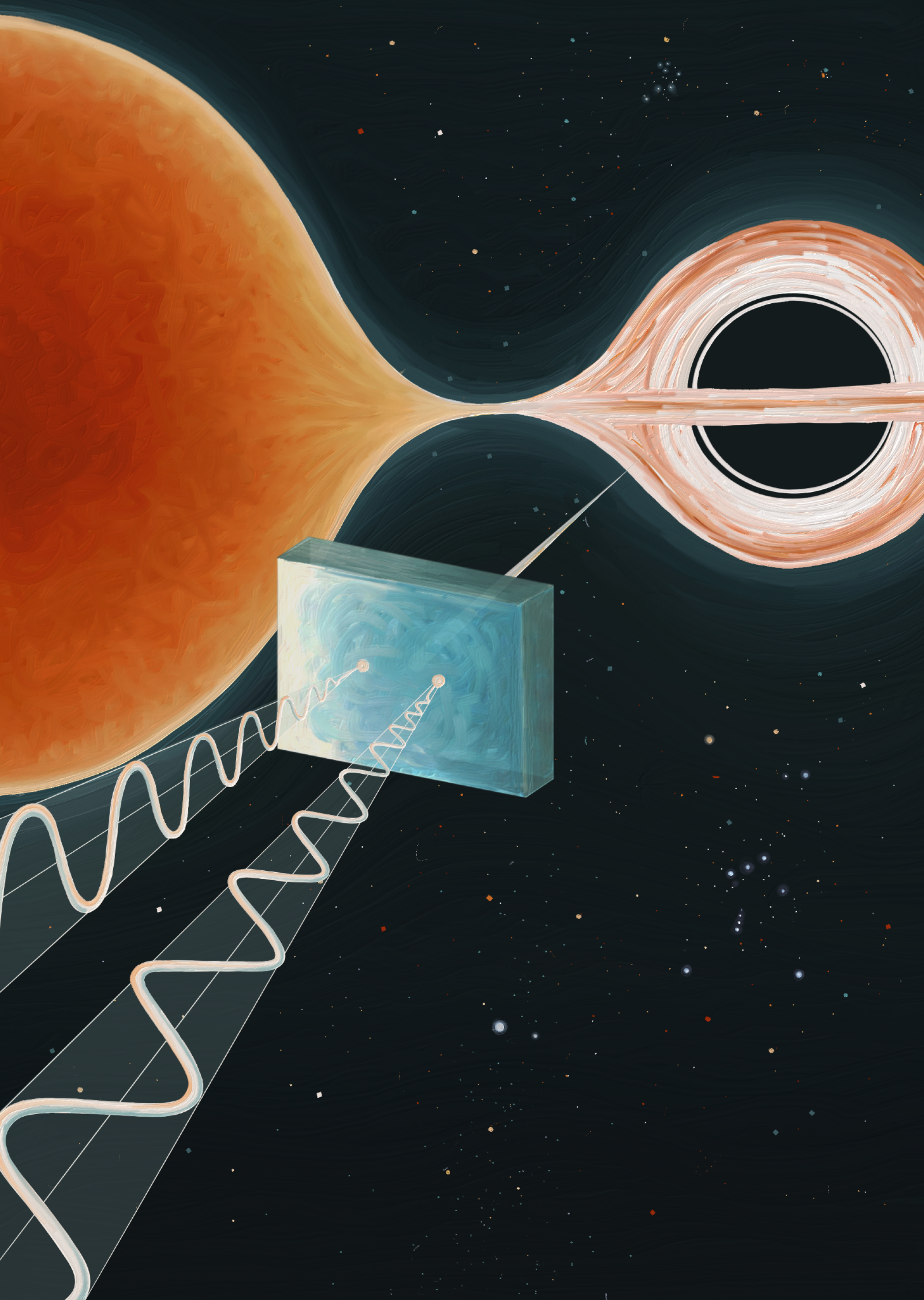




# X-ray polarimetry of black hole X-ray binaries

Results and models

**Vadzim Krautsou** <sup>1,2</sup>

<sup>1</sup> University of Helsinki, Finland

<sup>2</sup> University of Turku, Finland

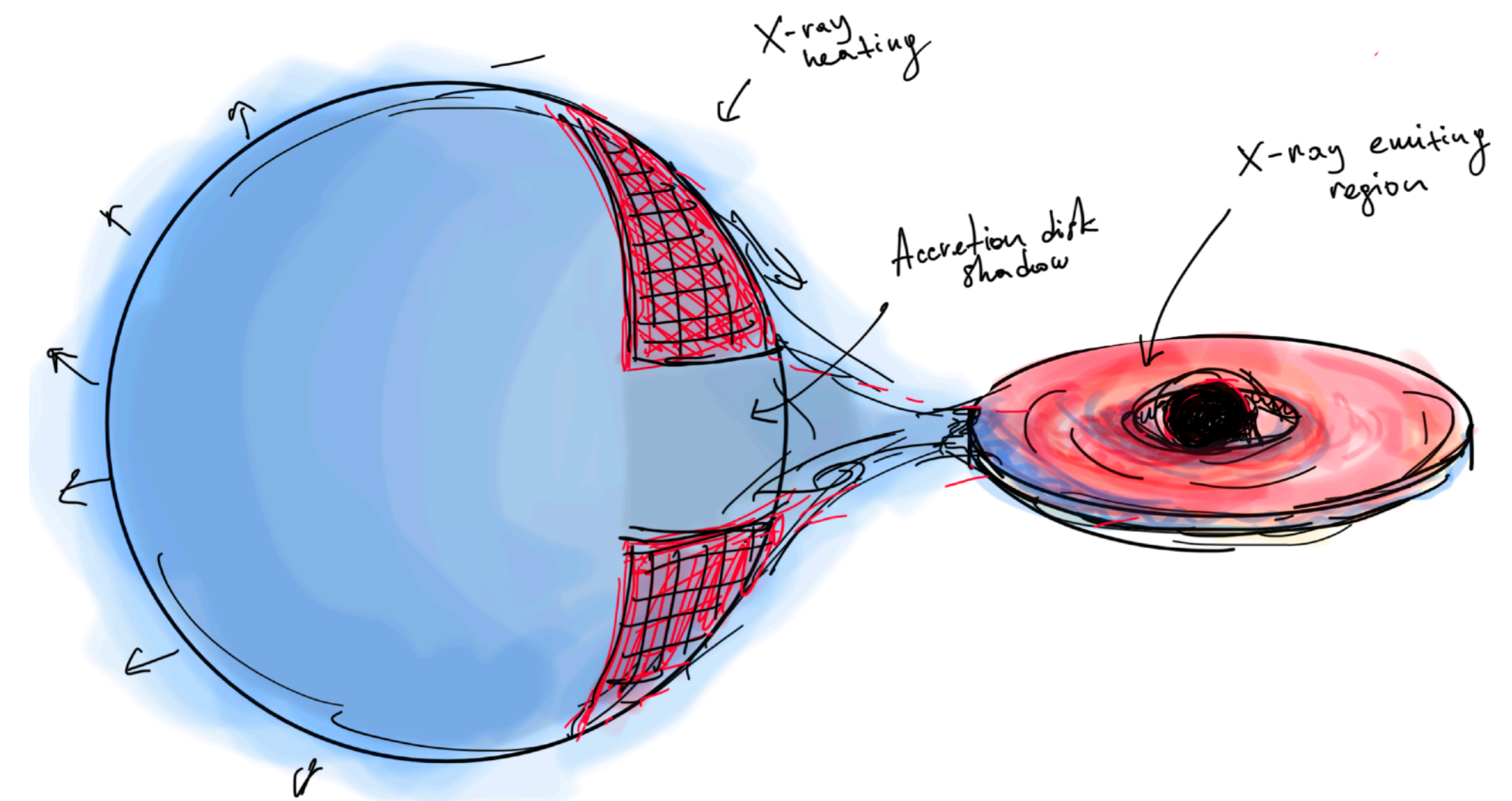
The Sixth Zeldovich meeting

14 July 2026



# Outline of the talk

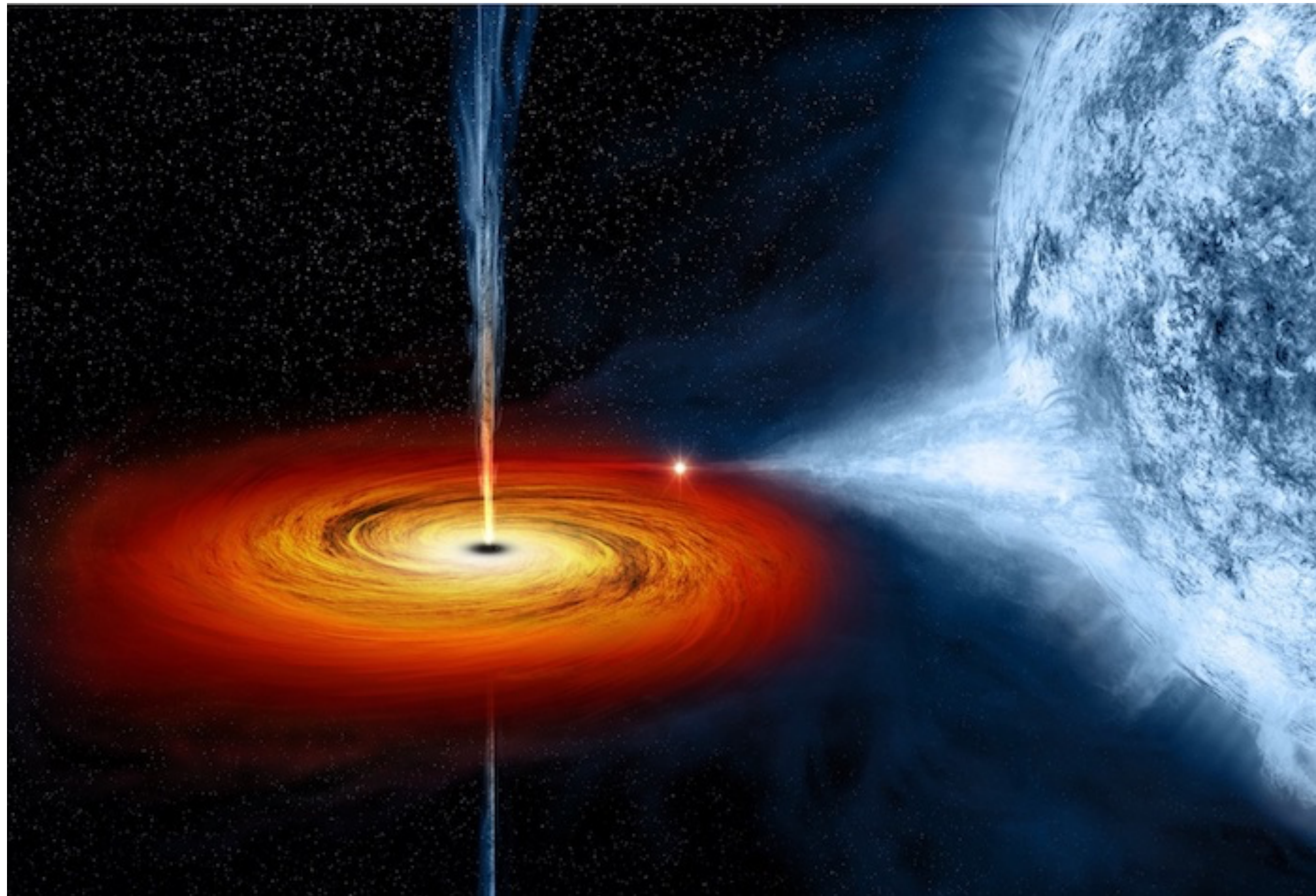
1. **Introduction to X-ray binaries**
2. **Introduction to polarization**
3. **Sources of polarization** in X-ray binaries
4. Main **observational results**
5. **Summary**





# Introduction

Definition of X-ray binary star



To be considered as an X-ray binary, a star must be:

- a binary star
- luminous in X-rays

The observed X-ray luminosity can be explained **only** if we assume that it is produced by the **most effective source of energy** – by accretion of matter onto the compact massive object.

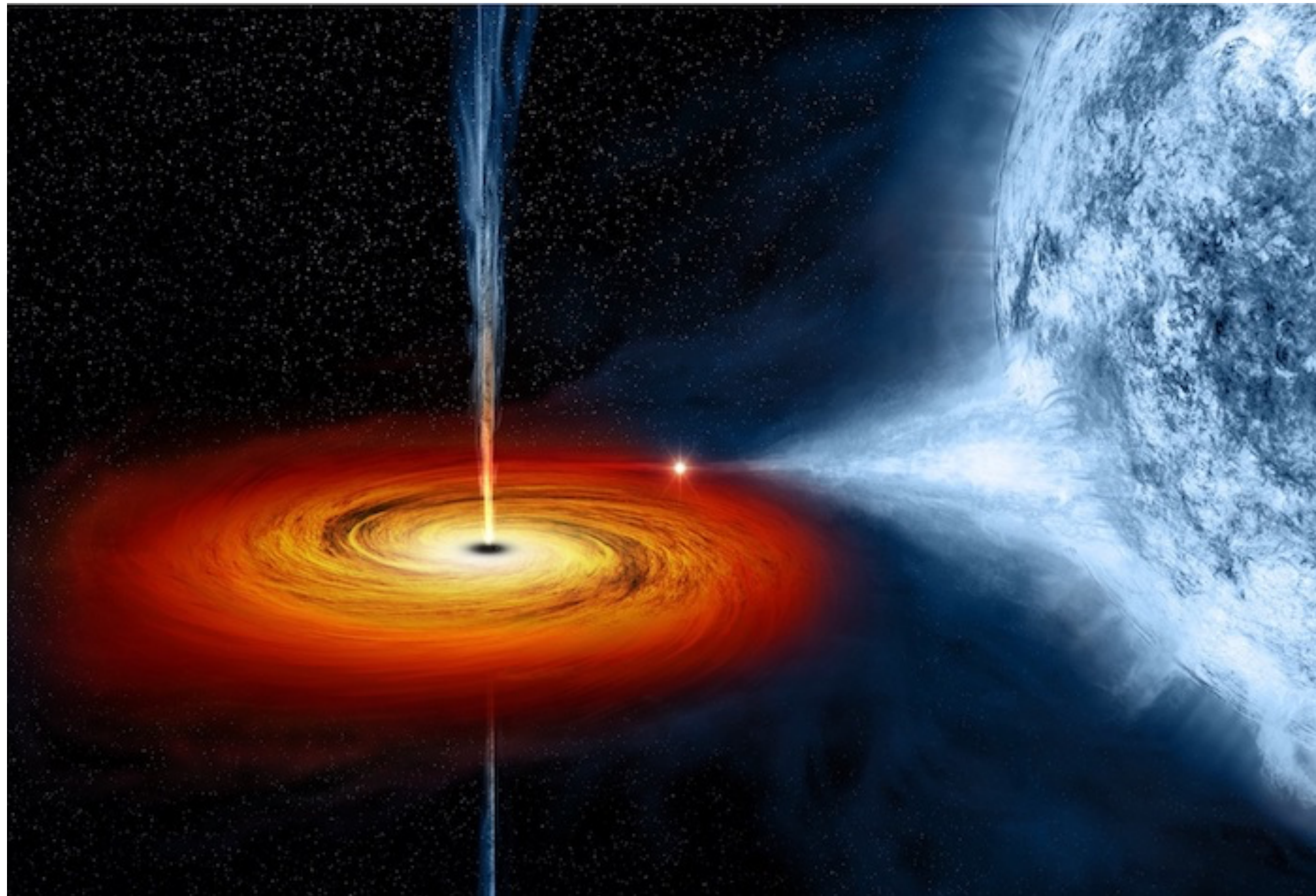
$$\eta = \frac{E(m)}{mc^2} \quad - \text{measure of efficiency}$$

$$\eta_{\text{nuc}} < 1 \% \quad \eta_{\text{acc}} \sim 10 \%$$



# Introduction

Definition of X-ray binary star



To produce X-rays via accretion, we should have:

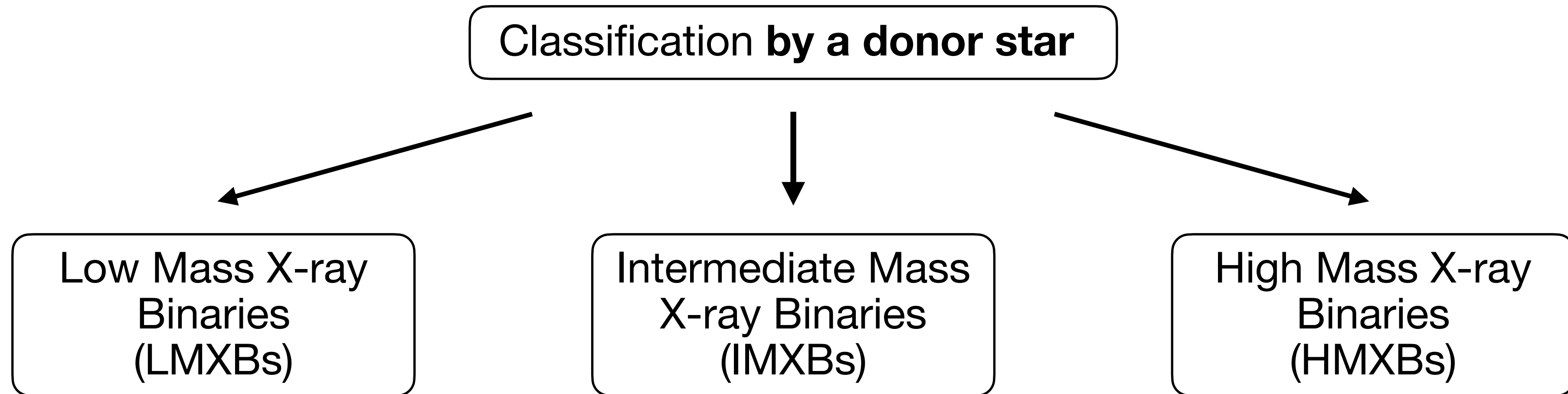
- **some matter to accrete**
- **the object on which the matter is accreted**

The matter is provided by a **donor star**.  
The accretion is done by an **accretor**.



# Introduction

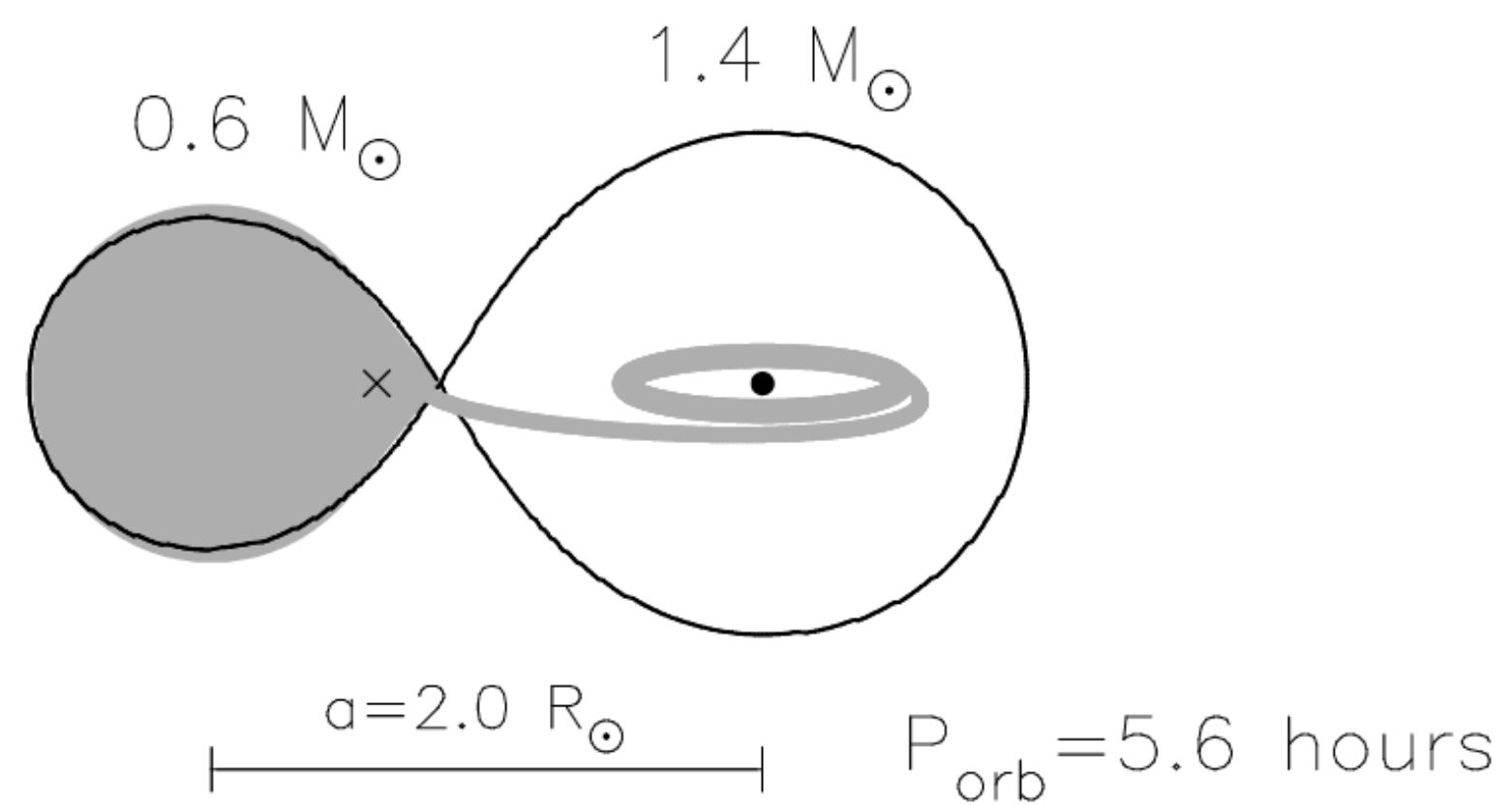
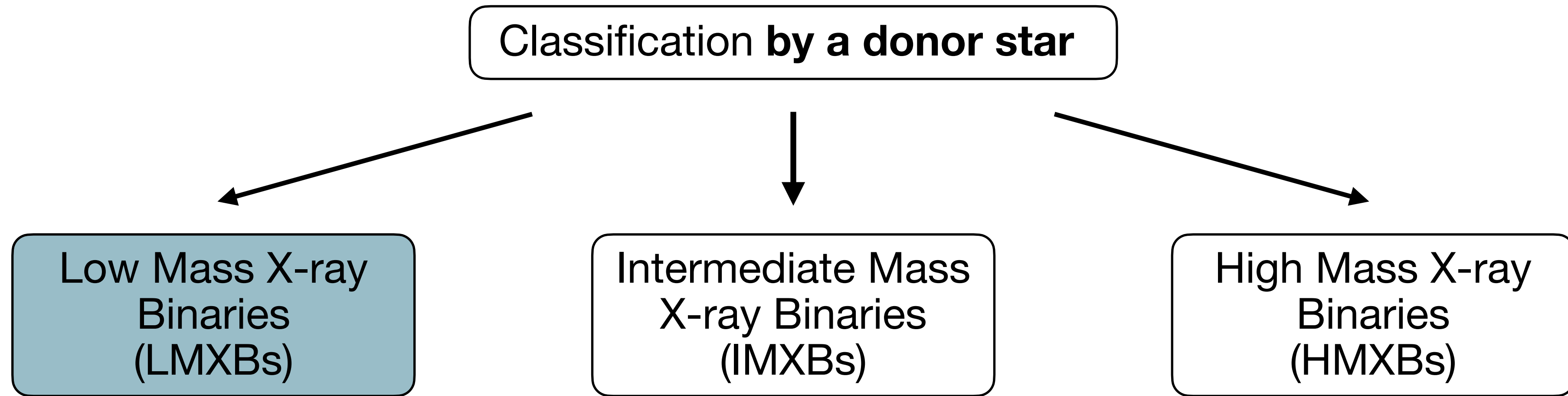
Classification of X-ray binaries





# Introduction

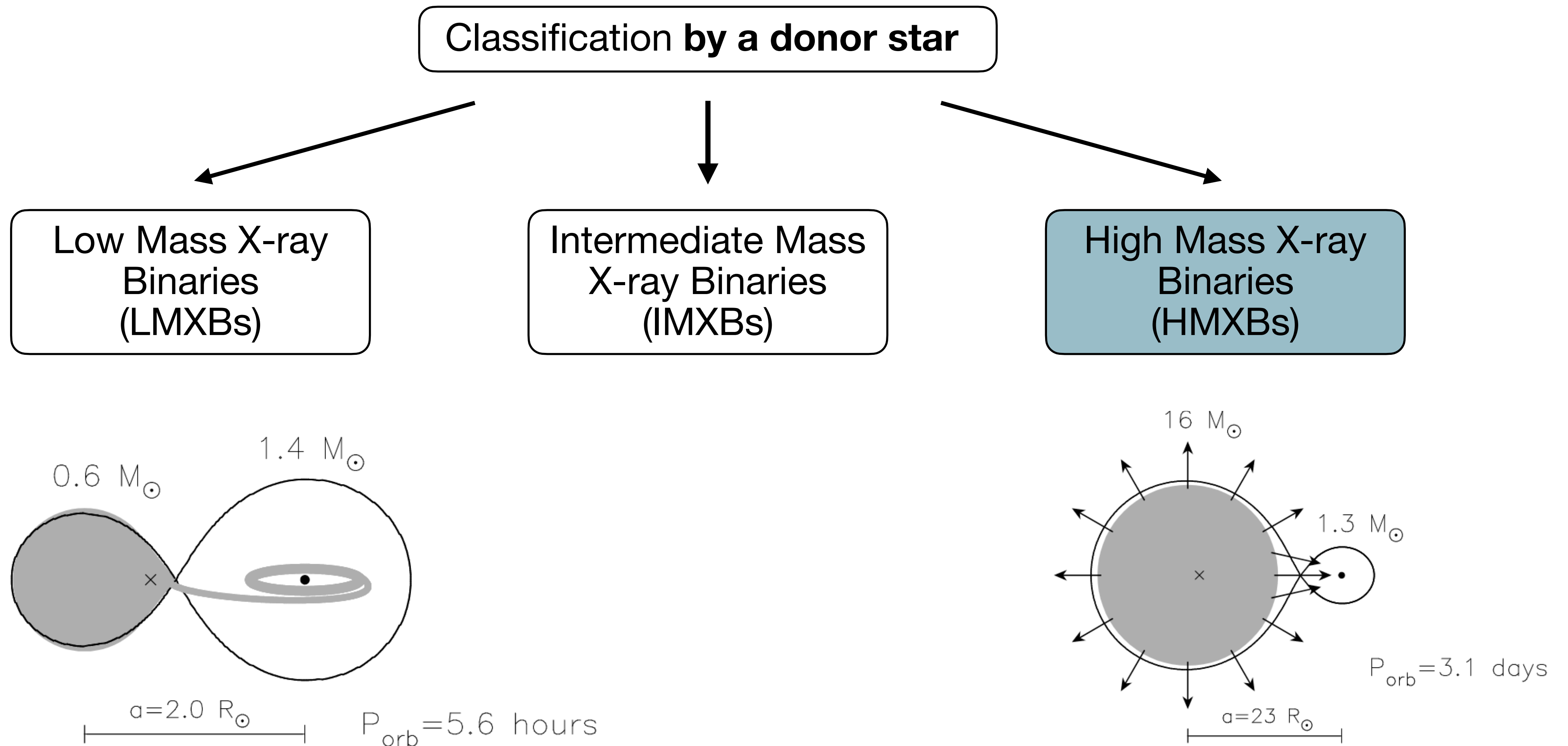
## Classification of X-ray binaries





# Introduction

## Classification of X-ray binaries





# Introduction

## Classification of X-ray binaries

Classification **by an accretor**

Neutron Star  
X-ray binary  
(NSXRBs)

Black Hole  
X-ray binary  
(BHXRBS)

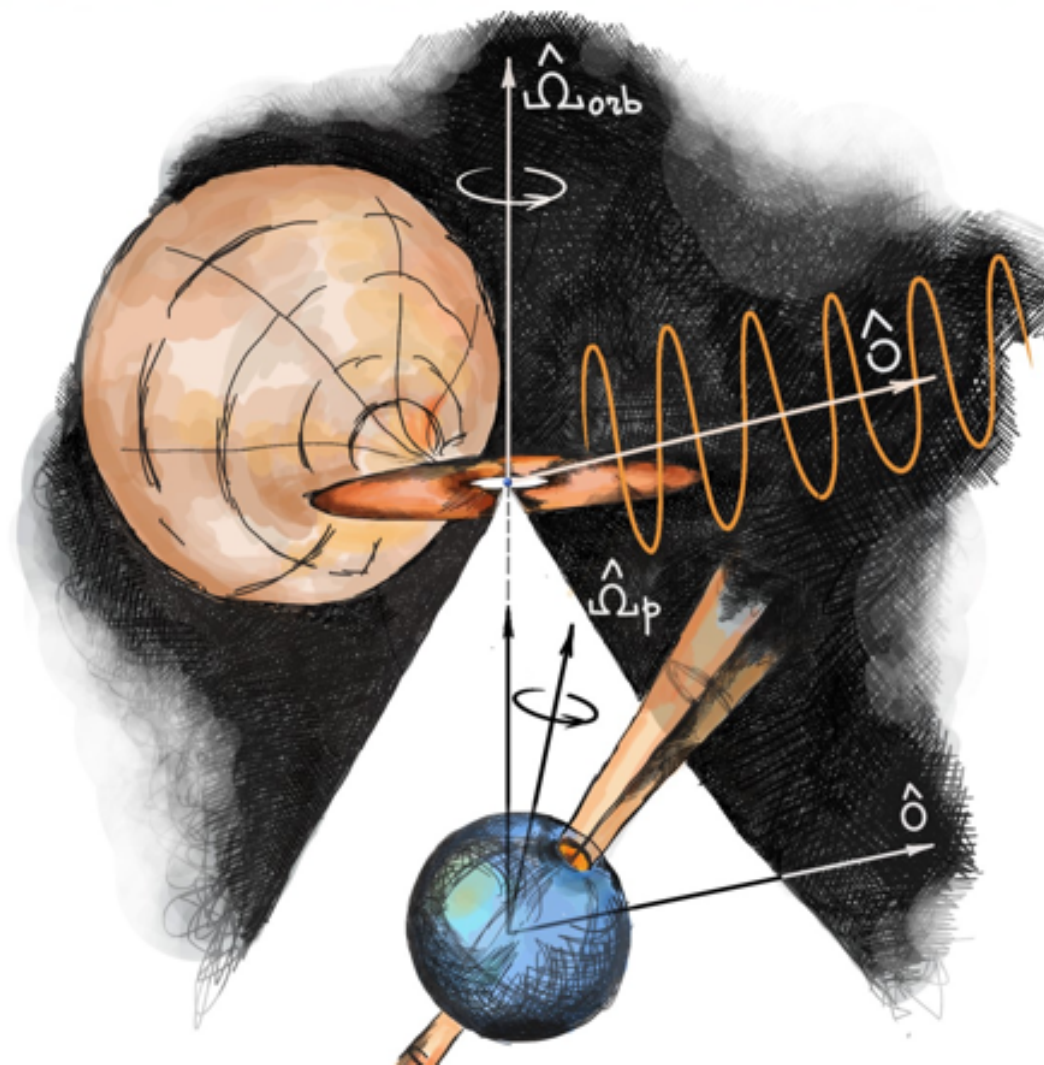


Image: Alexander Mushtukov

# Introduction

## Classification of X-ray binaries

Classification **by an accretor**

Neutron Star  
X-ray binary  
(NSXRBs)

