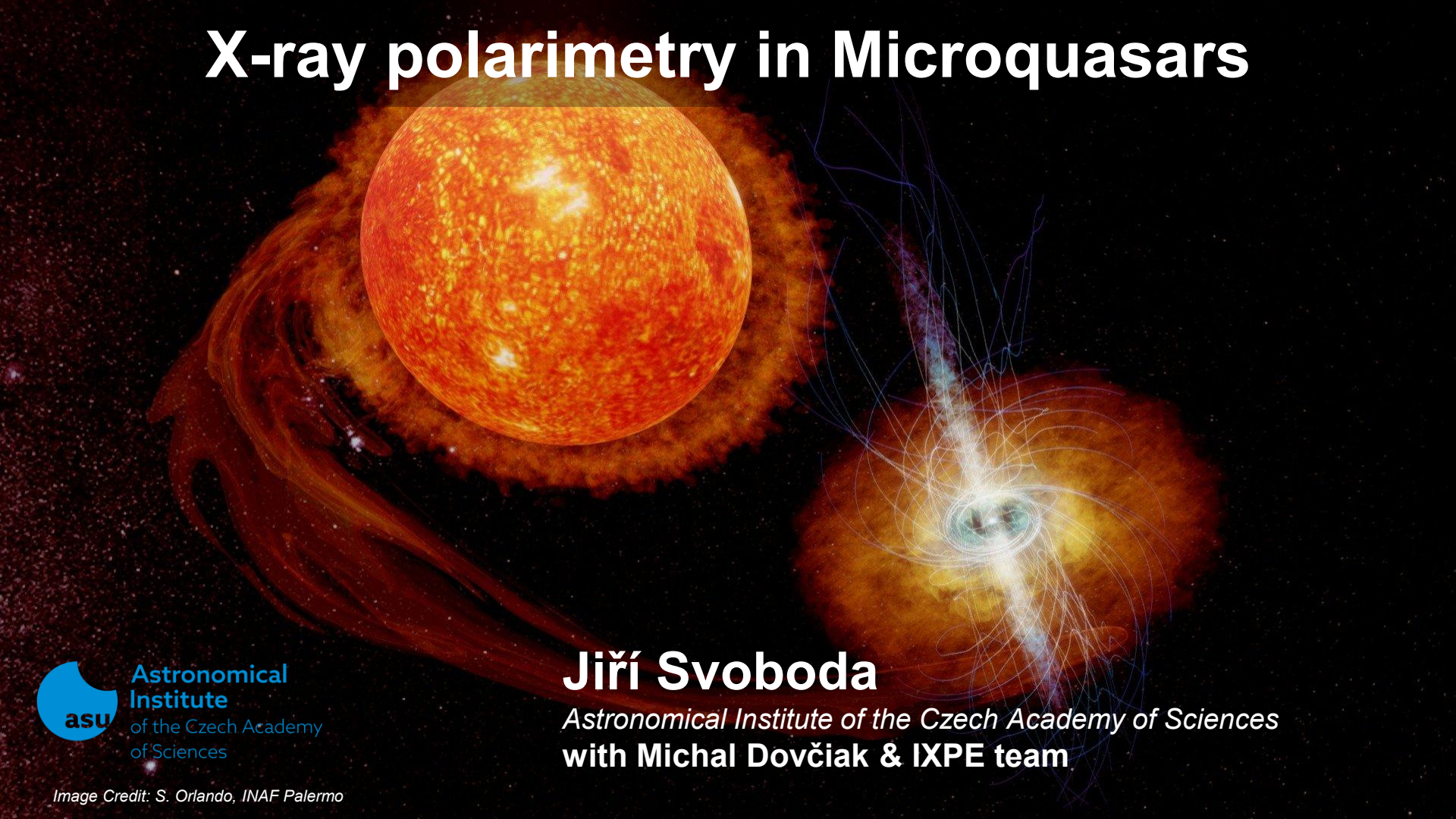
X-ray polarimetry in Microquasars



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Jiří Svoboda

Astronomical Institute of the Czech Academy of Sciences

with Michal Dovčiak & IXPE team

Image Credit: S. Orlando, INAF Palermo

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X-ray polarimetry of accreting compact objects

- probes the innermost accretion flow and the geometry of the scattering medium (**X-ray corona**), jets and winds
- complements the spectroscopy and timing

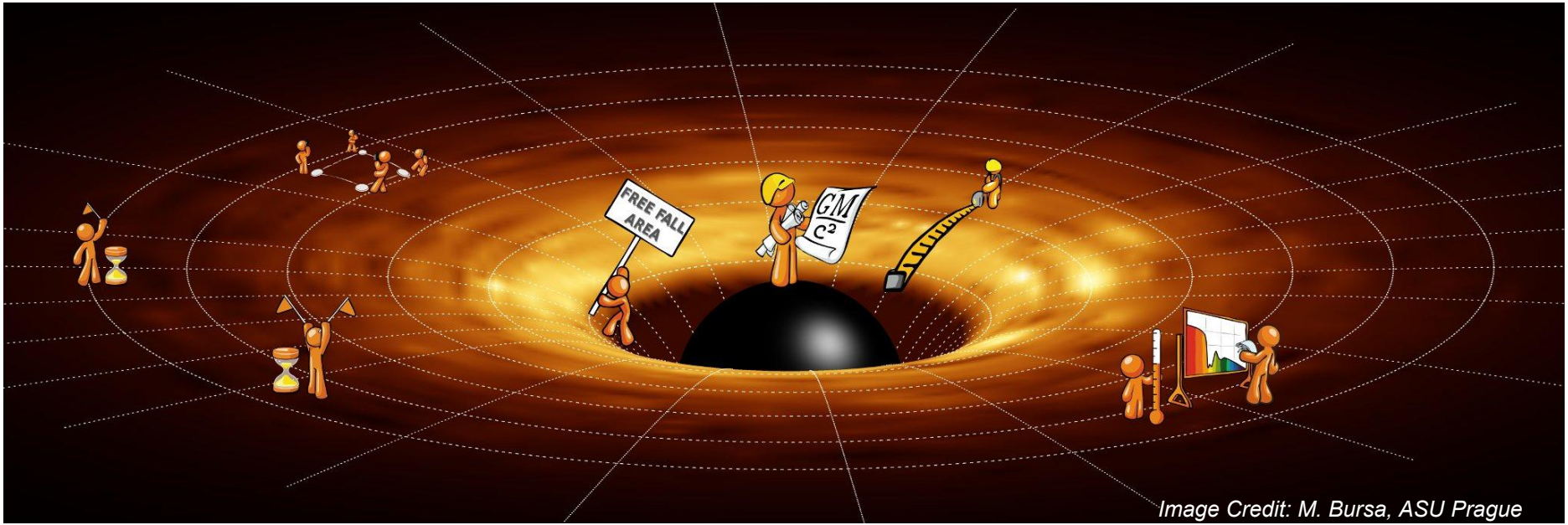

Image Credit: M. Bursa, ASU Prague

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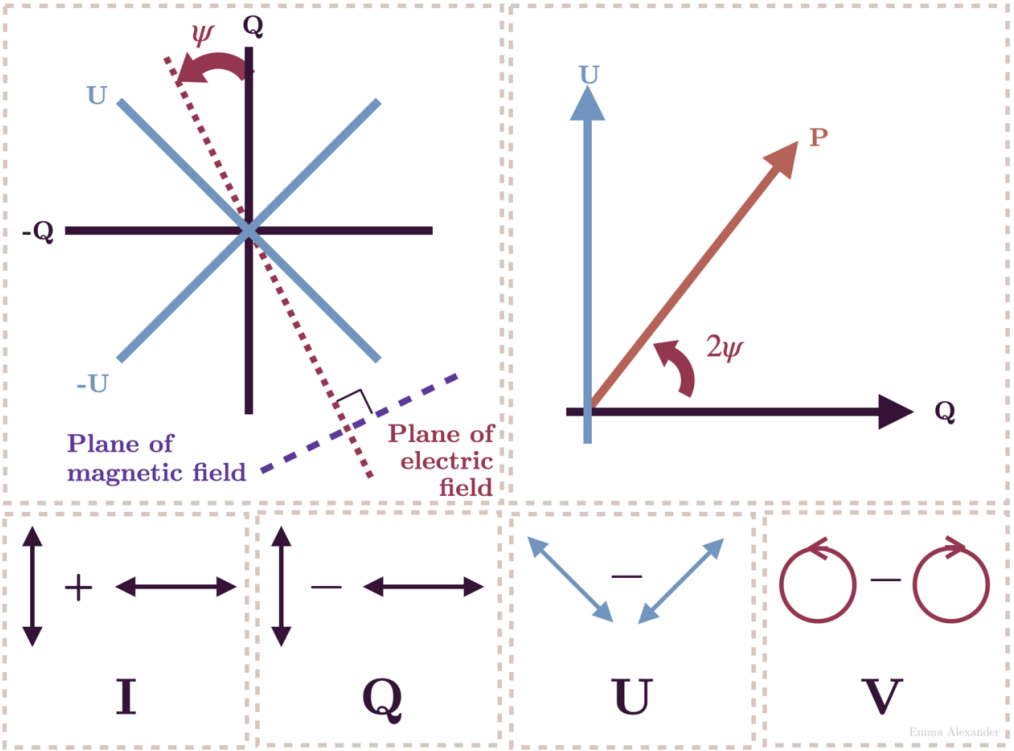
Polarization parameters



- Stokes parameters I, Q, U, V
- linear polarization: I, Q, U
  - **polarisation degree** (PD):

$$p = \frac{\sqrt{Q^2+U^2}}{I}$$

  - **polarisation angle** (PA):

$$\psi = \frac{1}{2}\arctan\frac{U}{Q}$$

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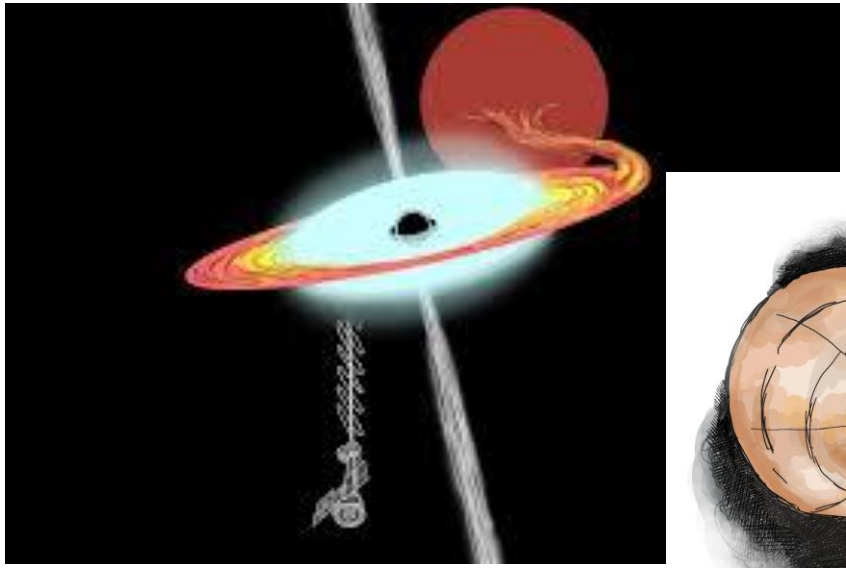
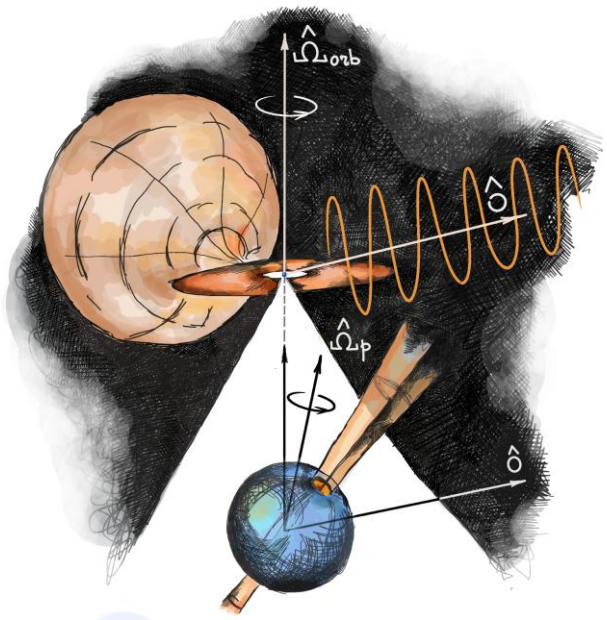
Black holes (BH), neutron stars (NS), pulsars, magnetars,…





Compact X-ray objects:

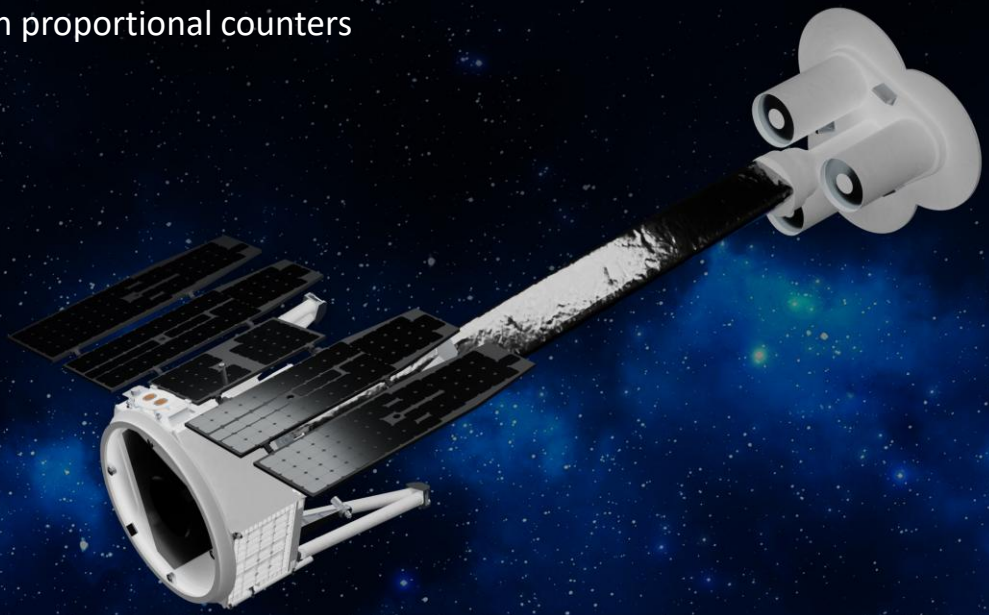
- variable accretion flow
- different emission components
- jets and magnetic fields

Origin of X-ray polarization:

- X-ray scattering
- synchrotron emission
- magnetized atmospheres

Imaging X-ray Polarimetry Explorer (IXPE)

- NASA/Italy Probe-category mission
- 3 Gas-Pixel Detectors based on proportional counters



IXPE scientific goals & measurements

I. Geometry of black-hole (BH) X-ray corona

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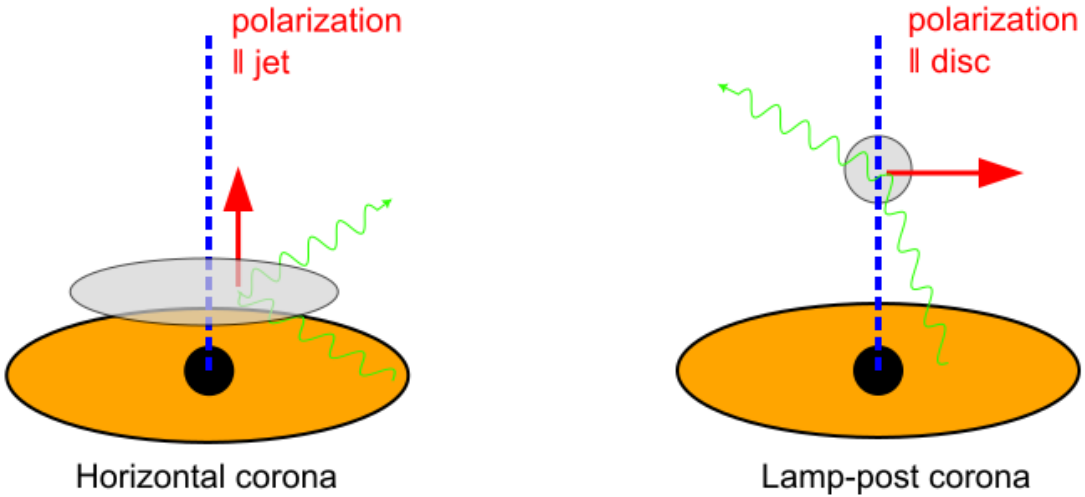
Polarization for different BH corona geometries

- photons scatter preferentially perpendicular to their electric polarisation vector, and the polarisation direction is conserved



- PD and PA depend on the inclination, the exact geometry of the X-ray corona, and its optical depth (single vs. multiple scattering)

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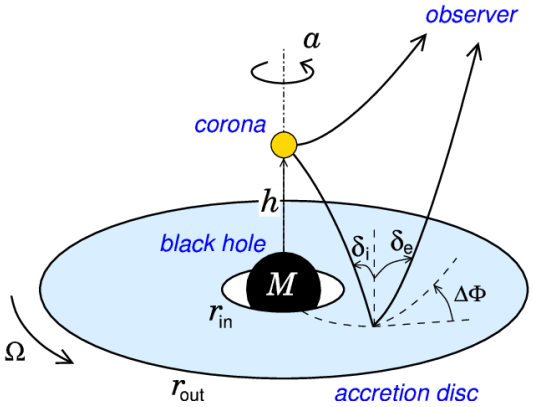
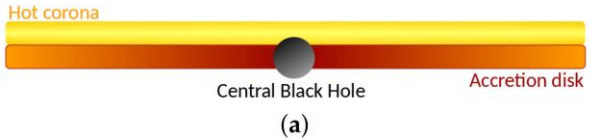
Geometry of the BH corona?

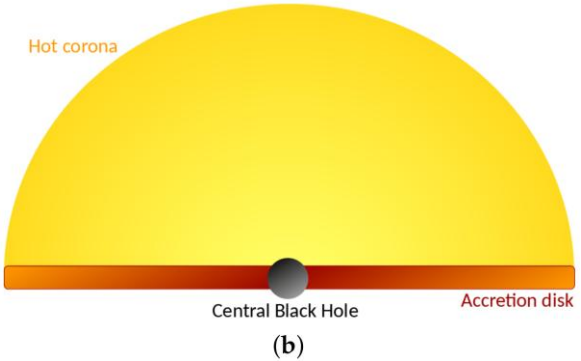
lamp-post geometry



„sandwiching“ slab geometry



spherical geometry

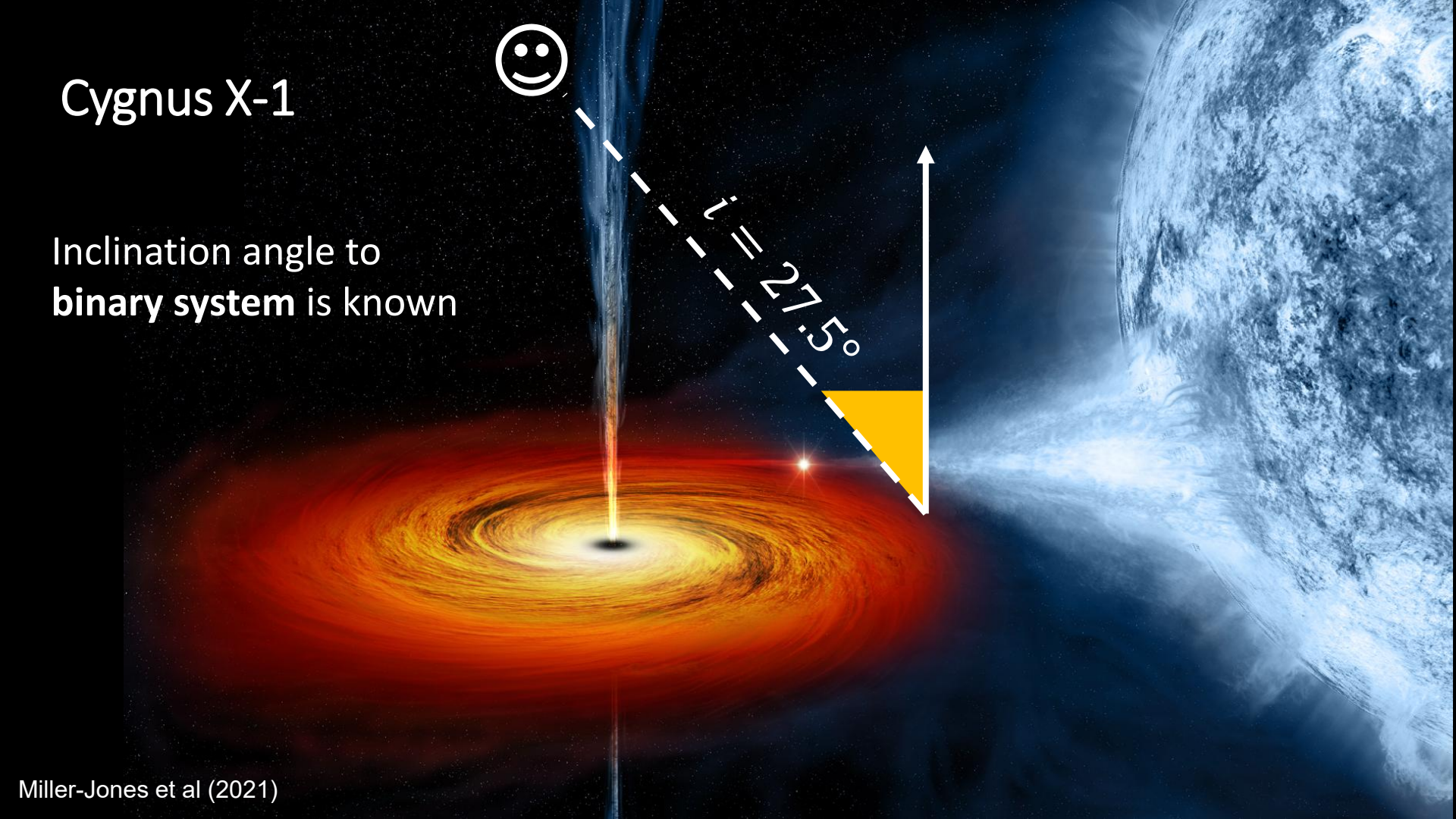


Original arguments in favour of the lamp-post geometry:

