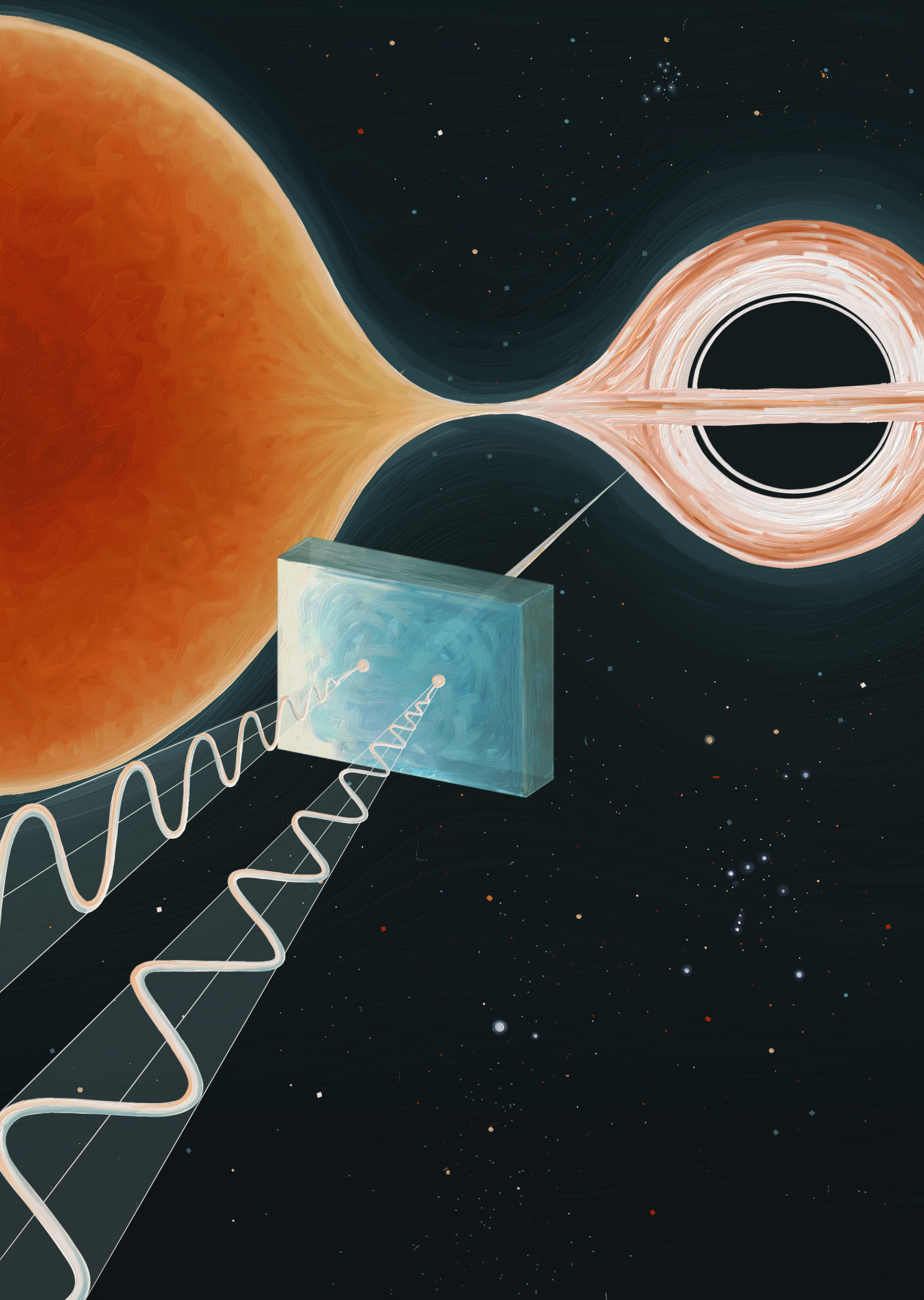




Polarization as a probe of physics around black holes

Connecting simulations with observations

Vadzim Krautsou

University of Turku, Finland

University of Helsinki, Finland

EXPAND Kickoff Conference, Lisbon Academy of Sciences

1 June 2026

Polarized Radiation

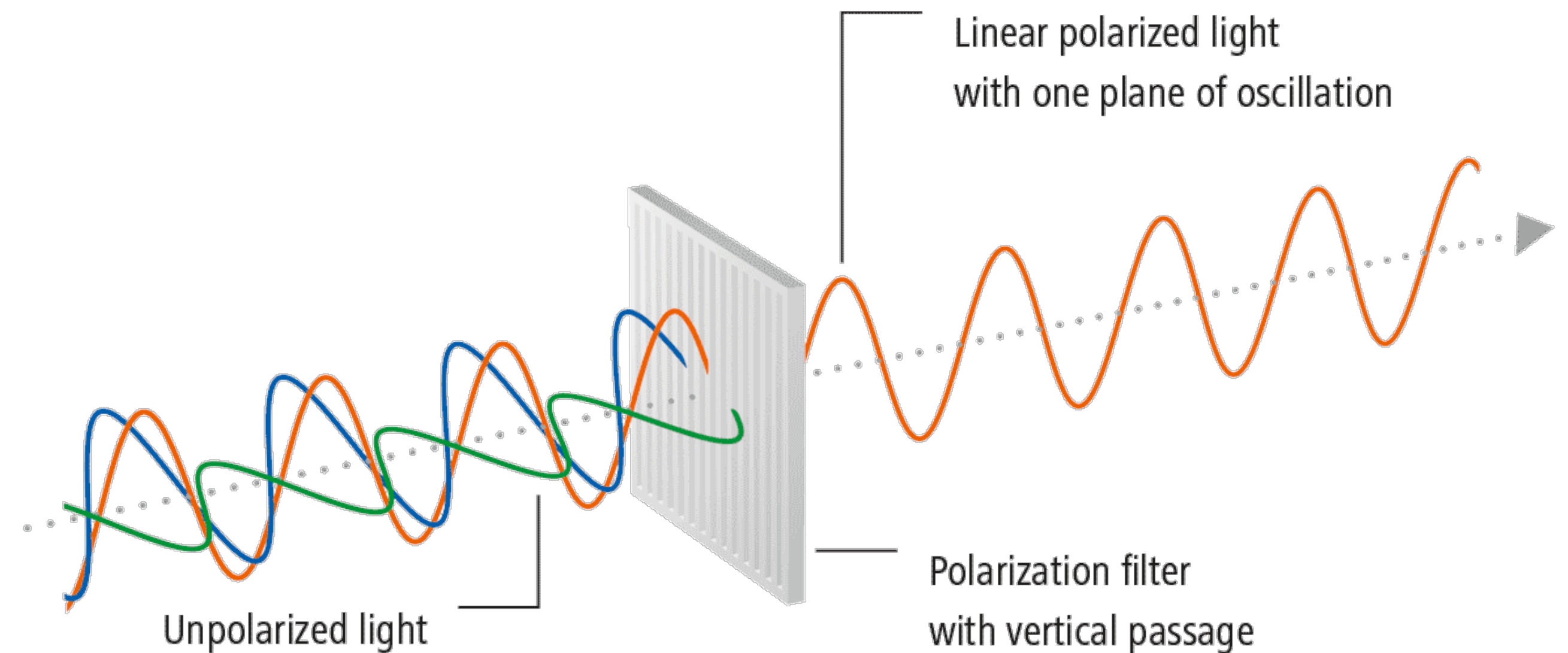
Polarization

Definition and description

The polarization of electromagnetic waves describes the **preferred direction of the electric field oscillations**.

If there is no preferred direction of oscillations, the light is **unpolarized**.

If the electric vector oscillates within one plane, the light is **linearly polarized**.



Polarization production

Sources of polarization

Polarized radiation is produced in several physical processes taking place in the BHXRBs, such as **synchrotron radiation** in the presence of an ordered magnetic field of the jet (hot accretion flow) or **scattering** of the accretion disk radiation **by electrons or dust**.

Polarization carries information about the geometrical properties of the emitting/scattering media.

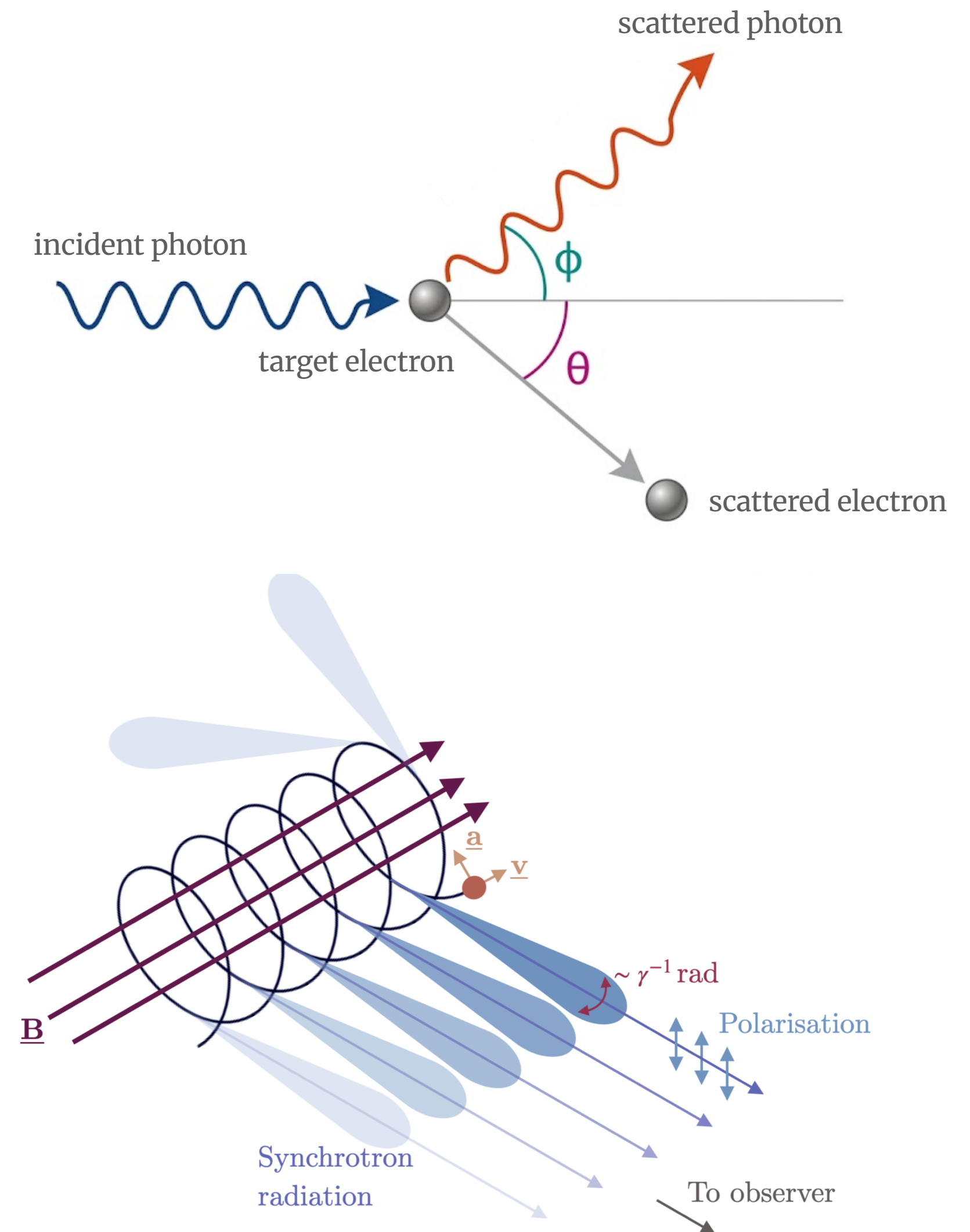
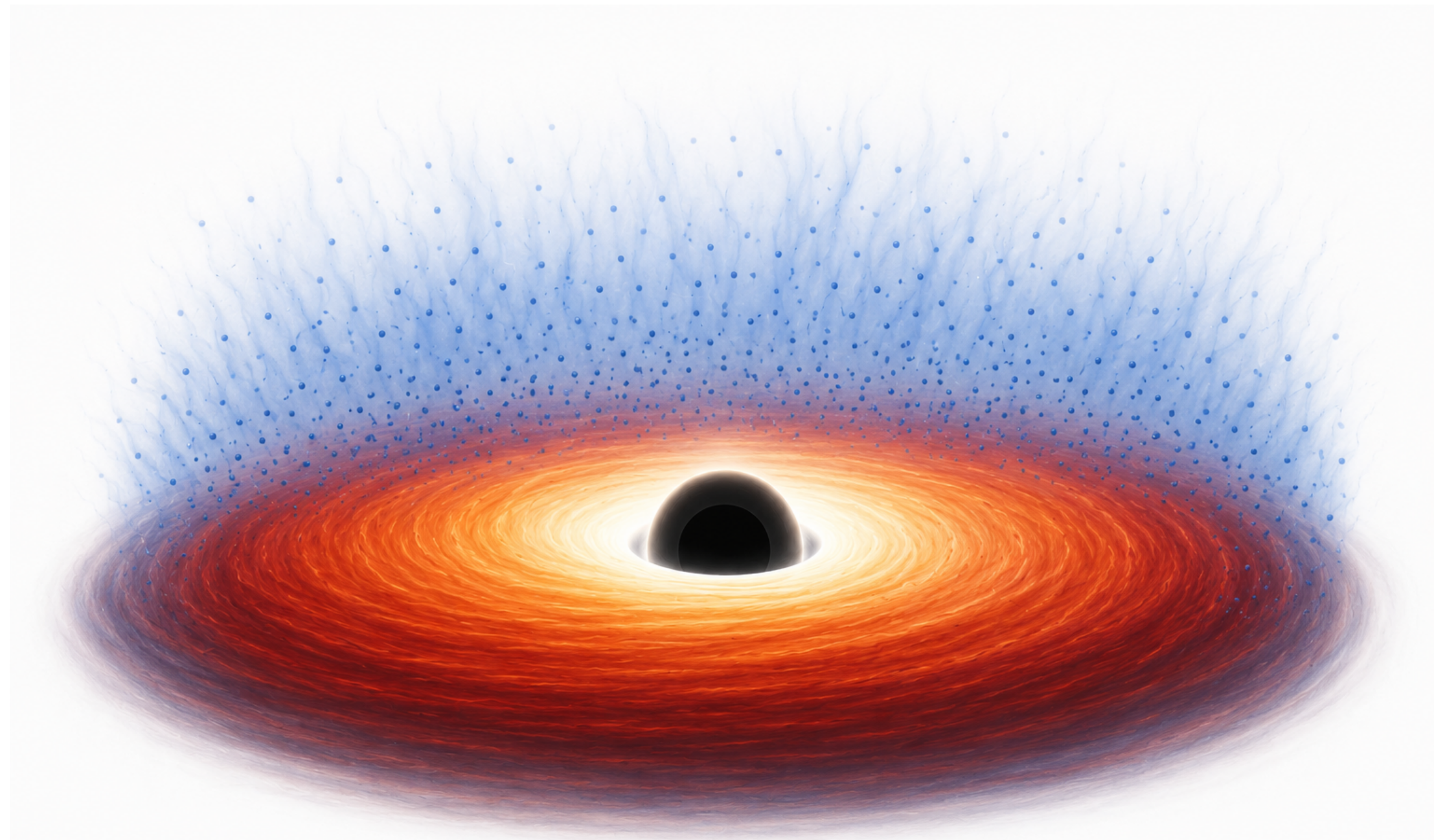


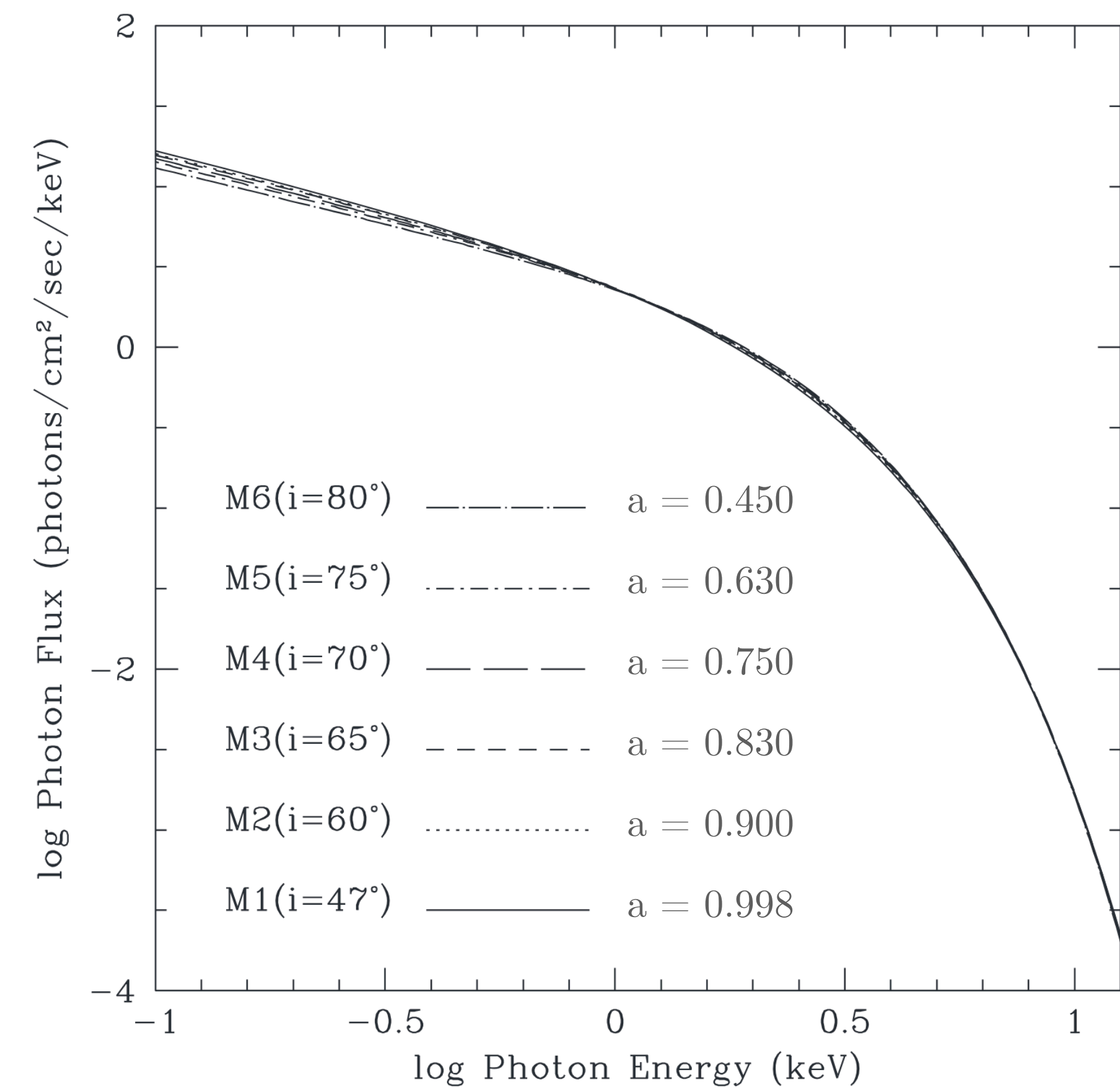
Image: Emma Alexander

Why polarization?



Spectra alone cannot be used to extract information about both BH spin and disk inclination!

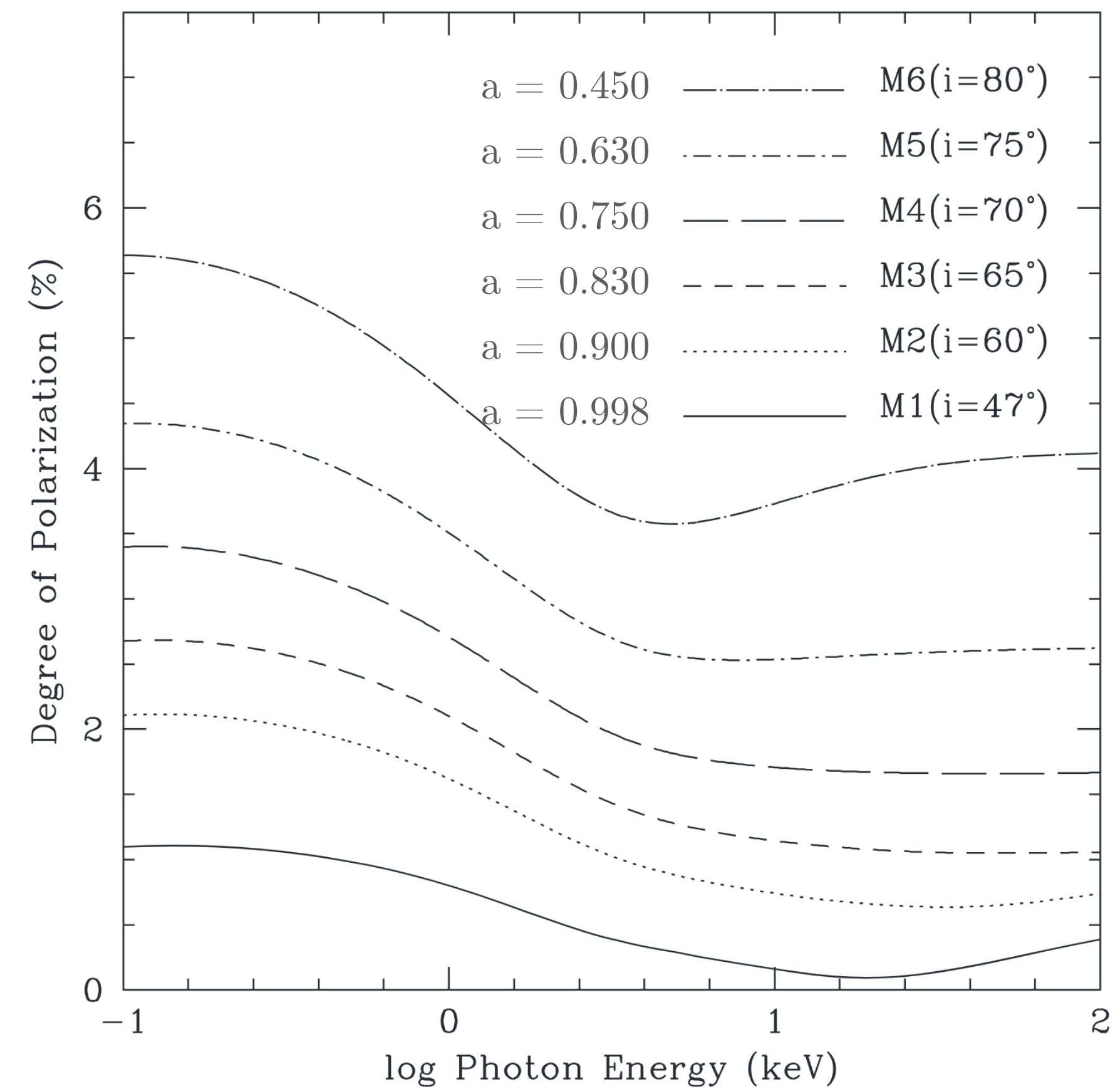
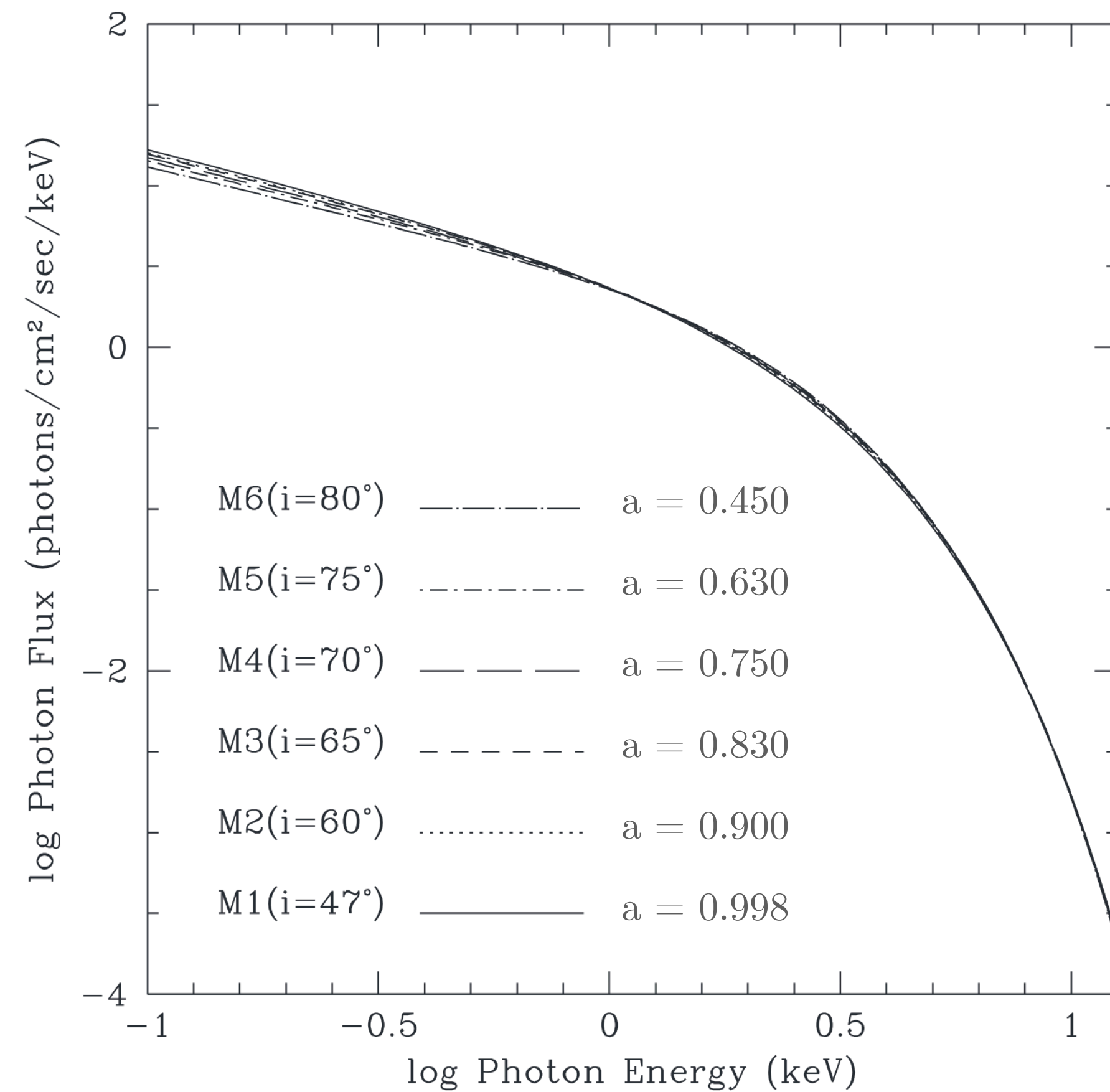
Example: Li, Narayan & McClintock 2009



