IXPE
Imaging
X-Ray
Polarimetry
Explorer

Поляриметрические наблюдения аккрецирующих черных дыр звездных масс спутником IXPE

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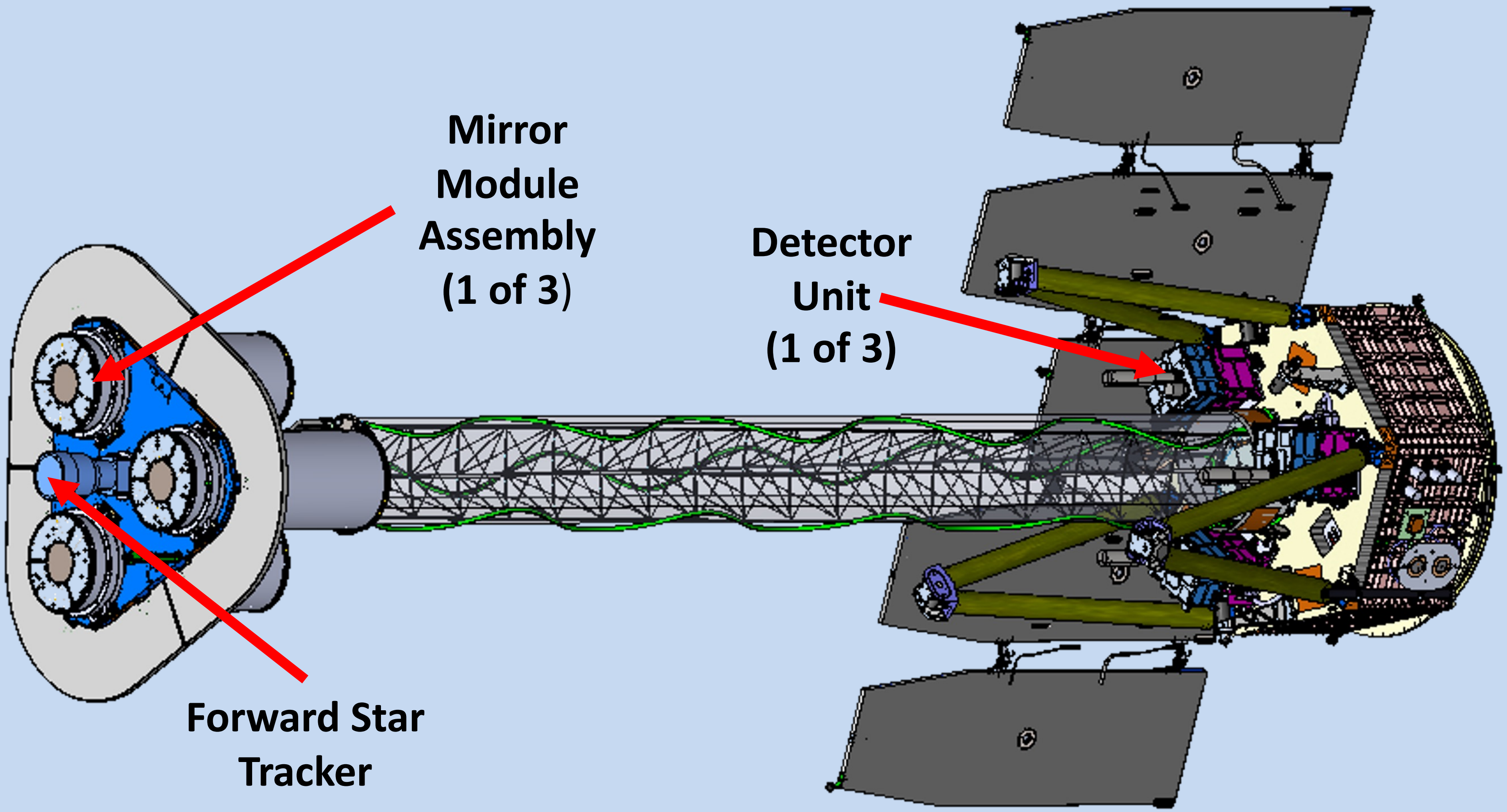
(University of Turku)

21 December 2023
ИКИ

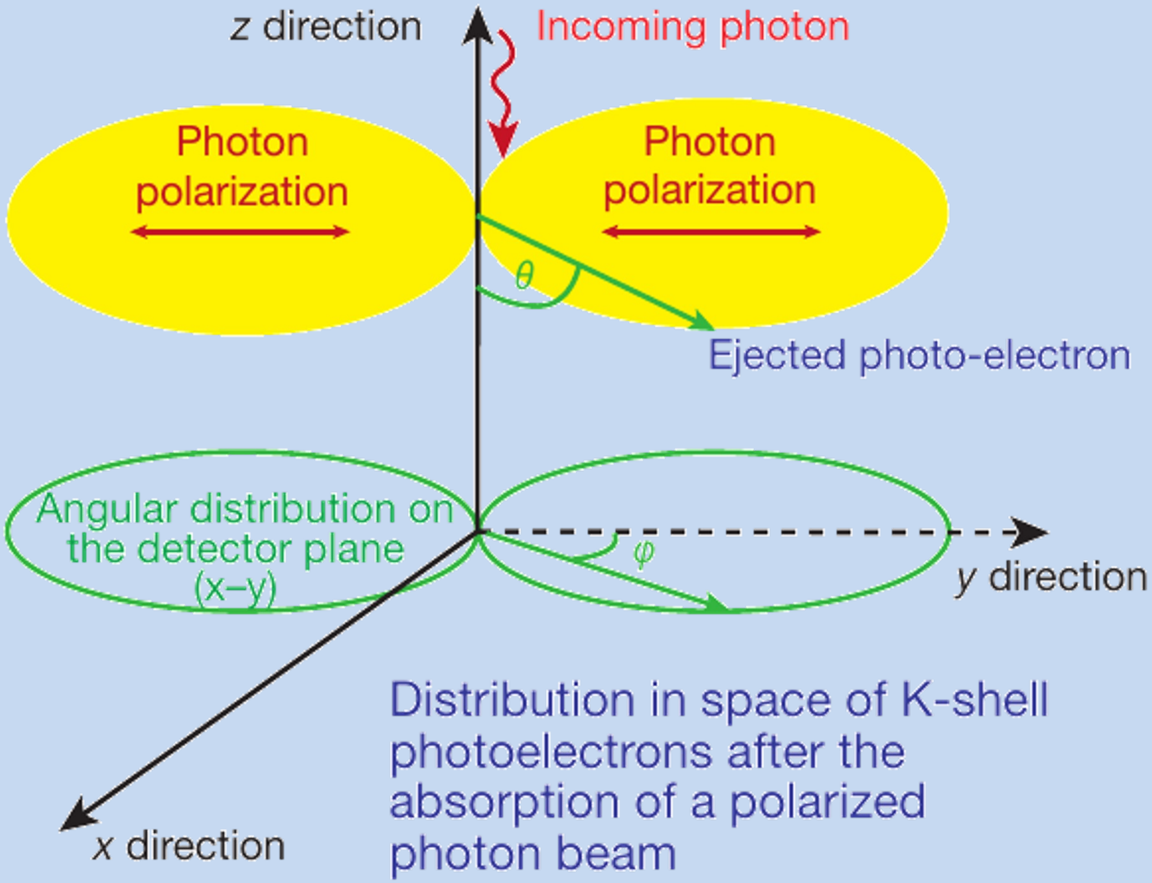
IXPE launched on 2021 Dec 9



5.2 m total length
4.0 m focal length

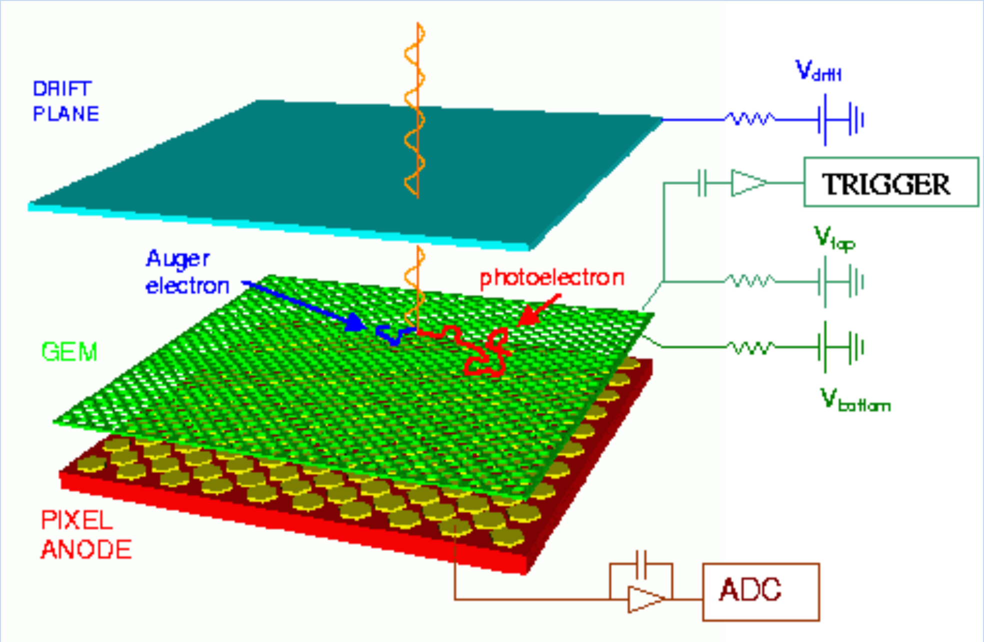
Detection Principle

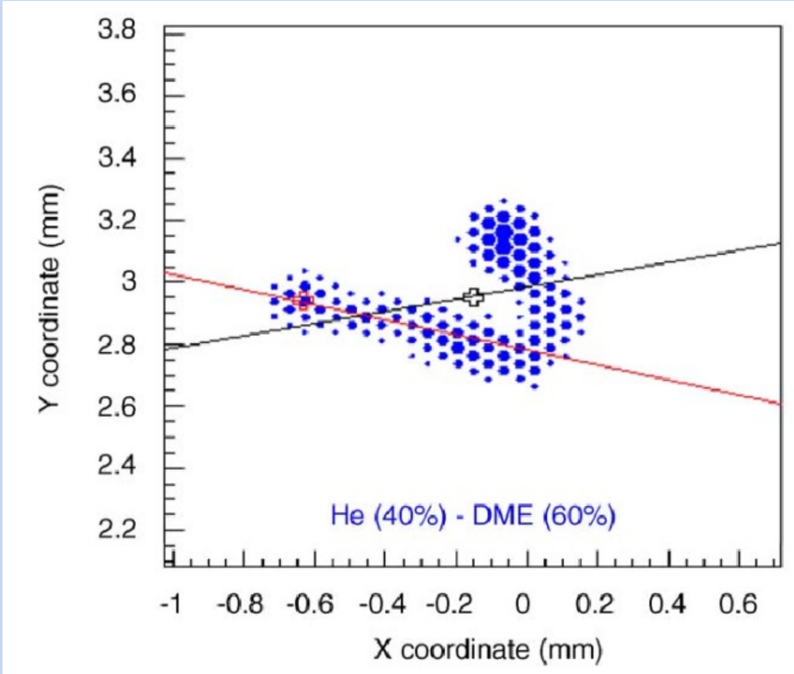
- **The detection principle is based upon the photoelectric effect**



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

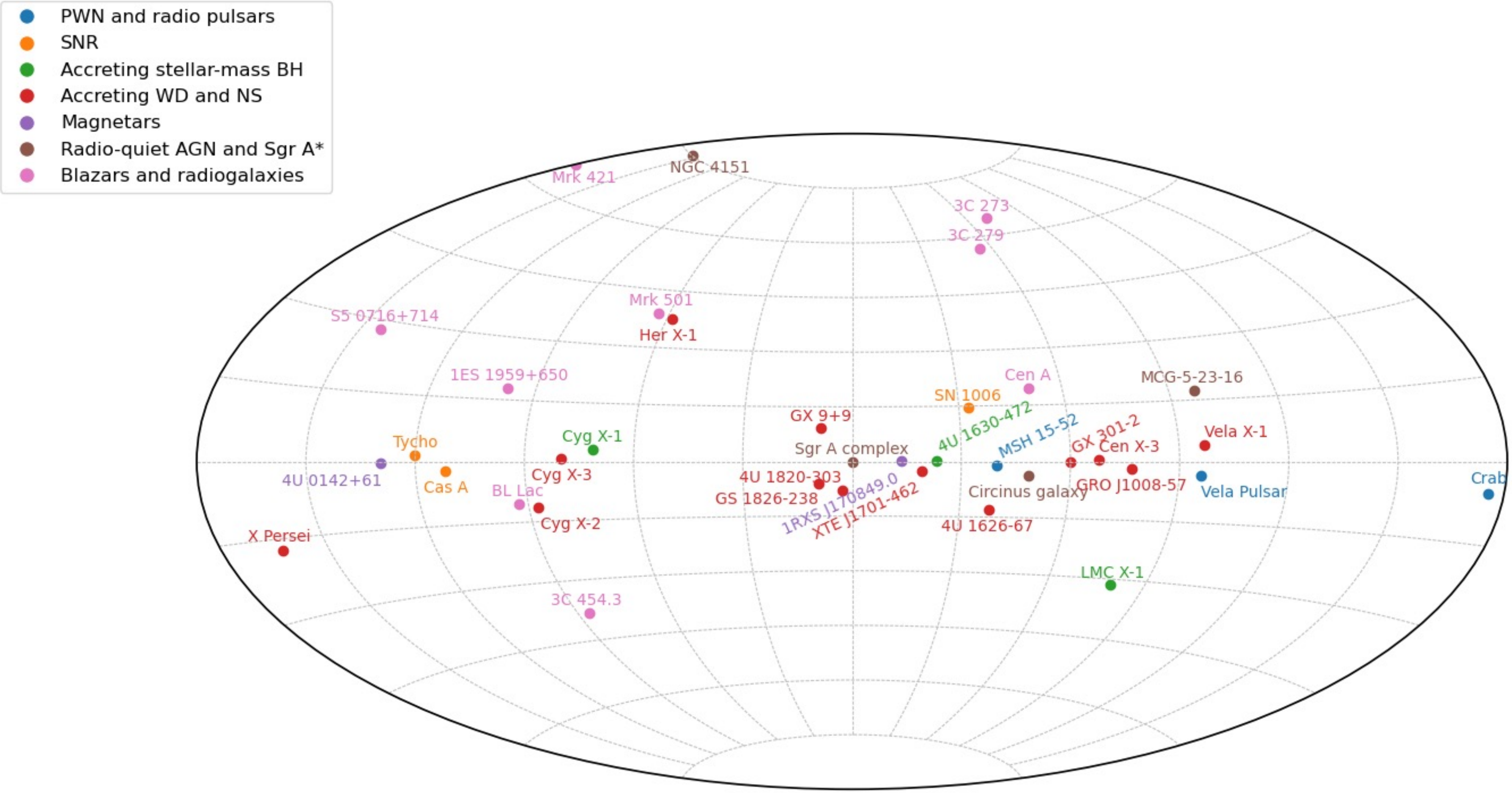
Gas Pixel Detector





- Include a Filter & Calibration wheel with
  - Filters for specific observations (very bright sources, background)
  - Calibrations sources (polarized and unpolarized, gain)

Sky map of source observed by IXPE in 1st year



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Black holes observed by IXPE

1. Stellar-mass black holes

Cyg X-1 (Science; ApJ subm.)
4U 1630-47 (ApJ Letters, ApJ subm.), LMC X-1 (MNRAS), Cyg X-3 (Nature Astro, subm), LMC X-3 (ApJ), SS 433 (ApJ Letters subm.) , Swift J1727.8-1616 (ApJ Letters, ApJ subm.)