- **microlensing** → compact corona (Chartas+09, Chen+15)
- **steep radial emisivity of reflection radiation** (Fabian+02,09, Wilkins+12,...)
  - but see Svoboda et al. (2012), Kammoun et al. (2019)

Cygnus X-1

Inclination angle to **binary system** is known



Miller-Jones et al (2021)

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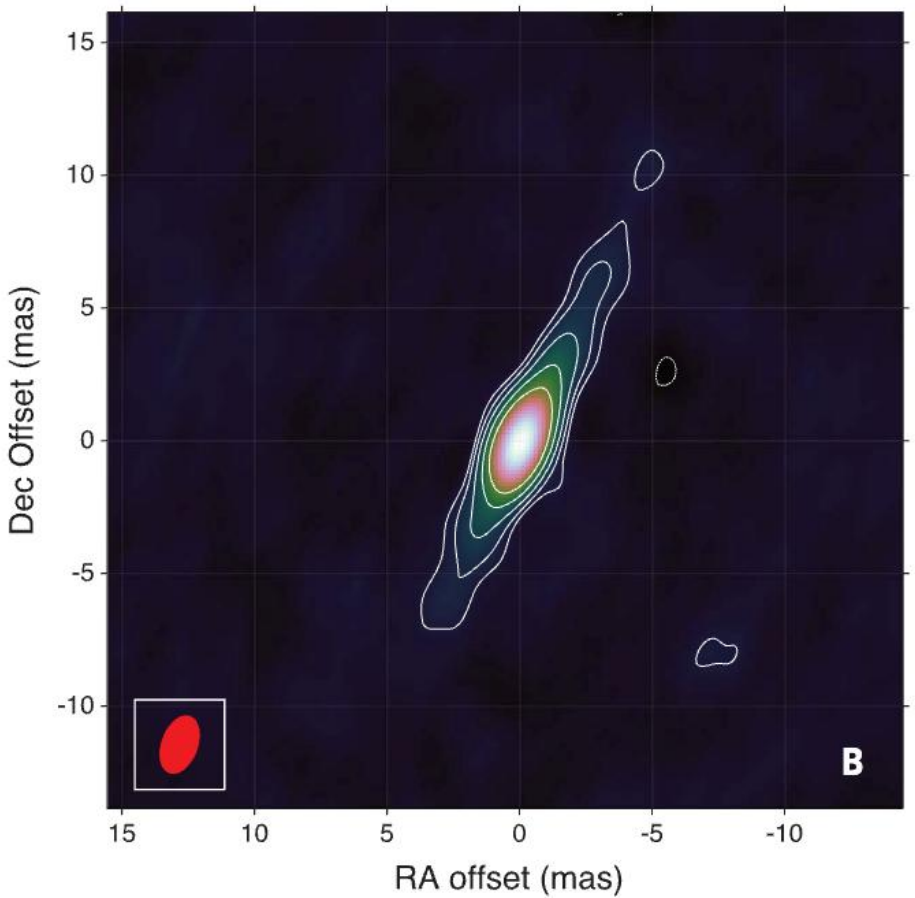
Cygnus X-1 jet

- steady jet resolved by VLBI
- we do **not** a priori know the inclination angle of the jet or inner disc



Miller-Jones et al (2021)

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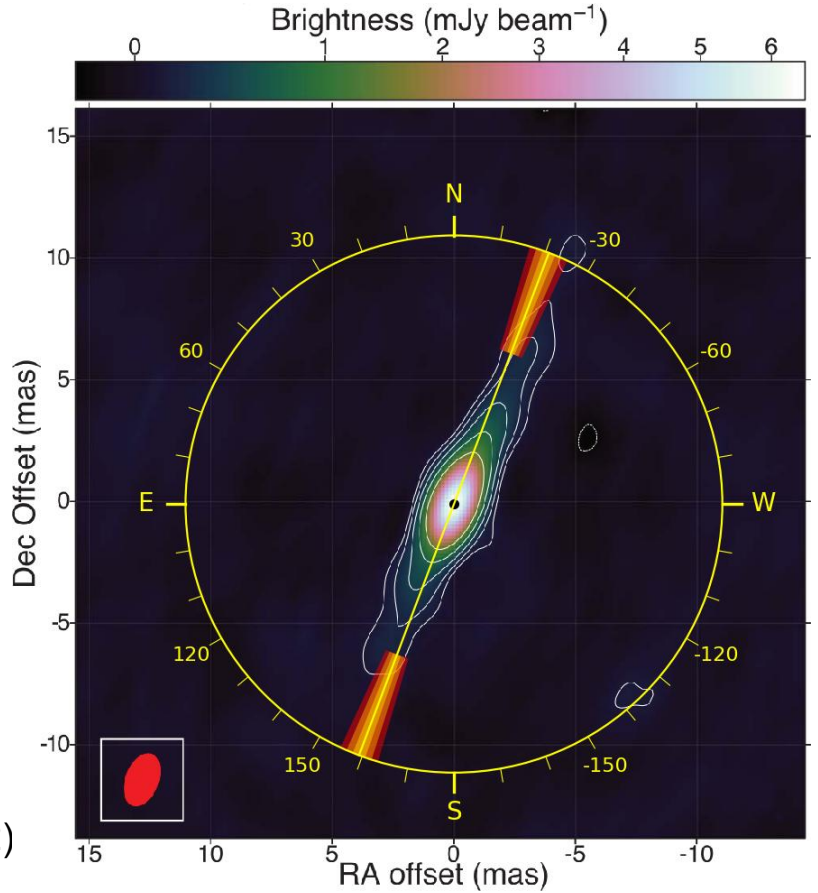
Results from the first IXPE observations of Cyg X-1

- 15-21 **May 2022** *(242 ks)*
- Cyg X-1 in the **hard state**
- measured polarisation:
  $\mathbf{4\%} \pm 0.2\%$ in 2-8 keV
  aligned with the jet
  $(-20.7° \pm 1.4°)$



Krawczynski et al. (2022)

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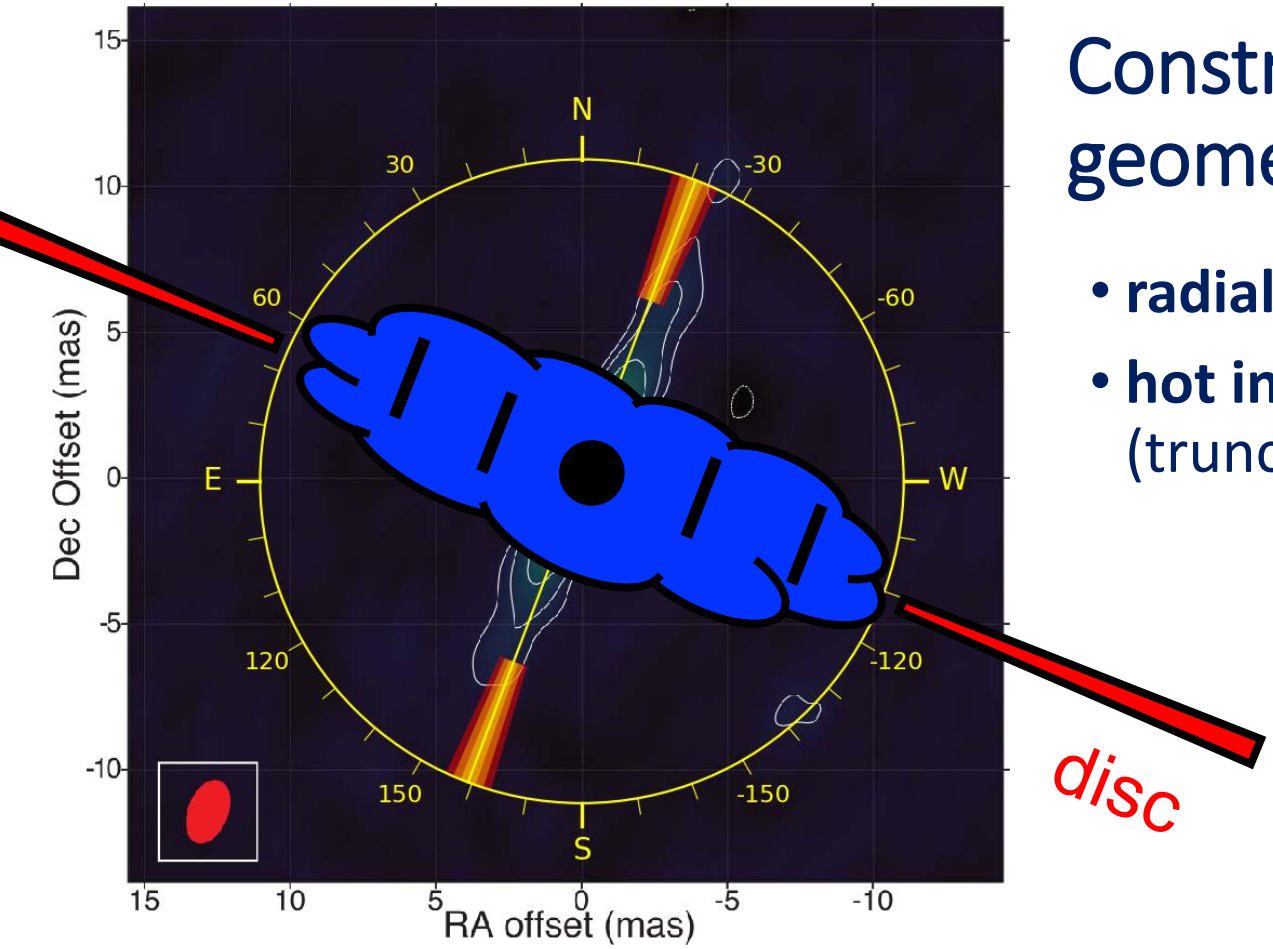
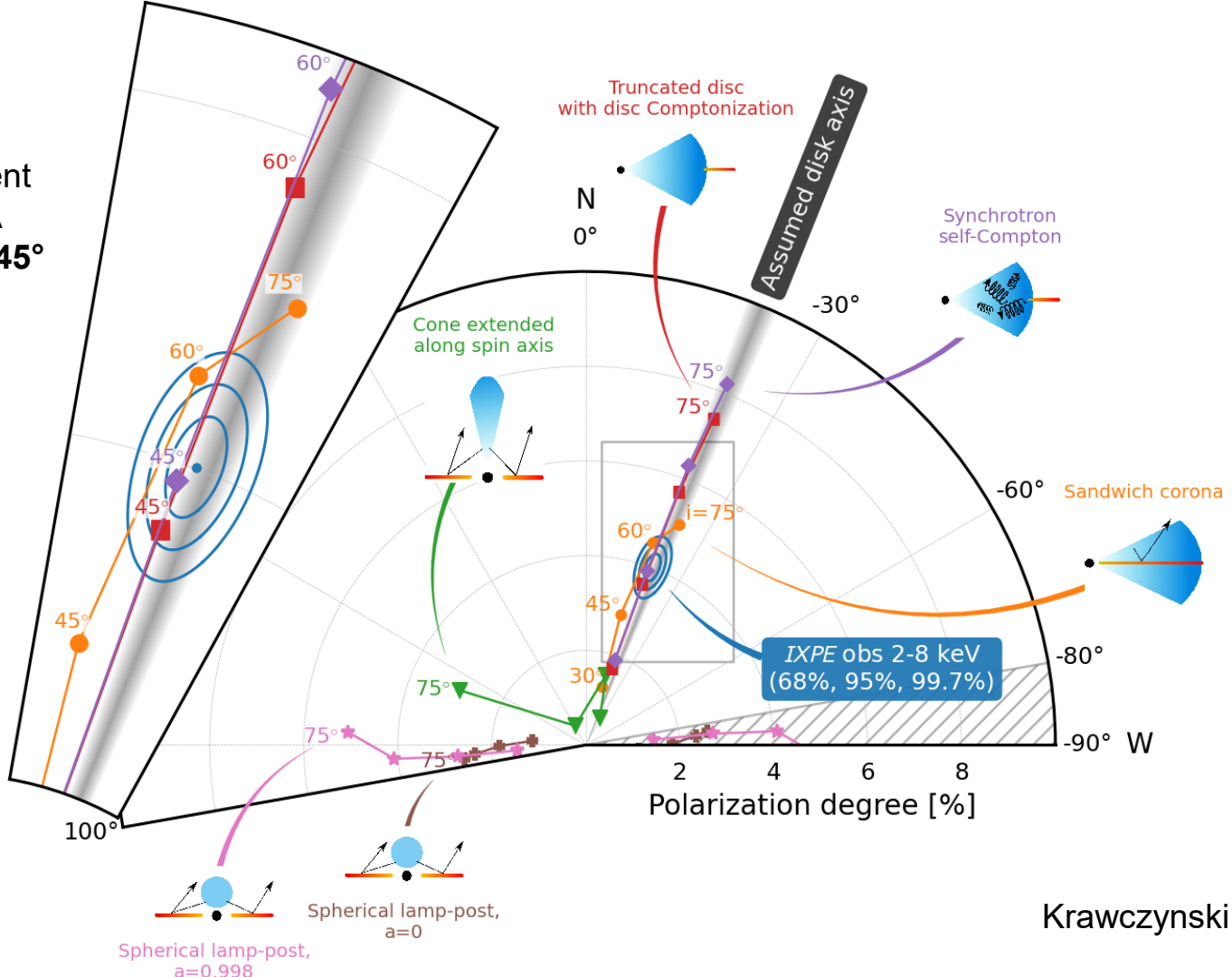


Constraints on the geometry of the corona

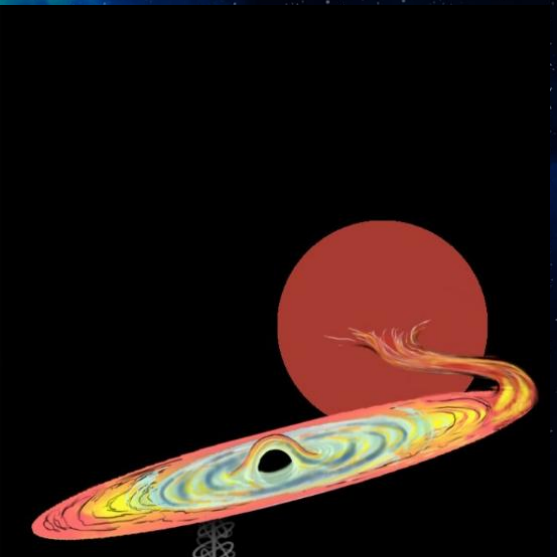
- **radially extended corona**
- **hot inner accretion flow** (truncated disc)

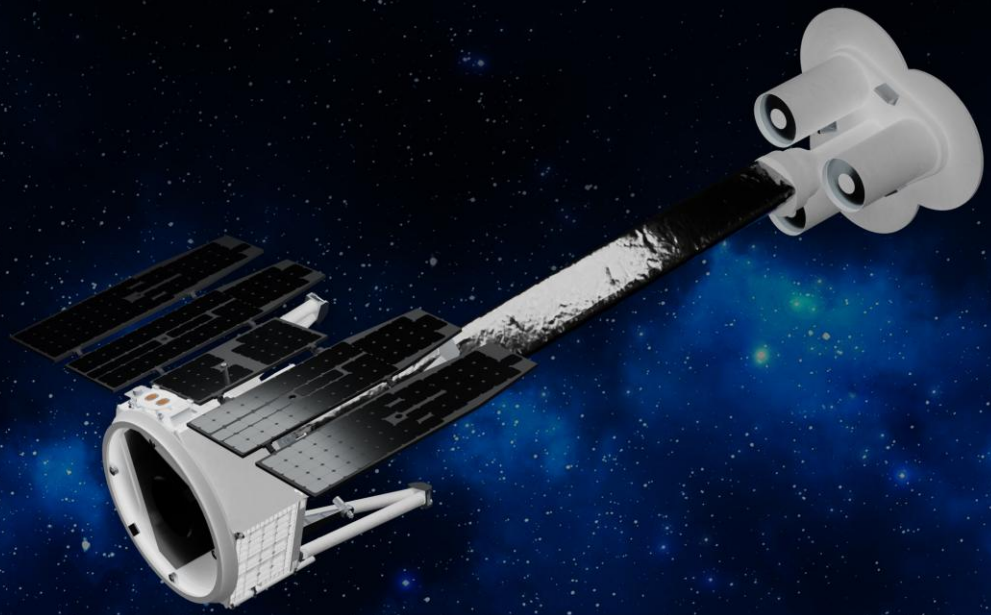
→ consistent
PD and PA
but **for i > 45°**



Krawczynski et al. (2022)

IXPE scientific goals & measurements





II. X-ray polarization in the soft state & BH spin measurements

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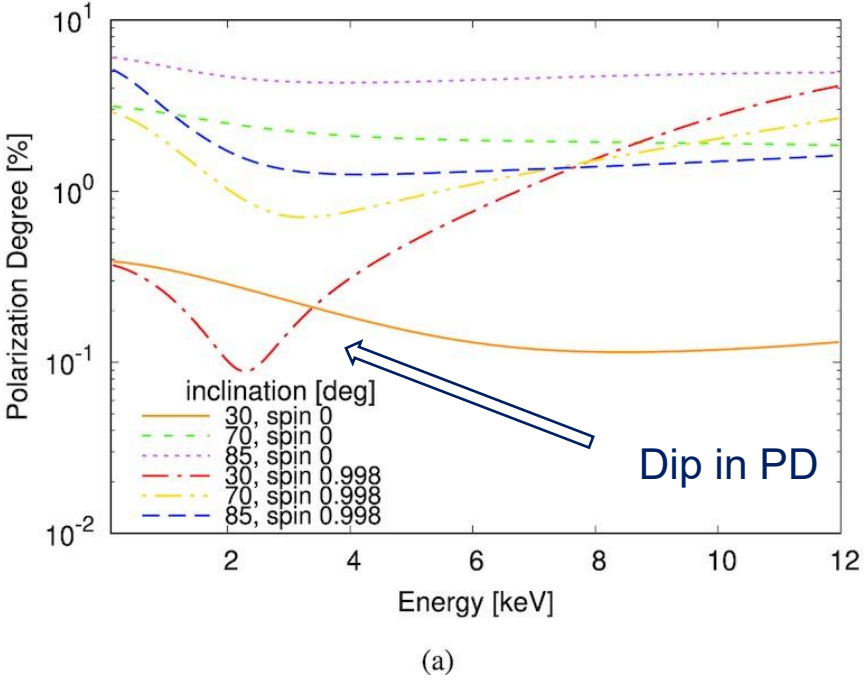
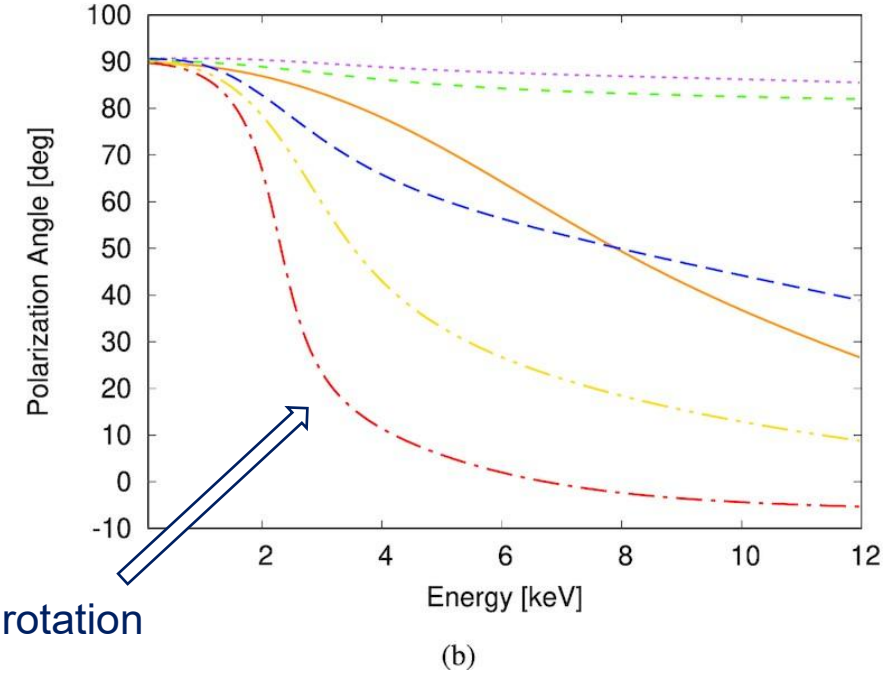
X-ray polarization constraints on BH spin