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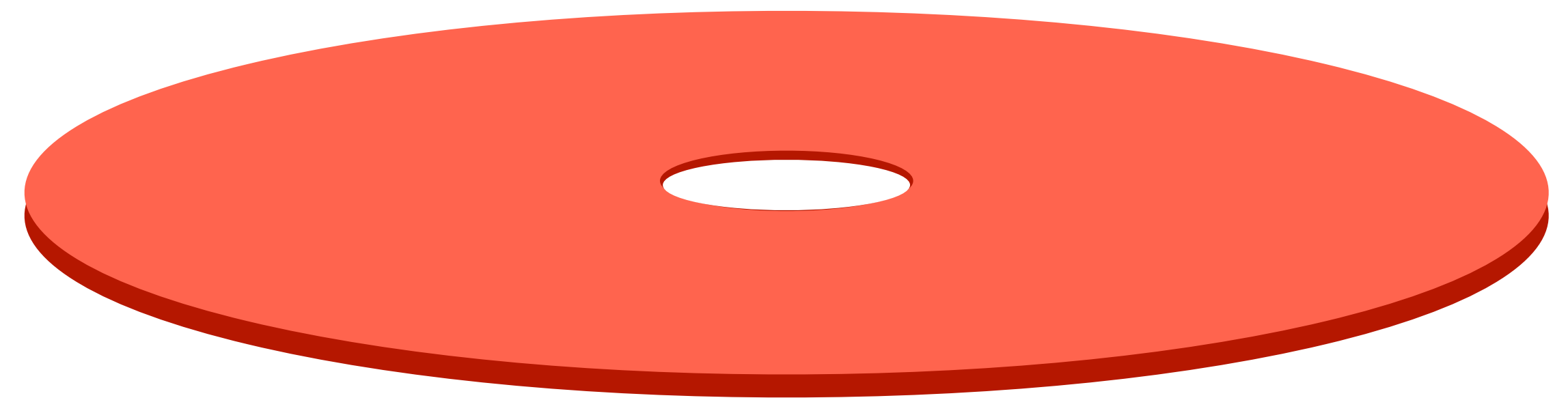
What contributes to the polarization?

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1. **Disk:** plane-parallel, electron scattering-dominated atmosphere (Shakura & Sunyaev 1973; Novikov & Thorne 1973).

$$\text{PD} = 11.7\% \frac{1 - \cos i}{1 + 3.58 \cos i}$$

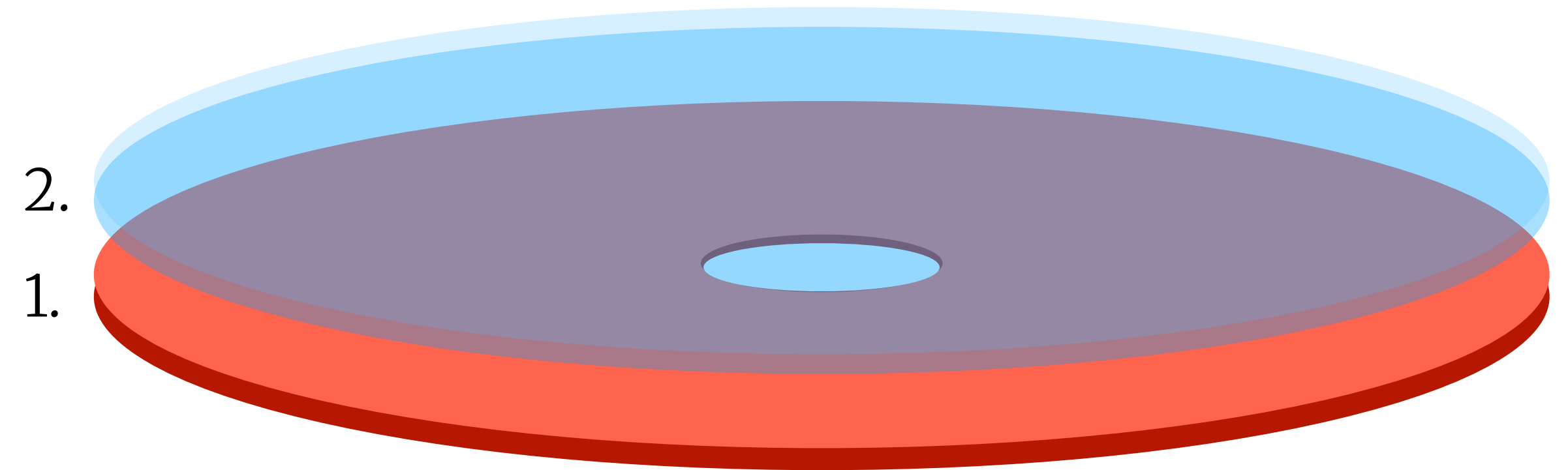
1.



What contributes to the polarization?

1. **Disk:** plane-parallel, electron scattering-dominated atmosphere (Shakura & Sunyaev 1973; Novikov & Thorne 1973).
2. **Corona:** hot, optically thin plasma in the vicinity of black hole. Inverse Compton scattering. Different geometries were proposed: **slab**, **lamppost**, **sphere**, **conical**, **wedge**, etc. (see e.g. Poutanen & Svensson 1996; Dovčiak et al. 2004, 2008; Kara et al. 2019; Krawczynski & Beheshtipour 2022).

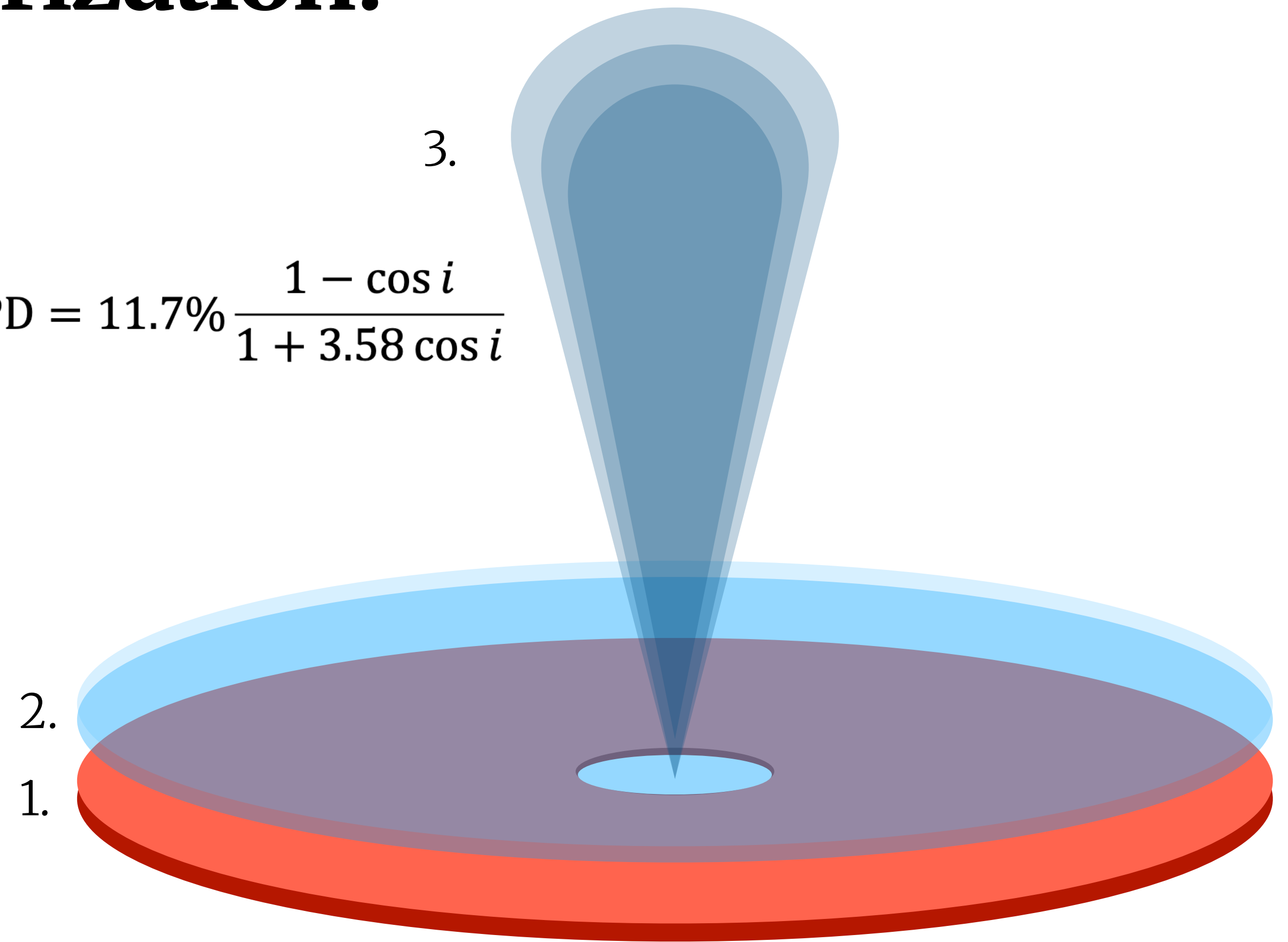
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What contributes to the polarization?

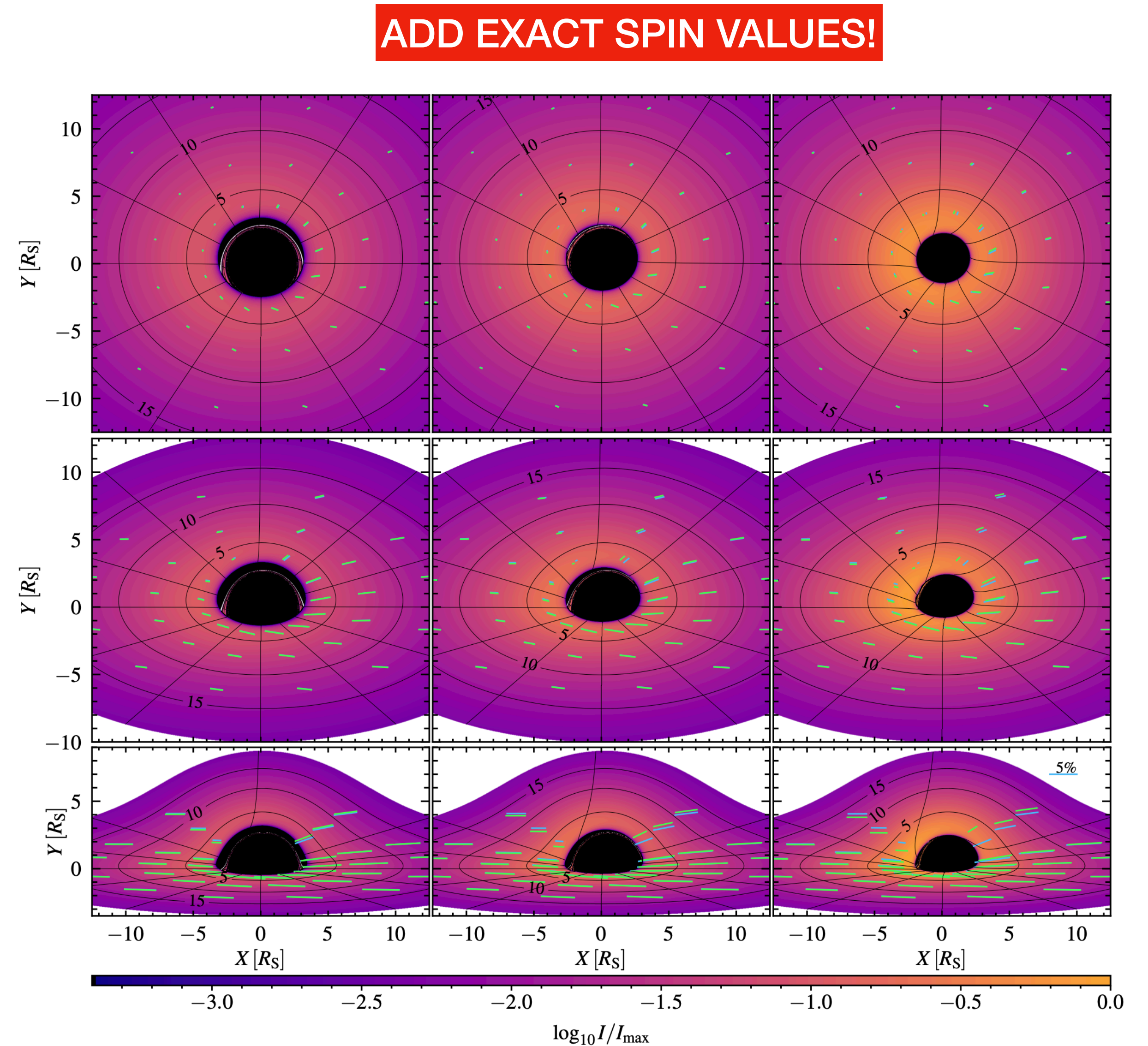
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3. **Jet? Outflow?** Synchrotron emission is highly polarized, however, even in radio the PD is quite small (Faraday rotation).

$$PD = 11.7\% \frac{1 - \cos i}{1 + 3.58 \cos i}$$



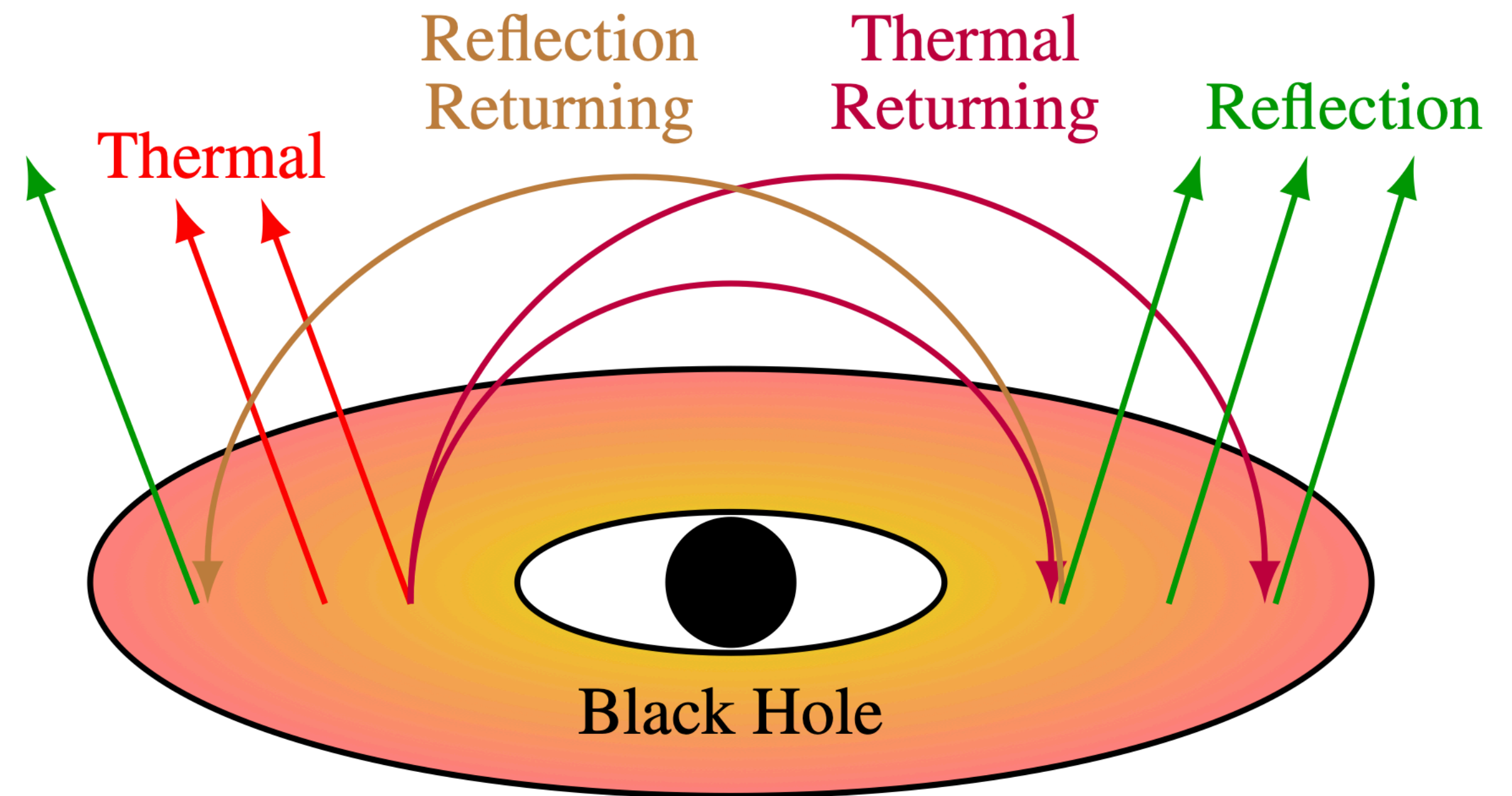
GR, SR, and other effects

1. **Gravitational lensing:** disk appears warped up toward the observer. Effectively lowers the inclination => lowers the PD.
2. **Beaming:** approaching side of the disk is seen at effectively lower i , but appear brighter => this lowers PD even more.



GR, SR, and other effects

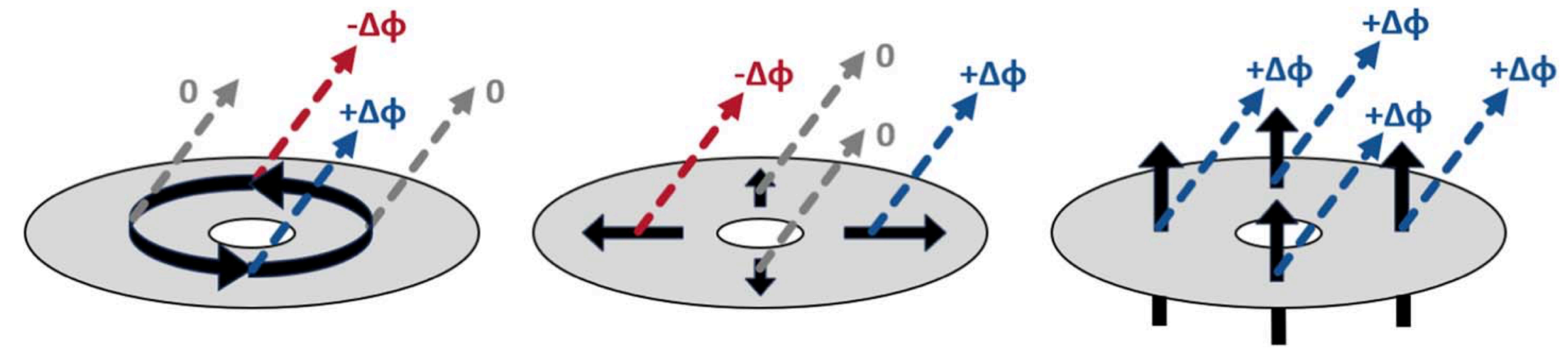
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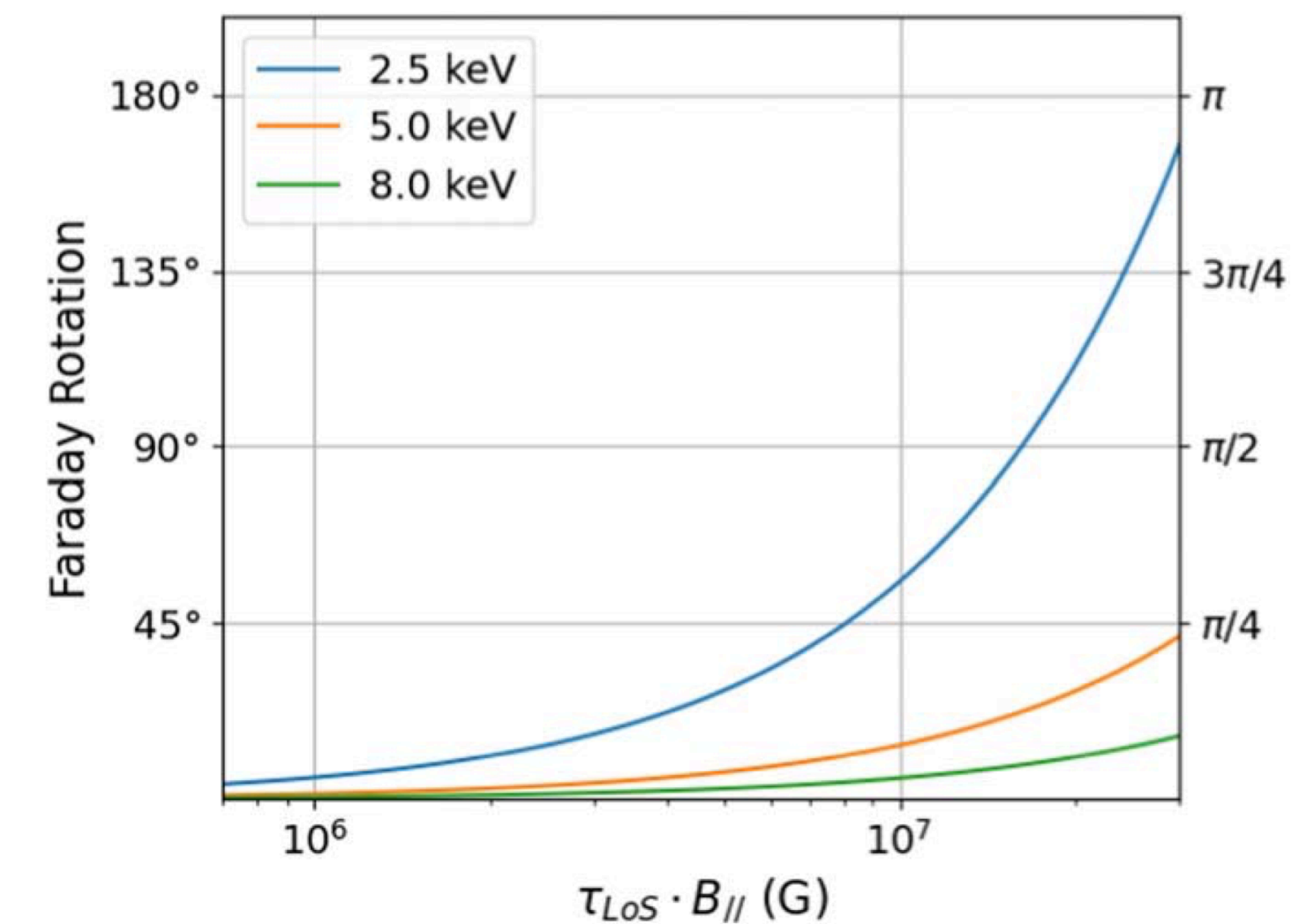
Kourmpetis et al. 2026

