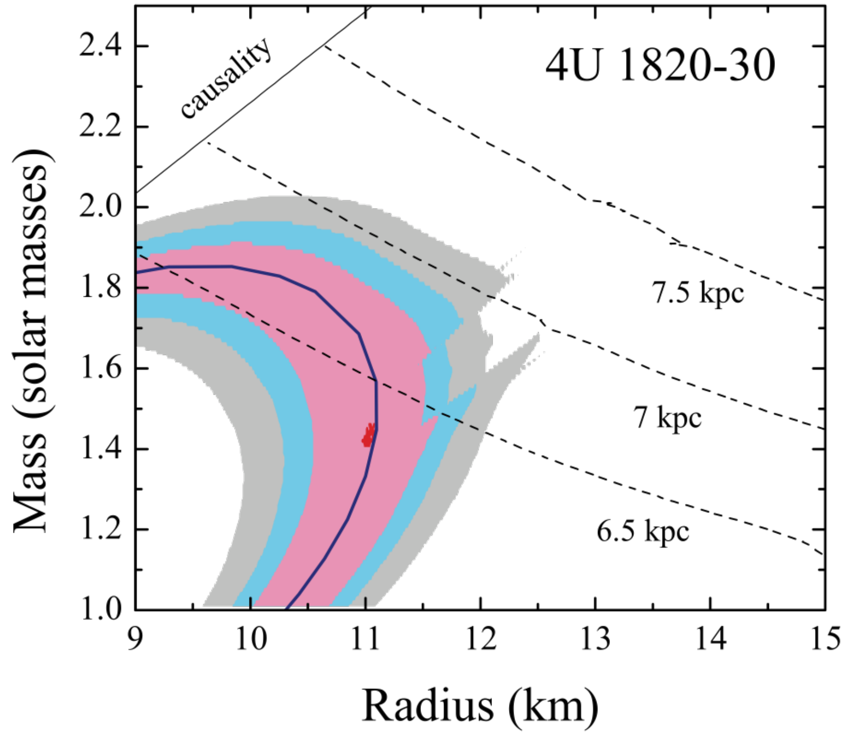


High persistent flux

Helium accreting NSs in systems 4U 1702-429 and 4U 1820-30

Direct cooling tail method. Result – χ^2 maps.



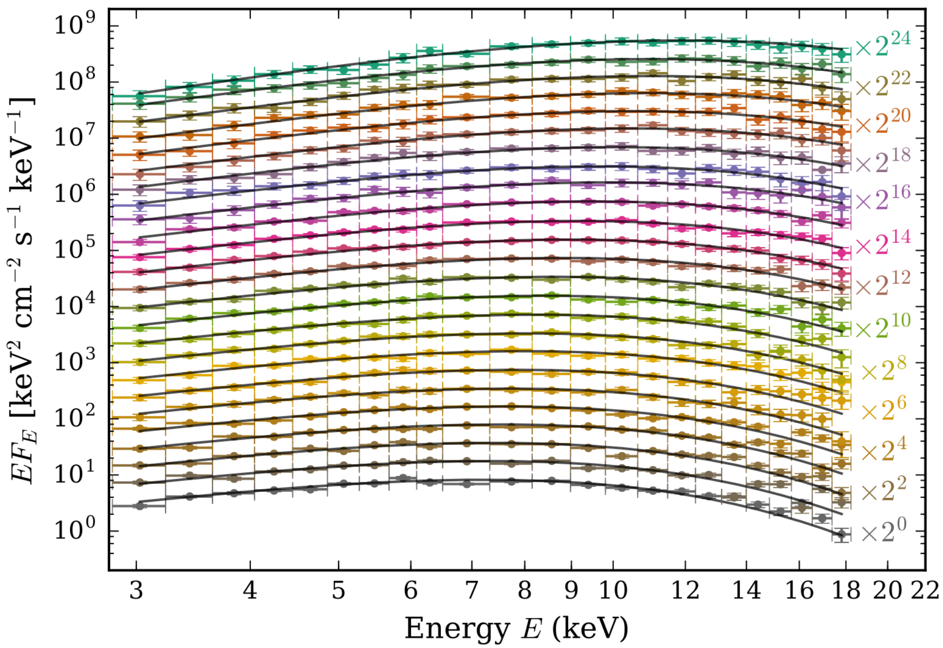


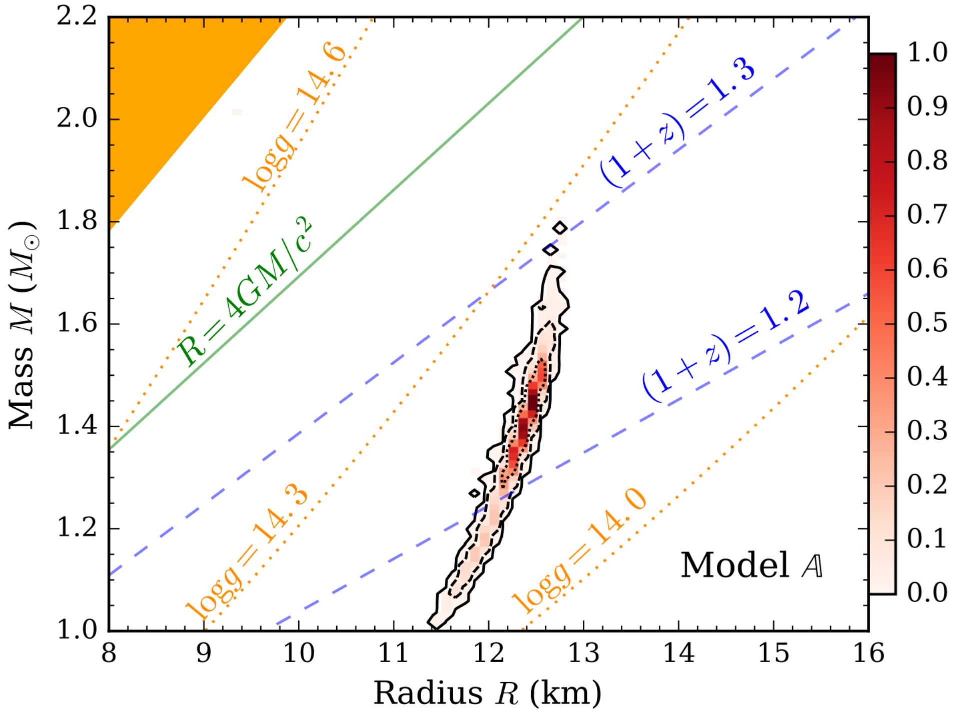
Helium accreting NS in system 4U 1702-429

