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IXPE Studies of Accreting Black Hole X-ray Binaries

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CDY seminar

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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.

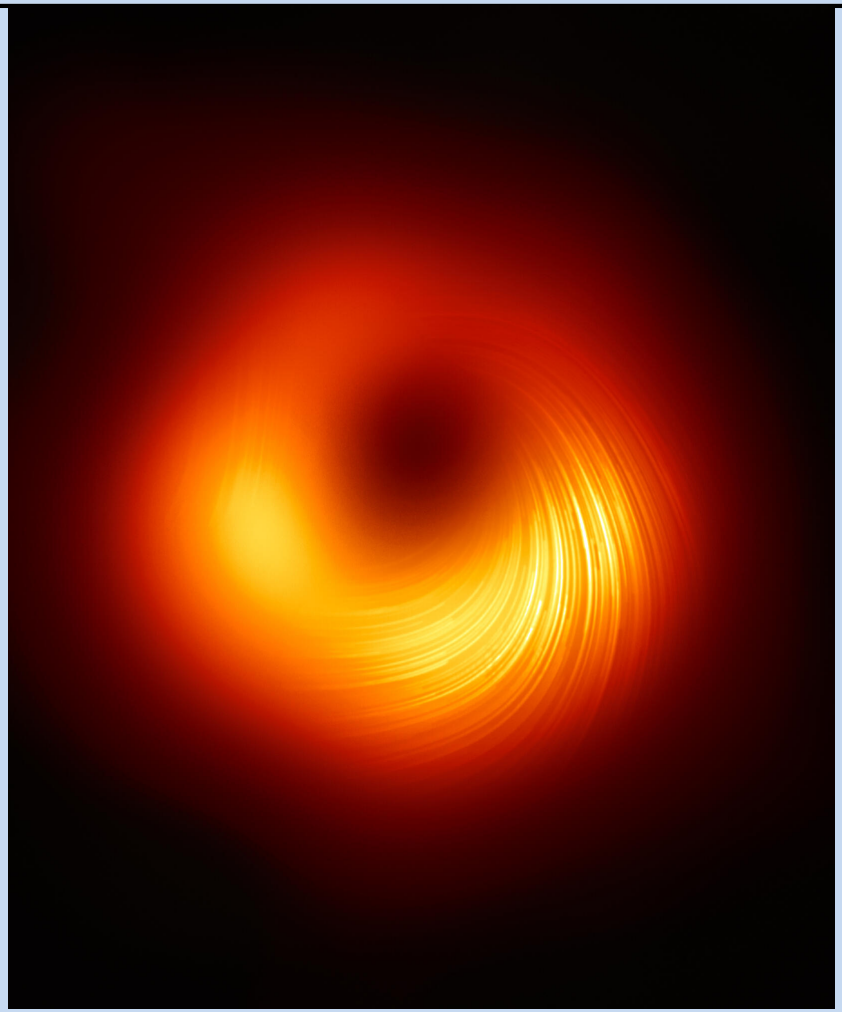

Image of a super-massive black hole in M87 with EHT and the magnetic field orientation.

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Introduction

Stokes parameters *I, Q, U, V* describe the polarization state of electromagnetic radiation.

In the X-rays, we cannot measure (in space) circular polarization, only the linear one.

Normalized Stokes parameters $q=Q/I$, $u=U/I$.

Preferential direction of the electric vector oscillations defines the polarization angle (PA) $= \frac{1}{2}\mathrm{atan}\frac{u}{q}$.

Polarization degree (PD) $= \sqrt{q^2+u^2}$

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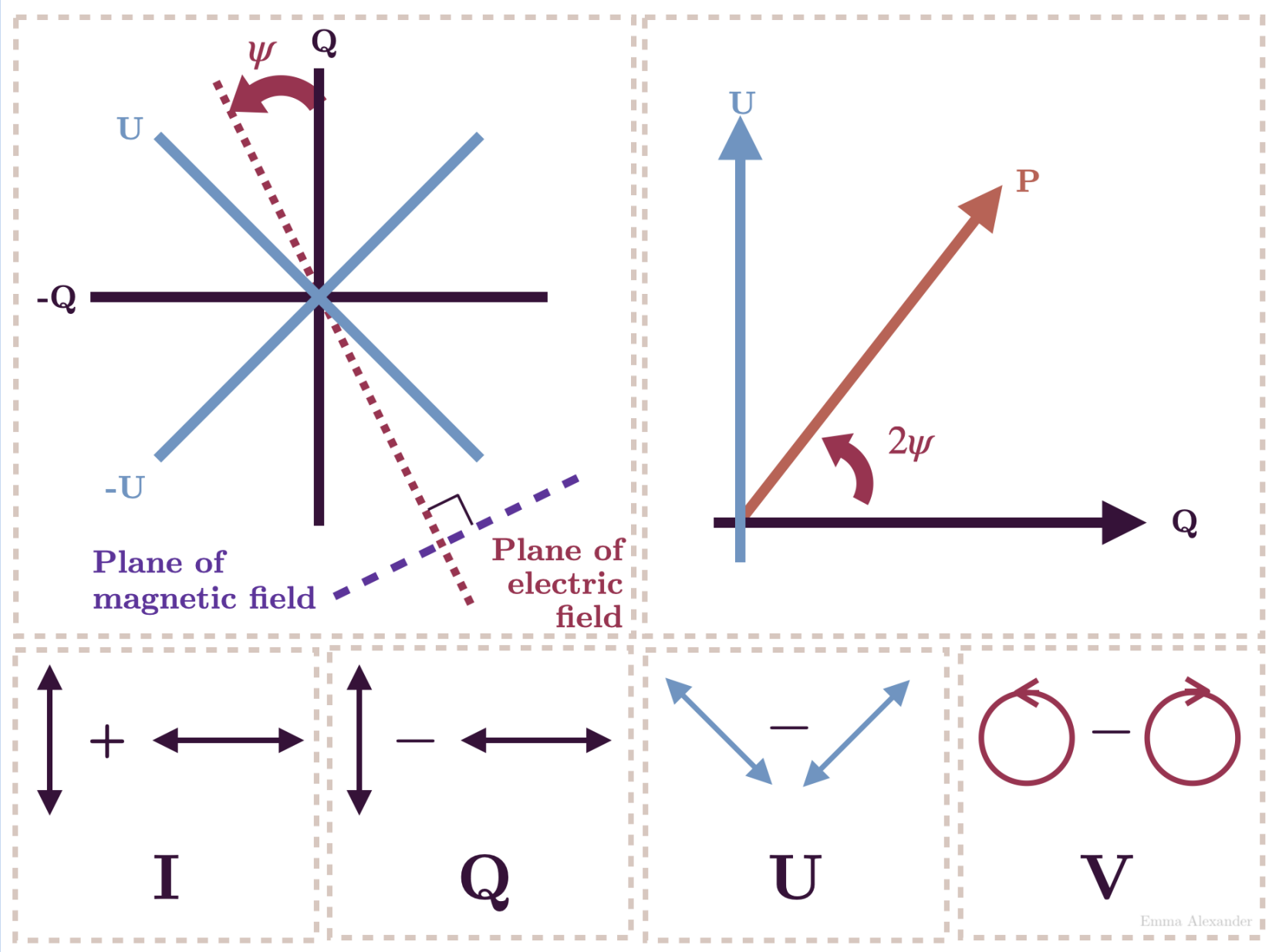
Introduction



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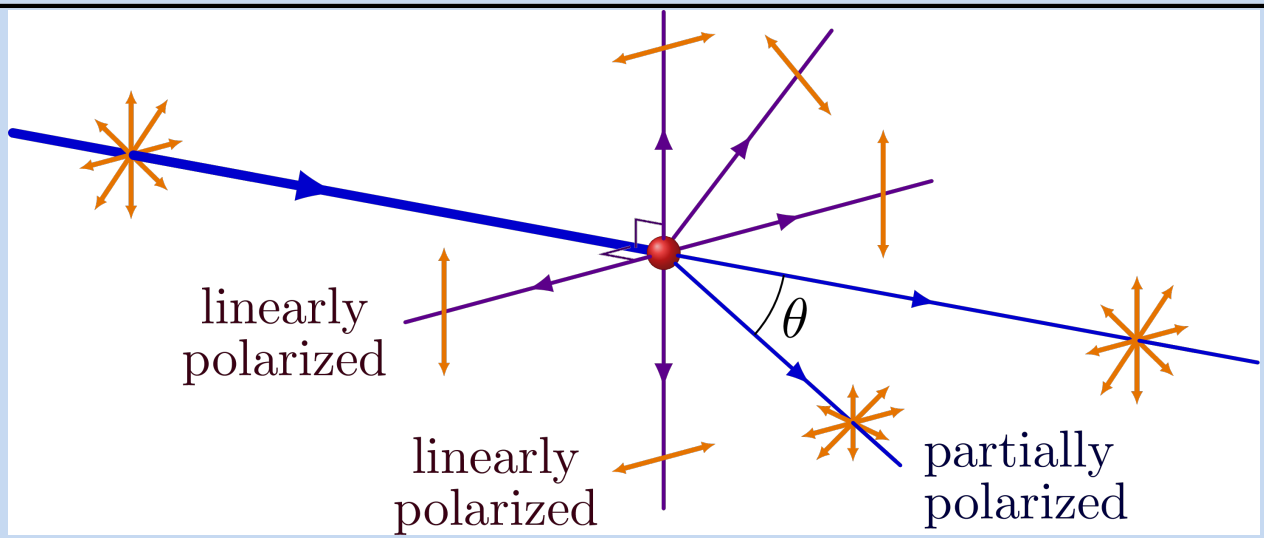
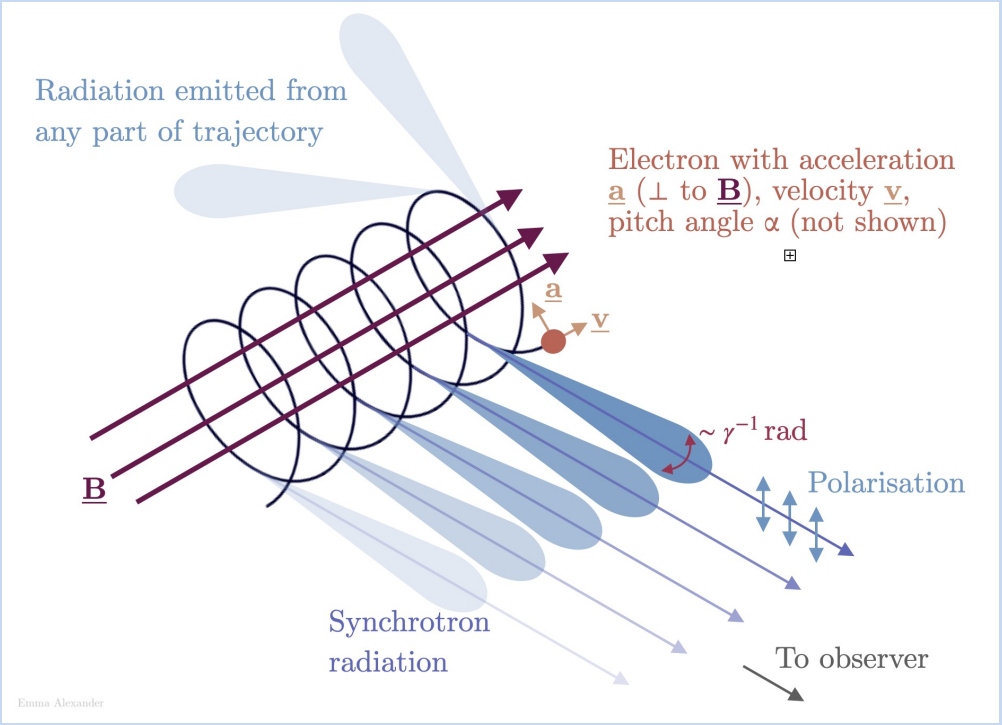
Introduction

Electron scattering



Synchrotron radiation



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Marshall Space Flight Center

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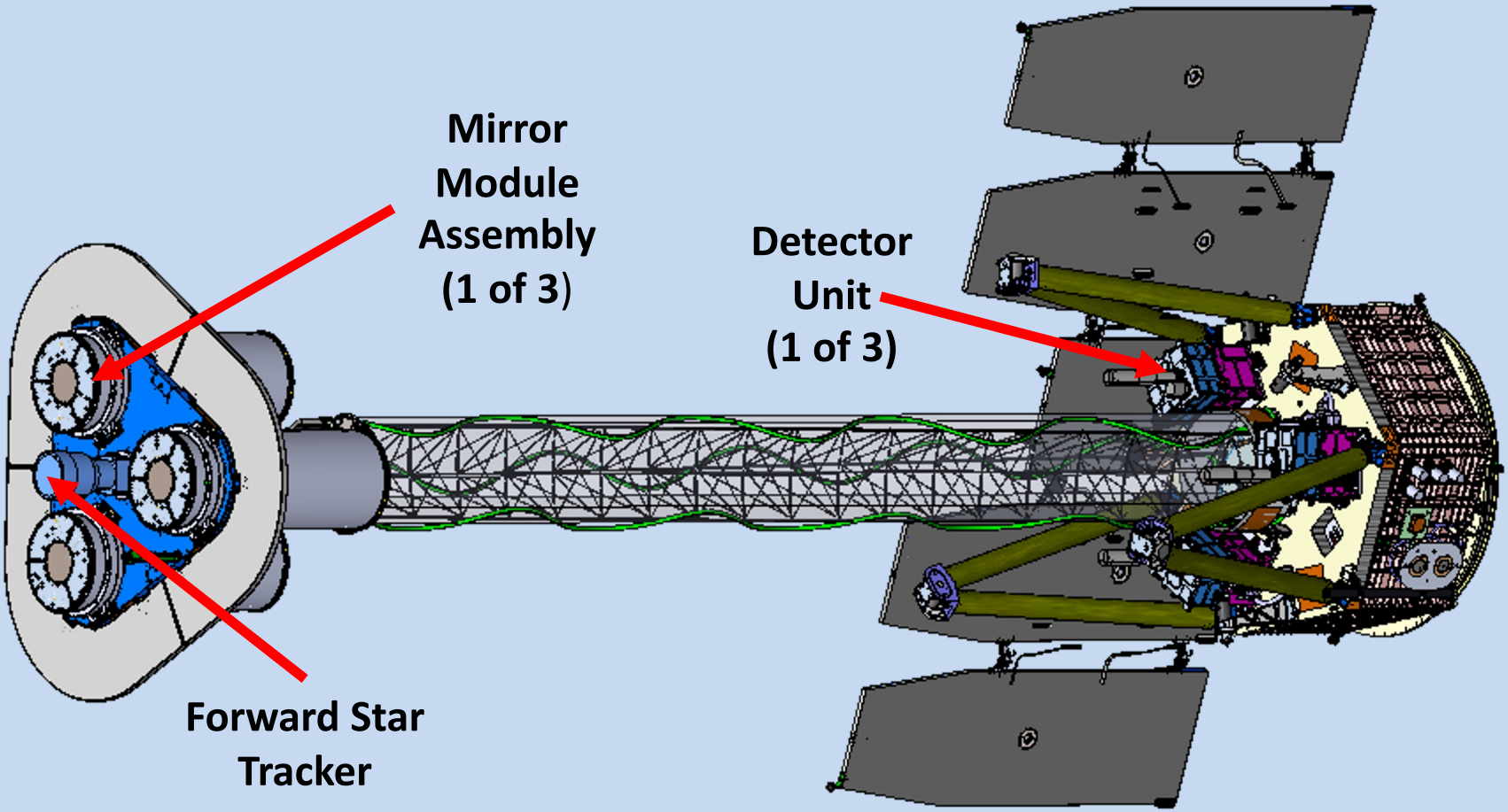
IXPE launched on 2021 Dec 9