Mikušincová+23

See also Connors+ 1980, Dovčiak+ 2008, Schnittman & Krolik (2009), Taverna+ 2020

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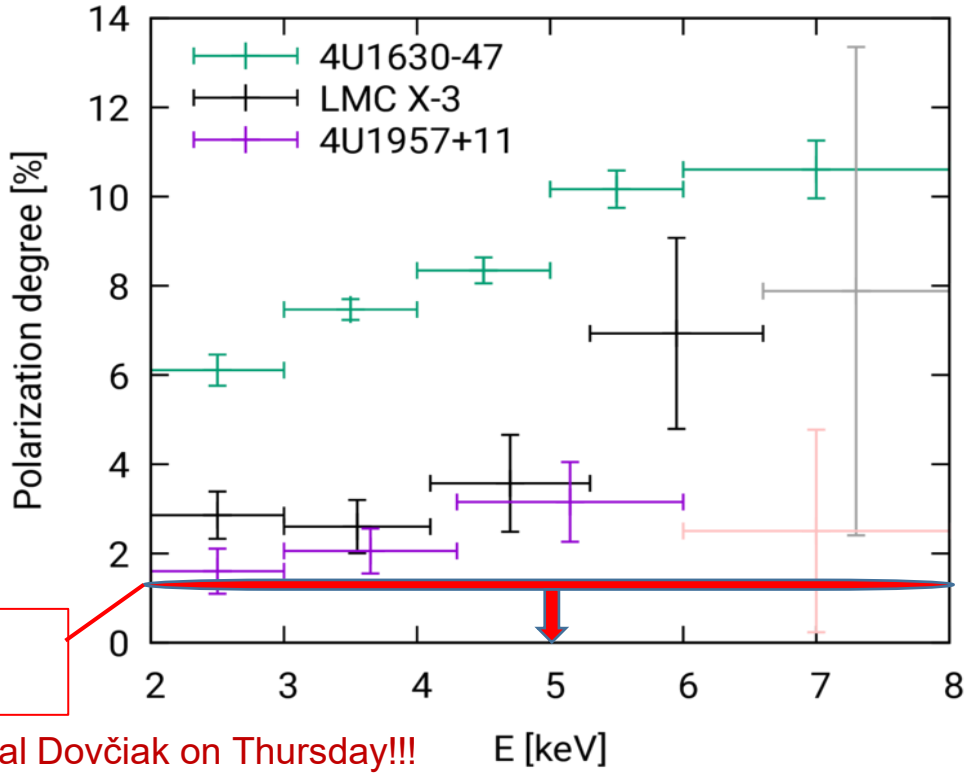
IXPE measurements of BHs in the soft state

- First measurement: 4U 1630-47
  - exceptionally high & mysterious (Ratheesh+23, Rodriguez Cavero+23)
- Highly-inclined sources:
  - 4U 1957+11 (Marra+23), LMC X-3 (Svoboda+24a)
- Low-inclined sources:
  - LMC X-1 (Podgorný+23), Swift J1727.8-1613 (Svoboda+24b), Swift J151857.0-572147 (Mundal+24), GX 339-4 (Mastroserio+25), MAXI J1744-294 (Marra+25)
  - only **upper limits ≤ about 1%**



LMC X-1, Swift J1727.8-1613, GX 339-4, Swift J151857.0-572147, MAXI J1744-294

+ new source – GRS 1739-278 - see talk by Michal Dovčiak on Thursday!!!

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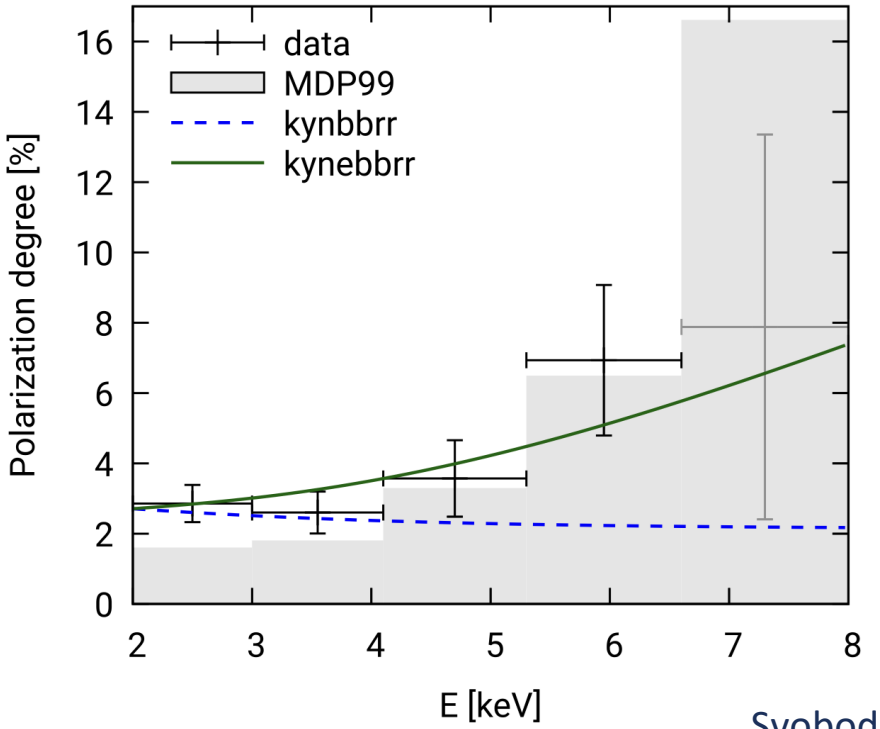
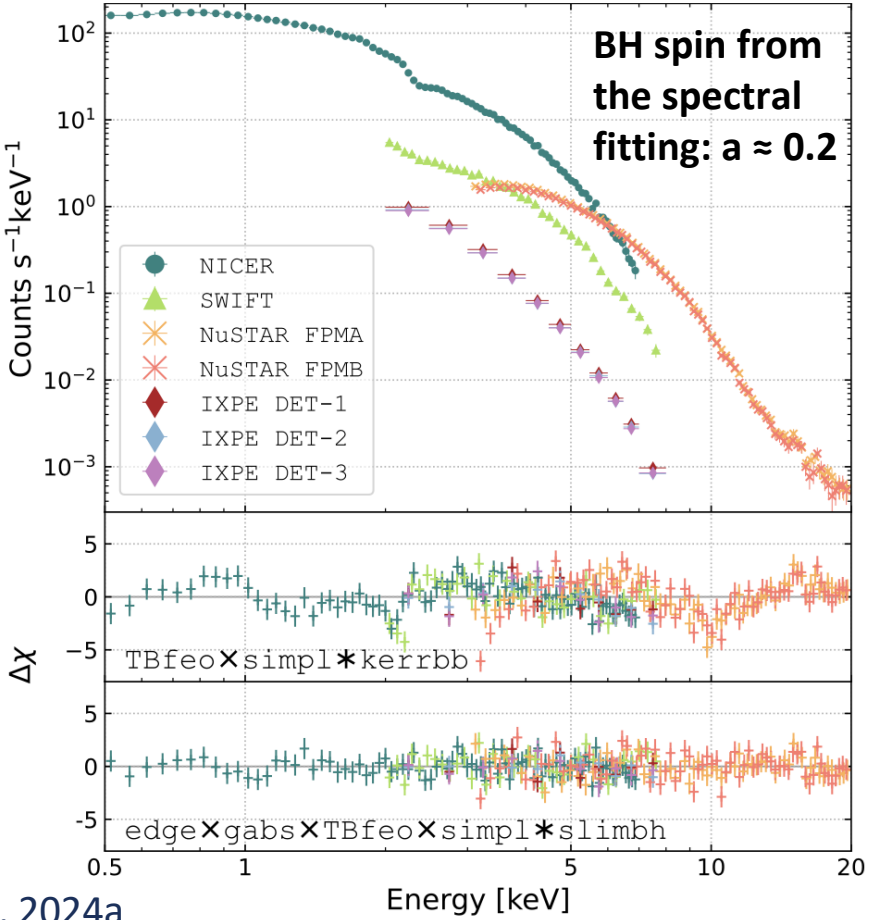
IXPE observation of LMC X-3





Svoboda et. al, 2024a

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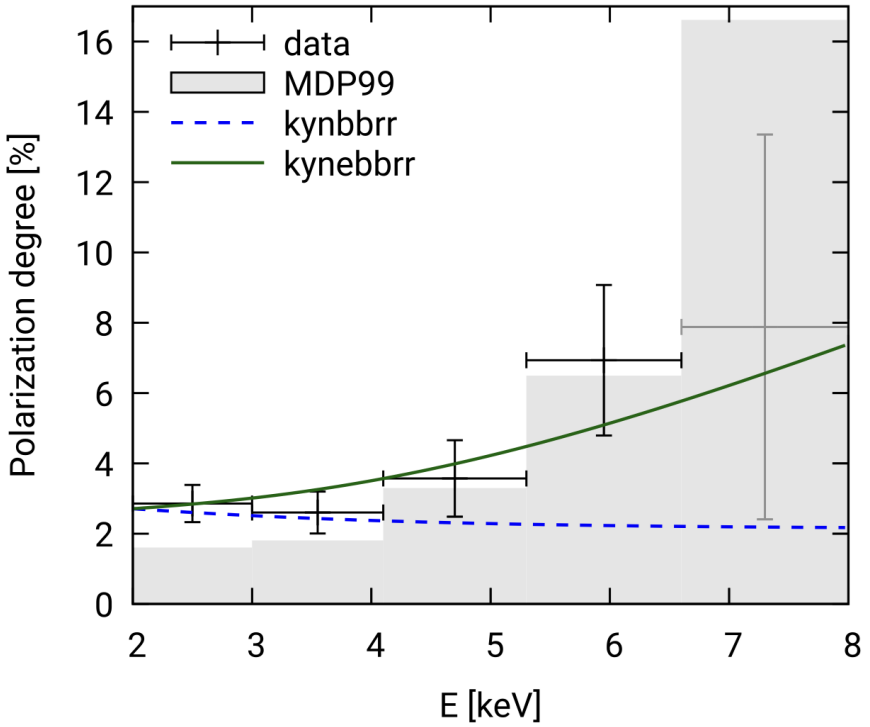
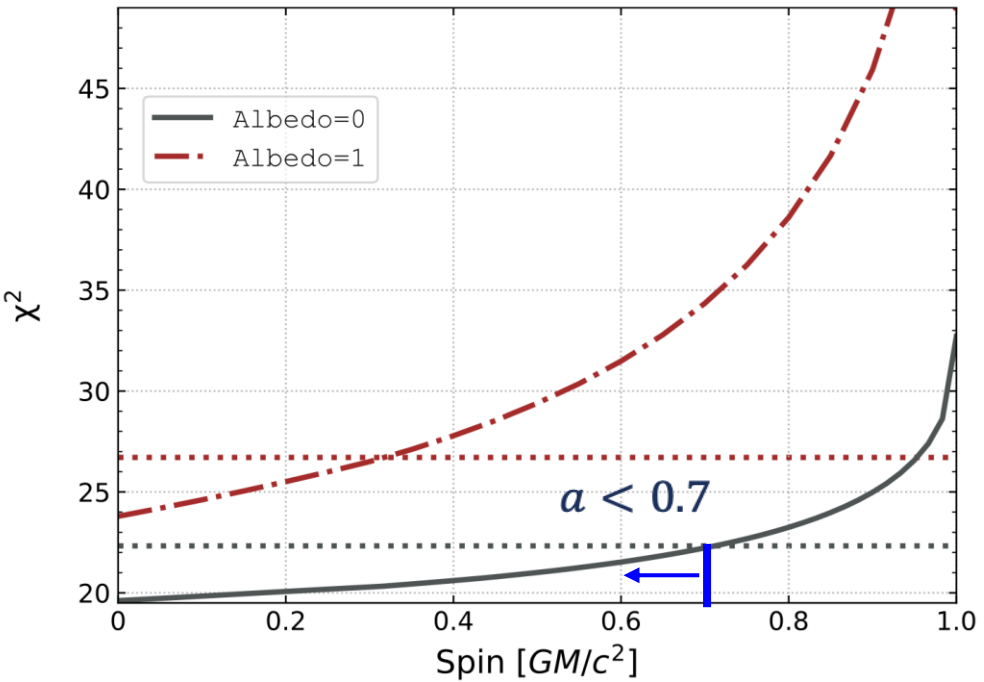
First spin measurement: LMC X-3



Fit of Q/I, U/I (independently of the spectrum)



Svoboda et. al, 2024a

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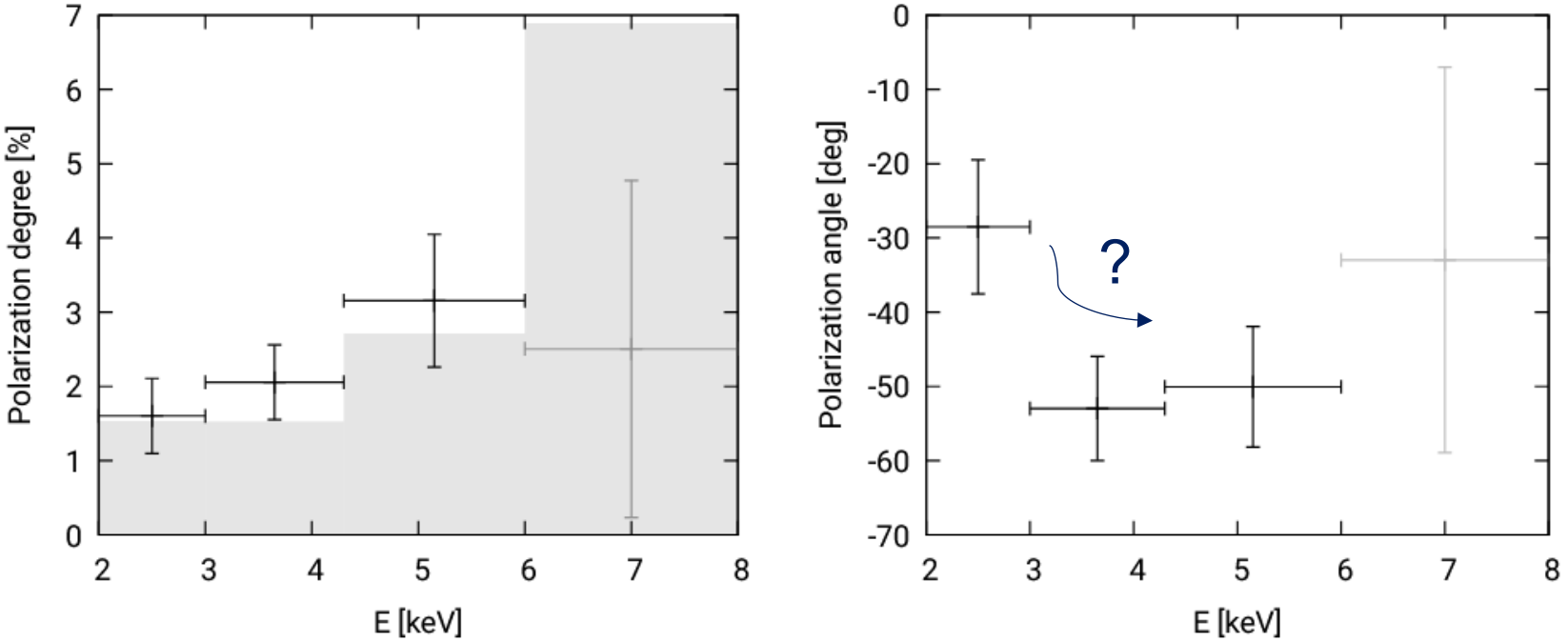
4U 1957+115 - indication of PA rotation?

Marra, L., et al.: A&A, 684, A95 (2024)



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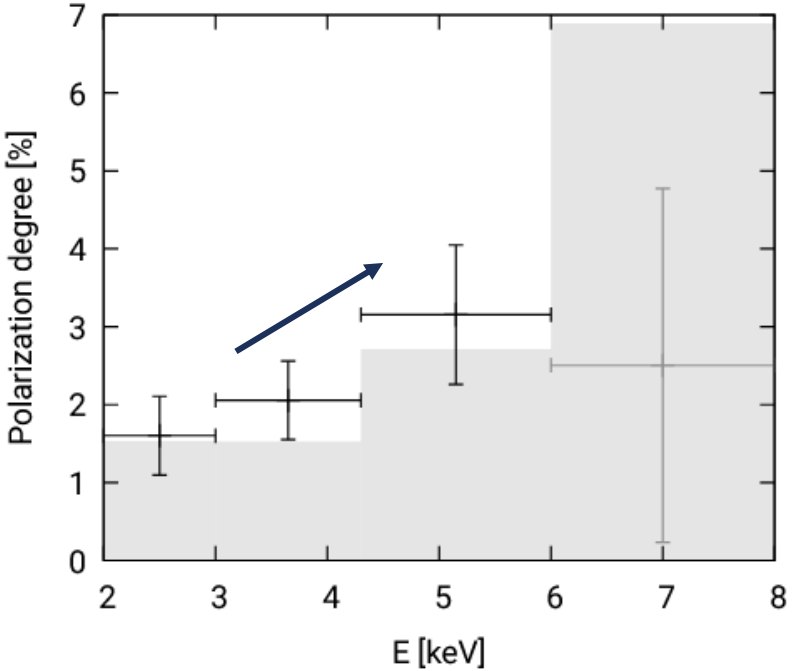
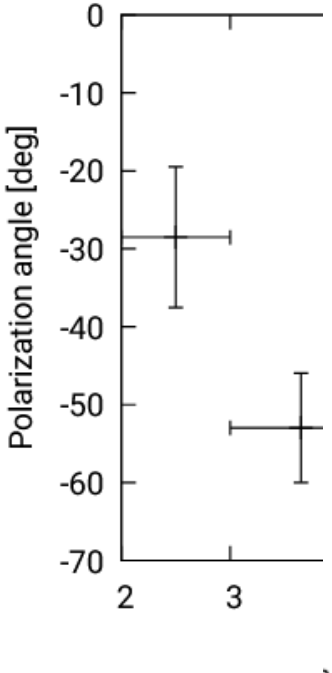
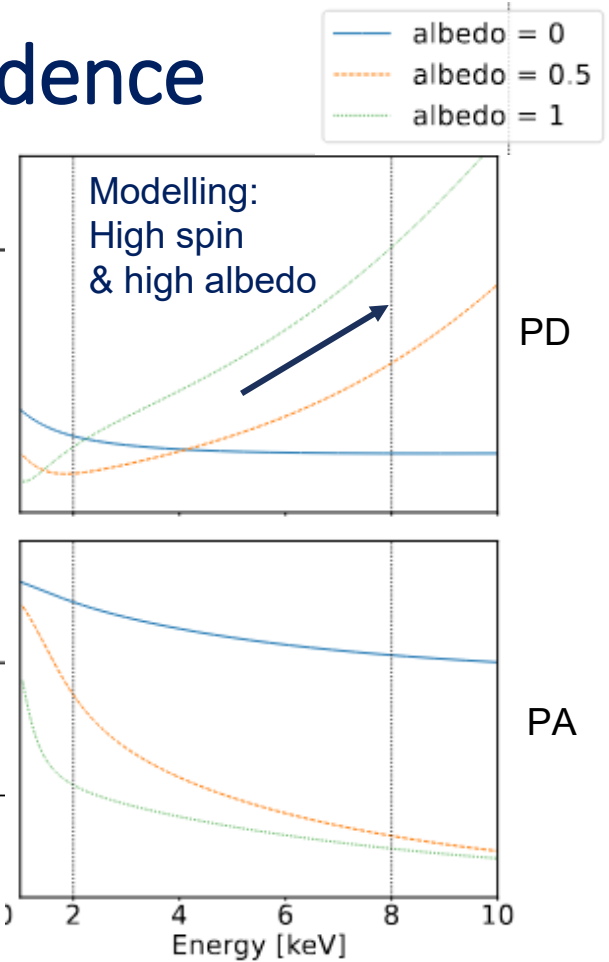
4U 1957+115 – PD energy dependence

Marra, L., et al.: A&A, 684, A95 (2024)