Direct spectrum fitting method

Nättilä et al. 2017

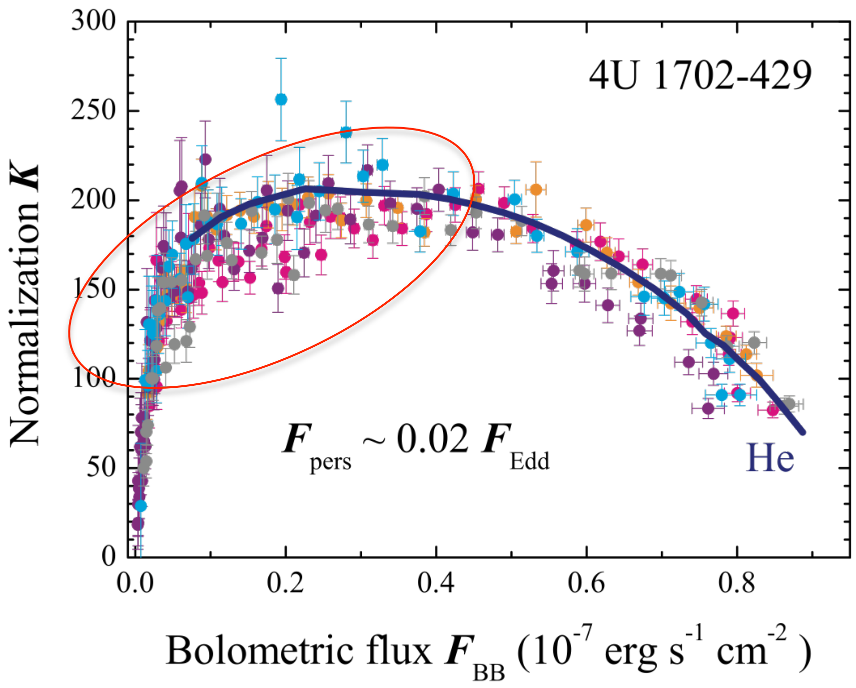
24 observed spectra were simultaneously fitted by model spectra of hot NS



