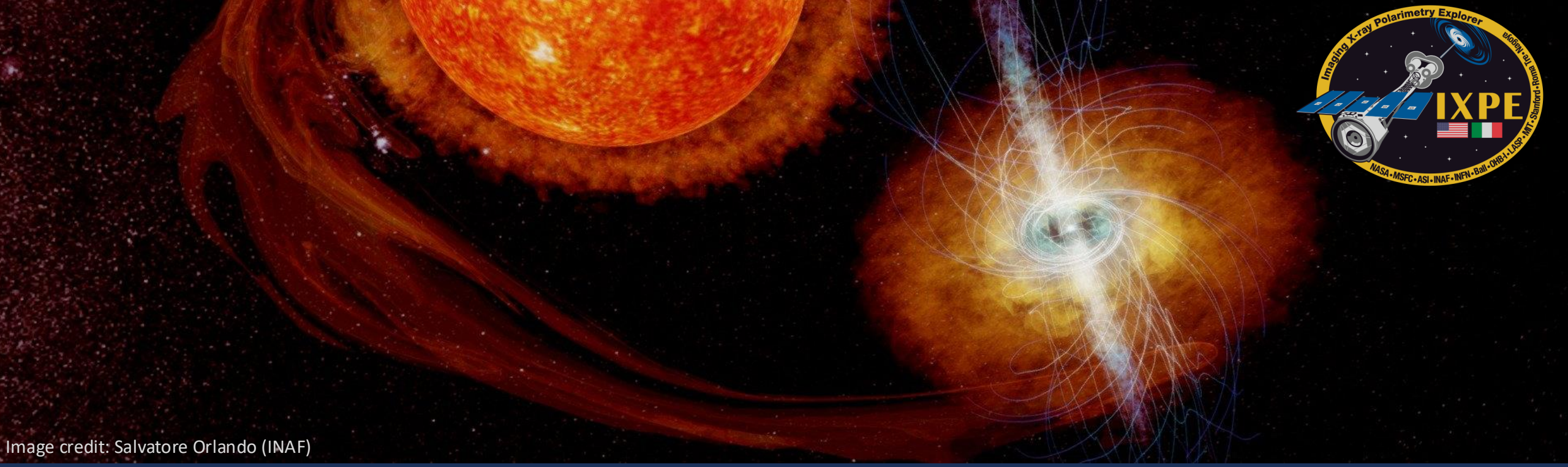
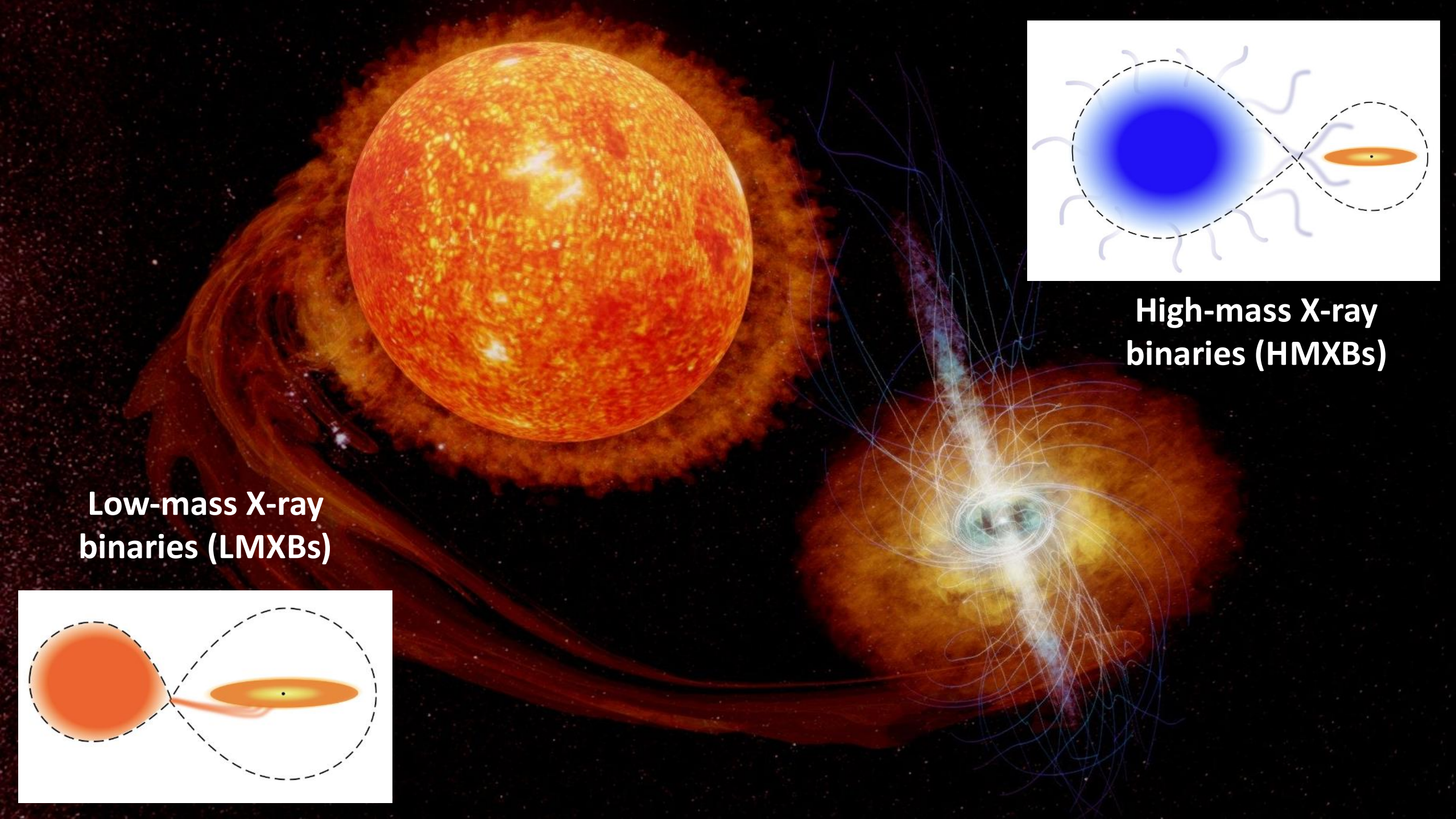


Image credit: Salvatore Orlando (INAF)

X-ray Polarization of Stellar Black Holes

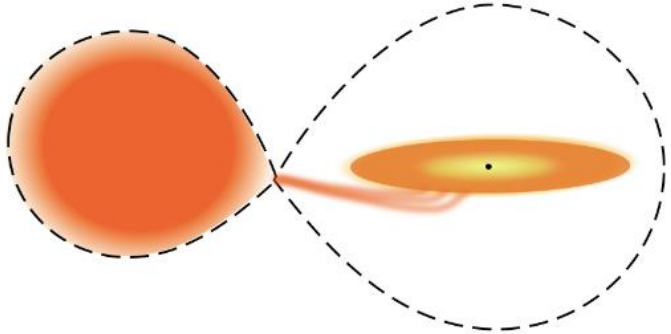
Nicole Rodriguez Cavero
Washington University in St. Louis

Frontiers in X-ray Polarimetry (FiXP) Academy 2025


High-mass X-ray binaries (HMXBs)
Low-mass X-ray binaries (LMXBs)

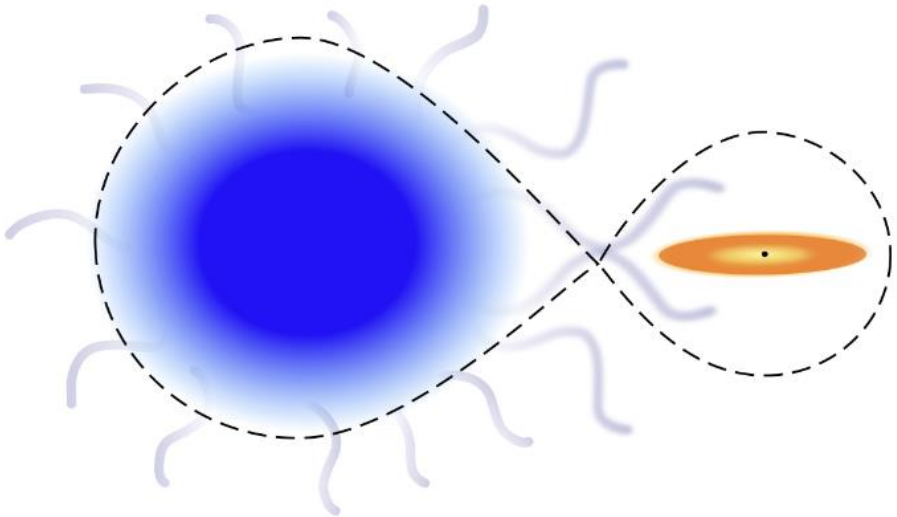
Stellar-Mass Black Holes

Low-mass X-ray binaries (LMXBs)



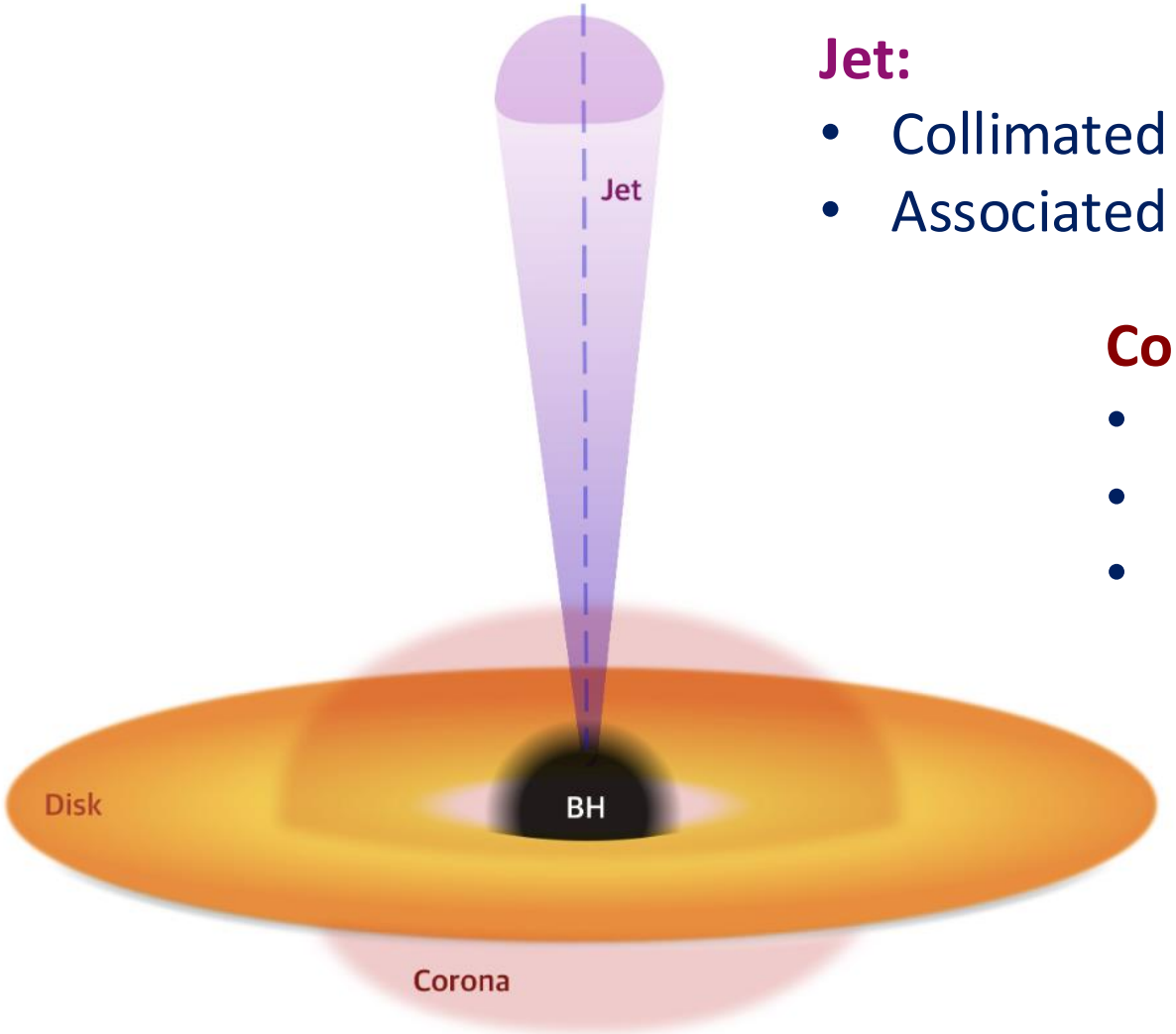
- Donor star $\mathrm{M} < 1 - 2M_{\odot}$
- K or M-type stars, sub giants, red giants
- Roche lobe overflow mass transfer

High-mass X-ray binaries (HMXBs)



- Donor star $\mathrm{M} > 10M_{\odot}$
- O or B-type massive stars, supergiants
- Stellar wind accretion

Stellar-Mass Black Holes



Jet:

- Collimated ionized plasma outflows
- Associated with BH spin-axis

Corona:

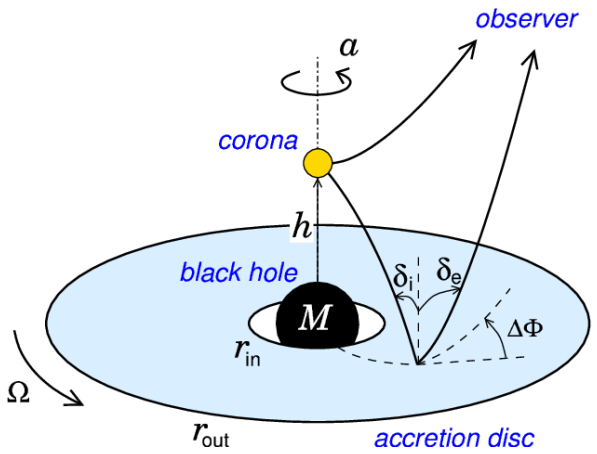
- Geometrically thick, optically thin
- $50 - 100$ keV, $0.1 \leq \tau \leq 1$
- Inverse Compton scattering processes

Disk:

- Shakura-Sunyaev thin disk at $\dot{M} < \dot{M}_{Edd}$
- Inner temperatures of $10^7\ K$
- Thermal-viscous instabilities

Corona Geometries

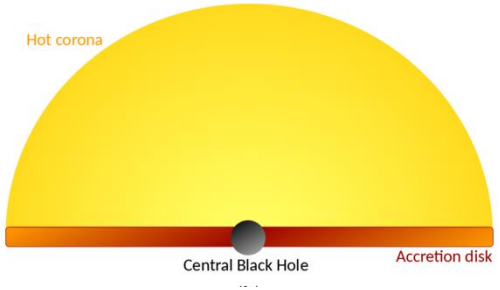
Lamp-post Geometry



Caballero-Garcia et. al (2017)

Sandwiching Slab Geometry

Spherical Geometry

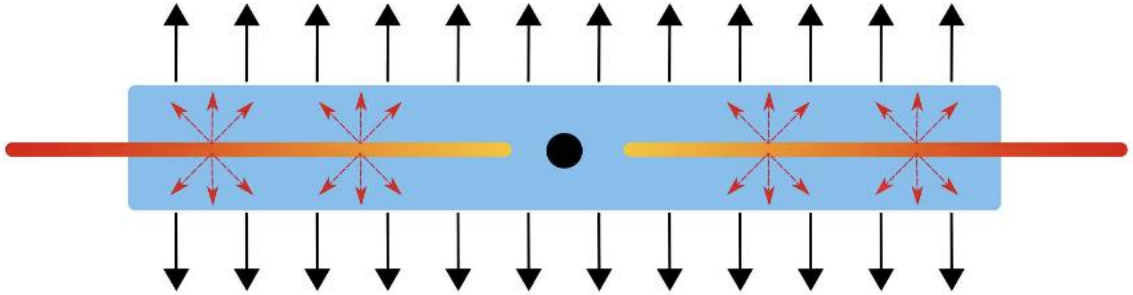


Marinucci et. al (2018)

Truncated Disk— Hot Inner Flow Geometry

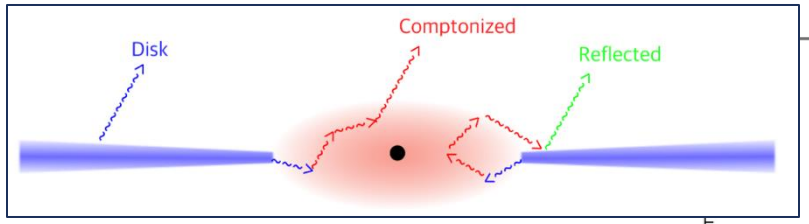
Nampalliwar & Bambi (2018)

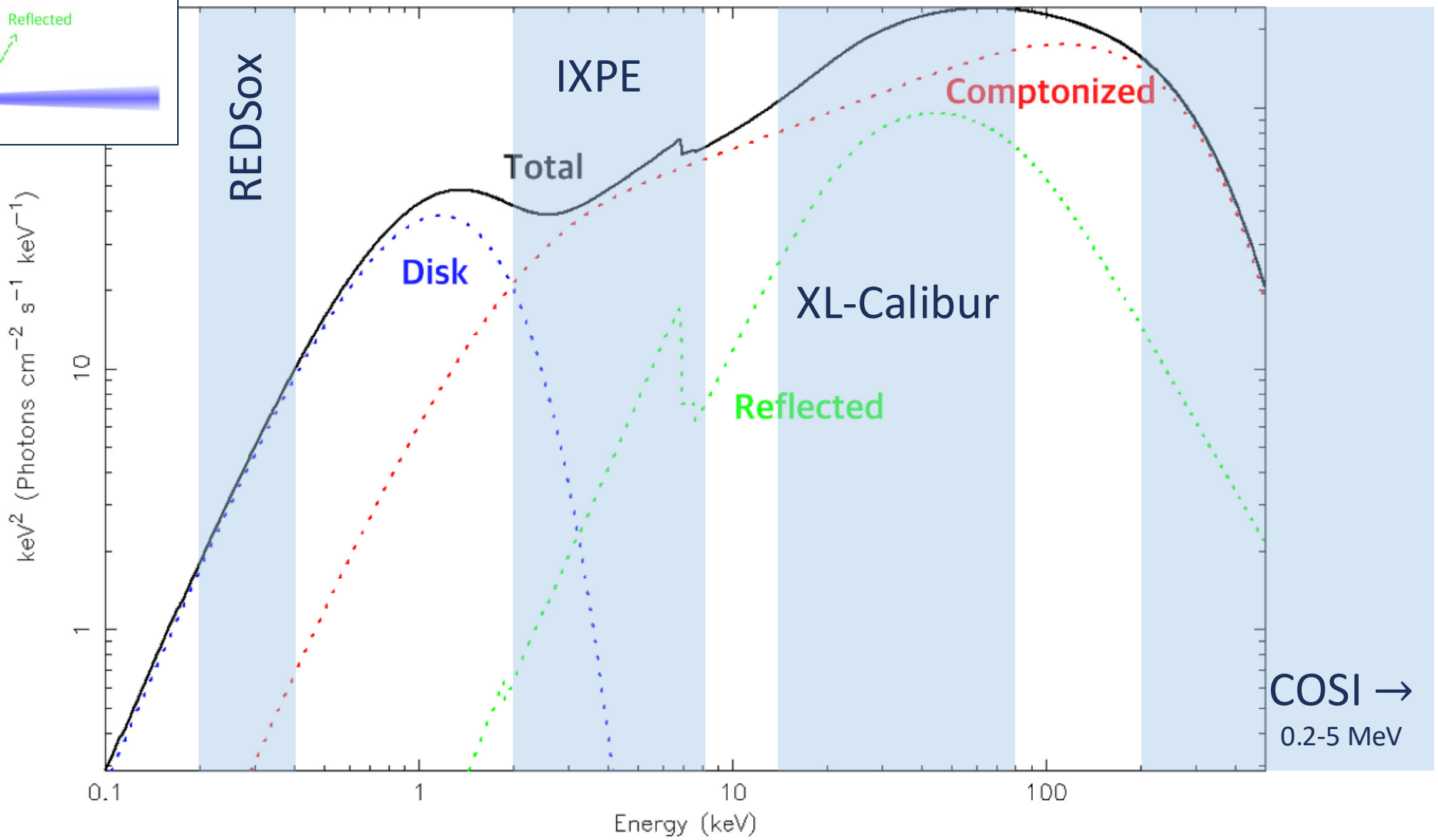
Outflowing corona



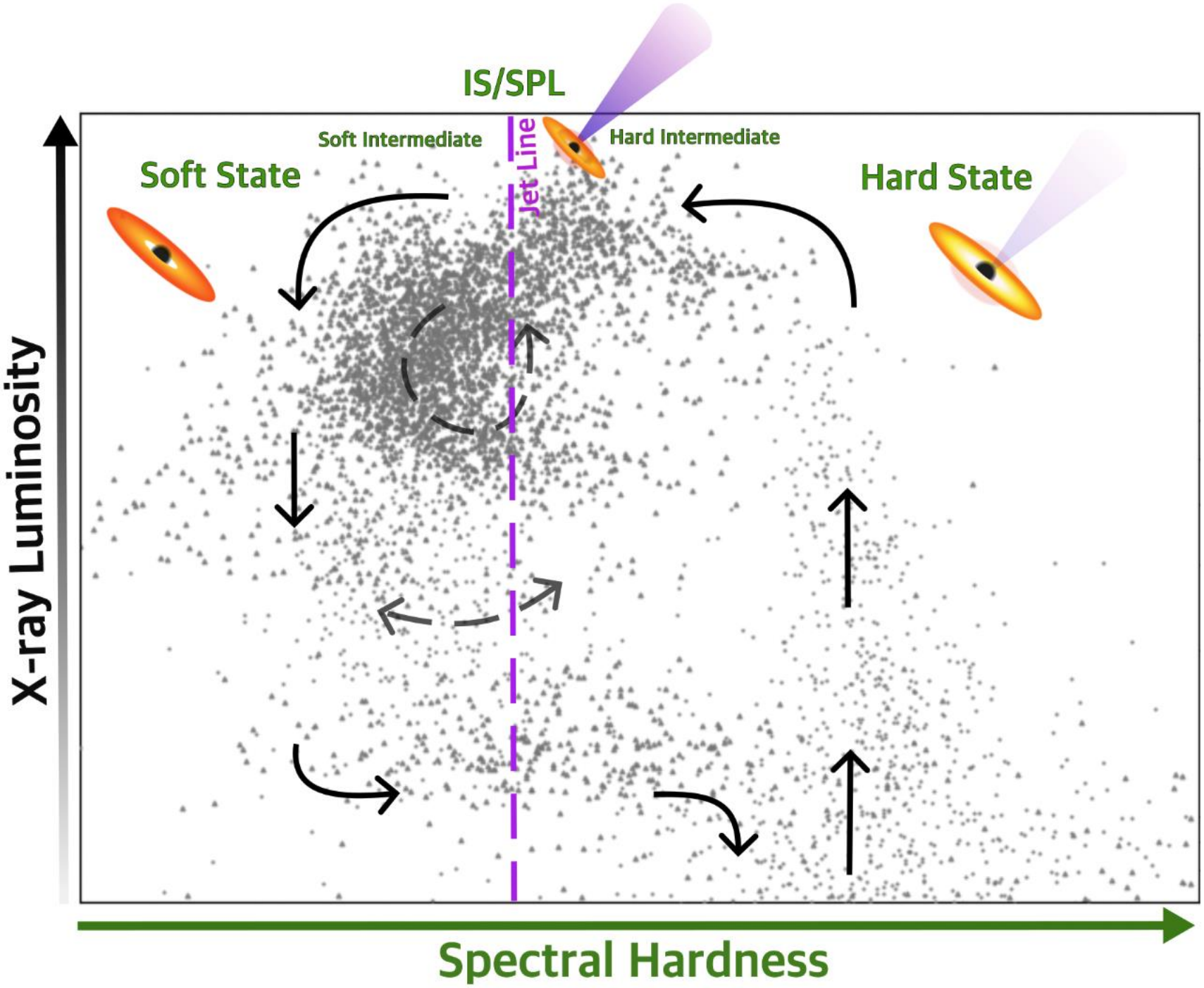
Poutanen et. al (2023)

BH X-Ray Energy Spectra



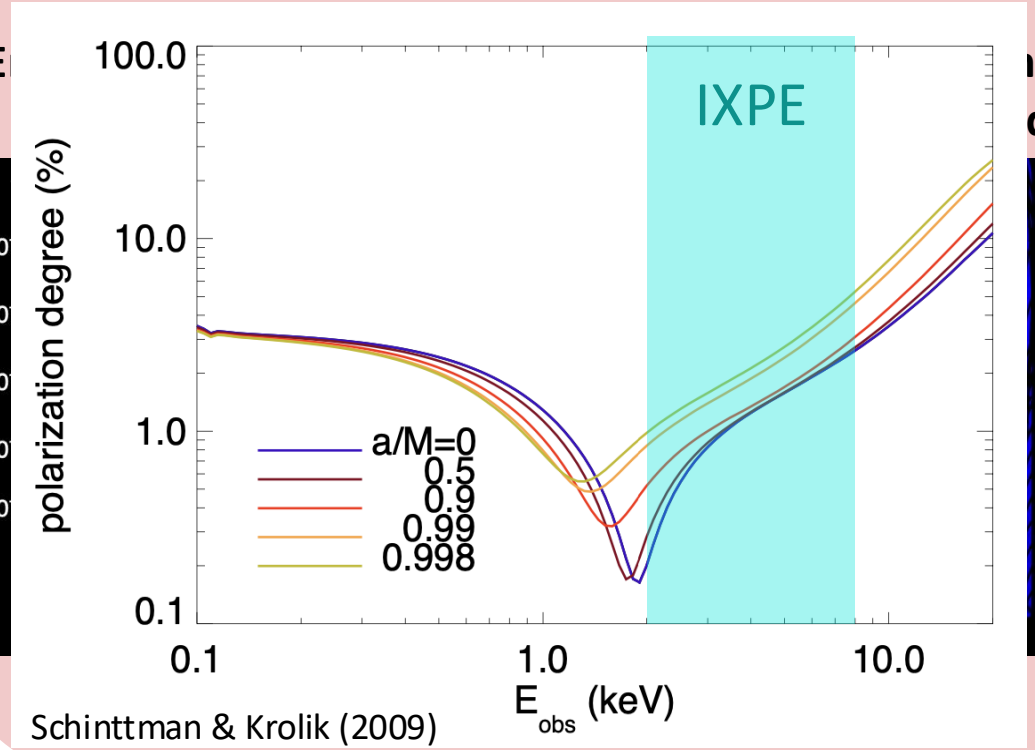


Spectral States



Polarization in Spectral States

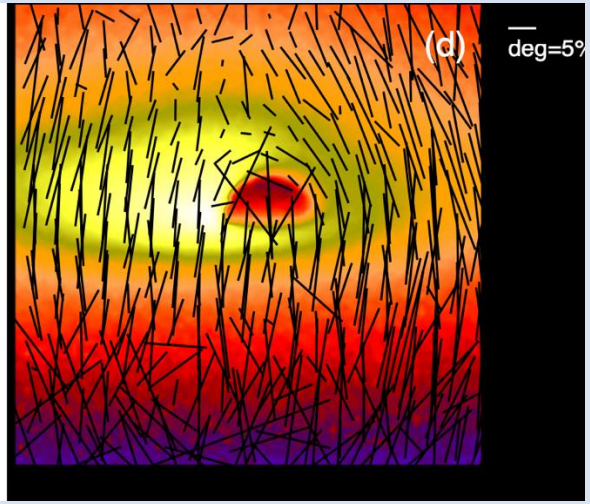
Soft State

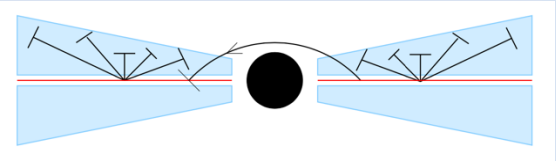


Schinttman & Krolik (2009)

