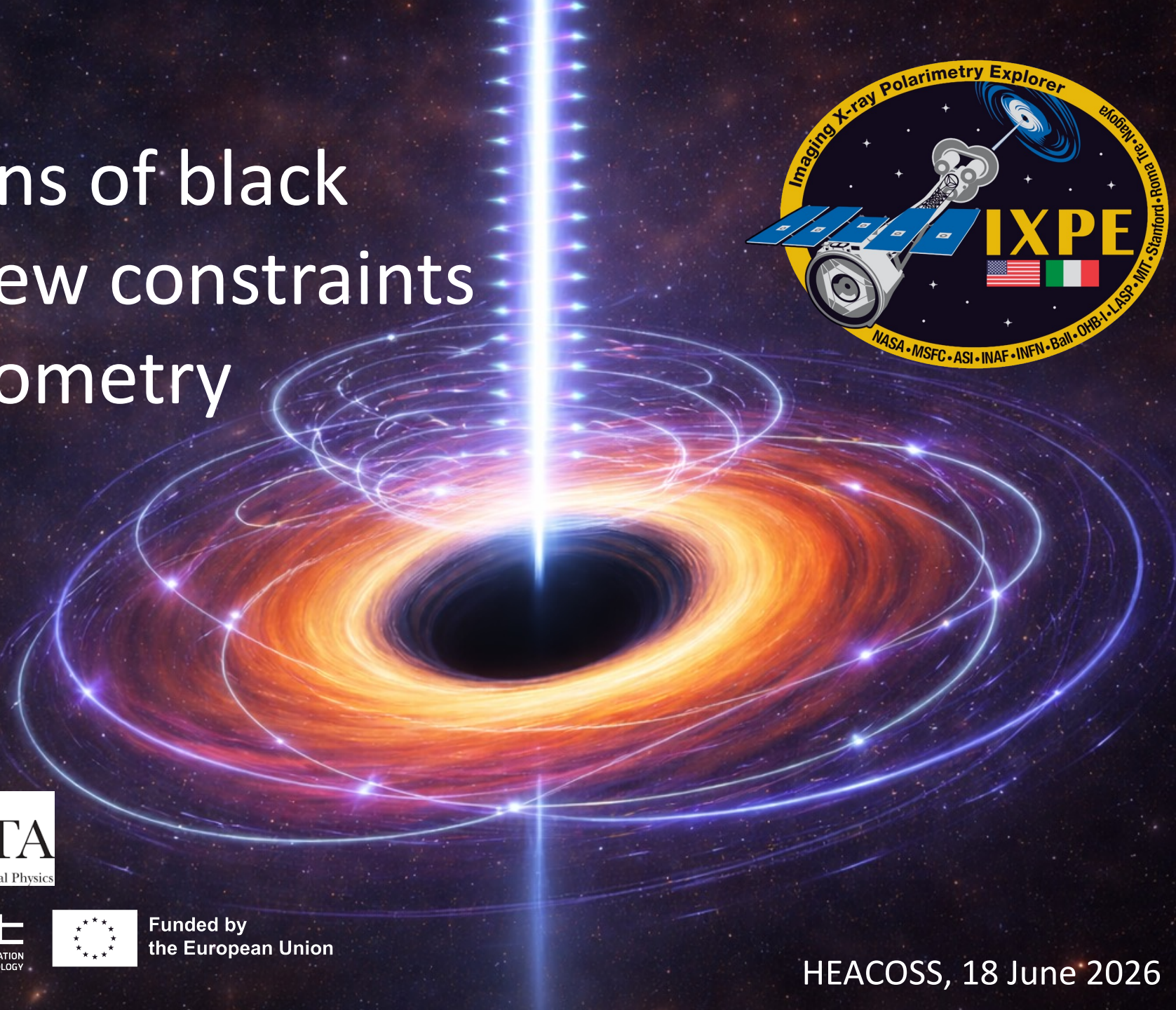
IXPE observations of black hole binaries: new constraints on accretion geometry



Alexandra Veledina

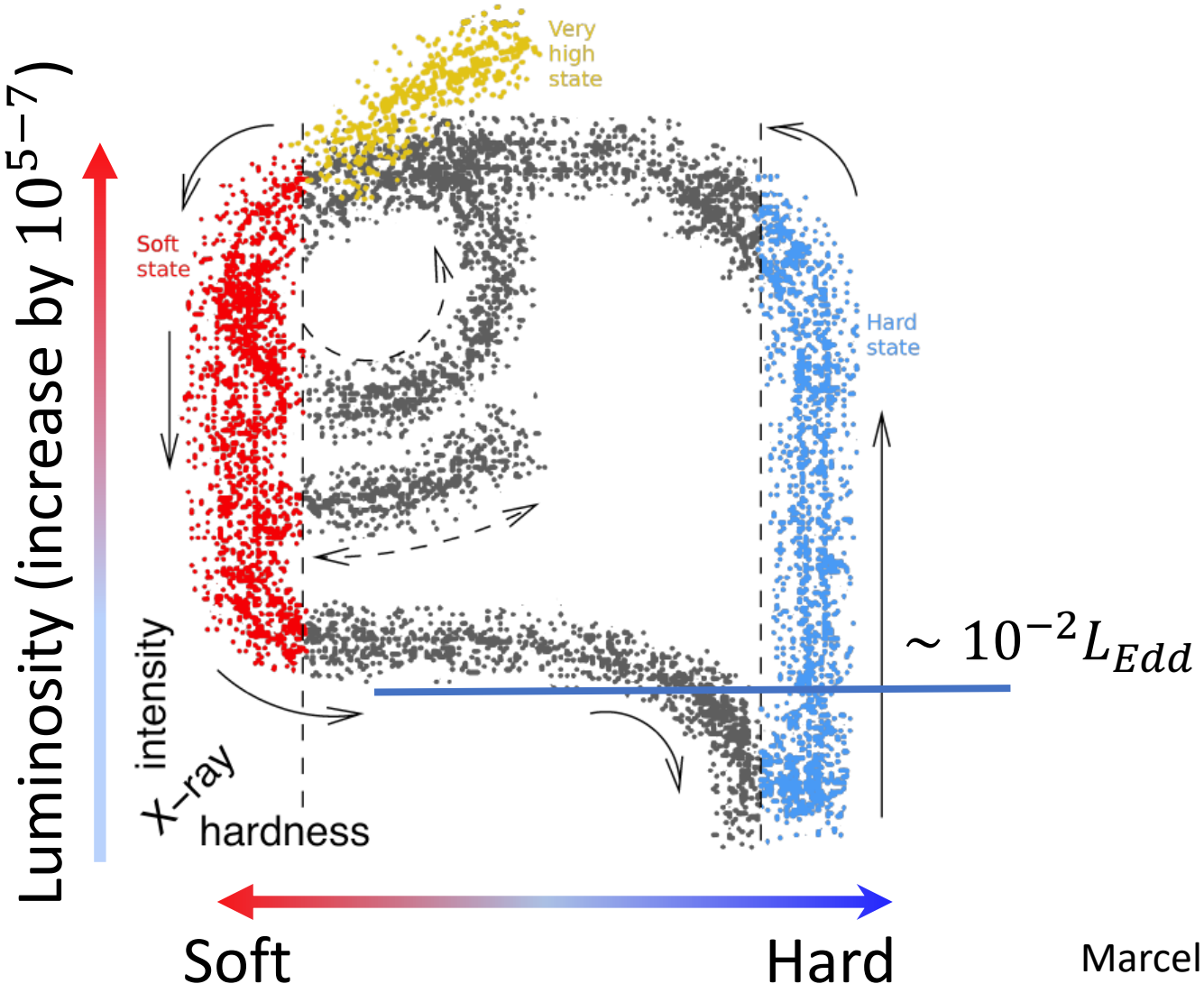
University of Turku, Finland

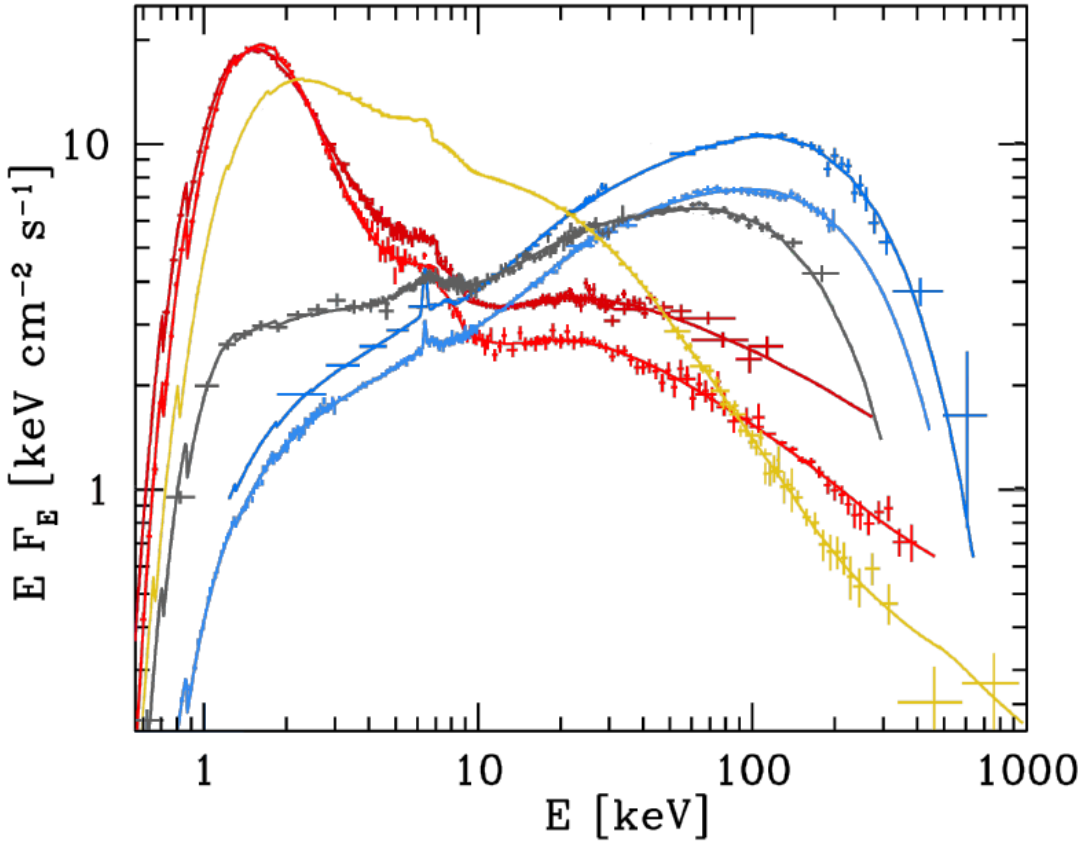
Nordita, Sweden

Funded by the European Union

HEACOSS, 18 June 2026

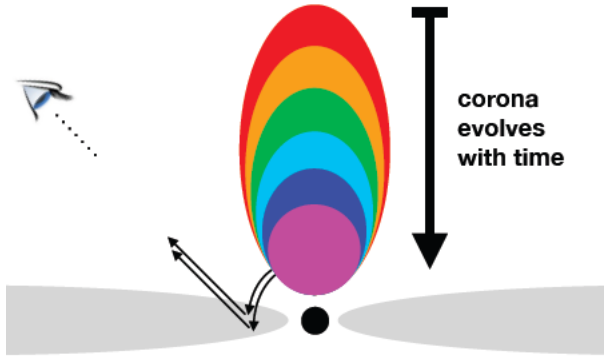
Spectral states of accreting black holes