Black Hole  
X-ray binary  
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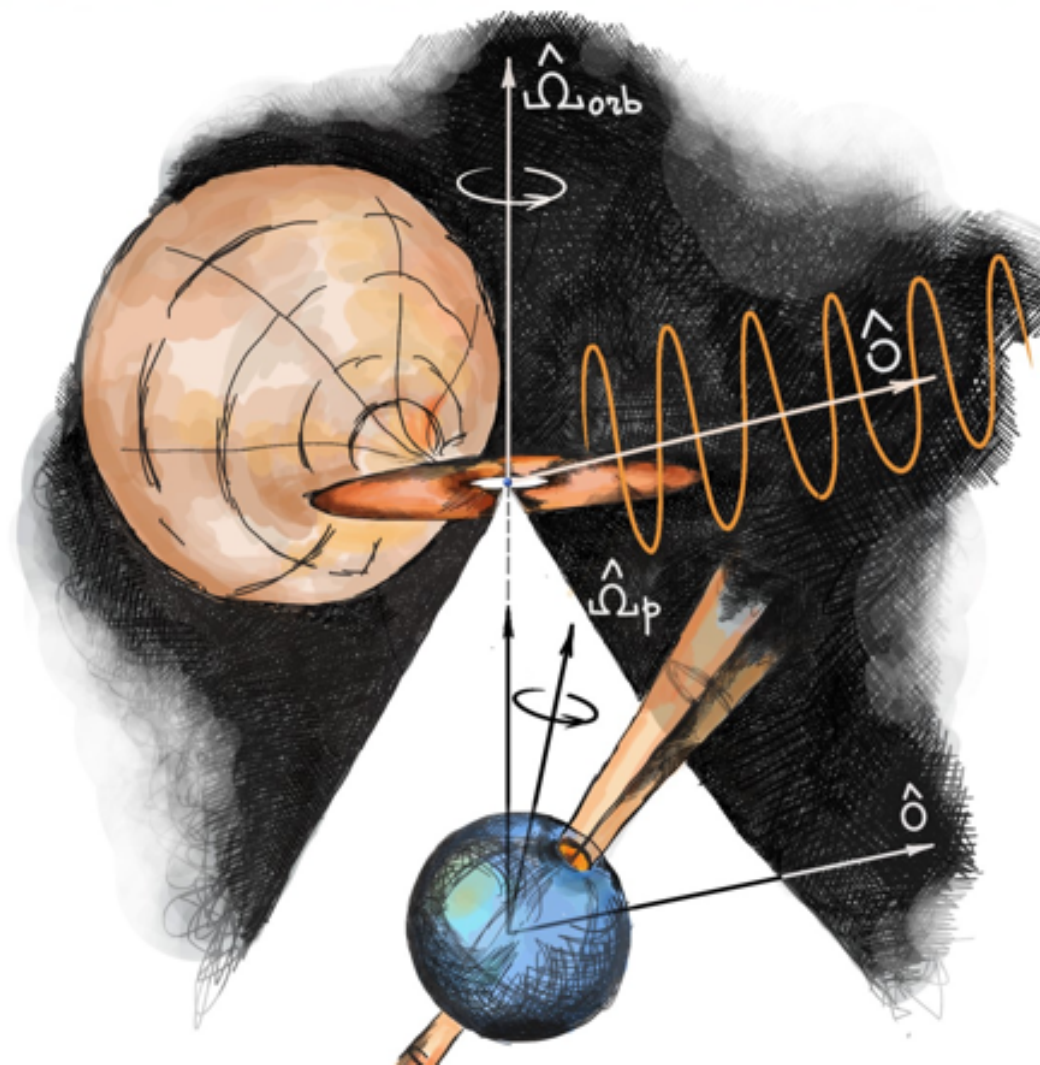
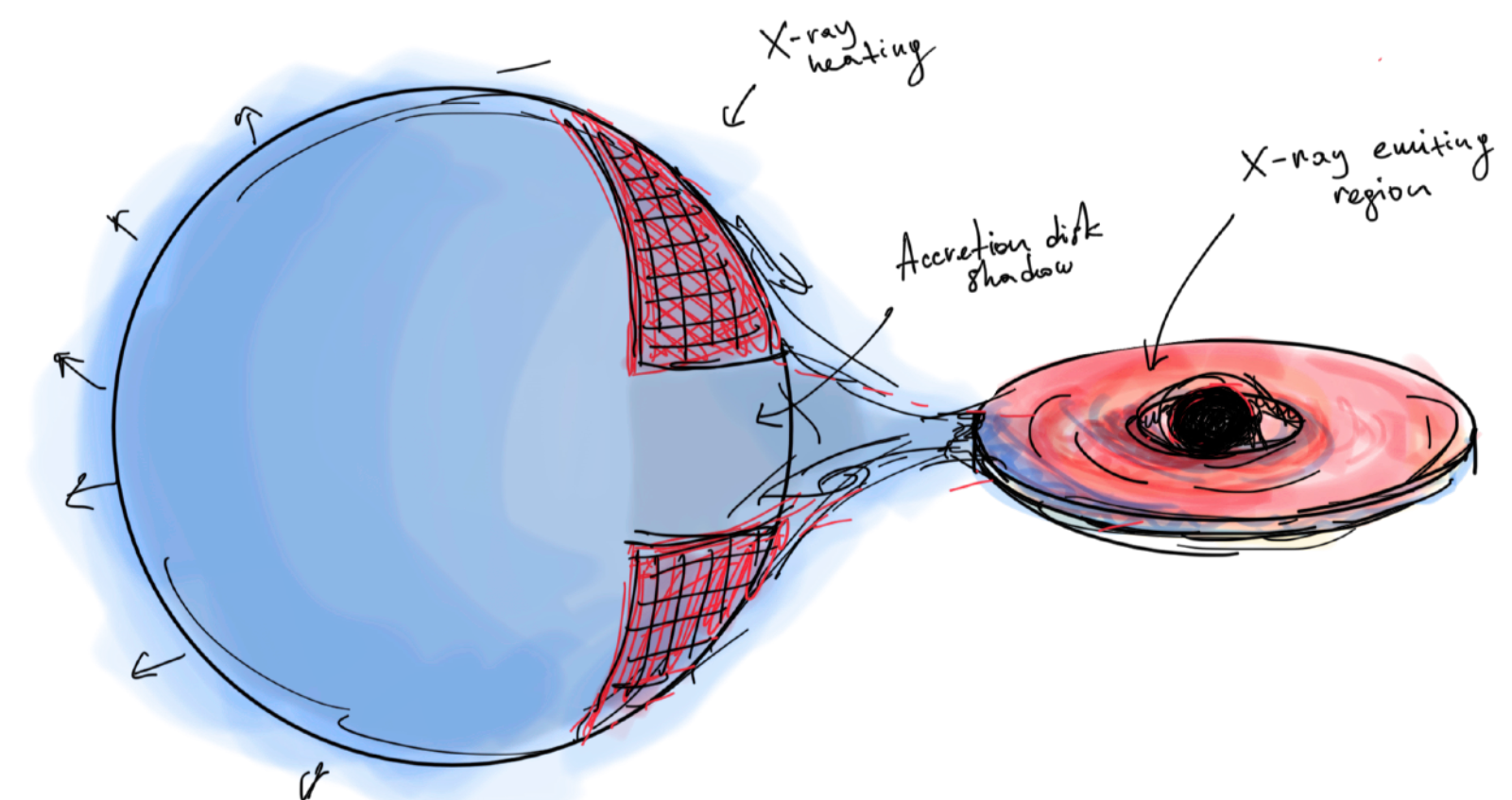


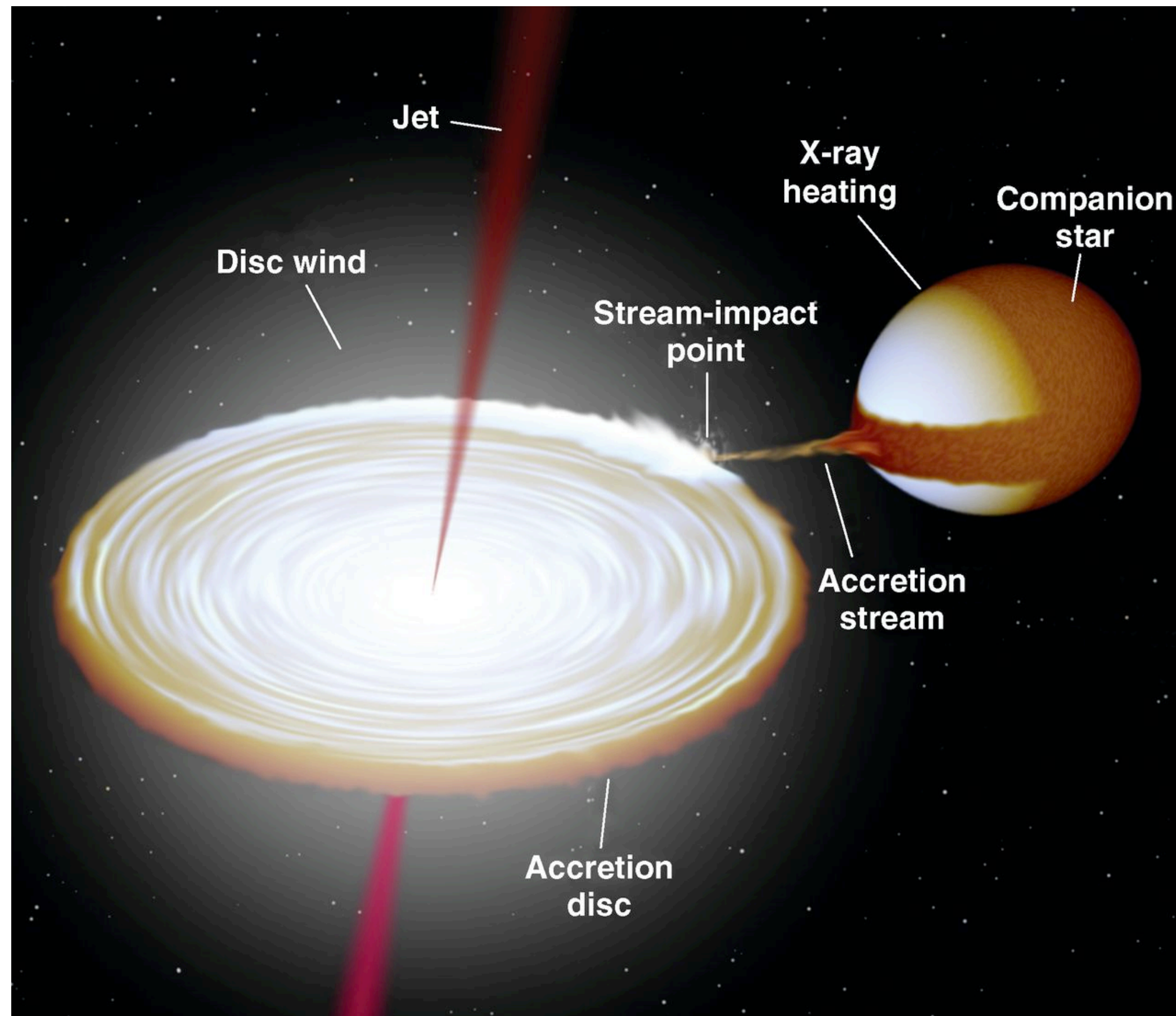
Image: Alexander Mushtukov





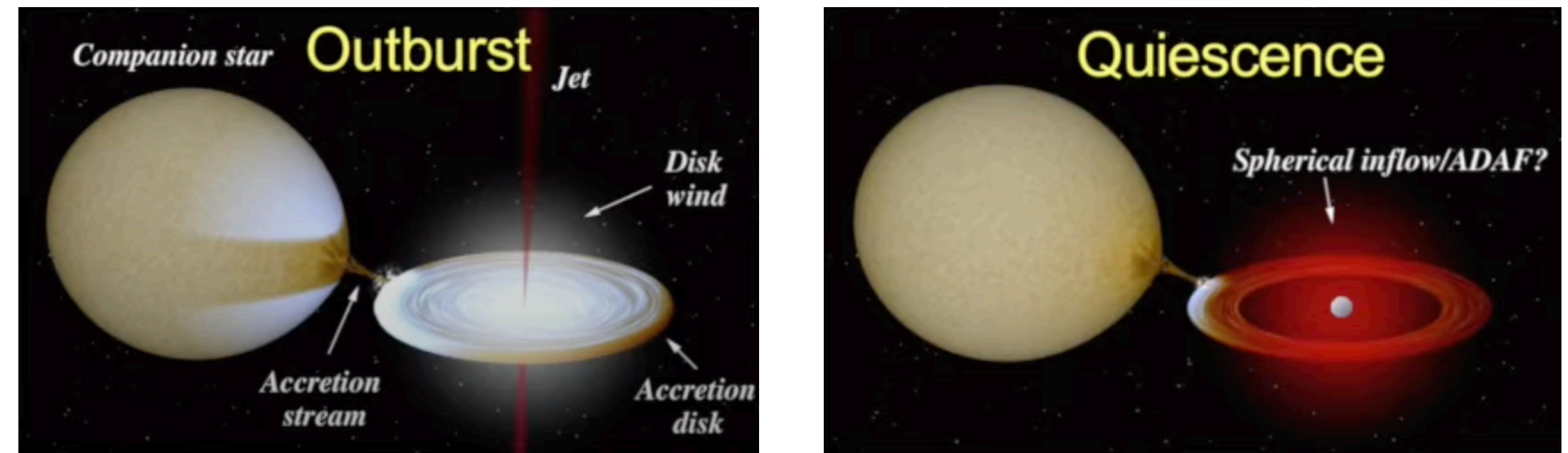
# Introduction

Geometry and spectra of X-ray binaries

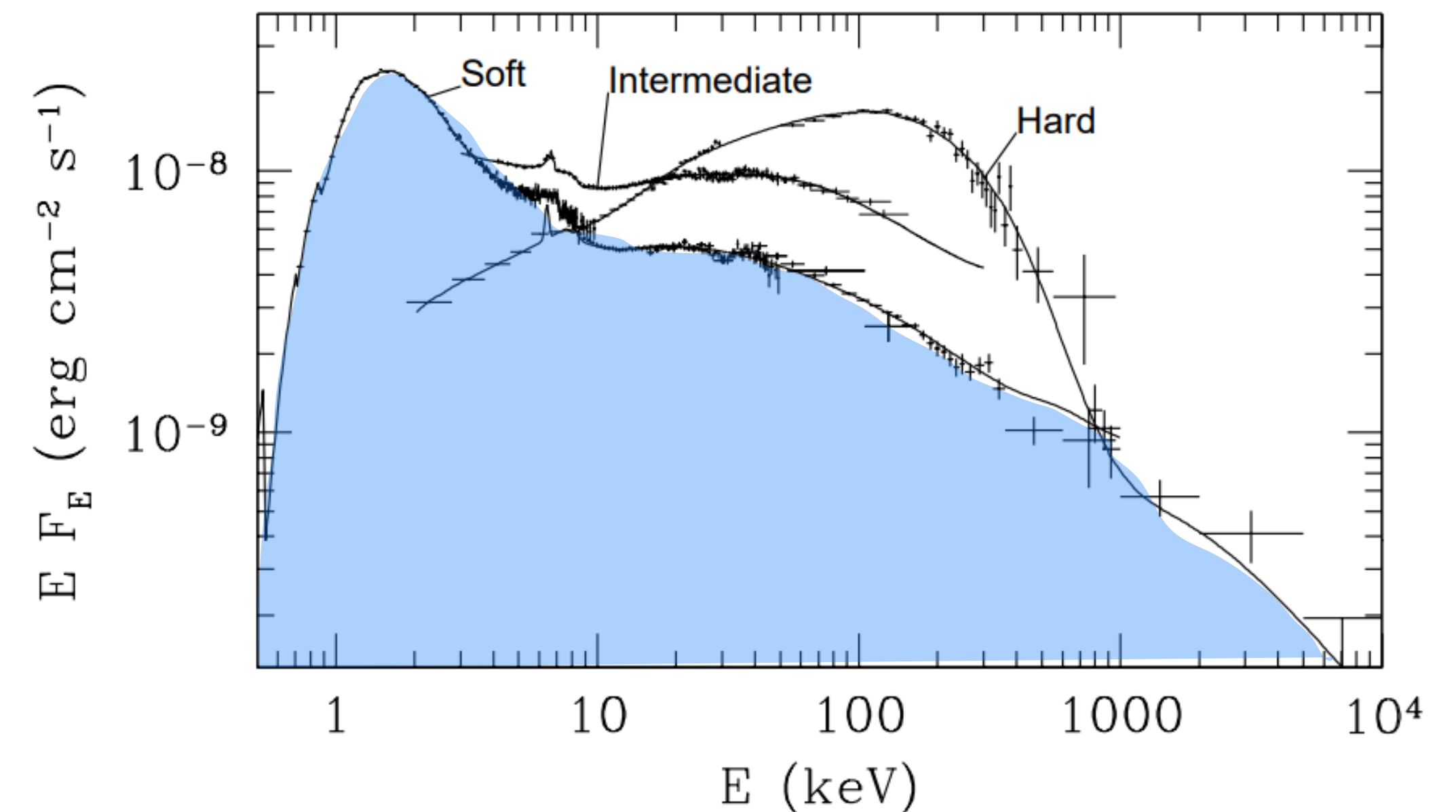


[Image produced with BinSim by Rob Hynes]

Spectrum of X-ray binary – product of a complex interplay between contribution of several components.



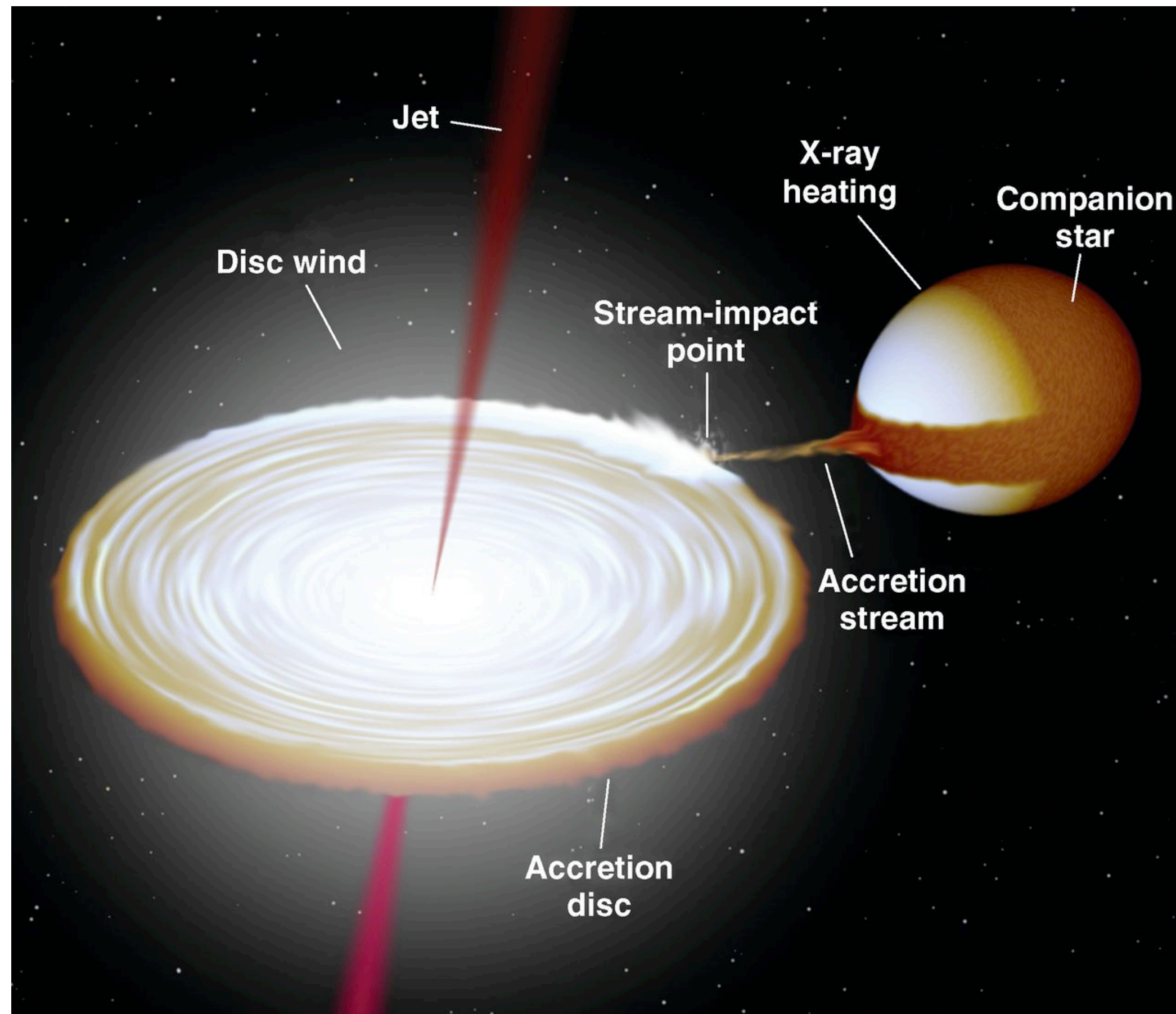
optical star + accretion disk + jet + wind + hot accretion flow  
+ ...





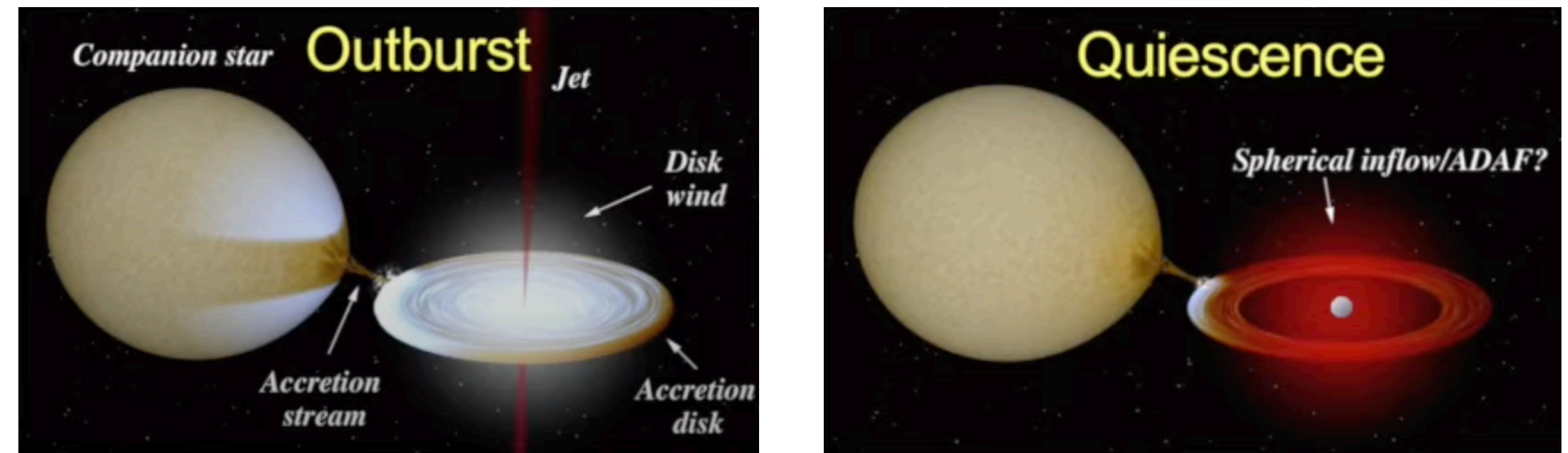
# Introduction

Geometry and spectra of X-ray binaries

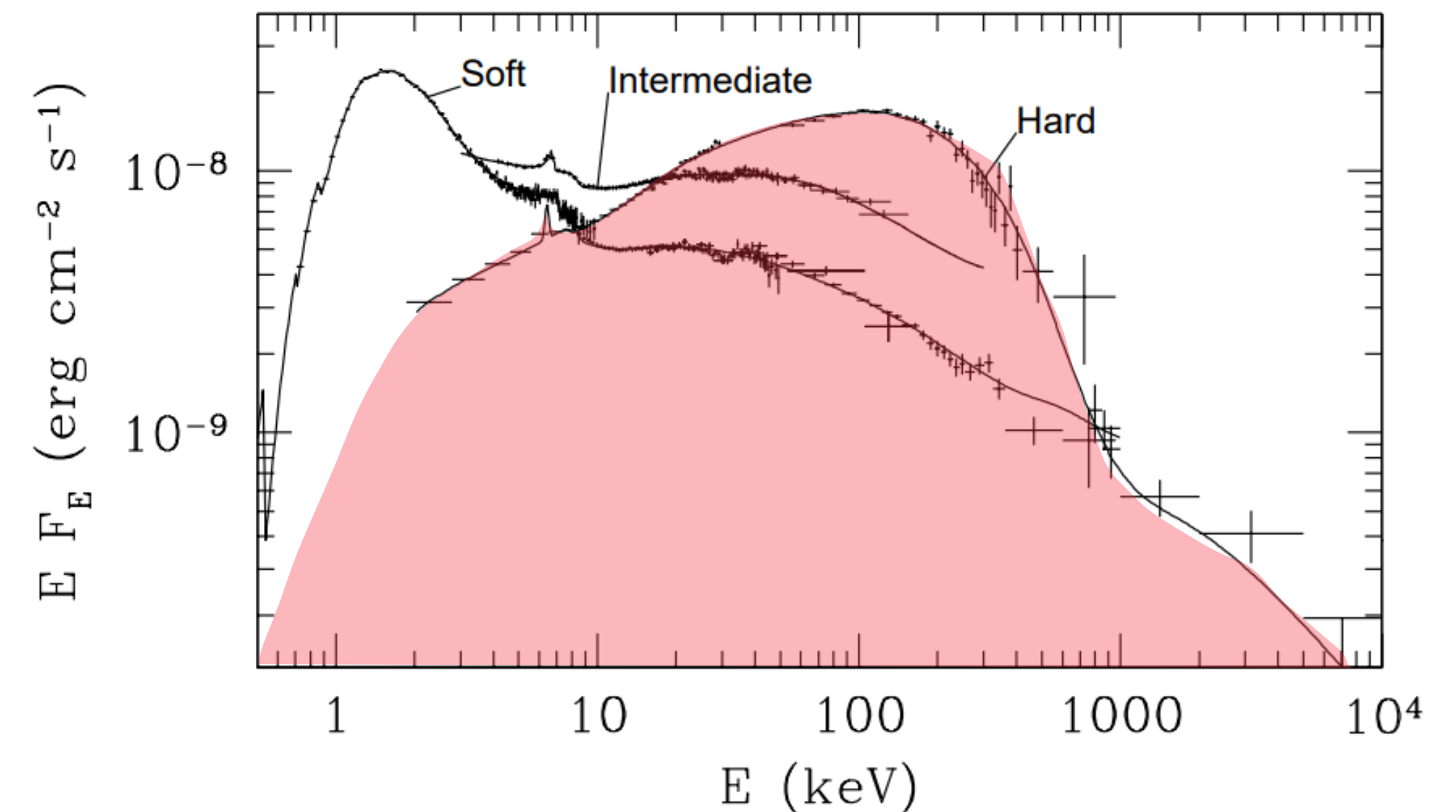


[Image produced with BinSim by Rob Hynes]

Spectrum of X-ray binary – product of a complex interplay between contribution of several components.



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# Polarized Radiation



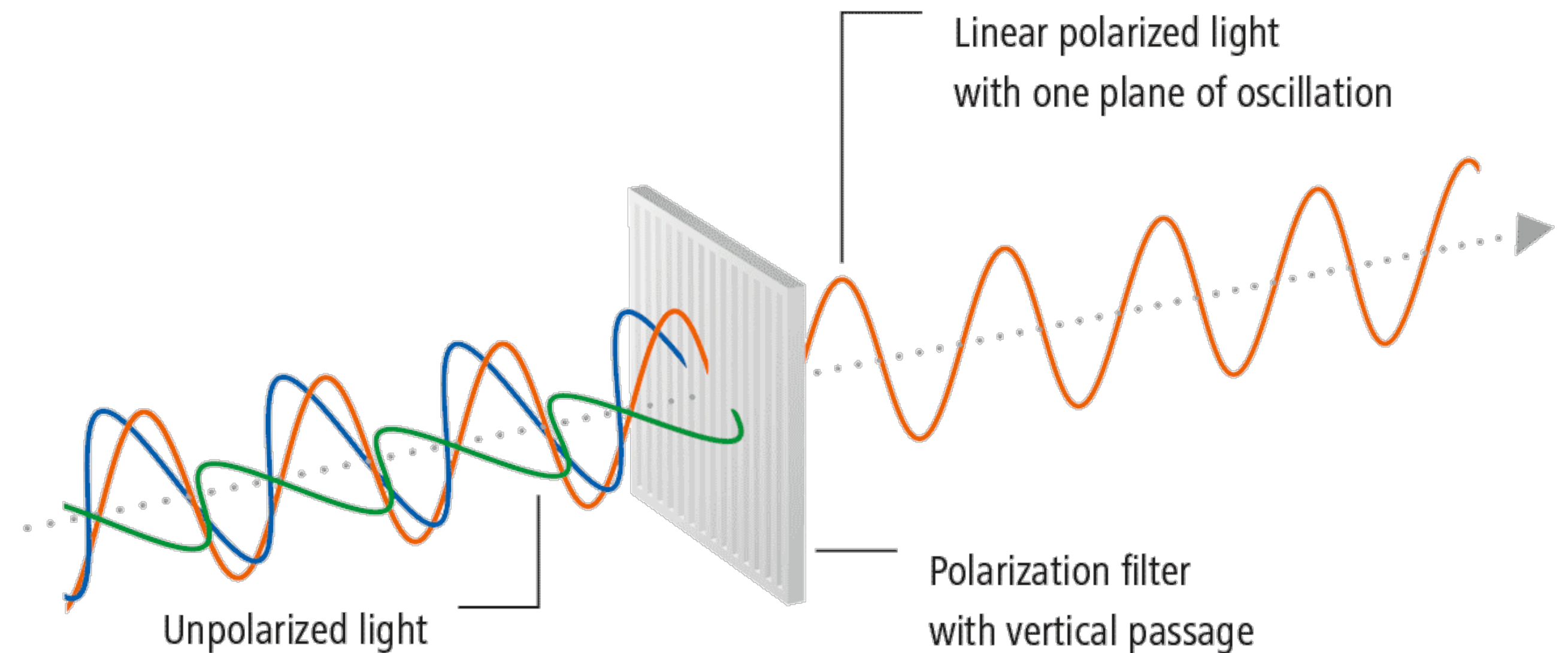
# Polarization

## 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**.

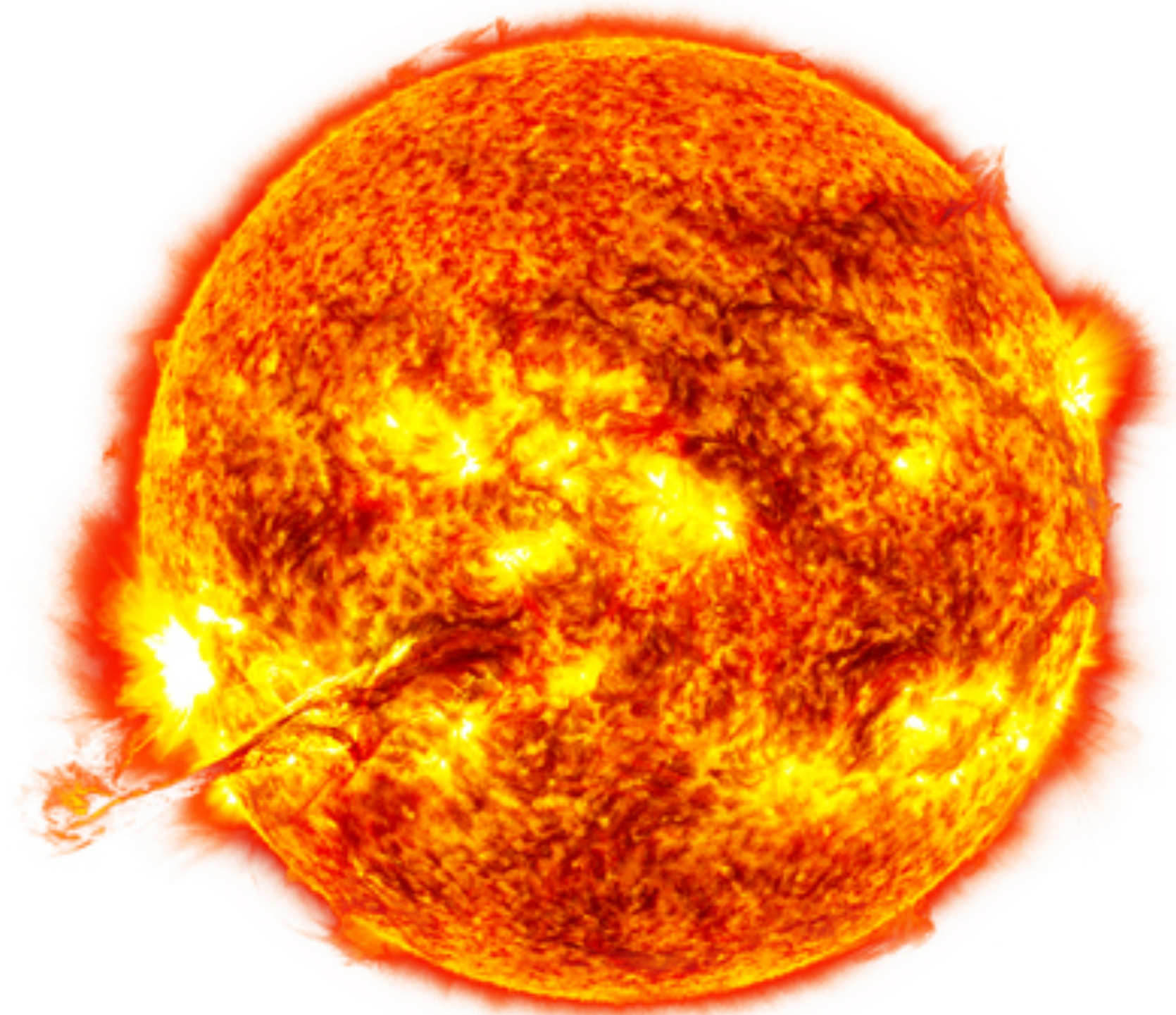
If the electric vector oscillates within one plane, the light is **linearly polarized**.



