Modelling the energy spectra of accreting X-ray pulsars at low accretion rate

Ekaterina Sokolova-Lapa

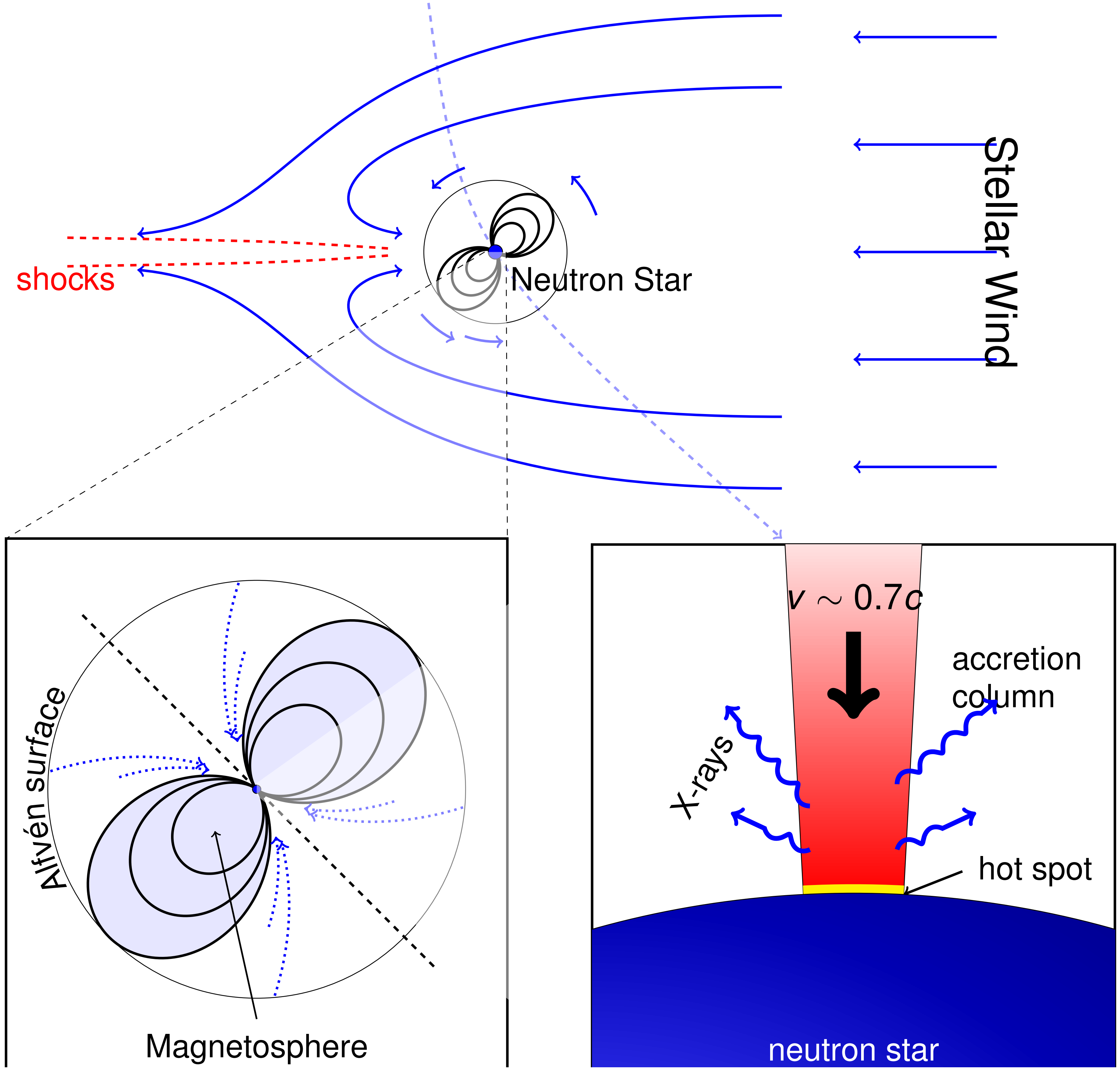
Dr. Remeis-Observatory & Erlangen Centre for Astroparticle Physics
University of Erlangen-Nuremberg

in collaboration with

M. Gornostaev (SAI MSU), S. Falkner (ECAP), J. Wilms (ECAP),
K. Postnov (SAI MSU), R. Ballhausen (ECAP), F.-W. Schwarm (ECAP),
F. Fürst (ESAC)

Karlovy Vary 2019

Neutron star
High-mass X-ray binaries



Wilms 2014, after Davidson & Ostriker, 1973

Magnetic Compton scattering

Strong B-field at NS poles:
quantisation of electron energies $\perp$ B-field lines

$$E_n = m_e c^2 \frac{\sqrt{1 + 2n(B/B_{crit})\sin^2\theta} - 1}{\sin^2\theta}$$

n - major quantum number

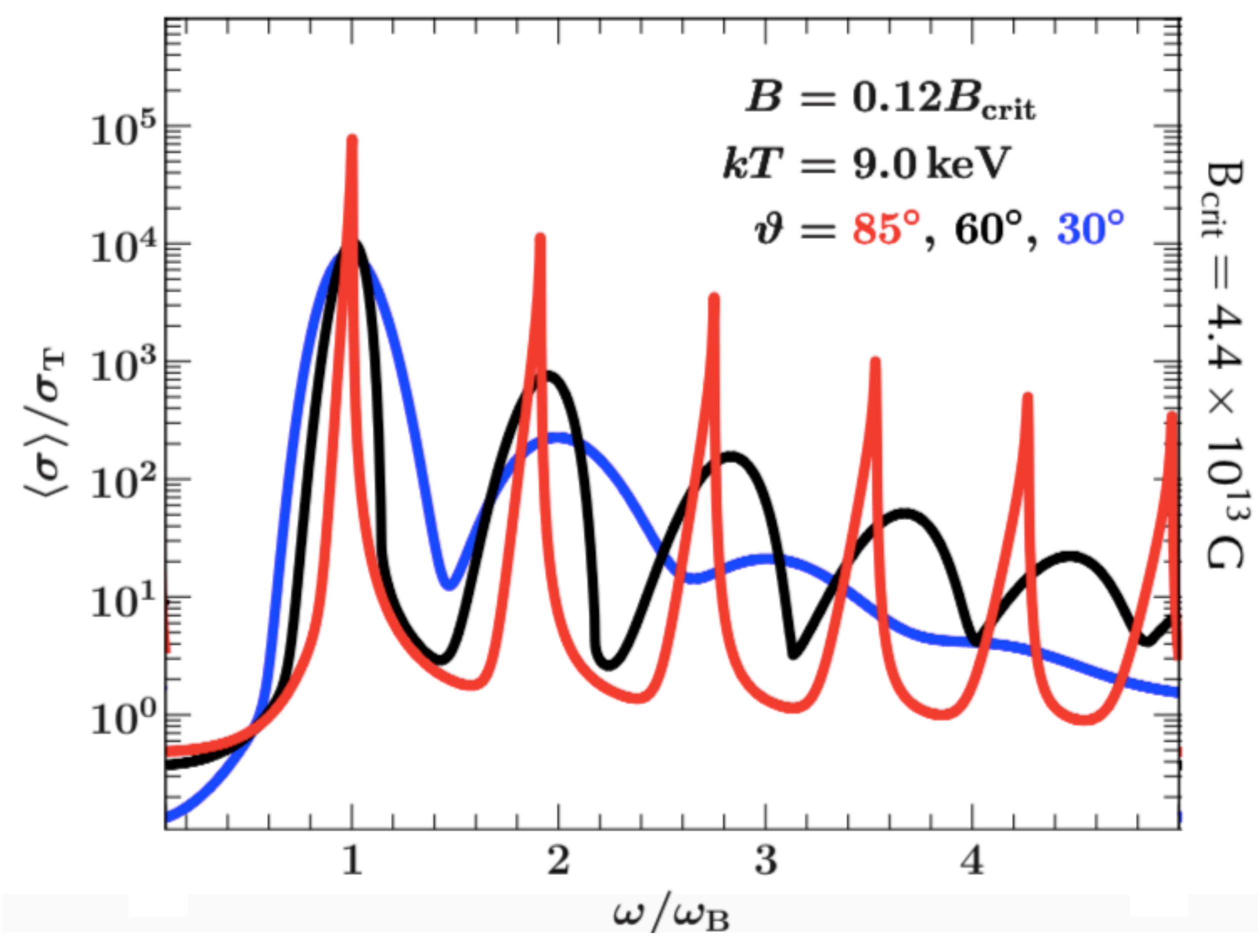
θ - angle between B-field and the photon propagation direction

