Neutron star masses and radii from X-ray bursts in low-mass X-ray binaries

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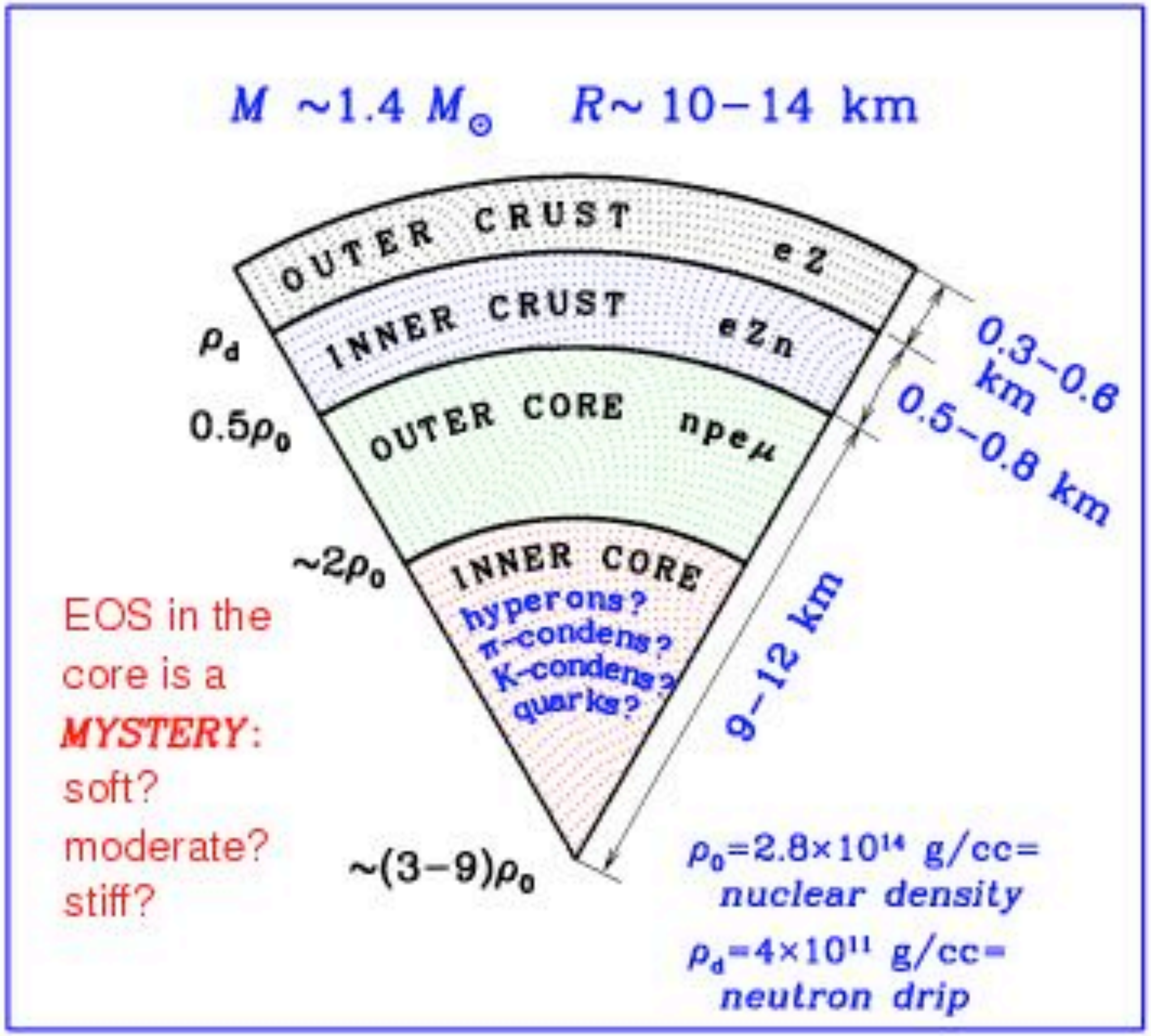
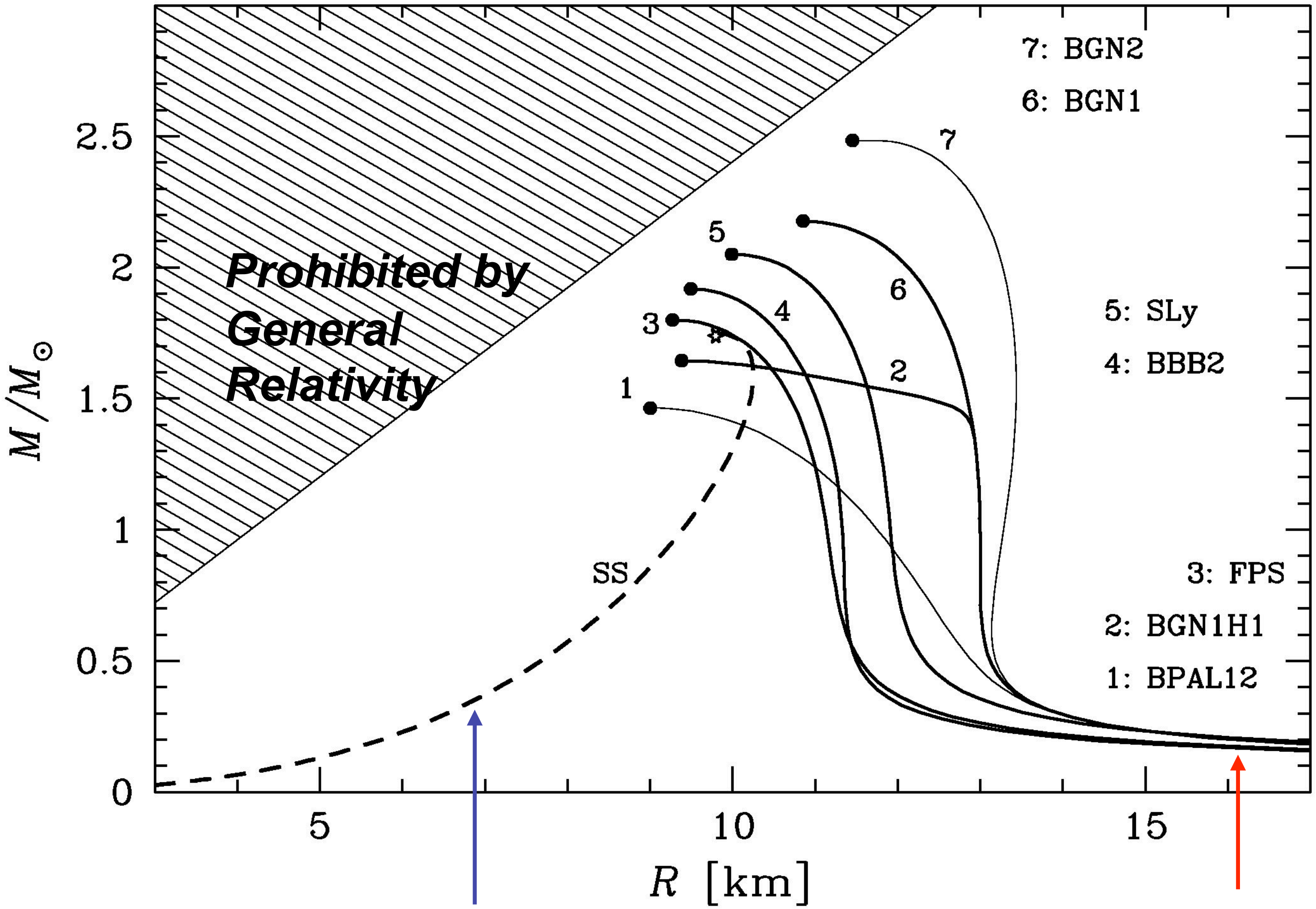
Neutron star structure



Main problem – inner core Equation of State (EoS)

Zoo of NS inner core EoS



Special family of low-mass strange stars

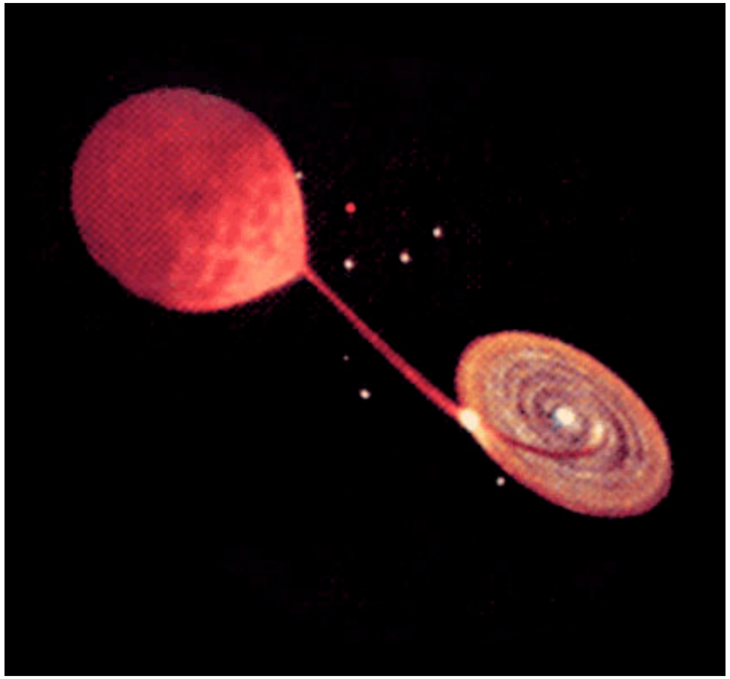
Universal low-mass curve

Solution – M and R from observations!

