The origin of the X-ray polarization in the soft state of Cyg X-1

Hybrid Comptonization scenario

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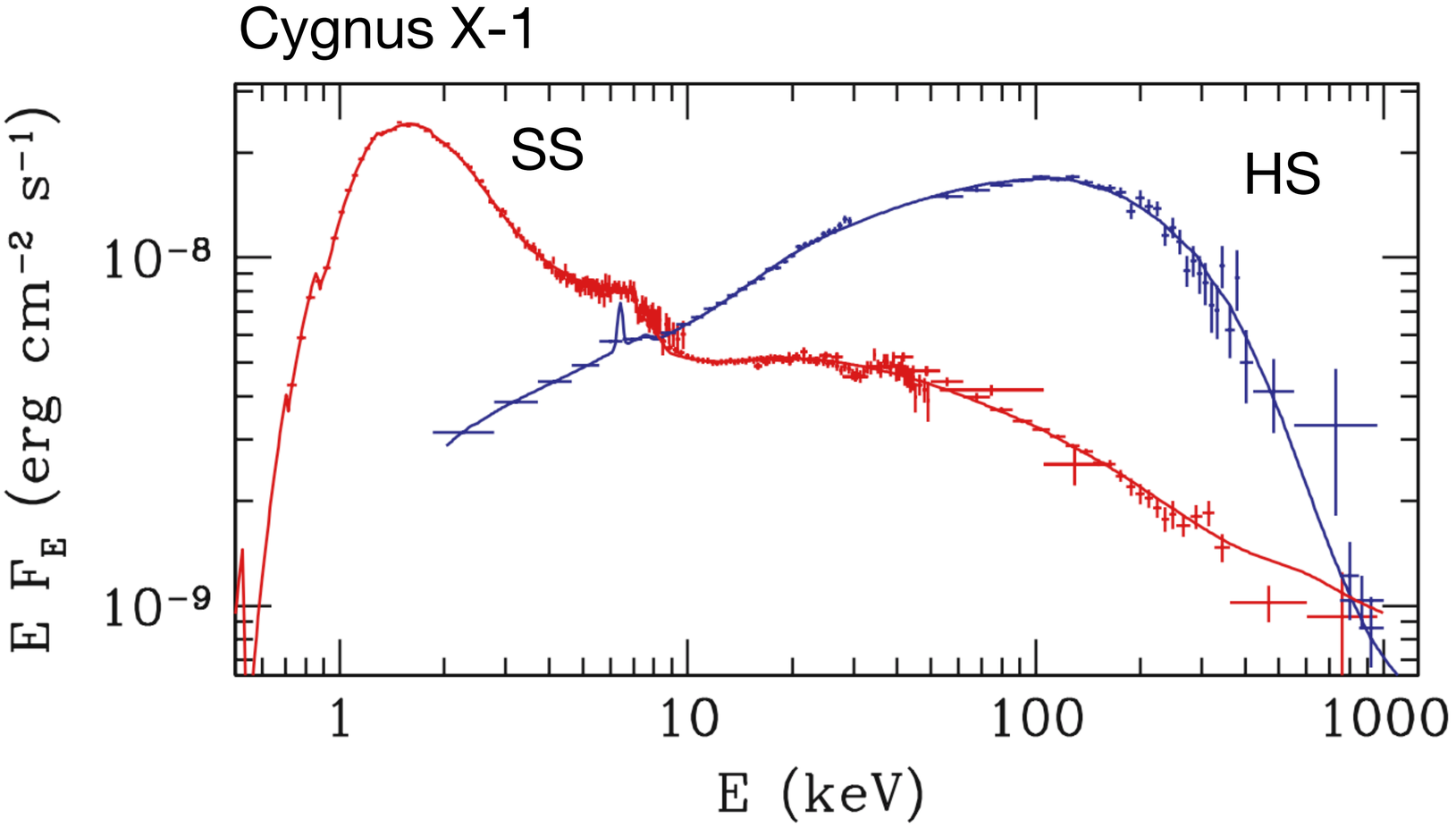
Plan

- Introduction to black hole X-ray binaries
- Soft state of Cygnus X-1
- Hybrid Comptonization model
- The role of X-ray polarization
- The first self-consistent spectro-polarimetric model of Cyg X-1 in the soft state

Black hole X-ray binaries

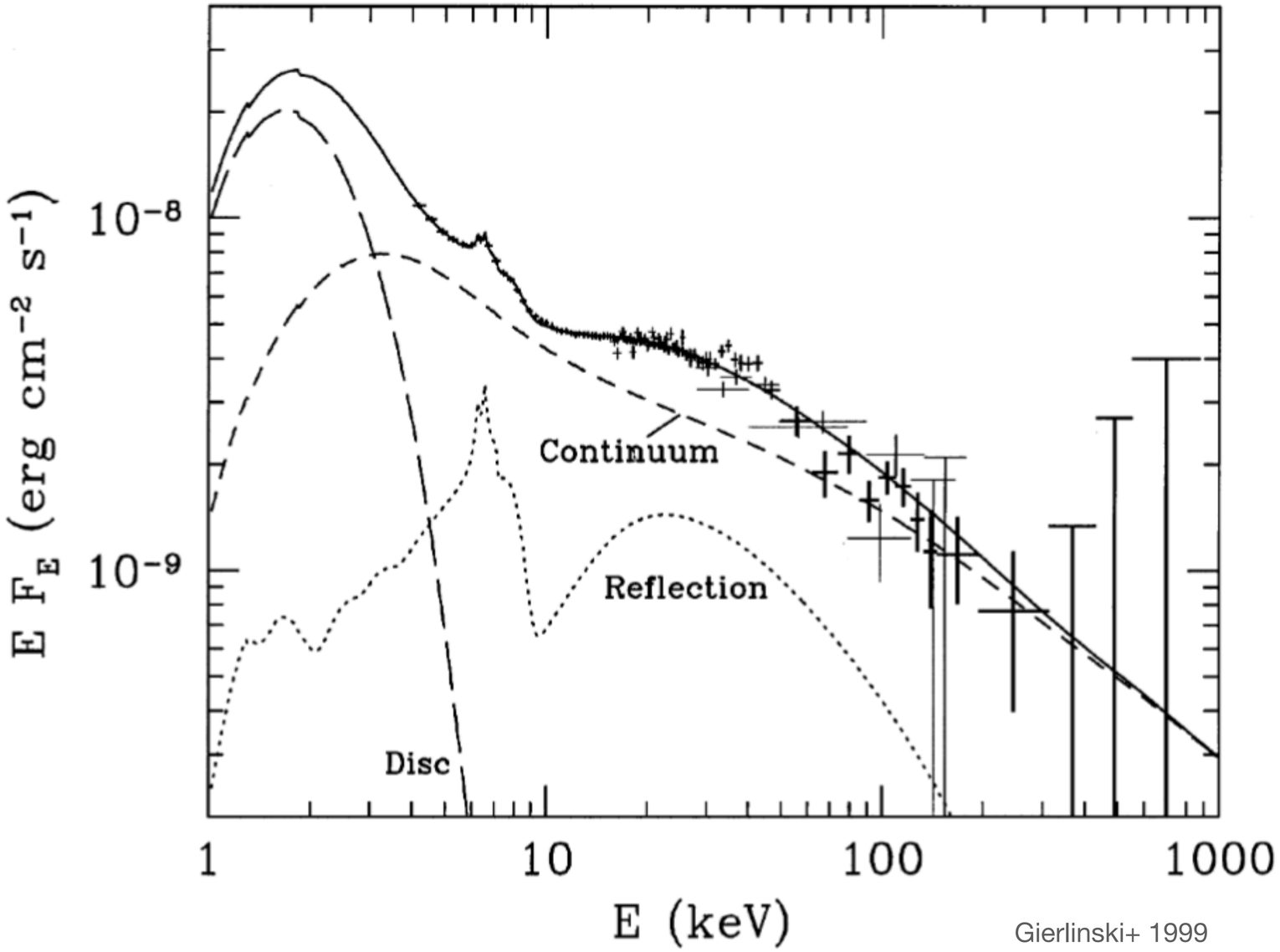
- Consist of a compact object — black hole — and a companion star
- Black hole accretes matter from the star
- Two distinct spectral states: hard (HS) and soft (SS)
- States are determined by different accretion mechanisms



