IXPE
Imaging
X-Ray
Polarimetry
Explorer

# *X-ray polarimetry as a tool to study the geometry of the emitting region in accreting black holes*


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**ReFCO, CAMK, Warsaw**

# Introduction

- EHT produced stunning images of the hot gas around supermassive black holes in the Milky Way and M87.
- Characteristic angular size of X-ray binary's emission region is nanoarcseconds, i.e. 1000 times smaller than the event horizon size of M87 or Sgr A*.
- Imaging is not possible.

- We need to find other ways to learn about source geometry.
- Polarimetry comes into play.

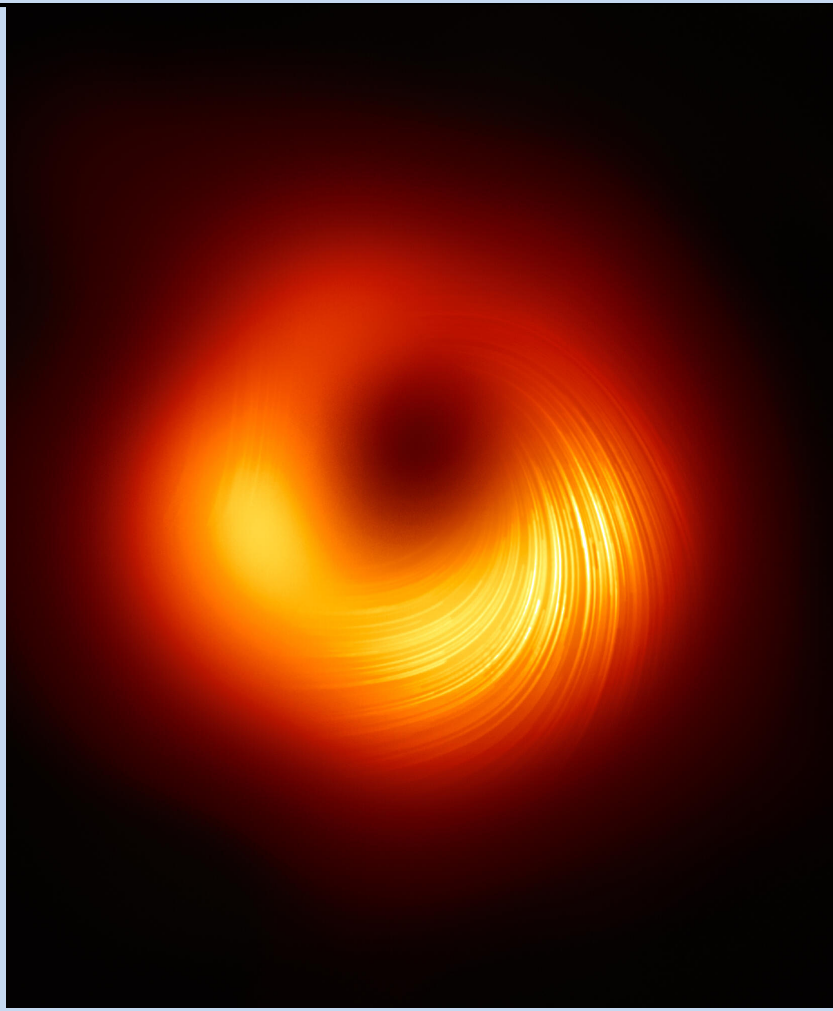
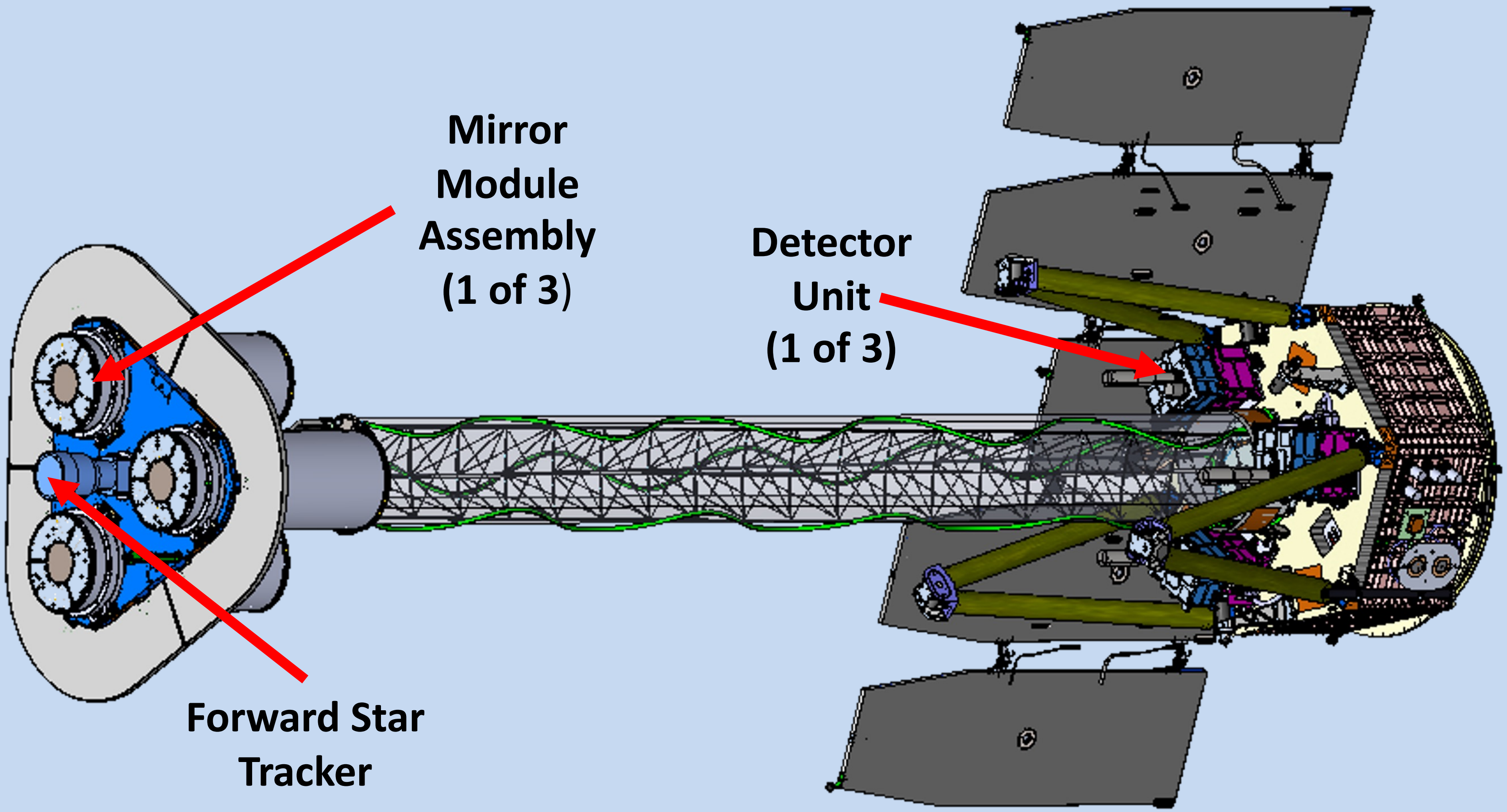


Image of a super-massive black hole in M87 with EHT and the magnetic field orientation.

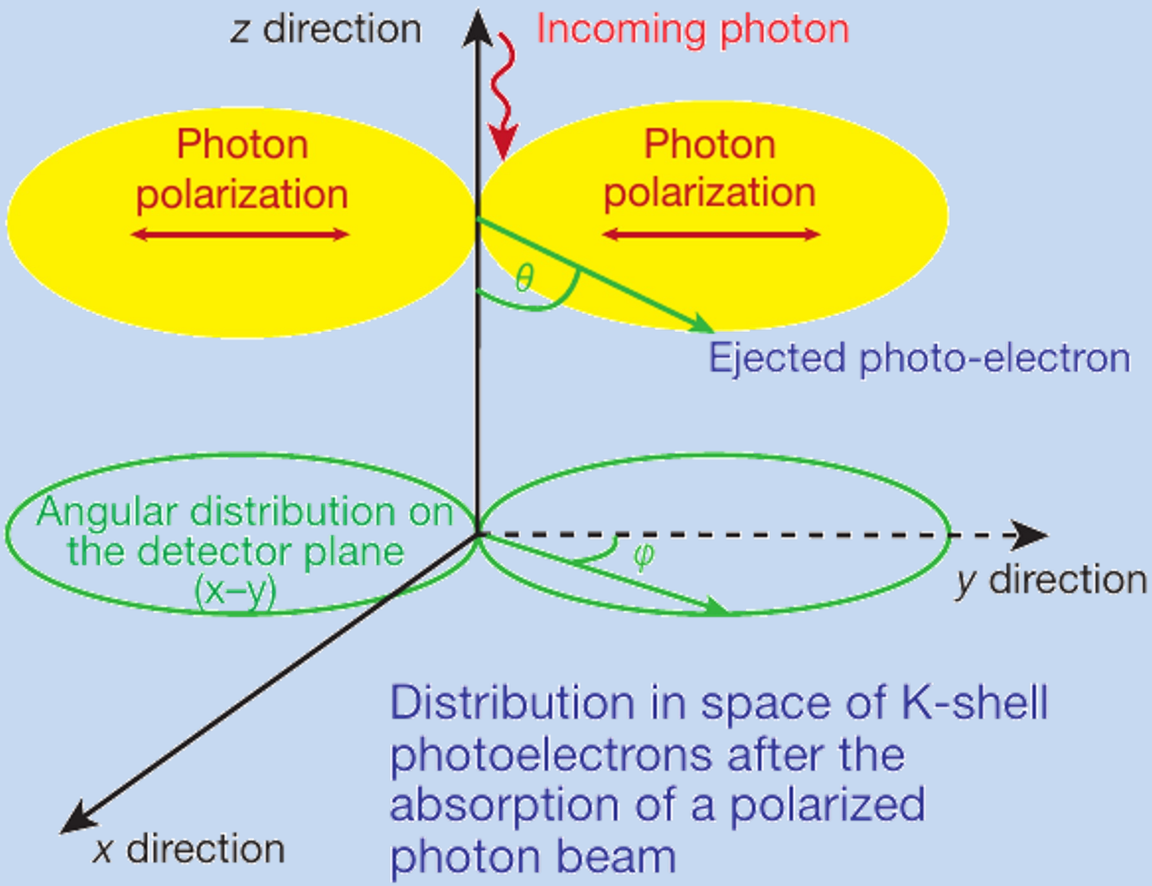
# IXPE launched on 2021 Dec 9




**5.2 m total length**
**4.0 m focal length**

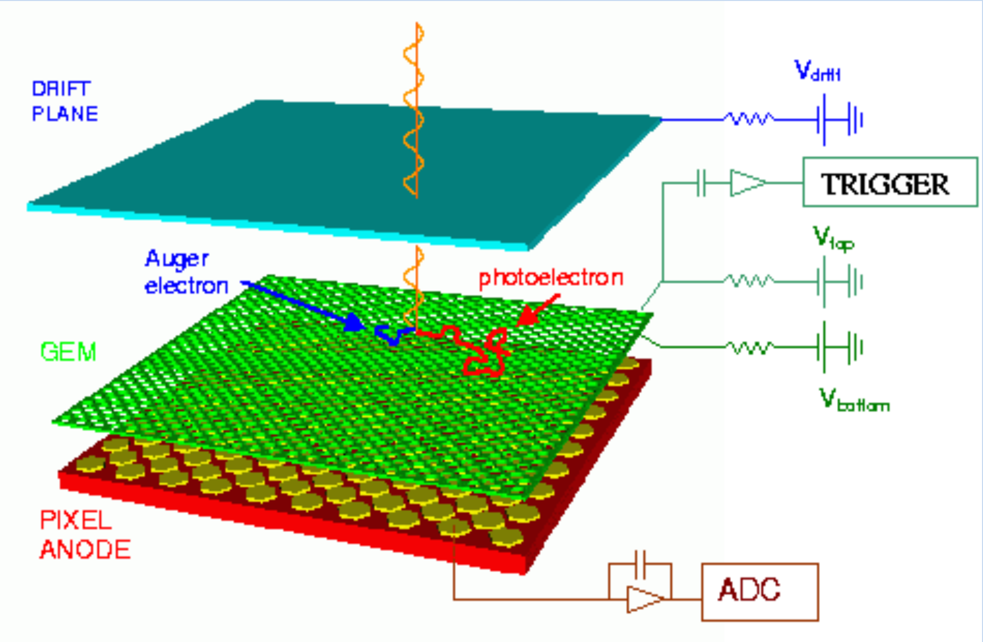
# Detection Principle

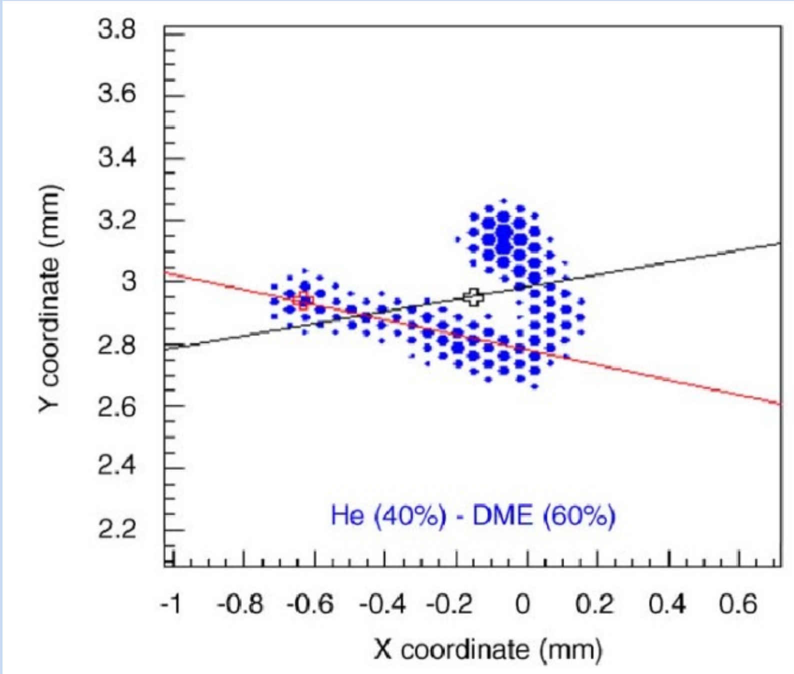
- **The detection principle is based upon the photoelectric effect**




$$\frac{d\sigma}{d\Omega} = r_0^2 Z^5 \alpha_0^4 \left(\frac{1}{\beta}\right)^{7/2} 4\sqrt{2}\sin^2\theta\cos^2\varphi \ , \quad \text{where} \quad \beta \equiv \frac{E}{mc^2} = \frac{h\nu}{mc^2}$$