$$B_{crit} = \frac{m_e^2 c^3}{e\hbar} \sim 4.4 \times 10^{13}\ \mathrm{G}$$

magnetic Compton scattering cross section

$$\langle \sigma(E,\theta) \rangle_{f_e} = \int_{-\infty}^{+\infty} \mathrm{d}p f_e(p,T)(1 - \beta\cos(\theta))\sigma_{rf}(E_{rf}, \theta_{rf})$$

$f_e(p,T)$ - relativistic Maxwellian distribution

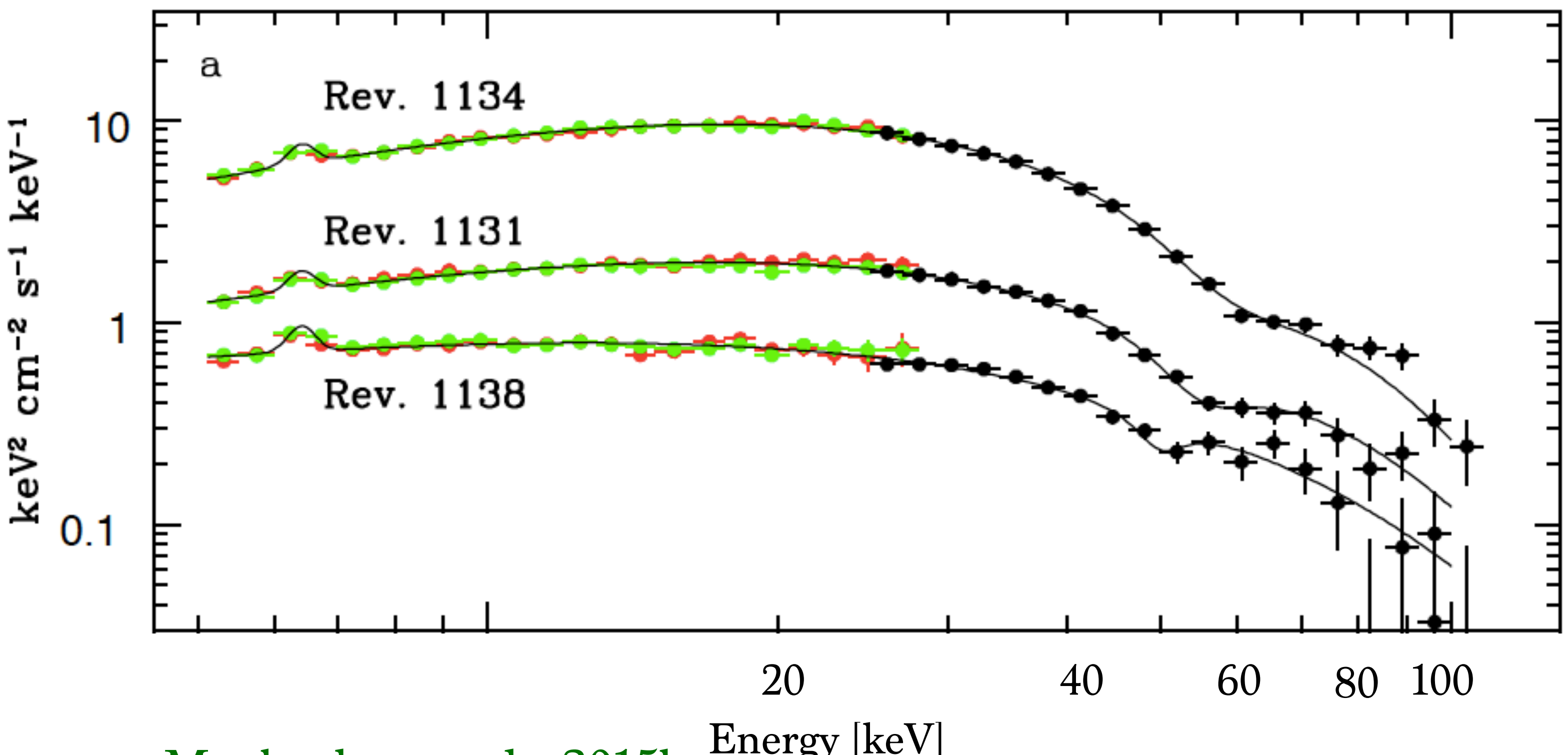


Schwarm et al., 2017a

ω_B – cyclotron frequency

Observations
spectral energy distribution

GX 304-1



Mushtukov et al., 2015b

X-ray spectral shape:

- Power low continuum with exponential cutoff
  (due to Compton scattering)
- Cyclotron line in absorption
  (due to strong B-field)
- Strong Fe Kα line at 6.4 ... 6.7 keV
  (due to fluorescence in circumstellar material)

Empirical continuum shape:

$$\mathrm{CUTOFFPL}: F_{\mathrm{ph}} \propto E^{-\Gamma} \exp(-E/E_{\mathrm{fold}})$$