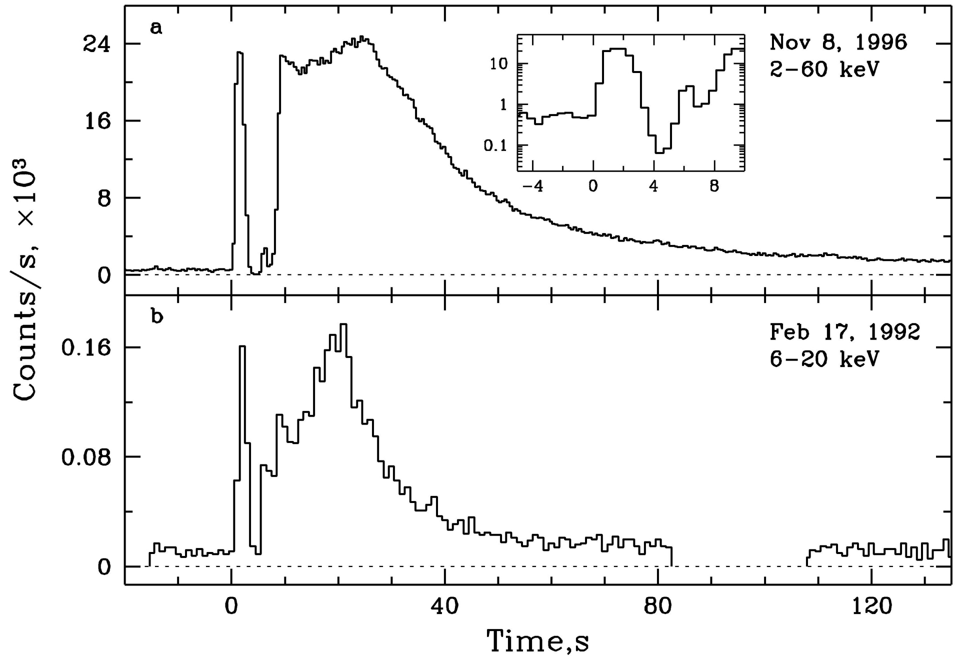
X-ray bursting neutron stars

- 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!!!)



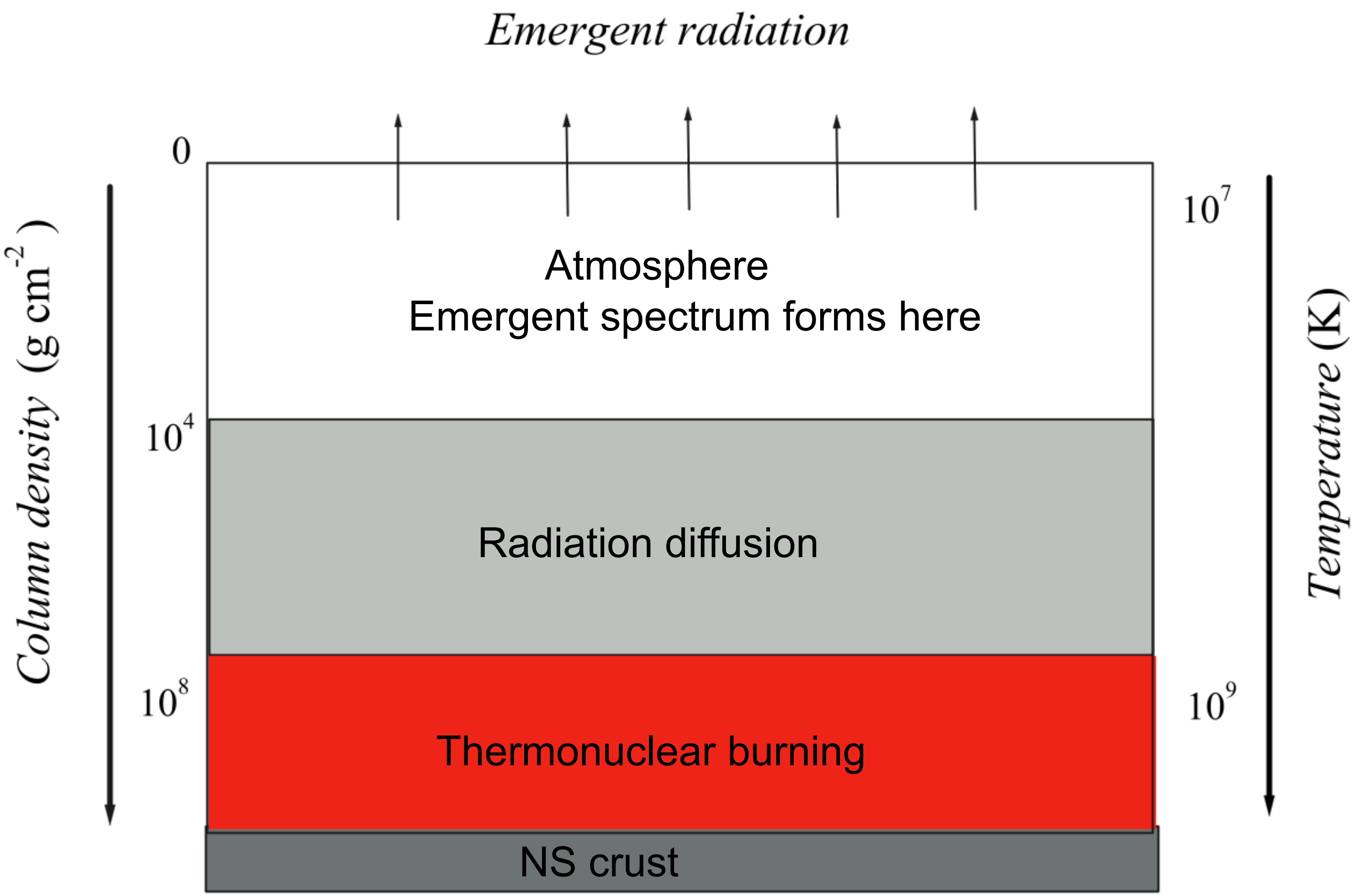
Low Mass X-ray Binary (artist veiw)



4U 1724-307 in Terzan 2

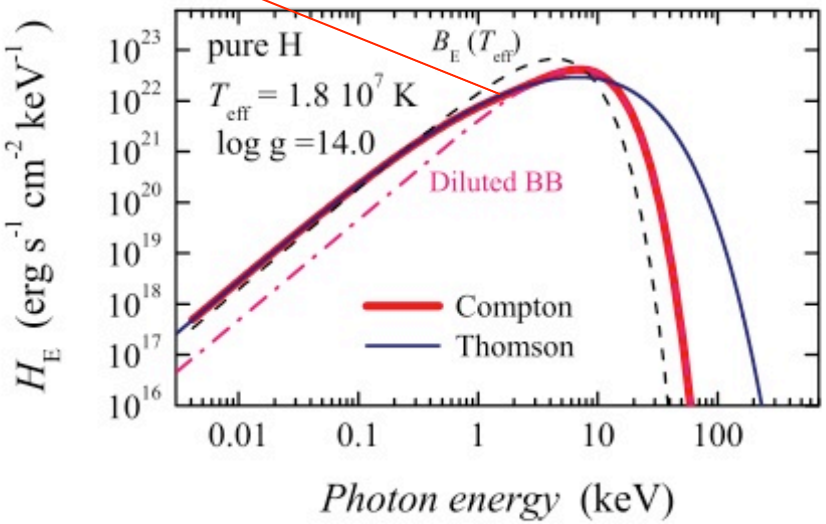
Figure from Molkov et al (2000)

Plane parallel model of the bursting layer



How emergent spectrum forms ?