# Gas Pixel Detector

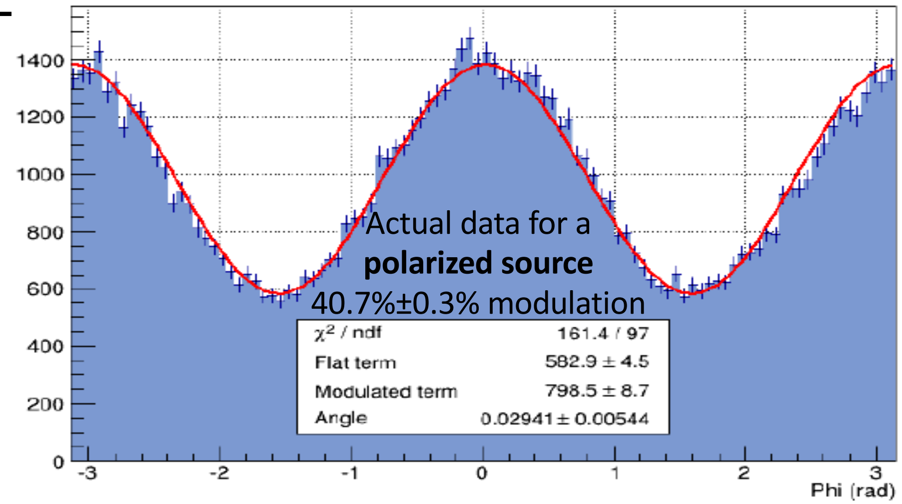


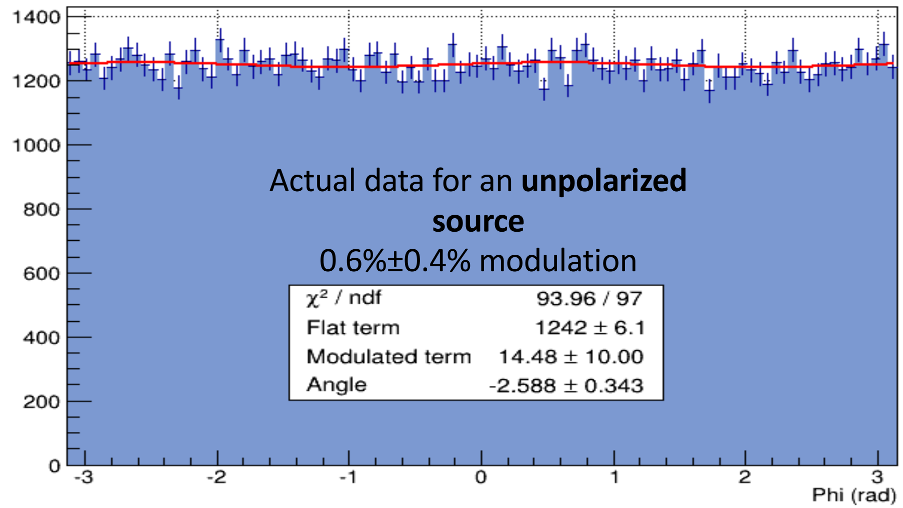



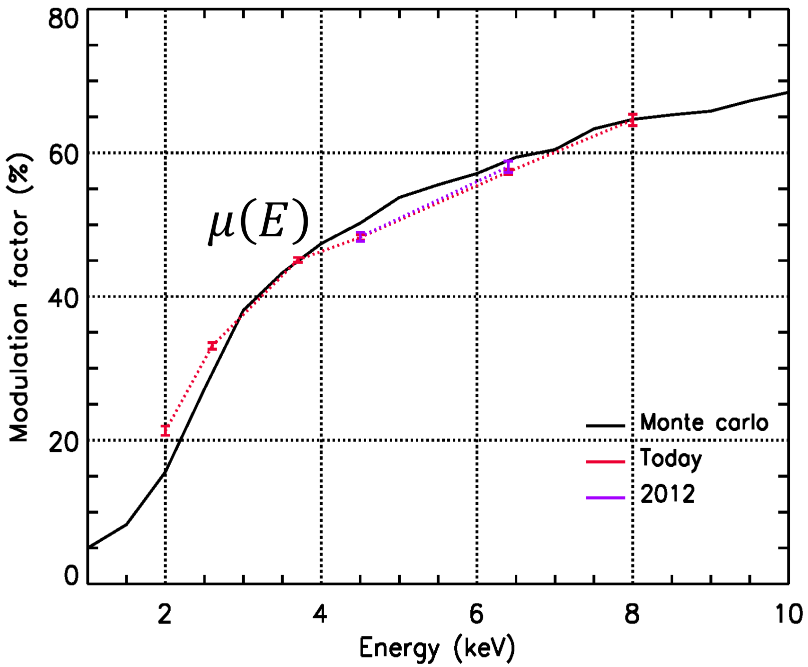
# POLARIZATION FROM MODULATION HISTOGRAM AND CALIBRATED MODULATION FACTOR



- **Polarization degree**
  - $\Pi = \text{Modulation}/\mu(E)$



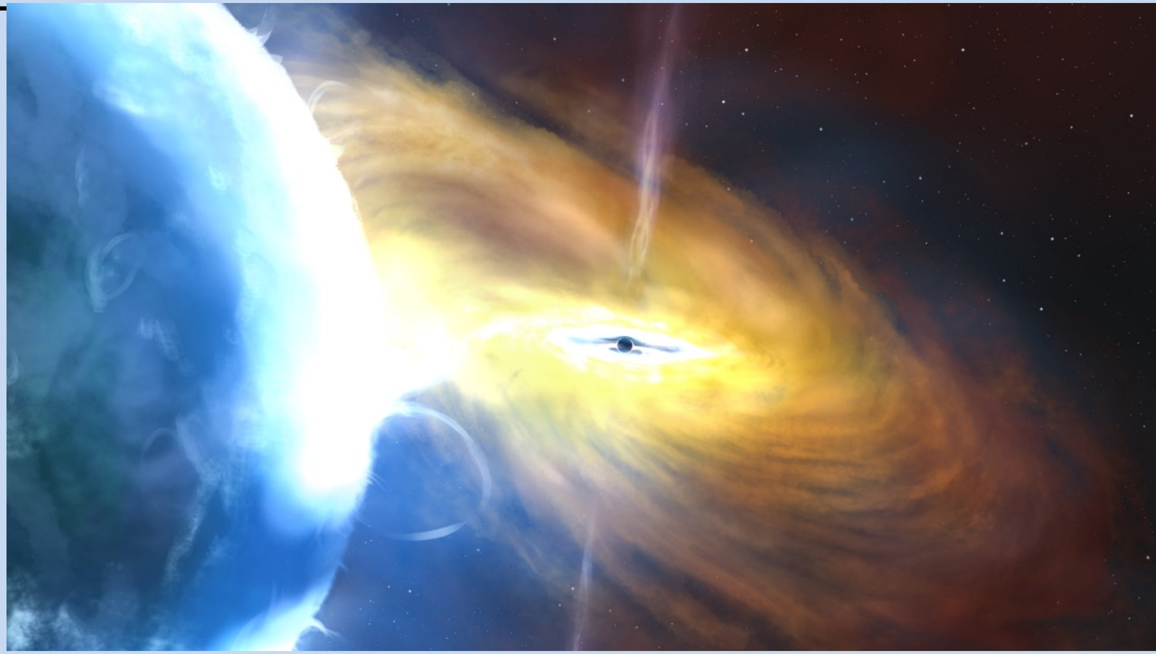





- **Polarization degree**
  - $\Pi = \text{Modulation}/\mu(E)$

# *Questions*

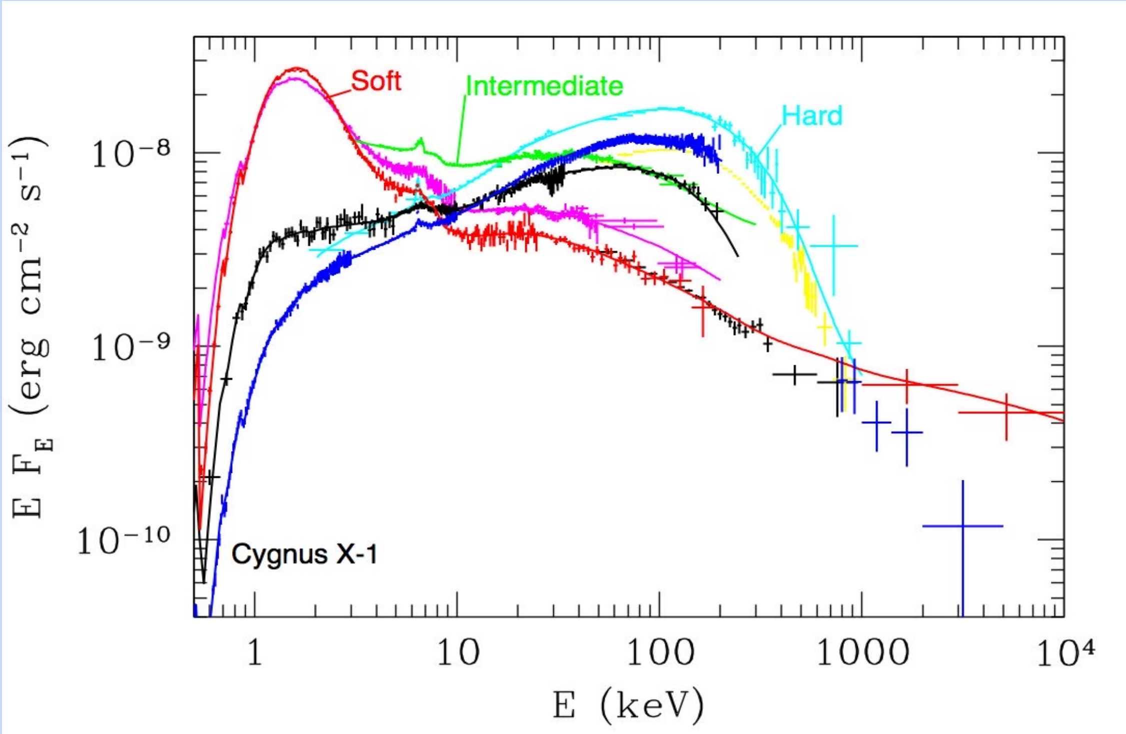


Geometry of the X-ray emitting region in the hard state: corona, hot flow, magnetic flares?

The structure of the accretion disk in the soft state.

Can we measure the black hole spin?

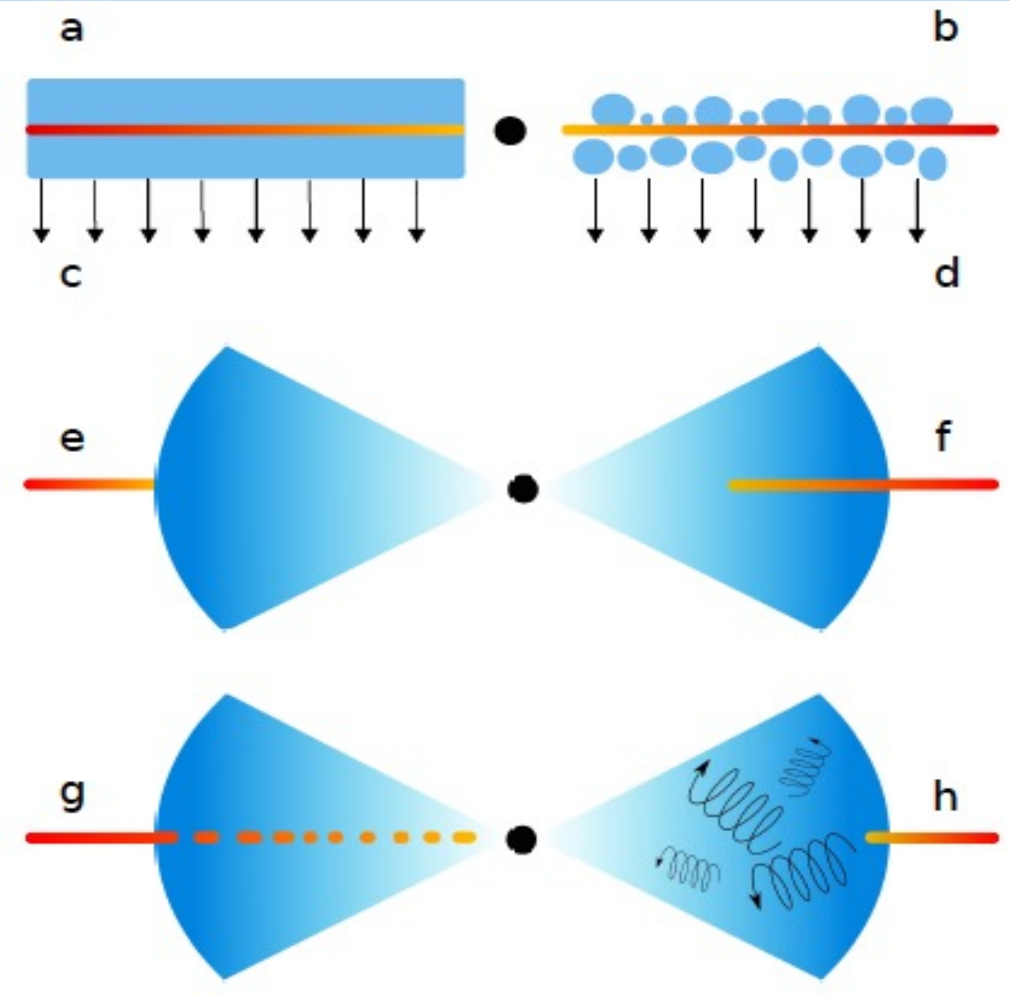
# Spectral states



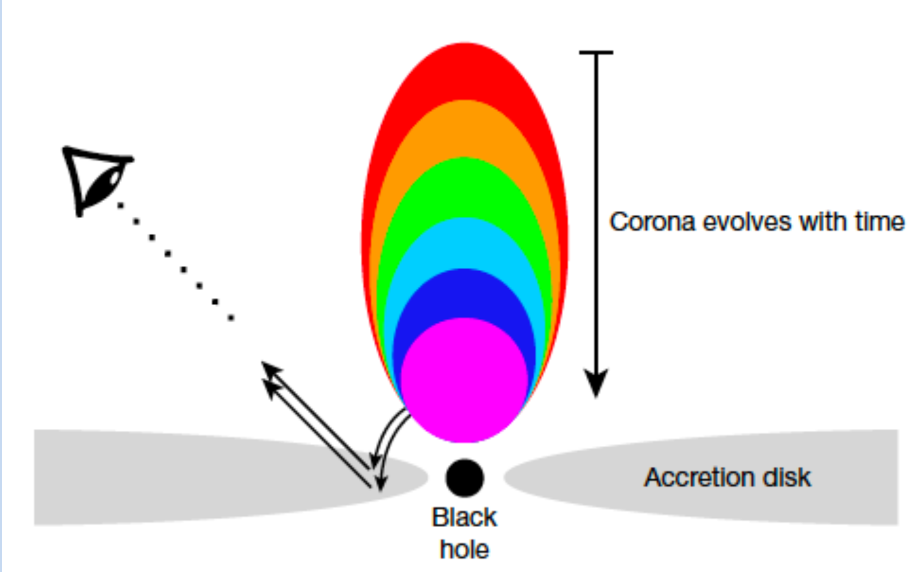

The hard state spectrum is produced by multiply Compton scattering (thermal Comptonization).
However, the geometry of emission region is unknown.

