

X-ray polarimetry in Microquasars

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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

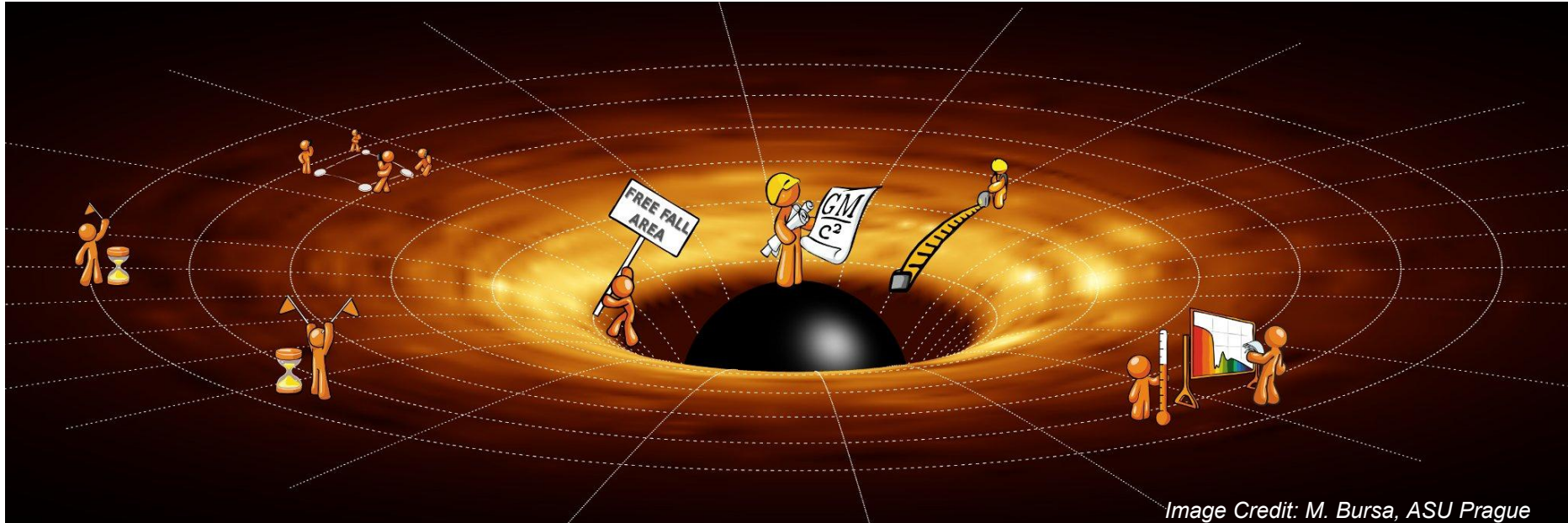
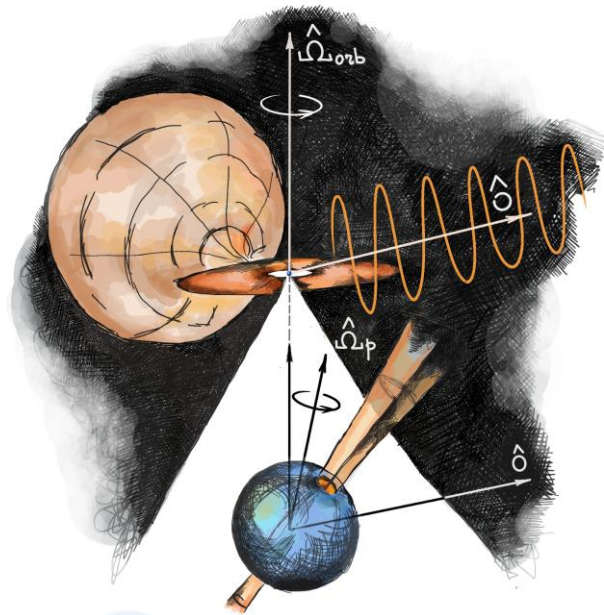
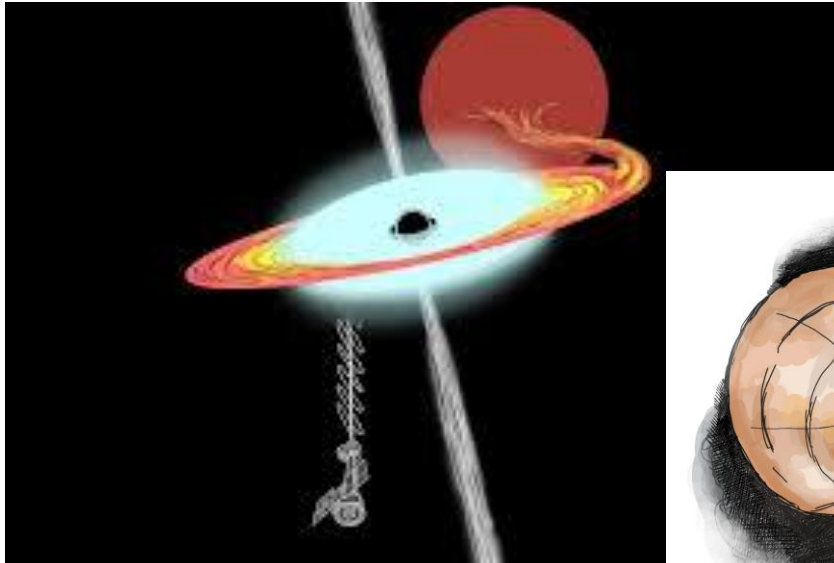


Image Credit: M. Bursa, ASU Prague

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:

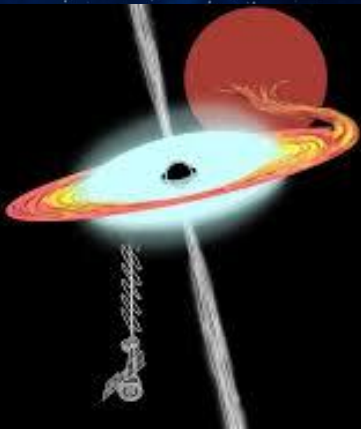
- X-ray scattering
- synchrotron emission
- magnetized atmospheres

Imaging X-ray Polarimetry Explorer (IXPE)

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



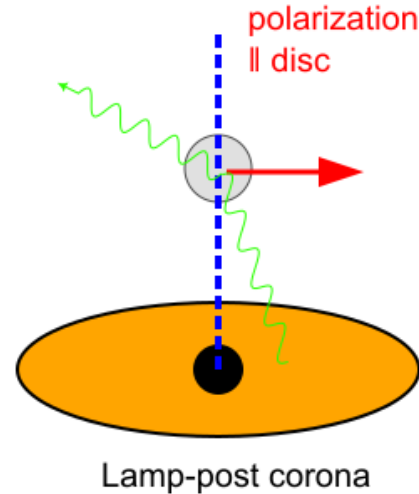
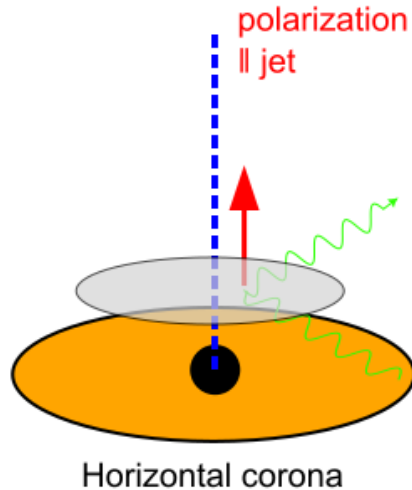
IXPE scientific goals & measurements



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

Polarization for different BH corona geometries

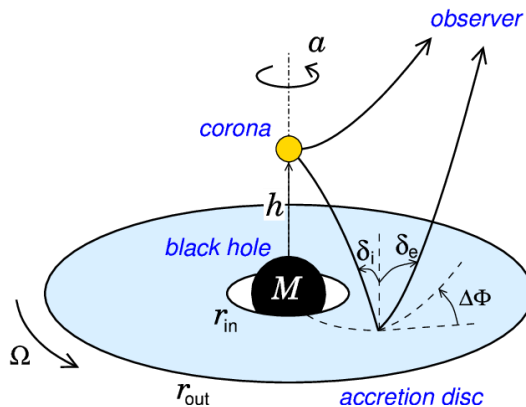
- photons scatter preferentially perpendicular to their electric polarisation vector, and the polarisation direction is conserved



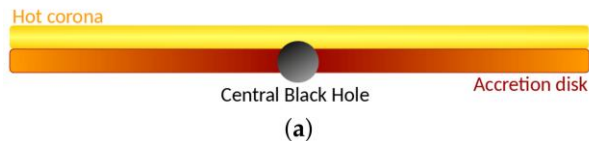
- PD and PA depend on the inclination, the exact geometry of the X-ray corona, and its optical depth (single vs. multiple scattering)

Geometry of the BH corona?

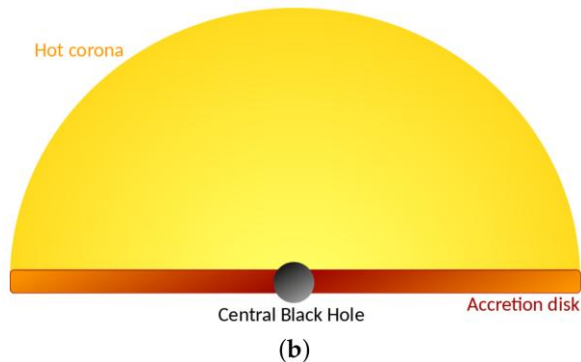
lamp-post geometry



„sandwiching“ slab geometry



spherical geometry



Original arguments in favour of the lamp-post geometry:

- **microlensing** $\rightarrow$ compact corona (Chartas+09, Chen+15)
- **steep radial emissivity 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

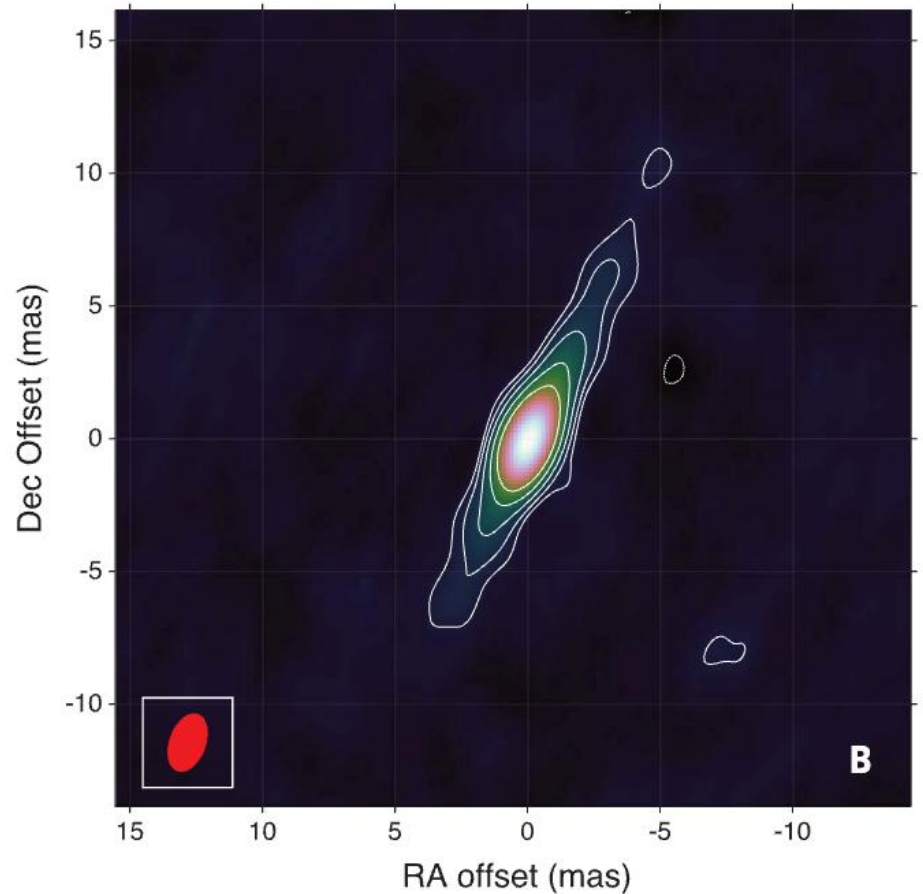


$i = 27.5^\circ$



Cygnus X-1 jet

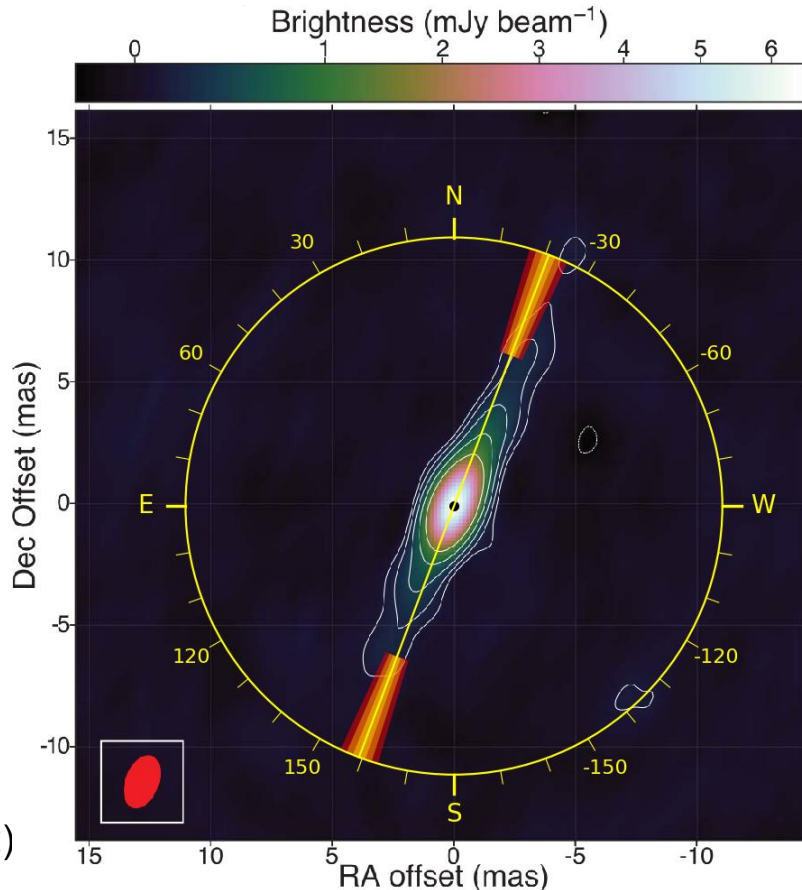
- steady jet resolved by VLBI
- we do **not** a priori know the inclination angle of the jet or inner disc

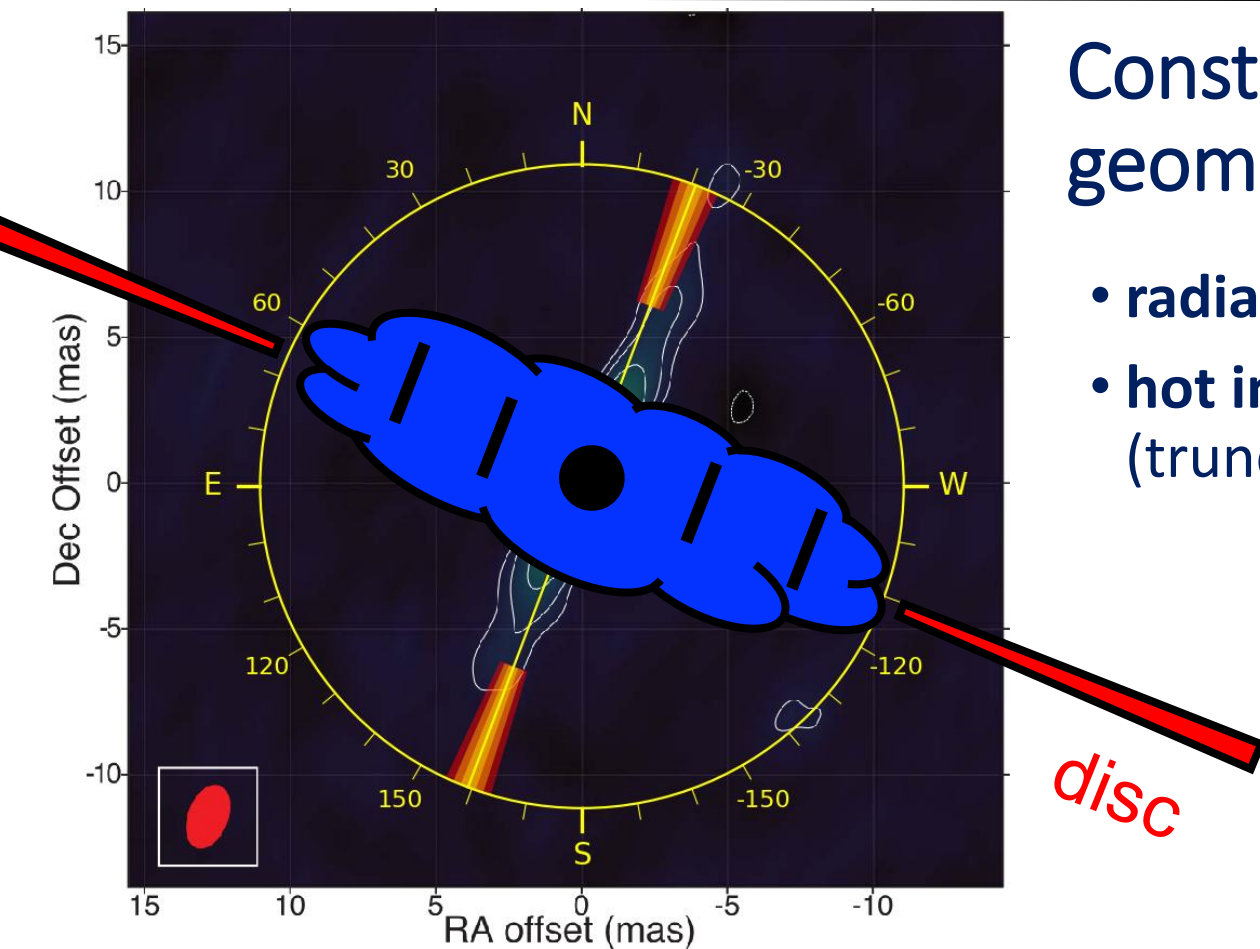


Results from the first IXPE observations of Cyg X-1

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

Krawczynski et al. (2022)





Constraints on the geometry of the corona

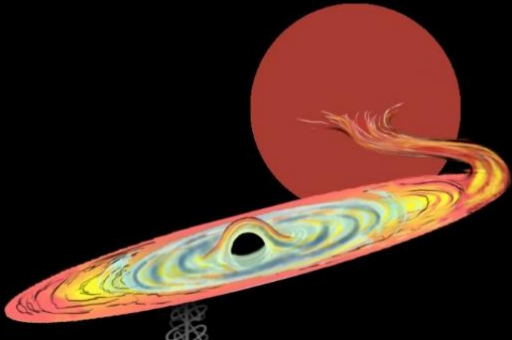
- radially extended corona
- hot inner accretion flow (truncated disc)

The figure is a polar plot showing the polarization degree [%] as a function of phase angle for various X-ray emission models. The radial axis represents the polarization degree from 0 to 100%, and the angular axis represents the phase angle from 0° to -90° W. Key features include:

- Truncated disc with disc Comptonization:** A red curve showing polarization increasing from ~10% at 0° to ~80% at -90°.
- Synchrotron self-Compton:** A purple curve showing polarization increasing from ~10% at 0° to ~80% at -90°.
- Sandwich corona:** An orange curve showing polarization increasing from ~10% at 0° to ~80% at -90°.
- IXPE obs 2-8 keV (68%, 95%, 99.7%):** A blue shaded region indicating the observed polarization range.
- Assumed disk axis:** A black line indicating the orientation of the disk axis.
- Cones and diagrams:** Various diagrams illustrate different emission geometries, including a cone extended along the spin axis, a spherical lamp-post with $a=0$, and a spherical lamp-post with $a=0.998$.