5.2 m total length
4.0 m focal length

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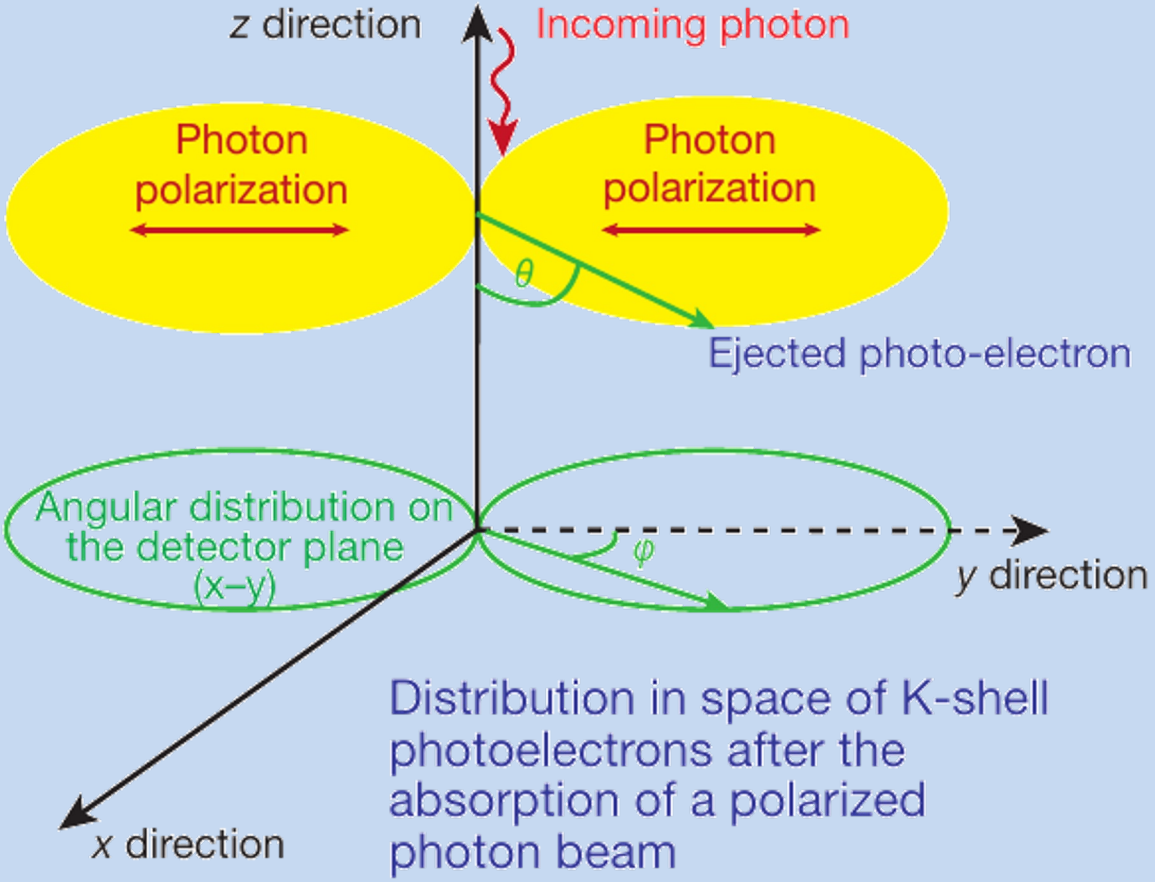
Detection Principle

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



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

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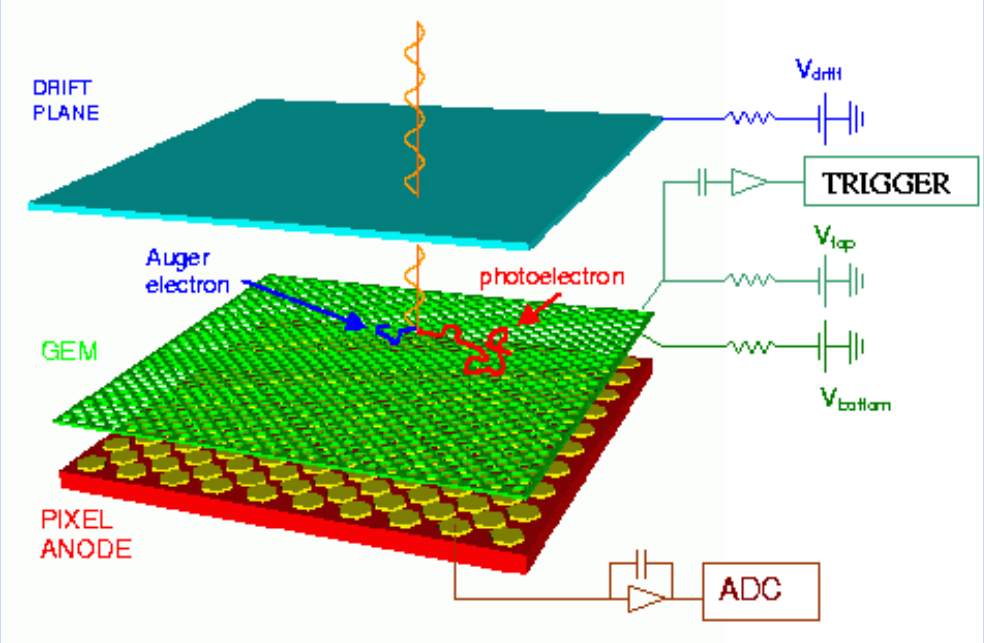
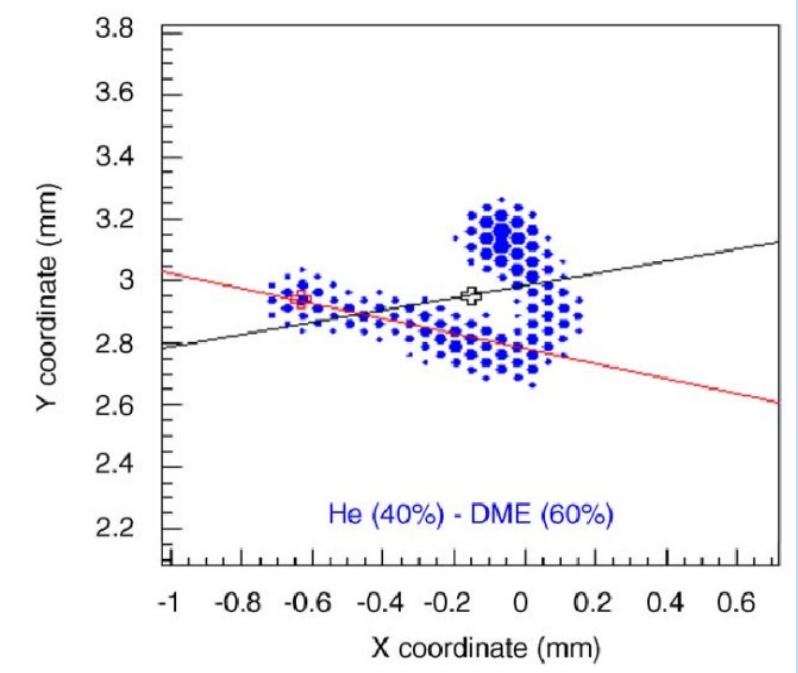
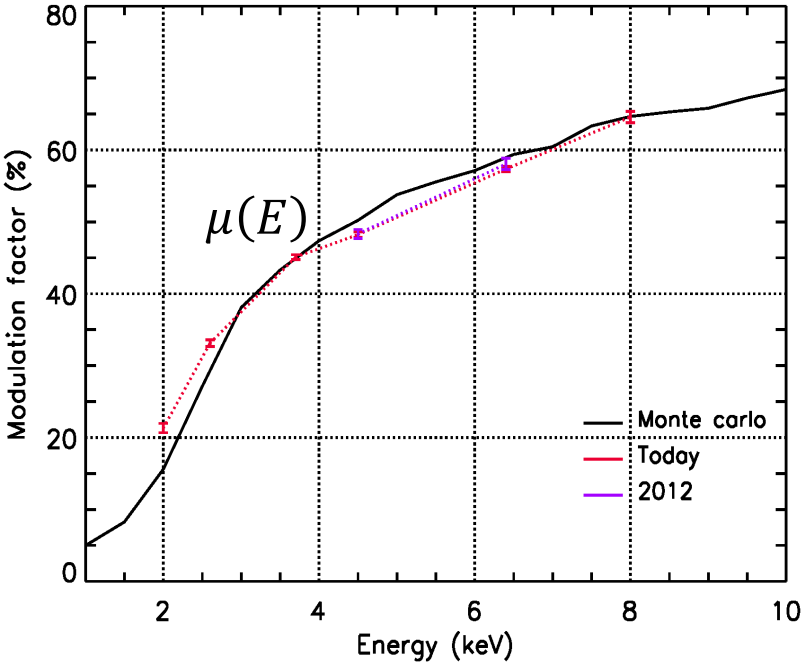
Gas Pixel Detector

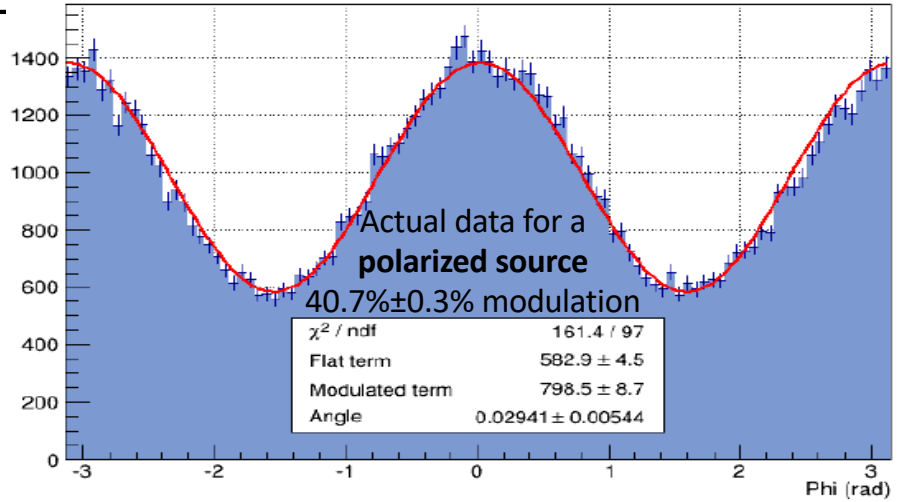


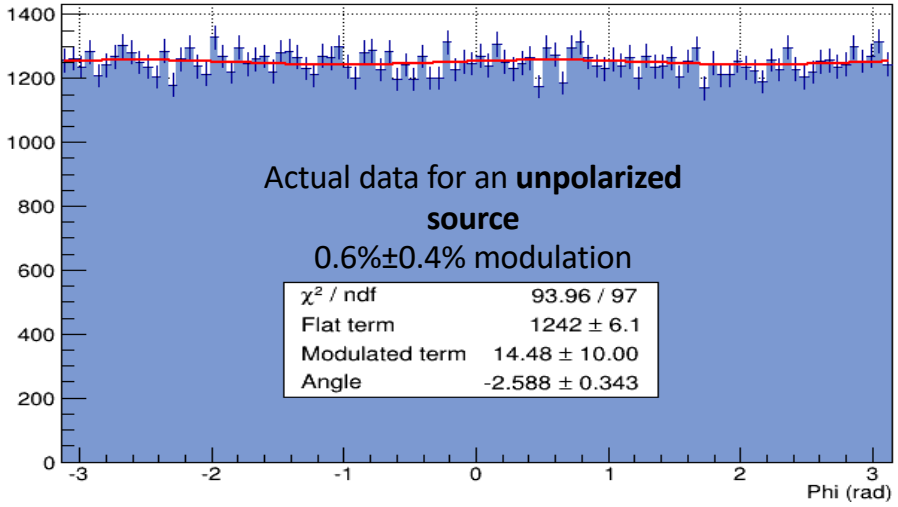


POLARIZATION FROM MODULATION HISTOGRAM AND CALIBRATED MODULATION FACTOR

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







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

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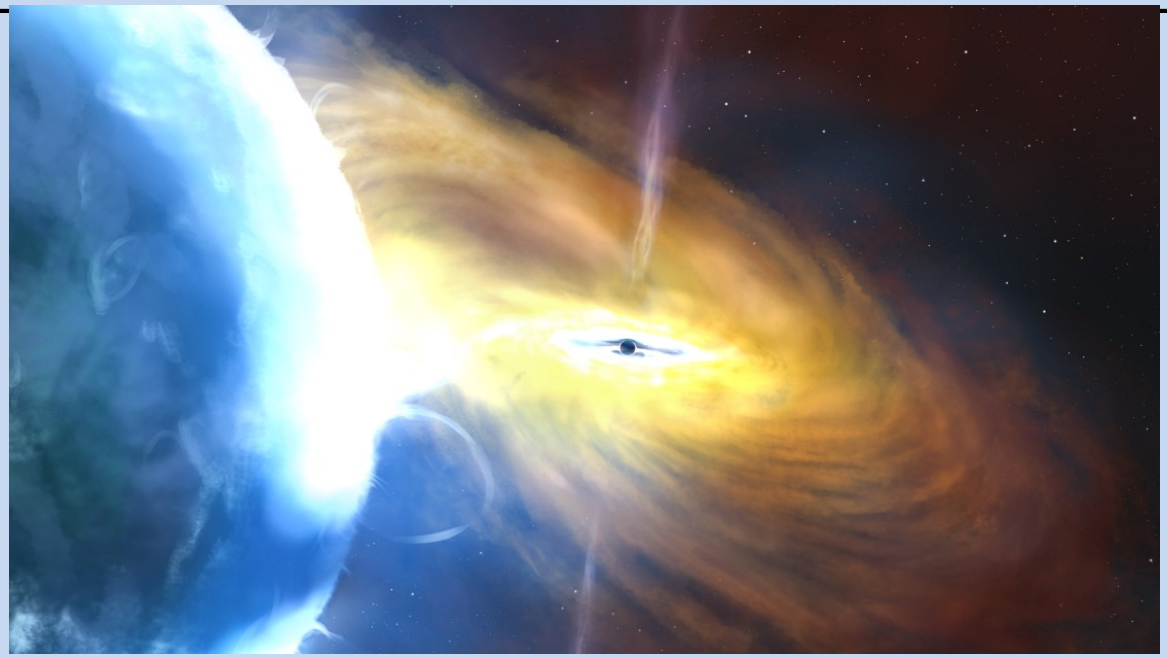
Questions



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?