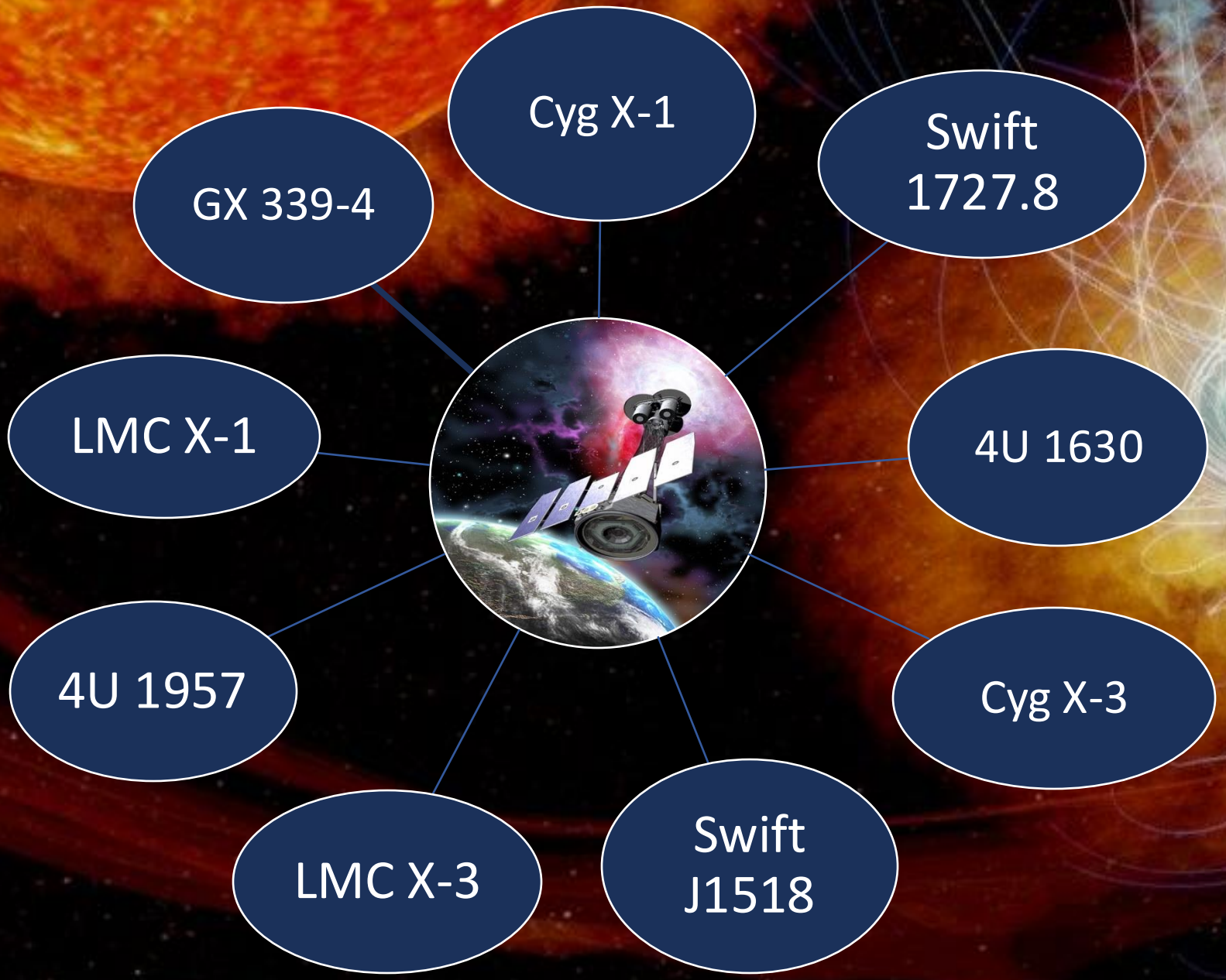
Hard State

Radiation scattered multiple times in the corona





Black Hole Observations



Black Holes Observed with IXPE

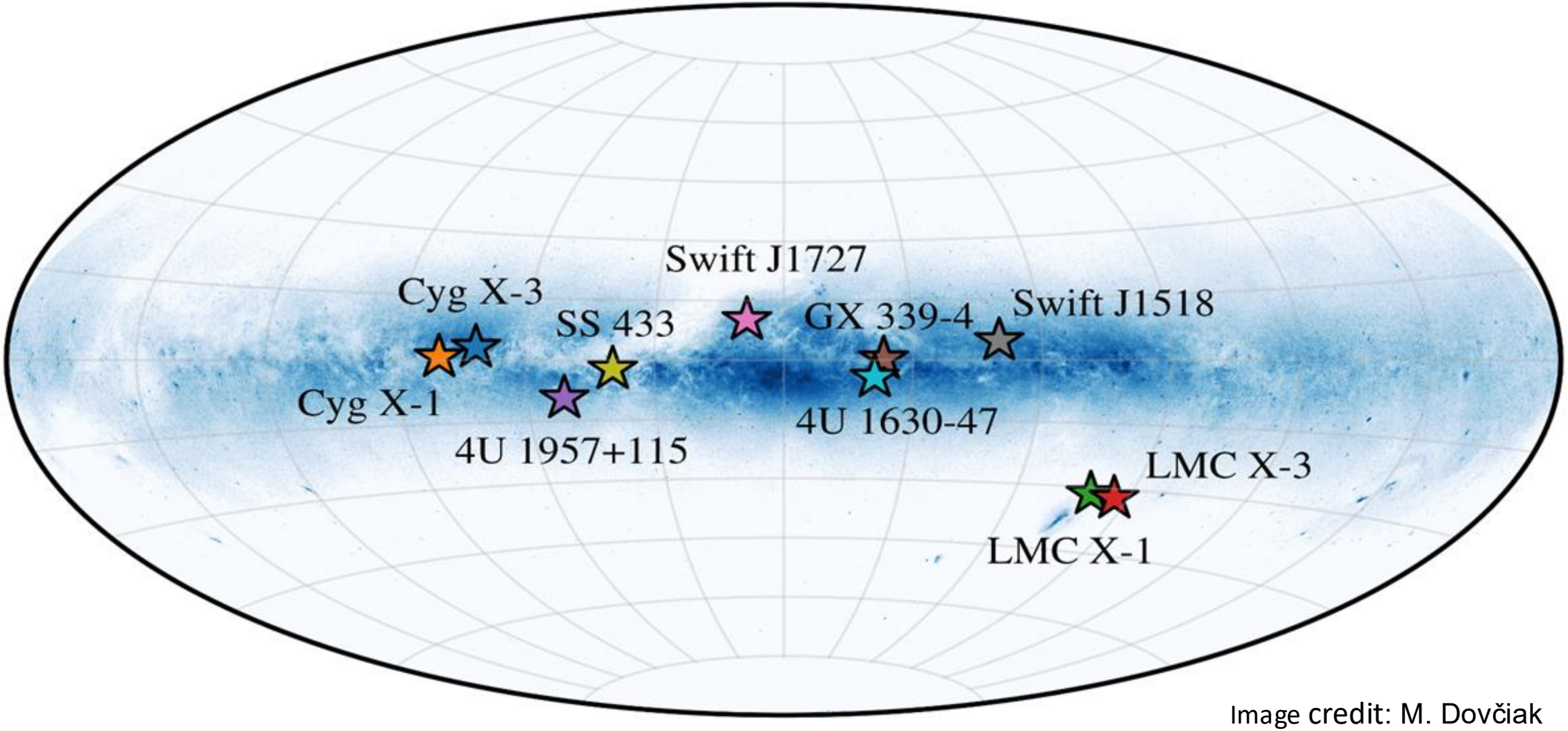
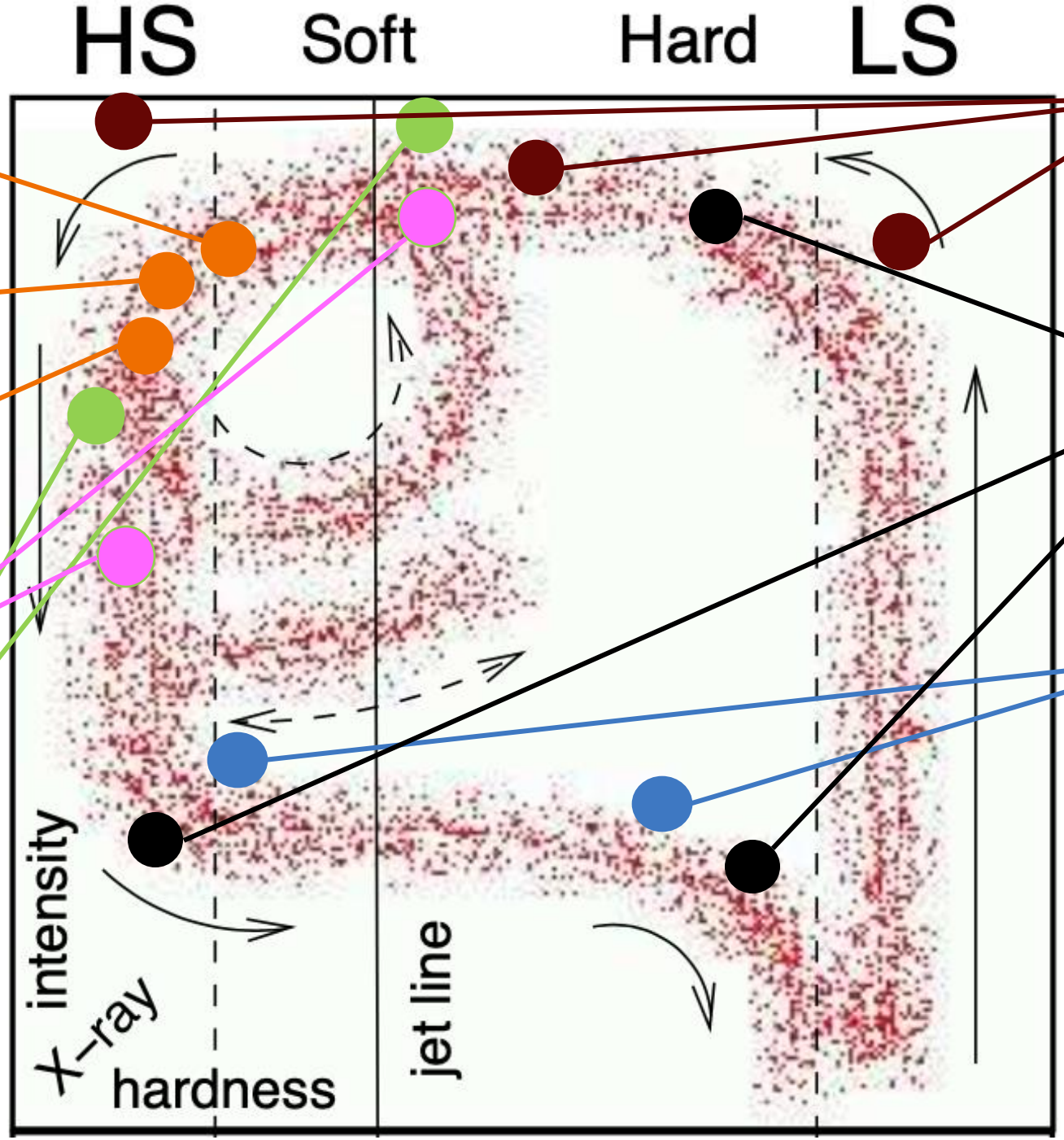


Image credit: M. Dovčiak

Spectral States



4U 1957+115

LMC X-1

LMC X-3

GX 339-4

4U 1630-47

Cygnus X-3

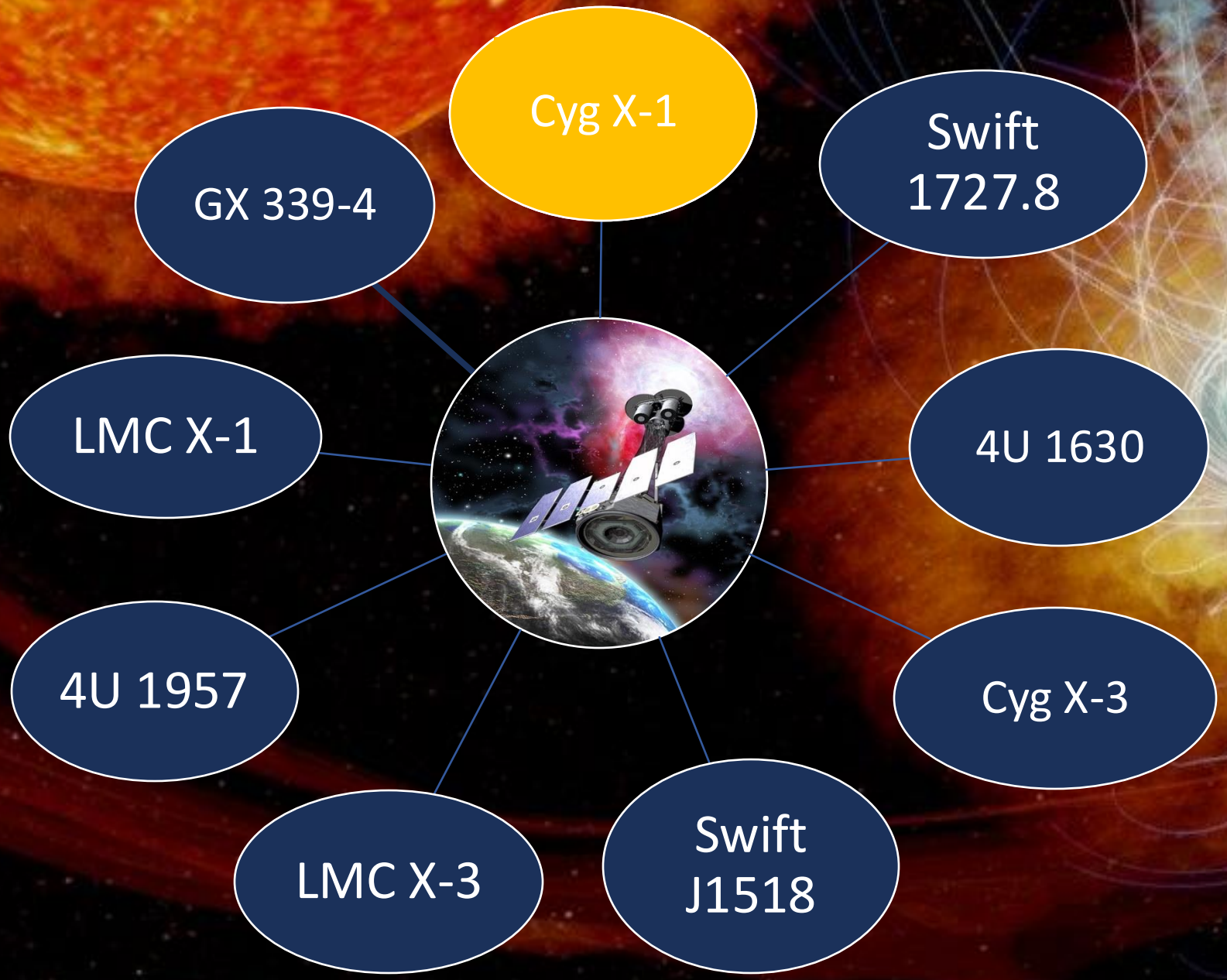
Swift J1727.8

Cygnus X-1

Disclaimer: Luminosity and hardness not drawn to scale

Fender et al. (2004)

Black Hole Observations

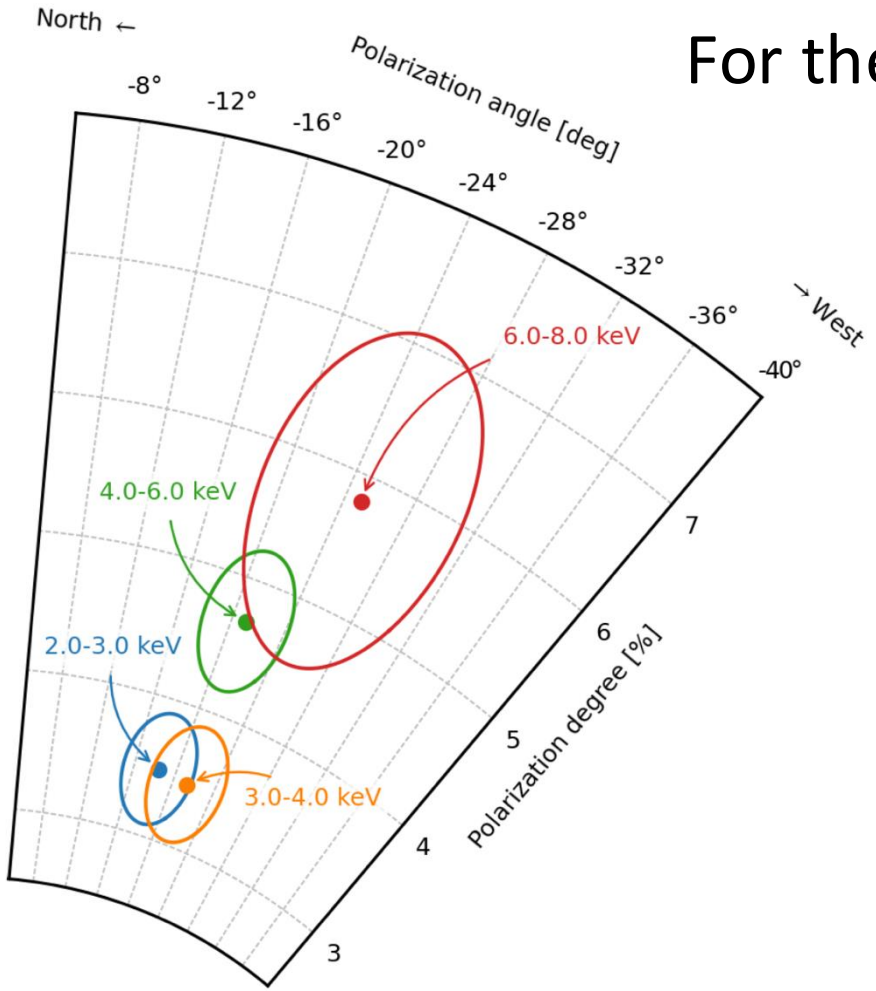


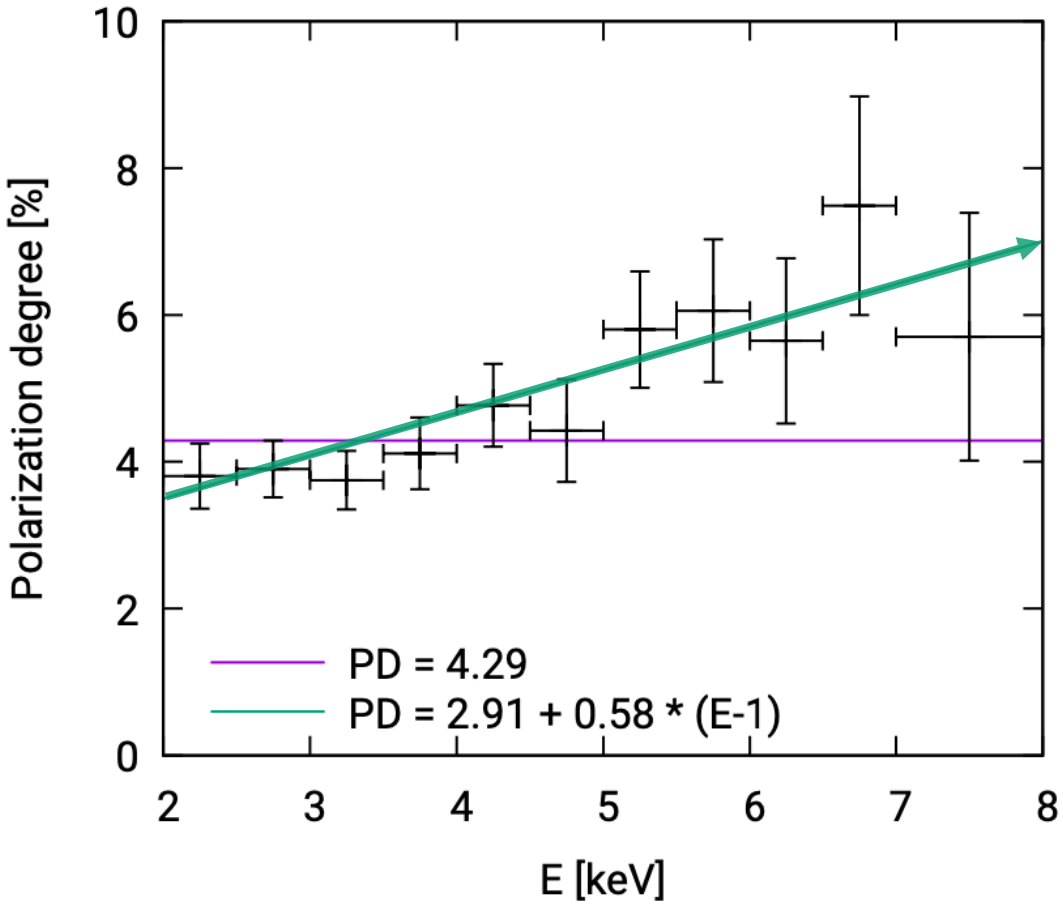
Cygnus X-1: Hard State

For the $2-8\ keV$ IXPE band ($>\mathbf{20\sigma}$): $\sim 242\ ks$

PD= $\mathbf{4.0 \pm 0.2}\%$, PA= $\mathbf{-20°.7 \pm 1°.4}$

Krawczynski+2022





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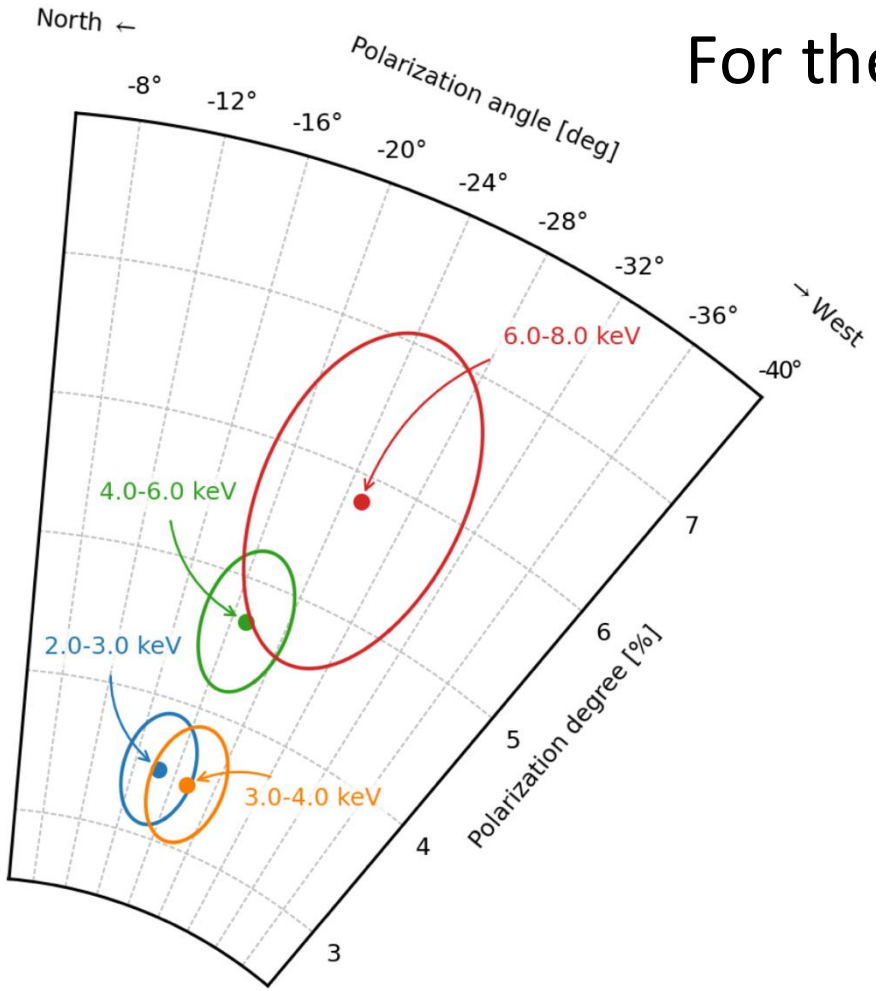
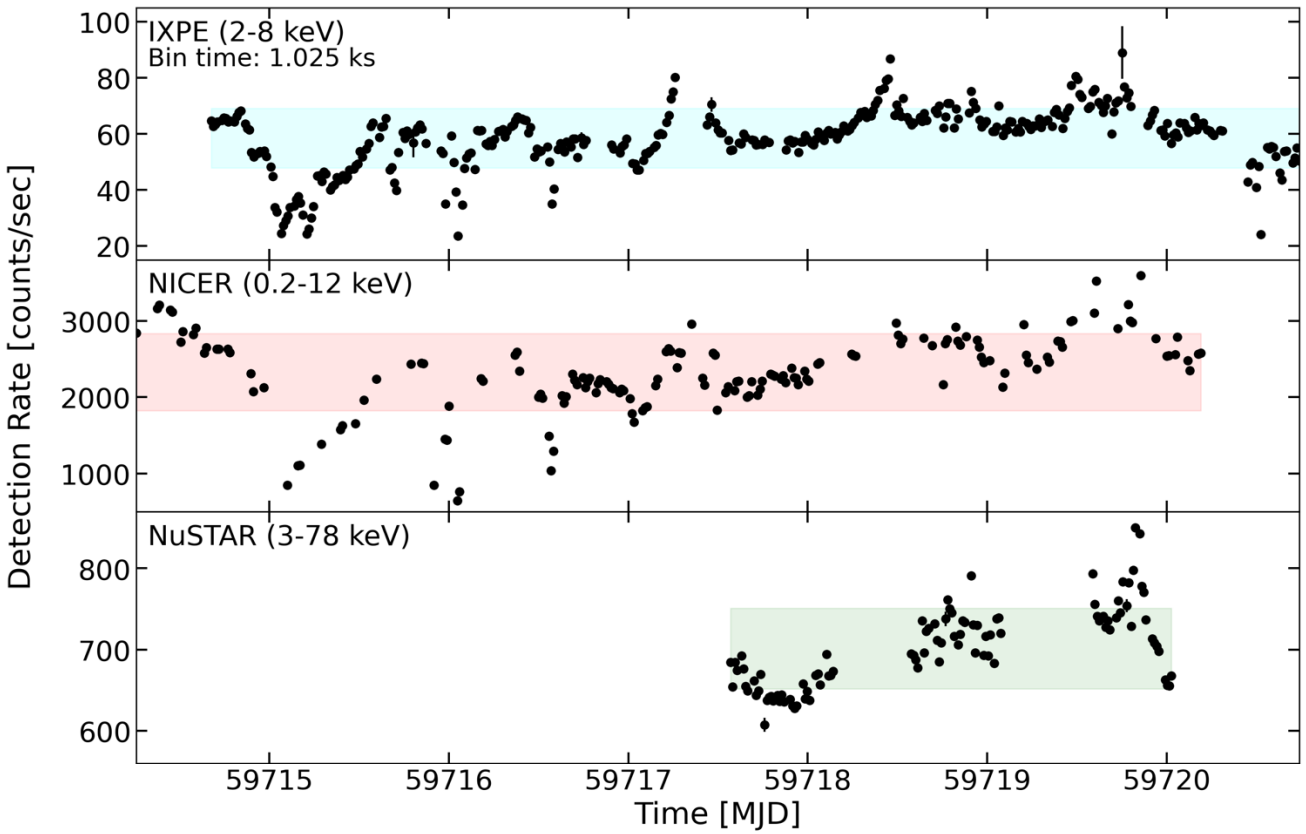




Cygnus X-1: Hard State

Krawczynski+2022

Reflected coronal emission

MBPO * TBABS * (DISKBB + XILLVERCP + RELXILLCP + NTHCOMP)

Cross-calibration model

Thermal disk emission

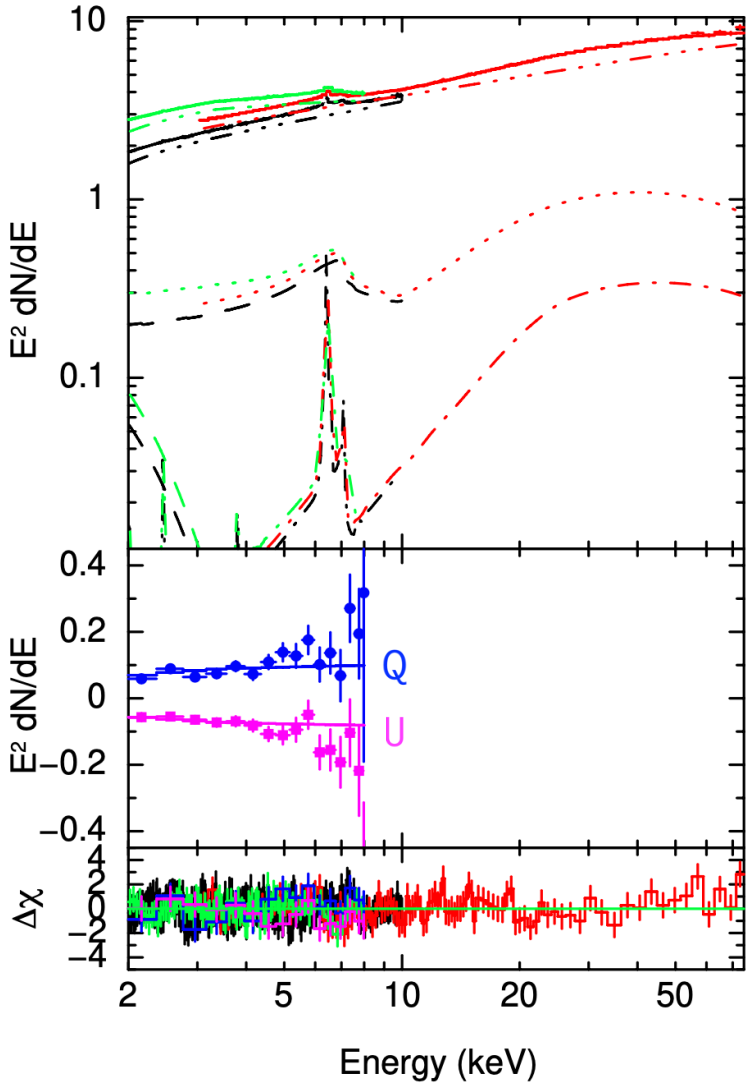
~0.6% of the $2-8\ keV$ flux

~0.5% and ~10% of the $2-8\ keV$ flux

Coronal power law

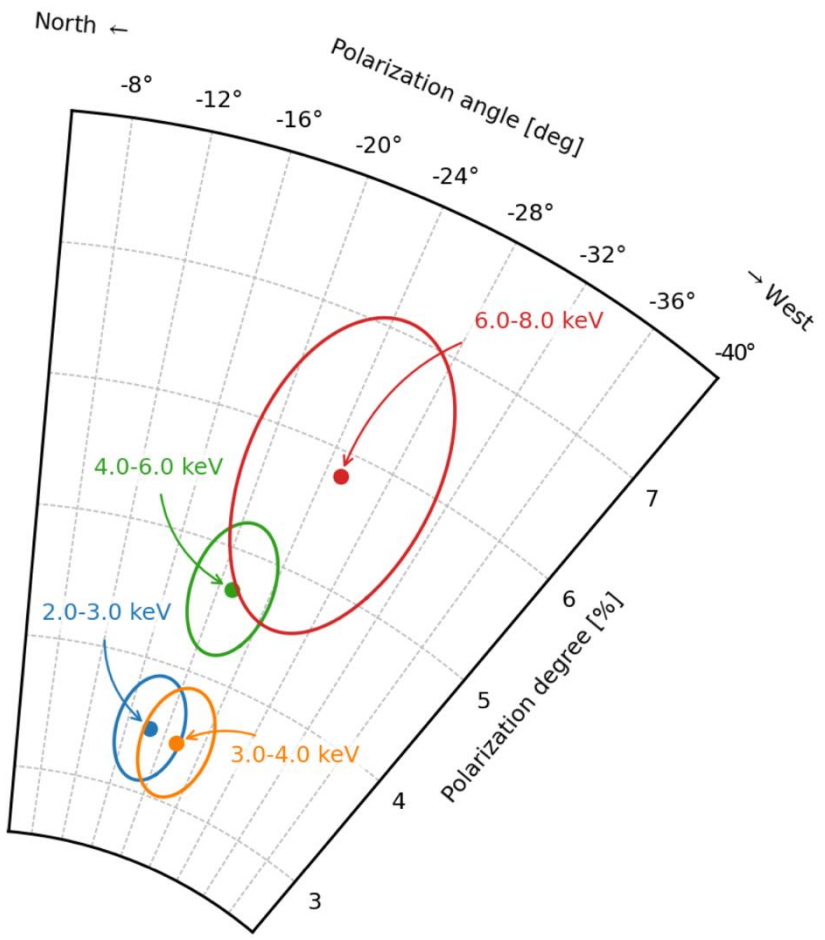
~90% of the $2-8\ keV$ flux

$$PD = 3.63 \pm 0.26\%$$
$$PA = -20°.5 \pm 2°.1$$
$$\chi^2/dof = 2380.4\ /\ 2415$$