Done+ 2007

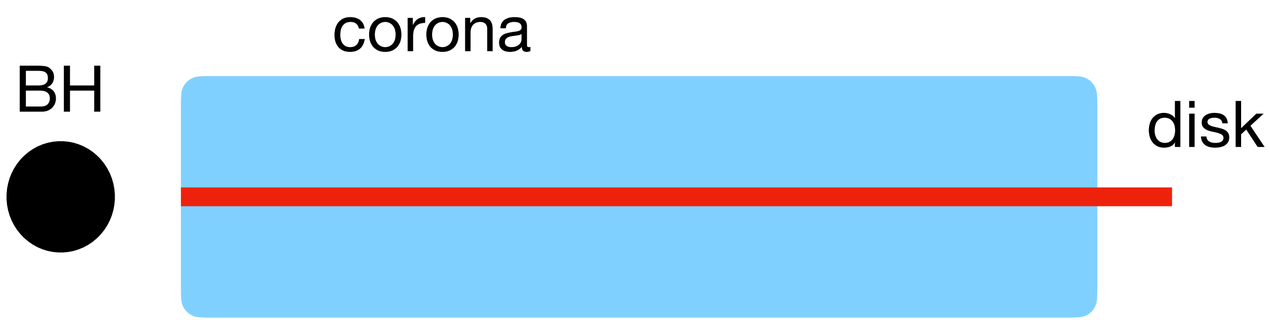
Cygnus X-1 (soft state)

- Cyg X-1 is a bright, persistent high-mass X-ray binary
- Consists of a black hole ($M \sim 21 M_\odot$) and an O-type companion star ($M_c \sim 41 M_\odot$)
- Orbital inclination $i = 27.5^\circ$
- Black hole spin:
  - $a \lesssim 0.1$ (Zdziarski+ 2024)
  - $a \gtrsim 0.92$ (Gou+ 2011)