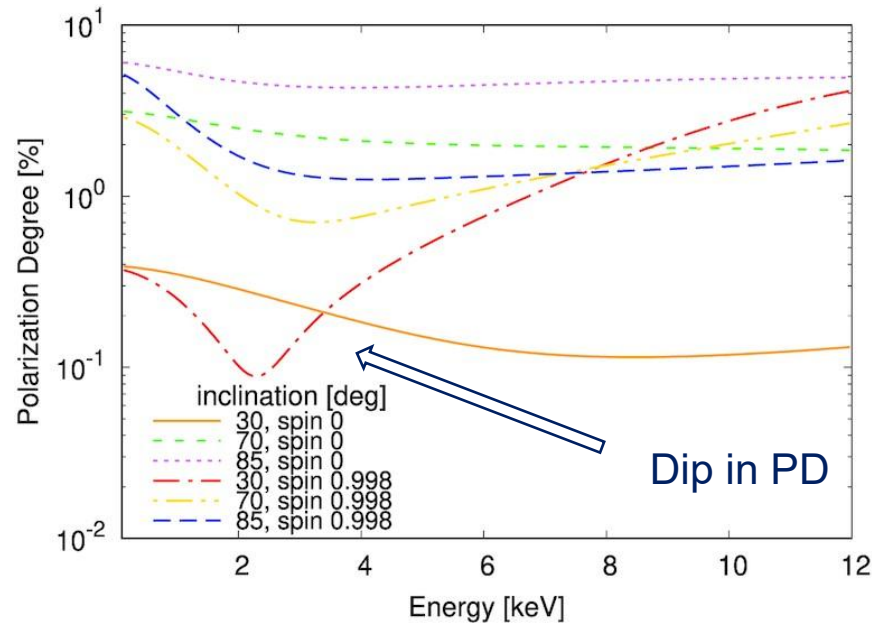
Krawczynski et al. (2022)

IXPE scientific goals & measurements

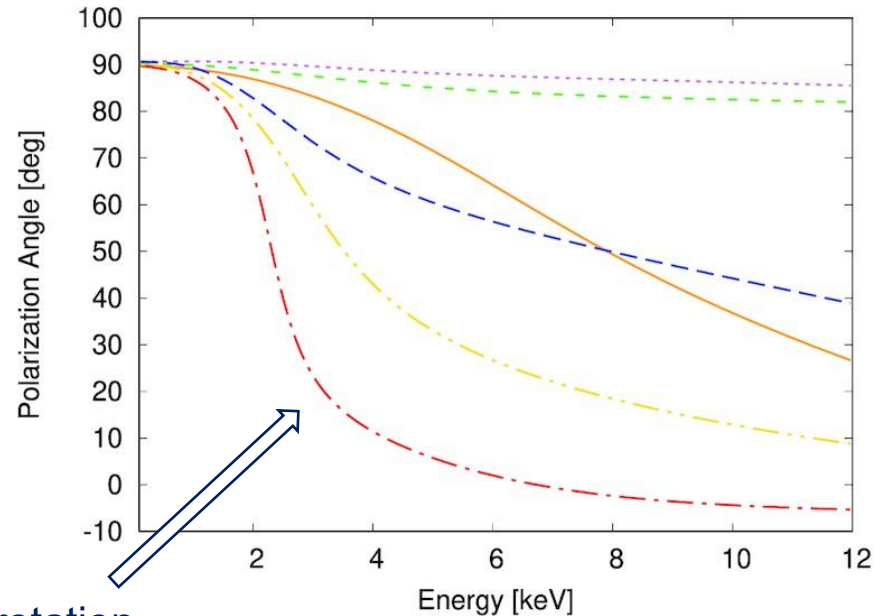


II. X-ray polarization in the soft state & BH spin measurements

X-ray polarization constraints on BH spin



(a)



(b)

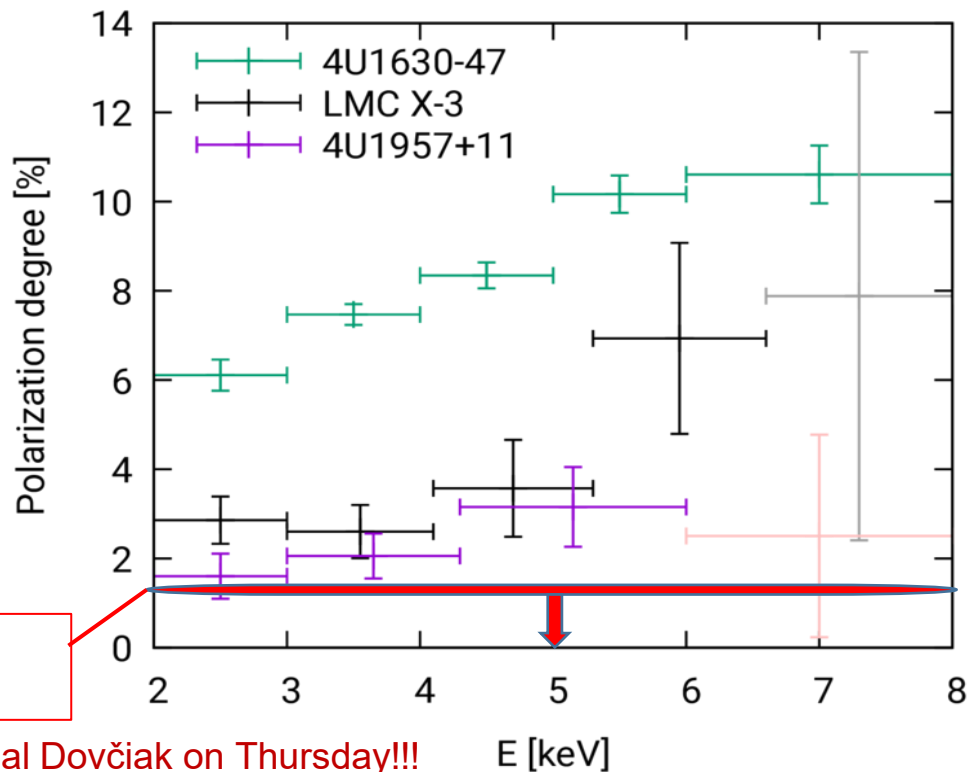
PA rotation

Mikušincová+23

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

IXPE measurements of BHs in the soft state

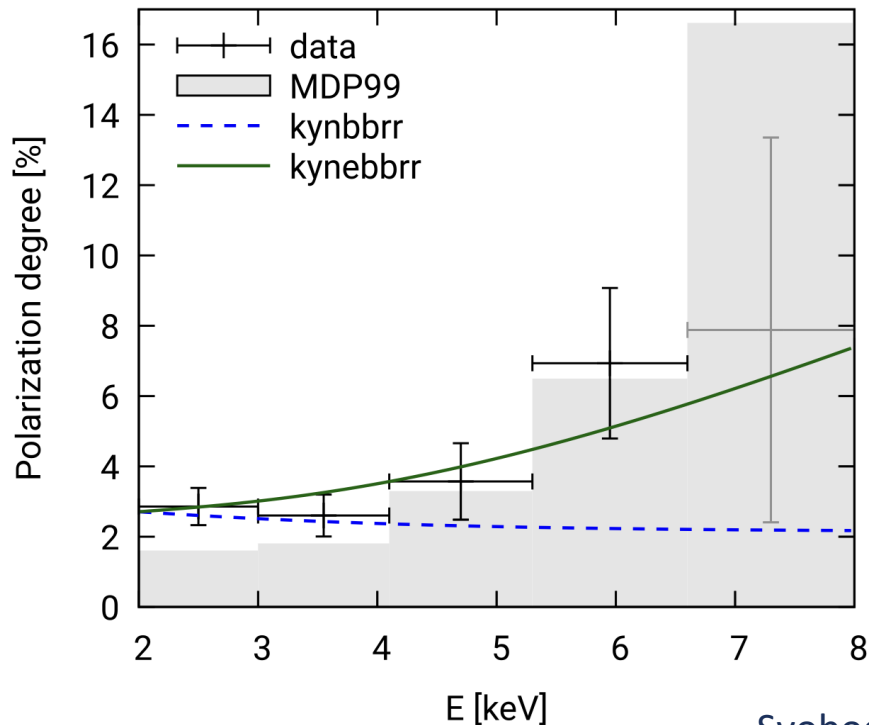
- First measurement: 4U 1630-47
 - exceptionally high & mysterious (Ratheesh+23, Rodriguez Caverro+23)
- Highly-inclined sources:
 - 4U 1957+11 (Marra+23), LMC X-3 (Svoboda+24a)
- Low-inclined sources:
 - LMC X-1 (Podgorný+23), Swift J1727.8-1613 (Svoboda+24b), Swift J151857.0-572147 (Mundal+24), GX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



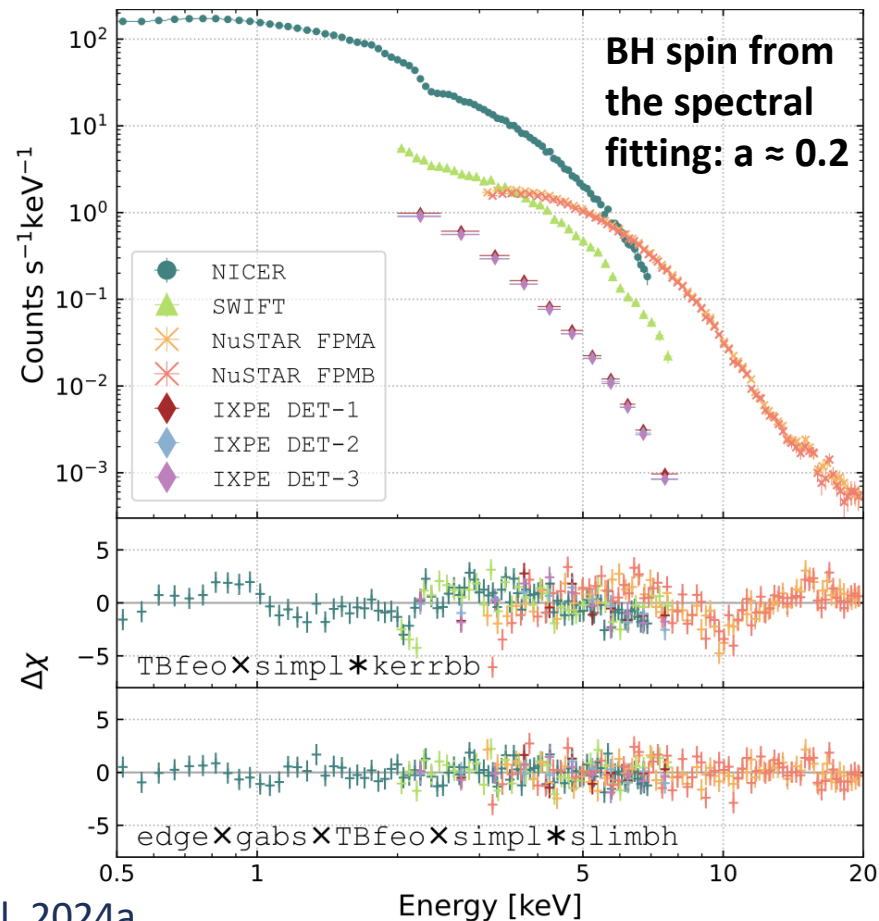
LMC X-1, Swift J1727.8-1613, GX 339-4,
Swift J151857.0-572147, MAXI J1744-294

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

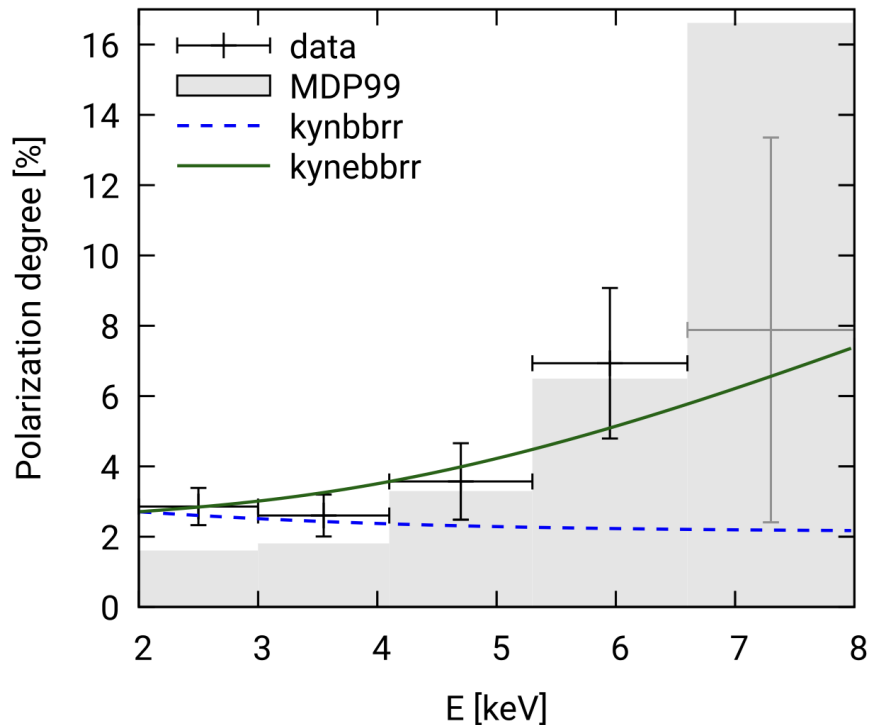
IXPE observation of LMC X-3



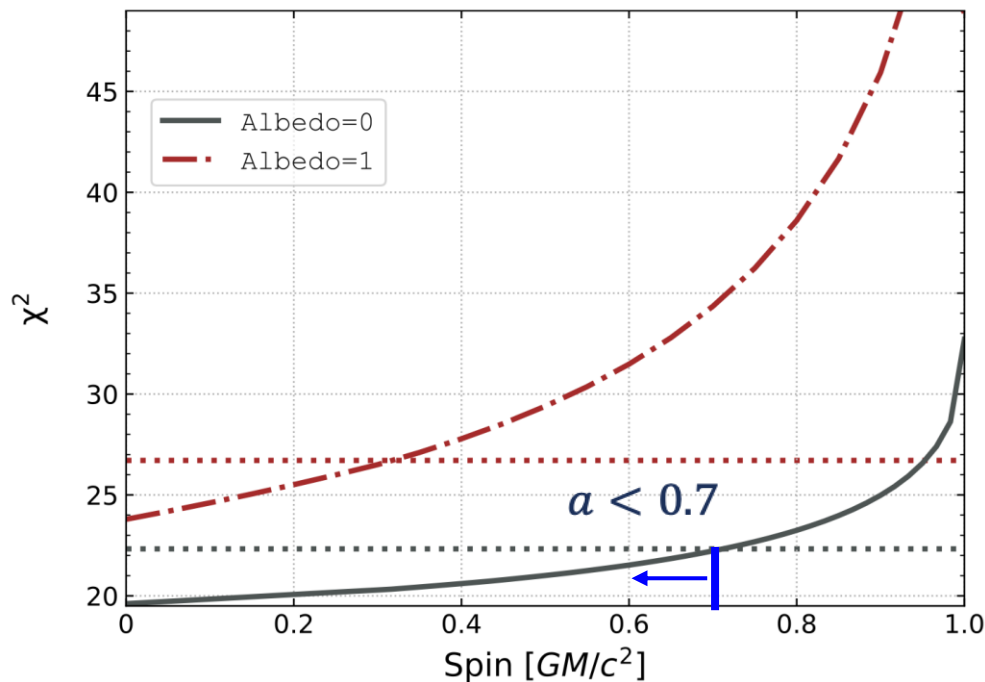
Svoboda et. al, 2024a



First spin measurement: LMC X-3

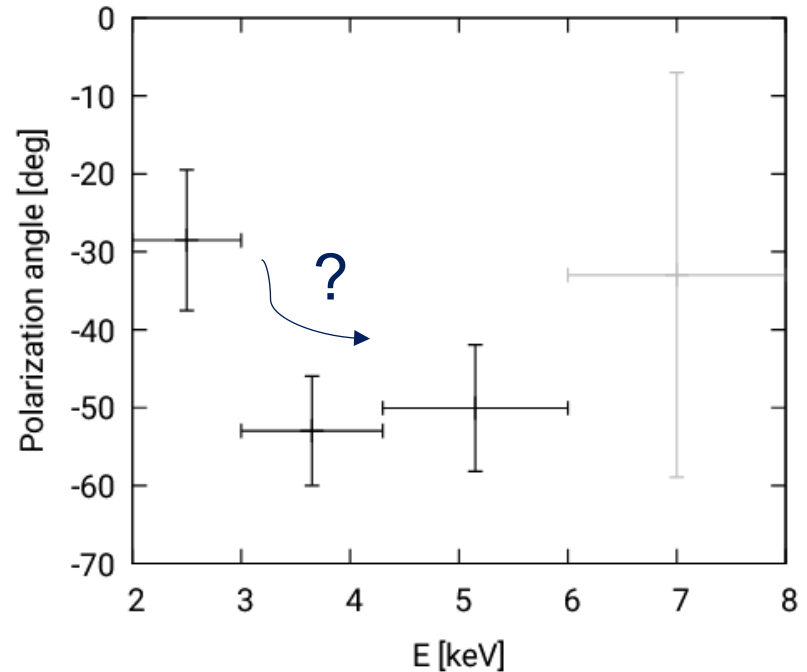
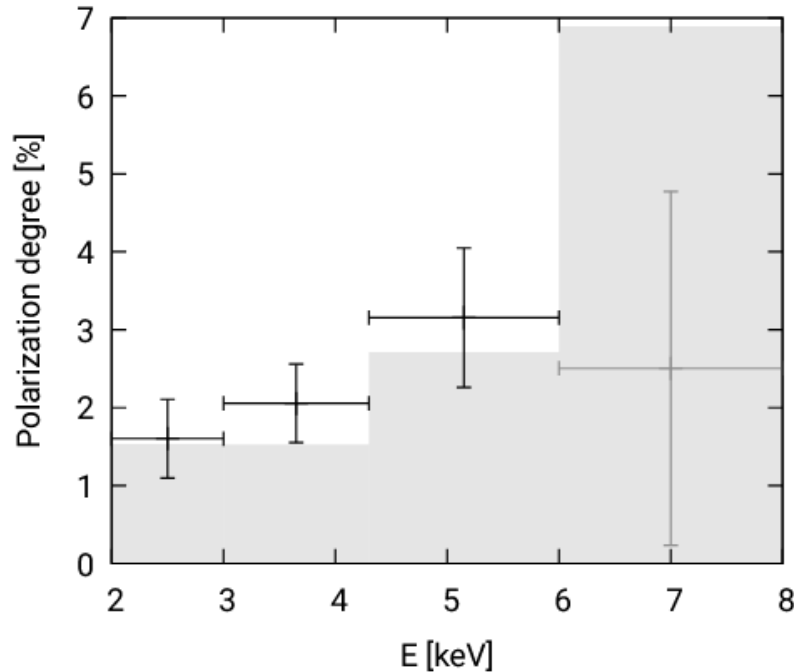