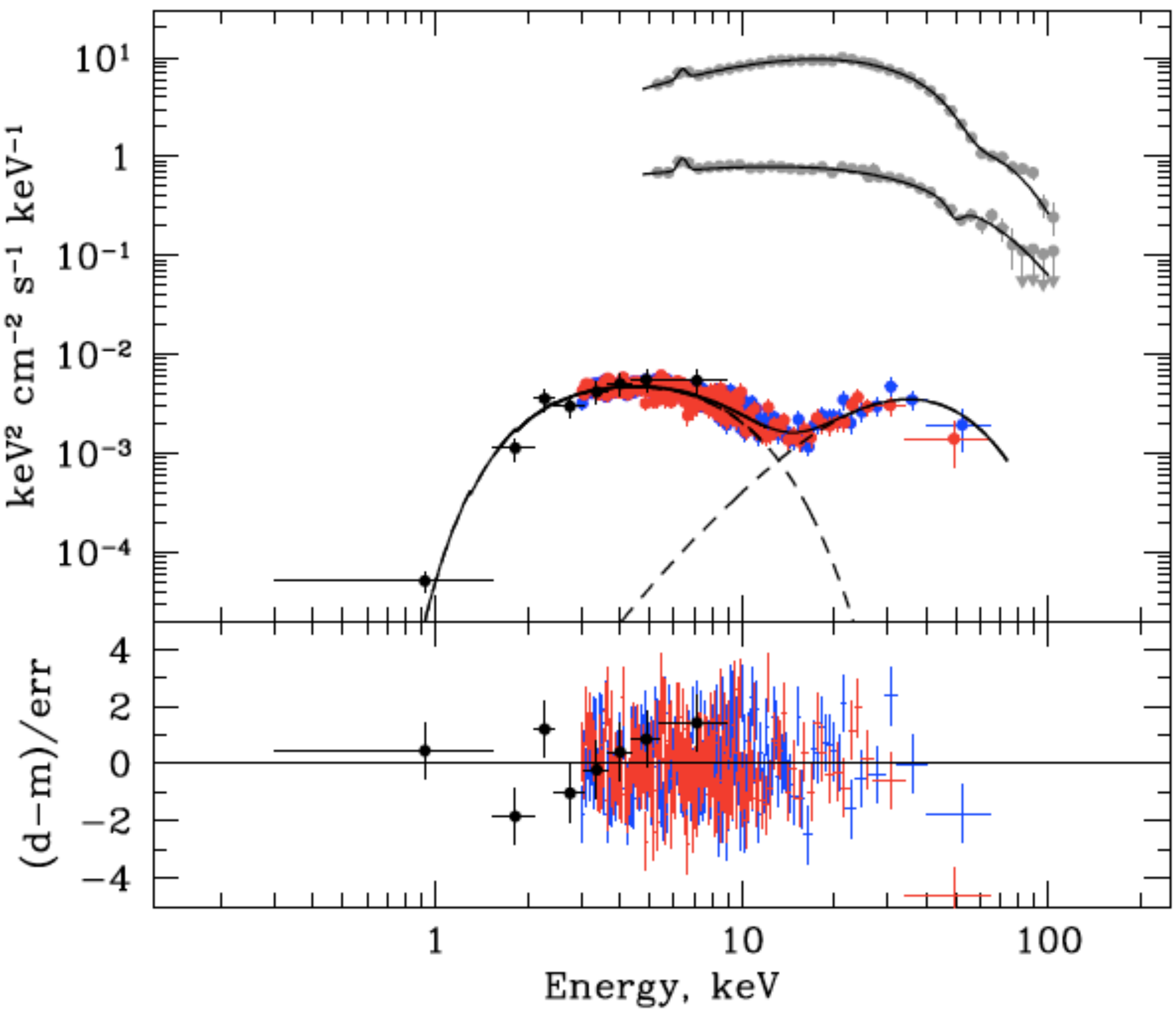
$$\mathrm{FDCUT}: F_{\mathrm{ph}} \propto E^{-\Gamma} \frac{1}{1+\exp((E-E_{\mathrm{cut}})/E_{\mathrm{fold}})}$$

$$\mathrm{NPEX}: F_{\mathrm{ph}} \propto (A_p E^{+\Gamma_1} + A_n E^{-\Gamma_2}) \exp(-E/E_{\mathrm{fold}})$$

Low accretion regime

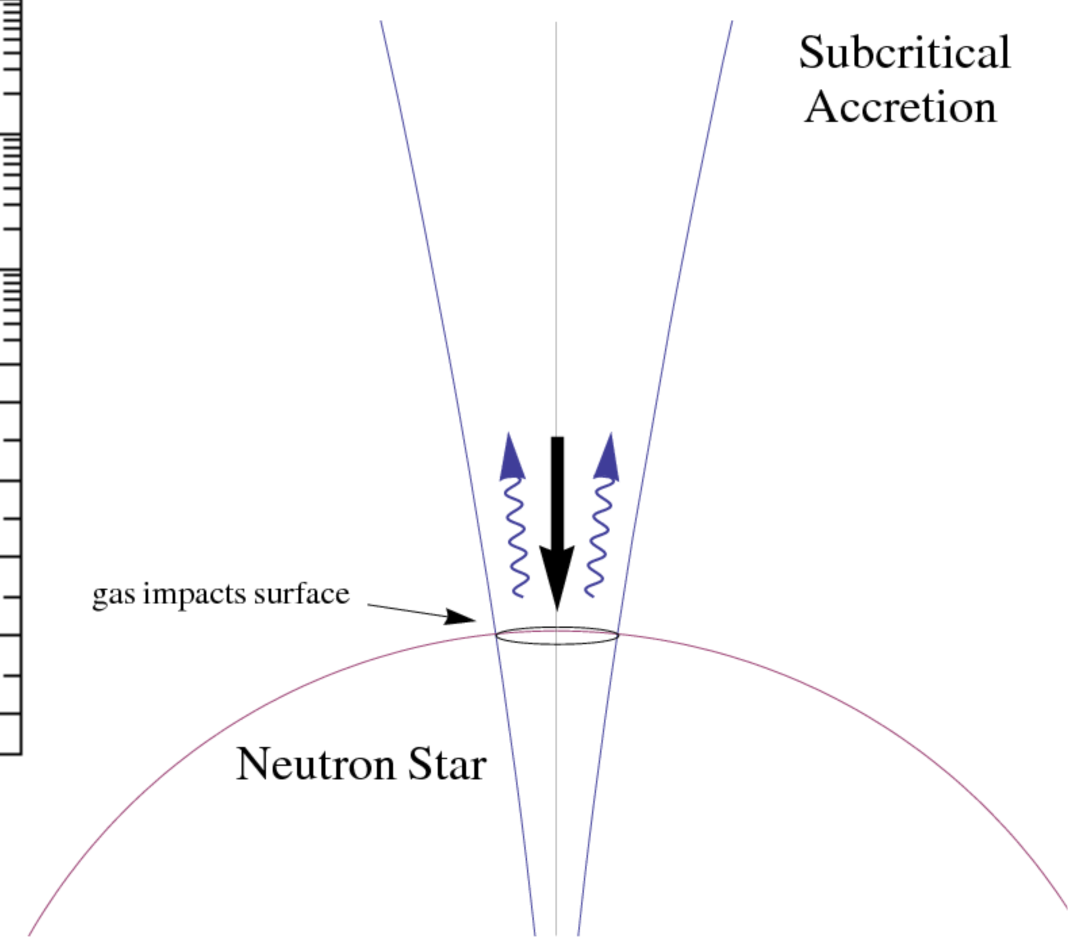
GX 304-1 observation by NuSTAR and Swift/XRT

Puzzling bimodal behaviour of GX 304-1 observed simultaneously by NuSTAR and Swift/XRT at lowest luminosity ever ($L \sim 10^{34}$ erg s^{-1}).