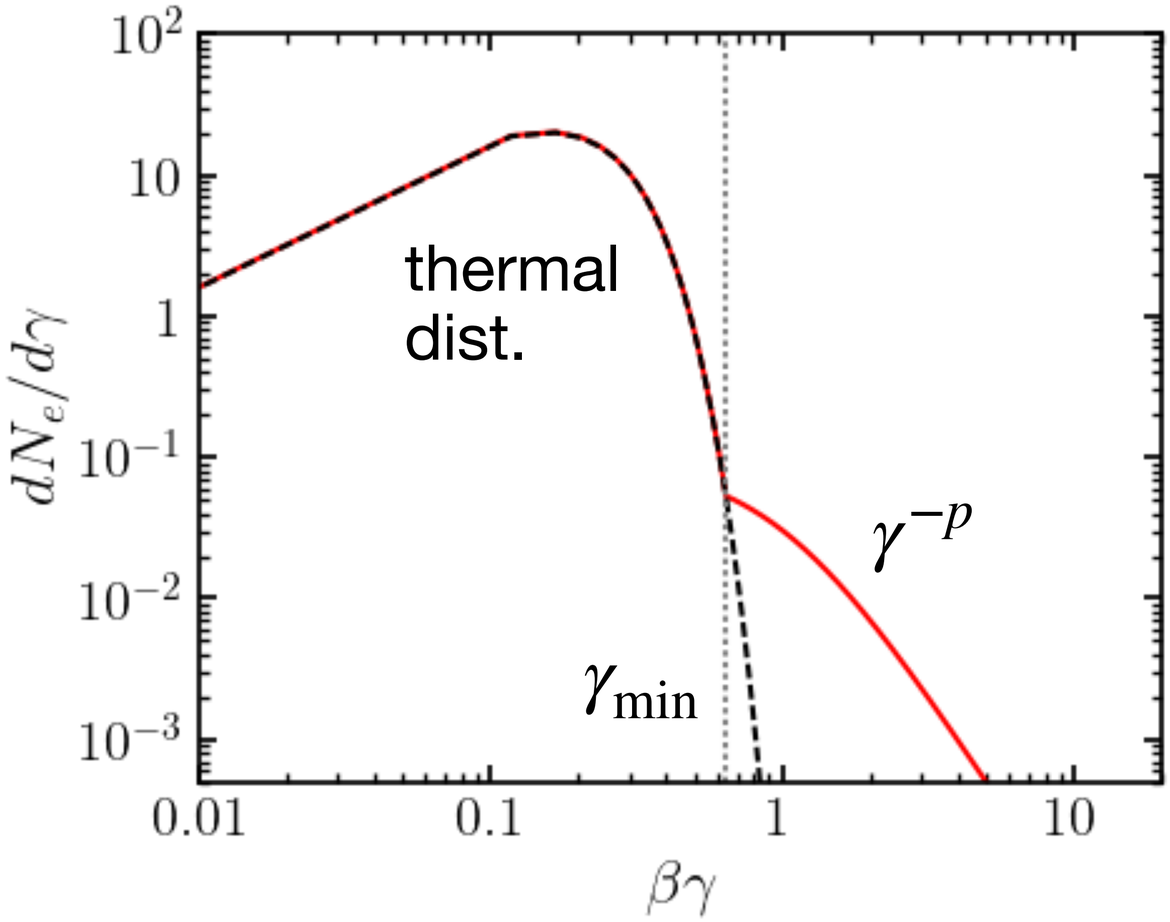


Gierlinski+ 1999

Hybrid Comptonization model

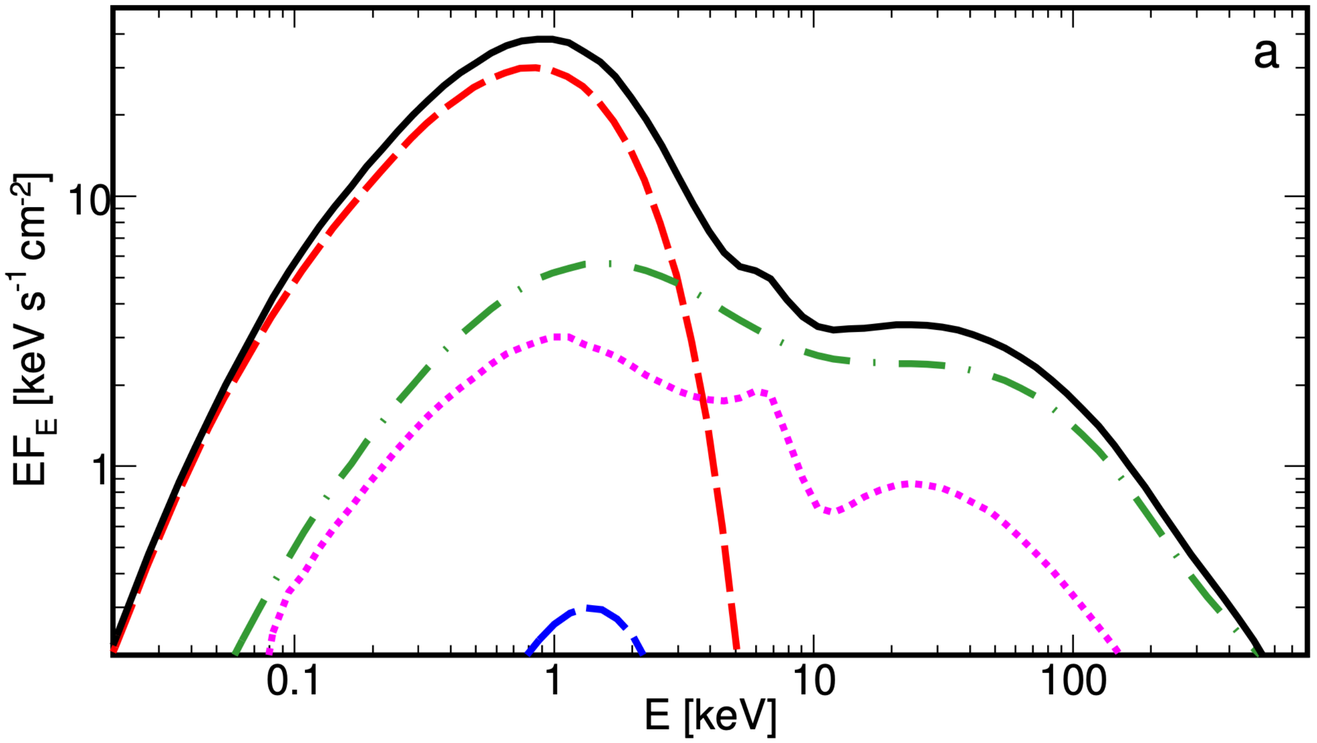


- Corona is a hot, optically thin medium above the disk
- Thermal and non-thermal electrons in the corona
- Multiple Compton scattering of disk emission



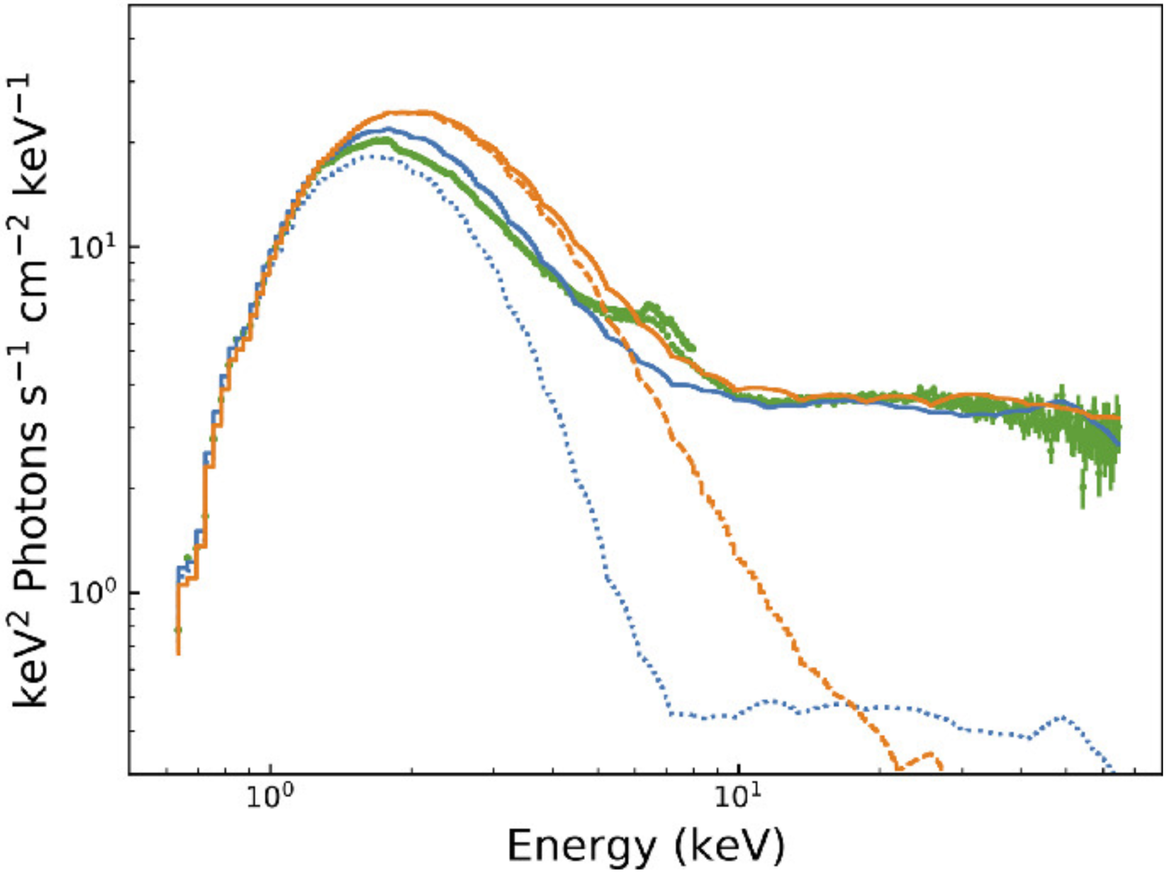
Bocharova+ (in prep.)

Other spectral models



Warm corona; $a = 0$

Niedzwiecki+ [arXiv:2603.10870]