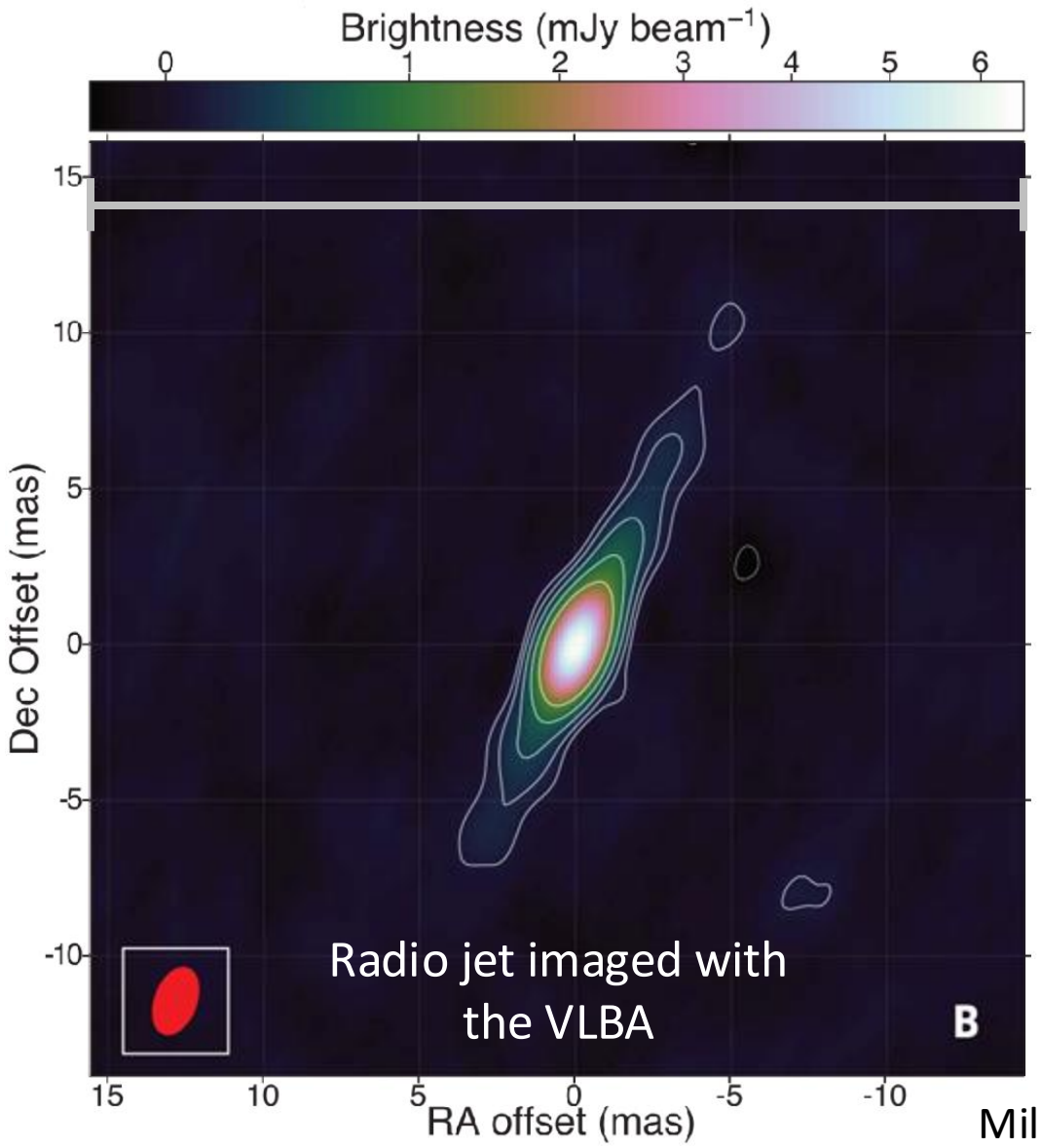


Cygnus X-1: Hard State

Krawczynski+2022



Krawczynski et. al (2022)

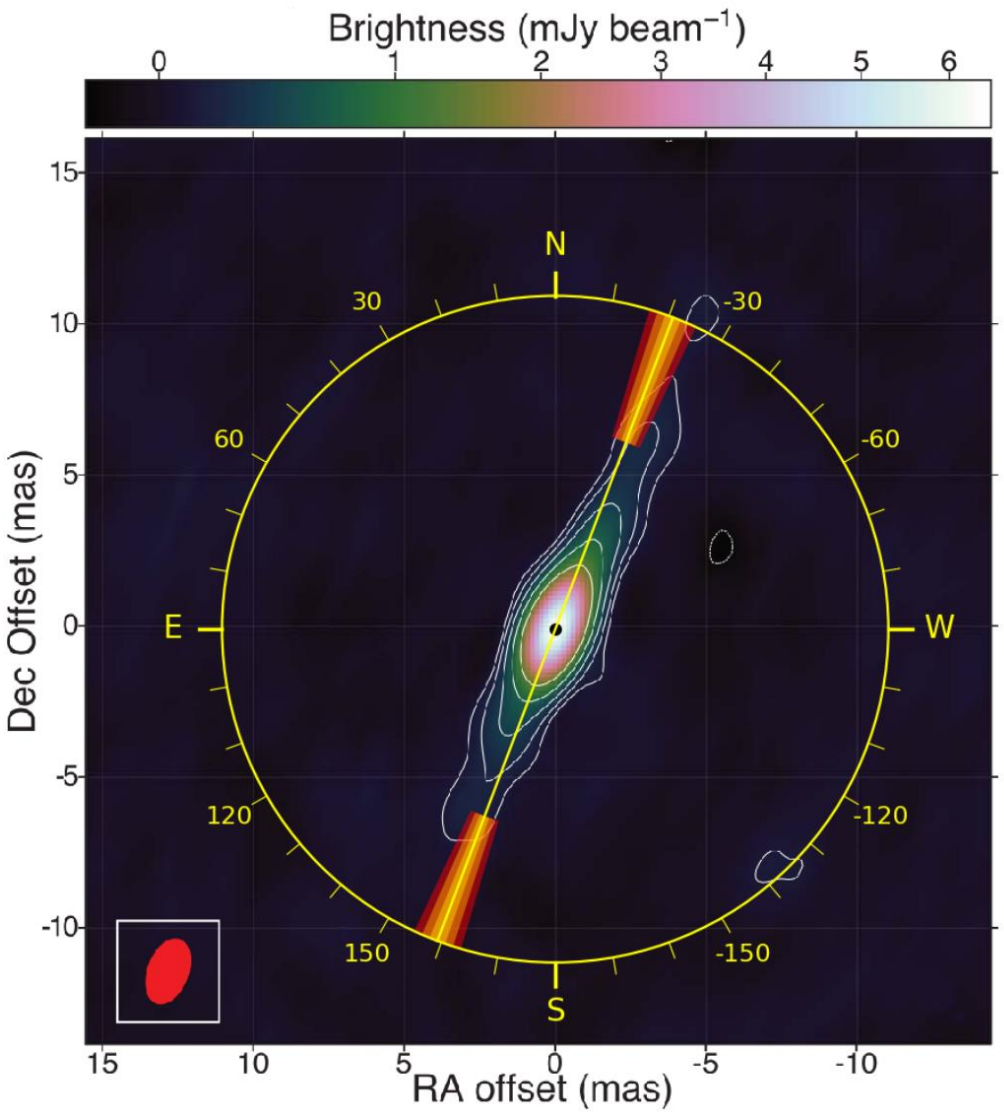


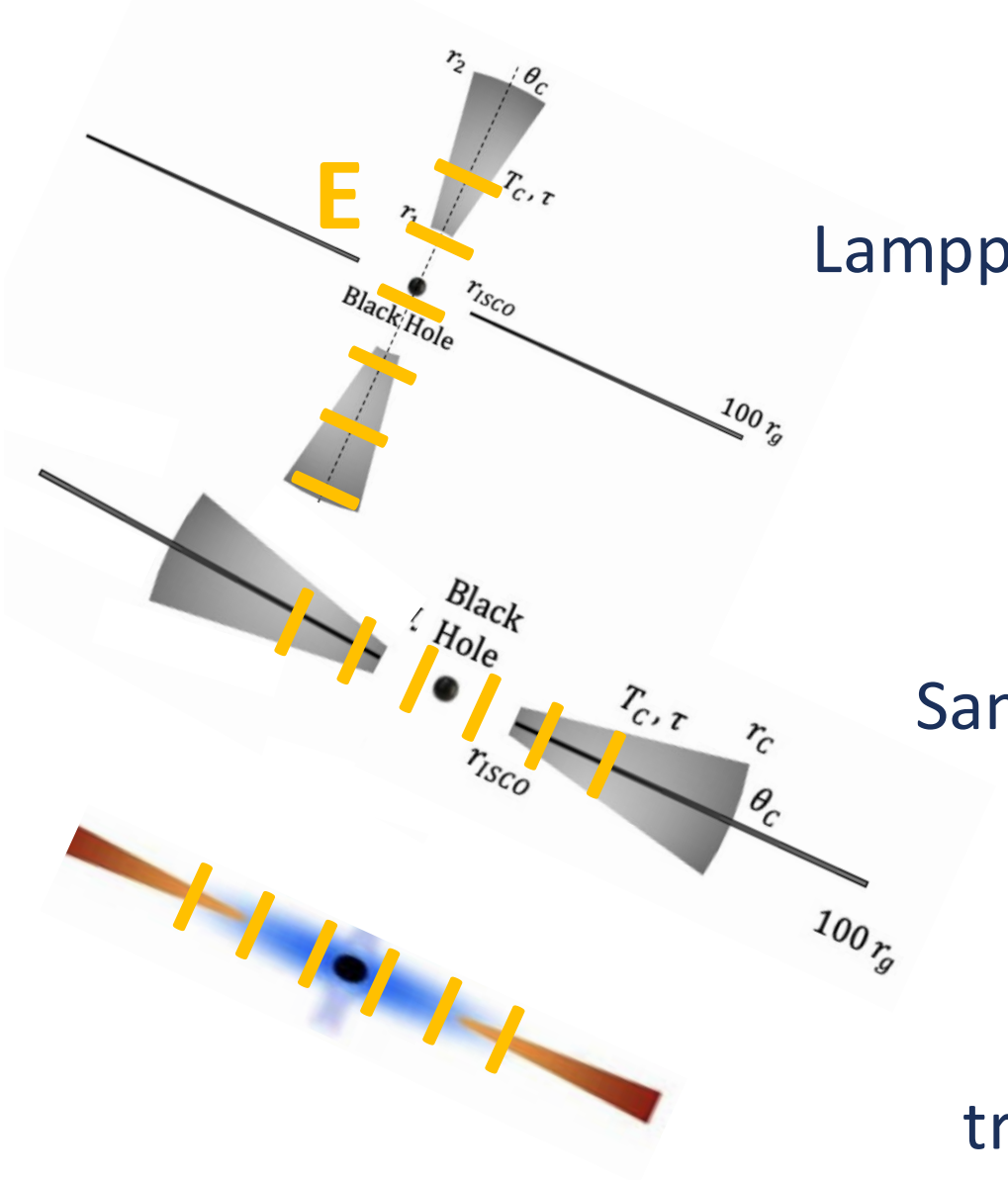
$10^{10} km$

Miller-Jones, *et al.* (2021)

Cygnus X-1: Hard State

Krawczynski+2022





Lamppost ✗

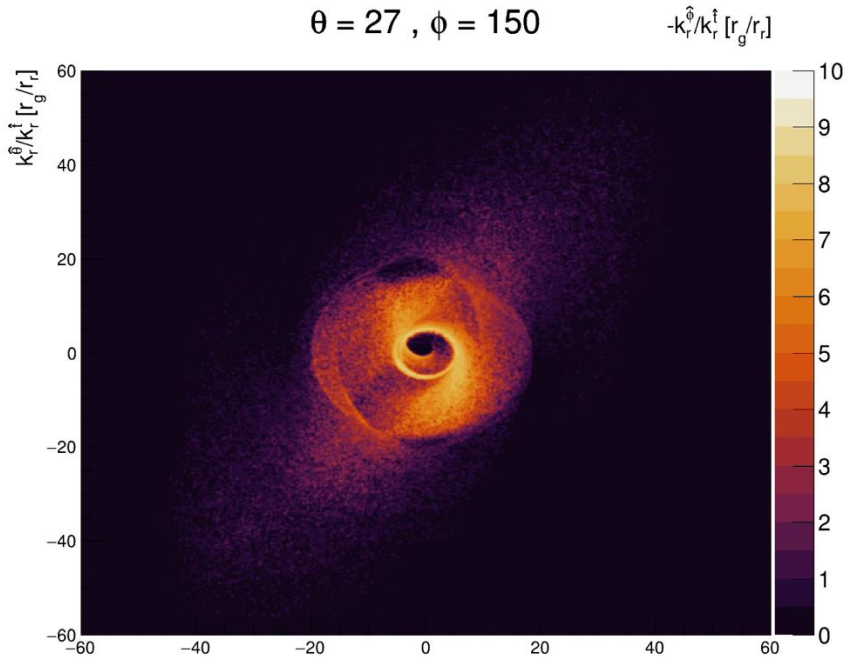
Sandwich ✓

Hot inner flow—truncated disk ✓

Cygnus X-1: Hard State

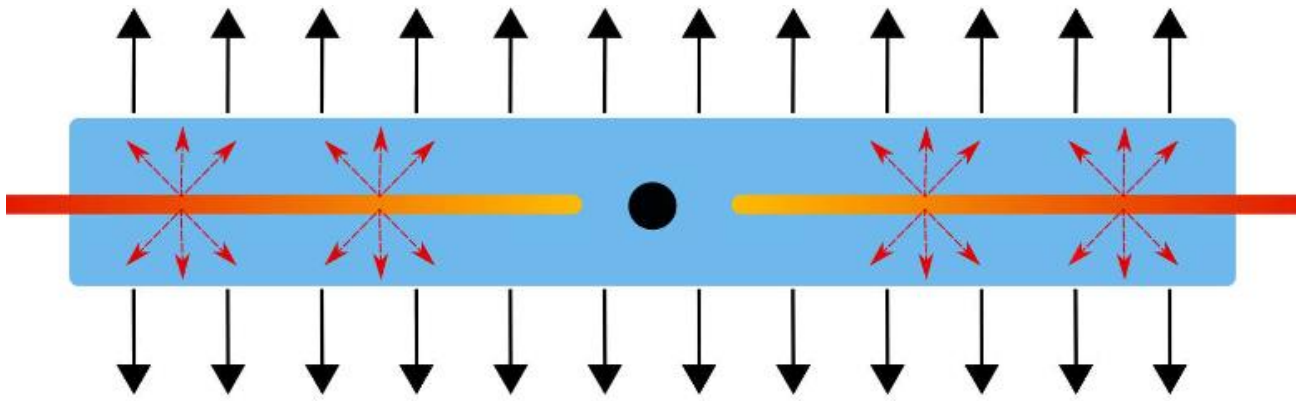
Higher than expected PD degree can be explained by:

- Inner Disk Inclination:



West+2023

- Outflowing Corona:



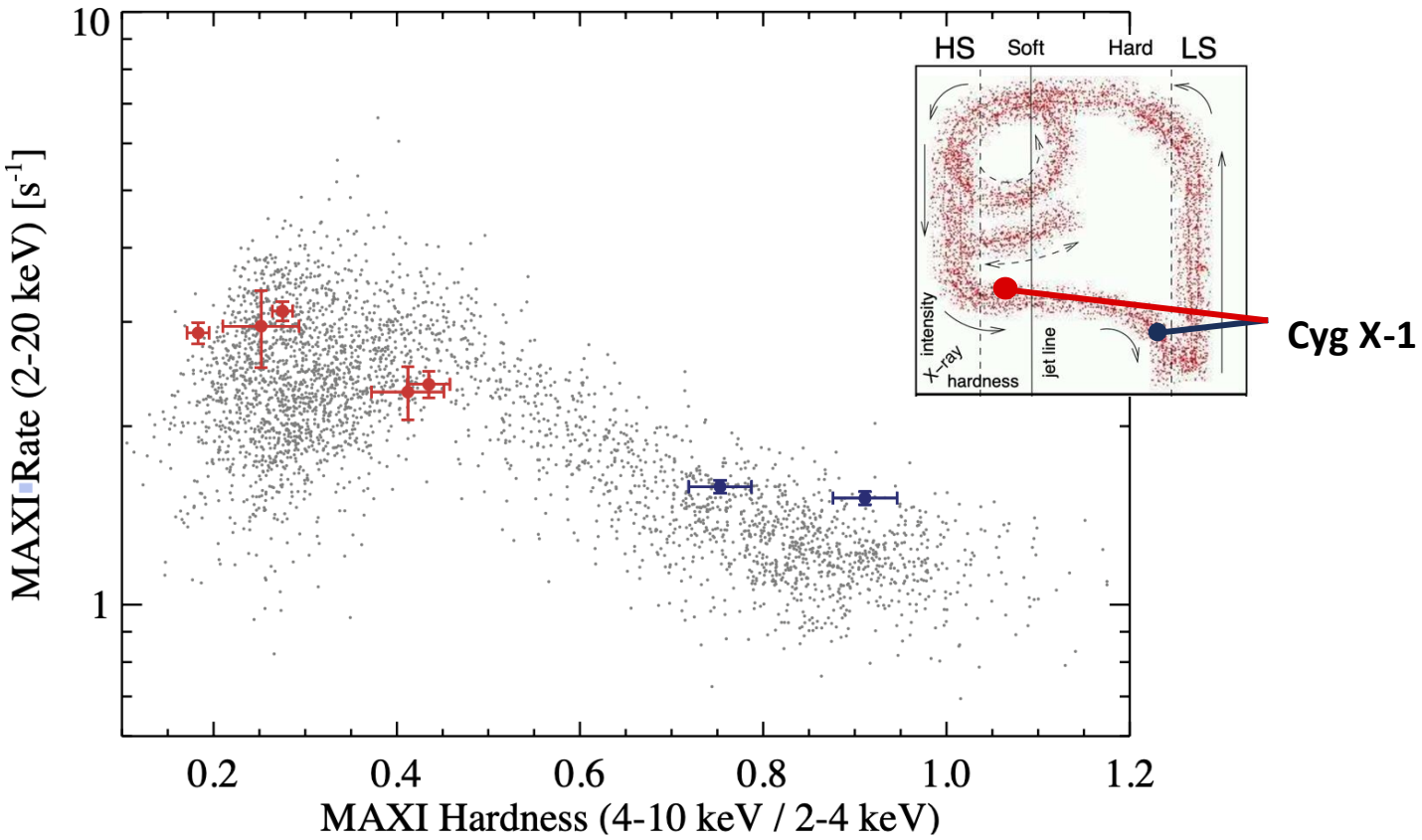
Poutanen+2023

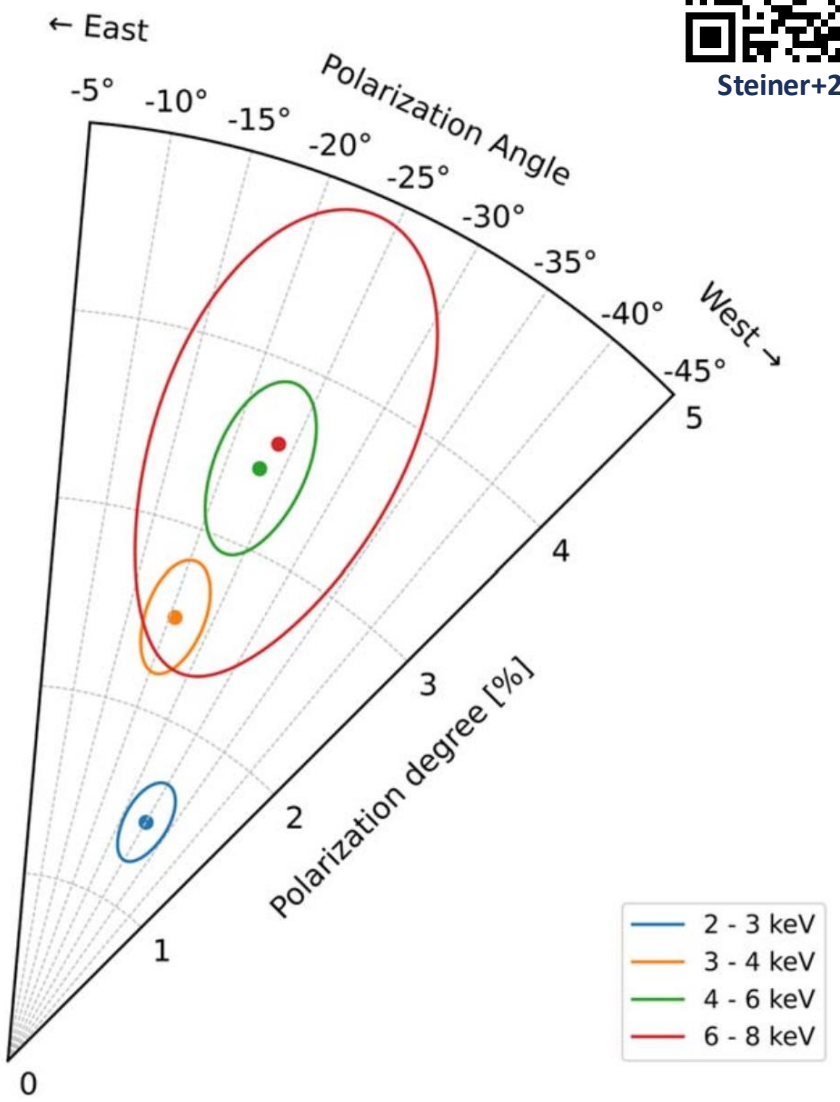
Cygnus X-1: Soft State

THE ASTROPHYSICAL JOURNAL LETTERS
Steiner+2024

For the $2-8\ keV$ IXPE band ($>\mathbf{15\sigma}$): $\sim 140\ ks$

PD= $\mathbf{1.99 \pm 0.13}\%$, PA= $\mathbf{-25°.7 \pm 1°.8}$

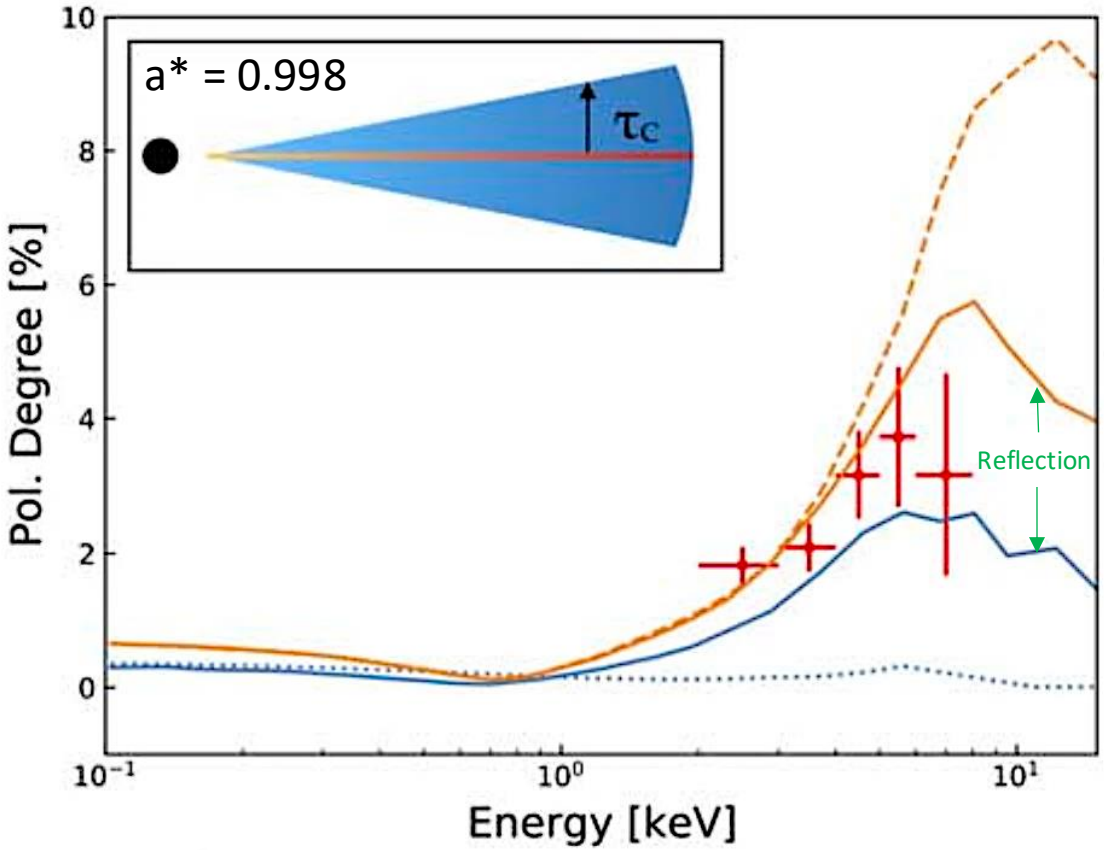


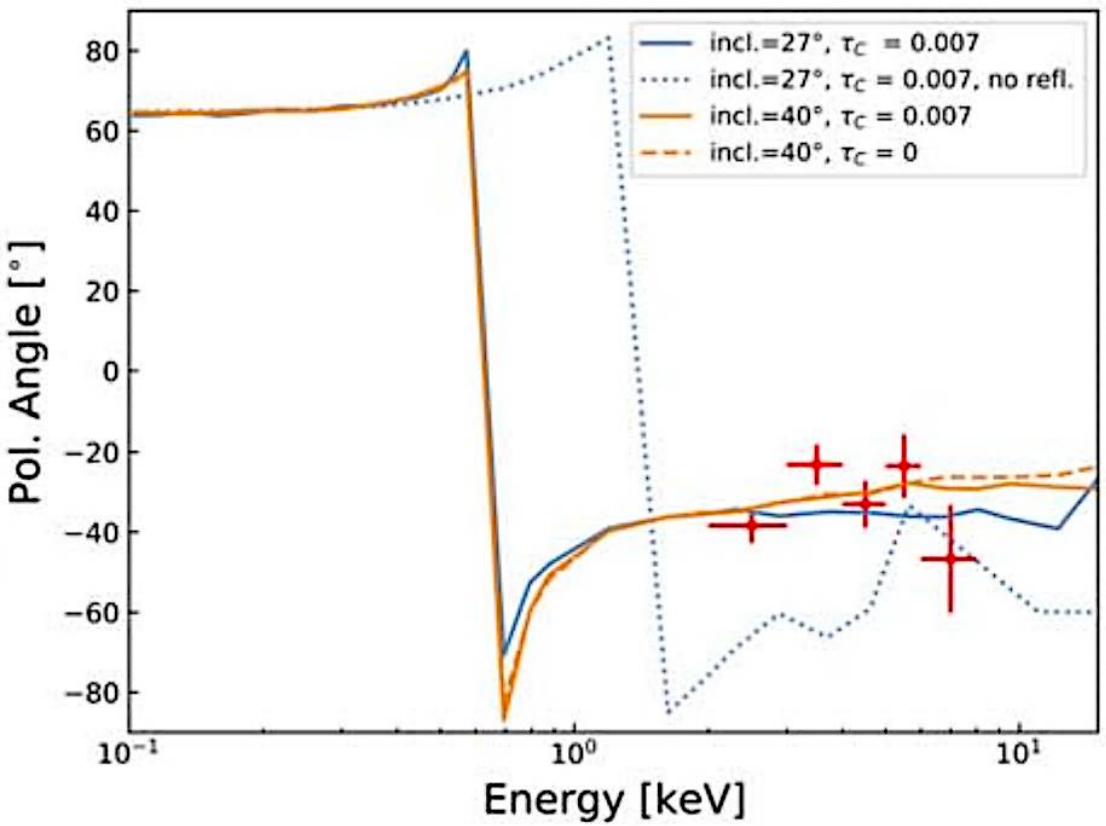


Cygnus X-1: Soft State

THE ASTROPHYSICAL JOURNAL LETTERS

Steiner+2024



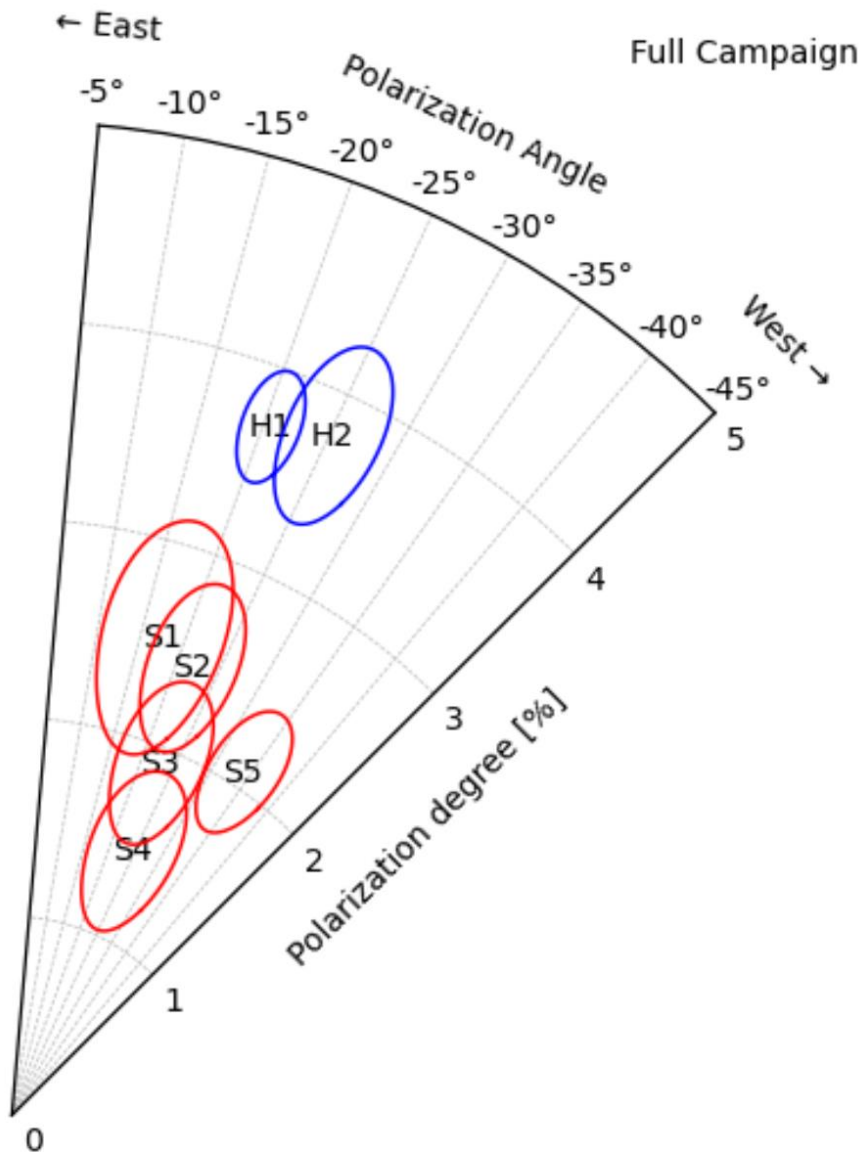


Retuning emission but no corona (no Comptonized reflection)