Fit of Q/I, U/I (independently of the spectrum)



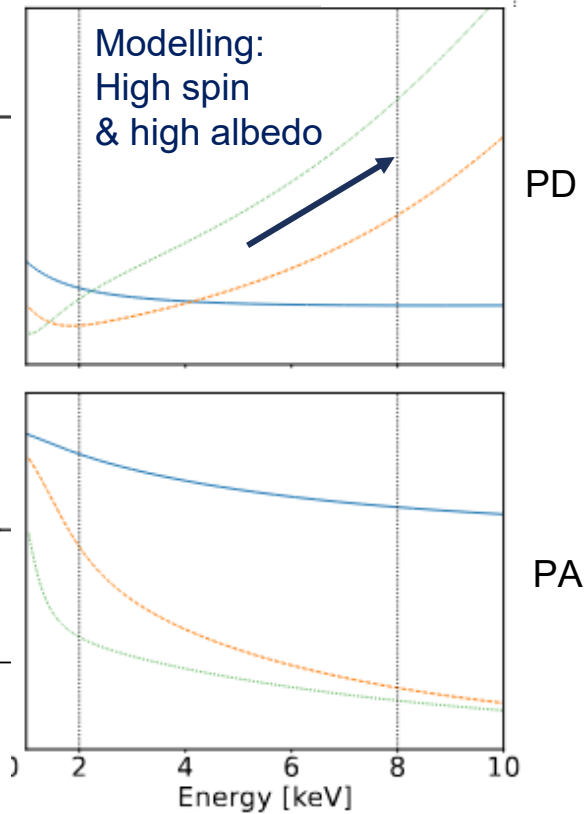
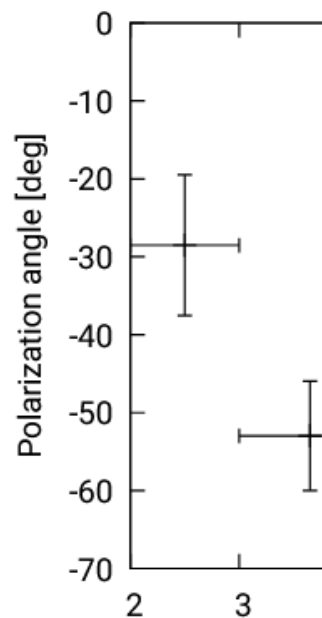
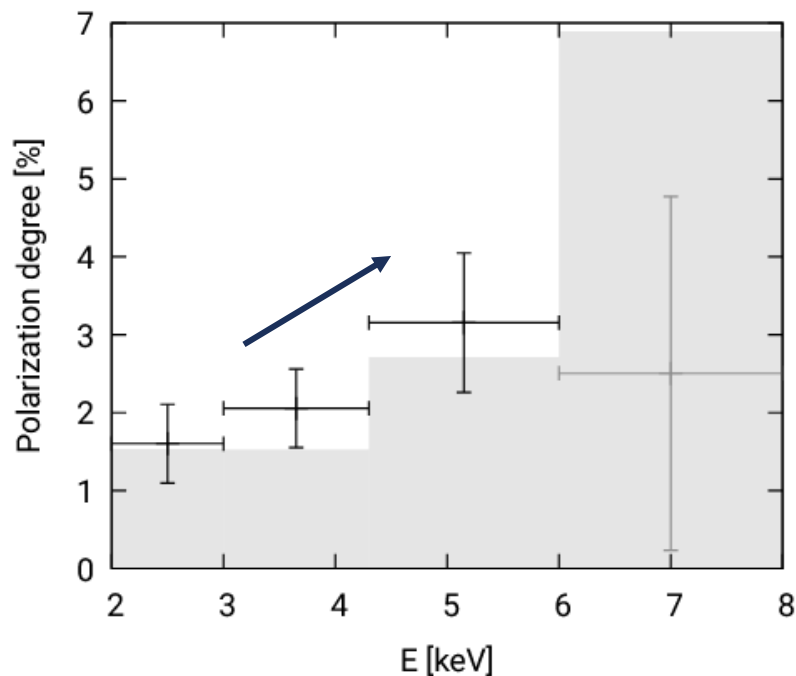
4U 1957+115 - indication of PA rotation?

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

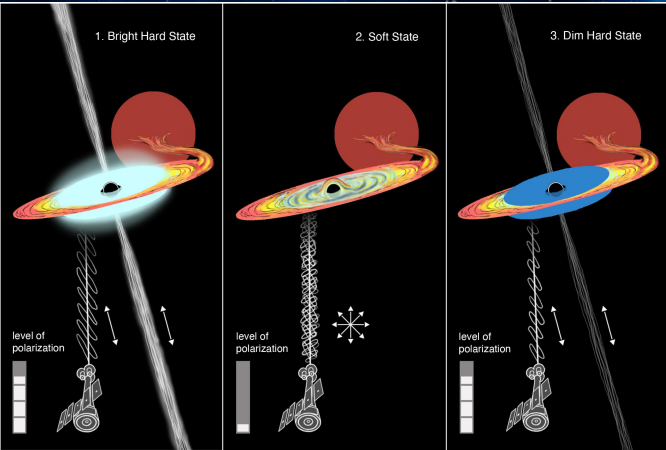


4U 1957+115 – PD energy dependence

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

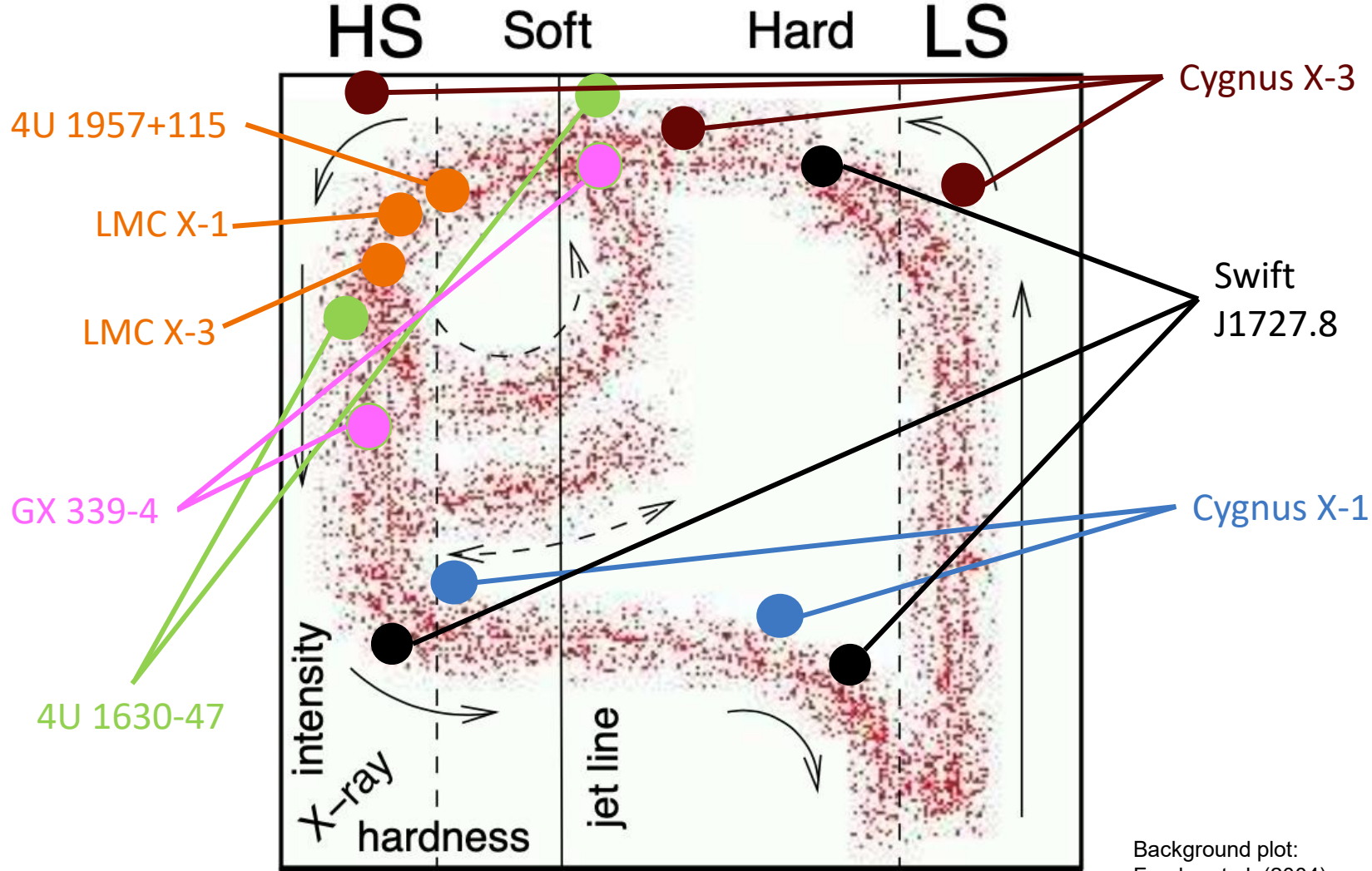


IXPE scientific goals & measurements



III. X-ray polarization across accretion states

Spectral States

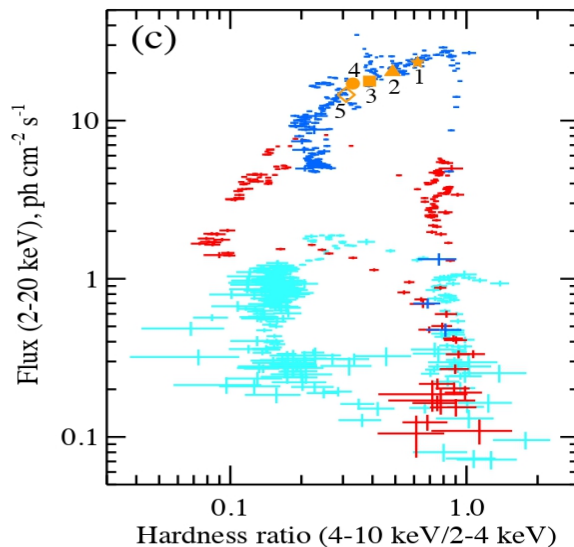
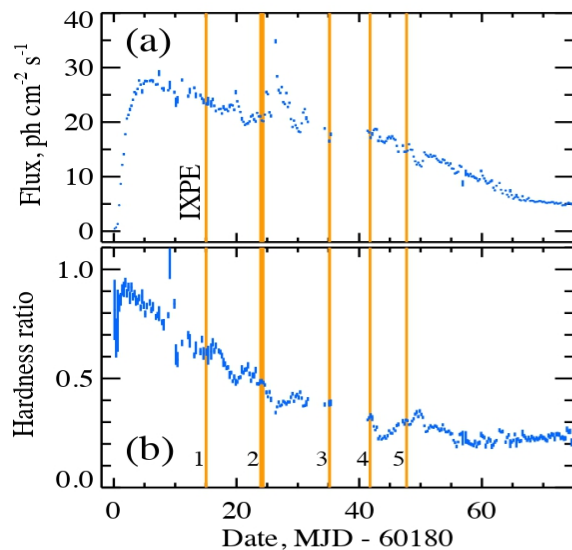


Disclaimer: Luminosity and hardness not drawn to scale

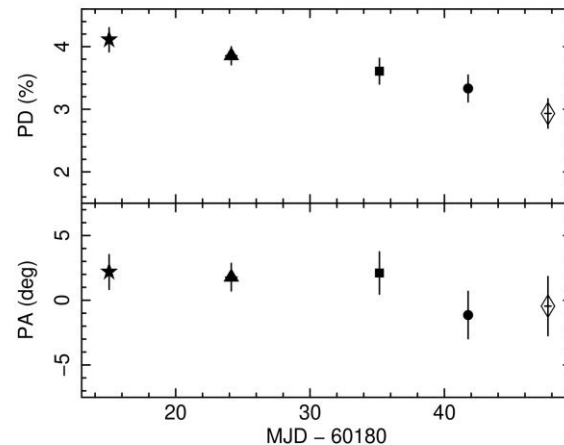
Background plot:
Fender et al. (2004)

Swift J1727-1613 – 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)

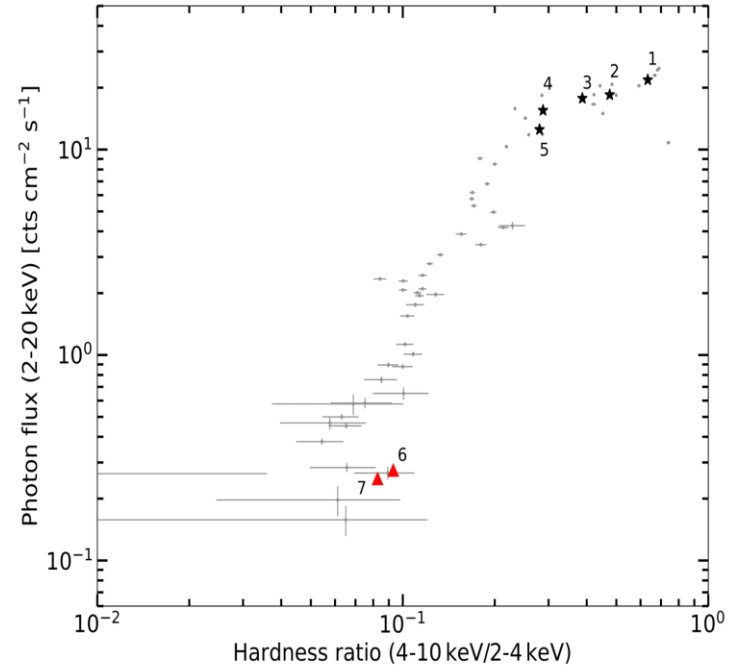
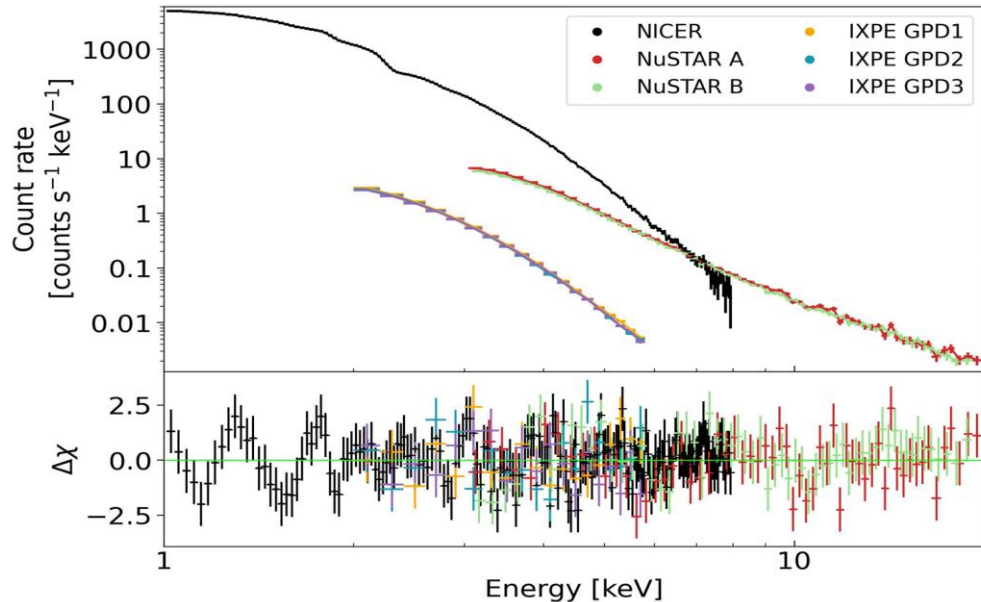