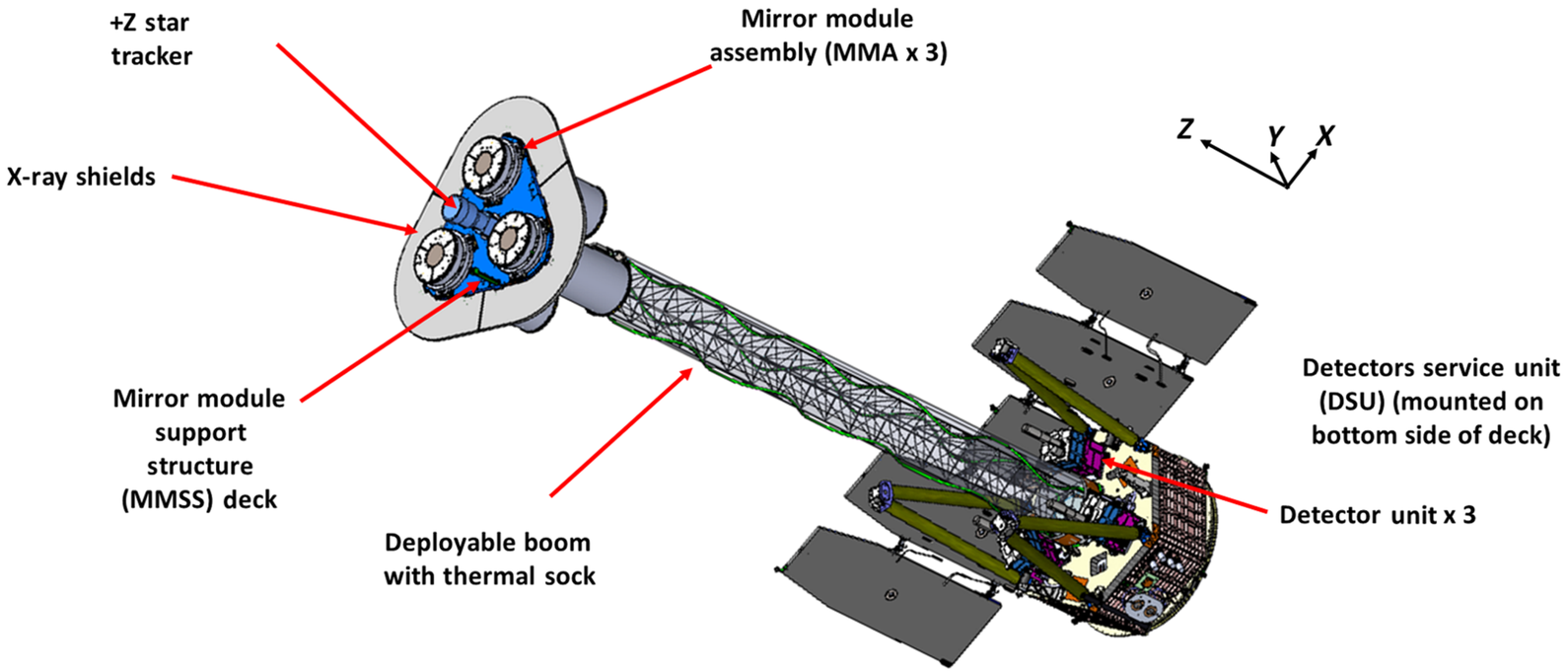


Returning radiation; $a \gtrsim 0.96$

Steiner+ 2024

Imaging X-ray Polarimetry Explorer (IXPE)

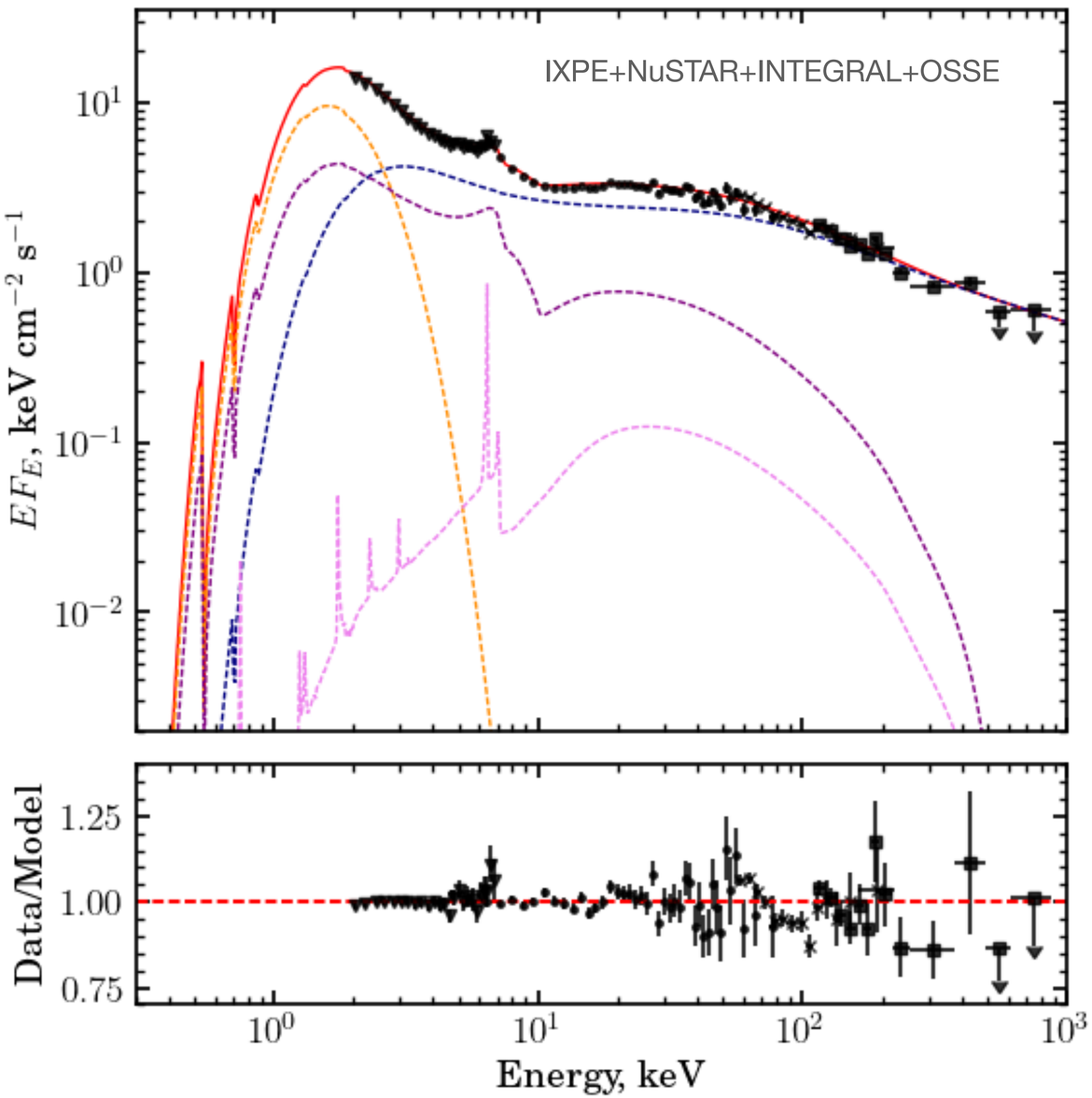
- Launched in December 2021
- 3 detector units (gas pixel detectors)
- Energy range: 2–8 keV
- FOV: $12.9' \times 12.9'$
- Angular resolution $\lesssim 30''$
- Spectral resolution $\lesssim 20\,\%$ at 6 keV