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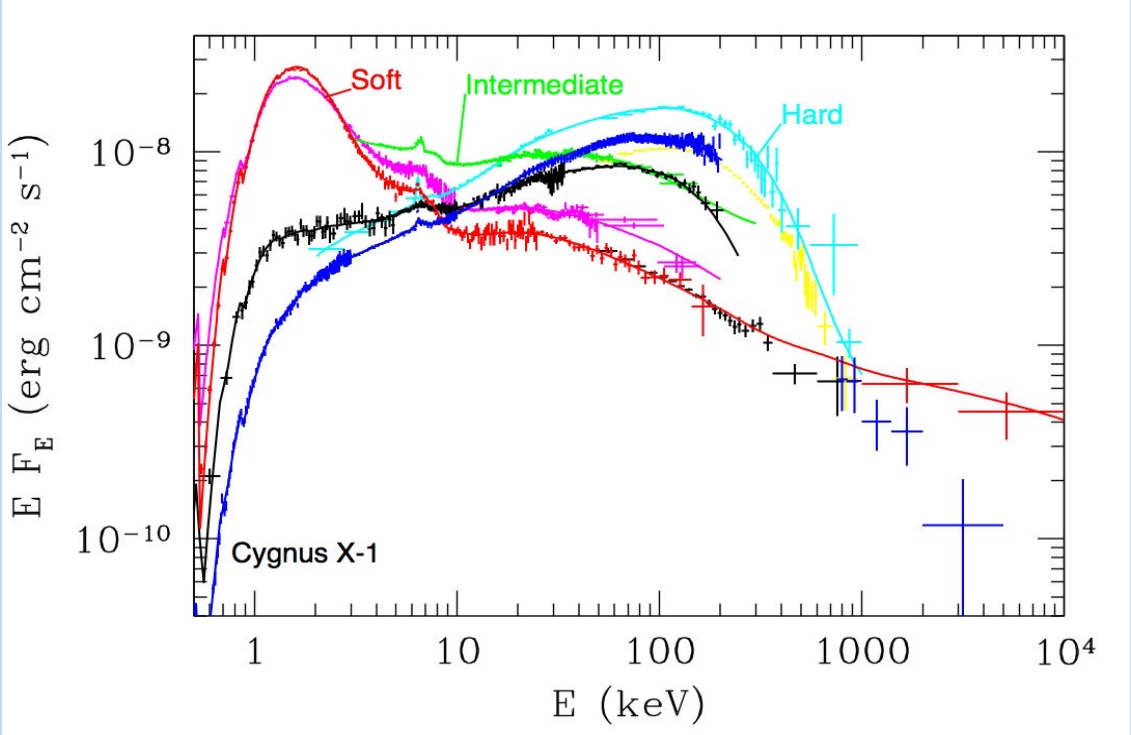
Spectral states



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

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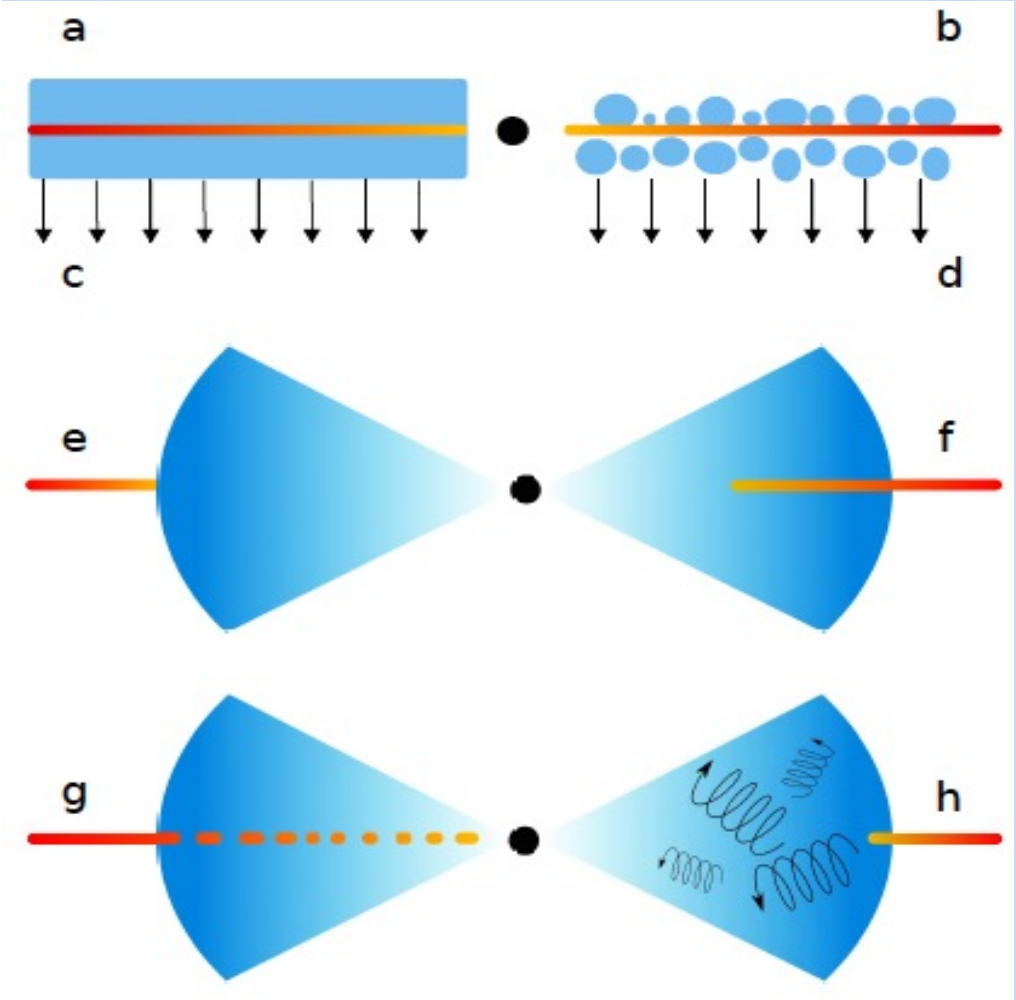
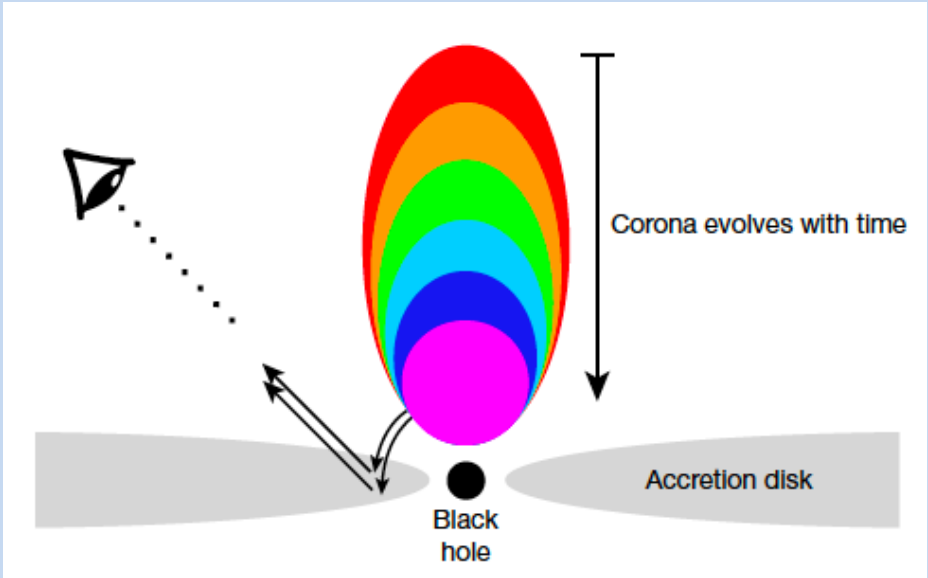
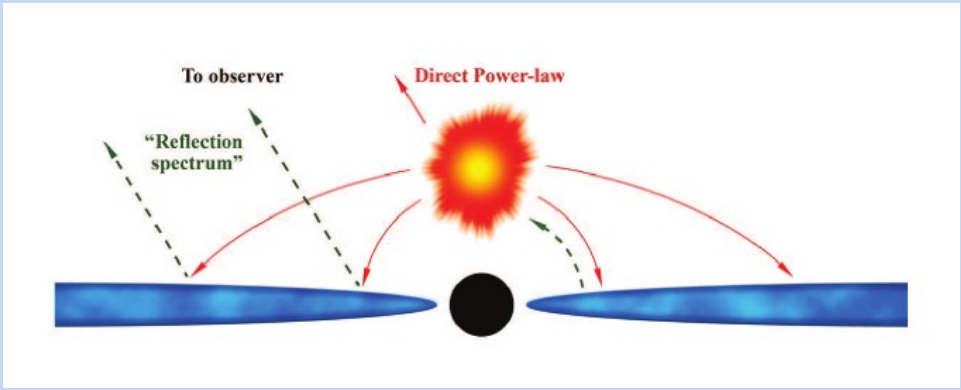
Hard state geometry



Poutanen et al. 2018



Kara et al.2019



Fabian et al.

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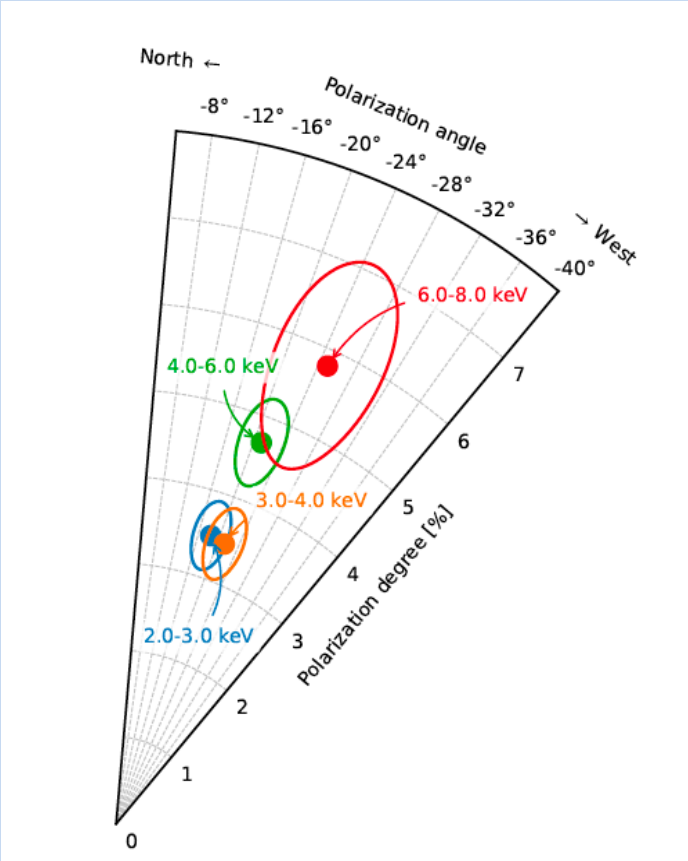
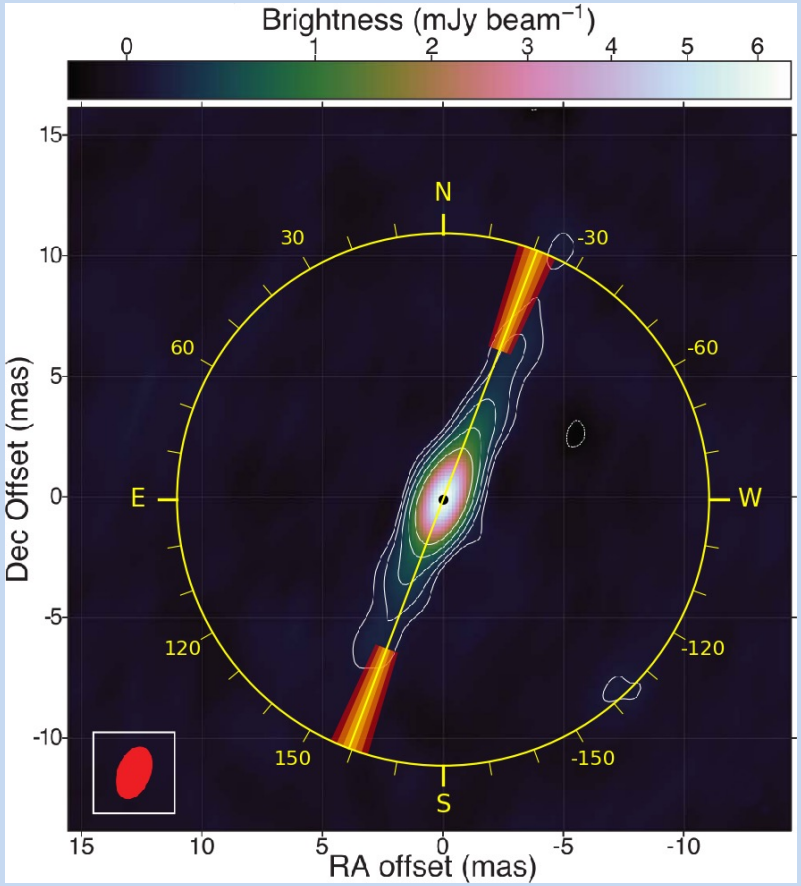
Cygnus X-1

