Atmospheres of X-ray bursting neutron stars

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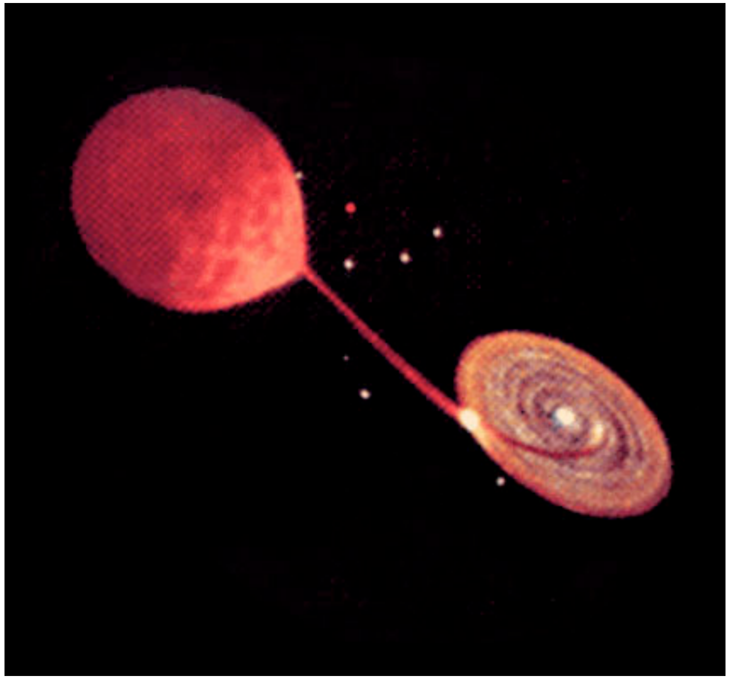
40 years of X-ray bursts: Extreme explosions in dense environments
June 18, 2015, ESA/ESAC Madrid, Spain

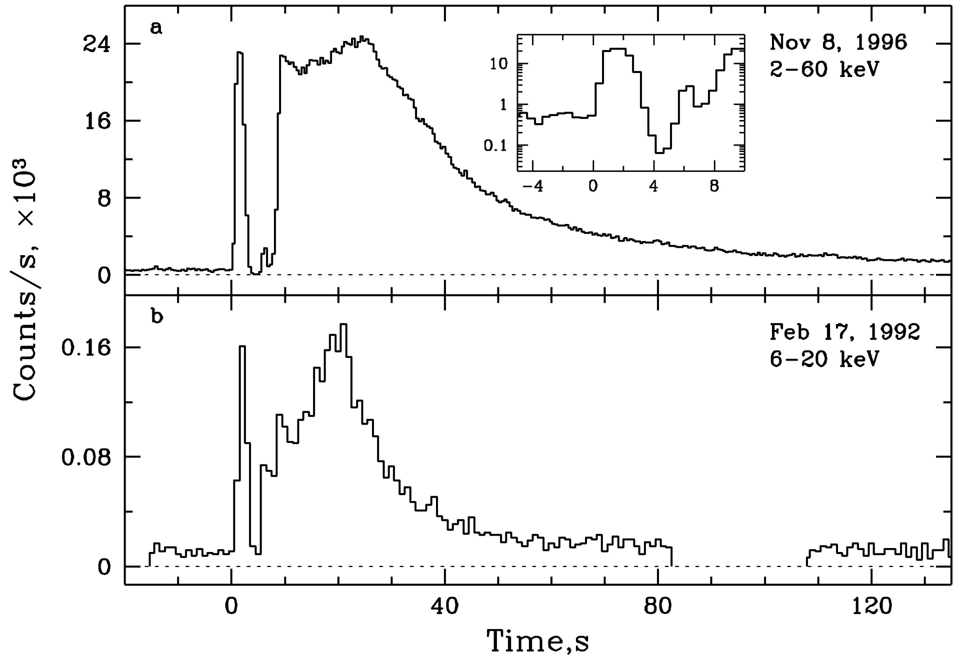
X-ray bursting neutron stars

- 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)
- Burst duration ~10 - 1000 sec

Ideal sources for NS masses and radii investigations (important for EOS!!!)



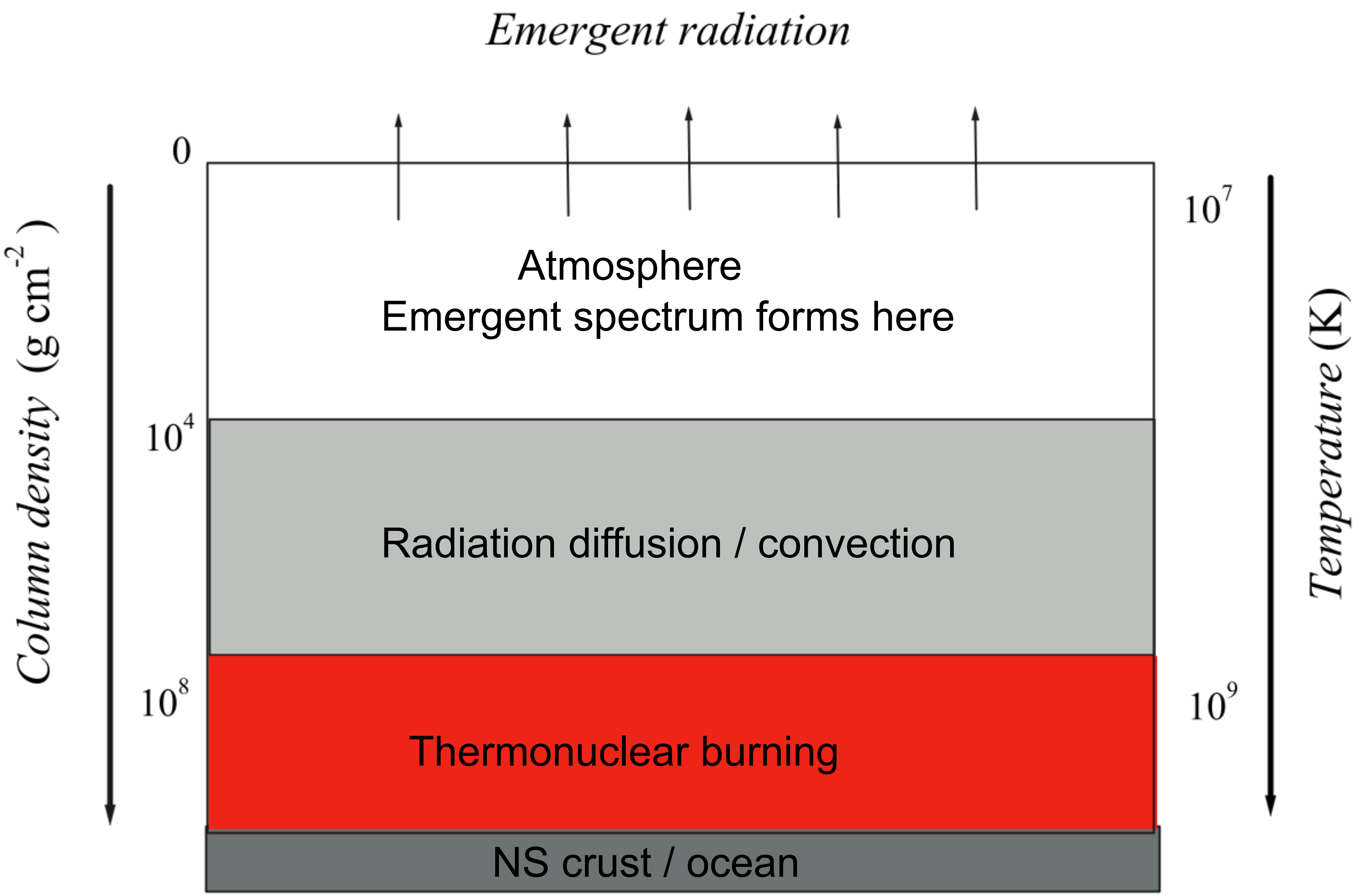
Low Mass X-ray Binary (artist veiw)



4U 1724-307 in Terzan 2

Figure from Molkov et al (2000)

Plane parallel model of the bursting layer



Atmosphere

is a thin plasma envelope between a source of energy and the open space. Energy transfers through the envelope and escapes through the open boundary.

Model atmosphere

is a result of a self consistent solution of all the equations describing all the basic physical laws:

- mass conservation,
- momentum conservation
- energy conservation
- energy transport
- plasma equation of state

Input parameters

Surface gravity $$g = \frac{GM}{R^2}(1+z)$$

Bolometric flux $$F = \sigma_{SB} T_{eff}^4$$

Effective temperature T_{eff}

or

Relative luminosity $l = F/F_{Edd}$

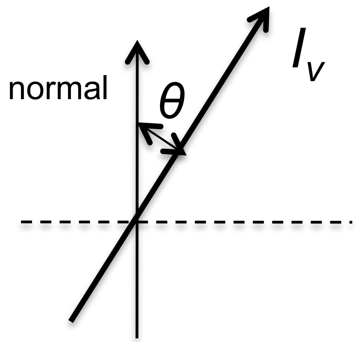
Chemical composition

Accretion – composition of the accreted matter

Low accretion – gravitational separation,
the lightest element domination

Powerful bursts – burning ashe ?

Basic equations



Hydrostatic equilibrium $$\frac{dP}{dm} = g - g_{rad}$$

Radiation transfer $$\mu \frac{\partial I_\nu}{\partial m} = (k_\nu + \sigma_e)(I_\nu - S_\nu)$$

$$\mu = \cos\theta$$

Radiation equilibrium $$\int k_\nu (J_\nu - B_\nu) d\nu - \boxed{\sigma_e \int \frac{4kT - h\nu}{m_e c^2} J_\nu \, d\nu} \approx 0$$

Equation of state $$P = NkT$$

-pressure ionization effects are included
- LTE approximation for number densities

Column density ***m*** – independent variable

$$dm = -\rho\, dz$$

Opacity

Opacity coefficient - inverted column density of the photon free path

$$k = m_{fp}^{-1} \qquad [k] = cm^2 g^{-1} \qquad \tau \approx k\, m$$

Two physically different processes

Electron scattering - photon changes direction only (Thomson, coherent)

$$\sigma_e = \sigma_T \frac{N_e}{\rho} \approx 0.2(1+X)$$ X is hydrogen mass fraction

Compton scattering – energy and momentum of photon are changed

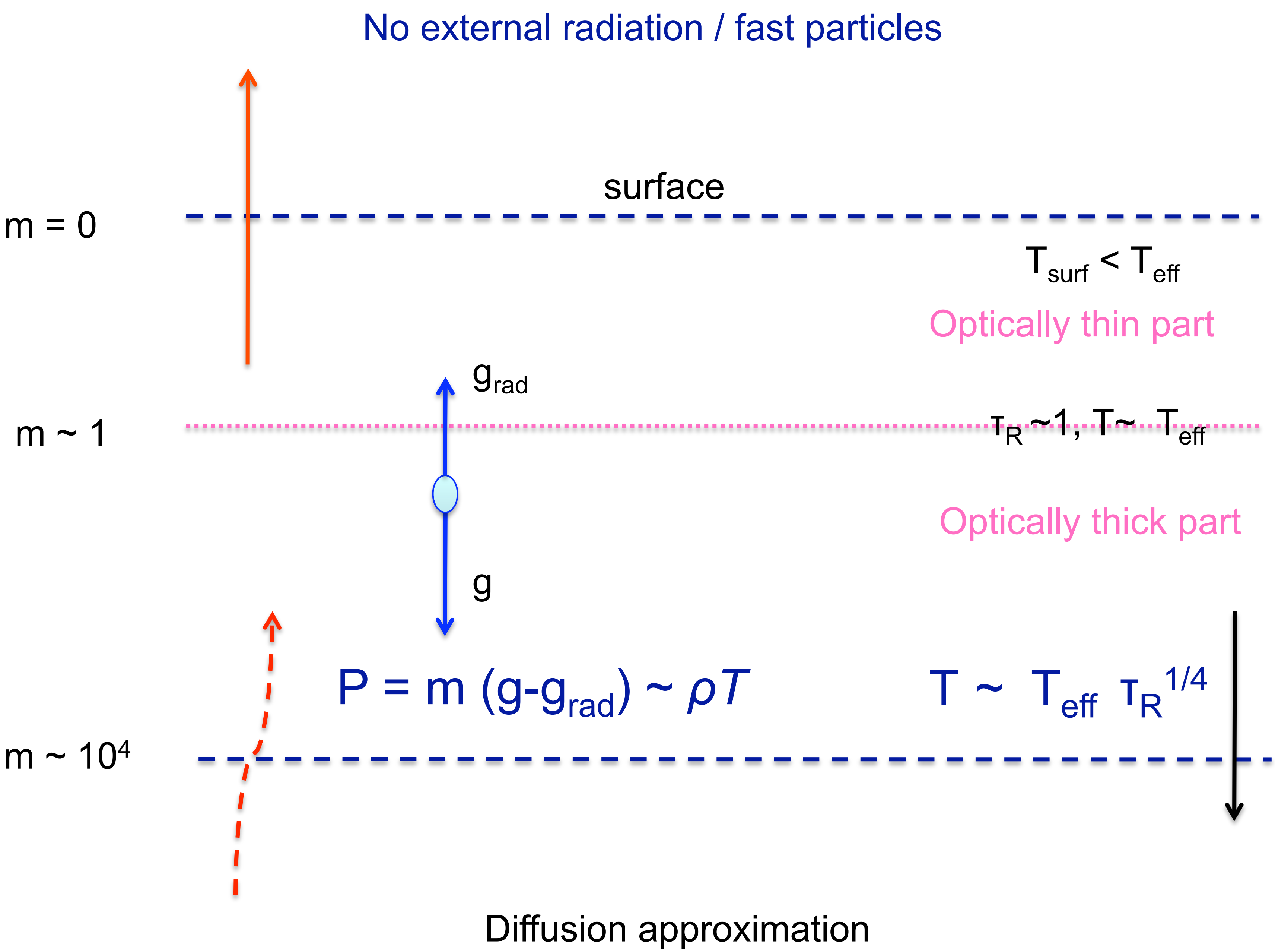
$$\sigma_e = \sigma_e(\nu, T)$$

True absorption opacity – interaction with two particles (ion and electron)