$$H_E \approx B_E \sqrt{\frac{k_{ff}}{k_{ff} + \sigma_e}}$$

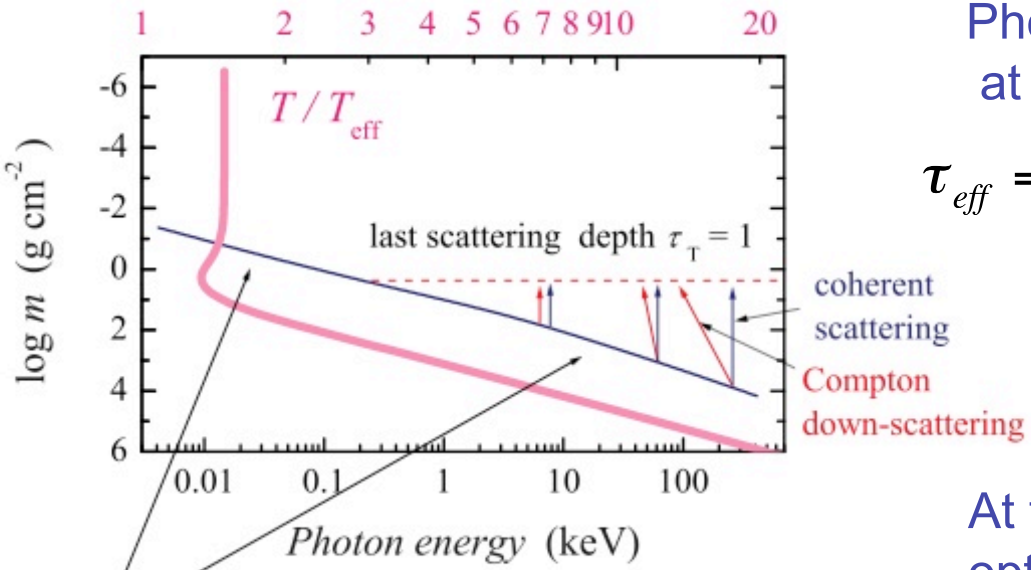


Due to Compton scattering the emergent spectrum close to the diluted blackbody.

$$F_\nu = \frac{1}{f_c^4} B_\nu(f_c T_{eff}), \quad f_c \approx 1.4 - 1.9$$

The apparent size of emitting area depends on the color correction factor f_c

$$R_\infty = R_{BB}\ f_c^{\ 2}$$



escaped photons are born at this depth

$\tau_{eff} = (\tau_T \tau_{ff})^{1/2} = 1$

Photons which we observe are emitted at the depth

$$\tau_{eff} = \sqrt{\tau_{ff}\tau_T} \approx 1$$

- thermalization depth

At this depth, electron scattering optical depth $\tau_T >> 1$

as $k_{ff}(E) \propto E^{-3}, \quad k_{ff} << \sigma_T \quad at \;\; E > 0.1 - 1\, kT_e$

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)

Basic equations

Hydrostatic equilibrium

$$\frac{1}{\rho}\frac{dP_{gas}}{dr} = -\frac{GM_{NS}}{R_{NS}^2(1-R_g/R_{NS})^{1/2}} + \frac{4\pi}{c}\int H_\nu (k_{ff}+\sigma_e)\,d\nu$$

Radiation transfer

Kompaneets operator

$$\frac{\partial^2 (f_\nu J_\nu)}{\partial \tau_\nu{}^2} = \frac{k_{ff}}{k_{ff}+\sigma_e}(J_\nu - B_\nu) - \frac{\sigma_e}{k_{ff}+\sigma_e}\frac{kT}{m_e c^2}x\frac{\partial}{\partial x}\left(\frac{\partial J_\nu}{\partial x} - 3J_\nu + \frac{T_{eff}}{T}xJ_\nu\left(1+C\frac{J_\nu}{x^3}\right)\right)$$

$$x = \frac{h\nu}{kT_{eff}} \qquad C = c^2h^2/2(kT_{eff})^3$$

Compton scattering

Radiative equilibrium

$$\int k_{ff}(J_\nu - B_\nu)dx - \sigma_e\frac{kT}{m_e c^2}\int\left(4J_\nu - \frac{T_{eff}}{T}xJ_\nu\left(1+\frac{CJ_\nu}{x^3}\right)\right)dx = 0$$

k_{ff} - true absorption opacity (mainly free-free transitions)

σ_e - Thomson electron scattering opacity

Accurate treatment using exact relativistic redistribution function for Compton scattering

Radiation transfer equation (RTE)

$$\mu \frac{dI(x,\mu)}{d\tau_{\rm x}} = I(x,\mu) - S(x,\mu), \qquad d\tau_{\rm x} = -(\sigma(x,\mu) + k(x))\,\rho(z)\,dz$$

Electron scattering opacity

$$\sigma(x,\mu) = \frac{\sigma_{\rm e}}{x} \int_0^\infty x_1\,dx_1 \int_{-1}^{1} d\mu_1\, R(x,\mu,x_1,\mu_1)\, \exp\left(-\frac{x_1 - x}{\Theta(z)}\right)\left(1 + \frac{C\,I(x_1,\mu_1)}{x_1^3}\right)$$

$$\sigma_{\rm e} = \sigma_{\rm T}\frac{n_{\rm e}}{\rho}, \quad C = \frac{h^2}{2m_{\rm e}^3\,c^4} \qquad \sigma_{\rm T} = 6.65 \cdot 10^{-25}\ {\rm cm}^2$$

$$x_1 = \frac{h\nu_1}{m_{\rm e}c^2}, \quad x = \frac{h\nu}{m_{\rm e}c^2},$$

$$\Theta(z) = \frac{kT(z)}{m_{\rm e}c^2}$$

Source function

$$S(x,\mu) = \frac{k(x)}{\sigma(x,\mu) + k(x)} B(x) + \frac{x^2}{\sigma(x,\mu) + k(x)}\left(1 + \frac{C\,I(x,\mu)}{x^3}\right)\int_0^\infty \frac{dx_1}{x_1^2}\int_{-1}^{1} d\mu_1 R(x,\mu,x_1,\mu_1) I(x_1,\mu_1),$$

Redistribution function (RF)

$$R(x,x_1,\mu,\mu_1) = \int_0^{2\pi} R(x,x_1,\eta)\,d\varphi, \qquad \eta = \mu\mu_1 + \sqrt{1-\mu^2}\,\sqrt{1-\mu_1^2}\cos\varphi$$

Model atmosphere calculations

(Suleimanov, Poutanen, Werner 2011, A&A 527, A139 / 2012, A&A, 545, A120)

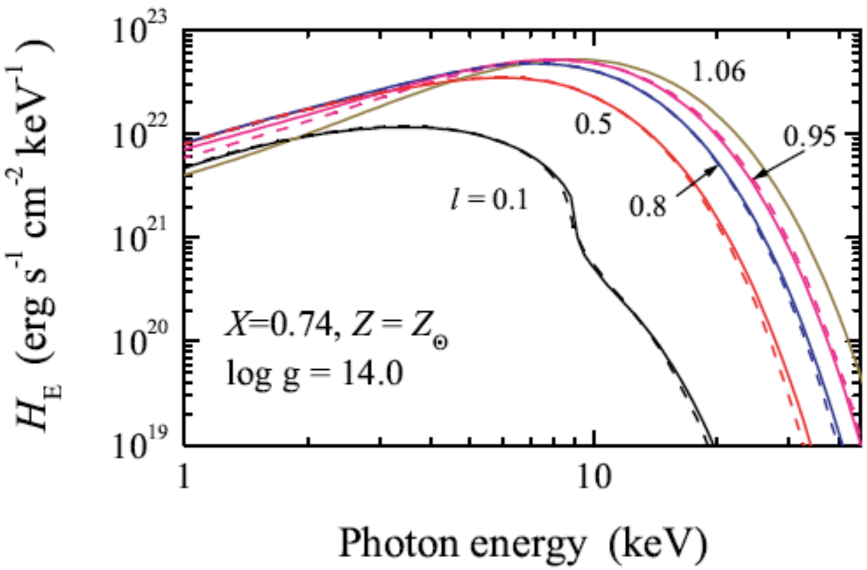
- 6 chemical compositions:
H, He, solar H/He with
Z = 1, 0.3,0.1,0.01 Z_{sun}