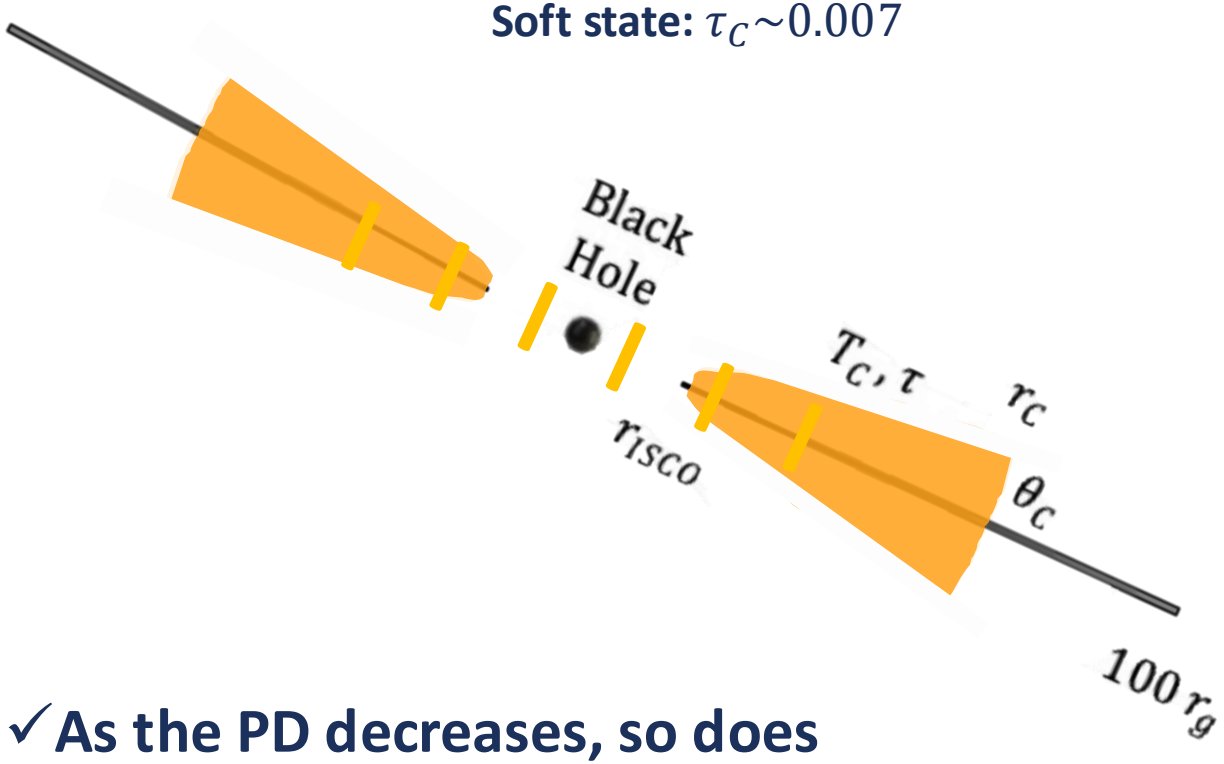
Only thermal, Removing both the coronal and returning emission

Cygnus X-1: Hard and Soft States

THE ASTROPHYSICAL JOURNAL LETTERS
Steiner+2024

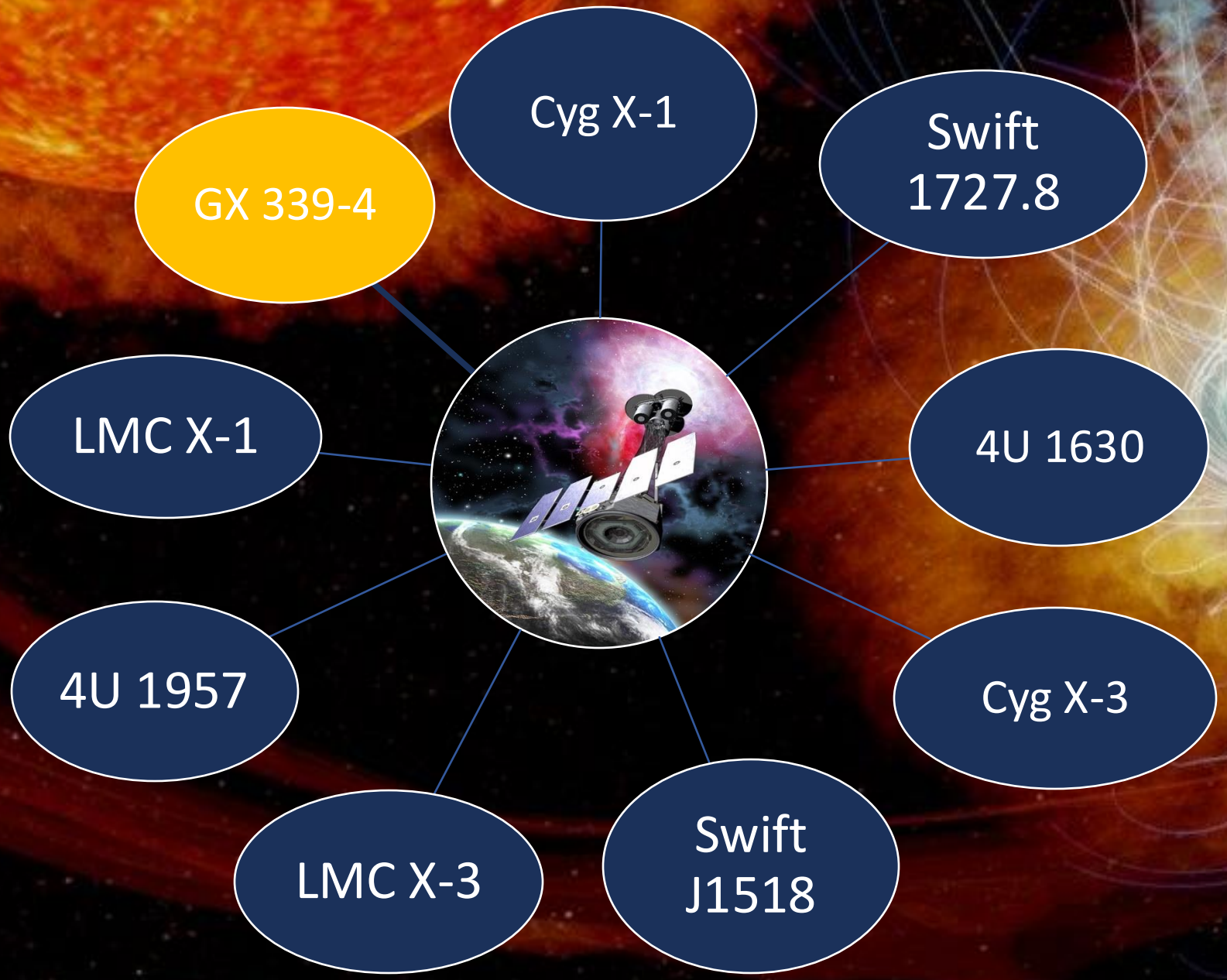


Hard state: $\tau_C \sim 0.35$
Soft state: $\tau_C \sim 0.007$



✓ **As the PD decreases, so does the corresponding τ_C**

Black Hole Observations



GX 339-4 Observations

THE ASTROPHYSICAL JOURNAL LETTERS

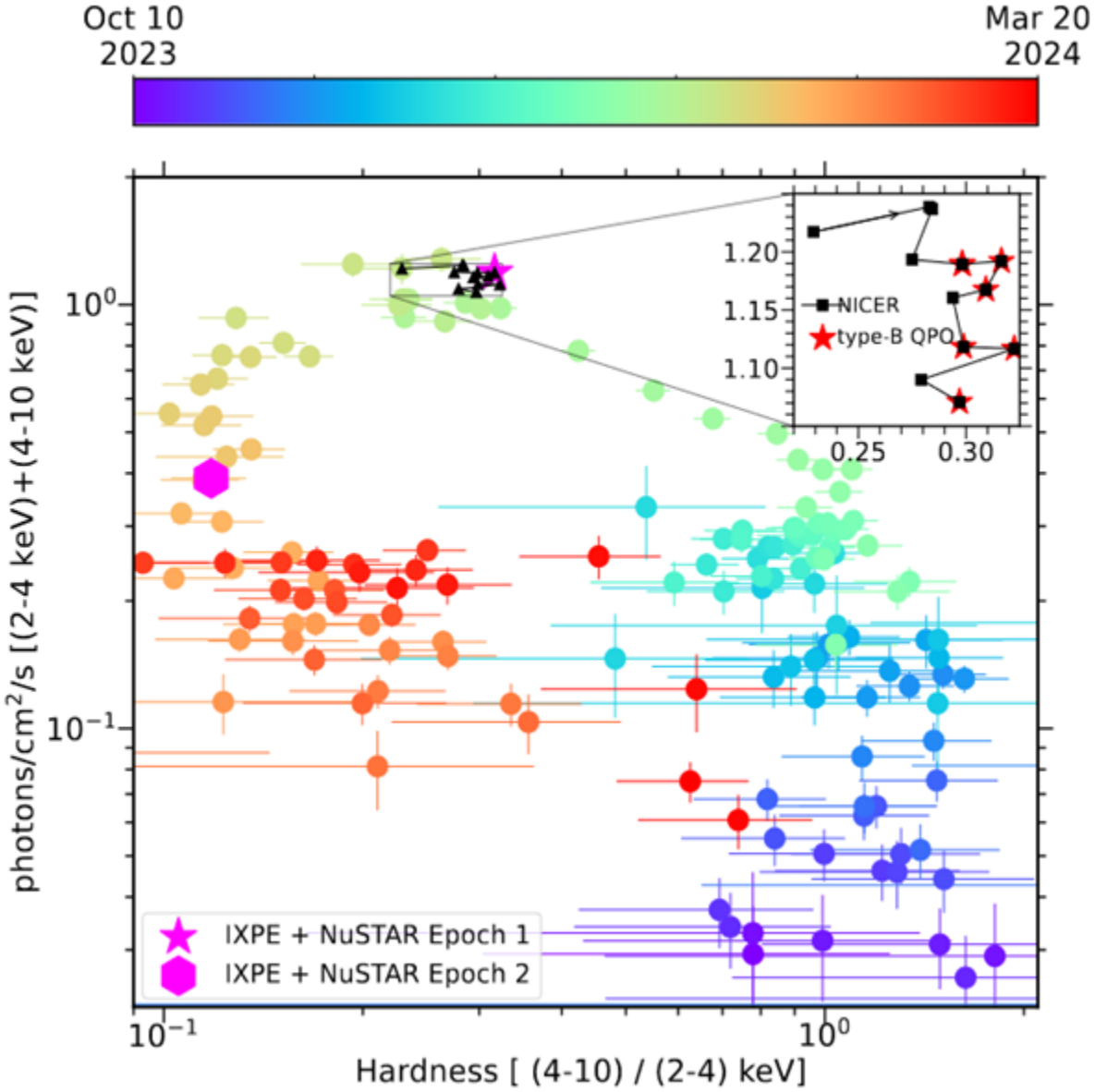
Mastroserio+2025

Soft-Intermediate state:

- PD < 1.1% in 2-8 keV
- **PD = 1.3 ± 0.3 % in 3-8 keV**

Soft state:

- PD < 1.2% in 2-8 keV

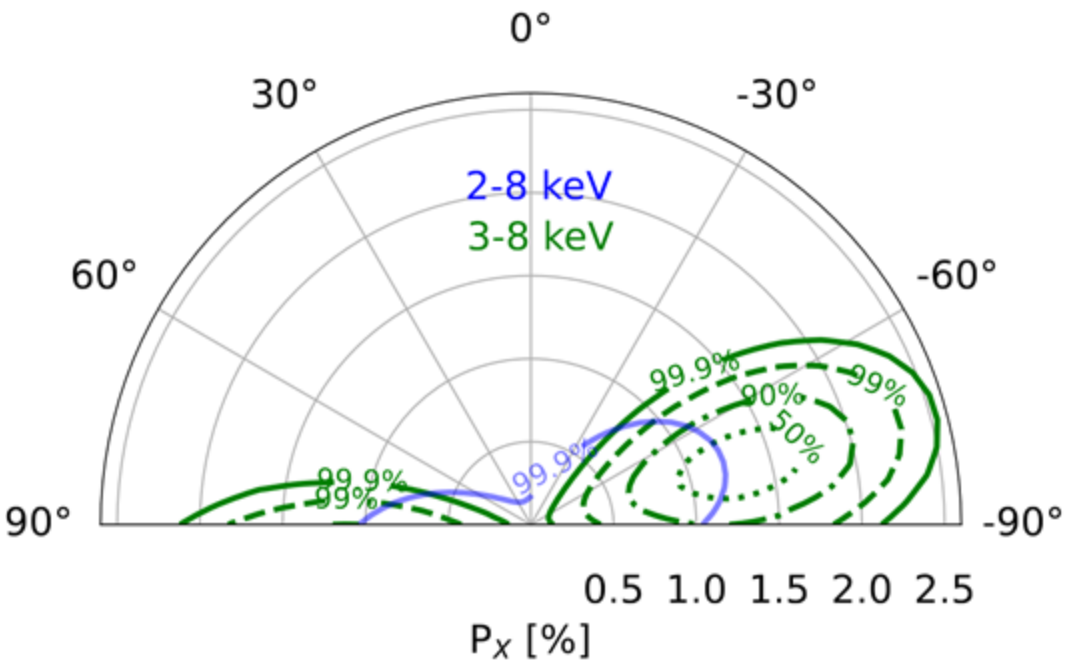


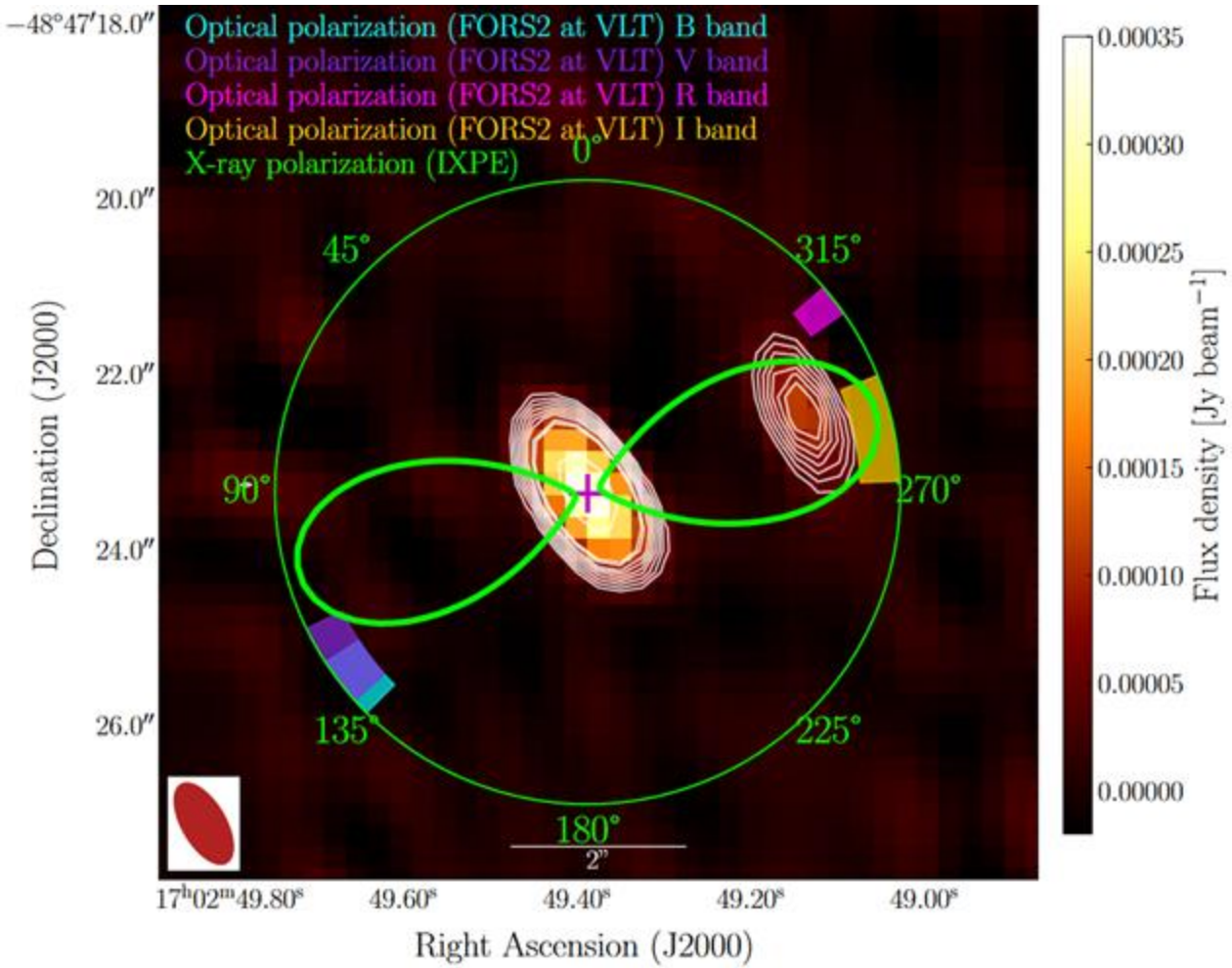
GX 339-4 Observations

THE ASTROPHYSICAL JOURNAL LETTERS

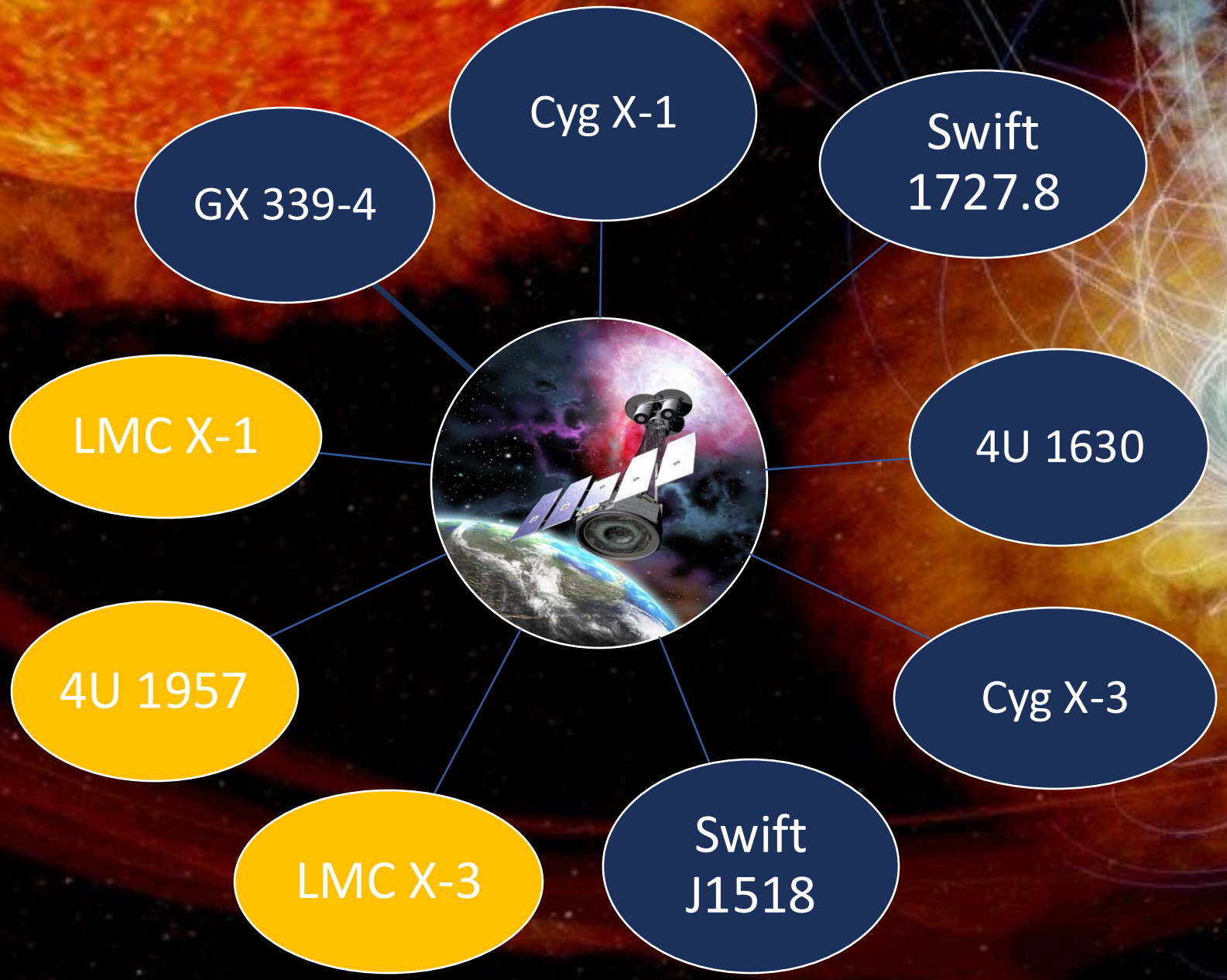
Mastroserio+2025

- ATCA radio observations of discrete jet ejection
  - At -69.5° on the plane of the sky
  - Consistent with the indicated PA!





Black Hole Observations

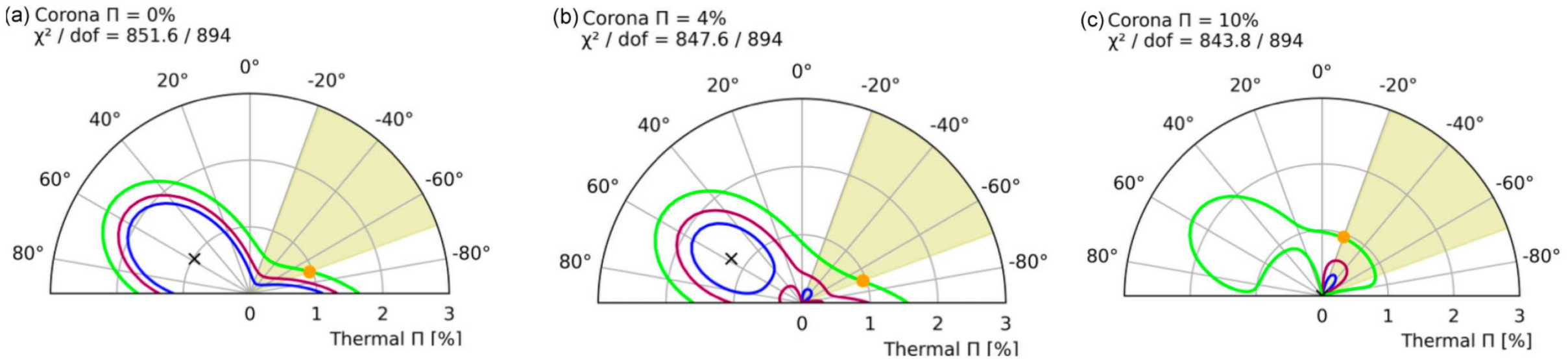


LMC X-1

Podgorný+2023

For the $2-8\ keV$ IXPE band:

- Minimum Detectable Polarization ≈ $\mathbf{1.1\%}$
- Corona PD: Upper limit of $\mathbf{2.2\%}$ (3σ) with PA: $\mathbf{51°.6 \pm 11°.8}$



✓ Disk polarization upper limits: $\mathbf{1.0\%}$, $\mathbf{0.9\%}$, $\mathbf{0.9\%}$ **

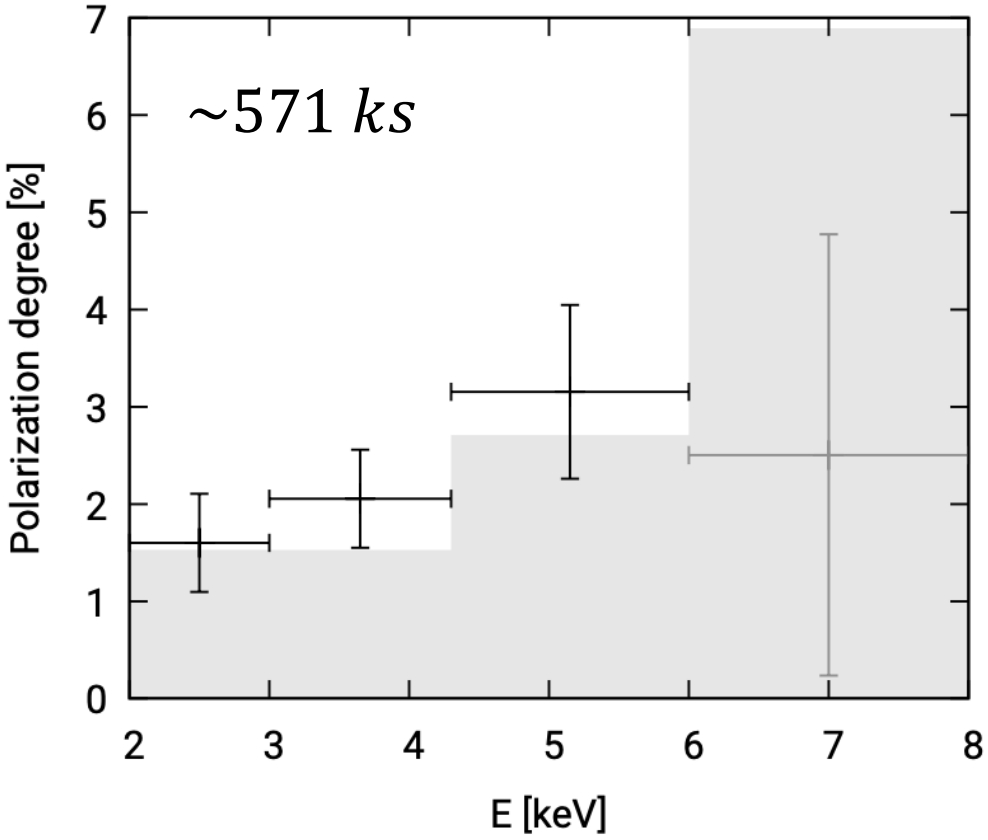
**assuming the orientation of the thermal emission

4U 1957+115: Soft State

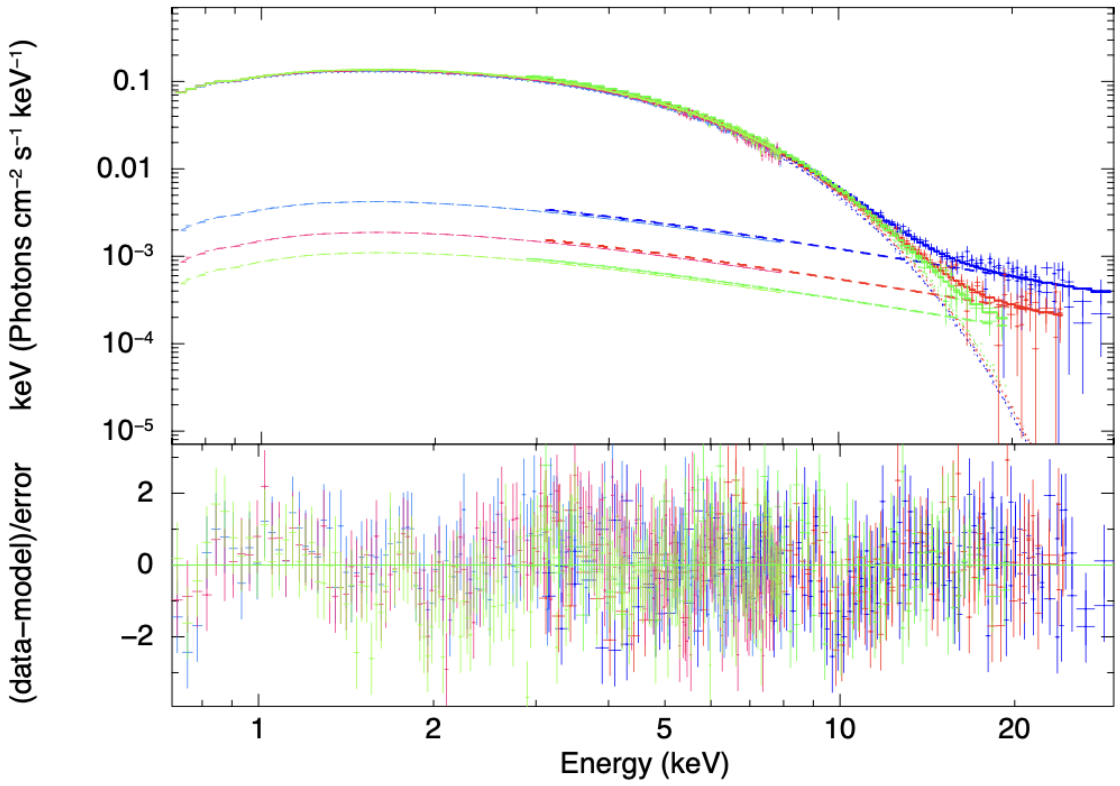
Marra+2024

For the $2-8\ keV$ IXPE band ($>\mathbf{3\sigma}$):

PD= $\mathbf{1.9 \pm 0.6}\%$, PA= $\mathbf{-41°.8 \pm 7°.9}$

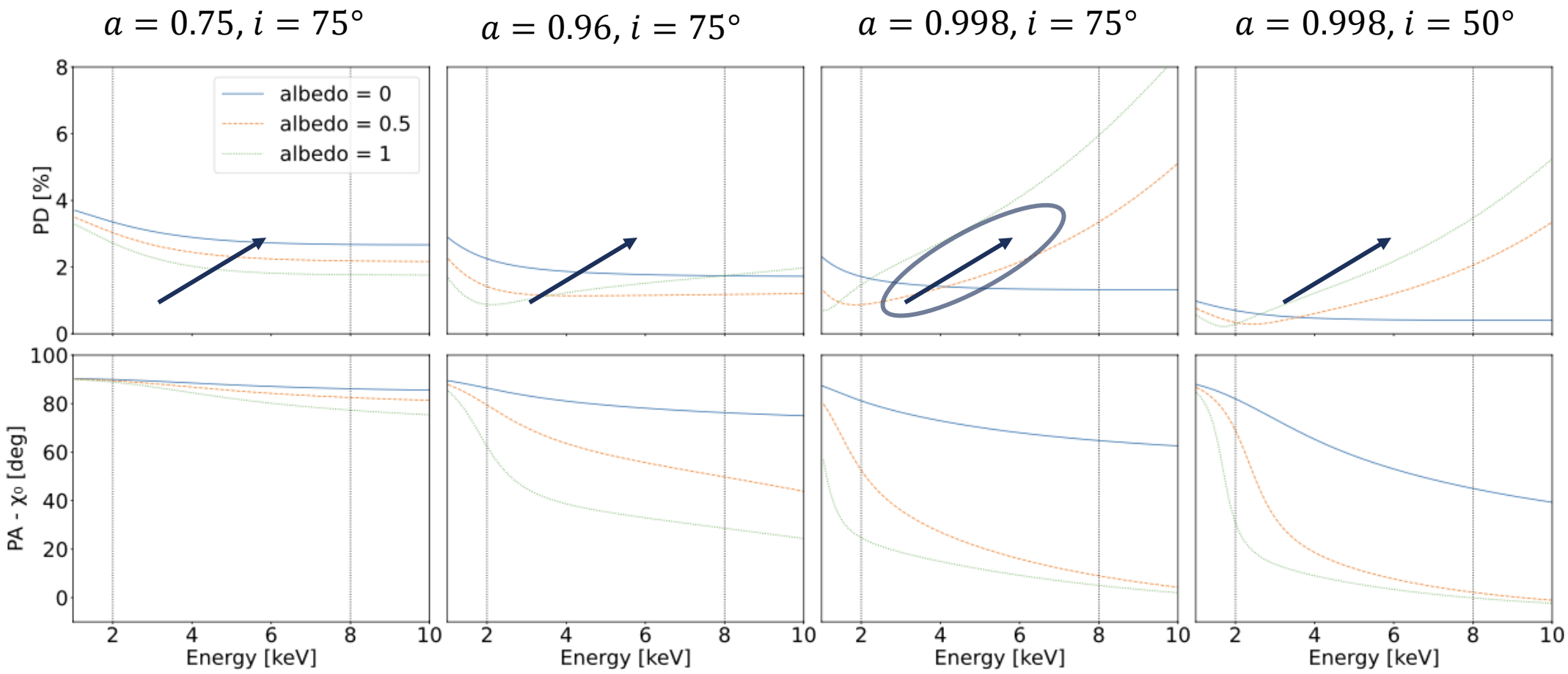


$\mathtt{tbabs} * (\mathtt{kerrbb} + \mathtt{expabs} * \mathtt{powerlaw})$.