Photon disappears

$$k_\nu \approx \sigma_\nu \frac{N_e N^+}{\rho} \propto \nu^{-3} \rho T^{-1/2}$$

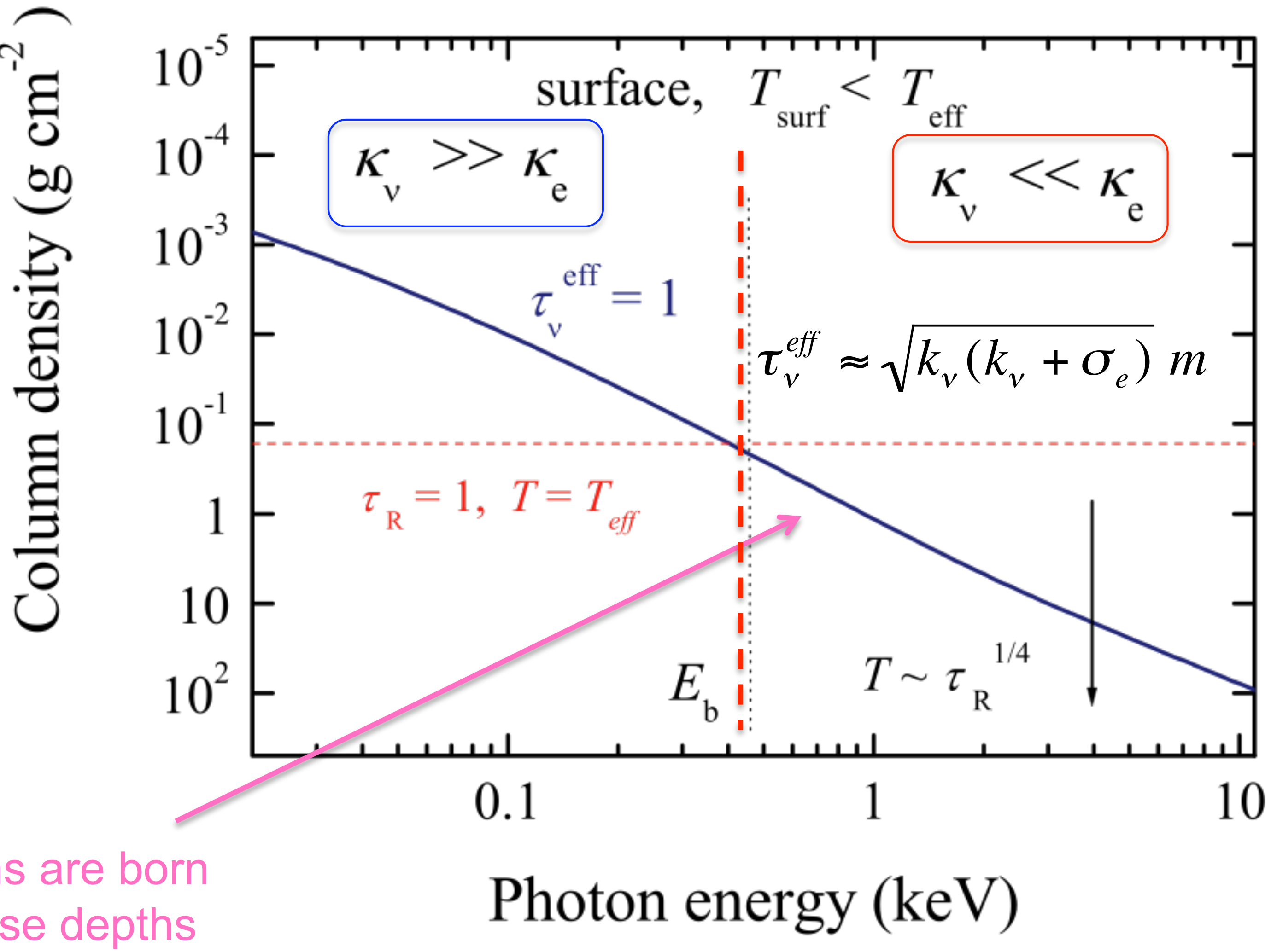
free-free opacity



No external radiation / fast particles
surface
m = 0
$T_{surf} < T_{eff}$
Optically thin part
g_{rad}
m ~ 1
$\tau_R \sim 1,\ T \sim\ T_{eff}$
Optically thick part
g
$P = m\,(g - g_{rad}) \sim \rho T$
$T \sim\ T_{eff}\ \tau_R^{1/4}$
m ~ 10^4
Diffusion approximation

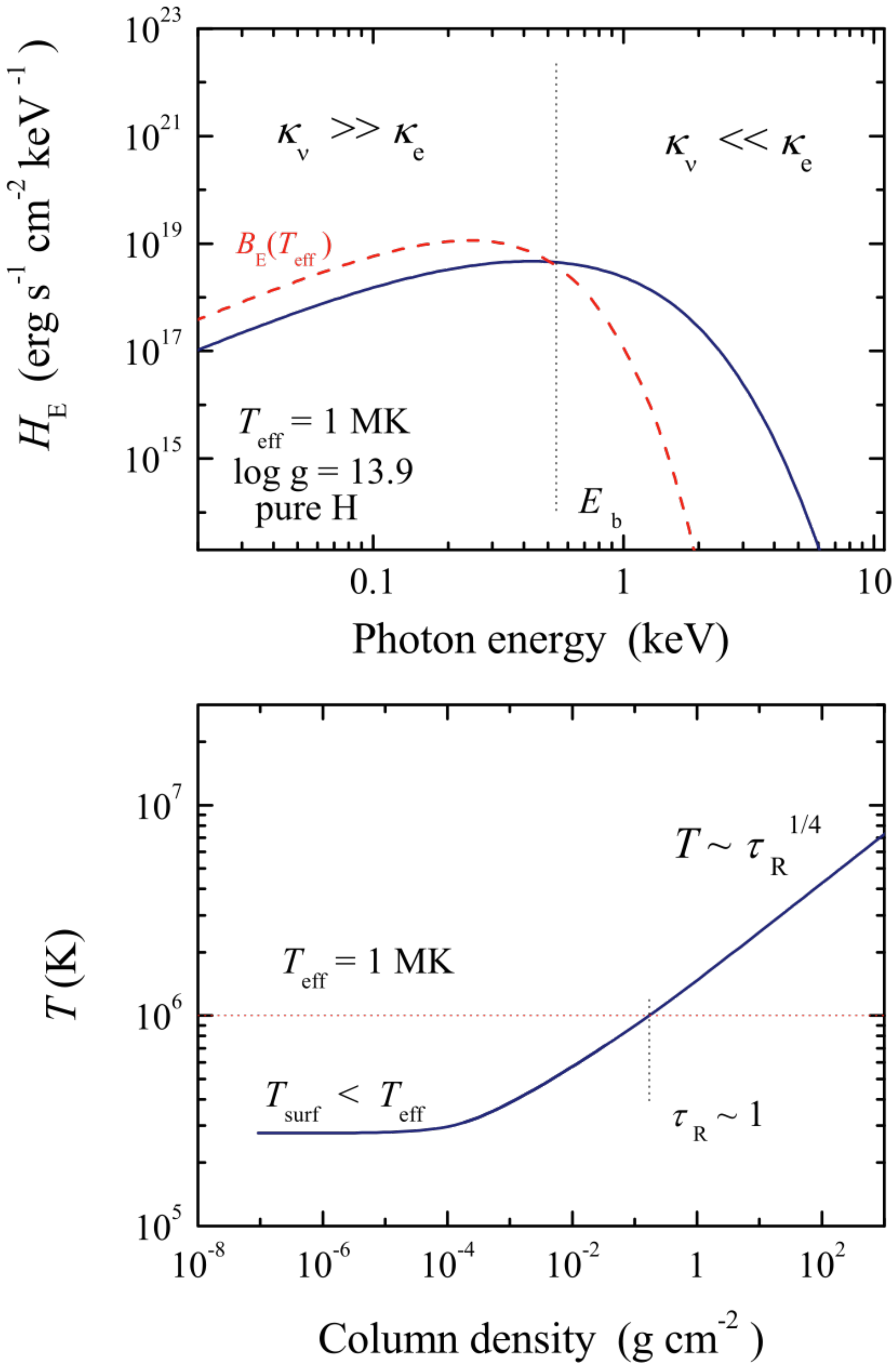
Spectrum formation

low T_{eff} atmospheres



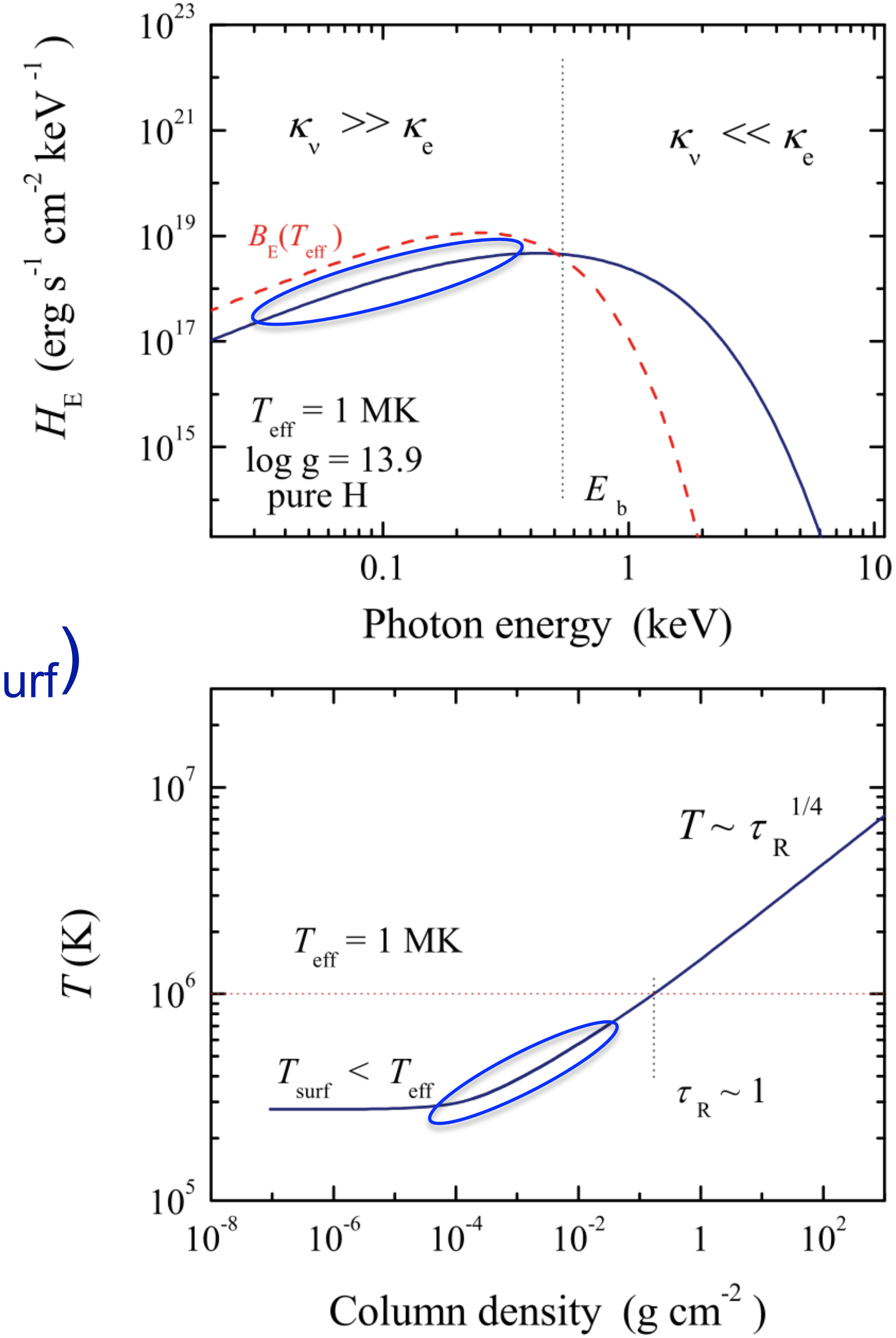
Photons are born at these depths

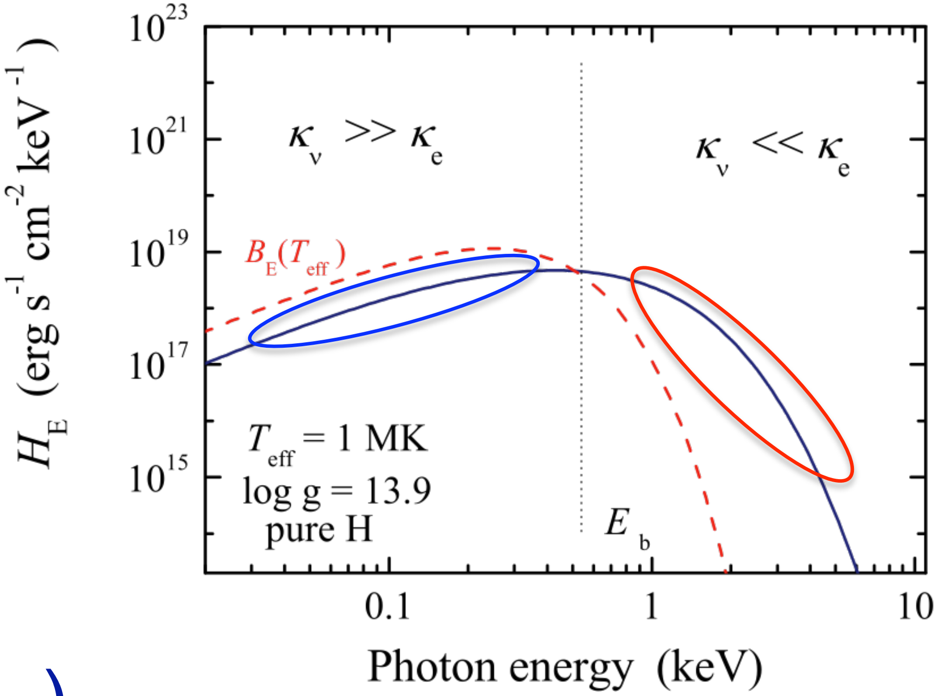
Two qualitatively different spectral bands