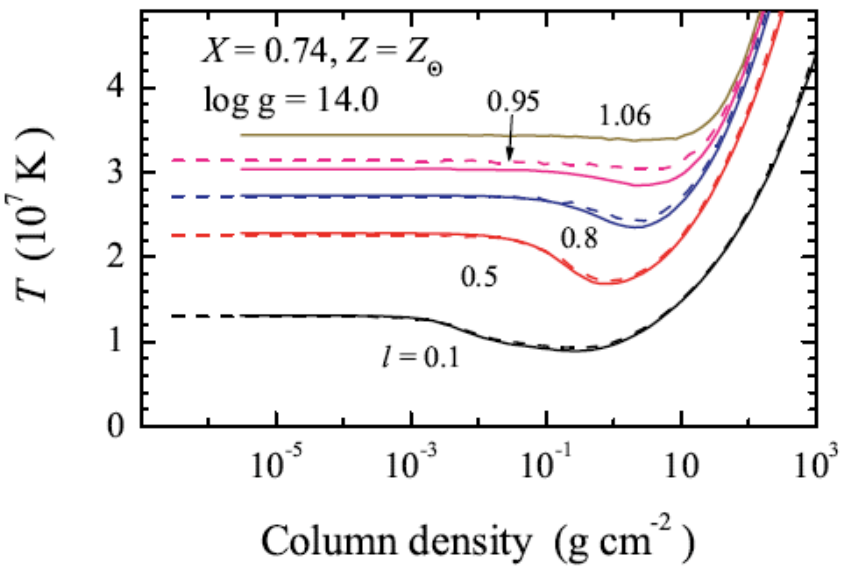
- 3 surface gravities:
log g = 14.0, 14.3 and 14.6

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

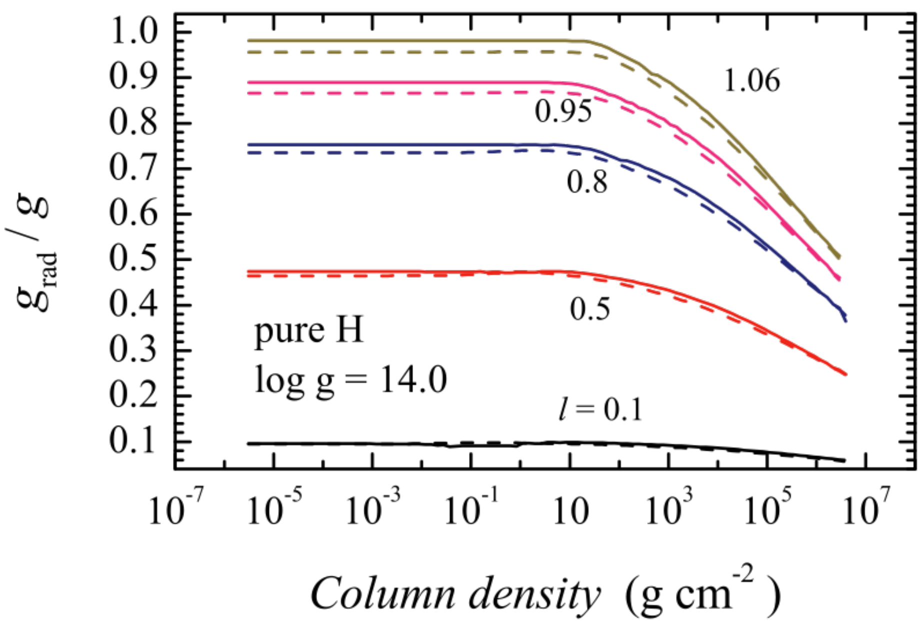
Dashed lines –
Kompaneets approximation

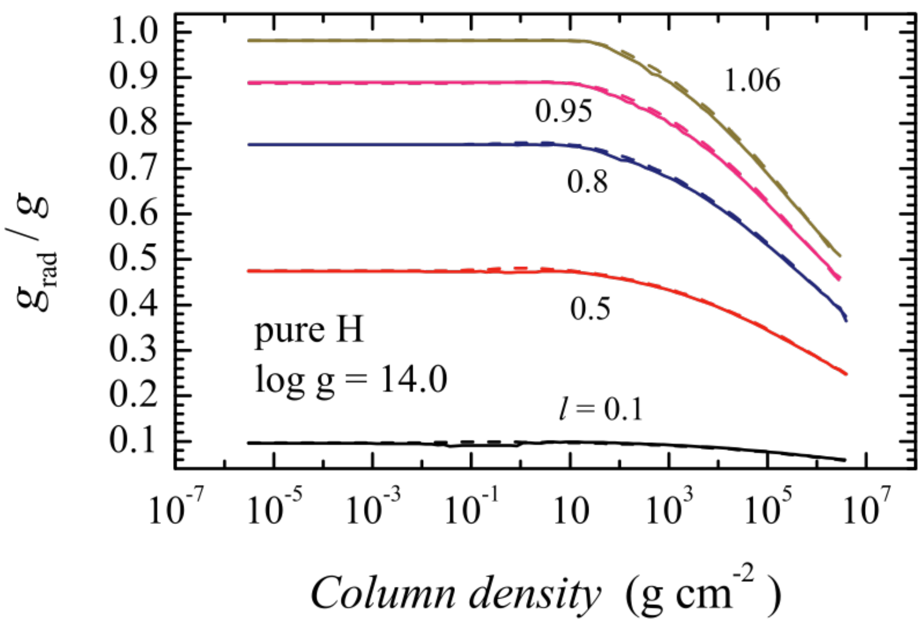
Solid lines – exact Compton scattering kernel





New set of atmosphere models. Radiative acceleration.





Dashed curves – Paczynski's (1983) approximation for averaged opacity

$$\sigma_e(T) \approx \sigma_e \left(1 + \left(\frac{T}{4.5 \times 10^8 K}\right)^{0.86}\right)^{-1}$$

Slightly improved approximation gives better result

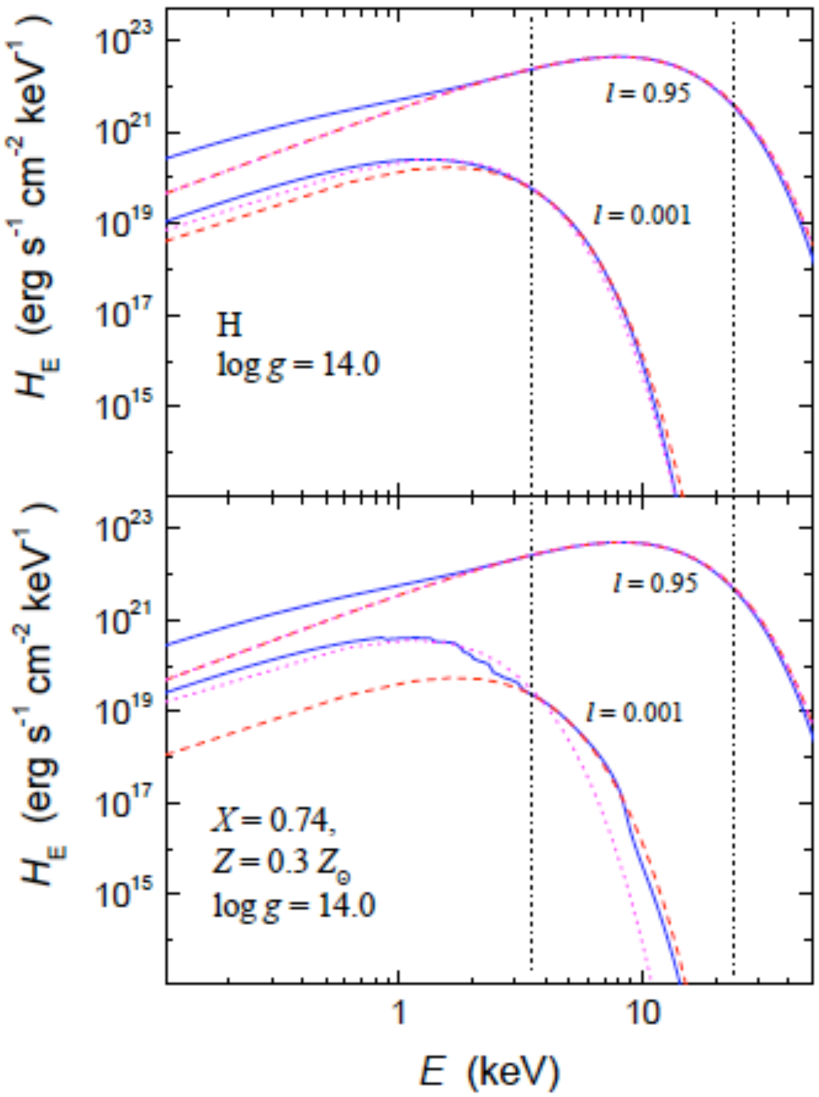
$$\sigma_e(T) \approx \sigma_e \left(1 + \left(\frac{T}{4.5 \times 10^8 K}\right)^{0.98}\right)^{-1}$$