# Polarization

Definition and description

Real life example of **unpolarized light** – sunlight.

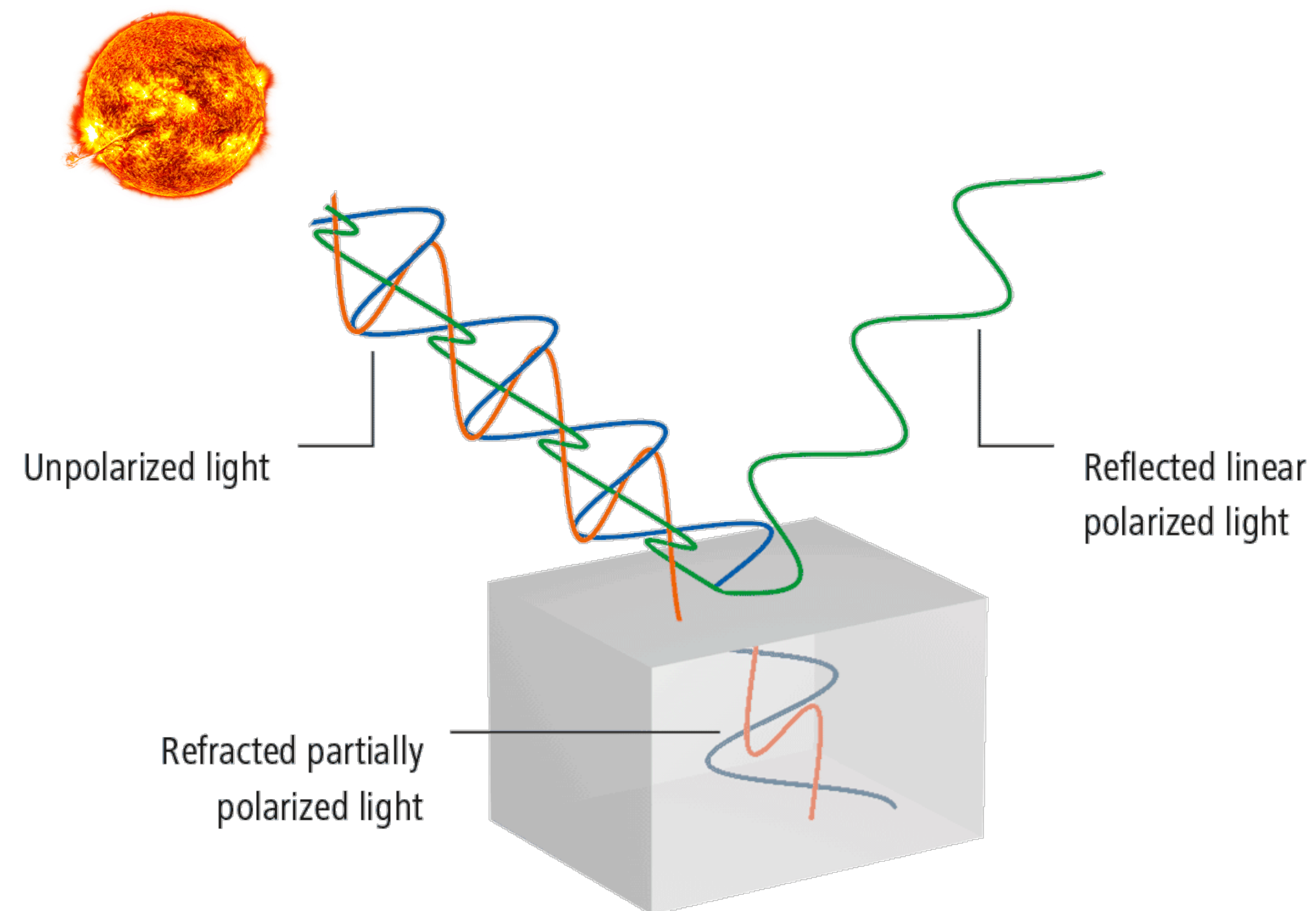




# Polarization

Definition and description

Real life example of **linearly polarized light** – reflected light.

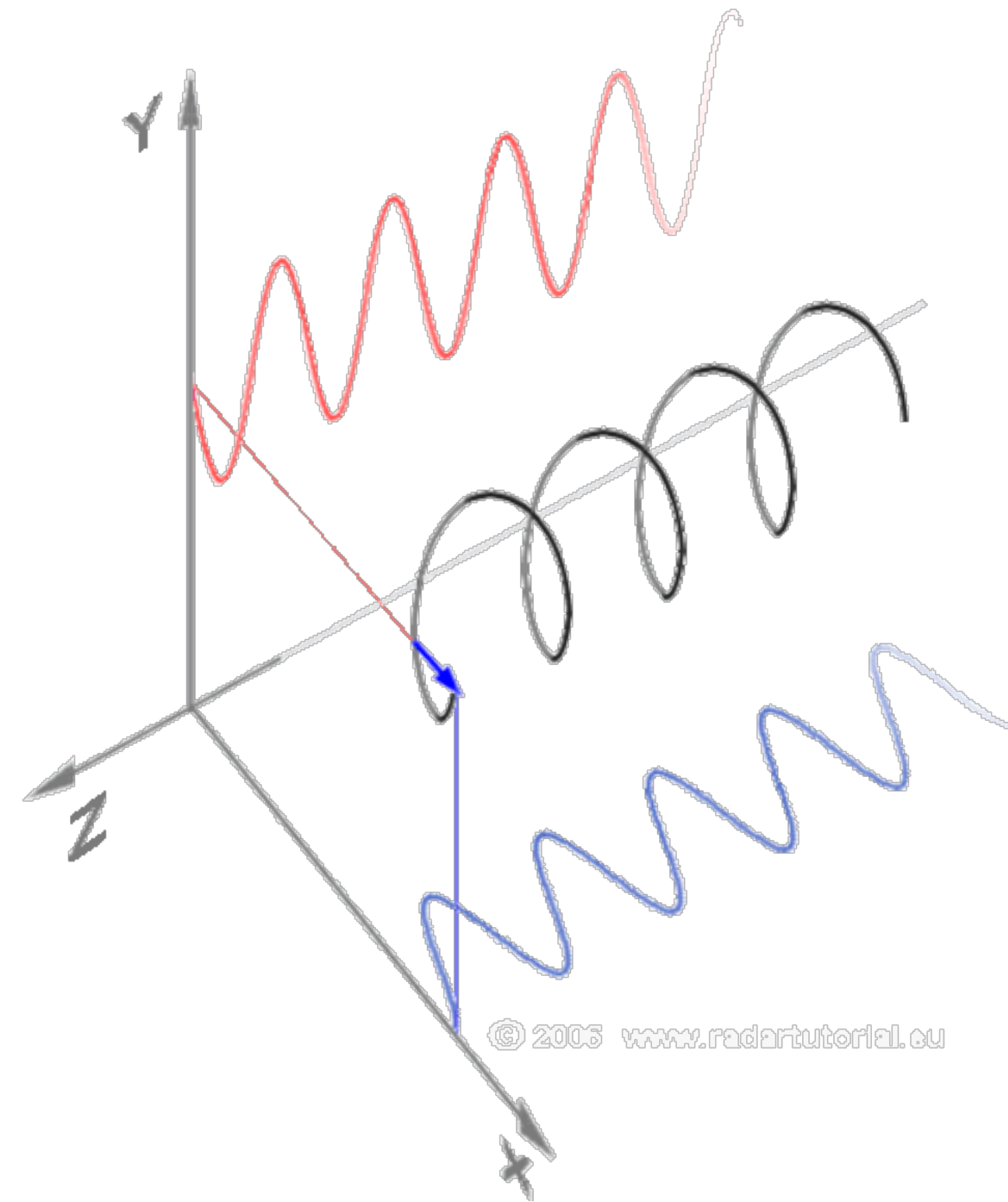


Reflection from the window, as seen without (left) and with (right) polarized glasses

# Polarization

Definition and description

Polarization of the light can be described with four numbers called **Stokes parameters**:



$$I = E_X^2 + E_Y^2 = E_{0^\circ}^2 + E_{90^\circ}^2$$

$$Q = E_X^2 - E_Y^2 = E_{0^\circ}^2 - E_{90^\circ}^2$$

$$U = E_{45^\circ}^2 - E_{-45^\circ}^2$$

$$V = E_{LCP}^2 - E_{RCP}^2$$

$$\mathbf{S} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$



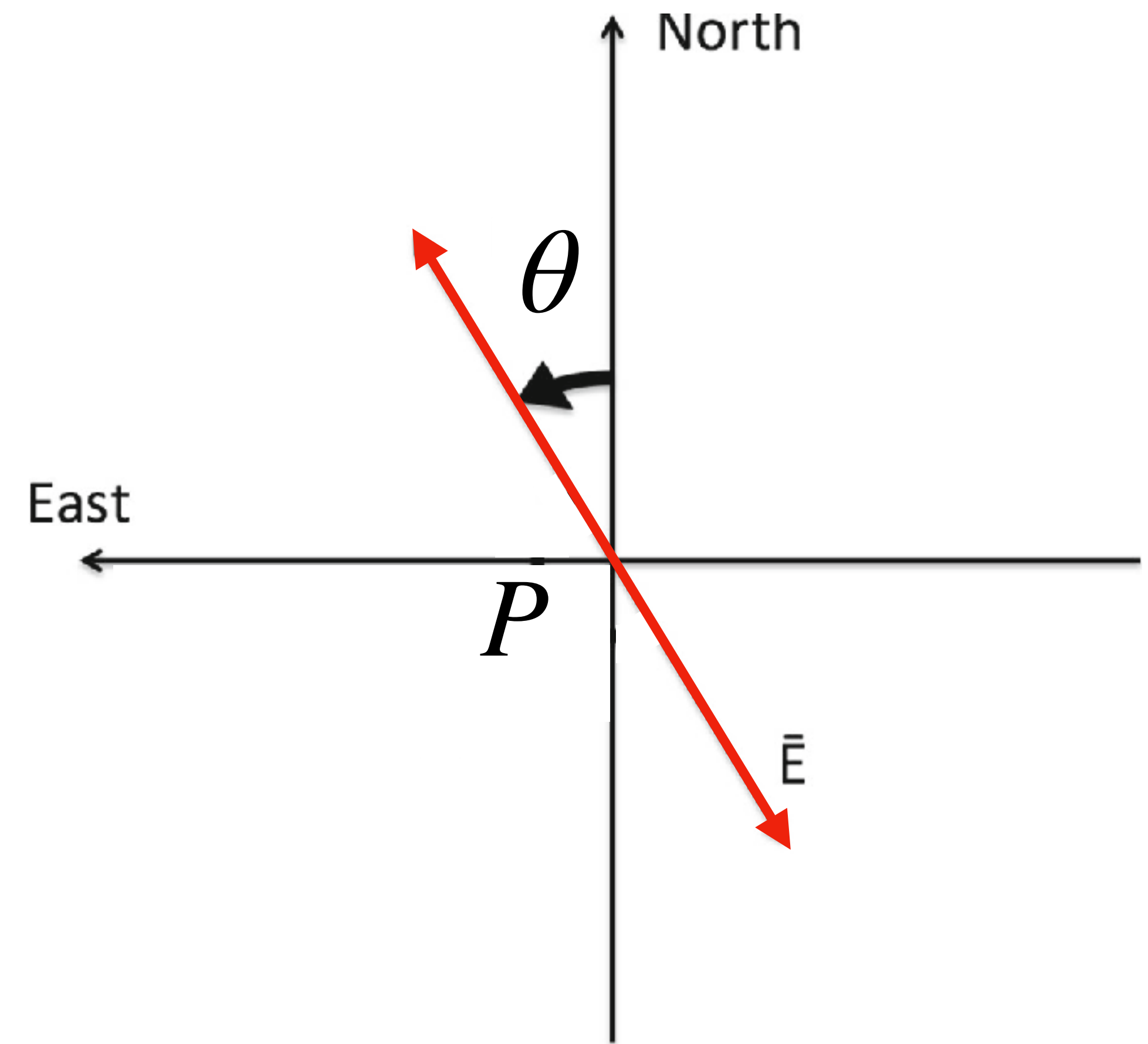
# Polarization

Definition and description

For linearly polarized light, Stokes parameter  $V = 0$ .

In astronomy we use **normalized Stokes parameters**:

$$q = \frac{Q}{I} \quad P = \sqrt{q^2 + u^2}$$
$$u = \frac{U}{I} \quad \theta = 0.5 \arctan \frac{u}{q}$$



Definition of the linear polarization on the sky

# 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 charged particles**.

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

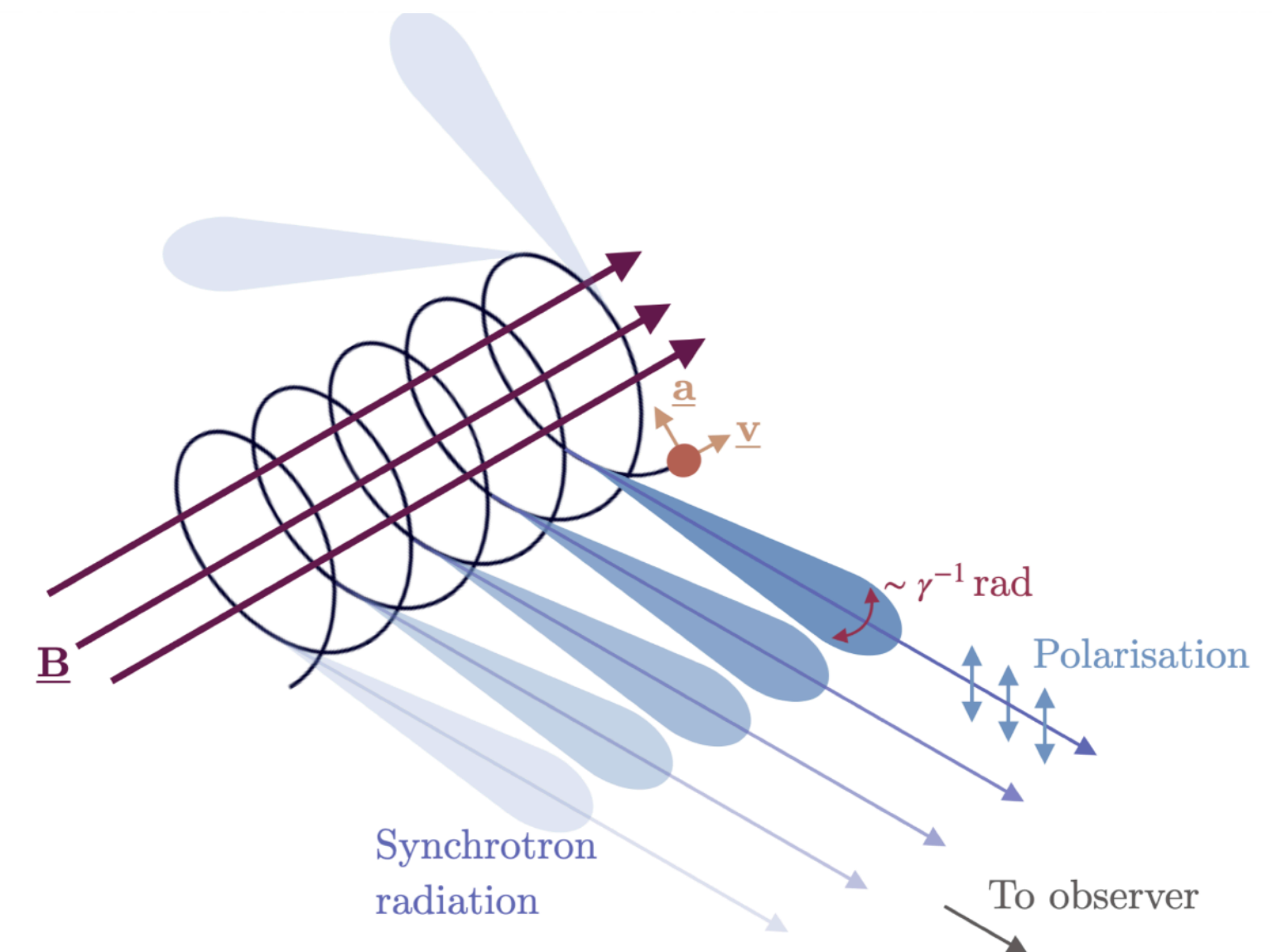
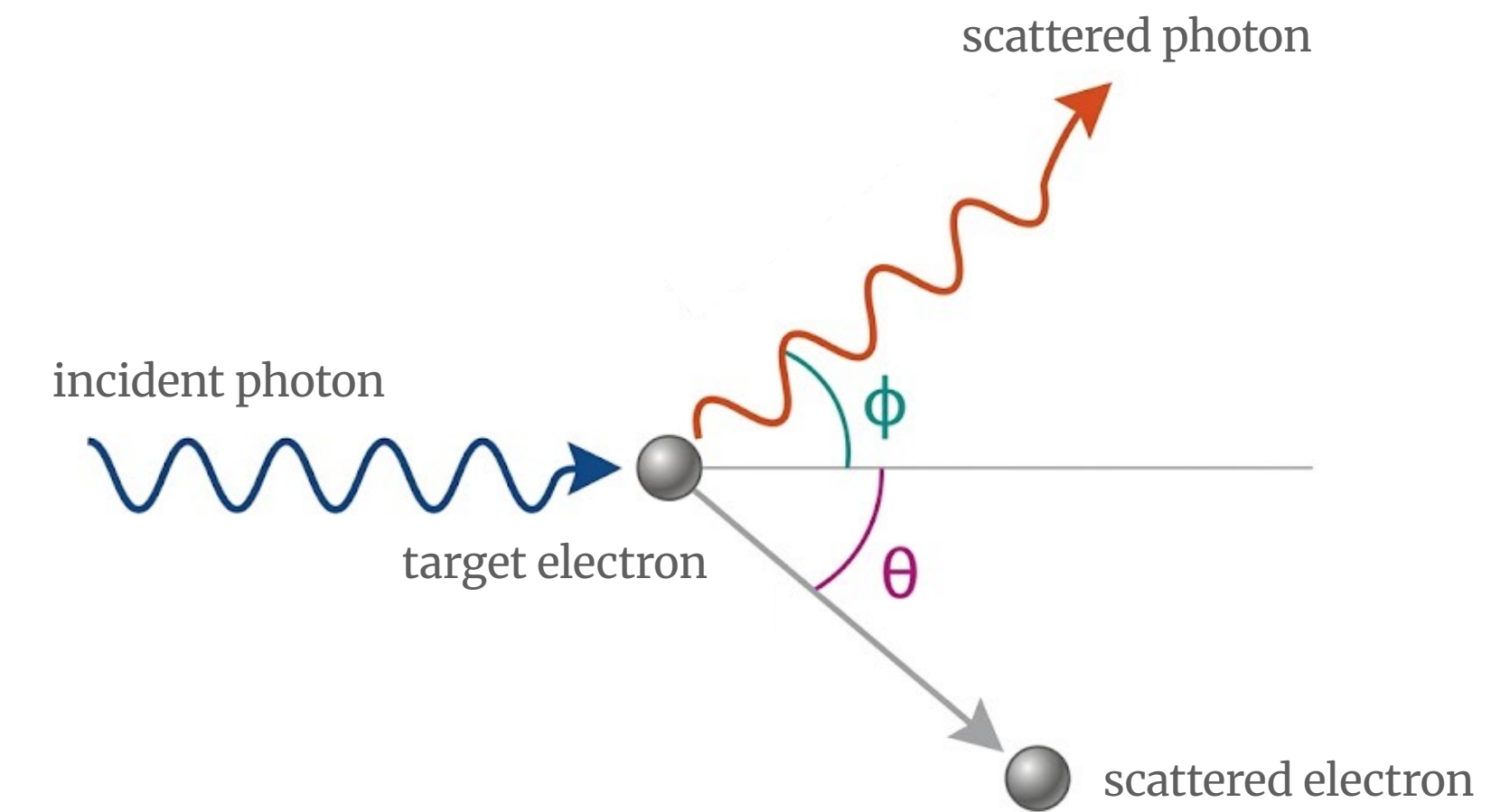
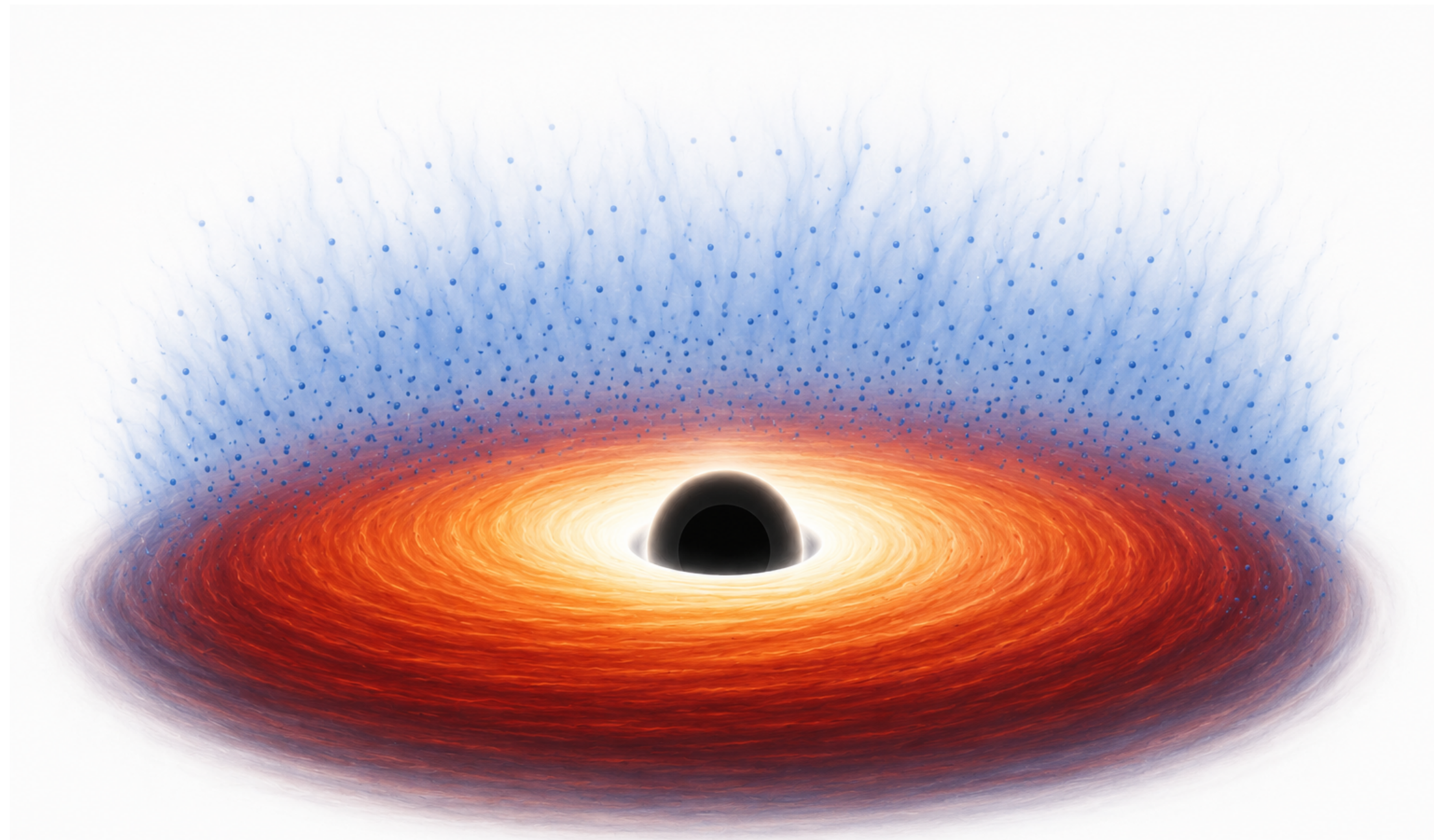


Image: Emma Alexander

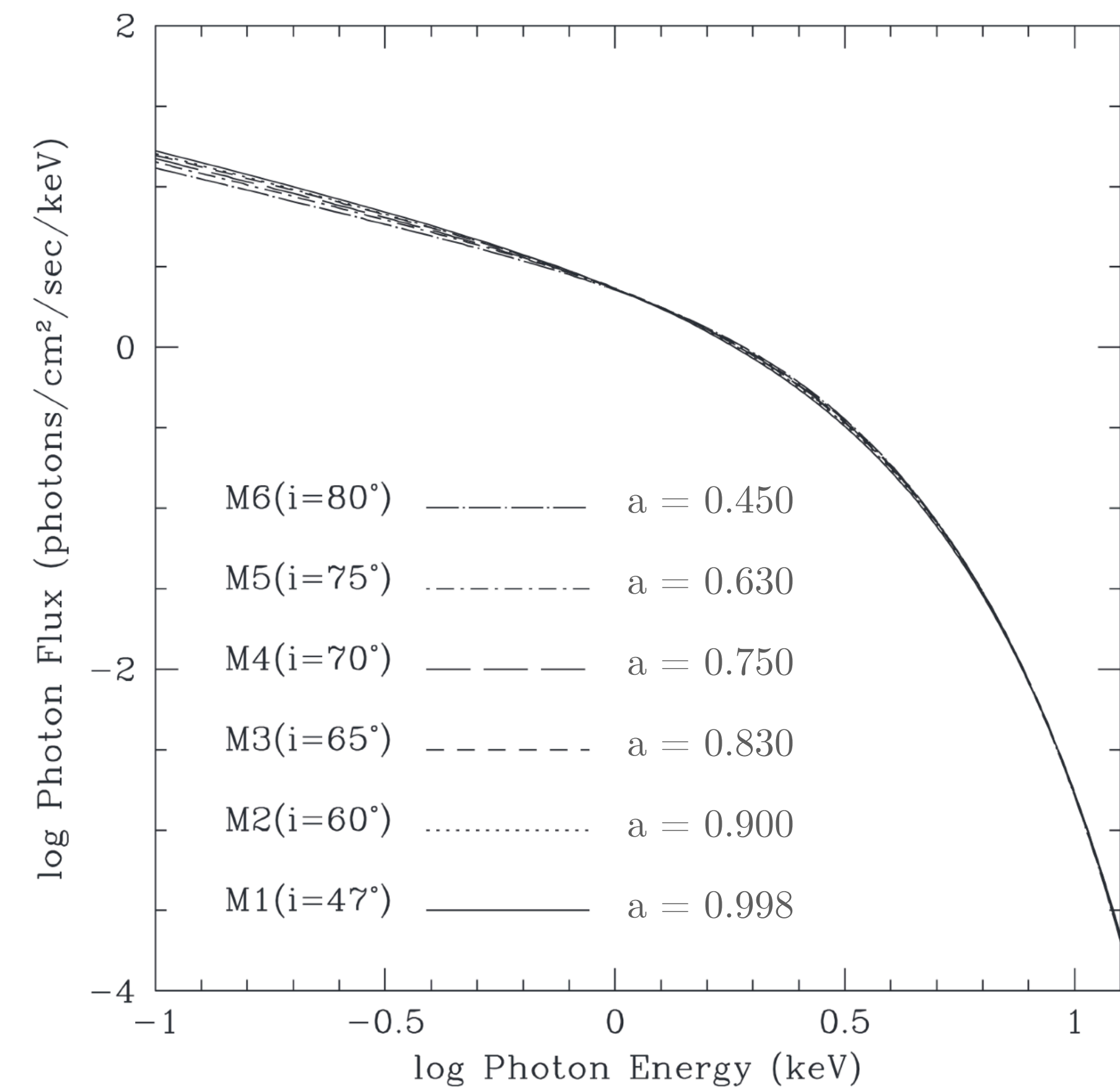


# Why polarization?



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

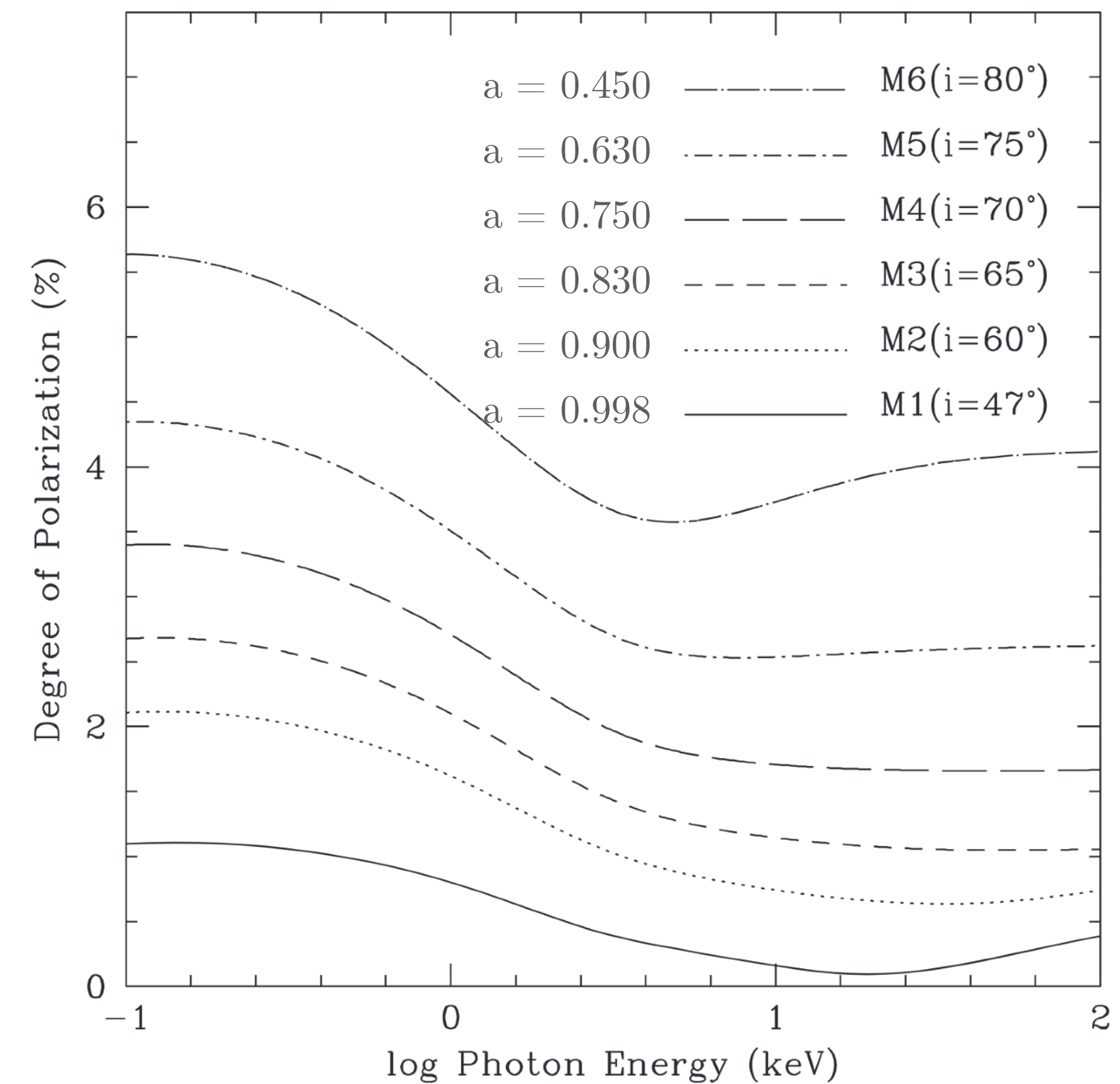
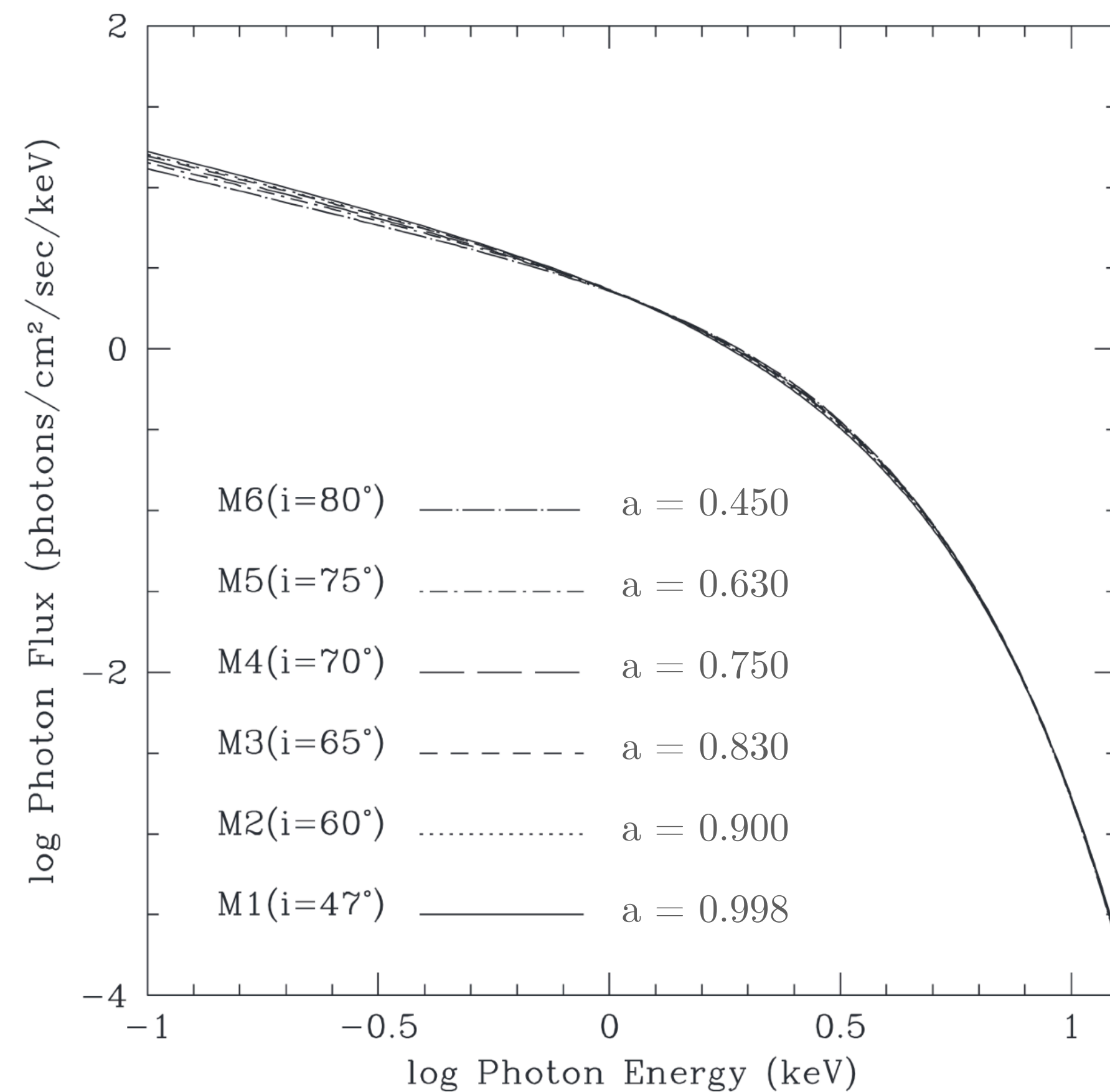
Example: Li, Narayan & McClintock 2009