GX 304-1 by Tsygankov et al., 2019

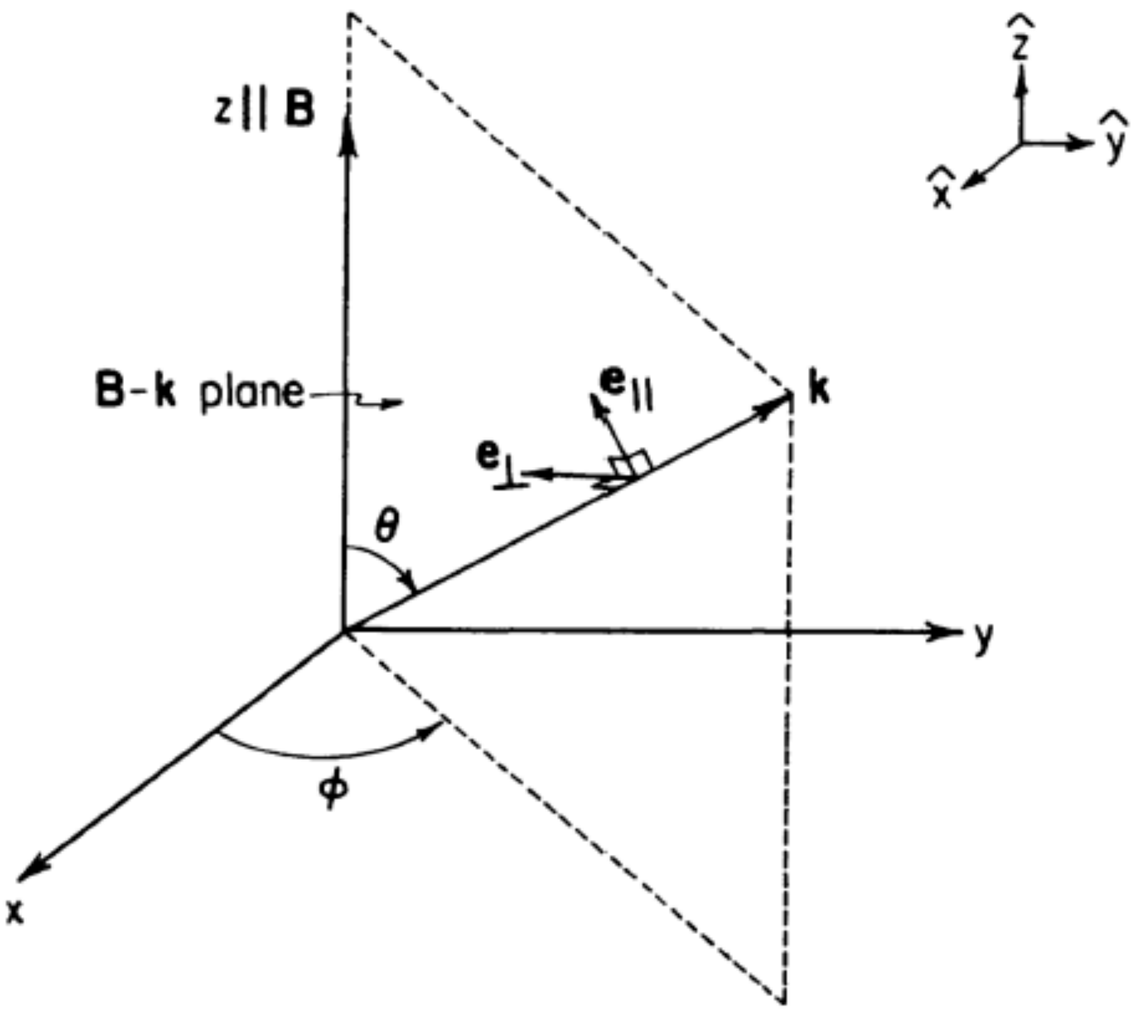
- cyclotron line at 15 keV?
- cyclotron emission?
- two polarized components?
  Lyubarskii 1988(a,b)