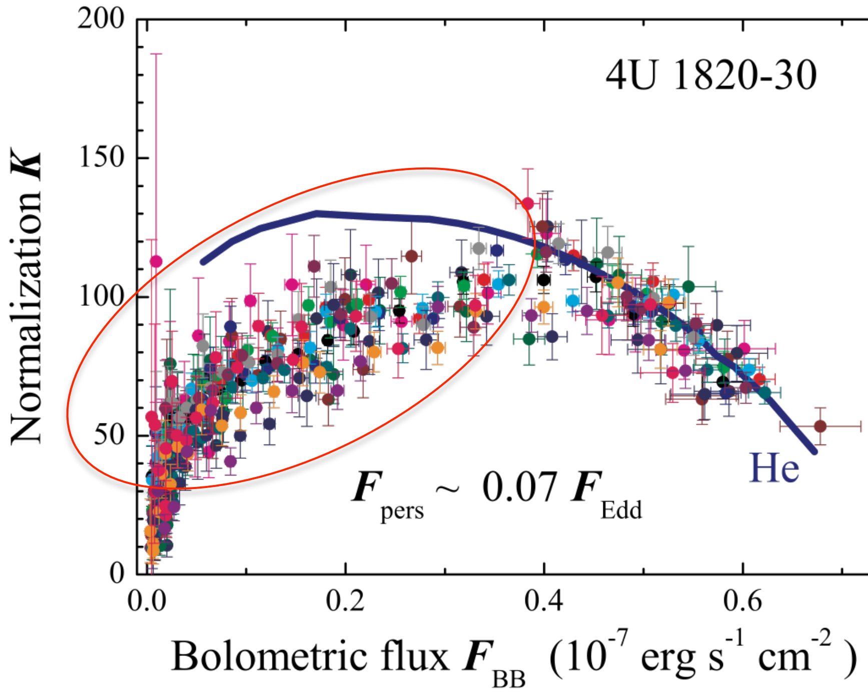


Comparison with observations

Deviation from theory depends on the persistent flux



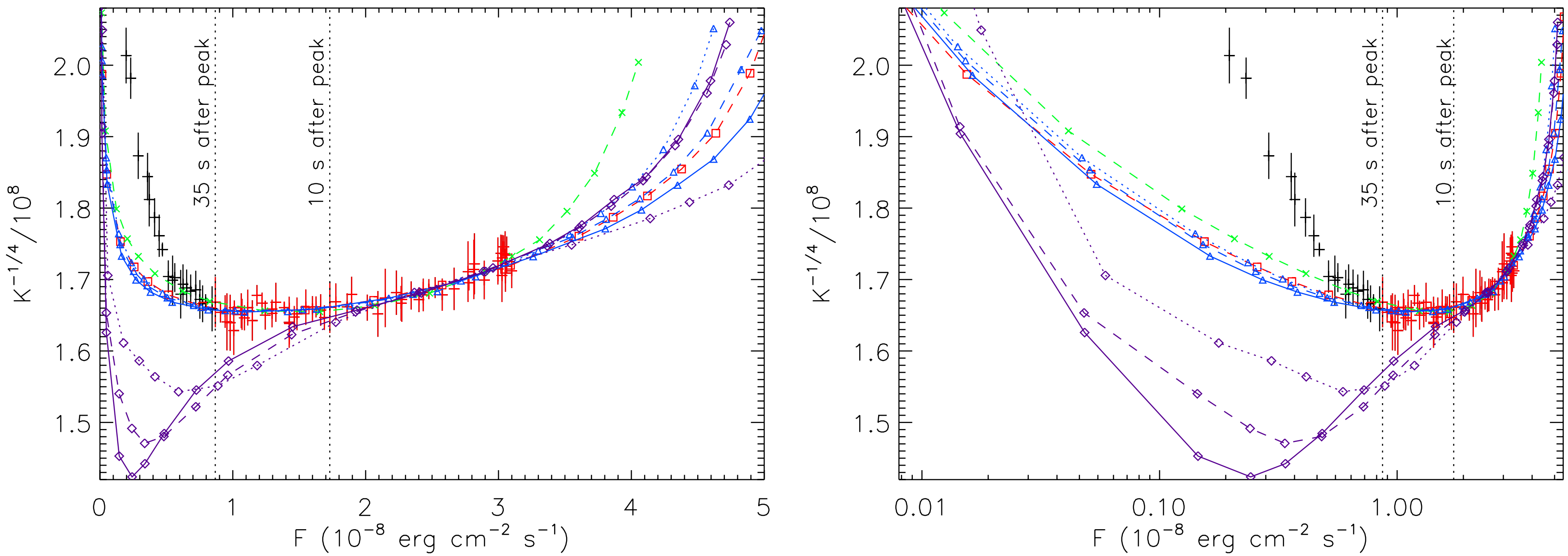
Low persistent flux



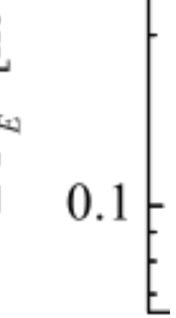
High persistent flux

“Clocked” burster GS 1826 - 24

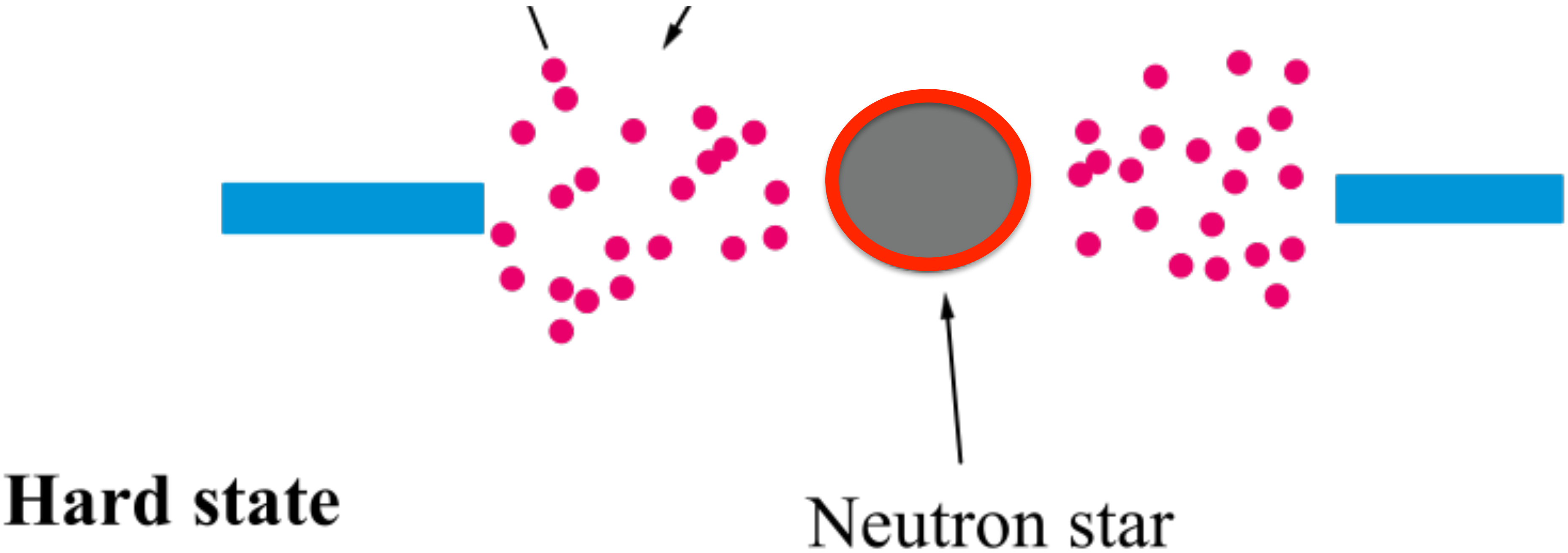
Its atmosphere has to have solar chemical composition (Heger et al. 2007). But the observed curve $K^{-1/4} - F_{BB}$ doesn’t show depression at $L \approx 0.1\, L_{Edd}$ typical for model curves computed for undisturbed atmospheres.



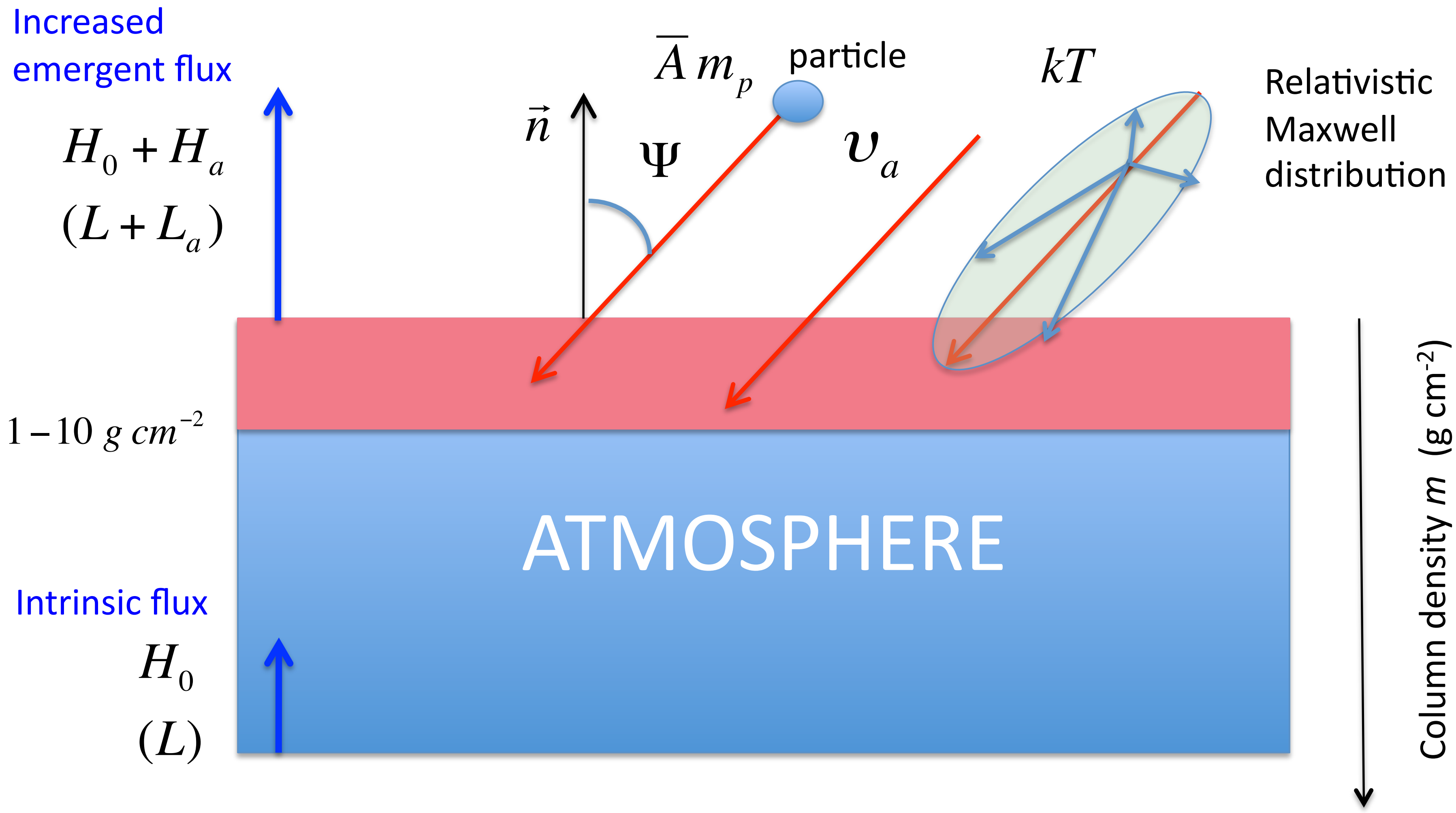
Figures from Zamfir et al. 2012



Possible solution: Accretion of hot plasma on the later burst phases



Accretion heated atmospheres



$\dot{m}_a(H_a, \bar{A}\, m_p, \upsilon_a, kT, \Psi)$ - local mass accretion rate, g s^{-1} cm^{-2}