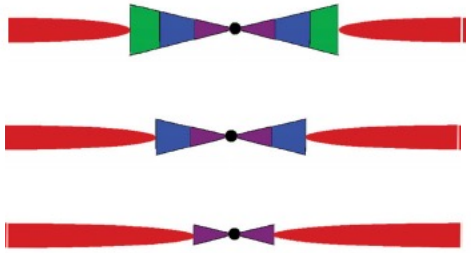




Marcel … AV, arXiv:2606.19952

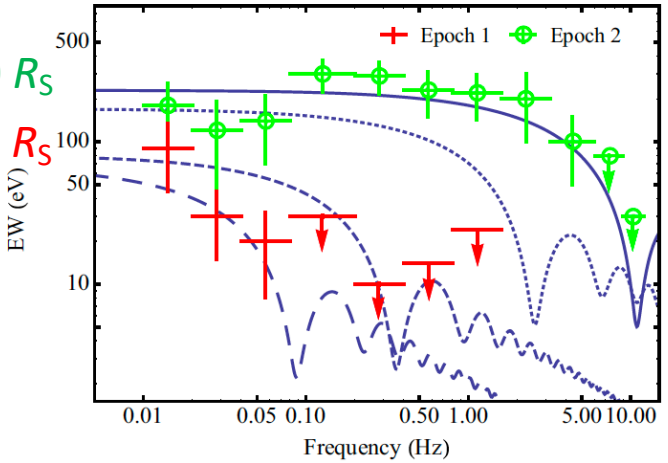
Why do we need polarization?



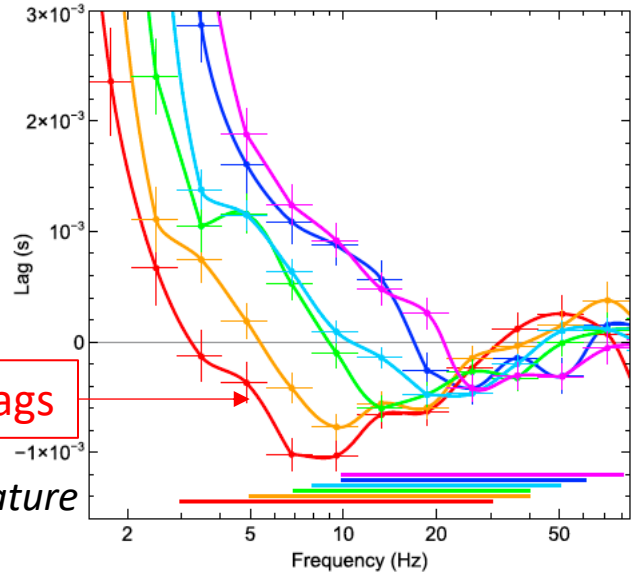


100 R_S

>1000 R_S

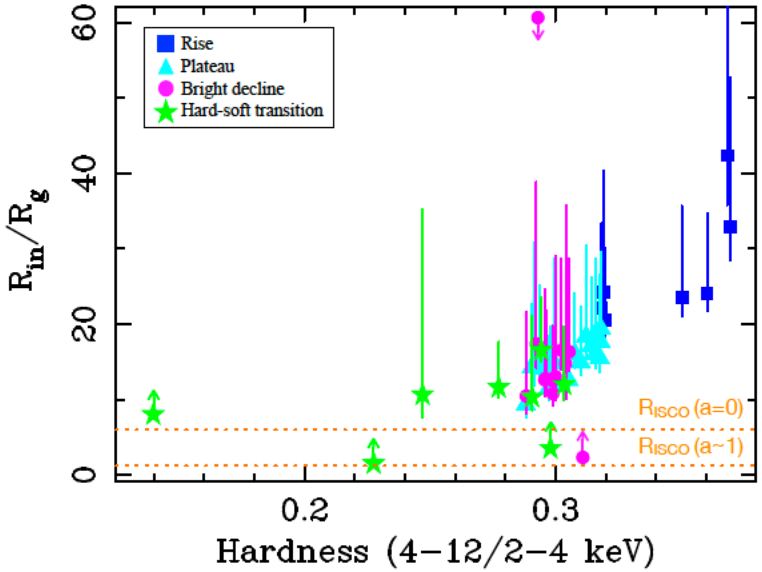


De Marco et al. 2021
Zdziarski et al. 2021
Axelsson & AV 2021



Reverberation lags

Kara et al. 2019, *Nature*
Buisson et al. 2019
Wang et al. 2021



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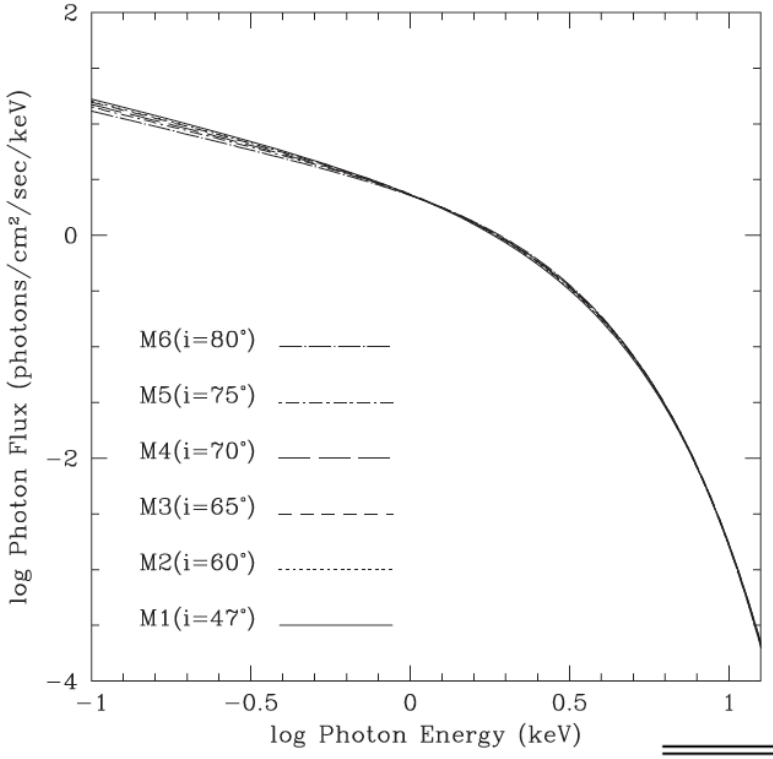
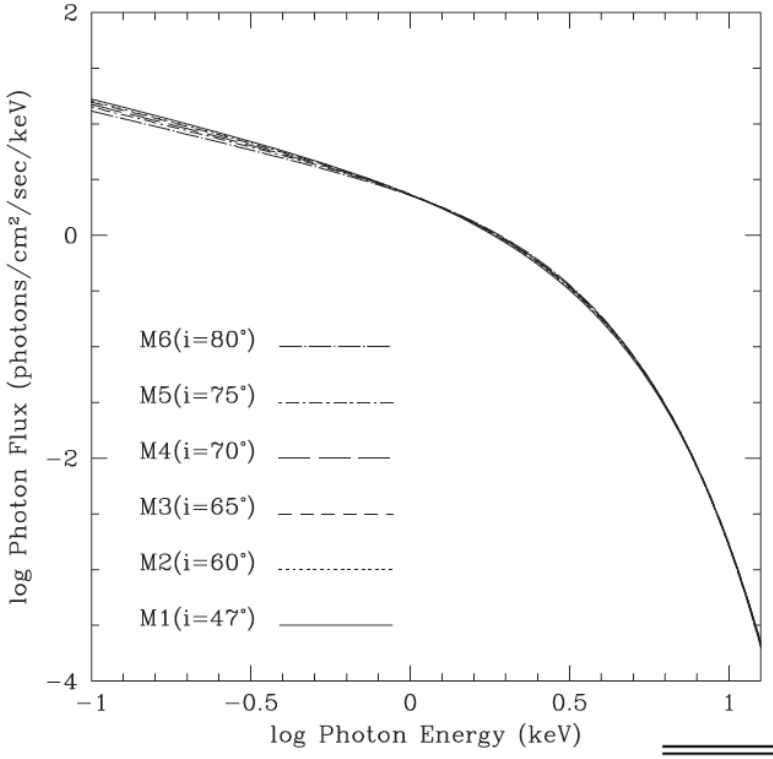
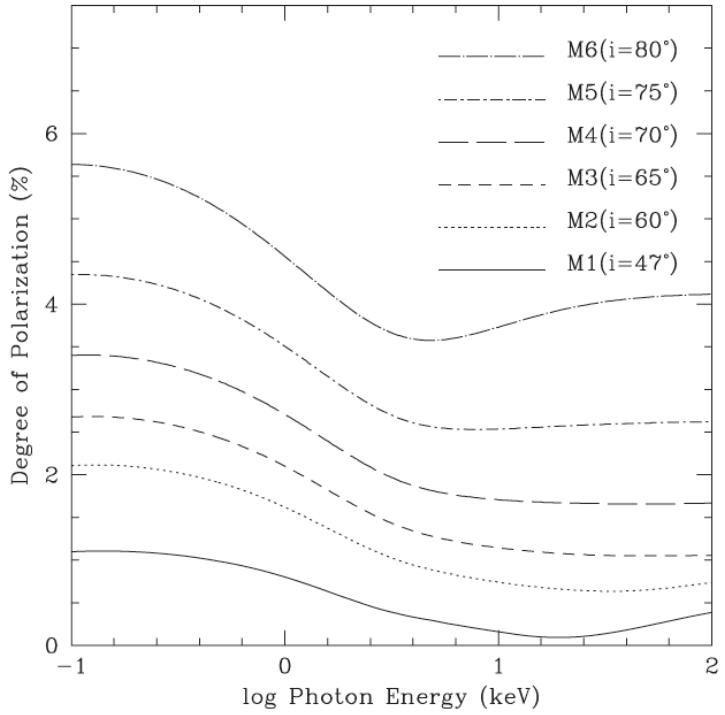


