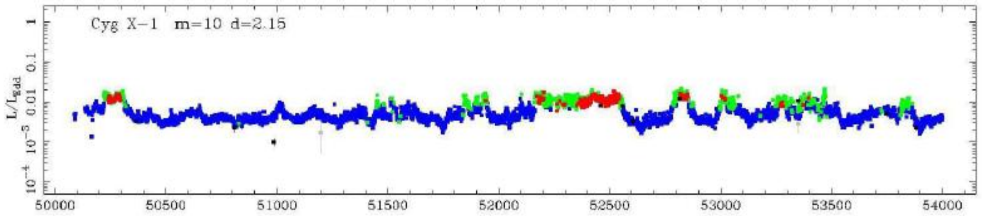
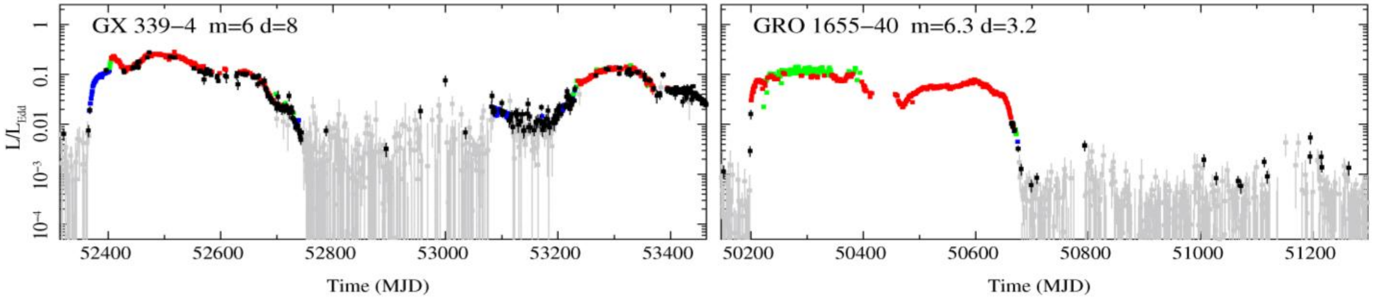
X-ray spectropolarimetric insights into the inner regions of accretion flows

Andrzej Niedźwiecki
University of Łódź, Poland

Black-hole X-ray binaries

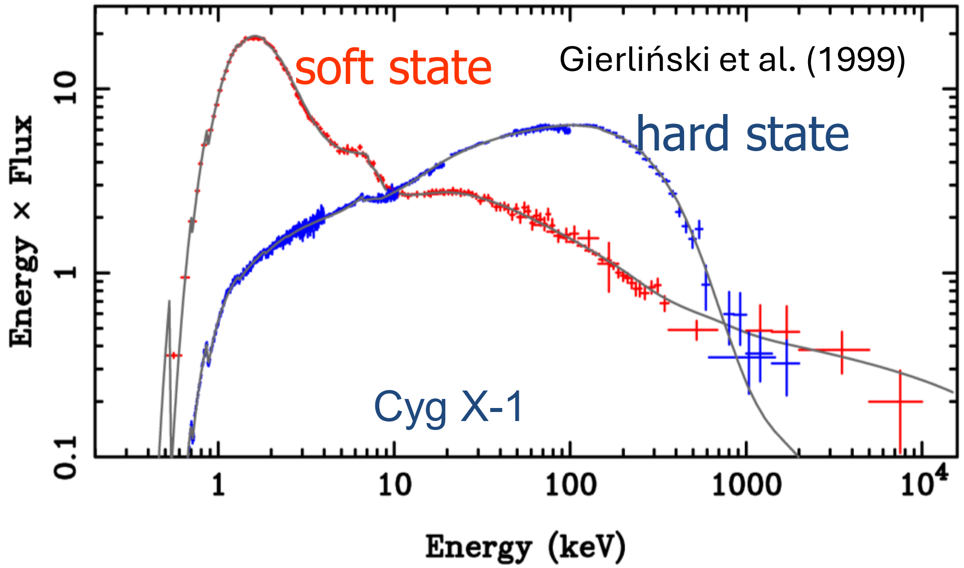
light curves in soft X-rays (Done, Gierliński, Kubota 2007)

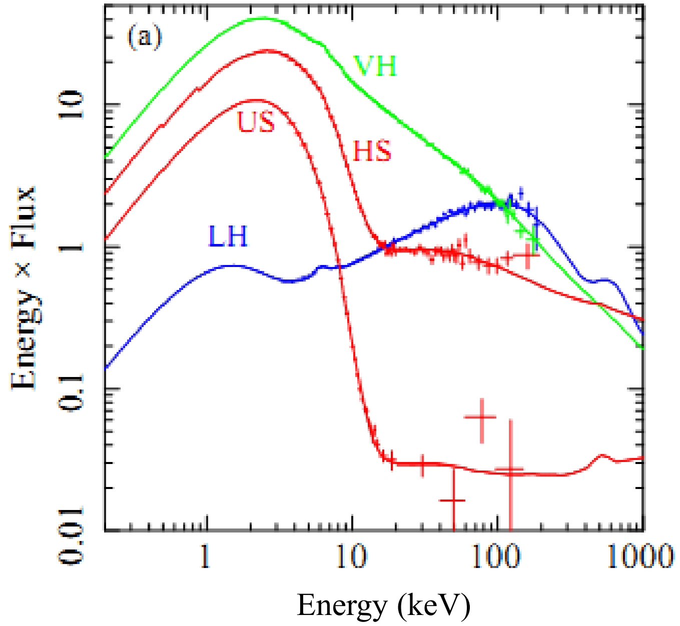




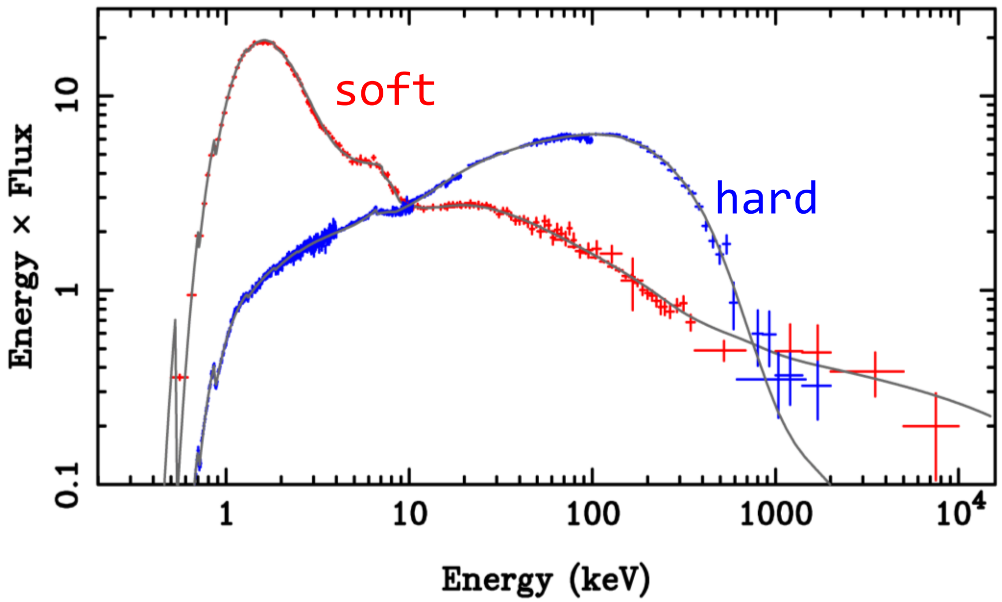
High-mass companion, persistent X-ray emission

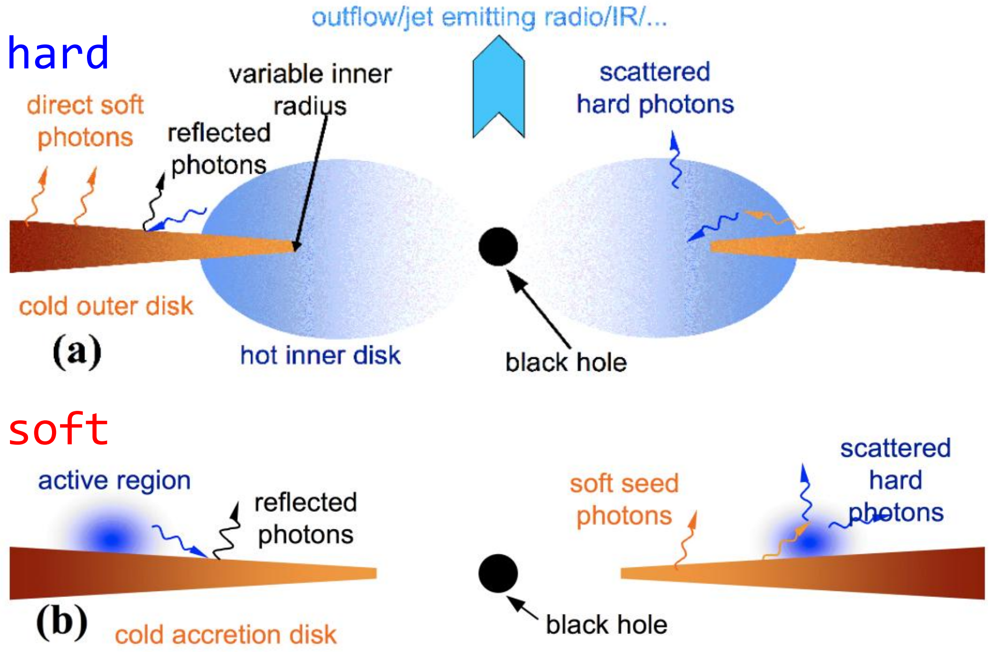
Low-mass companion, transient X-ray





tentative geometries





Zdziarski & Gierliński (2004)