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





X-ray polarization parallel to the jet

PD = 4.0 ± 0.2 %
PA = −20.7 ± 1.4 deg

Krawczynski et al. 2022, Science

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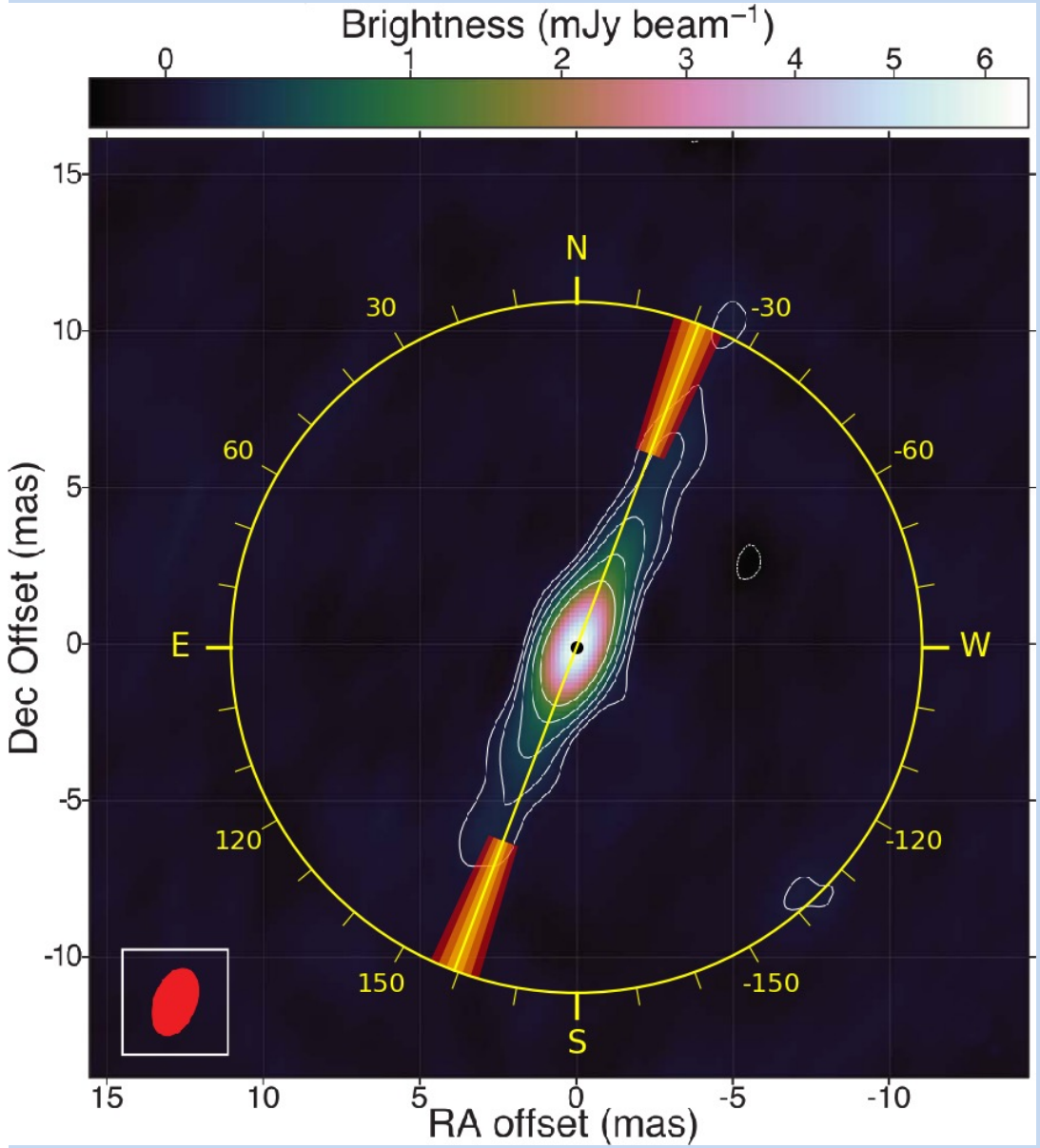
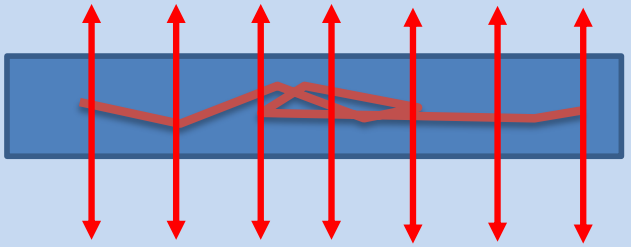
Cygnus X-1



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 produces polarization normal to the scattering plane.

- How to get 4% polarization?

Aberration in a mildly relativistic outflow? (JP, Veledina,Beloborodov 2023)
Scattering in equatorial wind? (Nitindala, Veledina,JP 2025)

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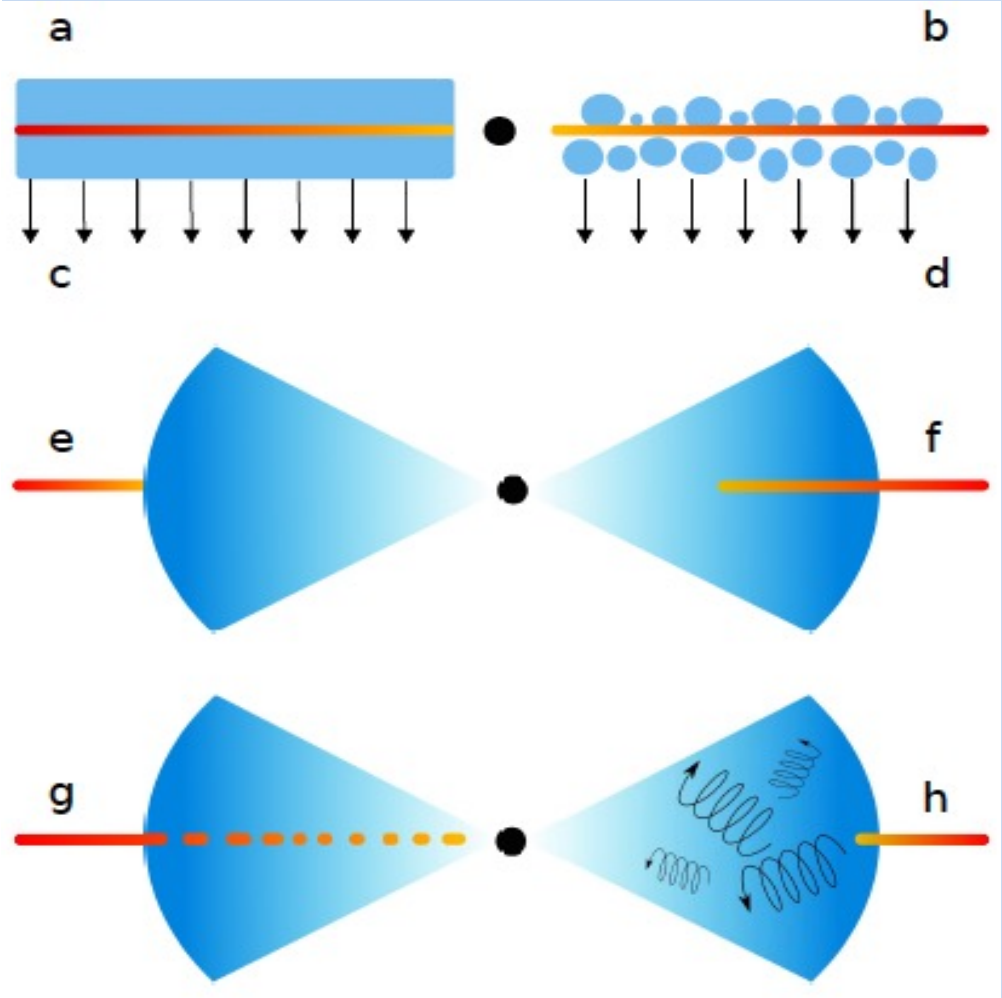
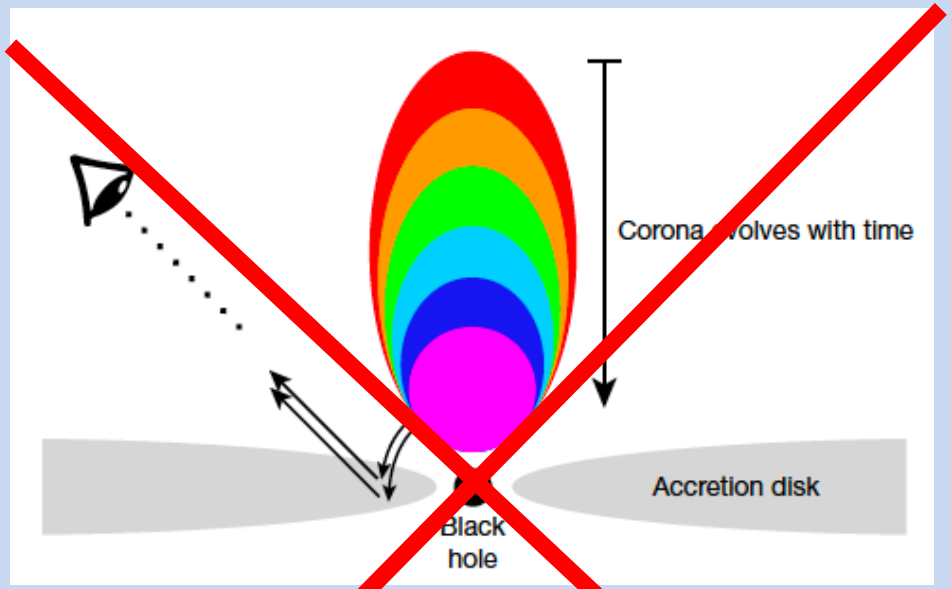
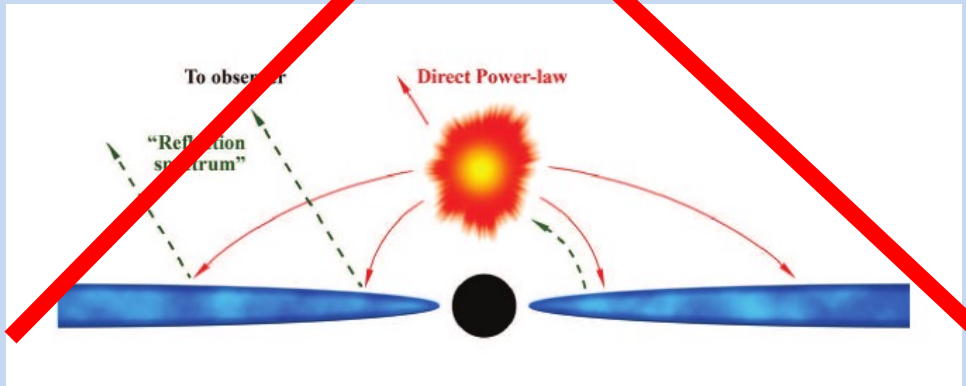
Hard state geometry

Jet and lamp-post models are rejected







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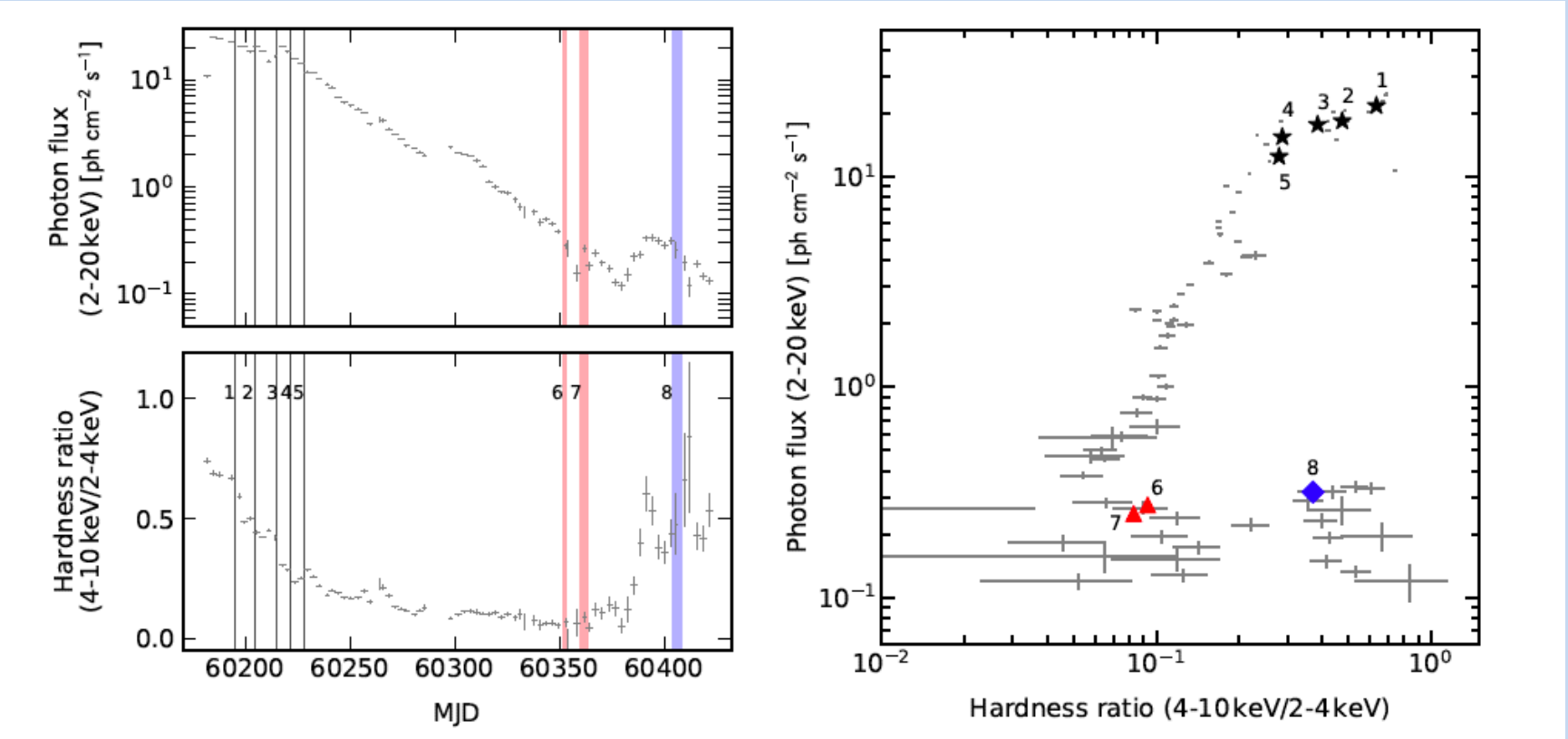
Swift J1727.8−1613