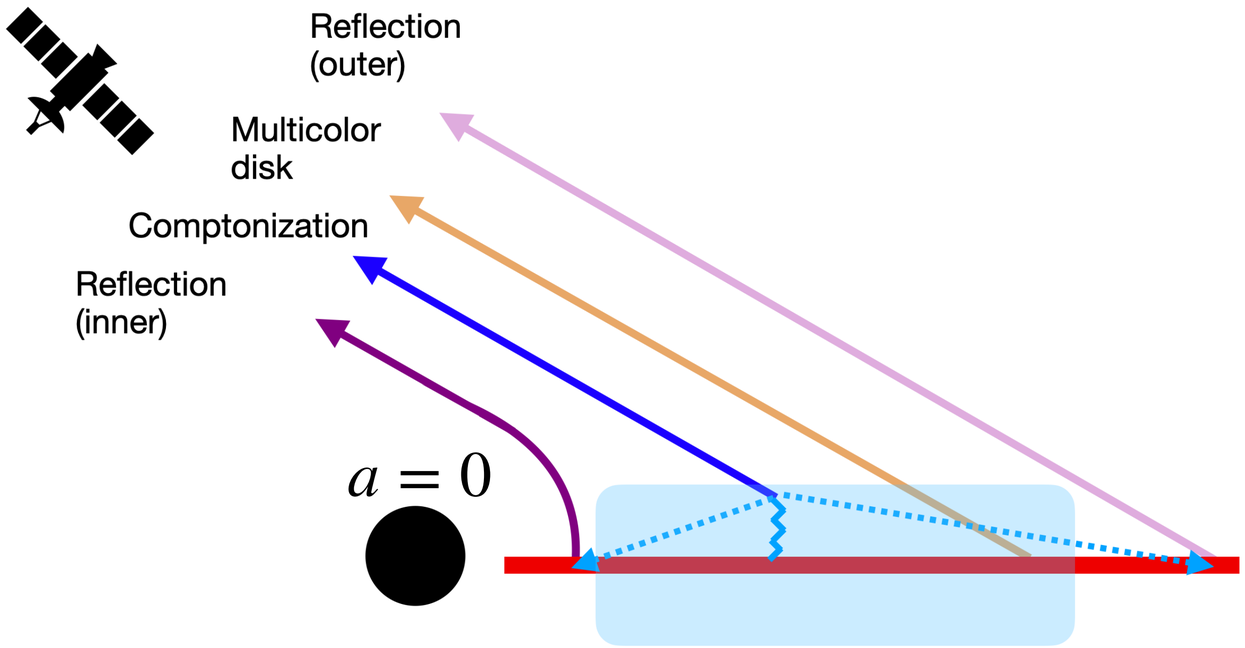


Weisskopf+ 2022

Spectral decomposition

tbfeo*plabs*(diskbb + comppsc*diskbb + cxilconv*comppsc*diskbb + relconv*cxilconv_1*comppsc*diskbb)

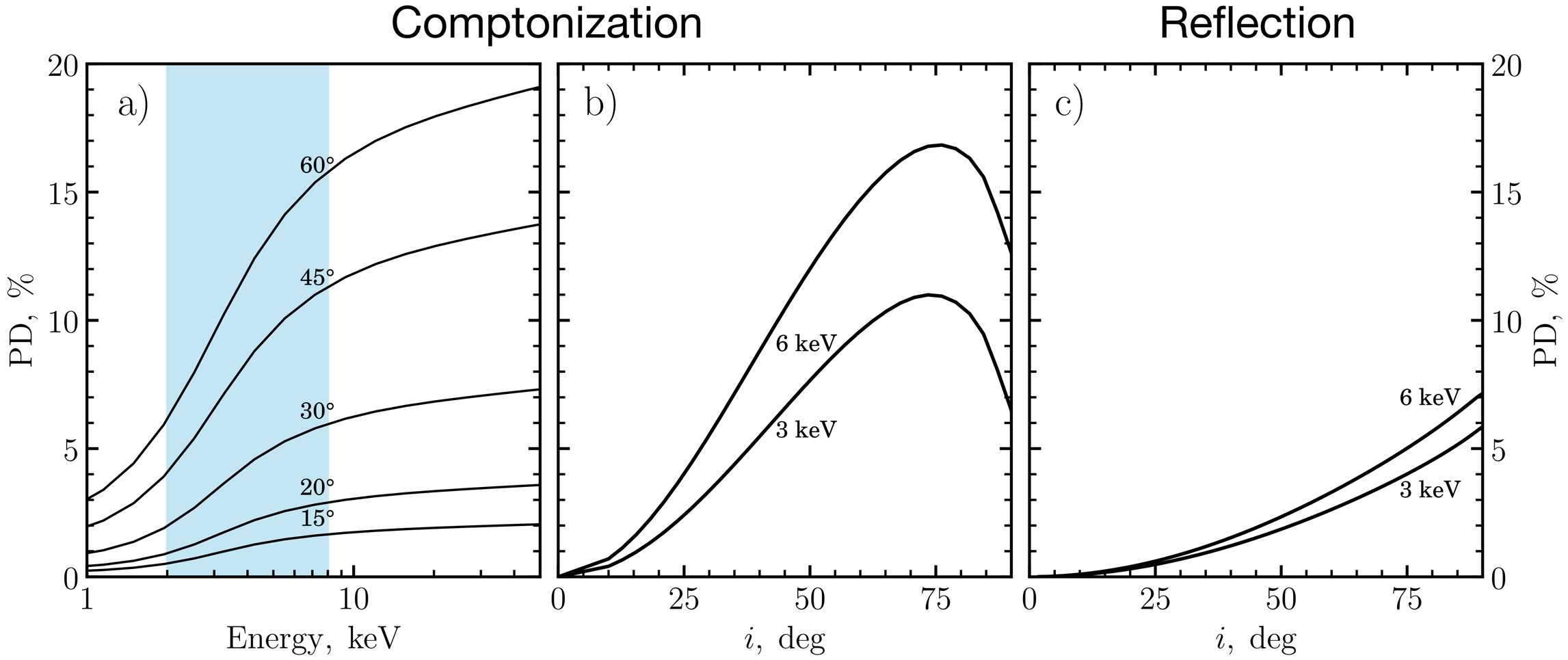




We assume that Comptonization and reflection (inner) components are polarized, while all other components are unpolarized

Bocharova+ (in prep.)