Accretion heated atmospheres
Short history

Larkin (1960) - fast particle stopping in plasma

Zeldovich & Shakura (1969) – NS surface heated by fast particles

Alme & Wilson (1973) – the first numerical computations

Bildsten et al. (1992) - analytical description, heavy ions destruction

Turolla et al. (1994) – "hot" solutions (T up to 10^{11} K)
Zampieri et al. (1995) – extension of AW73 computations
Zane et al. (1998) – spectra of "hot" solutions
Zane et al. (2000) – magnetized NS atmospheres heated by particles

Deufel et al. (2001) – application to hard quiescent spectra of LMXBs

Accretion heated atmospheres

Method of computation

The approach and the code used for undisturbed hot NS model atmospheres computations was accepted (Suleimanov et al. 2012)

Additionally

- energy generation in the heated layers $$\frac{dH}{dm} \approx -\dot{m}_a \upsilon_a \frac{d\upsilon_a}{dm}$$
- ram pressure force $$g_{ram} = \frac{dP_{ram}}{dm} \approx -\dot{m}_a \frac{d\upsilon_a}{dm}$$
- electron thermal conductivity (insignificant) $$H_C \approx k_C T^{5/2} \frac{dT}{dm}, \qquad \frac{dH_C}{dm} \neq 0$$

$$\frac{d\upsilon_a}{dm} \propto \upsilon_a^{-3} \rho^{-1} \frac{Z^2}{A}$$

Accretion heated atmospheres

Adopted parameters

Neutron star: $M = 1.67\ \mathrm{M}_\odot, \quad R = 12\ km, \quad \ell = L / L_{Edd}$

$$\upsilon_{ff} = \left(\frac{2GM}{R}\right)^{1/2} = 1.8 \times 10^{10}\, cm/s \approx\ 0.6\, c$$

$$kT_{vir} = \frac{GM\bar{A}m_p}{3R} \approx \bar{A}\, 61\ MeV\ (6.7 \times 10^{11}\, K)$$

Accretion flow: $\ell_a = L_a / L_{Edd} \qquad \upsilon_a = \eta\, \upsilon_{ff}, \quad \eta < 1$

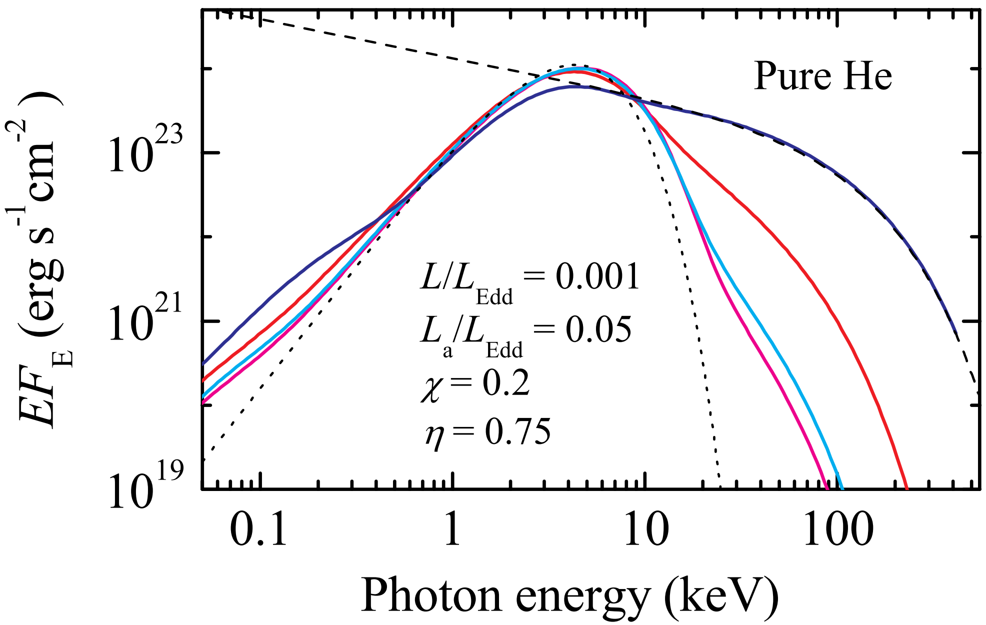
$$kT = \chi\, kT_{vir}, \quad \chi < 1 \qquad \Psi$$

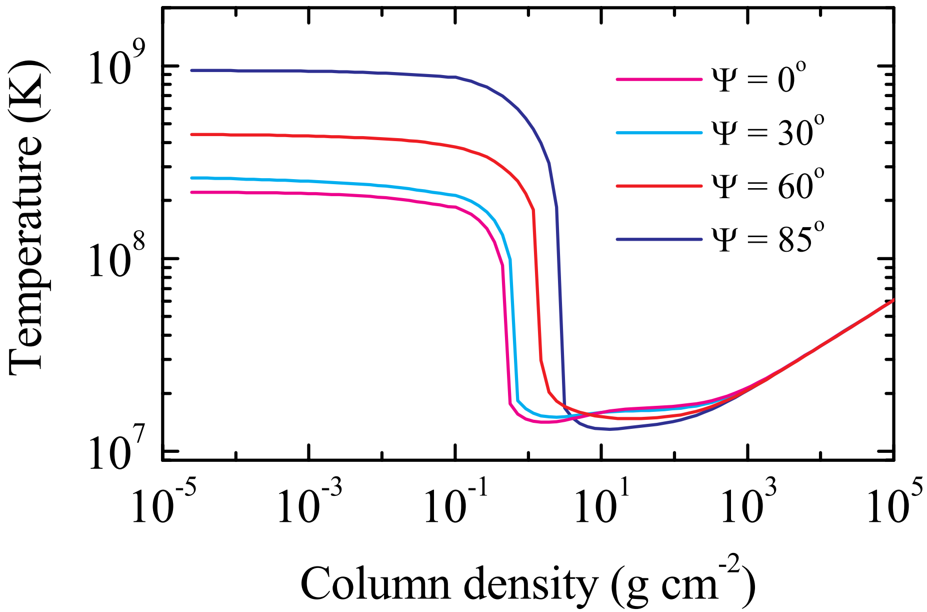
$\bar{A} = 1$ - pure hydrogen $\qquad \bar{A} = 4$ - pure helium