Polarization is sensitive to the geometry of the ”corona”, its dynamics and source of seed photons

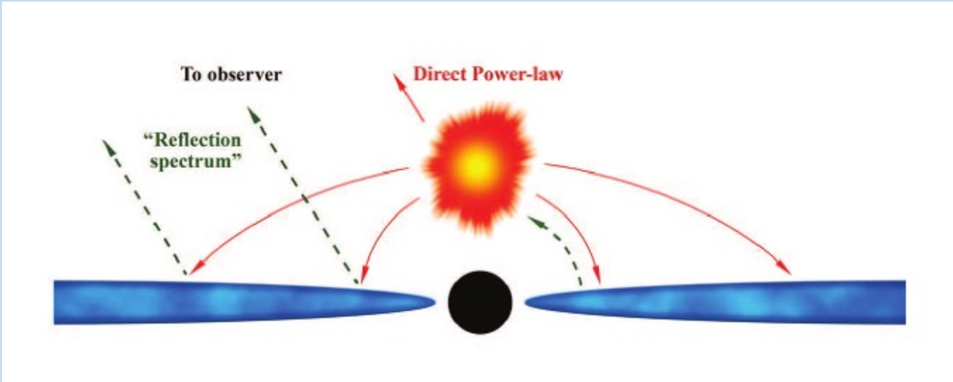
# Hard state geometry




Poutanen et al. 2018



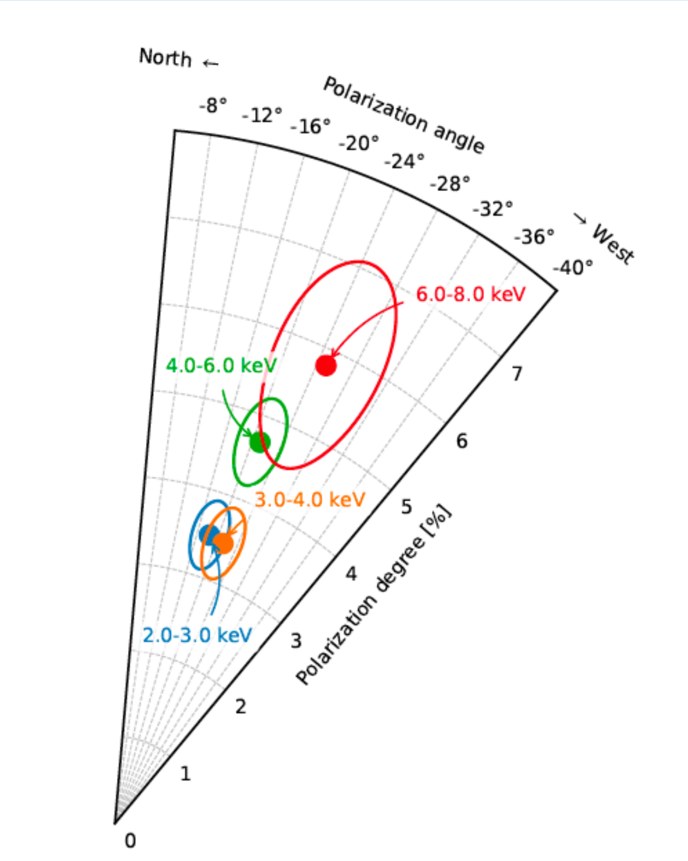

Kara et al.2019

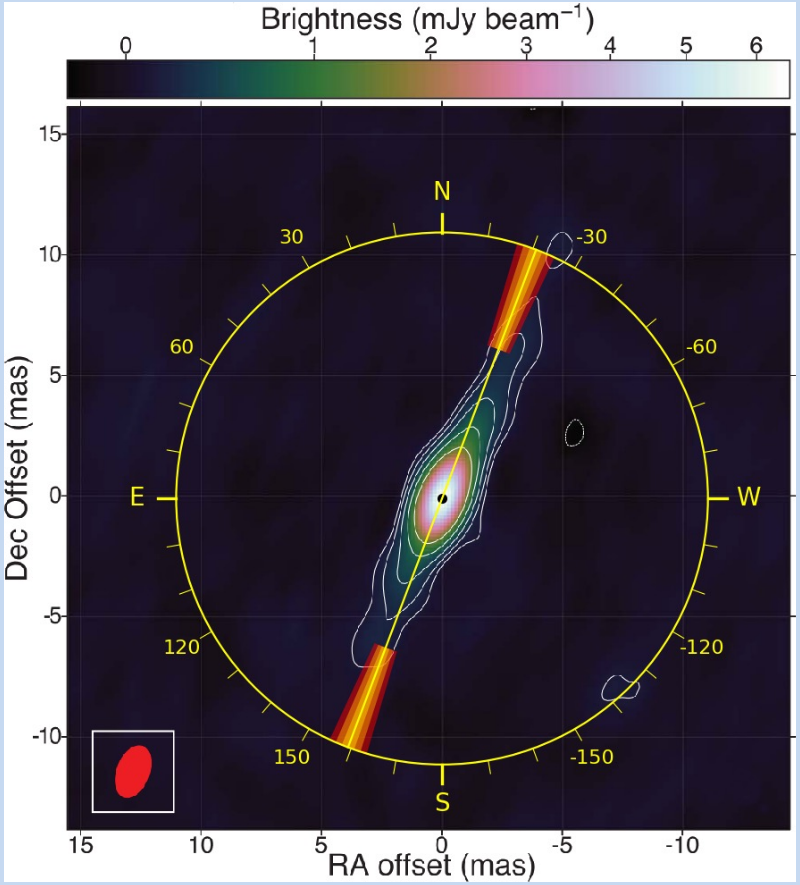



Fabian et al.

# Cygnus X-1

- **IXPE observed Cyg X-1 in the hard state in May and June 2022 as well as in 2024**



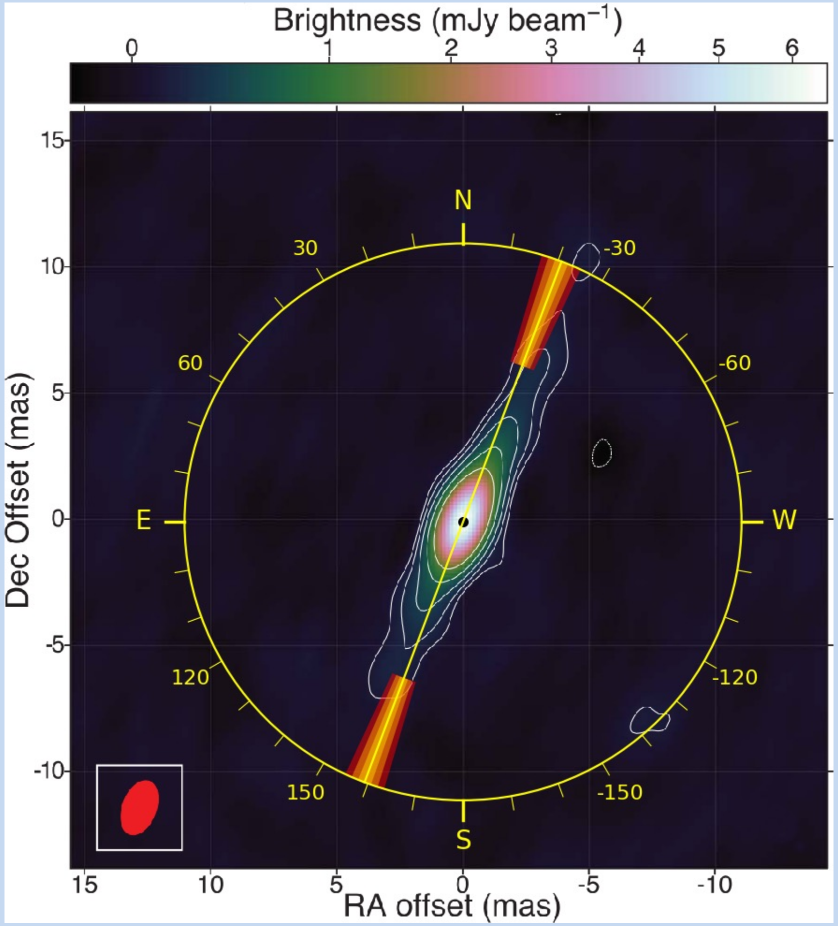




PD = 4.0 ± 0.2 %
PA = −20.7 ± 1.4 deg

X-ray polarization parallel to the jet

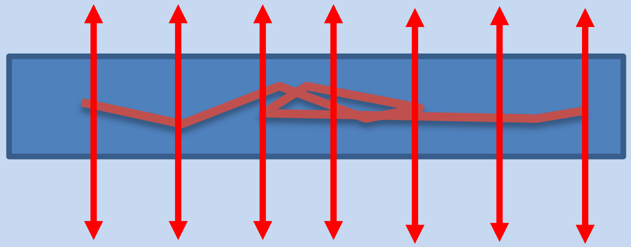
Krawczynski et al. 2022, Science

# Cygnus X-1




Krawczynski et al. 2022, Science

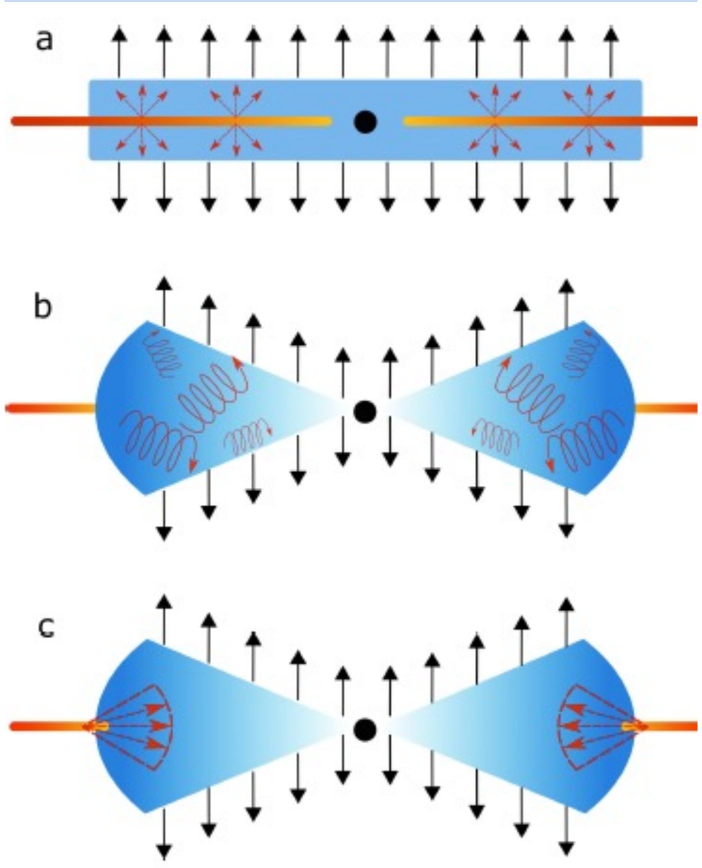
X-ray polarization parallel to the jet ⇒ X-ray emitting region is elongated perpendicular to the jet.

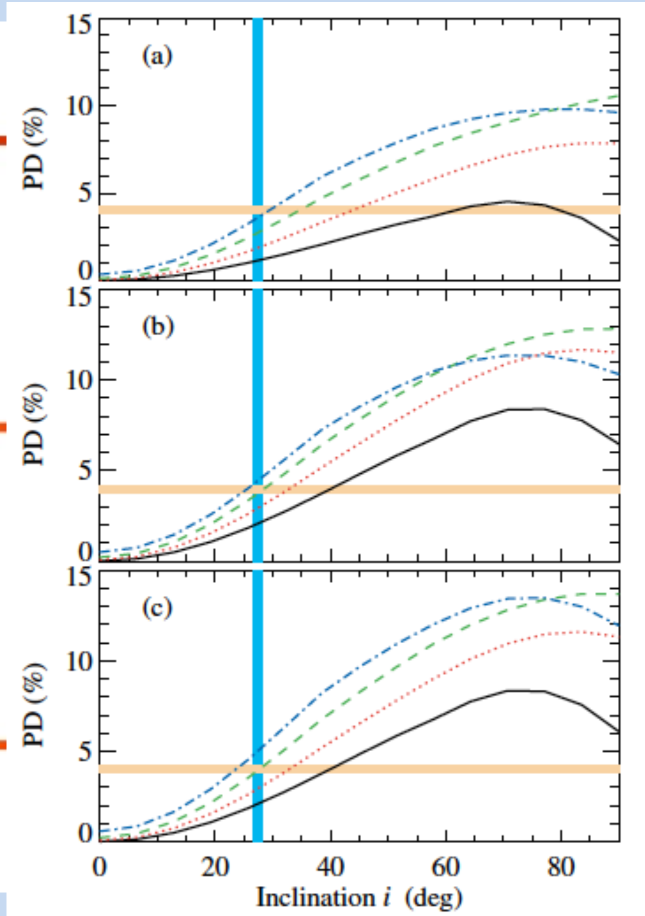


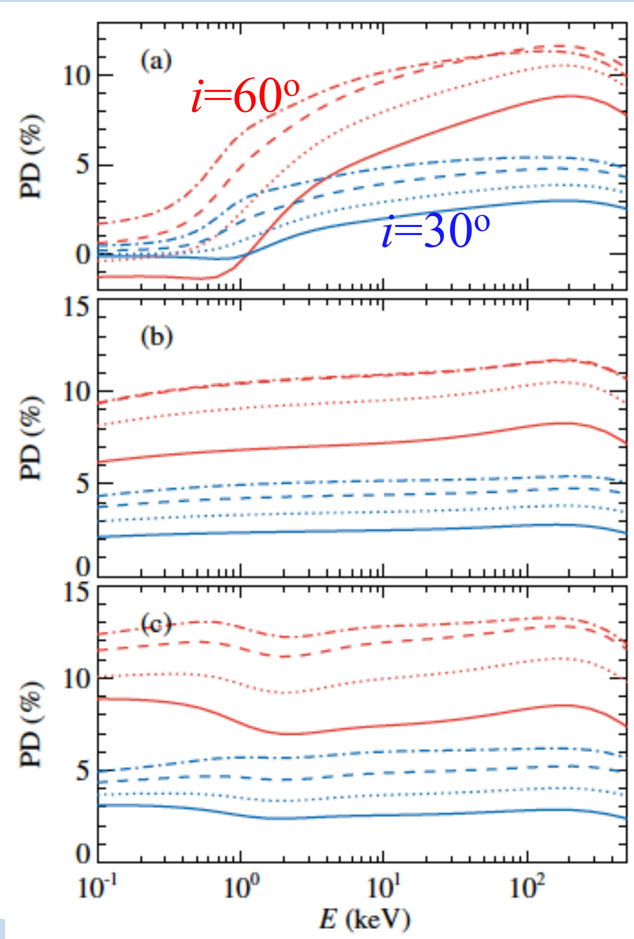
Polarization is perpendicular to the disk ⇒ scattering in the optically thin slab

- How to get 4% polarization at $i$=27.5 deg (Orosz+ 2007, Miller-Jones+ 2021)?
- Synchrotron from the jet is not feasible. Jet produces <5% of flux and $PD_{syn}$ for toroidal field is 8%.
- Note that inclination can be 35°-40° and $M_{BH} \approx 14 M_{\odot}$ (Ramachandran+2025)