Polarization evolution



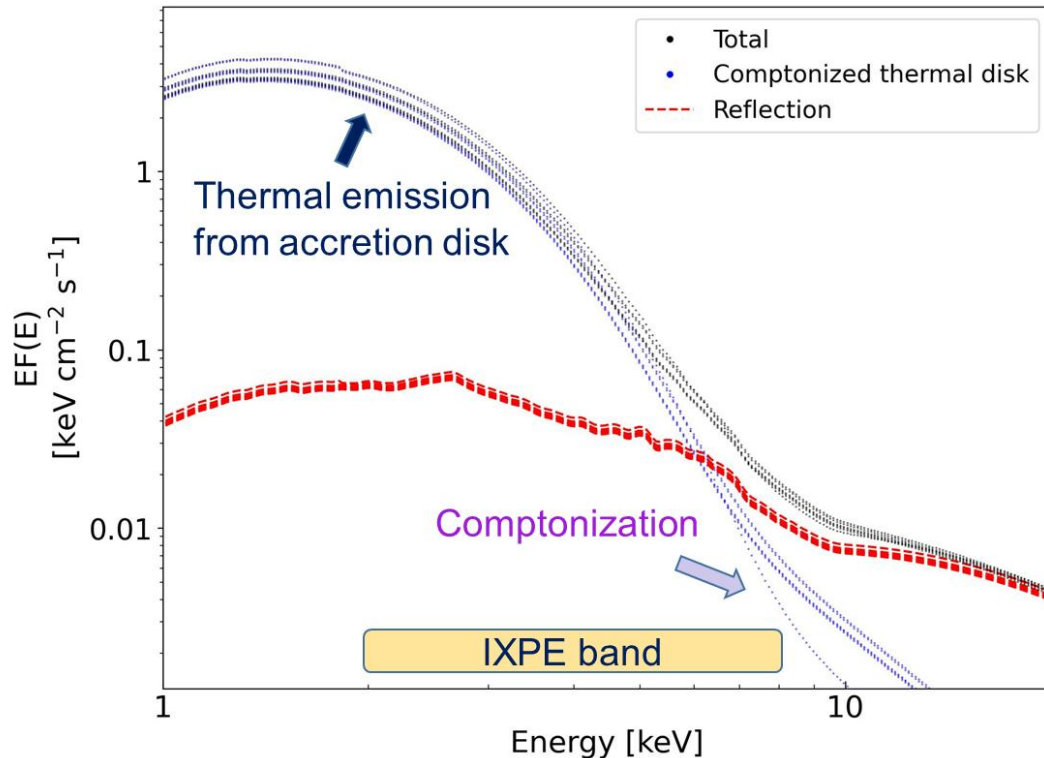
Swift J1727-1613 – soft state

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



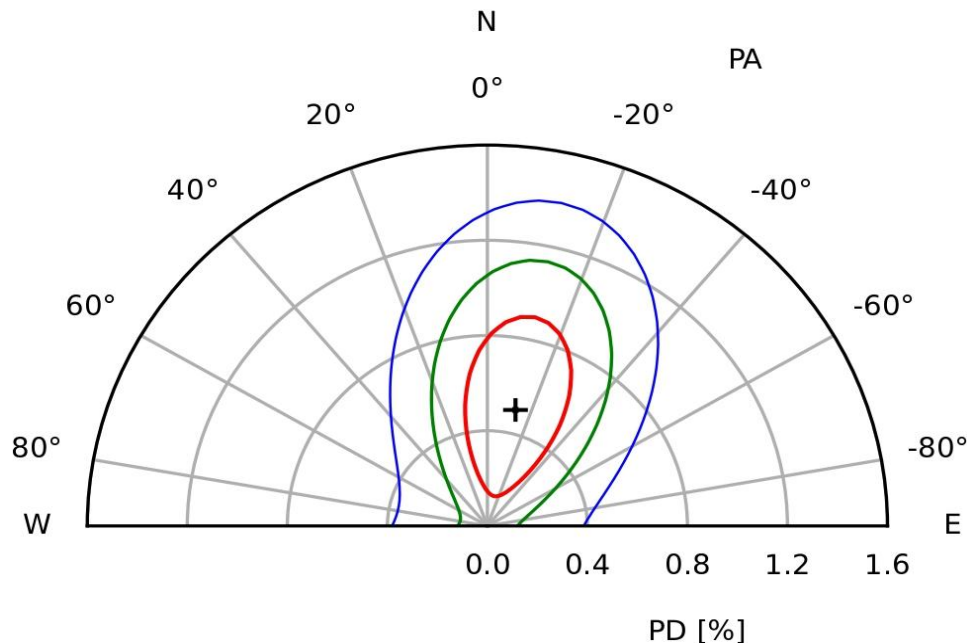
- very soft spectrum dominated by the thermal accretion-disk emission

Swift J1727-1613 – spectral fit



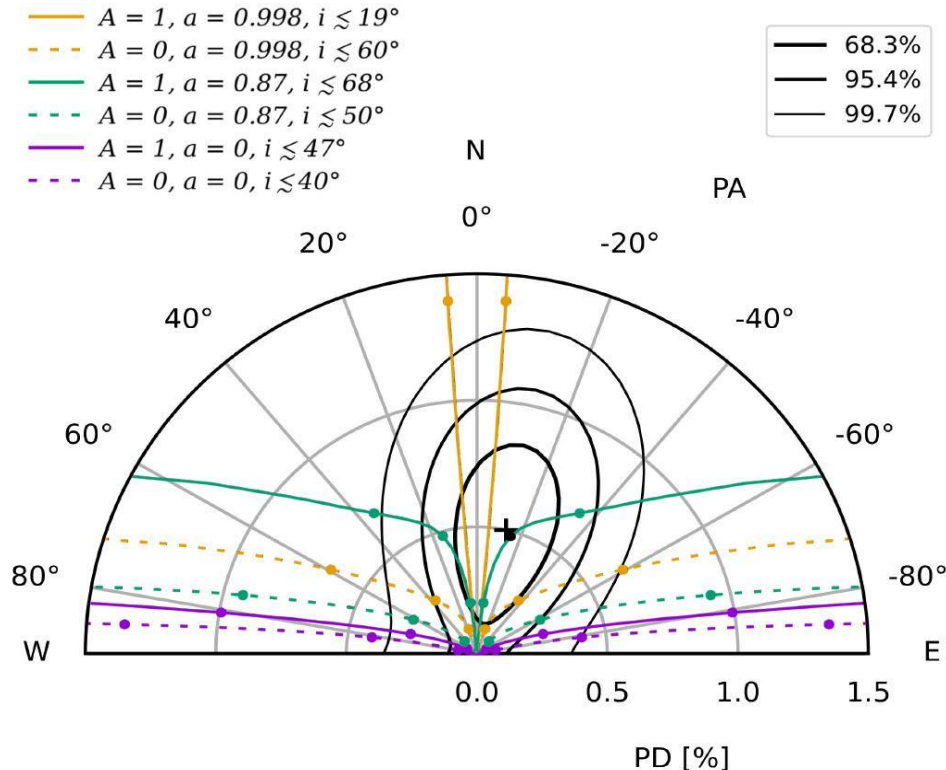
model component	parameter	value
neutral absorption	nH [10^{22} cm^{-2}]	≈ 0.24
accretion disk	L/L_{Edd}	$\approx 1\%$
	spin	≈ 0.9
	inclination	$\approx 38^\circ$
Comptonization	scattering fraction	$\approx 2\text{-}6\%$
	Photon Index	≈ 4.9
Reflection	L/L_{Edd}	$\approx 5 \times 10^{-7}$

Swift J1727-1613 – spectro-polarimetric fit



- **polarization degree (PD)** much lower than during the hard state: $PD \approx 0.5\%$
- 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

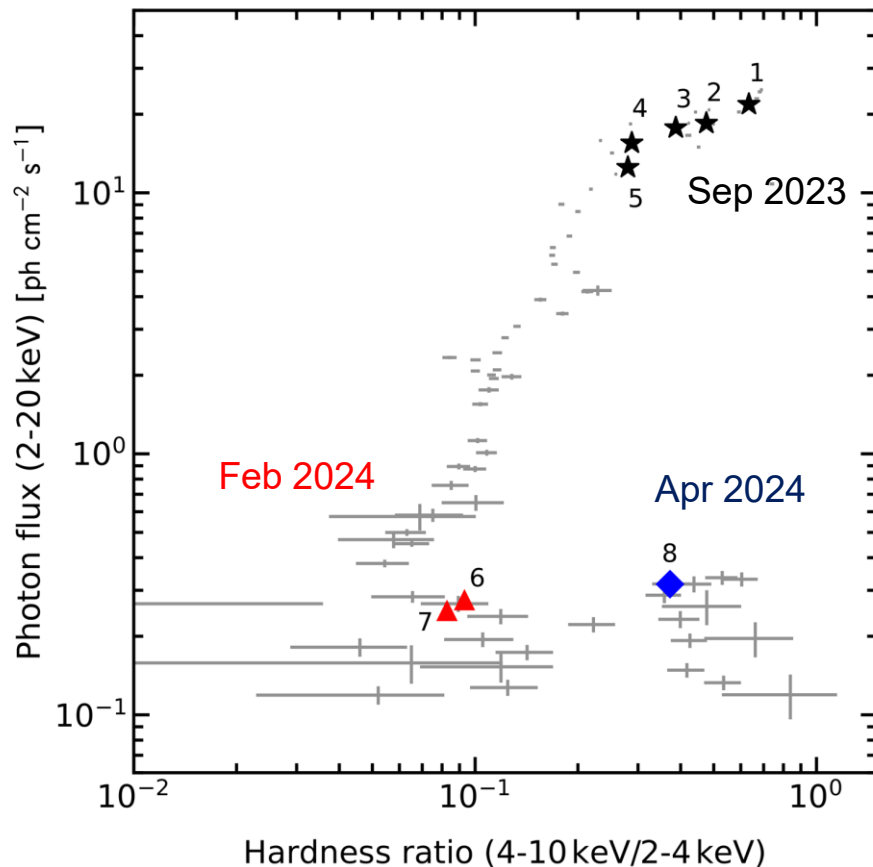
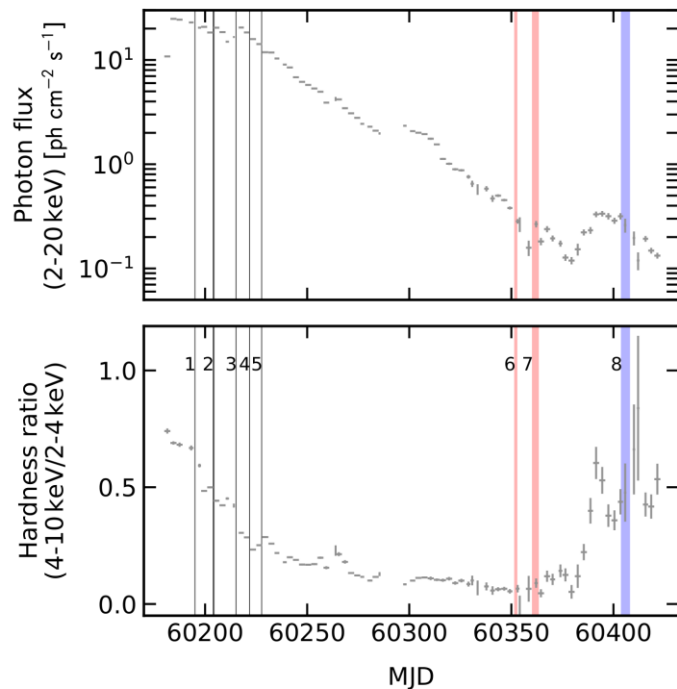
Relativistic model with self-irradiation



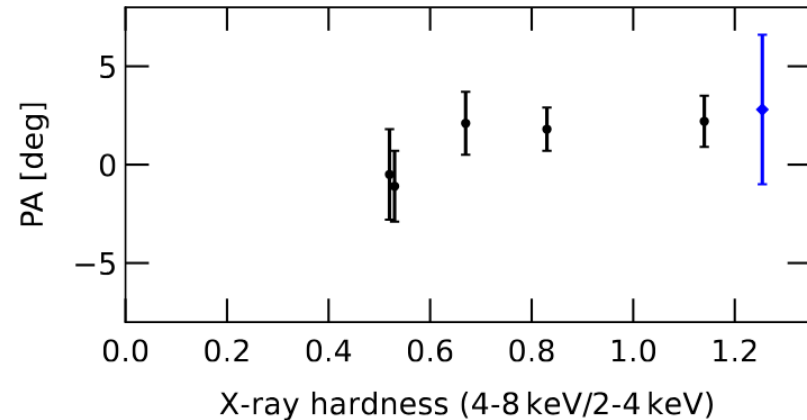
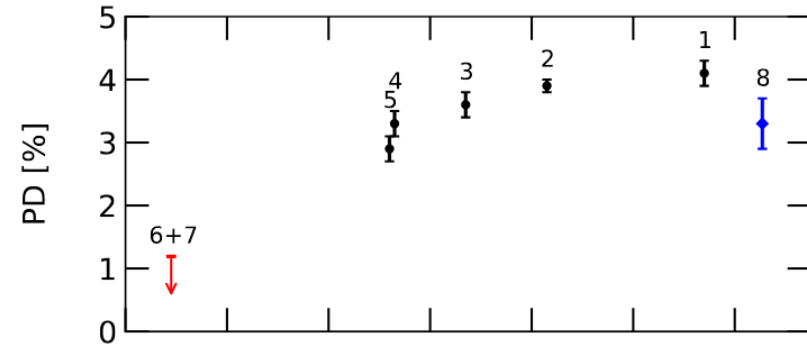
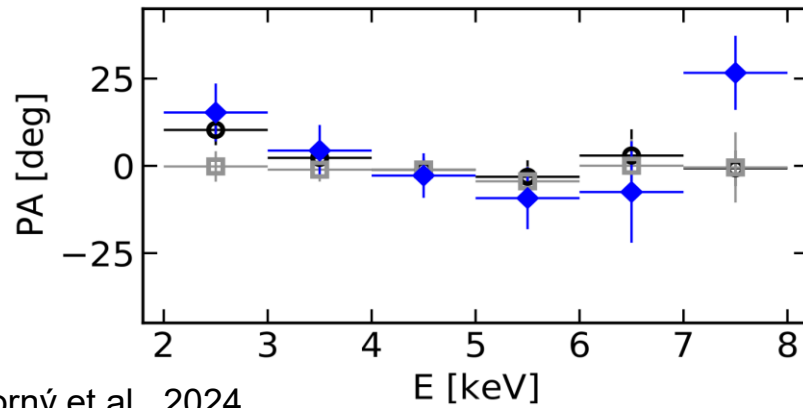
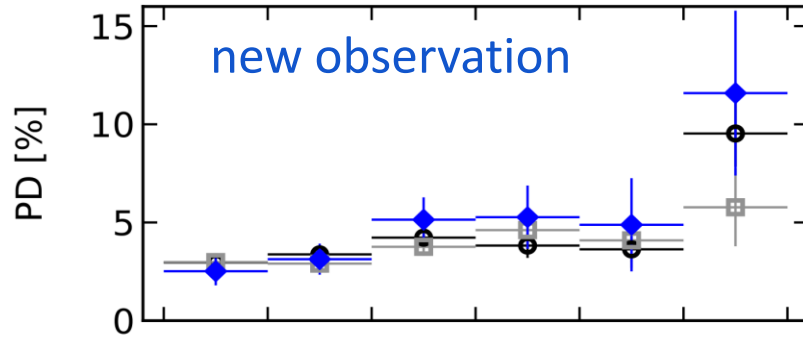
- large dependence on the black hole spin and albedo (self-irradiation)
 - low PD consistent also with higher inclinations
 - PA can be aligned with the perpendicular direction to the accretion disk (and thus, to the hard-state PA)
- the best-fit values of the spectral fit perfectly match the polarization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