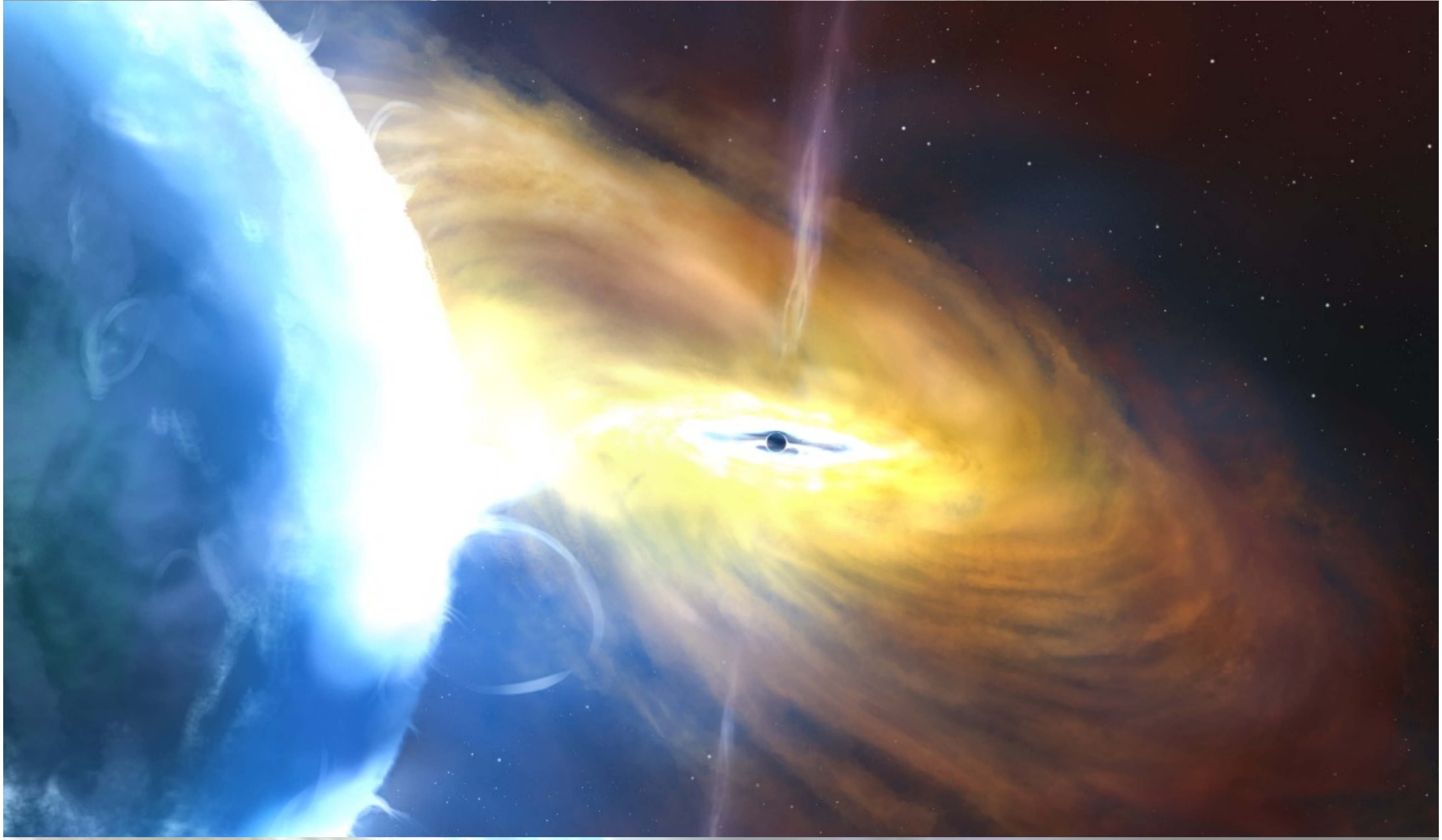
2. Seyferts and Milky Way BH

Circinus galaxy (MNRAS), NGC 4151 (MNRAS), MCG-05-23-16 (MNRAS x2), IC 4329A (MNRAS), Sgr A cloud (Nature)

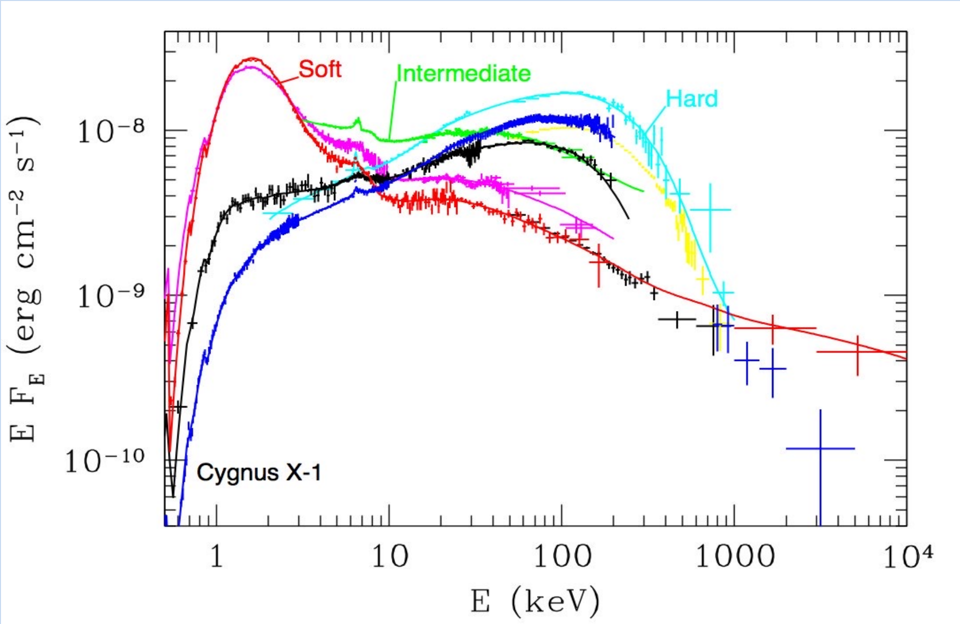
3. Blazars /radio galaxies

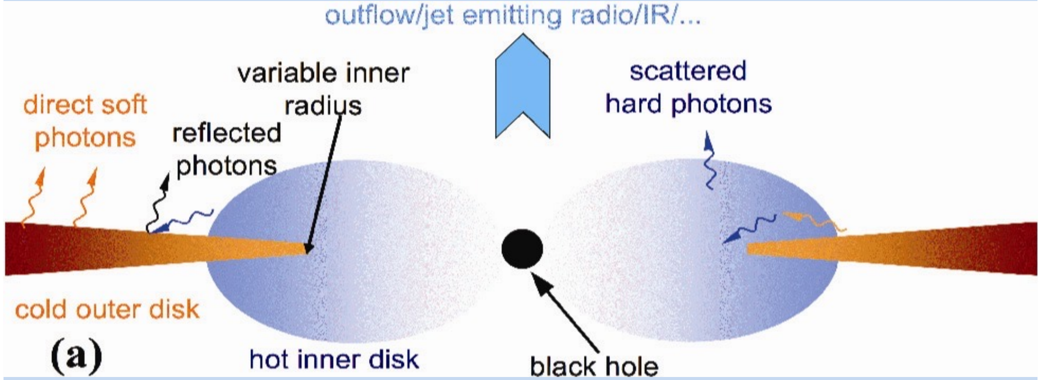
Mrk 501 (Nature, ApJ Letters subm.), Cen A (ApJ), Mrk 421 (Nature Astr., ApJ Letters, A&A), BL Lac (ApJ Letters x2), PG 1553+113 (ApJ Letters), 1ES 0229+200 (ApJ), 3C 273, 3C 279, 3C 454.3, S5 0716+714 (ApJ, subm), 1ES 1959+650 (ApJ subm.)

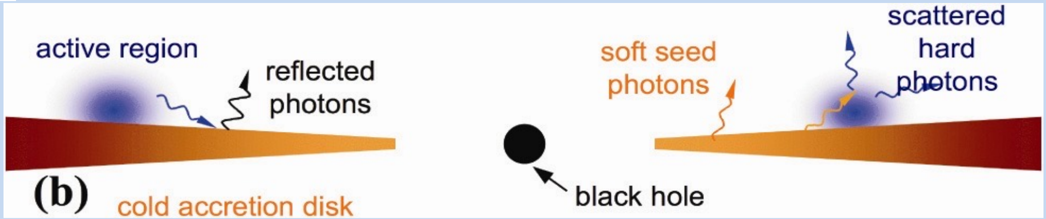
Stellar-mass black holes



Cygnus X-1 spectra







Hard state - standard cold outer disc + hot inner flow

Soft state - standard accretion disc plus nonthermal corona

Cygnus X-1 hard state geometry

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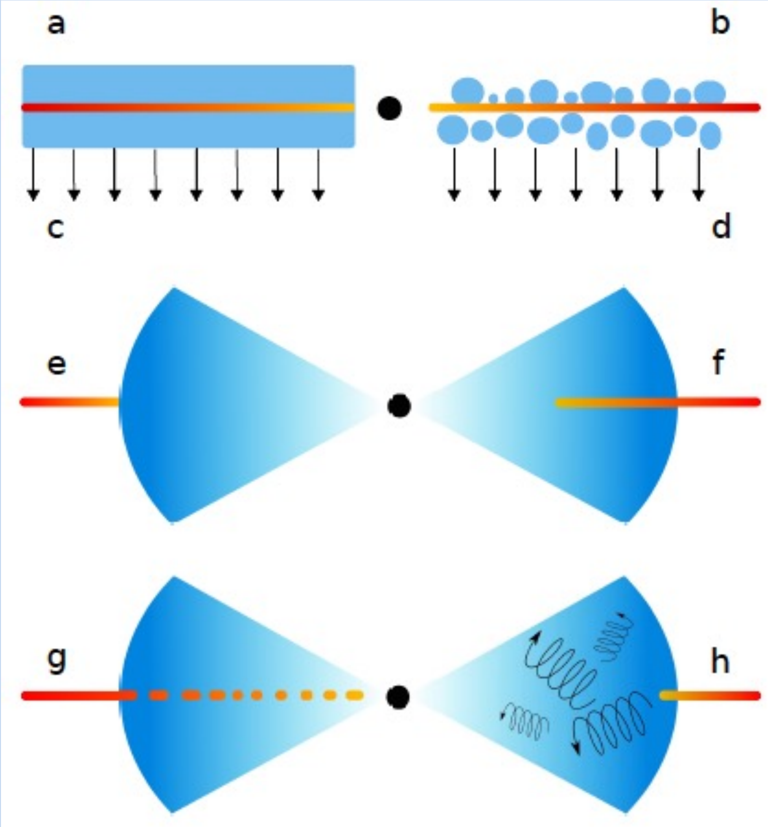
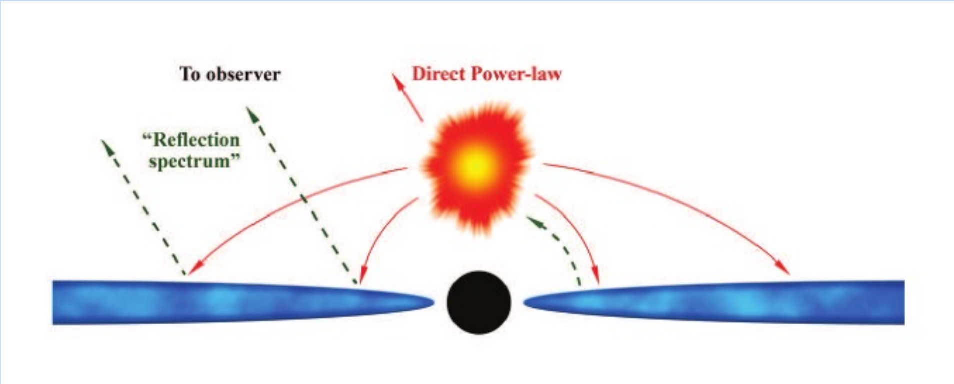


- The hard state spectrum is produced by multiply Compton scattering (thermal Comptonization)
- Polarization is sensitive to the geometry of the ”corona”, its dynamics and source of seed photons



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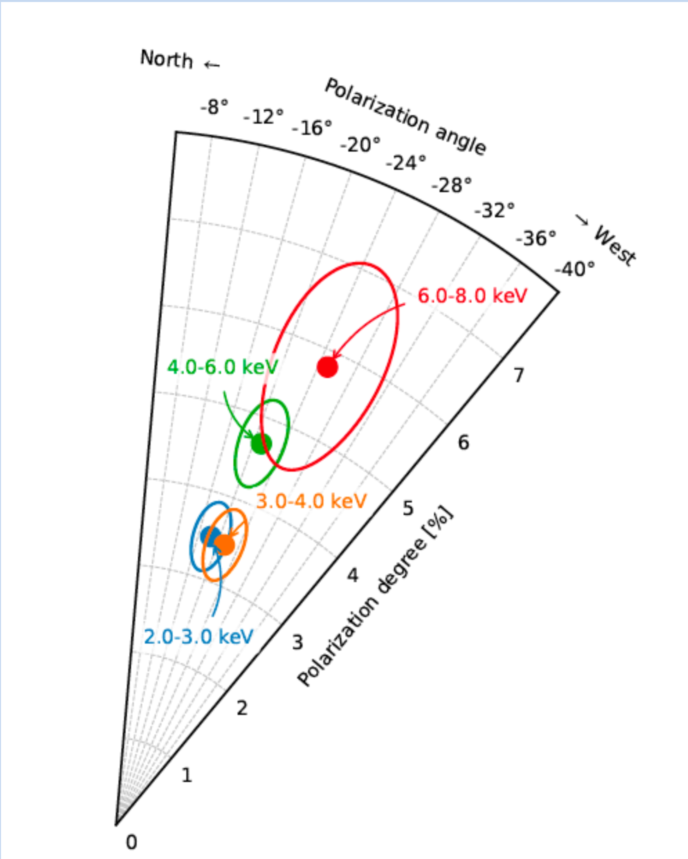
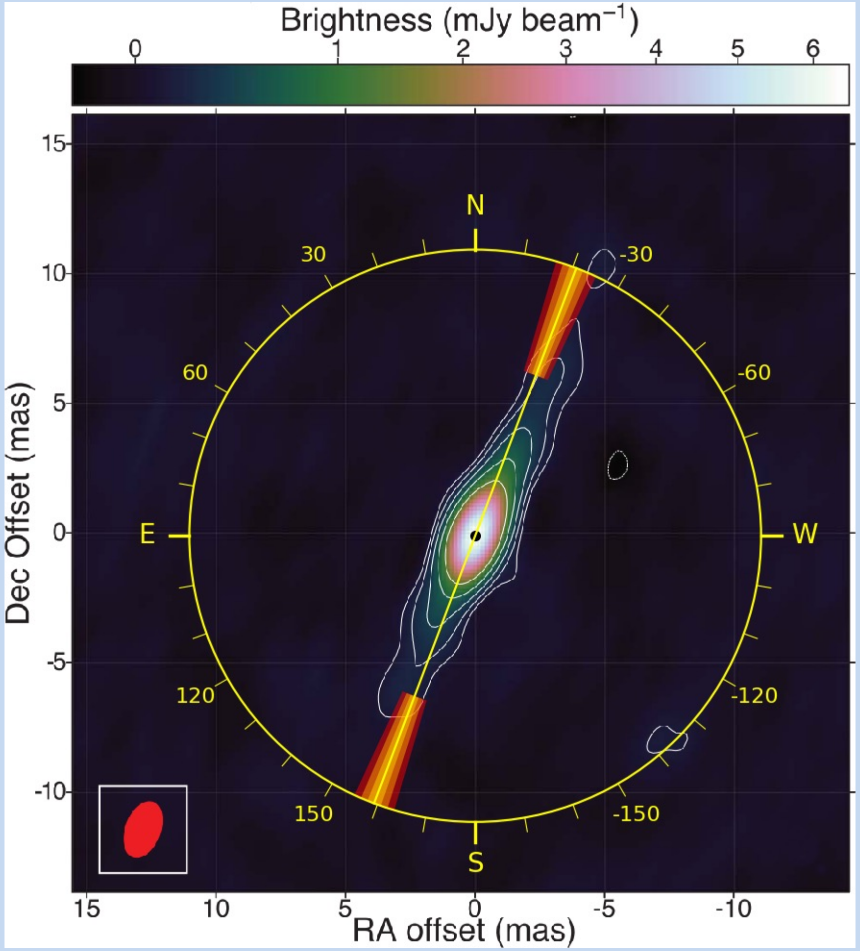
Cygnus X-1 – hard state