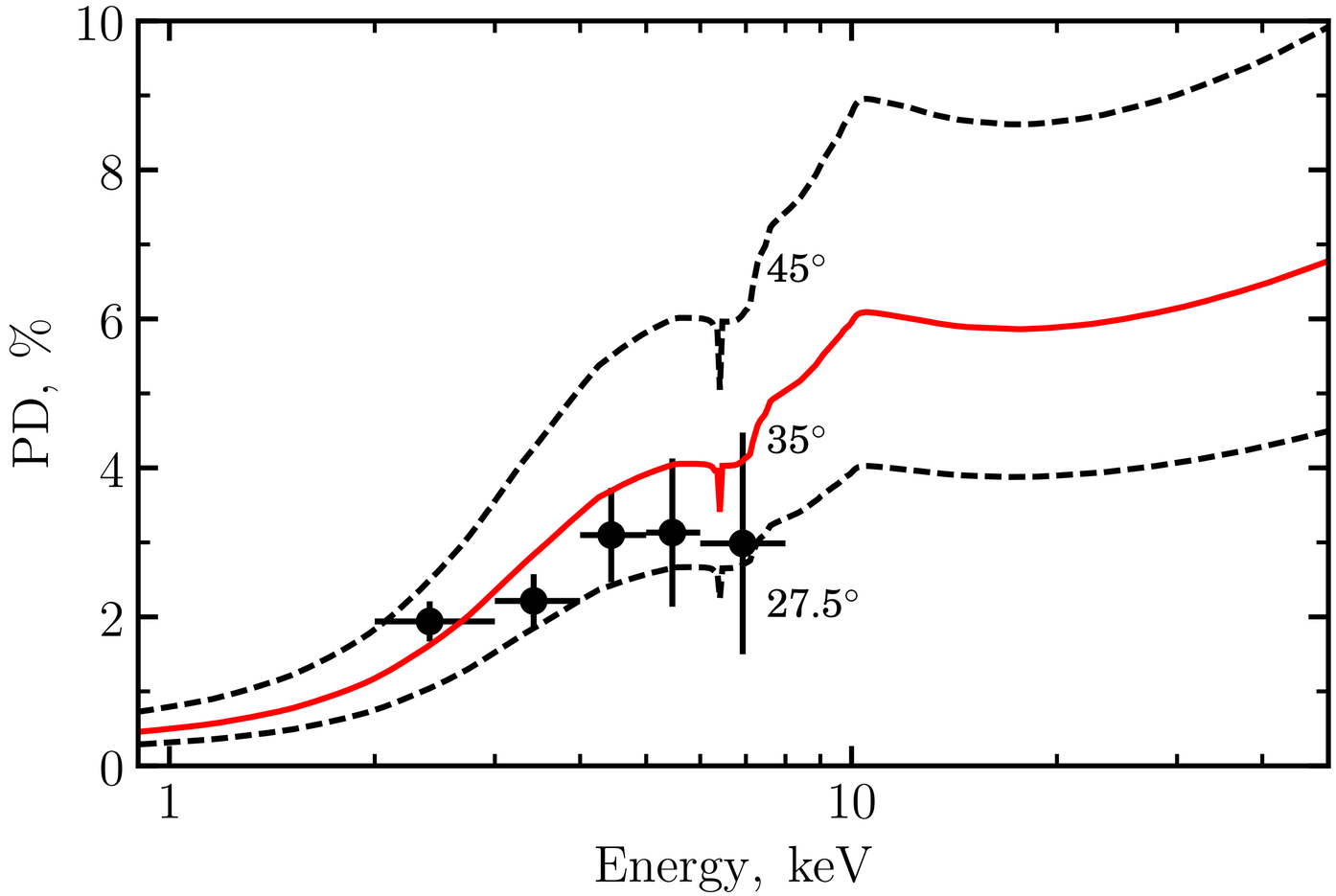
X-ray polarization



$$\mathrm{PD}(E) = \frac{F_{\mathrm{comp}}(E)\mathrm{PD}_{\mathrm{comp}}(E) + F_{\mathrm{refl}}(E)\mathrm{PD}_{\mathrm{refl}}(E)}{F_{\mathrm{tot}}(E)}$$

Bocharova+ (in prep.)

X-ray polarization



- Best fit spectrum model: $i = 35°$
- Optical observations: $i = 27.5°$
- With proposed misalignment between the orbital plane and the X-ray emitting region: $i = 45°$

Bocharova+ (in prep.)

Summary

We obtained a self-consistent spectro-polarimetric model for Cygnus X-1 in the soft state, which:

- simultaneously describes spectrum from 2 keV to 1 MeV and polarization in 2–8 keV energy range;
- assumes a non-rotating black hole ($a = 0$);
- does not require an outflow or high misalignment between the orbital plane and the X-ray emitting region.

References

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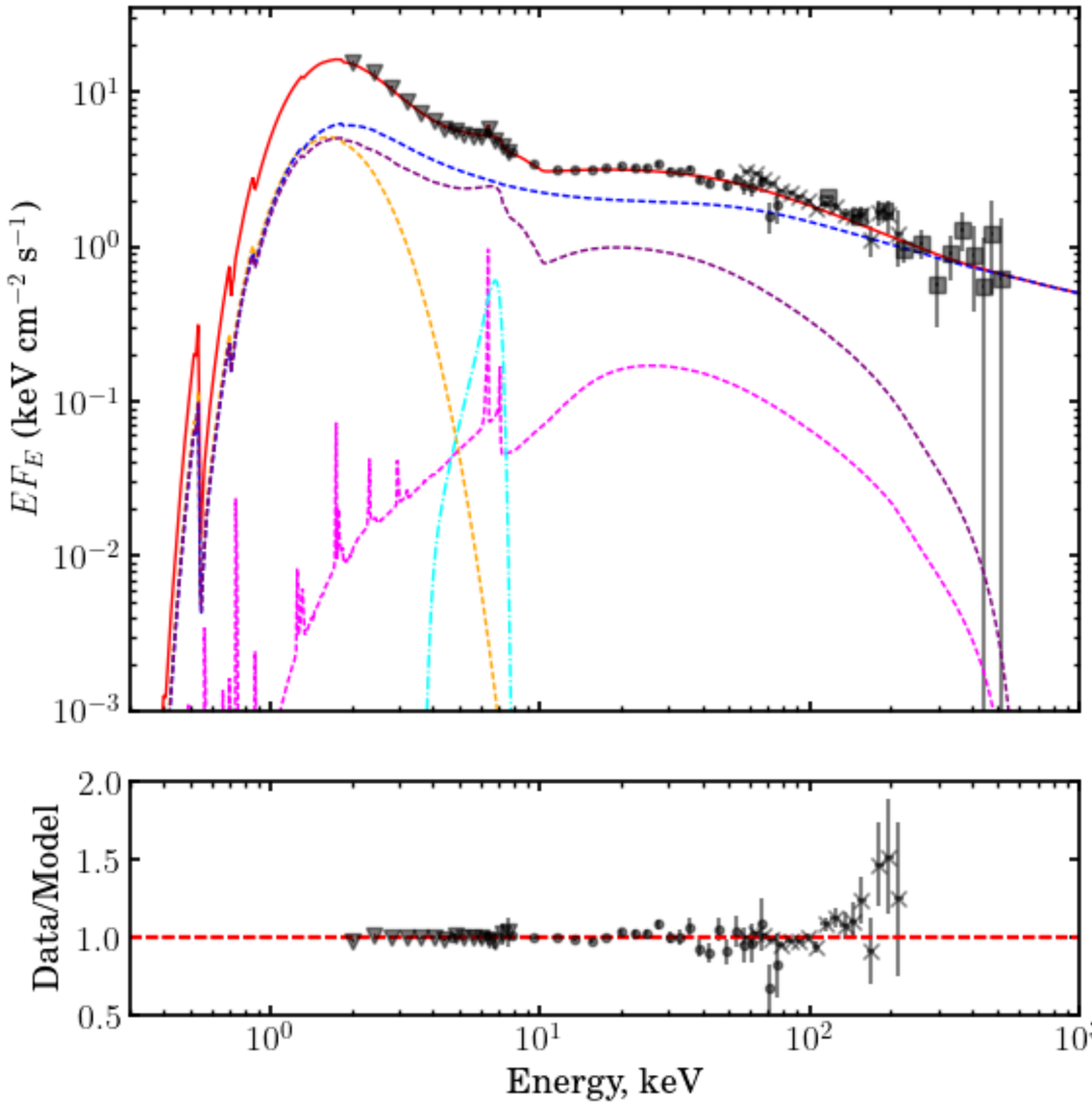
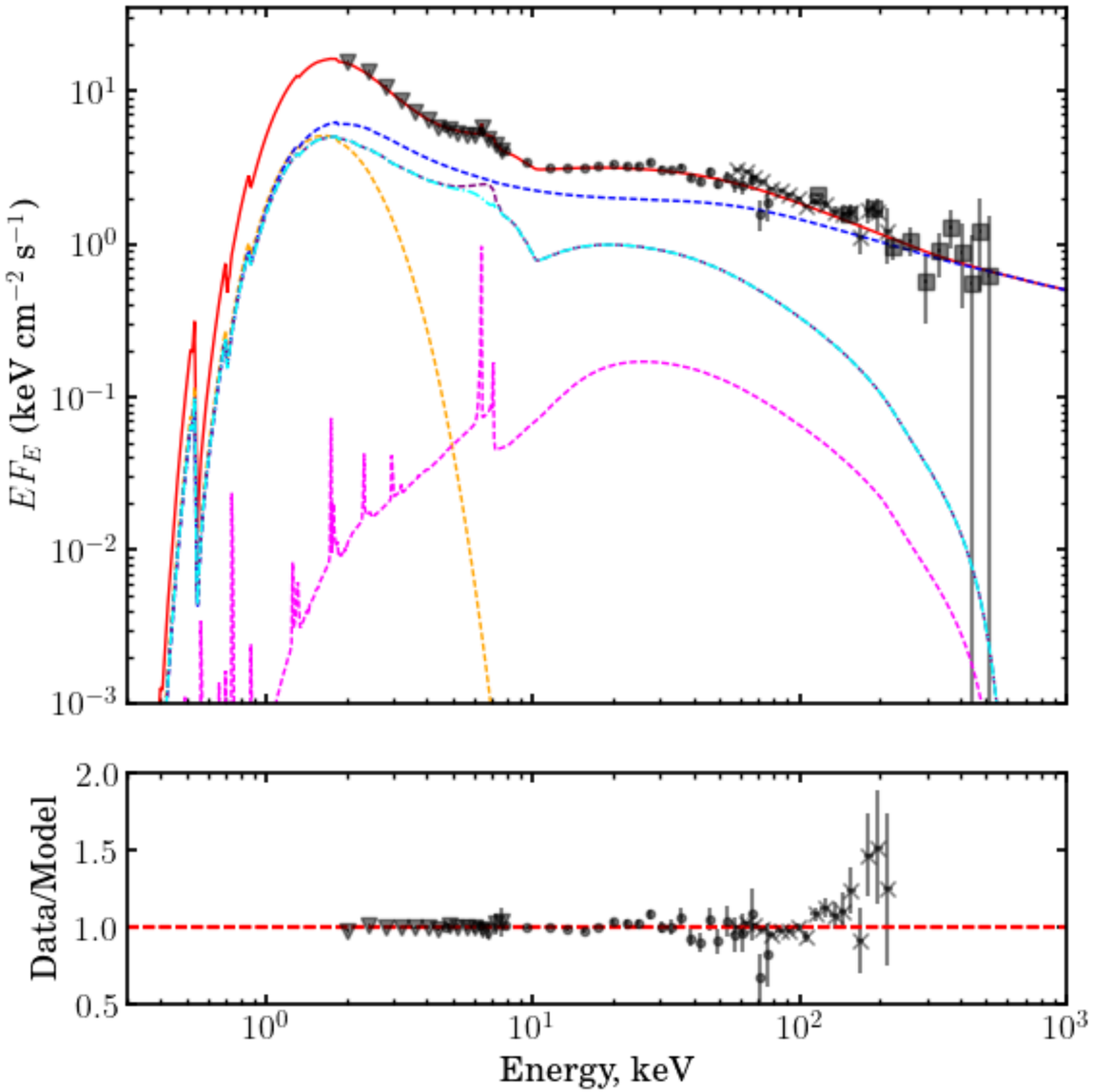
Backup slides