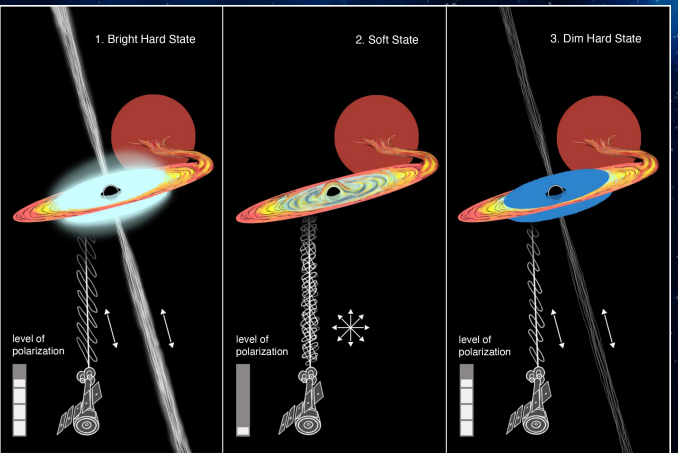






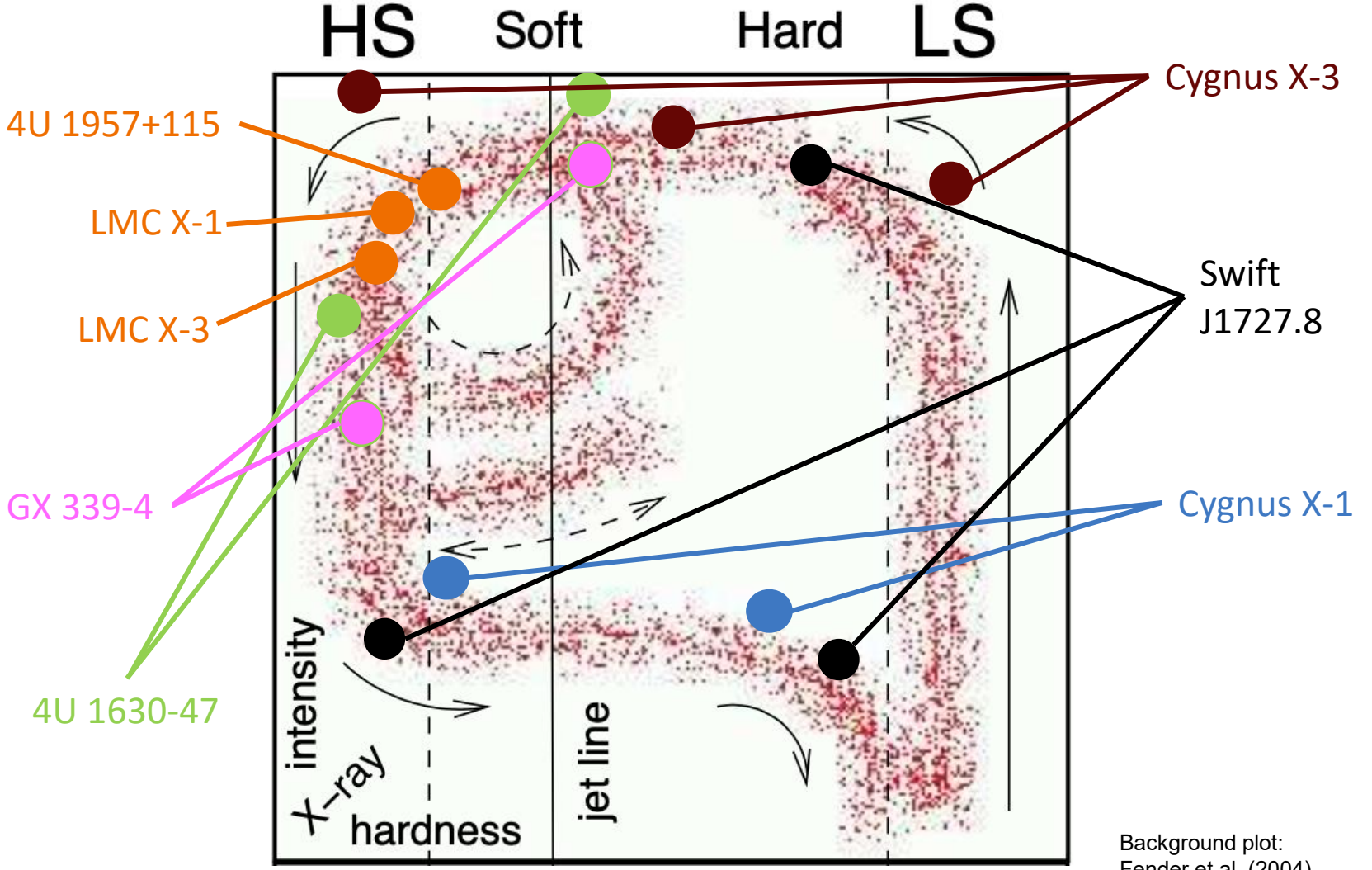
+ new observations being performed this autumn – stay tuned!

IXPE scientific goals & measurements



III. X-ray polarization across accretion states

Spectral States



Disclaimer: Luminosity and hardness not drawn to scale

Background plot:
Fender et al. (2004)

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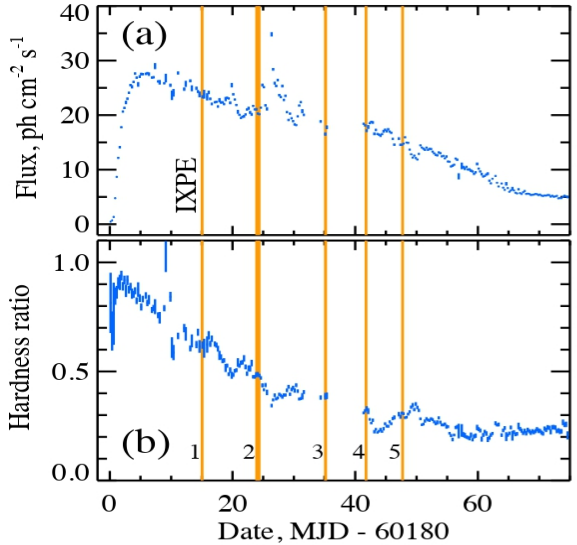
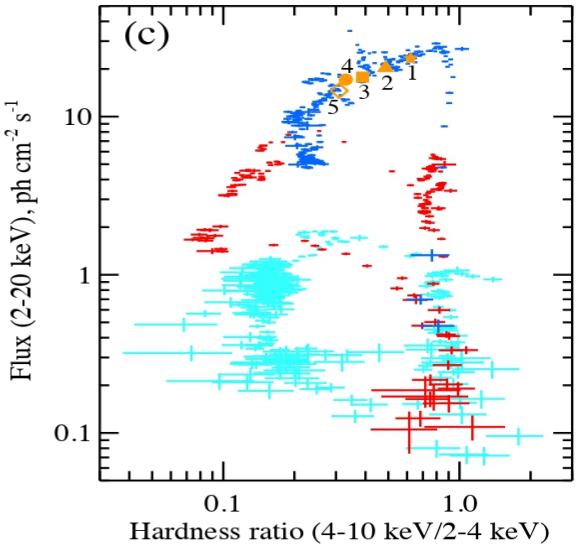
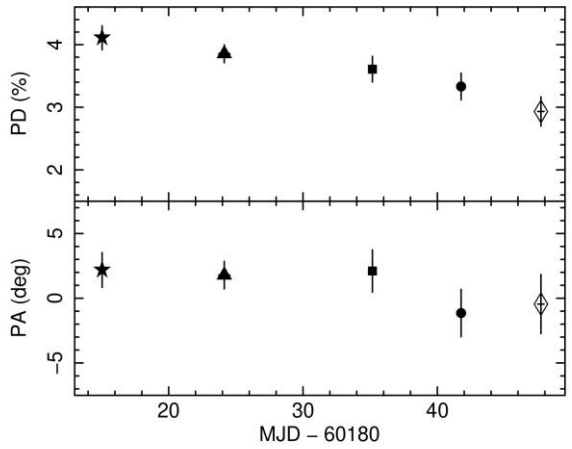
Swift J1727.8-1613 – hard state

- new XRB discovered in Aug 2023, reached flux ≈ 7 Crabs (in 2-20 keV)
  - brighter than any other recent black-hole XRB outburst
- *IXPE:* 5 observations in September during the hard/intermediate state and its transition to the soft state (Veledina+23, Ingram+24)





Polarization evolution



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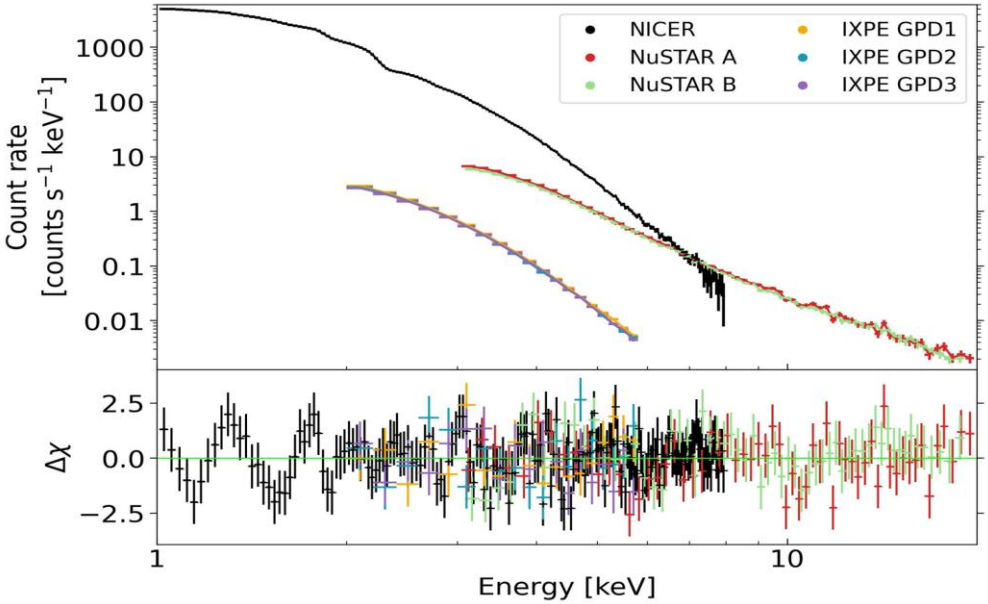
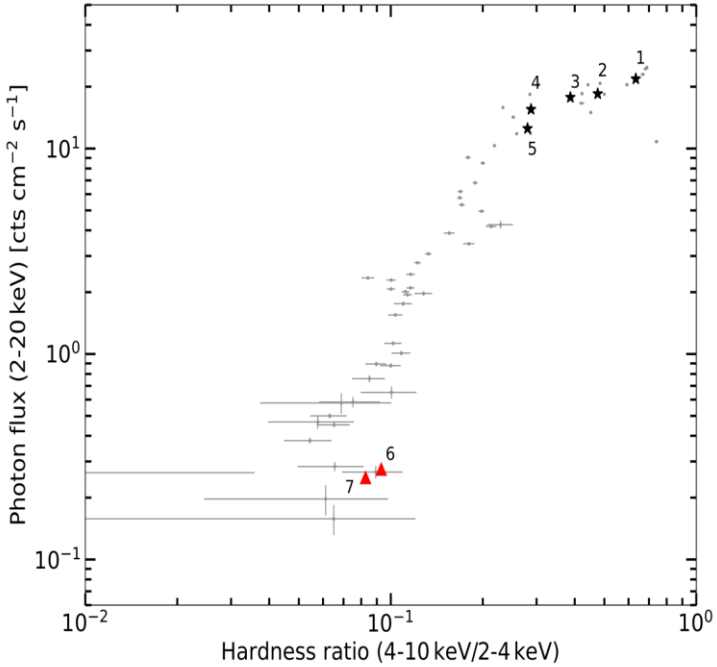
Swift J1727.8-1613 – soft state

- Soft state observations in Feb 2024
  - flux about two orders of magnitude weaker than during the outburst peak





- very soft spectrum dominated by the thermal accretion-disk emission

Svoboda et al., 2024b

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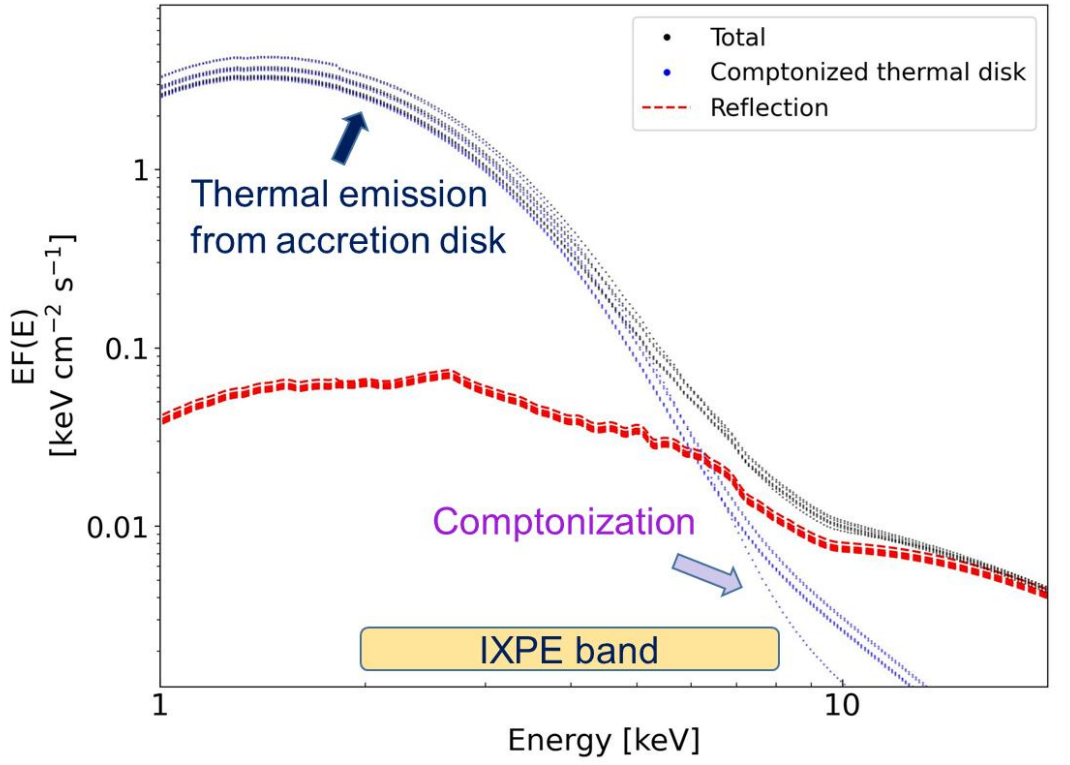
Swift J1727.8-1613 – spectral fit



model component	parameter	value
neutral absorption	nH [10^{22} cm^{-2}]	≈ 0.24
accretion disk	**L/L_{Edd}**	**≈ 1%**
	spin	**≈ 0.9**
	inclination	**≈ 38°**
Comptonization	**scattering fraction**	**≈ 2-6%**
	Photon Index	≈ 4.9
Reflection	L/L_{Edd}	≈ 5×10^{-7}

Svoboda et al., 2024b

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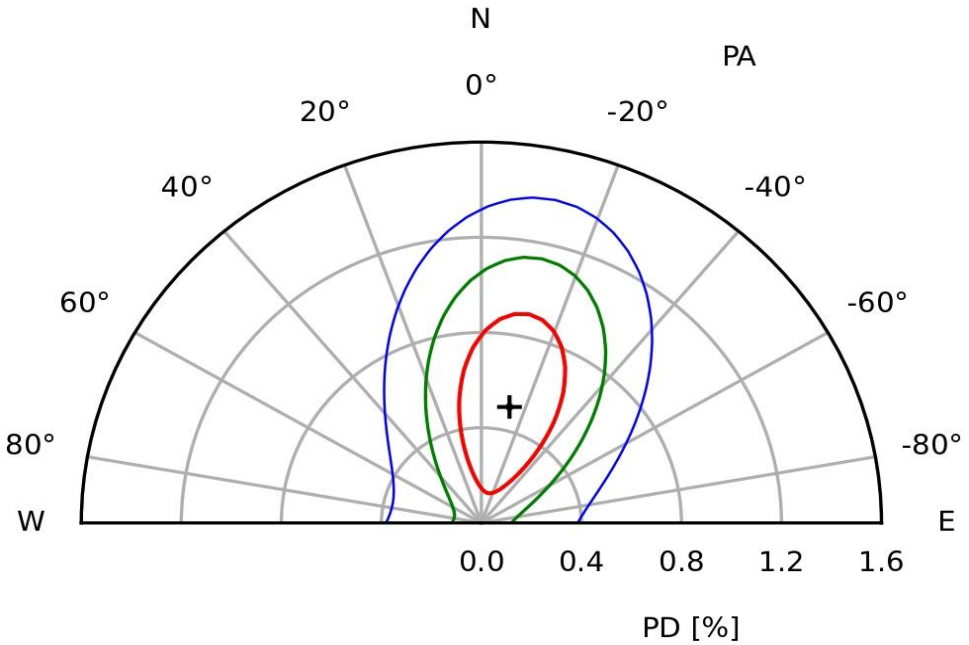
Swift J1727.8-1613 – spectro-polarimetric fit



- **polarization degree** (PD) much lower than during the hard state: PD ≈ 0.5%
- 99% confidence level gives only an upper limit of **PD < 1.2%**
- **polarization angle** (PA) **unconstrained** at the 2σ level
  - at 1σ only suggested to be aligned with the hard-state PA

Svoboda et al., 2024b

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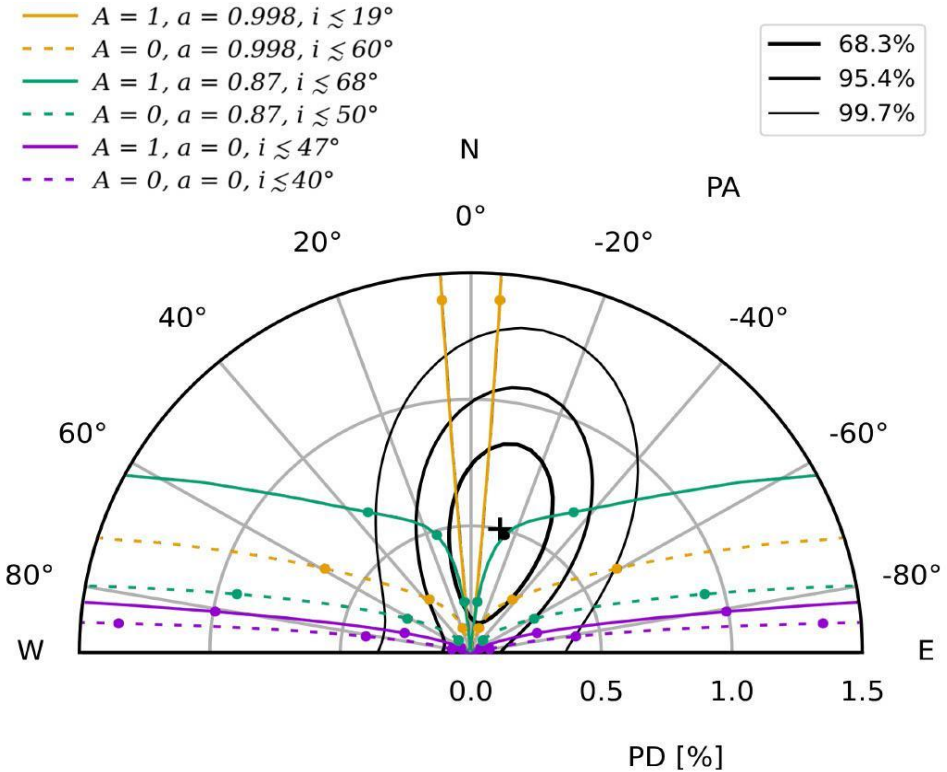
Relativistic model with self-irradiation



- large dependence on the black hole spin and albedo (self-irradiation)
  - low PD consistent also with higher inclinations
  - PA can be aligned with the perpendicular direction to the accretion disk (and thus, to the hard-state PA)
- the best-fit values of the spectral fit perfectly match the polarization measurements