Soft-to-hard transition

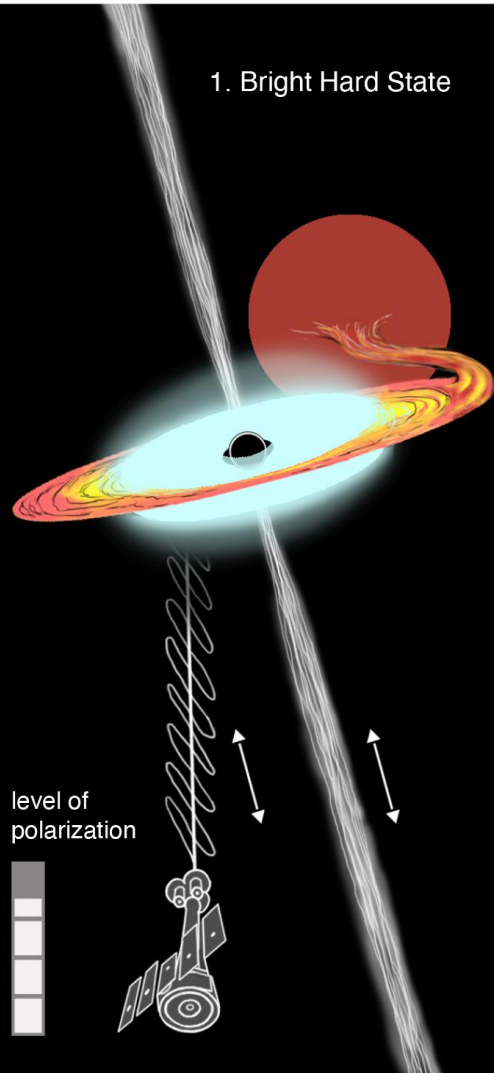
- observation in a dim low/hard state



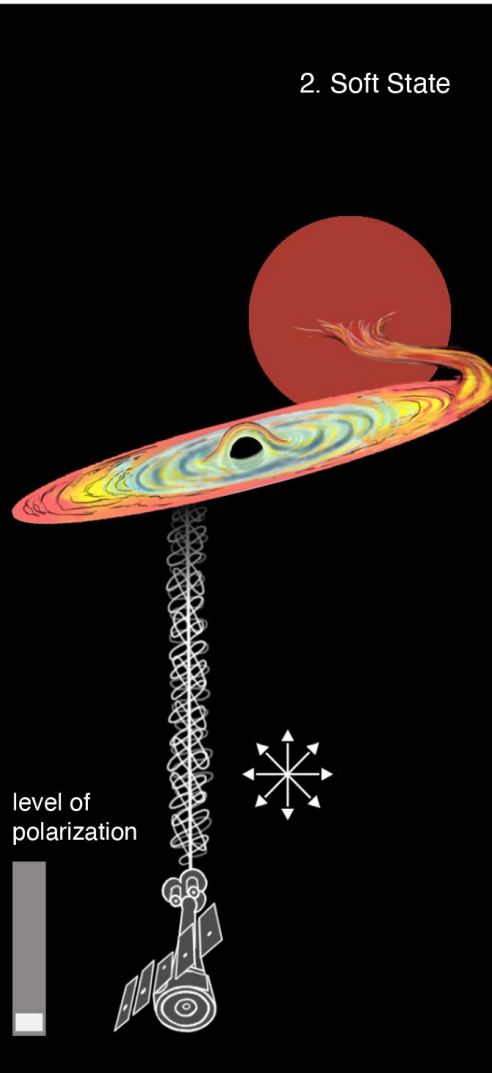
Recovery of the polarization properties



1. Bright Hard State



2. Soft State



3. Dim Hard State

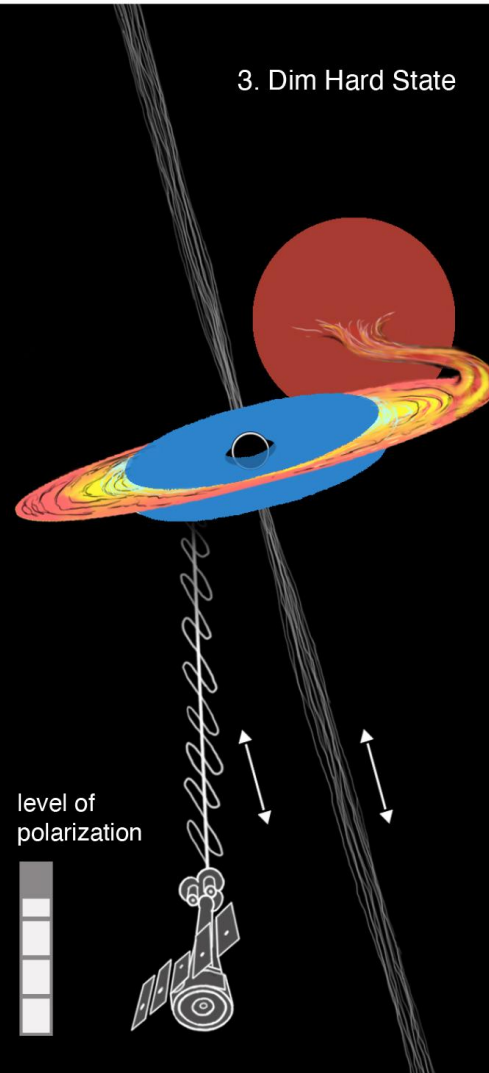
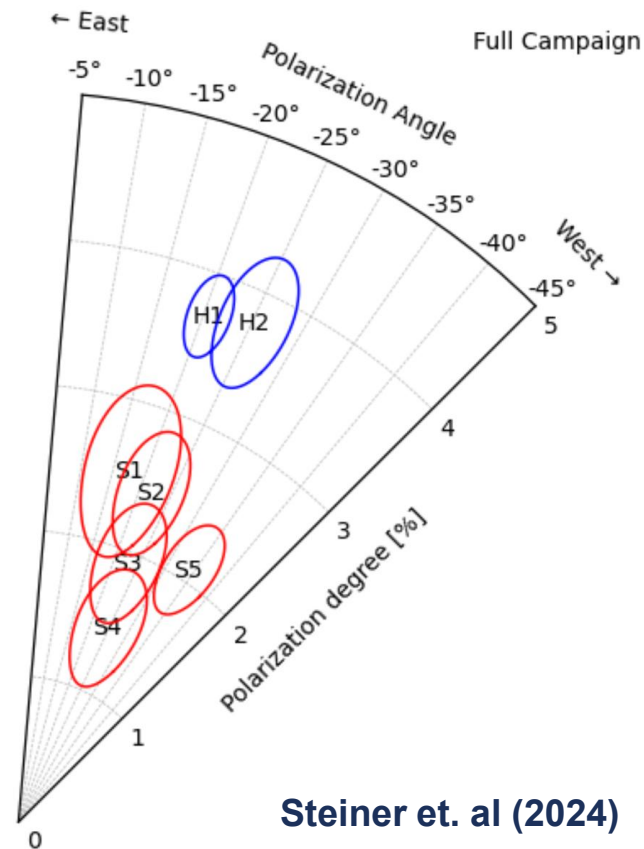
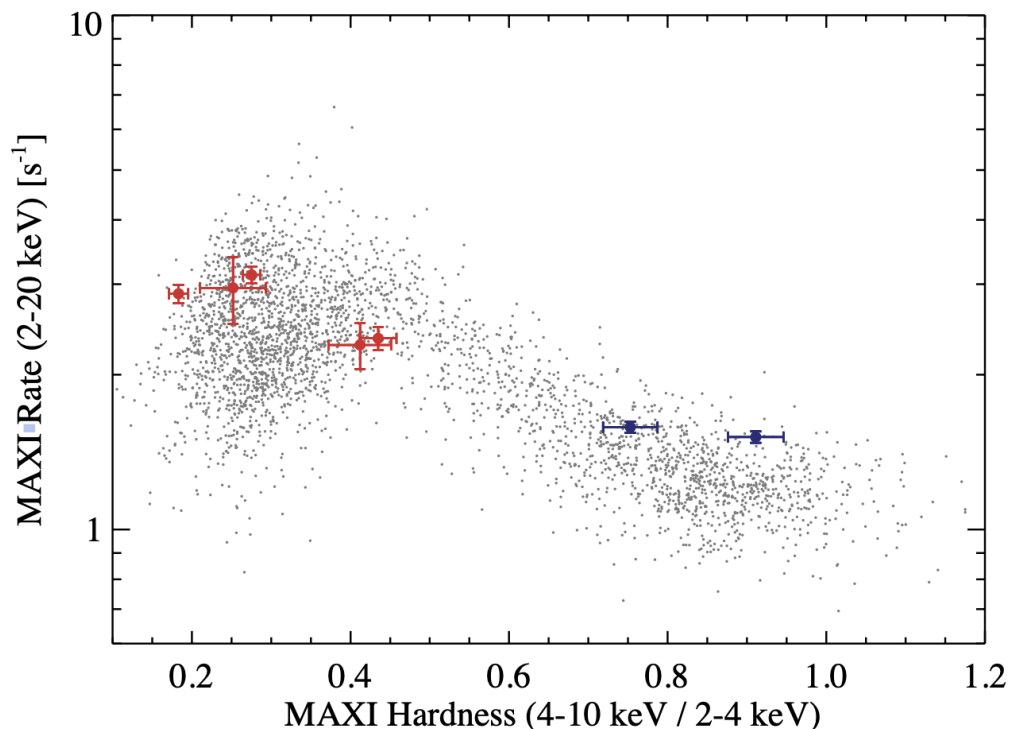


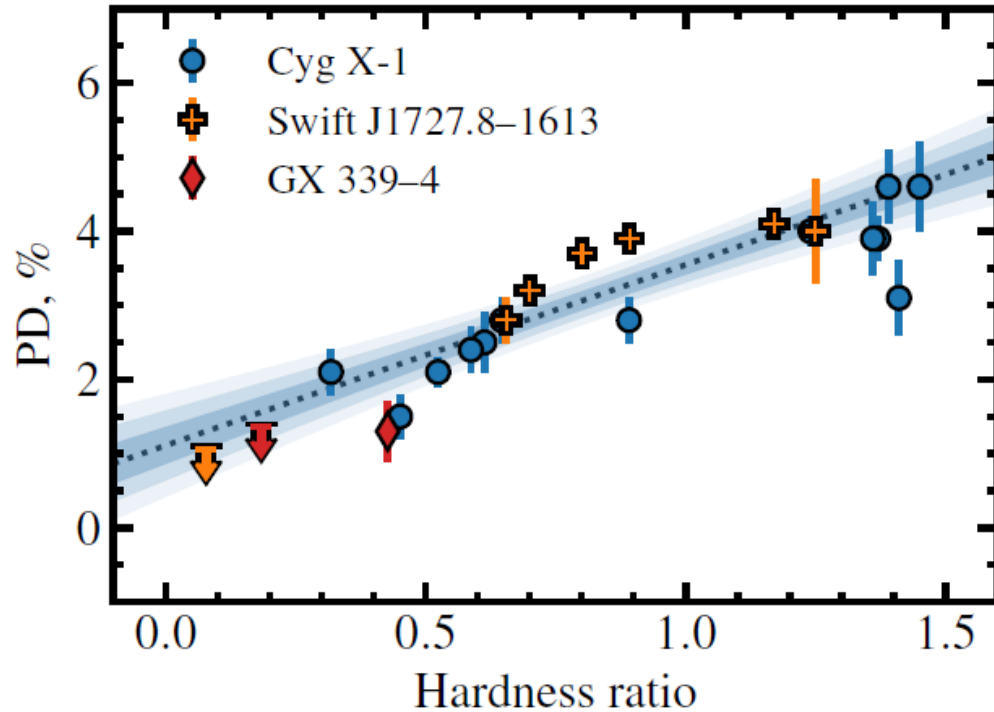
Illustration:

The IXPE observations of the Swift J1727.8-1613 system in different accretion states.

Cyg X-1 – comparison of states

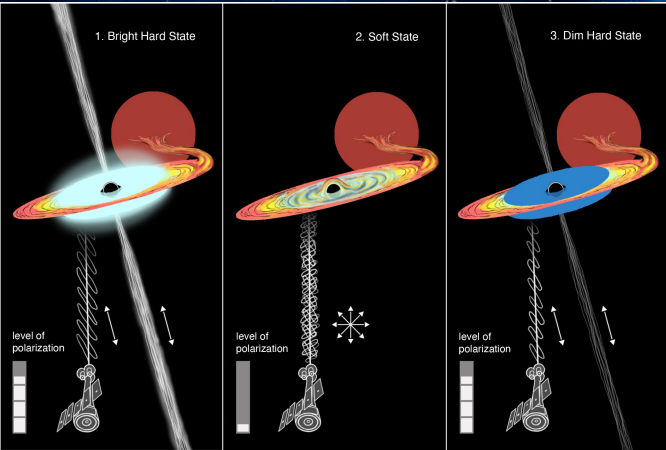


Comparison between the hard and soft states



- **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)

IXPE scientific goals & measurements



IV. Surprising results

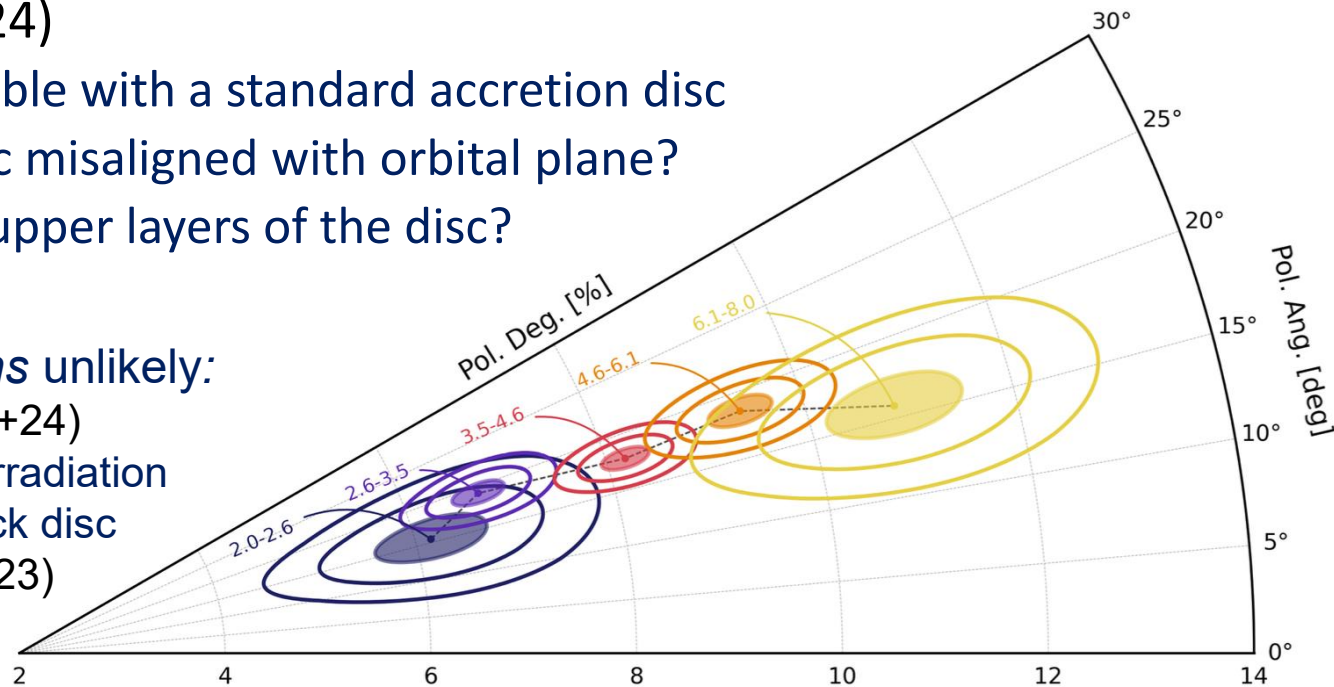
4U 1630-47

- **Extremely large polarization** in the soft state **PD = $8.3 \pm 0.2\%$** (Ratheesh+2024)

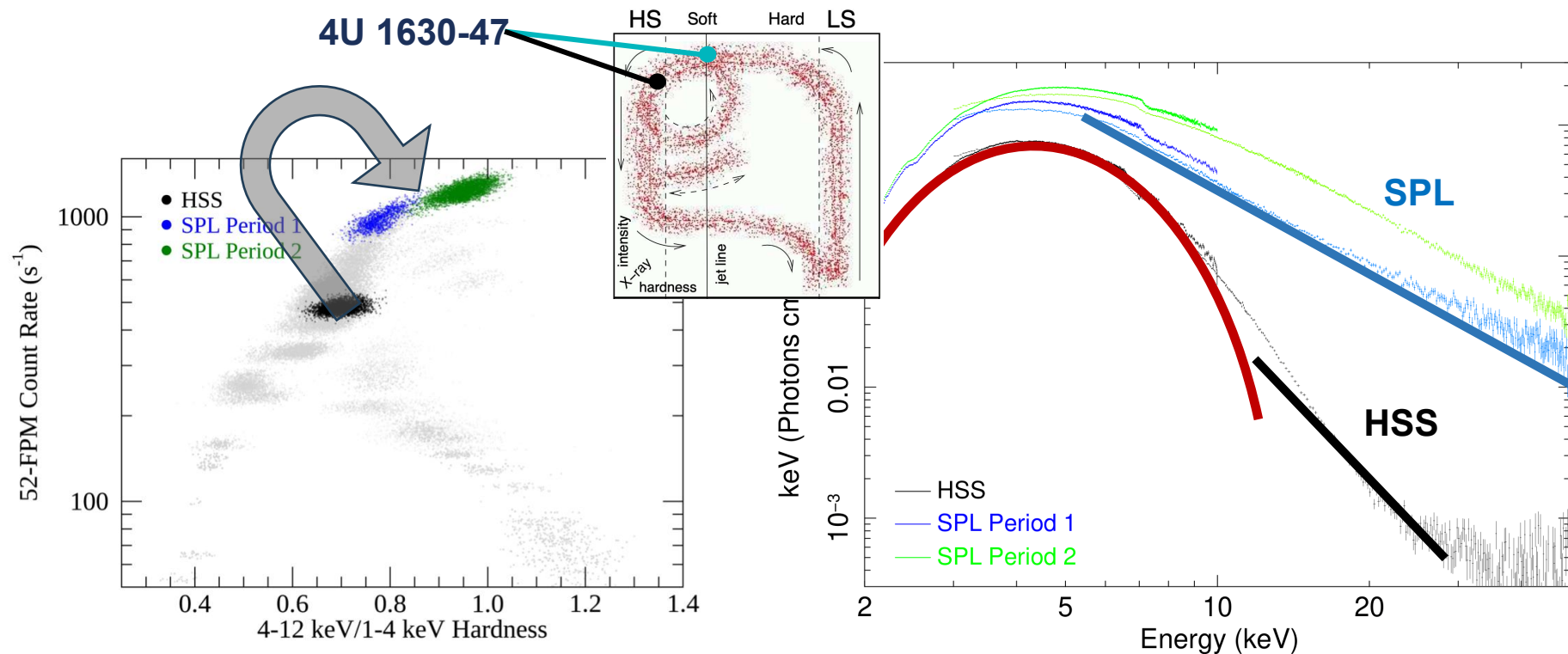
- not compatible with a standard accretion disc
- edge-on disc misaligned with orbital plane?
- outflowing upper layers of the disc?