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1. **Gravitational lensing:** disk appears warped up toward the observer. Effectively lowers the inclination => lowers the PD.
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4. **Faraday rotation:** depolarization + PA rotation



Barnier & Done 2024



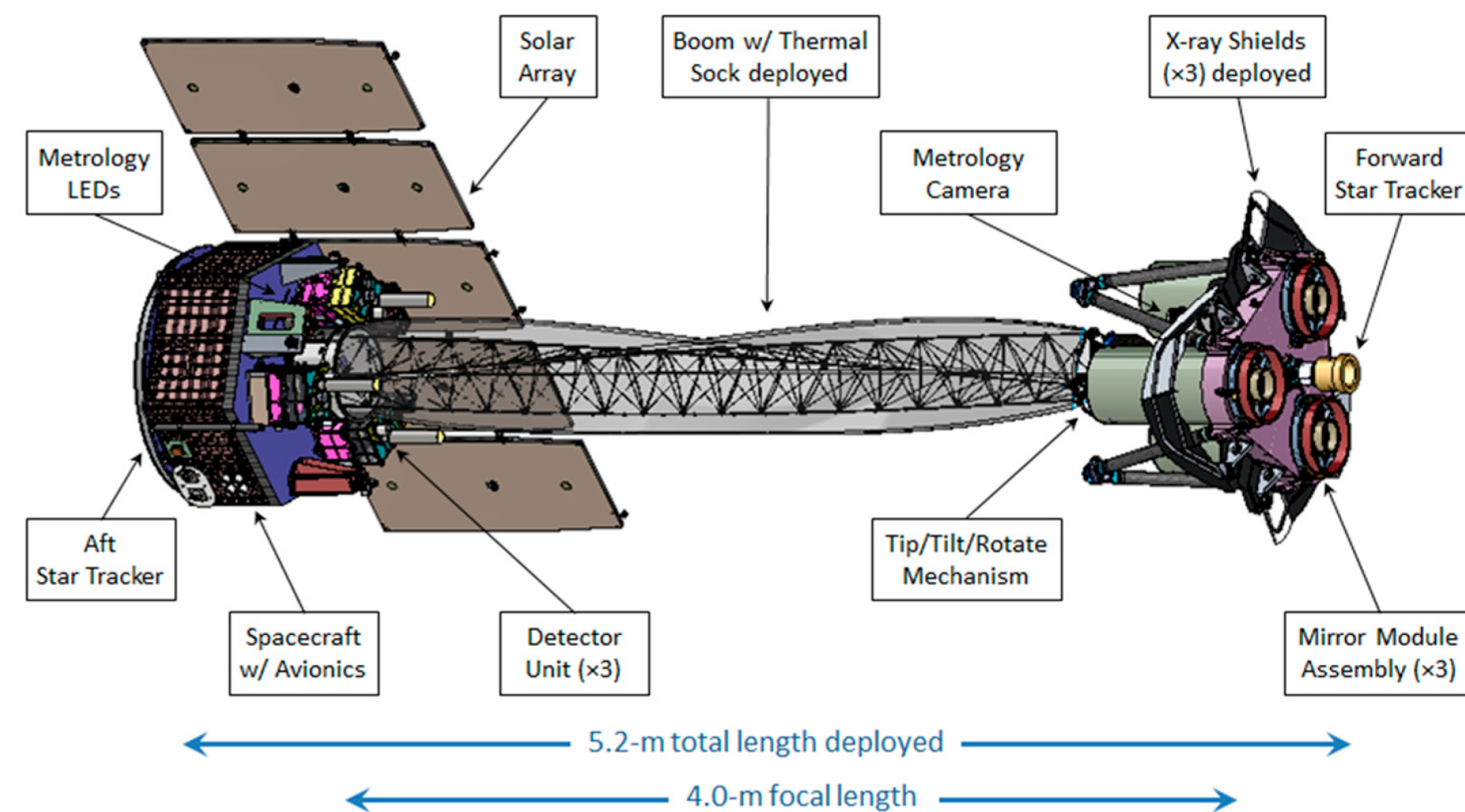
$$\Delta\Phi = 5.5 \tau_{\text{LoS}} \left(\frac{B_{\parallel}}{10^6 \text{ G}} \right) \left(\frac{E}{2.5 \text{ keV}} \right)^{-2} \text{ degrees.}$$

X-ray polarimetry

Current and future instruments

TODAY

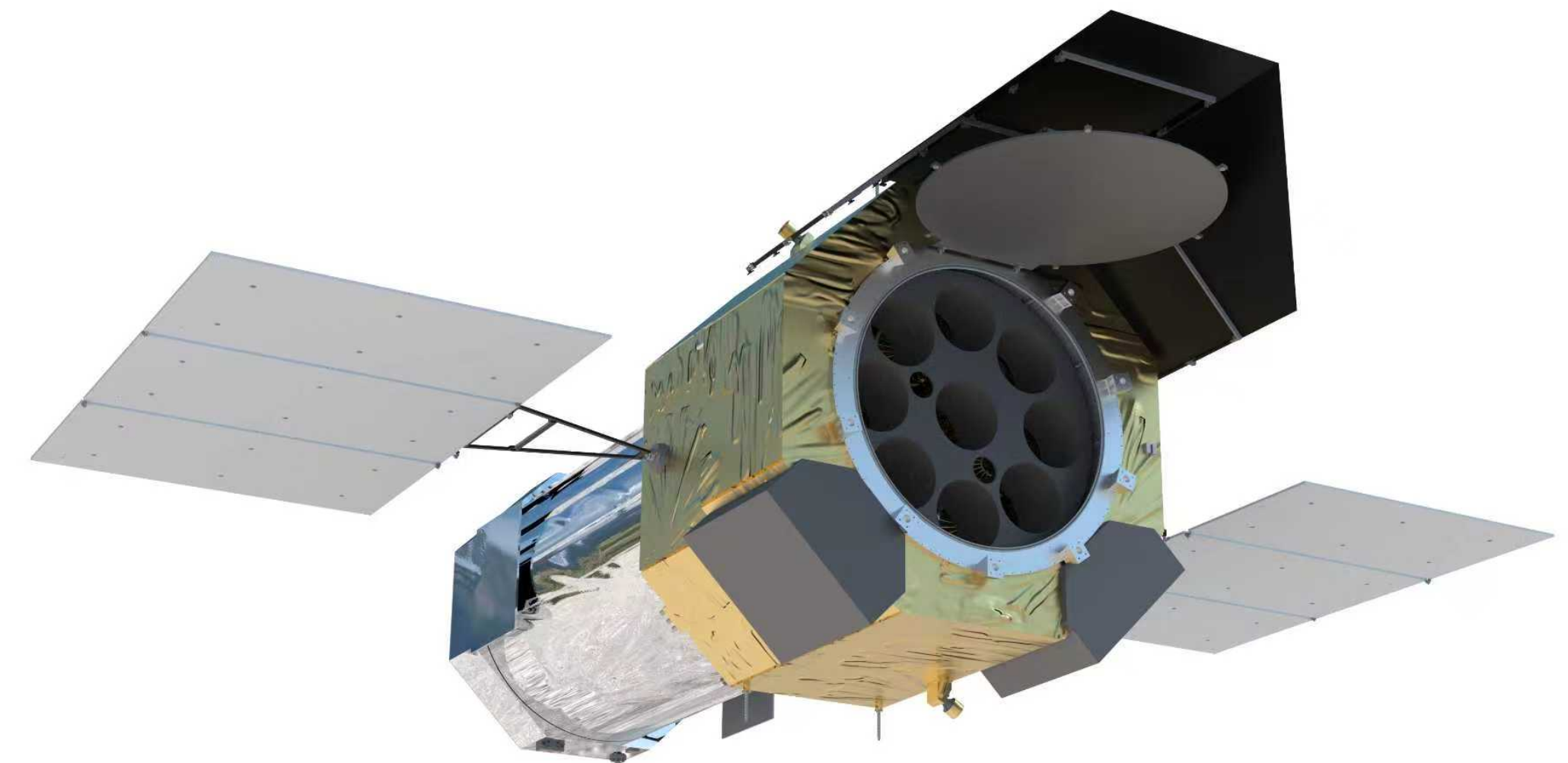
IXPE (Imaging X-ray Polarimetry Explorer)
first reliable X-ray polarization measurements, launched in 2021



>200 papers discussing IXPE results are published since 2021

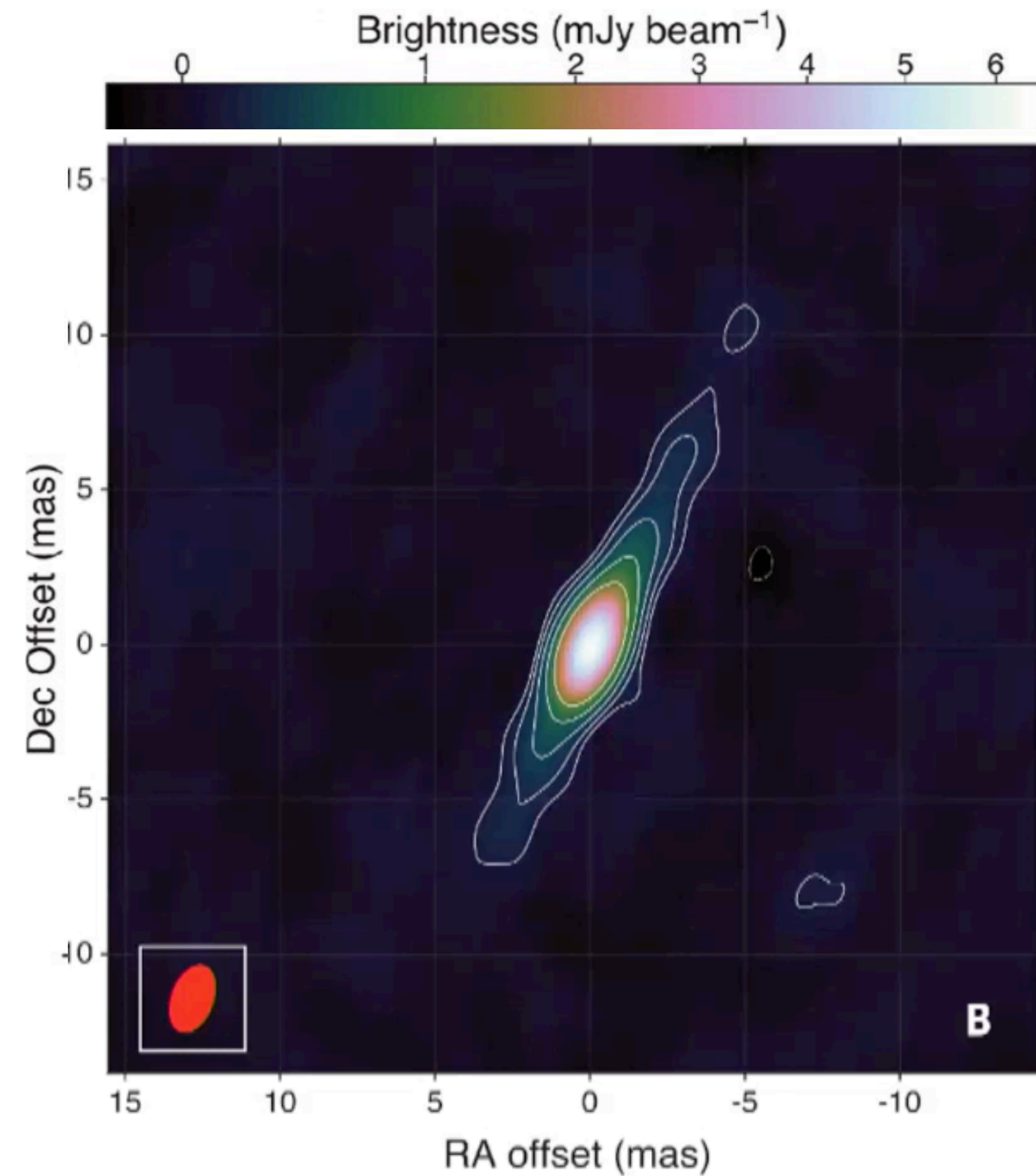
TOMORROW

eXTP (enhanced X-ray Timing and Polarimetry)
~3 times "better" than IXPE, launch planned for 2030



IXPE results: Cyg X-1

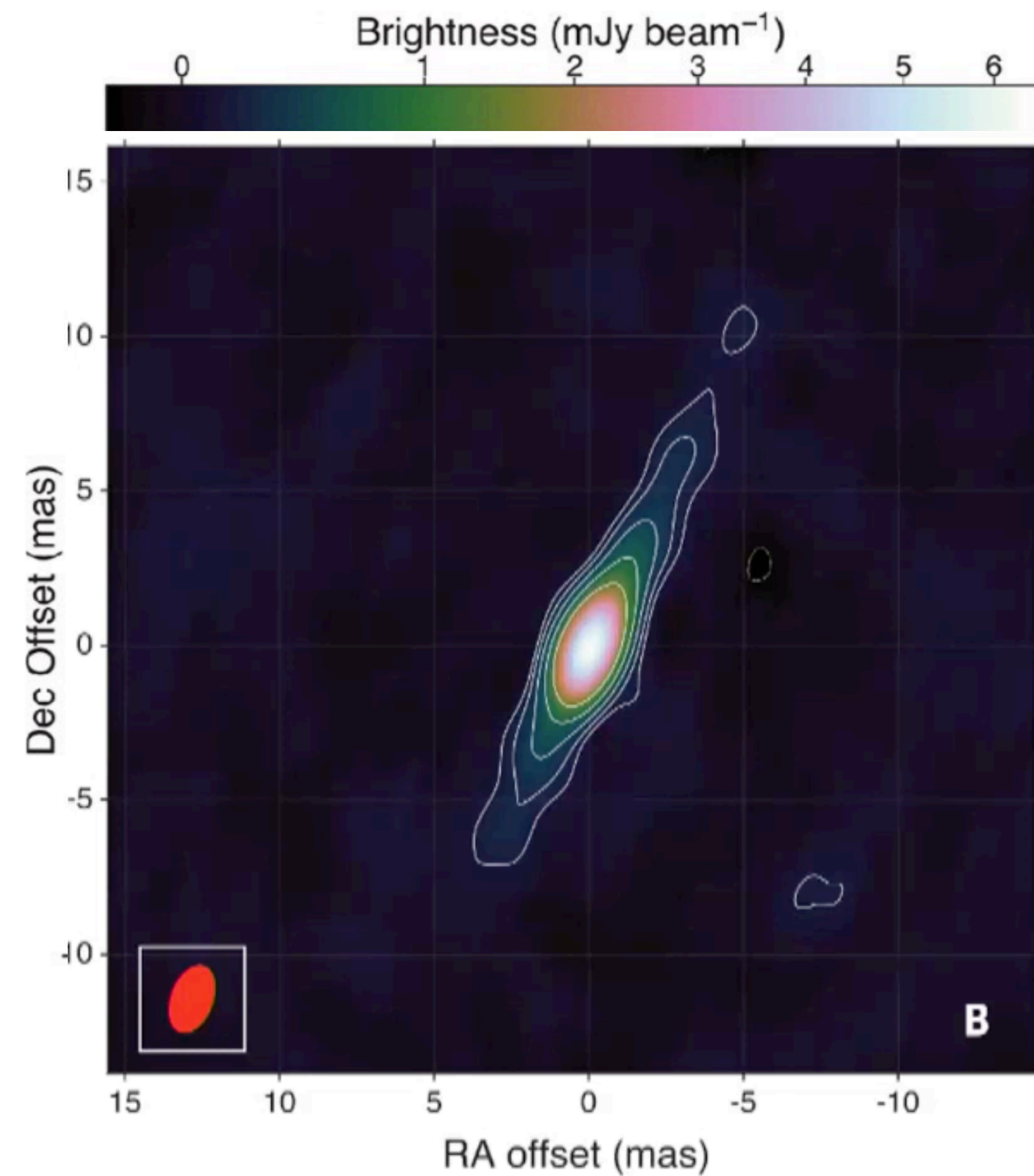
First reliable X-ray polarization measurement of BHXR



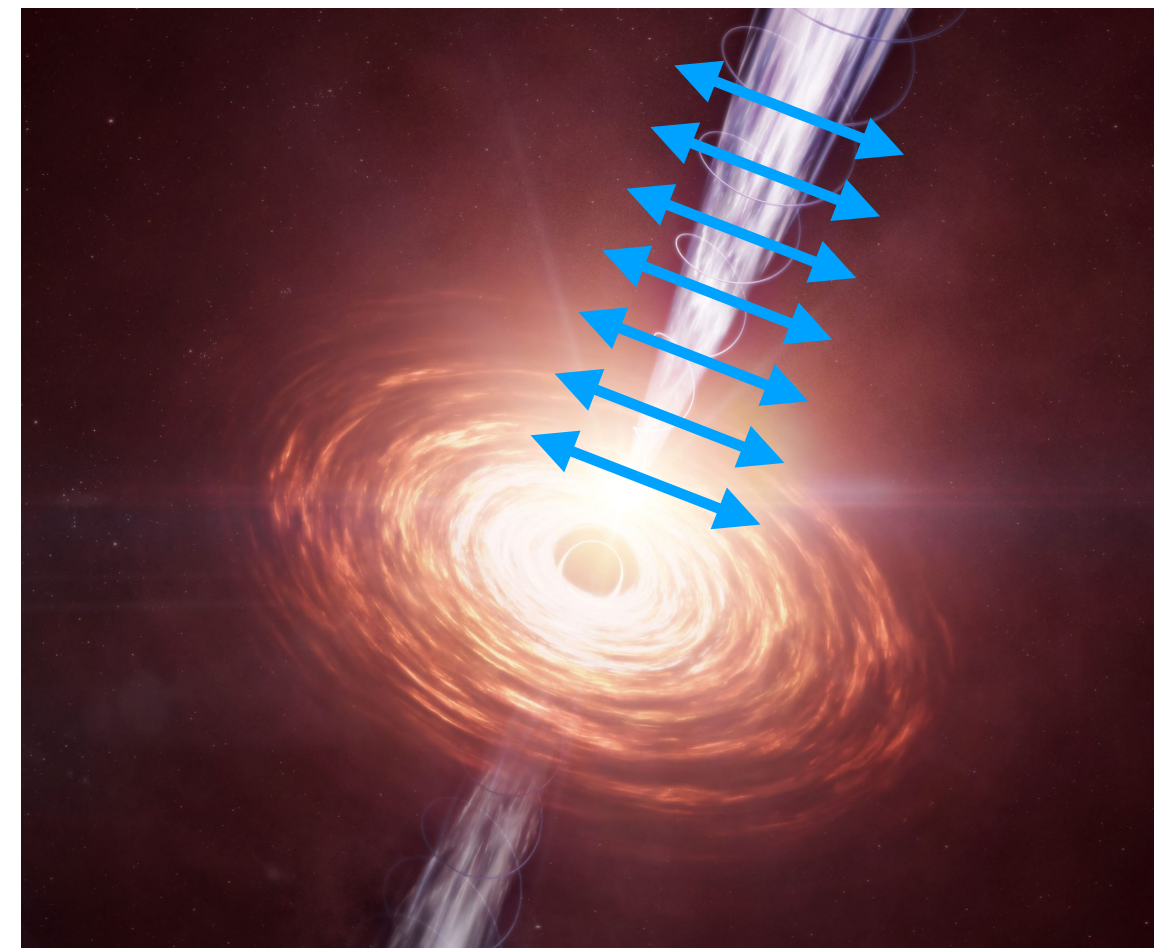
NASA/CXC/SAO/M. Weiss

IXPE results: Cyg X-1

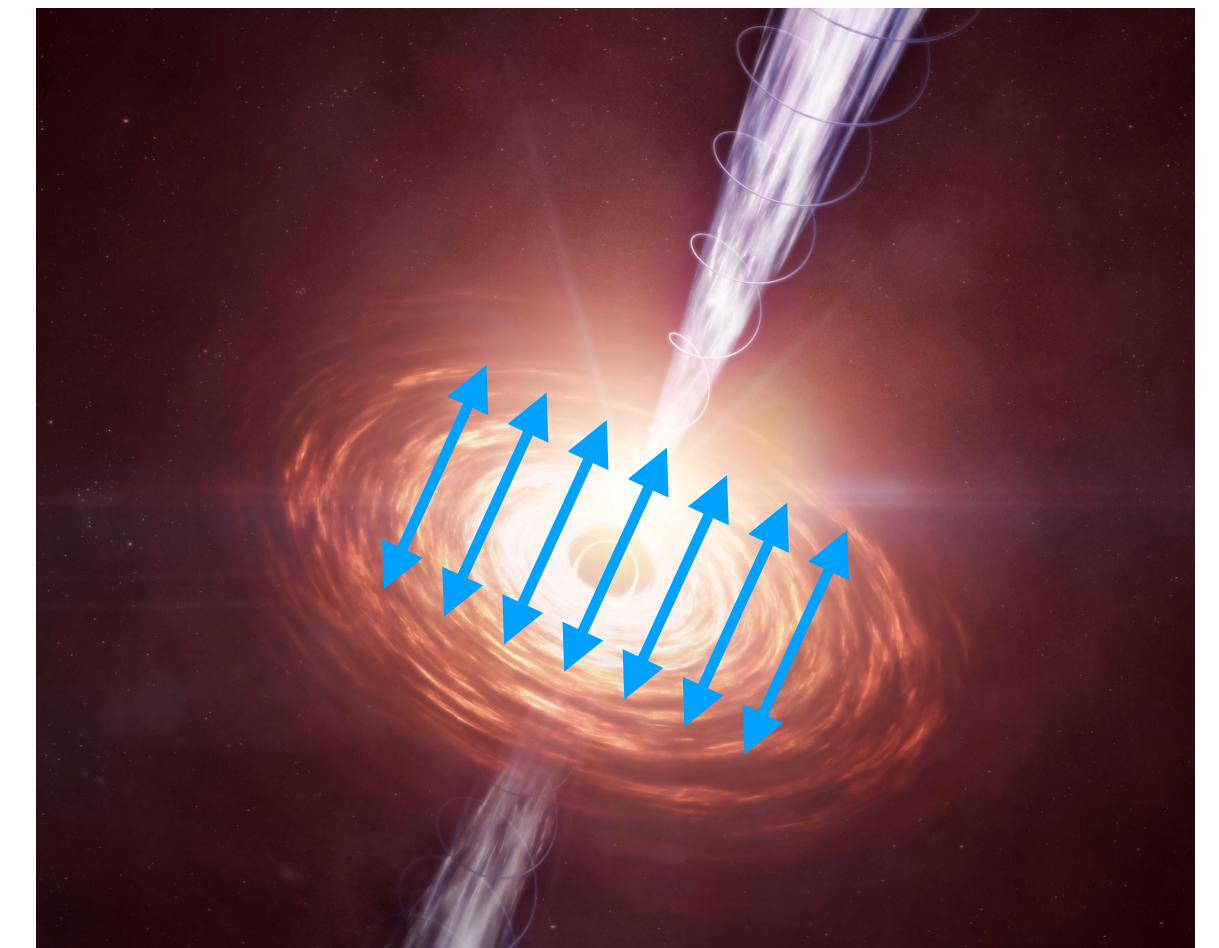
First reliable X-ray polarization measurement of BHXR