$\kappa_\nu >> \kappa_e$
$\kappa_\nu << \kappa_e$
$B_E(T_{eff})$
T_{eff} = 1 MK
log g = 13.9
pure H
E_b
H_E (erg s^{-1} cm^{-2} keV^{-1})
Photon energy (keV)
$T \sim \tau_R^{1/4}$
T_{eff} = 1 MK
$T_{surf} < T_{eff}$
$\tau_R \sim 1$
T (K)
Column density (g cm^{-2})

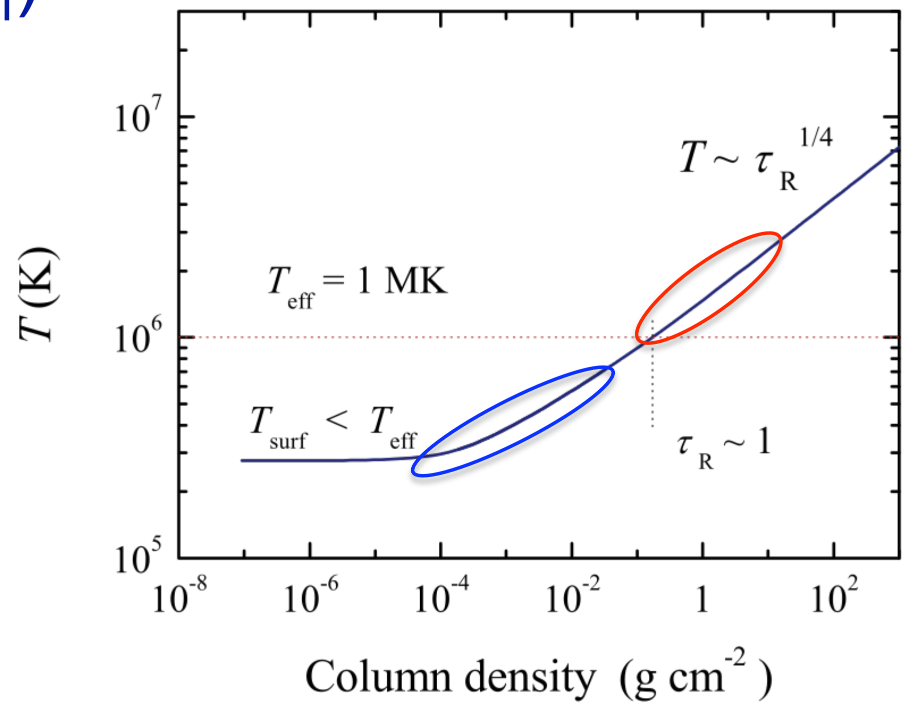
$F_\nu \approx B_\nu(T_{surf})$





$F_\nu \approx B_\nu(\mathrm{T_{surf}})$

$F_\nu \approx w_\nu B_\nu(\mathrm{T>T_{eff}})$



$$w_\nu \approx \sqrt{\frac{k_\nu}{k_\nu + \sigma_e}}$$

Spectrum formation
high T_{eff} atmospheres

Compton scattering
Is important !!!

$$F_\nu \approx w\, B_\nu(T_c)$$

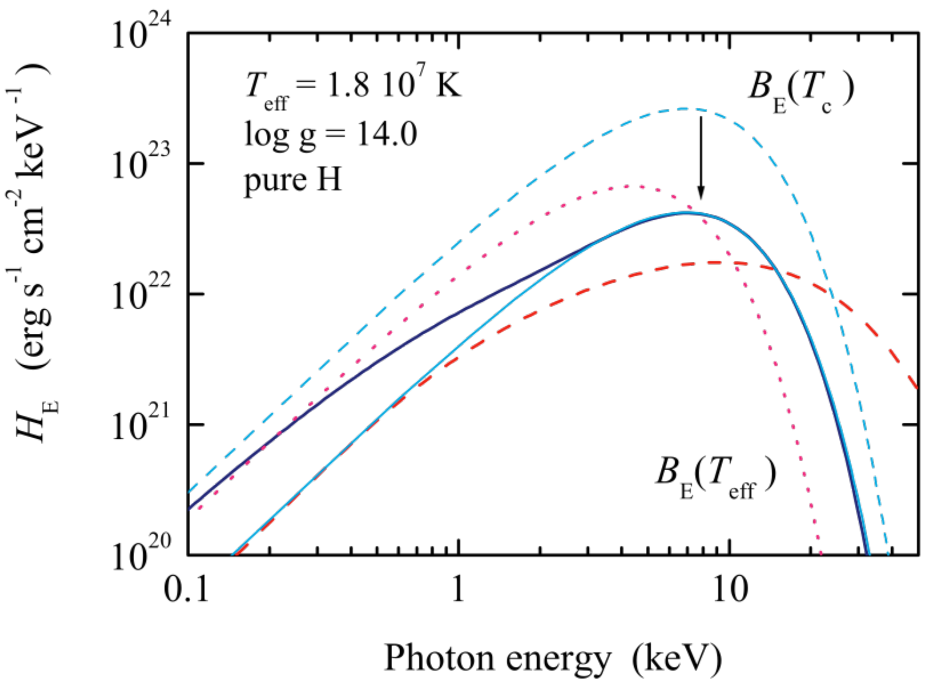
$T_c = f_c T_{eff}$ color temperature

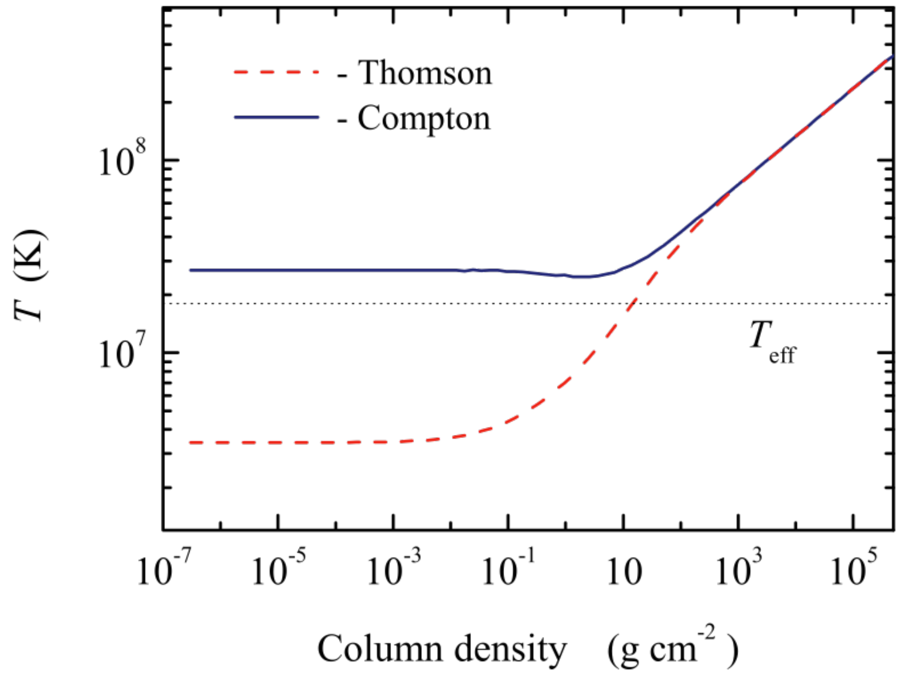
$f_c > 1$ color correction factor

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

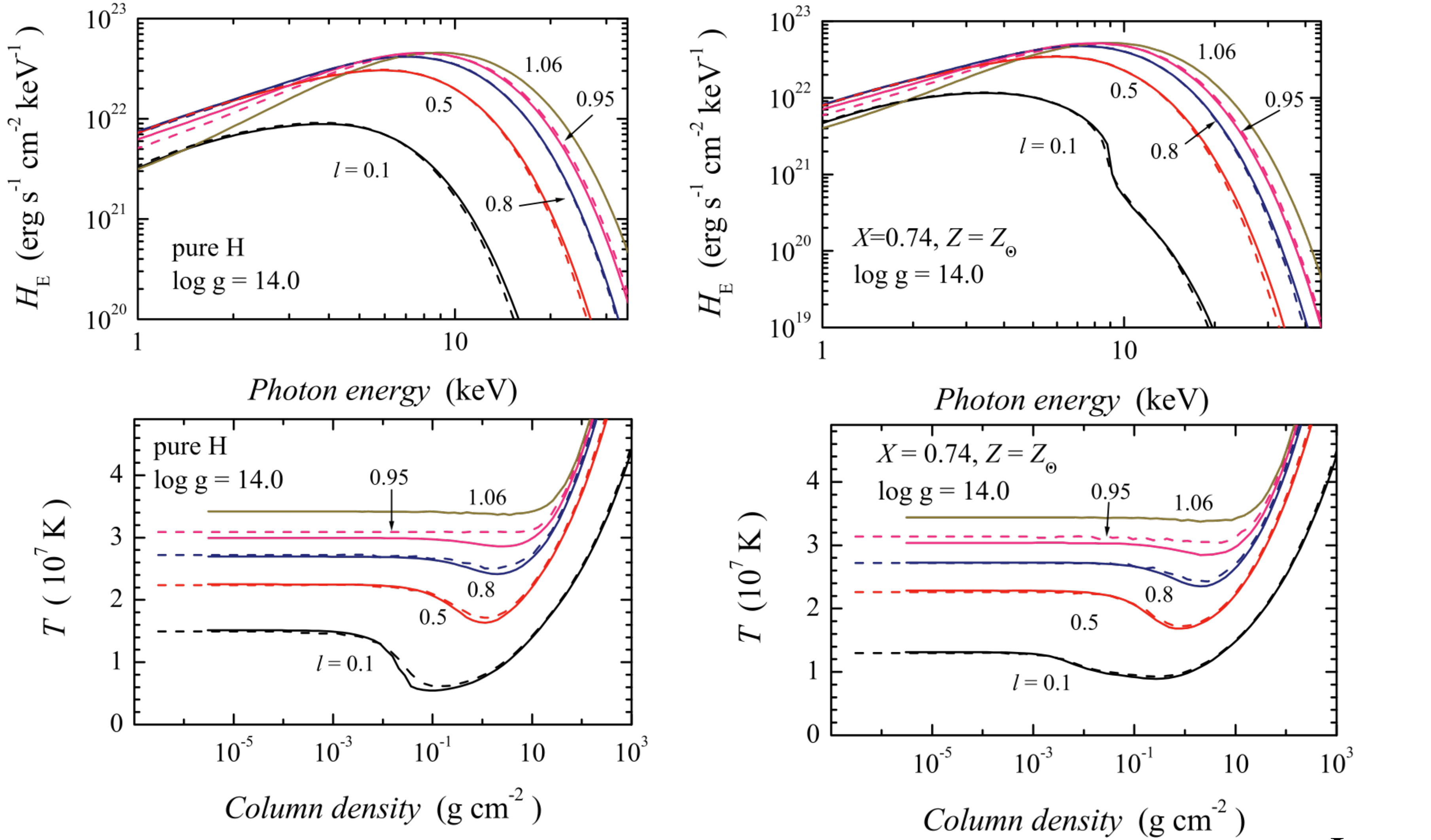
$$\boxed{F_\nu^{obs} \approx B_\nu(T_{BB})K = B_\nu(T_{BB})\frac{R^2(1+z)^2}{f_c^4 D^2}}$$

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





Set of accurate atmosphere models.
Comparison with the code employing Kompaneets operator



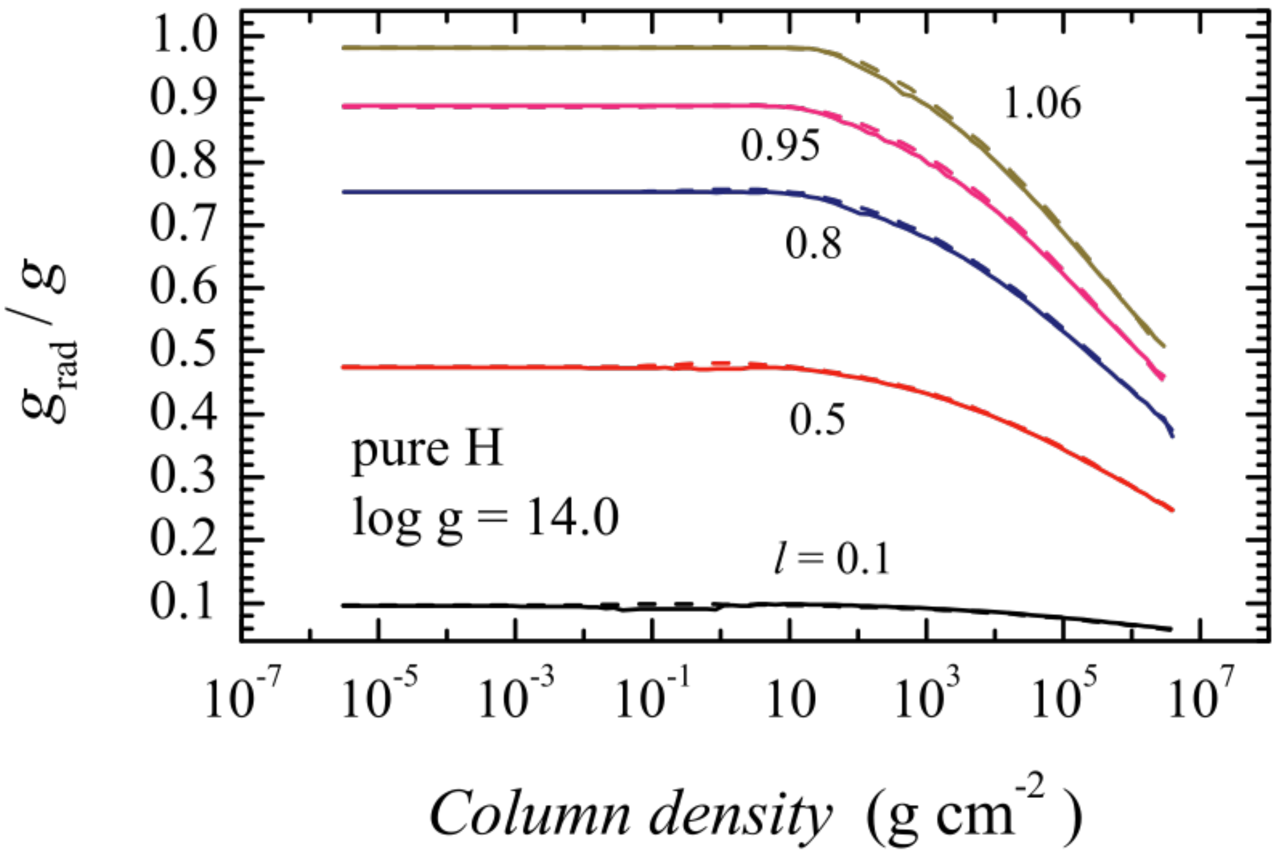
Models with larger ("super Eddington") luminosities are possible

$$l = \frac{L}{L_{Edd}}$$

$$L_{Edd} = \frac{cGM}{0.2(1+X)}(1+z)$$

Radiative acceleration.