Alternative explanations unlikely:

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

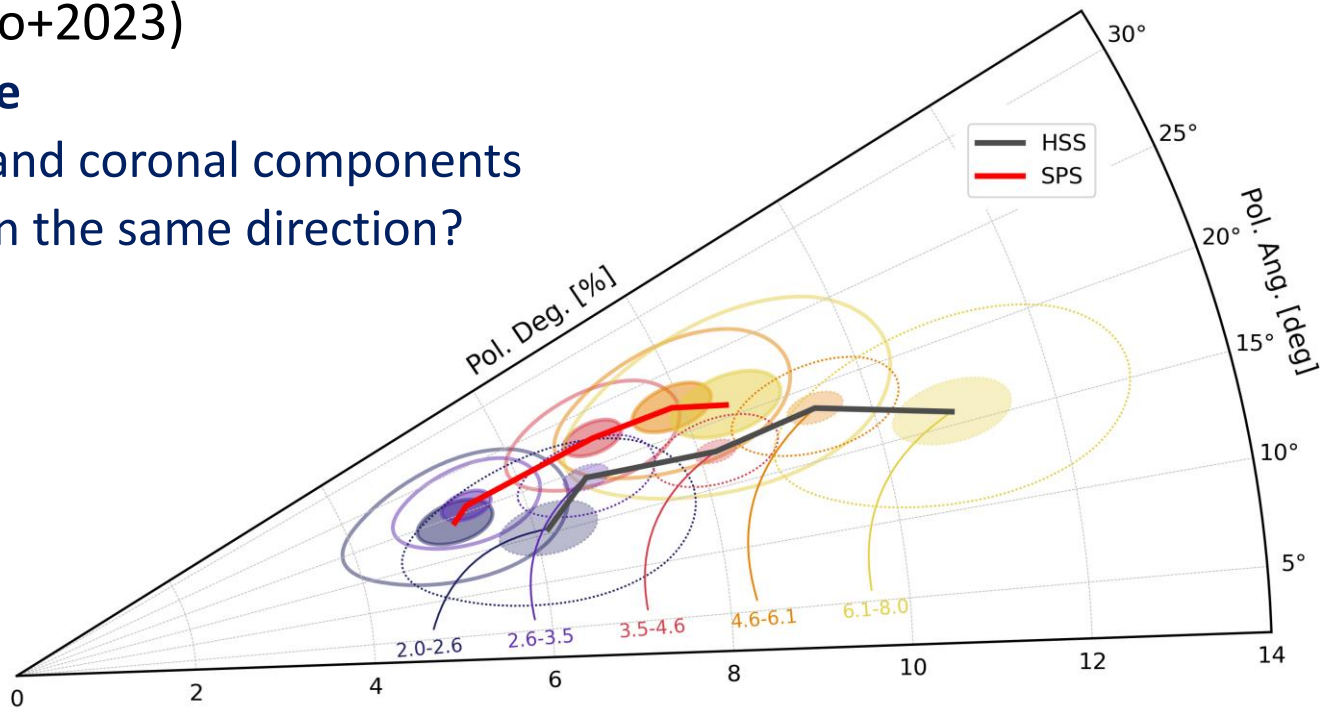


4U 1630-47: steep power-law state



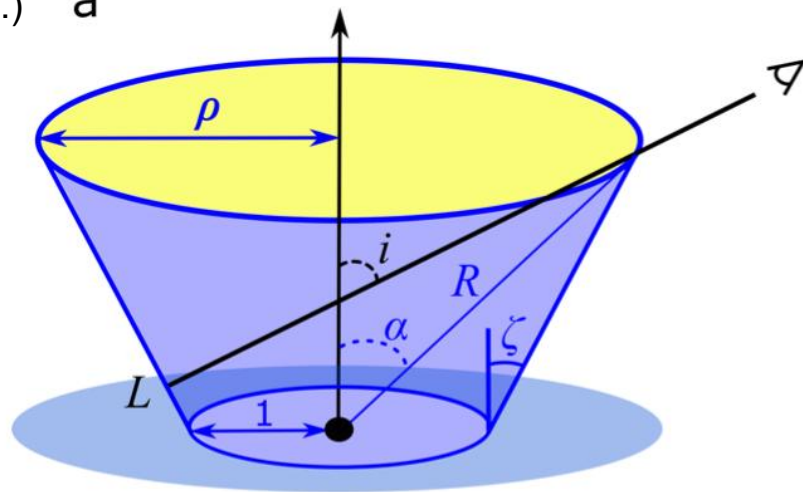
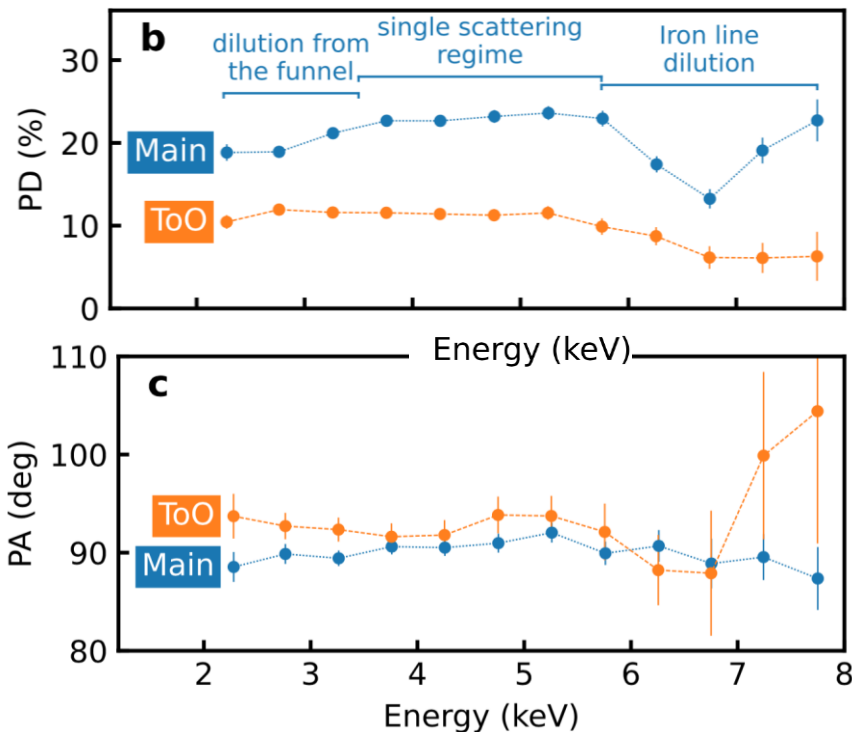
4U 1630-47

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



Cyg X-3 – hidden ultraluminous source?

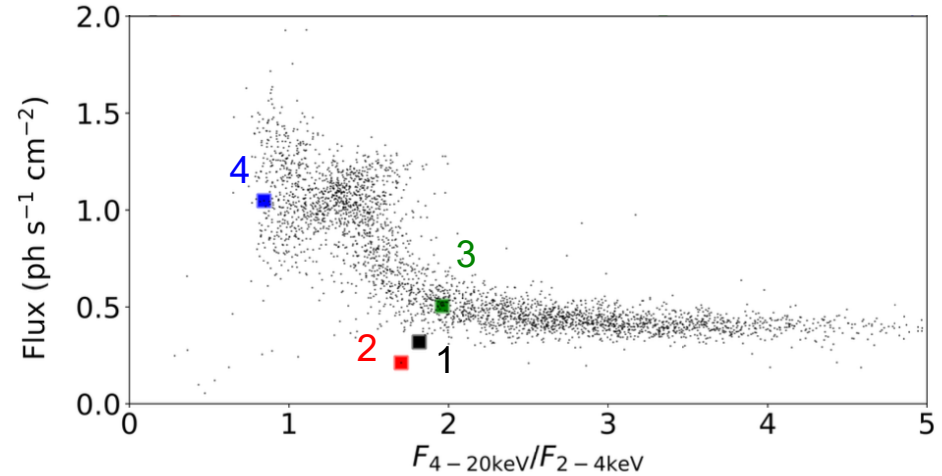
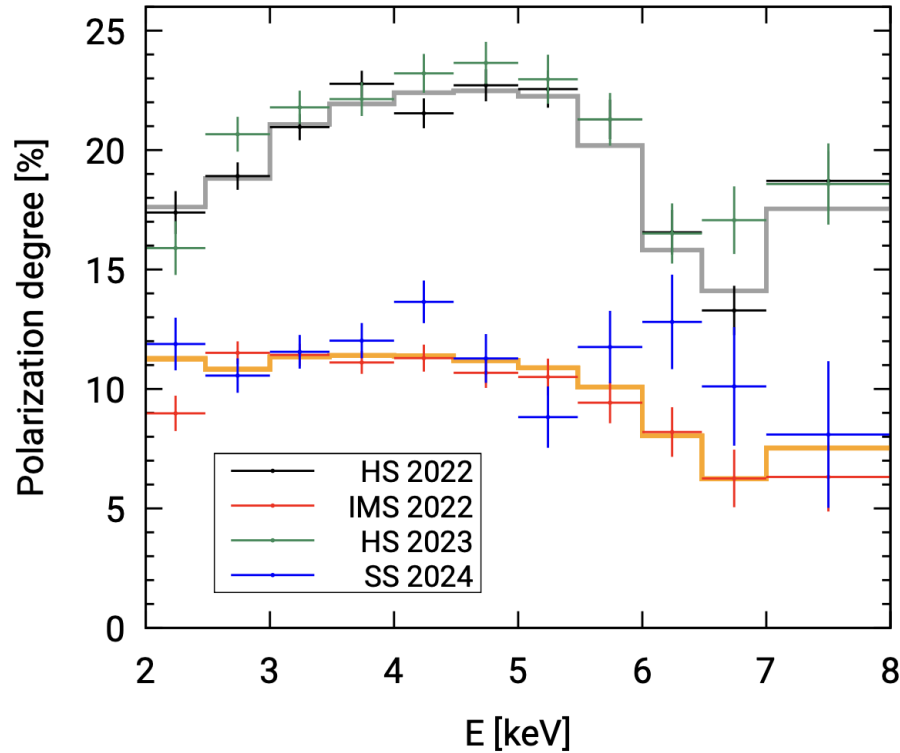
PD = $20.6 \pm 0.3\%$ (main obs.) PD = $10.4 \pm 0.3\%$ (ToO obs.) a



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

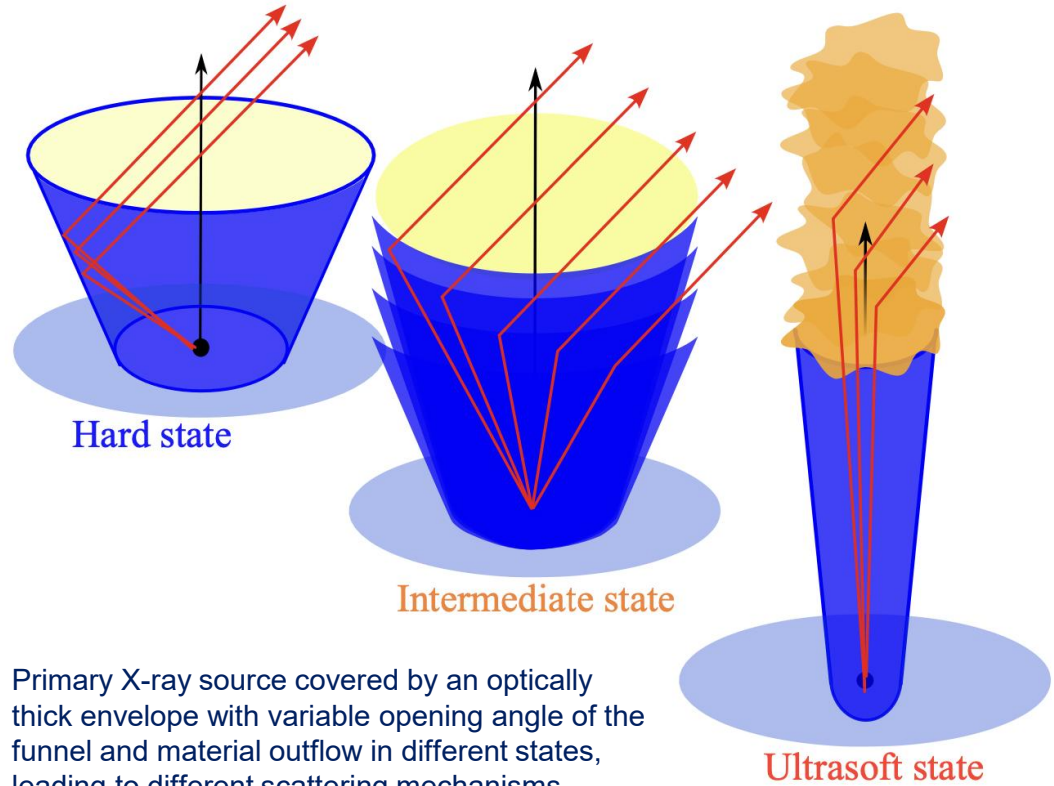
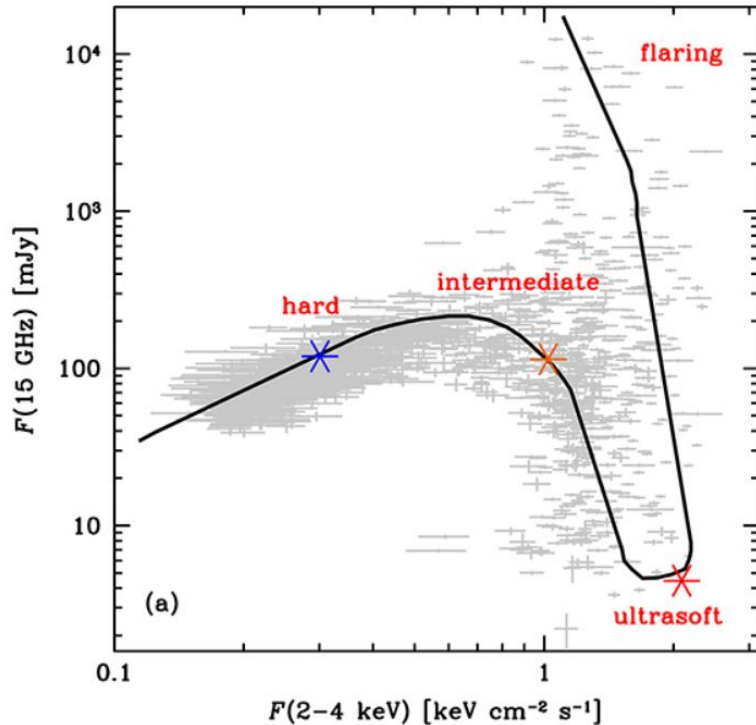
Veledina et. al (2024a)

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

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

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)

Conclusions – surprising results

- PD higher than expected in several sources
 - 4U 1630-47 (PD $\approx$ 6-10%) in soft and steep power-law state, no satisfactory explanation
 - Cyg X-3 (PD $\approx$ 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

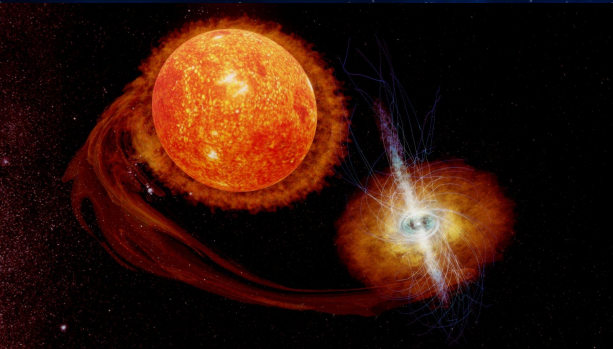
X-ray polarimetry proved to be a very useful tool for investigation of microquasars

Additional slides

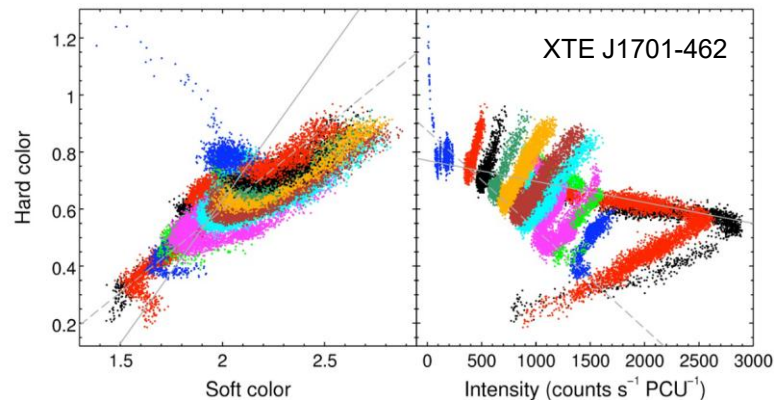
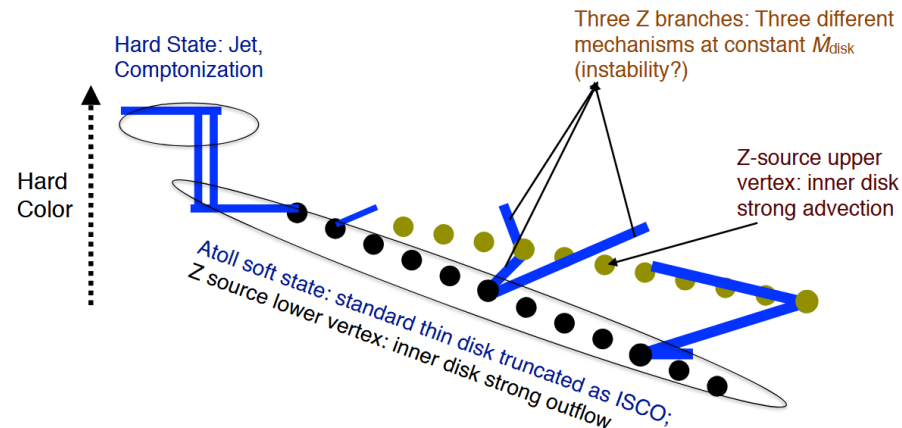
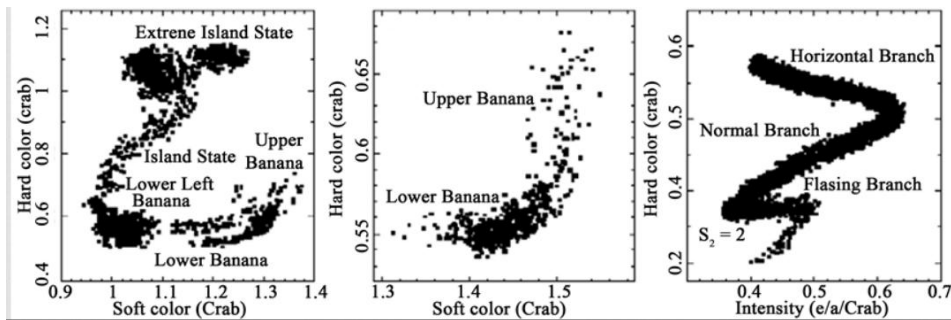
IXPE scientific goals & measurements