X-ray polarization predictions



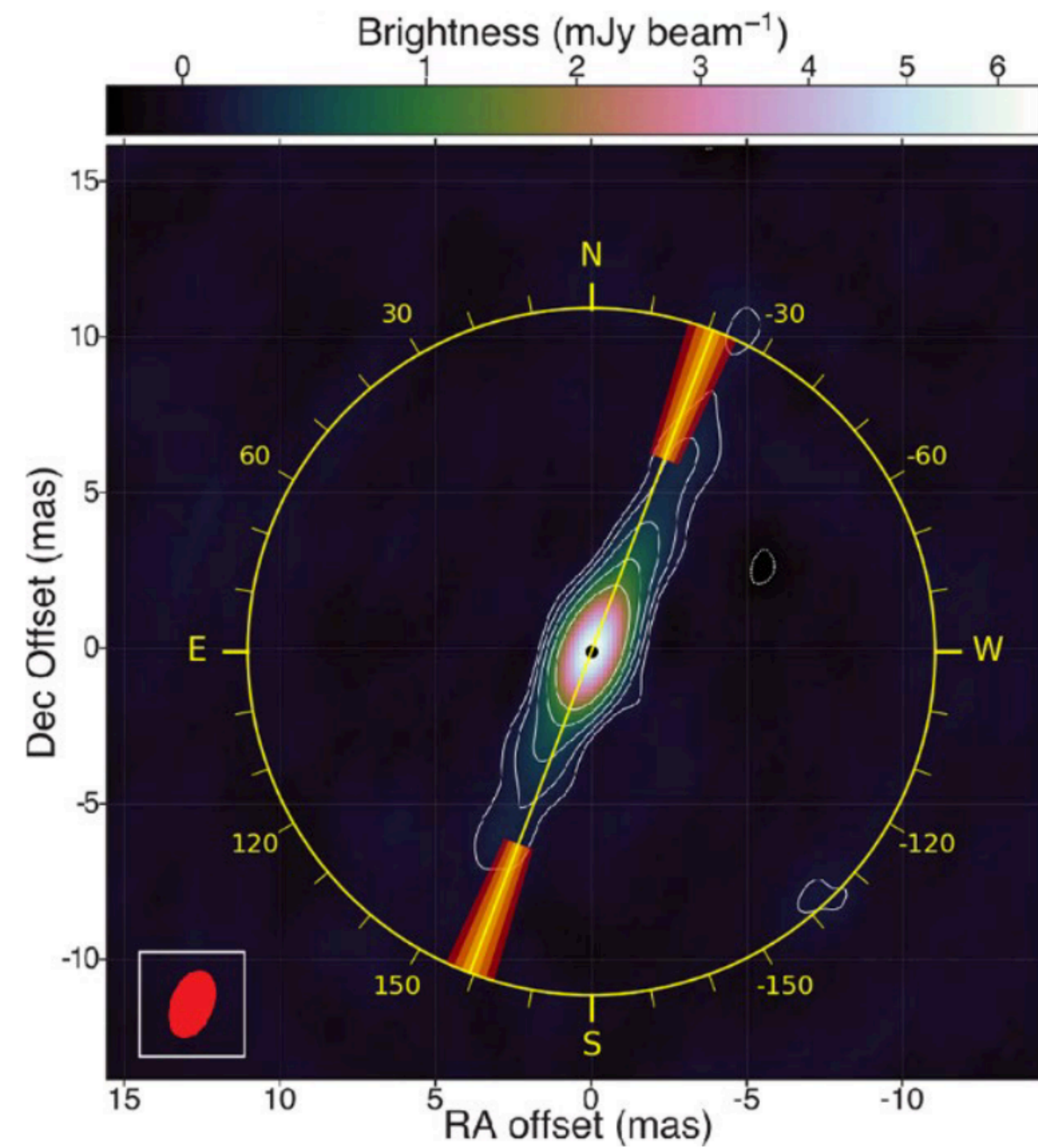
NASA/CXC/SAO/M. Weiss



NASA/CXC/SAO/M. Weiss

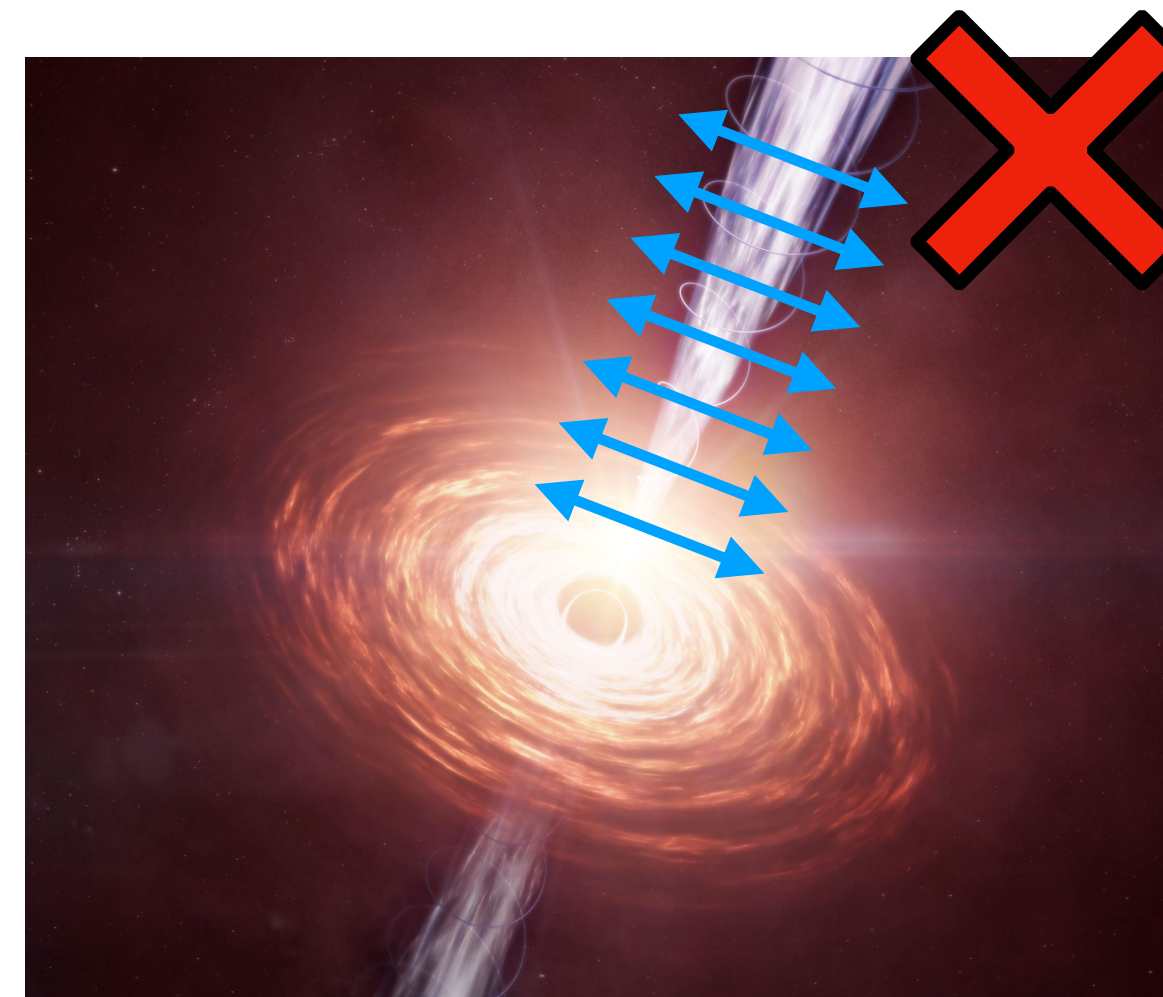
IXPE results: Cyg X-1

First reliable X-ray polarization measurement of BHXR

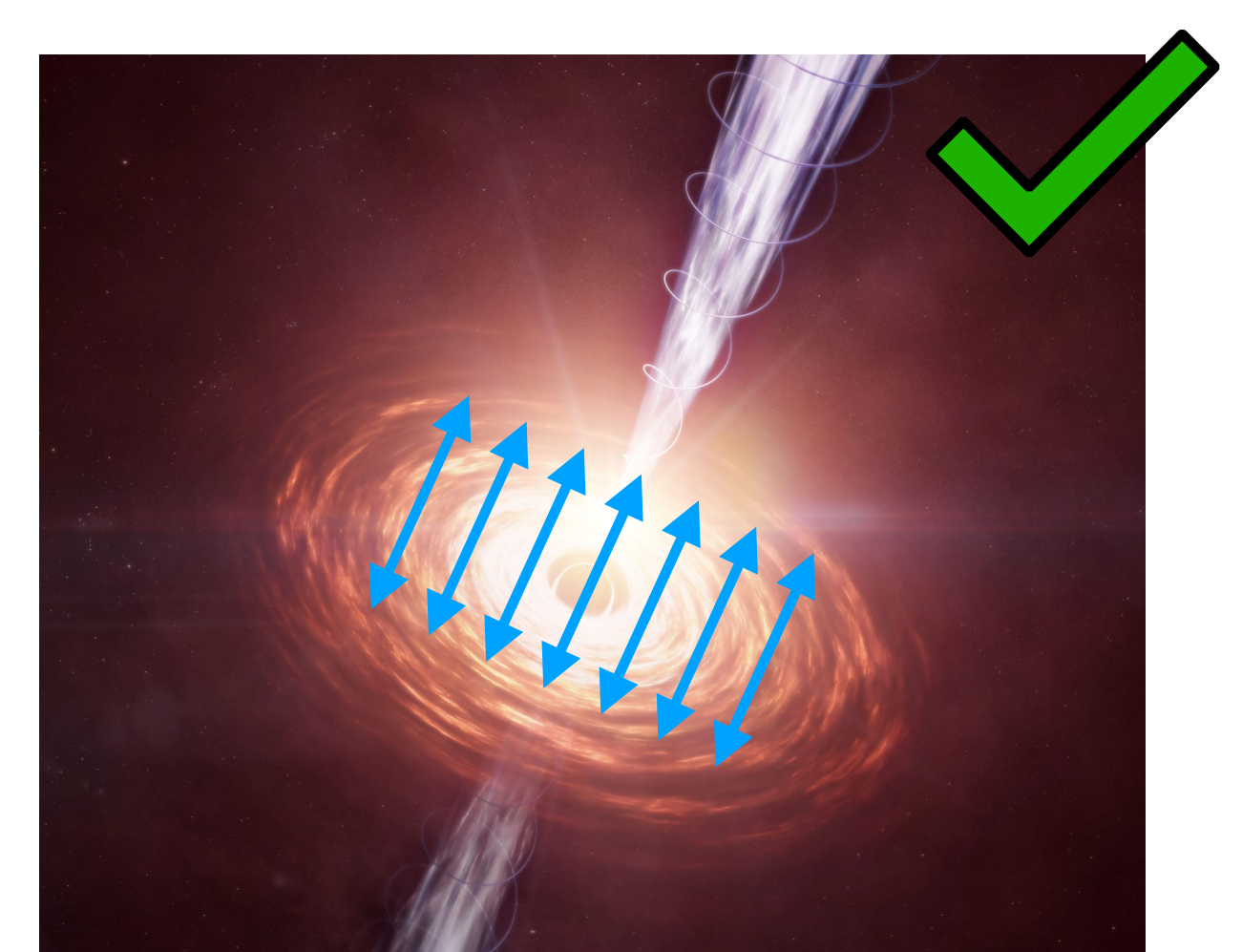


Krawczynski ... VK et al. 2022

X-ray polarization predictions



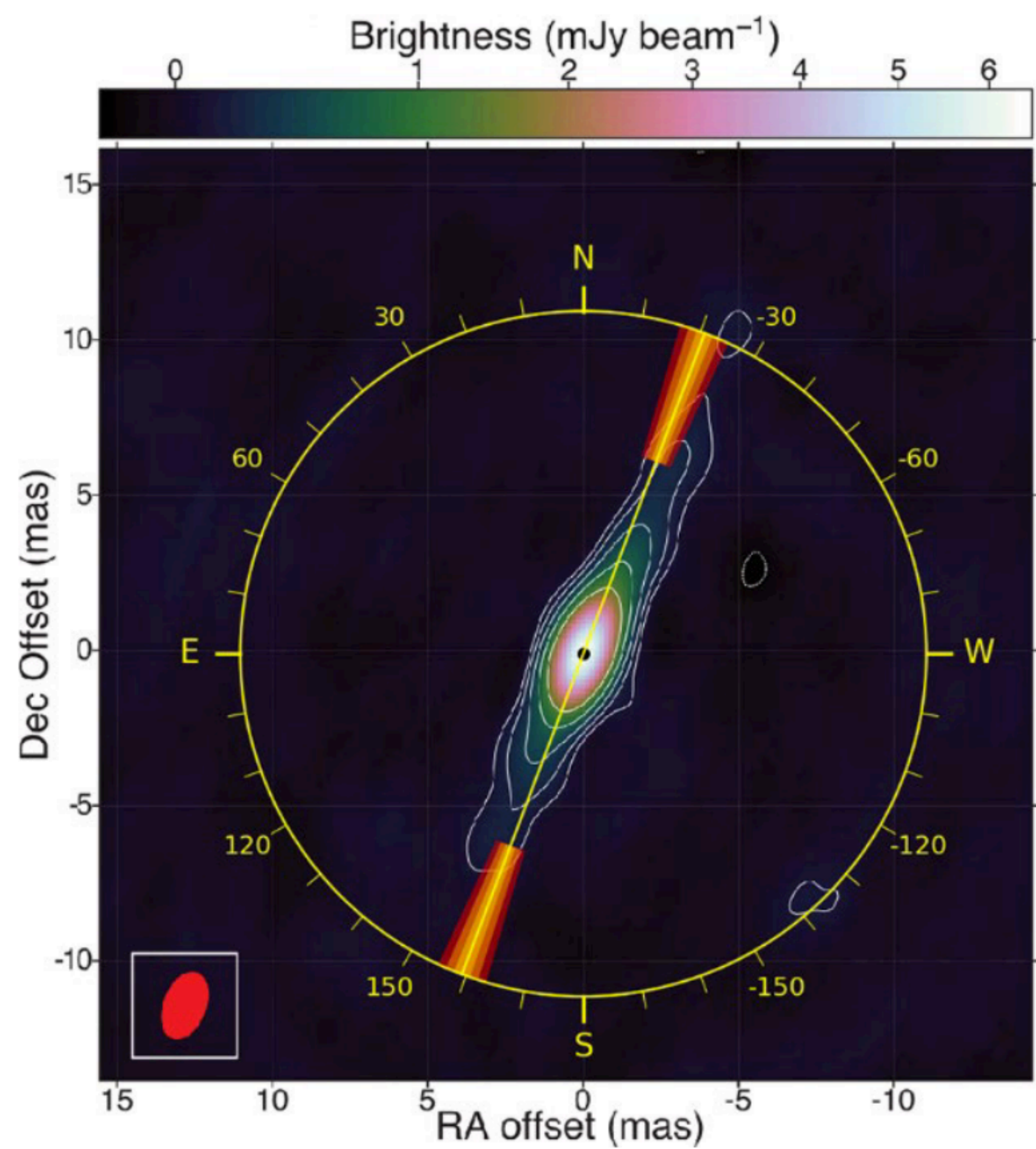
NASA/CXC/SAO/M. Weiss



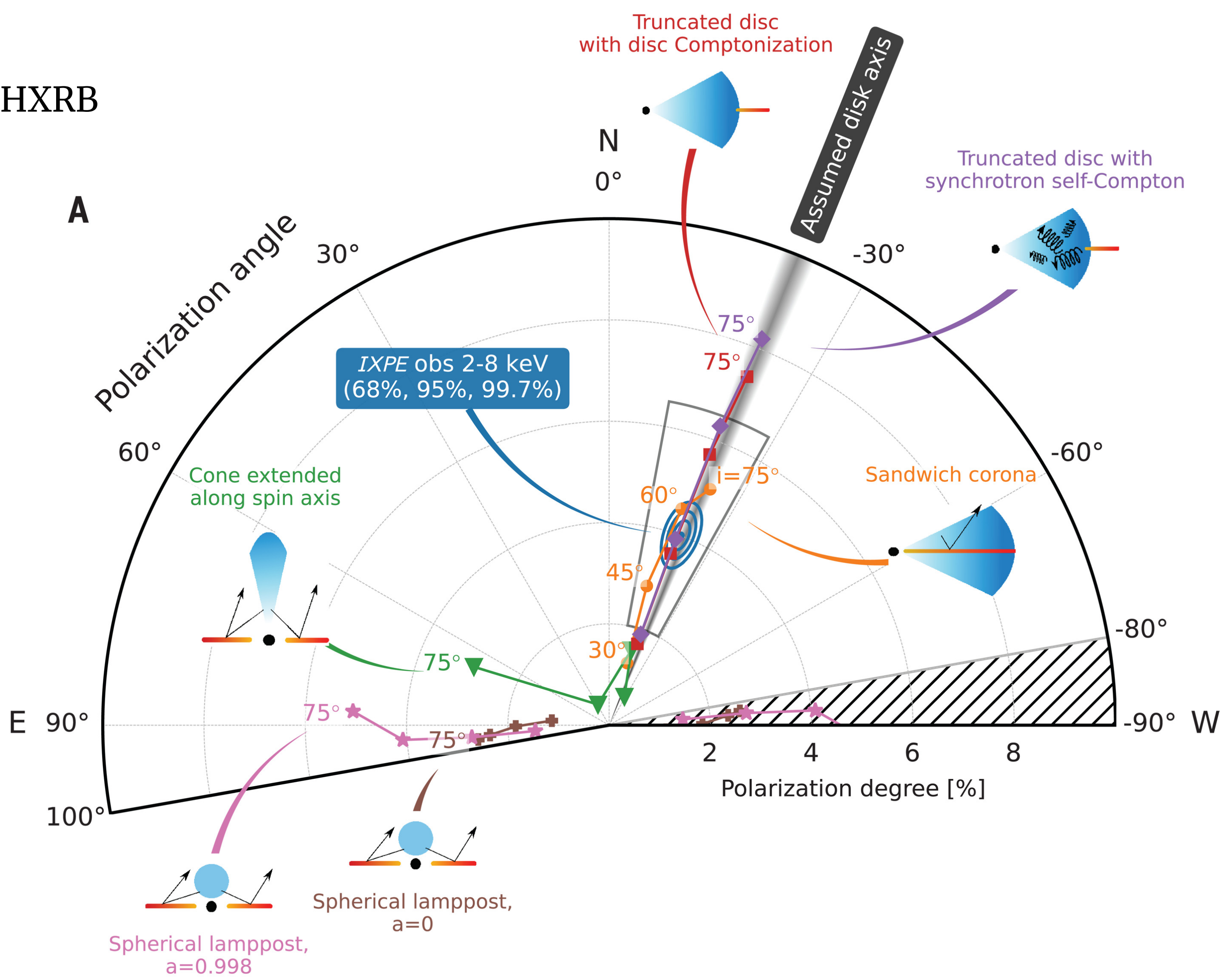
NASA/CXC/SAO/M. Weiss

IXPE results: Cyg X-1

First reliable X-ray polarization measurement of BHXR



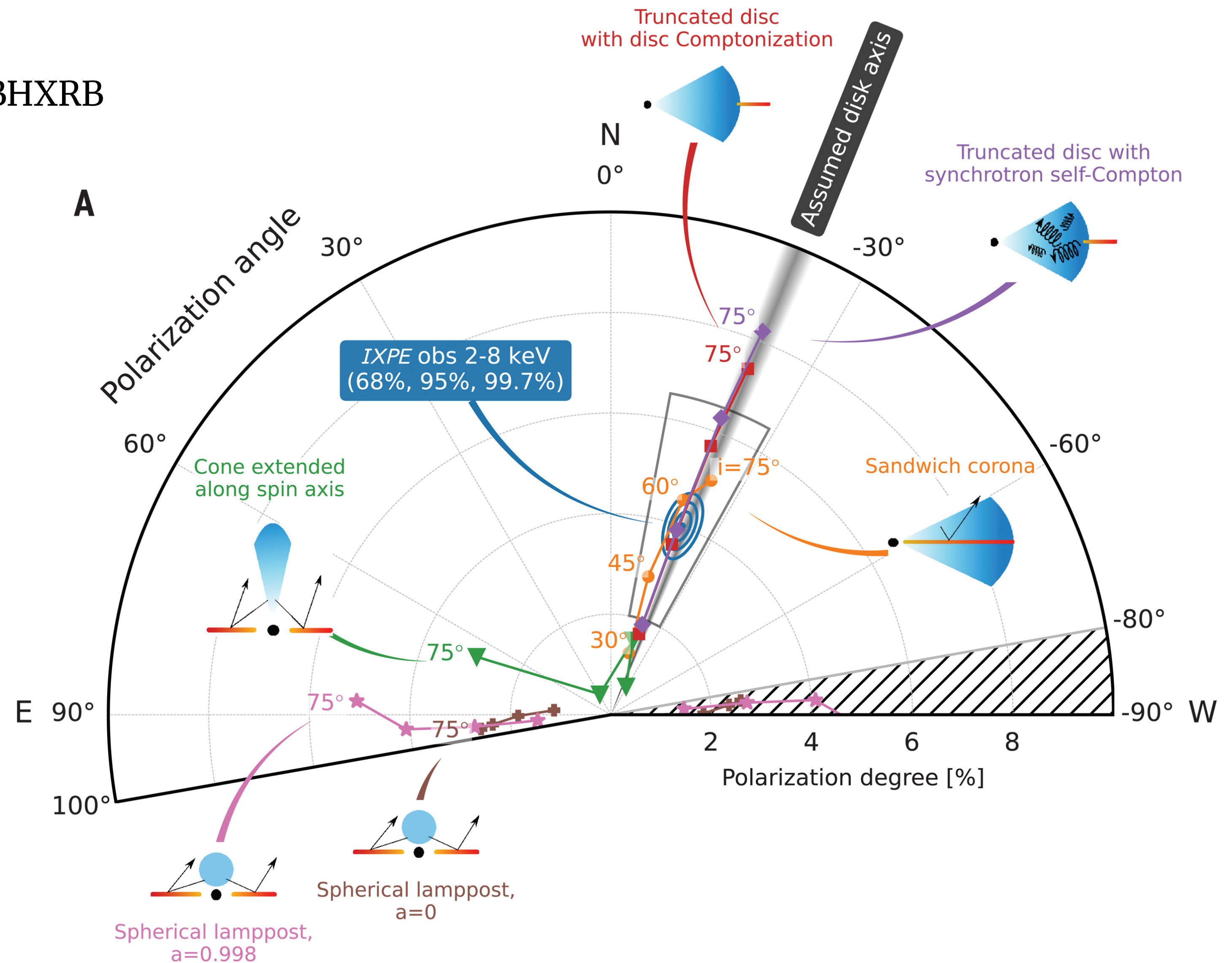