- **IXPE observed the source in May and June 2022.**



PD = 4.0 ± 0.2 %
PA = −20.7 ± 1.4 deg



Krawczynski et al. 2023

X-ray polarization parallel to the jet

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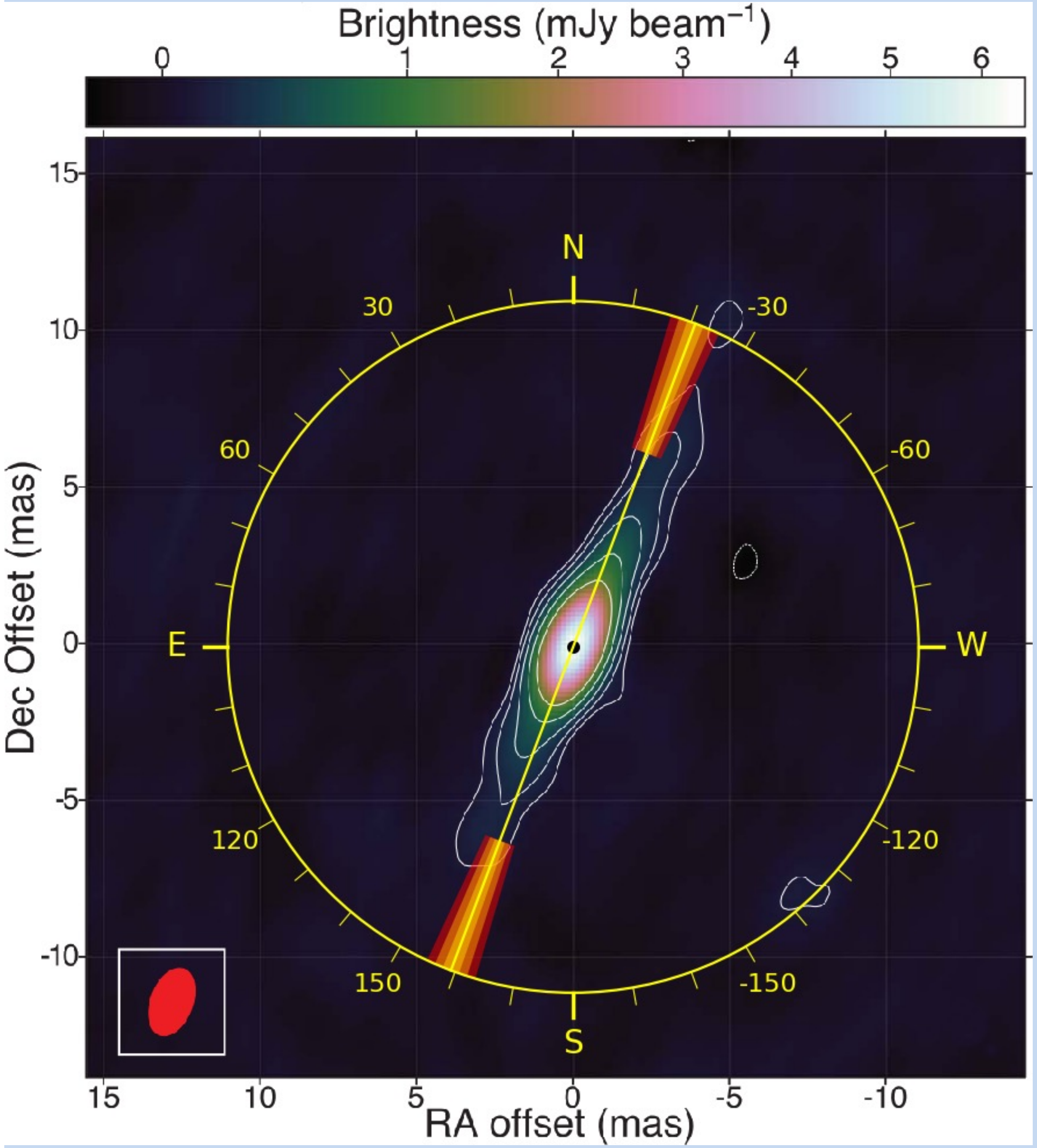
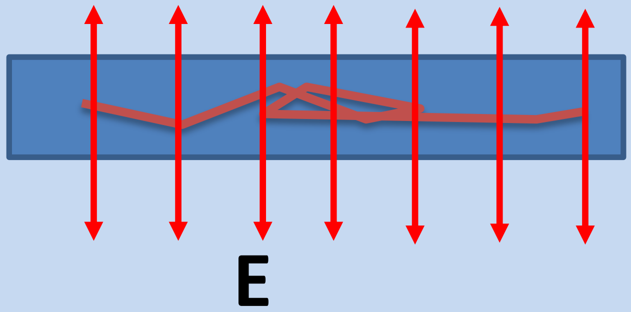
Cygnus X-1



- 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

- Jet and lamp-post models are rejected.
- Optical (intrinsic) polarization has the same angle ⇒ orbit perpendicular to the jet.
- How to get 4% polarization?

IXPE Cygnus X-1: polarization from Comptonization in different geometries

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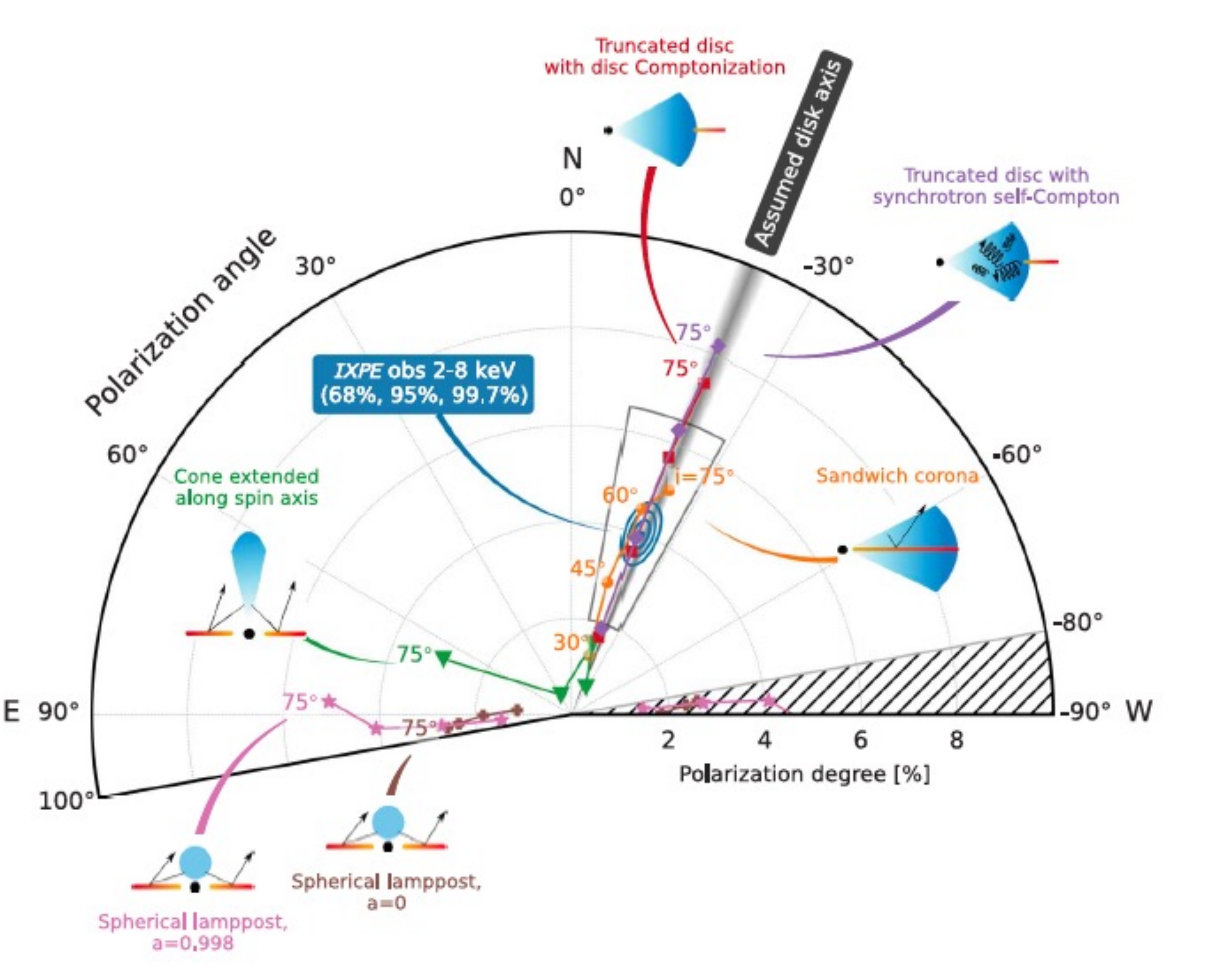
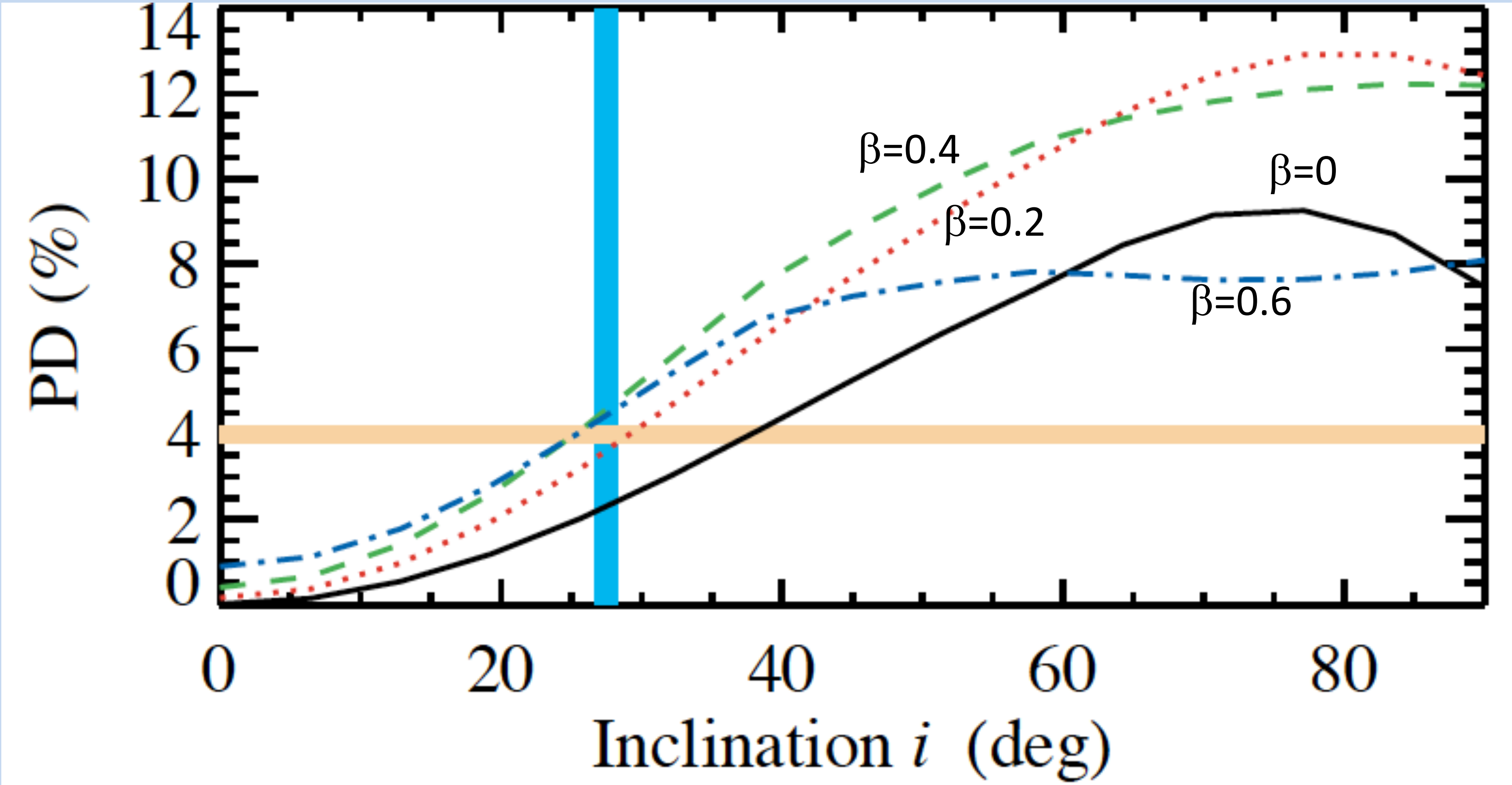


- Models of a jet or a lamppost are rejected.
- Hot flow or slab-corona are preferred, but slab-corona produces too soft spectra.
- Inclination of 40-45 deg is needed. Misalignment perpendicular to the sky plane?