# Comptonization in outflowing corona



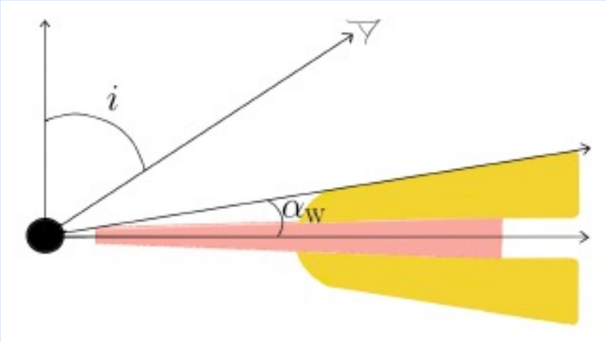




$\beta = 0,\ 0.2, 0.4, 0.6$

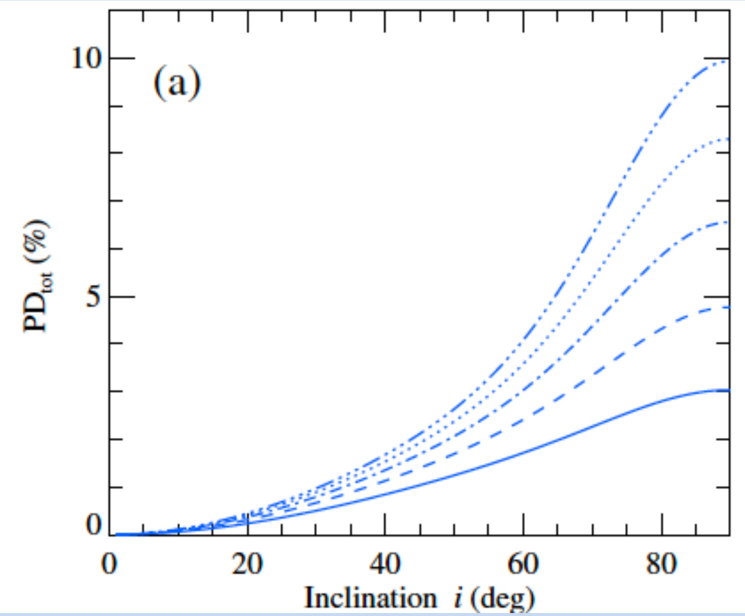
JP, Veledina, Beloborodov 2023

# Scattering in equatorial wind

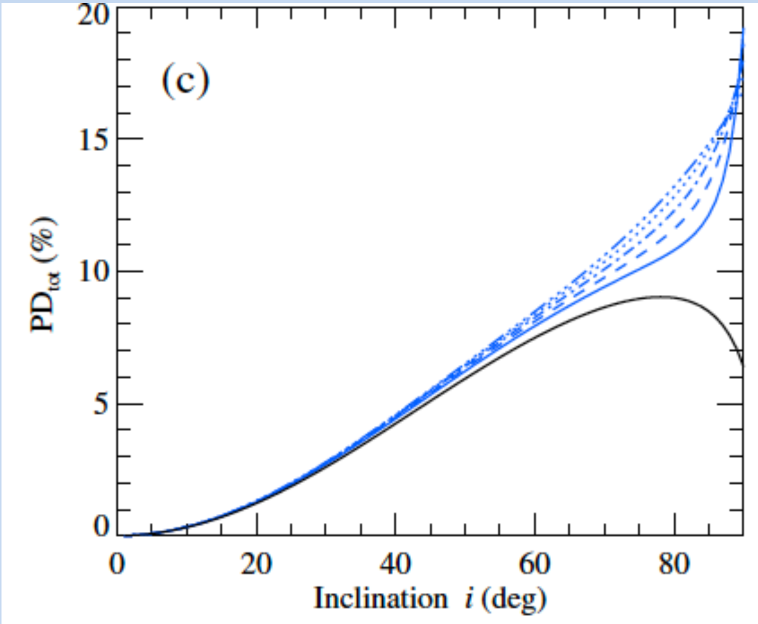



Wind opening angle=20°

Intrinsic source: unpolarized isotropic




Intrinsic source: Comptonization in a slab



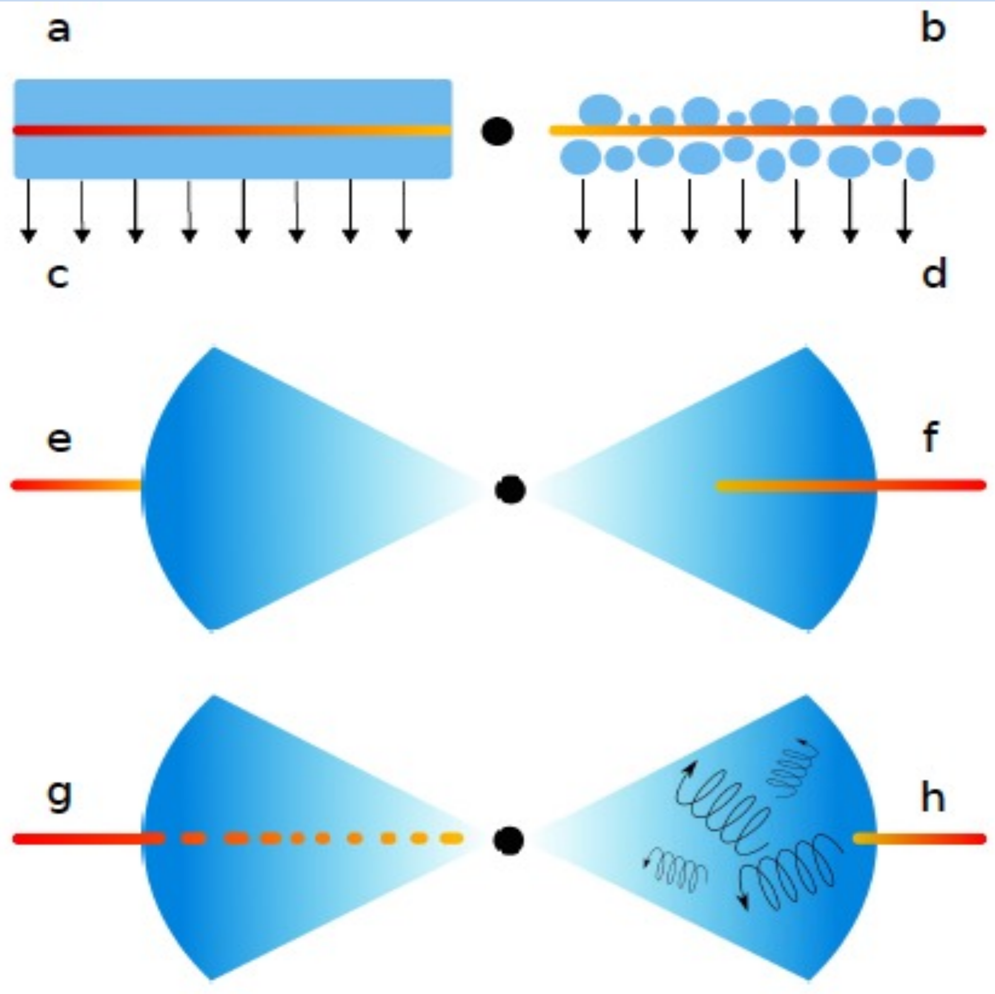

Equatorial optical depth

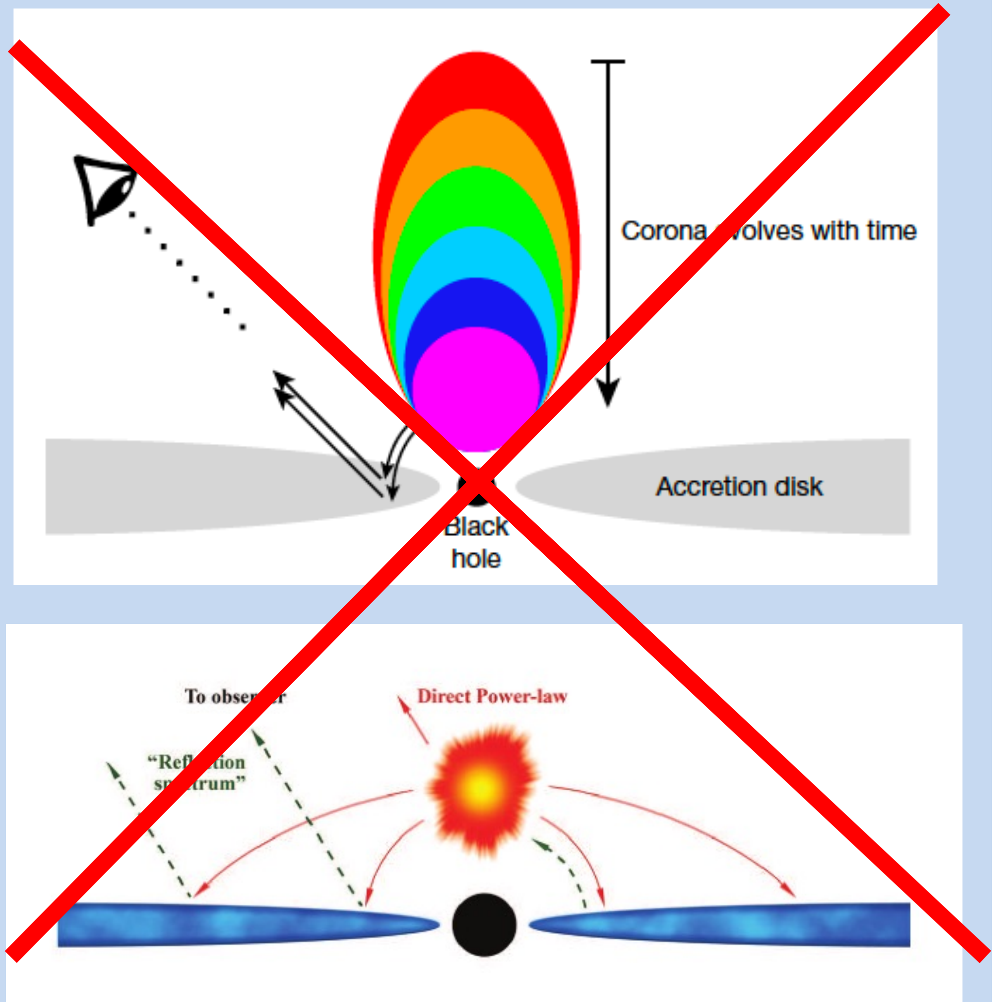
$\tau_0$ =0.5, 1.0, 1.25, 1.5

Nitindala, Veledina, JP 2025

# Hard state geometry

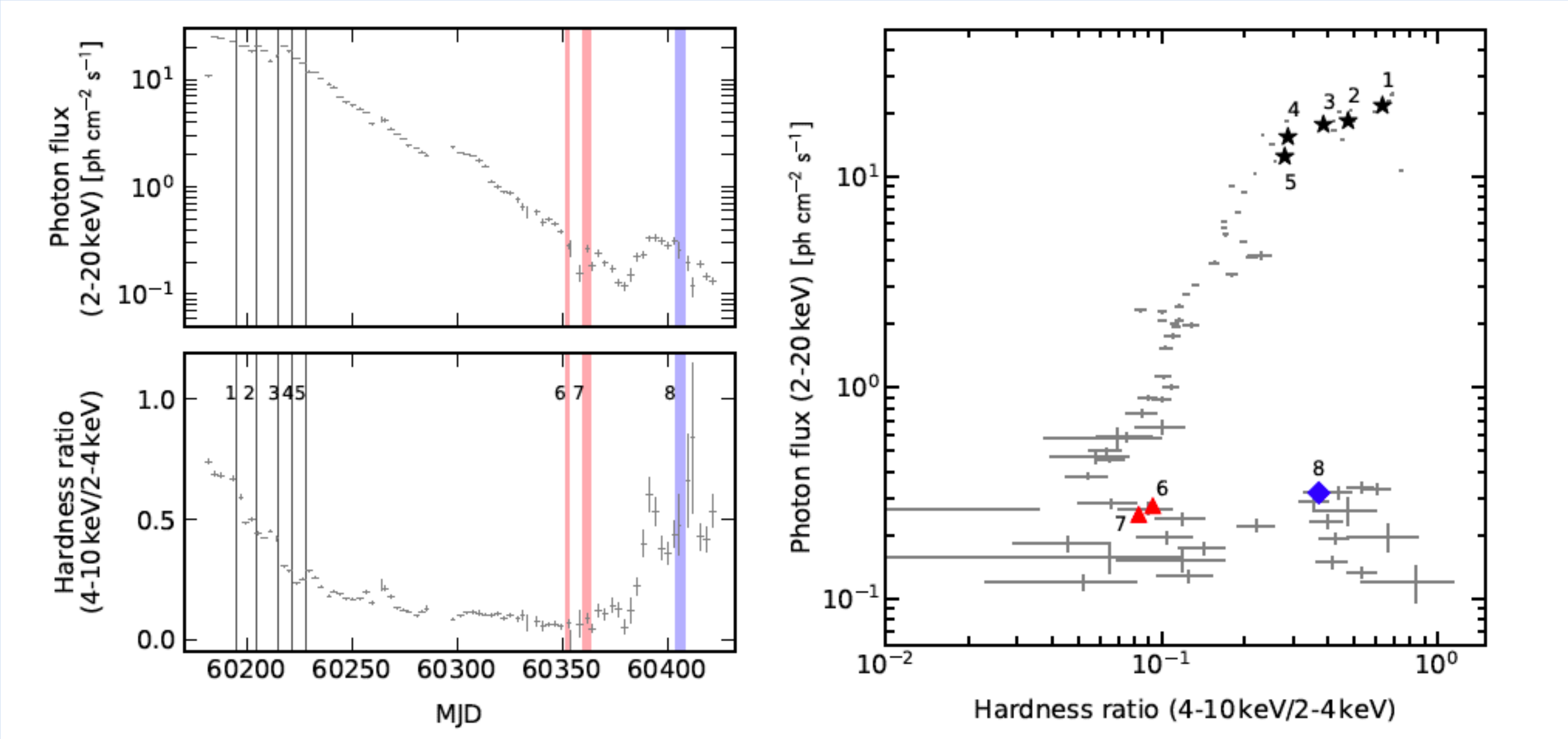
Jet and lamp-post models are rejected



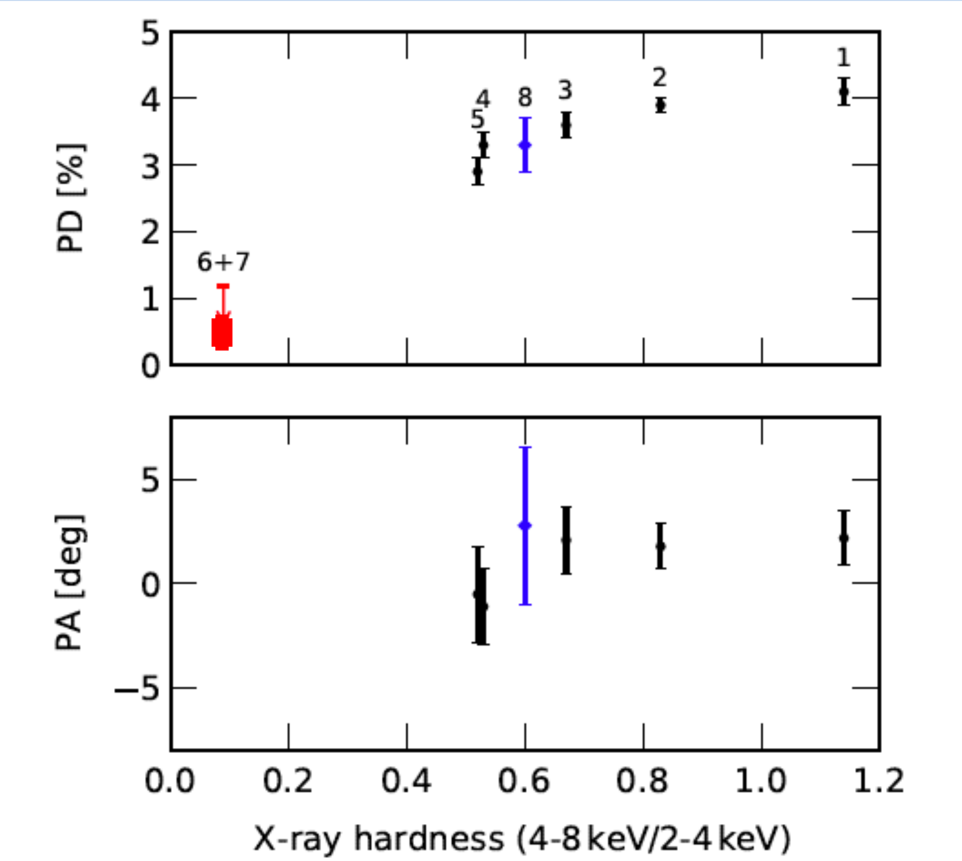
# Swift J1727.8–1613

Outburst starting from August 2023




Veledina+ 2023, Ingram+ 2024, Svoboda+2024, Podgorny+2024

# Swift J1727.8–1613




In the hard state
PD=4.1±0.2%, PA=2.2±1.3 deg
Sub-mm PA= −4.1±3.5 deg
We predicted jet to be directed along position angle 0.