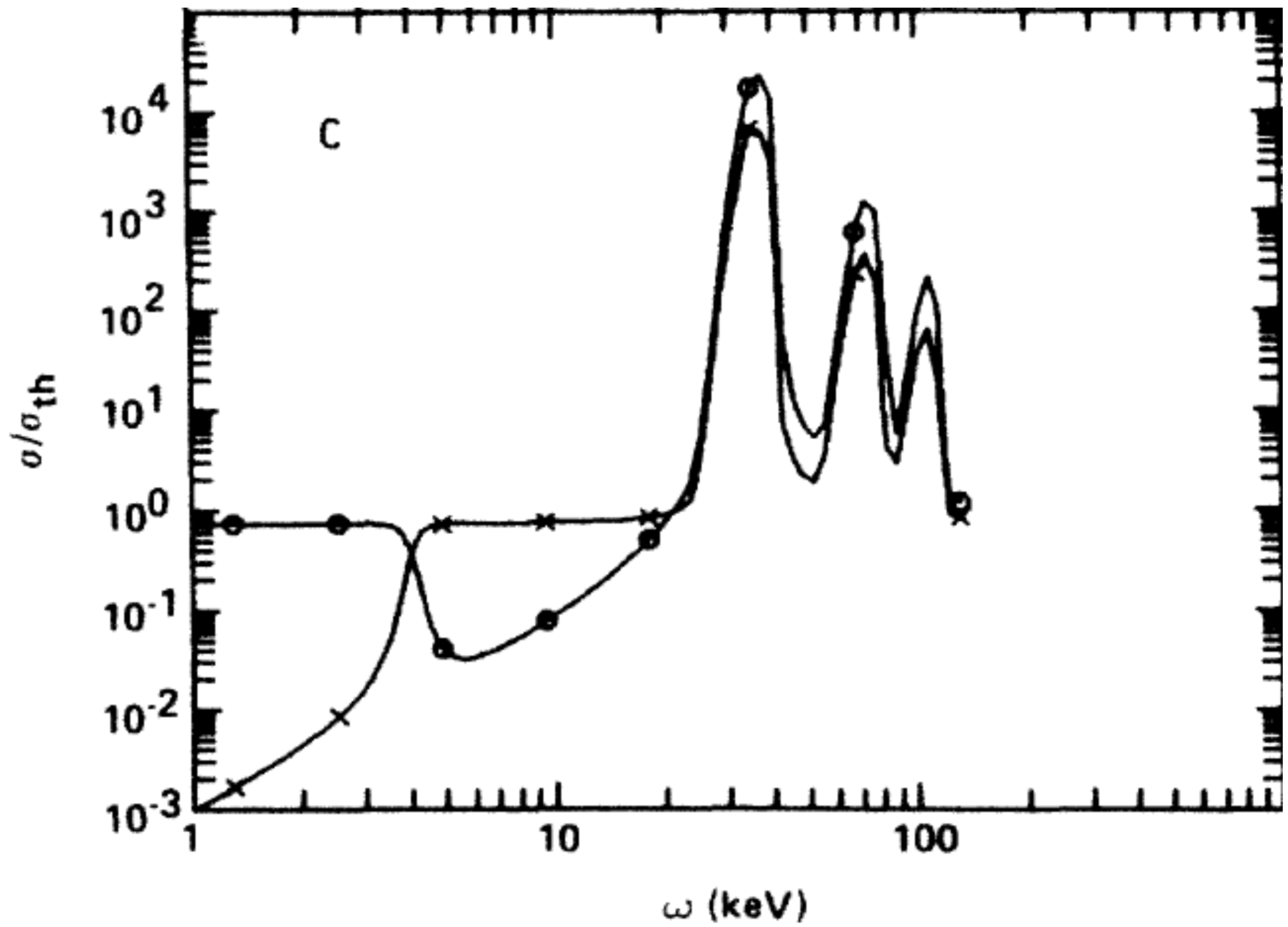
Becker et al., 2012

Low accretion regime
photon polarization modes

$e_{\parallel}$ – ordinary photons
$e_{\perp}$ – extraordinary photons



Wang et al., 1988



Cross section for two photon modes from Bussard et al., 1986

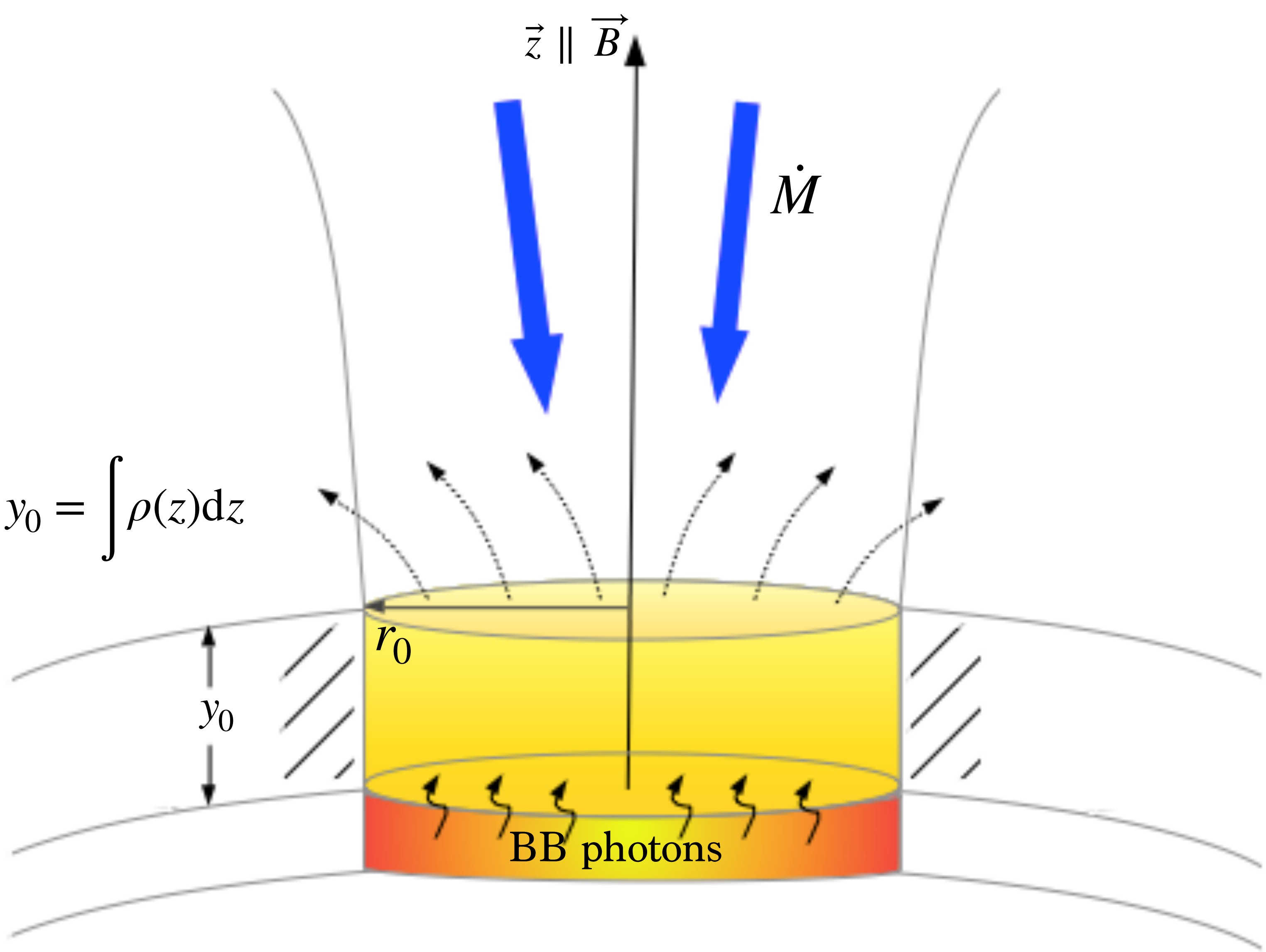
Low accretion regime
Atmosphere model

1D polarized radiative transfer

$$\frac{\mu^2}{\kappa}\frac{\partial^2 u_{\rm p}(E,\mu,z)}{\partial z^2} - \kappa u(E,\mu,z) + 4\pi \sum_{\rm p'=1,2} \int\int d\mu' dE' \frac{d^2\sigma_{\rm pp'}}{dE d\mu}(E,\mu \leftarrow E',\mu')\frac{E}{E'}u_{\rm p'}(E',\mu',z) + \alpha_{\rm ff}B(E) = 0$$

$\rm p = 1$ (extra), 2 (ord) $\quad \kappa = \kappa(E,\mu,z) = \sigma(E,\mu,z) + \alpha_{\rm ff}(E,\mu,z) \quad \mu = \cos\theta$

solved by Feautrier method



parameters of the model "polcap":

- $\dot{M}$ – accretion rate
- y_0 – total column density
- r_0 – polar cap radius
- B_0 – Bfield at the surface
- $T_{\rm BB}$ – seed BB photons temperature