4U 1957+115: Soft State

Marra+2024



✓ Polarimetric suggest a significant contribution of returning radiation

LMC X-3: Soft State

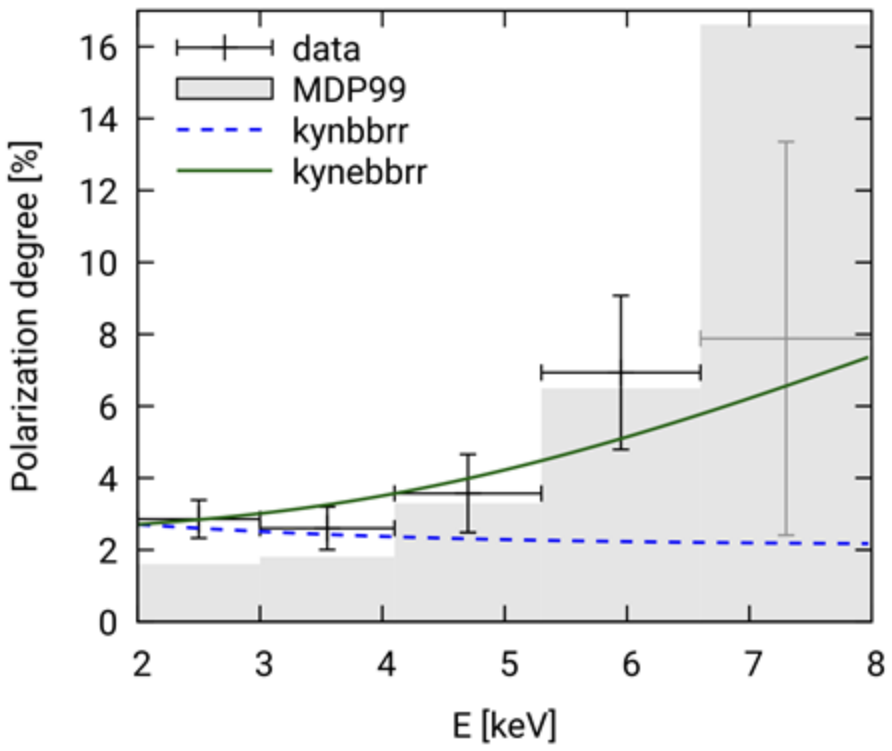
THE ASTROPHYSICAL JOURNAL

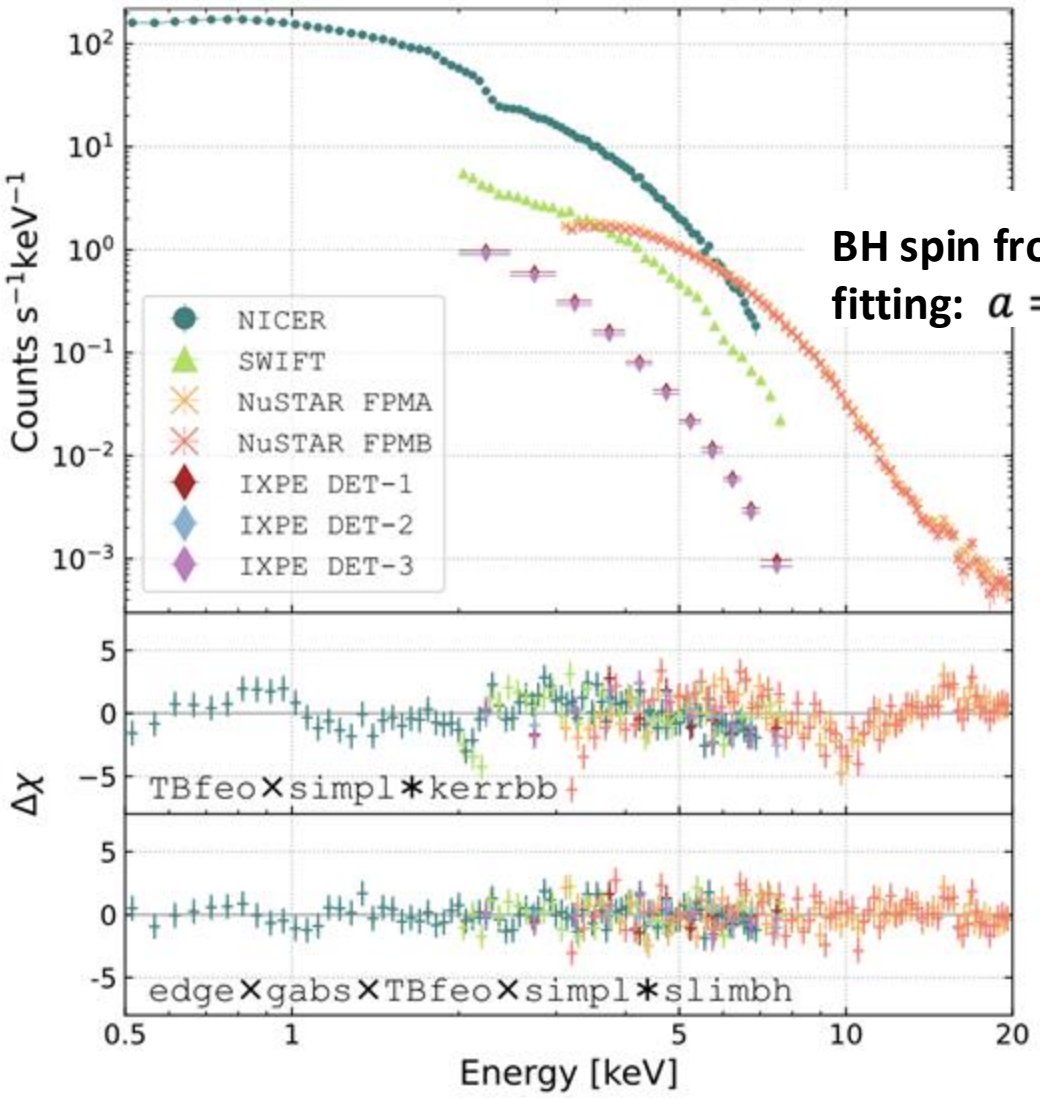
Svoboda+2024a

For the $2-8\ keV$ IXPE band ($>\mathbf{5\sigma}$):

PD= $\mathbf{3.2 \pm 0.6}\%$, PA= $\mathbf{-42° \pm 6°}$

$\sim 562\ ks$





BH spin from the spectral fitting: $a = 0.20 \pm 0.2$

LMC X-3: Soft State

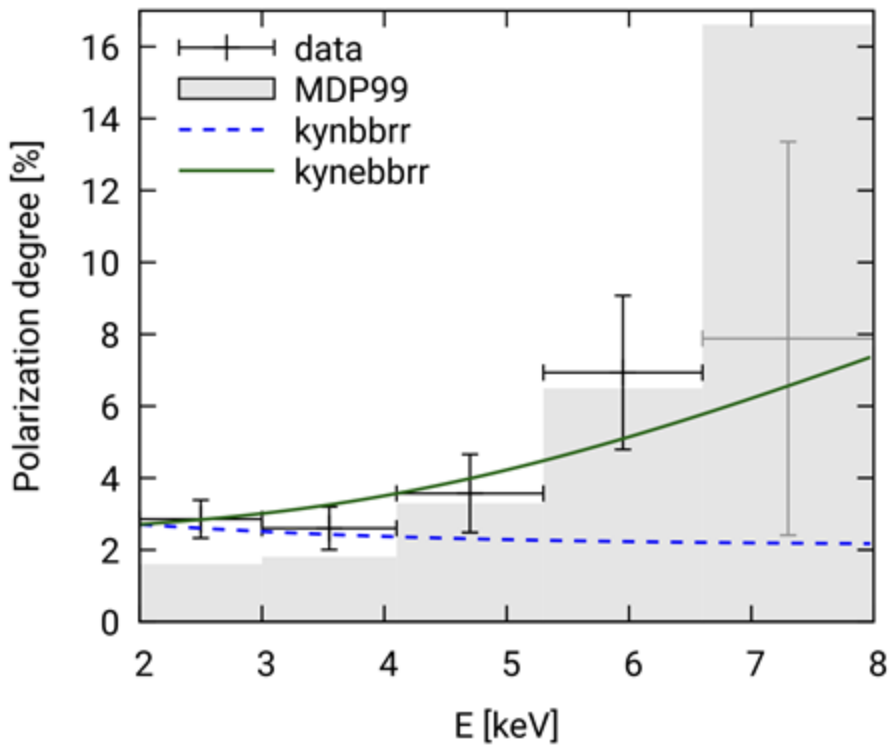
THE ASTROPHYSICAL JOURNAL

Svoboda+2024a

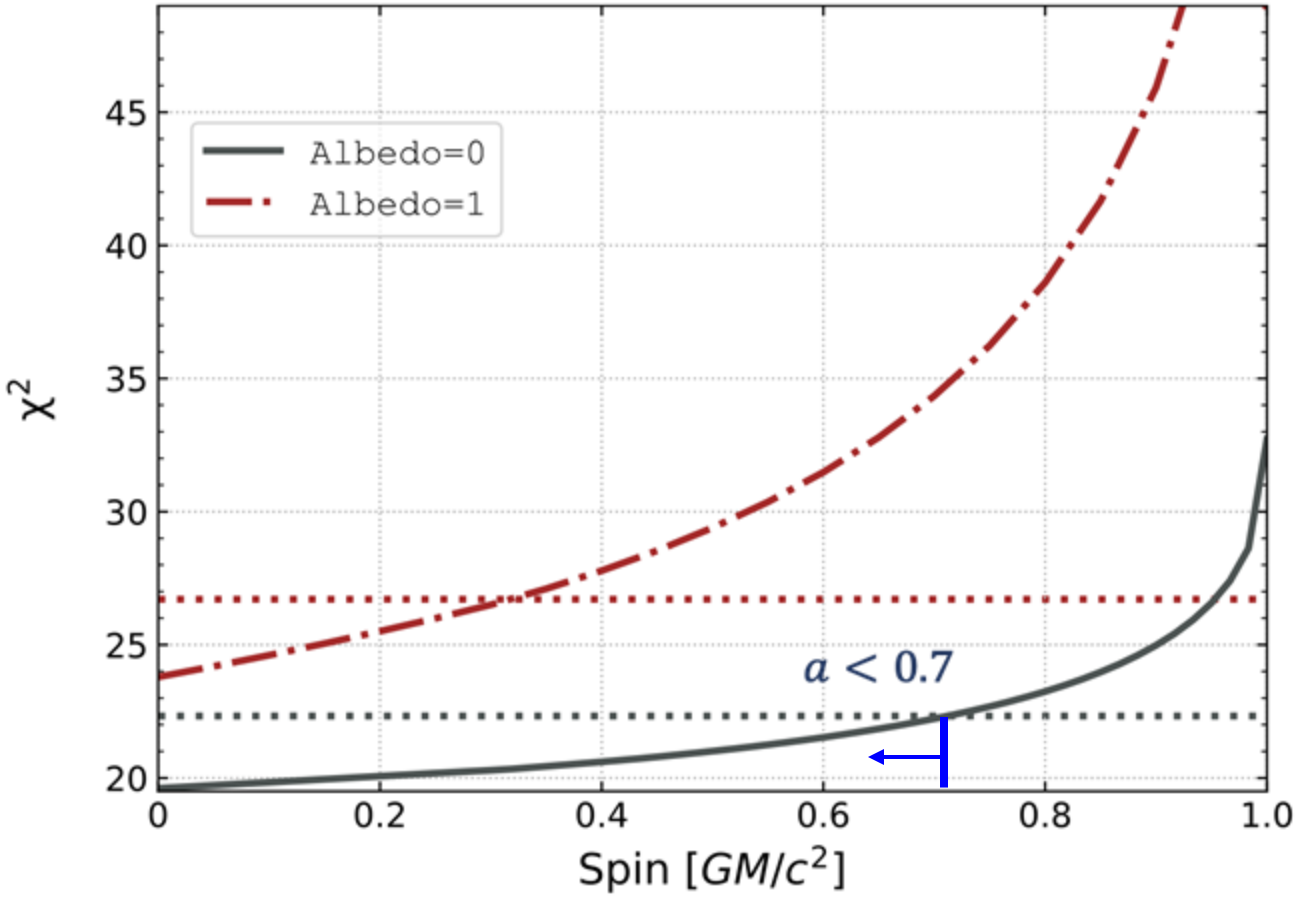
For the $2-8\ keV$ IXPE band ($>\mathbf{5\sigma}$):

PD= $\mathbf{3.2 \pm 0.6}\%$, PA= $\mathbf{-42° \pm 6°}$

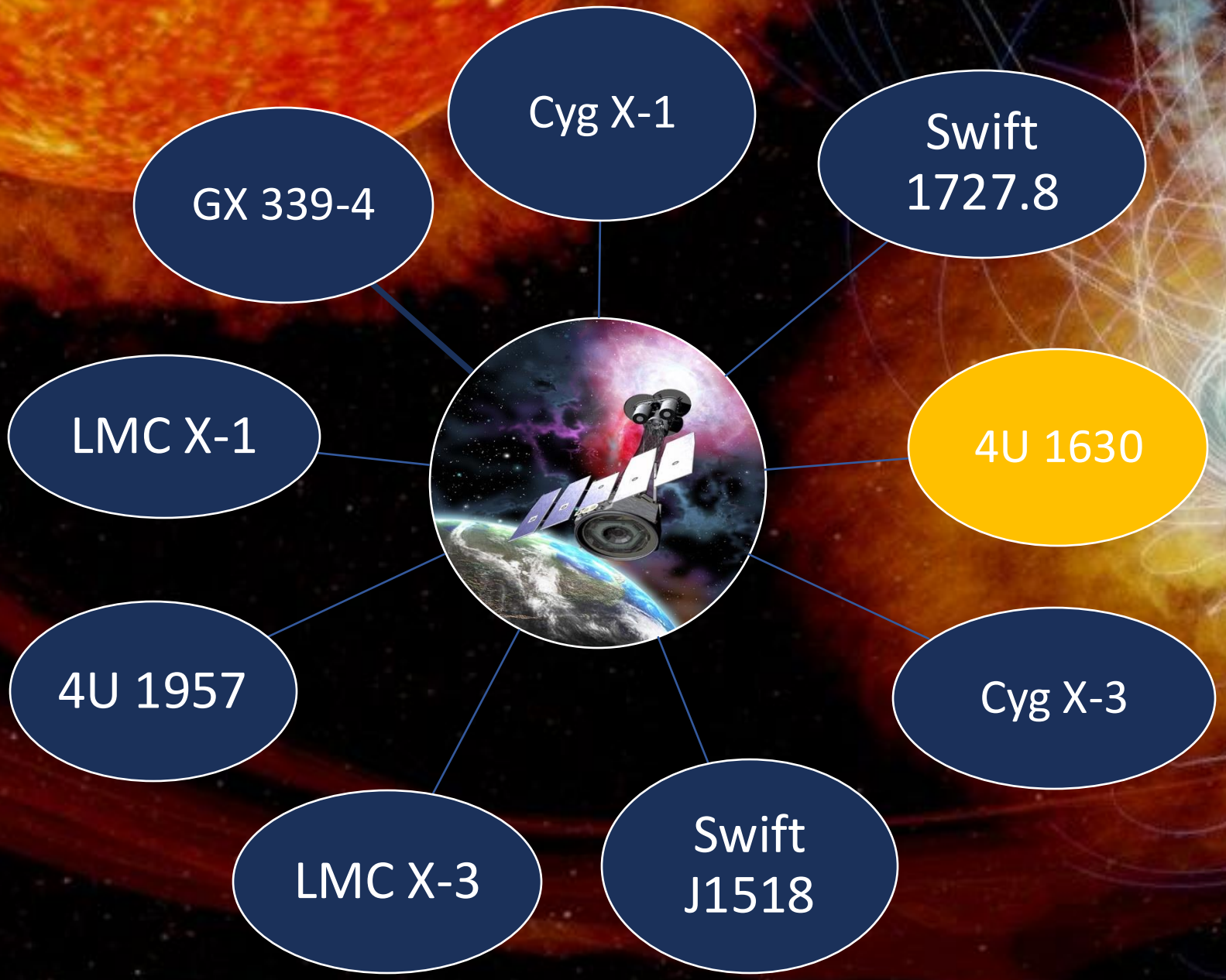
$\sim 562\ ks$



Spin constraints from polarization alone:



Black Hole Observations



4U 1630-47 Soft State

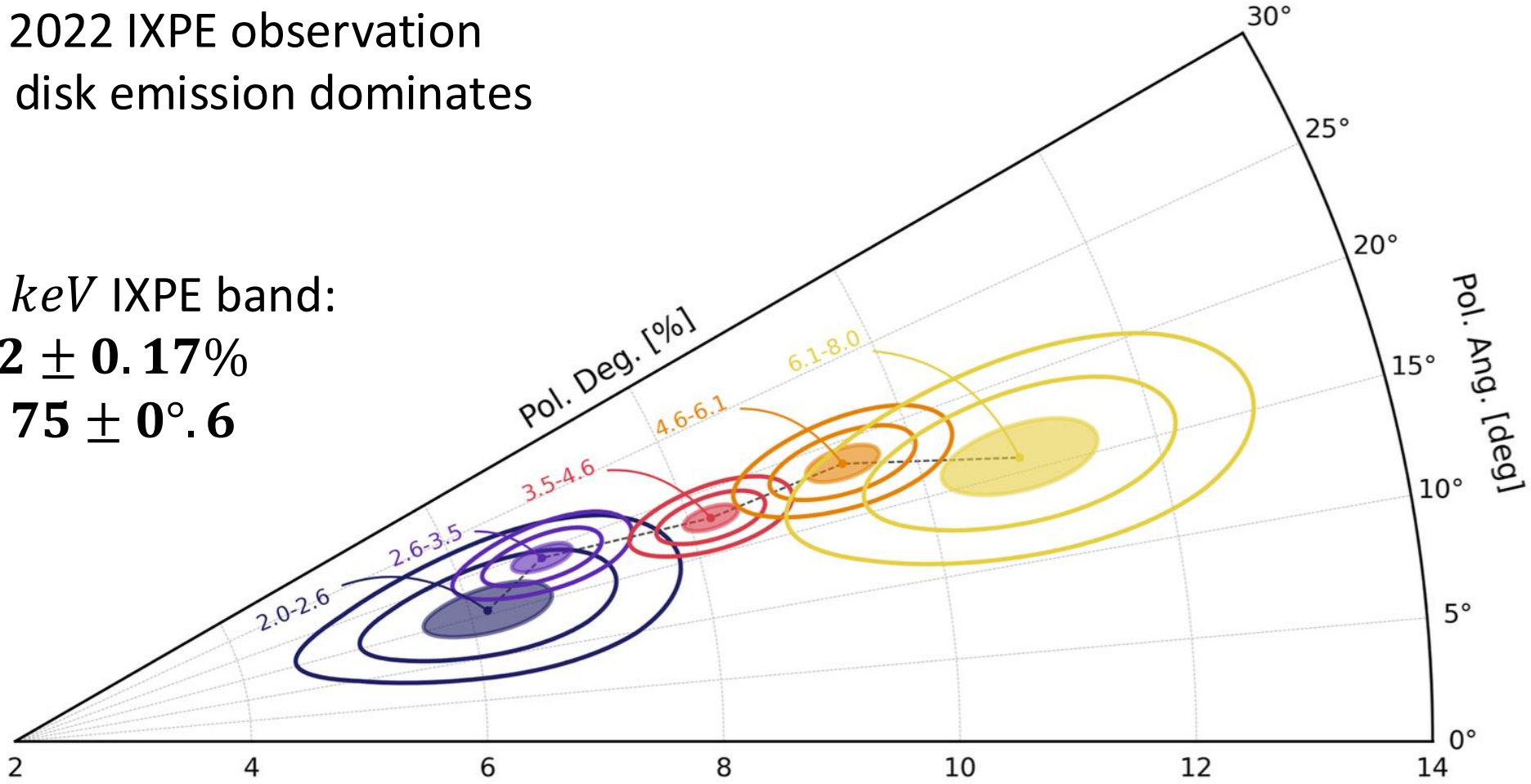
THE ASTROPHYSICAL JOURNAL

Ratheesh+2024

- August-September 2022 IXPE observation
- Soft state: Thermal disk emission dominates

For the $2-8\ keV$ IXPE band:

- EVPD: $\mathbf{8.32 \pm 0.17}\%$
- EVPA: $\mathbf{17°.75 \pm 0°.6}$

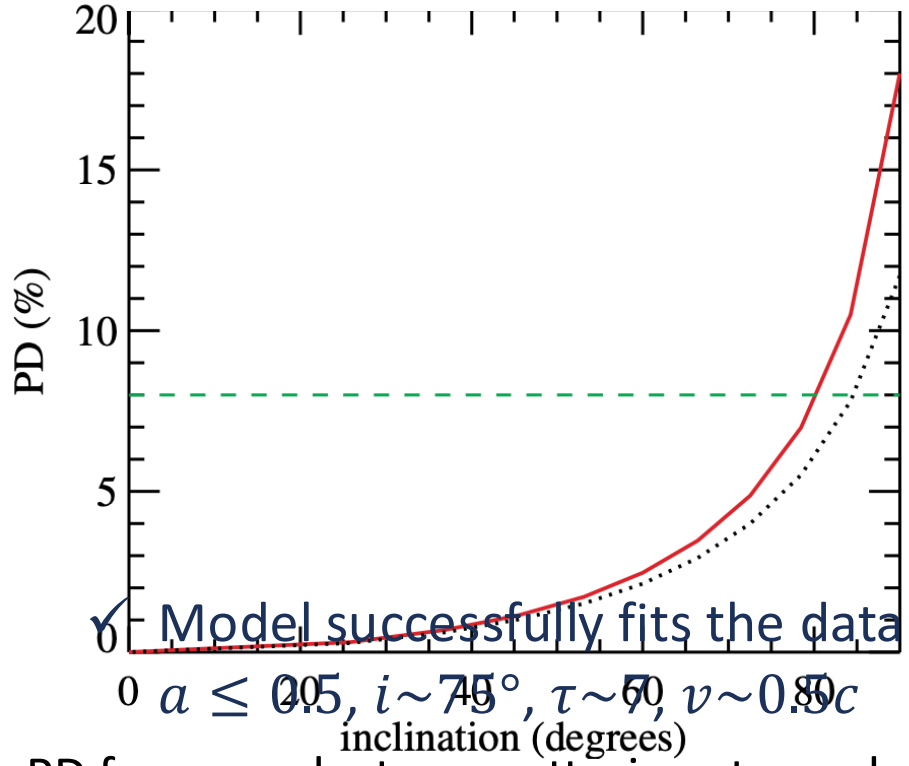


4U 1630-47 Soft State

THE ASTROPHYSICAL JOURNAL

Ratheesh+2024

Predictions



✓ Model successfully fits the data for:

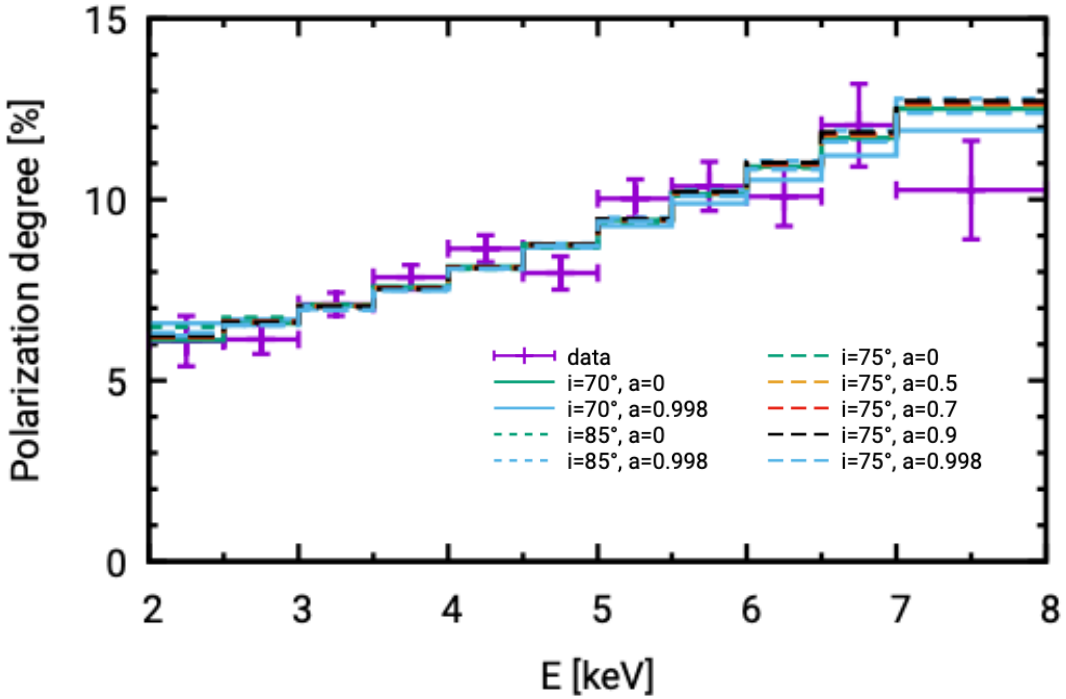
$a \leq 0.5,\ i \sim 75°,\ \tau \sim 7,\ v \sim 0.5c$

PD for pure electron scattering atmosphere (B) and partial ionization of matter (R).

Sobolev (1949), Chandrasekhar (1960)

Partially ionized slabs

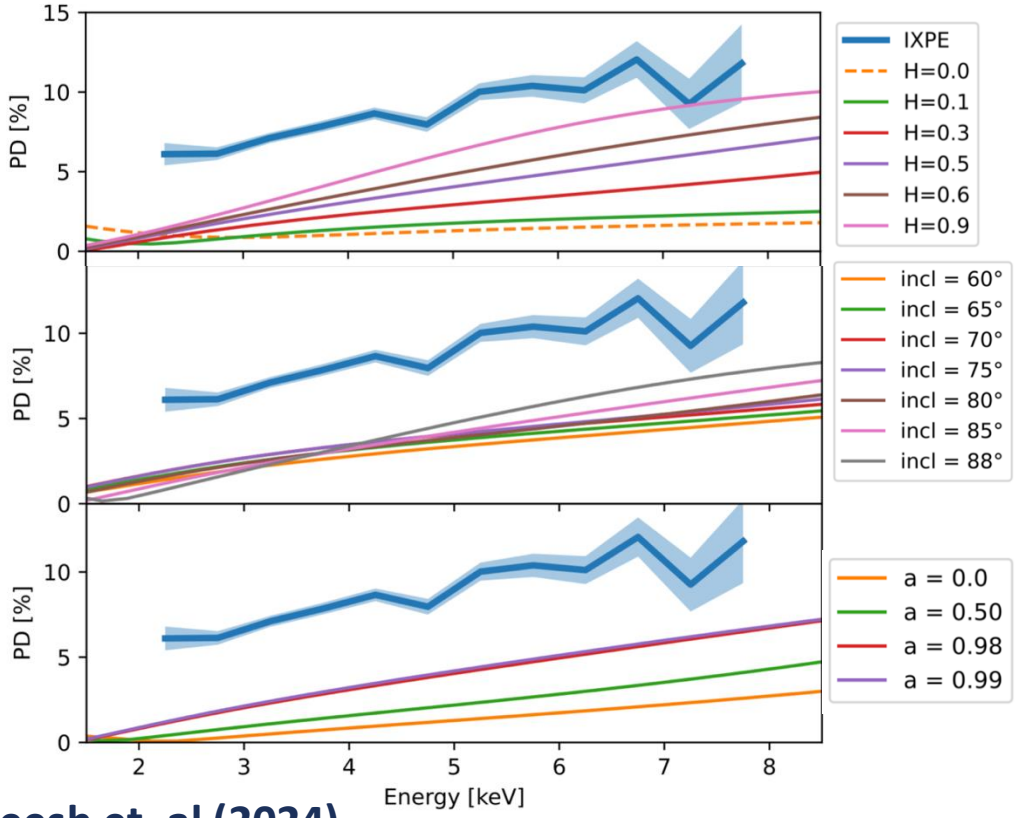
- PD increases with inclination and optical depth of the slab
- Best fits for optically thick slabs with vertical outflow velocity



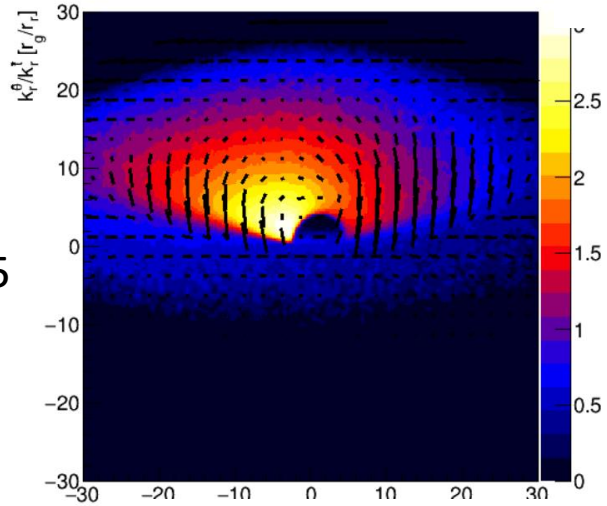
THE ASTROPHYSICAL JOURNAL

4U 1630-47 Soft State

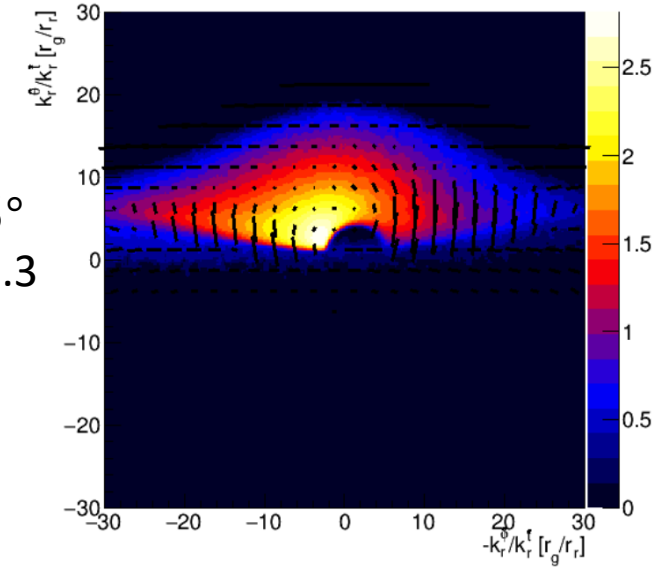
- High accretion rates: Slim or thick disks
  - Used model in West & Krawczynski 2023
- PD increases with scale height, spin, and inclination



$i = 75°$
H/R = 0.5



$i = 85°$
H/R = 0.3



Ratheesh et. al (2024)

Spectral States

(High) Soft State

- Dominated by thermal disk emission
- Non-thermal tail extending beyond 500 keV
- Photon index of $\Gamma \sim 2 - 2.2$

Steep Power Law State

(or Very High State)

- Competing thermal and power-law components
- $\Gamma > 2.4$
- Exhibits QPOs

(Low) Hard State

- Dominated by Comptonized and reflected emission
- Power law exhibits a cutoff at ~ 100 keV
- $1.5 \leq \Gamma \leq 2.0$