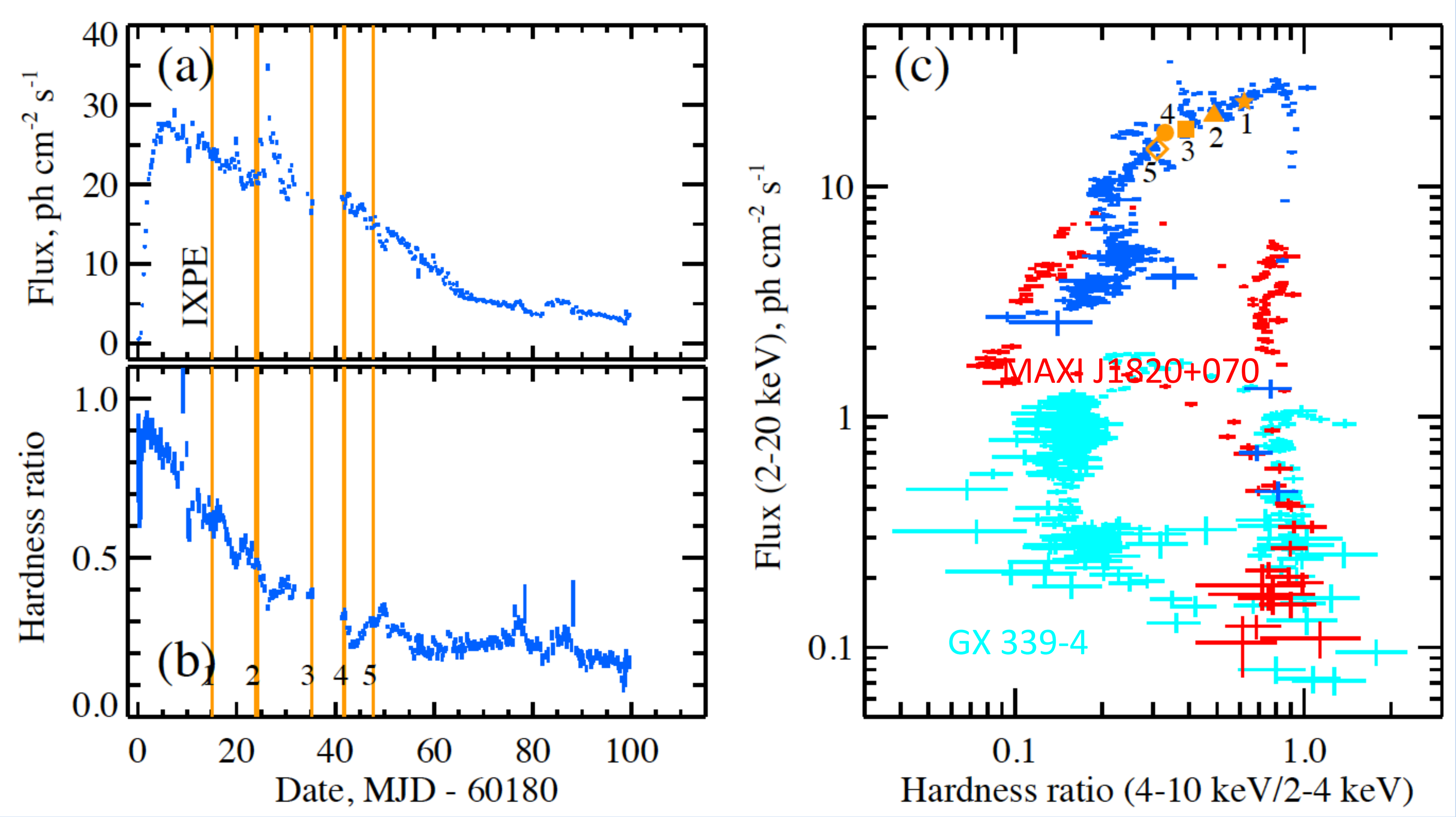
Cygnus X-1

- **Outflowing corona with β=v/c=0.4 gives a much higher polarization at low inclination (Beloborodov 1998, Poutanen, Veledina, Beloborodov 2023) because of relativistic aberration.**



Swift J1727.8-1613 – hard-intermediate state

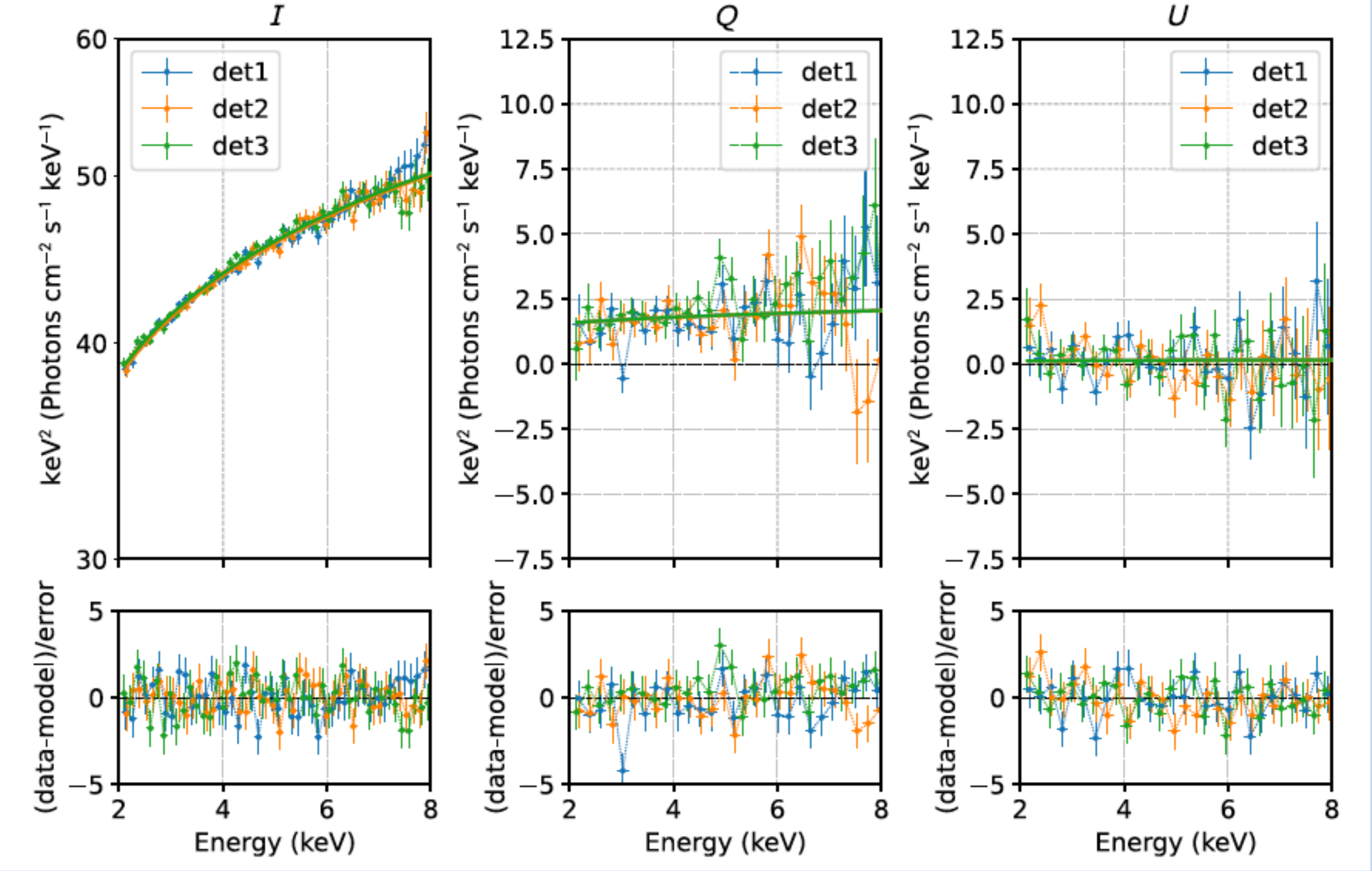
- **New transient discovered in August 2023**
- **IXPE observed 5 times**



MAXI X-ray monitor data

Swift J1727.8-1613 – hard-intermediate state

- New transient discovered in August 2023
- IXPE observed 5 times

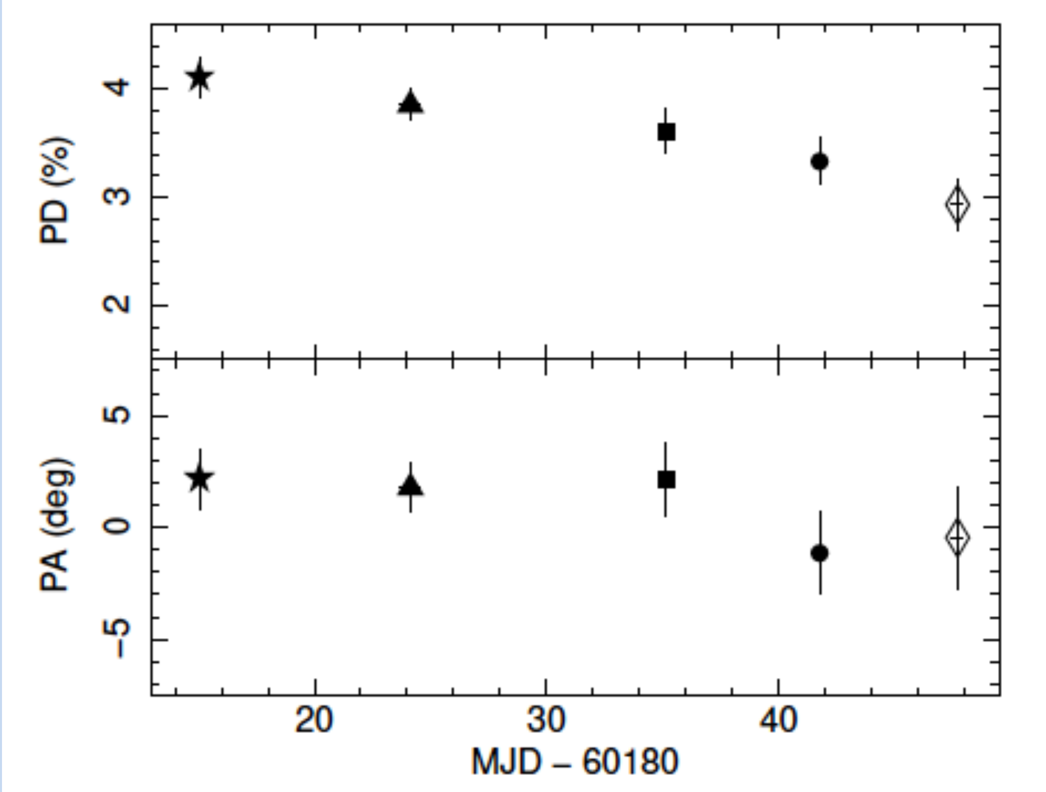


IXPE Imaging X-Ray Polarimetry Explorer

Swift J1727.8-1613 – hard-intermediate state

- **New transient discovered in August 2023**
- **IXPE observed 5 times**

Polarization degree drops when the source moves towards soft state; PA is constant

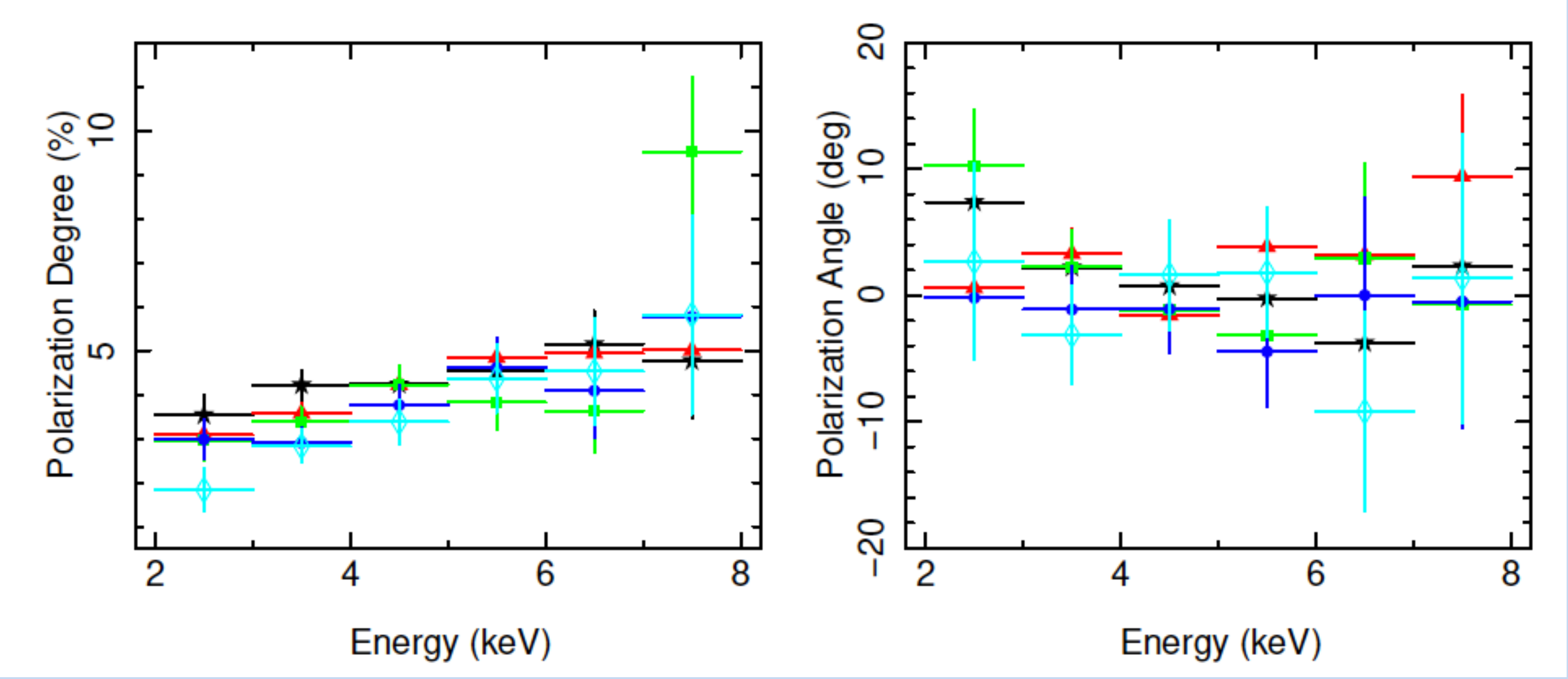


Swift J1727.8-1613 – hard-intermediate state

- **New transient discovered in August 2023**
- **IXPE observed 5 times**

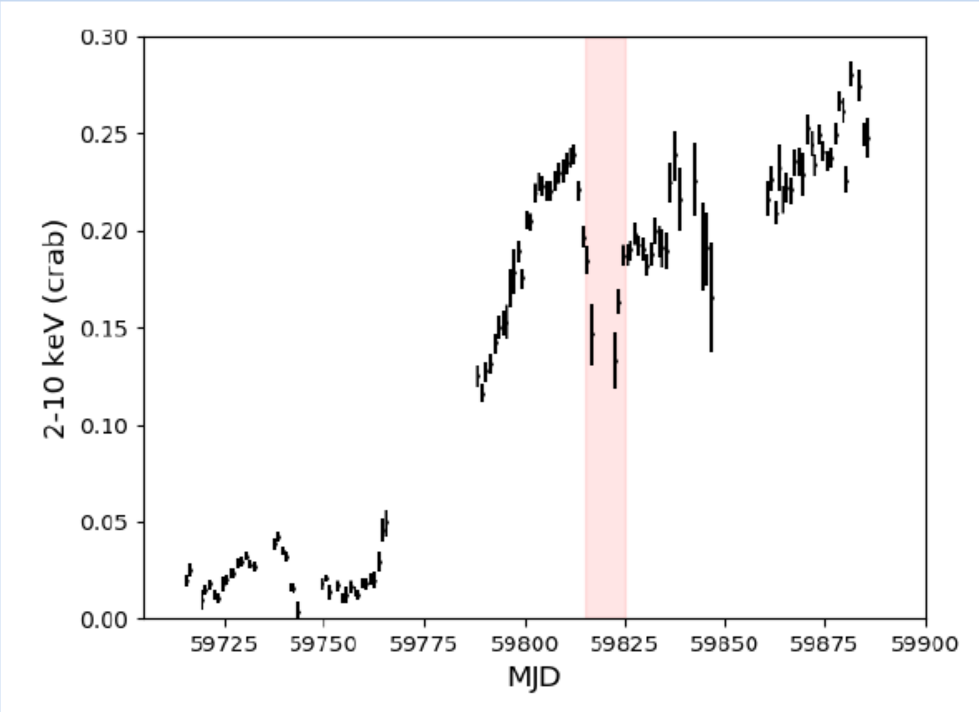
Polarization degree drops when the source moves towards soft state; PA is constant