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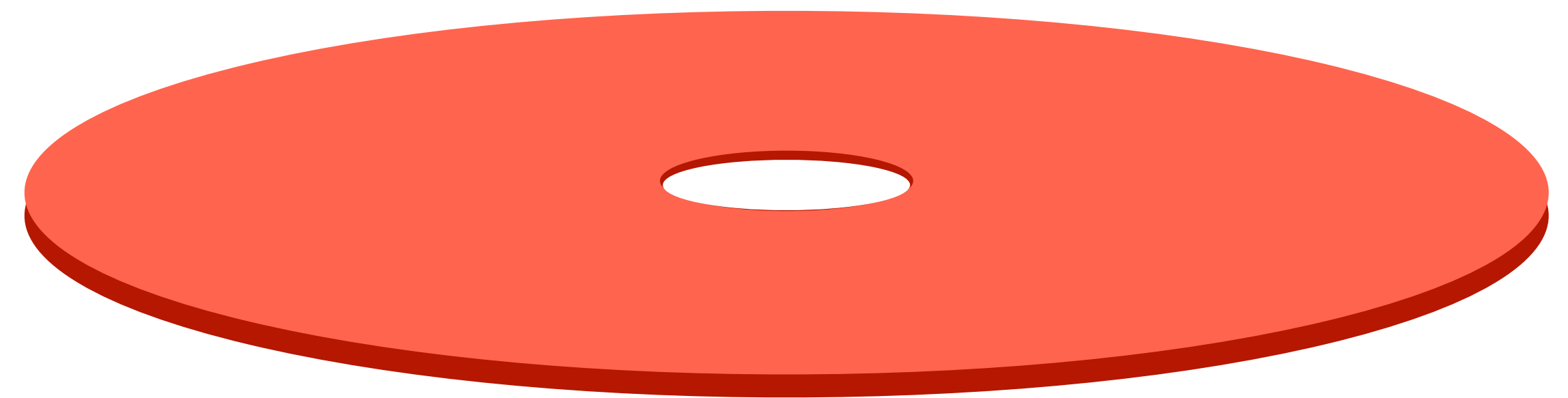
**What contributes to the polarization?**

# What contributes to the polarization?

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.

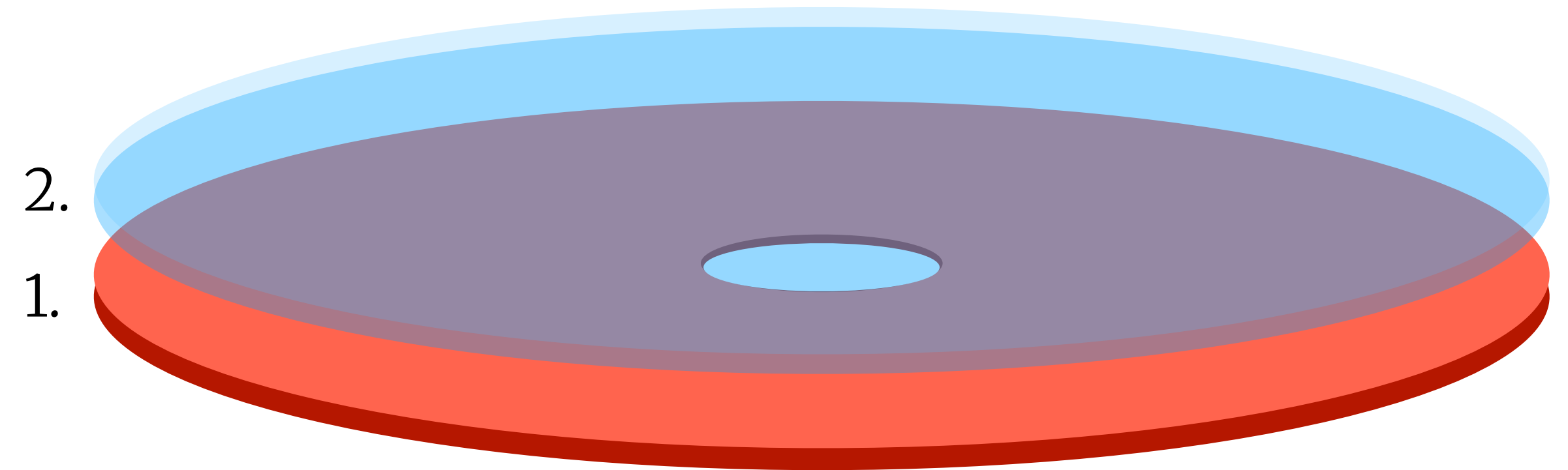




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1. **Disk:** plane-parallel, electron scattering-dominated atmosphere (Shakura & Sunyaev 1973; Novikov & Thorne 1973).
2. **Corona:** hot, optically thin plasma in the vicinity of black hole. Inverse Compton scattering. Different geometries were proposed: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

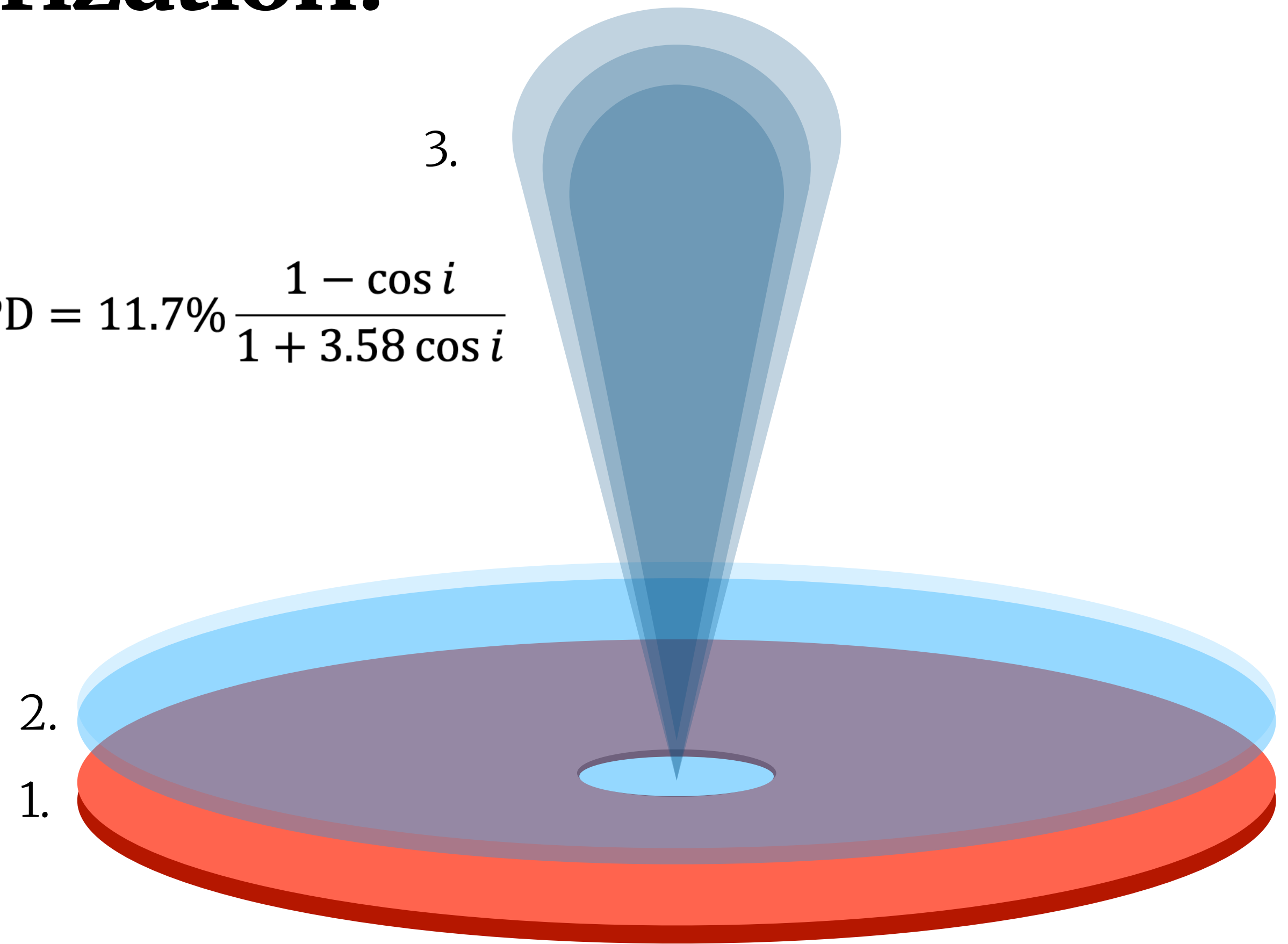
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# What contributes to the polarization?

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

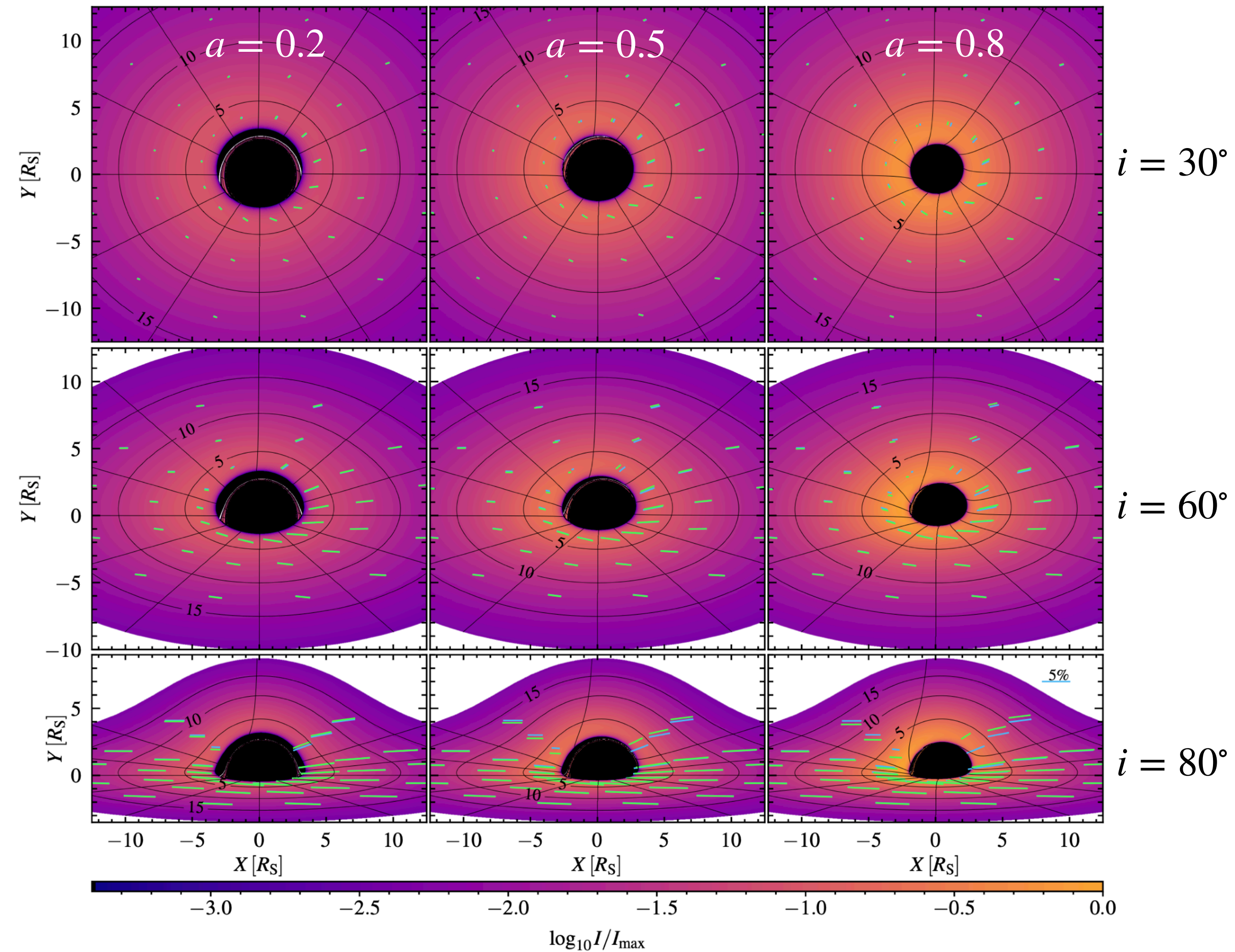
$$PD = 11.7\% \frac{1 - \cos i}{1 + 3.58 \cos i}$$





# GR, SR, and other effects

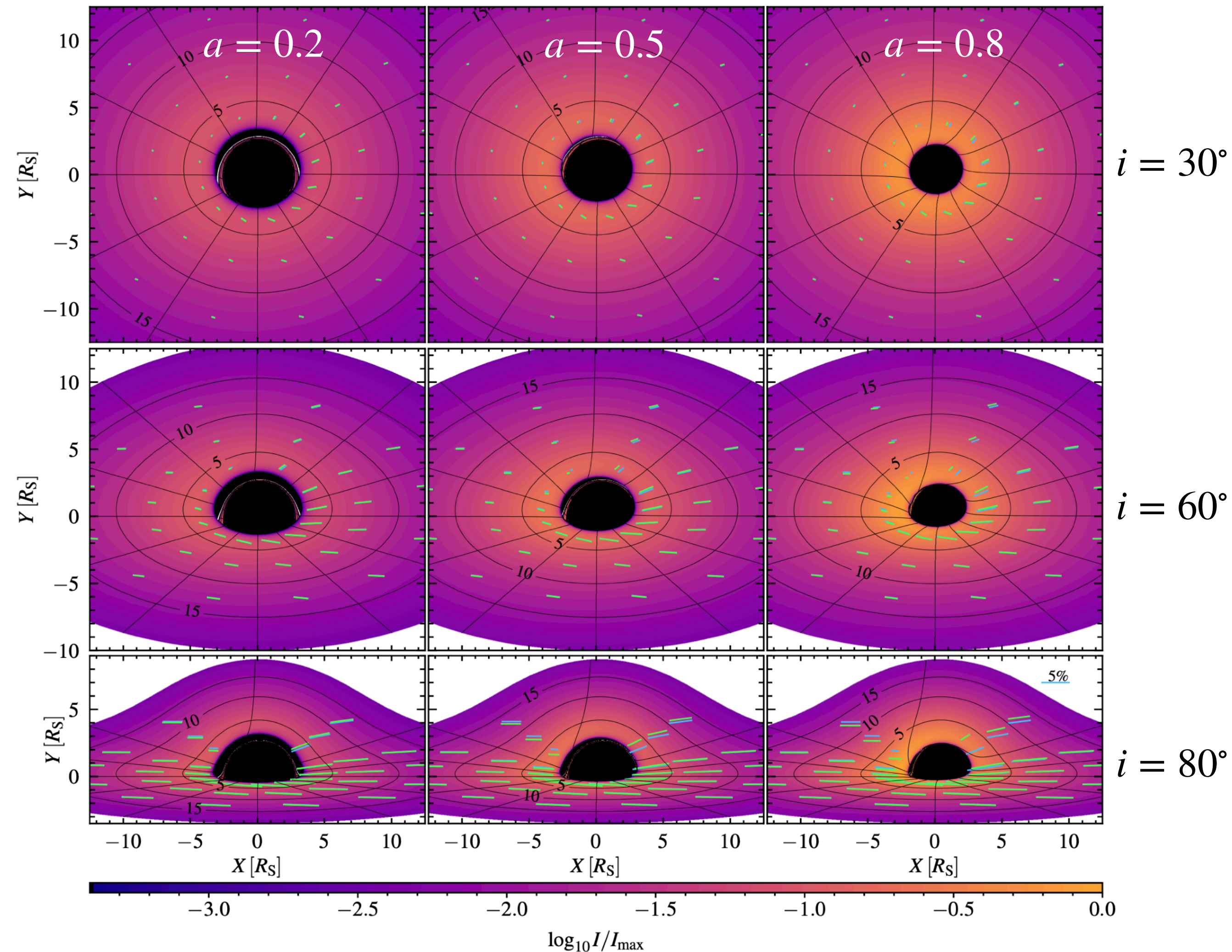
1. **Gravitational lensing:** disk appears warped up toward the observer. Effectively lowers the inclination => lowers the PD.





# GR, SR, and other effects

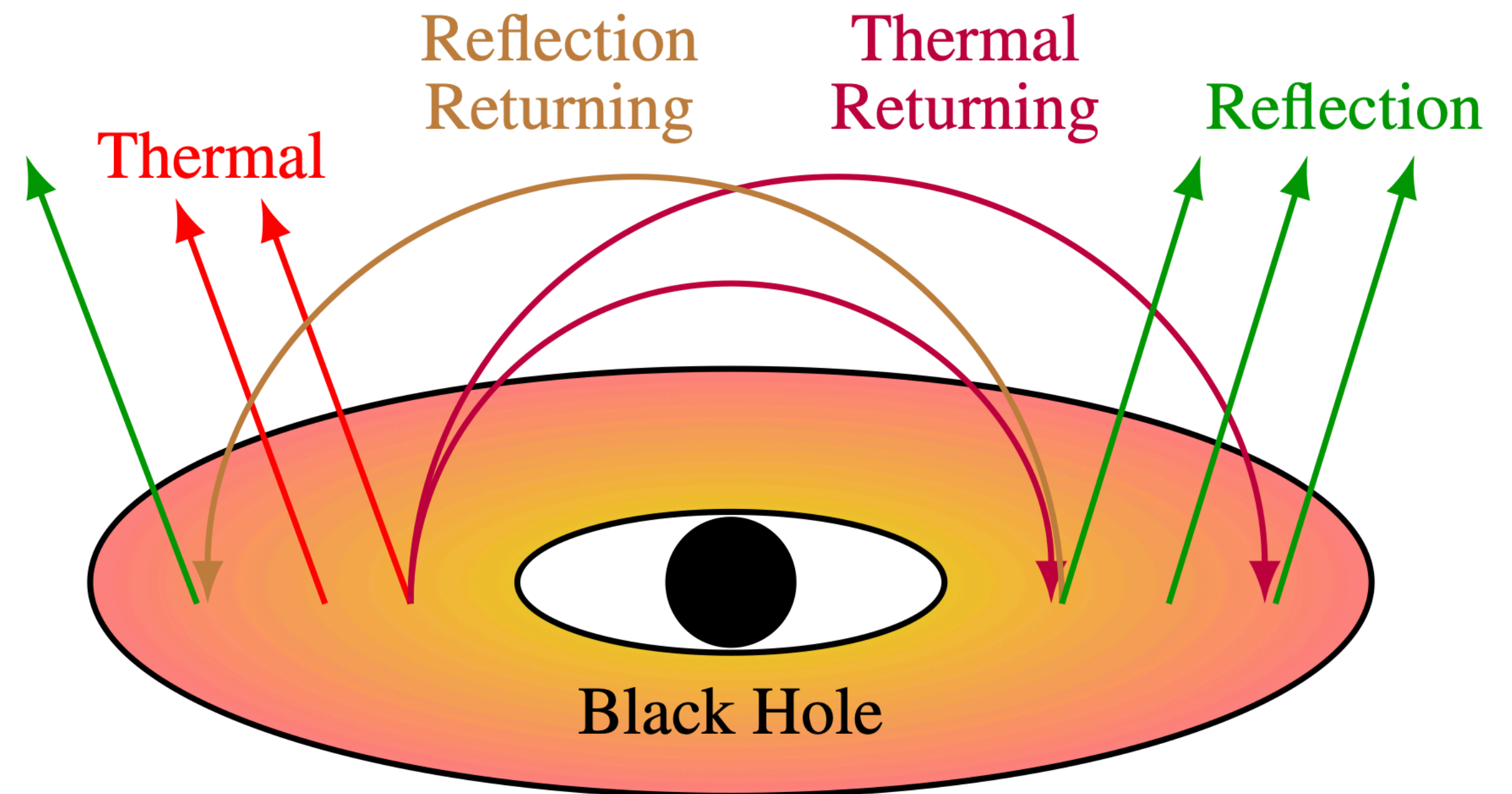
1. **Gravitational lensing:** disk appears warped up toward the observer. Effectively lowers the inclination => lowers the PD.
2. **Beaming:** approaching side of the disk is seen at effectively lower  $i$ , but appear brighter => this lowers PD even more.





# GR, SR, and other effects

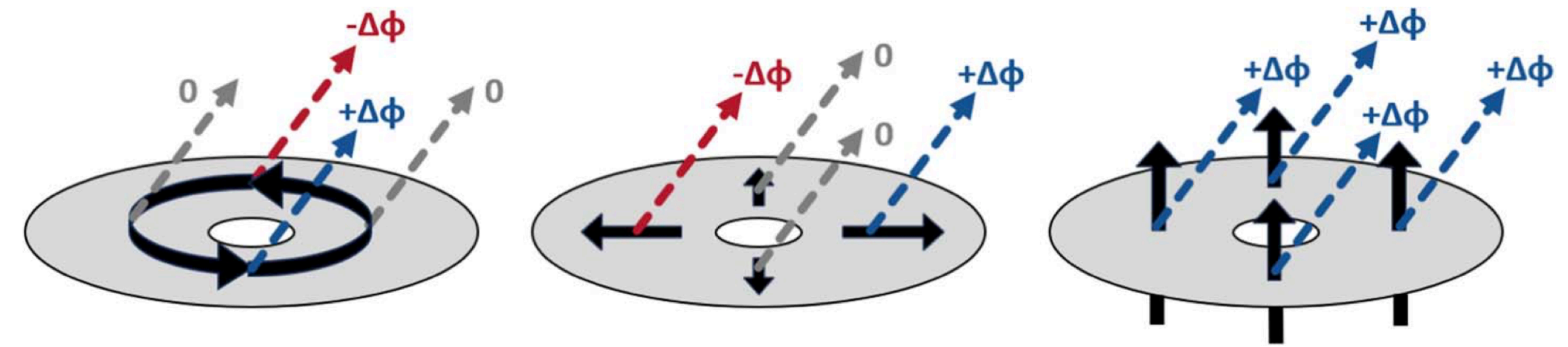
1. **Gravitational lensing:** disk appears warped up toward the observer. Effectively lowers the inclination => lowers the PD.
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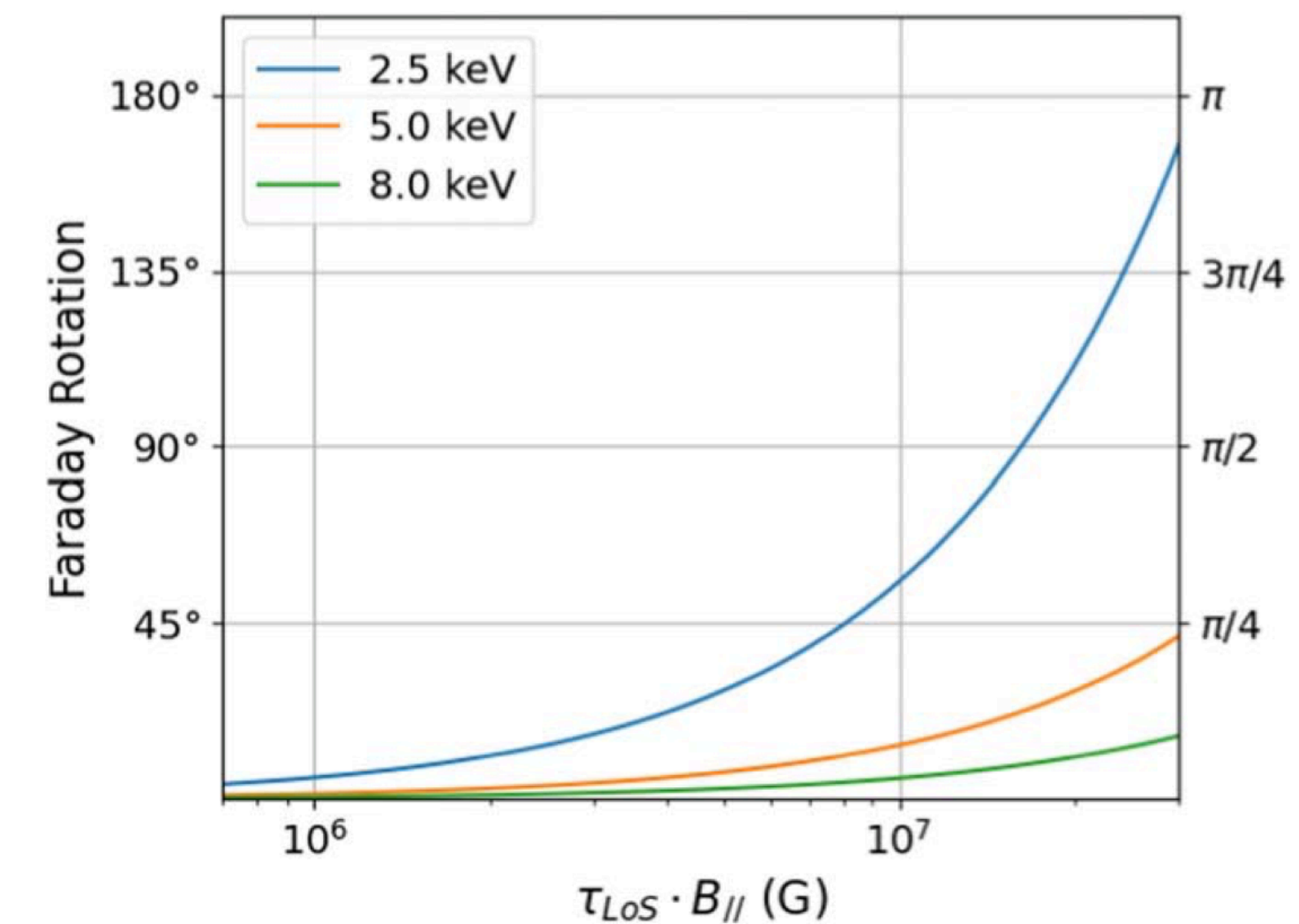
Kourmpetis et al. 2026

# GR, SR, and other effects

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3. **Returning radiation:** photons from one side of the disk strike the other side and reflect to the observer. the polarization is orthogonal to the usual disk PA => may have a substantial impact on the total PD and PA.
4. **Faraday rotation:** depolarization + PA rotation