Outburst starting from August 2023



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

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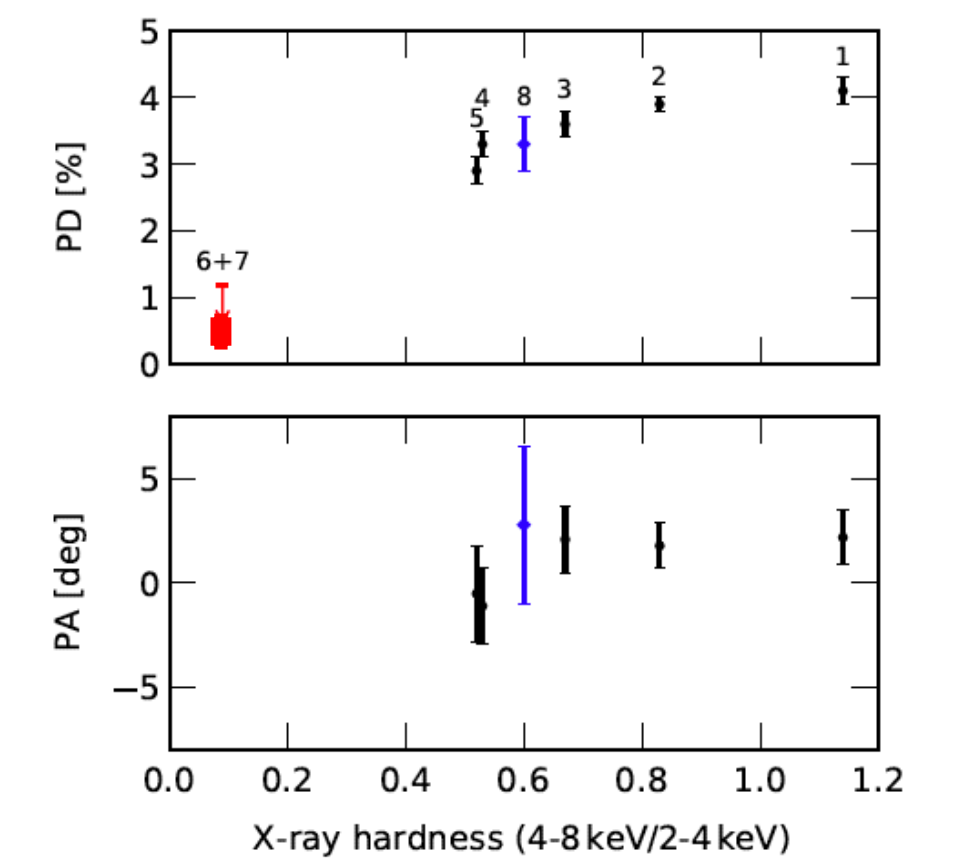
Swift J1727.8−1613



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

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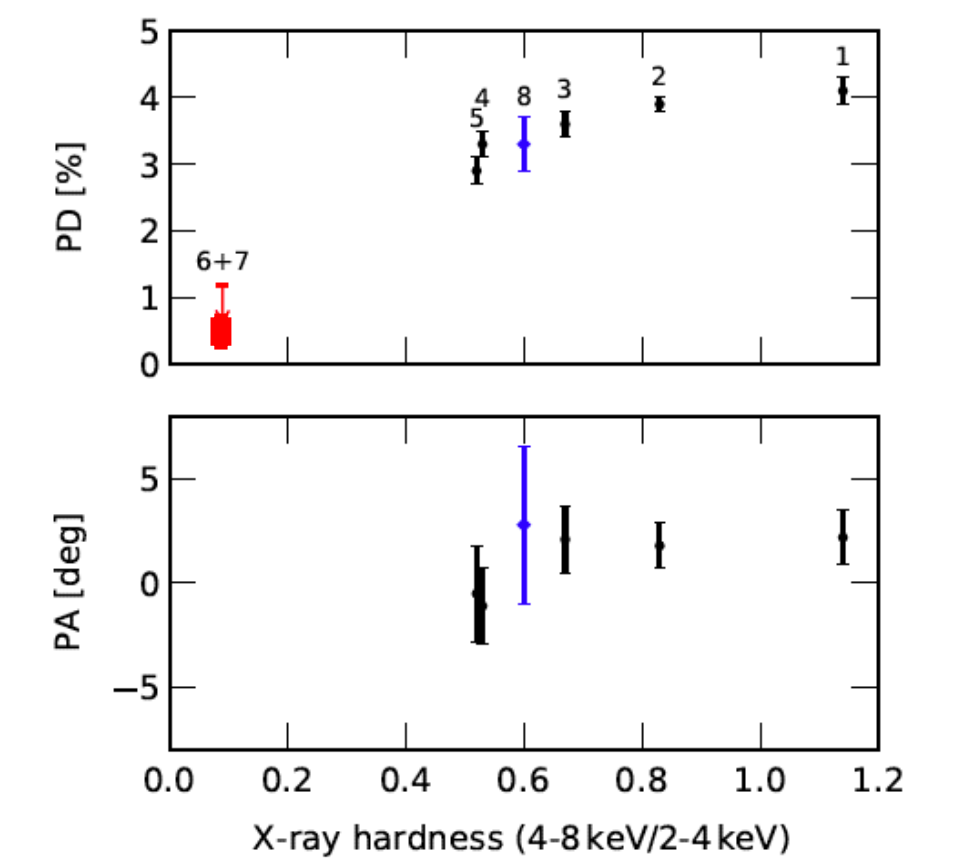
Swift J172



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PD=4.
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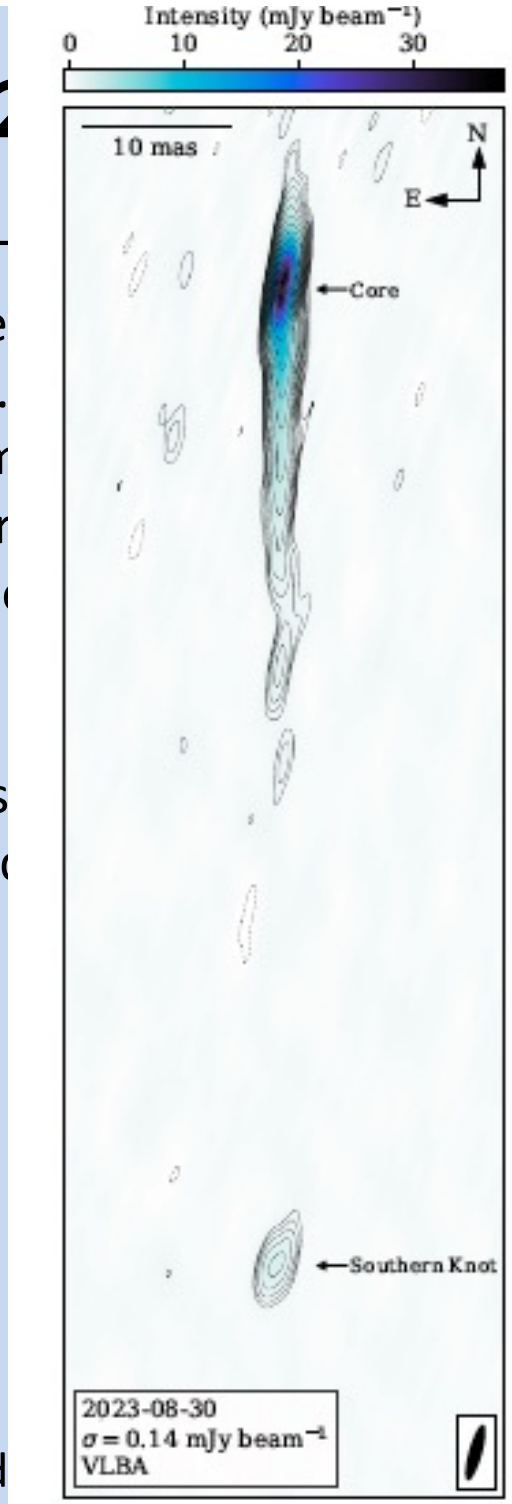

Veledina+ 2023, Ingram+ 2024, Svoboda+2024, Pod

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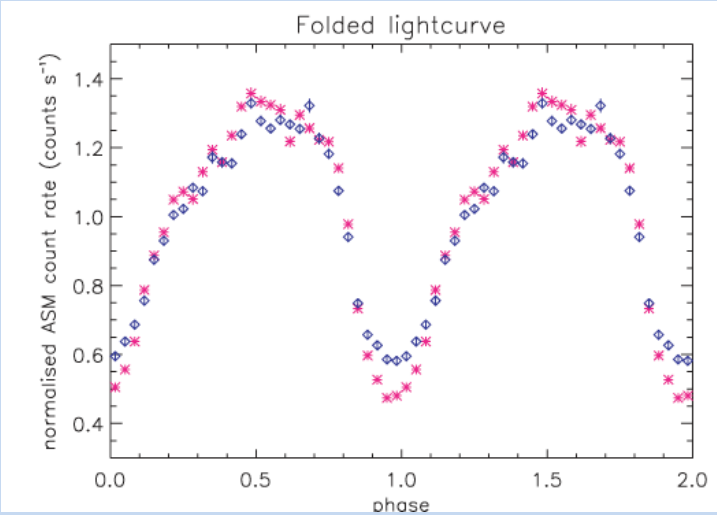
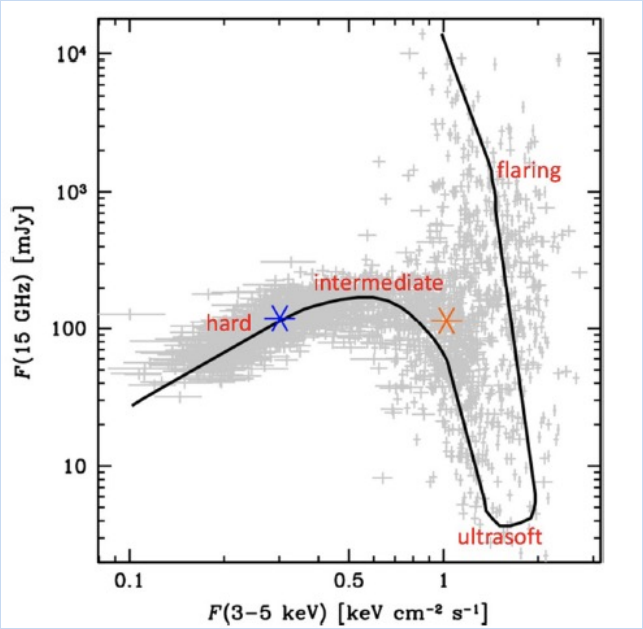
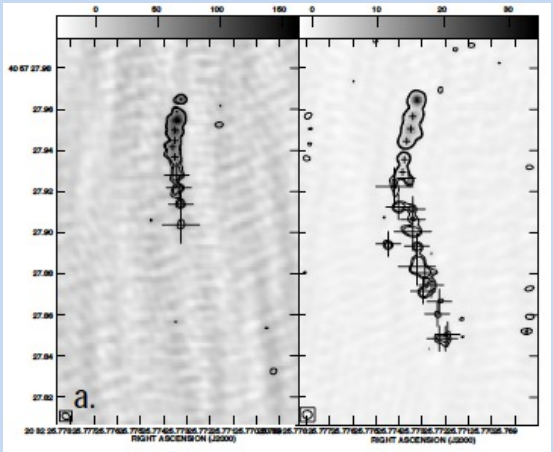
Cygnus X-3

- Orbits a Wolf-Rayet star with the period of $P_{\rm orb} = 4.8^{\rm h}$.
- 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.





Miodzuszewski et al. 2001



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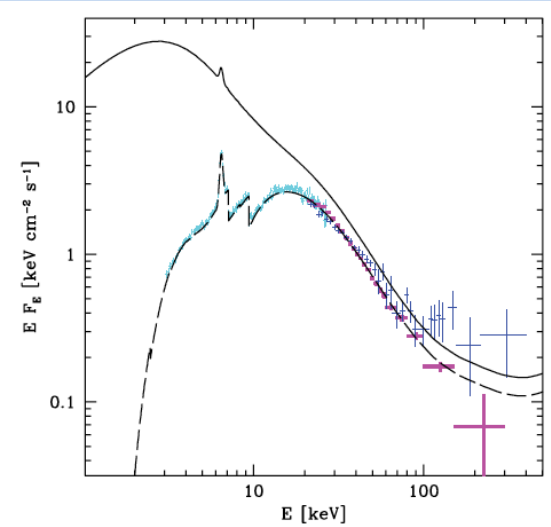
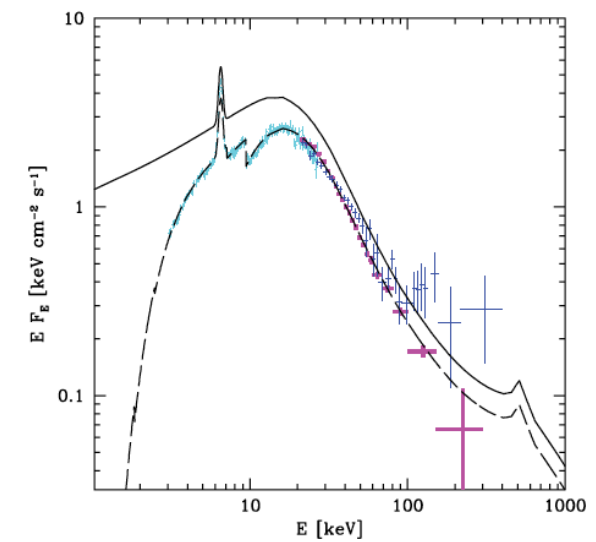
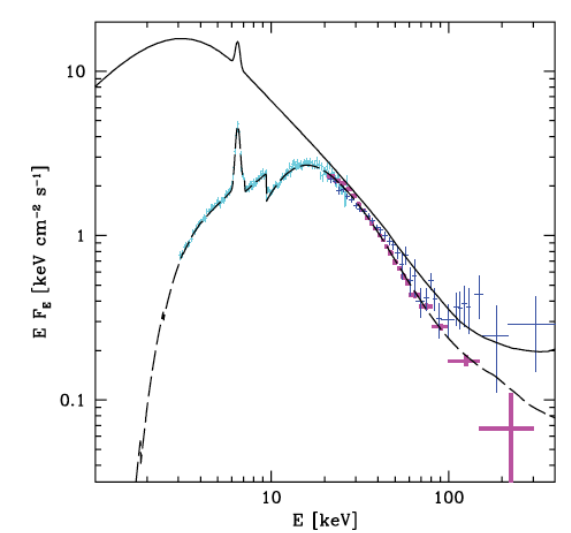
Cygnus X-3