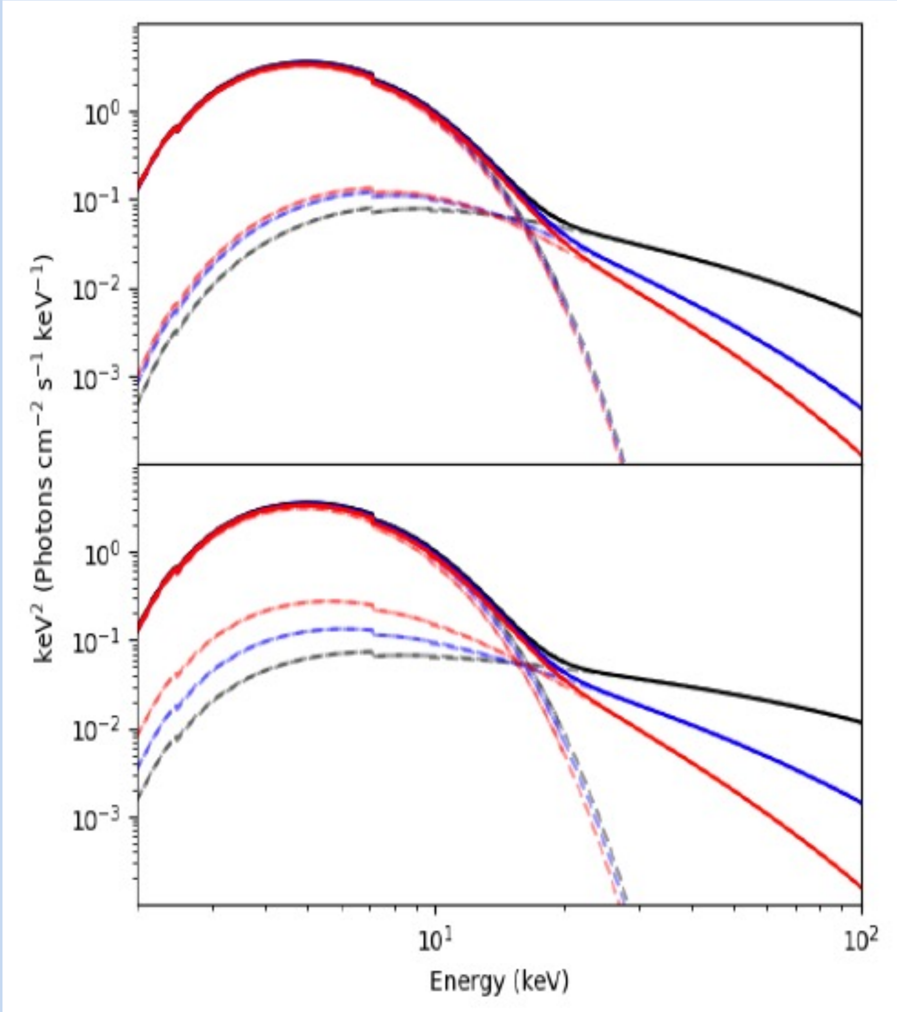
Polarization degree grows with energy, PA is constant



4U 1630–47 – soft state

- IXPE observed the source in August – Sept 2022
- Was in the soft state





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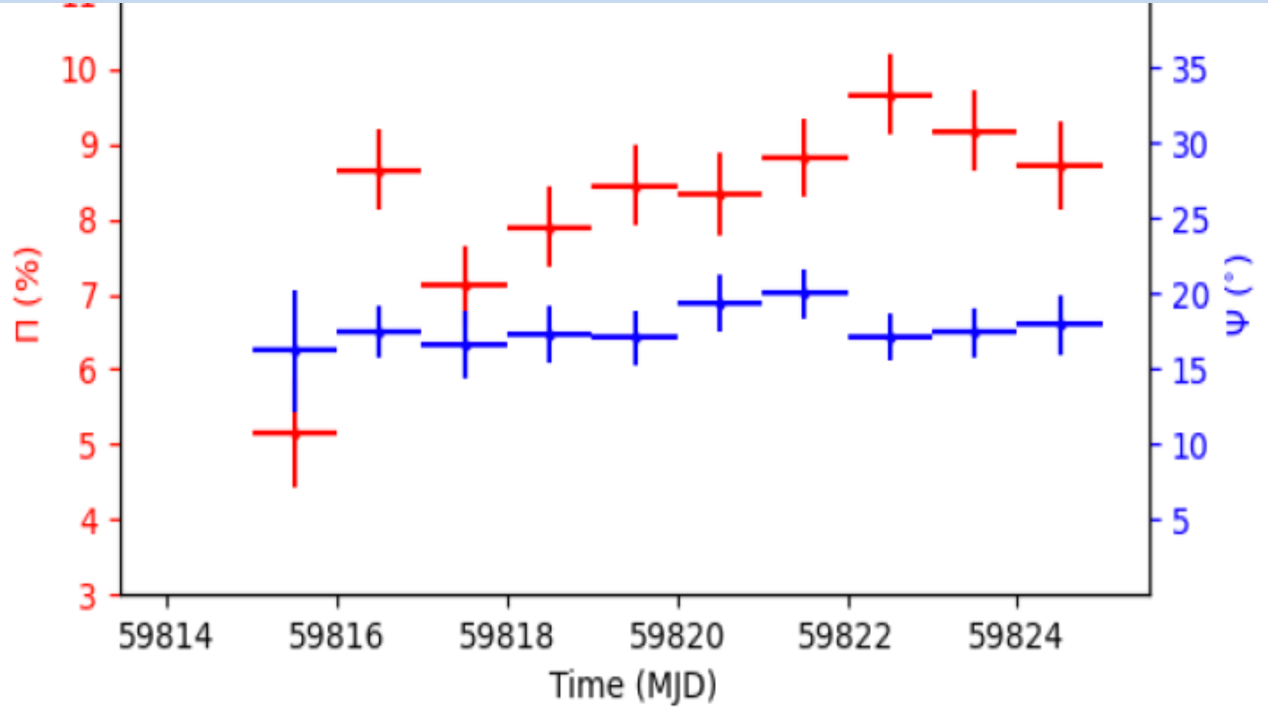
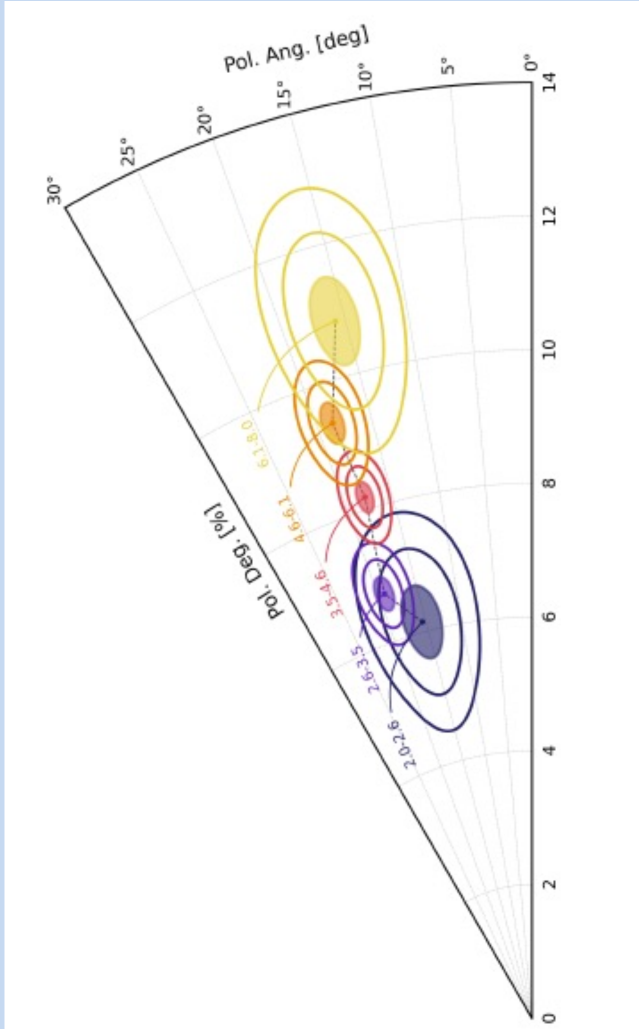
Marshall Space Flight Center

agenzia spaziale italiana

4U 1630–47 – soft state

- **IXPE observed the source in August – Sept 2022**
- **Was in the soft state**
- **PD varies from 5% to 9%.**
- **Average PD increases with energy from 6% to 11 %!**





4U 1630–47 – soft state

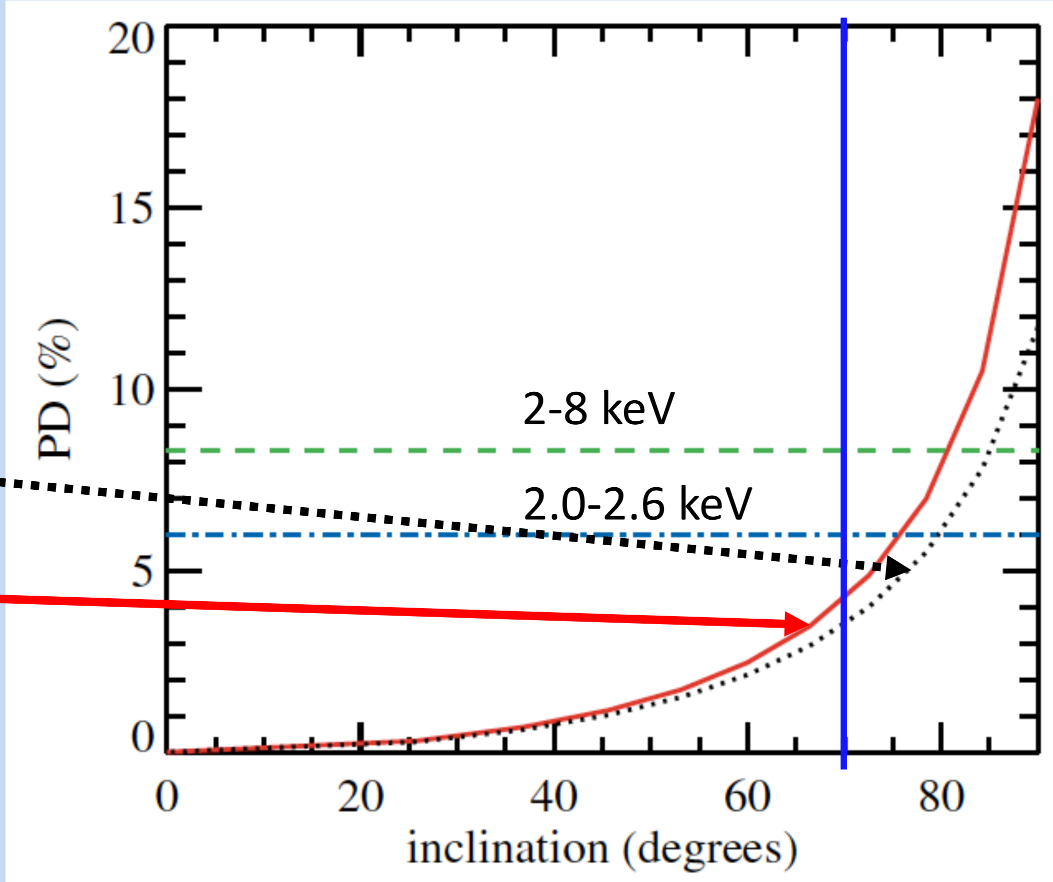
- IXPE observed the source in August – Sept 2022
- Was in the soft state
- PD varies from 5% to 9%.
- Average PD increases with energy from 6% to 11 %!

- Inclination about 70 deg.

- Impossible to explain the data with standard electron-scattering dominated accretion disk

- Including effect of absorption does not solve the problem

- Wind?



Polarization from scattering in a wind

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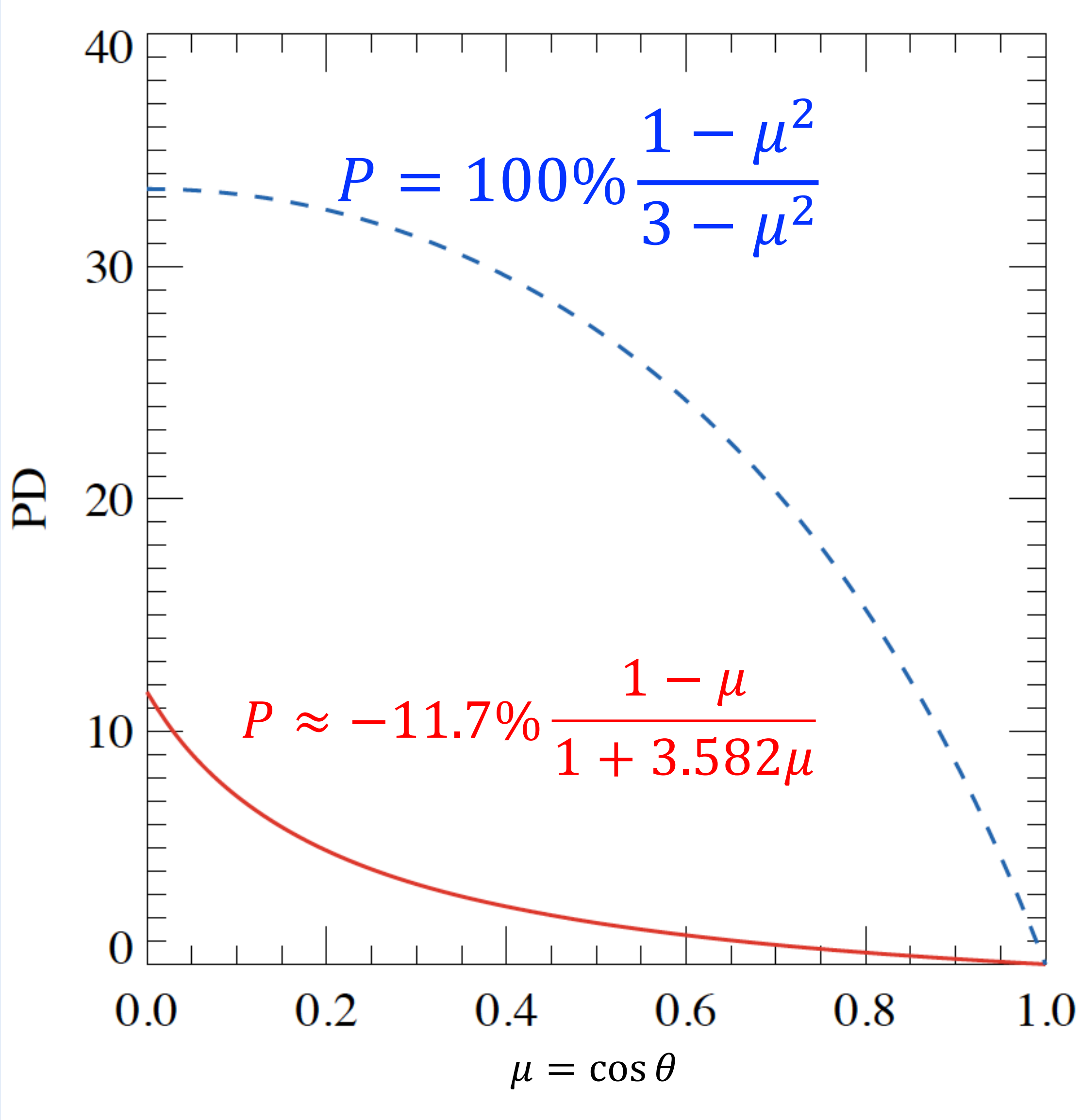
Thomson scattering in an equatorial wind.