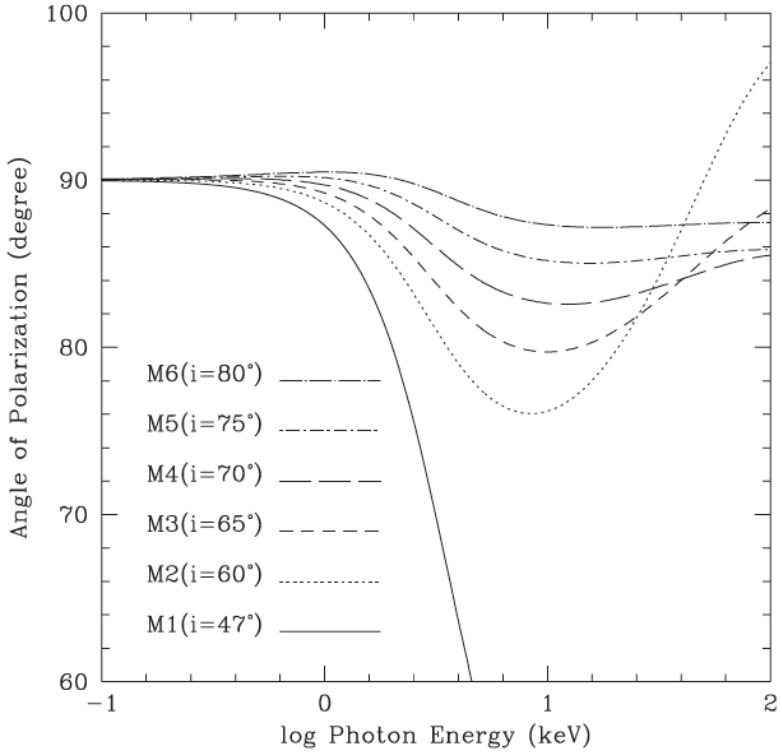
Li, Narayan & McClintock 2009

Model	a_*	$i_{\rm disk}$	$\dot{M}$
M1	0.998	47.0	0.48
M2	0.900	60.0	1.00
M3	0.830	65.0	1.40
M4	0.750	70.0	2.00
M5	0.630	75.0	3.20
M6	0.450	80.0	5.80

Why do we need polarization?







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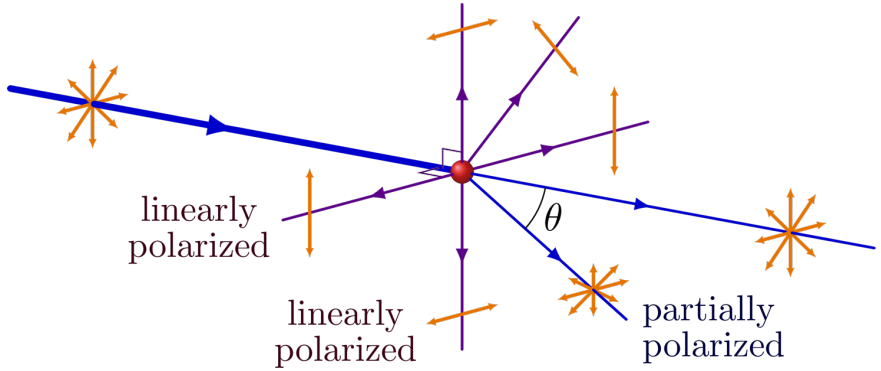
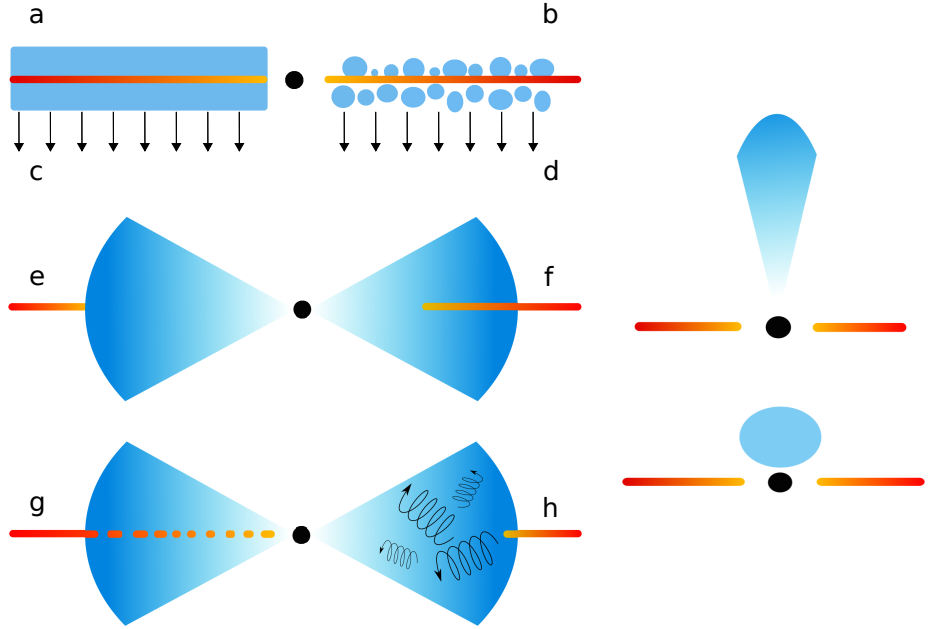
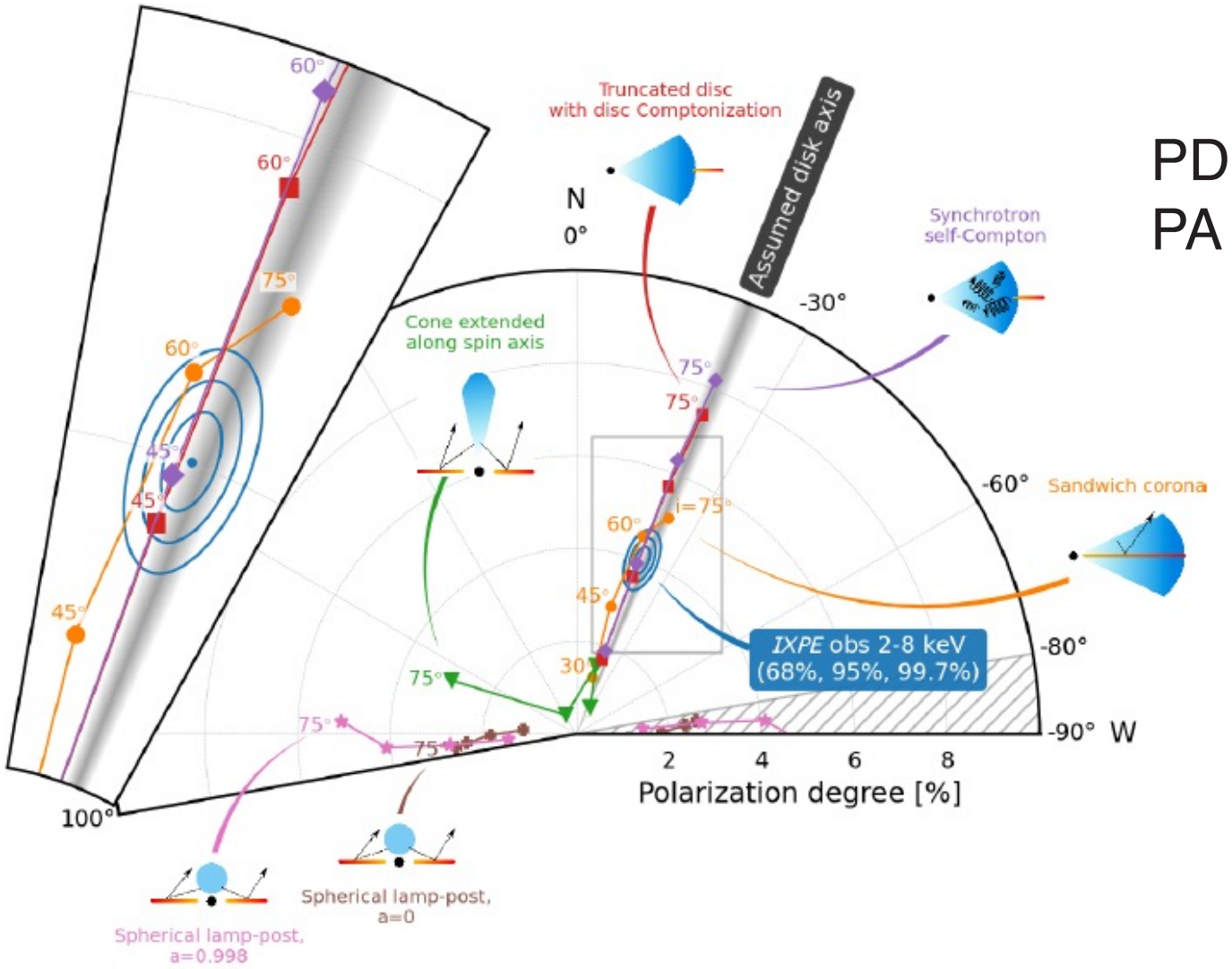
Hard state: expectations

- Sunyaev & Titarchuk 1985: Thomson scattering in a layer
- Matt et al. 1993: reflection
- Poutanen & Svensson 1996: Comptonization in slab corona (maximal polarization)
  - PD depends on the inclination and energy
  - **Up to** ~15% for highest energies, ~7% in IXPE band for $i \sim 80°$
  - PA aligned with disc axis (orthogonal to disc plane)
- Dovciak et al. 2004, 2008: lamppost corona, low polarization (spherical symmetry)
- Schnittman & Krolik 2010: returning radiation (some enhancement as compared to lamppost)
- Krawczynski & Beheshtipour 2022: cone-like corona (similar to slab, but PA orthogonal to disc axis)