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

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

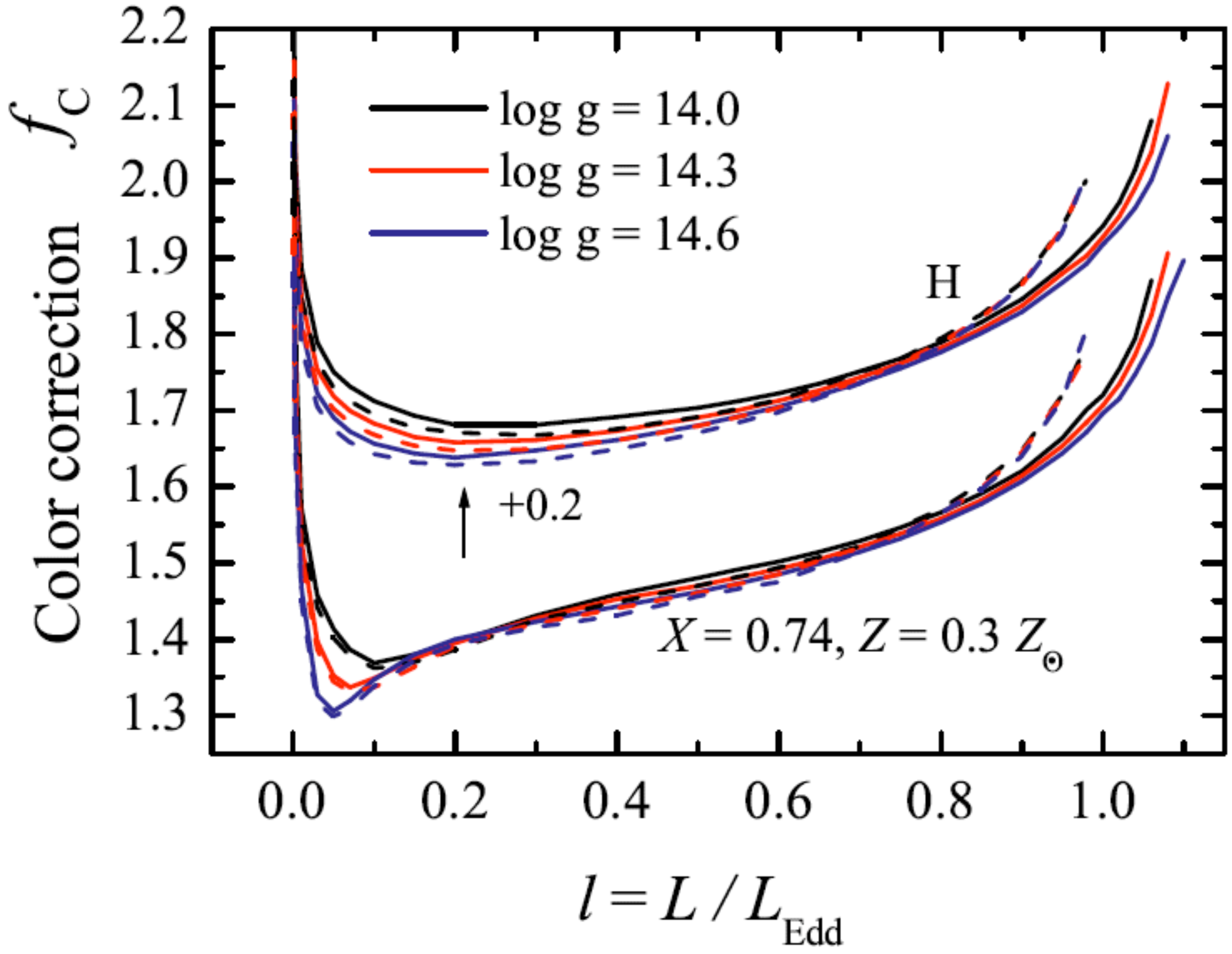
$$F_E = wB_E(f_c T_{eff})$$



Minimizing deviations in photon number flux

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

Color correction f_c calculations



Dashed lines – Kompaneets approximation

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

Solid lines – exact Compton scattering kernel

Basic relations

$$L_{Edd} = \frac{4\pi GMc(1+z)}{0.2(1+X)} = 4\pi R^2 \sigma_{SB} T_{Edd}^4$$

Eddington luminosity

electron scattering

Hydrogen mass fraction

Max possible $T_{\rm eff}$

$$F_{obs}(Edd) = \frac{L_{Edd}}{d^2(1+z)^2}$$

observed flux, which corresponds to Eddington luminosity

$$F_{obs} = \sigma T_{BB}^4 \frac{R_{BB}^2}{d^2} = \sigma T_{BB}^4 K$$

observed flux with fitting parameters

$$F_E \approx \frac{1}{f_c^4} B_E(f_c T_{eff})$$

observed spectrum is close to the diluted blackbody

color correction (hardness) factor

from $L_{obs} = L_{BB}$ $\longrightarrow$ $R_{BB} = \frac{R}{f_c^2}(1+z)$

Cooling tail method

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

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

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

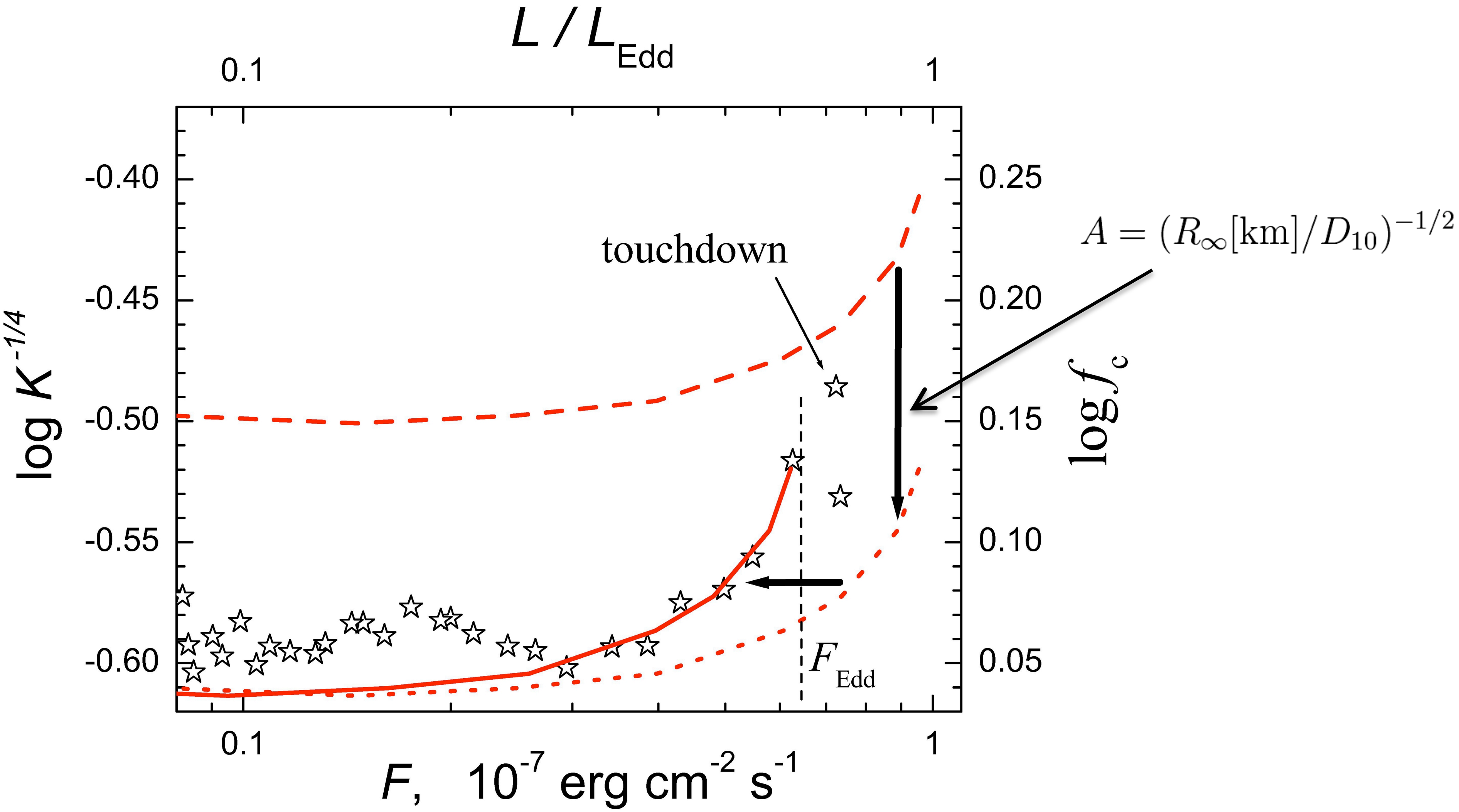
- From the fits a more reliable estimate of the Eddington flux and apparent radius can be obtained.