Krawczynski ... VK et al. 2022



IXPE results: Cyg X-1

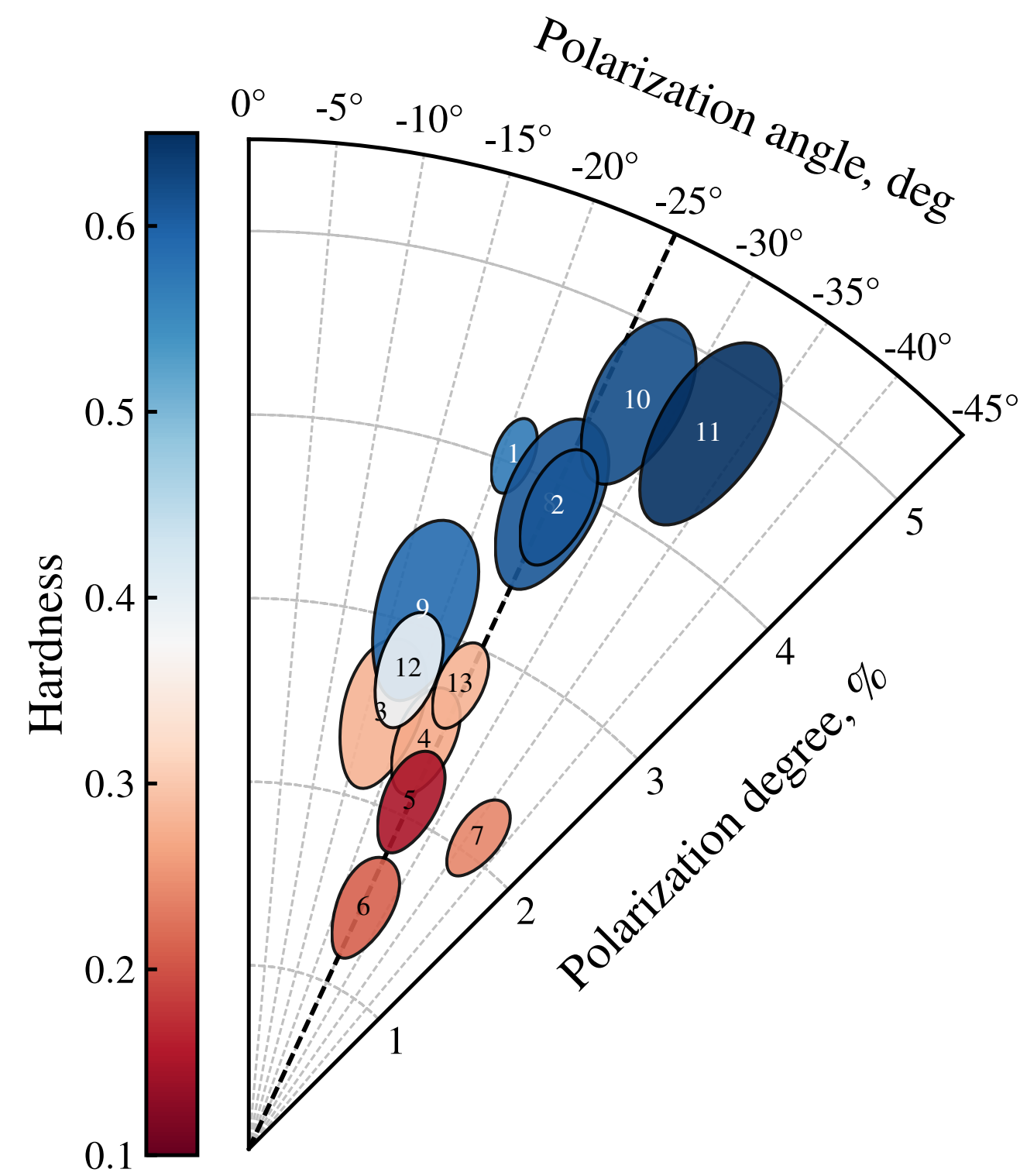
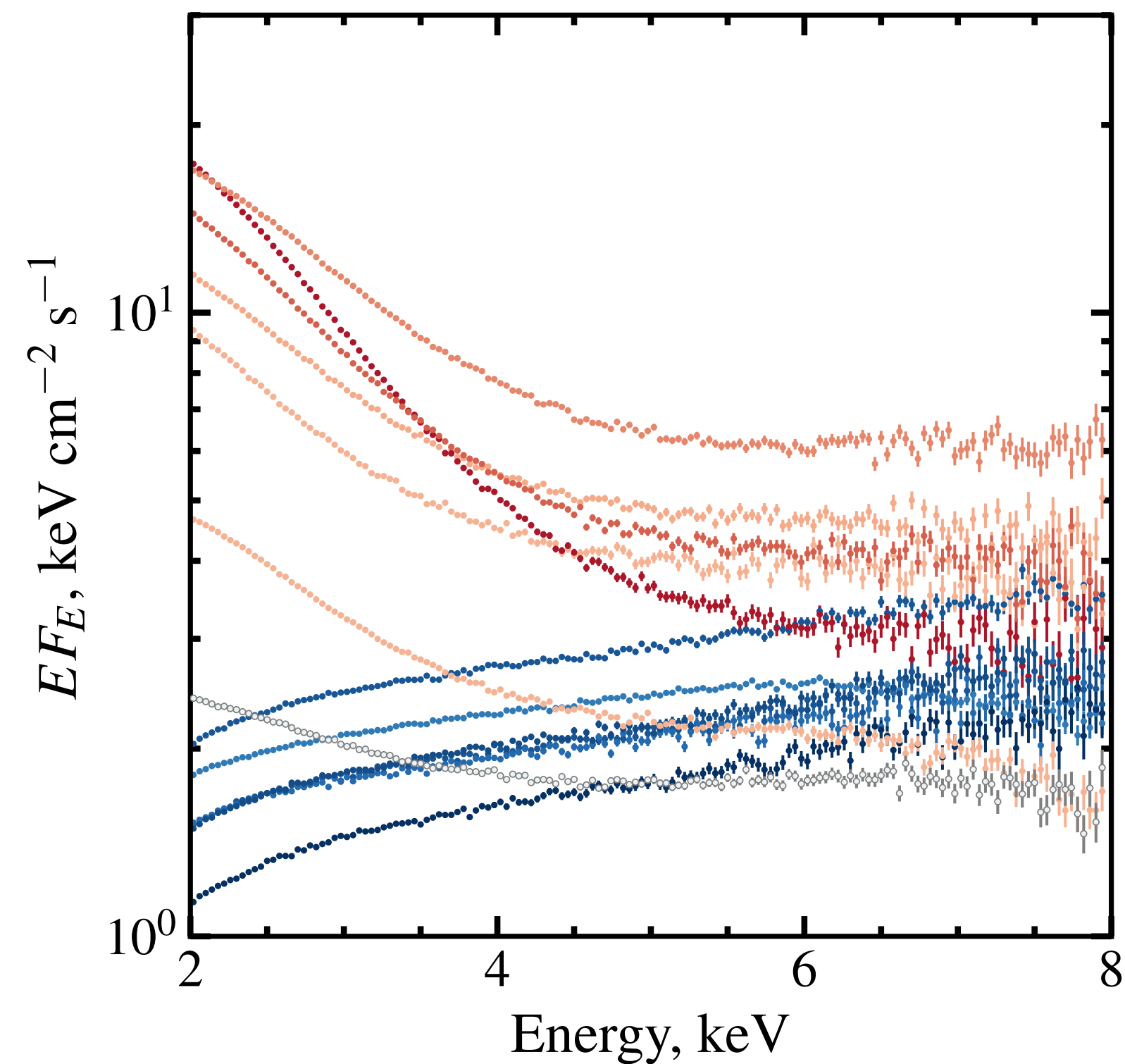
First reliable X-ray polarization measurement of BHXRB

High PD requires higher inclination => **jet-disk misalignment?**

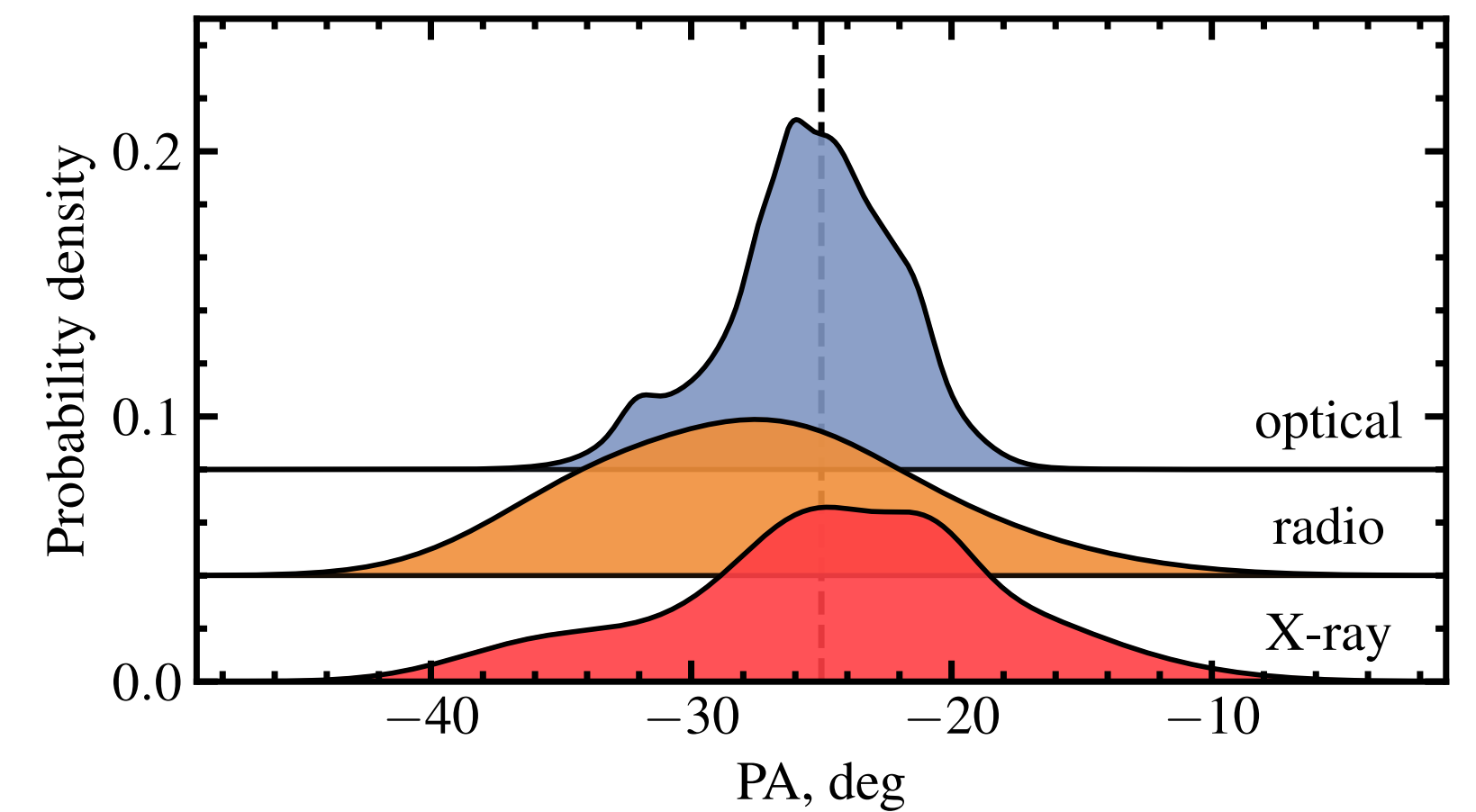


IXPE results: Cyg X-1

Attempts to explain Cyg X-1 observations



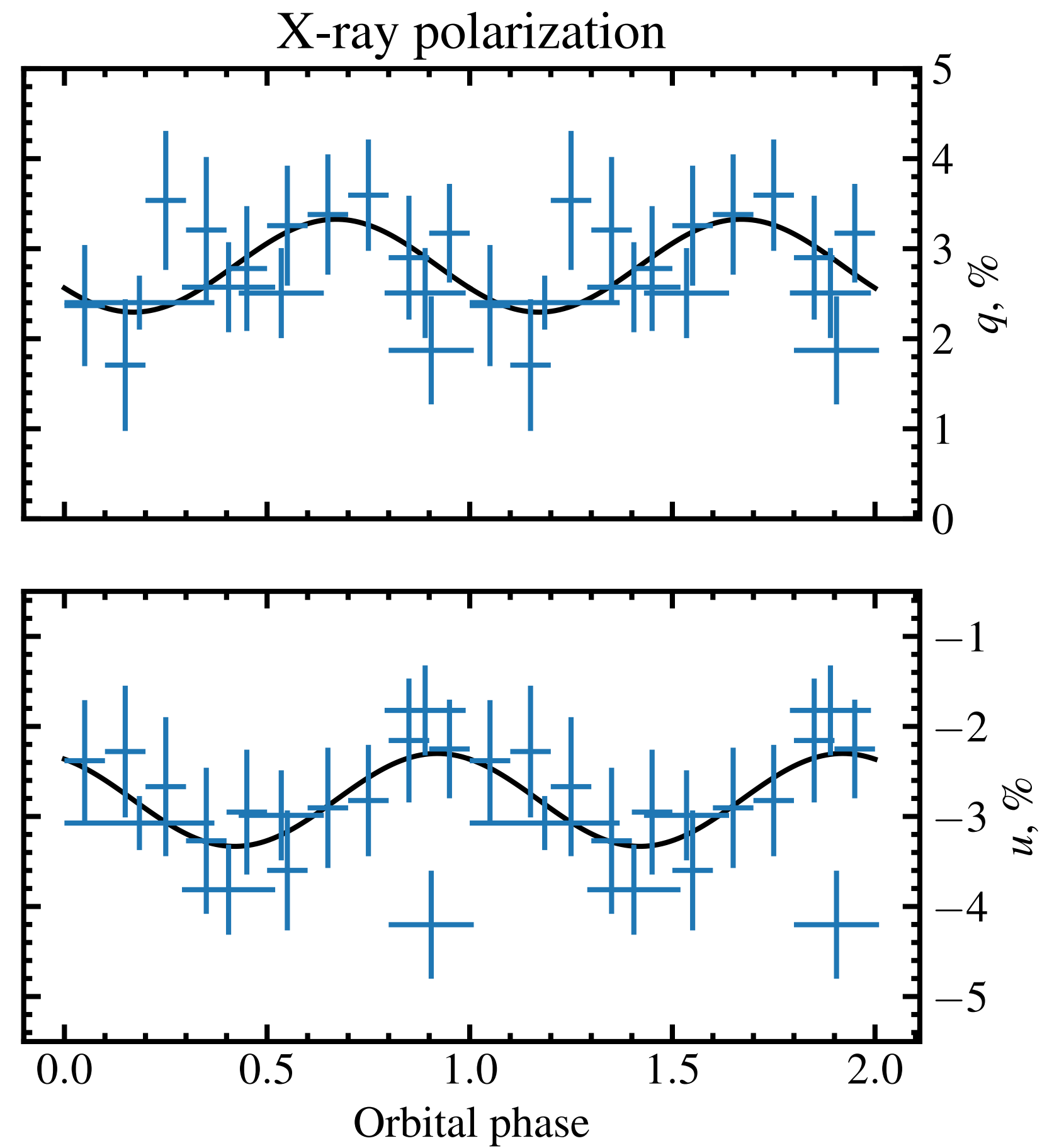
Long-term disk precession is not confirmed, we need something else.



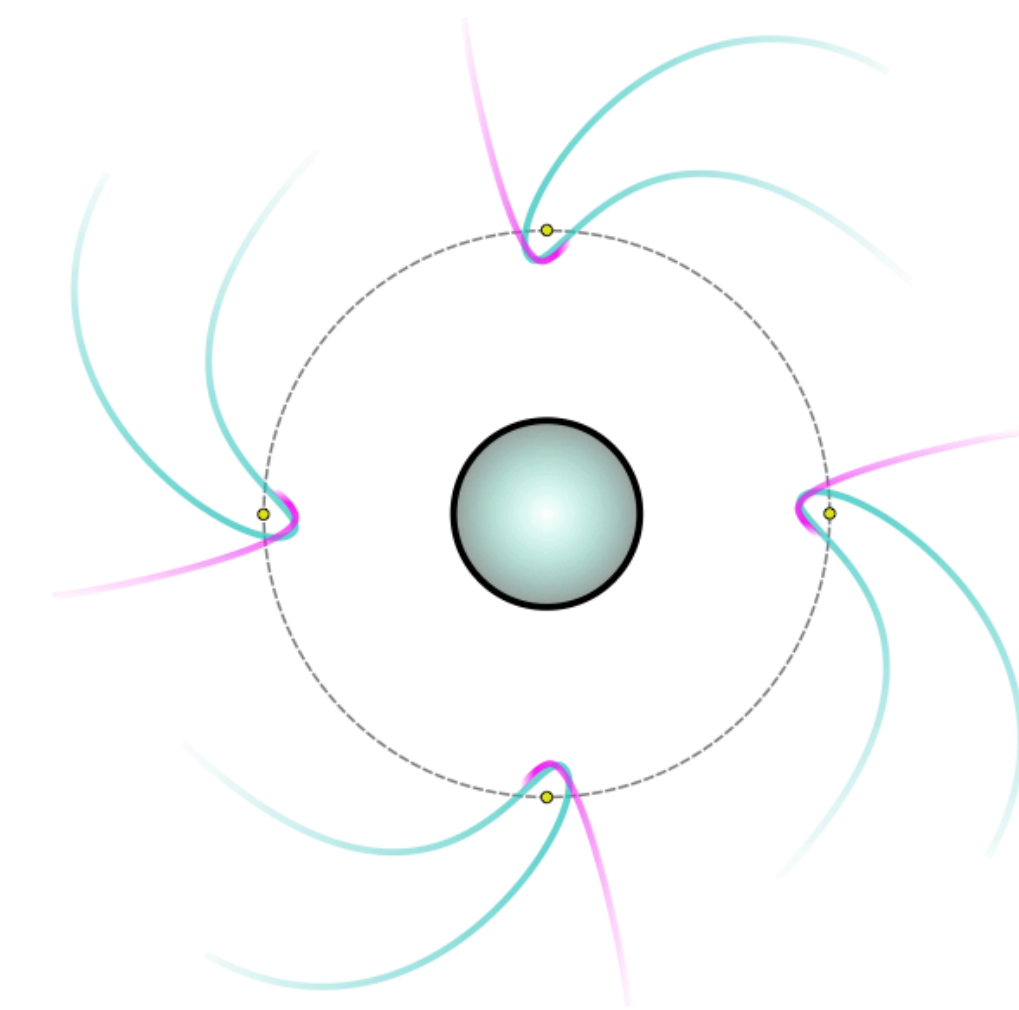
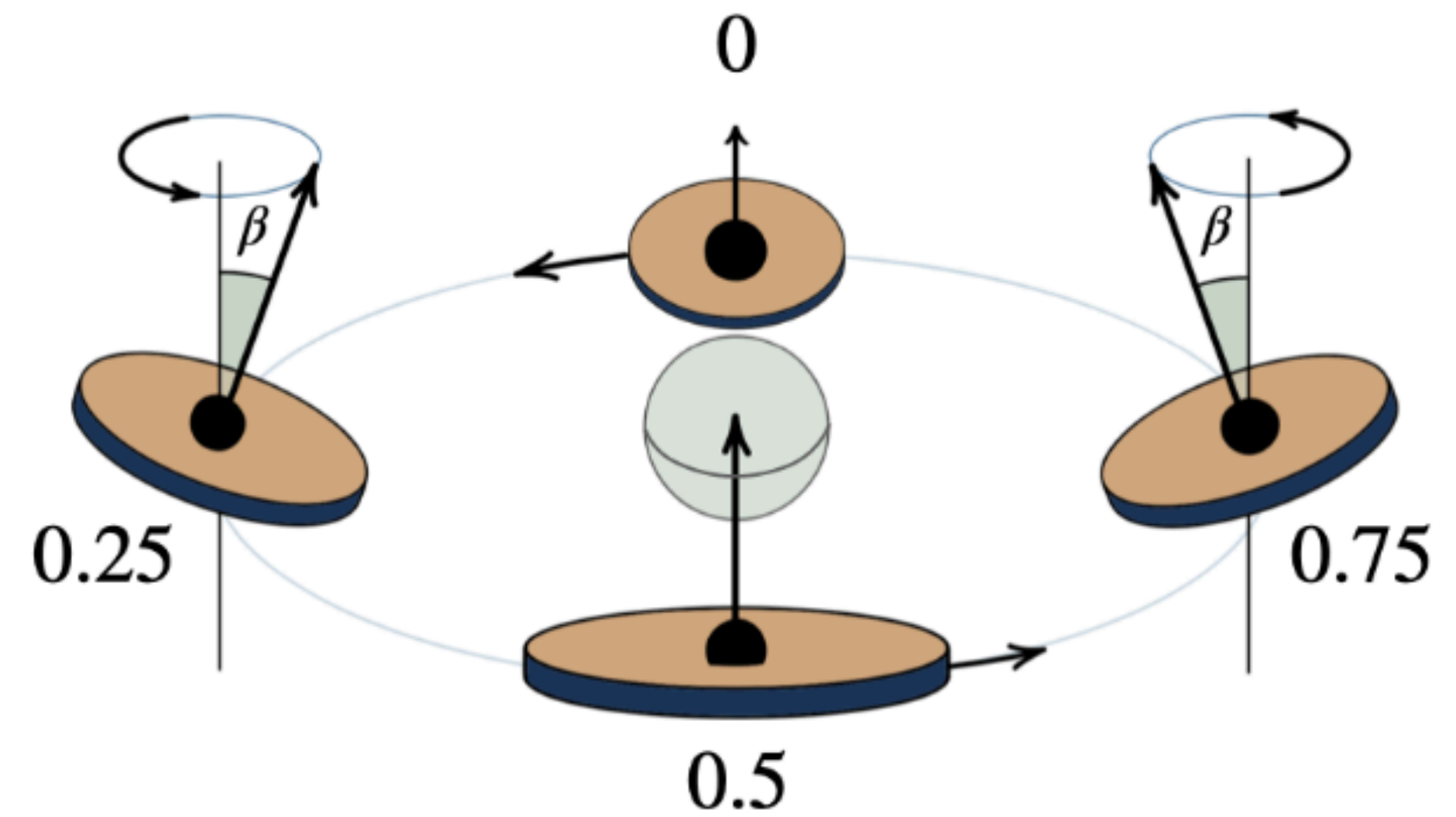
Kravtsov et al. 2025