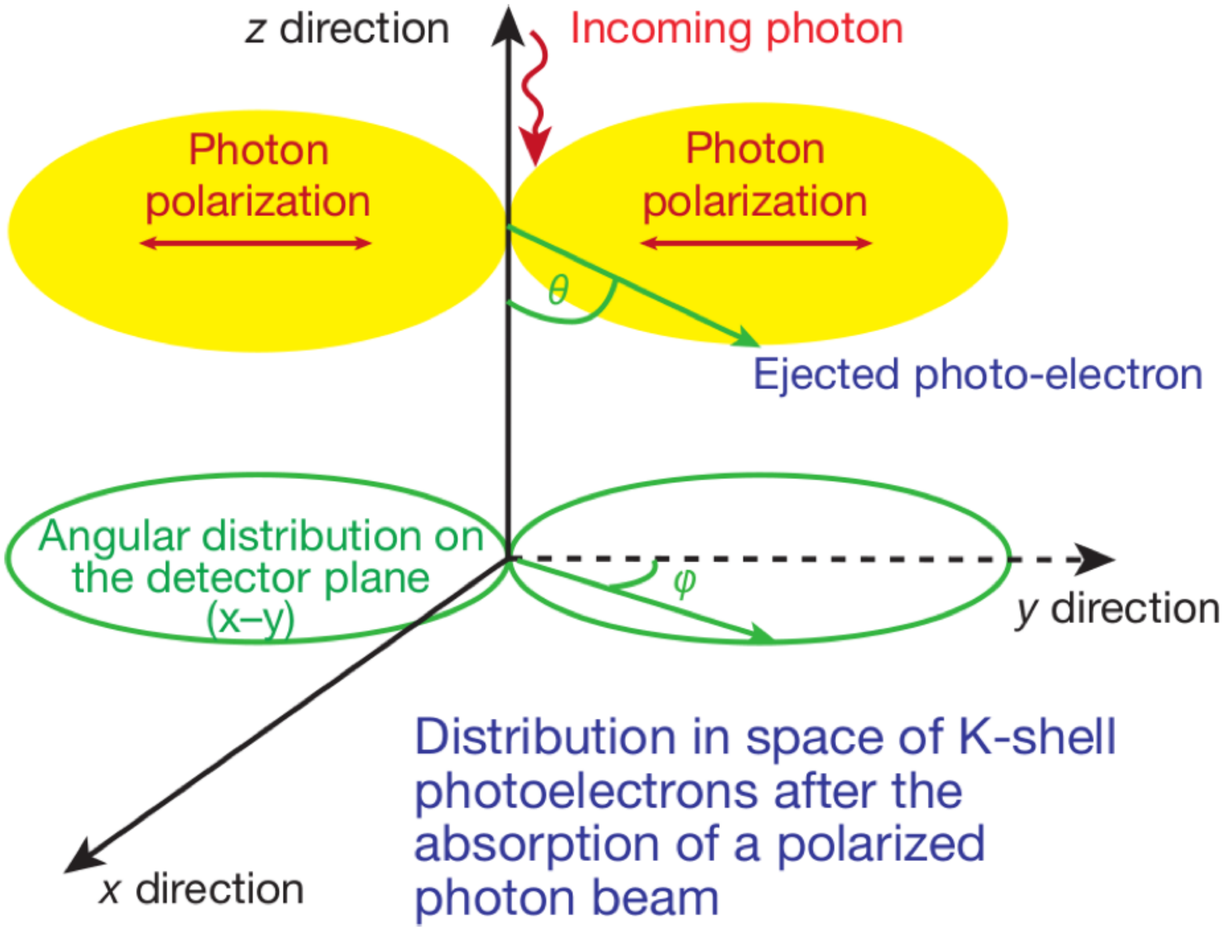
Subtract the iron line from the reflection continuum