4U 1630-47 SPL State

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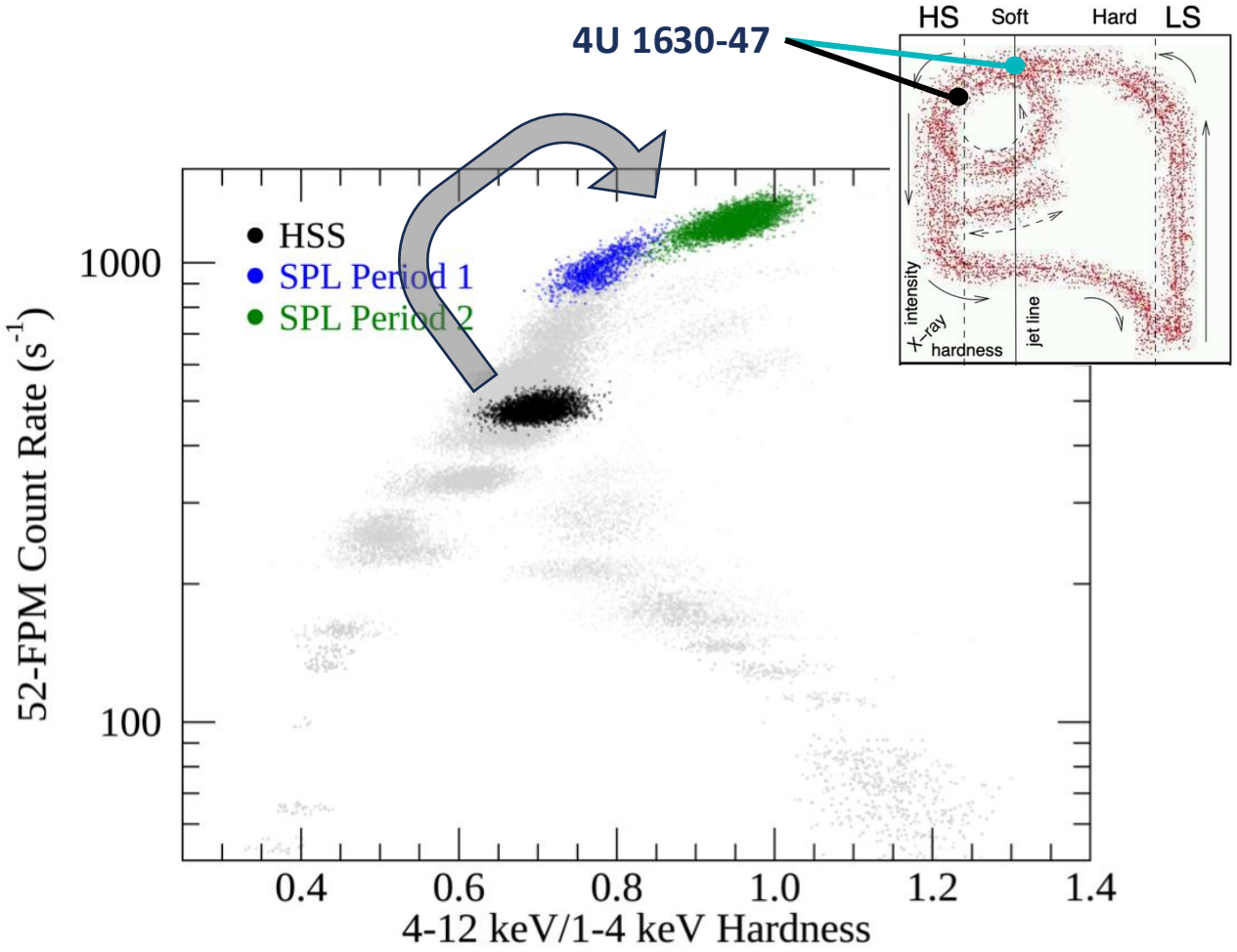
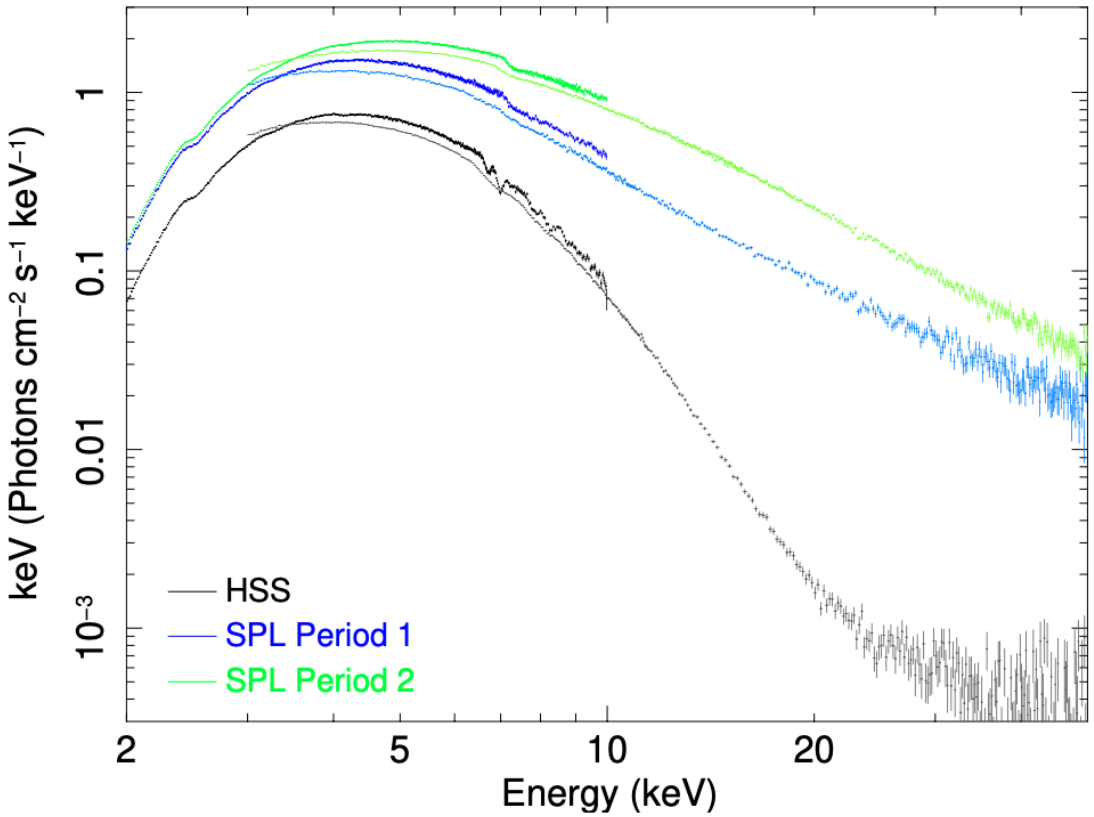
Rodriguez Cavero+2023





4U 1630-47 SPL State

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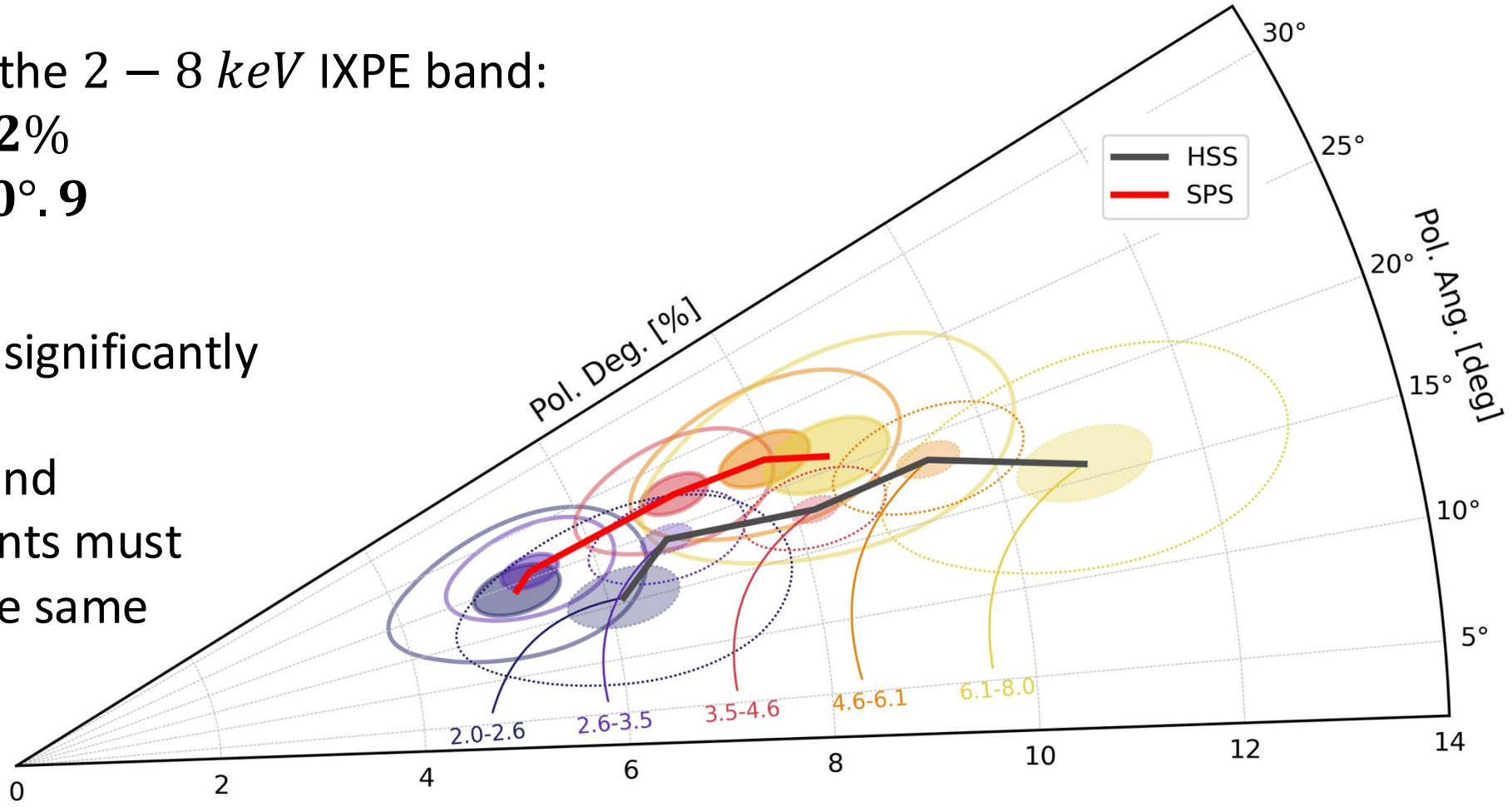
Rodriguez Cavero+2023

SPL observation in the $2-8\ keV$ IXPE band:

- EVPD: $\mathbf{6.8 \pm 0.2\%}$
- EVPA: $\mathbf{21^{\circ}.3 \pm 0^{\circ}.9}$

➢ PA should change significantly but it doesn't so both thermal and coronal components must be polarized in the same direction



4U 1630-47 SPL State

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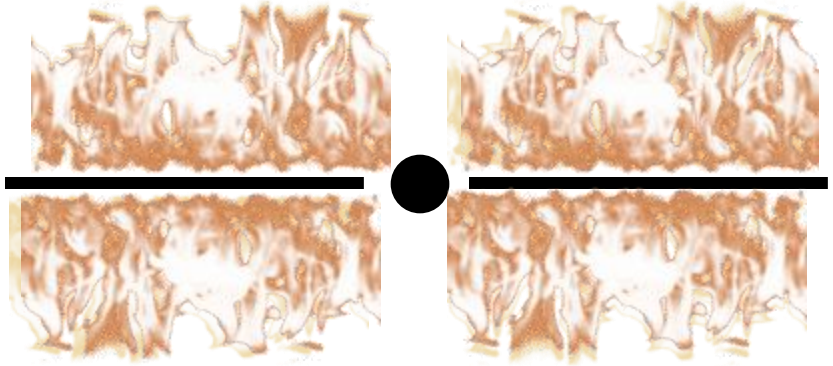
Rodriguez Cavero+2023

- PA should change significantly but it doesn't so both thermal and coronal components must be polarized in the same direction

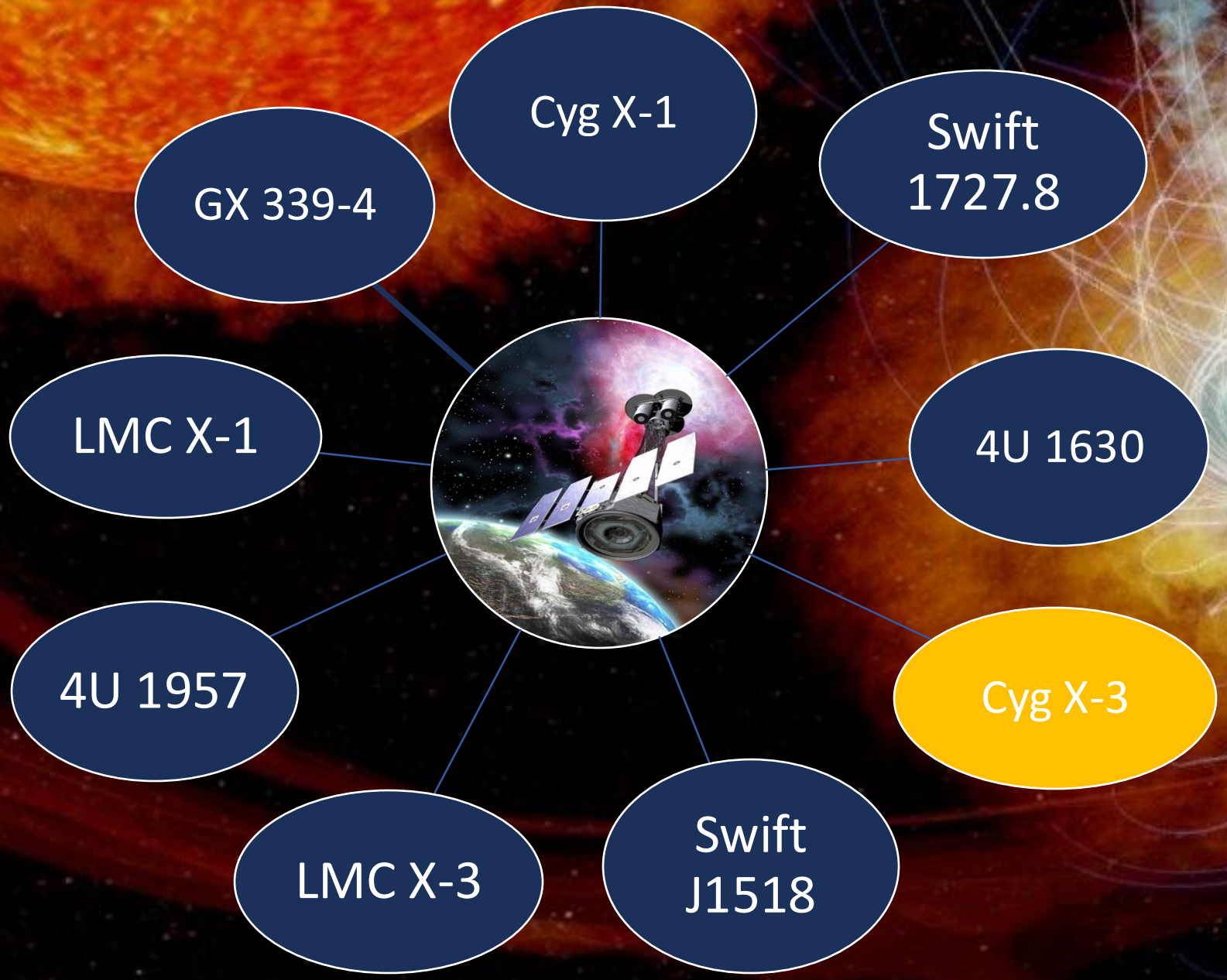
Both states must employ similar emission processes with different scattering mechanisms

From primarily elastic to inelastic scattering



Ionized plasma atmosphere

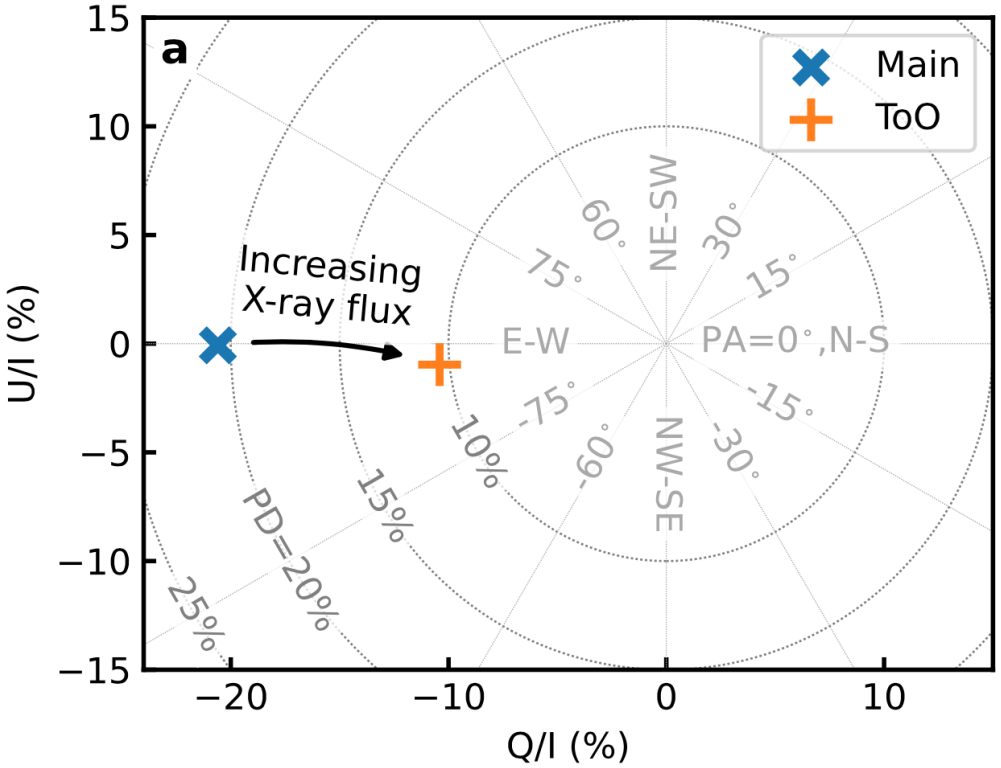
Black Hole Observations



Cyg X-3: Hard and Intermediate State

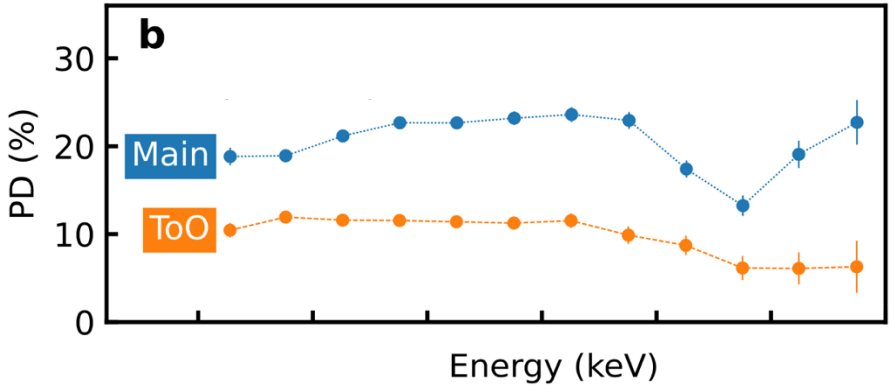
nature astronomy

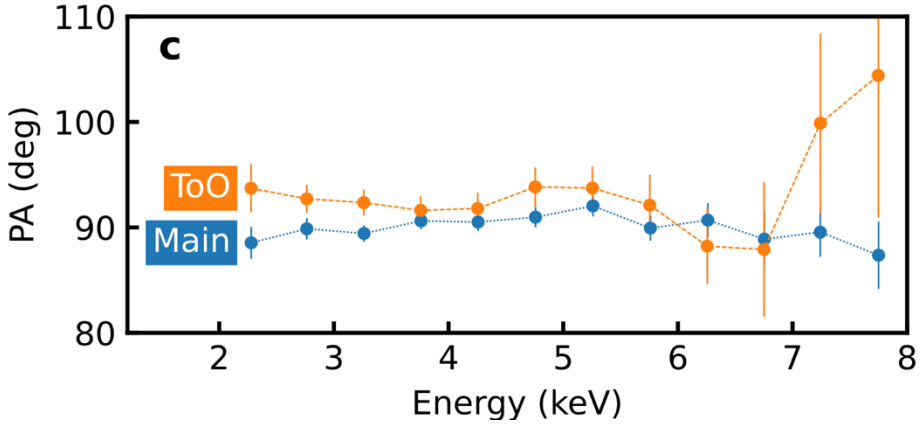
Veledina+2024a



For the $2-8\ keV$ IXPE band:

- EVPD: $\mathbf{20.6 \pm 0.3}\%$ (Main), $\mathbf{10.4 \pm 0.3}\%$ (ToO)
- EVPA: $-\mathbf{89°.9 \pm 0°.4}$ (Main)





Main observation ($\sim 538\ ksec$):

- October 2023

ToO ($\sim 199\ ksec$):

- December 2023

Cyg X-3: Hard and Intermediate State

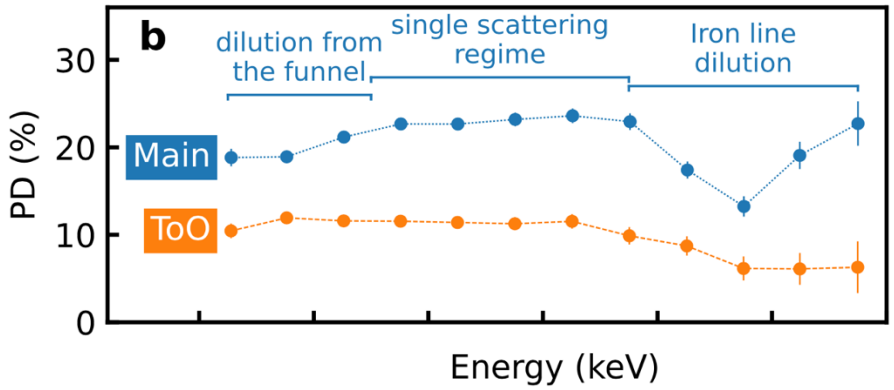
nature astronomy

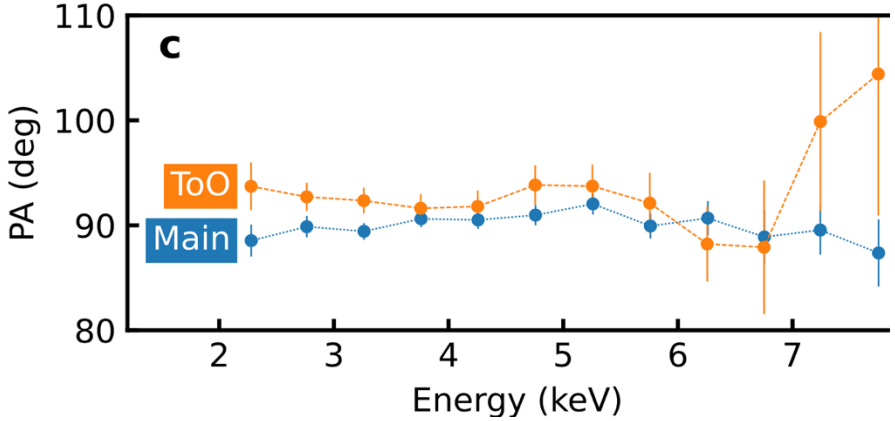
Veledina+2024a

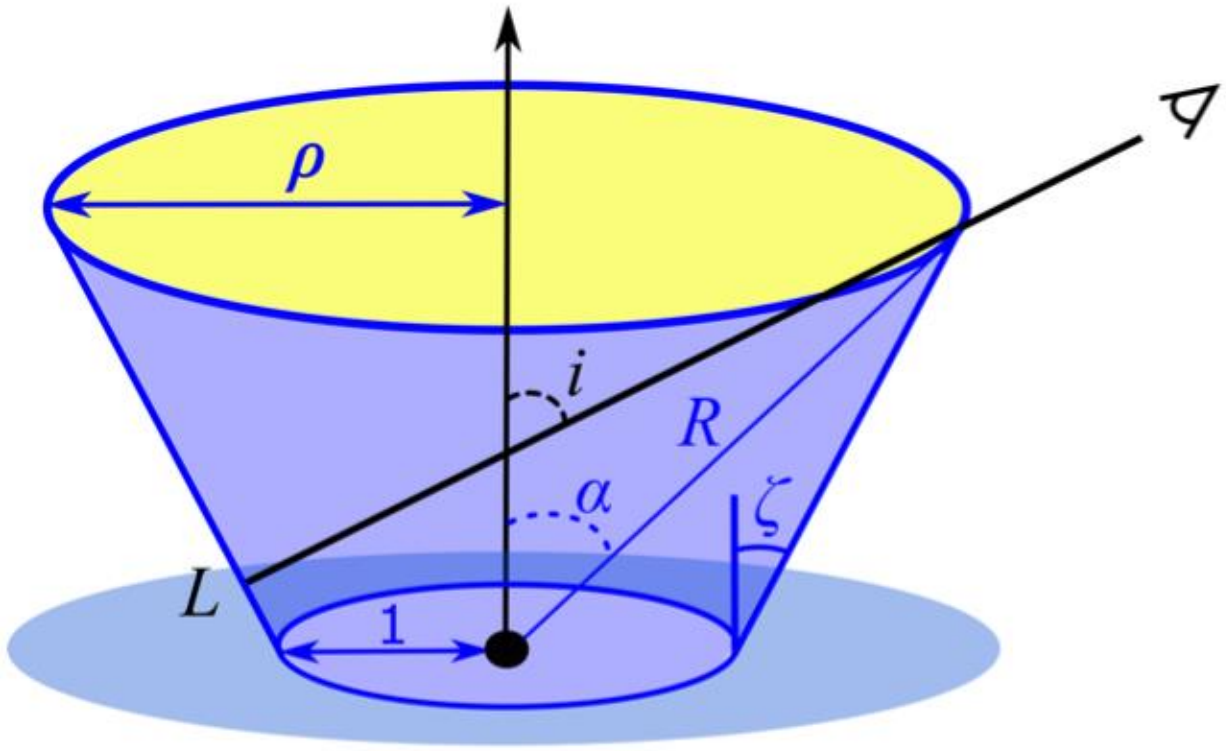
For the $2-8\ keV$ IXPE band:

Hard state: PD= $\mathbf{20.6 \pm 0.3}\%$, PA= $\mathbf{-89°.\pm 0°.4}$ ($> \mathbf{68\sigma}$)

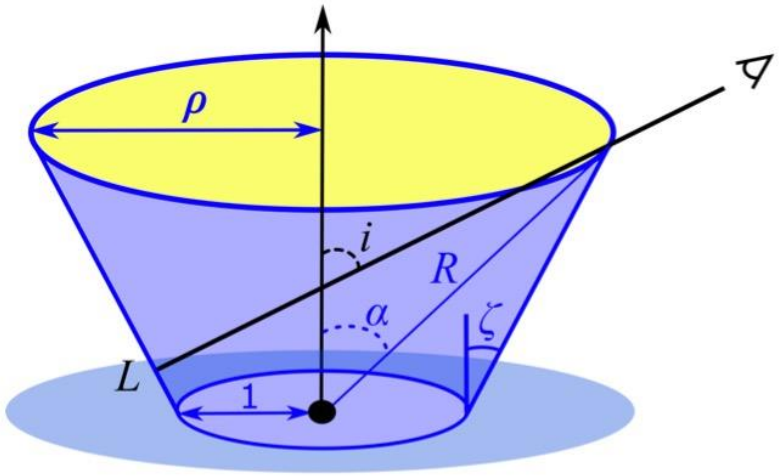
Intermediate state: PD= $\mathbf{10.4 \pm 0.3}\%$ ($> \mathbf{34\sigma}$)