and we use now our theoretical dependences

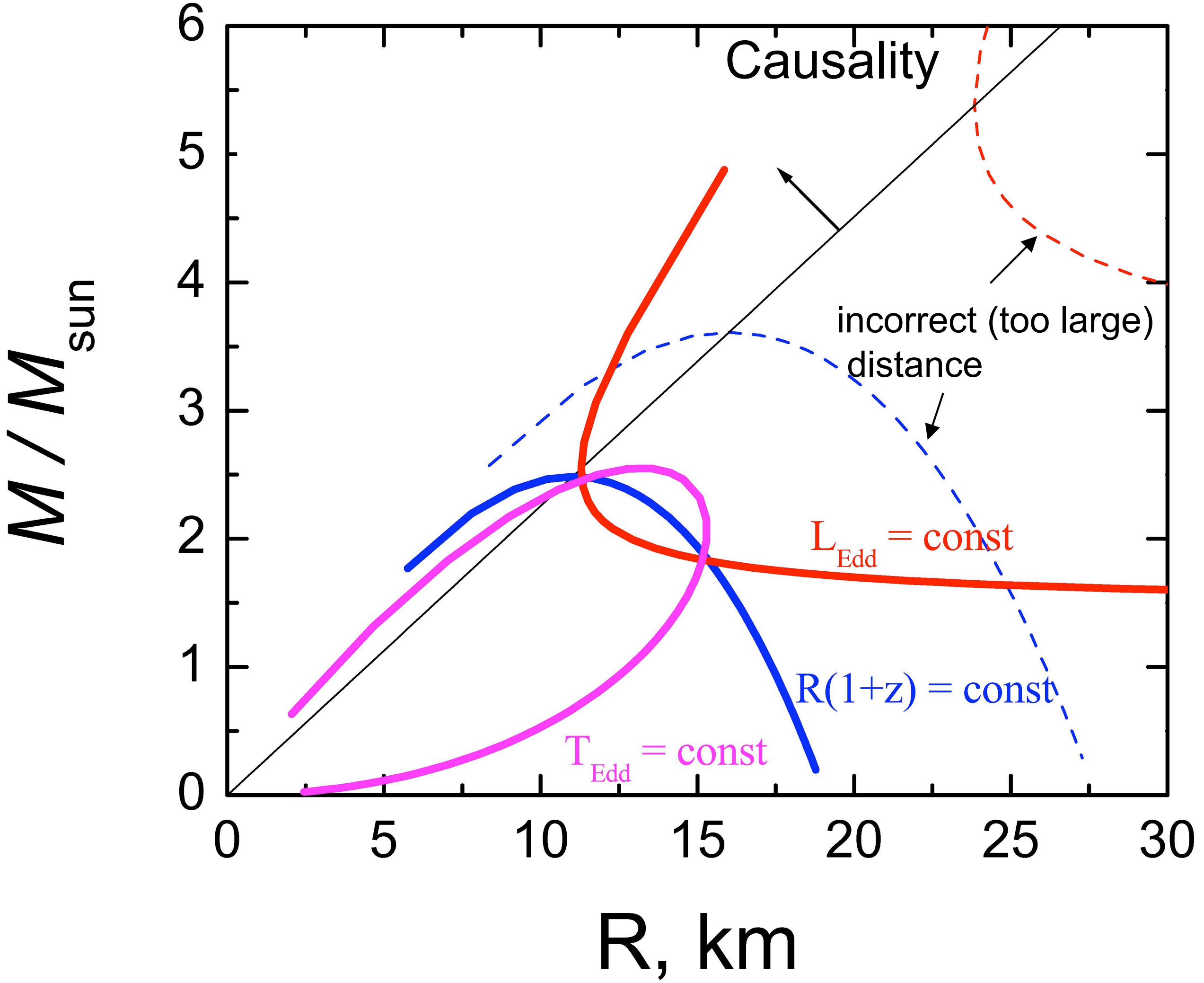
f_c vs. $F/F_{\rm Edd}$

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

Cooling tail method



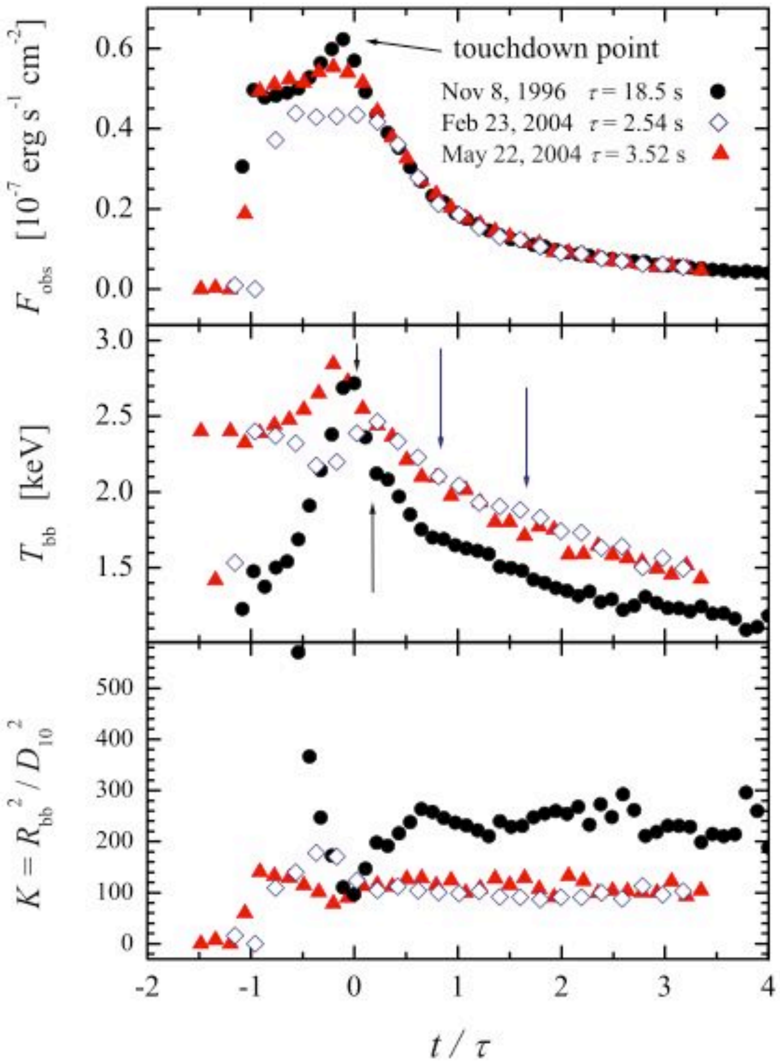
Three curves on *M-R* plane

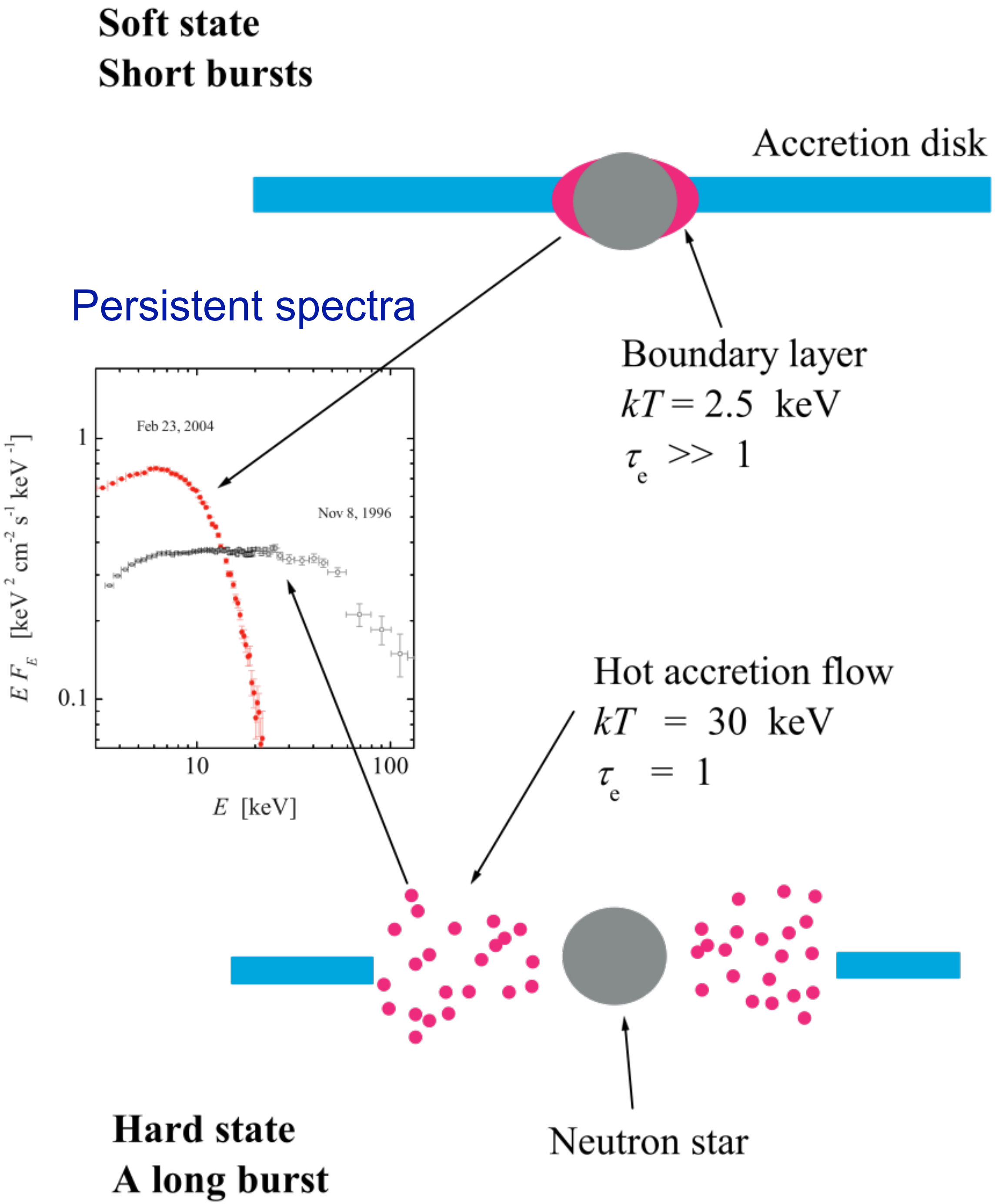


$$T_{\mathrm{Edd},\infty} = \left(\frac{gc}{\sigma_{\mathrm{SB}}\kappa_{\mathrm{e}}}\right)^{1/4} \frac{1}{1+z} = 6.4 \times 10^9 \, A \, F_{\mathrm{Edd}}^{1/4} \, \mathrm{K}.$$

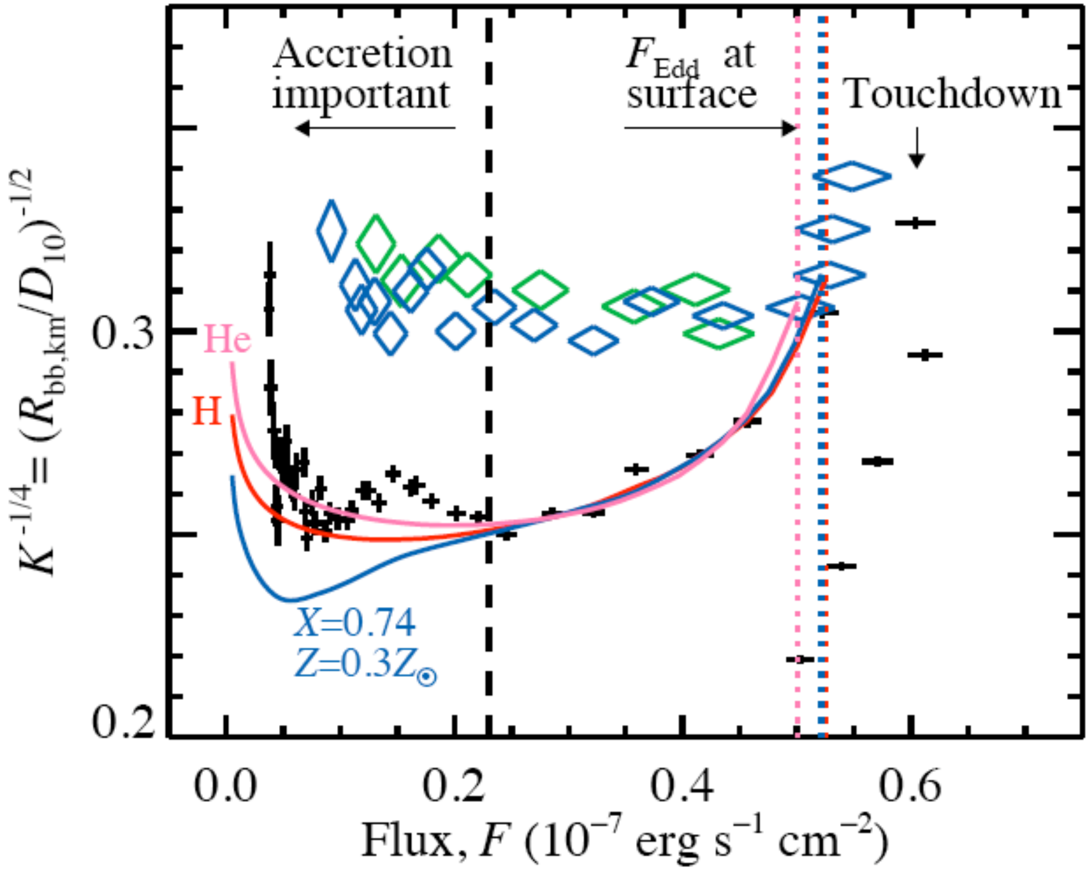
Two states of LMXB and Two types PRE bursts