Svoboda et al., 2024b

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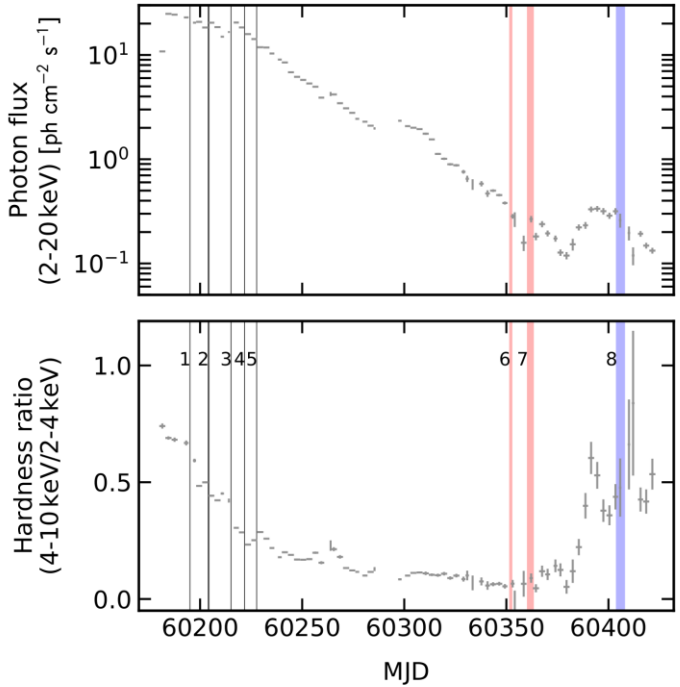
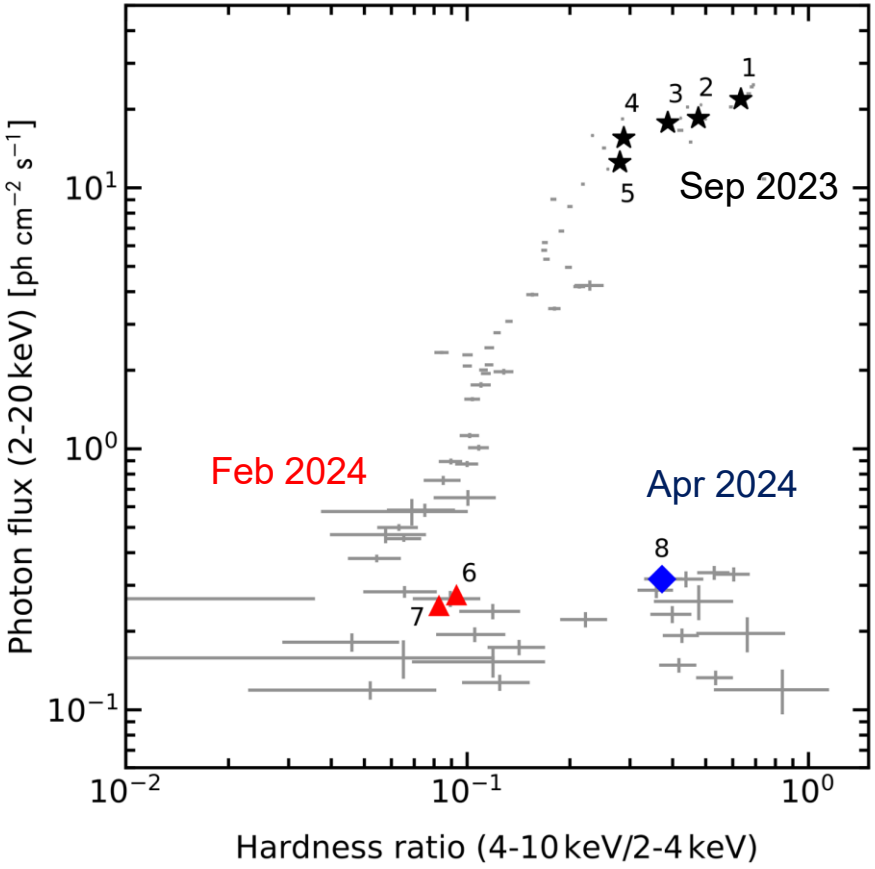
Soft-to-hard transition

- observation in a dim low/hard state





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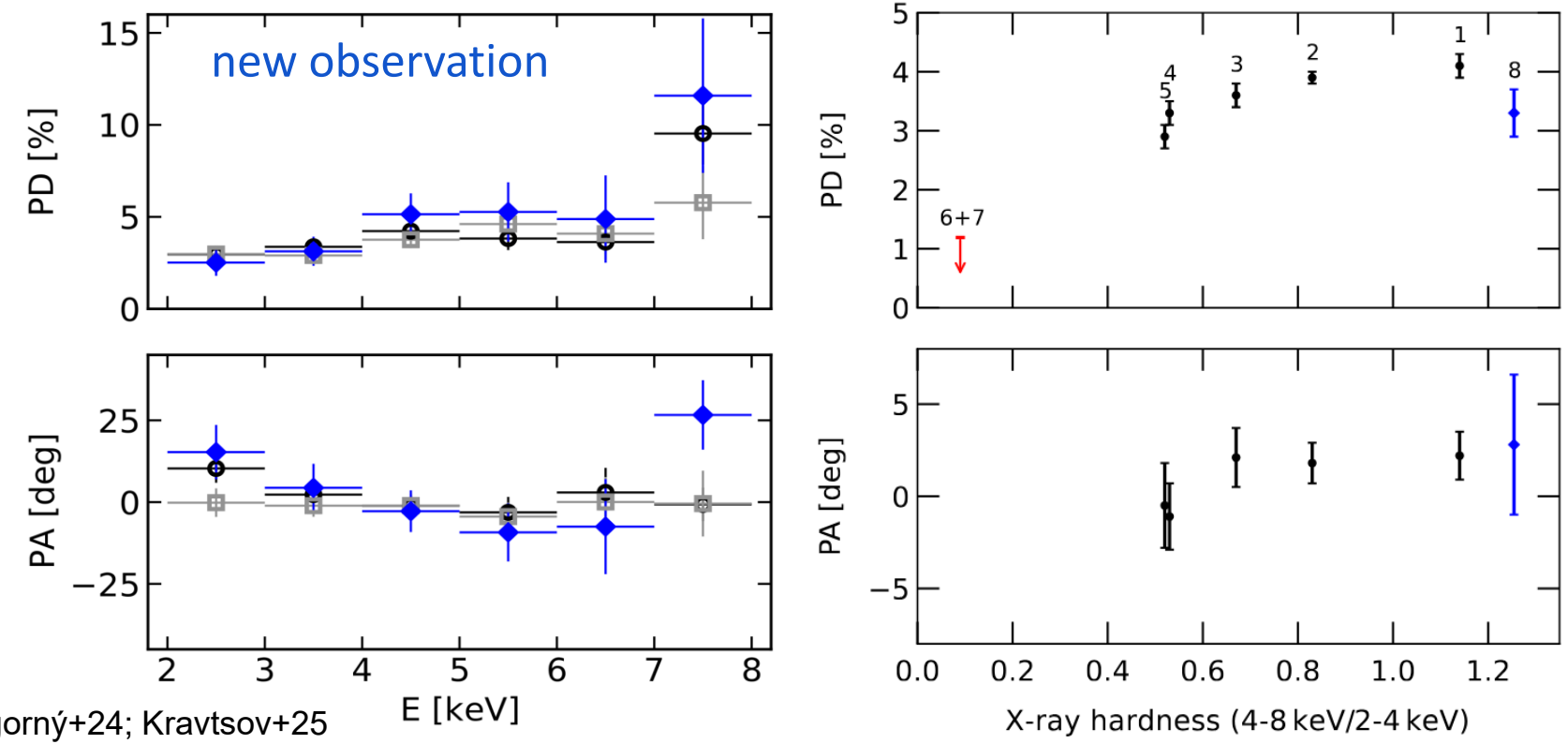
Recovery of the polarization properties



Podgorný+24; Kravtsov+25

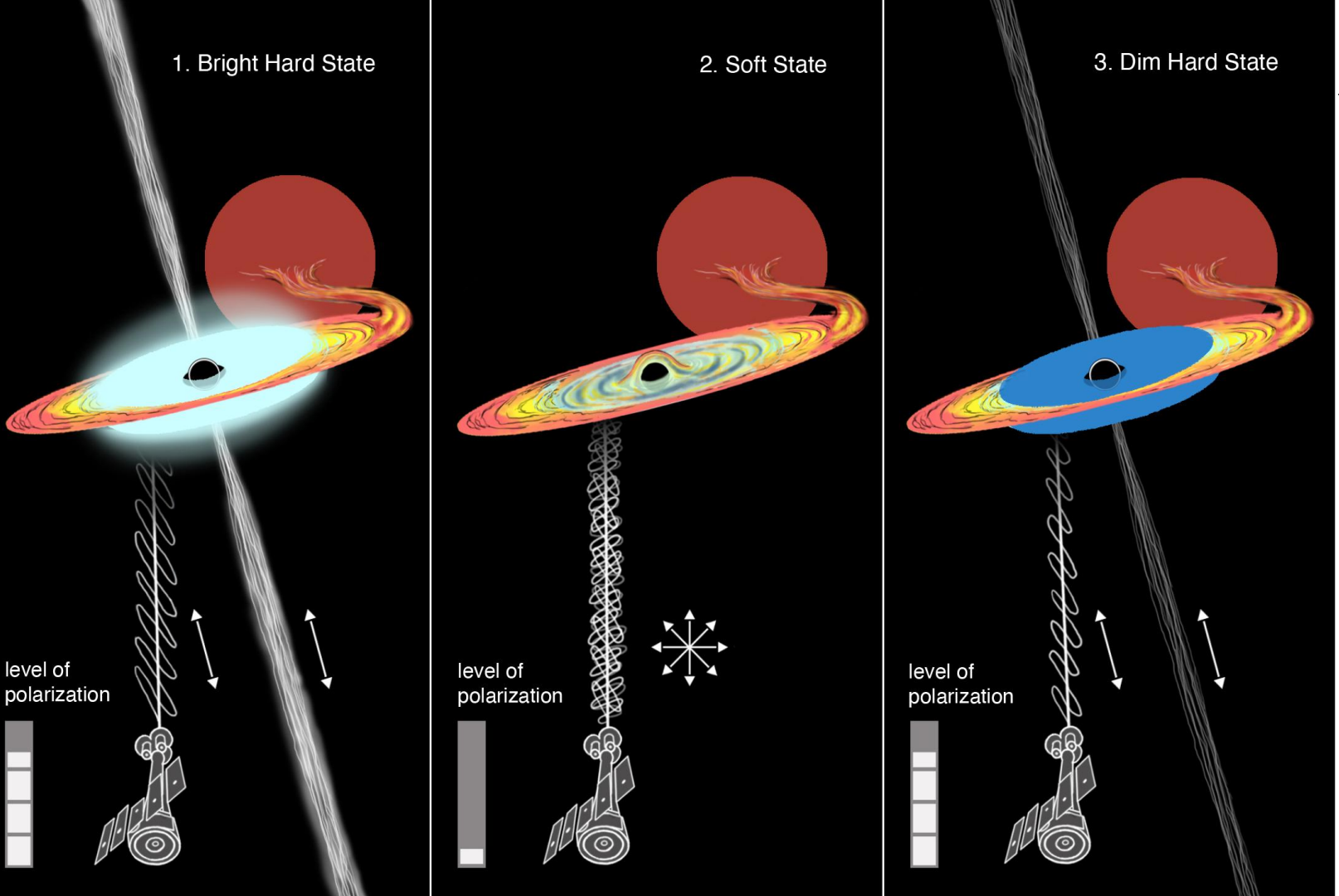


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Illustration:
The IXPE observations of the Swift J1727.8-1613 systém in different accretion states.

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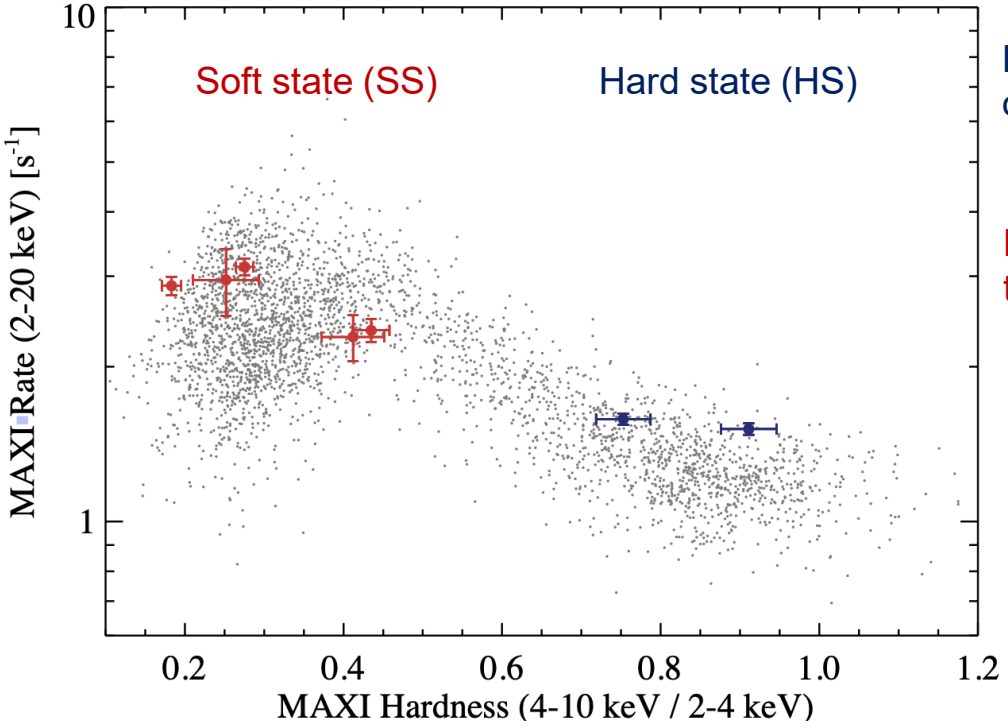
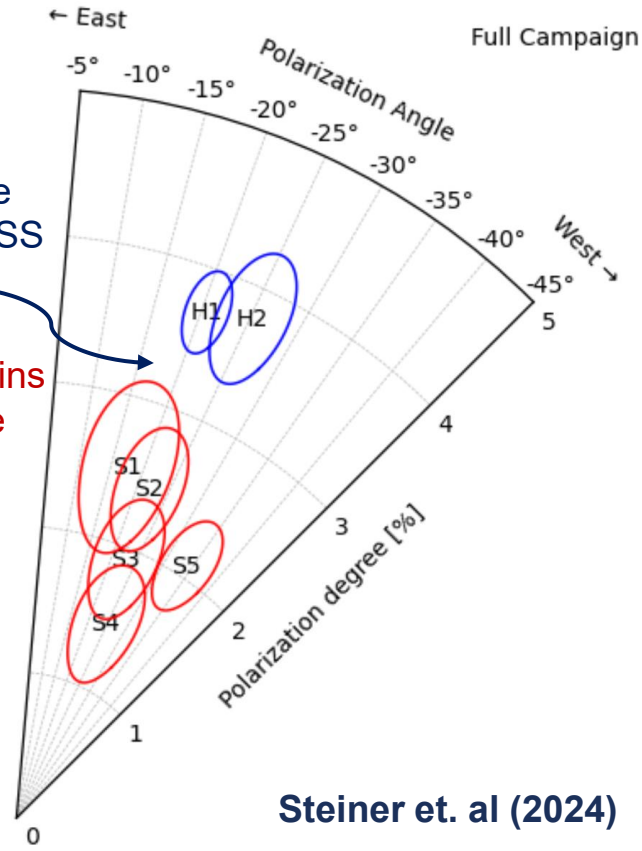
Cyg X-1 – comparison of states



Decrease of PD in SS

PA remains the same



Steiner et. al (2024)

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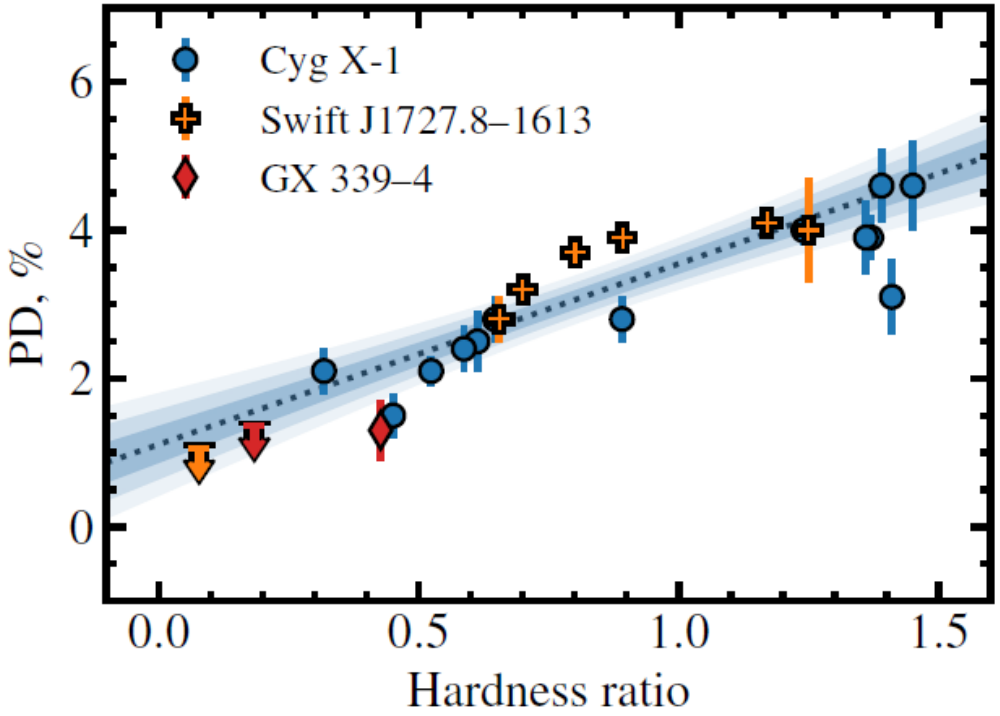
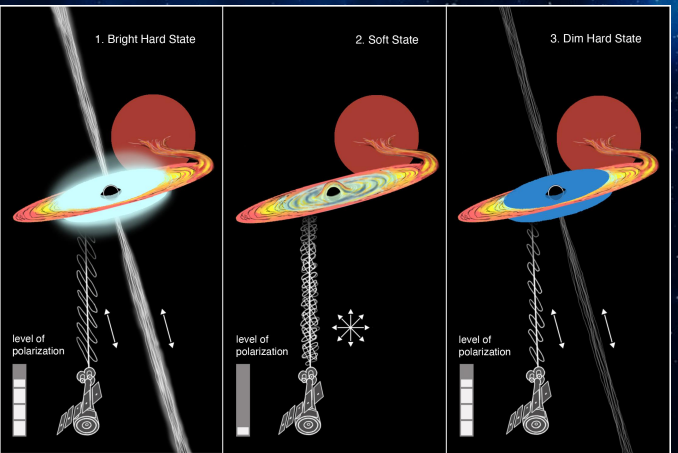
Comparison between the hard and soft states



- **Polarization fraction: hard state >> soft state**
- **Polarization angle:** stable, not yet any evidence for a change (in Cyg X-1 and Swift J1727.8-1613 explained as due to high spin and thus, large contribution of the returning radiation)

Kravtsov+2025, see also Brigitte & Svoboda (2024)

IXPE scientific goals & measurements



IV. Surprising results

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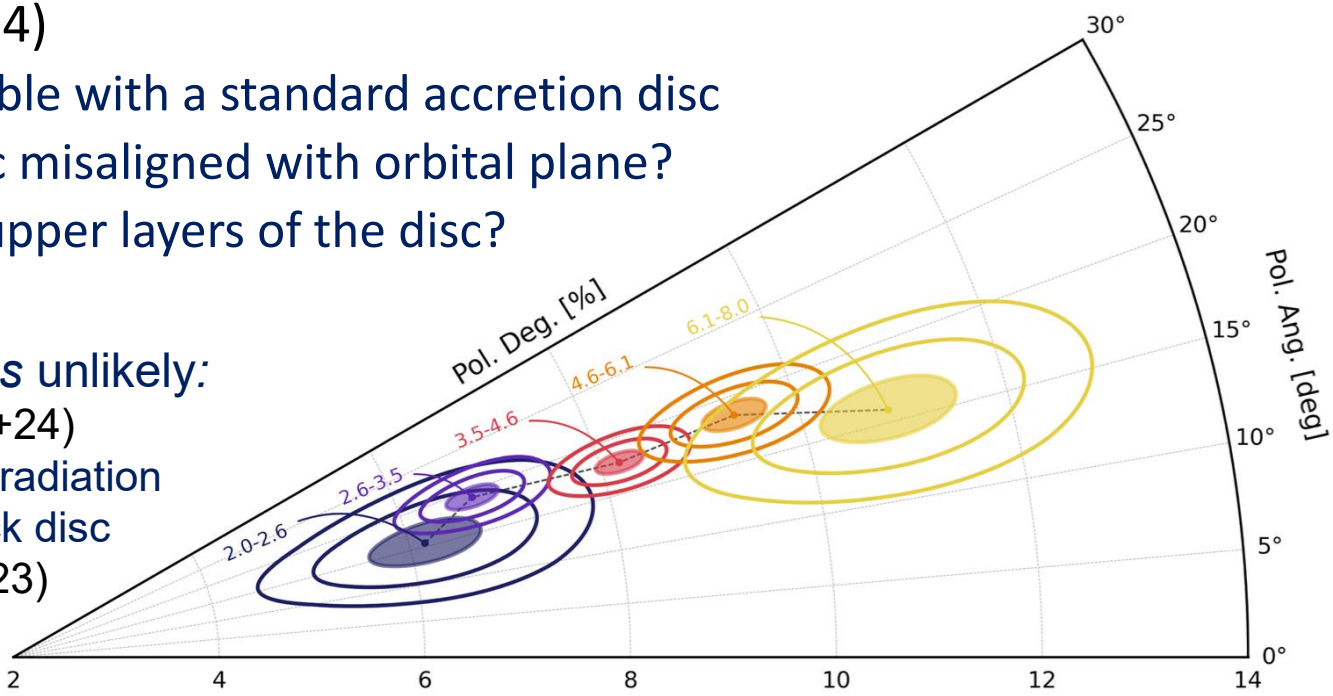
4U 1630-47

- **Extremely large polarization** in the soft state **PD = 8.3 ± 0.2%** (Ratheesh+2024)
  - not compatible with a standard accretion disc
  - edge-on disc misaligned with orbital plane?
  - outflowing upper layers of the disc?