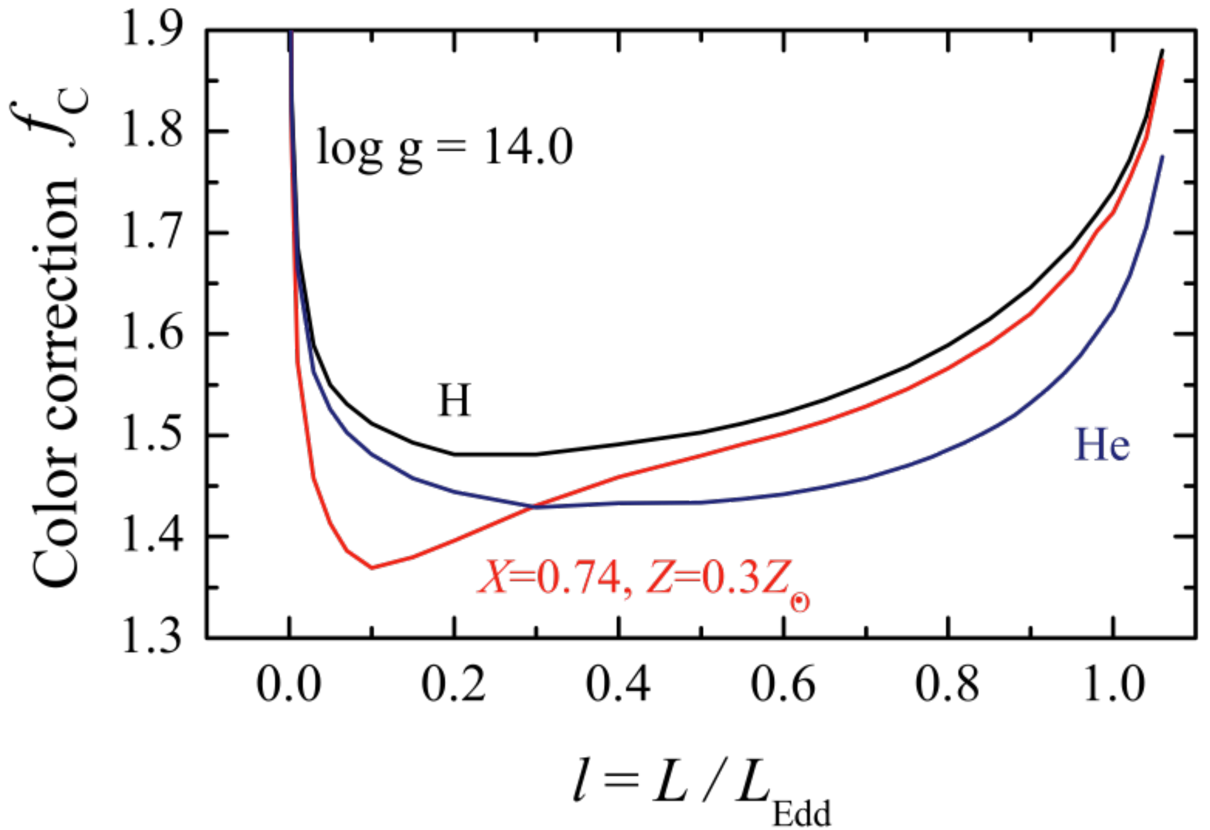
Klein-Nishina reduction in work



$$\sigma_e(T) \approx 0.2(1+X)\left(1+\left(\frac{kT}{39.4\ keV}\right)^{0.976}\right)^{-1}$$ Improved Paczynski's approximation

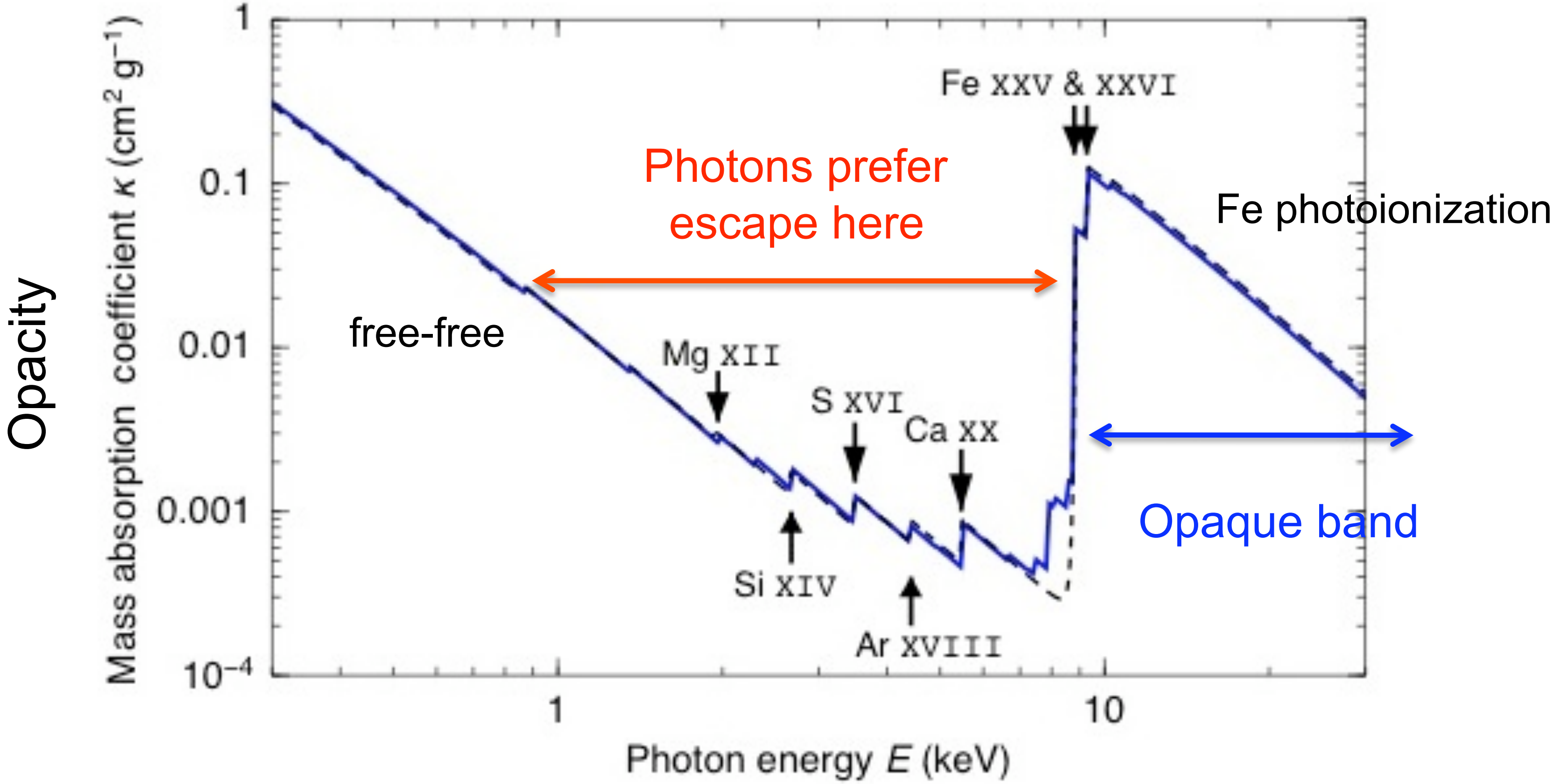
Used approximation $$g_{rad} = \sigma_e(T)\,\frac{\sigma_{SB} T_{eff}^4}{c}$$

Results of color correction f_c calculations in energy range 3-20 keV



$P = m\,(g - g_{rad}) \sim \rho T \longrightarrow \rho,\ k_\nu \downarrow \longrightarrow$ Hard photons are born in the deeper hotter layers

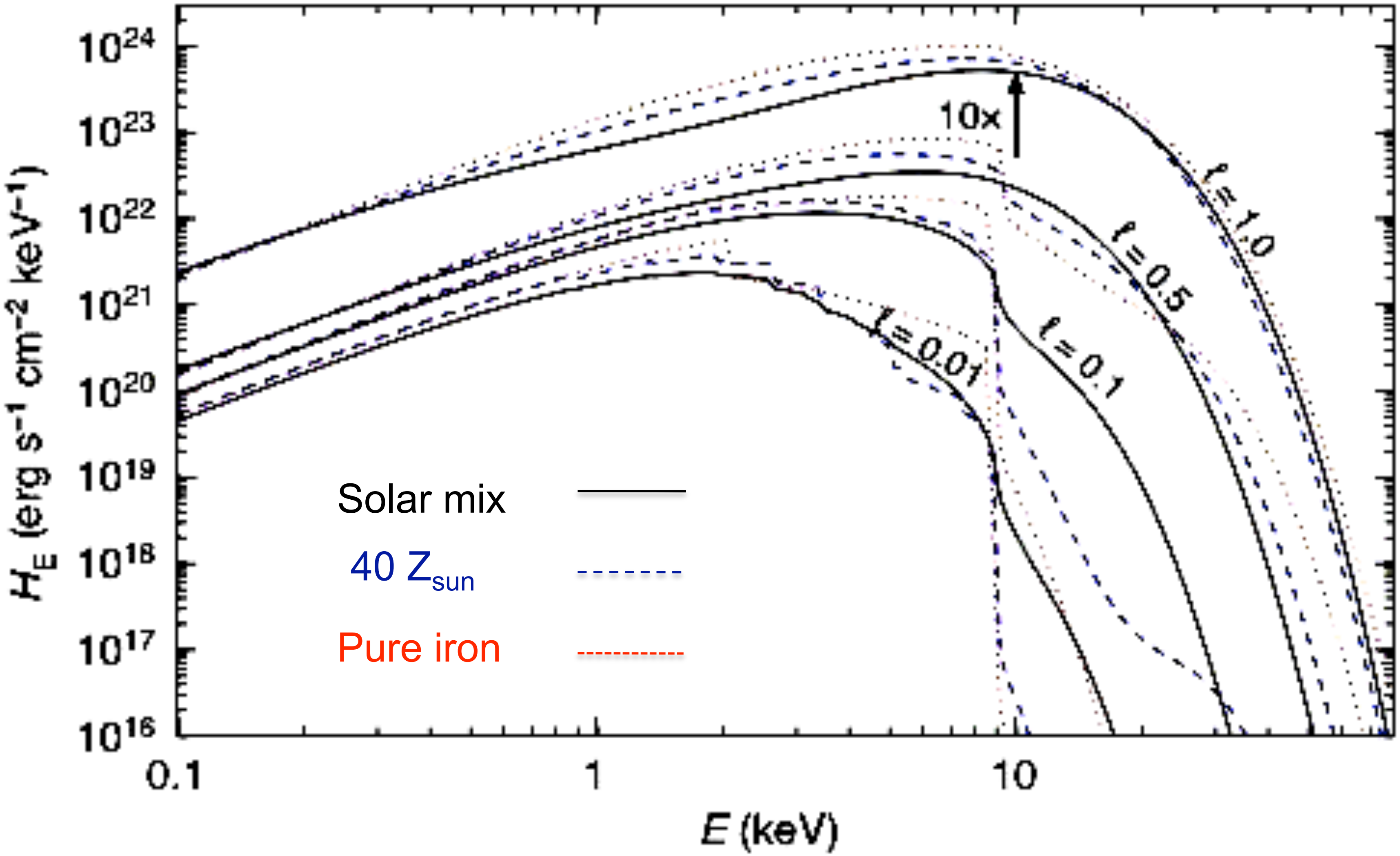
Heavy metal atmospheres. Opacity.



Solar mix, $T=10^7$ K, $P=10^{13}$ dyn cm^{-2}

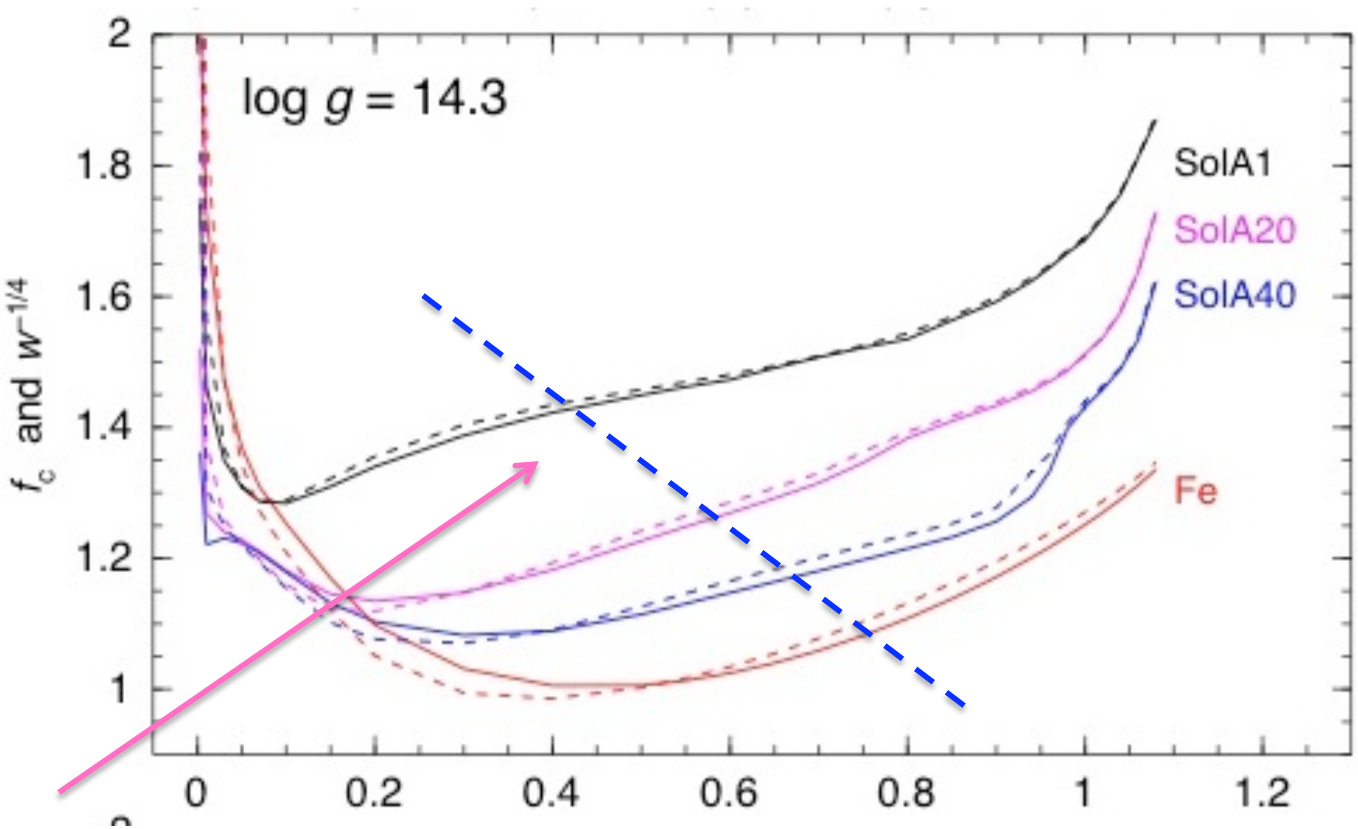
J. Nättilä et al. 2015, submitted

Heavy metal atmospheres. Spectra.