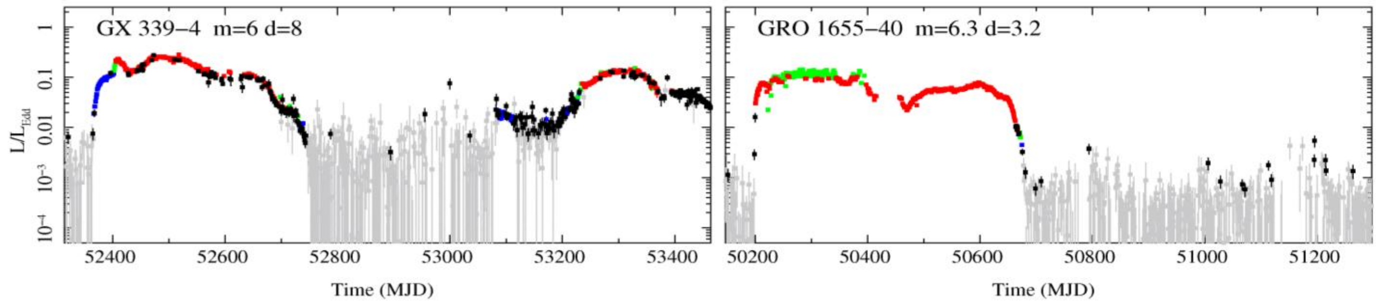
Soft: optically thick down to the ISCO (Shakura & Sunyaev 1973, Novikov & Thorne 1974) with magnetic flares (e.g. Galeev, Rosner, Vaiana 1979)

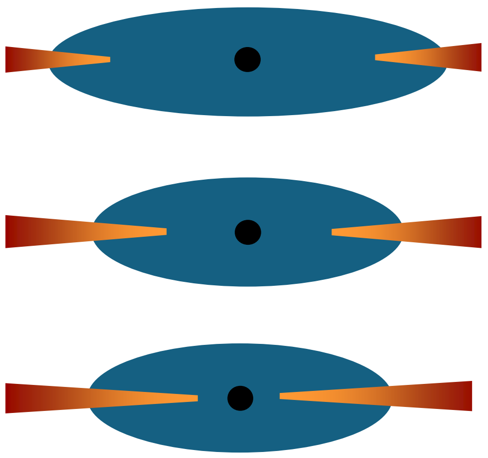
Hard: transition to an optically thin, hot accretion flow (Shapiro, Lightman Eardley 1976, Narayan et al. 90's), exist below a few % of L_{Edd}, large scale magnetic field may be important (GRMHD)

Natural association of the hard-soft transition with the disk reaching the ISCO

But: mechanism of transition unclear, challenged by claims of the presence of the untruncated disk in the hard state

Spectral evolution of transients





Varying truncation radius of the disk (e.g. Esin et al. 1997, Done et al. 2007) consistent with:

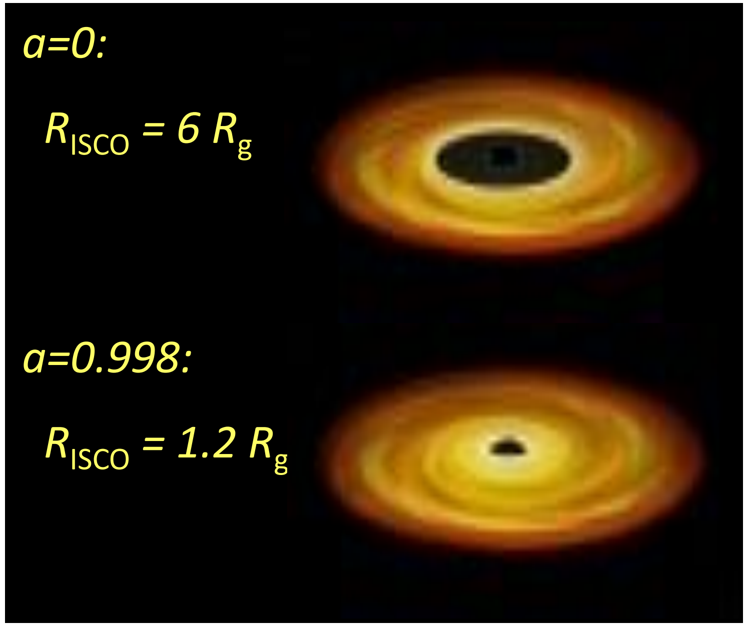
- an increase in the amount of reflection correlated with L,
- an increase in the broadening of reflection features correlated with L,
- characteristic frequencies in the power spectra increasing with L and correlated with the energy spectra

But

- S&S1973 disk (with the heating depending on the total pressure) are should be unstable at $L/L_{Edd} \geq 0.05$ (when radiation pressure dominates over gas pressure inside the disk) giving rise to strong limit cycle variabilty on the time scale of an hour – not observed (GRS1915+104, 4U1630 show such behaviour but at $\sim L_{Edd}$)
- hard states observed at high luminosities (only on the rise to the outburst peak), ~0.3 L_{Edd}, at which hot flow should collapse – supported by large scale magnetic field?
- claims of the presence of the untruncated disk in the hard state (lamp-post model)

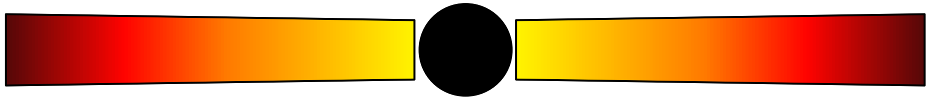
Black hole spin estimations

- Thermal disk spectrum
- Reflection spectrum
- Polarization (returning radiation)