- 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







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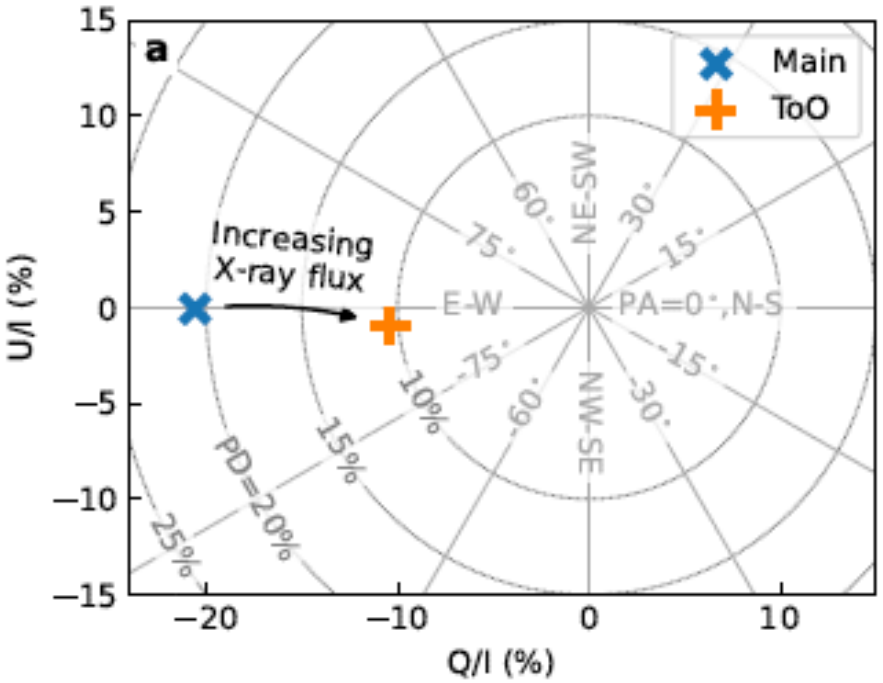
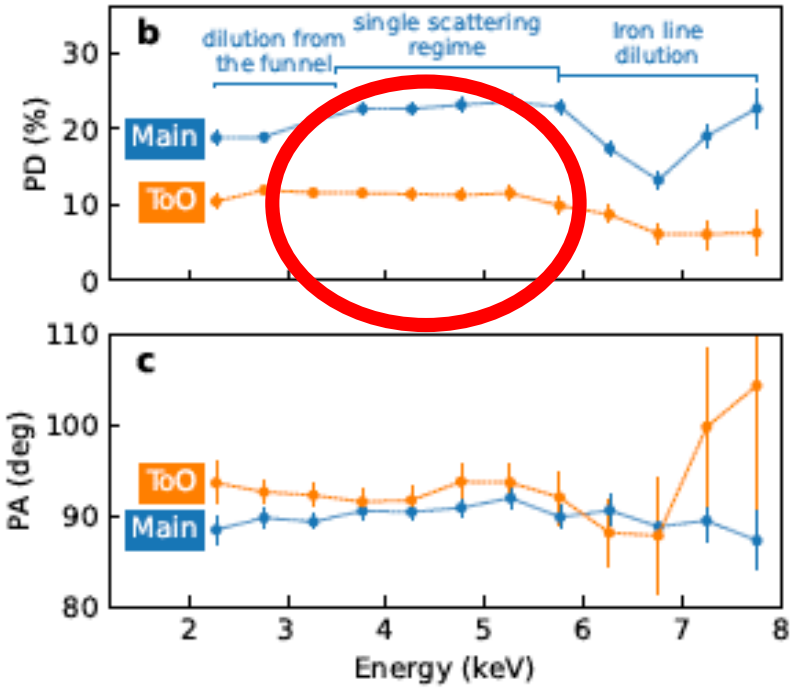
IXPE observations of Cygnus X-3





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

PD = 20.6 +/- 0.3 %
PA = 90.1 +/- 0.4°

PA perpendicular to the jet!

PD = 10.4 +/- 0.3 %
PA = 92.6 +/- 0.7°

Veledina et al. 2024, Nat Astro

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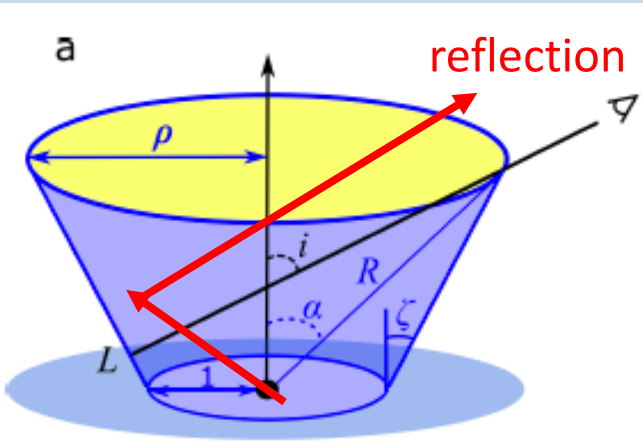
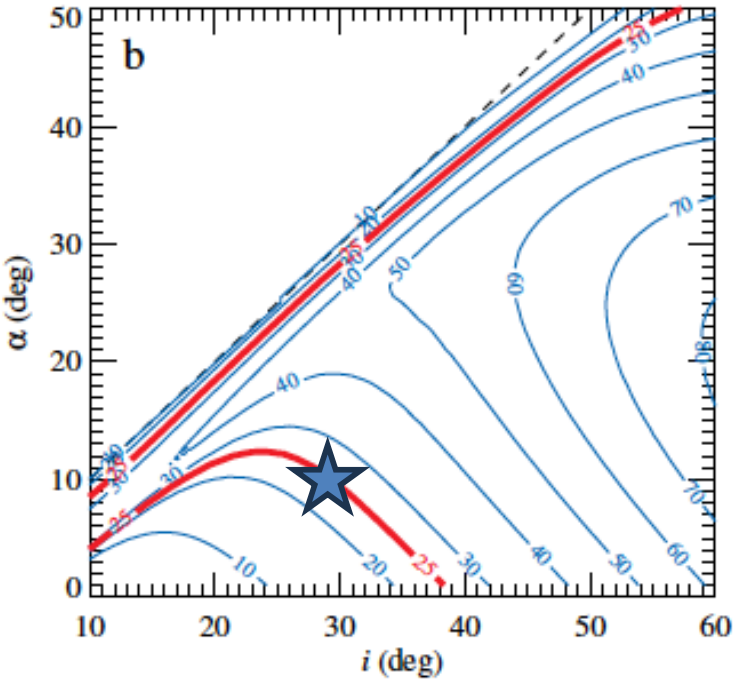
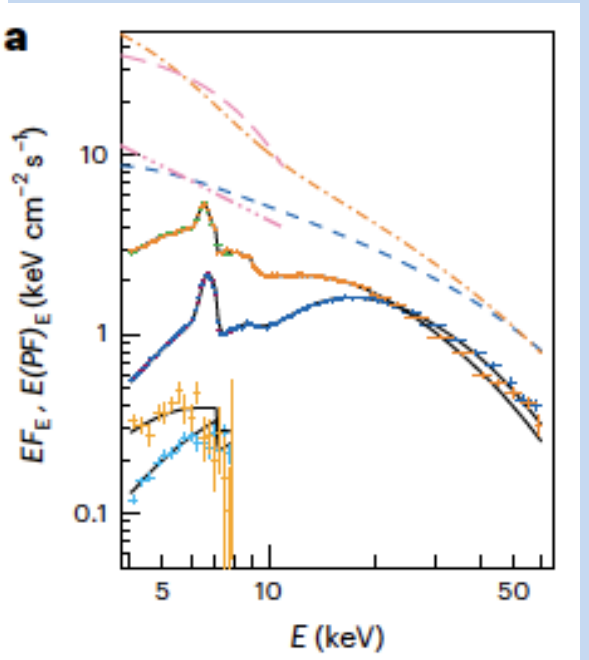
X-ray polarization: reflection from the funnel wall







- PA $\perp$ 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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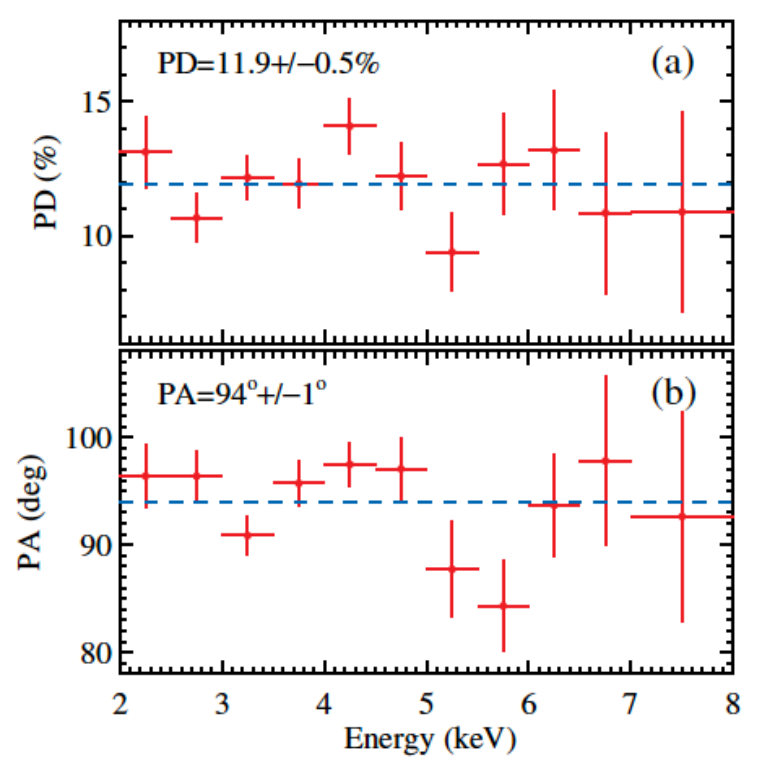
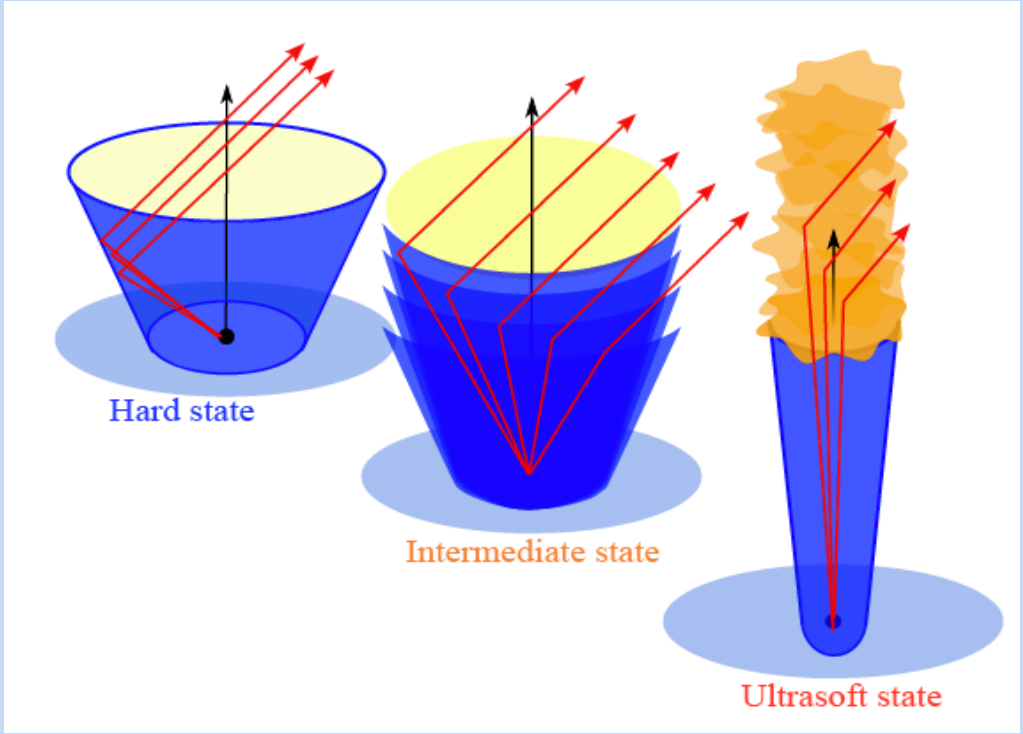
X-ray polarization: reflection within the funnel

- In the (ultra-)soft state, the spectrum is blackbody-like, very weak iron line, the PD was expected to be very low.
- However, it turned out to be PD=12% at nearly the same PA=94°. No energy dependence (in particular around Fe line).





Veledina et al. 2024, A&A Letters

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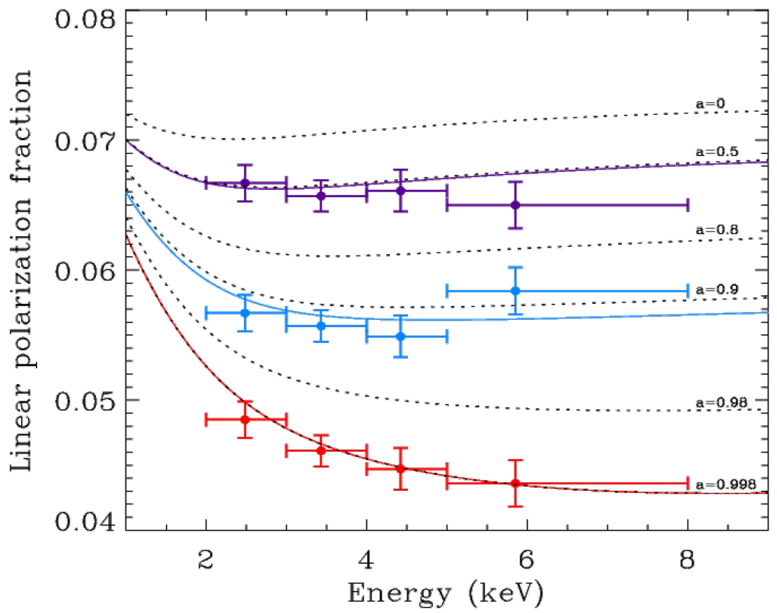
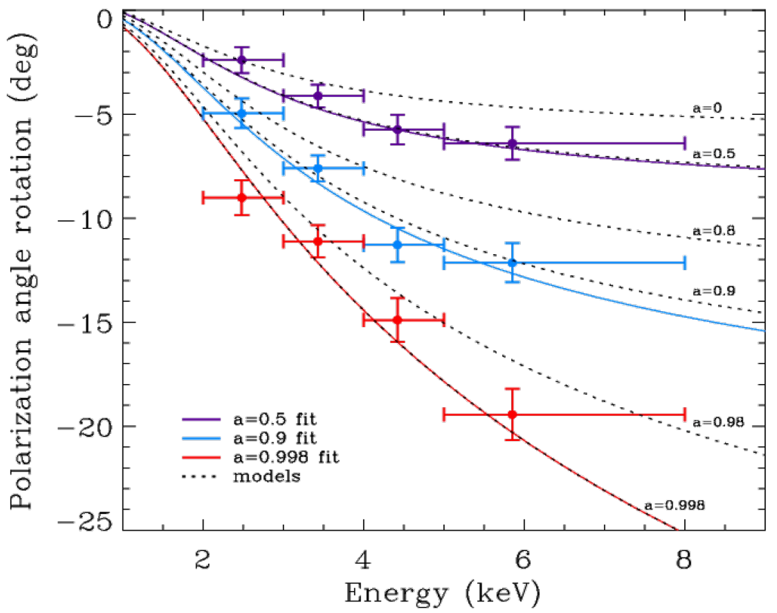
Soft state

- **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)