It was measured at −0.60±0.07 deg (Wood+2024)

Veledina+ 2023, Ingram+ 2024, Svoboda+2024, Podgorny+2024

Marshall Space Flight Center

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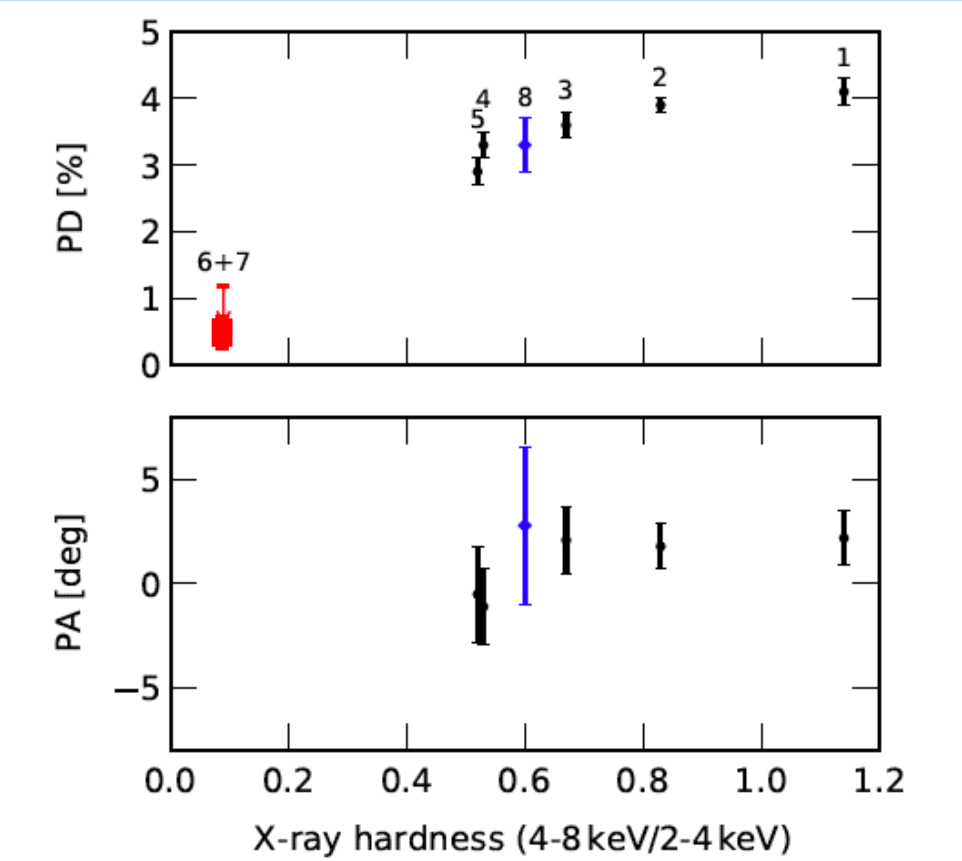
# Swift J172

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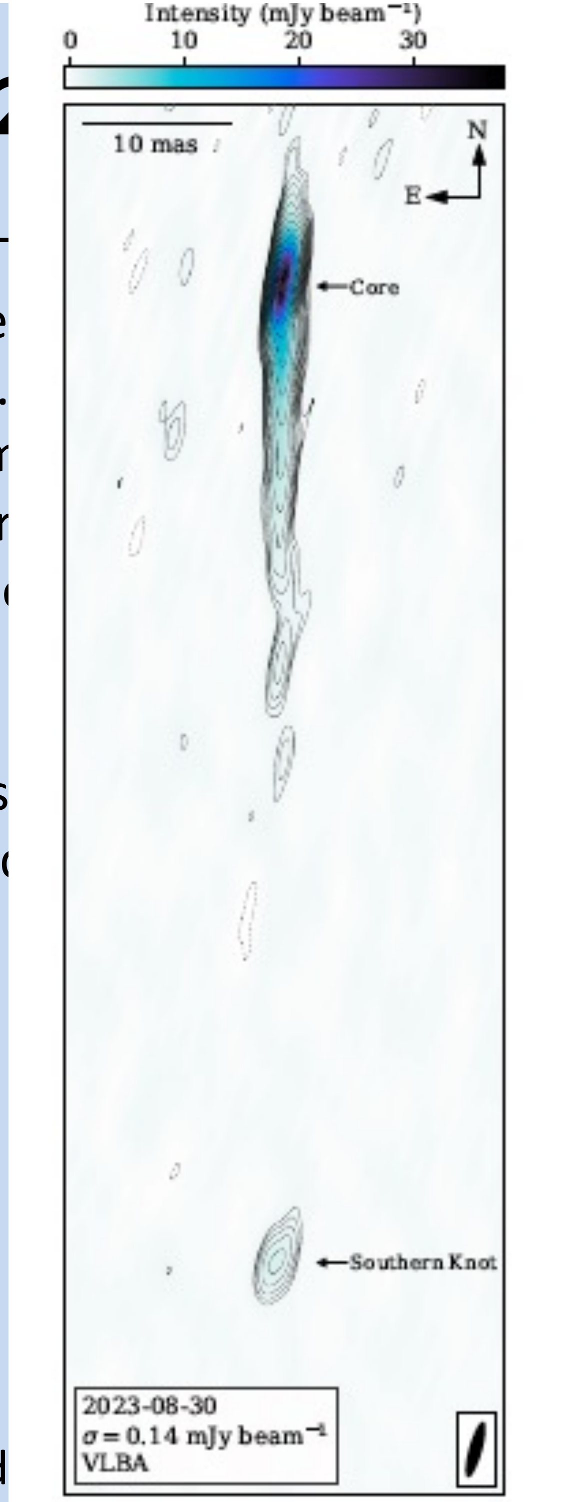


Veledina+ 2023, Ingram+ 2024, Svoboda+2024, Pod

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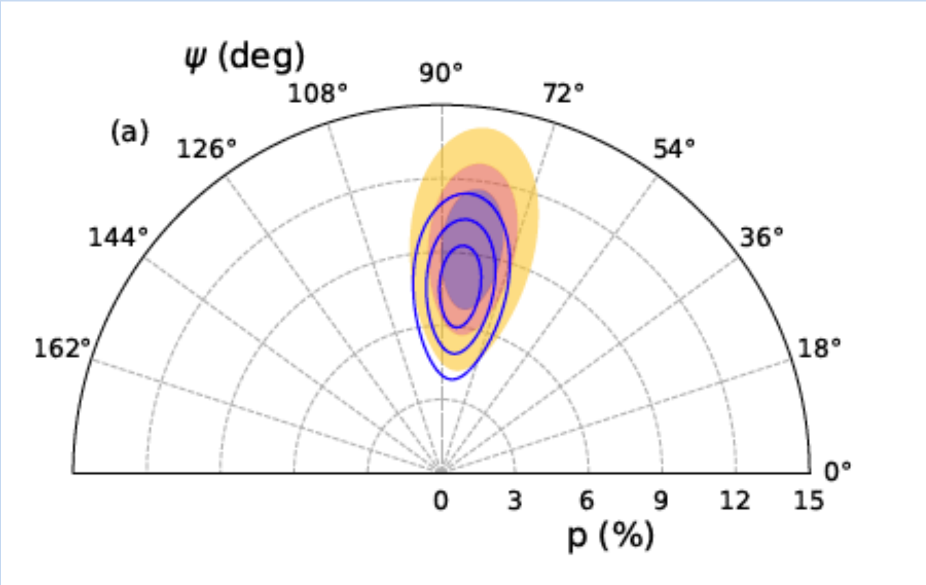
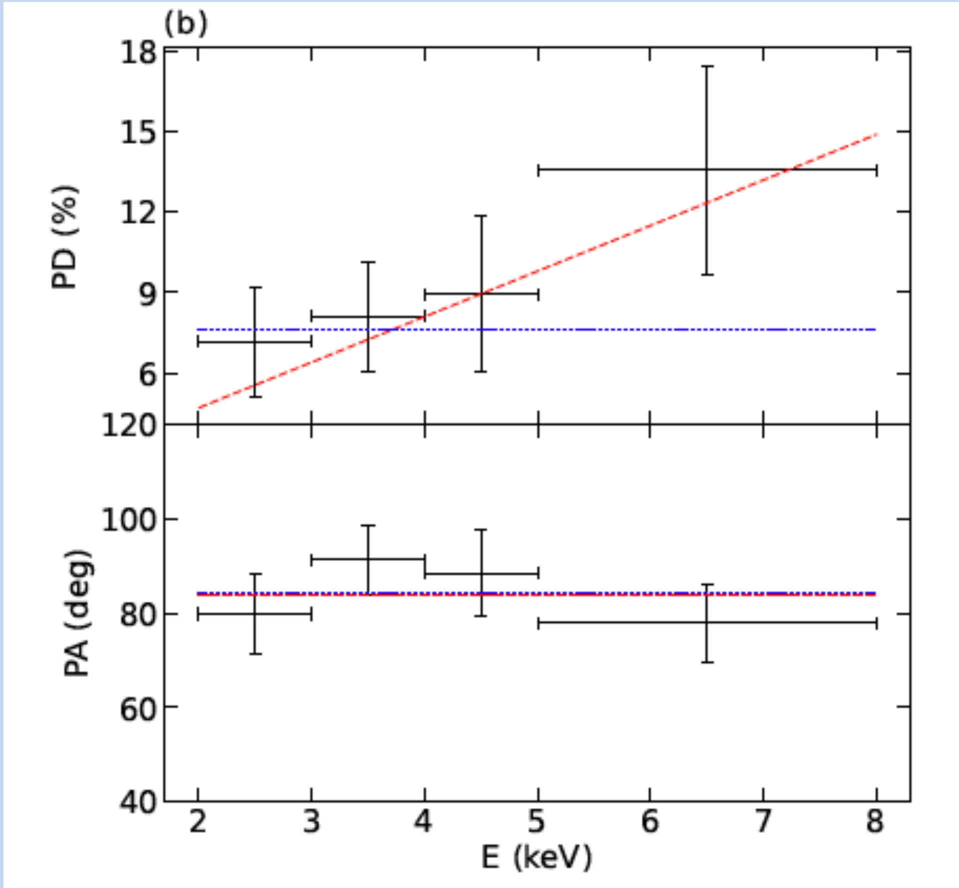
# IGR J17091–3624




In the hard state
PD=9.1±1.6%, PA=83±2 deg

Inclination is at least 60 deg

Ewing+ 2025

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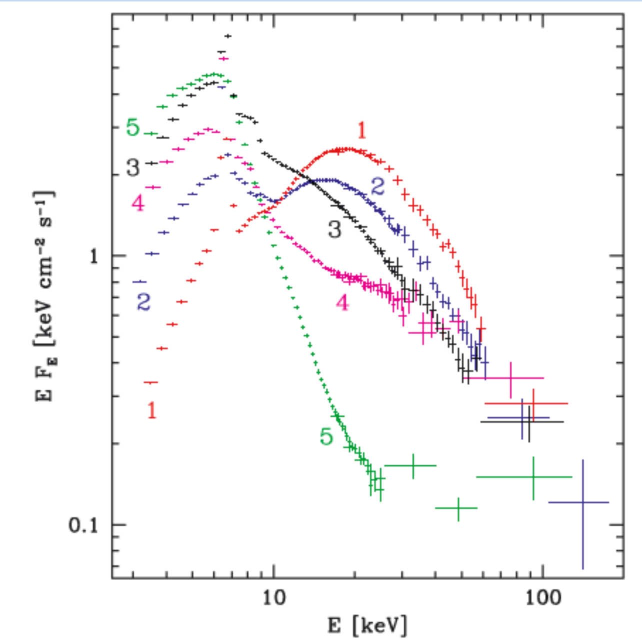
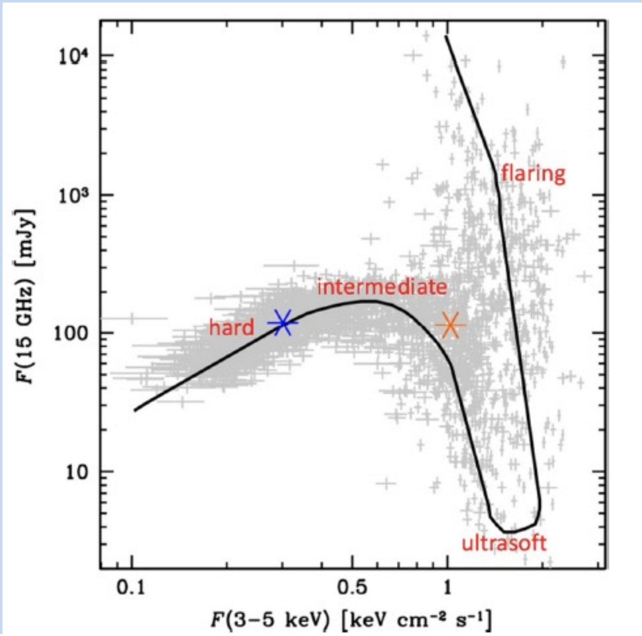
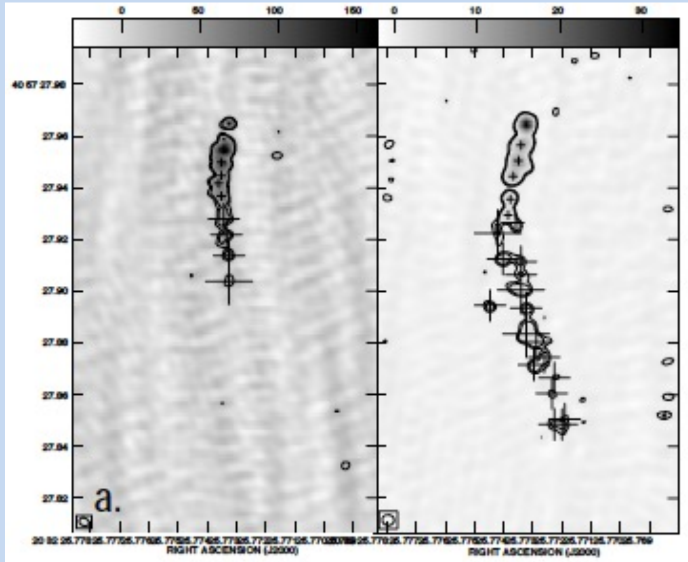
# Cygnus X-3

- Orbits a Wolf-Rayet star with the period of $P_{\mathrm{orb}} = 4.8^{\mathrm{h}}$.
- Inclination $i$=29.5°±1.2° from IR and X-ray photometric orbital variability from absorption (Antokhin et al. 2022).
- Strong radio source. Jet in the N-S direction.