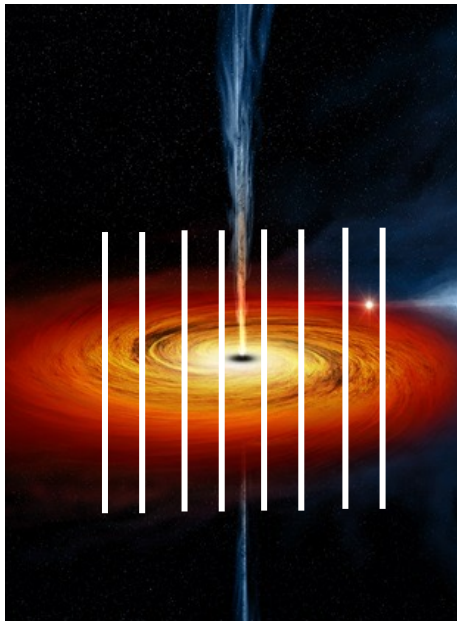




IXPE observations of Cyg X-1: surprise #1



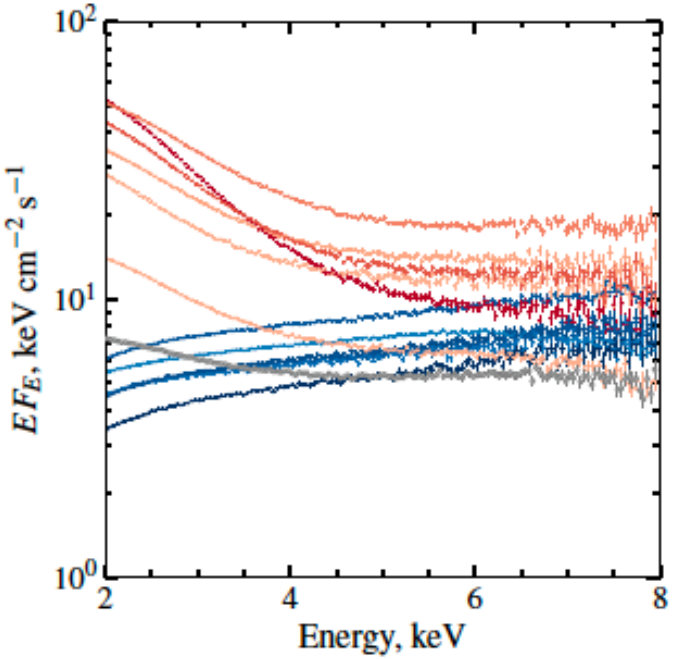
PD = 4.0 ± 0.2%
PA = -21° ± 1°

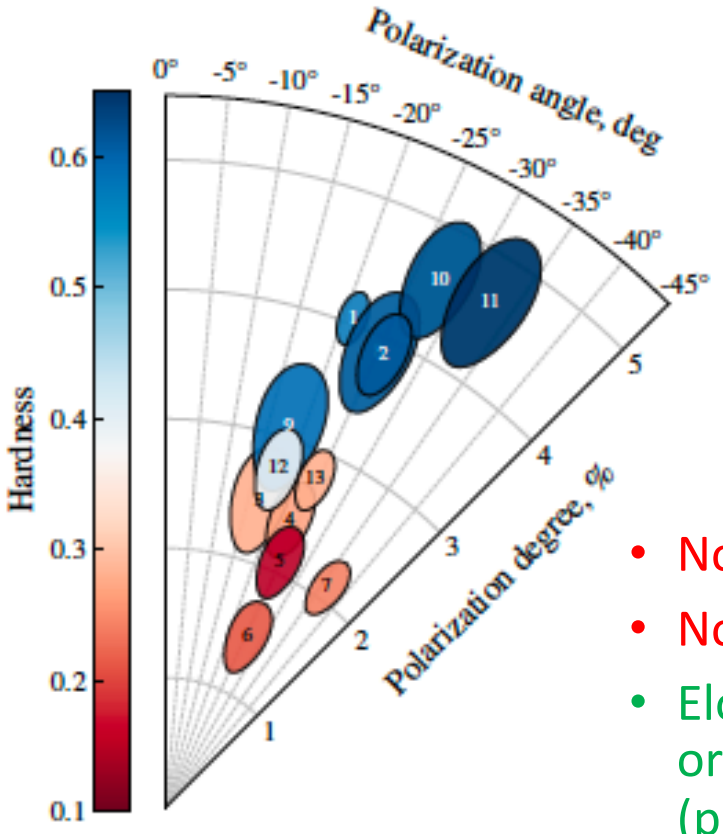


- Not cone-like
- Not spherical lamppost
- Elongated in the direction orthogonal to the jet (presumably, along the disc)
- Warp? Precession?

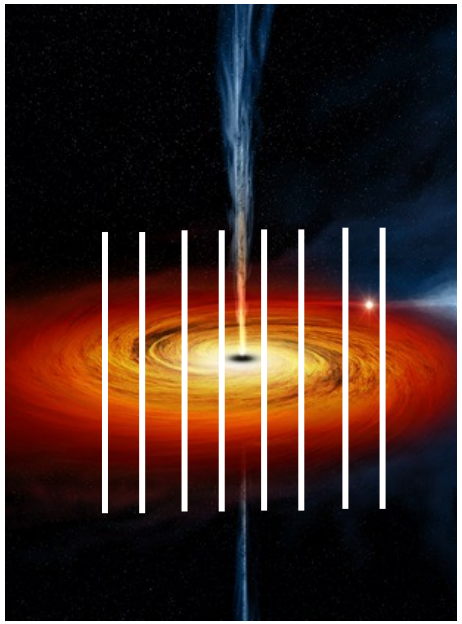
Krawczynski… AV, et al. 2022, *Science*

IXPE observations of Cyg X-1





Kravtsov, Bocharova, AV et al. 2025

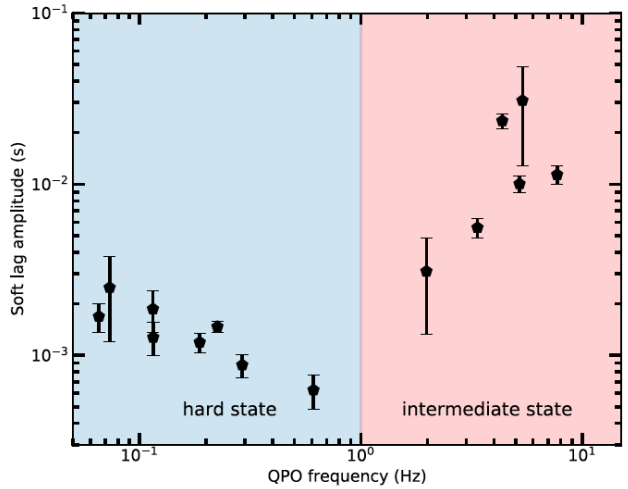


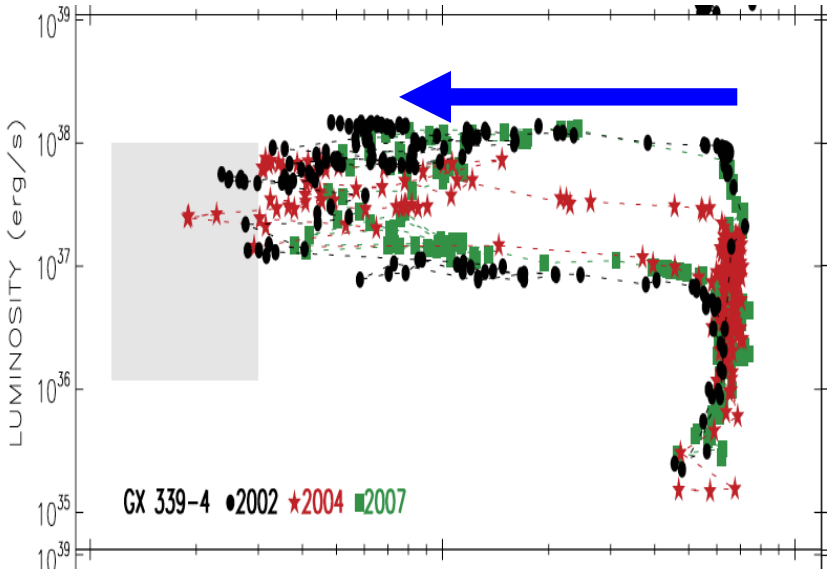
- Not cone-like
- Not spherical lamppost
- Elongated in the direction orthogonal to the jet (presumably, along the disc)
- Warp/windy accretion/outflow?

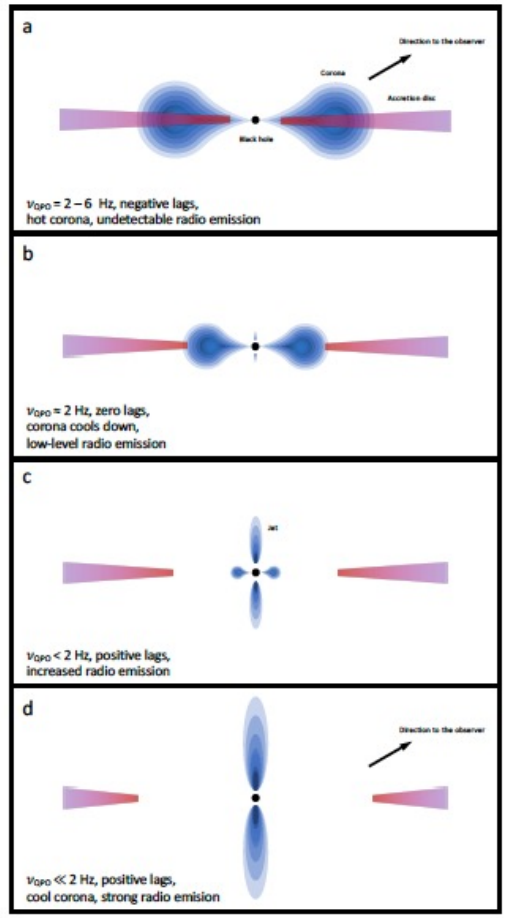
Poutanen, AV, Beloborodov 2023
Tomaru et al. 2024
Nitindata, AV et al. 2025

Evolution of accretion geometry in LMXBs?