Barnier & Done 2024



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



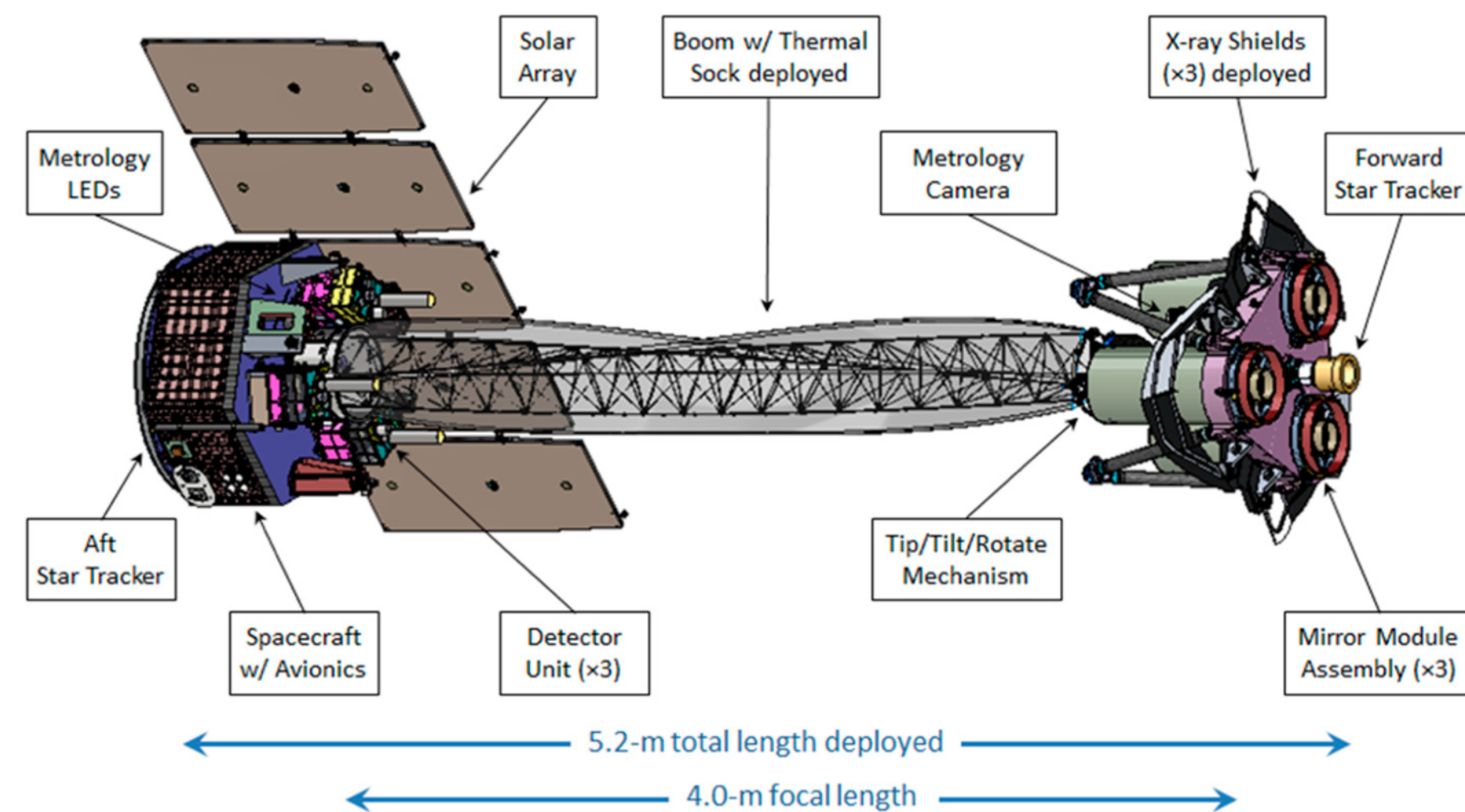
# **X-ray polarimetry**

# X-ray polarimetry

Current and future instruments

## TODAY

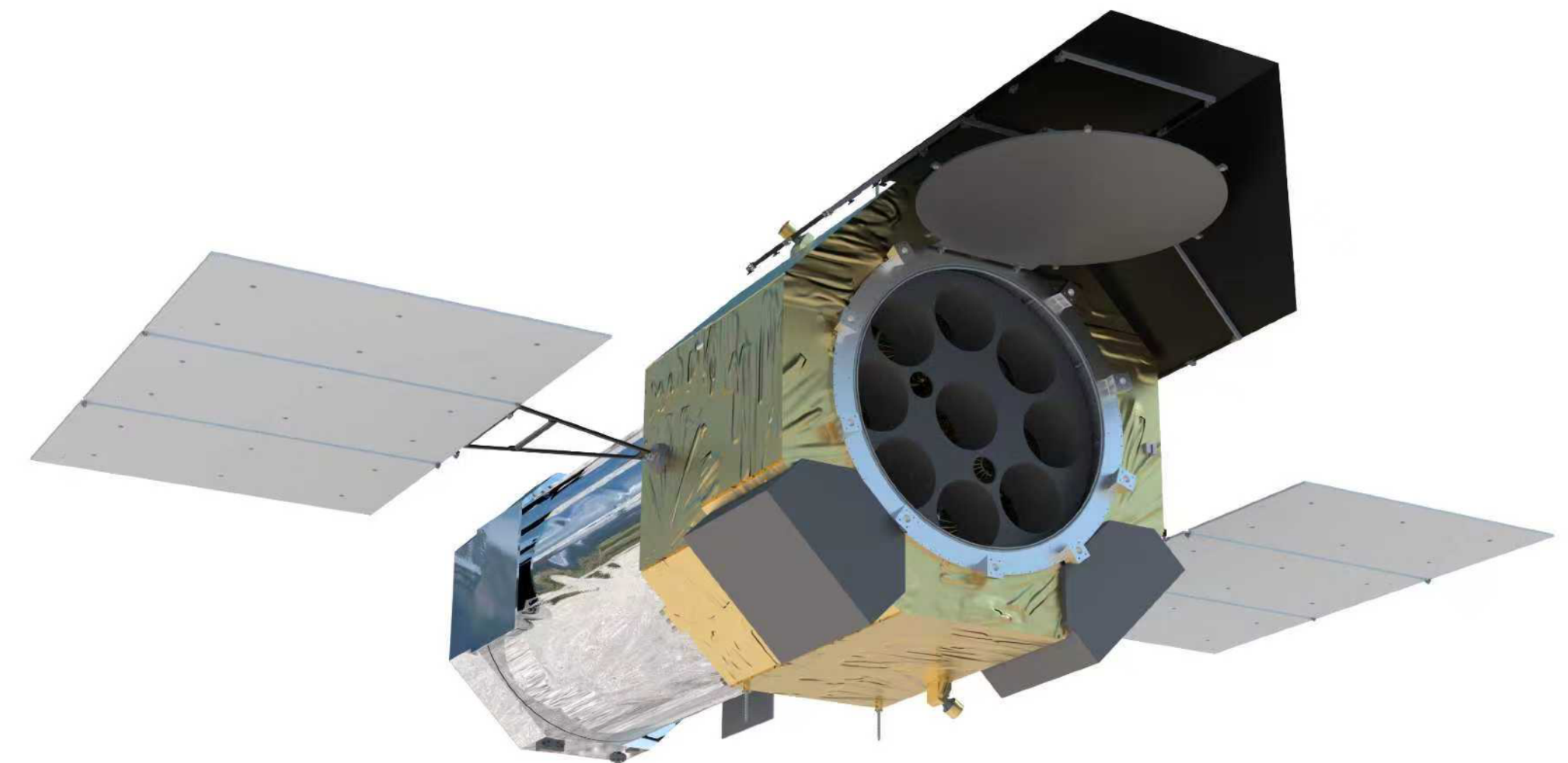
**IXPE** (Imaging X-ray Polarimetry Explorer)  
first reliable X-ray polarization measurements, launched in 2021



>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



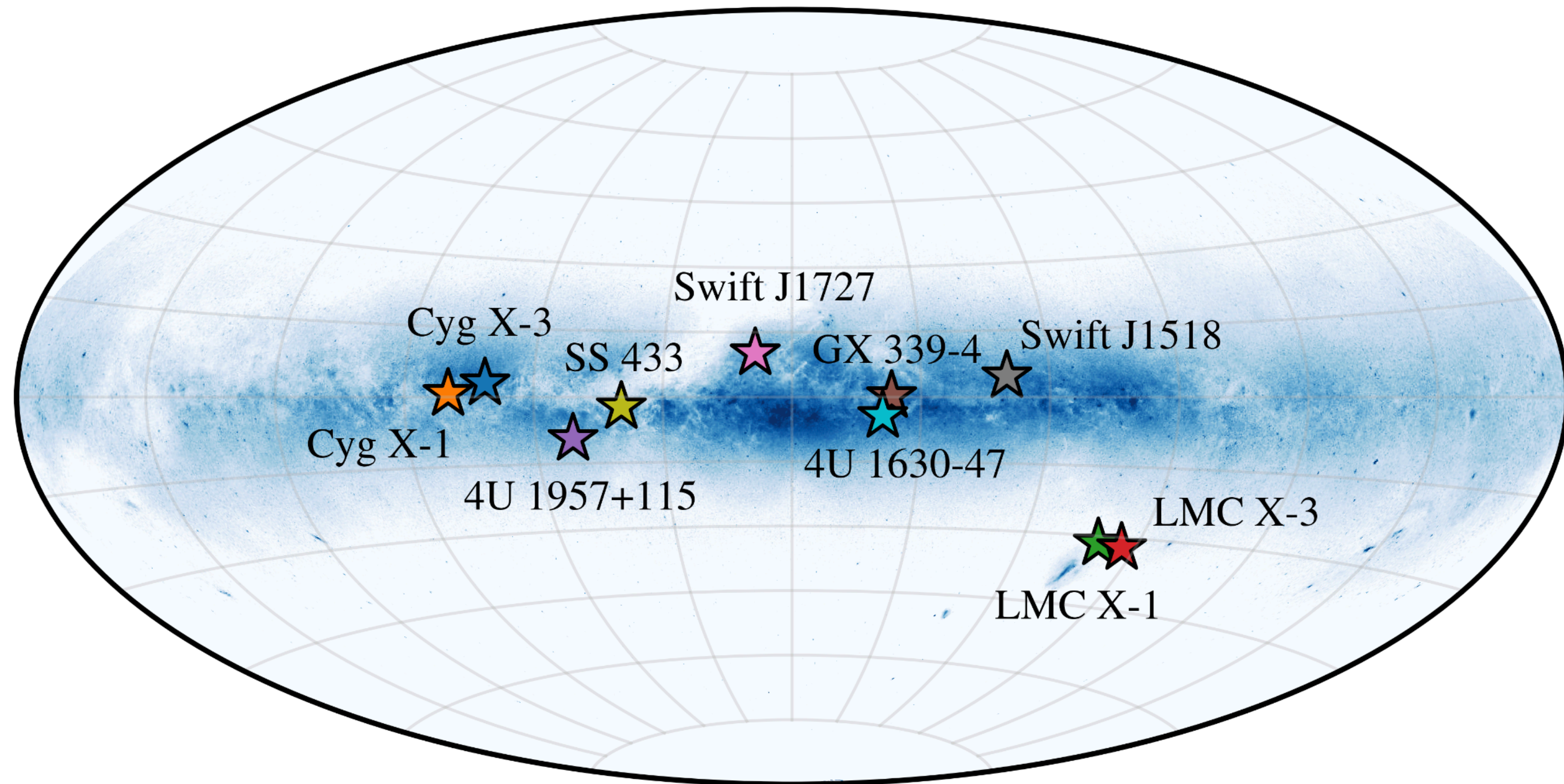


# IXPE observations of BHXRBs

Since launch, **15 black hole X-ray binaries** have been observed.

Non-zero X-ray polarization has been detected in 12 sources!

See talk by **Giorgio Matt** after lunch on more IXPE results (AGNs, Magnetars, Pulsars and more!)



Dovciak ... VK et al. 2024

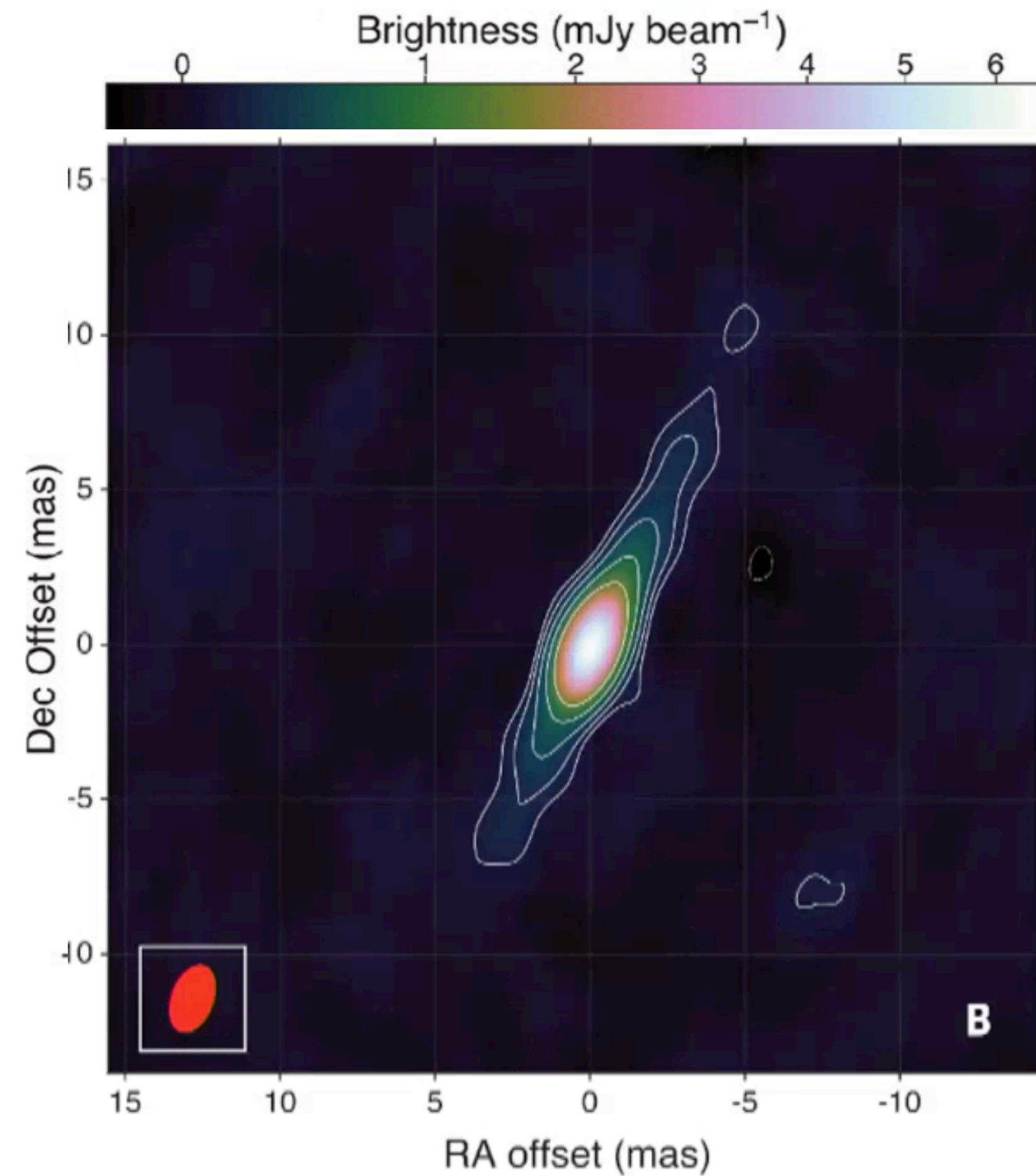
# Cyg X-1

First observed black hole X-ray binary!



# IXPE results: Cyg X-1

First reliable X-ray polarization measurement of BHXR

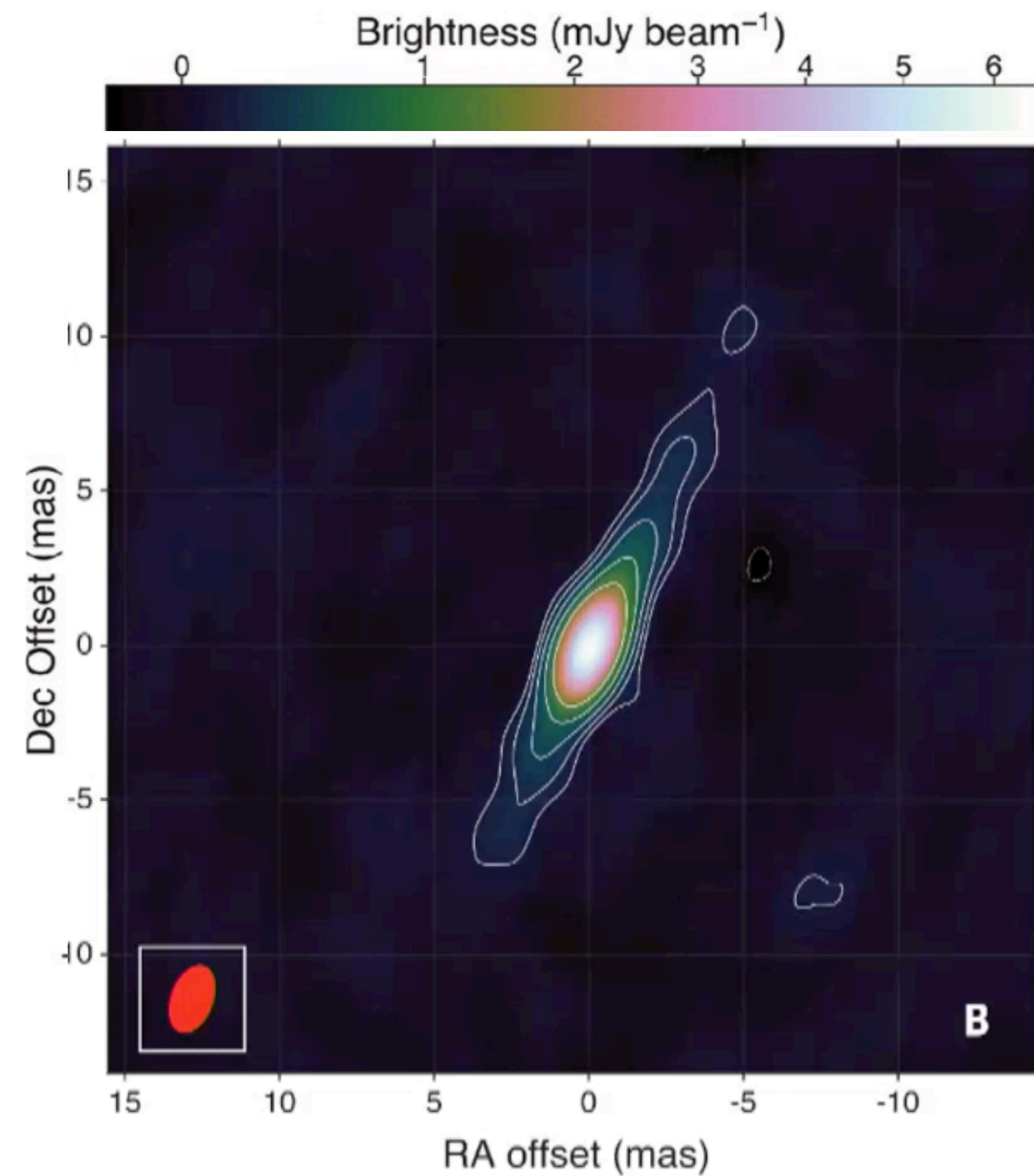


NASA/CXC/SAO/M. Weiss

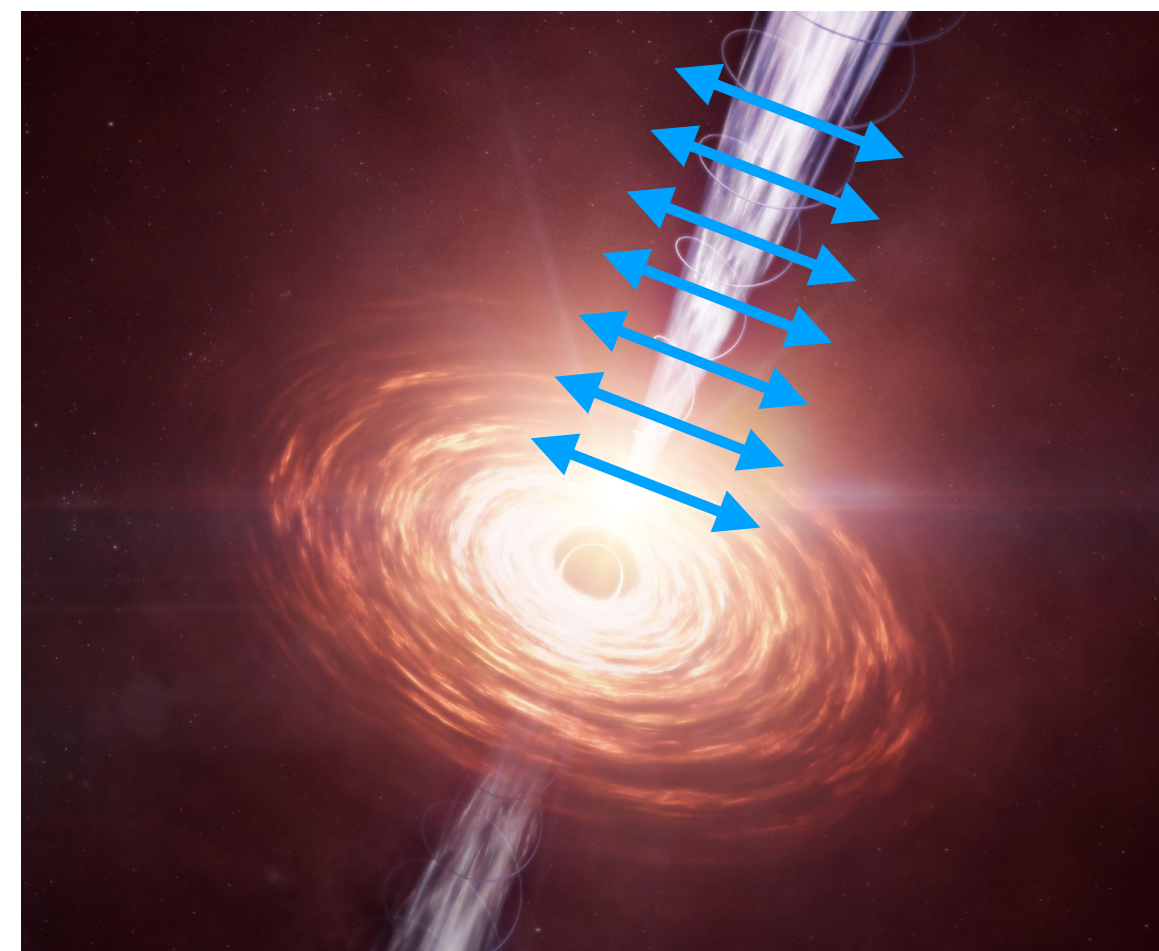


# IXPE results: Cyg X-1

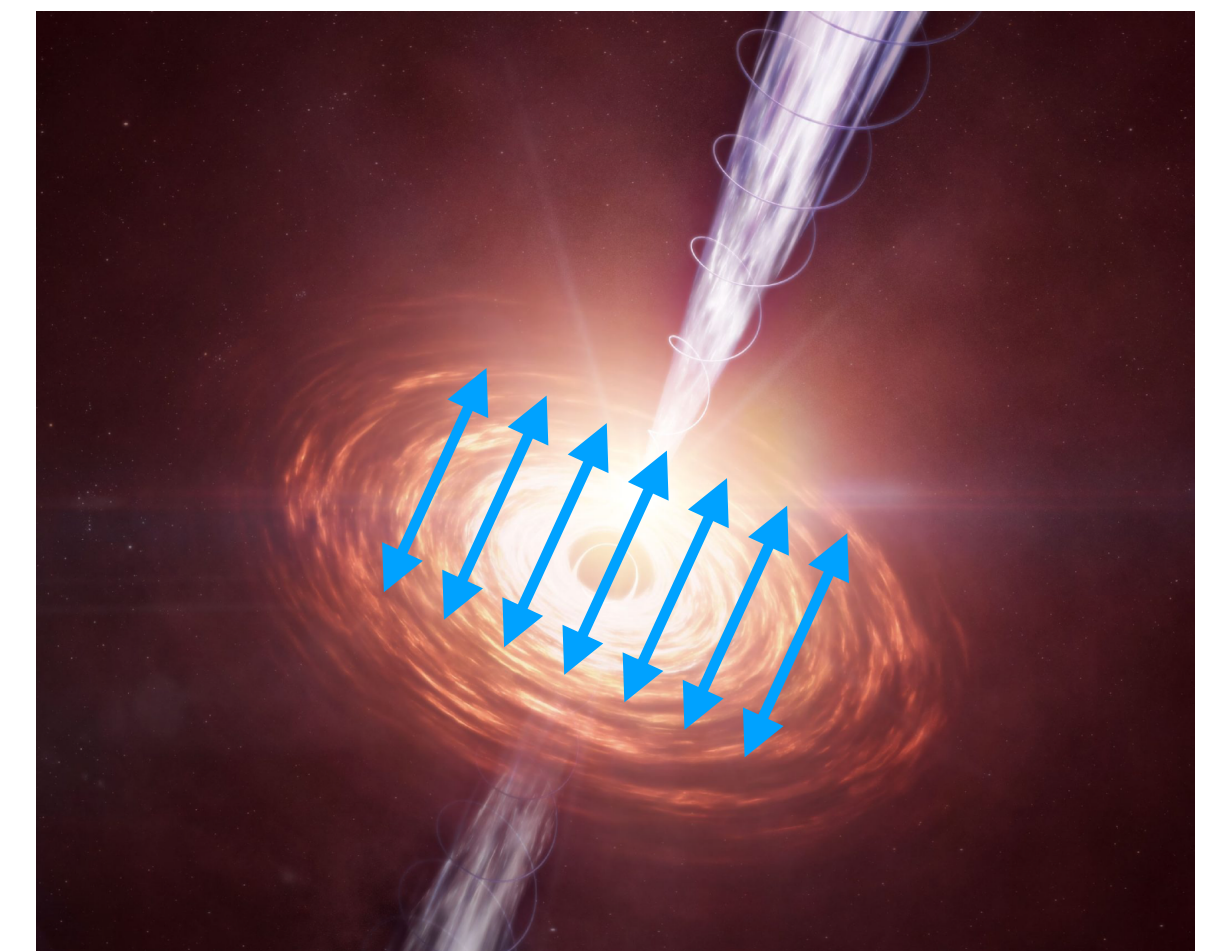
First reliable X-ray polarization measurement of BHXR



X-ray polarization predictions



NASA/CXC/SAO/M. Weiss

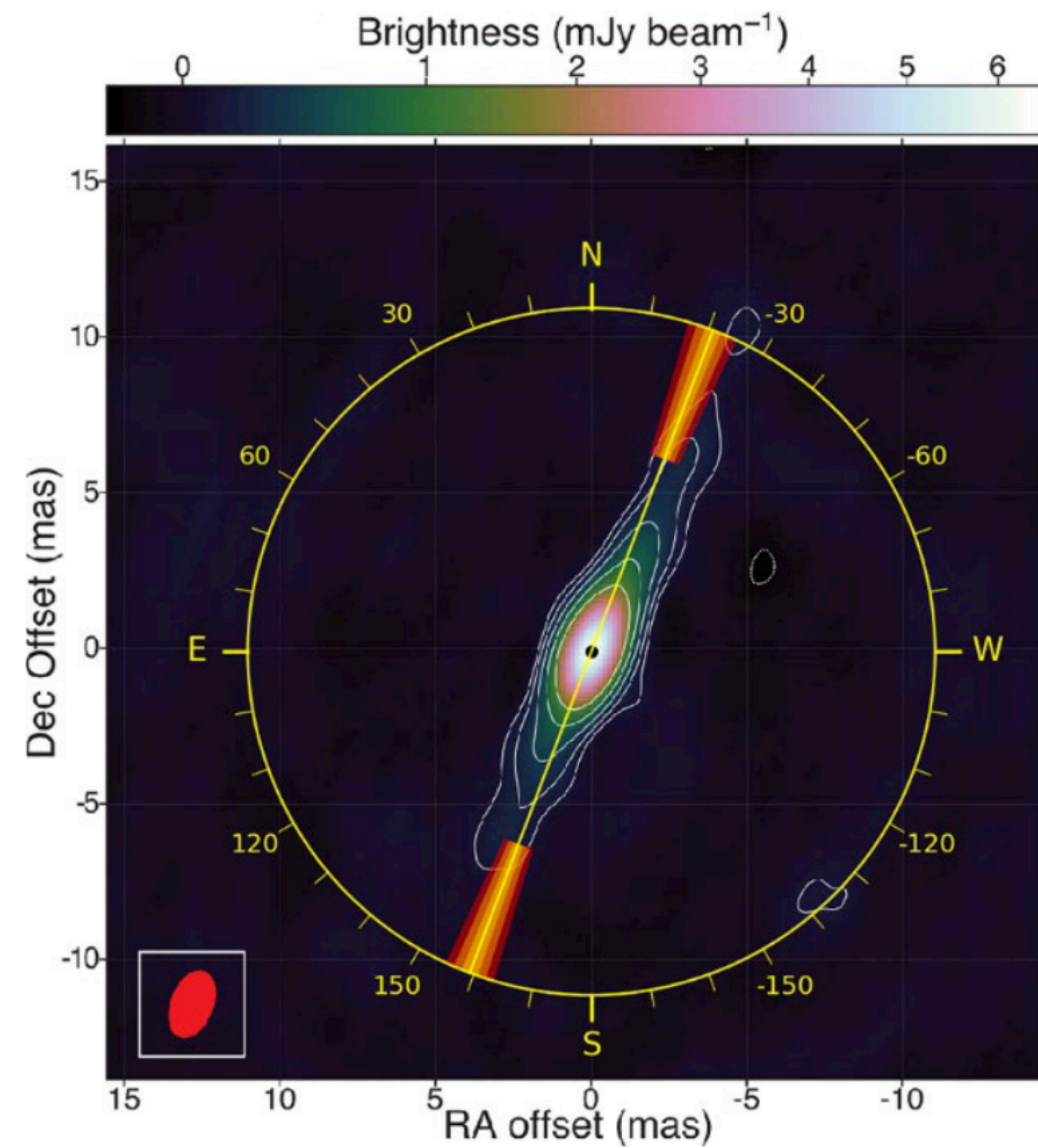


NASA/CXC/SAO/M. Weiss



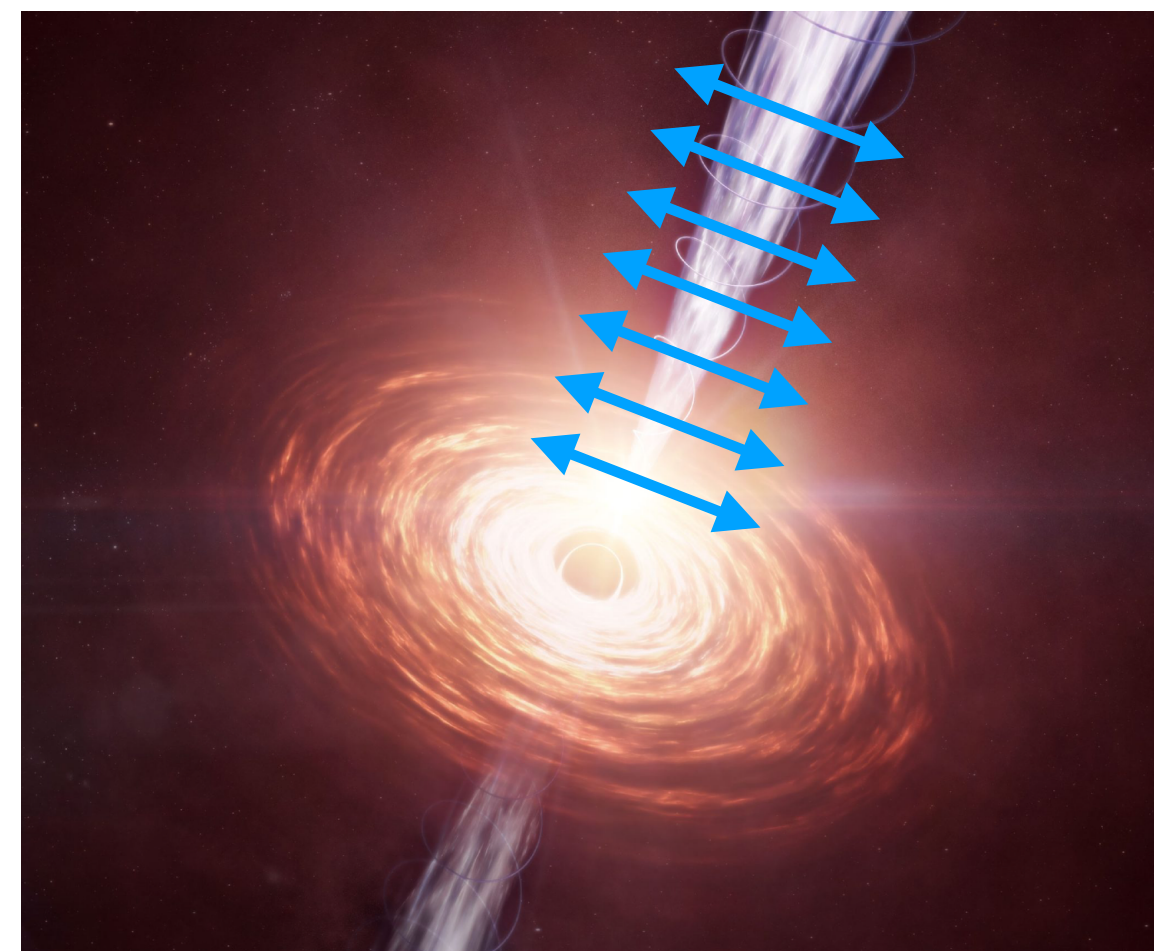
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First reliable X-ray polarization measurement of BHXR