$\bar{A} \approx 1.3$ - solar hydrogen/helium mix

Low luminosity accretion heated atmospheres with various impact angles Ψ

$$L = 0.001\, L_{Edd} \quad L_a = 0.05\, L_{Edd} \quad \chi = 0.2 \quad \eta = 0.75$$





Blackbody and exponential cutoff power law model are also shown

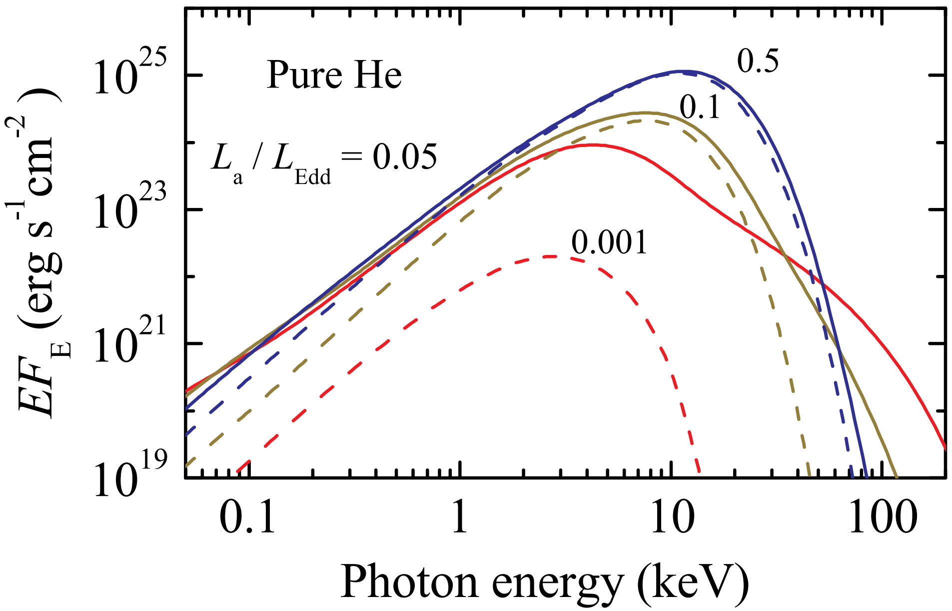
$$E^{-\Gamma} \exp(-E / E_{cut})$$

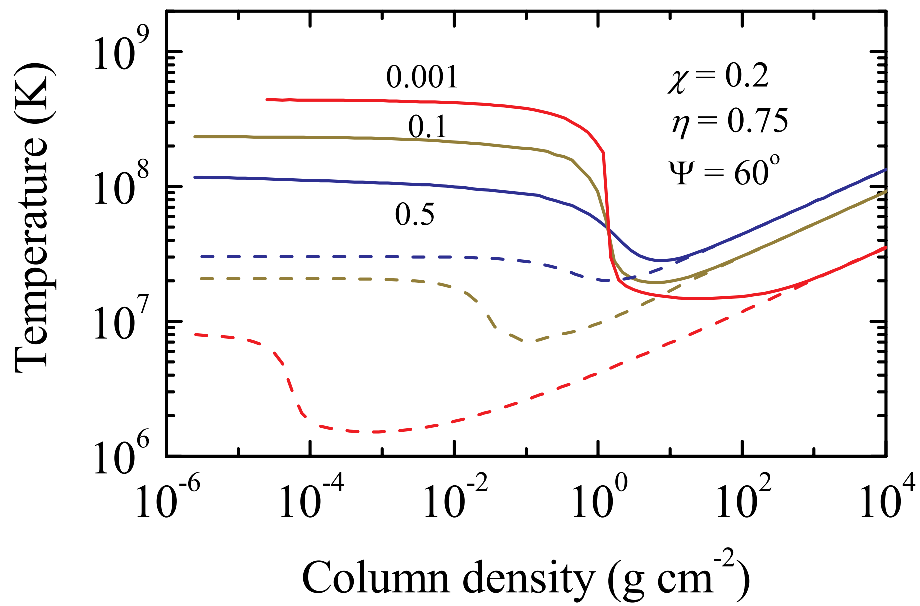
$\Gamma = 2.45 \quad E_{cut} = 85\ keV$ and $T_{BB} = 1.1\ keV$

Helium atmospheres heated by α- particles for different intrinsic luminosities.

All the accretion parameters are fixed..

$$L_a = 0.05\,L_{Edd} \quad \eta = 0.75 \quad \chi = 0.2 \quad \Psi = 60°$$





Dashed curves correspond to the undisturbed atmospheres

Solid curves correspond to the heated atmospheres

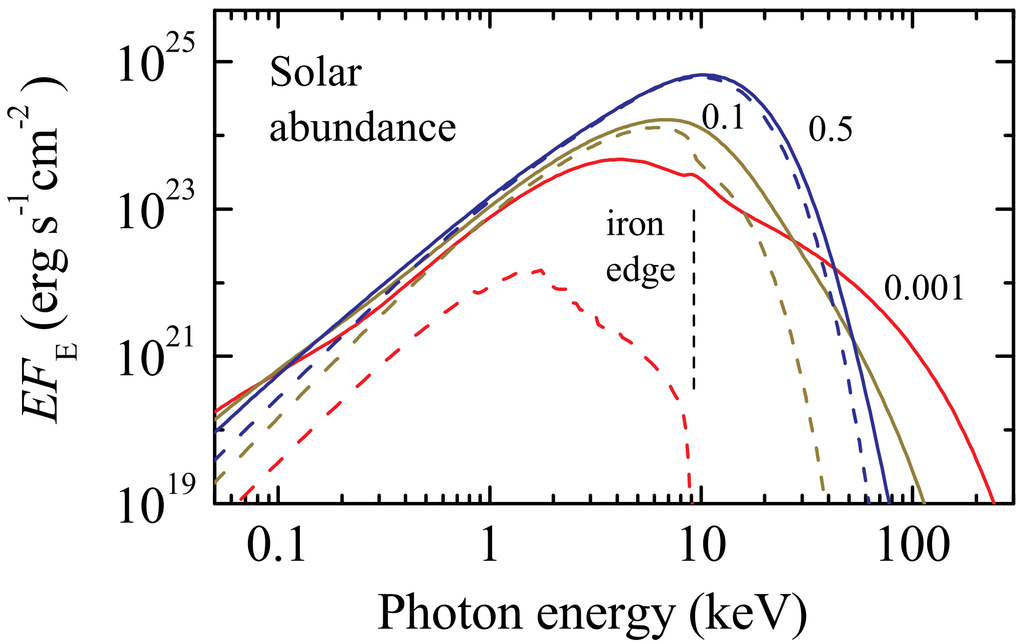
Accretion heated atmospheres with solar composition.