Transition from quiescence to outburst peak and back: change of accretion geometry



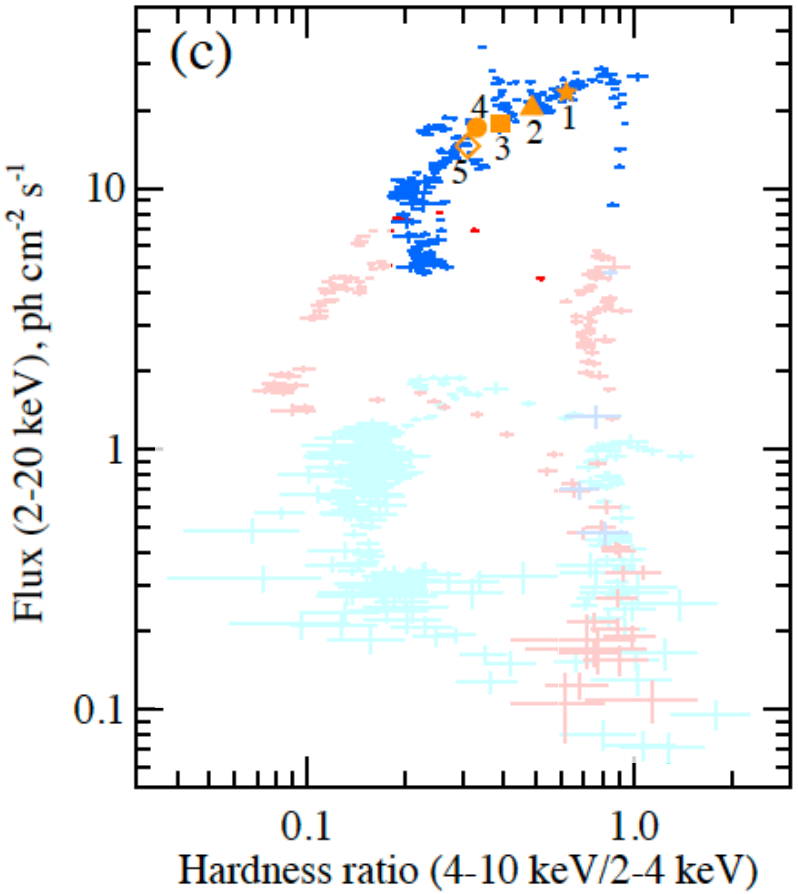


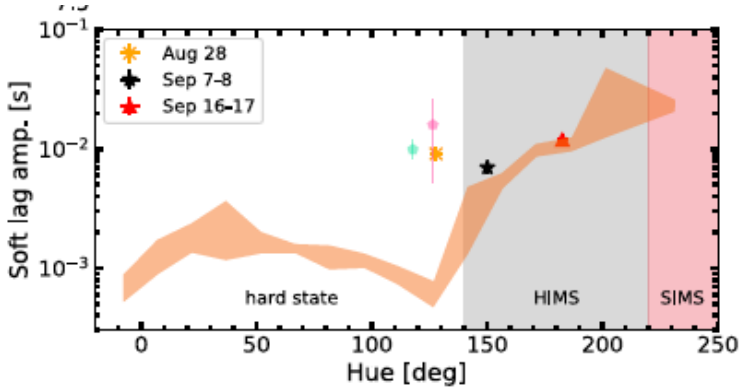


Hard state ⟷ **Soft state**

Wang et al. 2022
Mendez et al. 2022
Kylafis & Reig 2024
Uttley & Malzac 2024

Exceptionally bright LMXB Swift J1727.8–1613



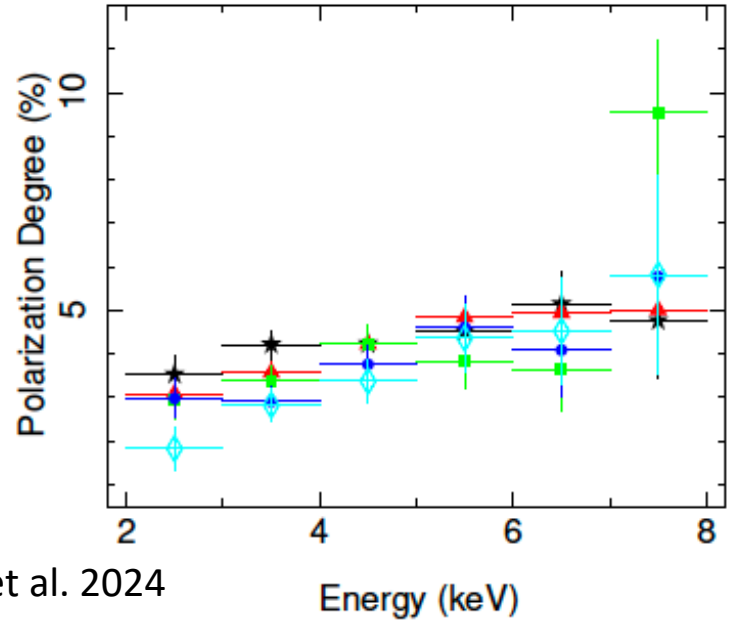


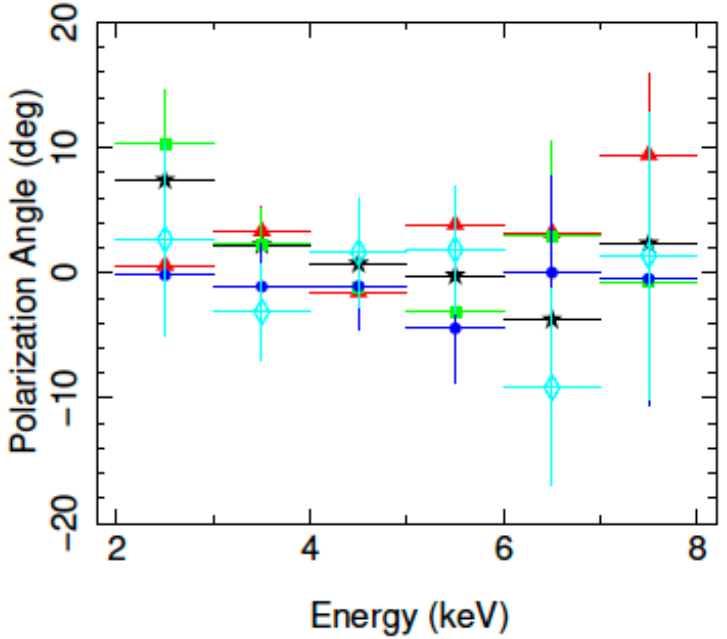
Hard state ⟷ **Soft state**

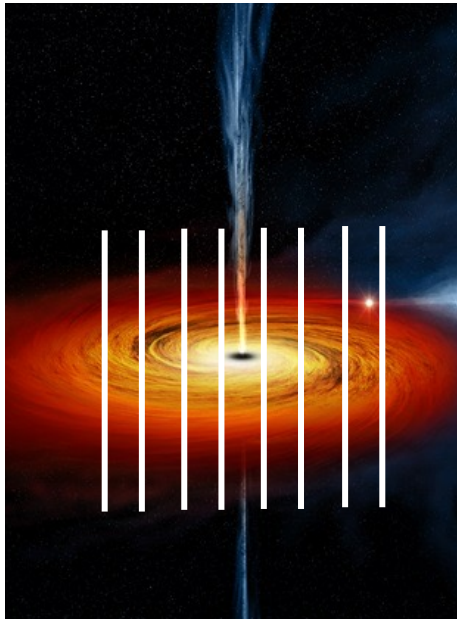
Exceptionally bright LMXB Swift J1727.8–1613