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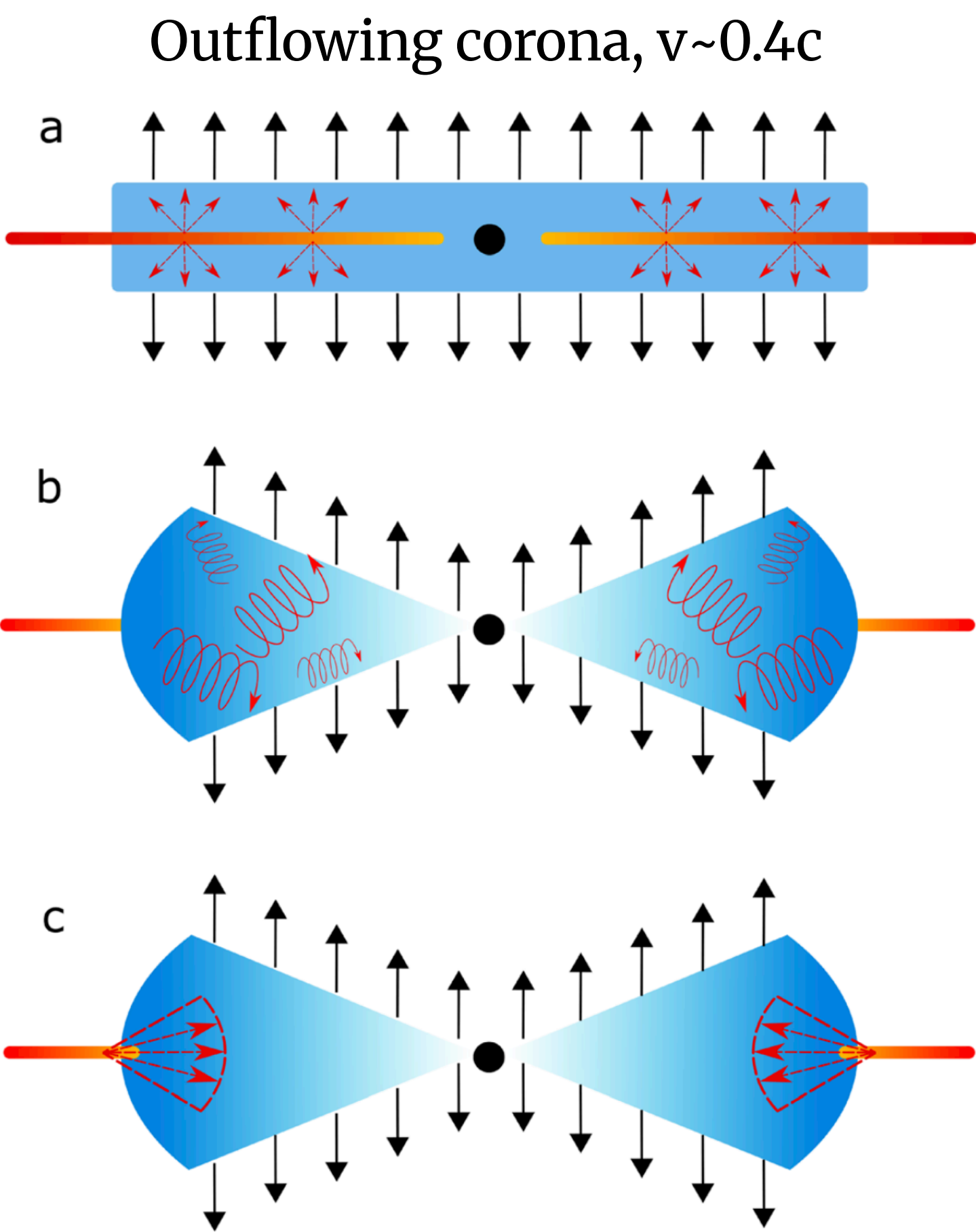
Kravtsov et al. 2025



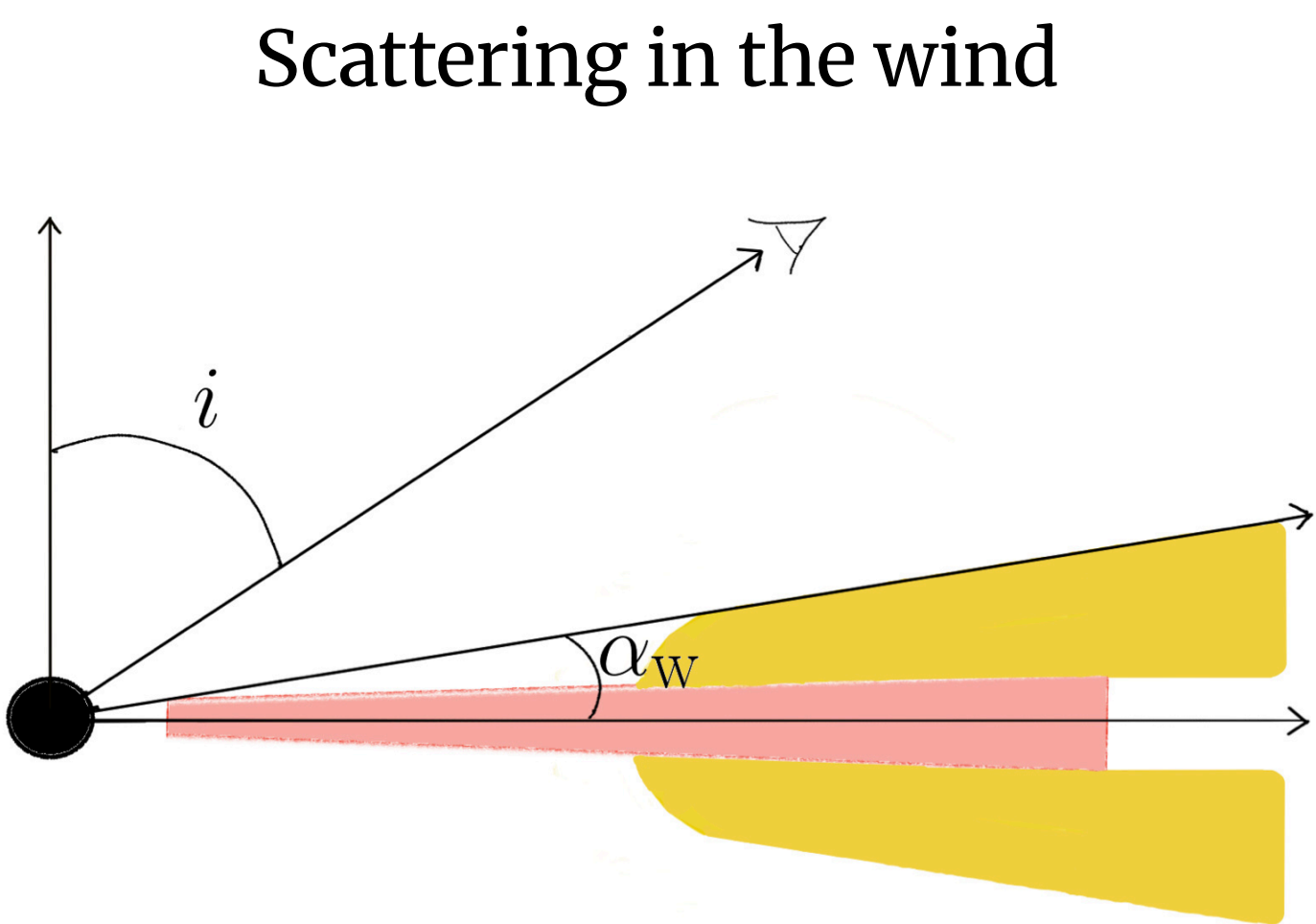
Ahlberg et al. 2025

IXPE results: Cyg X-1

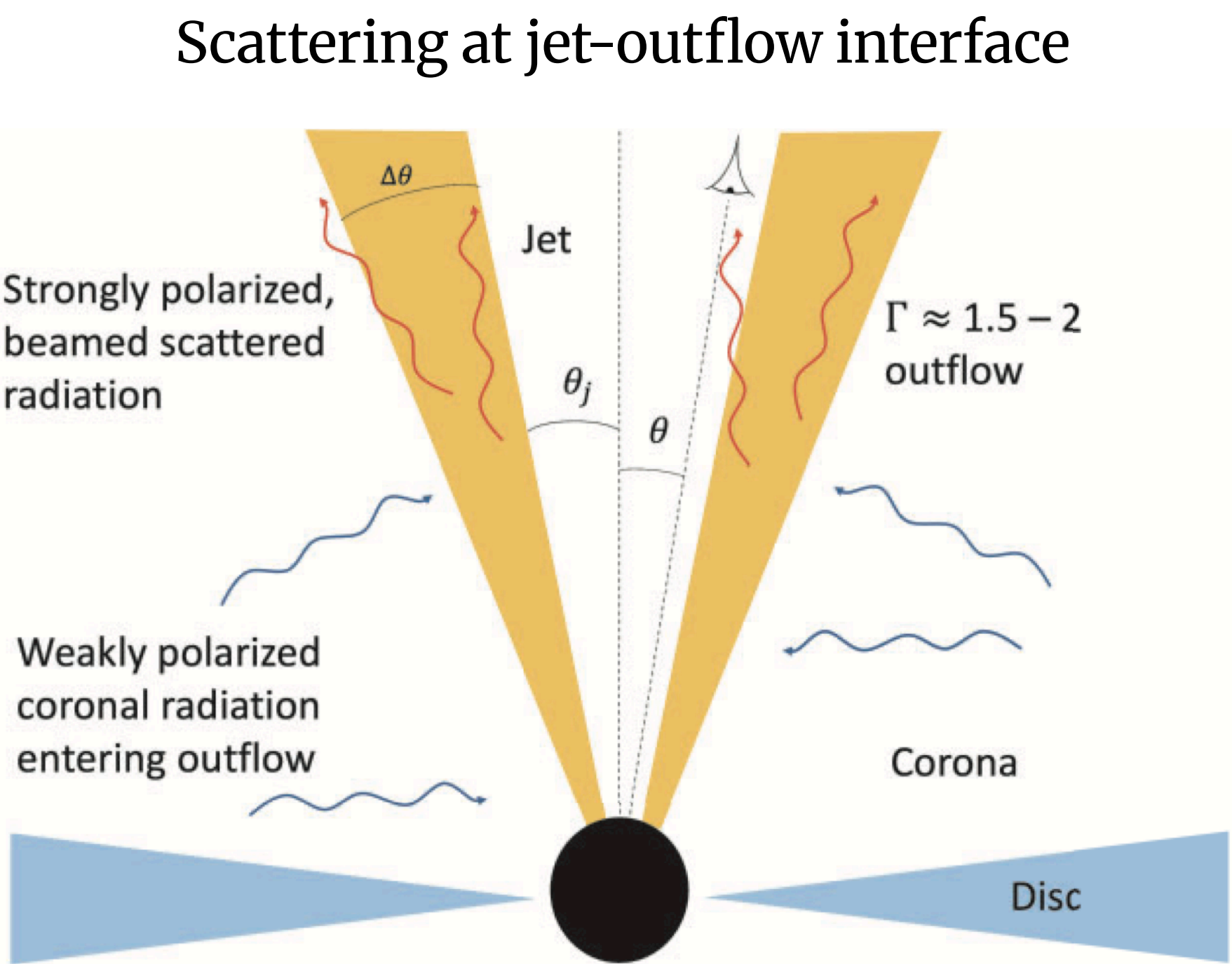
Attempts to explain Cyg X-1 observations



Poutanen, Veledina, Beloborodov 2023



Nitindala et al., 2025

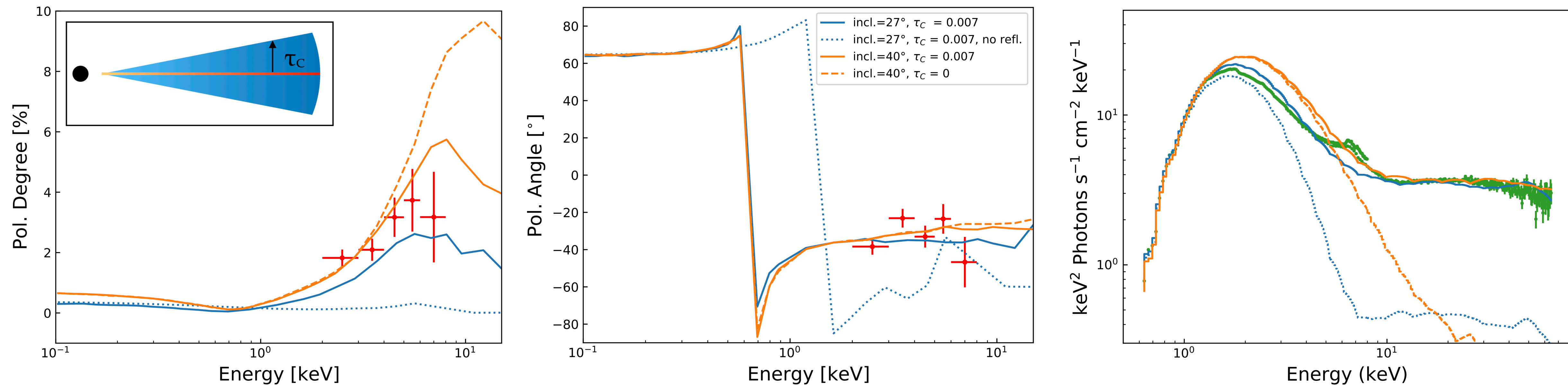


Dexter & Begelman 2024

IXPE results: Cyg X-1

Spectrapolarimetric modeling is a must

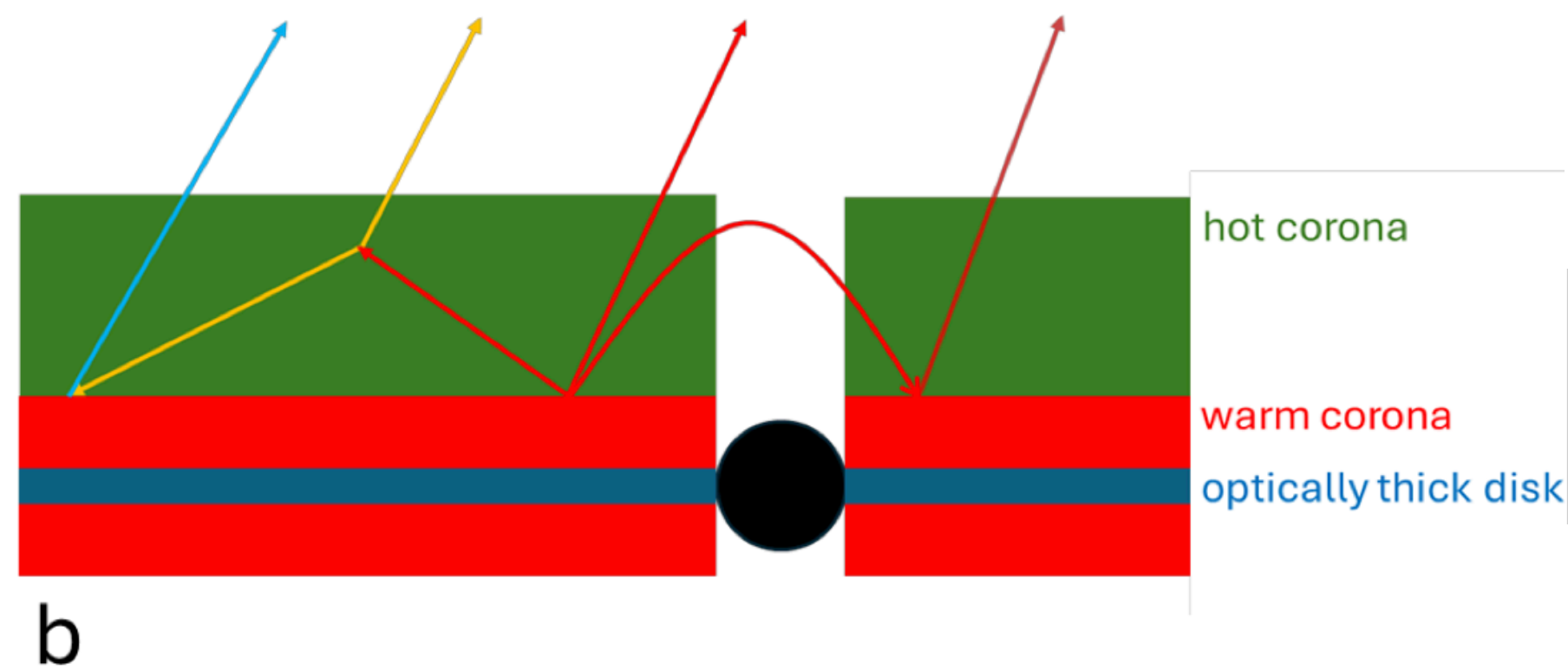
Spin $a > 0.96$, dominant role of returning radiation and GR effects



Steiner ... VK et al., 2024

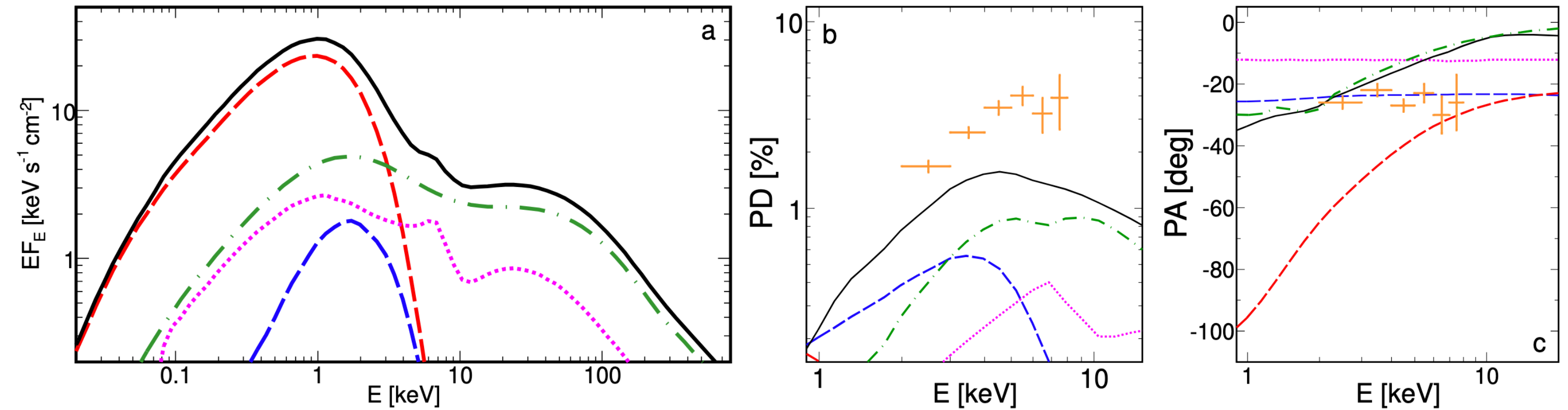
IXPE results: Cyg X-1

Spectrapolarimetric modeling is a must

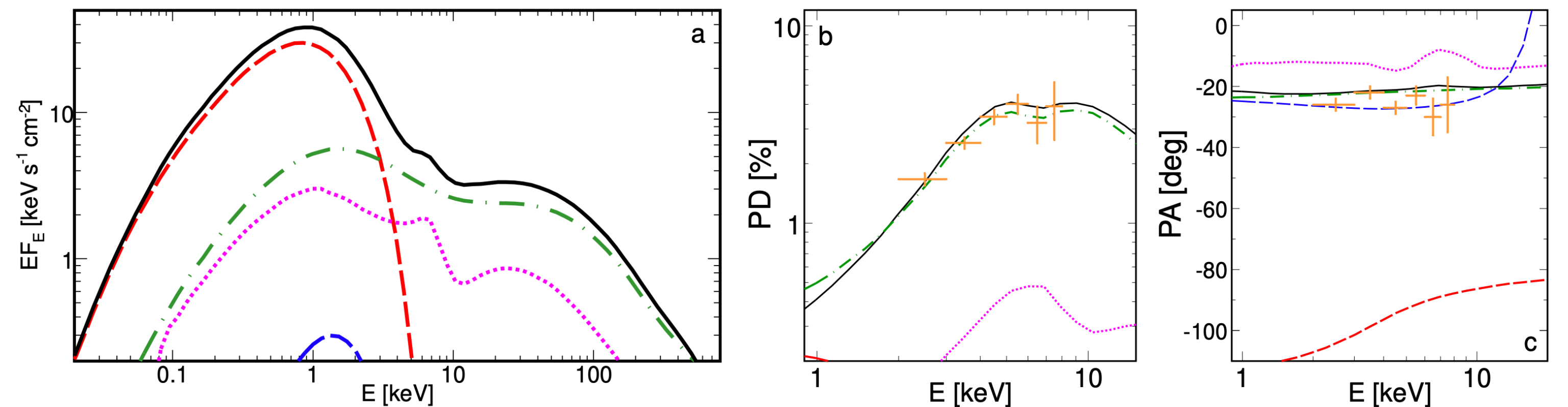


Comptonization and reflection

Spin $a > 0.998$



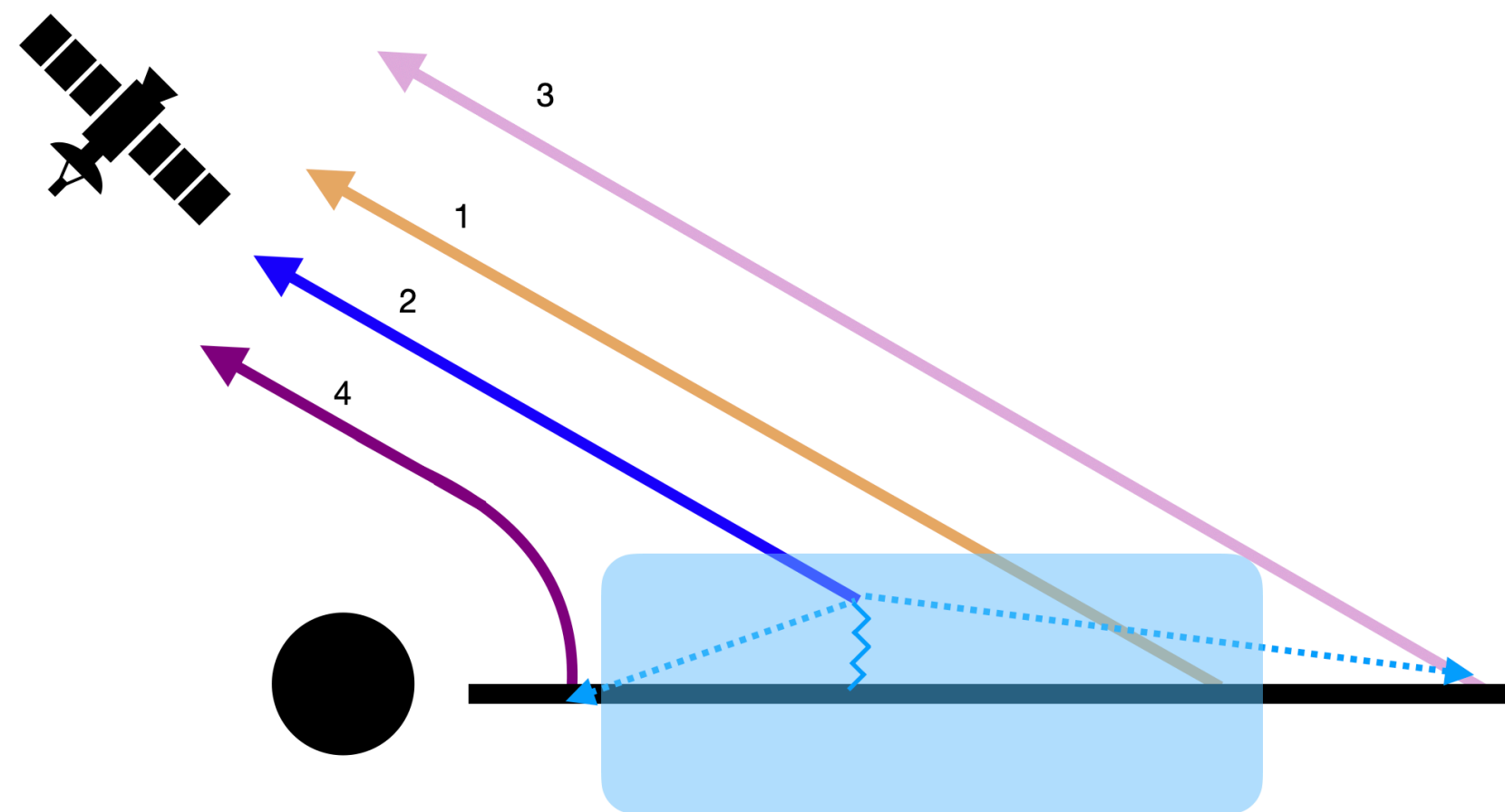
Spin $a = 0$, outflow with $\beta = 0.3$