Alternative explanations unlikely*:*

- thermal wind (Tomaru+24)
- reflection of disc self-irradiation for a geometrically thick disc (West & Krawczynski 23)



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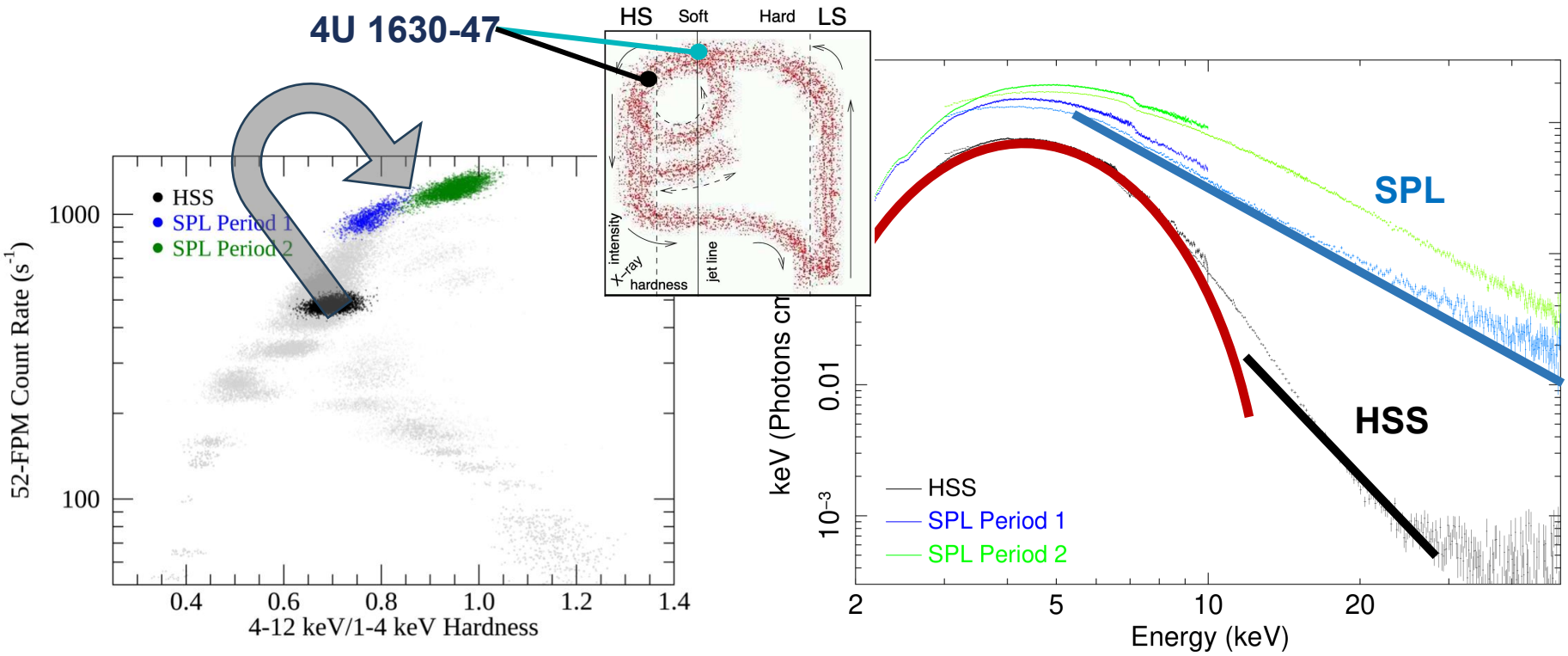
4U 1630-47: steep power-law state



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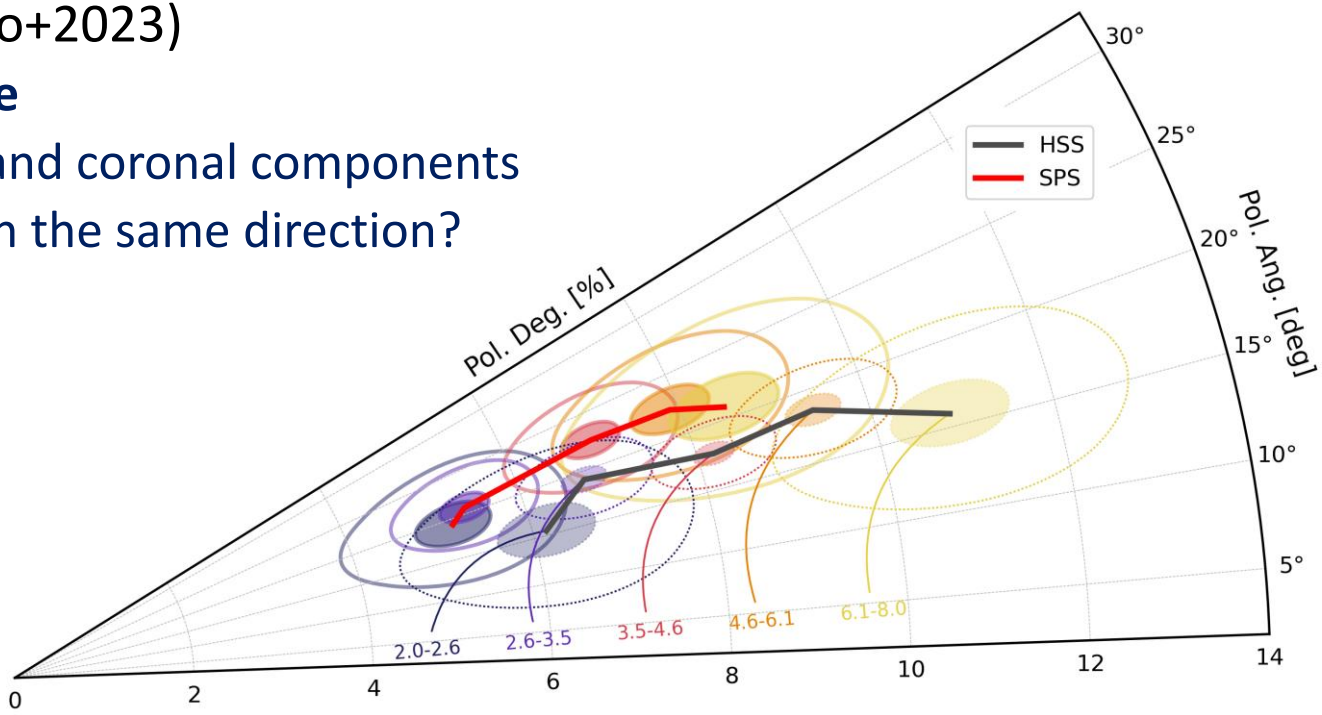
4U 1630-47

- **large polarization** also in the steep power-law state **PD = 6.8 ± 0.2%** (Rodriguez Cavero+2023)
  - **PA not variable**
  - both thermal and coronal components are polarized in the same direction?



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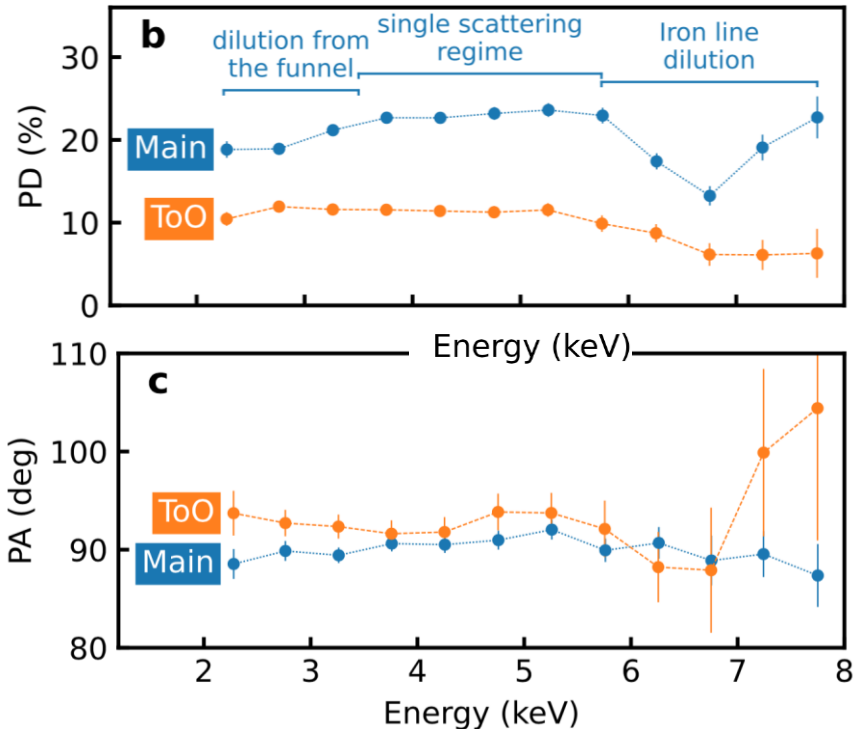
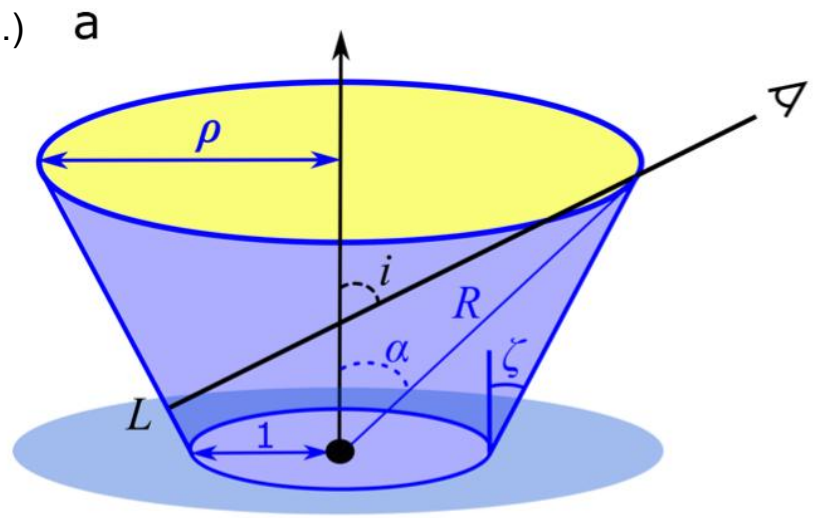
Cyg X-3 – hidden ultraluminous source?

PD = 20.6 ± 0.3% (main obs.) **PD = 10.4 ± 0.3%** (ToO obs.)





✓ Reflected emission from a very narrow $\alpha \leq 15°$ funnel

Veledina et. al (2024a)

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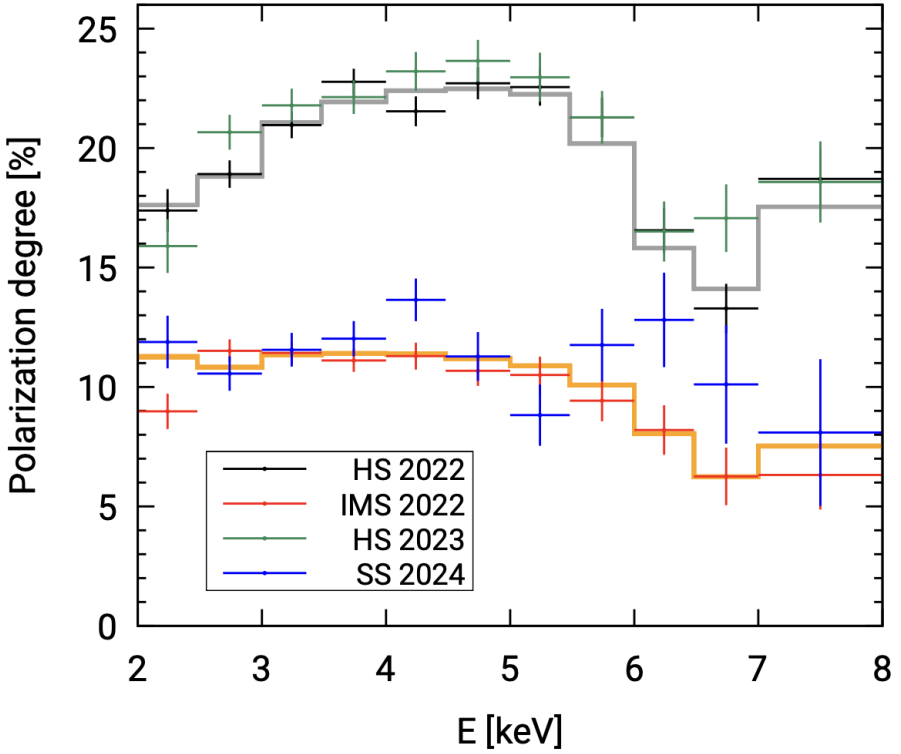
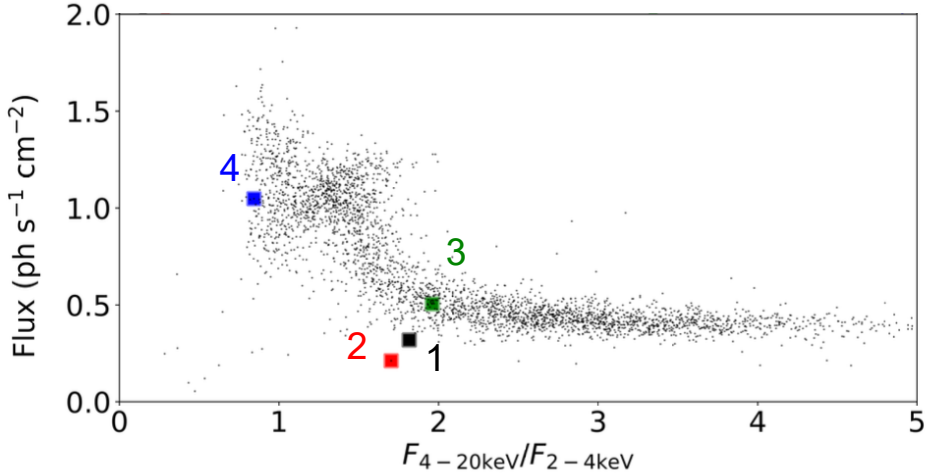
Cyg X-3 – hidden ultraluminous source?





Spectral State	Polarization degree [%]	Polarization angle [deg]
HS	20.6 ± 0.3	90.1 ± 0.4
IMS	10.4 ± 0.3	92.6 ± 0.7
HS	21.4 ± 0.4	92.2 ± 0.5
SS	11.9 ± 0.4	94.0 ± 1.0

Veledina+24b, Mikušincová+ submitted, Rodriguez-Cavero+ in prep.

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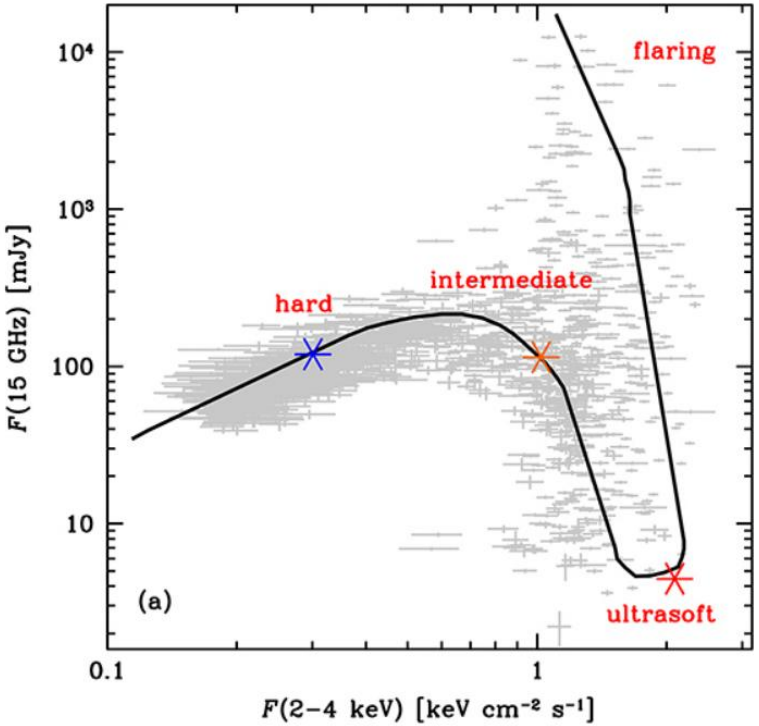
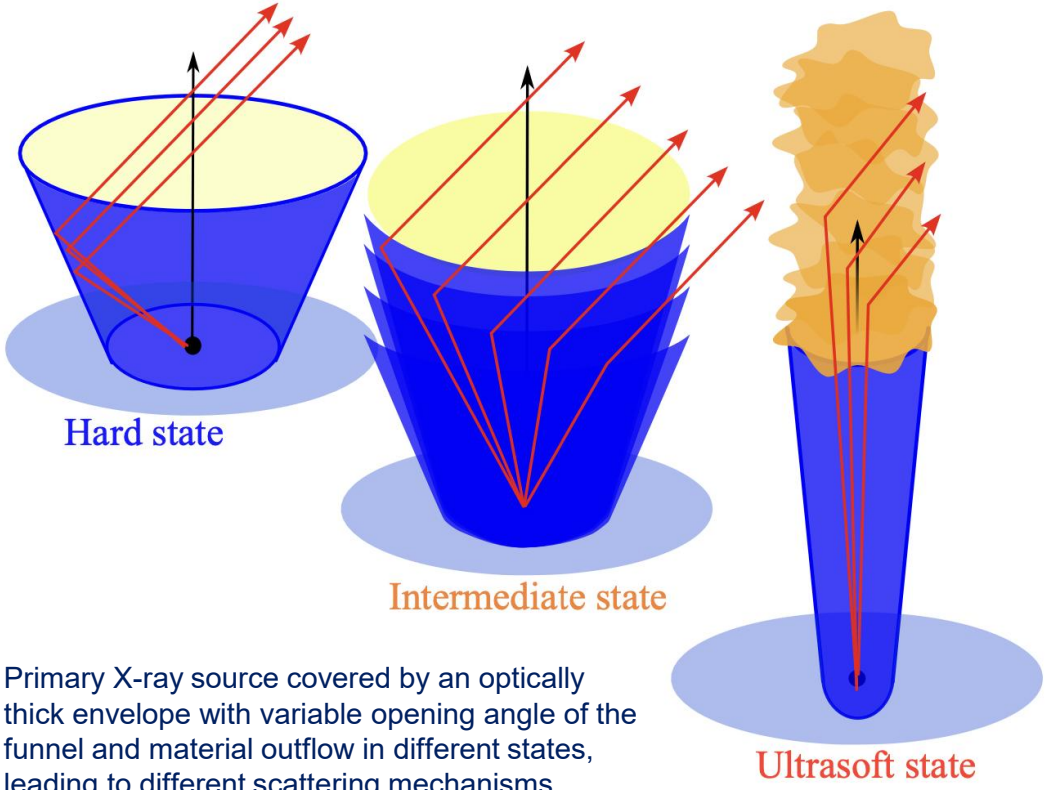
Cyg X-3





Primary X-ray source covered by an optically thick envelope with variable opening angle of the funnel and material outflow in different states, leading to different scattering mechanisms

Veledina+24b, Mikušincová+25 submitted

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Conclusions – main results

- X-ray polarization measurements put useful constraints on microquasars
- **Geometry of the corona**
  - radially extended rather than a lamp-post geometry or jet
  - not changing configuration in different spectral states?
- **Inclination** of the inner accretion discs
  - the higher inclination the higher polarization fraction
- **Black hole spin** constraints
  - the first BH spin measurements possible in LMC X-3
  - tentative indication of PA rotation in 4U 1957+11
  - not changing PA in different states in Cyg X-1 (and Swift J1727) as a sign of high spin (relativistic aberration → strong effect of returning radiation)

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Conclusions – surprising results

- **PD higher than expected in several sources**
  - 4U 1630-47 (PD ≈ 6-10%) in soft and steep power-law state, no satisfactory explanation
  - Cyg X-3 (PD ≈ 10-20%) a hidden ultraluminous X-ray source with high polarization due to observing largely scattered emission
- **PD increasing with energy**
  - quite common in all observations in both soft and hard states

X-ray polarimetry proved to be a very useful tool for investigation of microquasars

Further reference:
Dovčiak et al., 2024, IXPE View of BH XRBs during the First 2.5 Years of the Mission, https://ui.adsabs.harvard.edu/abs/2024Galax..12...54D