J. Nättilä et al. 2015, submitted

Heavy metal atmospheres. Color correction factors.



Diluted blackbody approximation
is not good below this line

J. Nättilä et al. 2015, submitted

Cooling tail method

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

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

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

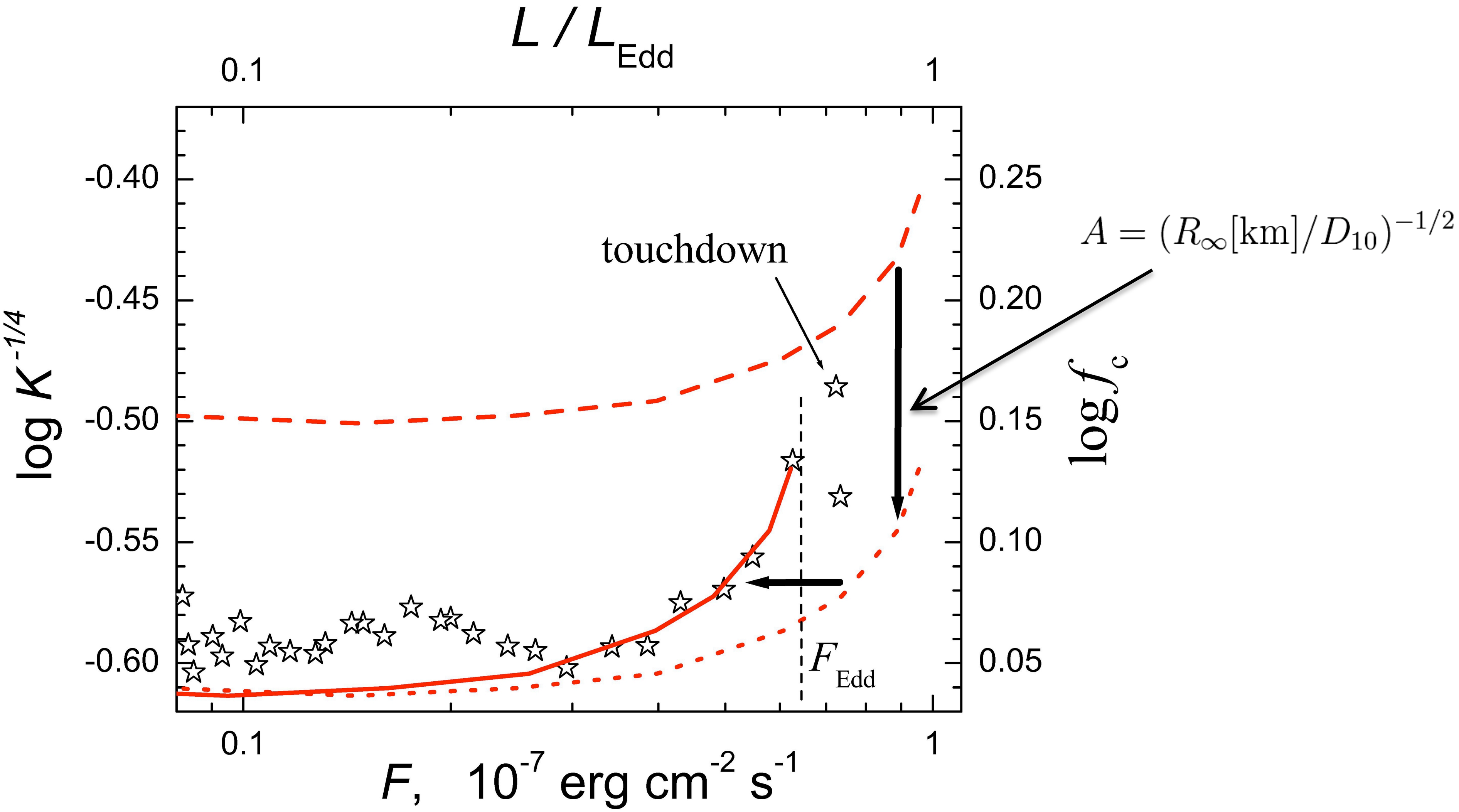
•From the fits a more reliable estimate of the Eddington flux and apparent radius can be obtained.

and we use now our theoretical dependences

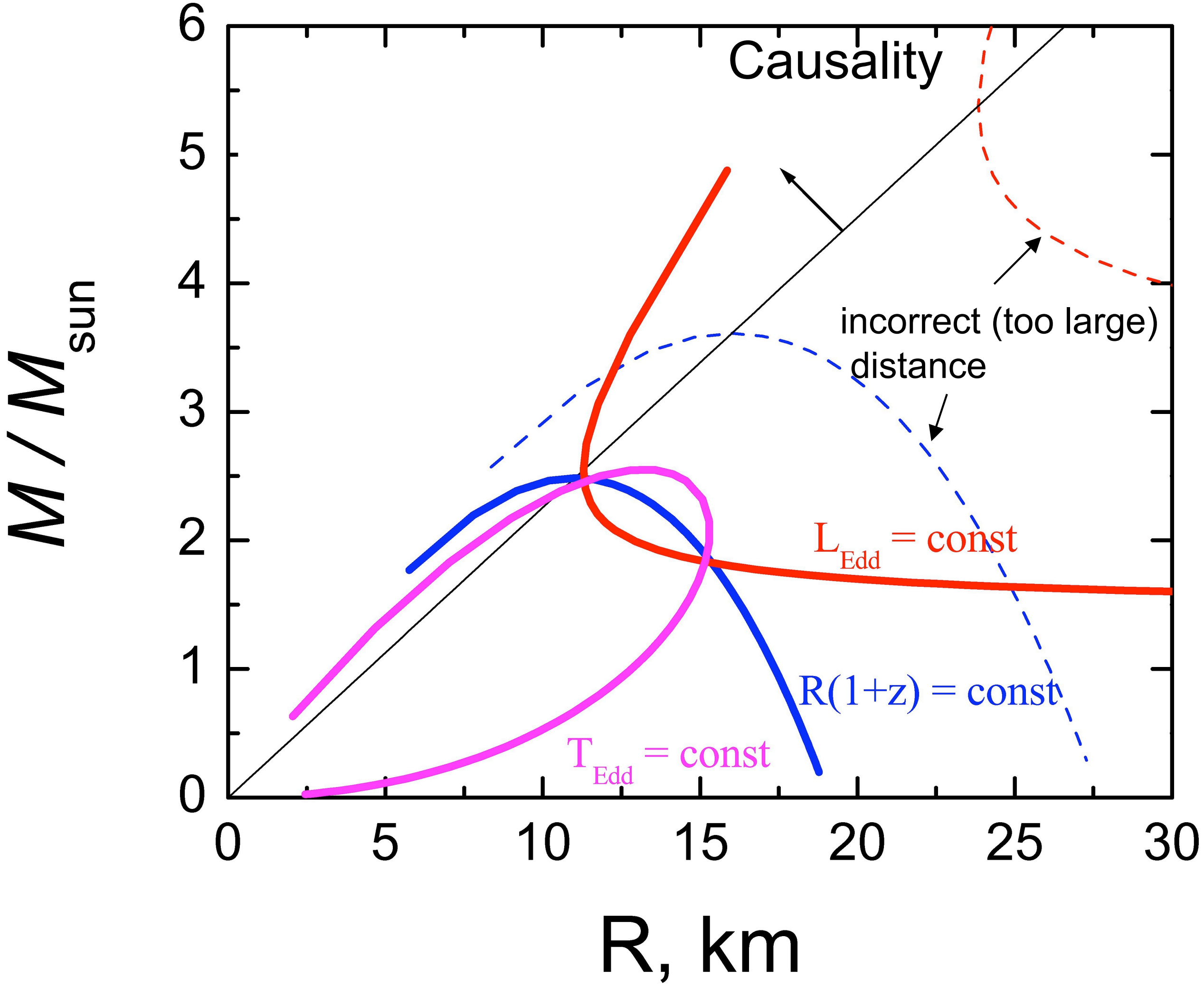
f_c vs. $F/F_{\rm Edd}$

to find two fitting parameters: A and $F_{\rm Edd}$.