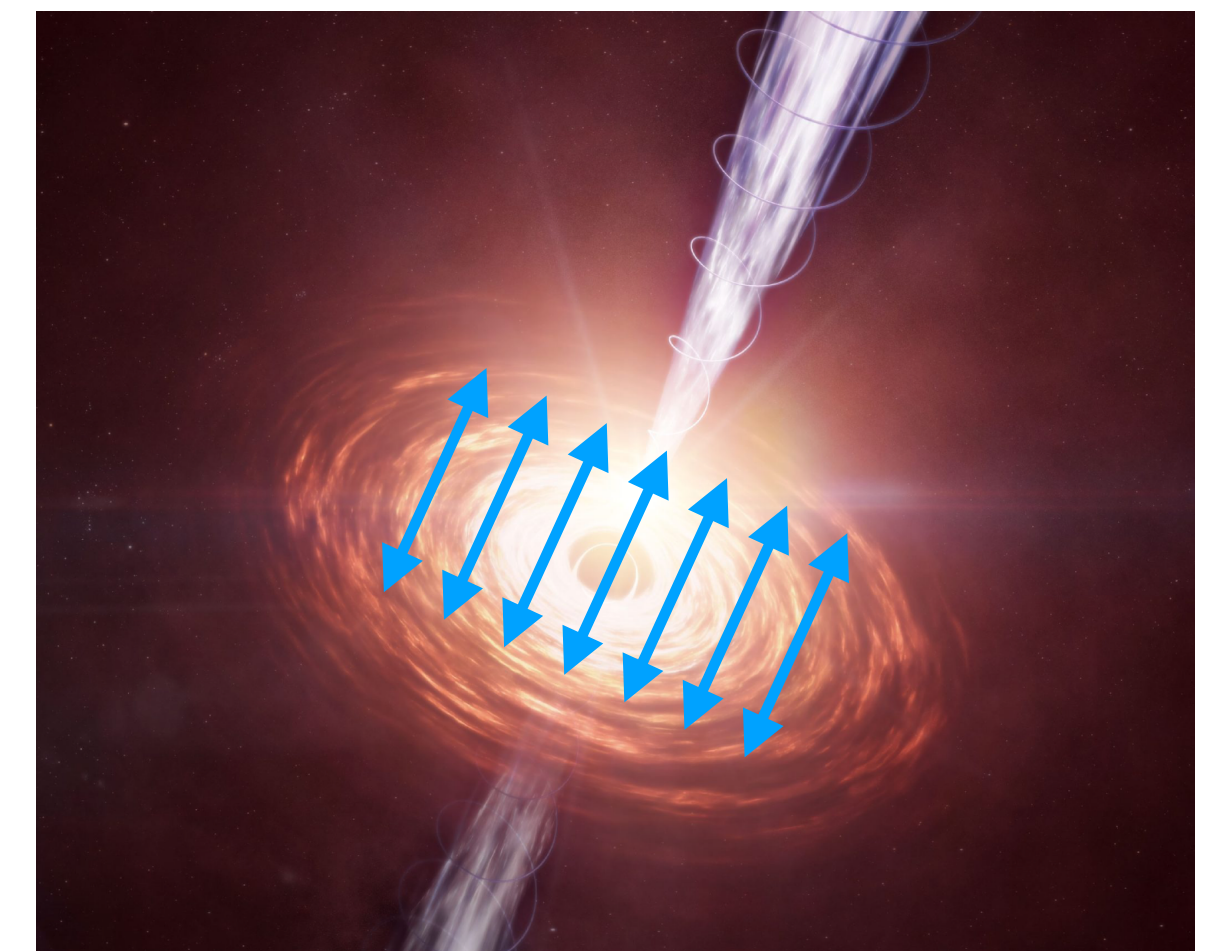


Krawczynski ... VK et al. 2022

X-ray polarization predictions



NASA/CXC/SAO/M. Weiss

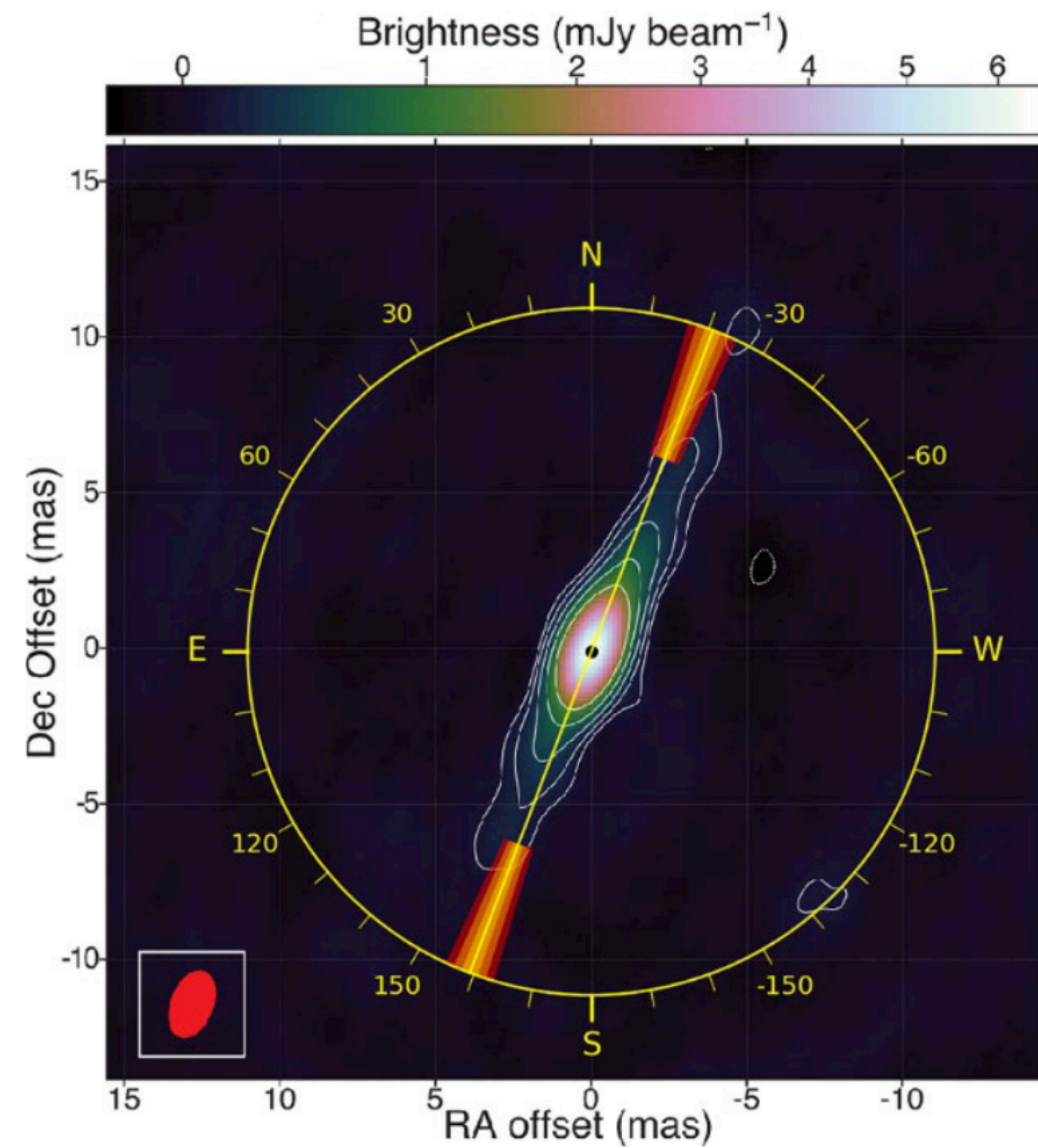


NASA/CXC/SAO/M. Weiss



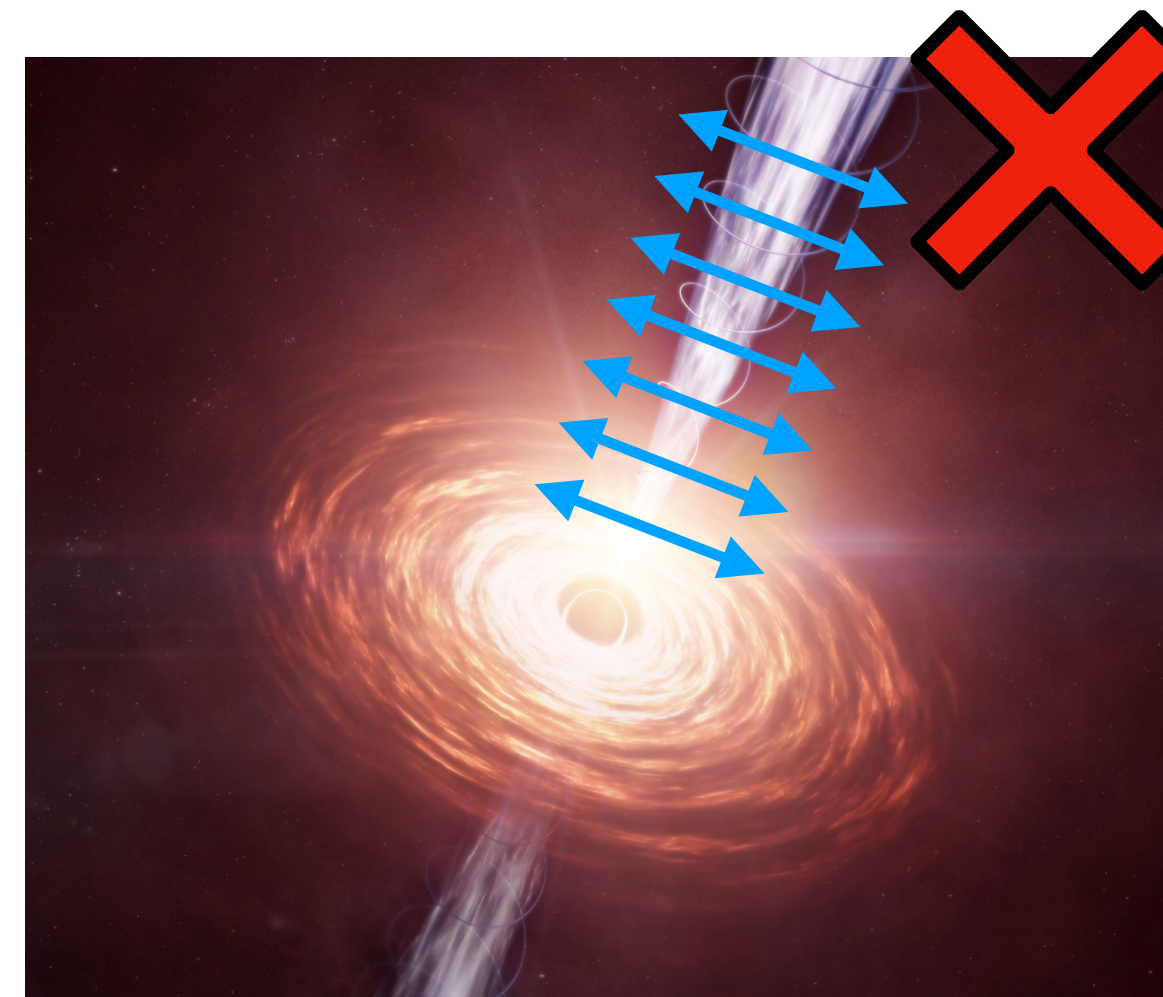
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First reliable X-ray polarization measurement of BHXR

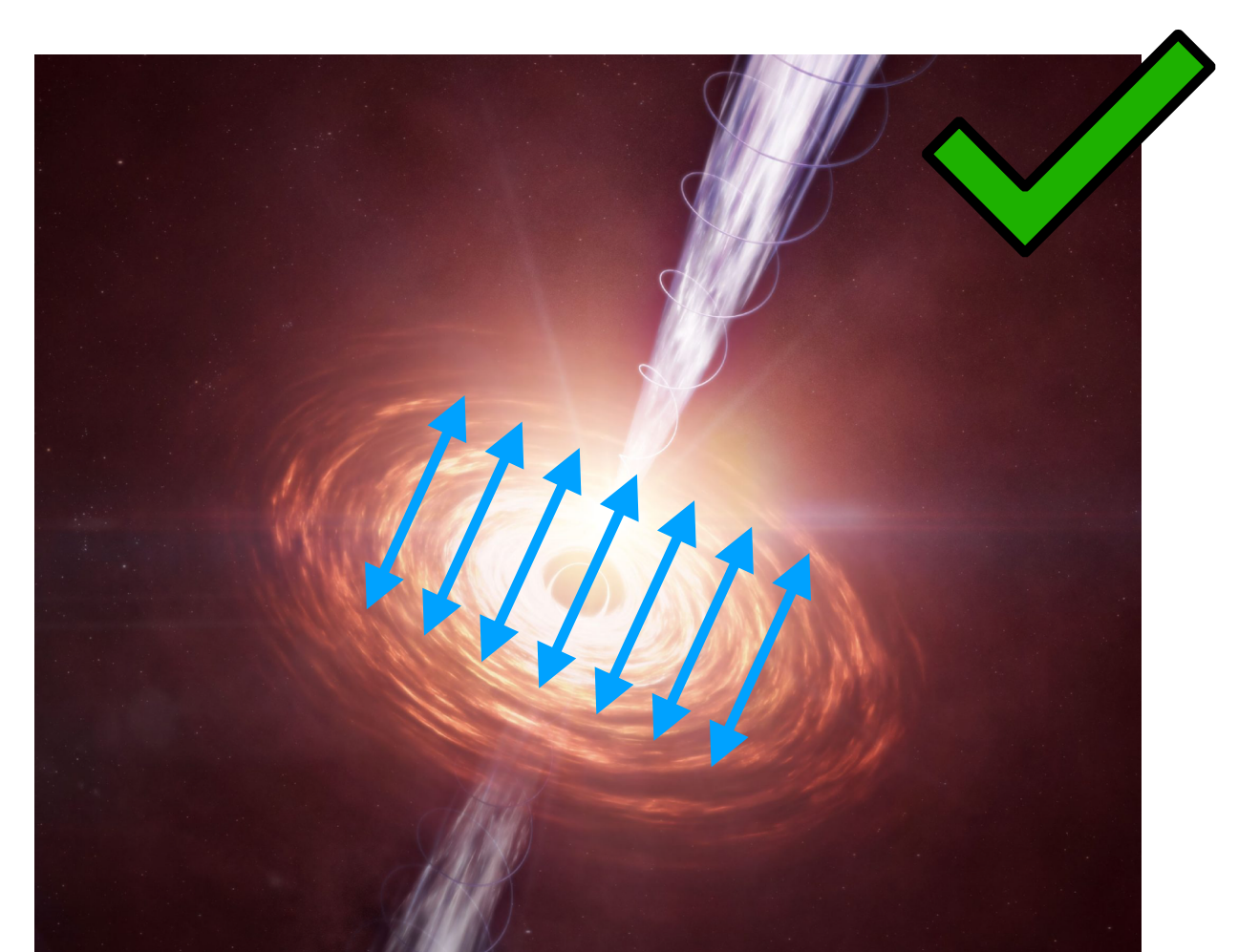


Krawczynski ... VK et al. 2022

X-ray polarization predictions



NASA/CXC/SAO/M. Weiss

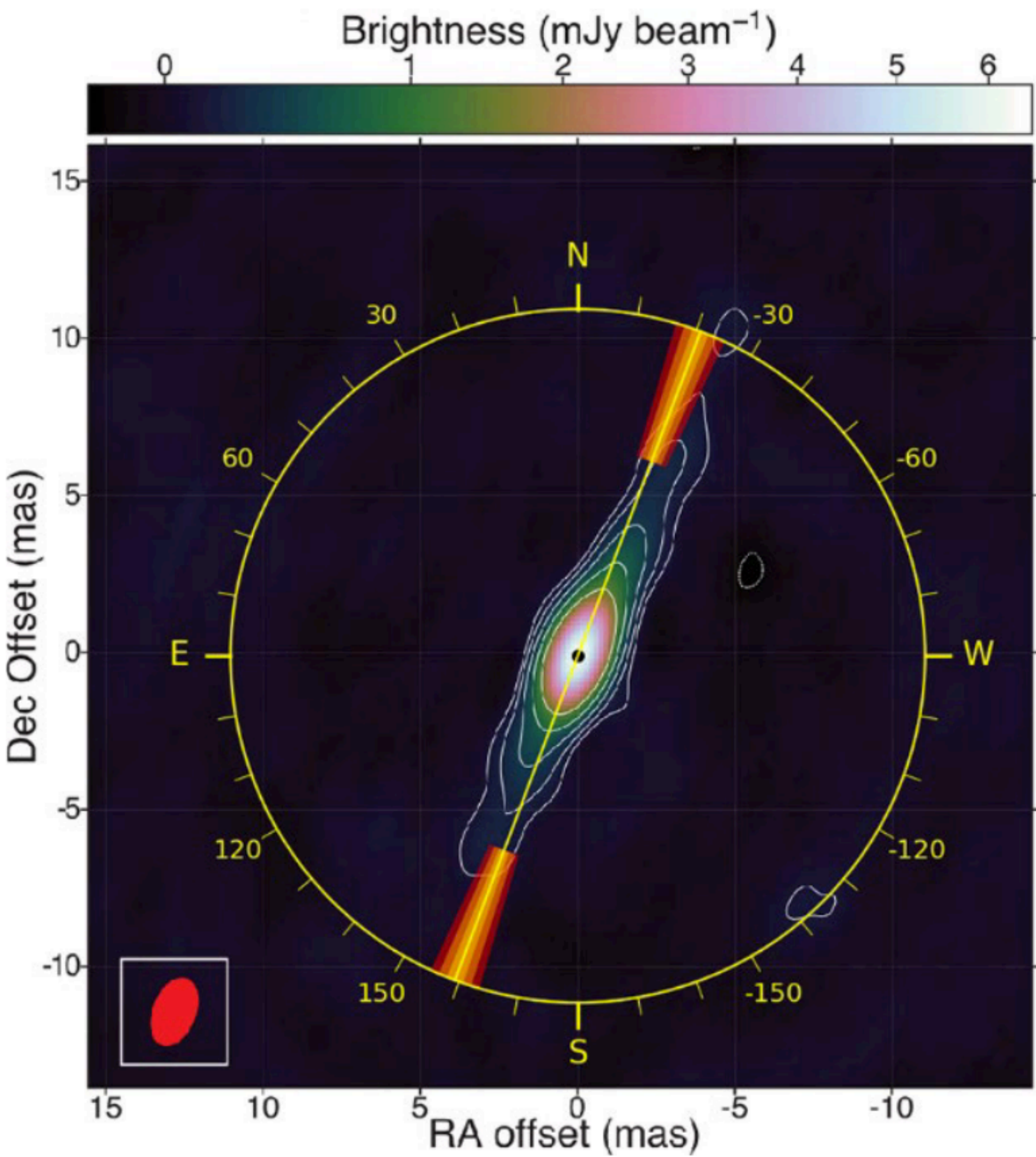


NASA/CXC/SAO/M. Weiss

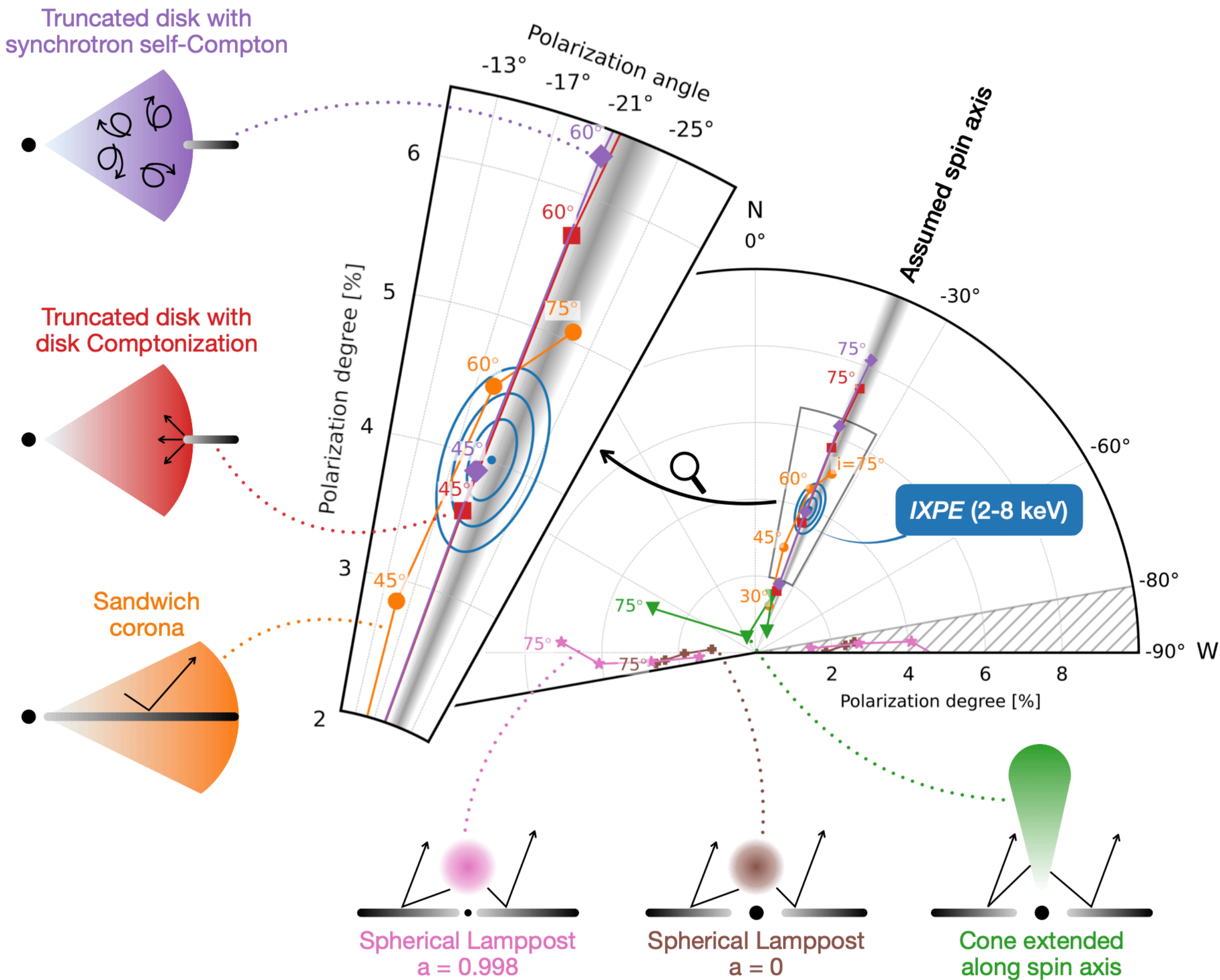


# IXPE results: Cyg X-1

First reliable X-ray polarization measurement of BHXR



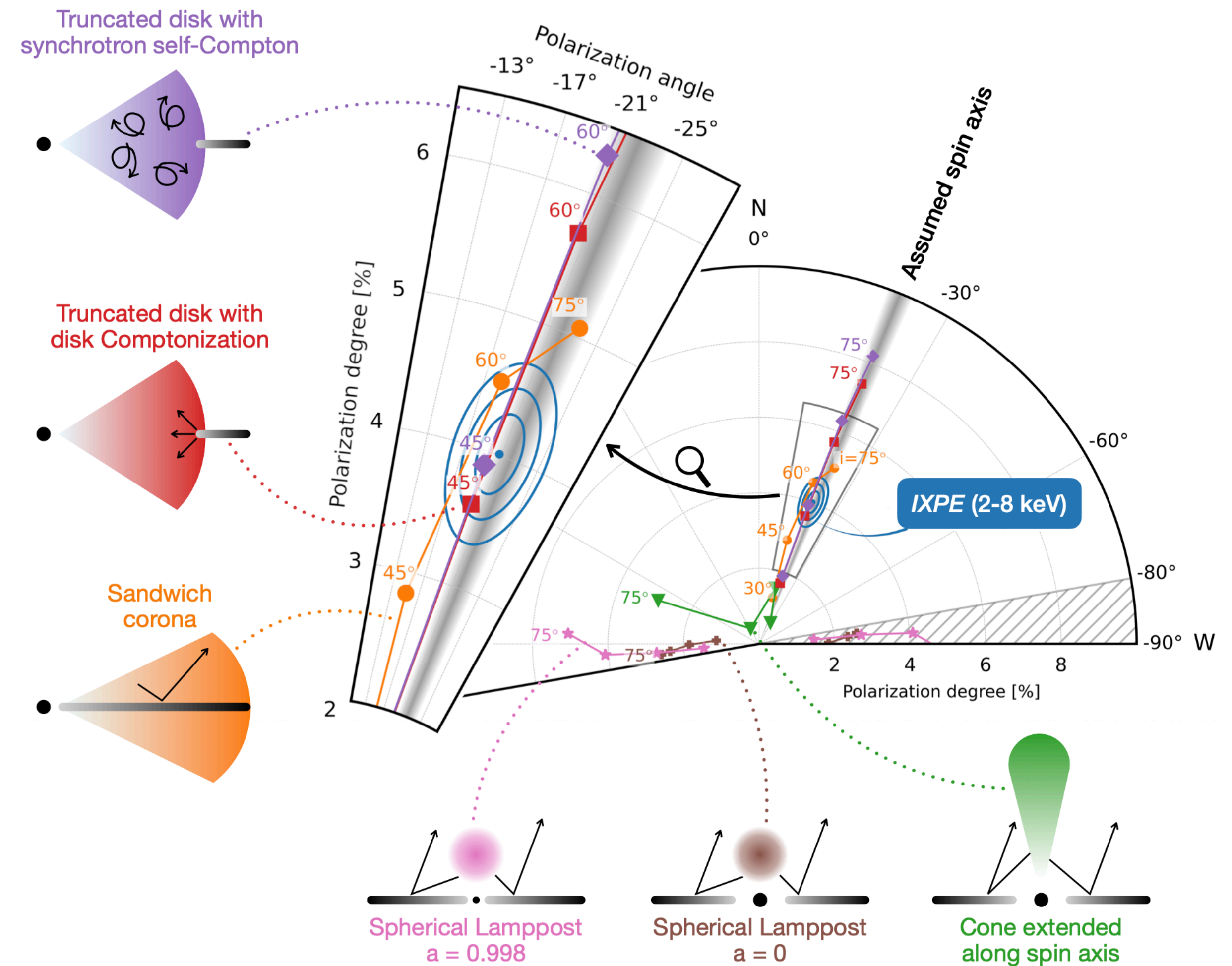
Krawczynski ... VK et al. 2022



# IXPE results: Cyg X-1

First reliable X-ray polarization measurement of BHXRB

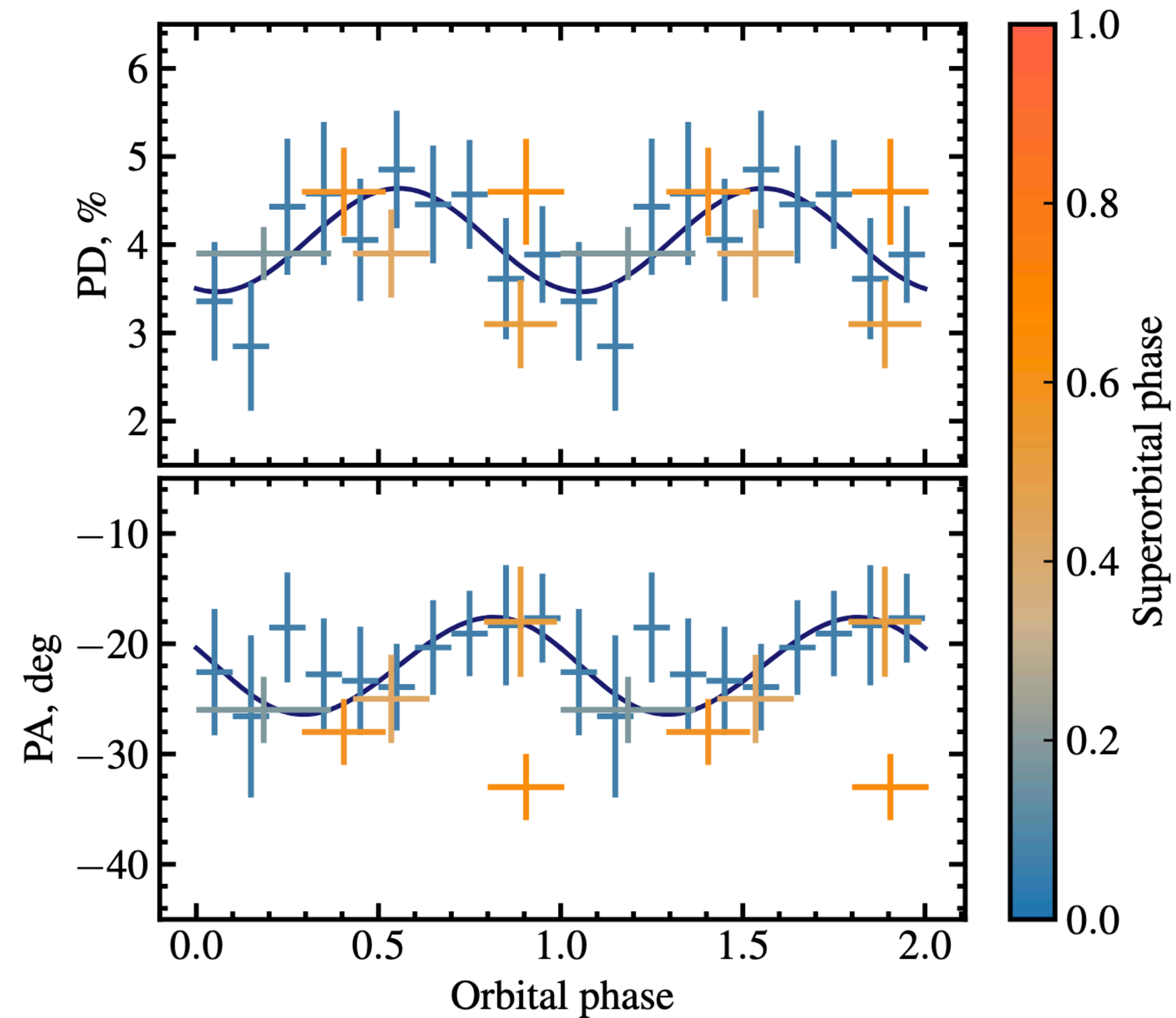
High PD requires higher inclination => **jet-disk misalignment?**