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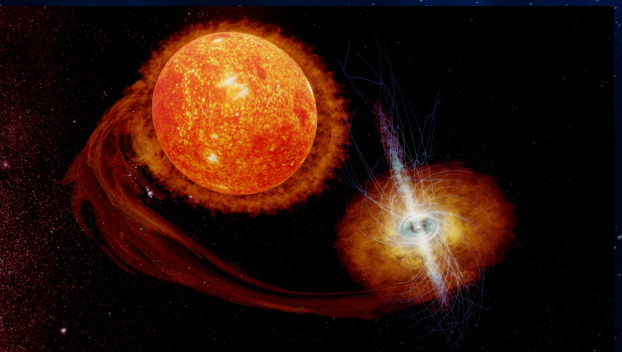
Additional slides

IXPE scientific goals & measurements



V. Neutron star Low-Mass X-ray Binaries

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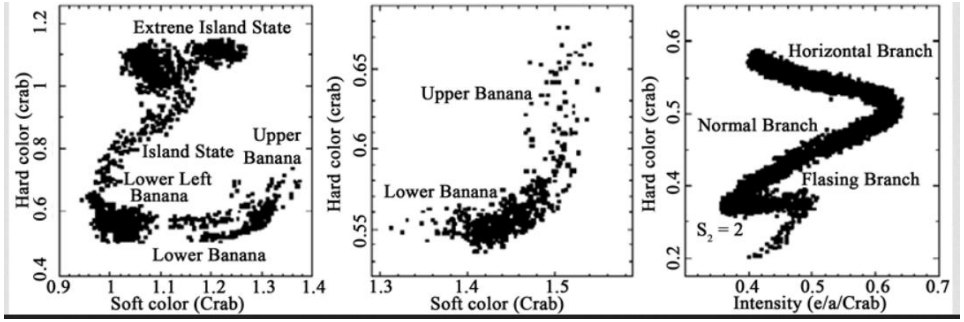
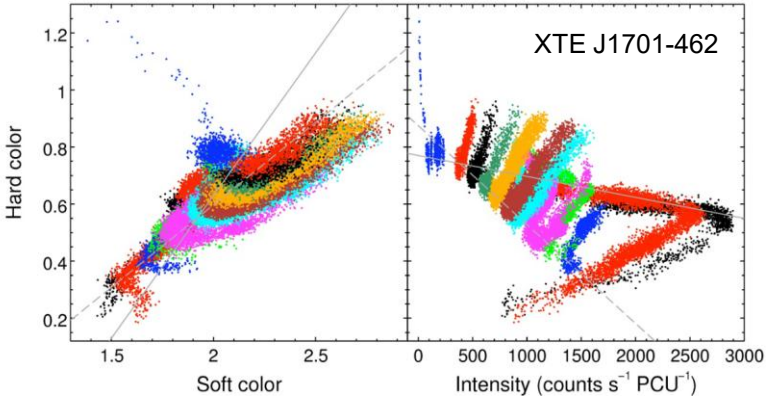
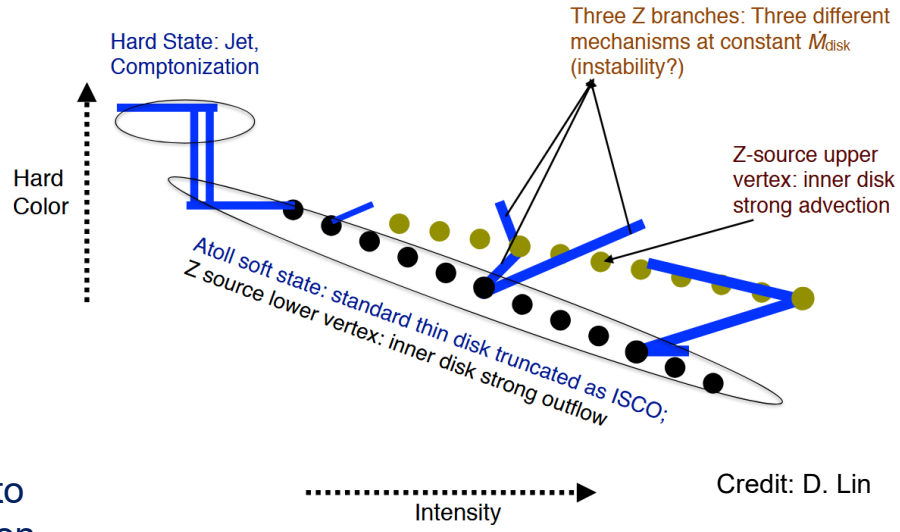
Neutron stars - different classes

van der Klis 2006





Fridriksson+15



Credit: D. Lin

- NS states evolve according to the accretion rate changes

Neutron Stars → **Z - sources**, **Atoll sources**

Accretion rate
X-ray luminosity

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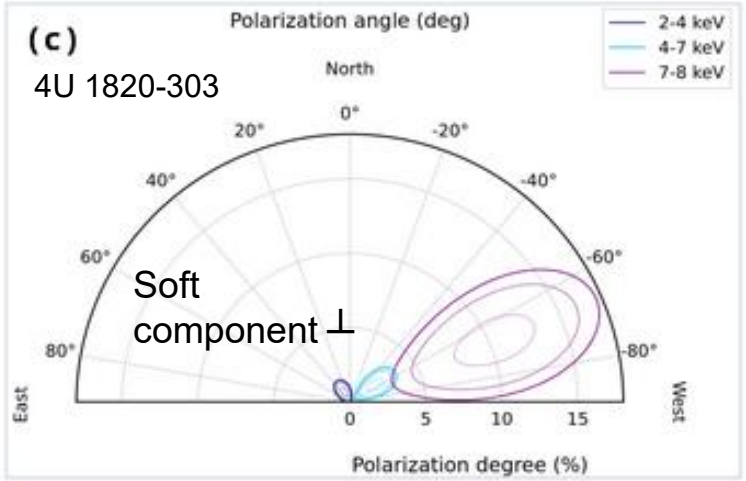
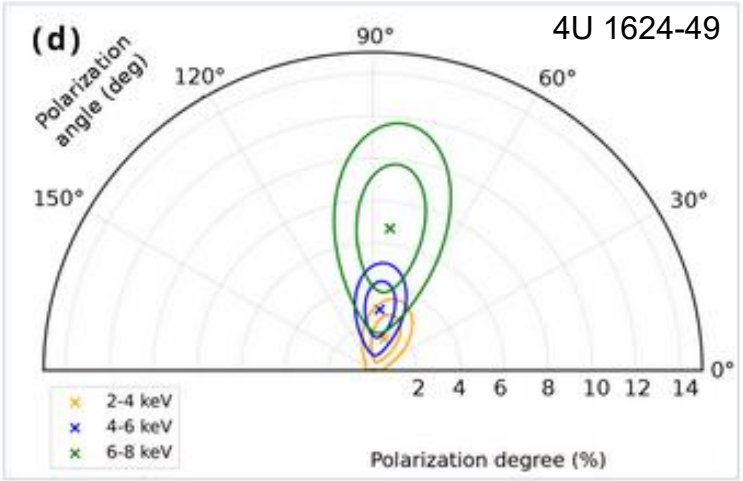
X-ray polarization of Atoll sources

- PD is usually very low at low energies
- averaged PD at 2-8 keV: measurements or upper limits around 1% (Ursini+24)
  - exceptions: 4U 1624-49 with PD ≈ 3.1% and 4U 1728-44 with PD ≈ 1.9% (hard state, Kashyap+25)
- **PD increasing with energy**





Di Marco+23, Saade+24, Ursini+24

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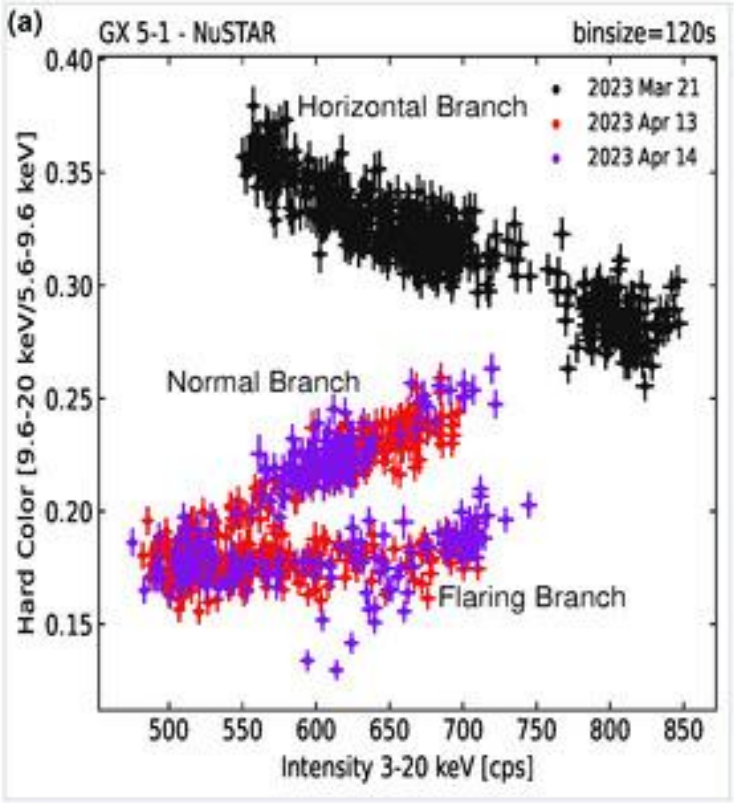
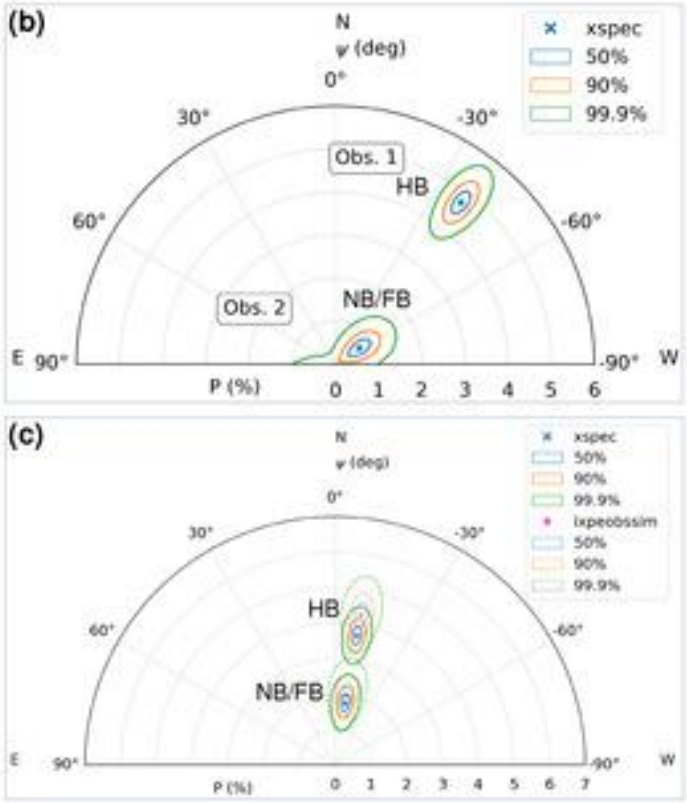
X-ray polarization of Z-sources





Horizontal Branch:
- hard spectrum
- **high PD**

Normal/Flaring Branch:
- soft spectrum
- **low PD**

Ursini+24, Gnarini+25

See talk by Andrea Gnarini

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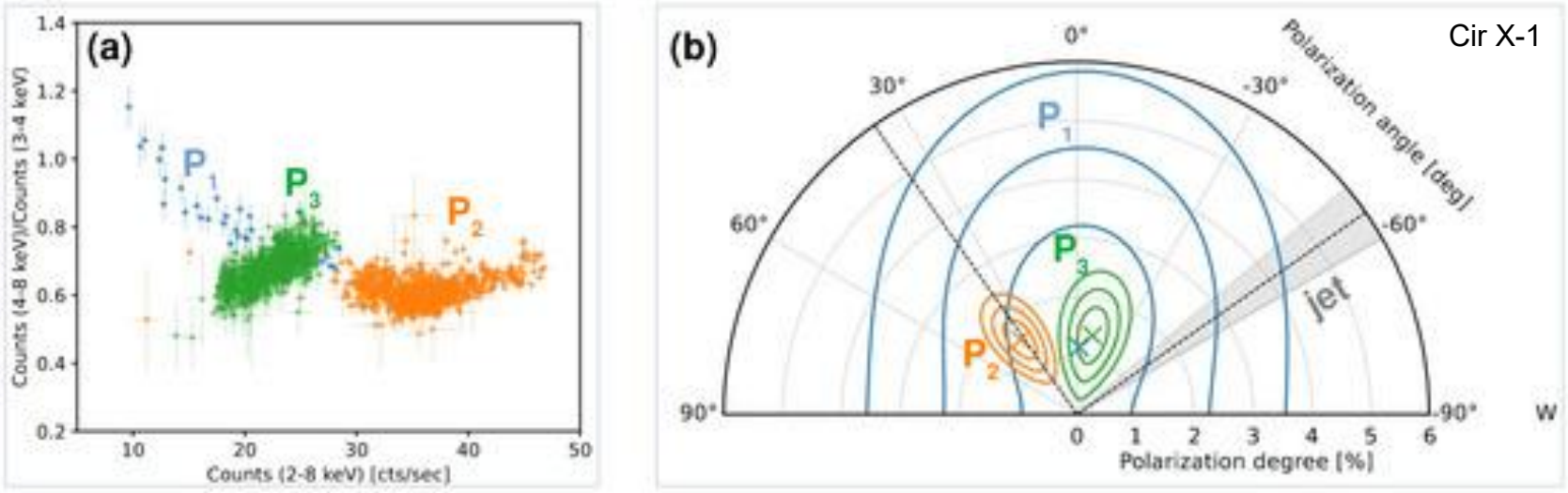
NS LMXB – common features and peculiar sources

- PD higher in the hard state and lower in the soft state
- PD increasing with energy
- Peculiar sources: Cir X-1, GX 13+1 – PA variability



Rankin+24, Ursini+24

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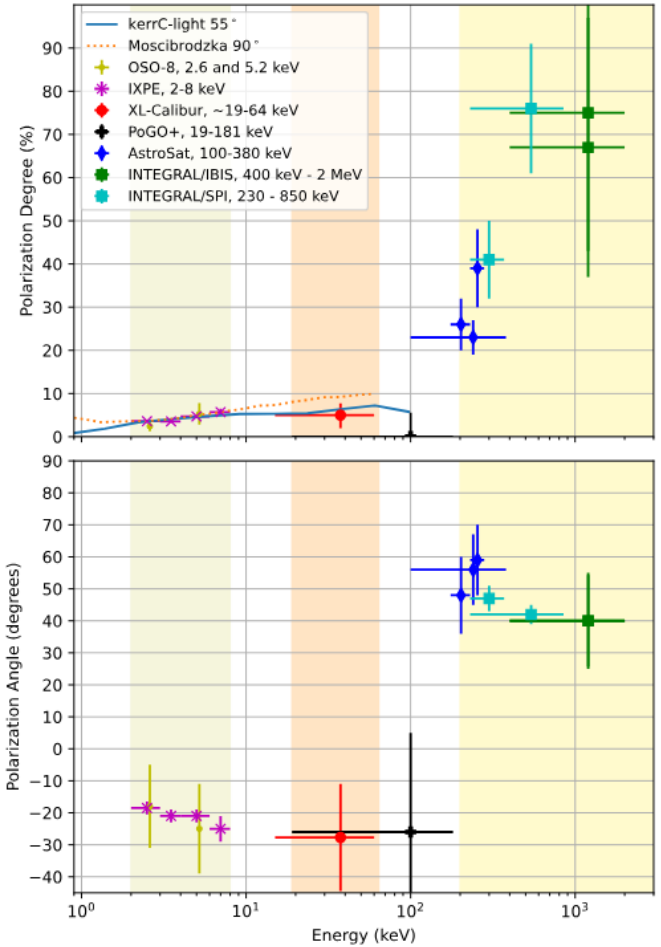
Hard X-ray polarimetry of Cyg X-1

- Hard X-ray polarization measurements
  - very high PD and different PA with Integral/IBIS and SPI (Laurent+11, Rodriguez+15), likely connected with the jet
- XL-Calibur – balloon experiment (Washington State University, NASA/JAXA/Swedish mission, 6-day, July 2024)
  - new measurements of Cyg X-1 in 19–181 keV (Awaki+2025)



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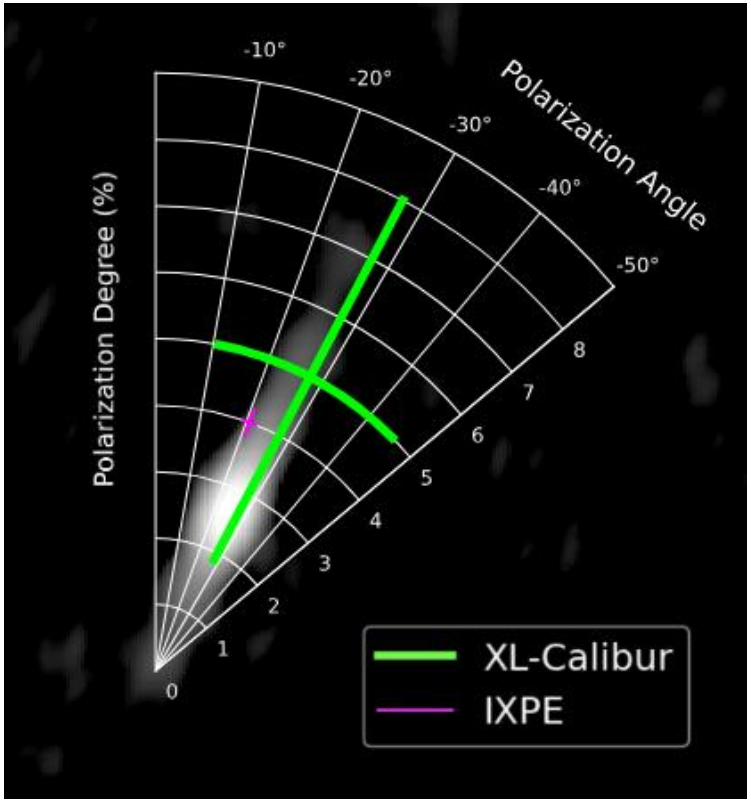
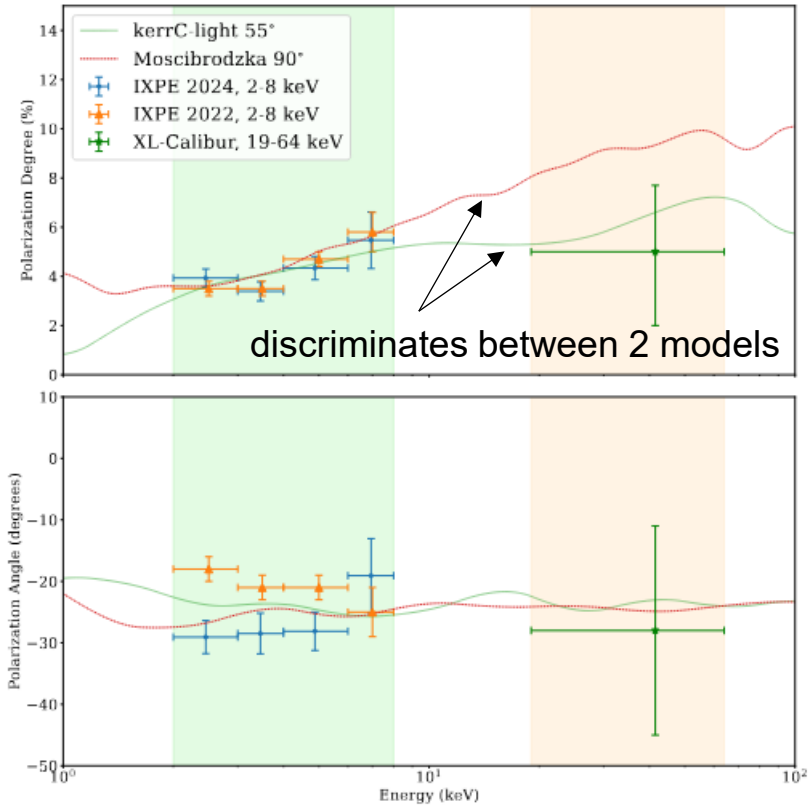
Hard X-ray polarimetry of Cyg X-1