Cooling tail method

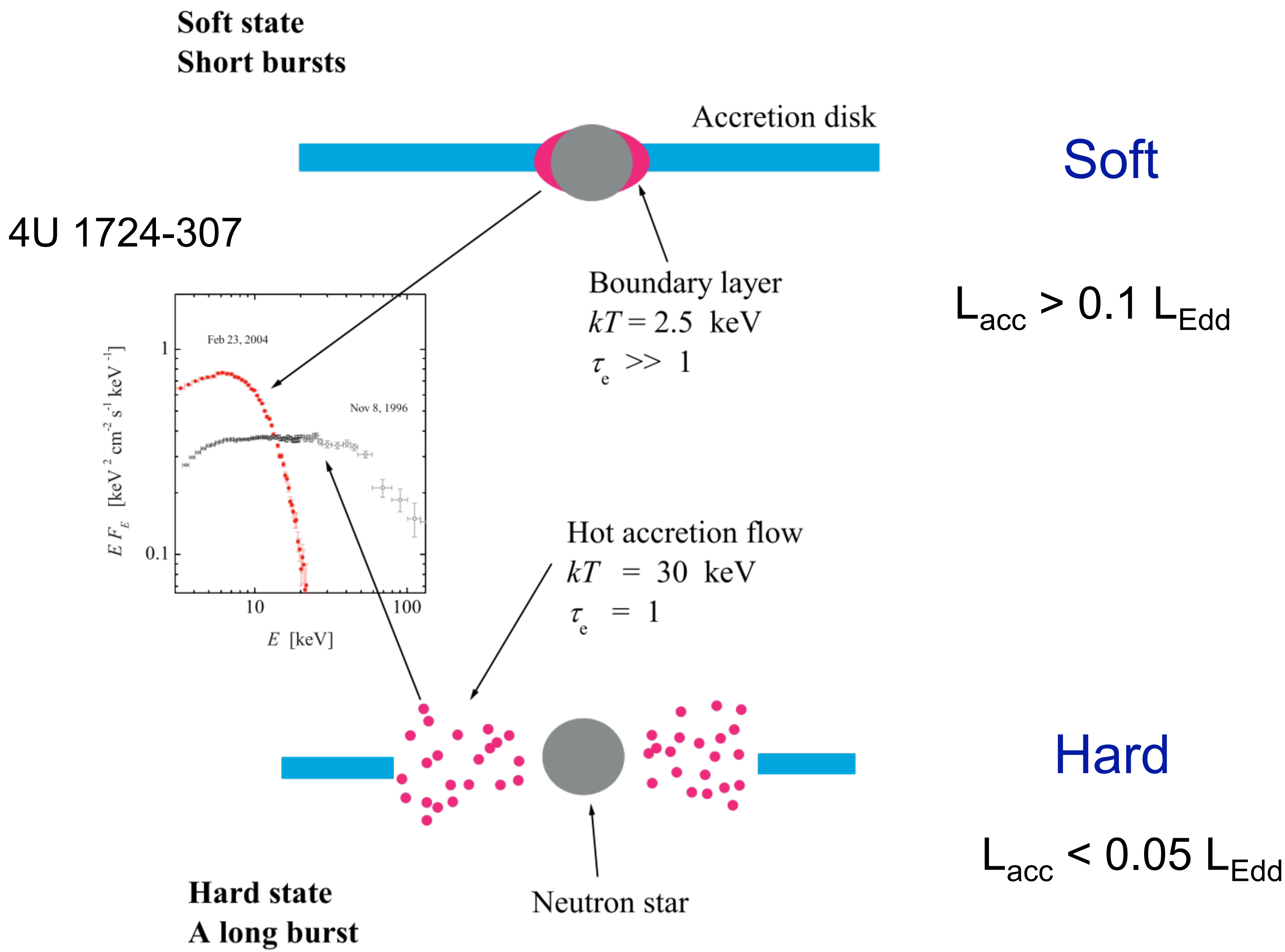


Three curves on *M-R* plane

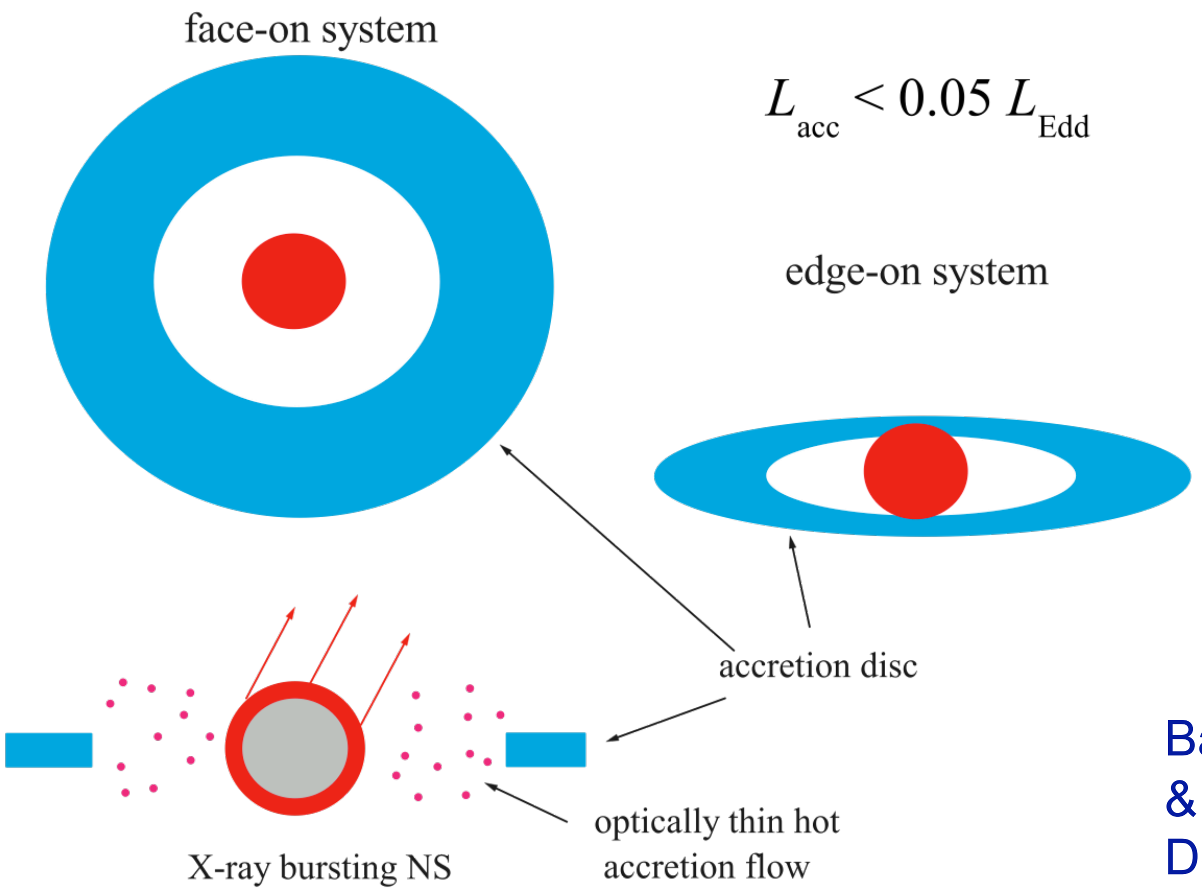


$$T_{\mathrm{Edd},\infty} = \left(\frac{gc}{\sigma_{\mathrm{SB}}\kappa_{\mathrm{e}}}\right)^{1/4} \frac{1}{1+z} = 6.4 \times 10^{9}\, A\, F_{\mathrm{Edd}}^{1/4}\ \mathrm{K}.$$

Two limit quiescent spectral states of LMXBs



Hard spectral states of LMXBs

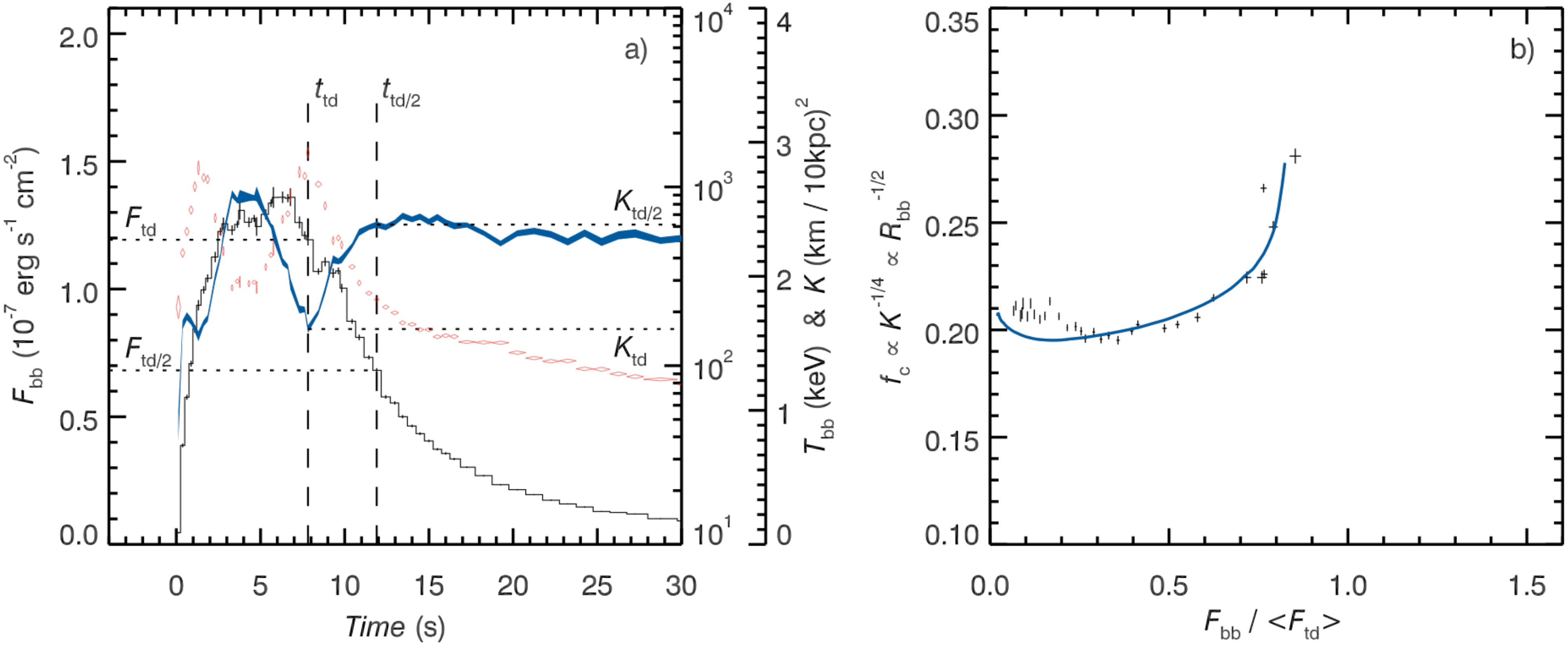


Ballantyne's & Degenaar's & Ji's talks

Influence of optically thin accretion flow is insignificant

X-ray burst at hard quiescent spectral state

4U 1608-52



Kajava et al. 2014

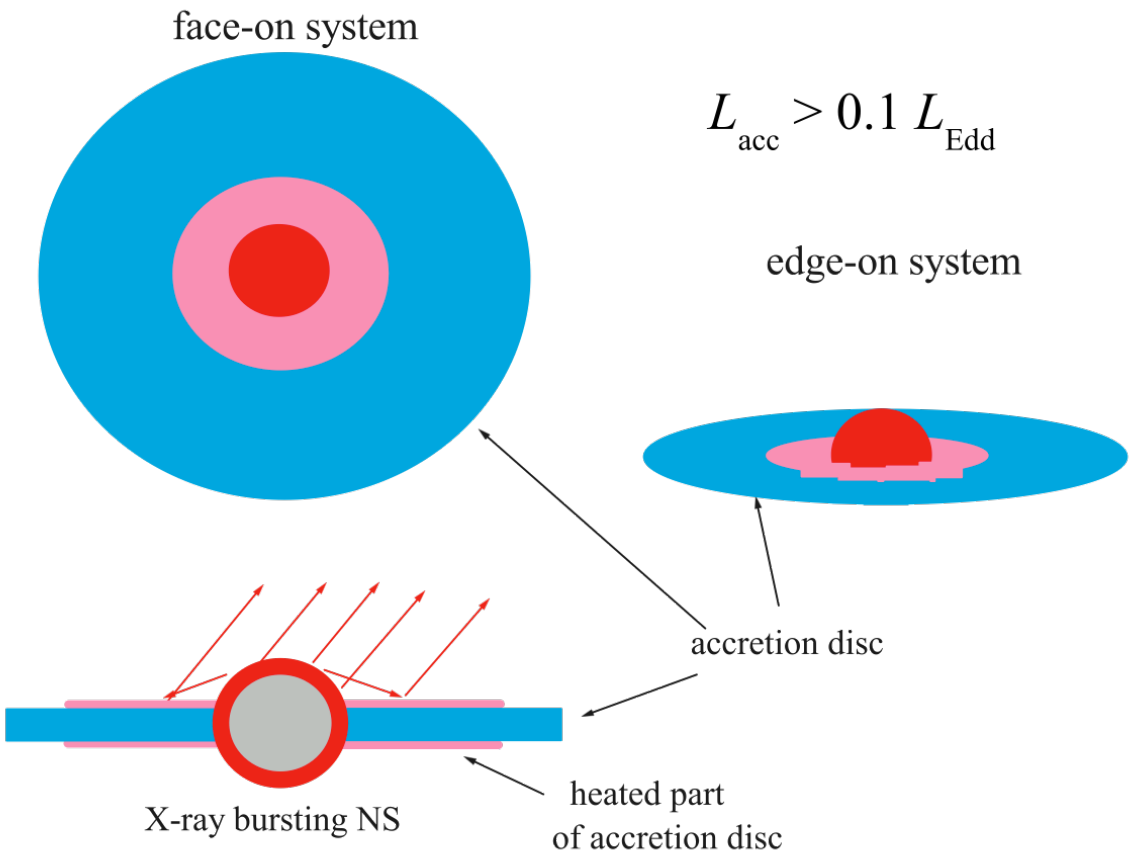
X-ray burst at soft quiescent spectral state

$\cos i \approx 1$

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

$\cos i \approx 0$

Ballantyne's
&
Degenaar's
&
Ji's
talks



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

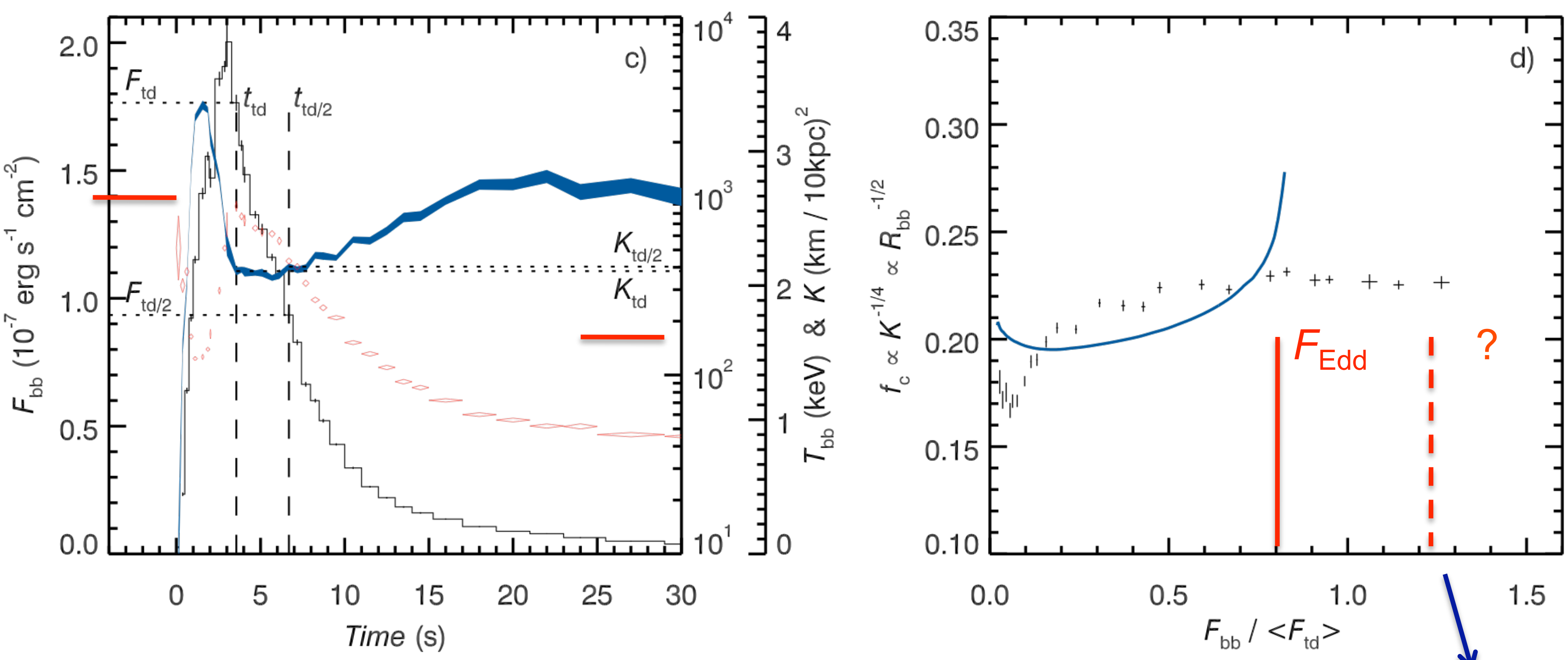
Input of accretion disc reflection is significant for face-on systems