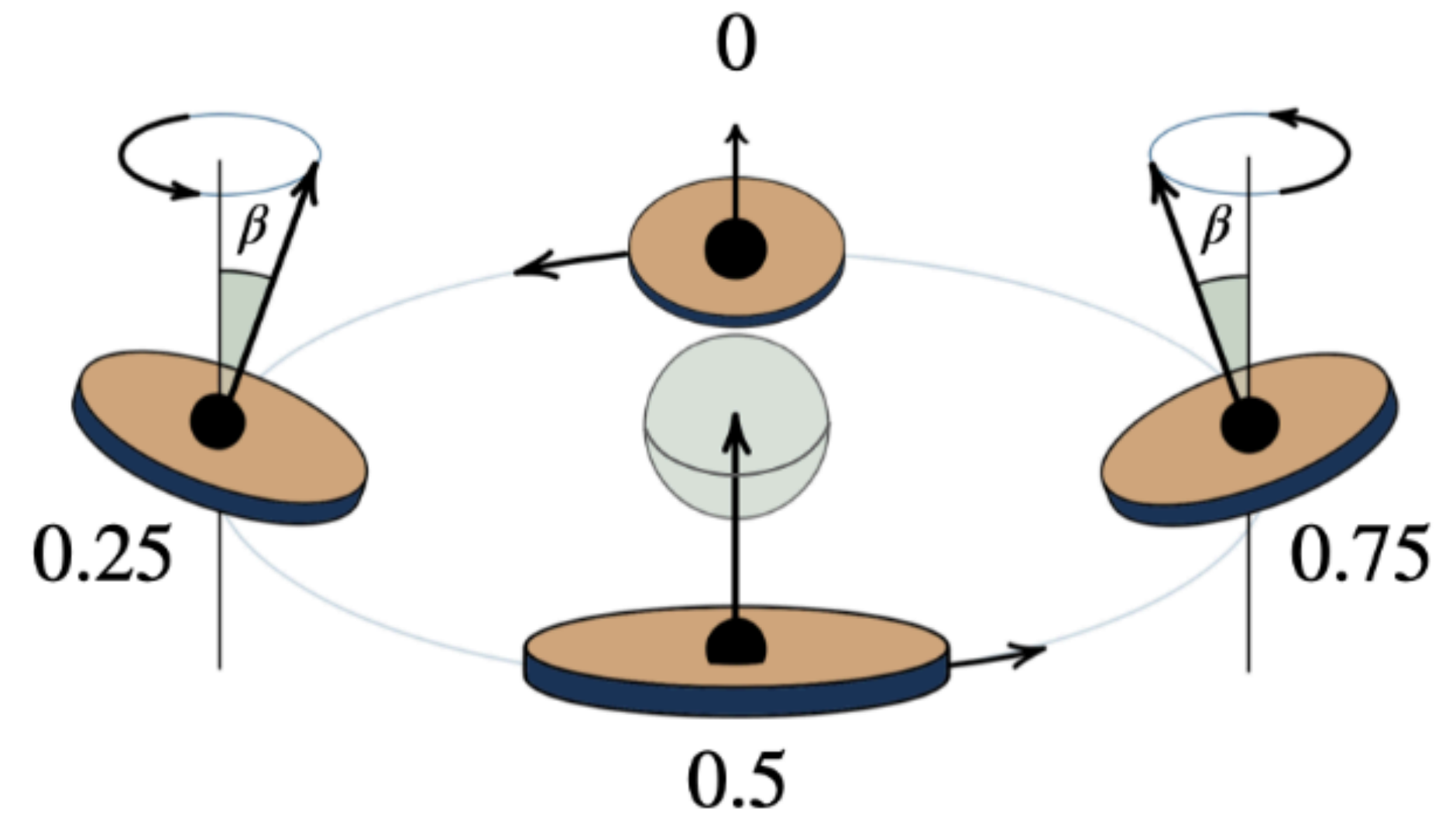


# IXPE results: Cyg X-1

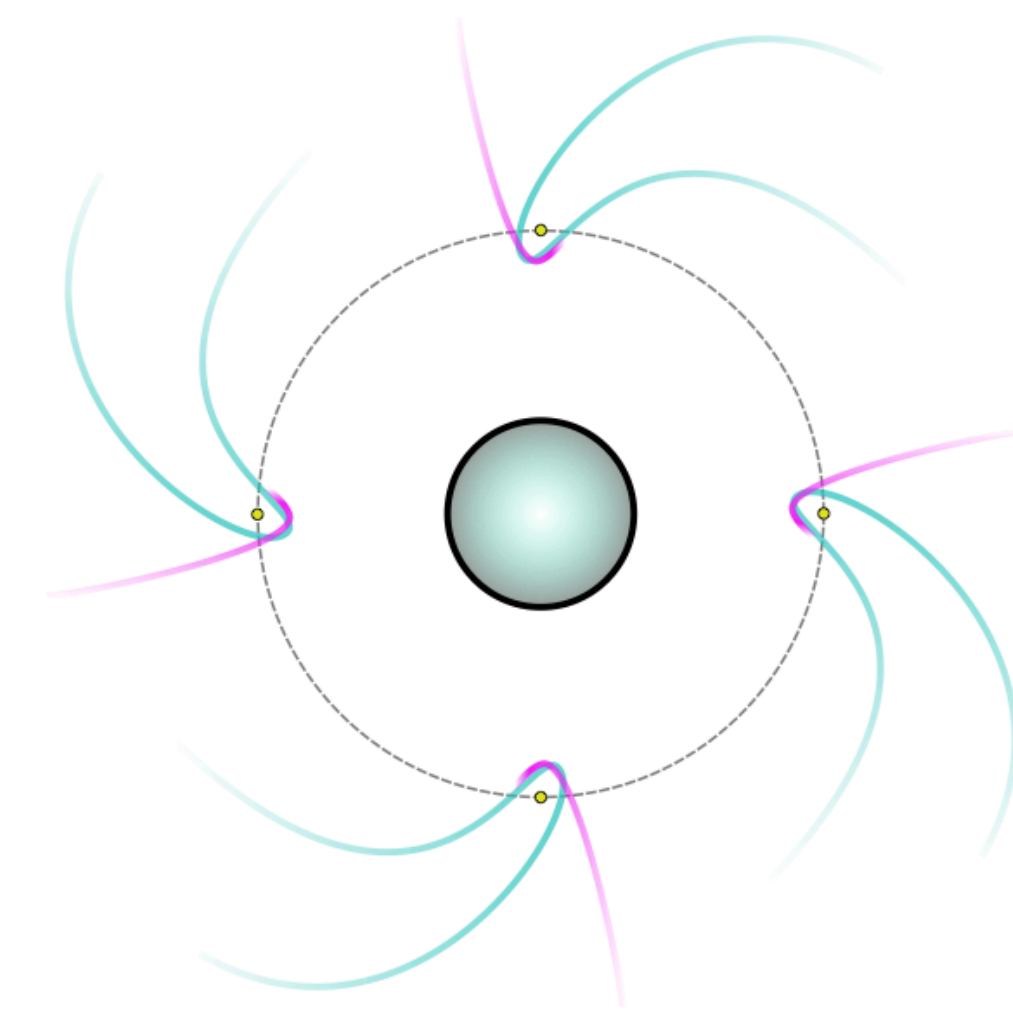
Attempts to explain Cyg X-1 observations



Kravtsov et al. 2025



Kravtsov et al. 2025

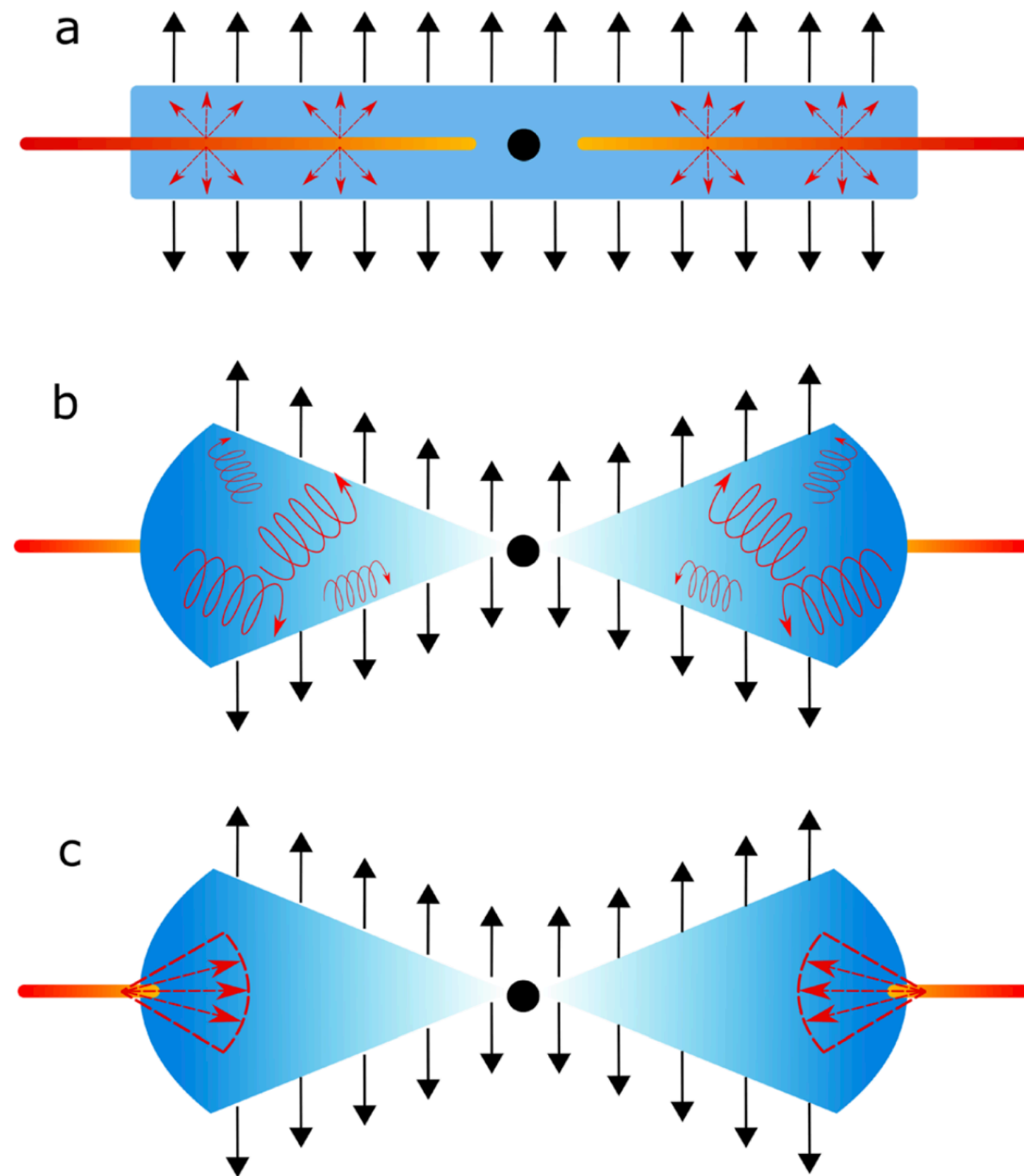


Ahlberg et al. 2025

# IXPE results: Cyg X-1

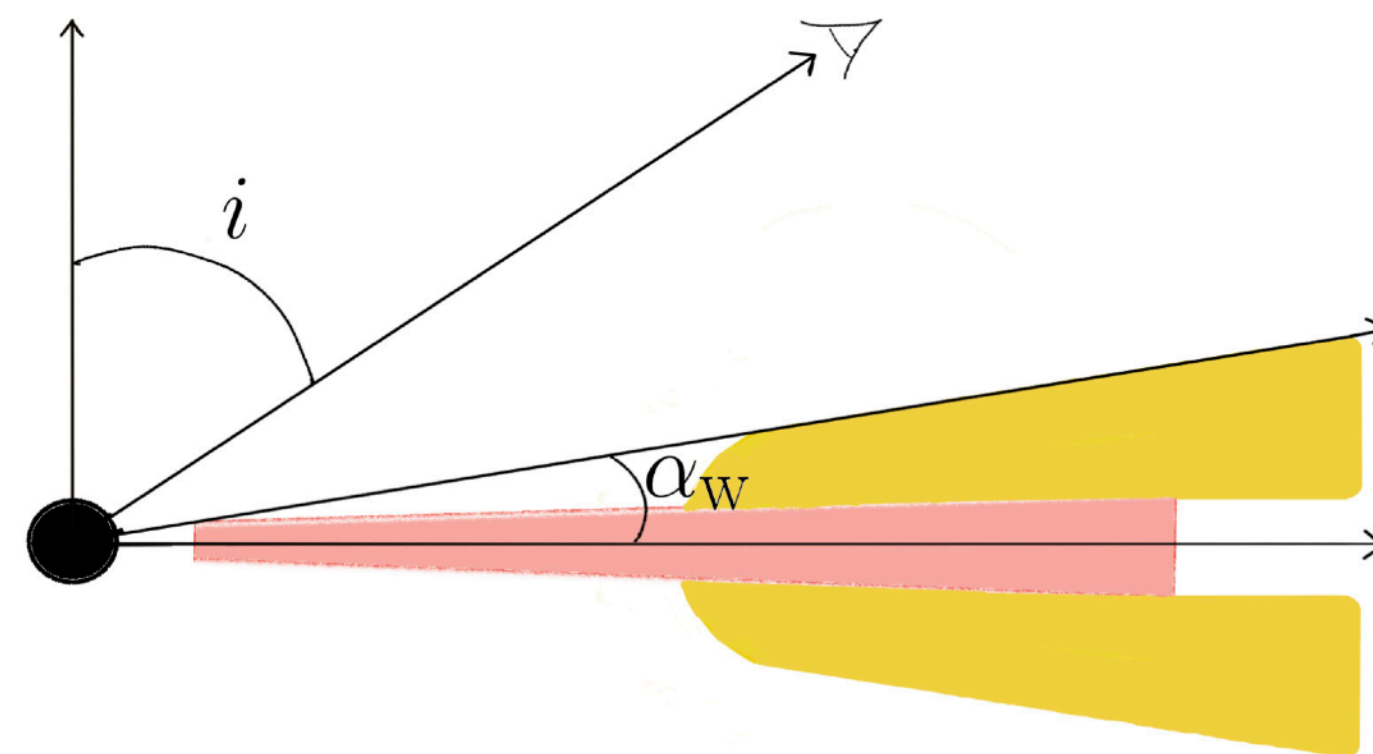
Attempts to explain Cyg X-1 observations

Outflowing corona,  $v \sim 0.4c$



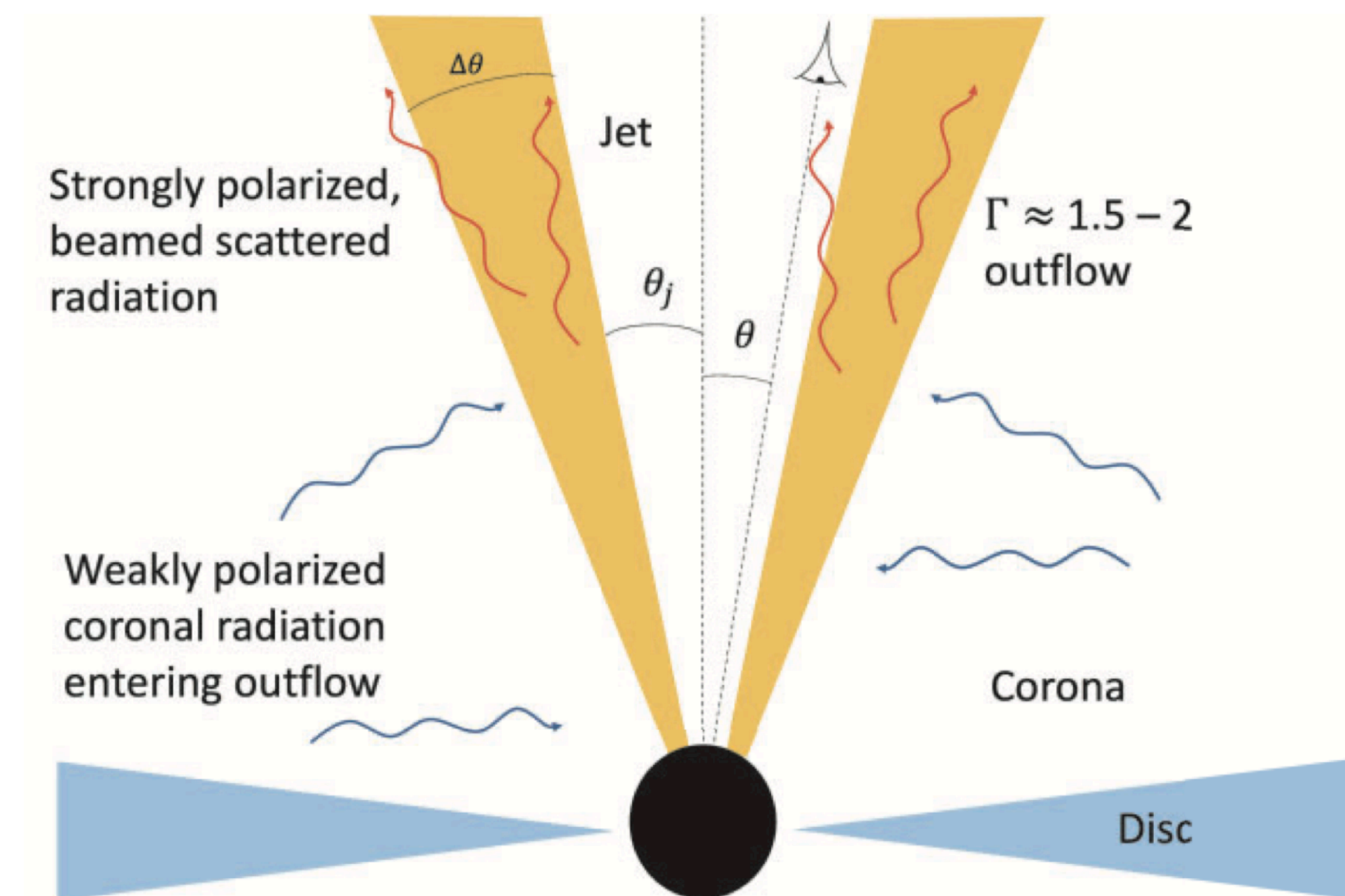
Poutanen, Veledina, Beloborodov 2023

Scattering in the wind



Nitindala et al., 2025

Scattering at jet-outflow interface



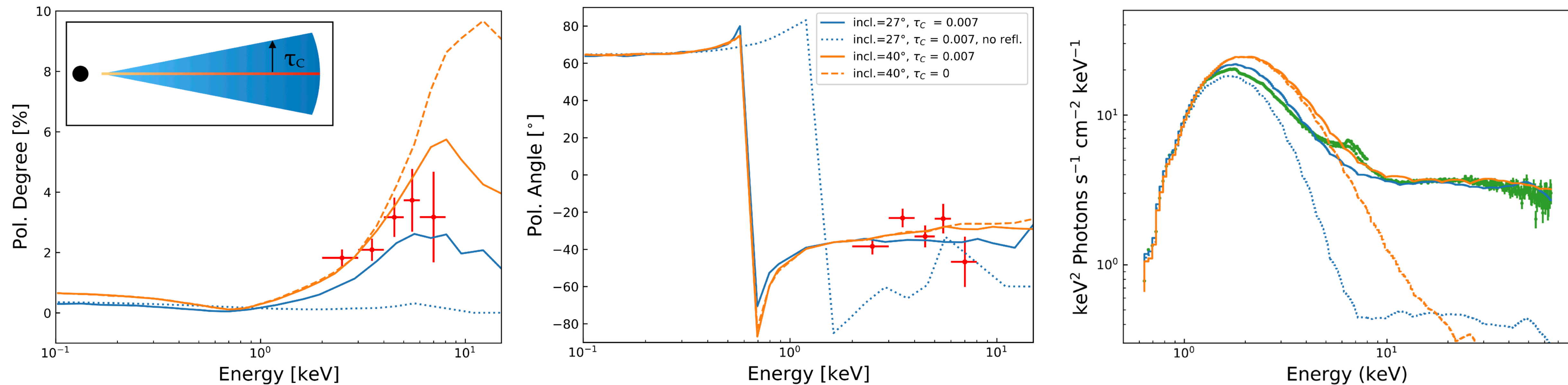
Dexter & Begelman 2024



# IXPE results: Cyg X-1

Spectrapolarimetric modeling is a must

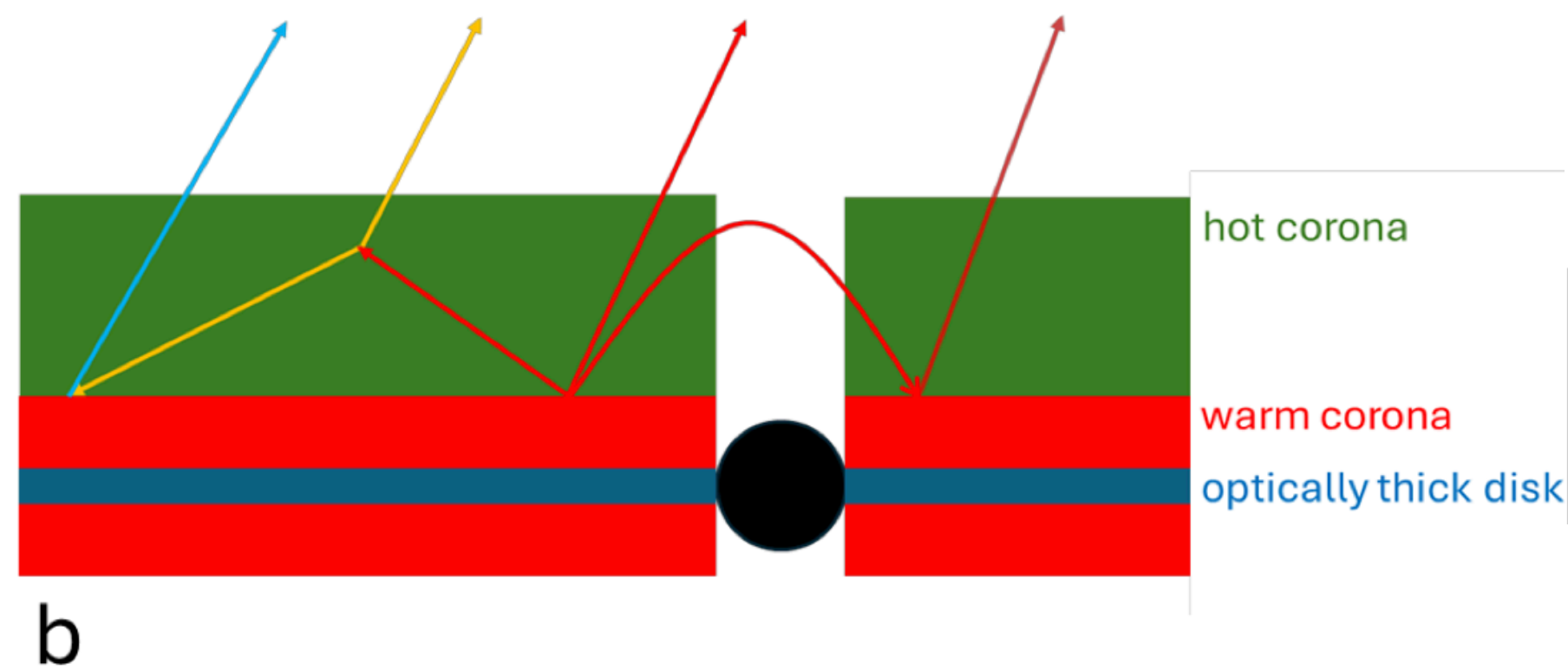
Spin  $a > 0.96$ , dominant role of returning radiation and GR effects