Sunyaev & Titarchuk 1985

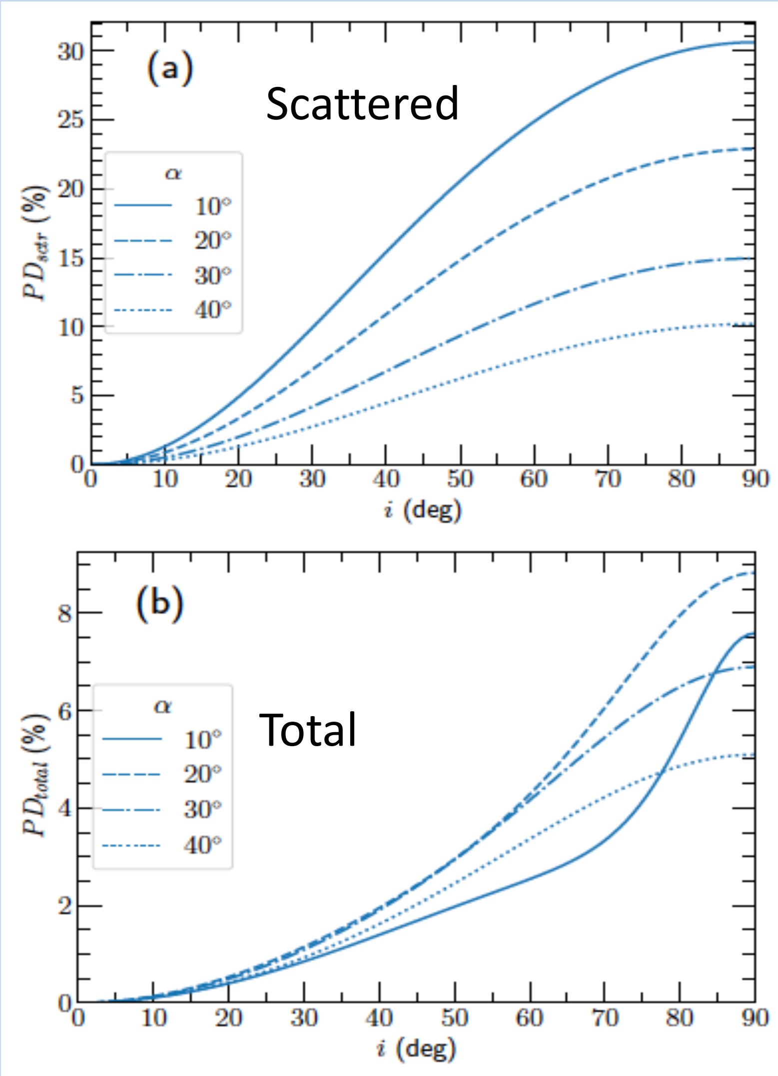
Chandrasekhar-Sobolev (optically thick electro-scattering dominated) case



Polarization from scattering in a wind

Thomson scattering in an equatorial wind.

Scattering of isotropic source radiation in a wind of various opening angles.



Nitindala, Veledina, JP 2024

Cygnus X-3 – an obscured ULX

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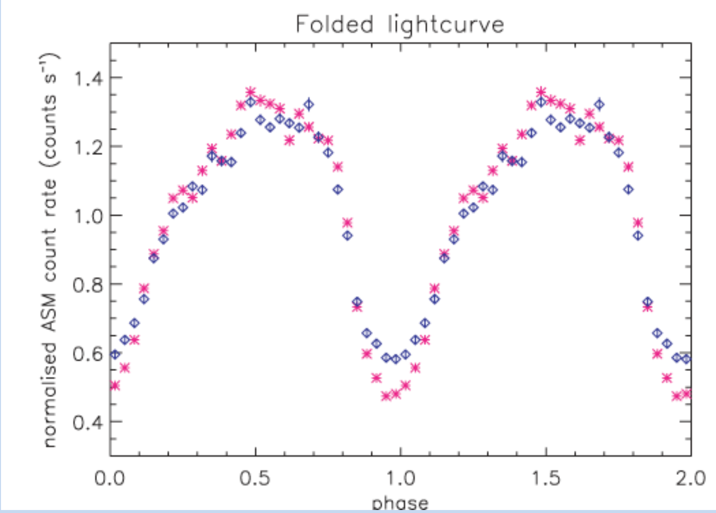
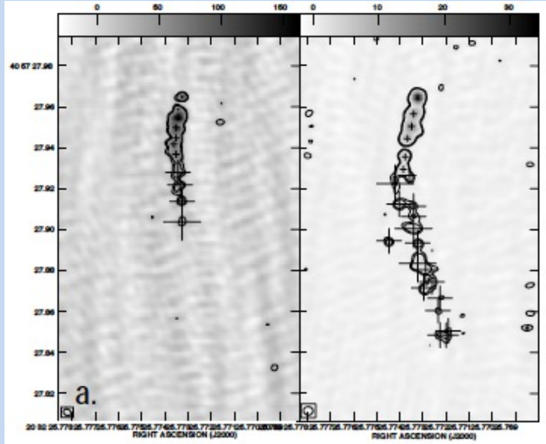
- Discovered in X-rays in 1966 (Giacconi et al. 1967)
- High ISM absorption, no optical counterpart; IR orbital variability and polarization.
- Distance 7.4+/-1.1 kpc
- X-ray orbital modulations with orbital period $P_{\mathrm{orb}} = 4.8^{\mathrm{h}}$.
- Also IR modulation and IR and X-ray lines all indicate the same orbital period. Inclination i=29.5°±1.2° from IR and X-ray photometric orbital variability from absorption (Antokhin et al. 2022).
- The only Galactic source with a compact object in a binary orbit with a Wolf-Rayet companion; progenitor of the double degenerate system, similar to LIGO targets (Belczynski et al. 2013)



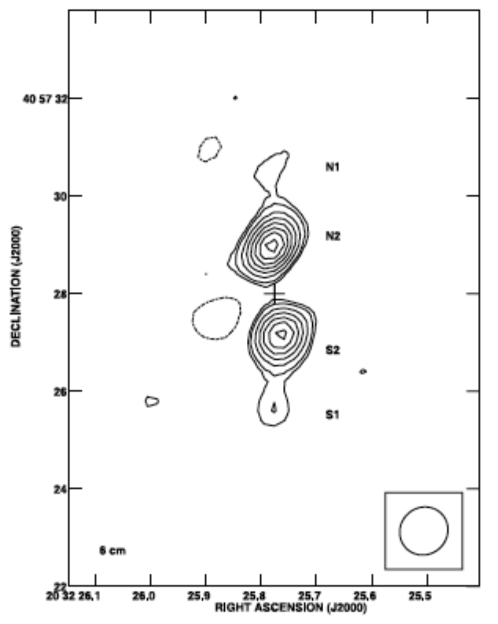
Cygnus X-3 – an obscured ULX

- Radio counterpart (Braes & Miley 1972), among the brightest radio sources (detected fluxes as high as 20 Jy, Corbel et al. 2013)
- N-S orientation of radio ejections

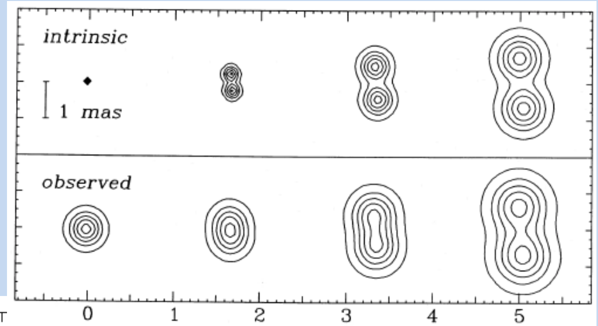
Miodzuszewski et al. 2001

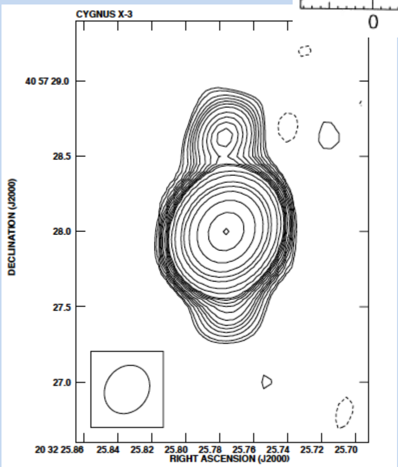


Marti et al. 2001



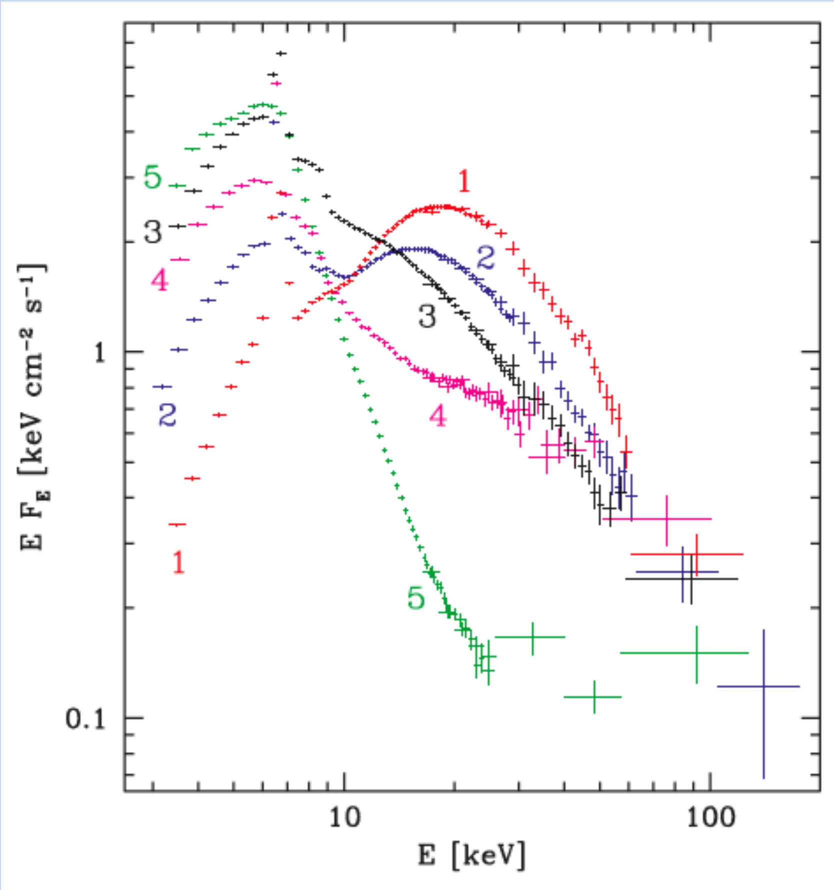
Molnar et al. 1988

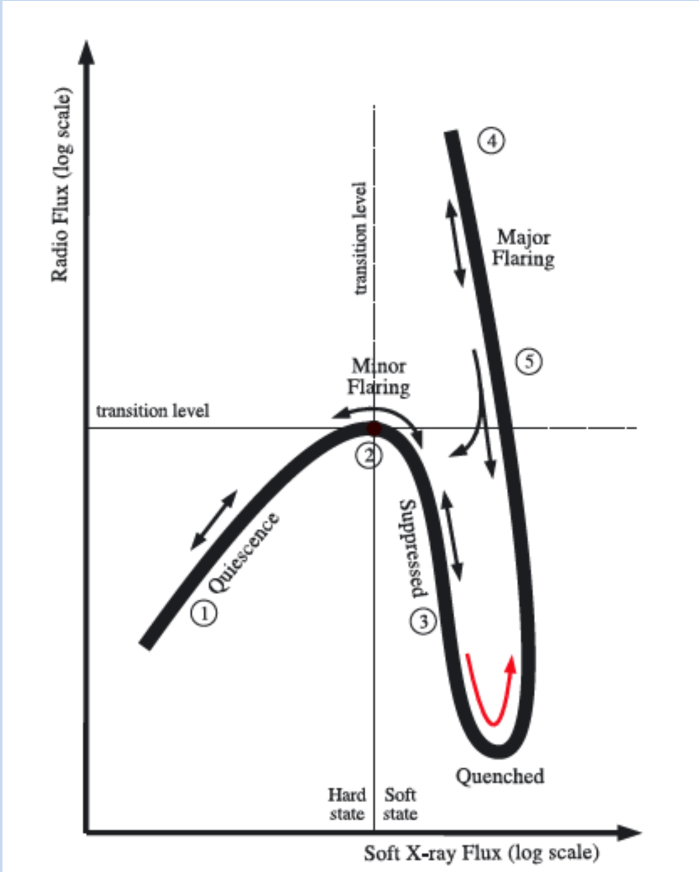




Cygnus X-3 – an obscured ULX

- Evolution through different states: X-ray and radio correlations. Changes of accretion geometry?