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

X-ray burst at soft quiescent spectral state

4U 1608-52

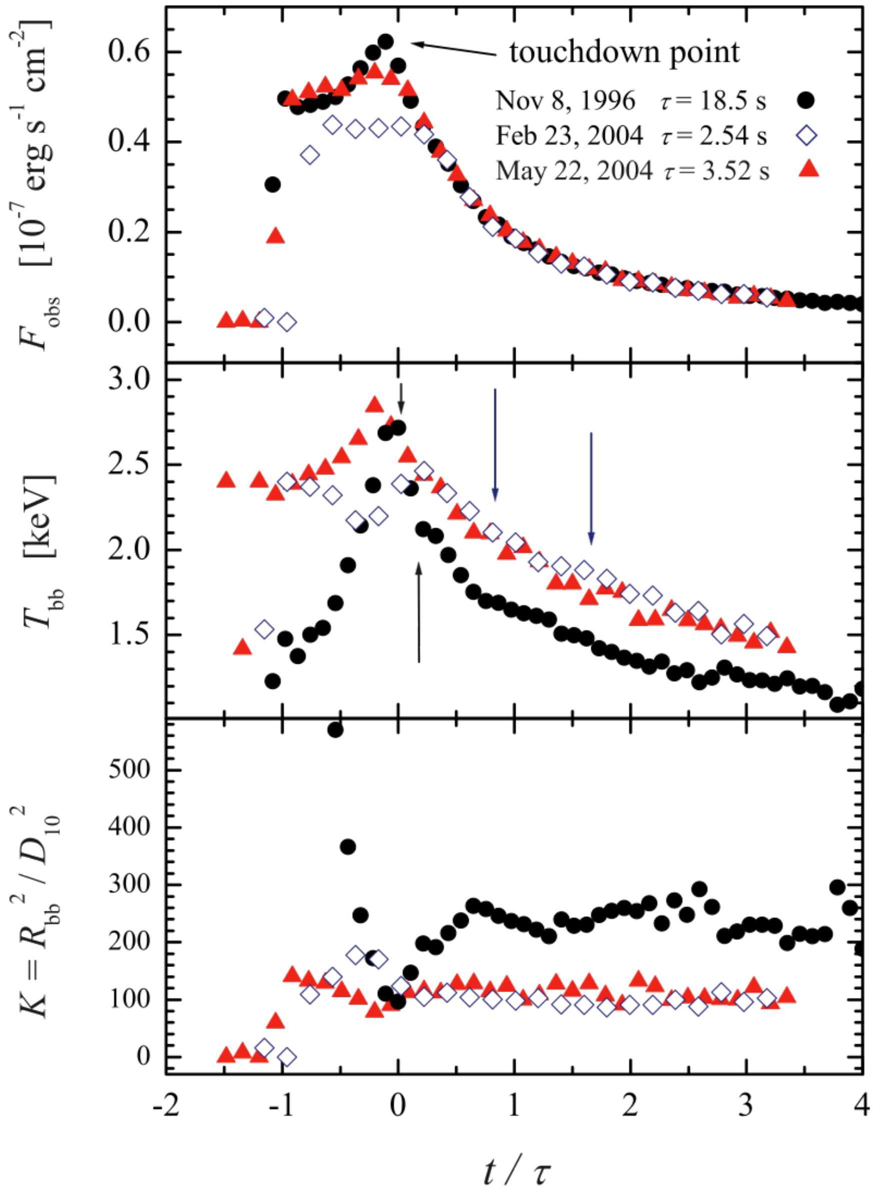
Probably, face-on system



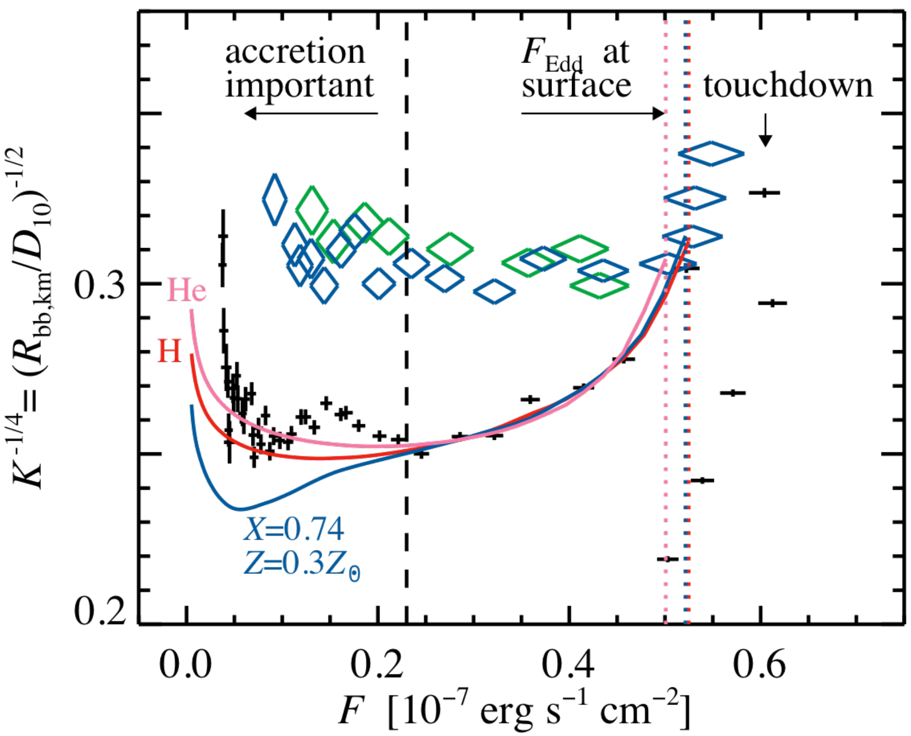
Kajava et al. 2014

$$L_{Edd} = \frac{cGM}{0.2(1+X)}(1+z) \qquad \xi_b^{-1} \approx \frac{1}{2} + \cos i$$

X-ray bursts at soft and hard quiescent spectral states

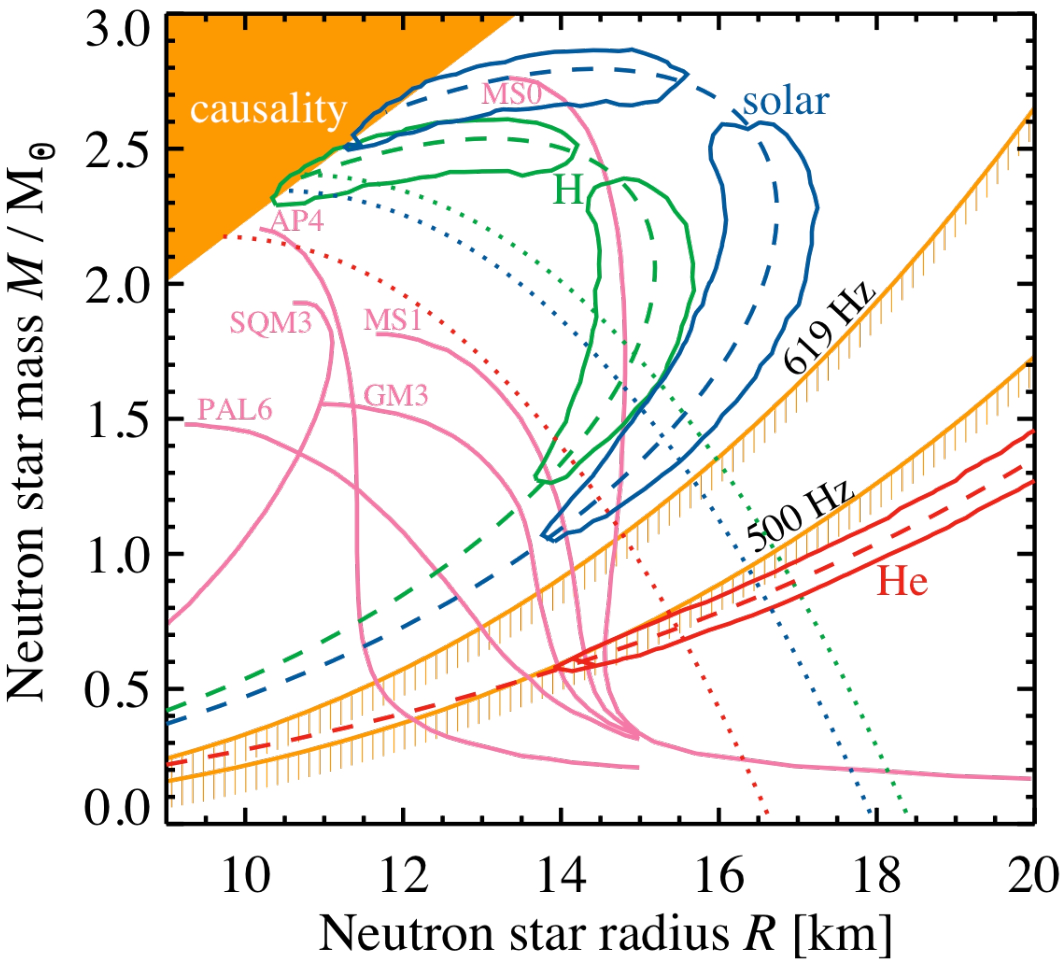


4U 1724-307



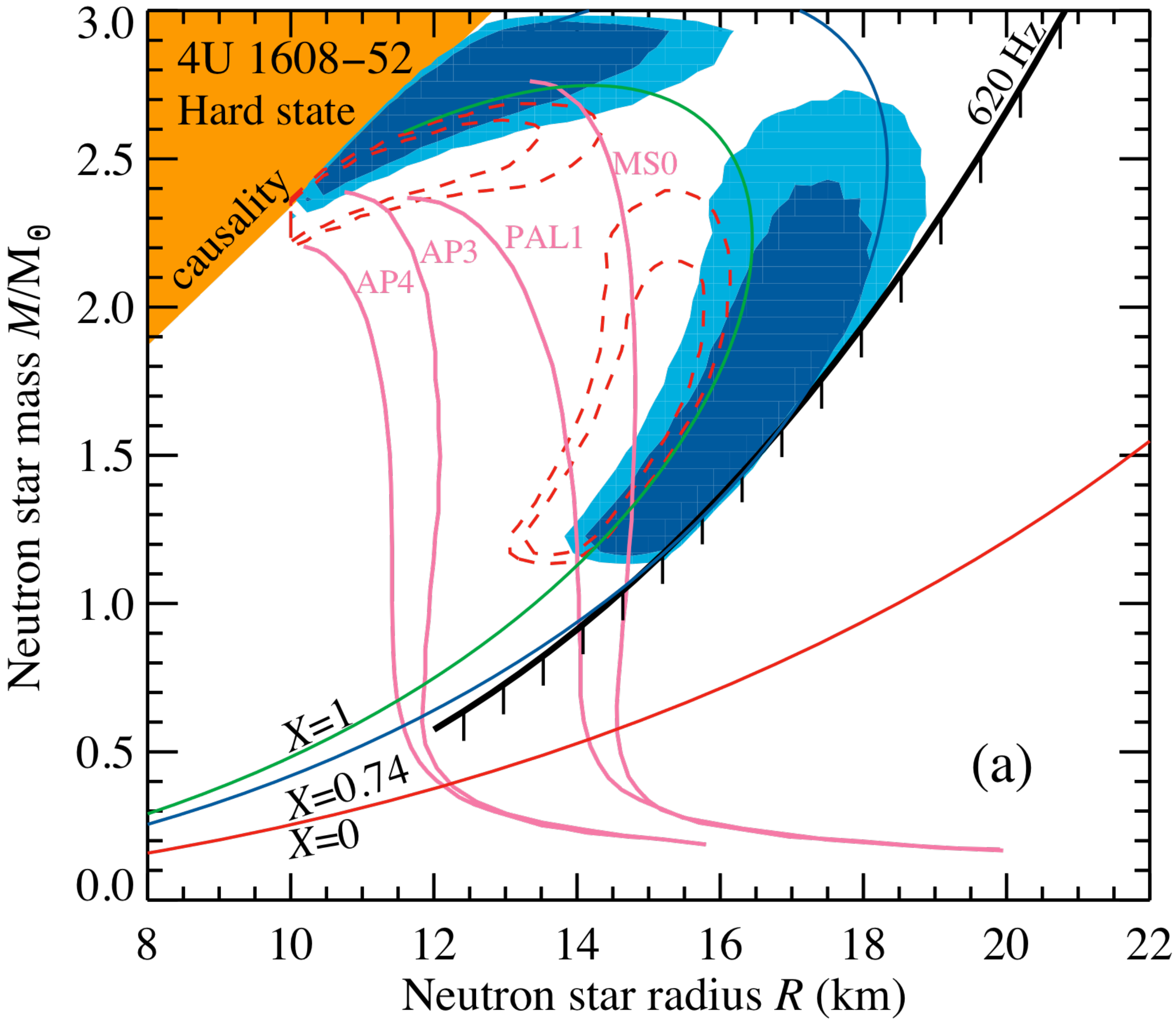
Probably, edge-on system

4U 1724-307



Suleimnov et al. 2011

4U 1608-52



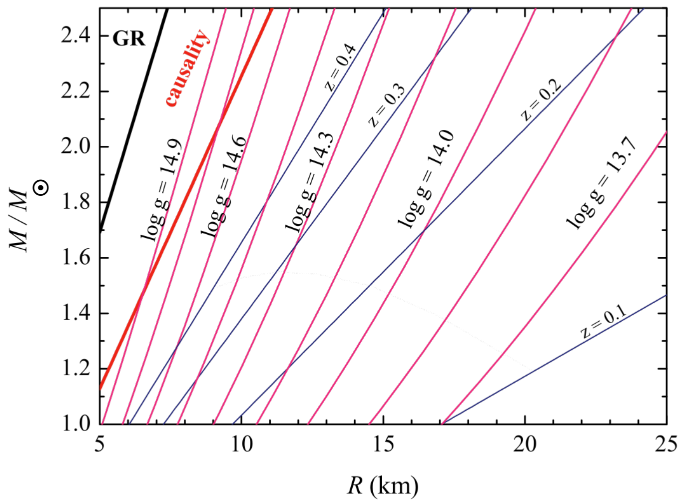
Poutanen et al. 2014

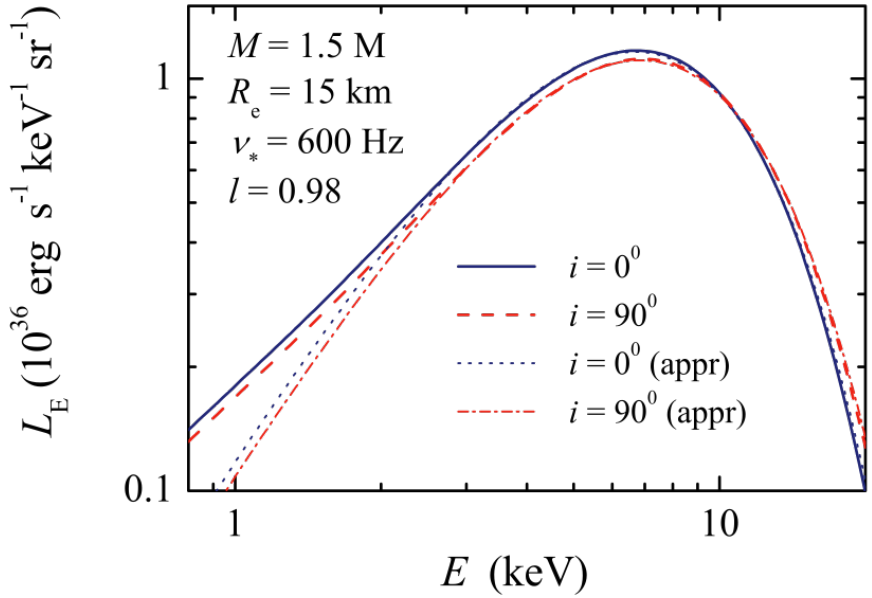
Effect of NS rotation: I. Doppler boosting