PD=4% → 3%

Polarization detection at about 20σ level





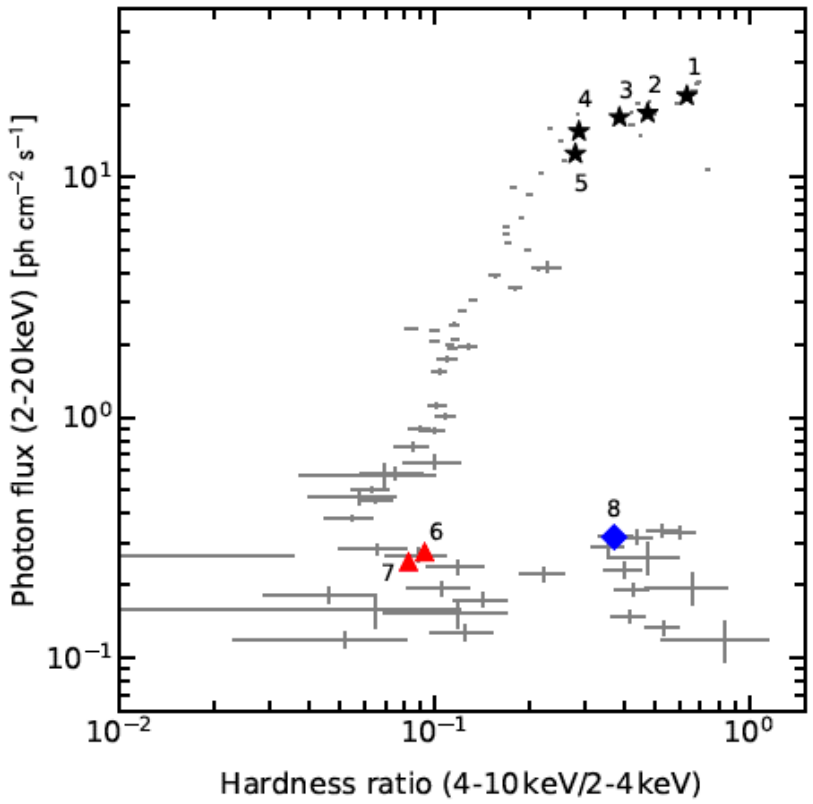


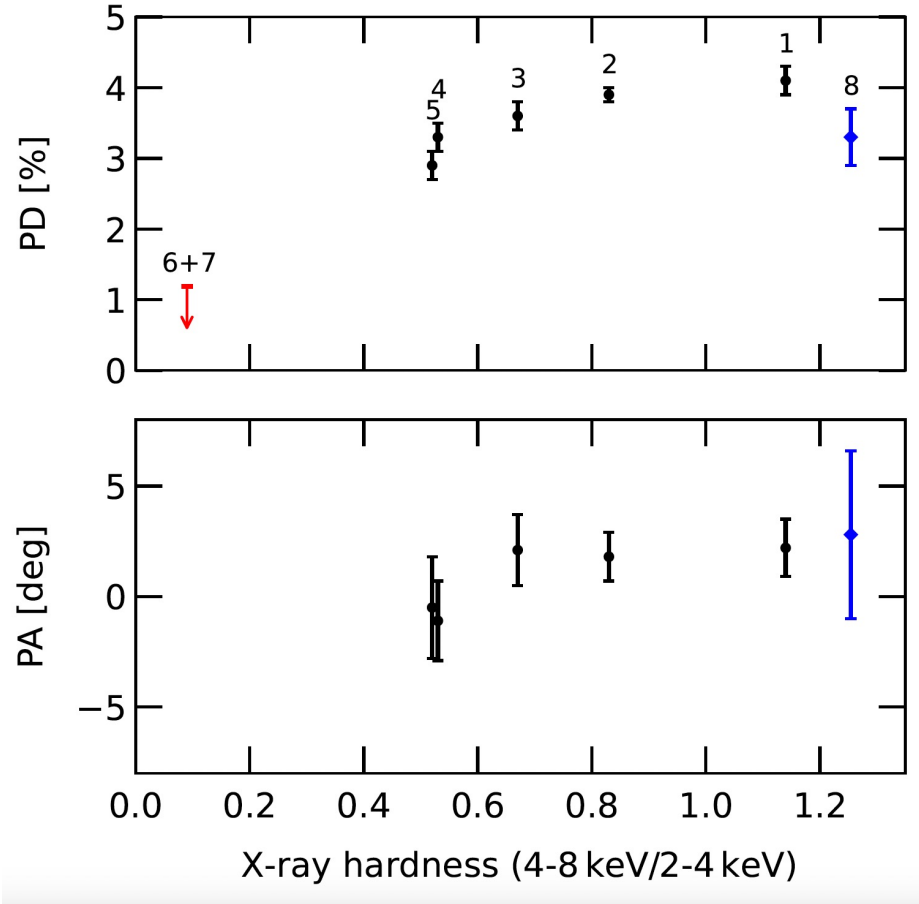
AV et al. 2023
Ingram, Bollemeijer, AV et al. 2024

- Aligned with the jet direction
- No significant changes of PA with energy or spectral state
- PD decreases as source makes transition to the soft state
- An increasing trend with energy
- Jet launching/collimation: from radii that are either aligned with BH spin or experience rapid precession around its axis