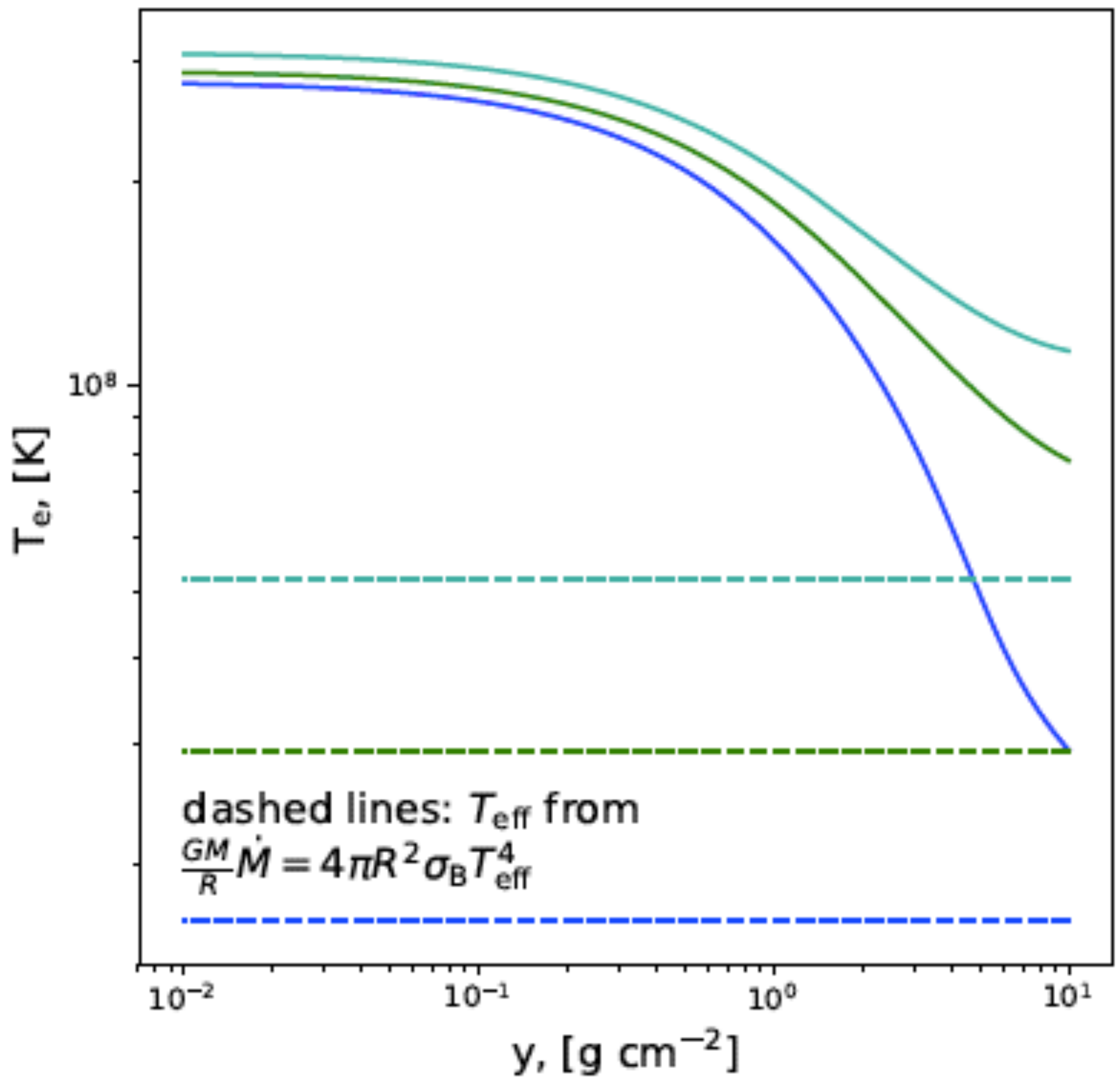
Low accretion regime
Atmosphere model

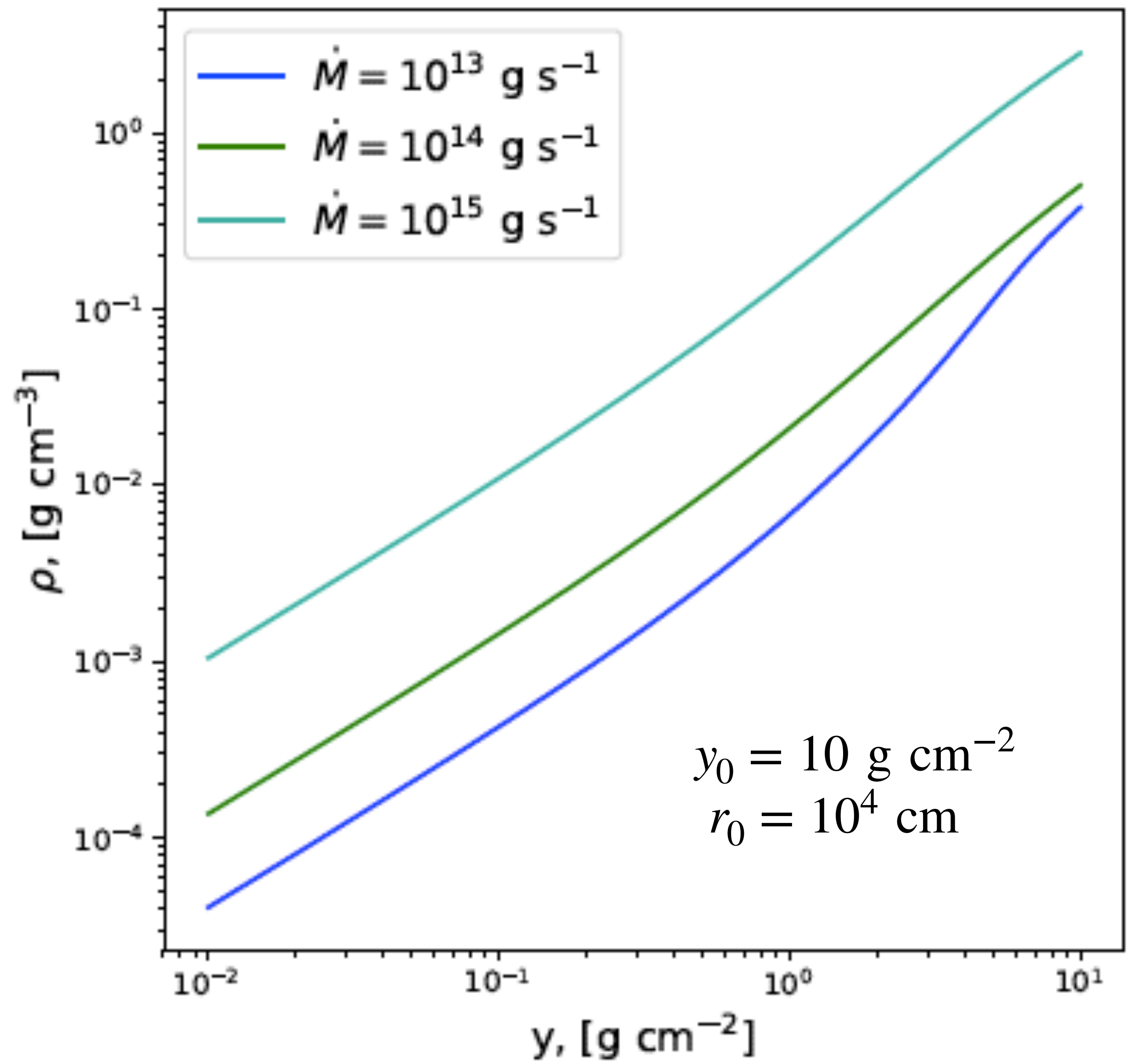
Energy balance equation
+
eq. of hydrostatic equilibrium