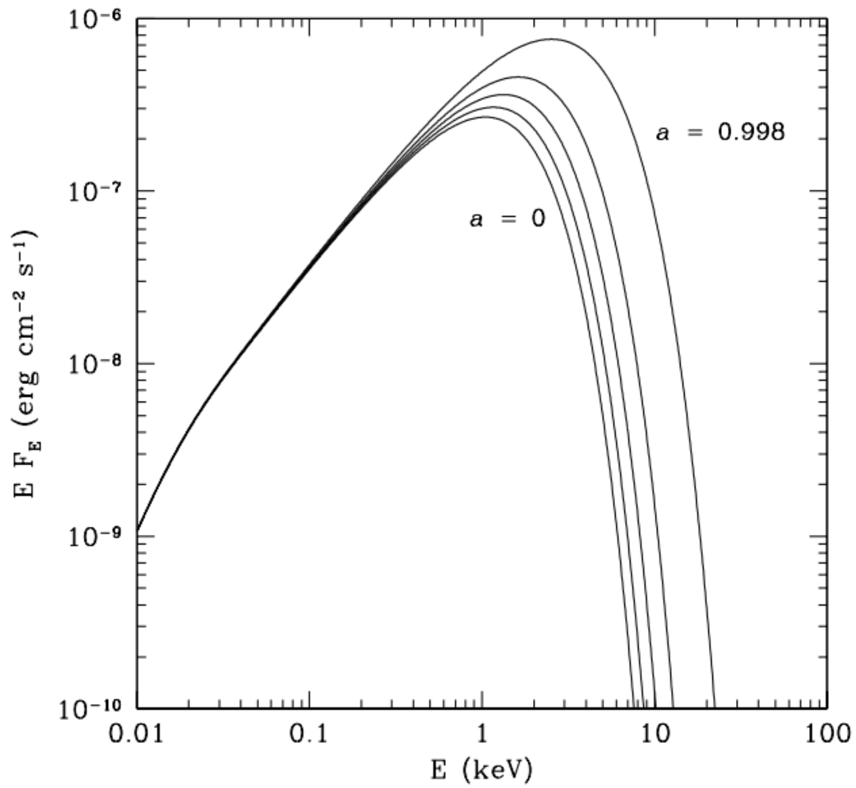


$$a = \frac{J}{cMR_g} \qquad R_g = \frac{GM}{c^2}$$

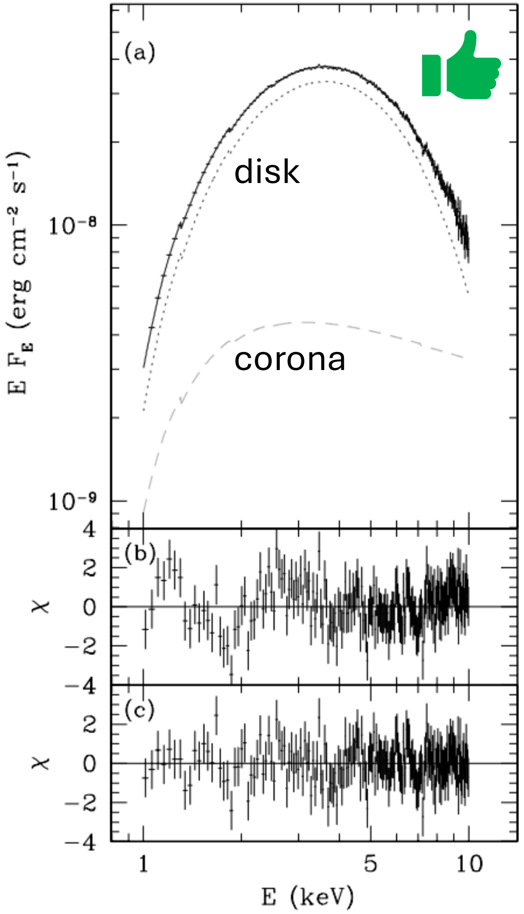
Thermal disk spectrum

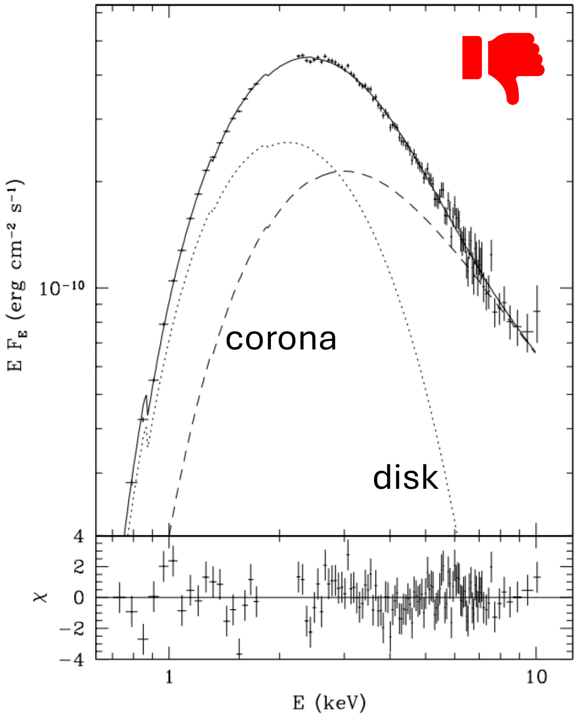


multi-color BB emission of a Keplerian disk



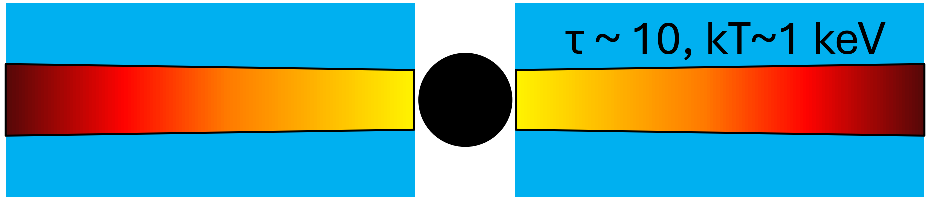
only works for a "clean" disk component



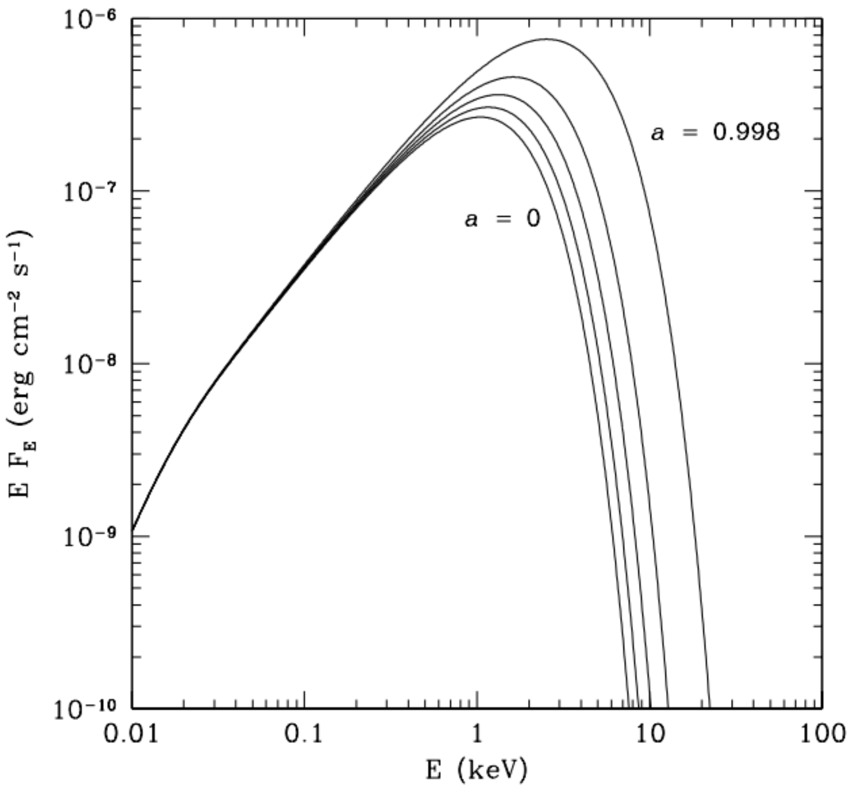


Gierliński, Niedźwiecki, Ebisawa (1999)

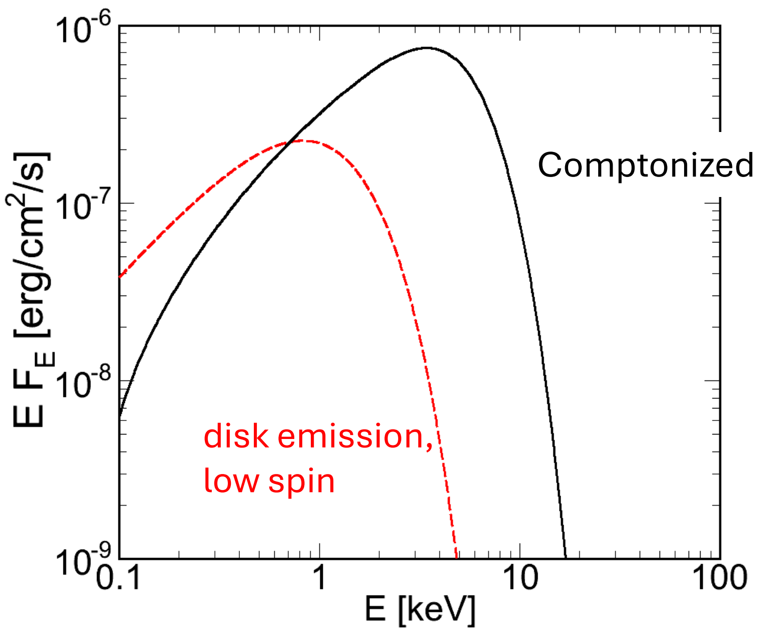
But do we ever observe a "clean" disk component?



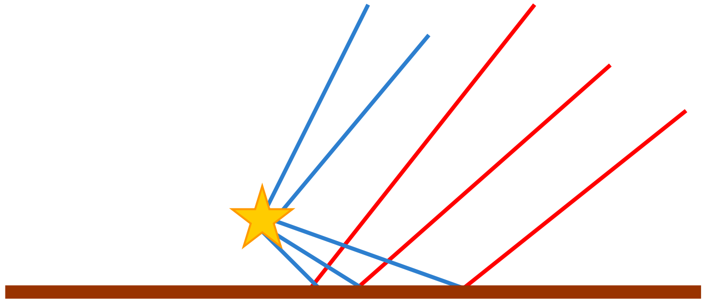
Presence of a dissipative, warm corona has theoretical (MHD simulations) and observational (soft excess) suport and alleviates the problems associated with the observed absence of radiation-pressure instability.

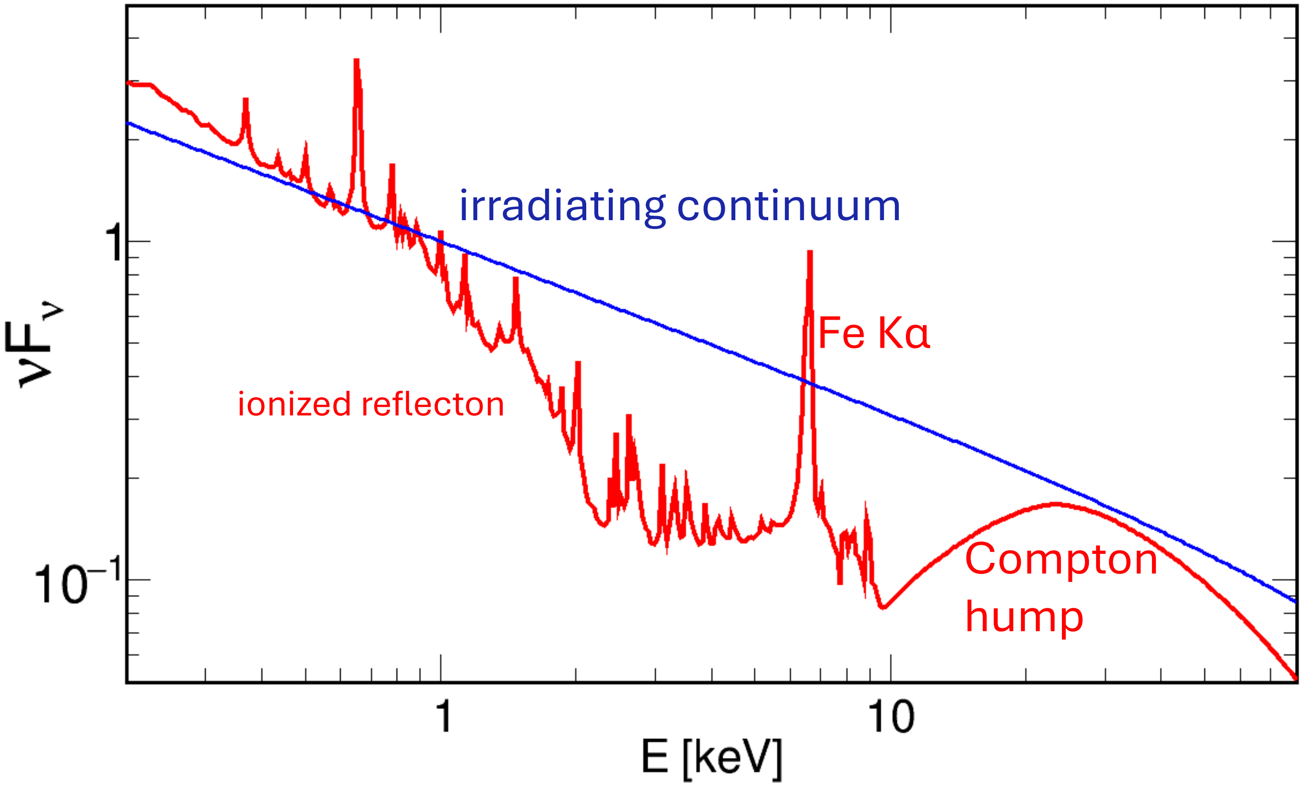


Belczynski+ (2024), Zdziarski+ (2024, 2025): optically thick Comptonization mimics the high-spin BH disk