V. Neutron star Low-Mass X-ray Binaries



van der Klis 2006



- NS states evolve according to the accretion rate changes

Neutron Stars

Z - sources

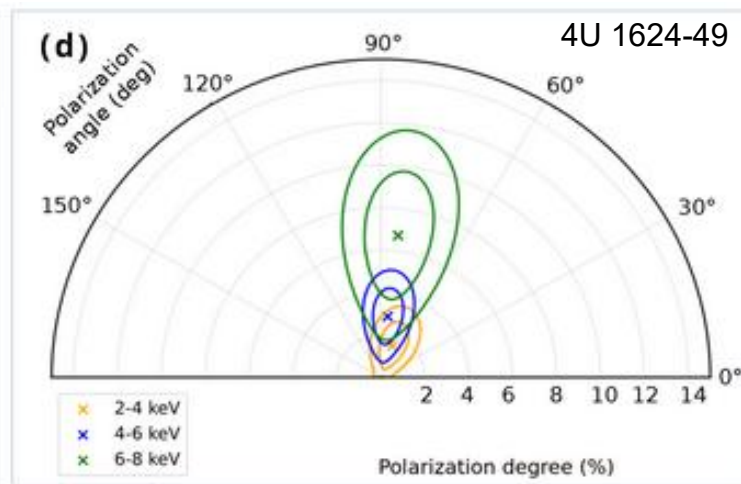
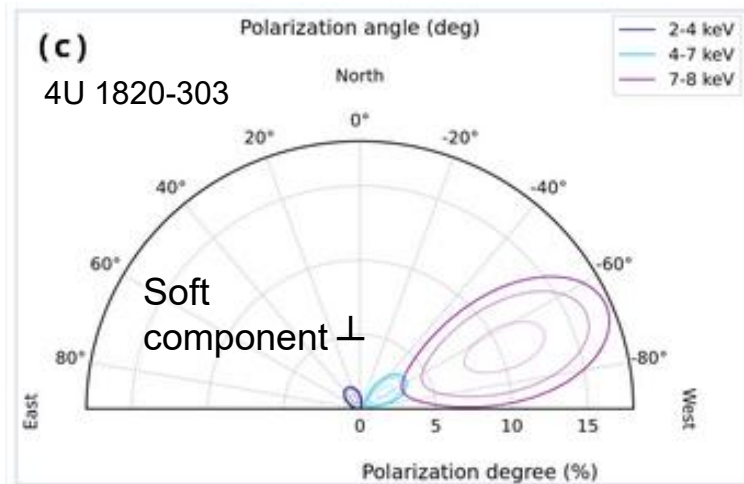
Atoll sources

Accretion rate
X-ray luminosity

Credit: D. Lin

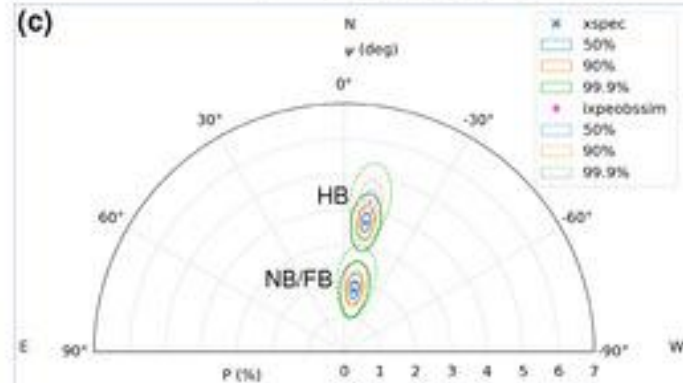
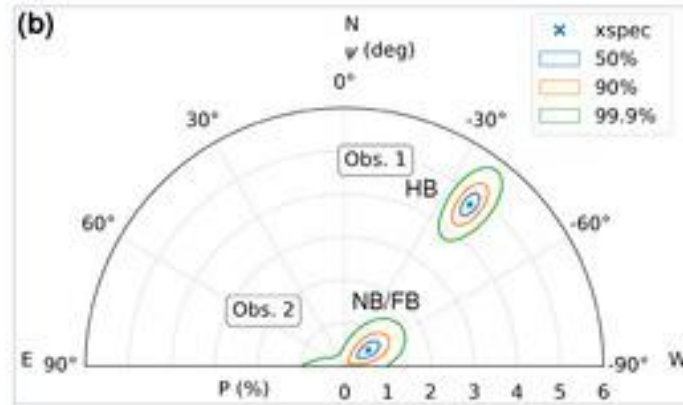
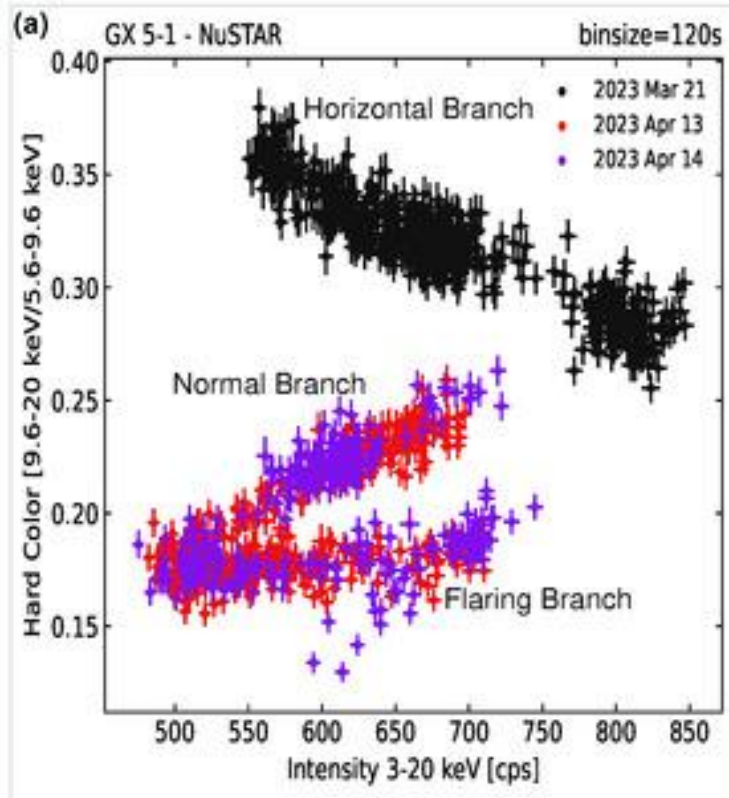
X-ray polarization of Atoll sources

- 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 $\approx$ 3.1% and 4U 1728-44 with PD $\approx$ 1.9% (hard state, Kashyap+25)
- **PD increasing with energy**



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

X-ray polarization of Z-sources



Horizontal Branch:

- hard spectrum
- high PD

Normal/Flaring Branch:

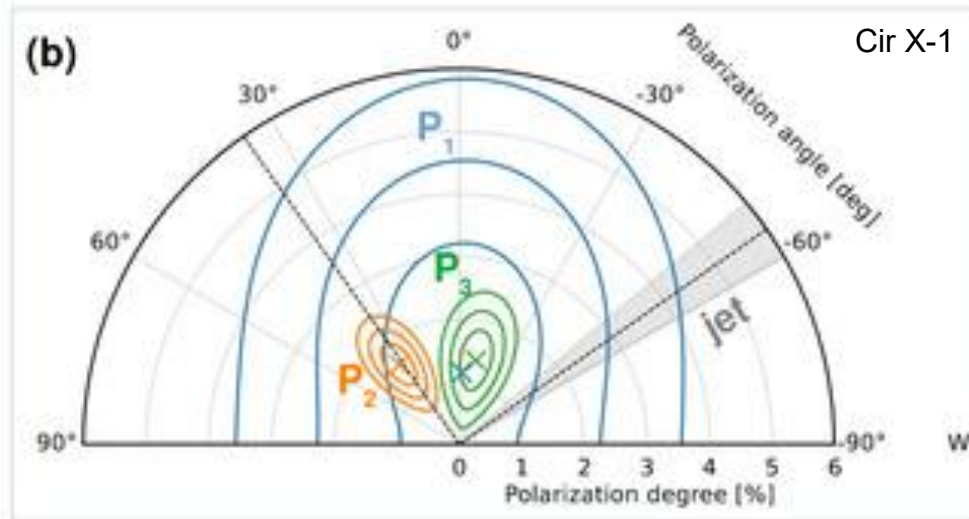
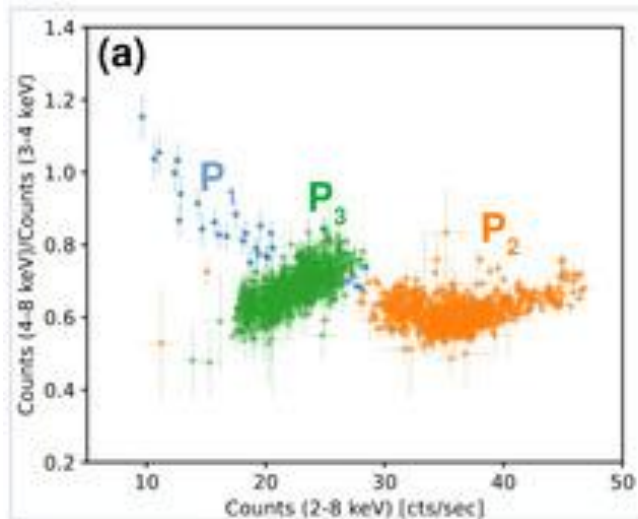
- soft spectrum
- low PD

Ursini+24, Gnarini+25

**See talk by
Andrea Gnarini**

NS LMXB – common features and peculiar sources

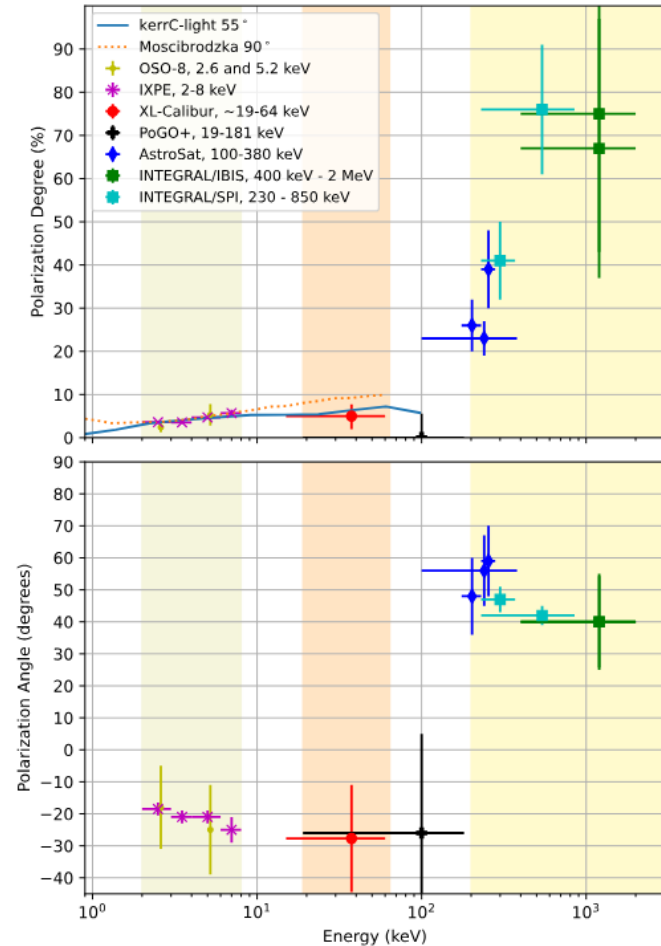
- PD higher in the hard state and lower in the soft state
- PD increasing with energy
- Peculiar sources: Cir X-1, GX 13+1 – PA variability



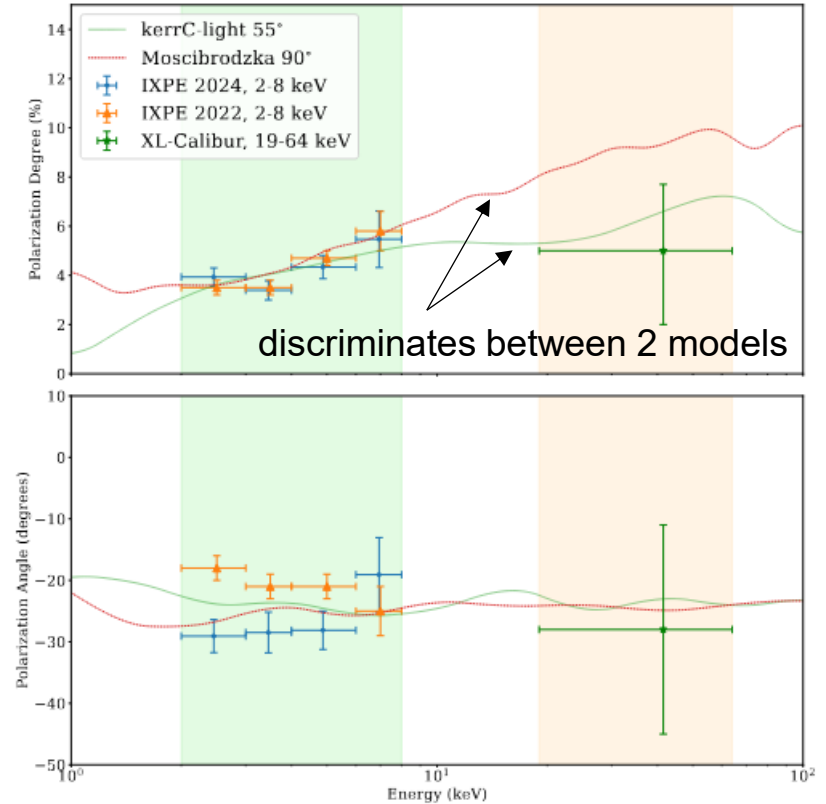
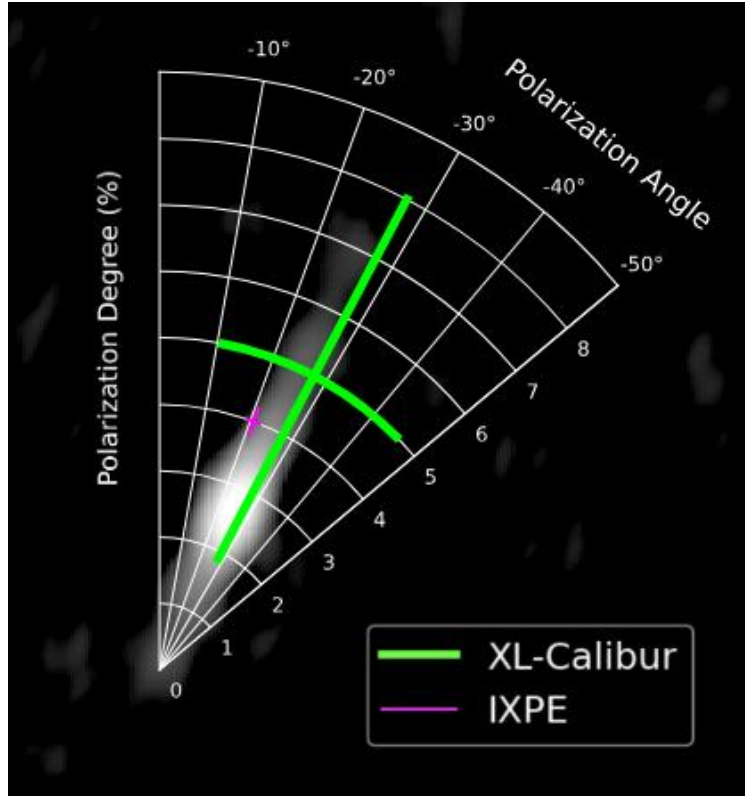
Rankin+24,
Ursini+24

Hard X-ray polarimetry of Cyg X-1

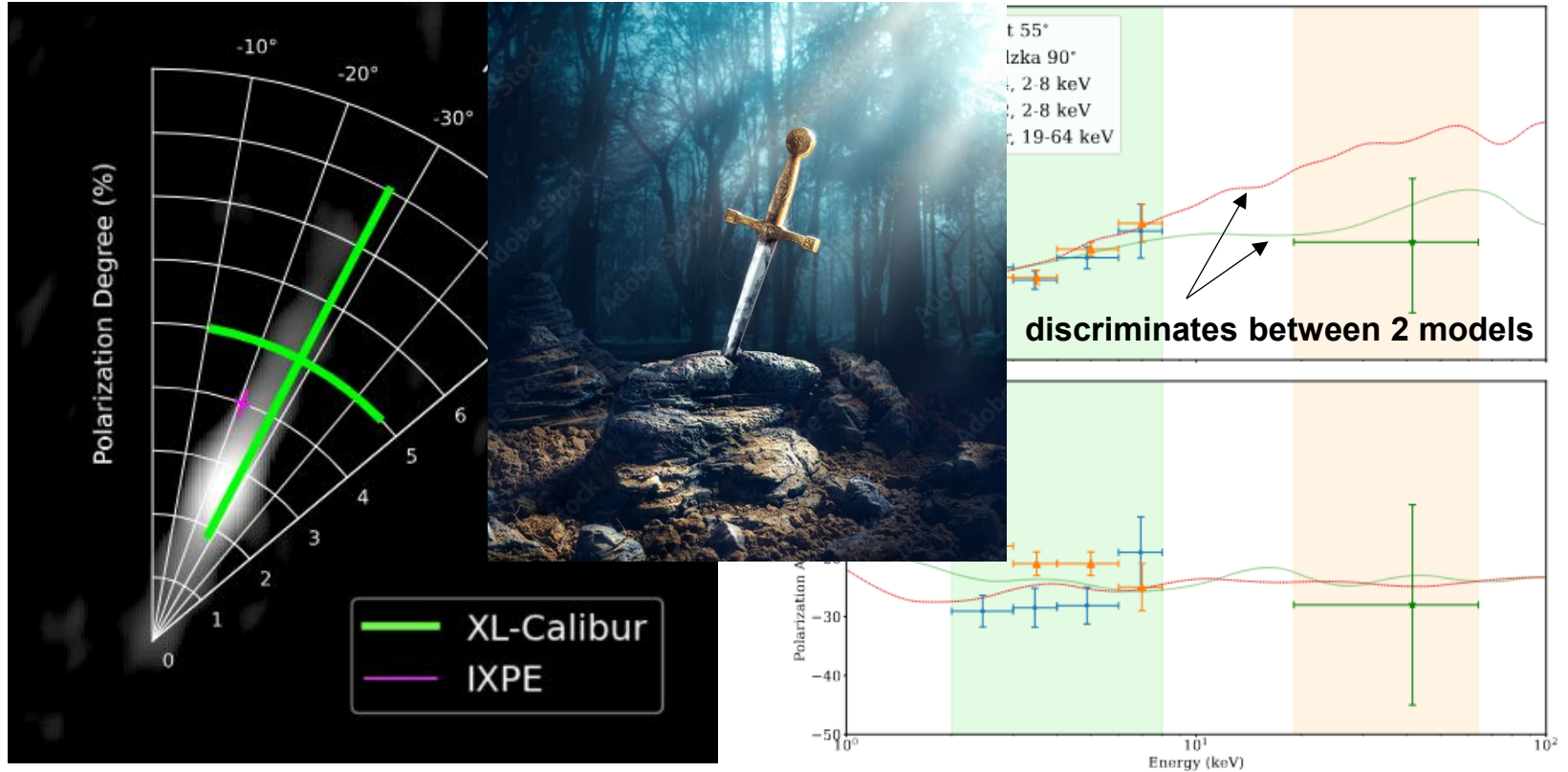
- Hard X-ray polarization measurements
 - very high PD and different PA with Integral/IBIS and SPI (Laurent+11, Rodriguez+15), likely connected with the jet
- XL-Calibur – balloon experiment (Washington State University, NASA/JAXA/Swedish mission, 6-day, July 2024)
 - new measurements of Cyg X-1 in 19–181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