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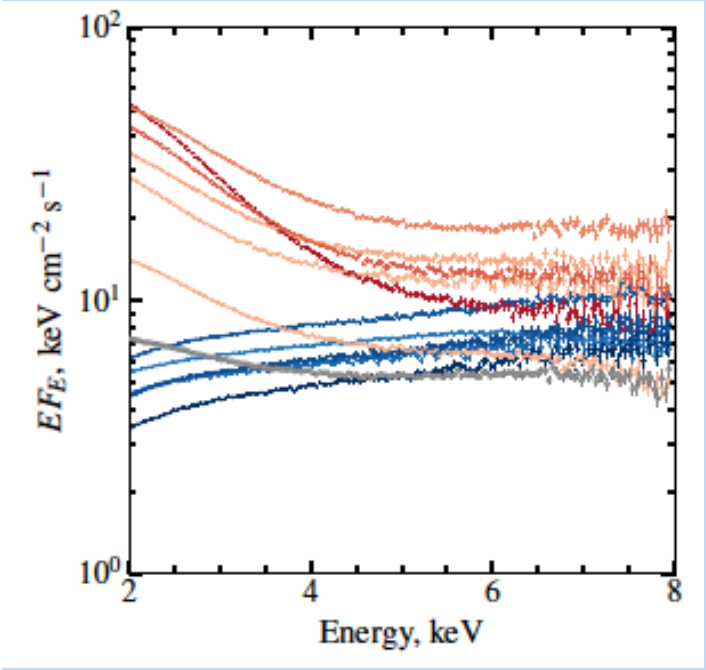
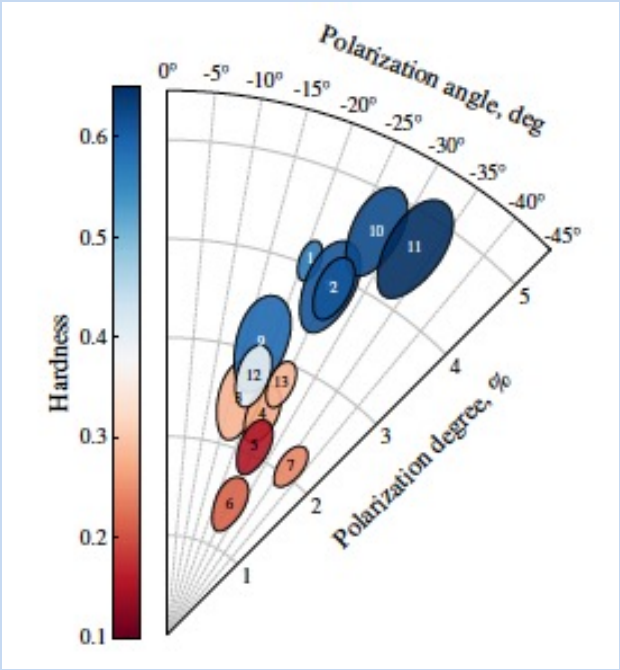
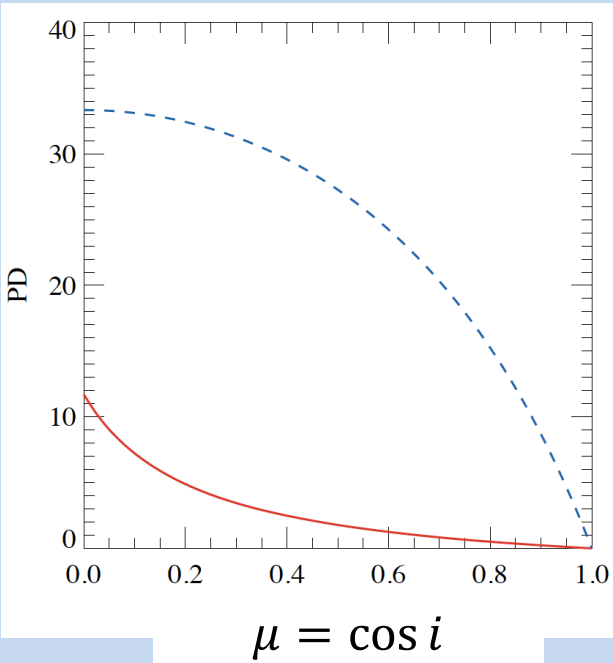
Hard - soft state comparison: Cygnus X-1





- **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.**



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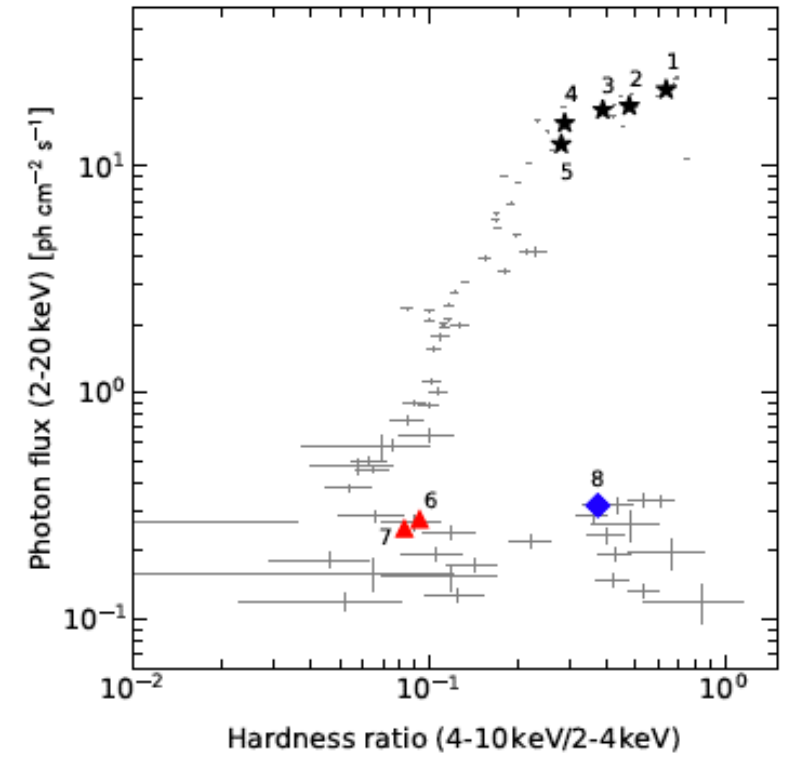
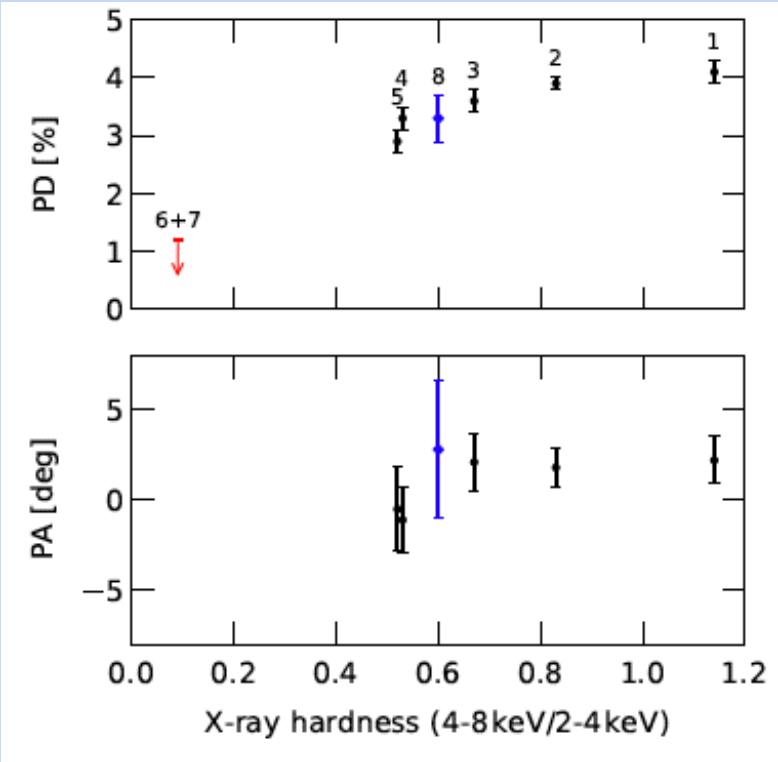
Hard - soft state comparison: Swift J1727.8-1613





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

- **In the soft state polarization degree drops.**

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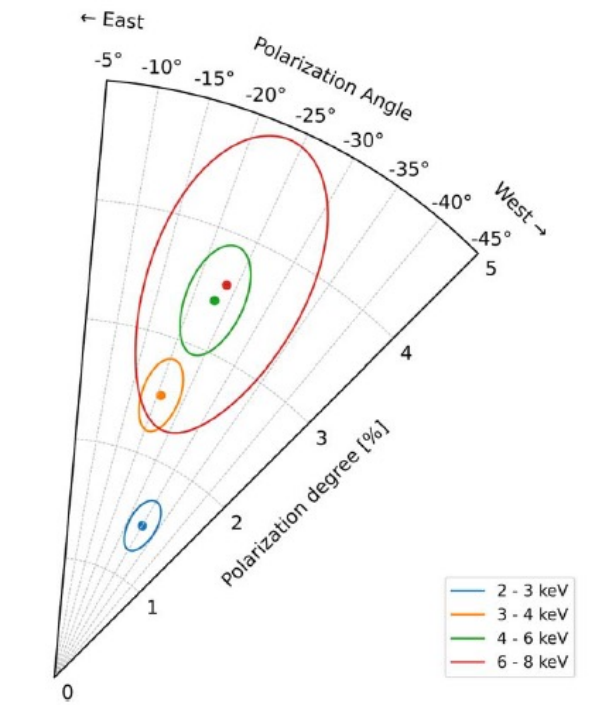
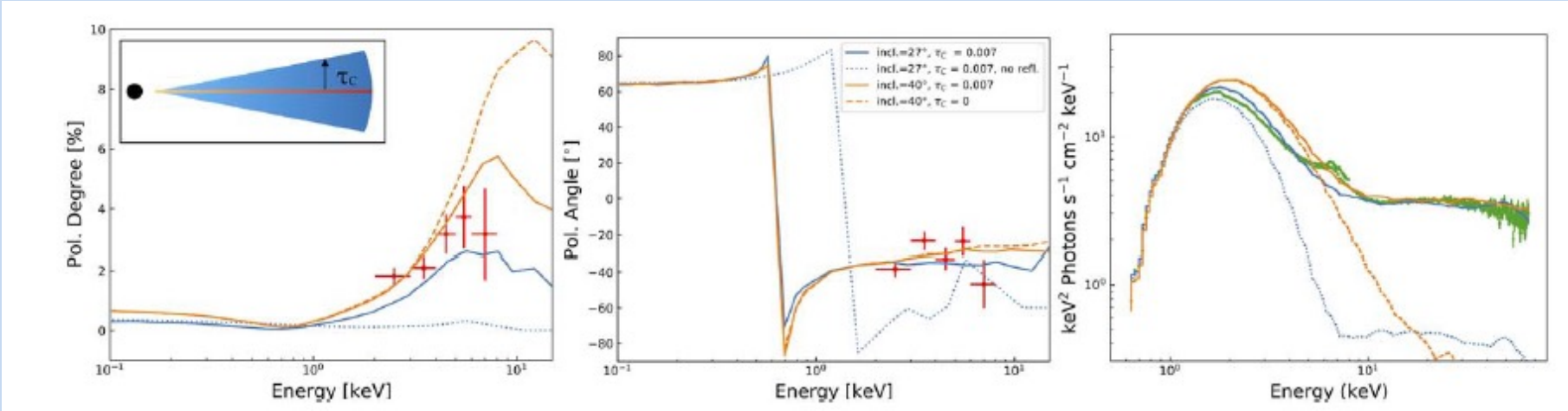
Soft state: Cygnus X-1



- **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°.**



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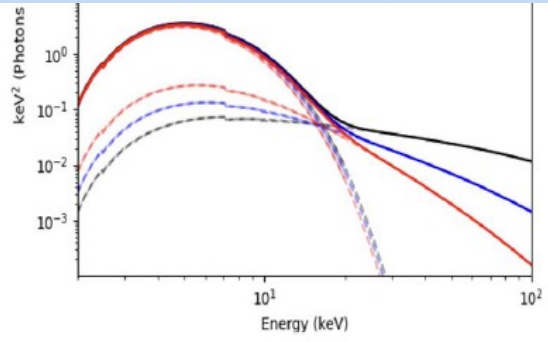
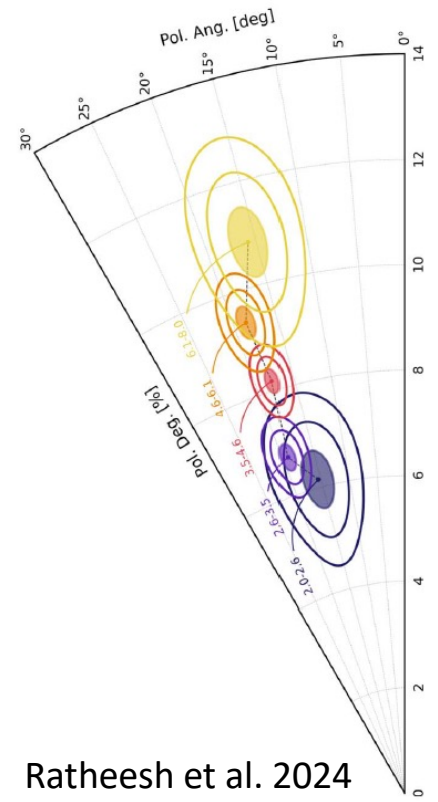
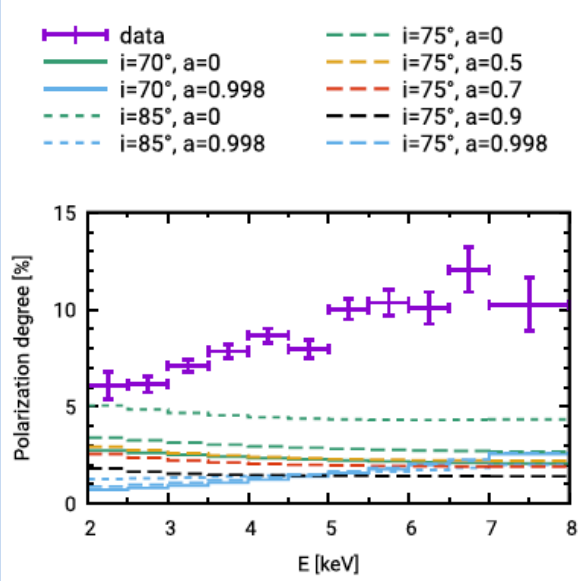
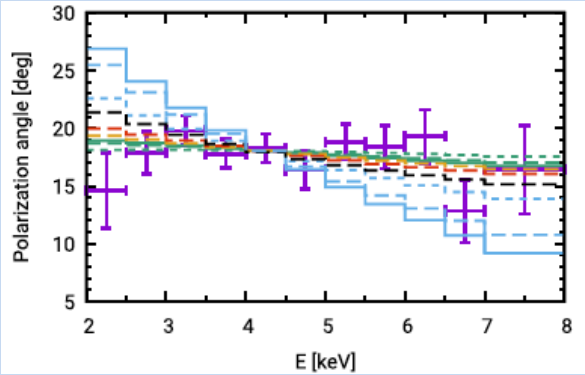
Soft state: 4U 1630-47



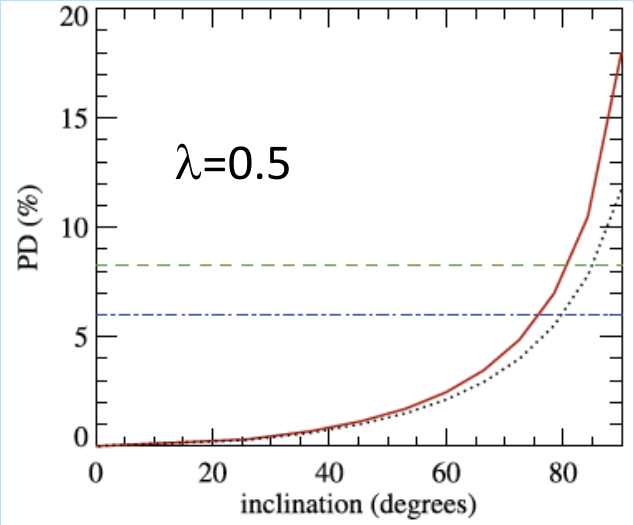


Ratheesh et al. 2024





- 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 λ=**0.5**).