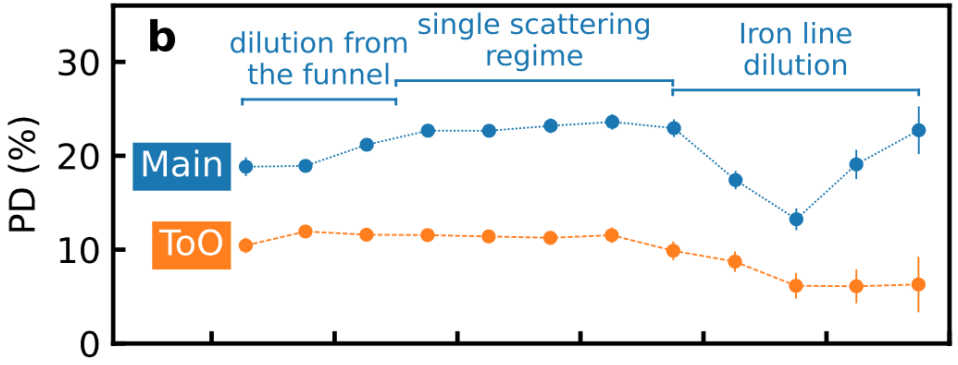


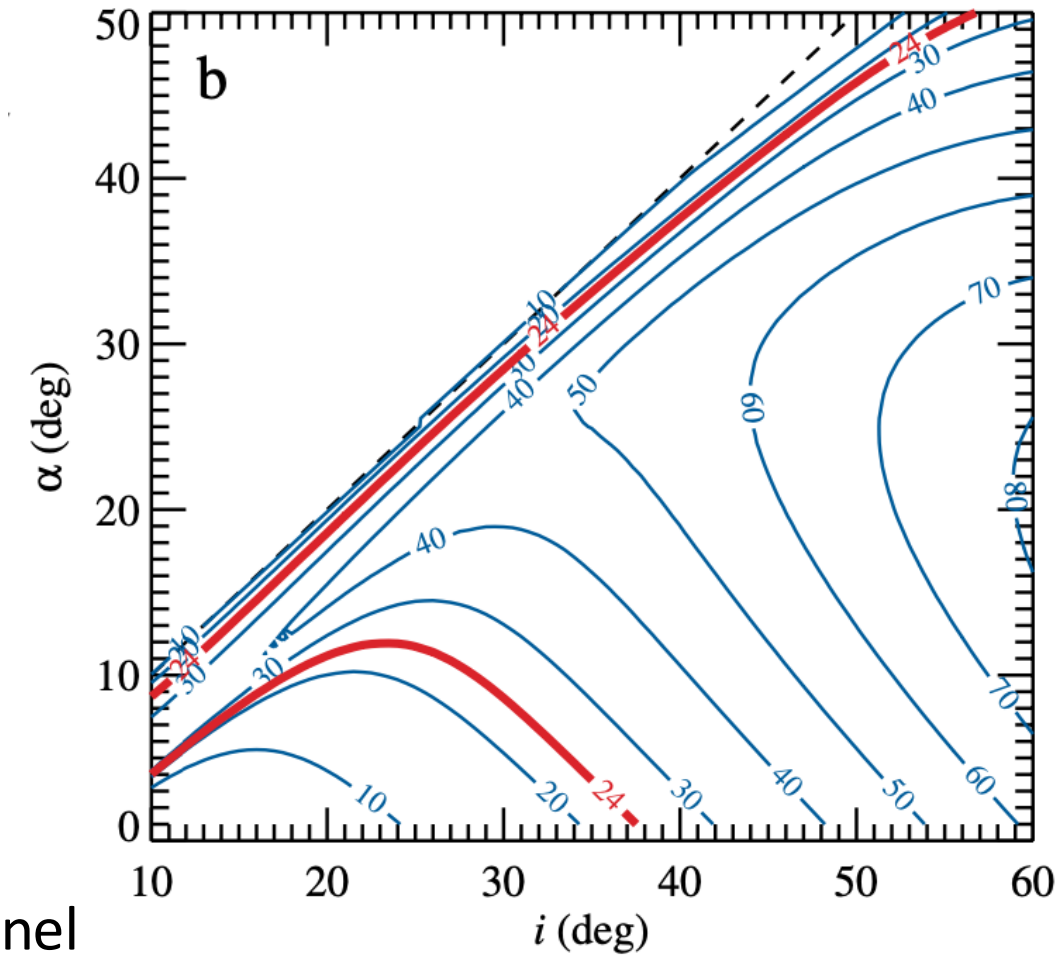




Cyg X-3: Obscured source & reflected light







Veledina+2024a

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

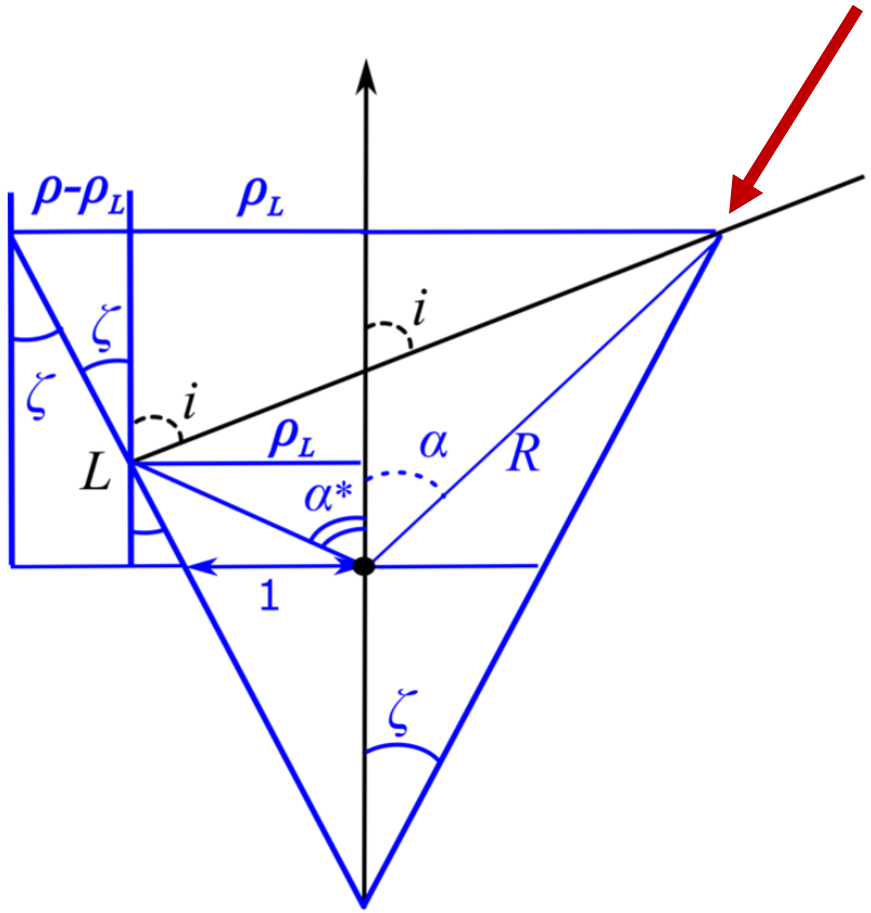
Cyg X-3: Hidden ULX source

Luminosity:

$$F_{obs} = 1.53 \times 10^{-9}\ ergs\ cm^{-2}s^{-1}$$

$$L_{\mathrm{ULX}} = \frac{2\pi}{\Omega_{\mathrm{refl}}} \frac{4\pi D^2 F_{\mathrm{obs}}}{a}$$

- See Equations A3-A8 in Veledina, Muleri, Poutanen et. al (2023)



- Apparent luminosity for an observer viewing down the funnel: $\mathrm{L} \geq 5.0 \times 10^{39}\ ergs\ s^{-1}$ (2-8 keV)

✓ Appear as a ULX to an extragalactic observer along the axis of the funnel

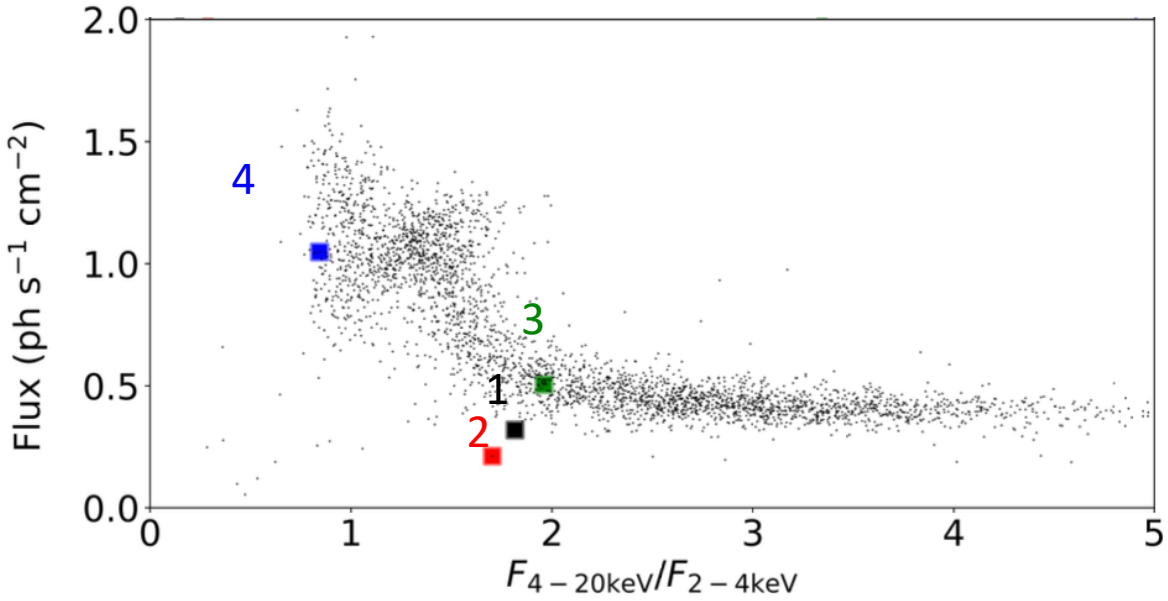
Cyg X-3: Soft State

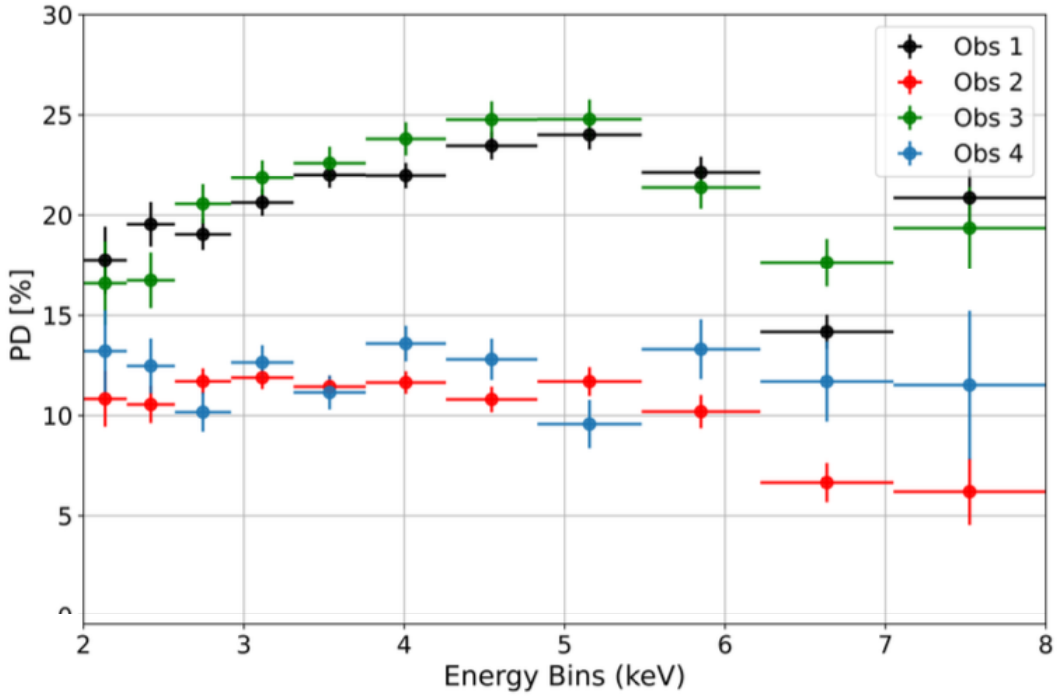
For the $2-8\ keV$ IXPE band ($>\mathbf{23\sigma}$):

PD= $\mathbf{11.9 \pm 0.5}\%$, PA= $\mathbf{94° \pm 1°}$

Veledina+2024a

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

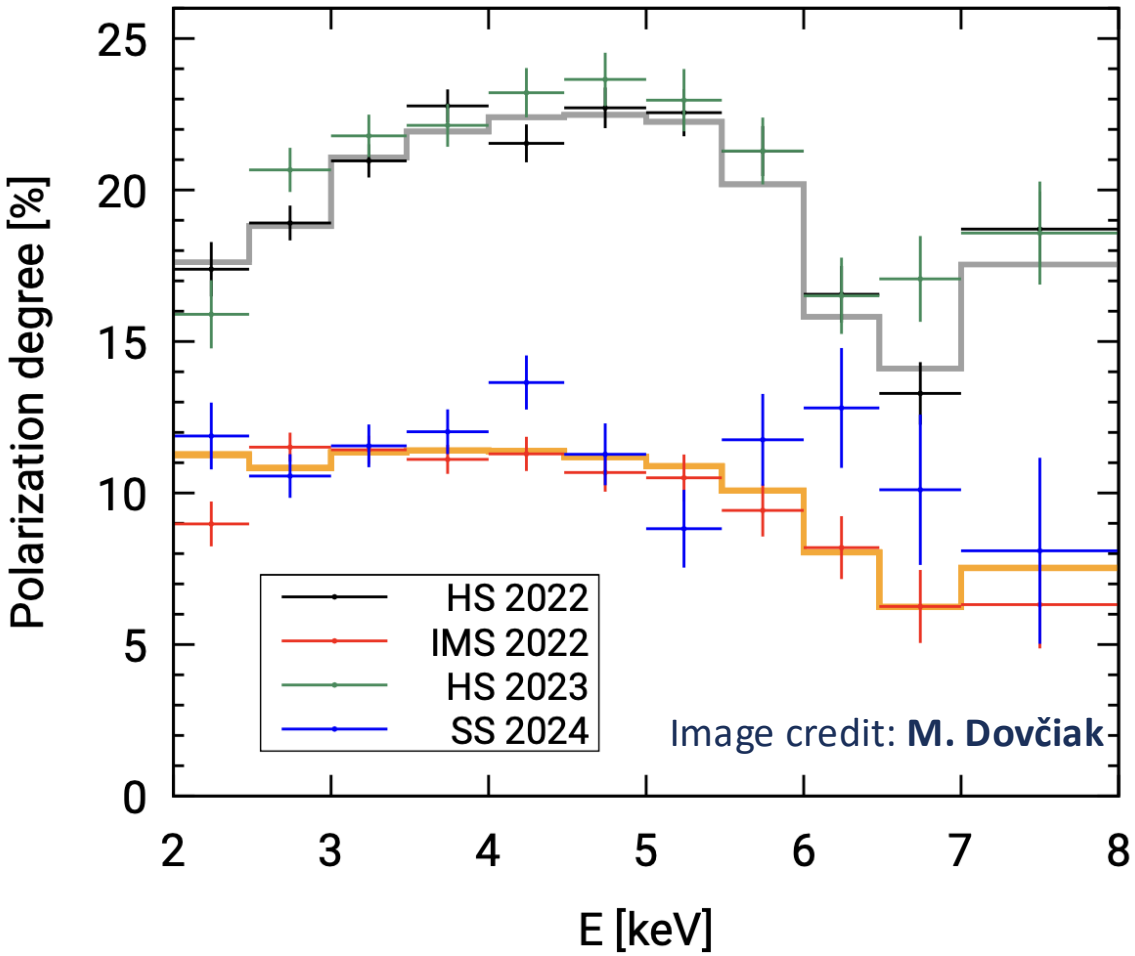


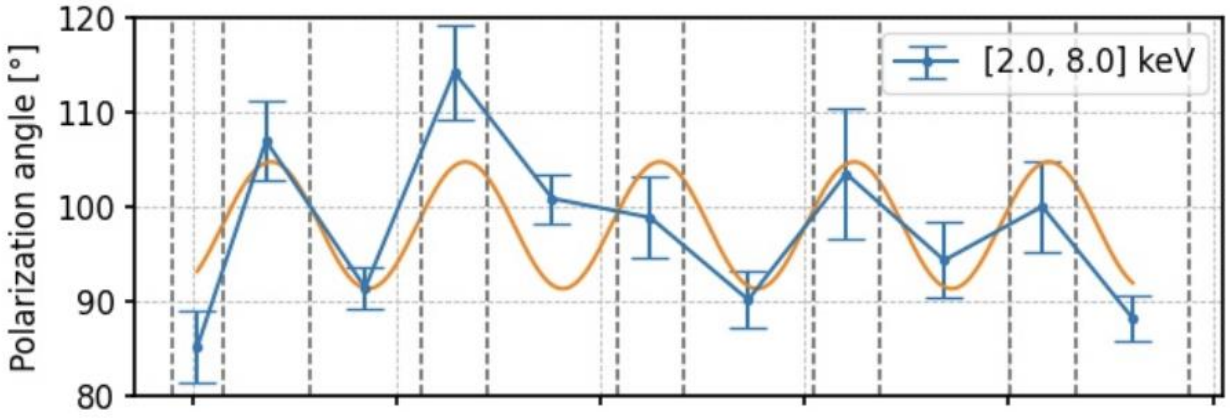


Rodriguez Cavero+2024 (in progress)

Cyg X-3: Ionization

Rodriguez Cavero+2024 (in progress)



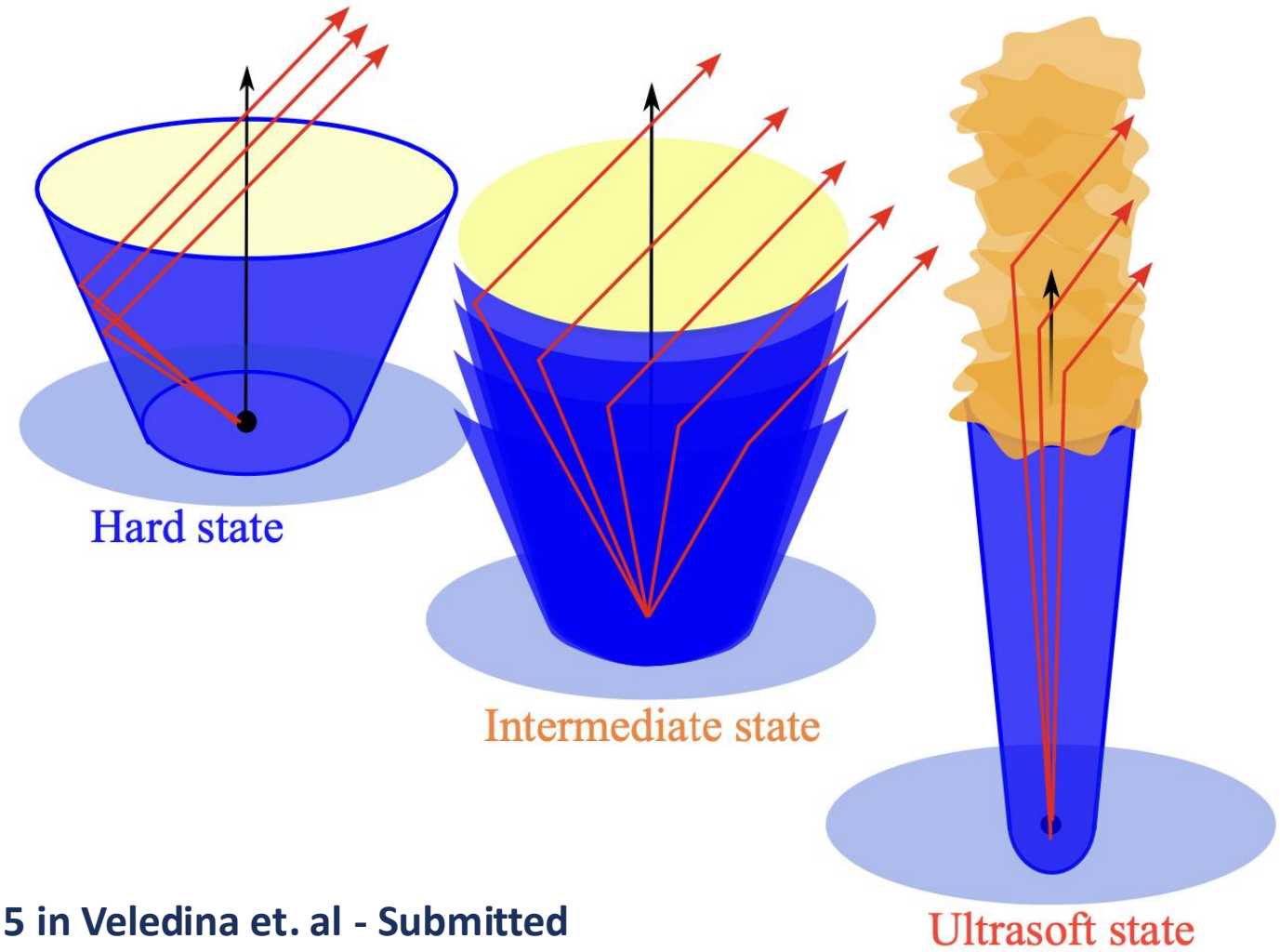


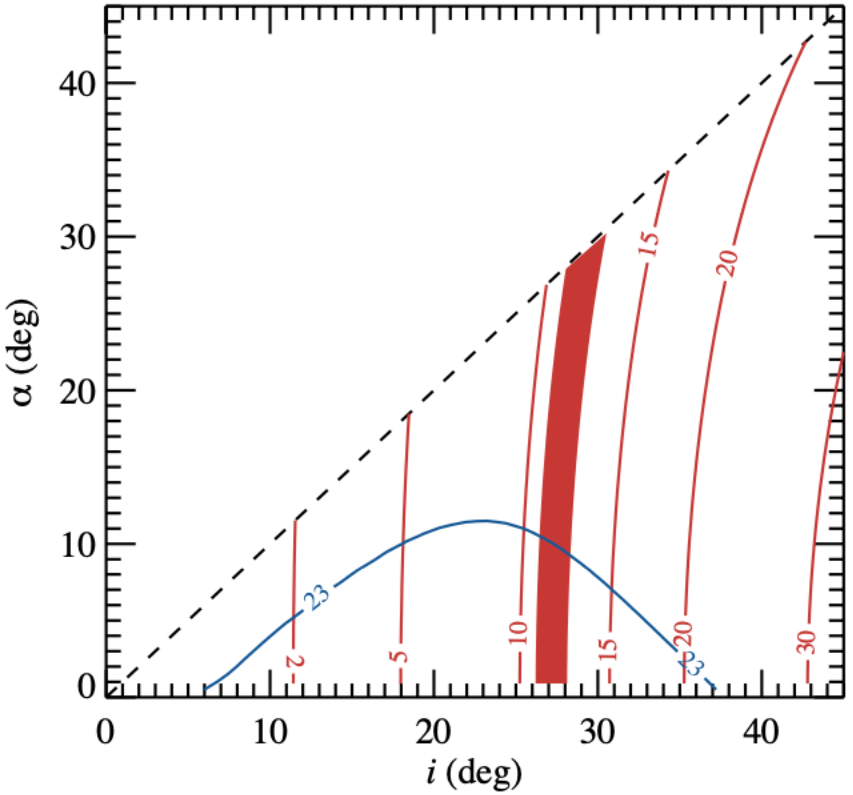
Highly ionized reflector model

PA variability must be explained by geometrical variations

Cyg X-3: Inclination and Geometry

Veledina+2024b

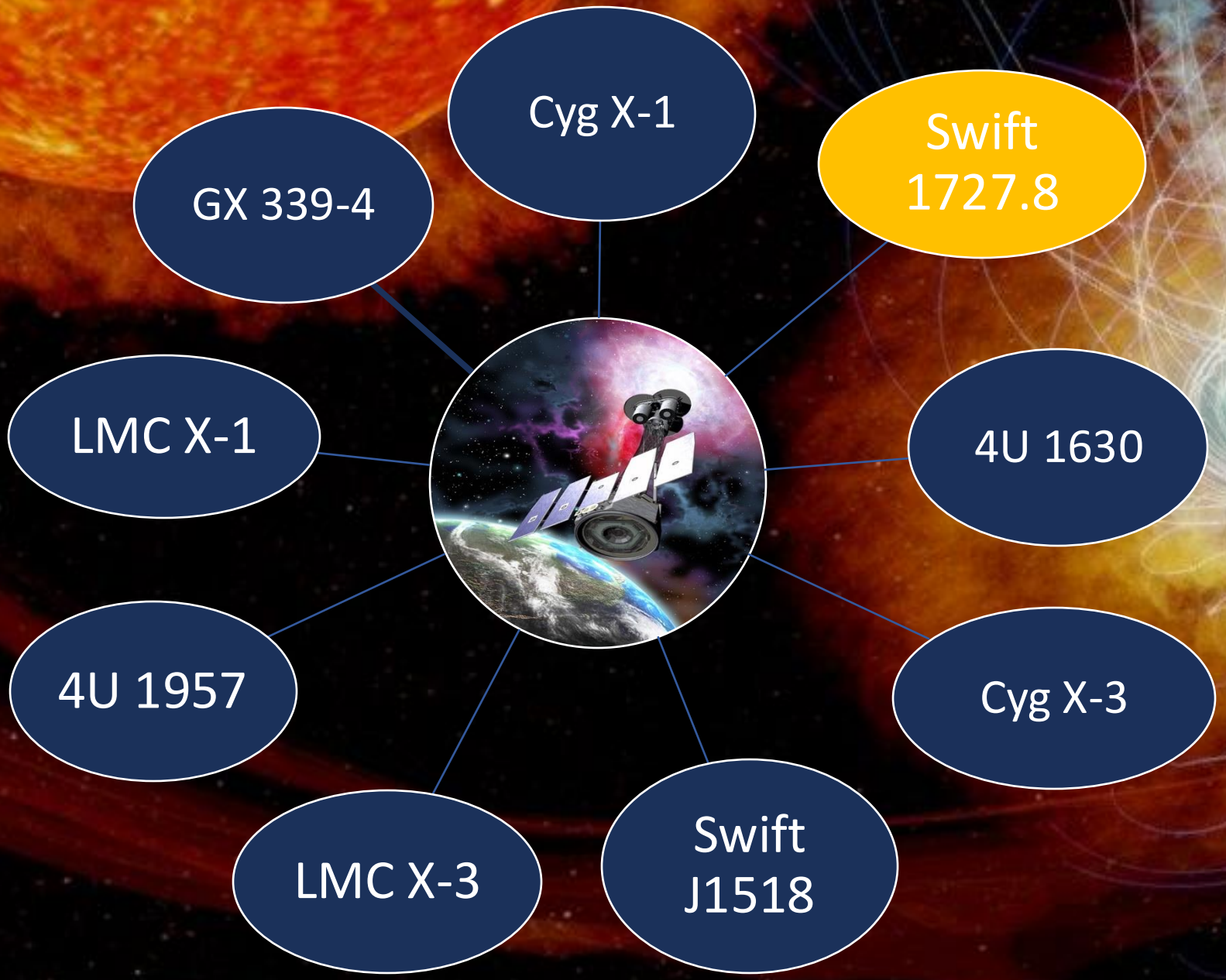




$$26° < i < 28°$$

Fig. 5 in Veledina et. al - Submitted

Black Hole Observations



Swift J1727.8-1613

All IXPE papers for the source

- New X-ray Binary discovered in 2023
- Brighter than any other recent black-hole XRB outburst: Flux ≈ 7 Crabs (in 2-20 keV)

5 IXPE Observations:

Hard state: PD = $\mathbf{4.1 \pm 0.2}\%$, PA= $\mathbf{2^\circ.2 \pm 1^\circ.3}$ $(> \mathbf{20\sigma})$ Veledina+2023

Intermediate state: PD decreased from $\sim\mathbf{4}\%$ to $\sim\mathbf{3}\%$, PA constant Ingram+2024

→ Hard-to-Soft

Soft state: PD $\leq \mathbf{1}\%$ Svoboda+2024

Intermediate state: PD = $\mathbf{3.3 \pm 0.4}\%$, PA= $\mathbf{3^\circ.3 \pm 0^\circ.4}$ $(> \mathbf{8\sigma})$ Podgorny+2023

→ Soft-to-Hard

Swift J1727.8-1613: Hard State

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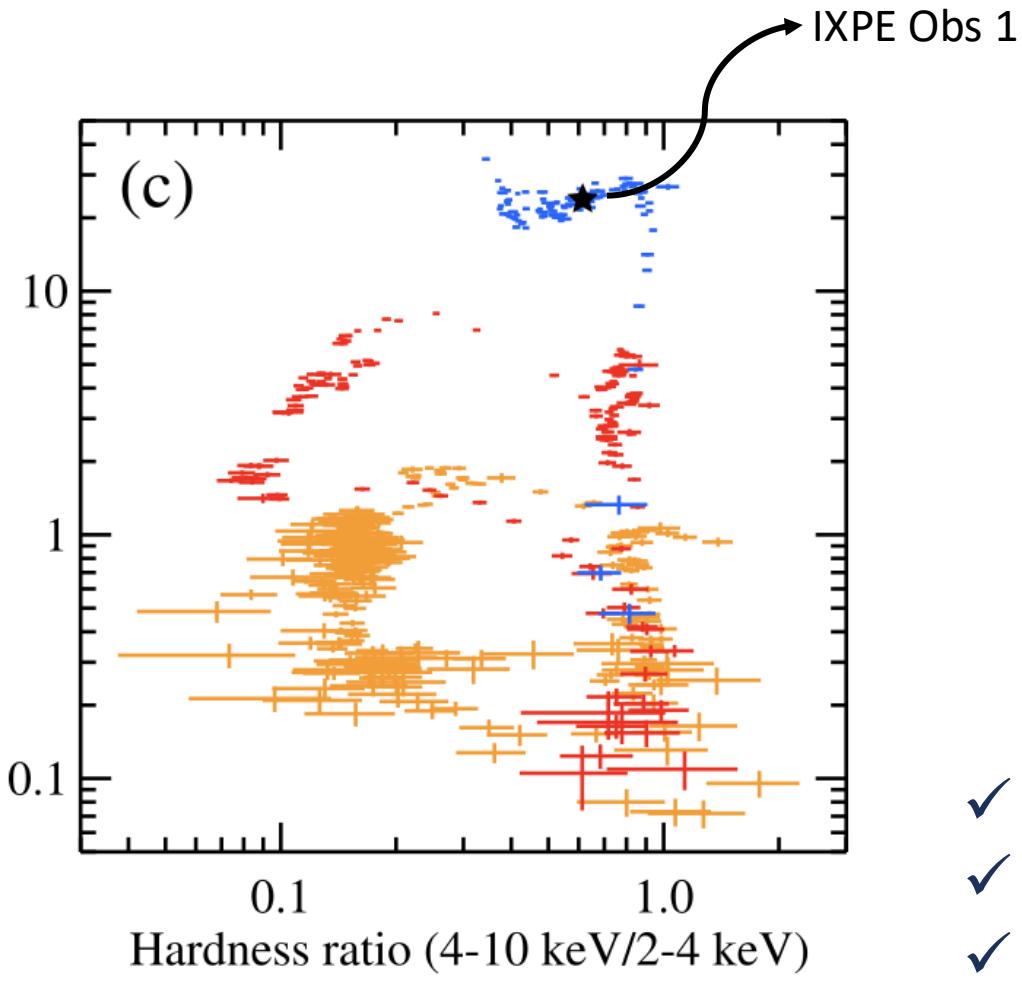
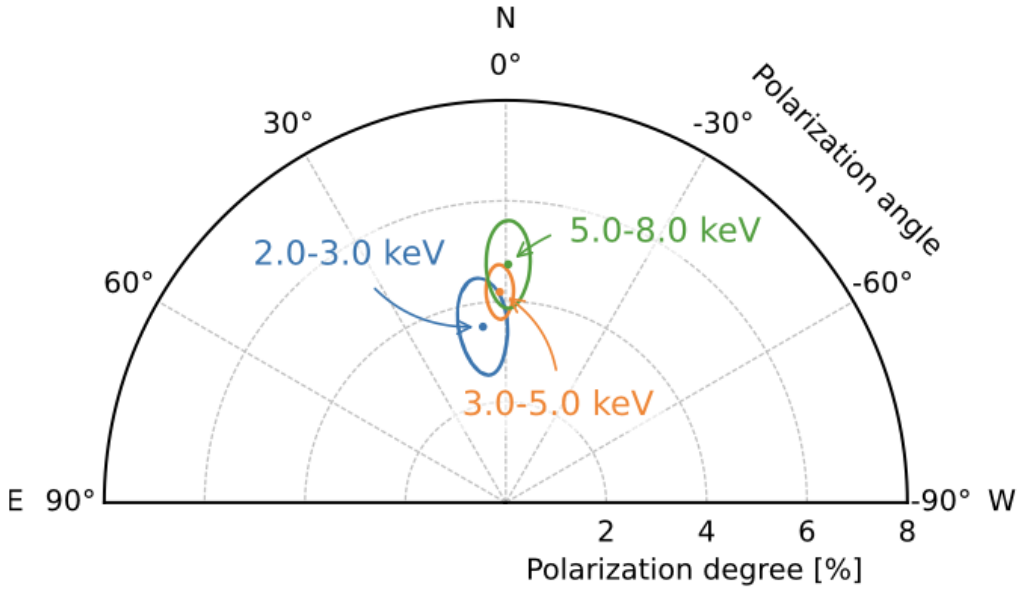
Veledina+2023



PD = $\mathbf{4.1 \pm 0.2}\%$, PA= $\mathbf{2^\circ.2 \pm 1^\circ.3}$ ($> \mathbf{20\sigma}$)



- ✓ Alignment of X-ray, optical, submillimeter PA
- ✓ Similar corona properties of Cyg X-1
- ✓ Inclination of the system constrained to $i \sim 30^\circ - 60^\circ$