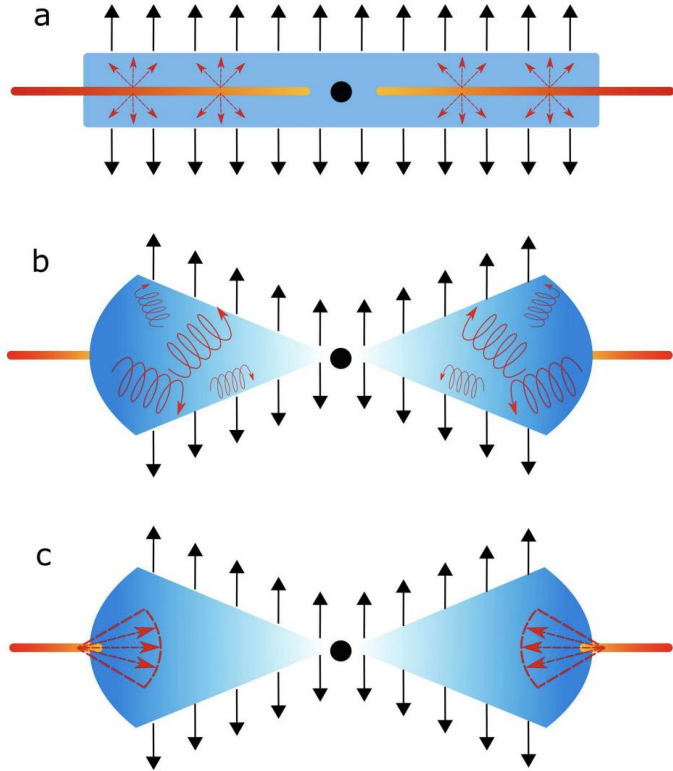
Hard X-ray polarimetry of Cyg X-1



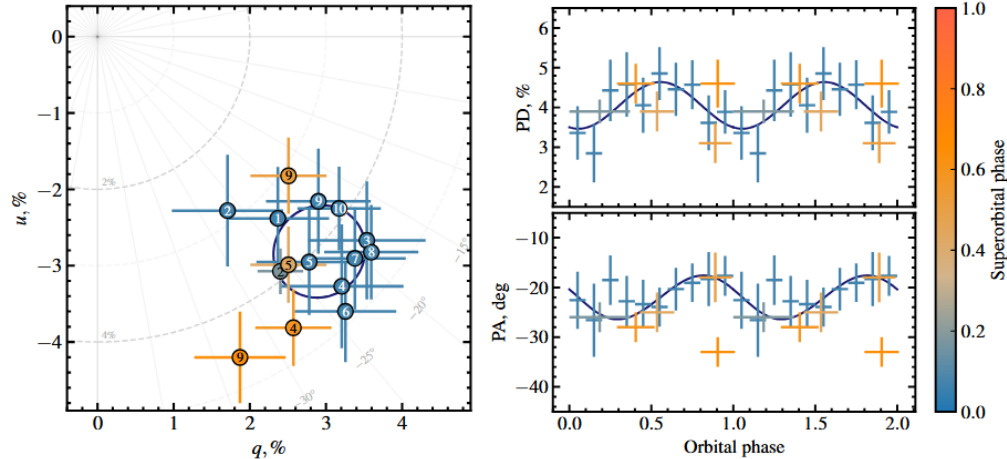
Hard X-ray polarimetry of Cyg X-1



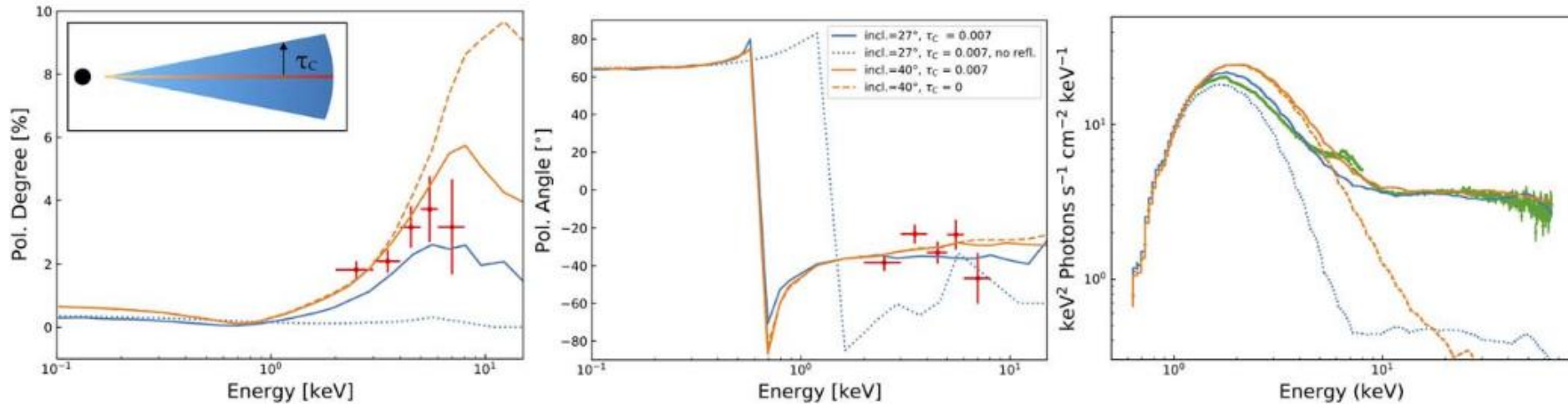
Cyg X-1 outflowing corona?



- Polarisation of 4% can be obtained with $i = 30^\circ$ 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)



Cyg X-1 – spectro-polarimetric modelling

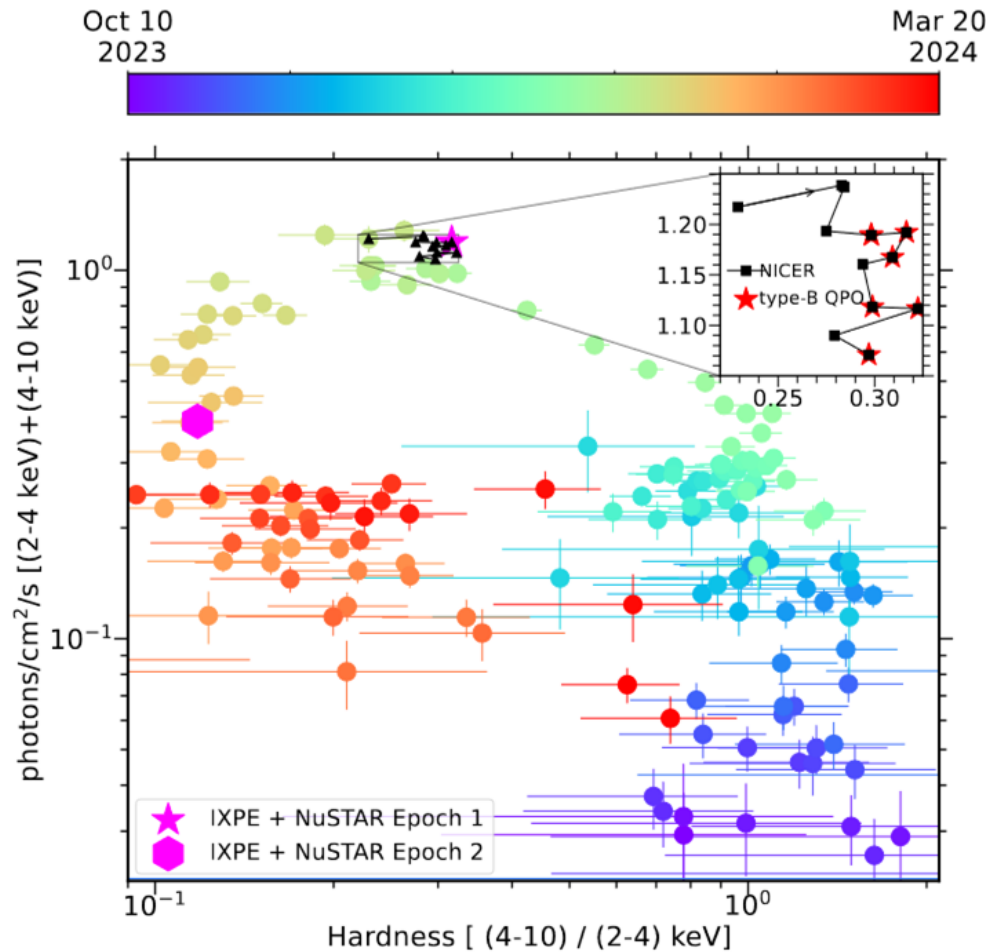
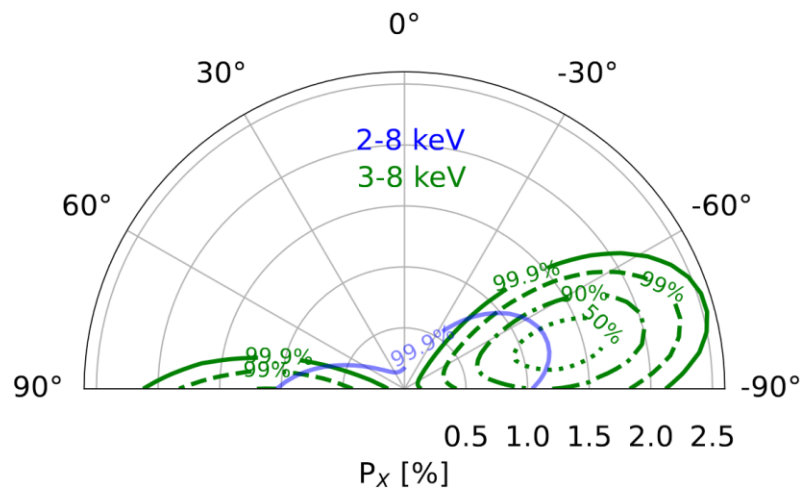


- kerrC simulations with a hot wedge-shaped corona
 - high spin $a = 0.998$
 - can explain polarization as well as the measure spectrum

Steiner et. al (2024)

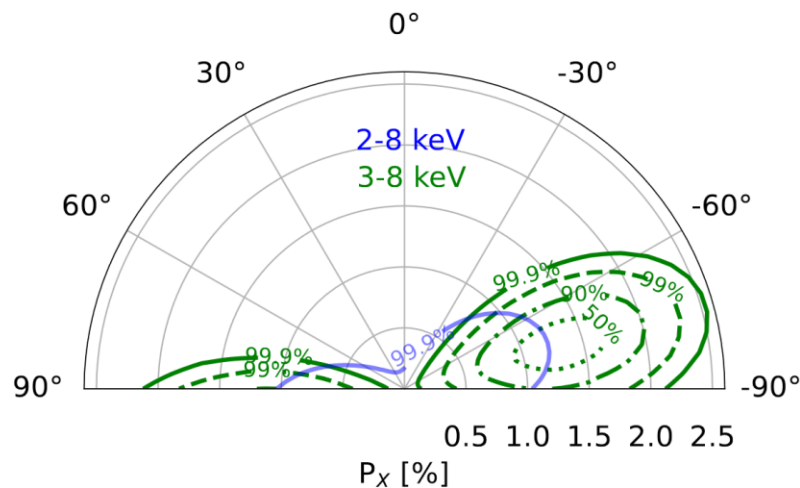
GX 339-4

- 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?

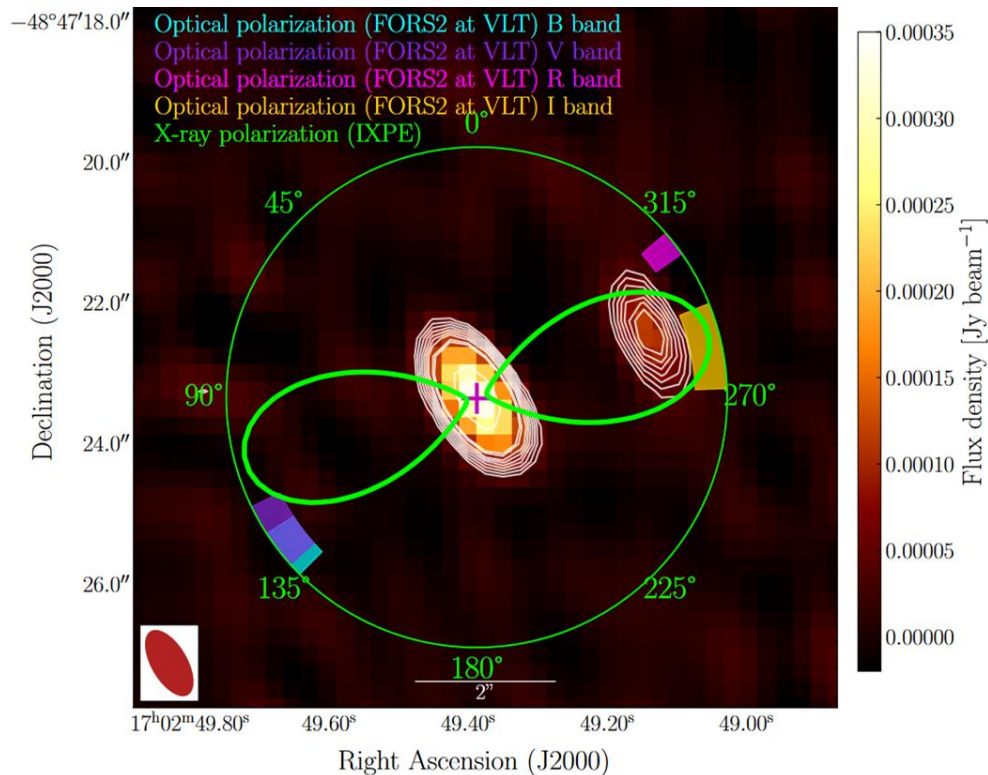


GX 339-4

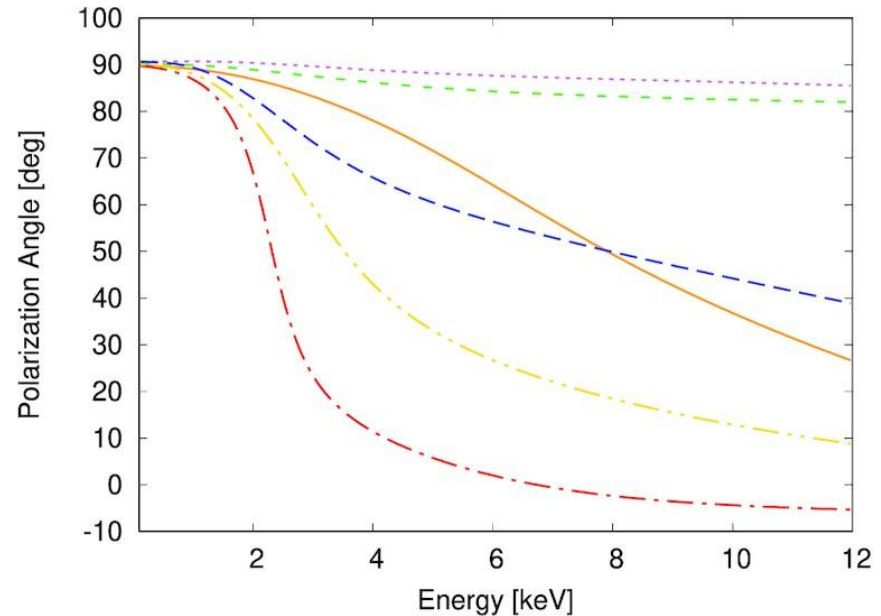
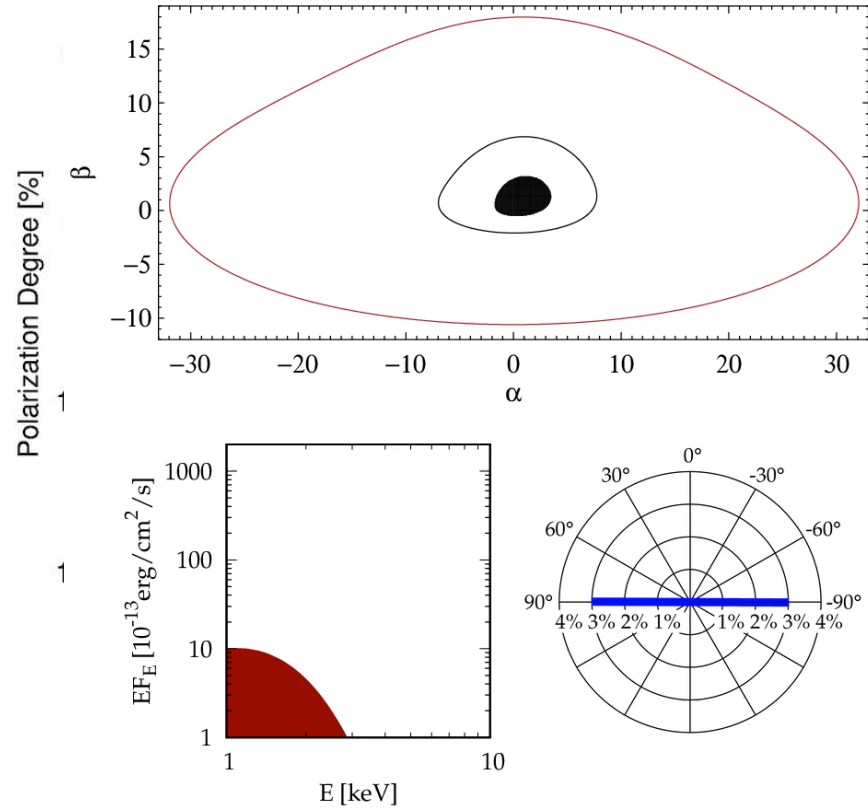
- in the soft/intermediate state in 3-8 keV: **PD = 1.3 ± 0.3 %** (Mastroserio+25)
 - in 2-8 keV only an upper limit
 - depolarization by perpendicularly-oriented thermal component?



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



X-ray polarization constraints on BH spin – PA rotation



(b)

Mikušincová+23