Decay of Swift J1727.8–1613: surprise #2

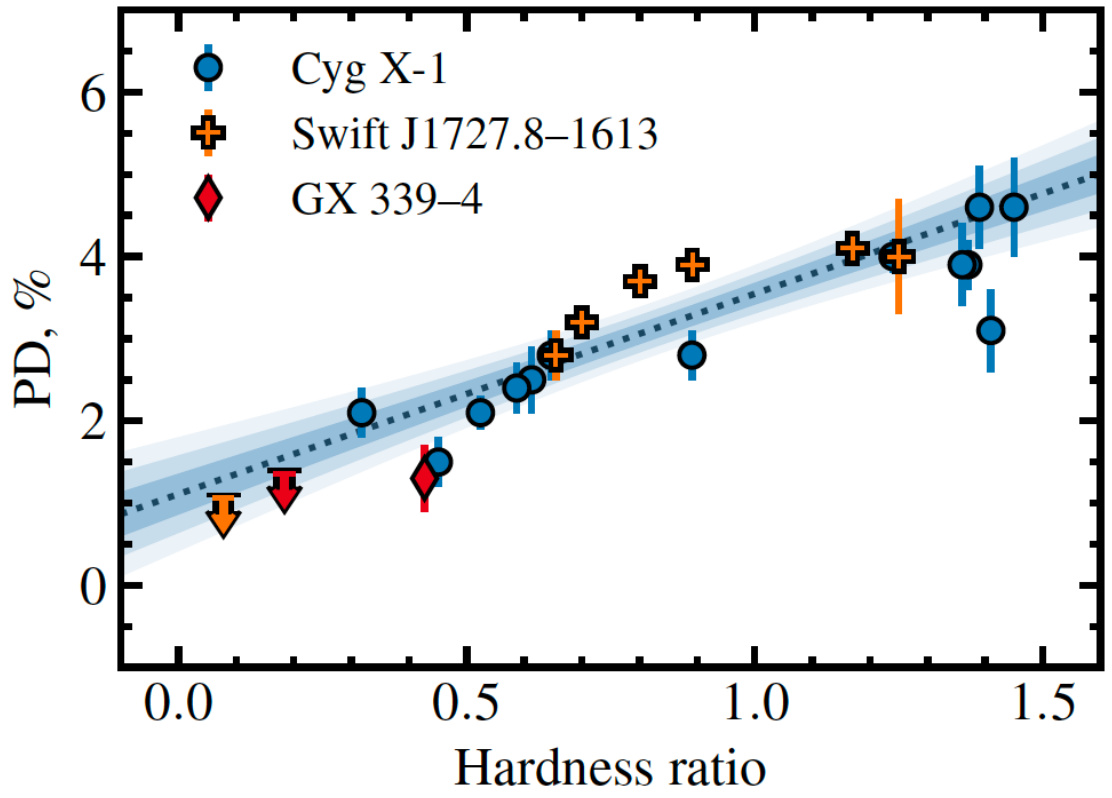
- Decaying hard state





Svoboda …AV et al. 2024
Podgorny … AV et al. 2024

Comparison between X-ray binaries

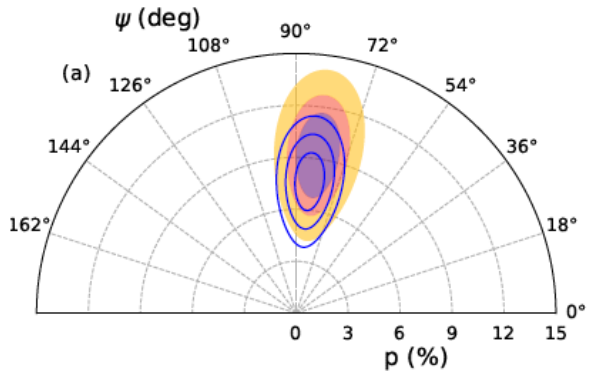


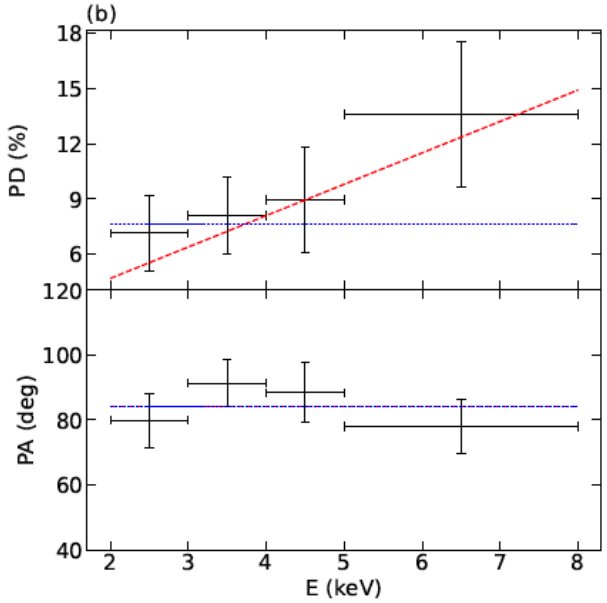
inclinations $i \approx 30° - 40°$

Soft state ⟵ ⟶ **Hard state**

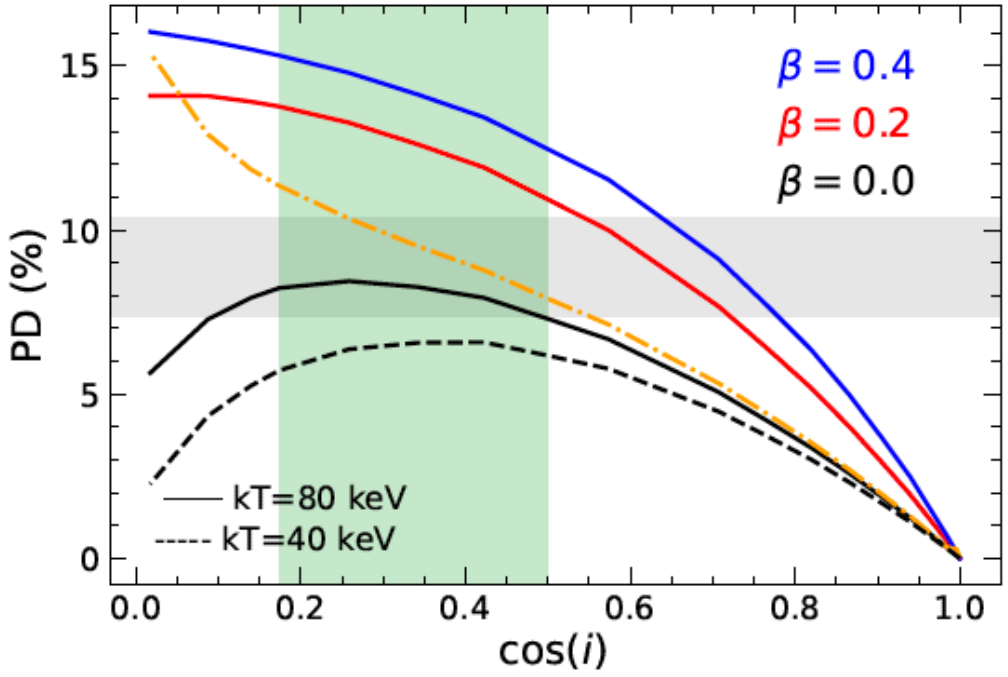
Kravtsov, Bocharova, AV et al. 2025

High-inclination source: IGR J17091−3624: the sane source, at last



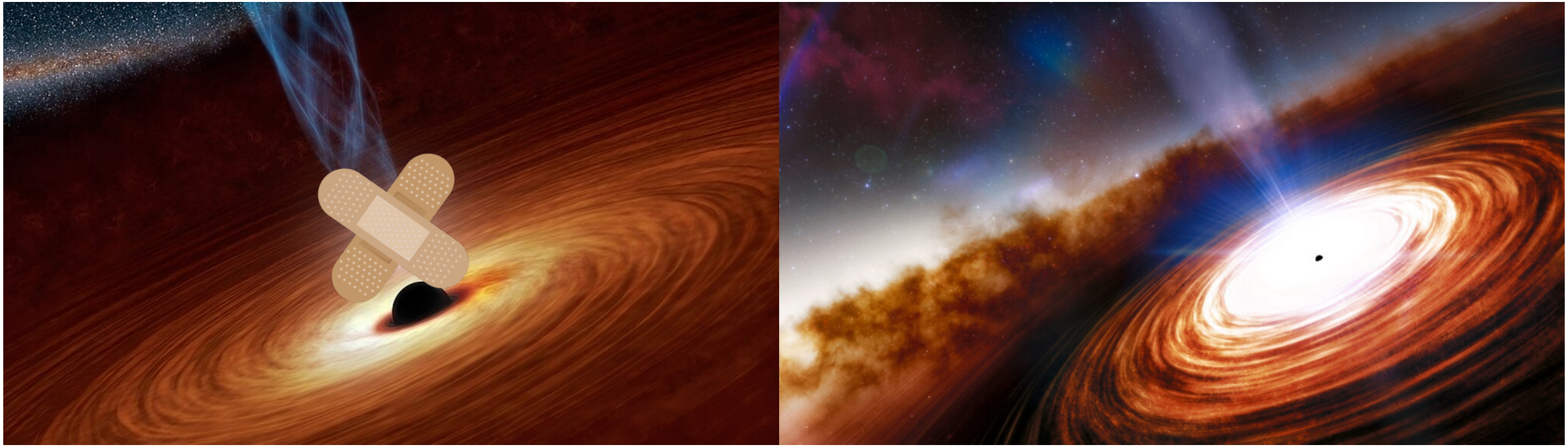


- Behaviour typical to hard-state XRB at high inclination: hard spectrum, QPOs, aperiodic dips
- High PD: 8-9%
- Aligned with optical *R* and *I* polarization



Ewing … AV et al. 2025

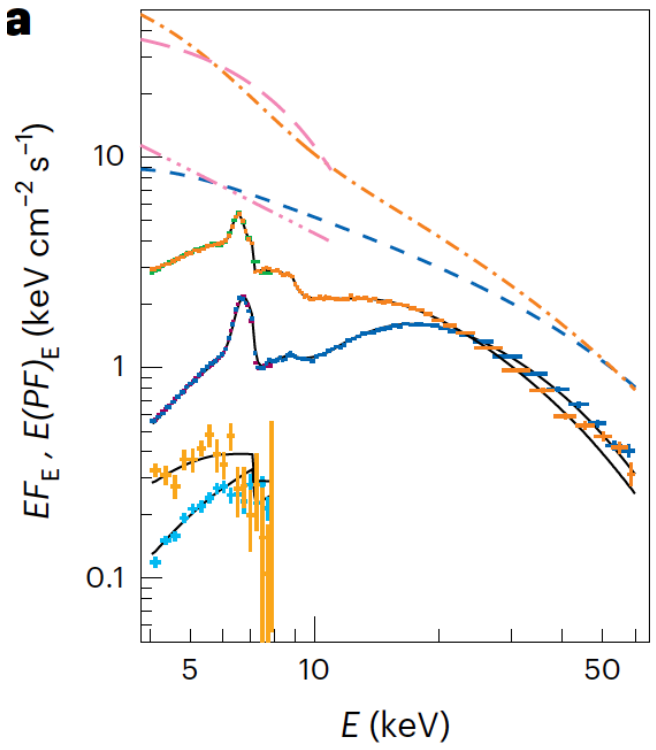
Shape of corona in X-ray binaries

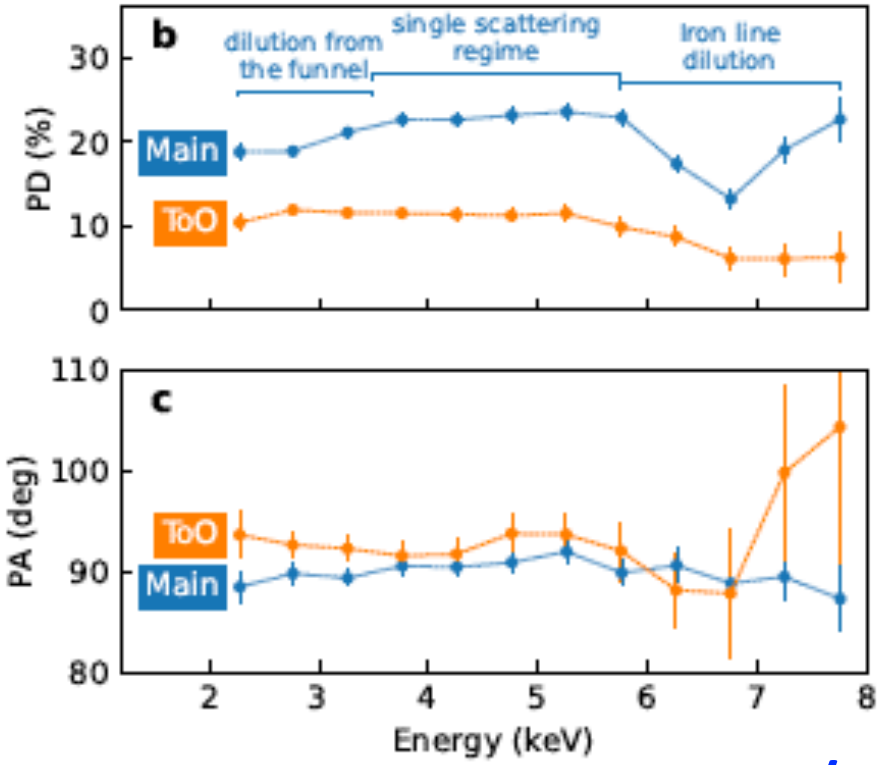


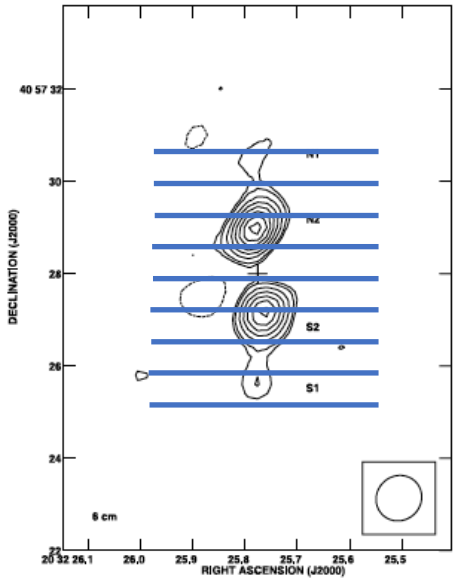
Results are consistent with extended slab corona

Krawczynski … AV et al. 2022, *Science*
AV et al. 2023
Ingram… AV et al. 2024
Podgorny… AV et al. 2024
Mastroserio et al. 2024
Ewing … AV et al. 2025
Kravtsov, Bocharova, AV et al. 2025

IXPE observations in 2022: surprise #3



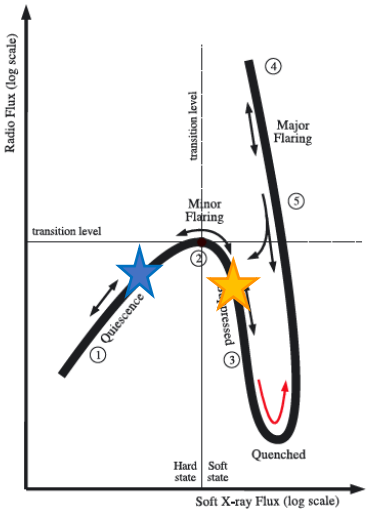




PD = 20.6 +/- 0.3 %

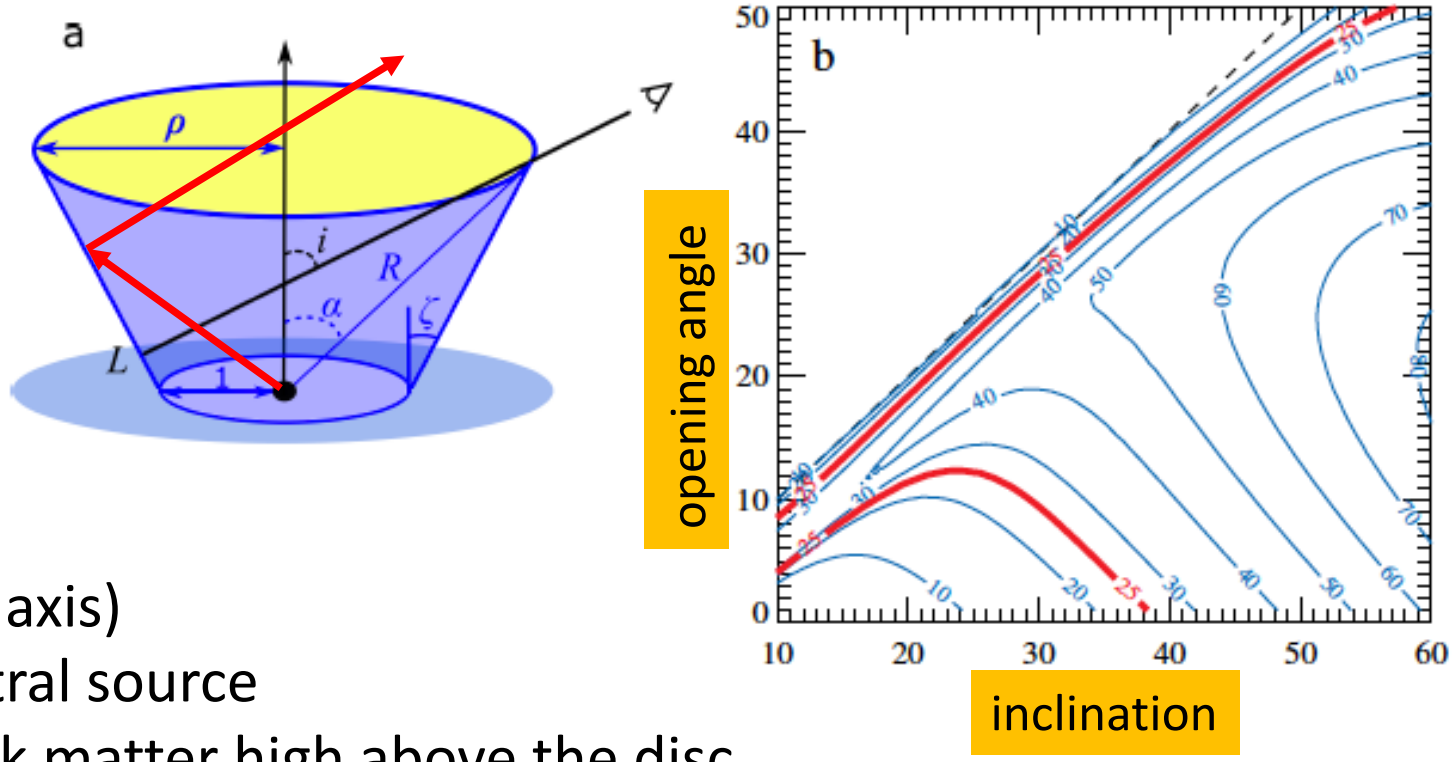
PA = 90.1 +/- 0.4°

- **High polarization!**
- **Polarization ⊥ to the jet direction**
- Constant PD/PA with energy -> single scattering
- Prominent orbital variability