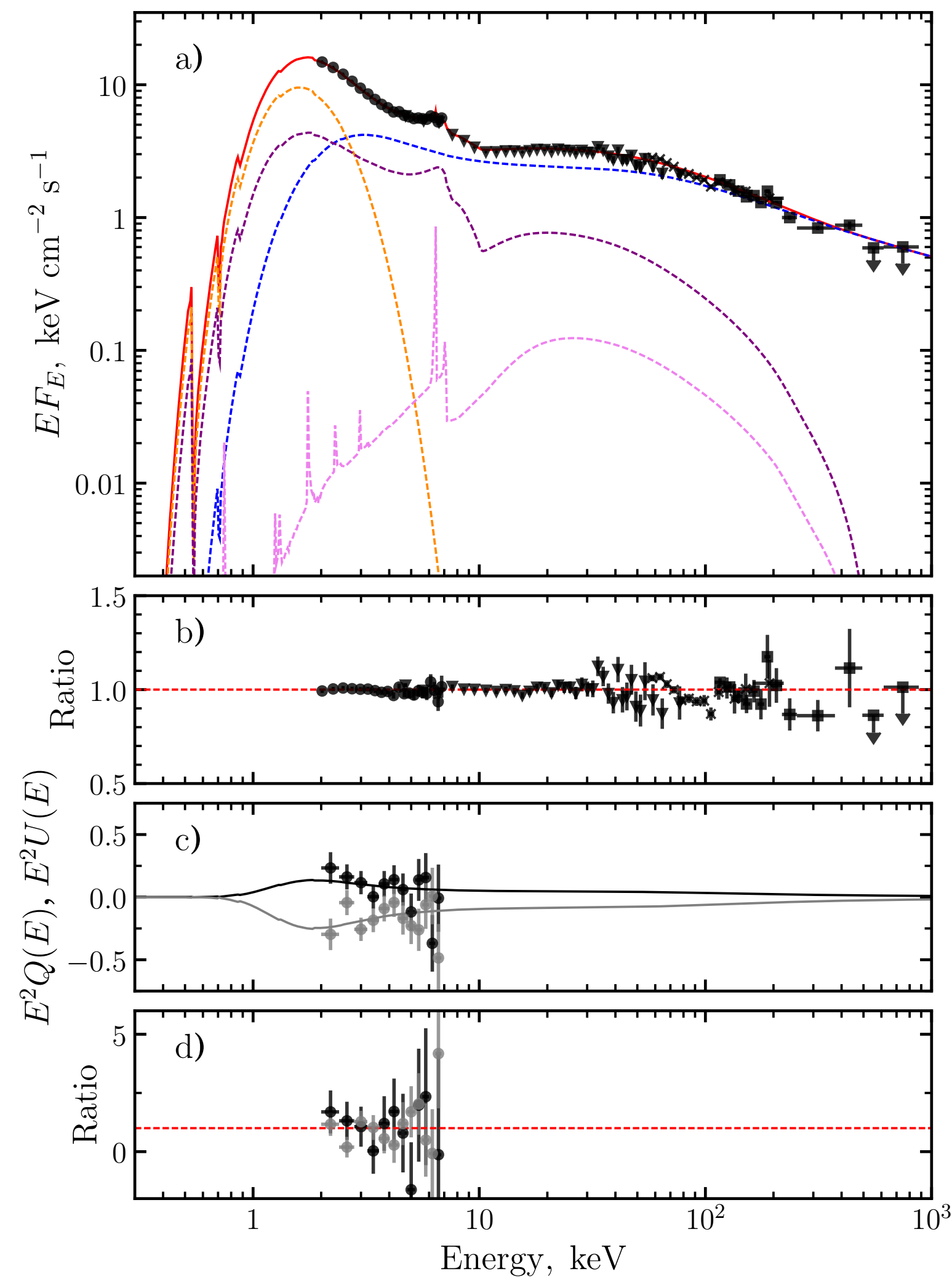
Niedźwiecki et al. 2026

IXPE results: Cyg X-1

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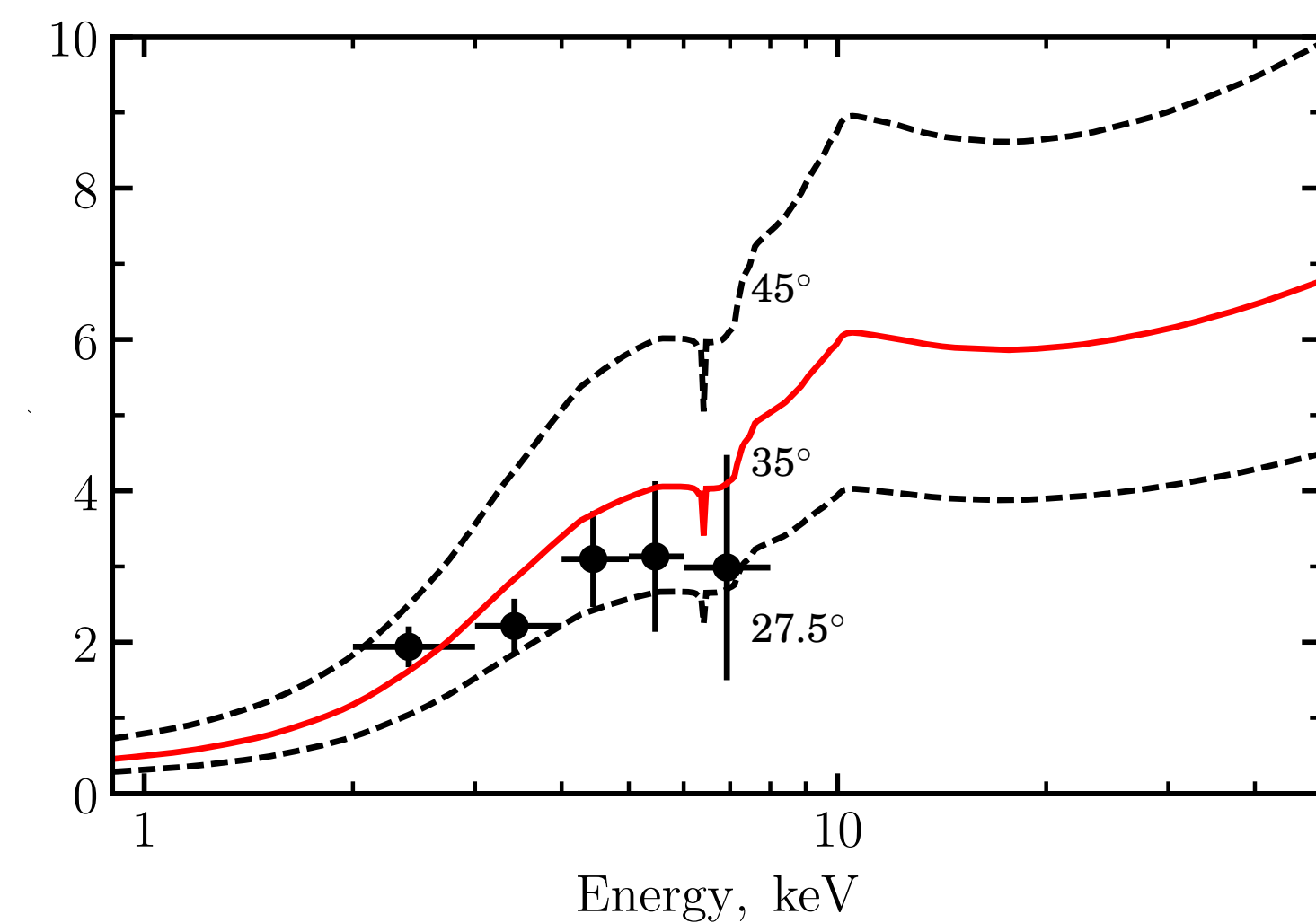


Comptonization and reflection



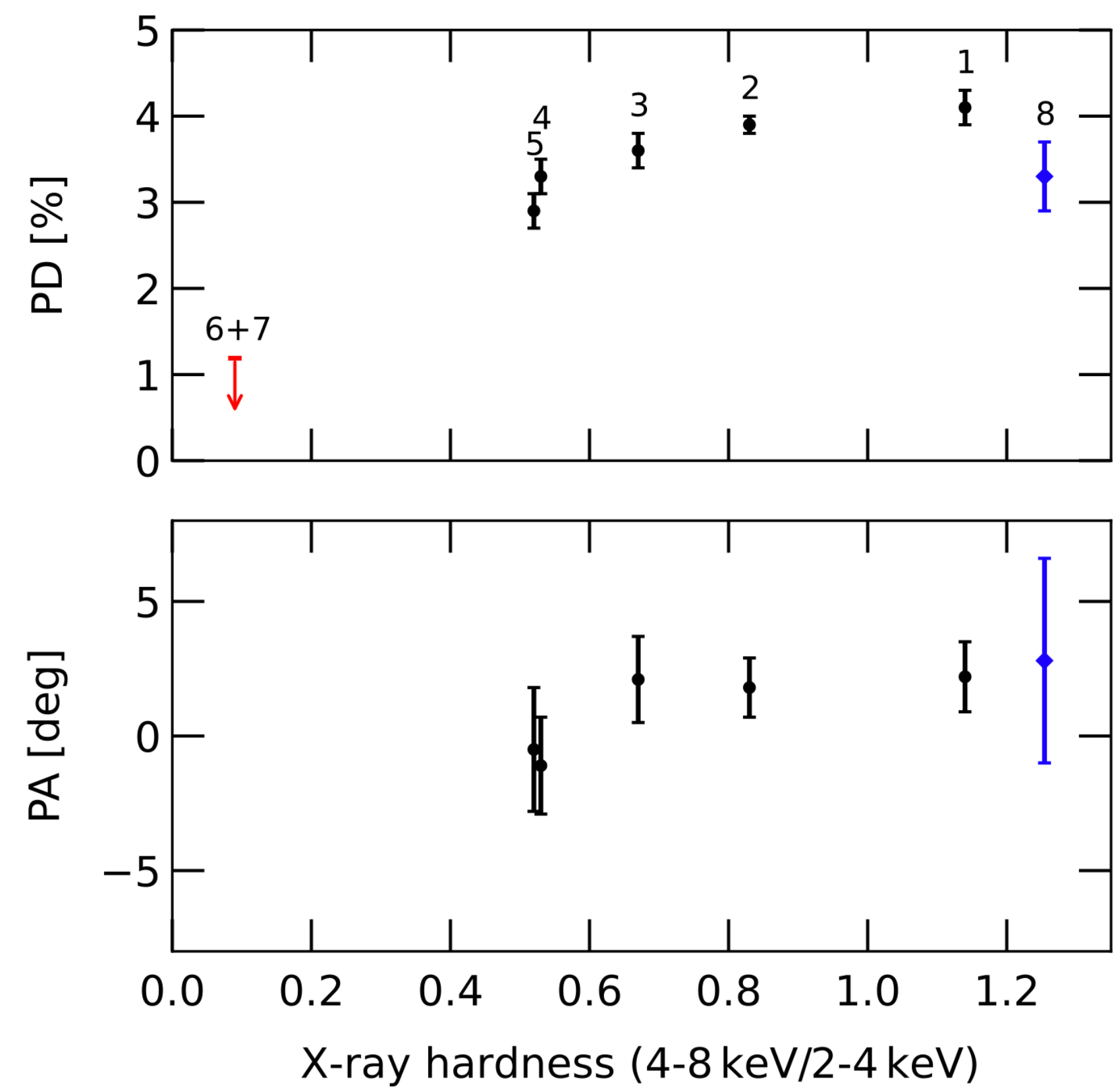
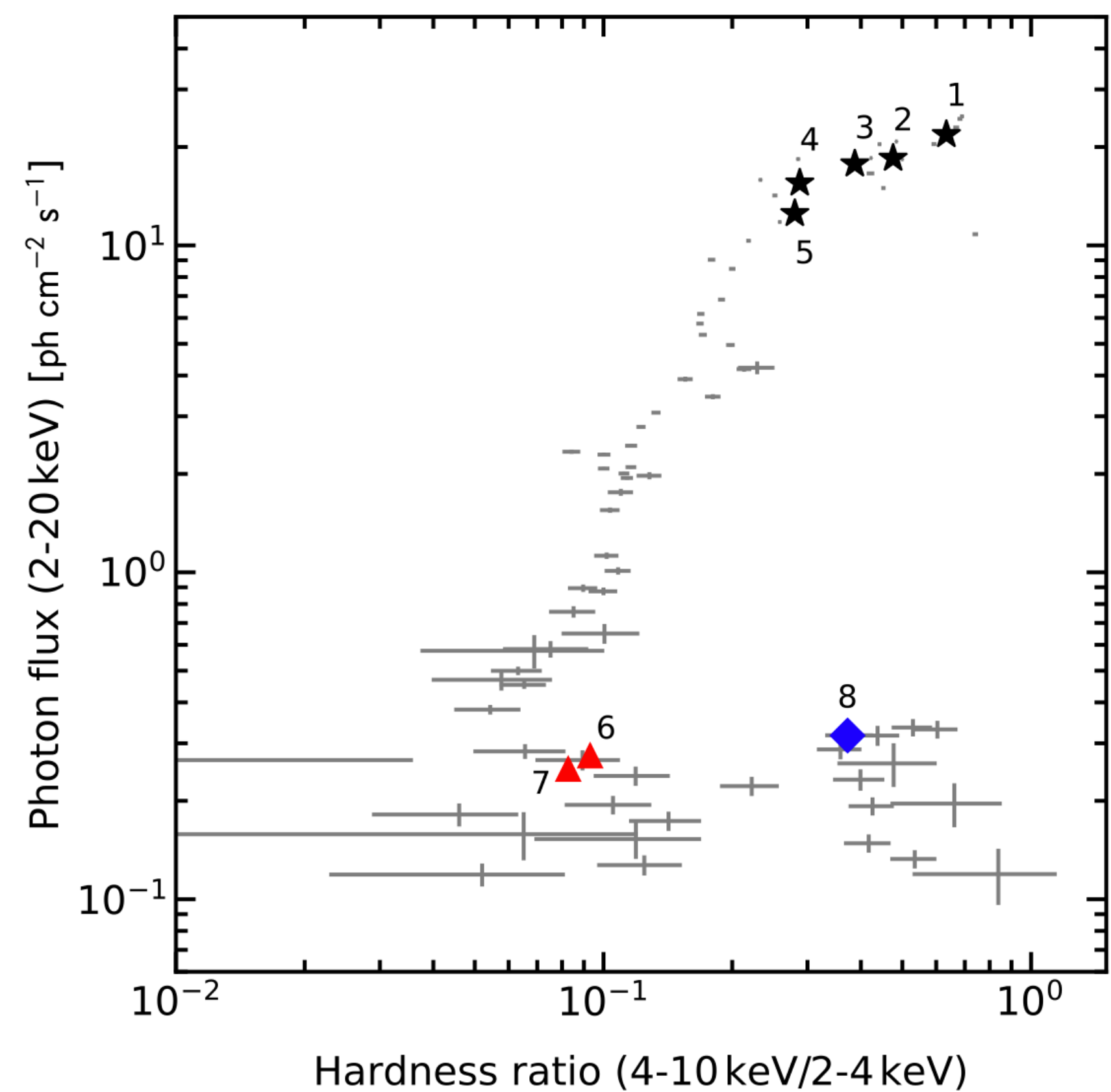
Bocharova et al., in prep

Spin $a = 0$



IXPE results: Swift J1727.8-1613

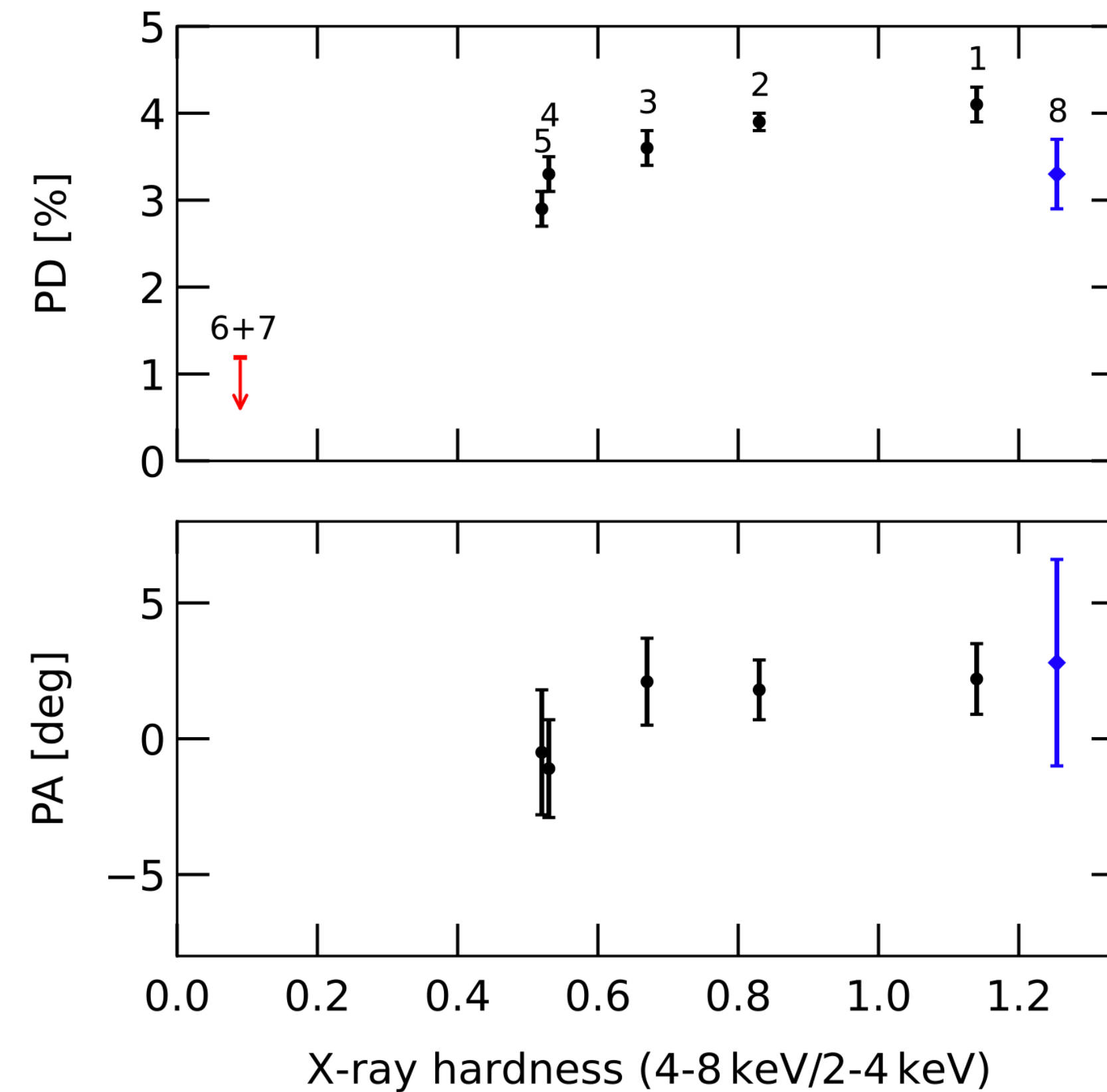
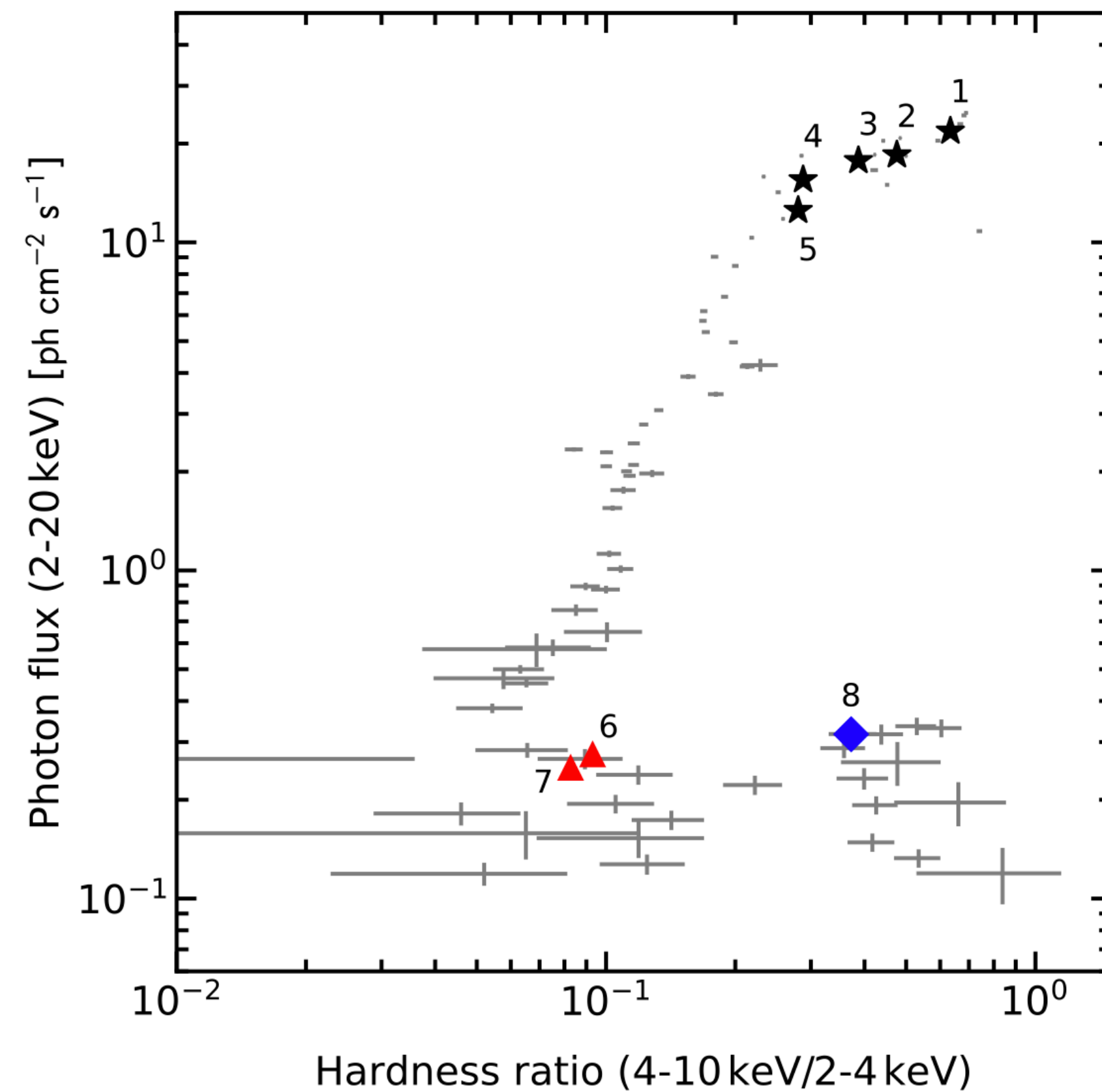
Exceptionally bright LMXB



IXPE results: Swift J1727.8-1613

Exceptionally bright LMXB

PD and PA are stable across 100x changes in flux!