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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.

➢ Identified Cyg X-3 with an ULX.

➢ Puzzling high polarization in the soft state of 4U 1630-47: pure es 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."

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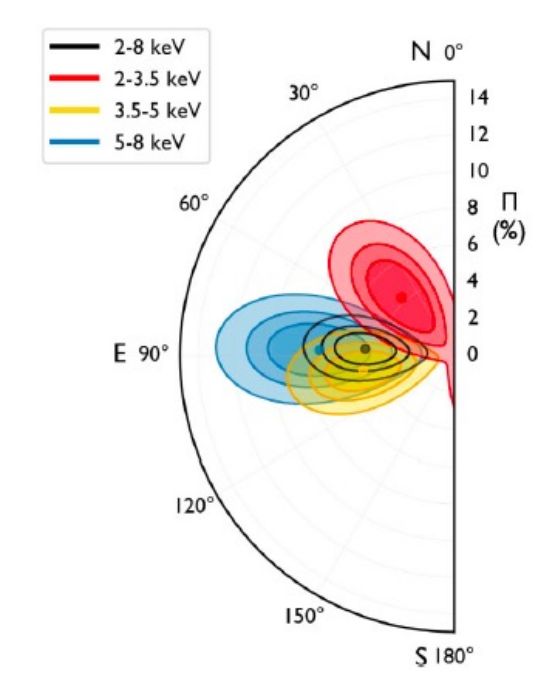
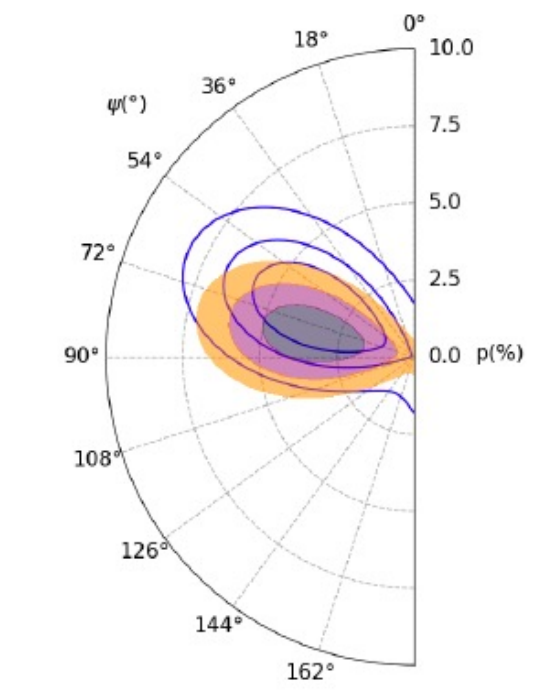
Seyfert 1 galaxies

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



Gianolli et al. 2023

IC 4329A: PD=3.3±1.1 %, PA=78º±10º.
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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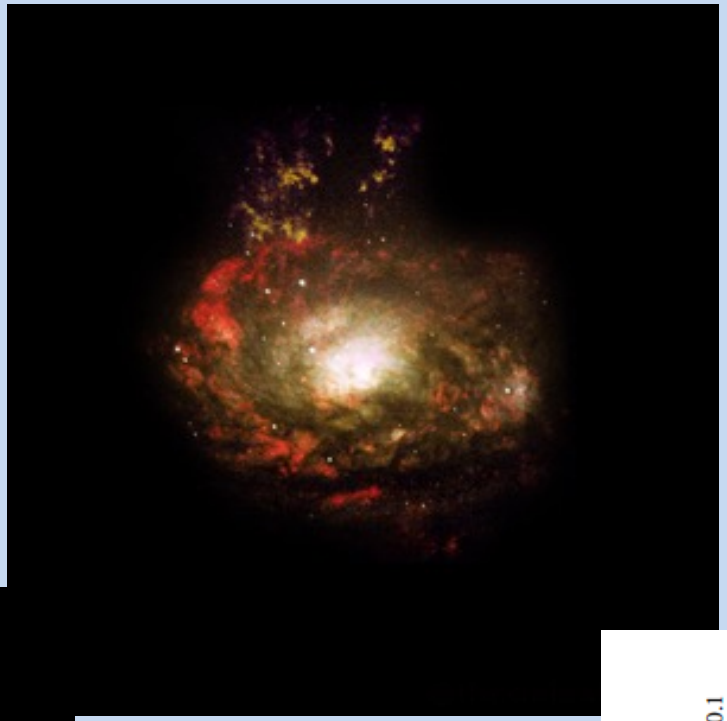
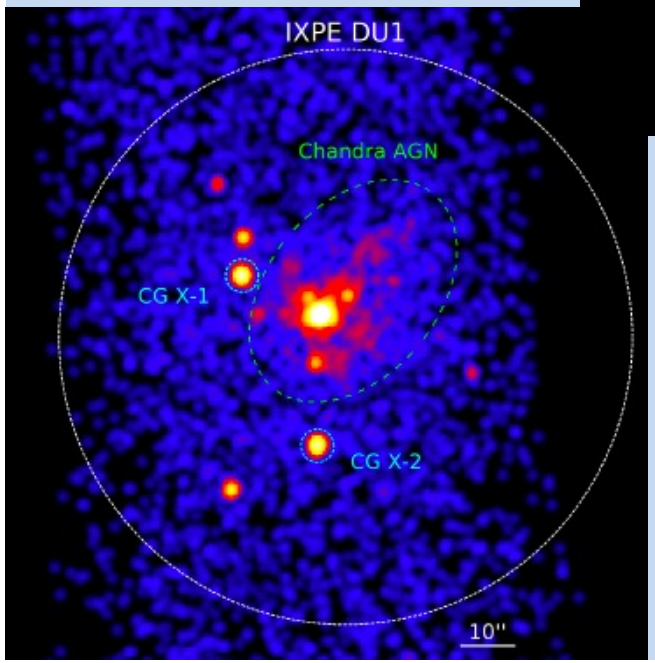
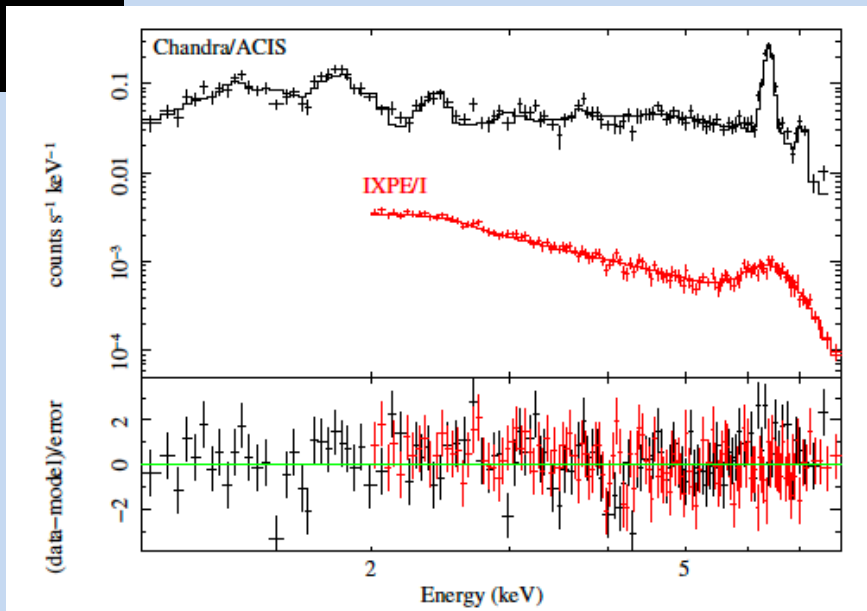
Circinus galaxy (Seyfert 2)







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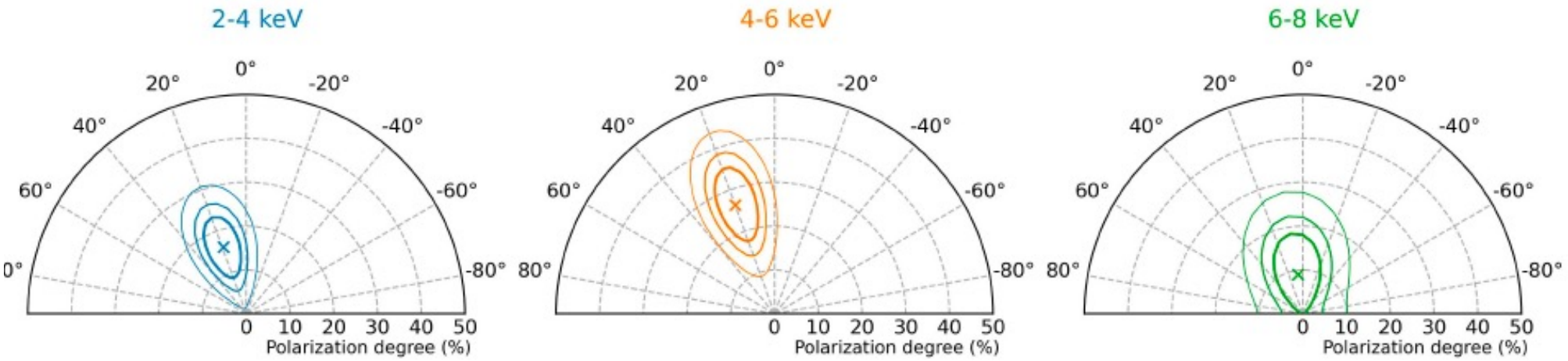
Circinus galaxy (Seyfert 2)

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

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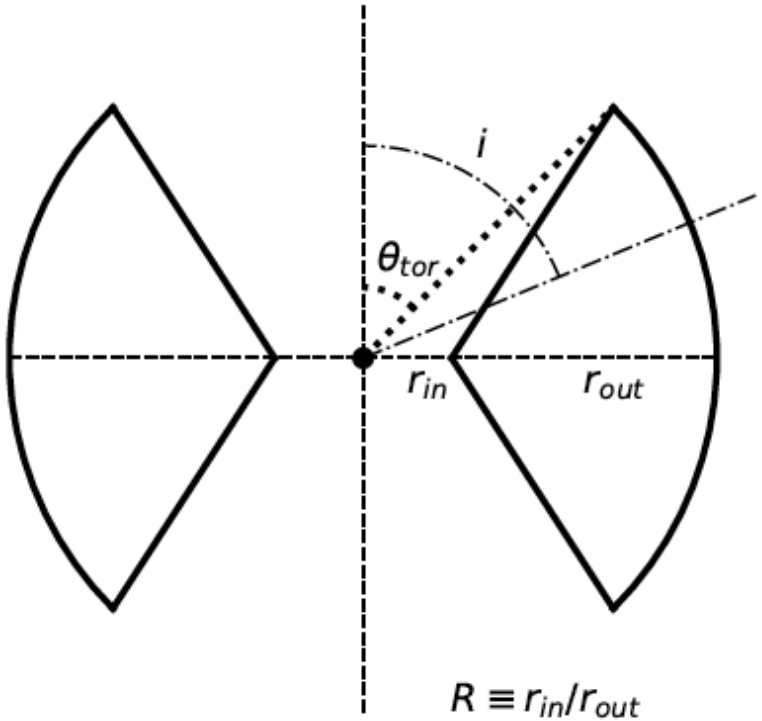
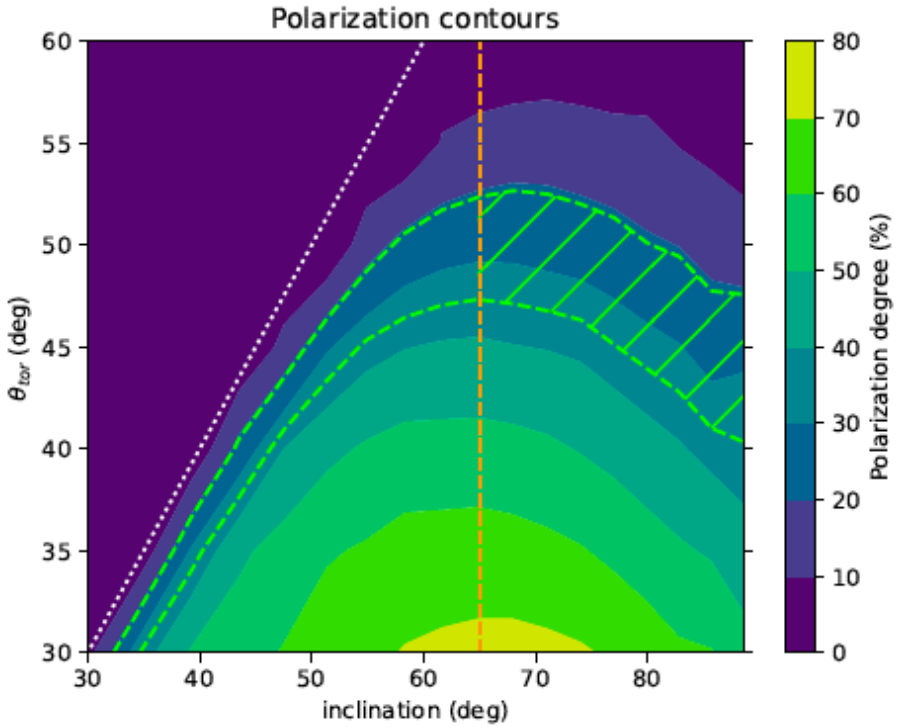
Circinus galaxy (Seyfert 2)





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.