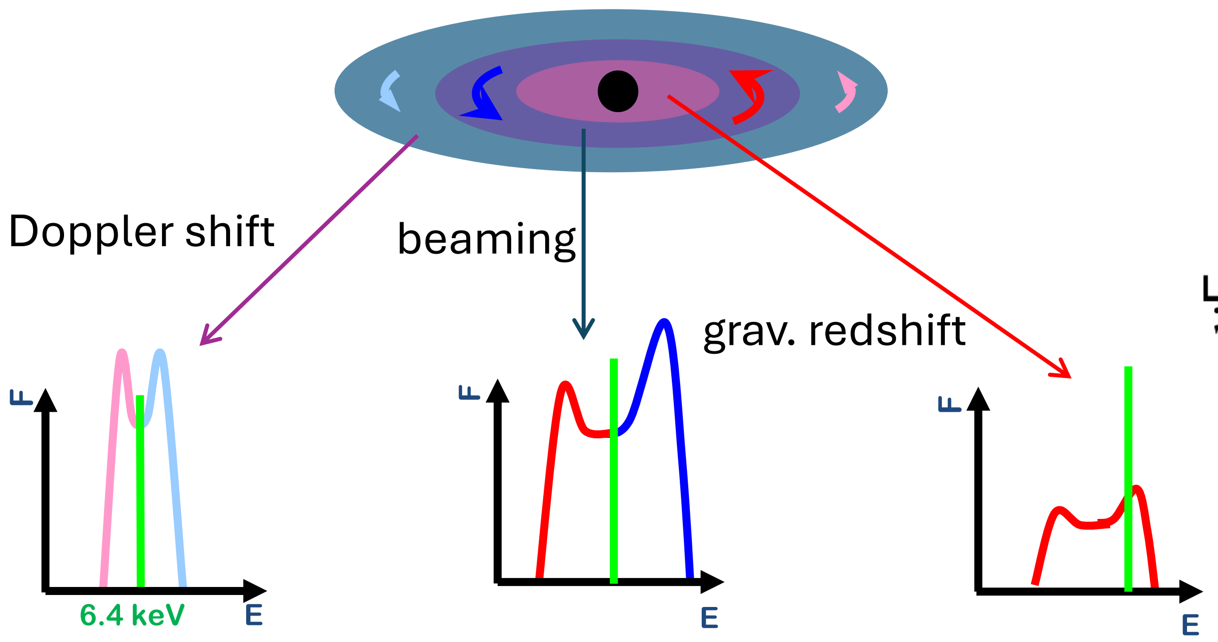


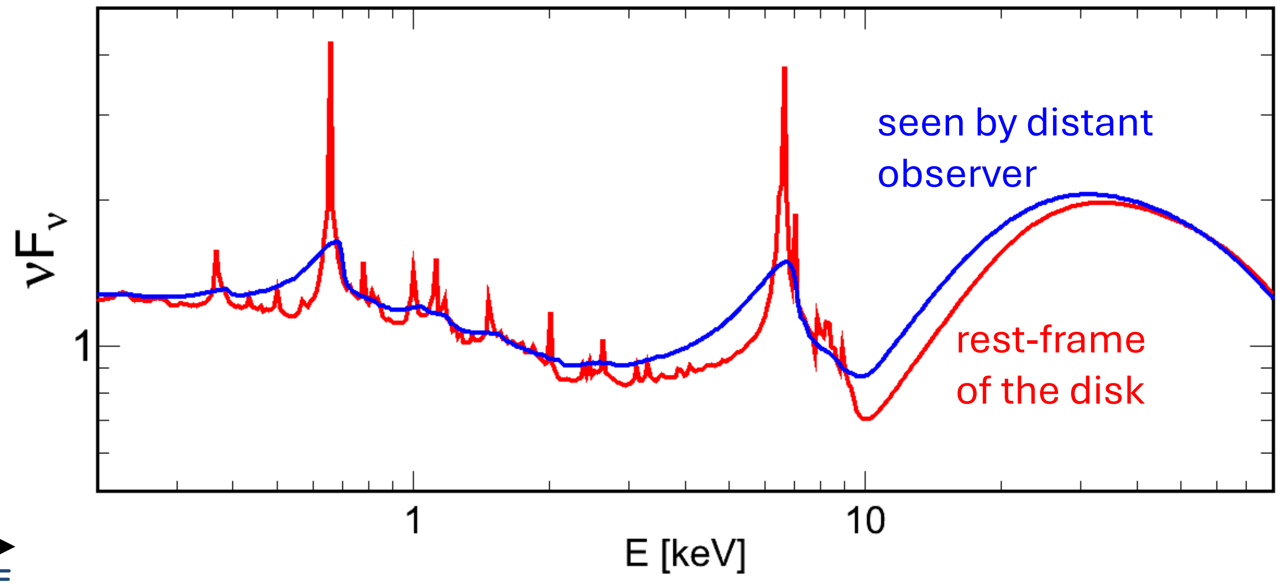
X-ray reflection





Reflection from disc: relativistic distortion

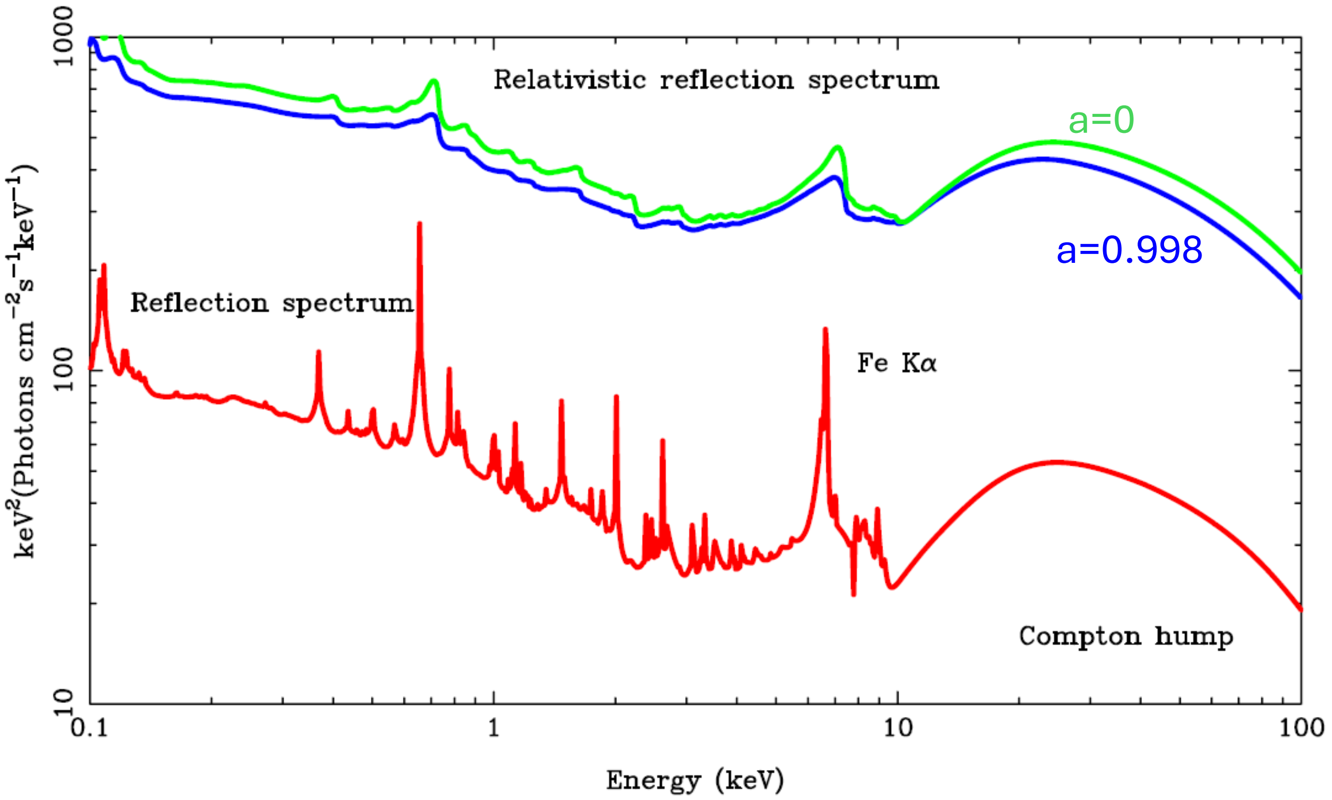




Details of relativistic distortion depend on:

- inclination angle of the observer
- radial distribution of the emisivity of reflection
    - geometry of X-ray corona
    - BH spin

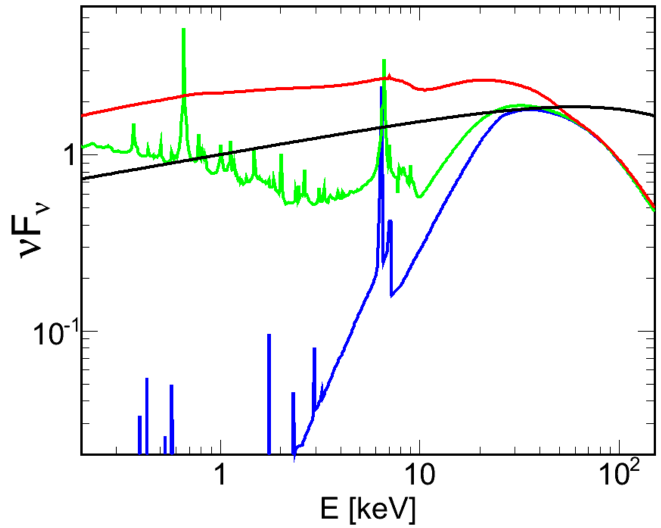
Reflection from disc: BH spin



Problems:

- deconvolution from other spectra components strongly model dependent,
- accuracy of rest frame reflection model

rest-frame reflection for different ionization states

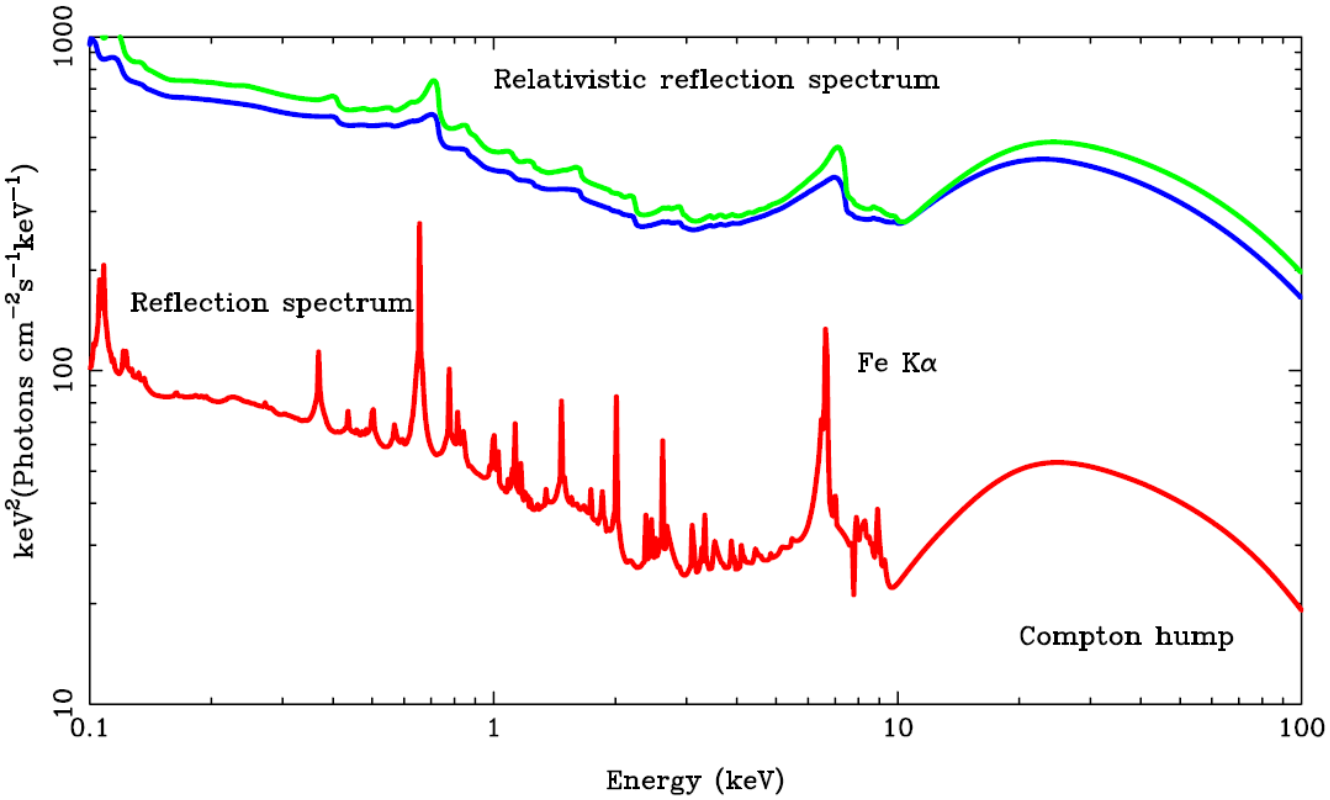


using **the same spectral data**:

a ~ 0.998 in Cyg X-1 (Parker+ 2015), MAXI J1820+070 (Buisson+ 2019), NGC4151 (Beuchert+ 2018), GX 339-4 (Garcia+ 2016)

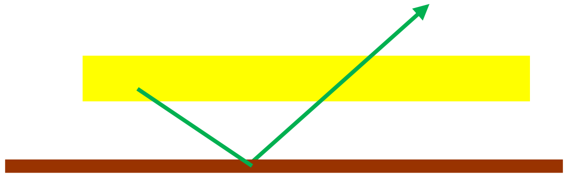
a ~ 0 in Cyg X-1 (Basak+ 2017), MAXI J1820+070 (Zdziarski+ 2019), NGC 4151 (Szanecki+ 2021), GX 339-4 (Dziełak+ 2019)

Reflection from disc: BH spin

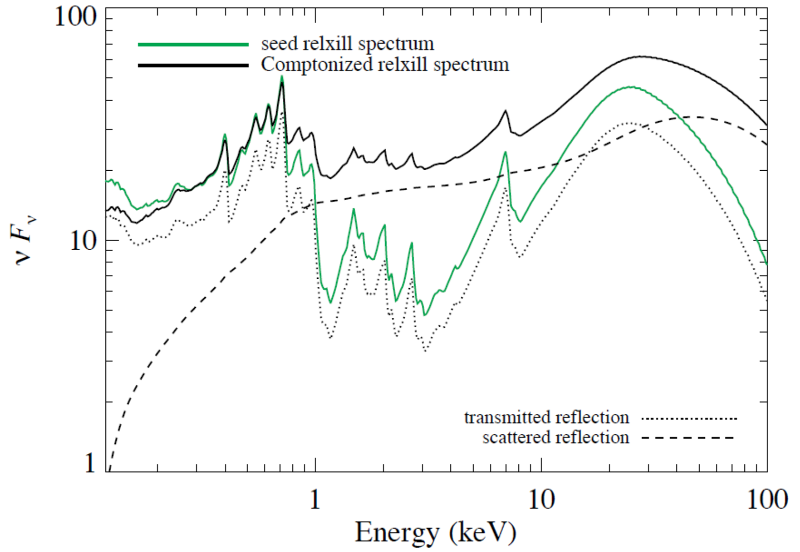


Problems:

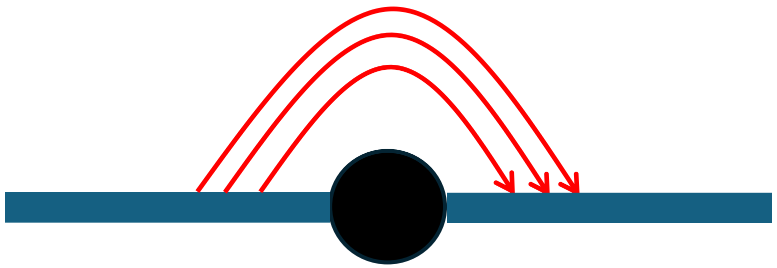
- scattering of reflected radiation in the corona should broaden the spectrum - effect largely overlooked in the reflection literature



Steiner et al. (2017)

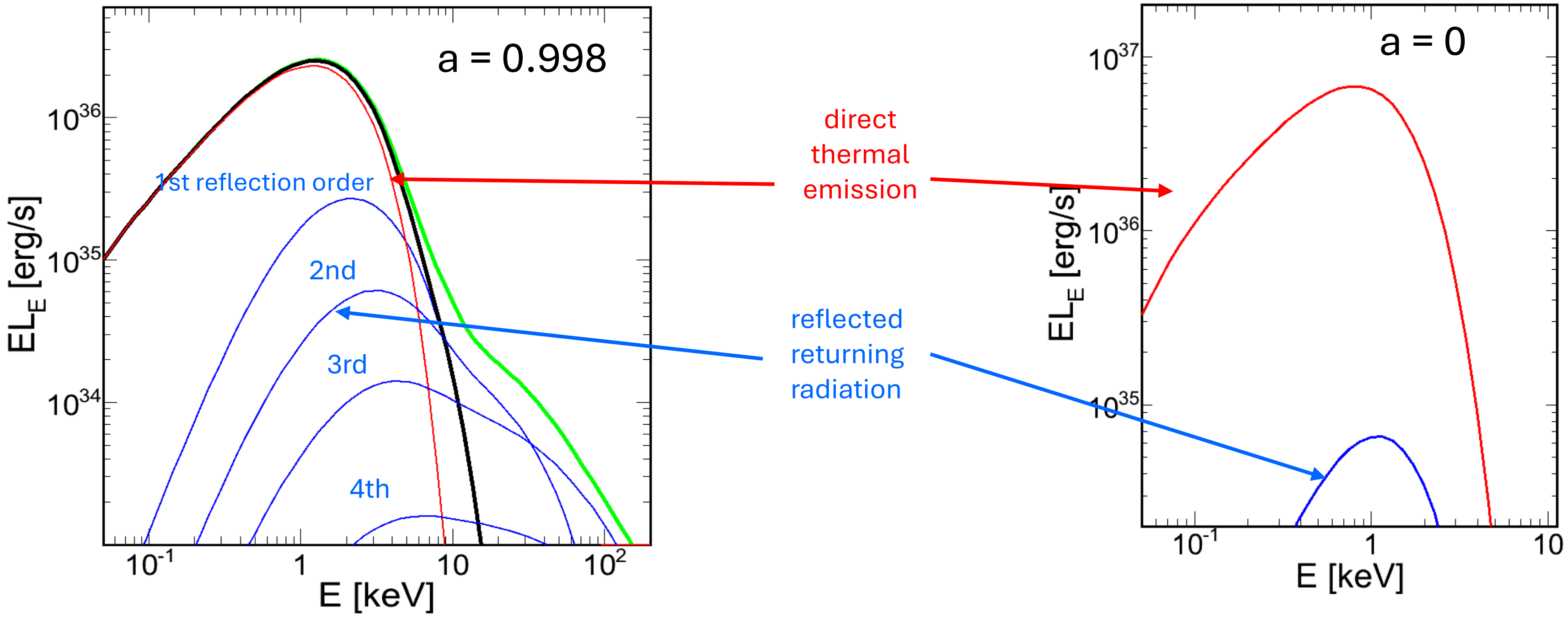


Returning radiation



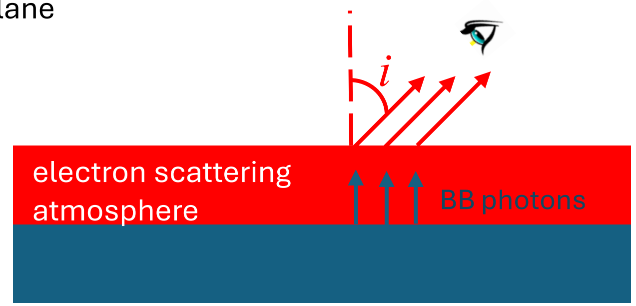
Cunningham (1976): photons emitted from one part of the disk can be bent by gravitational lensing and return to another part of the disk and, depending on the ionization state of the disk surface, get either absorbed or reflected. For strongly ionized disks, gives rise to a distinct spectral component

important only for rapidly rotating BHs: ~10% of emitted radiation can return, reflection strongly polarized (10%)
for weakly rotating BHs negligible (less than 1%)