Swift J1727.8-1613: Hard-to-Soft Transition

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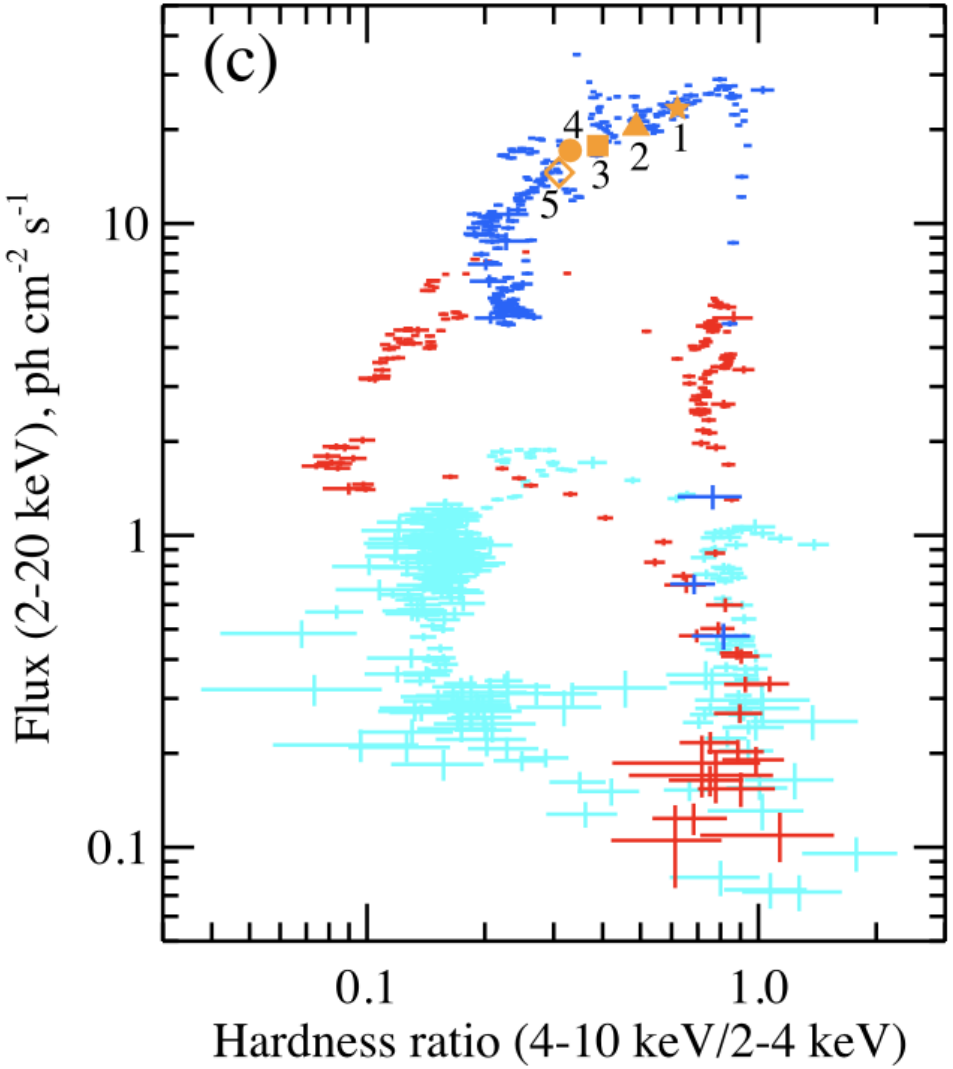
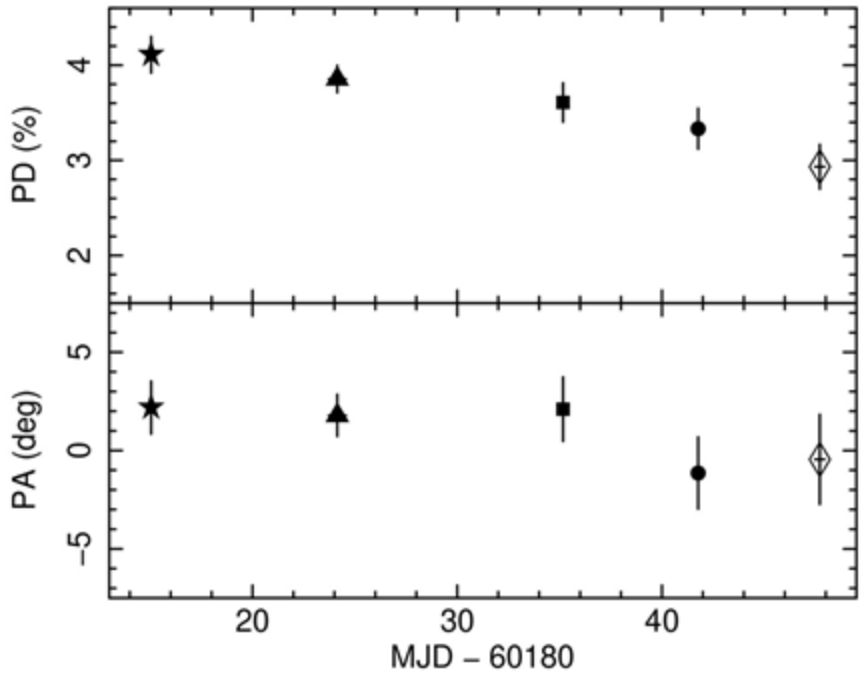
Ingram+2024





- Average PD decreasing as the source transits from the hard to the soft state
- PA roughly consistent with being constant

Swift J1727.8-1613: Soft State

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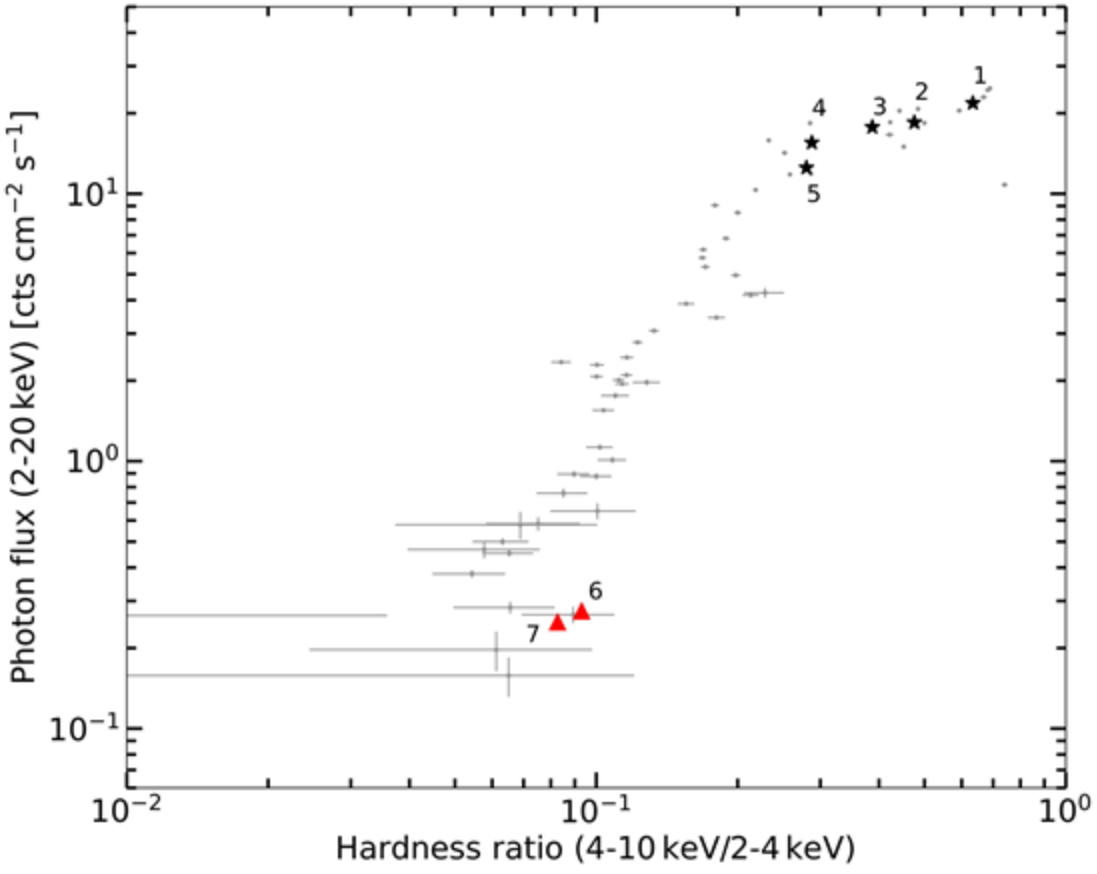
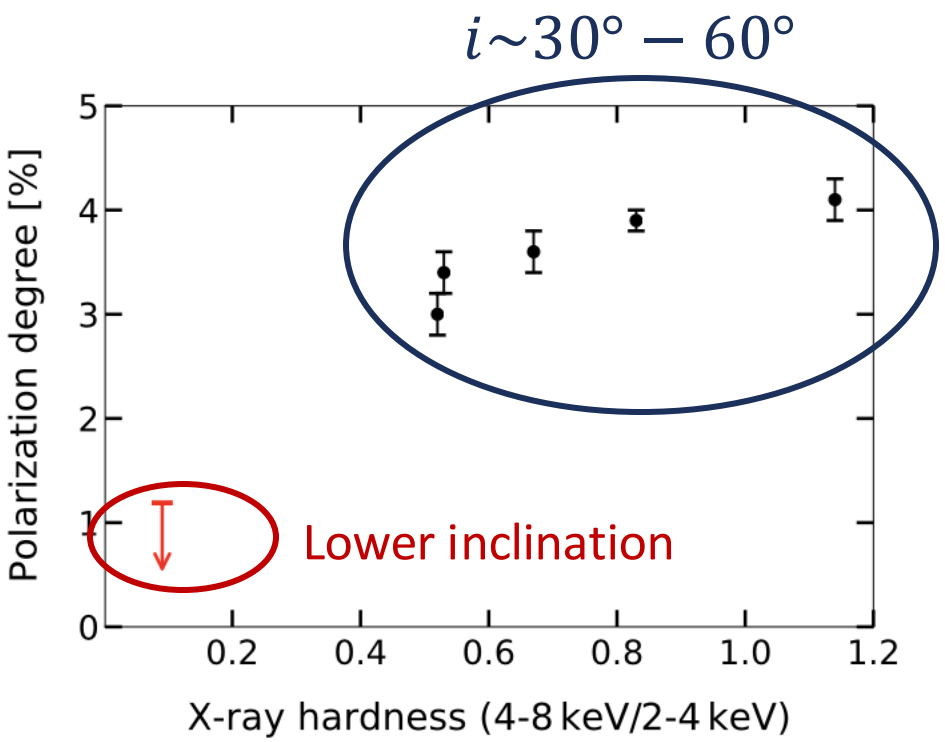
Svoboda+2023





Intermediate inclination: $i \sim 30° - 50°$

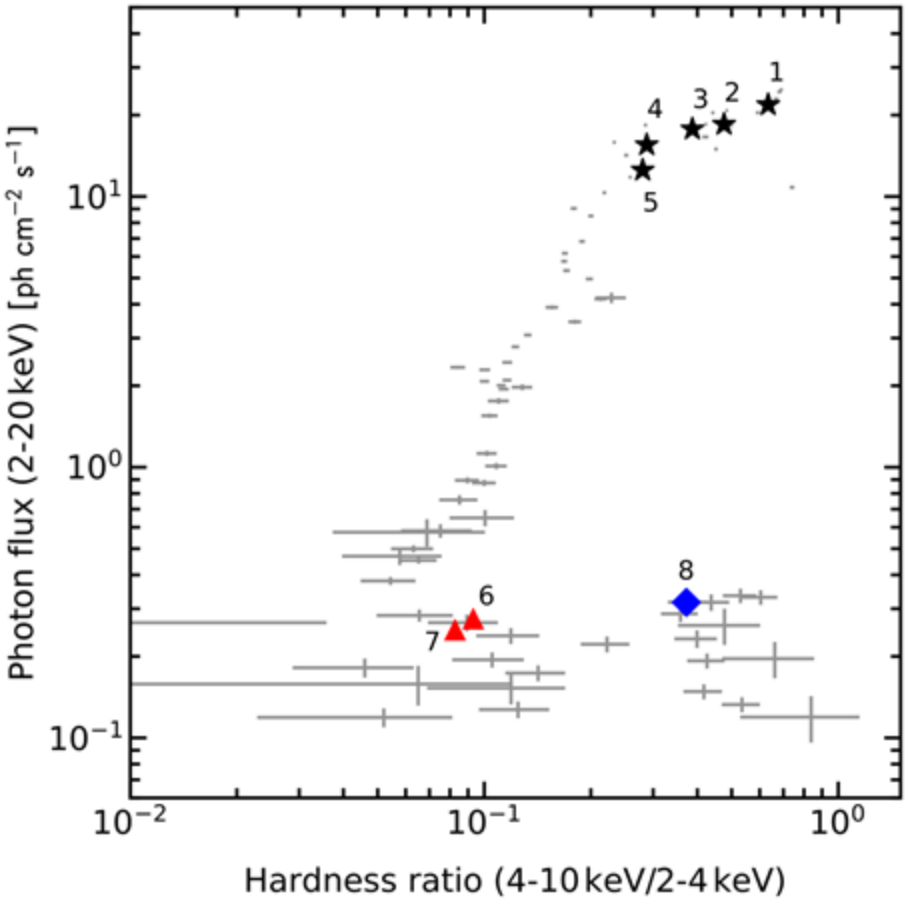
- ✓ X-ray polarization is sensitive to the accretion state

Swift J1727.8-1613: Soft-to-Hard Transition

Podgorny+2024

Hard-to-Soft: PD decreased from $\sim\mathbf{4}\%$ to $\sim\mathbf{3}\%$

Soft-to-Hard : PD = $\mathbf{3.3 \pm 0.4}\%$, PA= $\mathbf{3^\circ.3 \pm 0^\circ.4}$ $(> \mathbf{8\sigma})$



Bright hard state

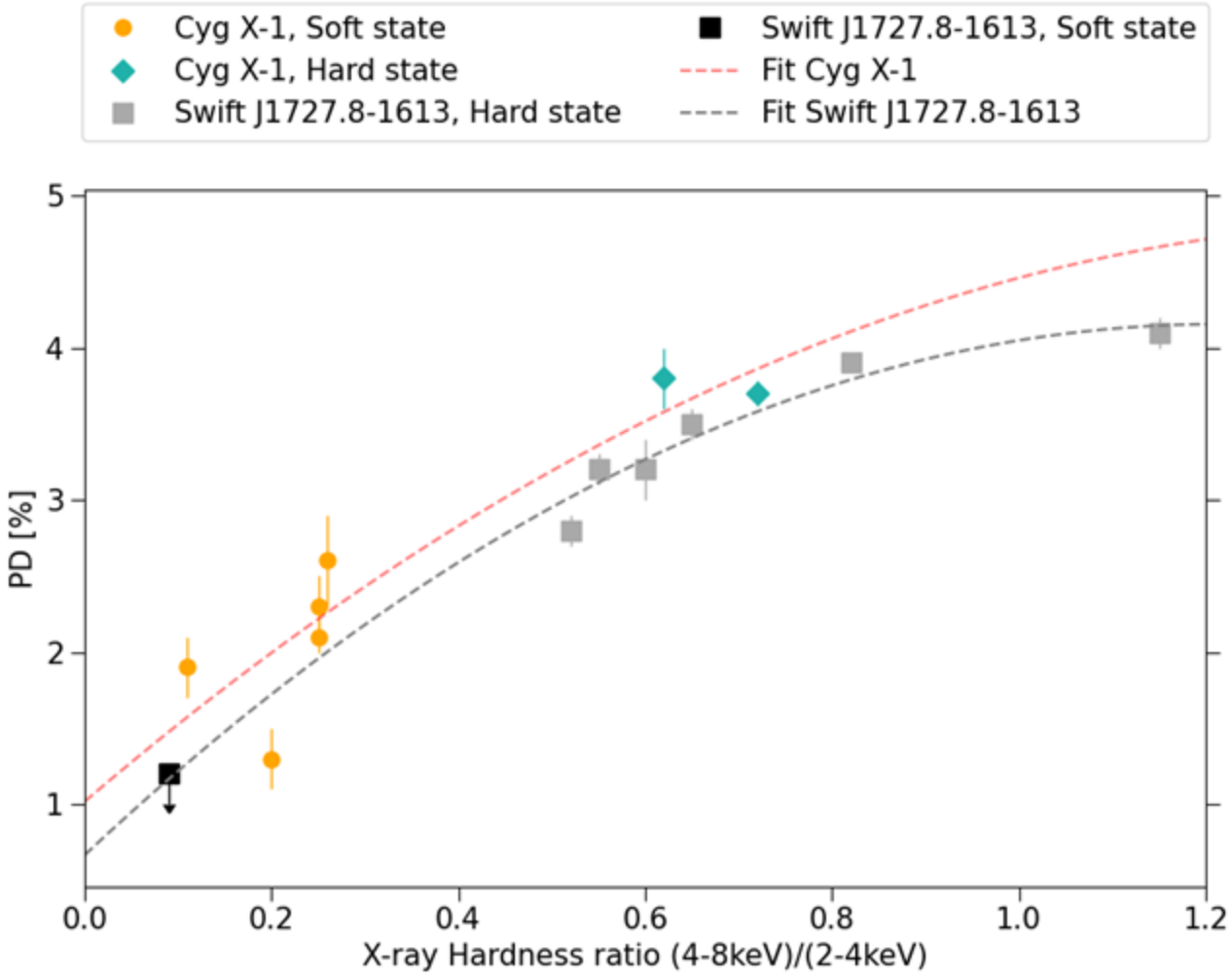
Luminosity differs by 2 orders of magnitude

Dim hard state

Same polarization properties!

✓ Accretion properties must be the same despite difference in luminosity

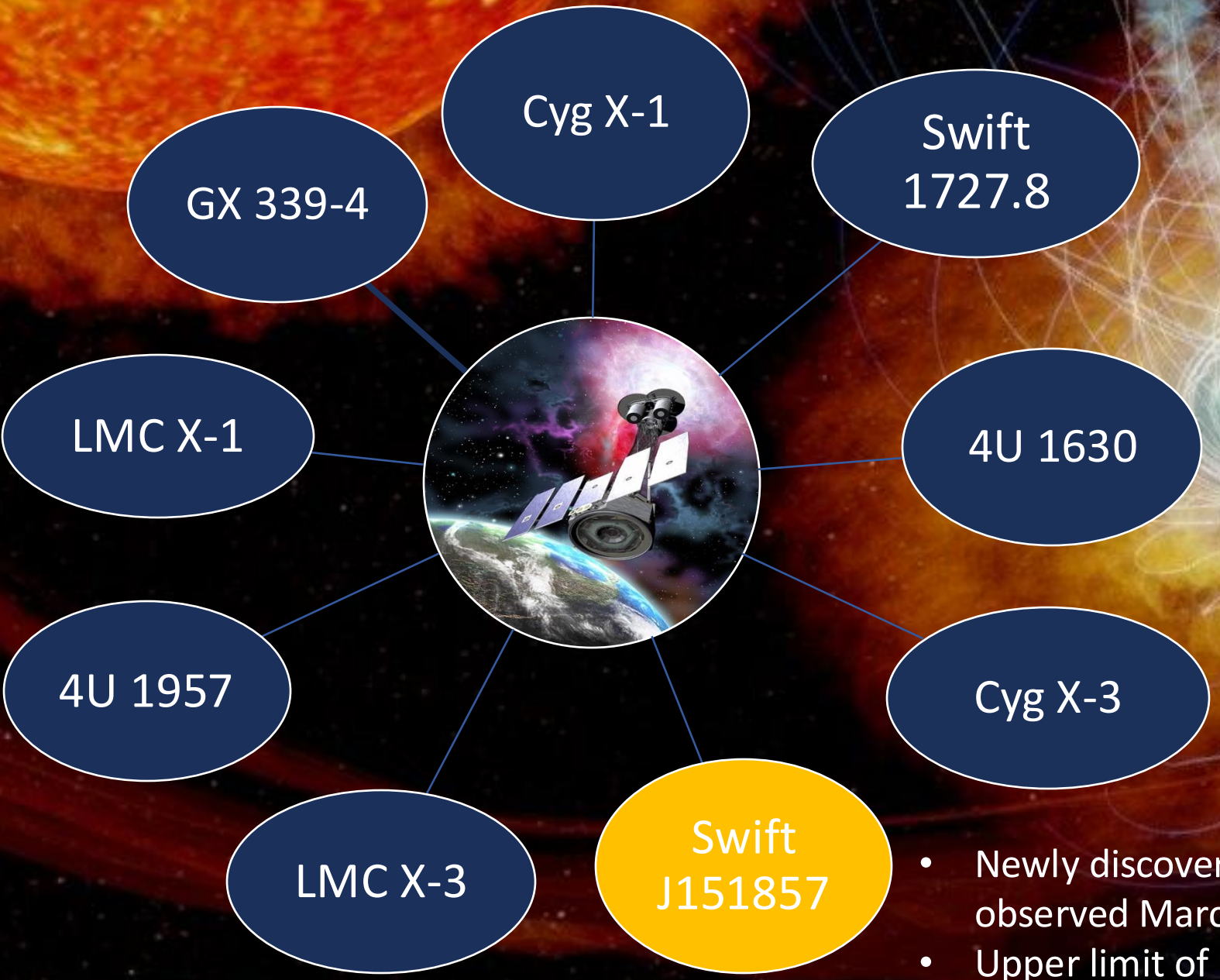
Comparison of Swift J1727.8-1613 and Cyg X-1



Brigitte et. al (in preparation)

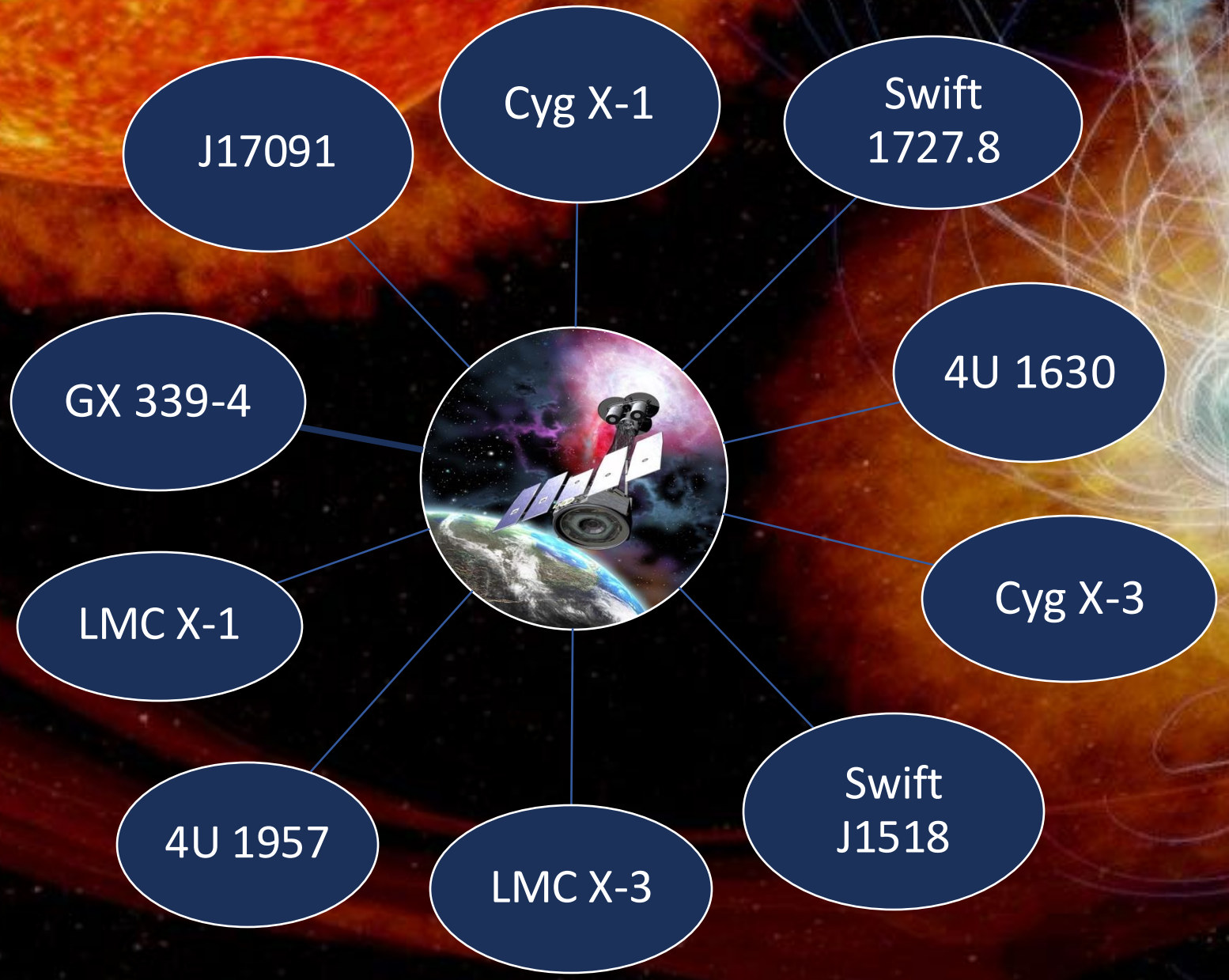
Black Hole Observations

Ling+2024



- Newly discovered transient source observed March 18, 2024
- Upper limit of 0.2%

Black Hole Observations

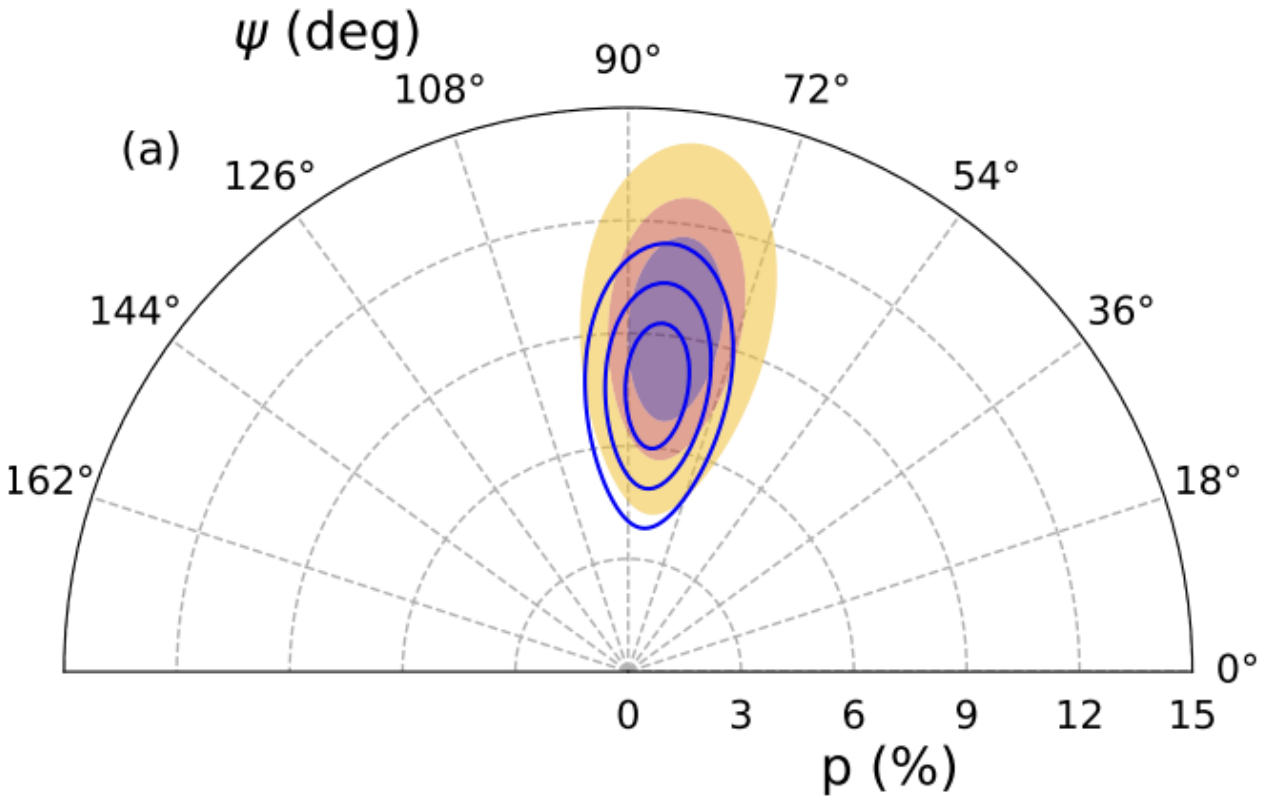


IGR J17091–3624: Hard State

Ewing+2025
(Submitted)

For the $2-8\ keV$ IXPE band ($>\mathbf{5\sigma}$):

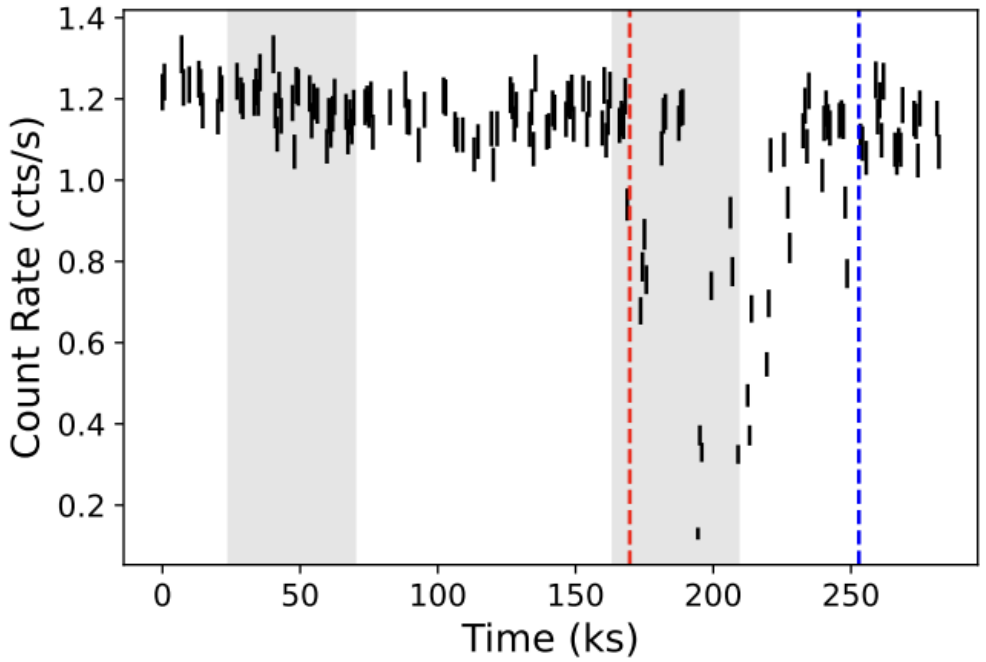
PD= $\mathbf{9.1 \pm 1.6}\%$, PA= $\mathbf{83}° \pm \mathbf{5}°$



Such a high PD requires either:

✓ High inclination angle

✓ Mildly relativistic outflow



Summary: IXPE & BH X-Ray Binaries

IXPE successfully measured the X-ray polarization of 11 accreting BH

- 3 observed in **different spectral states**:
  - Decrease of PD in soft state
  - Constant PA across states

Surprising Results:

✓PD increasing with energy

✓Higher PD than expected in several sources: e.g., 4U1630-47 (Rathesh+24, Rodriguez Cavero+23), Cyg X-3 (Veledina+24)

Main Results:

✓Corona geometry:
- Radially extended rather than lamp-post geometry or jet
- Persistent configuration in different spectral states

✓Spin measurements:
- The first BH spin constraints possible in LMC X-3 (Svoboda+24) and 4U 1957+11 (Marra+24)