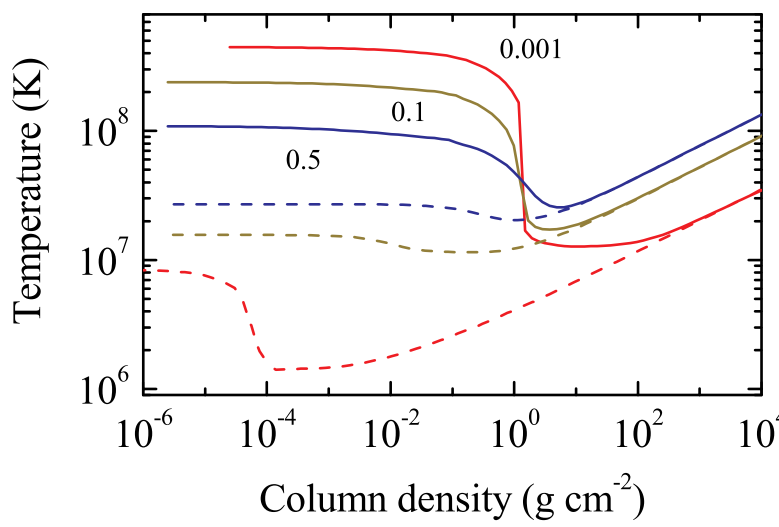
All the accretion parameters are fixed.

Iron absorption edge disappears

in the spectra of the heated atmospheres

$$L_a = 0.05\, L_{Edd} \quad \eta = 0.75 \quad \chi = 0.3 \quad \Psi = 60^\circ$$





Dashed curves correspond to the undisturbed atmospheres

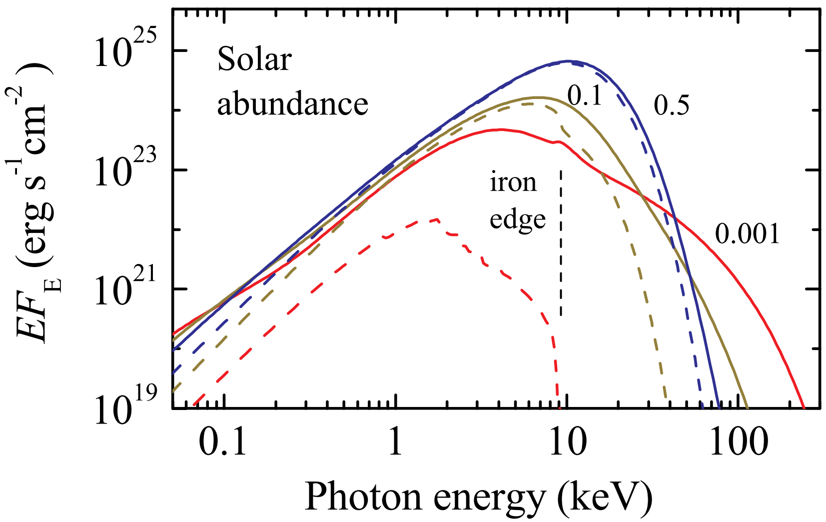
Solid curves correspond to the heated atmospheres

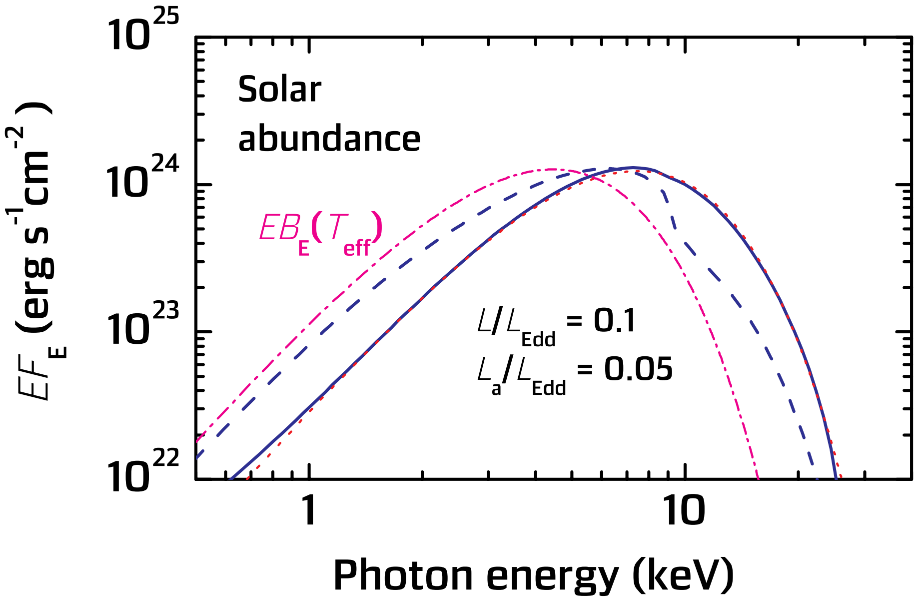
Accretion heated helium atmospheres. Fixed parameters.