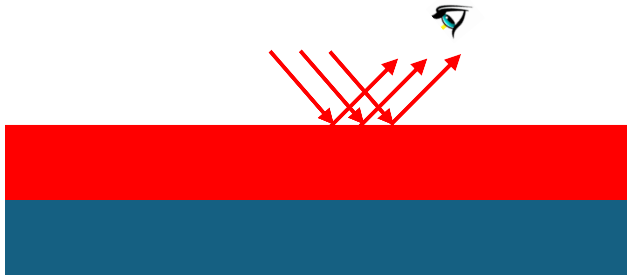


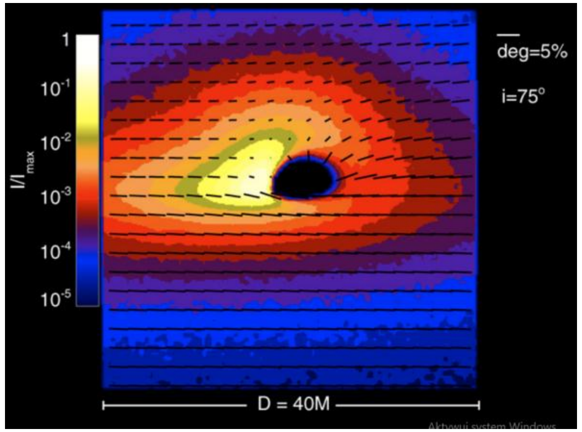
Polarization of a relativistic thermal disk

thermal disk emission: polarization **parallel** to the disk plane



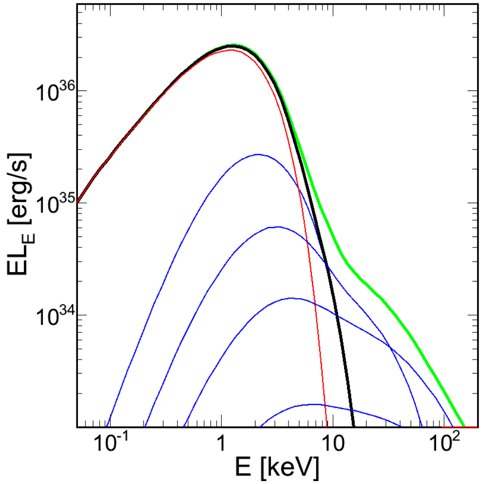
reflection: polarization **perpendicular** to the plane of scattering

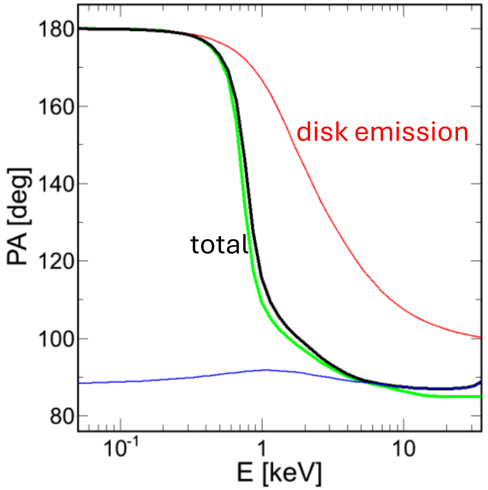


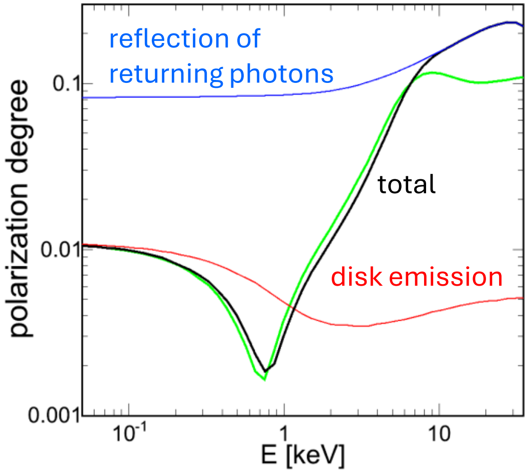


Schnittman & Krolik (2009): simulated image of an accretion disk around a BH with polarization vectors projected onto the image plane; SR + GR change the angle and degree of polarization (Stark & Connors 1977, Connors+ 1980)

retBB prediction for parameters relevant for Cyg X-1:







green: total with multiple reflection, black: total with 1st order

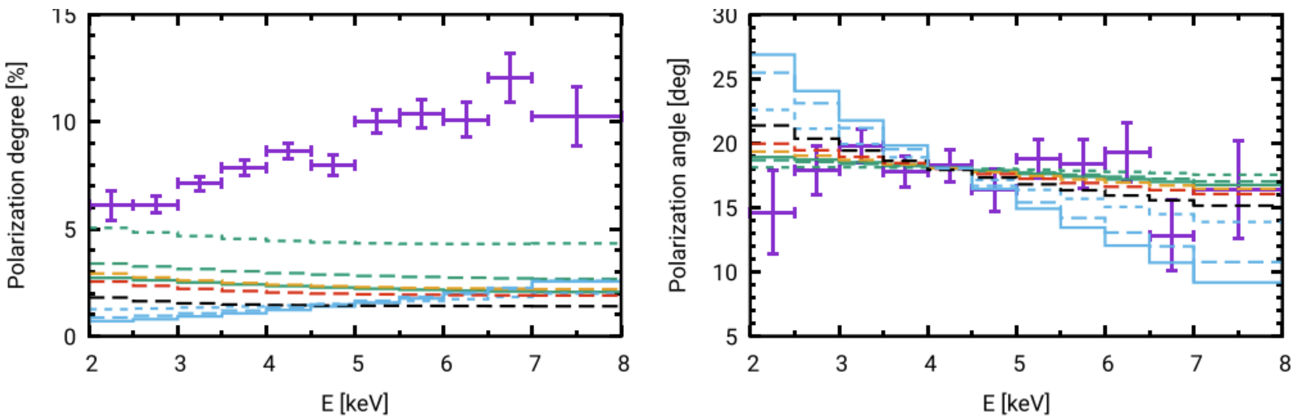
At low energies: direct emission from large radii, radiation weakly polarized in direction parallel to the disk surface. At higher energies: a larger contribution of reflected returning photons with a high degree of polarization vertical to the disk. At the **transition point between horizontal and vertical polarization** little net polarization observed.

Measuring the BH spin through X-ray polarization; soft-state data

the rate of PA rotation and the suppression of PD as a function of energy are sensitive to BH spin, making them potential diagnostic tools (Schnittman & Krolik 2009, Krawczynski 2012)

however, neither a characteristic depolarization nor PA rotation have been observed in the soft states of BH XRBs

4U 1630-47 (Ratheesh+ 2024)

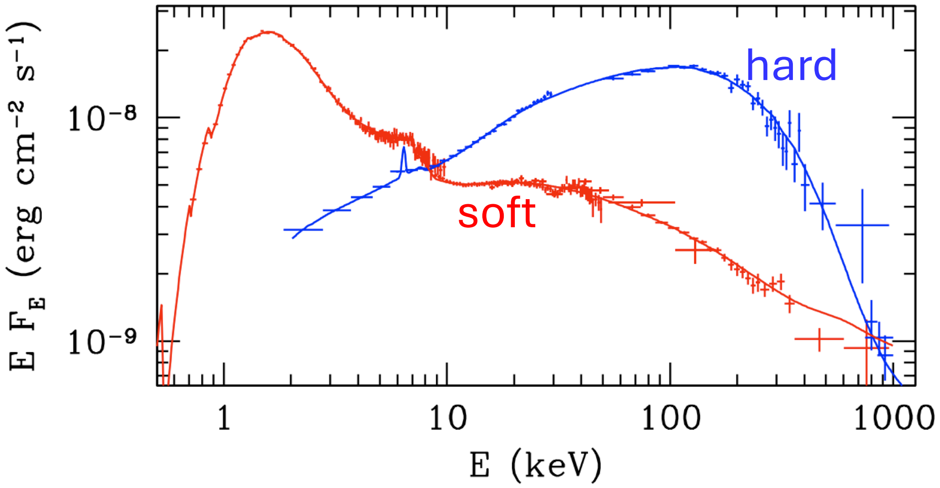


similar characteristics: PD increasing with energy and constant PA observed in other soft-state data: LMC X-3 (Svoboda+ 2024), 4U 1957+115 (Marra+ 2024), Cyg X-1 (Steiner+ 2024), GRS 1739-278 but with lower values of PD