Szostek + 2008

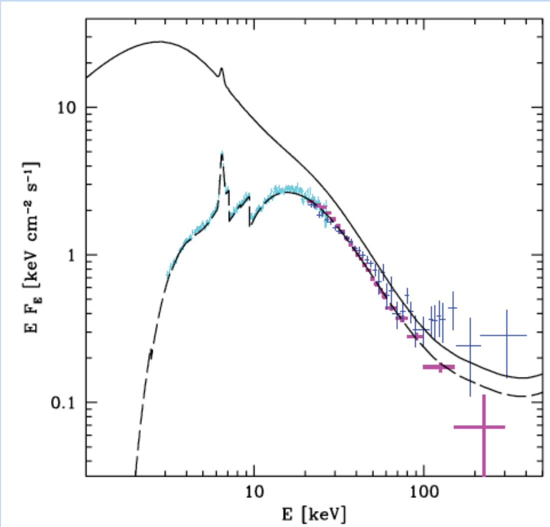


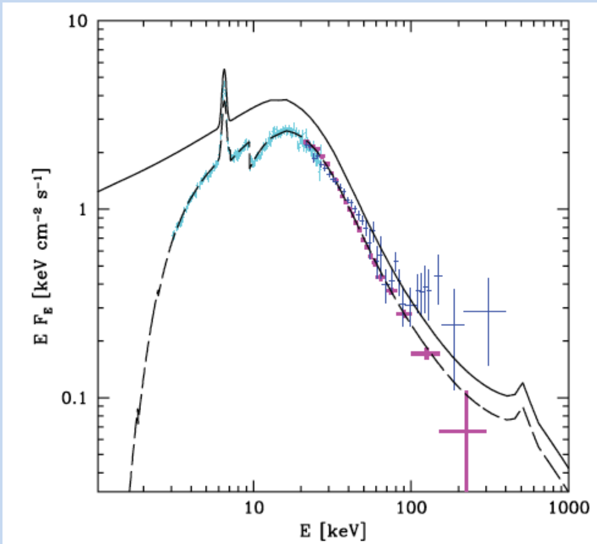



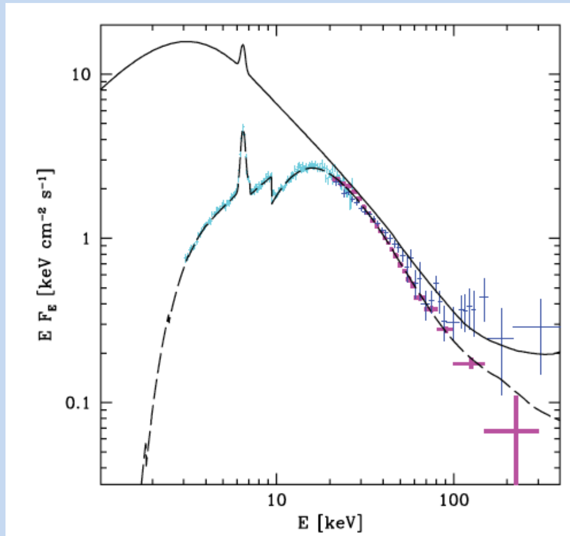

Miodzuszewski + 2001

# Cygnus X-3

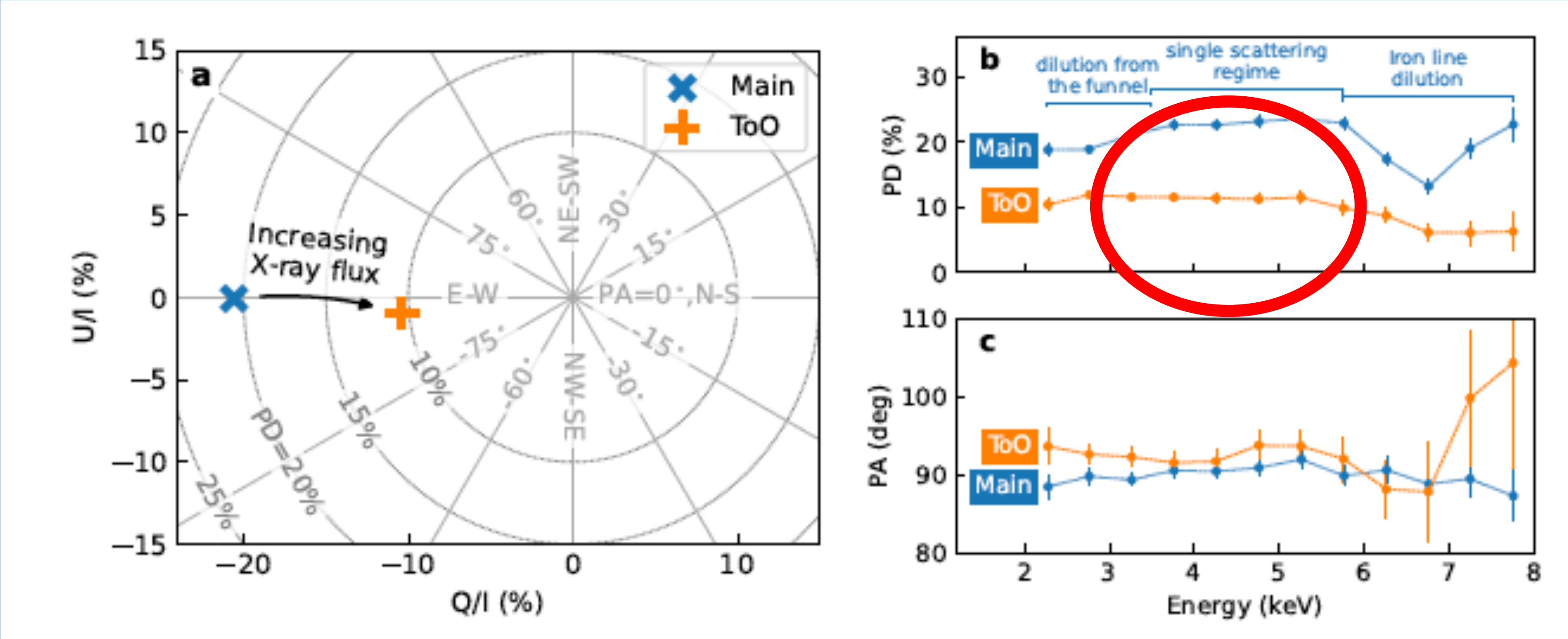
- Spectral modelling is uncertain (Hjalmarsdotter et al. 2009, Zdziarski et al. 2010): hard-state spectra can be explained with (i) soft spectrum, severely absorbed by WR wind; (ii) standard hard spectrum; (iii) reflection-dominated spectrum
- Often compared to the other accreting high-mass BH X-ray binary Cyg X-1, but is not quite the same



# IXPE observations of Cygnus X-3




Main observation: 14-19 Oct, 31 Oct-6 Nov 2022
ToO observation: 25-29 Dec 2022

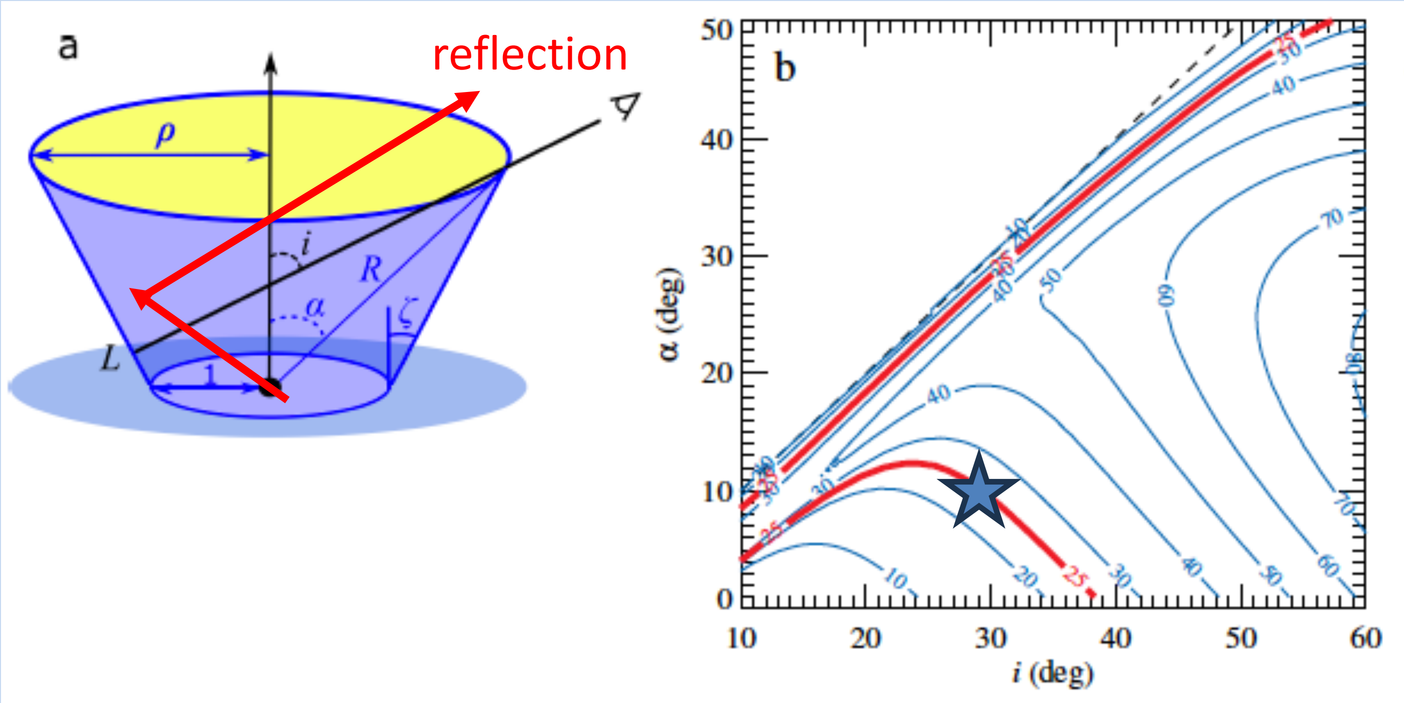
**PD = 20.6 +/- 0.3 %**
**PA = 90.1 +/- 0.4º**

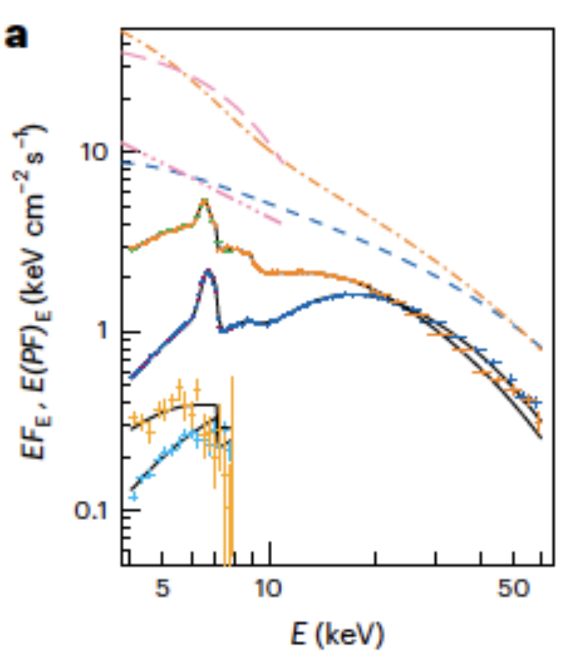
PA perpendicular to the jet!

**PD = 10.4 +/- 0.3 %**
**PA = 92.6 +/- 0.7º**

Veledina et al. 2024, Nat Astro

# X-ray polarization: reflection off the funnel wall




- PA ⊥ jet (/binary axis). High PD: we do not see central source
- $i \approx 30^o$ hence optically thick matter high above the disc.
- Modelling gives high intrinsic luminosity in excess of $10^{39}$erg/s.
- **Cygnus X-3 is a hidden ULX !**

Veledina et al. 2024, Nat Astro

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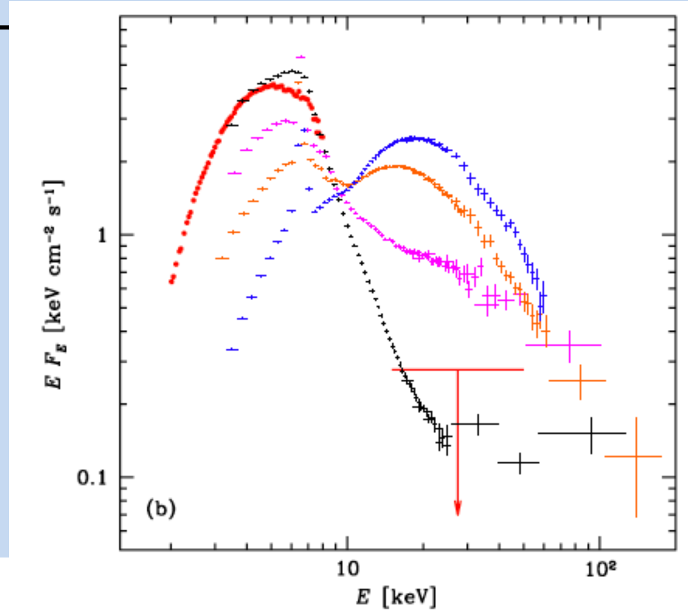
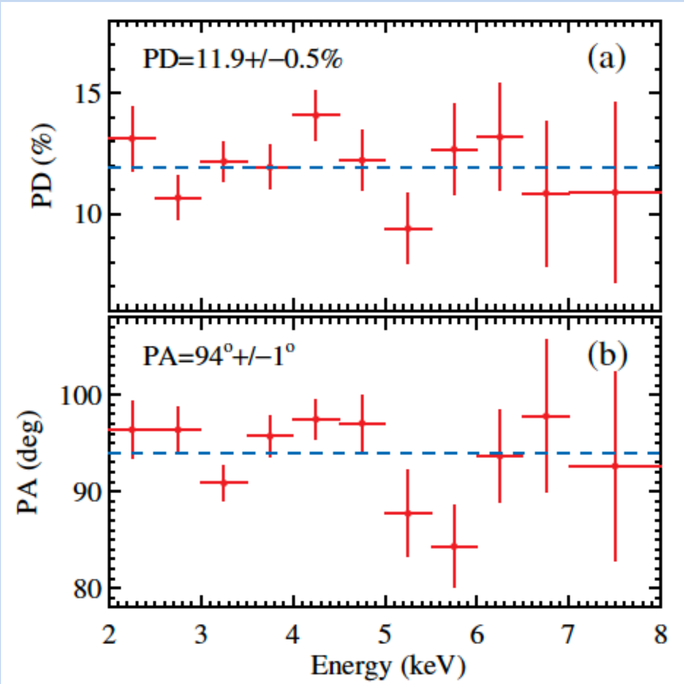
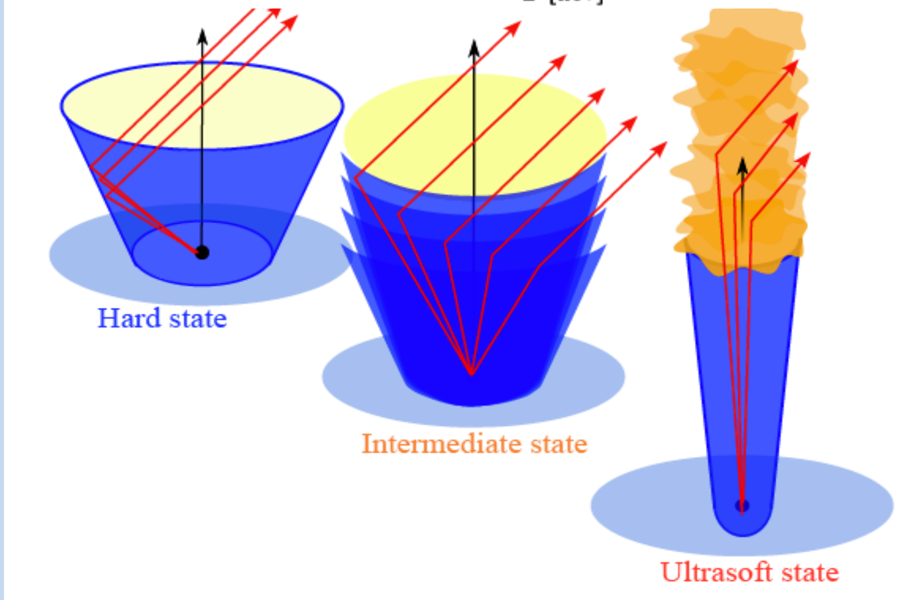
# X-ray polarization: reflection within the funnel

- In the (ultra-)soft state, the spectrum is blackbody-like, very weak iron line, the PD was expected to be very low.
- But PD=12% at PA=94°. No energy dependence.