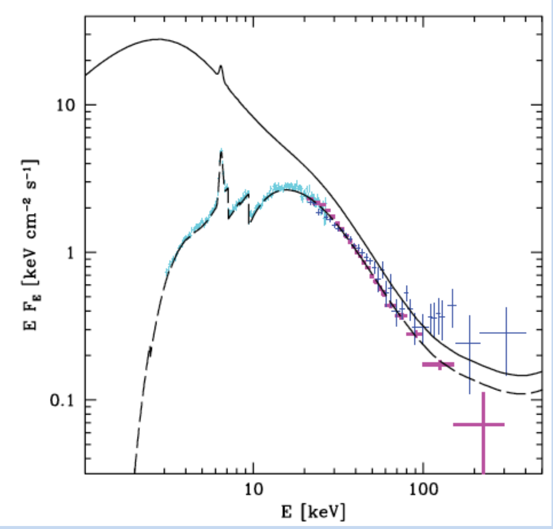


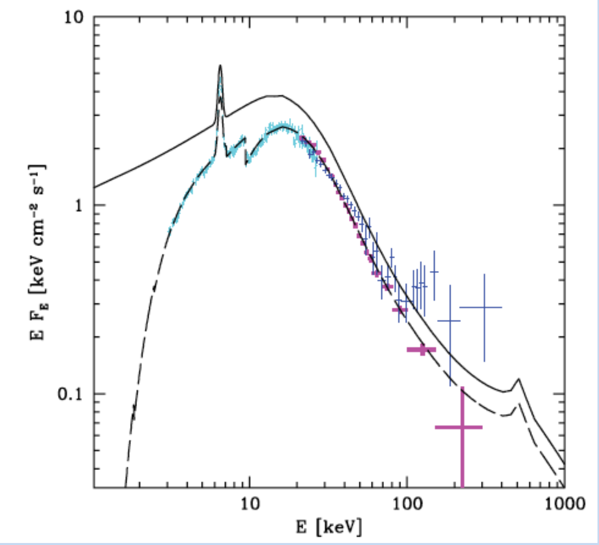


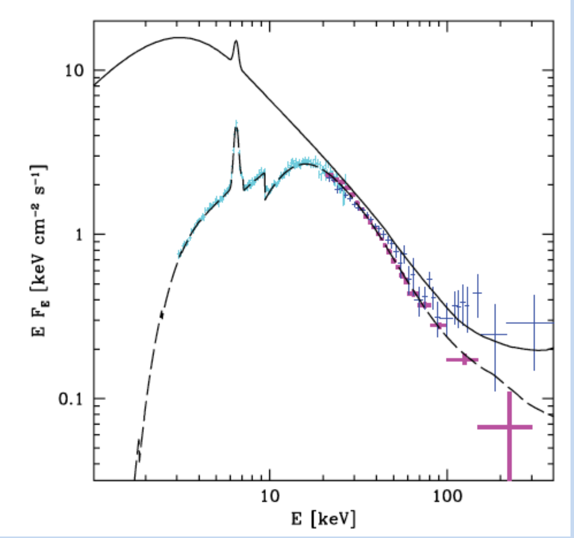
Szostek et al. 2008

Cygnus X-3 – an obscured ULX

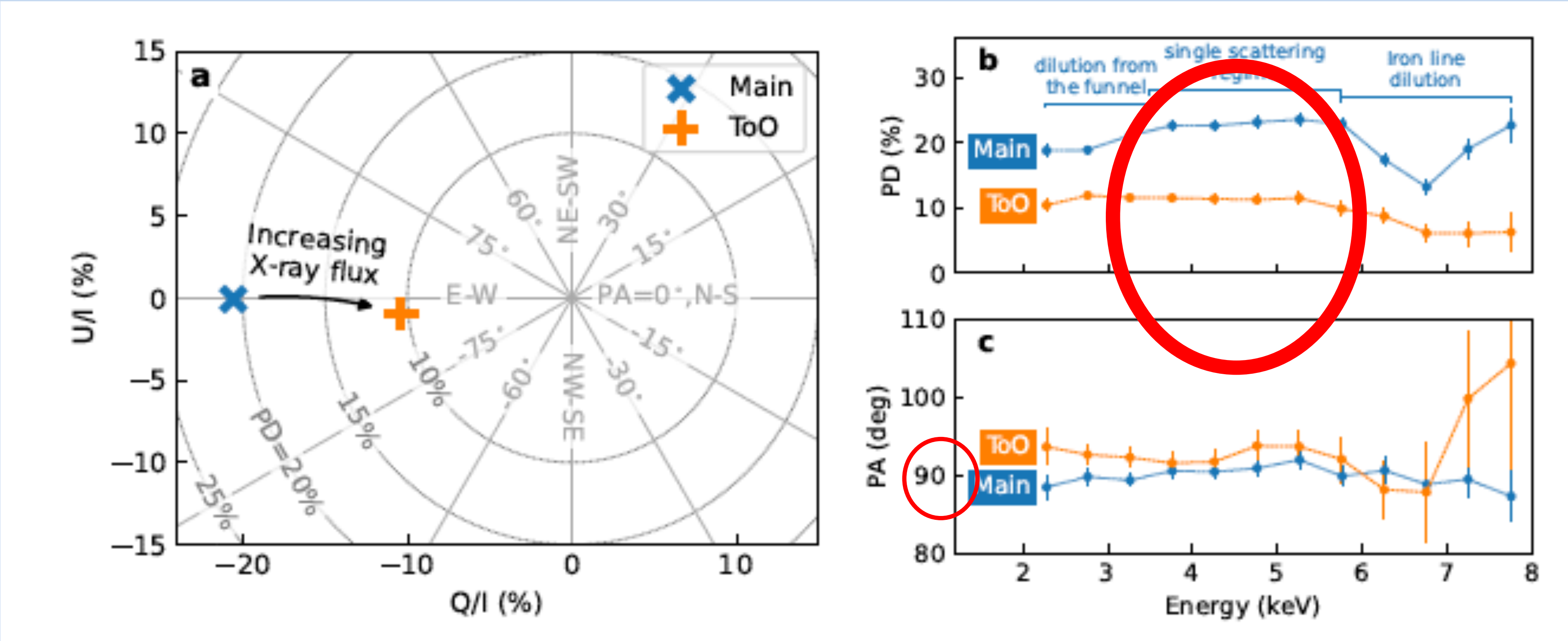
- Spectral modelling is uncertain (Hjalmarsdotter et al. 2009, Zdziarski et al. 2010): hard-state spectra can be explained with (i) soft spectrum, severely absorbed by WR wind; (ii) standard hard spectrum; (iii) reflection-dominated spectrum
- Often compared to the other accreting high-mass BH X-ray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







IXPE observations



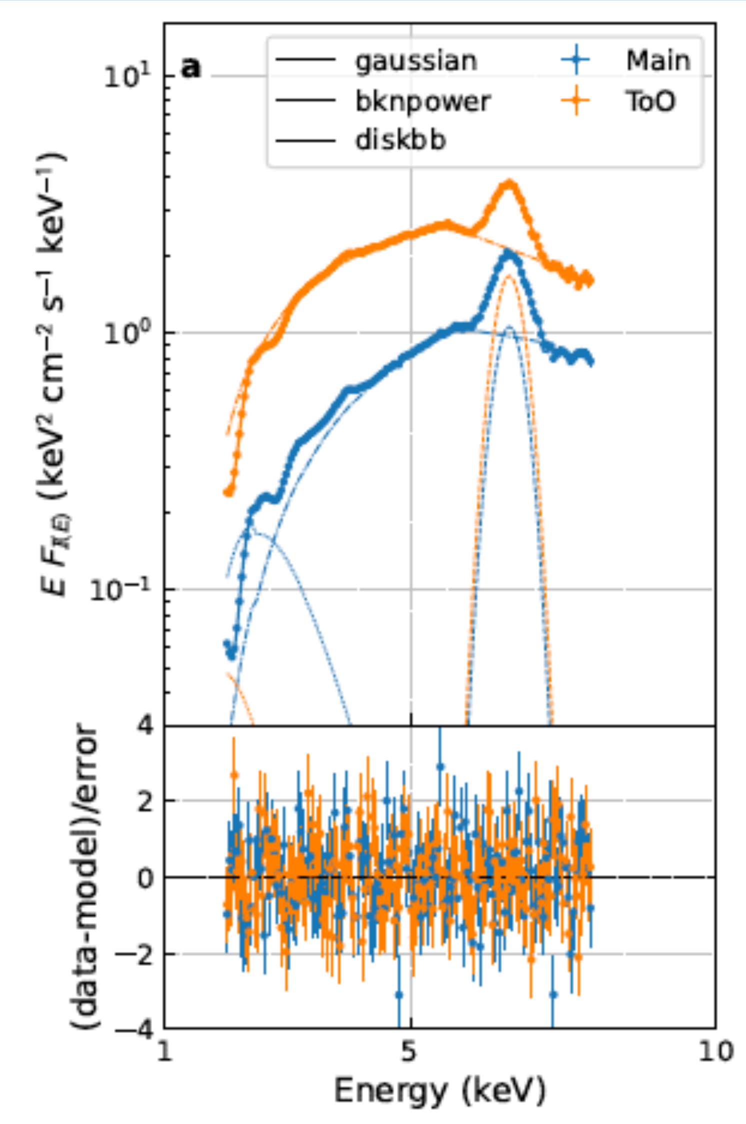
Main observation: 14-19 Oct, 31 Oct-6 Nov 2022
ToO observation: 25-29 Dec 2022

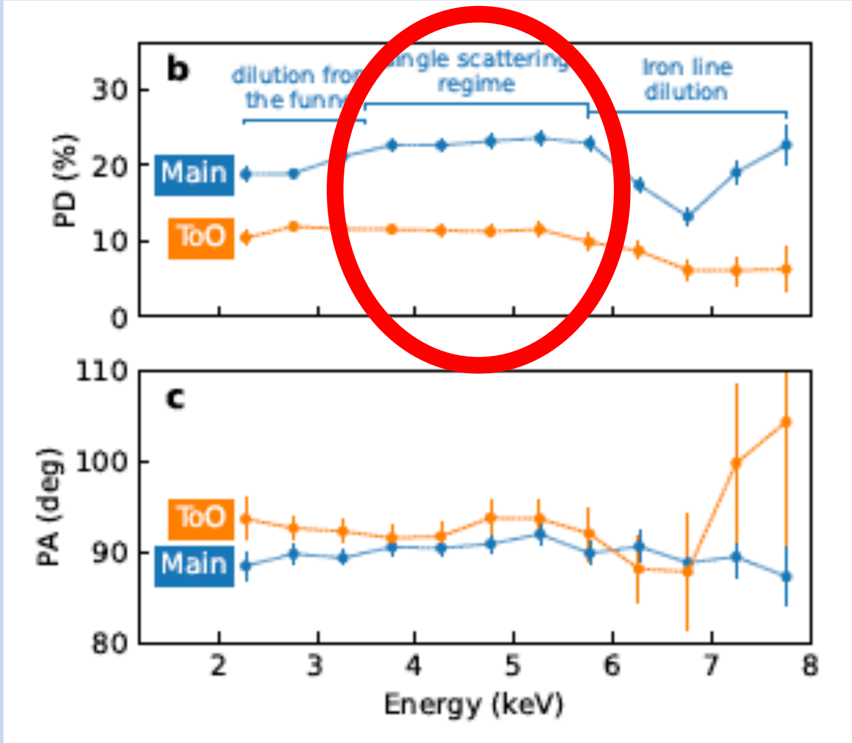
PD = 20.6 +/- 0.3 %
PA = 90.1 +/- 0.4°

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

PA perpendicular to the jet!