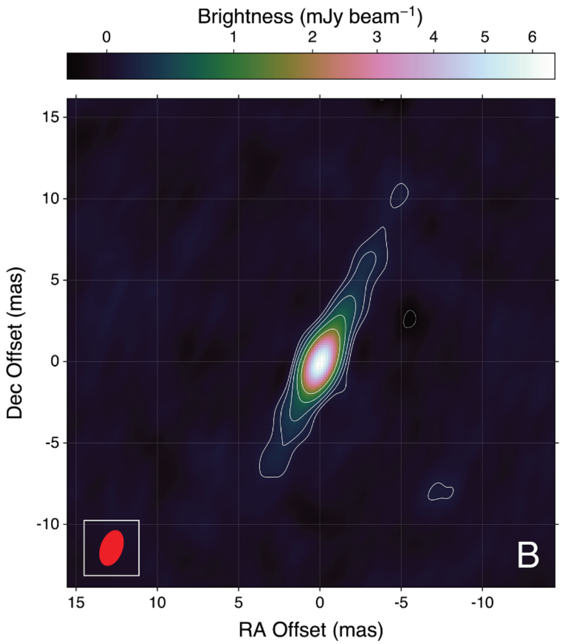
Cyg X-1

- persistent X-ray source, the only BH HMXB known in our Galaxy
- Miller-Jones+ (2021): **d = 2.22±0.18 kpc, M_{BH} = (21.2 ± 2.2) $M_\odot$** and inclination of the orbit **i = 27. 5º ± 0.8º**, Ramachandran+ (2025), using a modern stellar atmosphere model: **M_{BH} ≈ (12.7–17.8) $M_\odot$** and **i ≈ 34º**
- monitored essentially continuously by every major X-ray mission for over 50 years, **two main accretion states**
- collimated, milliarcsec-scale **radio-jet** persistent in hard state, PA ~ 23º

X-ray spectral states in Cyg X-1 (Gierliński+ 1999)



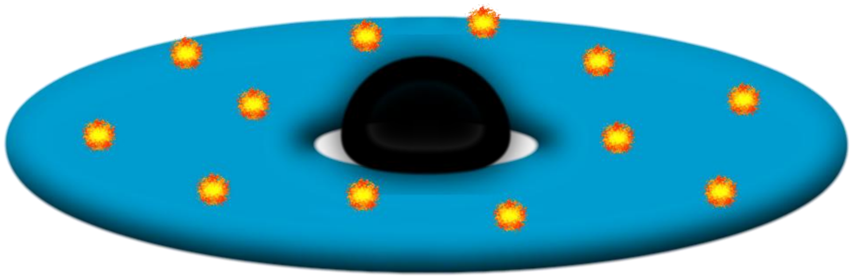
radio image of the jet (Miller-Jones+ 2021)

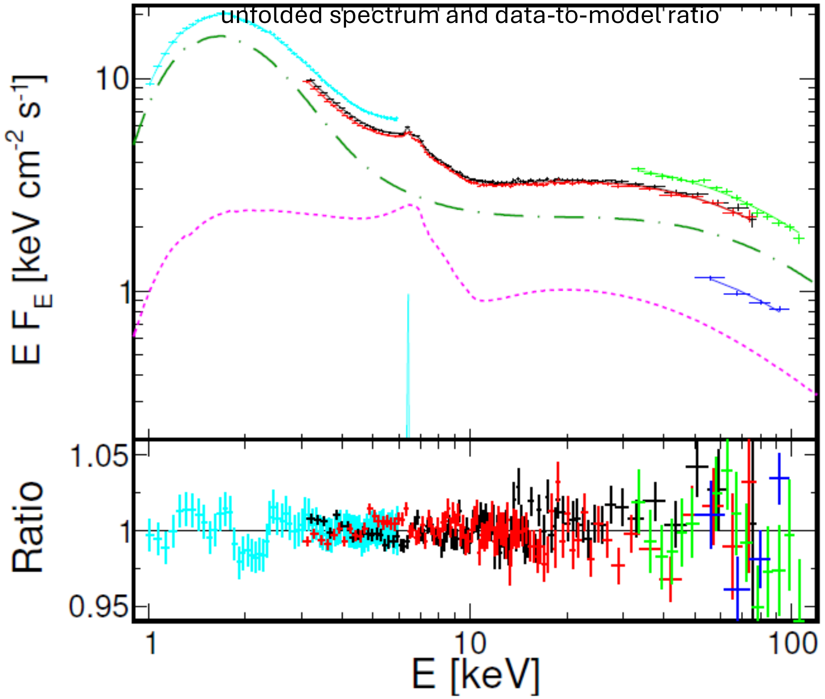


- slow proper motion (~10 km/s) of the binary with respect to parent star association, so the BH was formed with a low natal kick – **small inclination of the BH spin axis from the orbital axis** (M-J+ 2021: at most 10°)
- IXPE measurements : **the polarization angle of the X-ray emission aligned with the position angle of the radio jet** in the plane of the sky both in the hard (Krawczynski+ 2022) and soft state (Steiner+ 2024)

Spectral model for Cyg X-1 in the soft state

- NICER, NuSTAR, INTEGRAL/ISGRI data taken simultaneously with the IXPE observation in 2023
- convolution versions of Comptonization and reflection models, Comptonization of reflection taken into account
- the continuum and the reflection **methods for estimation of BH spin** coupled in the spectral model
- two versions: with and without a warm, optically thick layer covering the disk
- very good spectral fits with both versions of the model, but different spin values:
  without a warm corona, χ^2/dof = 660/636, fitted spin = 0.99±0.1
  with a warm corona, χ^2/dof = 654/634 , fitted spin ~ 0 (<0.19)





coronal outflow needed to explain the observed polarization degree.
Beloborodov+ (1999, 2017): magnetic flares dominated by e± pairs that are accelerated away from the disk by radiation pressure

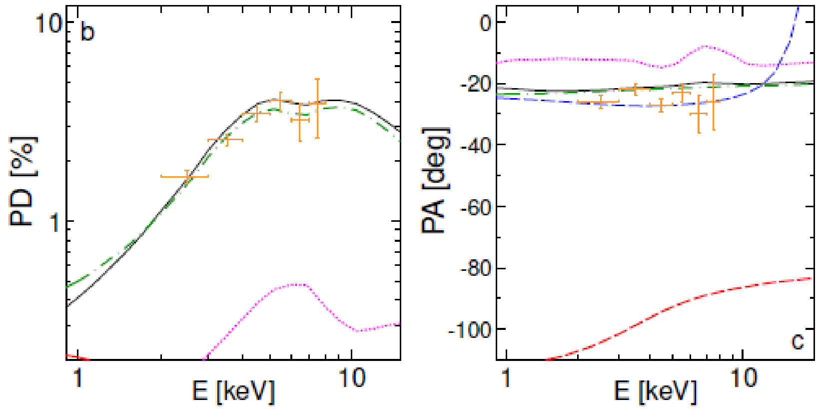
Niedźwiecki+ (2026)

Cyg X-1 in the soft state: polarization signal

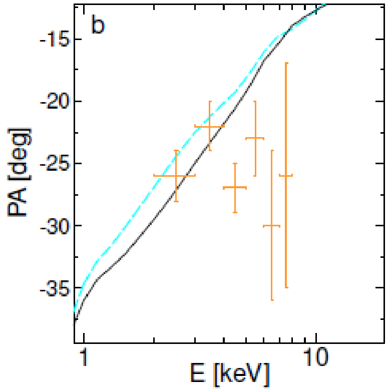
polarization fully dominatedby Comptonization in the hot corona

contribution of the reflected returning component negligible

good agreement with IXPE measurements for a slowly rotating BH and an outflow in the corona with v=0.3c

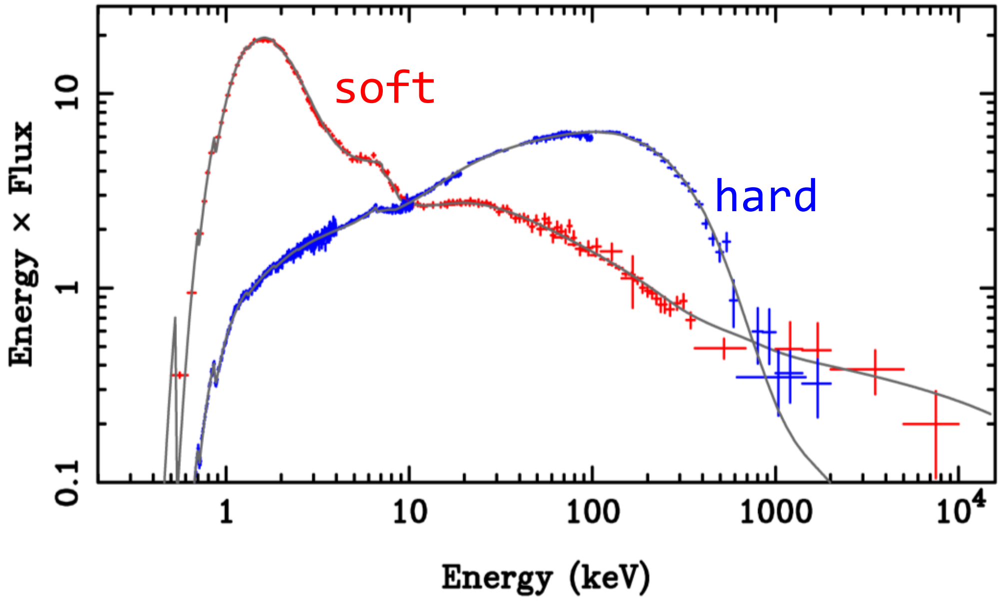


energy-dependent rotation of the PA due to SR and GR effects, making the high-spin model inconsistent with the observed PA:



Niedźwiecki+ (2026)