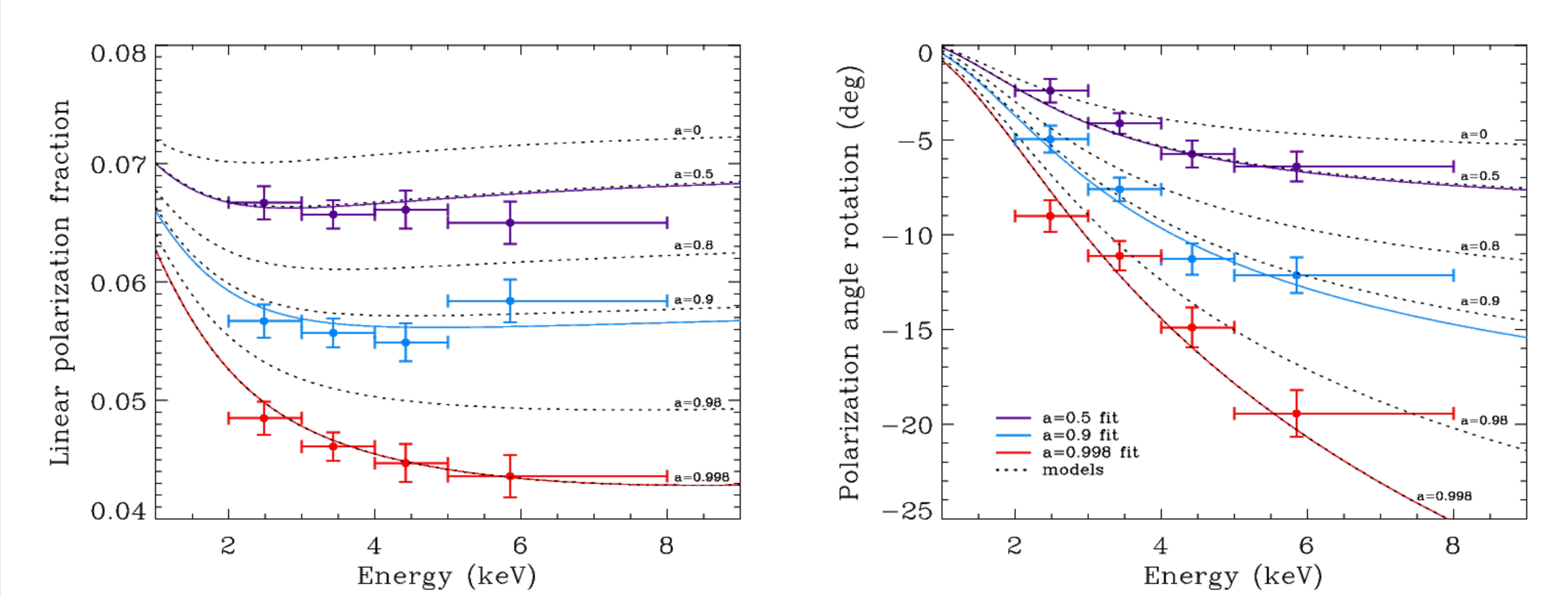




Veledina et al. 2024, A&A Letters

# Soft state

- **Polarization angle was predicted (Connors et al. 1980, Dovciak et al. 2008) to show strong energy dependence.**
- **The amplitude depends on the black-hole spin**

  - Scattering polarizes the thermal disk emission
  - Polarization rotation is greatest for emission from inner disk
    - Inner disk is hotter, producing higher energy X-rays
  - Priors on disk orientation constrain the black hole spin
    - a = 0.50±0.04; 0.900±0.008; 0.99800±0.00003 (200-ks observation)



# *Hard - soft state comparison: Cygnus X-1*

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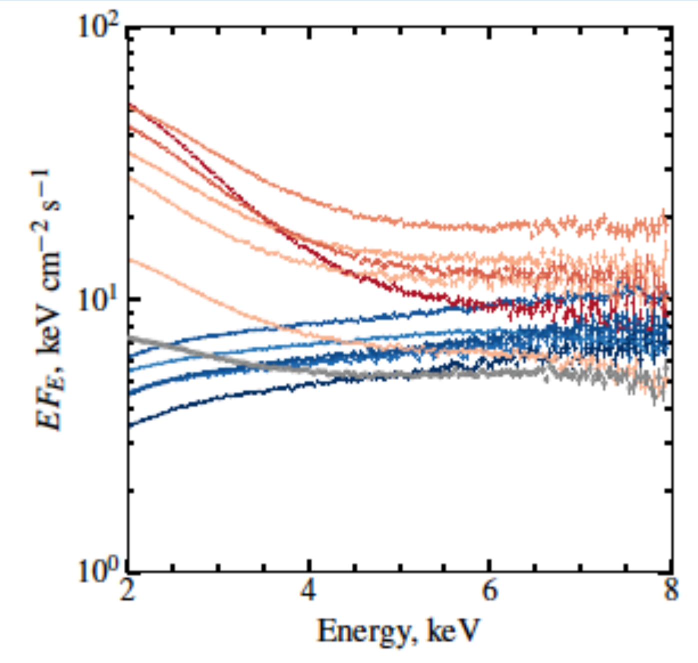
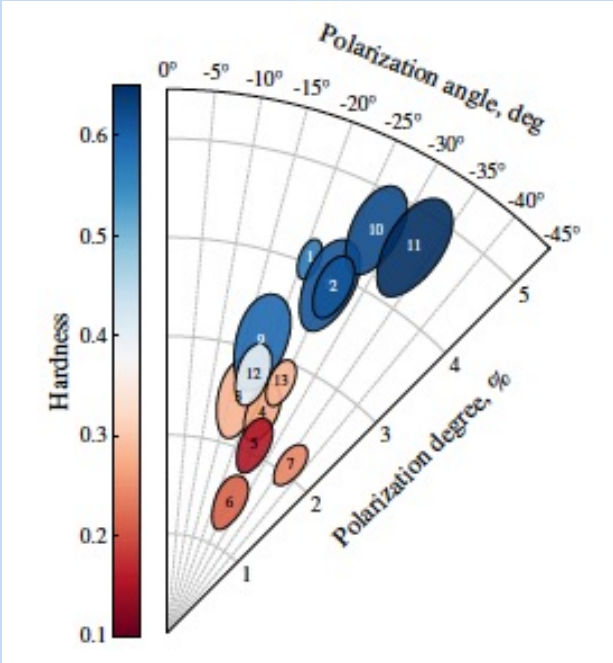
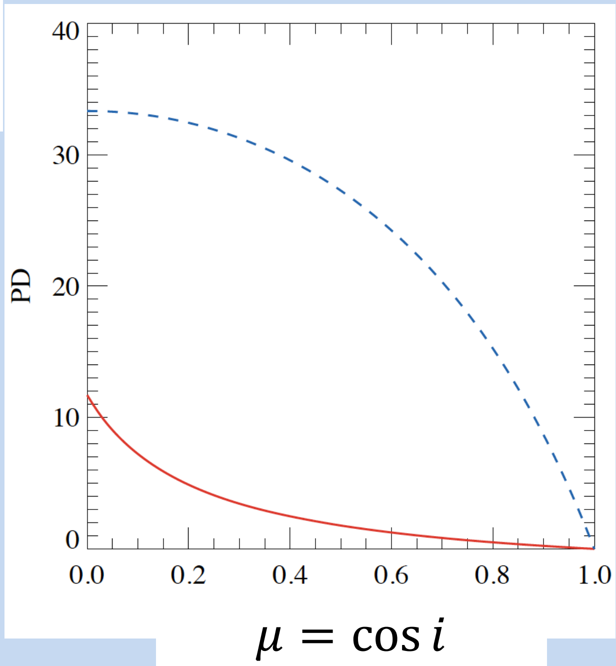


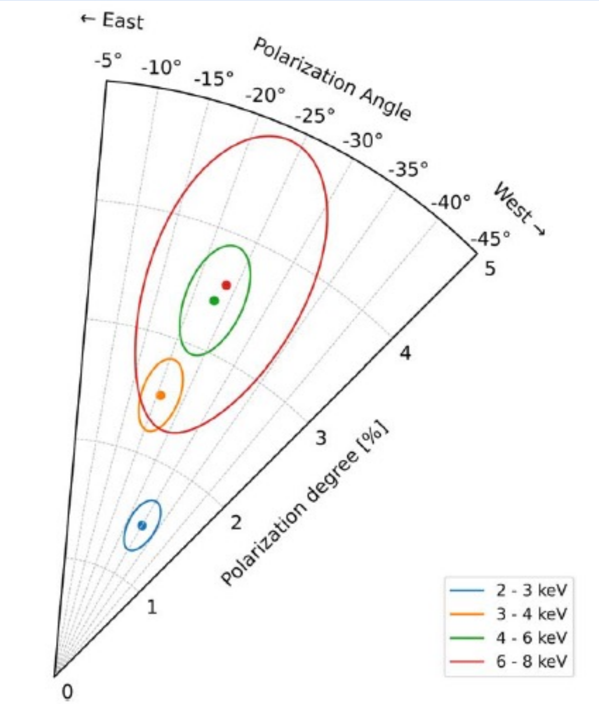

Steiner et al. 2025; Kravtsov et

Soft state:
PD = 2.0 ± 0.2 %
PA = −26 ± 2 deg



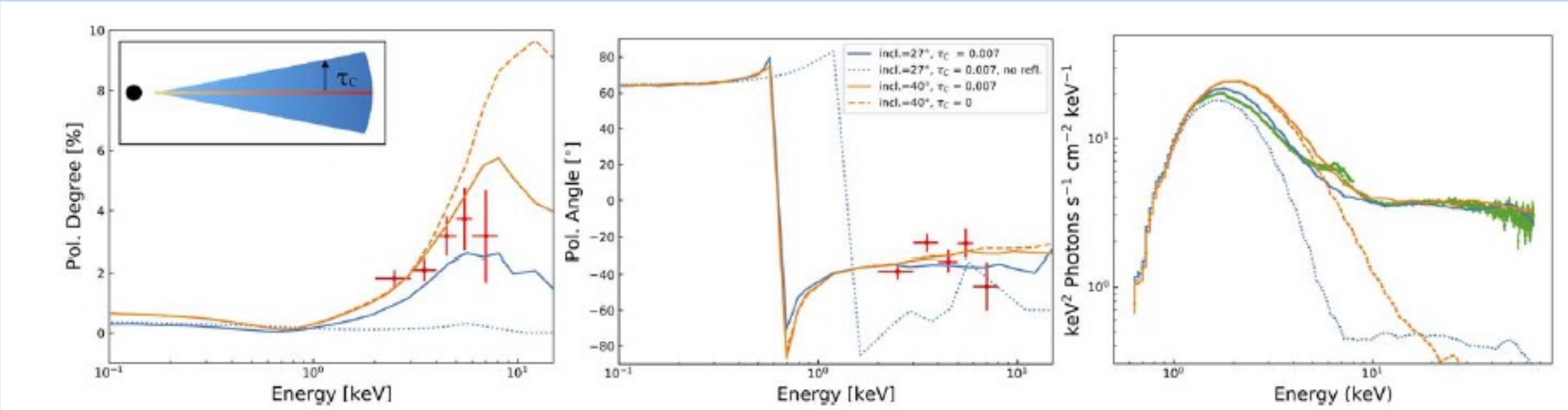

- **In the soft state polarization degree drops**
- **It is not surprising: the PD is the electron-scattering dominated atmosphere is very low at small inclinations.**
- **but the angle remains the same! This is not expected.**

# Soft state: Cygnus X-1

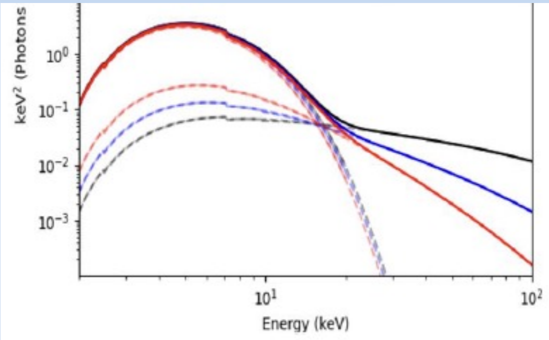


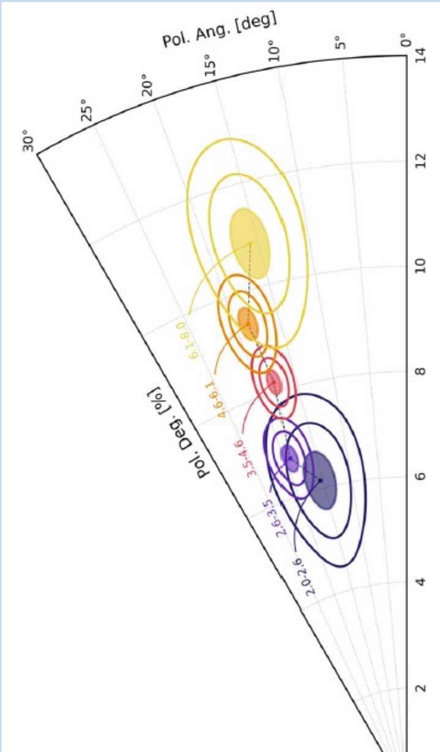

- PD grows with energy.
- Steiner et al. 2024 modeled the SED and polarization using kerrC model assuming spin a=0.998, disk albedo =1.
- Returning radiation was found to dominate the polarization signal.

- A reasonable fit was obtained for an inclination *i*=40°.

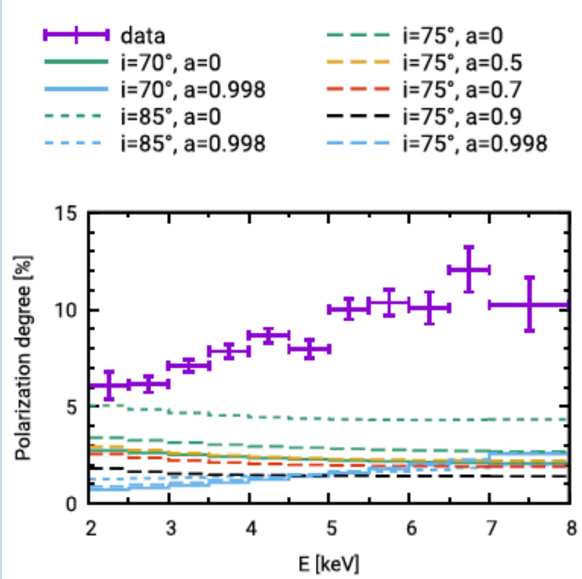


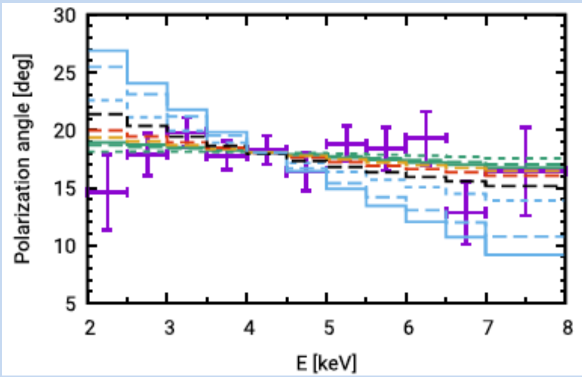
# *Soft state: 4U 1630–47*



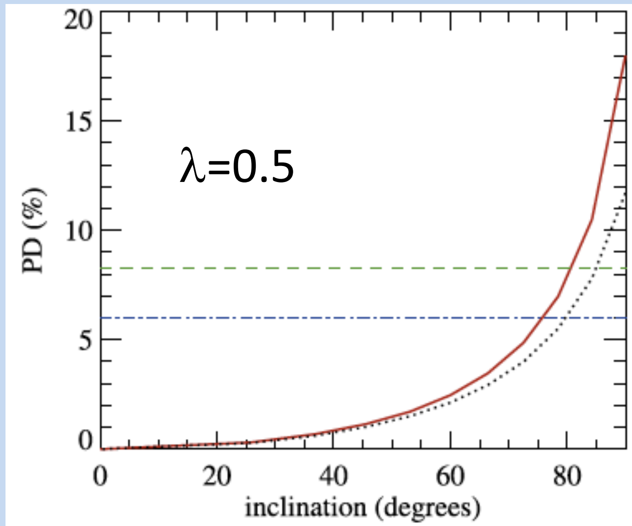




Ratheesh et al. 2024




- Very high PD, which grows with energy.
- PA is constant.
- Electron-scattering atmosphere is rejected: the fit requires i=85 deg, a>0.99, $M_{BH}$>50 $M_{\odot}$.
- Absorption in the atmosphere can increase PD (see below example with albedo for single scattering $\lambda$=**0.5**).