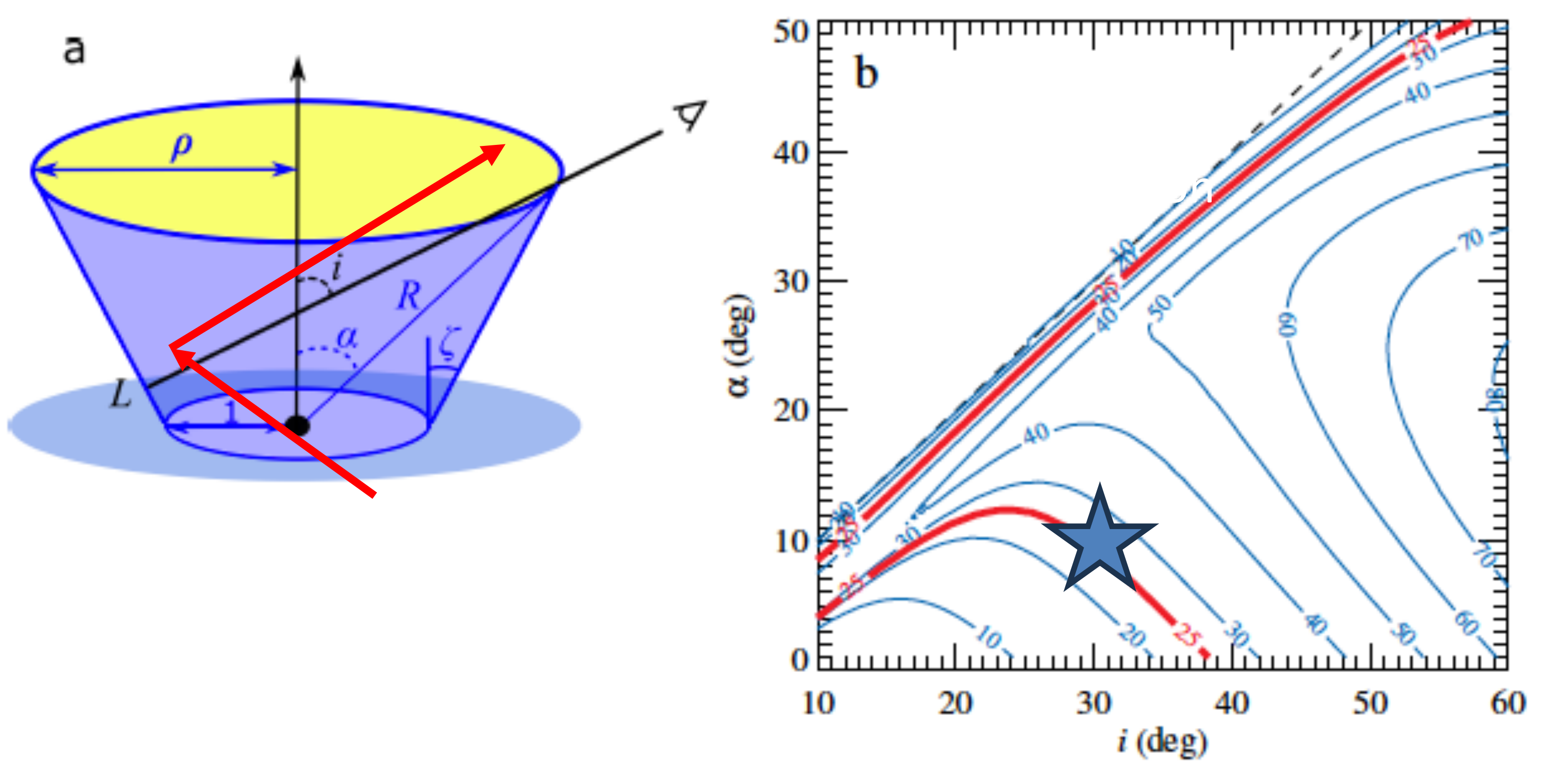
IXPE observations





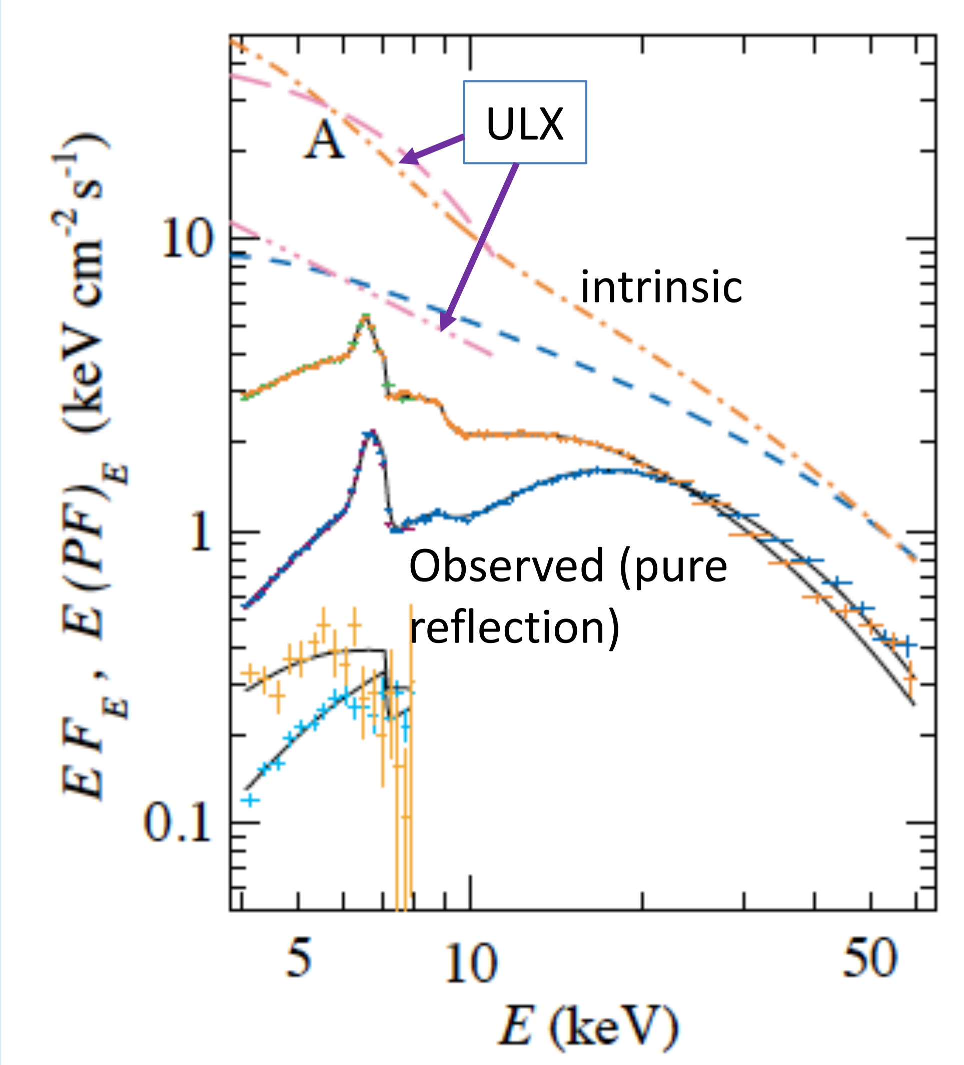
Broken power-law+gaussian (Fe Kα) +diskbb+several prominent abs/emission lines (guided by NICER)

X-ray polarization

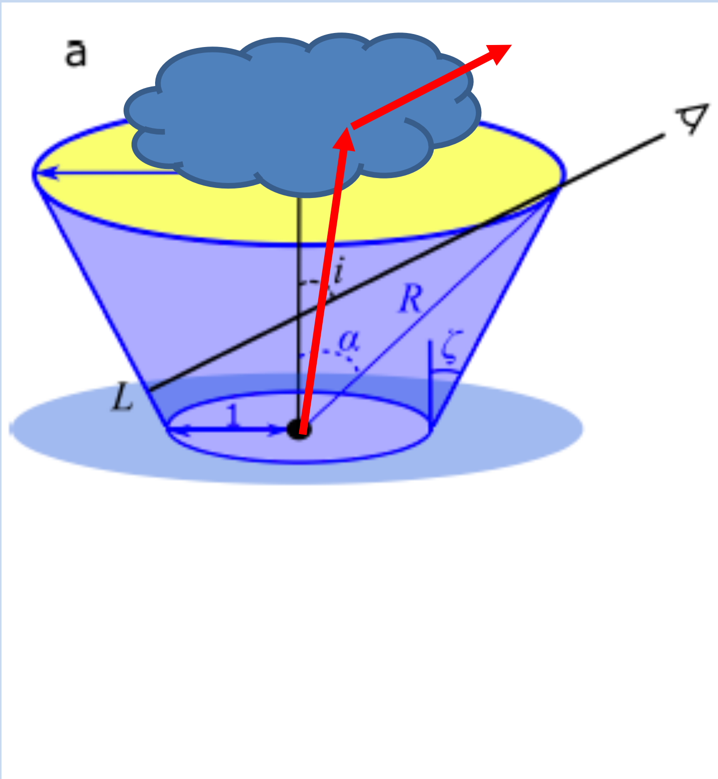


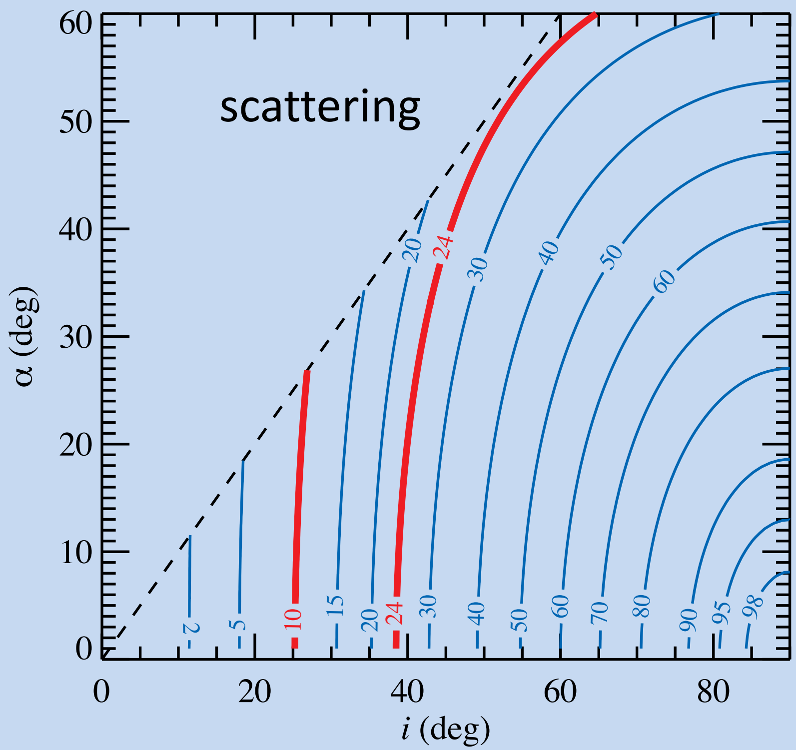
- PA ⊥ jet (/binary axis). High PD: we do not see central source
- $i \approx 30^{\mathrm{o}}$ hence optically thick matter high above the disc strong ⇒ accretion disk wind
- Modelling gives high intrinsic luminosity in excess $5\text{x}10^{39}$erg/s ⇒ hidden ULX

Cygnus X-3 – SED



Average polarization

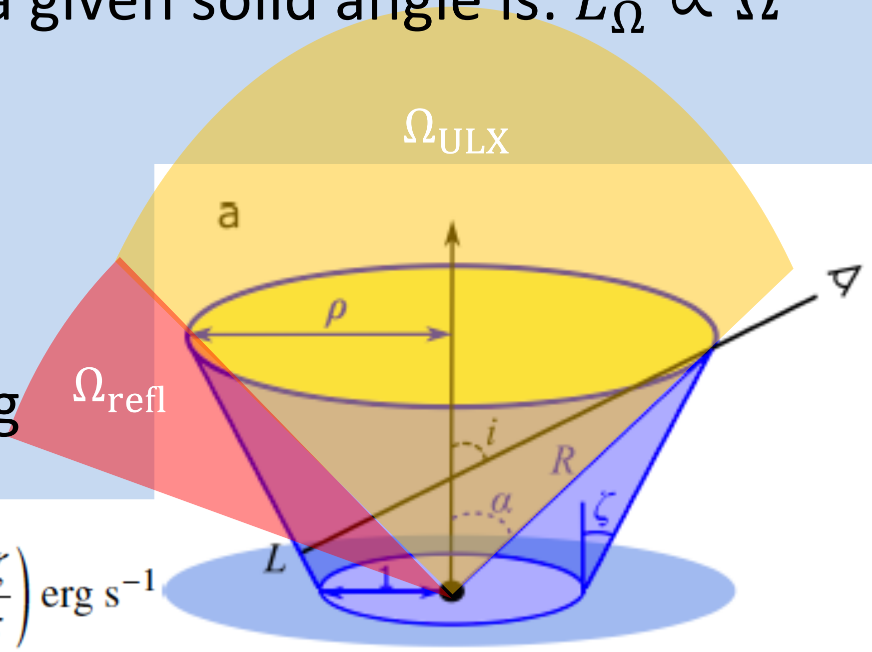




- PD $\perp$ jet(/binary axis)
- High PD: we do not see central source
- $i \approx 30^{\mathrm{o}}$ hence optically thick matter high above the disc

Intrinsic & apparent luminosity estimates

- Luminosity estimates: simple case when the intrinsic X-ray source is isotropic, the luminosity escaping in a given solid angle is: $L_{\Omega} \propto \Omega$
- $L_{ULX} \geq 5\times10^{39}\mathrm{erg\ s^{-1}}$



- Bolometric luminosity from modelling

$$L_{\mathrm{X,bol}} = \frac{4\pi D^2 f_{\mathrm{bol}} F_{\mathrm{unabs}}}{a}\left(1+\frac{\Omega_{\mathrm{ULX}}}{\Omega_{\mathrm{refl}}}\right) \approx 5\times10^{38}\left(1+\frac{1-\cos\zeta}{\Omega_{\mathrm{refl}}/2\pi}\right)\mathrm{erg\ s^{-1}}$$

- Depending on the funnel opening angle, up to $5\times10^{39}\mathrm{erg\ s^{-1}}$

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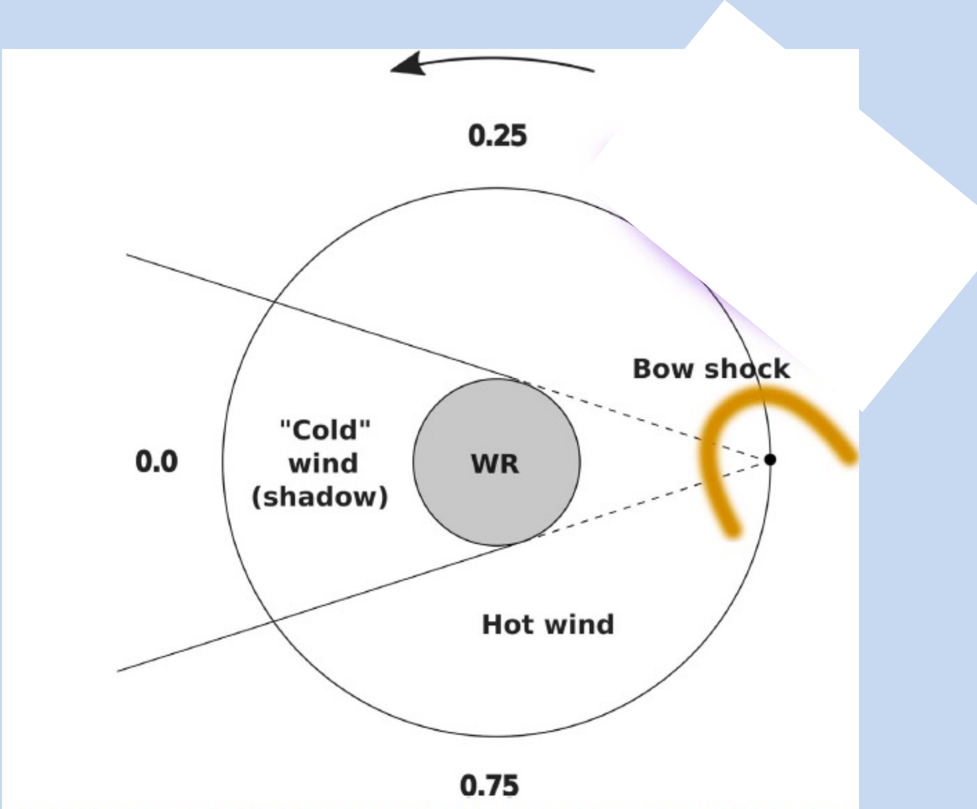
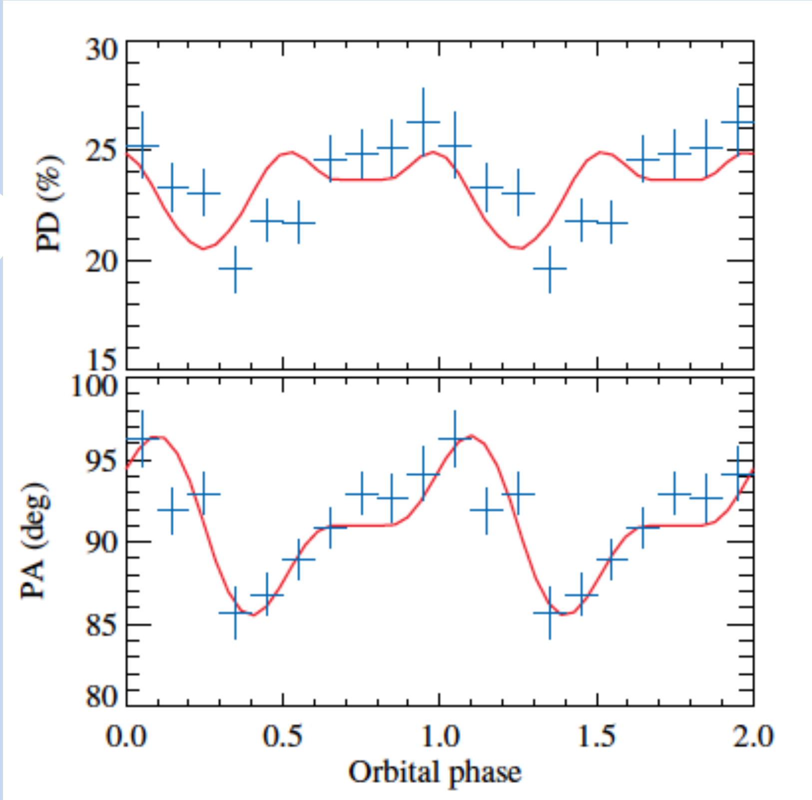
Intrinsic & apparent luminosity estimates

- **Masses and intrinsic luminosity**
  - From mass functions (Fe XXVI emission and He I absorption lines): $M_{WR}/M_X = 3.8^{+1.7}_{-1.4}$ (Vilhu et al. 2009)
  - Using mass loss rate of WR stars: $M_X \simeq 2.4^{+2.1}_{-1.1} M_\odot$ (Zdziarski et al. 2013), however, reanalysis showed another subtype of WR star and the mass estimate $M_X \leq 5 M_\odot$ (Koljonen & Maccarone 2017)
  - X-ray & IR photometry: $M_X \simeq 7.2 M_\odot$ (Antokhin et al. 2022)
- **Super-Eddington accretion**

High-amplitude polarization variability





Scattering of the X-ray emission at the inner surface of the bow shock can produce the observed orbital variability.
In this case, we deduce that the binary rotates counterclockwise.

Conclusions

IXPE opened a new “X-ray polarimetry” window to the Universe.

Observations of X-ray polarization revolutionize our understanding of accreting black holes.