Steiner ... VK et al., 2024

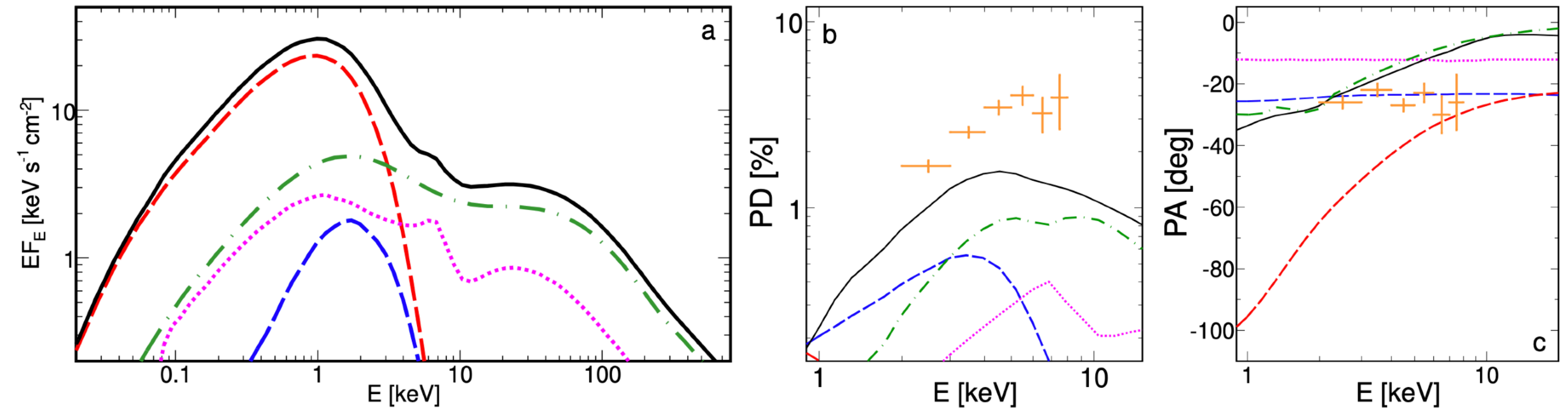
# IXPE results: Cyg X-1

Spectrapolarimetric modeling is a must

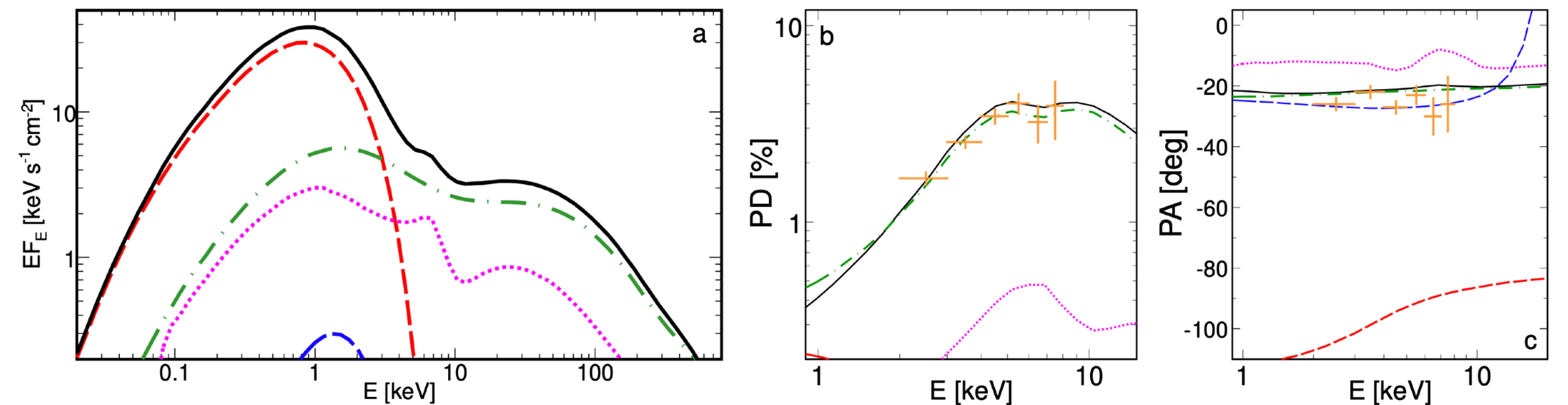


Comptonization and reflection

Spin  $a > 0.998$



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

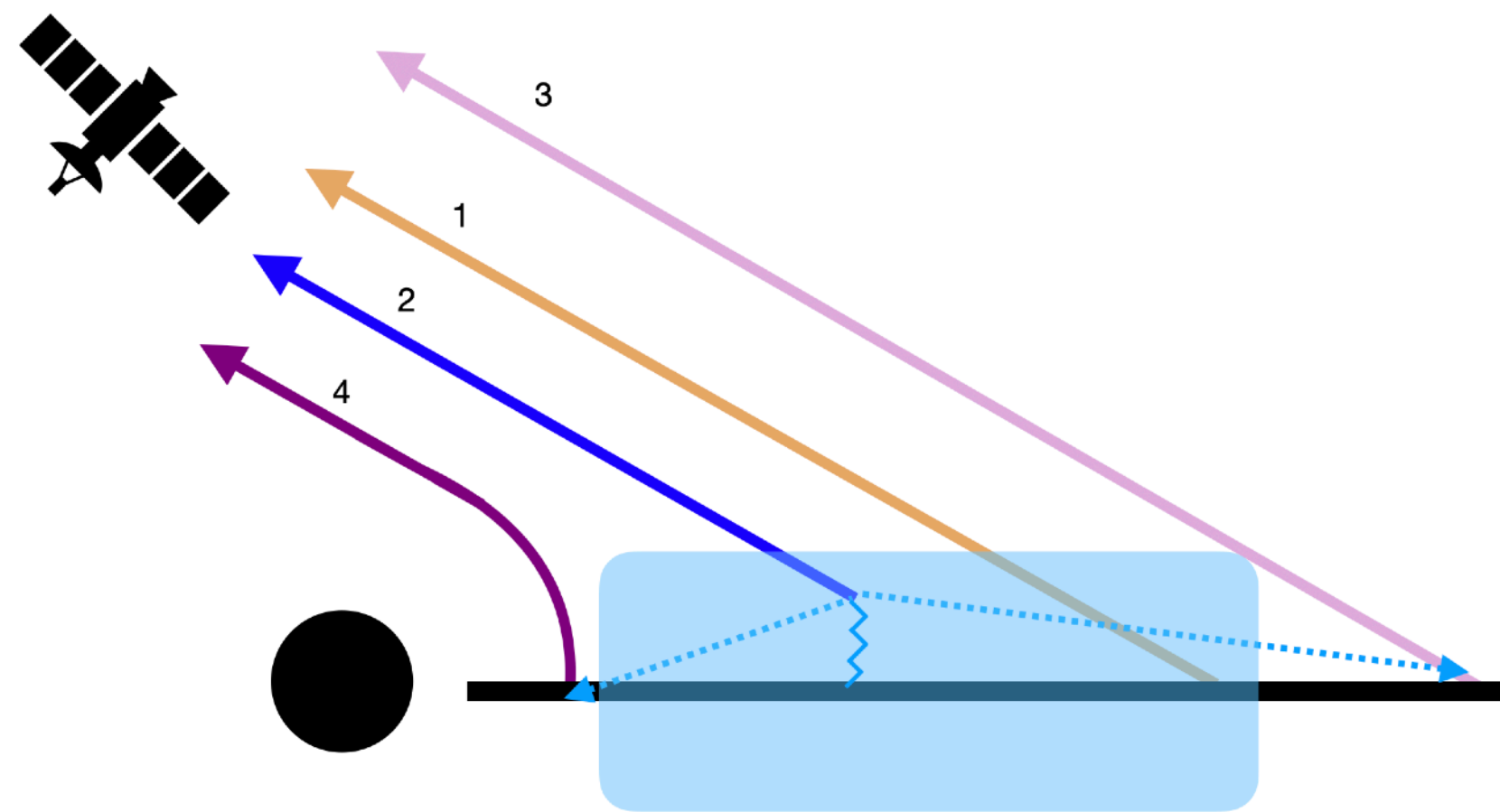


Niedźwiecki et al. 2026

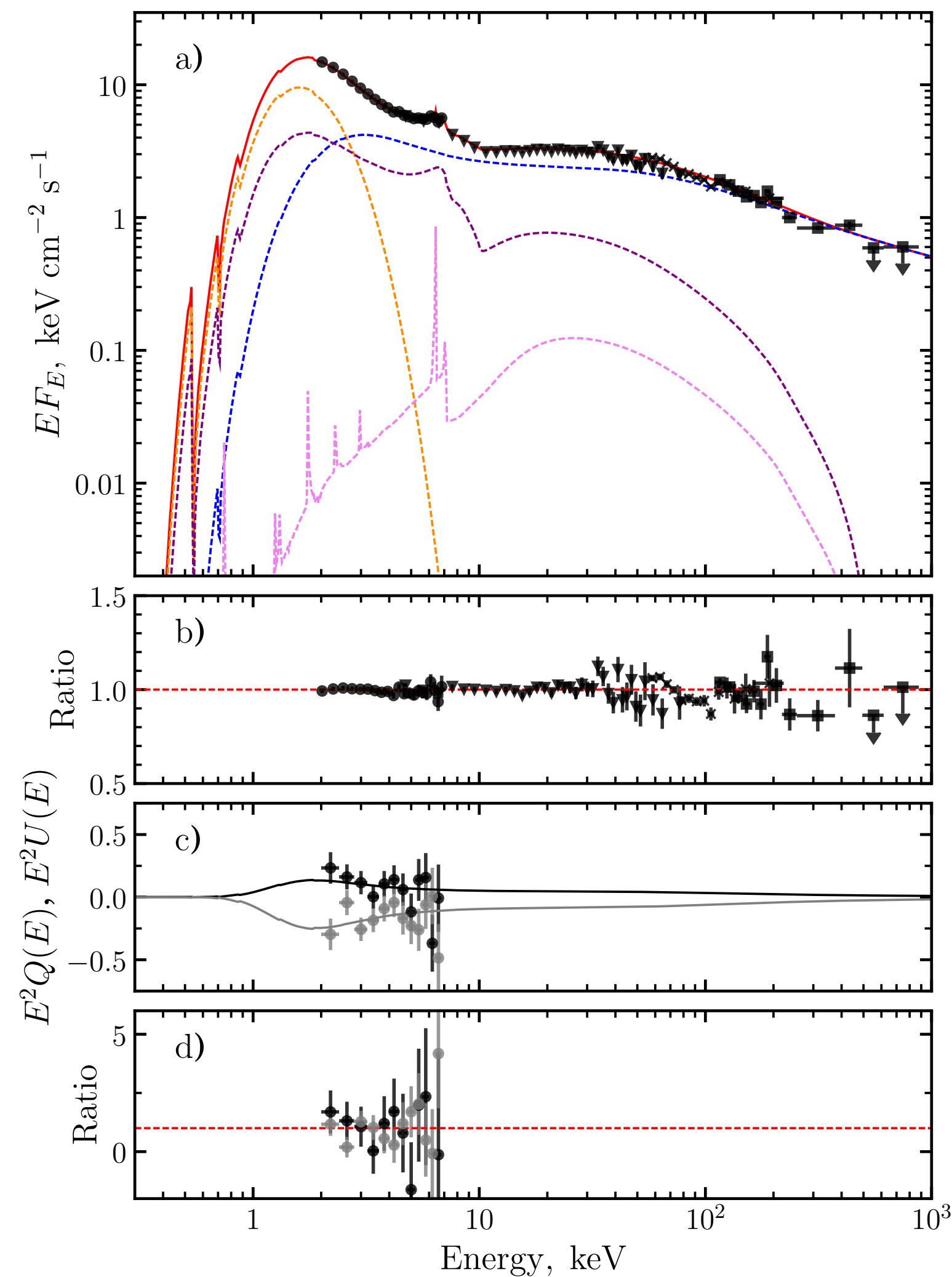


# IXPE results: Cyg X-1

Spectrapolarimetric modeling is a must

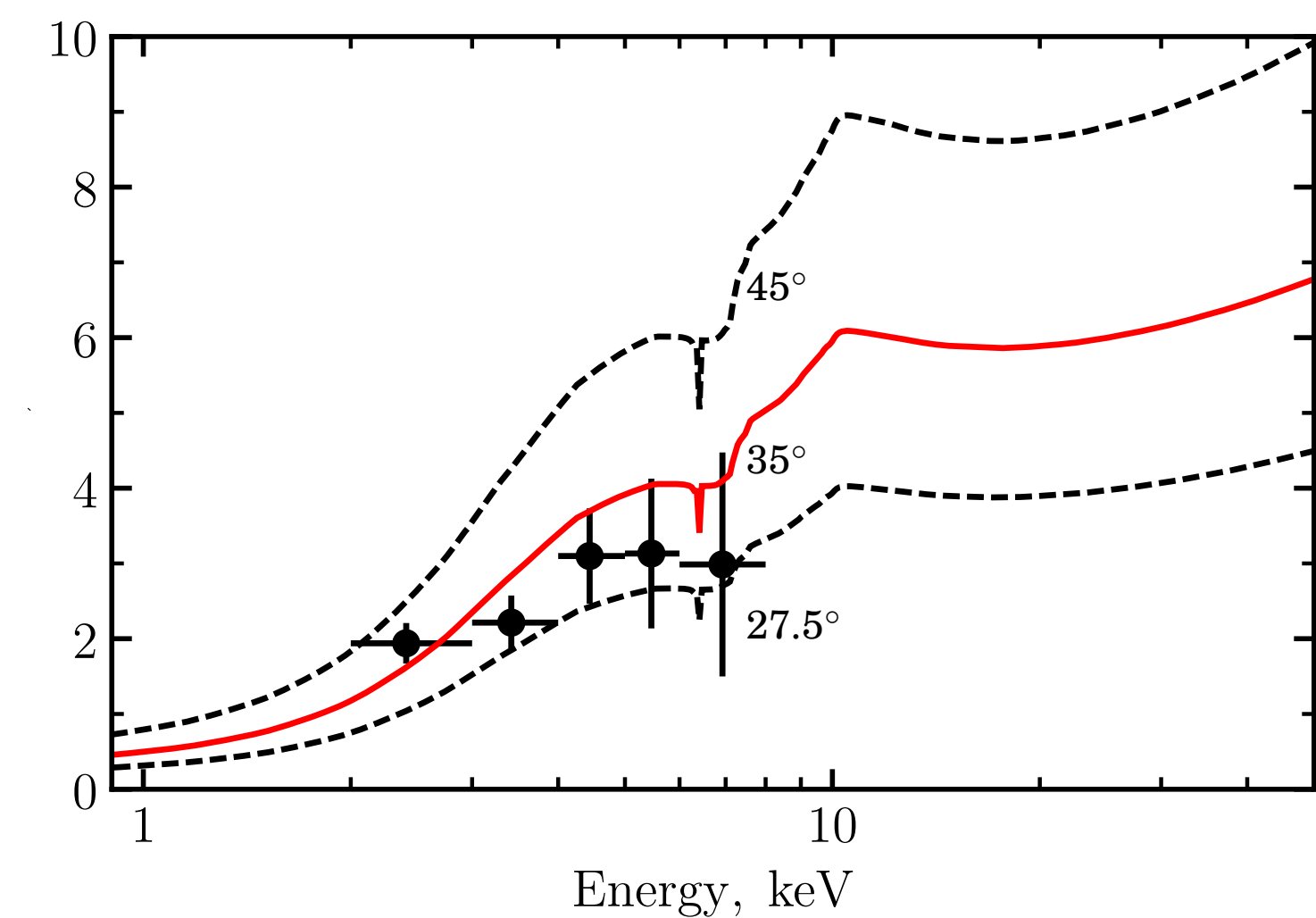


Comptonization and reflection



Bocharova et al., in prep

Spin  $a = 0$



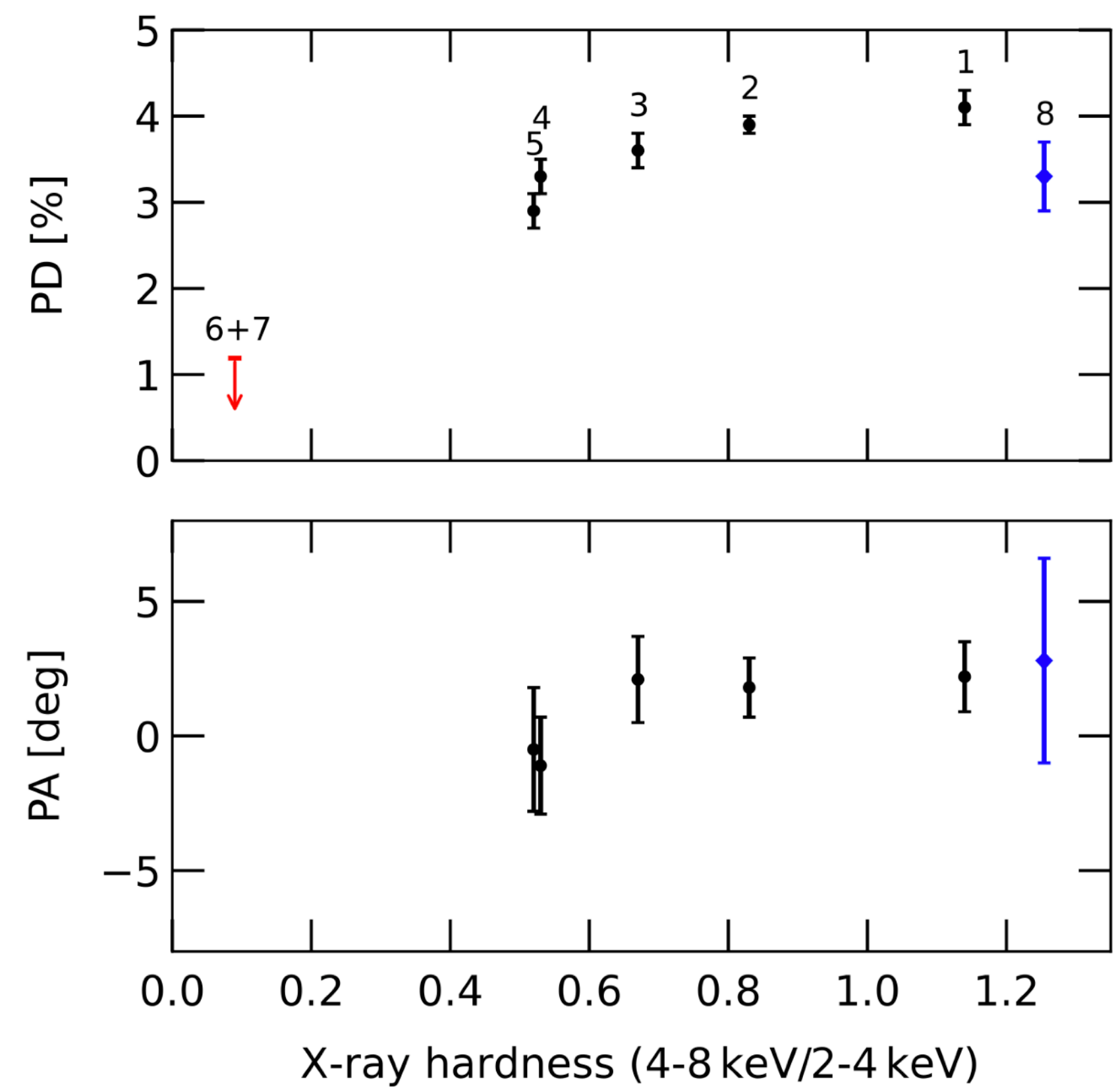
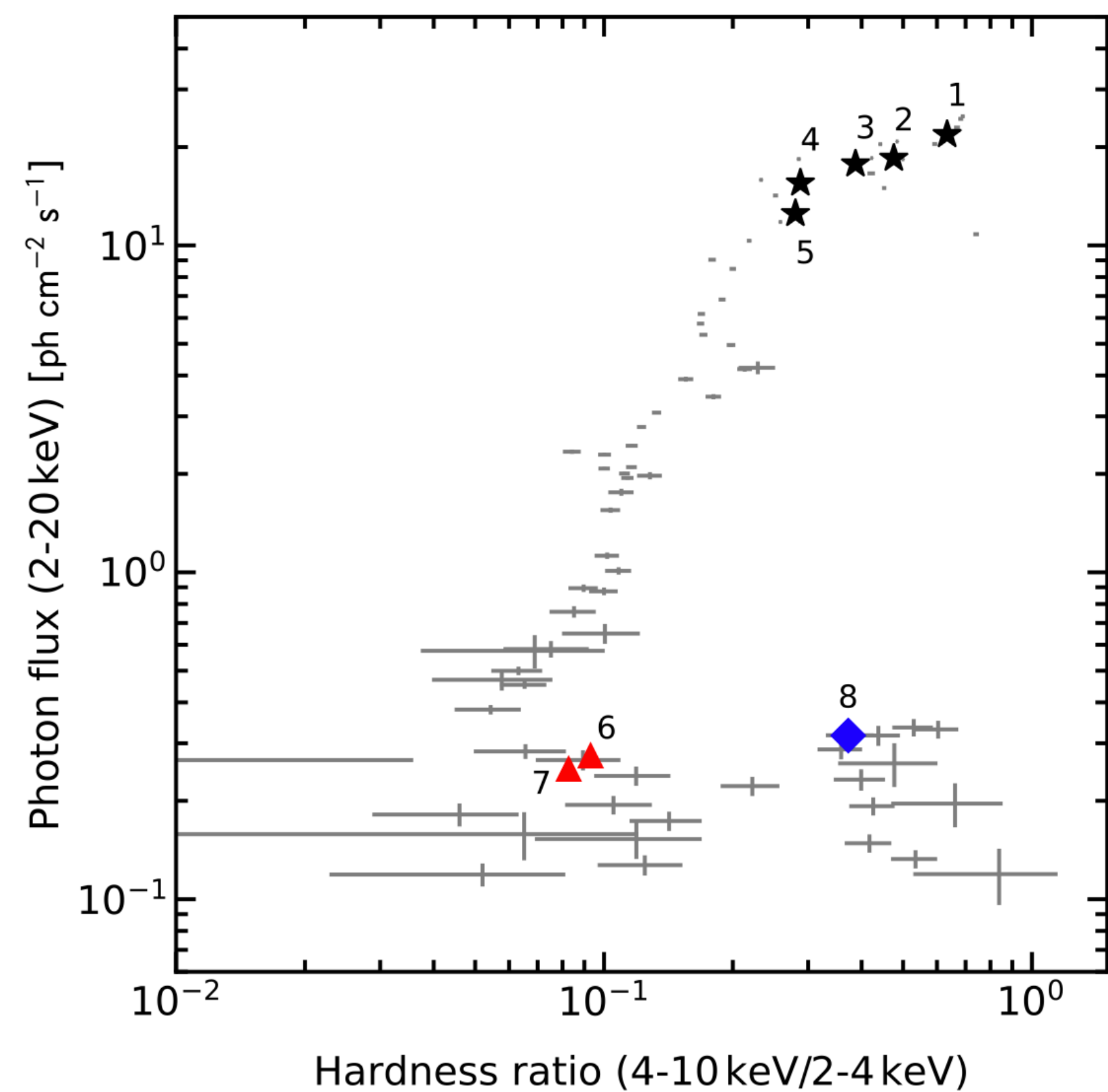
**Swift J1727.8–1613**

Captured in all states



# IXPE results: Swift J1727.8-1613

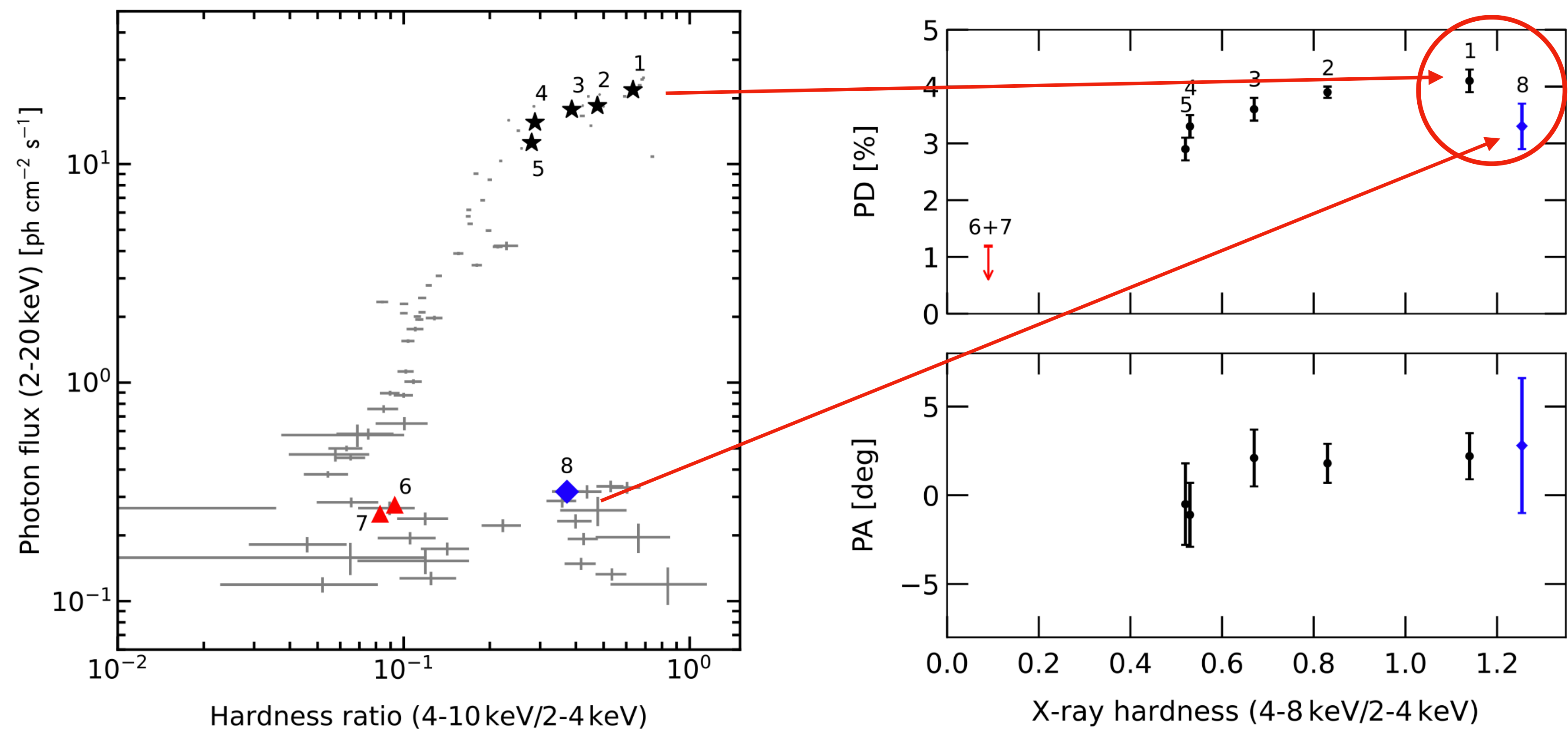
Exceptionally bright LMXB



# 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



**Cyg X-3: Obscured source**

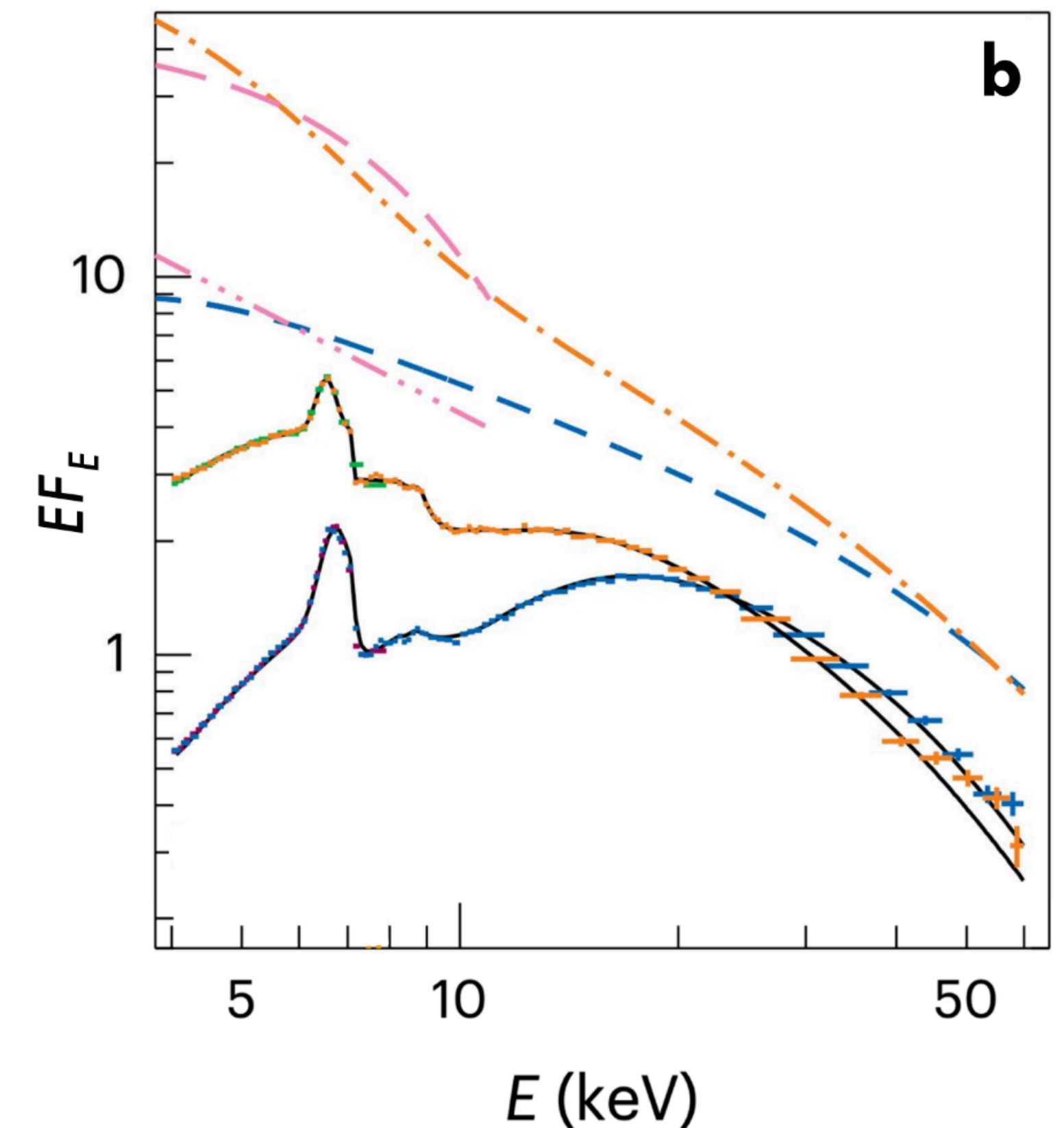
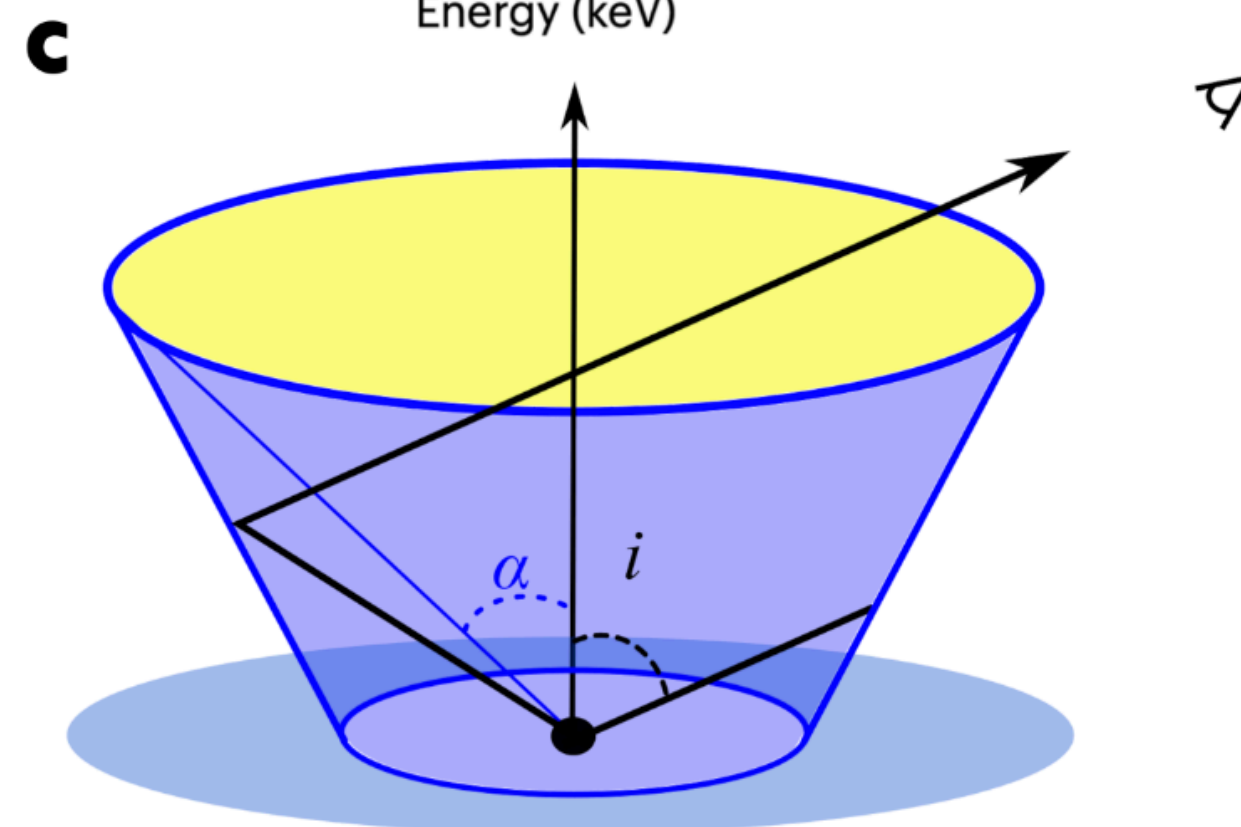
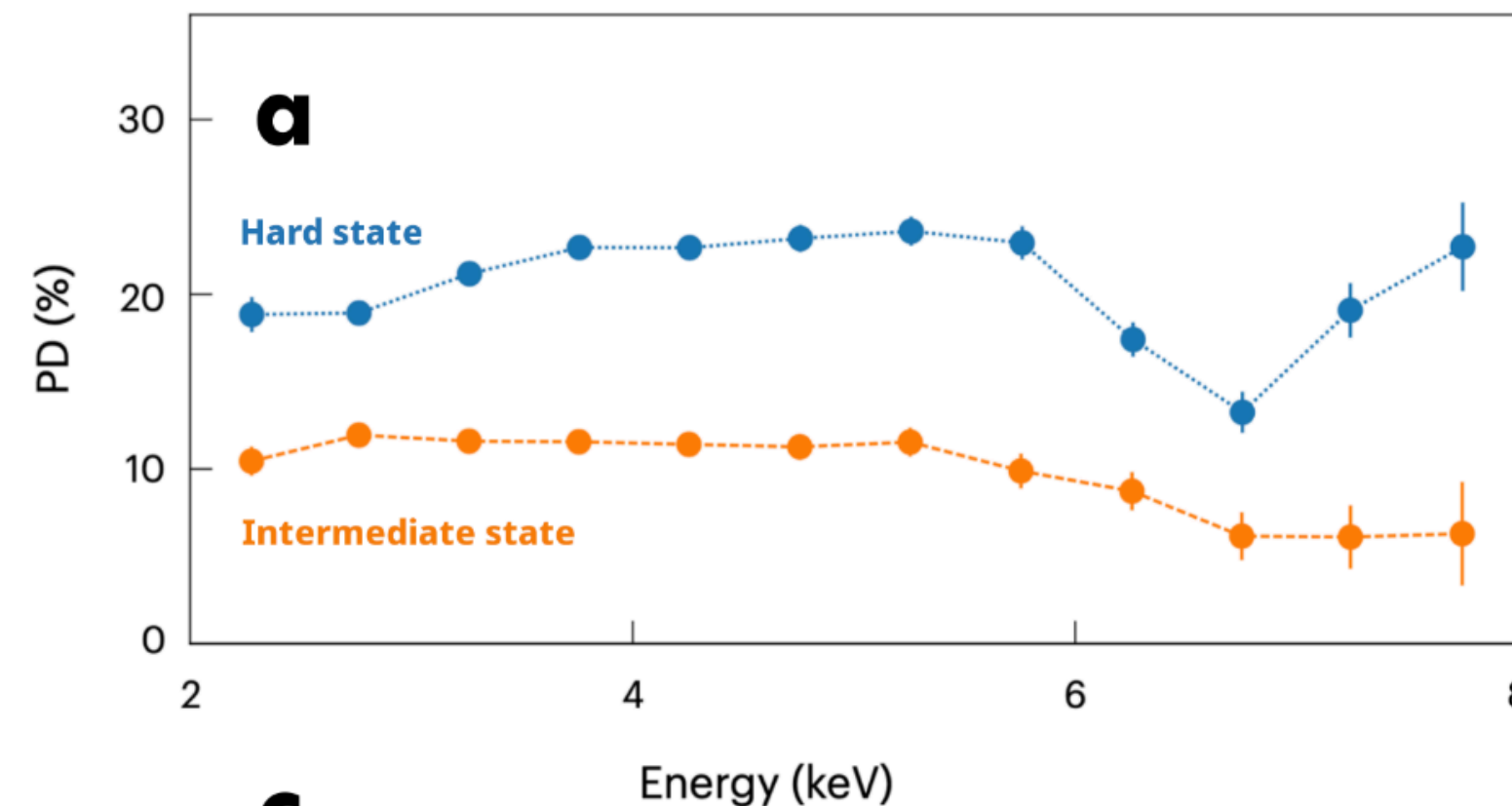
# IXPE results: Cyg X-3

Record-high PD

Very high polarization (up to 29%!).

Can be explained only if **the direct emission from the source is hidden** and we see only reflection.

This suggests that Cyg X-1 is a galactic ULX!

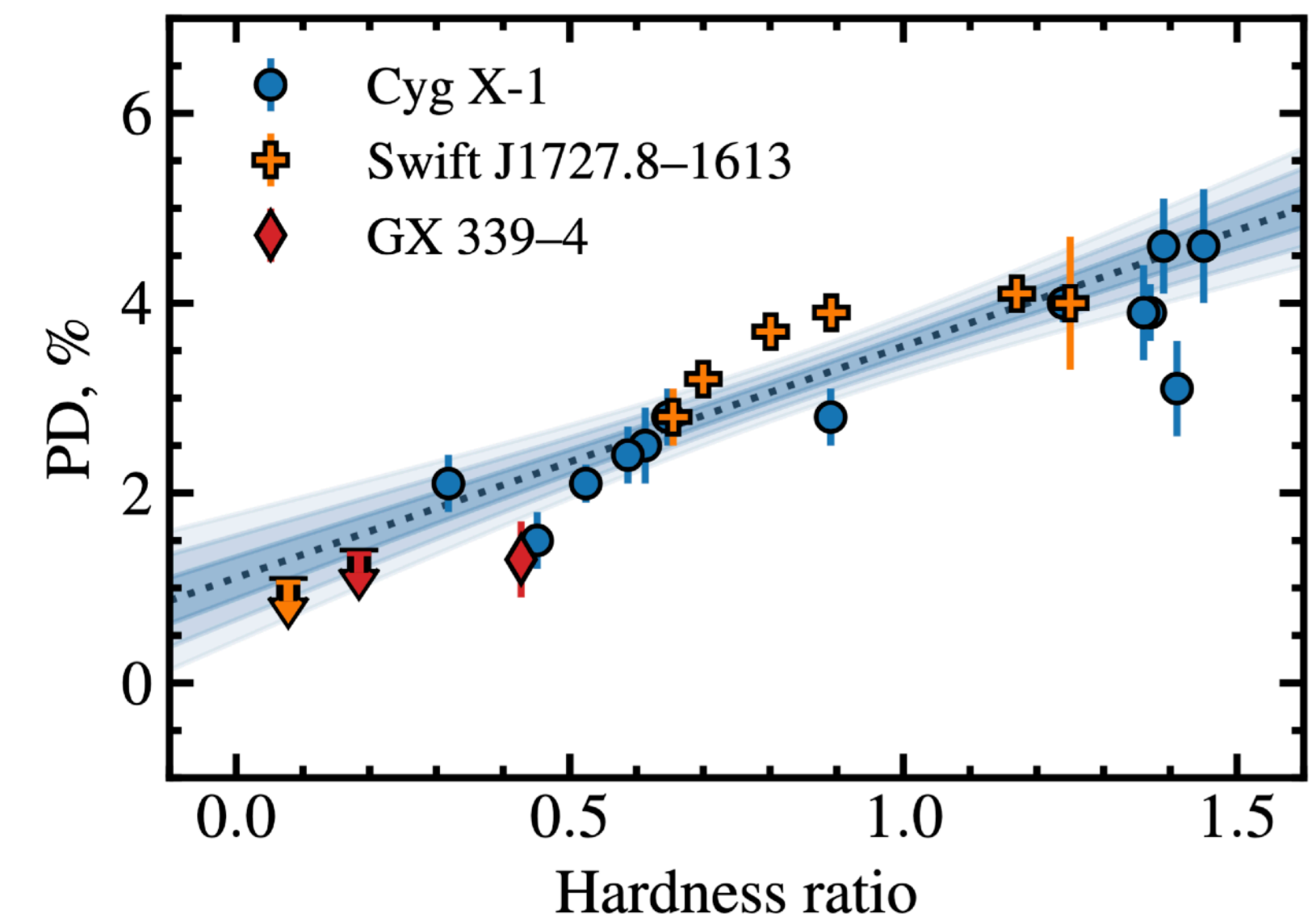
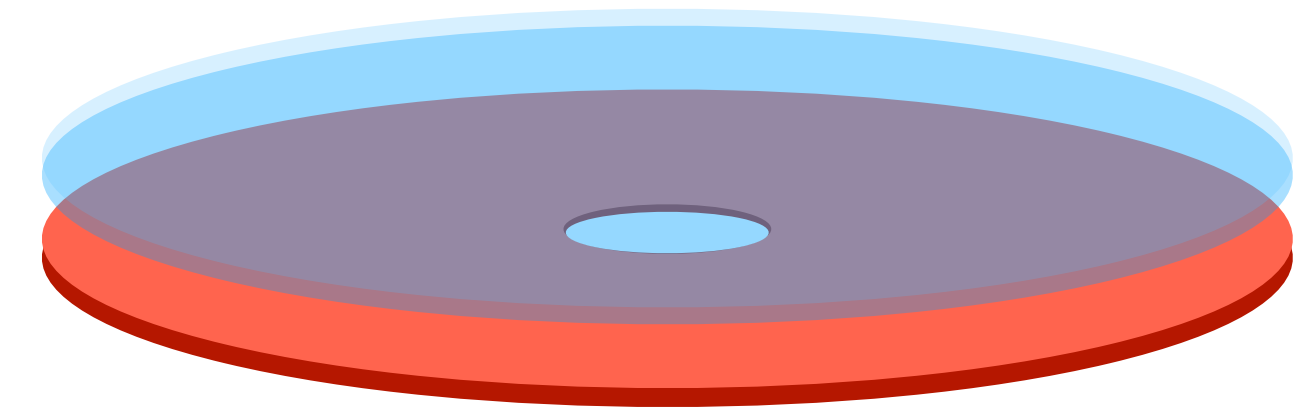


Veledina et al., 2024, Marcel et al., 2026



# IXPE results on BHXRBS: main takeaways

1. **The PA of X-ray polarization is aligned with the jet** in all the sources with known jet orientation: Cyg X-1, Swift J1727.8–1613, GX 339–4, IGR J17091–3624. This implies that **the corona is radially extended!**
2. The **X-ray polarization is stable during dramatic changes of luminosity** (2 orders!) – Swift J1727.8–1613. This indicates that corona does not change the geometrical properties during the state transitions.
3. The **polarization degree is always higher in the harder states**.
4. Shows that some sources may be obscured and beamed (Cyg X-3), giving more evidence for ULX models.



Kravtsov et al. 2025



# 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!