How the "pseudo-observed" spectra were computed

$$\boxed{F_{"obs"} = F_{l+la} - F_{0.001+la}}$$

$$l = L / L_{Edd} \qquad l_a = L_a / L_{Edd}$$

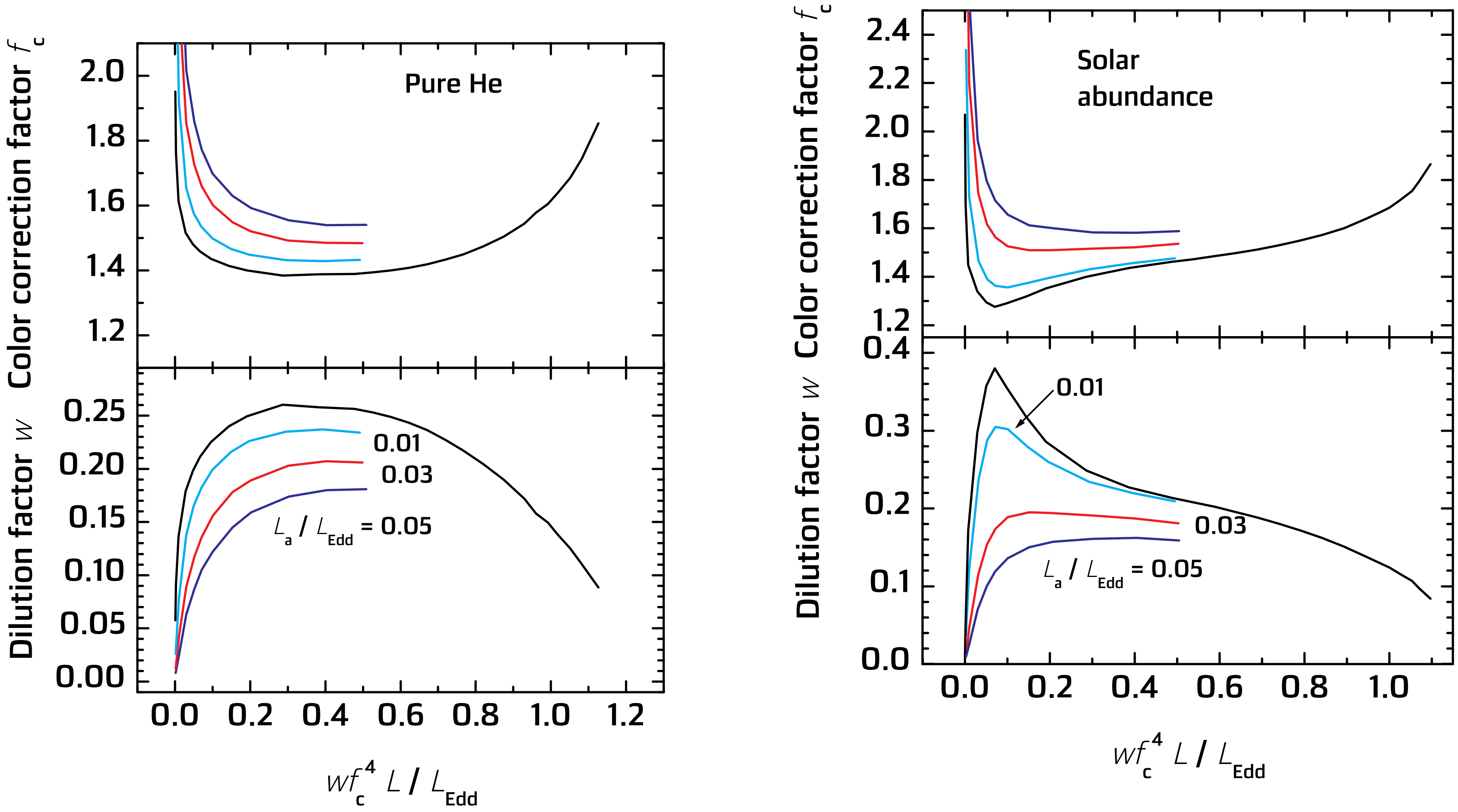




$$L_a = 0.05\, L_{Edd} \qquad \eta = 0.75 \qquad \chi = 0.2 \qquad \Psi = 60^\circ$$

Model curves for the heated atmospheres

Color correction factors f_C are larger, and dilution factors w are smaller. Value of deviations is proportional to the accretion rate.



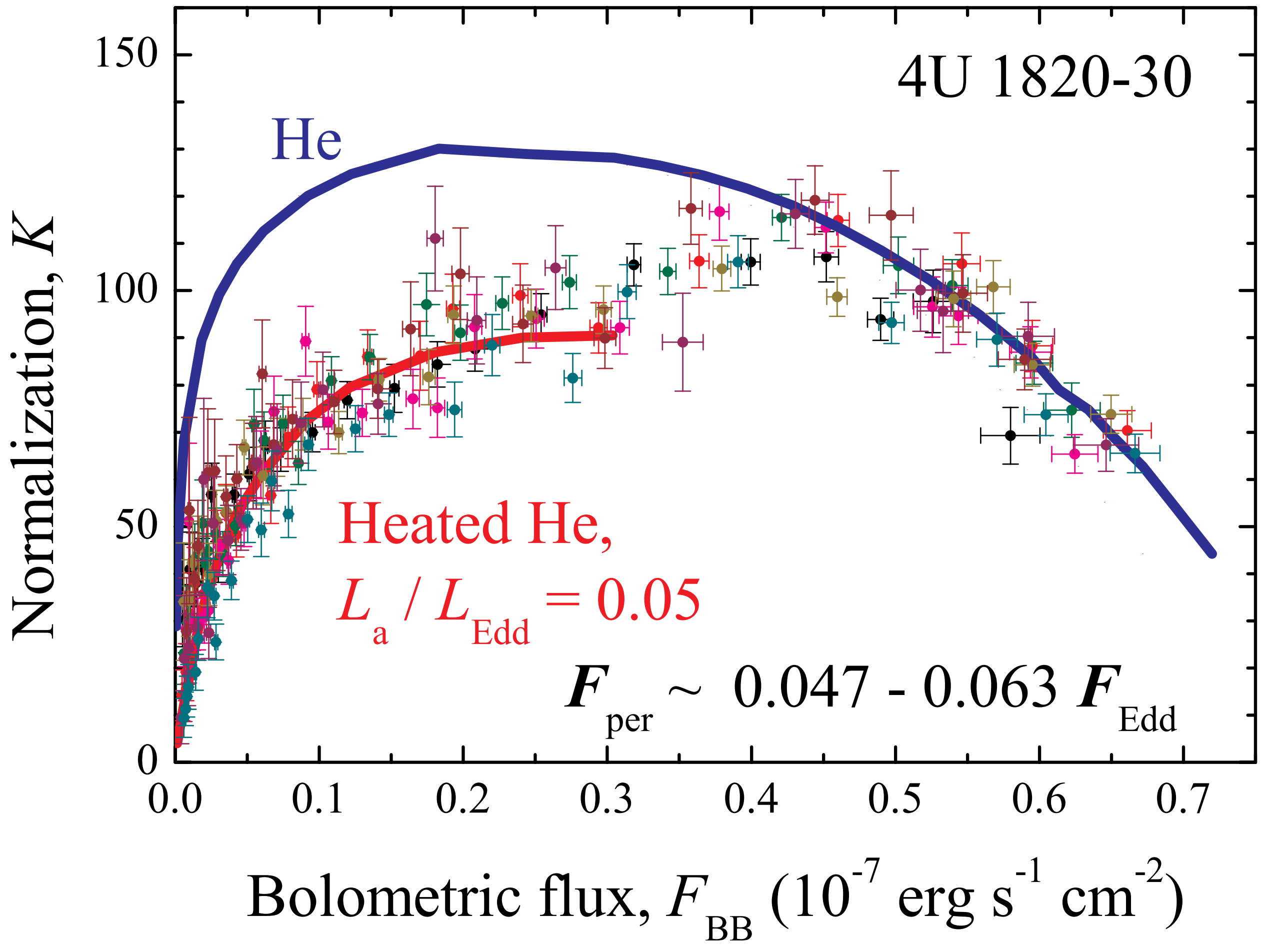
$$\eta = 0.75 \quad \chi = 0.2 \quad \Psi = 60^\circ$$