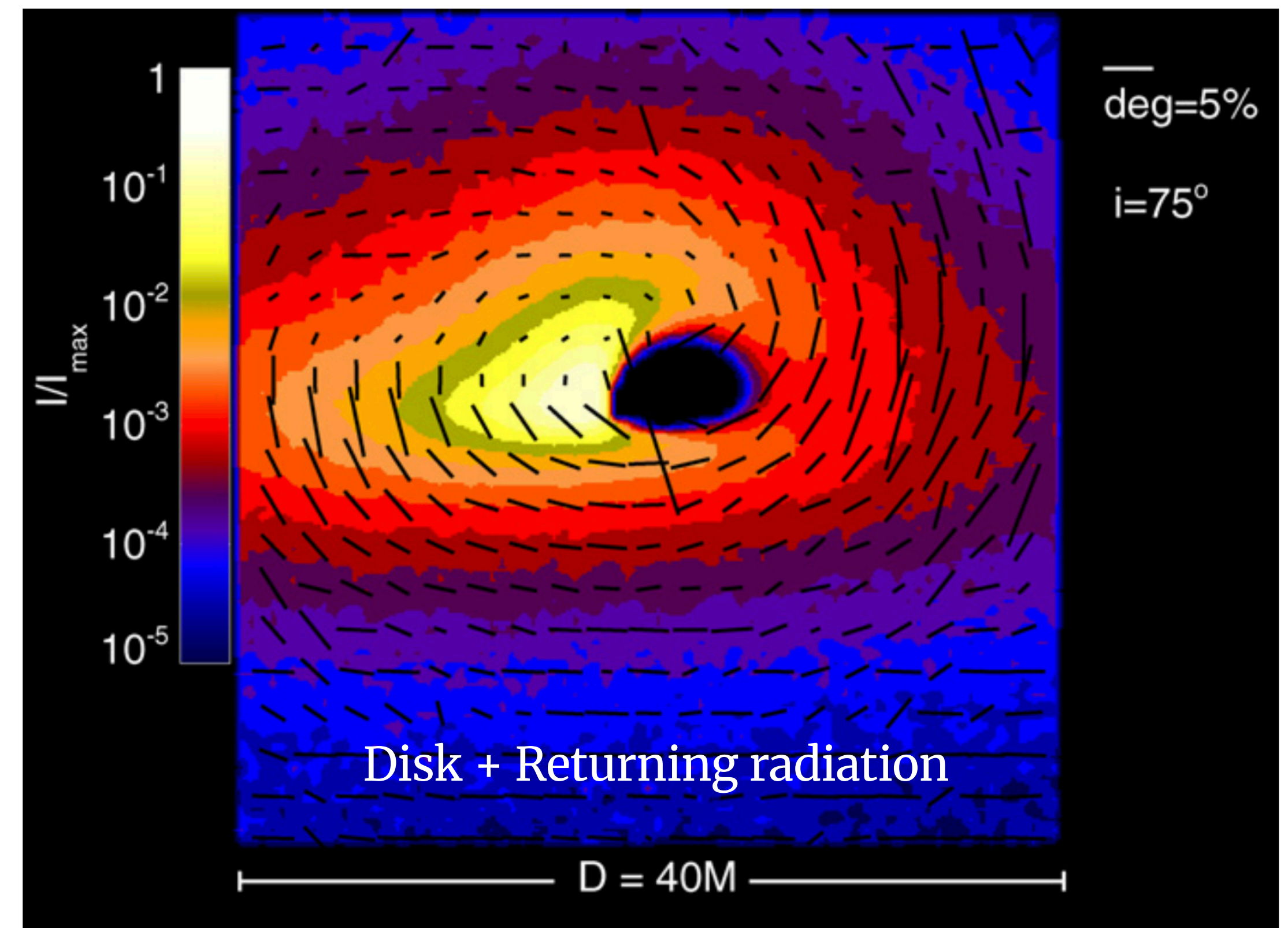
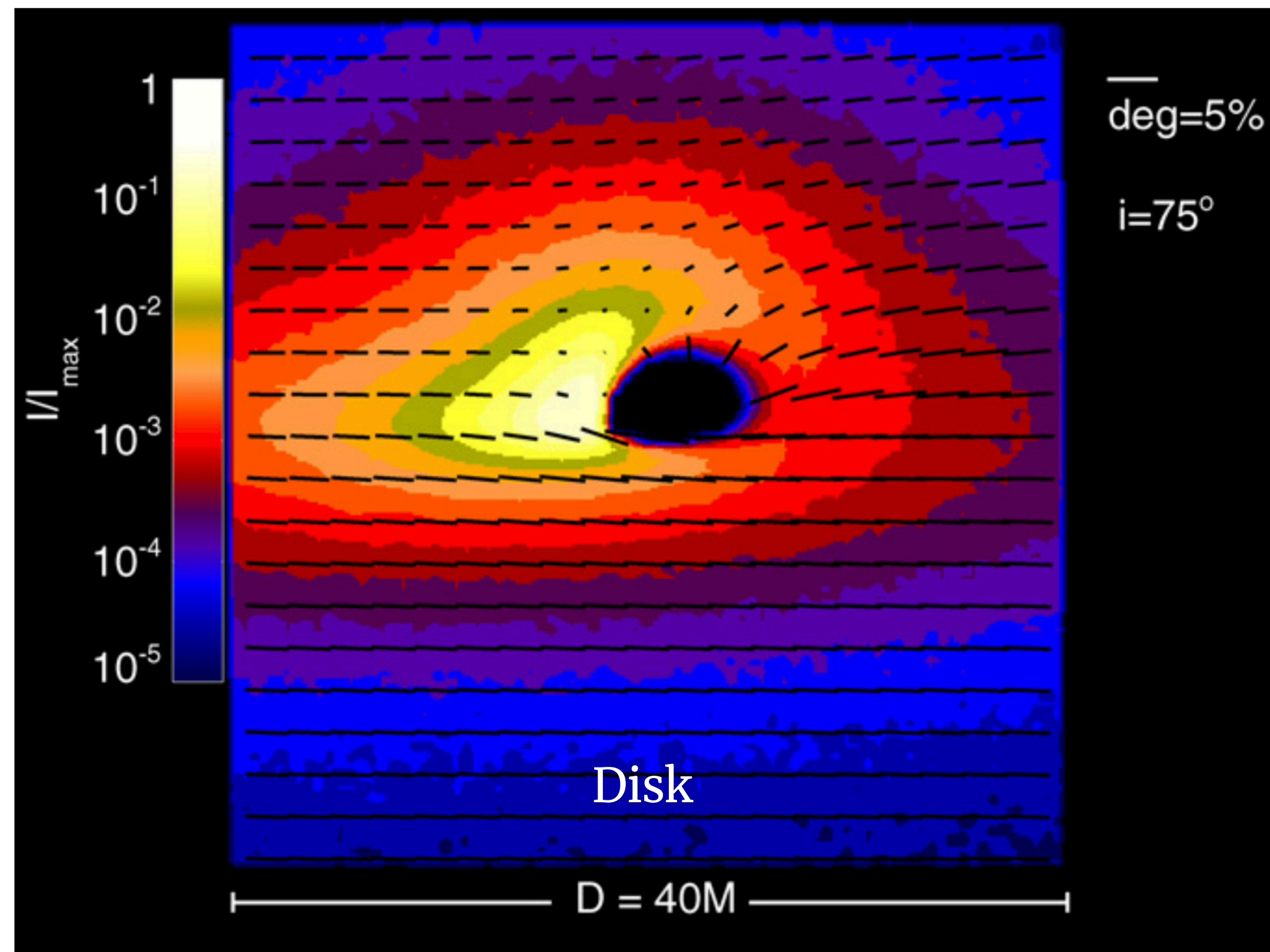


Podgorny ... VK et al., 2024; Svoboda ... VK et al., 2024

Examples of simulations

Polarization from accreting black holes

Ray-traced images of the Novikov-Thorne disk around black hole with $a = 0.99$



J. D. Schnittman & J. H. Krolik 2009

Examples of simulations

Polarization from accreting black holes

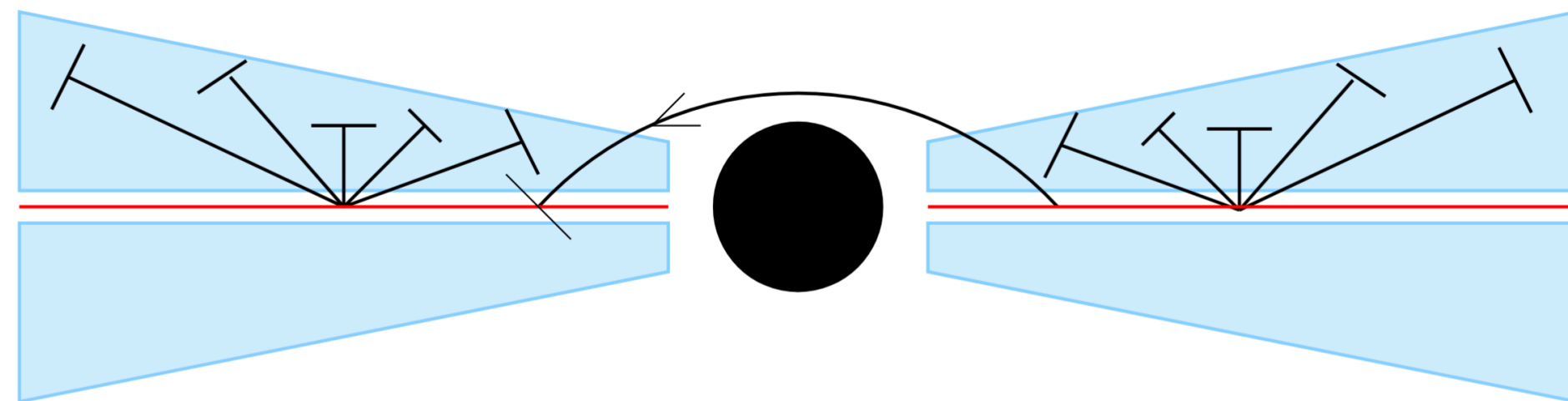
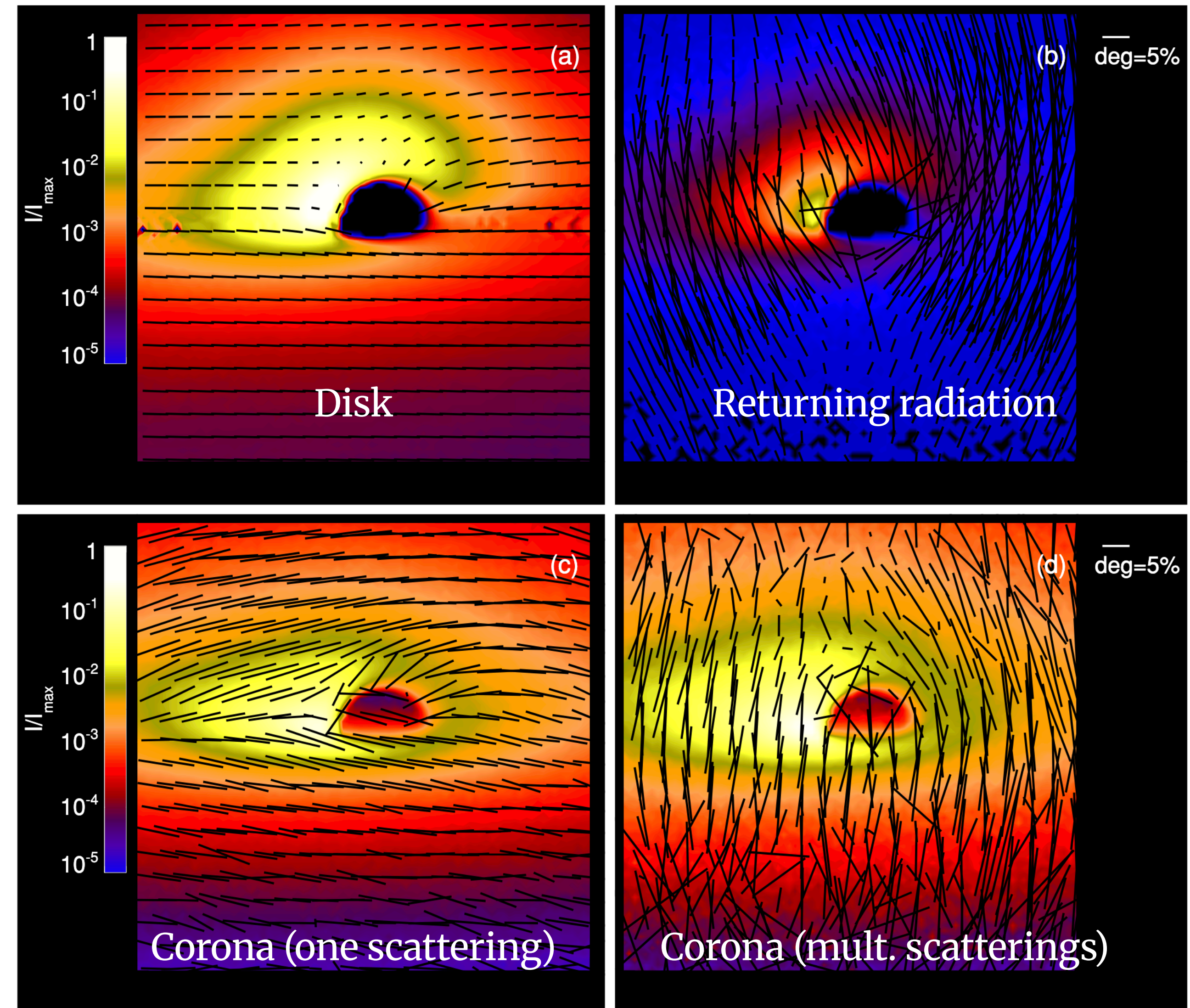


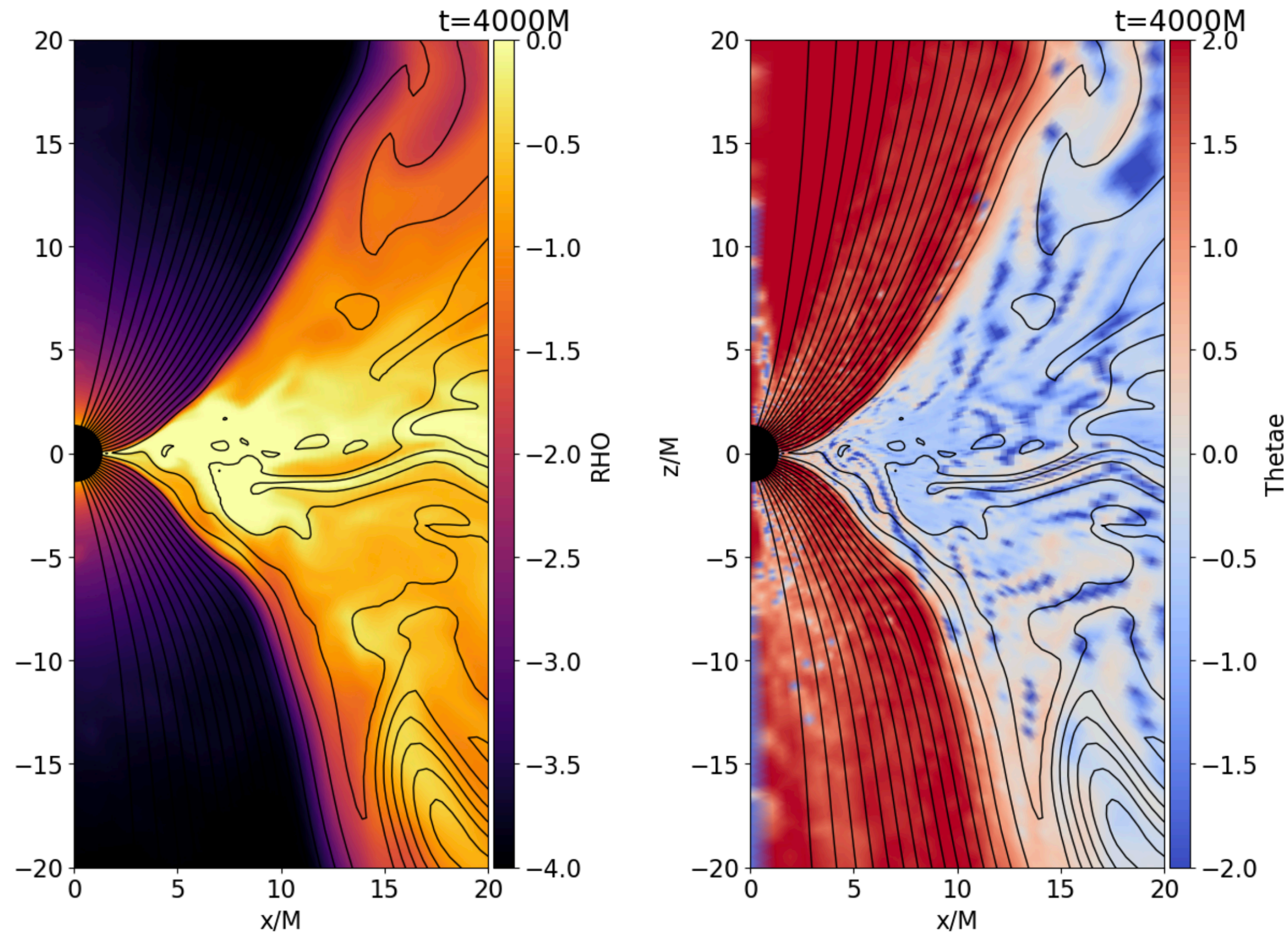
Figure 1. Schematic diagram of the disk and corona for the sandwich geometry.

Disk + Corona (Monte-Carlo GR ray tracing)

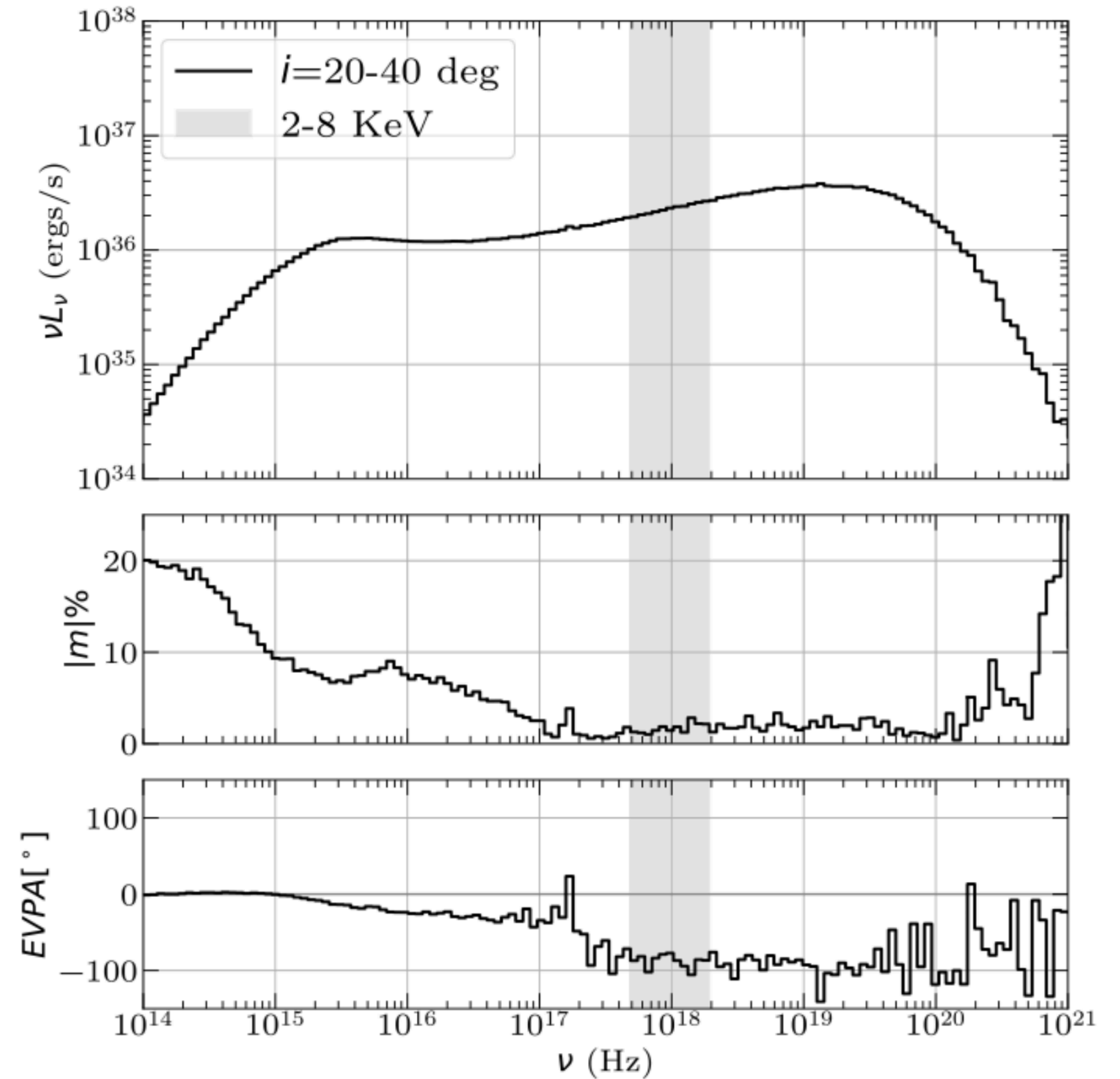


Examples of simulations

Polarization from accreting black holes

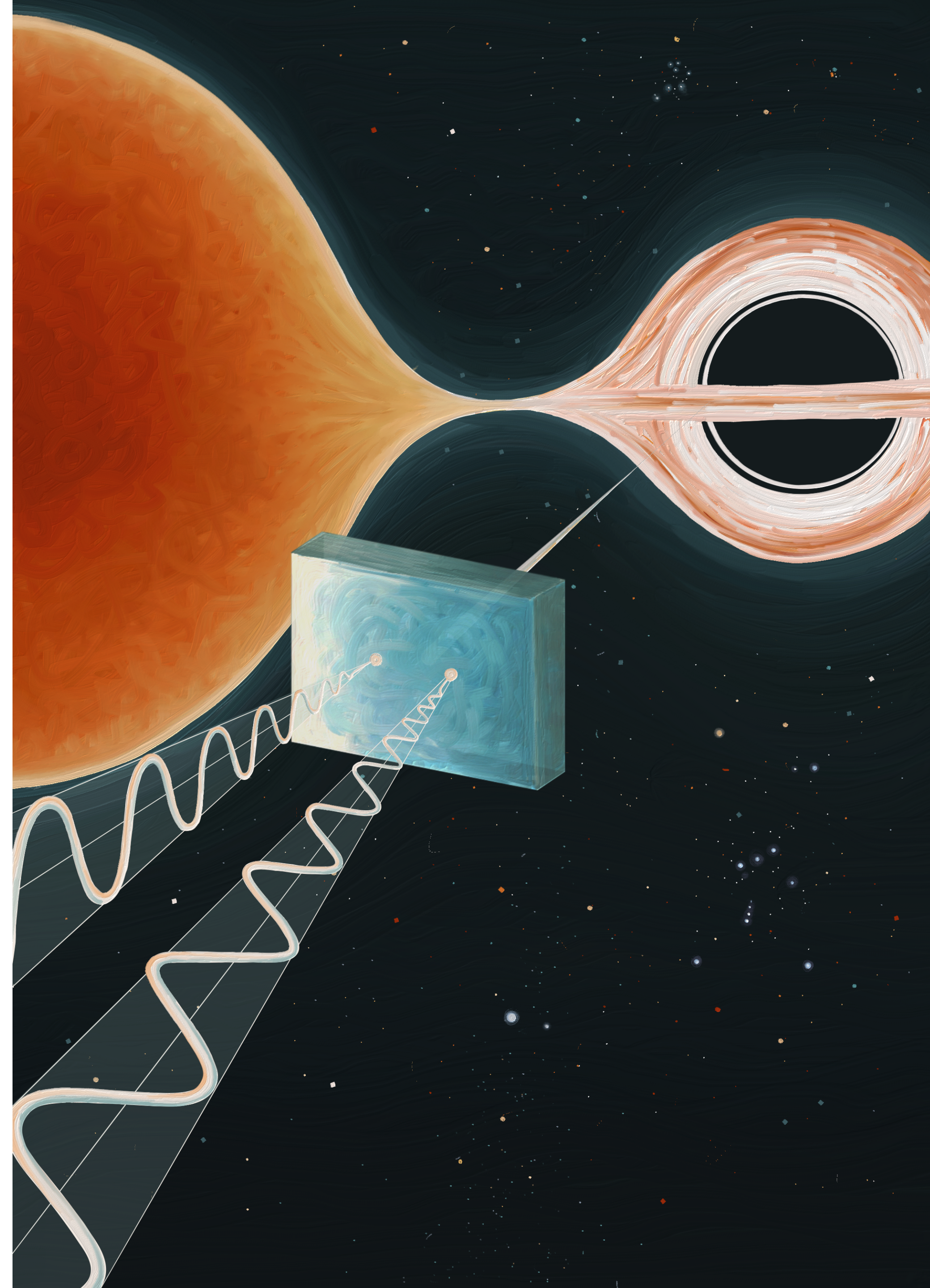


GRMHD + polarized radiative transport



Main takeaways

1. **Polarization adds information** about the medium surrounding compact objects in X-ray binaries
2. **Numerical models should be consistent with recent X-ray polarization measurements**
3. We are still in the **very early era of X-ray polarimetry**, some prediction for the future missions like eXTP will be highly appreciated!



Backup slides