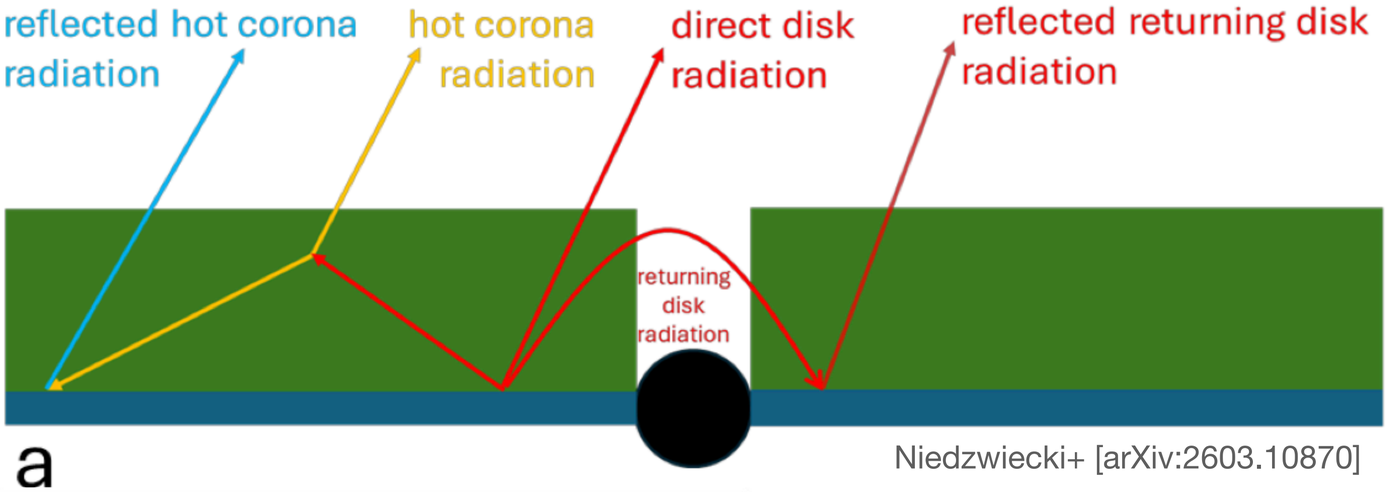
IXPE detection principle

- Photoelectric effect is a dominant process at $E < 10$ keV
- Distribution of photoelectrons depends on the initial polarization angle
- The main challenge is to reconstuct the direction of the photoelectron



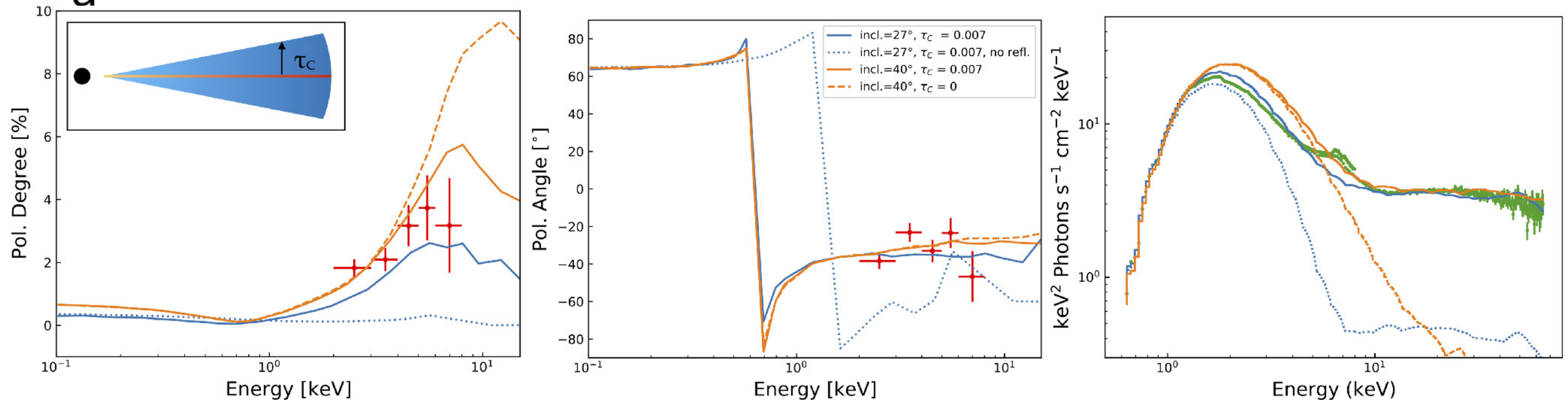
Soffitta+ 2021

Returning radiation model



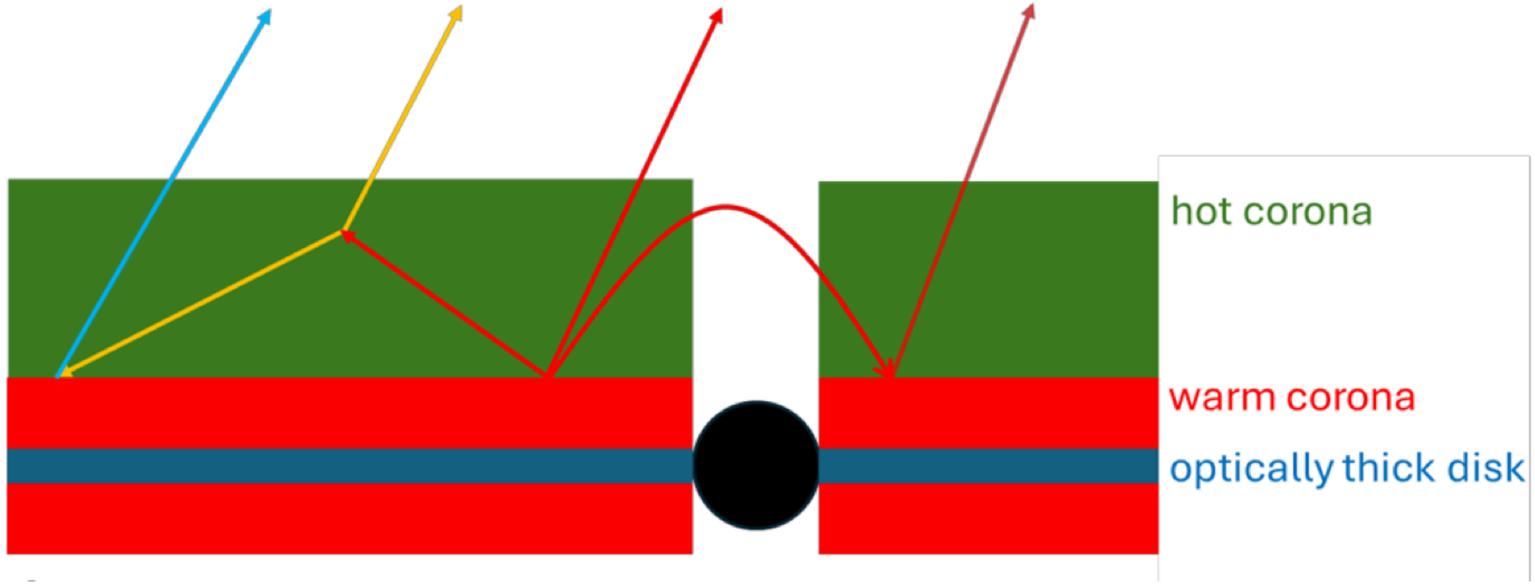
$$a_* = 0.998$$

Niedzwiecki+ [arXiv:2603.10870]



Steiner+ 2024

Warm corona model



$a_* = 0$

outflow $v = 0.3c$

Niedzwiecki+ [arXiv:2603.10870]