4U 1724-307





Cooling tails of PRE bursts from 4U 1724-307



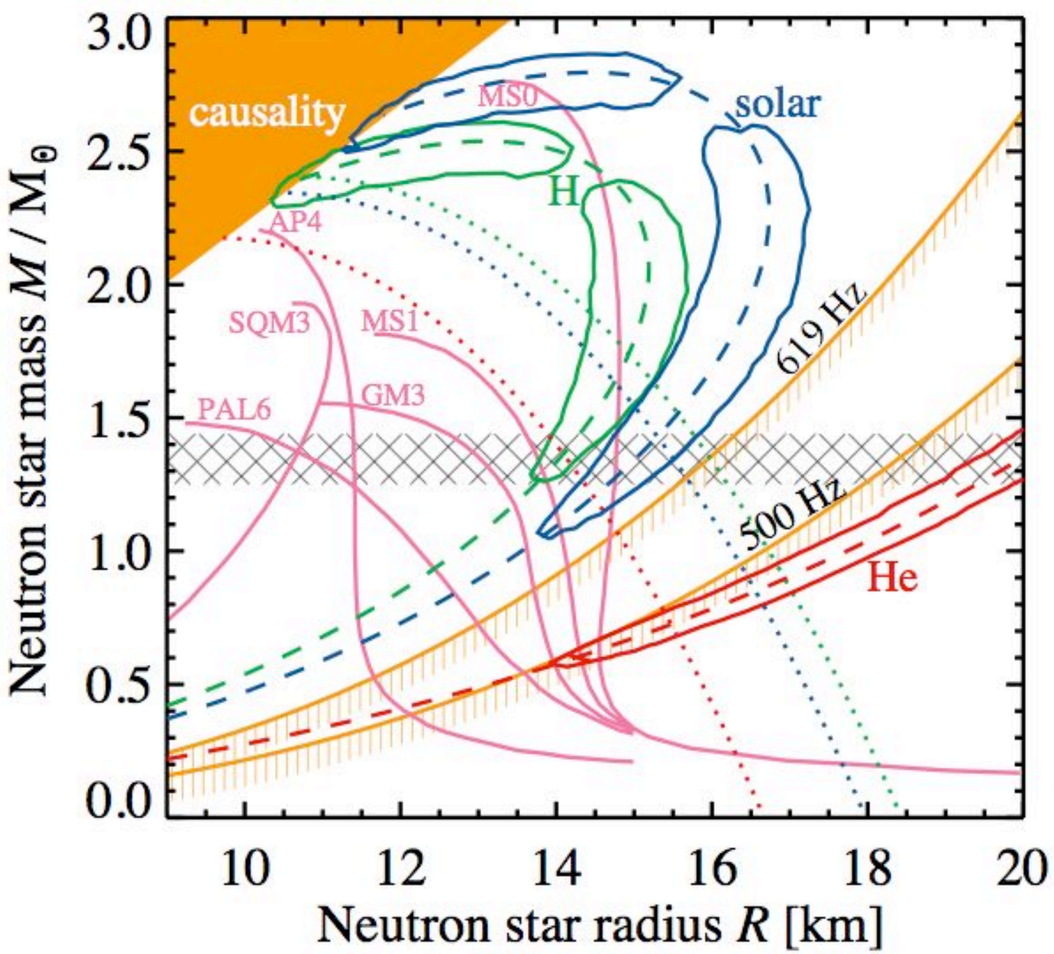
Suleimanov et al. (2011)

- Crosses: Long, >150 sec, PRE burst during hard/low state on Nov 8, 1996.
- Diamonds: two short PRE bursts on Feb 23 and May 22, 2004 during soft state.
- Spectral evolution is spectacularly different!

M-R relation - 4U 1724-307

- From the best-fit *A* and F_{Edd}, we can get constraints on *M* and *R* if we assume some distance distribution (we take flat in 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.