# *Conclusion*

- IXPE has opened a new window to the Universe.
- Observations of X-ray polarization has revolutionized our understanding of black hole X-ray binaries.
- IXPE allows to measure geometry of emission region in accreting black holes.

- In the hard state, emission (hot flow) region ⊥ jet. Lamp-post, jet - rejected.
- Cyg X-3 is identified with an ULX.
- PA in the soft state of Cyg X-1 same as in the hard state- role of returning radiation?
- Puzzling high polarization in the soft state of 4U 1630–47: pure electron scattering is rejected; influence of absorption? scattering is the wind?

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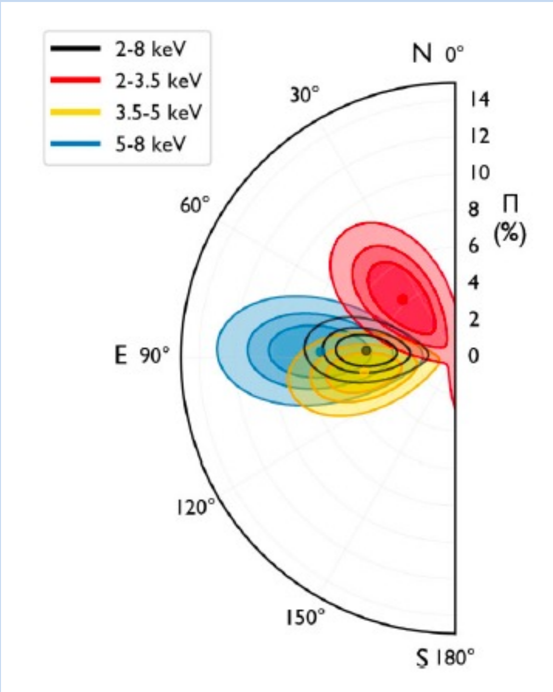
# *Conclusion*

- The 2024 Bruno Rossi Prize has been awarded to Dr. Martin Weisskopf, Dr. Paolo Soffitta, and the IXPE team for their development of the Imaging X-ray Polarimetry Explorer whose novel measurements advance our understanding of particle acceleration and emission from astrophysical shocks, black holes and neutron stars

- The Bruno Rossi Prize is awarded annually in honor of Bruno Rossi "for a significant contribution to High Energy Astrophysics, with particular emphasis on recent, original work."

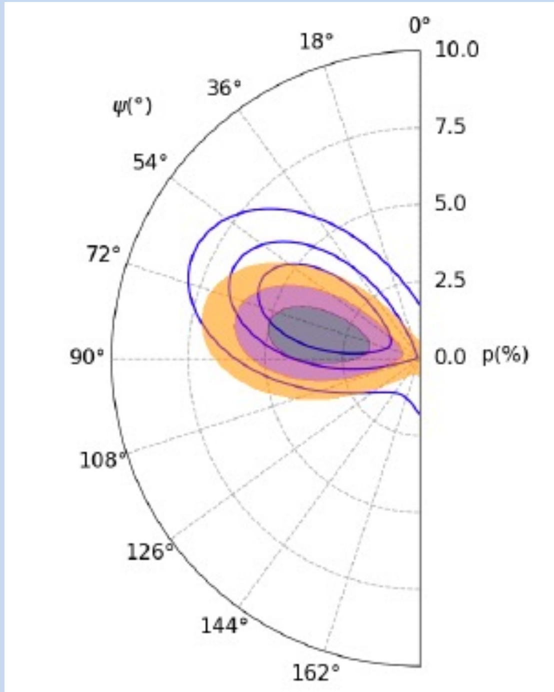
# Seyfert 1 galaxies

NGC 4151; PD=4.9±1.1 %, PA=86°±7°. PA is parallel to the extended radio emission with position angle of 83°.




Gianolli et al. 2023

IC 4329A: PD=3.3±1.1 %, PA=78°±10°. PA parallel to the jet.




Ingram et al. 2023

- **Geometry – slab, similar to Cyg X-1. Not a lamp-post or a sphere.**
- **Black hole spins are usually determined using a lamp-post model of the emission region at the spin axis. Our results imply that the spins are likely systematically affected.**

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X-Ray
Polarimetry
Explorer

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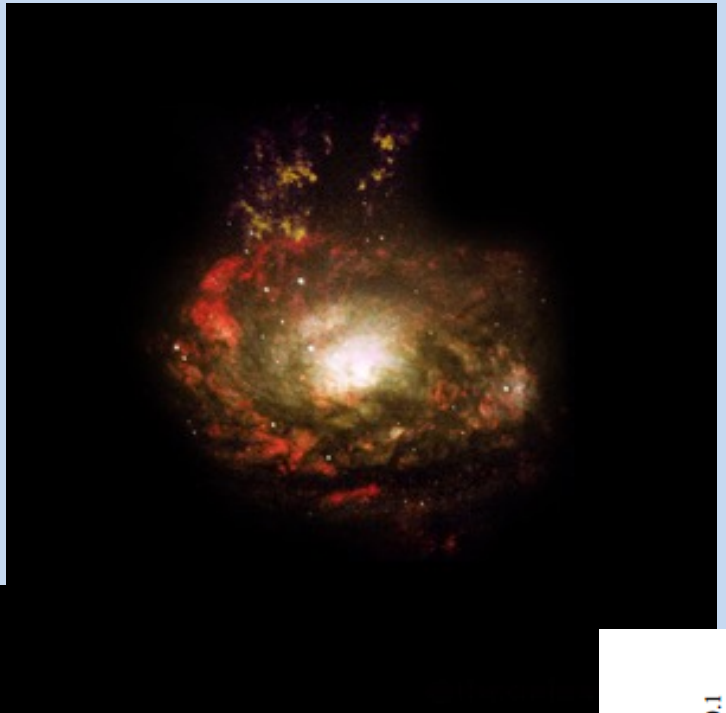
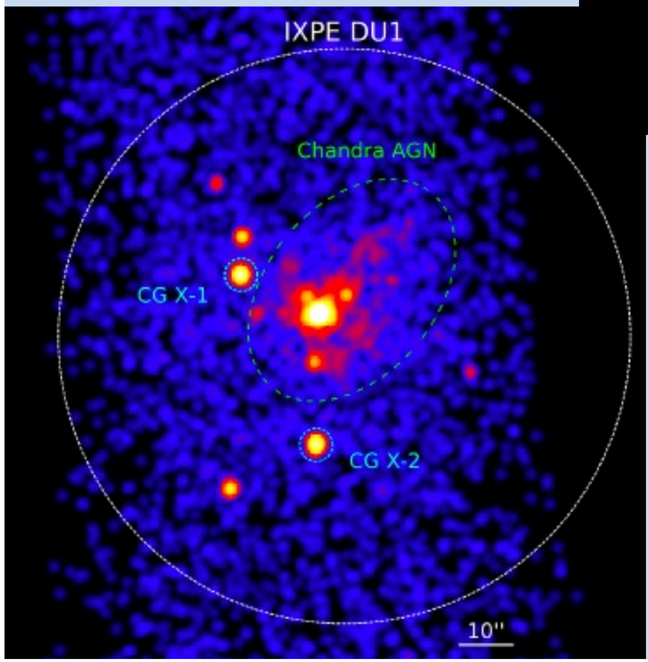
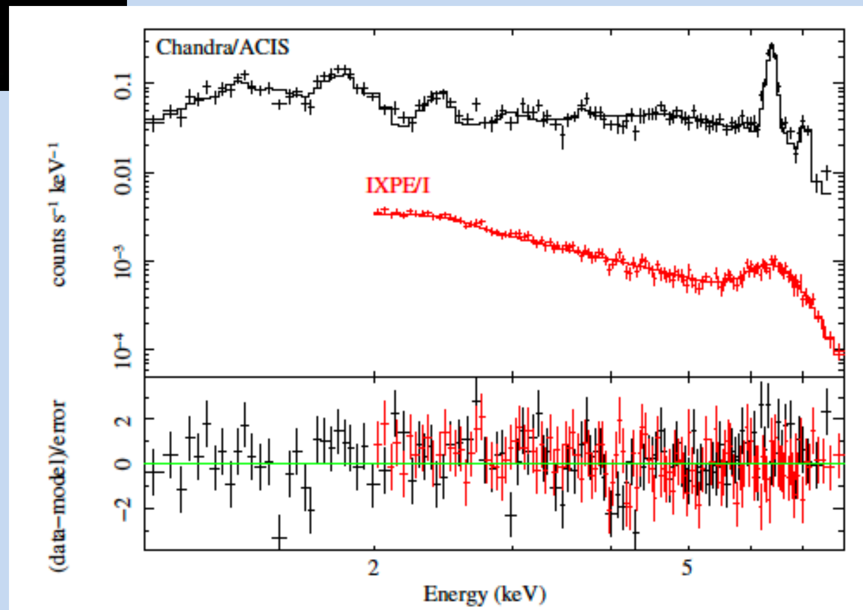
# *Circinus galaxy (Seyfert 2)*

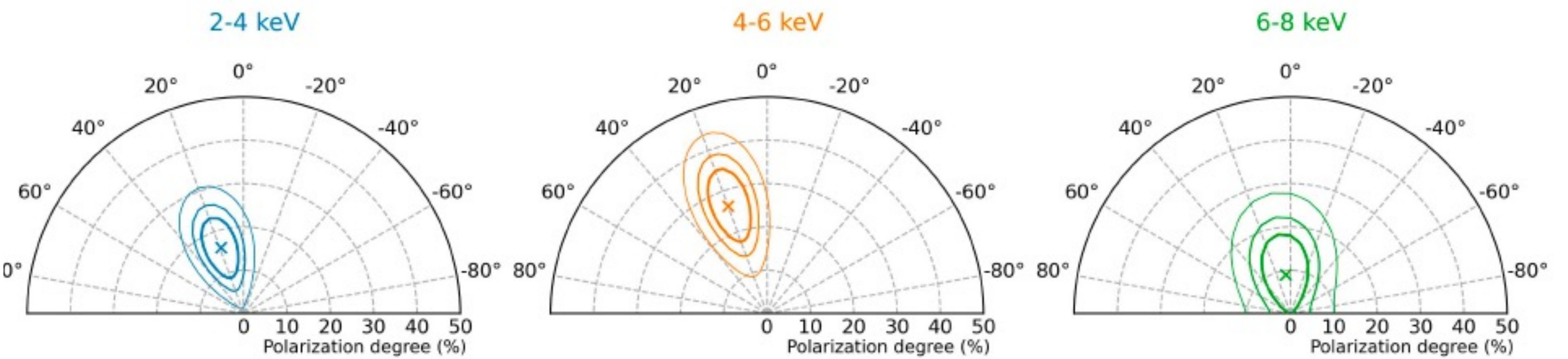




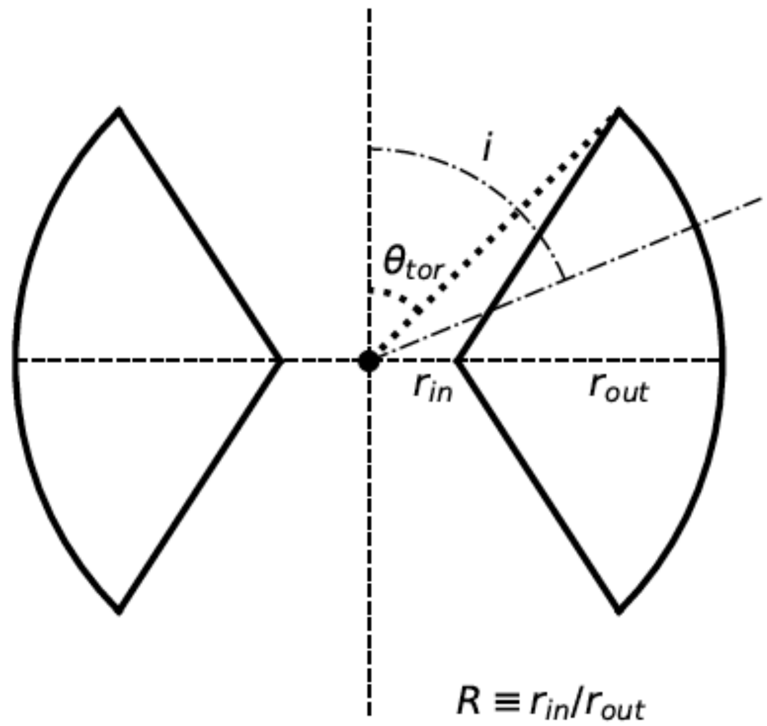
# *Circinus galaxy (Seyfert 2)*

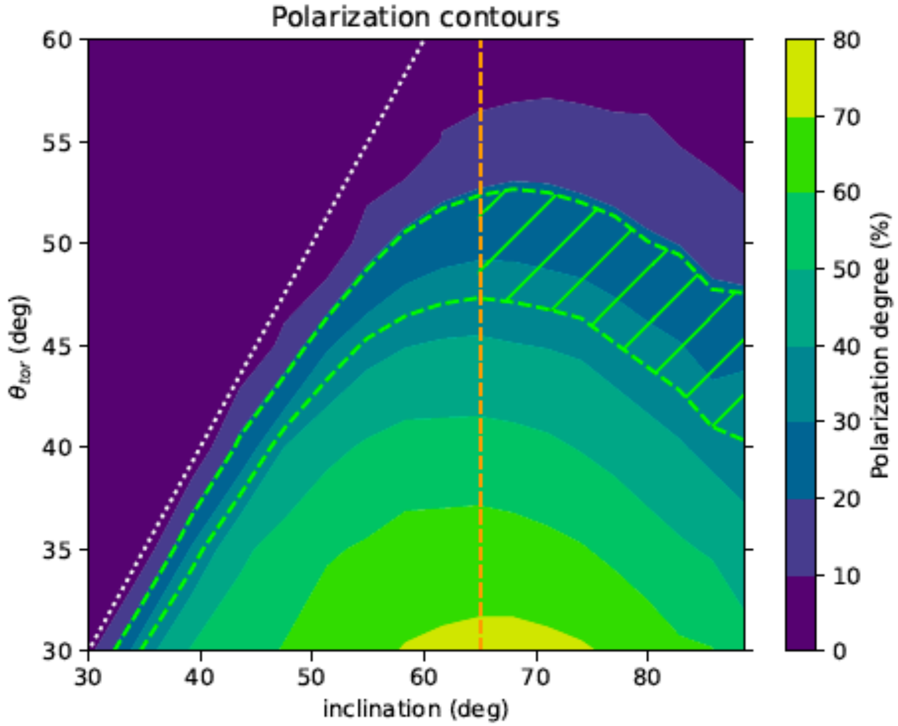
| Energy | P.D. (%) | P.A. (deg) |
|---|---|---|
| 2–8 keV | 17.6 ± 3.2 | 16.9 ± 5.3 |
| 2–4 keV | 16.0 ± 4.9 | 19.1 ± 8.9 |
| 4–6 keV | 26.3 ± 5.7 | 20.2 ± 7.5 |
| 2–6 keV | 20.0 ± 3.8 | 19.1 ± 5.5 |
| 6–8 keV | < 24.5 | - |




Ursini et al. 2023

# *Circinus galaxy (Seyfert 2)*




Single scattering by a toroidal surface gives 25% polarization for 45 deg opening angle of the torus and 65 deg inclination.

X-ray polarization support unification scheme of AGNs.