Physical inconsistencies of lamp-post models

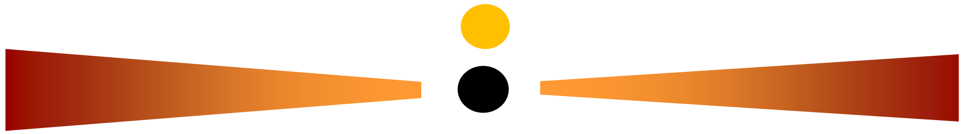


Rest-frame luminosity of the lamp much higher than observed L due to

- photon advection
- time dilation
- redshift

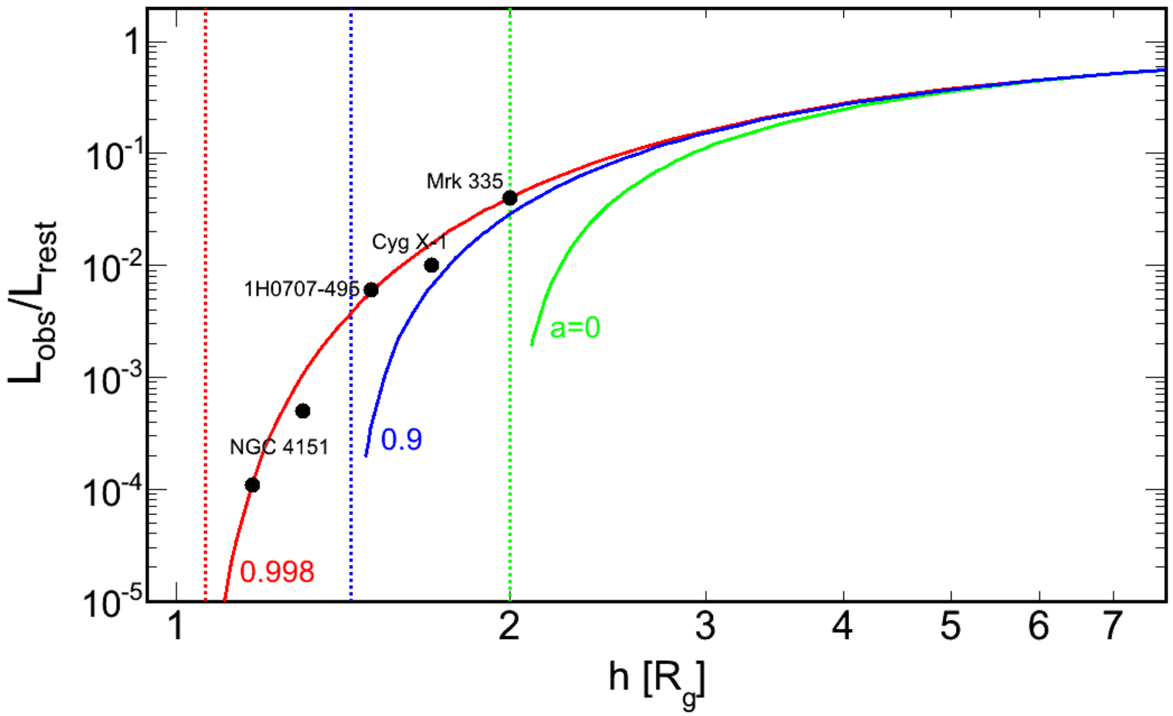
pair production rate orders of magnitude higher than the annihilation rate
(Niedźwiecki, Zdziarski & Szanecki 2016)

hard and soft



Fitted LP height in the unit of R_g

NGC 4151 (Beuchert+ 2017):	$h = 1.17^{+0.0015}_{-0}$	a=0.998
NGC 4151 (Keck+ 2015):	$h = 1.3^{+0.1}_{-0}$	a=0.98±0.01
Cyg X-1 (Parker+ 2015):	$h = 1.2^{+0.5}_{-0}$	$a=0.998^{+0}_{-0.28}$
Mrk 335 (Parker et al. 2014):	$h = 1.2^{+1.1}$	a>0.994
1H0707-495 (Fabian et al. 2012):	$h \simeq 1.5$	a=0.998
XTE J1752-223 (Garcia+ 2018):	$h = 1.17^{+0.85}_{-0.07}$	a=0.998



Summary

- Estimates of BH spin from reflection fitting and disk-continuum fitting are uncertain due to the intrinsic complexity of spectral decomposition.

- Estimates of an untruncated disk in the hard state are subject to similar uncertainties, as well as physical-consistency issues in the underlying lamp-post geometry; in Cyg X-1, they are also inconsistent with the observed polarization.

- The polarization observed in the soft state of Cyg X-1 is consistent with being produced by Comptonization in a corona undergoing a semi-relativistic outflow with a velocity of $\simeq 0.3c$.

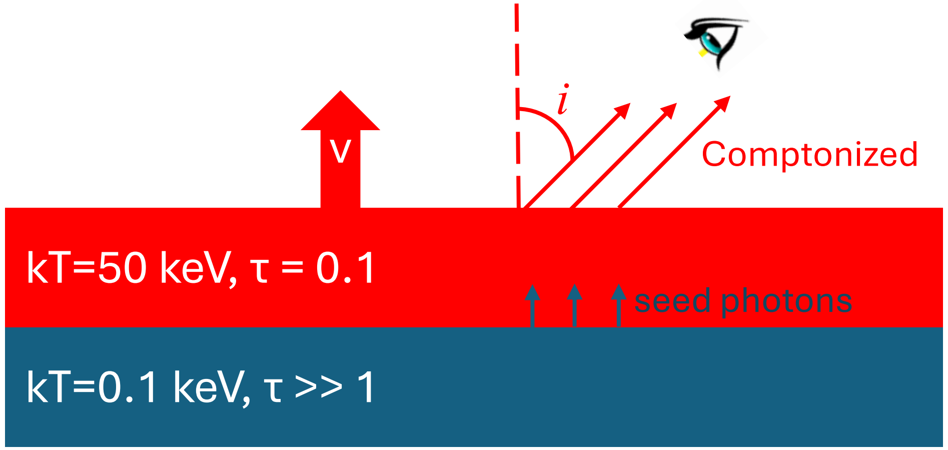
- The spectral solutions for Cyg X-1 admit either low or high black-hole spin values, depending on the adopted model setup.

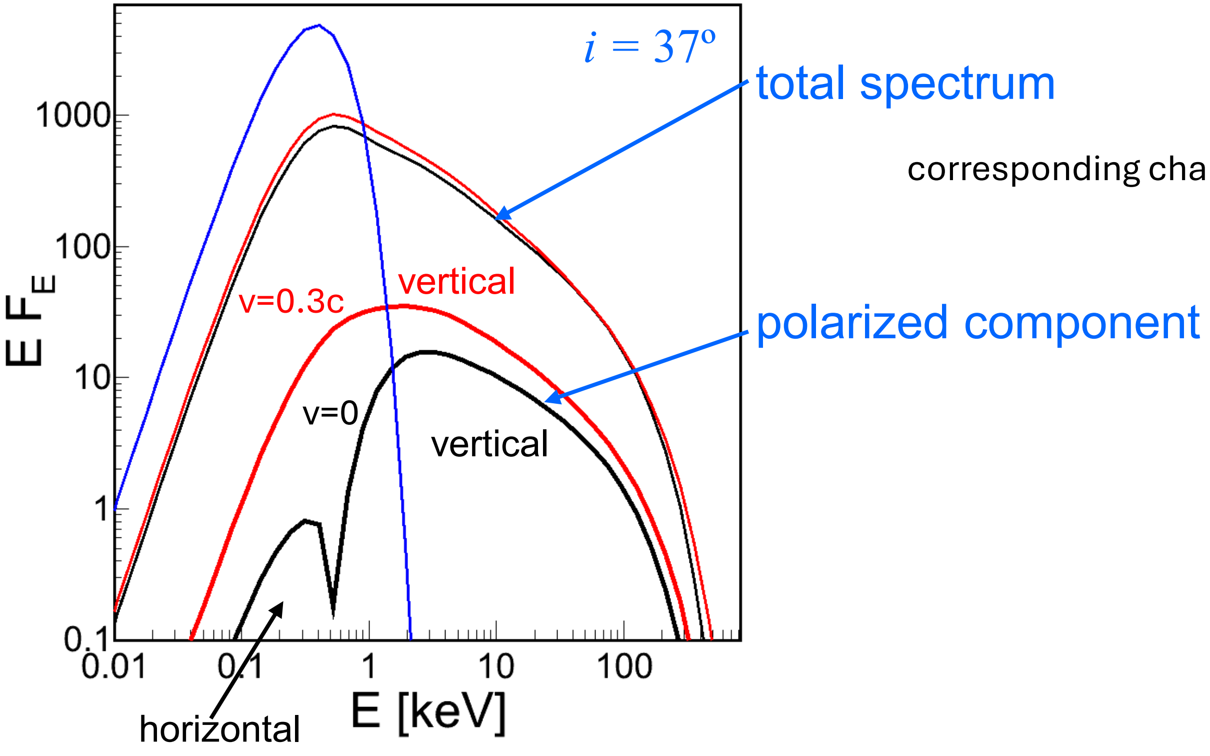
- However, the observed polarization strongly favors a low spin. At high spin, the polarization angle would inevitably rotate significantly across the energy band, which is not consistent with the observations.

- Apart from this rotation of the polarization angle, general-relativistic effects do not play a significant role in producing the observed polarization. In particular, we find that returning disk radiation contributes negligibly.

Polarization by thermal Comptonization, effect of bulk motion

- motion of the Comptonizing plasma away from the source of seed photons at sub-relativistic speeds: weak effect on the energy spectrum but strong effect on the polarized component, especially at the energies of the first order scattering, which is polarized horizontally to the slab for a static plasma, but vertically if it moves away
- it allows us to reconcile the hard state polarization with the low inclination of Cyg X-1 (Poutanen+ 2023), and it appears to be crucial for the soft state as well





corresponding changes in the PD as a function of energy