Burster in ultracompact system 4U 1820 -- 30

Both model curves have the same fitting parameters

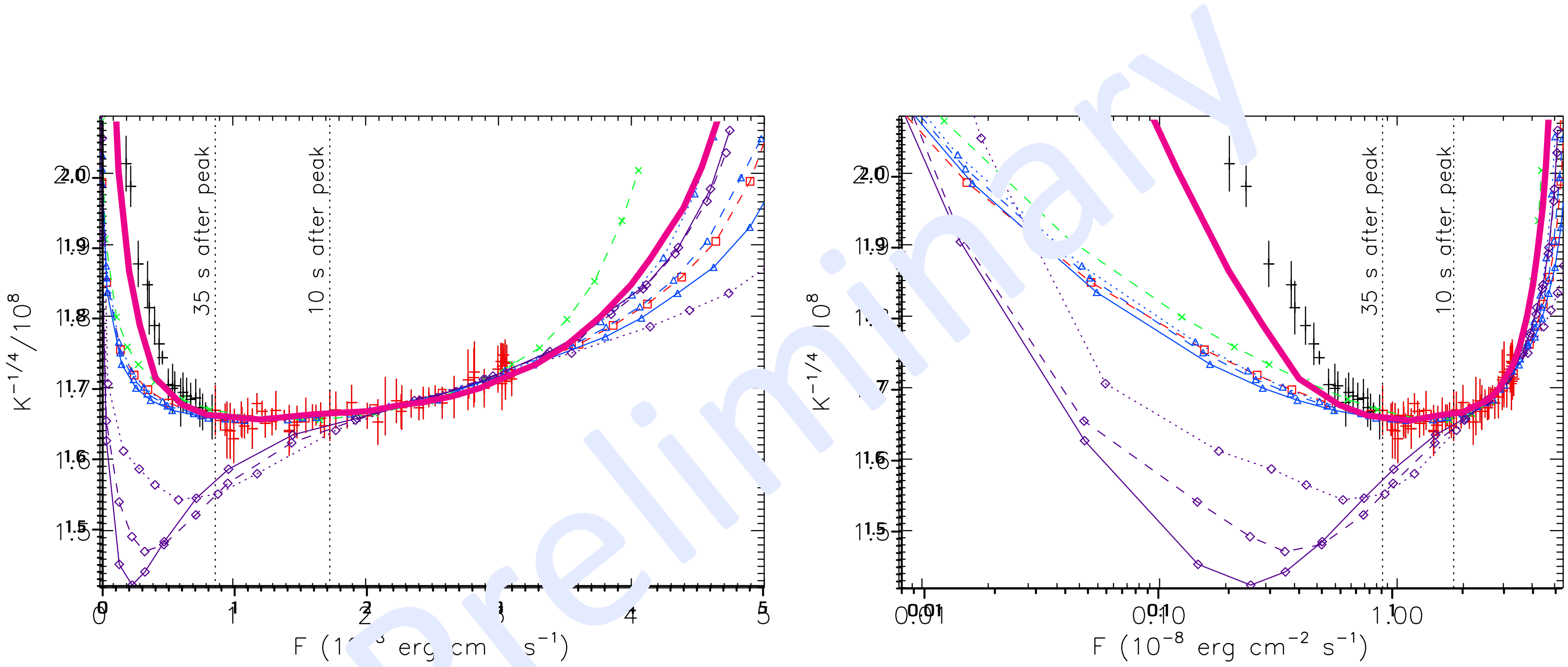
$$F_{Edd} = 0.6\,(10^{-7}\ erg\ s^{-1}cm^{-2})$$

$$\Omega = R^2(1+z)^2/D^2 = 500\ km^2/(10\,kpc)^2$$



“Clocked” burster GS 1826 - 24

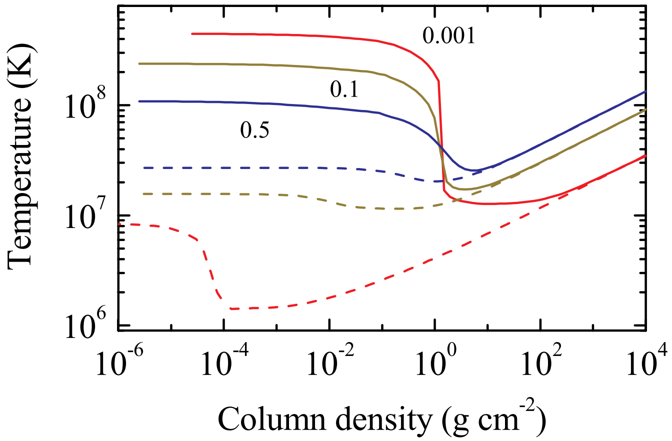
But the observed curve better fitted with the “heated” model curve



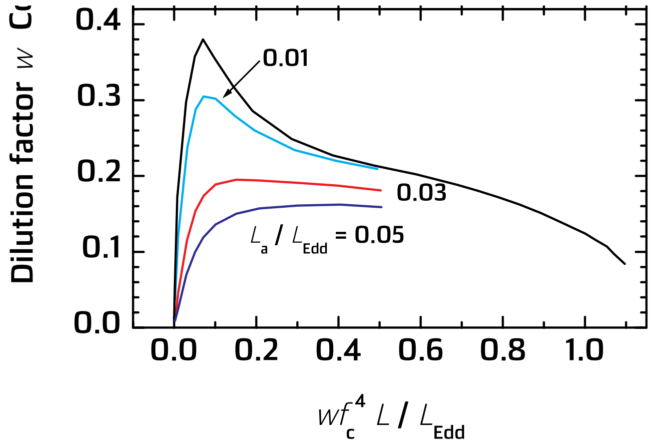
Preliminary

Figures from Zamfir et al. 2012

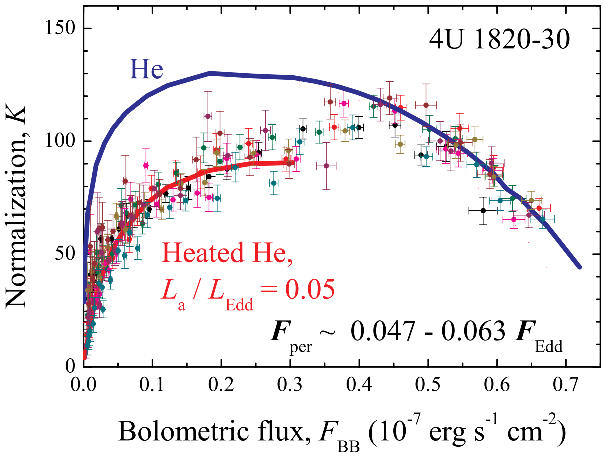
Conclusions



A method for computation of NS atmospheres heated by fast particles was developed.



Color correction factors f_C are large for heated atmospheres, and dilution factors w are smaller.



Model curves $w - wf_c^4 L/L_{Edd}$ are well fitting the observed curves $K - F_{BB}$ at the later phases of the X-ray bursts.