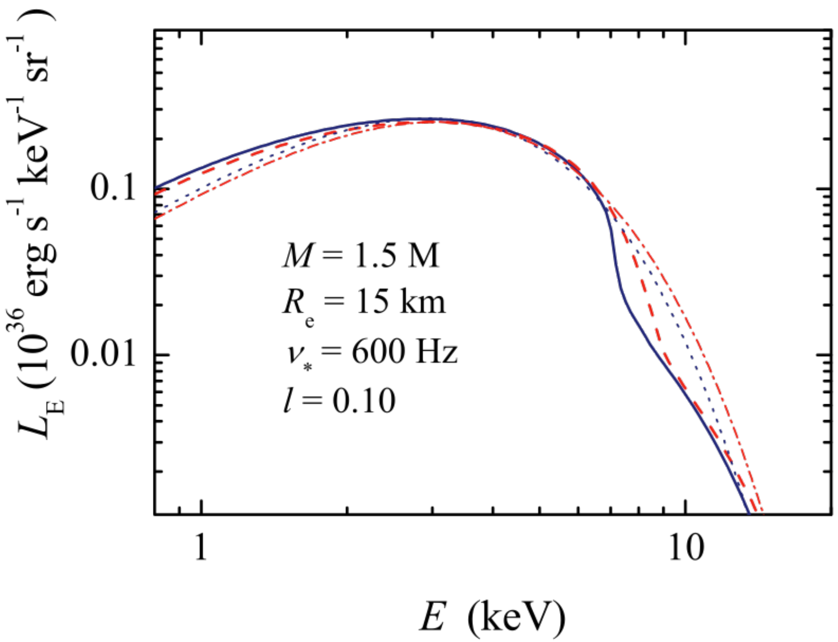
Methods of spectra computations

1. **Exact:** The computed local spectra for given $T_{eff}(\theta)$ and log $g(\theta)$ (two local l = 0.98 and 0.1, solar ab.) 18 latitude rings

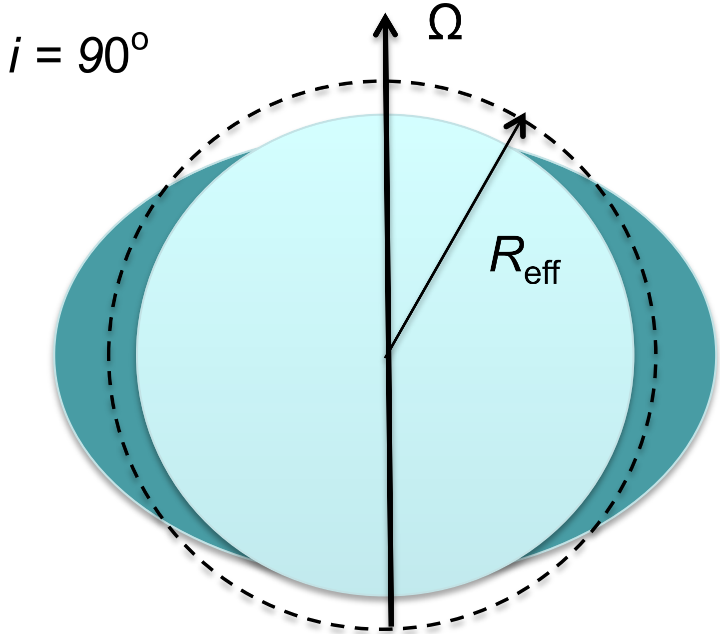
2. **Approximate:** BB approximation: parameters w and f_C are interpolated for given $T_{eff}(\theta)$ and log $g(\theta)$ from the preliminary computed tables (two local l = 0.98 and 0.1, solar ab.) 18 latitude rings

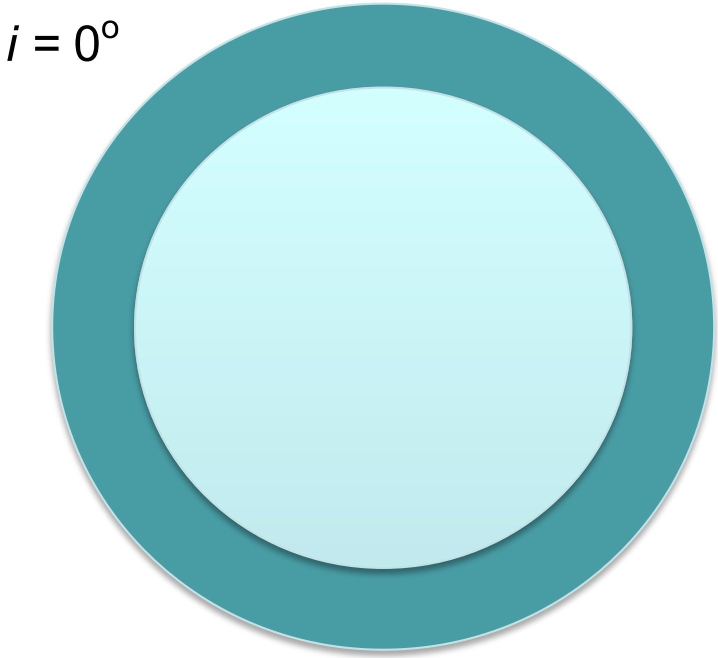


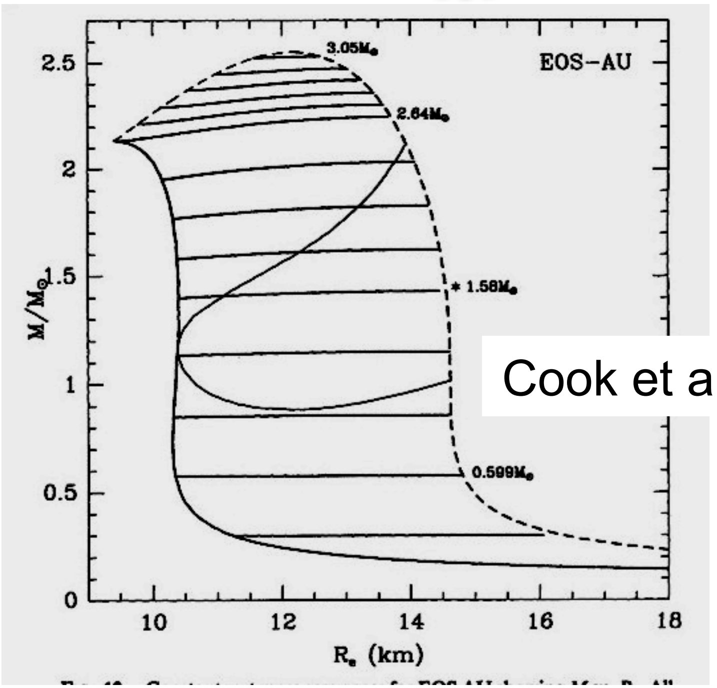




Effect of NS rotation: II. Apparent area increase

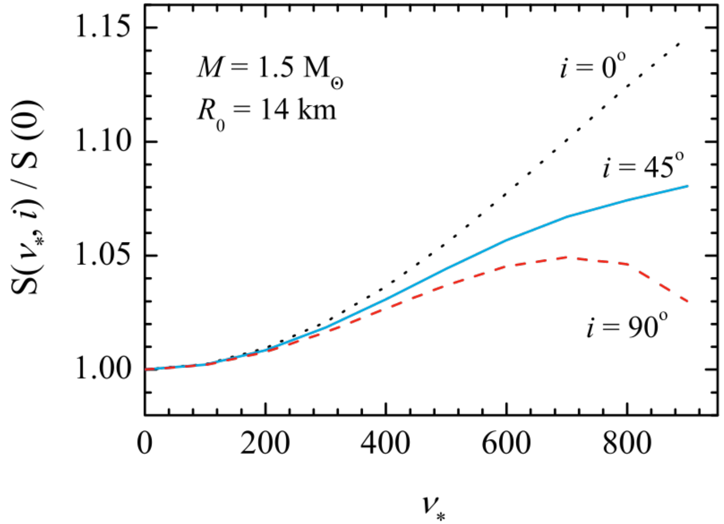






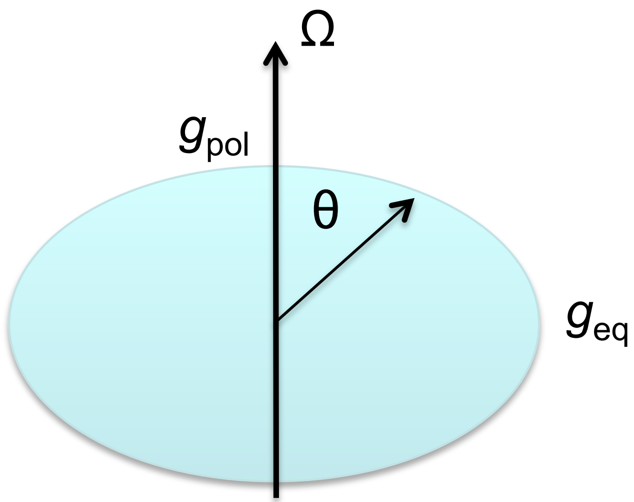
Cook et al. 1994

$$S_{obs}\,(\Omega, i\,) \;>\; S_{obs}\,(\Omega{=}0)$$



Effect of NS rotation: III. Eddington limit.

Decreasing of $L_{\rm Edd}$ due to rotation



$$g_{\rm pol} \approx GM / R^2_{\rm pol}$$

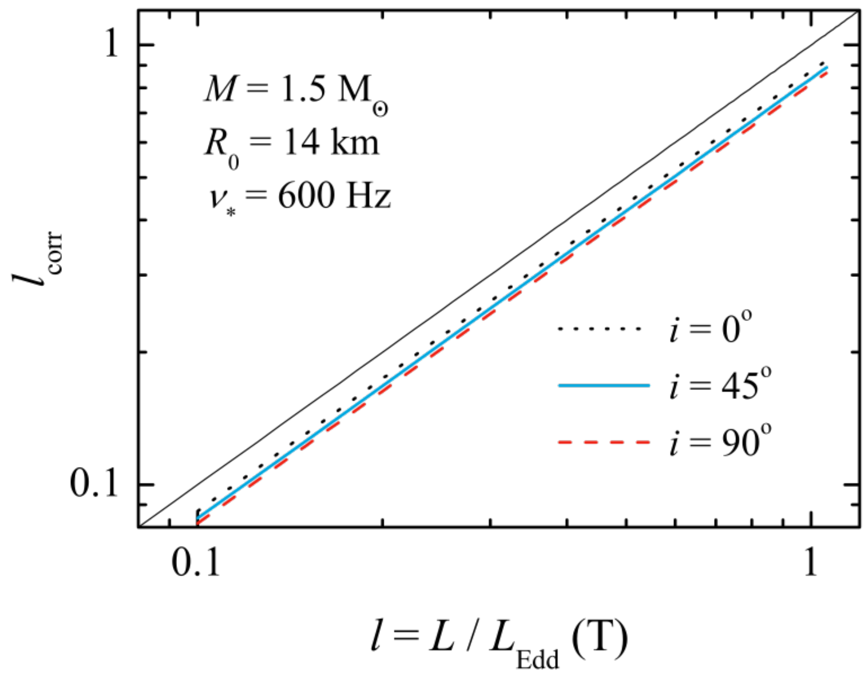
$$g_{\rm eq} \approx GM / R^2_{\rm eq} - \Omega^2 R_{\rm eq}$$

$$\sigma T^4_{\rm Edd}(\theta) \approx g(\theta)\, c / \sigma_T$$

After integration over the surface

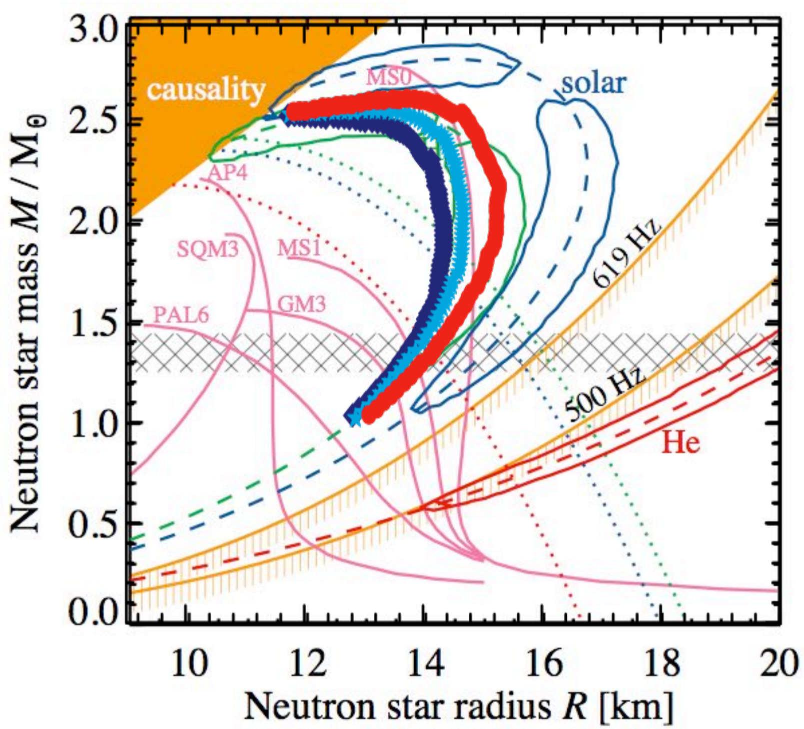
$$L_{\rm Edd}(\Omega, i, \text{obs}) < L_{\rm Edd}(0, \text{obs})$$

$$l_{corr} = L(\Omega, i, \text{obs}) / L_{\rm Edd}(0, \text{obs})$$



Effect of NS rotation: conclusion

Fast rotation reduce the derived radius *R* of a static NS obtained from the cooling tail method



ν=600 Hz

i =0°

i =45°

i =90°

Conclusions

The method of model atmospheres is a very powerful tool.

BUT

For X-ray bursting NSs, it could be used ONLY:

- for bursts in hard spectral persistent states
- for non-expanded photospheres, $L < L_{\rm Edd}$
- before accretion starts $L > 0.3$ -0.5 $L_{\rm edd}$

Nevertheless, there are many systematic uncertainties like atmosphere chemical composition and NS fast rotating