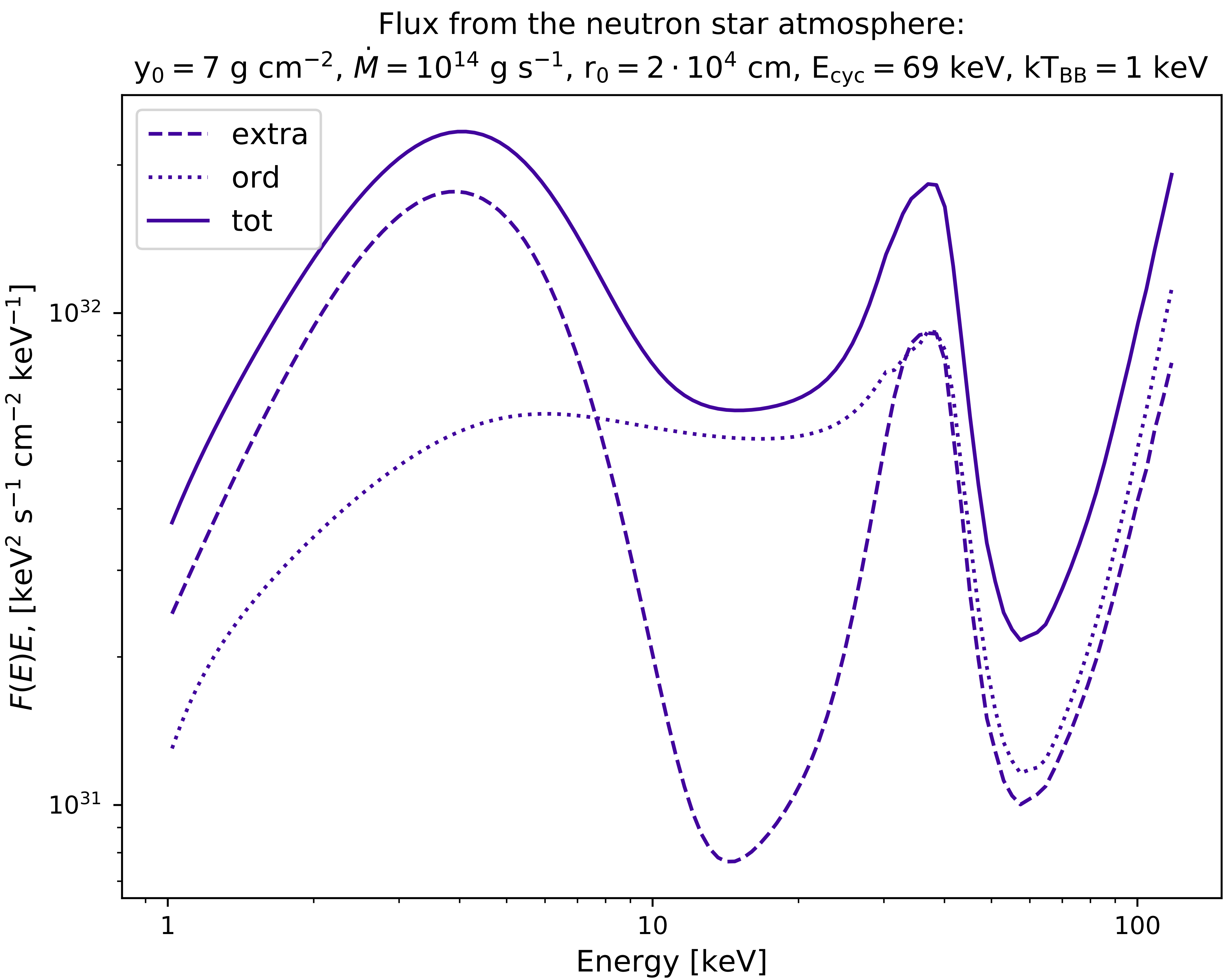
→

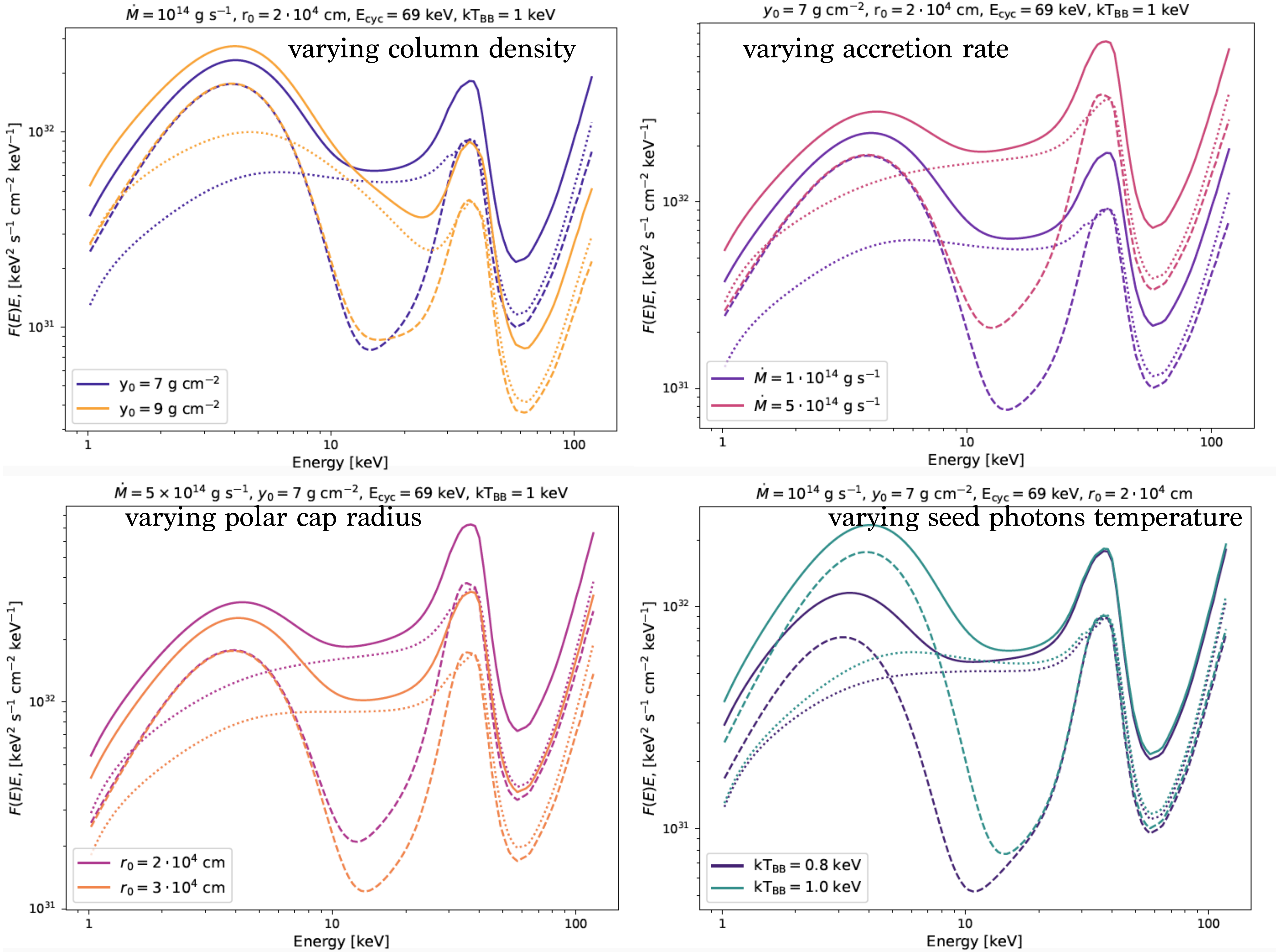
electron temperature and density profile