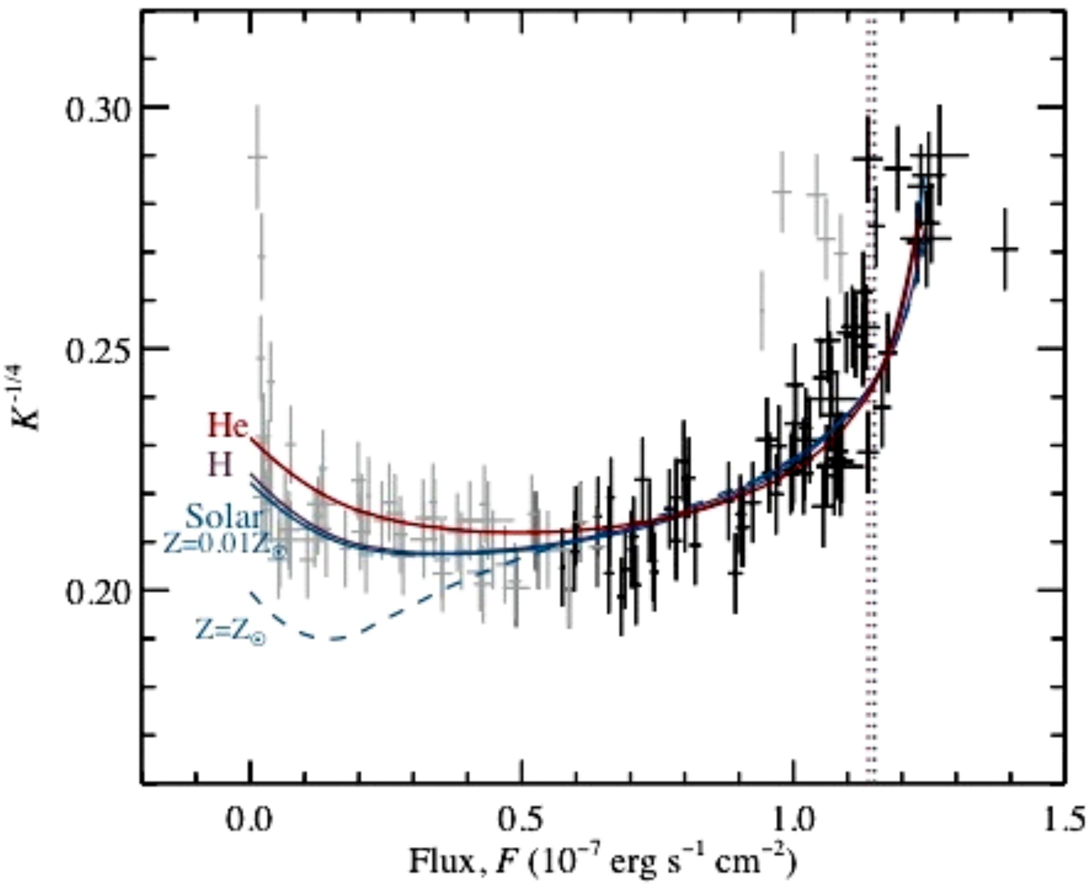


Contours are elongated along T_{Edd}=const track

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

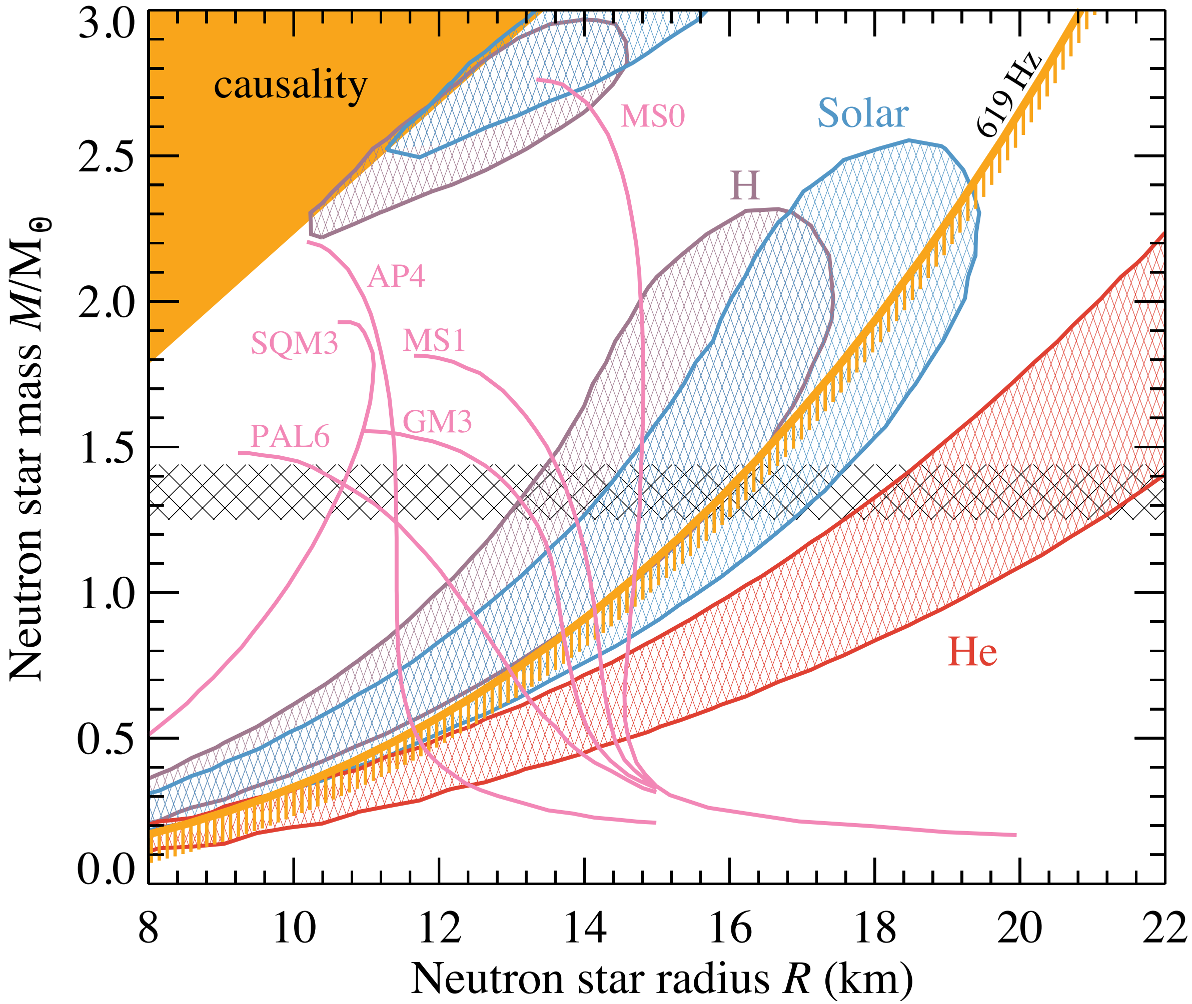
Cooling tails of PRE bursts from 4U 1608-52

Bursts in hard persistent states are taken



Poutanen et al. 2012 (in preparation)

M-R relation - 4U 1608-52



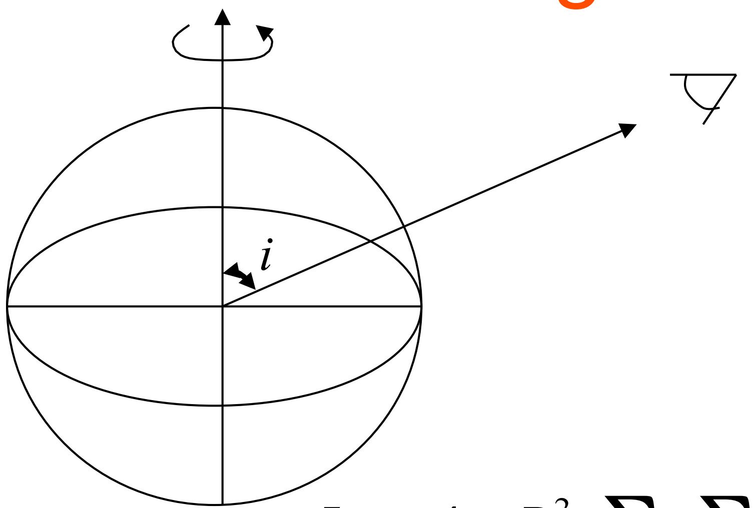
Results are similar to 4U 1724-307

Poutanen et al. 2012 (in preparation)

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).

Integration over NS surface



Gravitational redshift, light bending
and relativistic Doppler effect are included

(see Poutanen & Gierlinski 2003)

$$L_E = 4\pi\ R_{NS}^2 \sum_j \sum_i \eta^3 \delta_{ij}{}^3 I_{E'}(\cos\alpha_{ij}', \theta_i) \cos\alpha_{ij}' \cos\theta_i\ \Delta\theta_i \Delta\varphi_j$$