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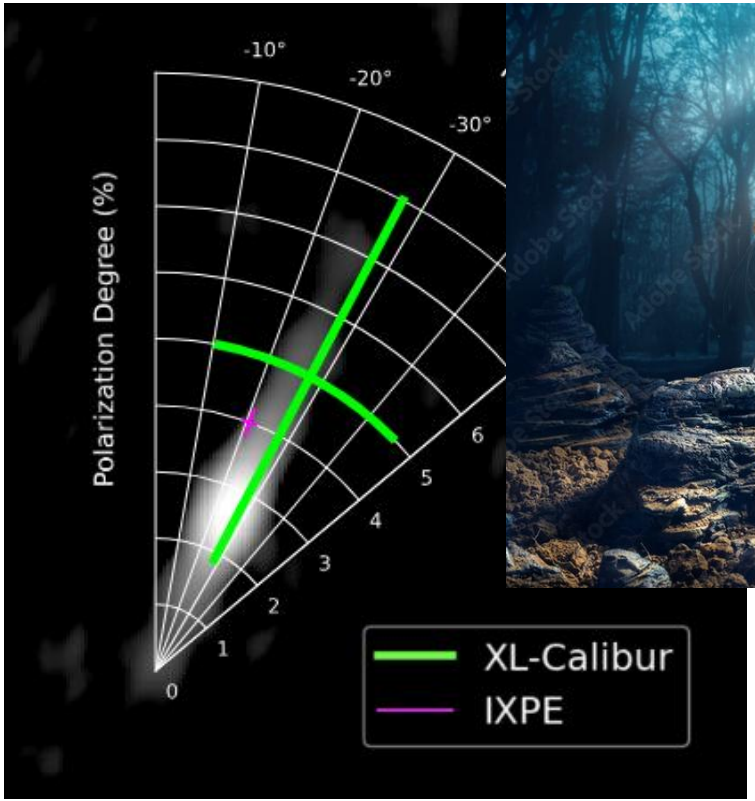
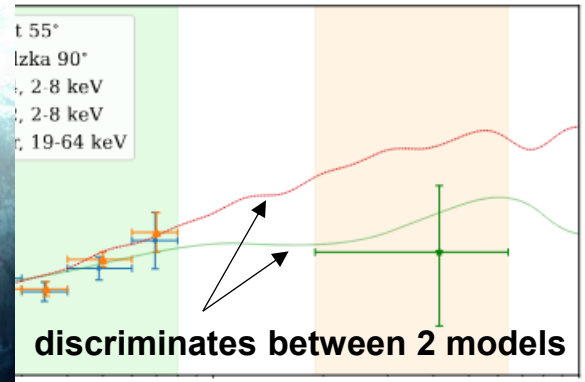
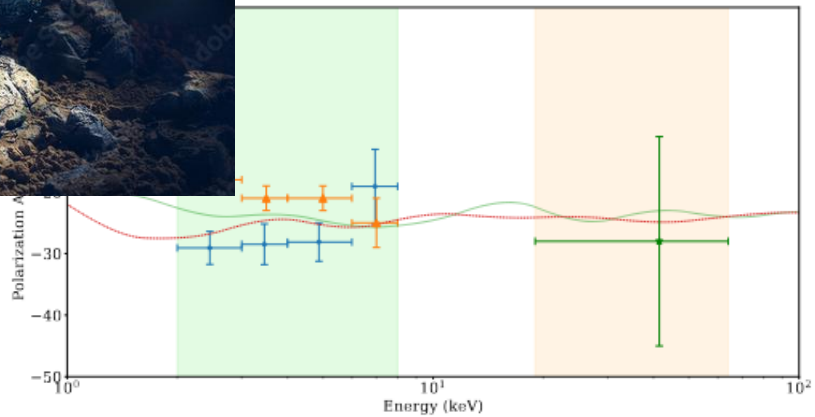
Hard X-ray polarimetry of Cyg X-1







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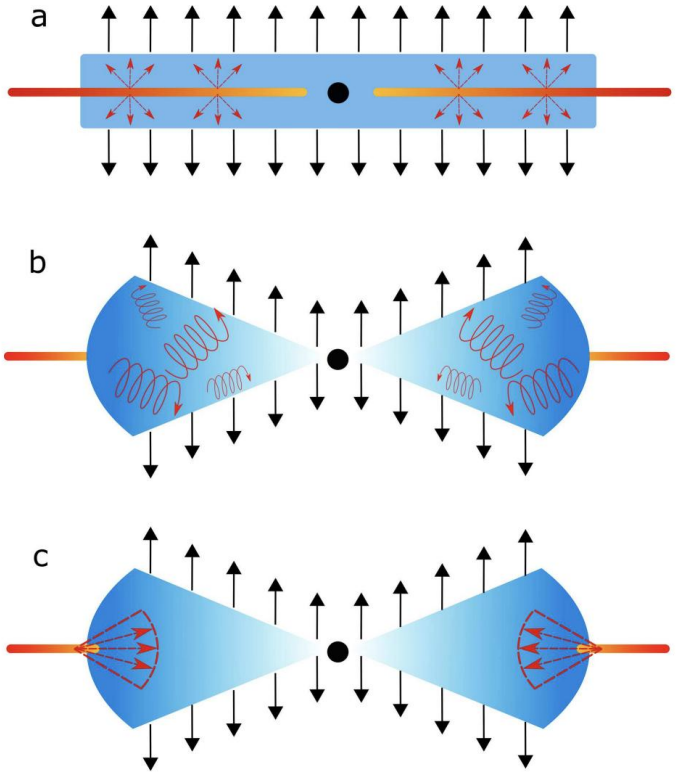
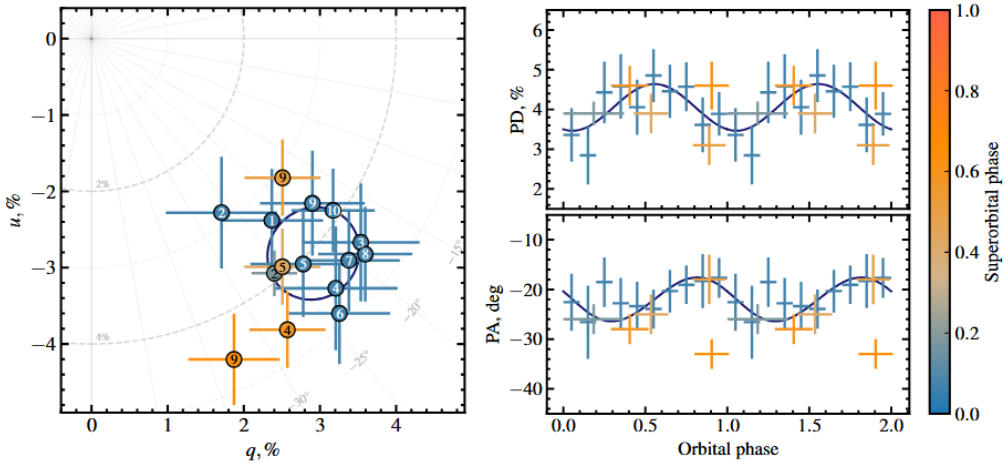
Cyg X-1 outflowing corona?



- Polarisation of 4% can be obtained with $i = 30°$ from an outflowing corona if there is a $v \approx 0.4c$ vertical bulk velocity (Poutanen+23)
- GRRMHD simulations (Moscibrodzka+24)
- Orbital variations detected (Kravtsov+25)



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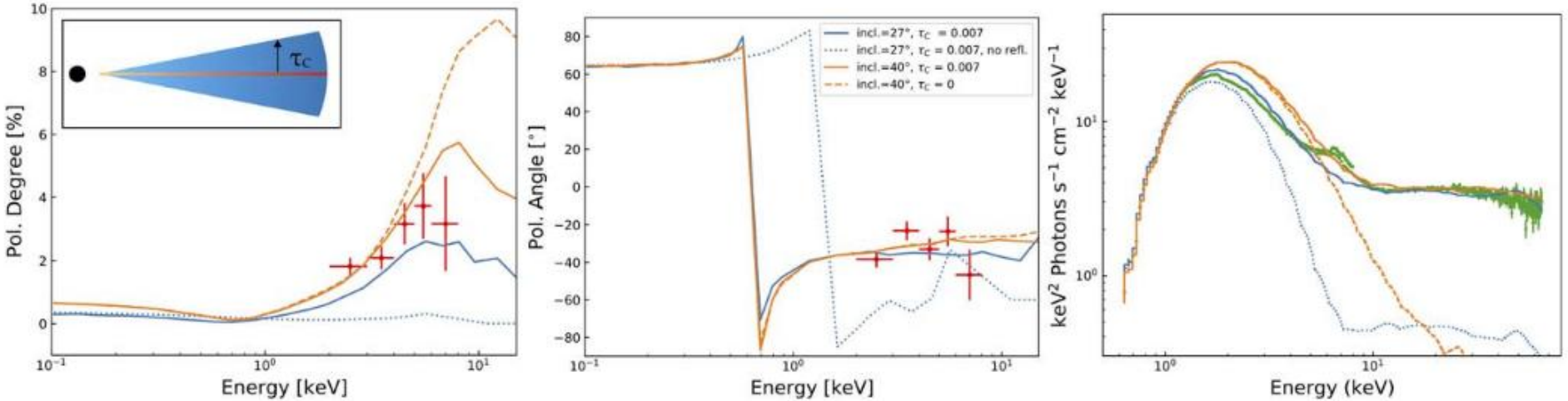
Cyg X-1 – spectro-polarimetric modelling



- kerrC simulations with a hot wedge-shaped corona
  - high spin a = 0.998
  - can explain polarization as well as the measure spectrum

Steiner et. al (2024)

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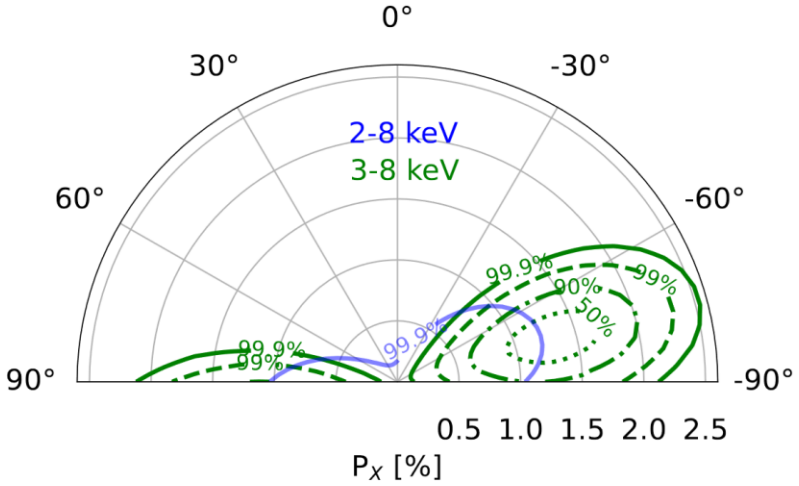
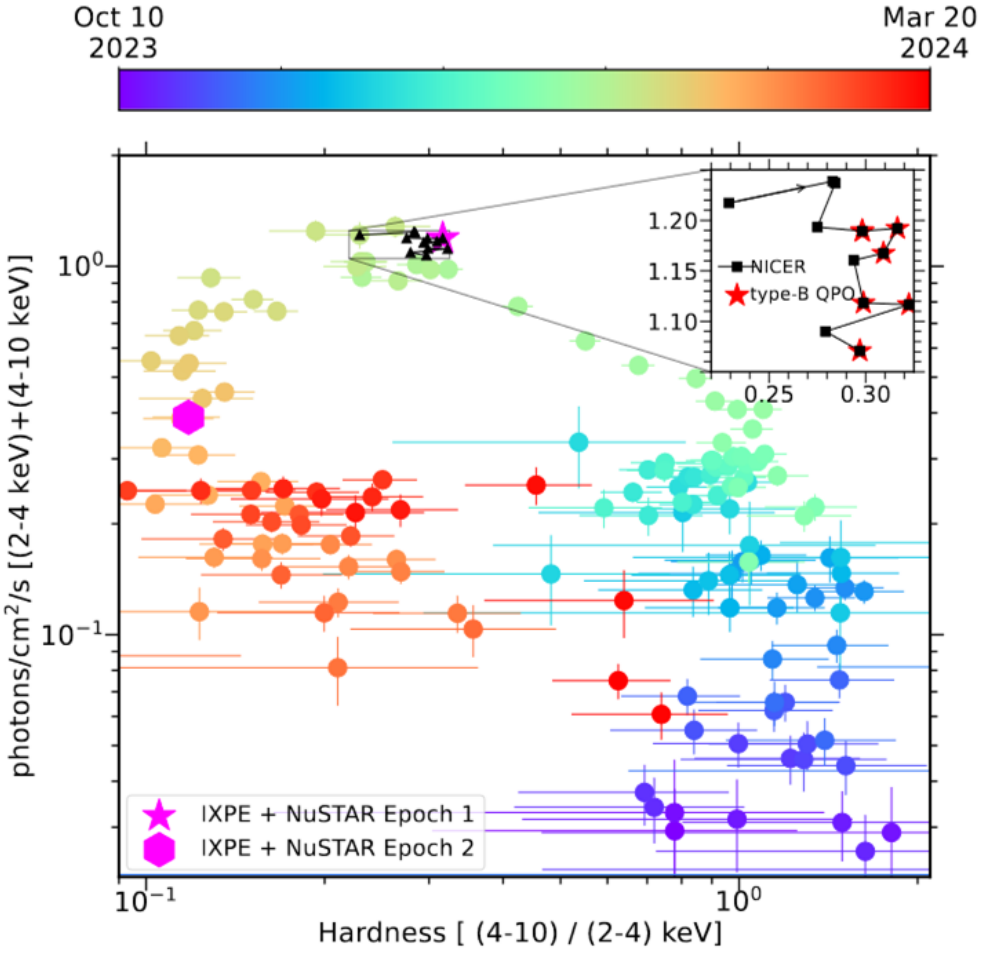
GX 339-4

- in the soft/intermediate state in 3-8 keV: **PD = 1.3 ± 0.3 %** (Mastroserio+25)
  - in 2-8 keV only an upper limit
    - depolarization by perpendicularly-oriented thermal component?





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GX 339-4

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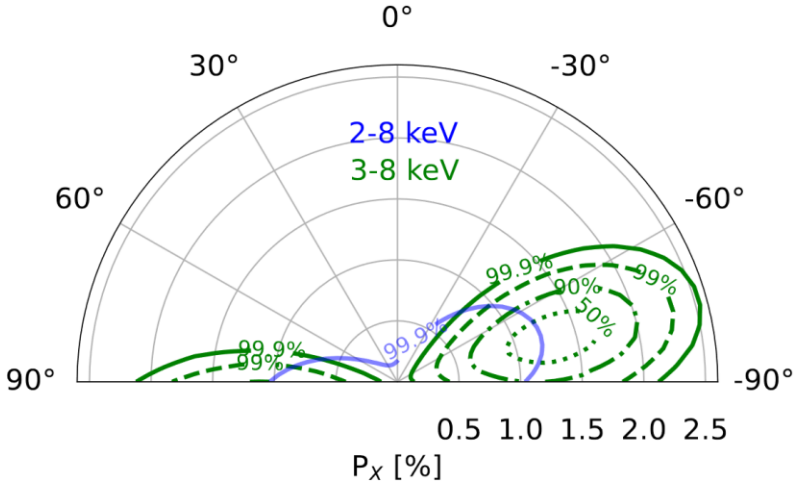
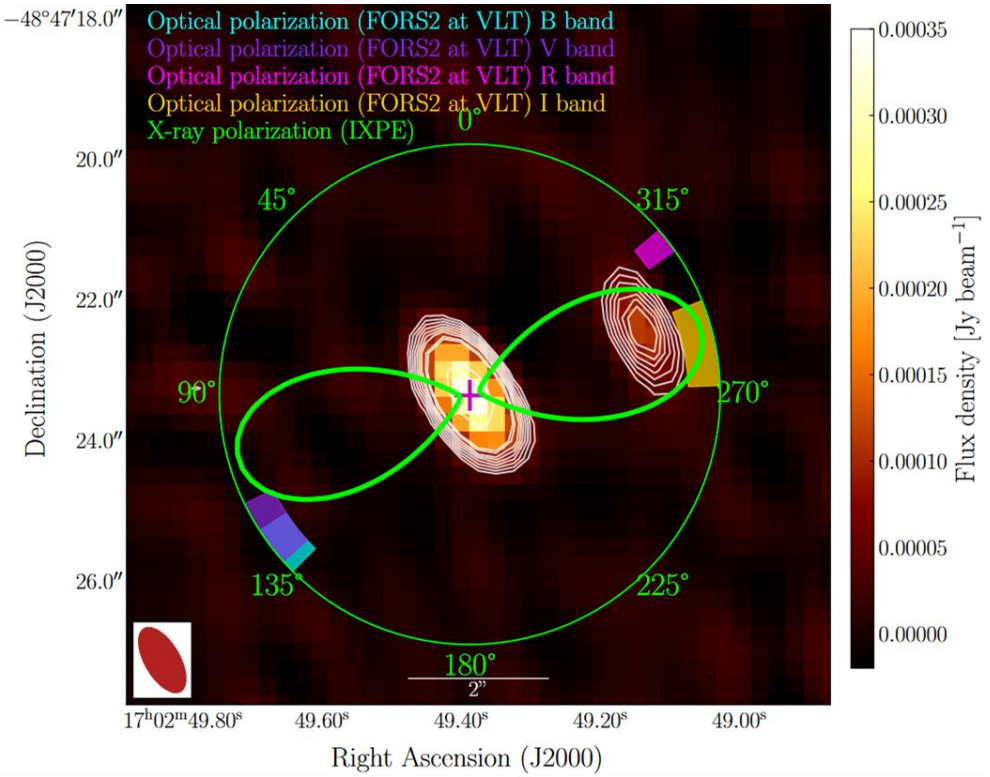


Comparison to the optical polarization and radio jet ejecta (all aligned):



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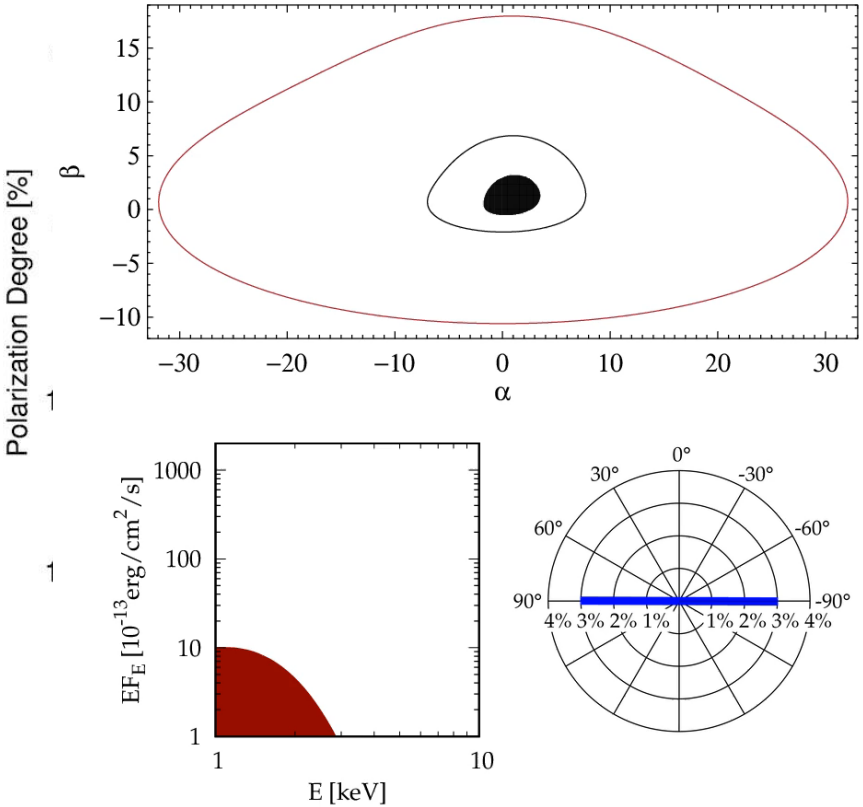
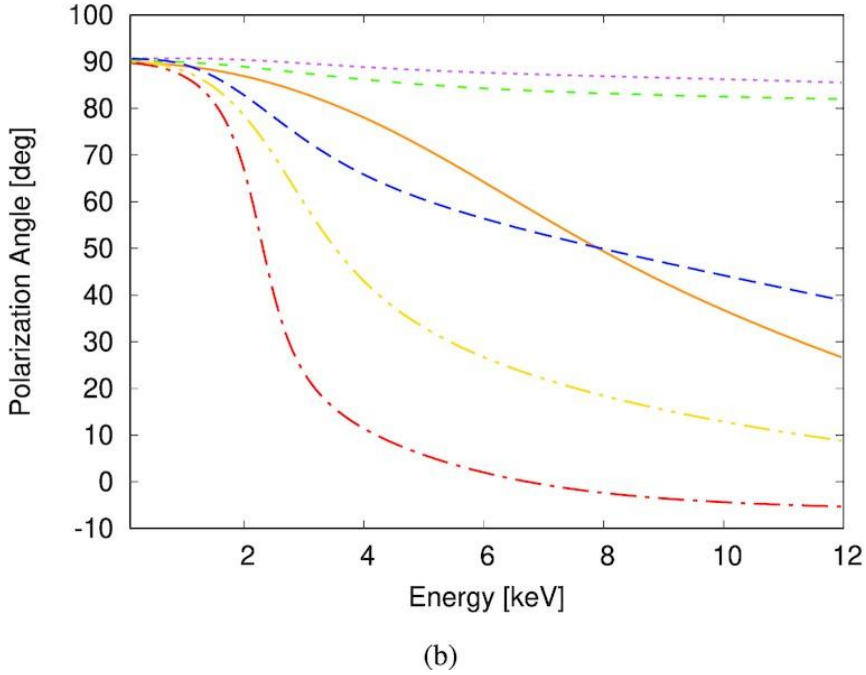
X-ray polarization constraints on BH spin – PA rotation





Mikušincová+23