Zel'dovich & Shakura 1969



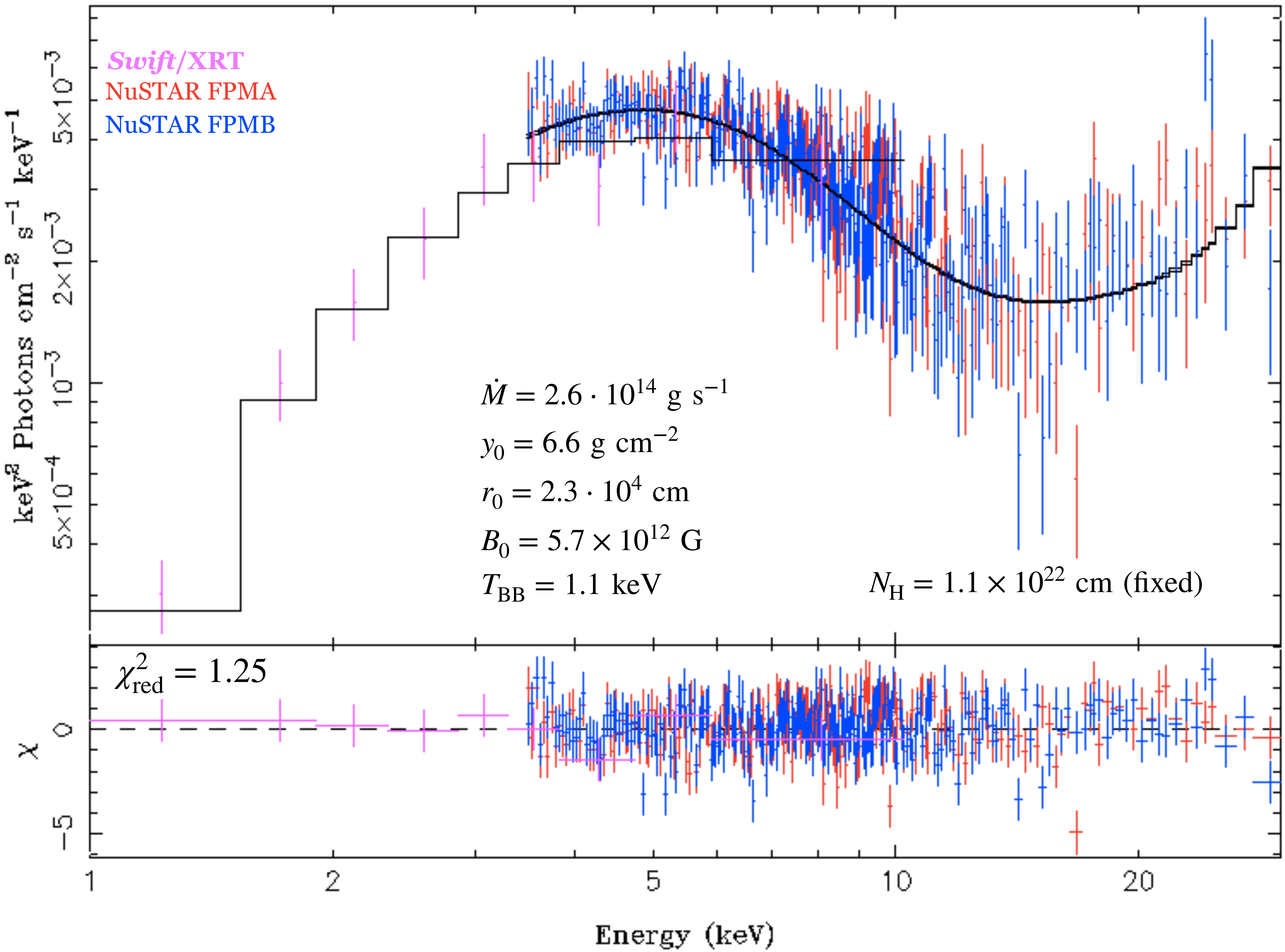



Flux from the neutron star atmosphere:
$y_0 = 7$ g cm^{-2}, $\dot{M} = 10^{14}$ g s^{-1}, $r_0 = 2 \cdot 10^4$ cm, $E_{cyc} = 69$ keV, $kT_{BB} = 1$ keV
extra
ord
tot
10^{32}
10^{31}
$F(E)E$, [keV^2 s^{-1} cm^{-2} keV^{-1}]
1
10
100
Energy [keV]



$\dot{M} = 10^{14}$ g s^{-1}, $r_0 = 2 \cdot 10^4$ cm, $E_{cyc} = 69$ keV, $kT_{BB} = 1$ keV
varying column density
$y_0 = 7$ g cm^{-2}
$y_0 = 9$ g cm^{-2}
$y_0 = 7$ g cm^{-2}, $r_0 = 2 \cdot 10^4$ cm, $E_{cyc} = 69$ keV, $kT_{BB} = 1$ keV
varying accretion rate
$\dot{M} = 1 \cdot 10^{14}$ g s^{-1}
$\dot{M} = 5 \cdot 10^{14}$ g s^{-1}
$\dot{M} = 5 \times 10^{14}$ g s^{-1}, $y_0 = 7$ g cm^{-2}, $E_{cyc} = 69$ keV, $kT_{BB} = 1$ keV
varying polar cap radius
$r_0 = 2 \cdot 10^4$ cm
$r_0 = 3 \cdot 10^4$ cm
$\dot{M} = 10^{14}$ g s^{-1}, $y_0 = 7$ g cm^{-2}, $E_{cyc} = 69$ keV, $r_0 = 2 \cdot 10^4$ cm
varying seed photons temperature
$kT_{BB} = 0.8$ keV
$kT_{BB} = 1.0$ keV
$F(E)E$, [keV^2 s^{-1} cm^{-2} keV^{-1}]
Energy [keV]
10^{31}
10^{32}
1
10
100

tbnew_simple * detconst * polcap



Summary

- The presented model for polar cap emission of the accreting magnetized neutron star is intended to explain the peculiar two-component spectrum observed at low luminous state of the X-ray pulsar GX 304-1

- The spectral shape can be explained by contribution of two polarization photon modes

- What can be done next:

  investigation of the parameter space of the table model, finding the parameter constraints

  applying more sophisticated atmosphere model

  including light-bending effect and geometry of the emission regions to analyze phase-resolved spectra and model the pulse-profile