AV et al. 2024, *Nature Astronomy*

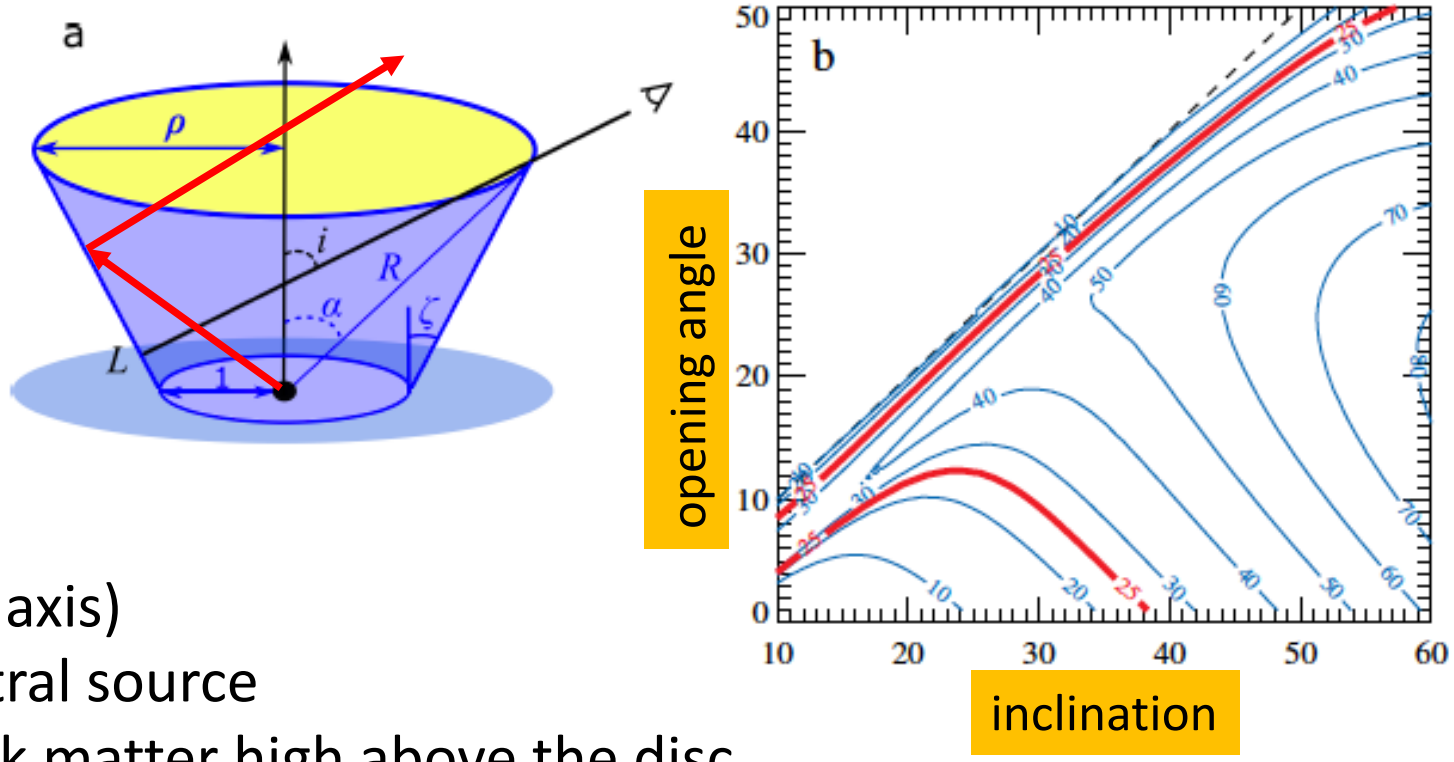
Astronomical puzzle Cyg X-3



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

AV et al. 2024, *Nature Astronomy*

Astronomical puzzle Cyg X-3



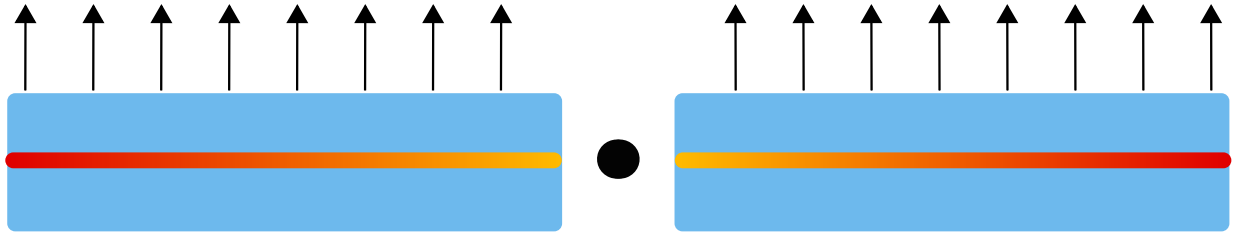
- Polarization $\perp$ jet (& binary axis)
- High PD: we do not see central source
- $i \approx 30^{o}$ hence optically thick matter high above the disc
- Apparent luminosity along the funnel: $L_{ULX} \geq 5{\times}10^{39}\mathrm{erg\ s^{-1}}$
- Bolometric luminosity: $> 3{\times}10^{39}\mathrm{erg\ s^{-1}}$ for opening angle 15^{o}

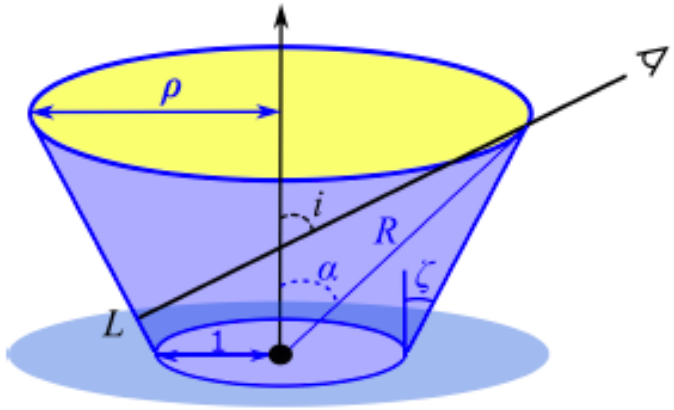
Super-Eddington accretion

AV et al. 2024, *Nature Astronomy*

Hard-state sources

- Cyg X-1 (Krawczynski et al. 2022)
- Swift J1727.8-1613 (AV et al. 2023, Ingram et al. 2024, Podgorny et al. 2024)
- Cyg X-3 (AV et al. 2024): funnel
- GX 339—4 (Mastroserio et al. 2025)
- IGR J17091−3624 (Ewing et al. 2025)

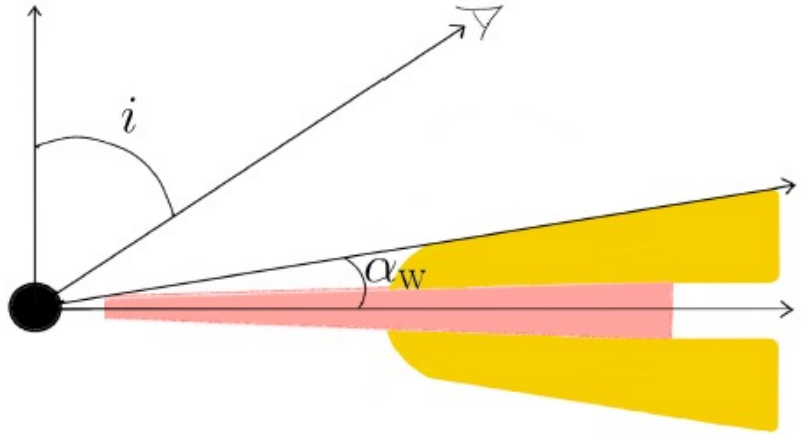


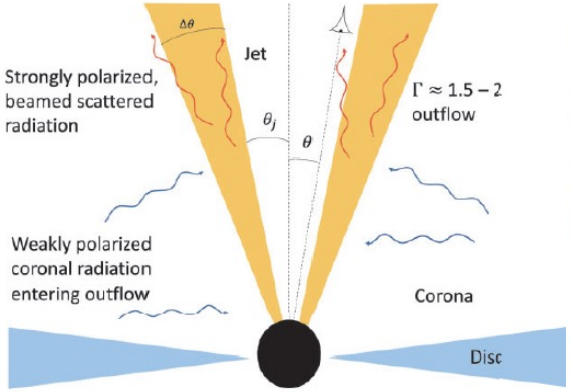


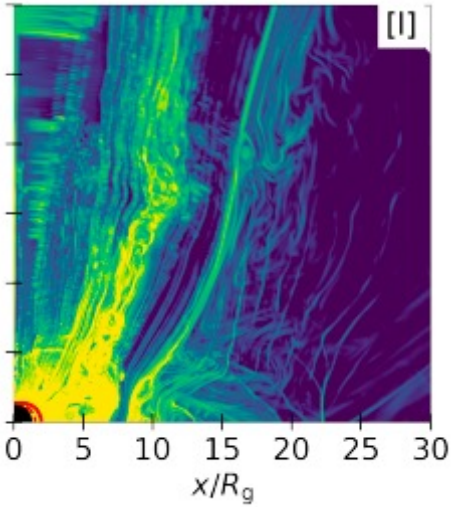
- PA=const: constraints on relativistic effects & magnetic fields
- High PD for sources at intermediate inclinations
- PD is the same for hard state at vastly different luminosities: puzzling

Alternative suggestions for polarization production

- Wind:
  - Nitindala, AV, Poutanen 2024: single scattering in the outer wind; need to have significant outflow optical depth, otherwise – only boost of corona polarization
- Jet sheath:
  - Dexter & Begelman 2024: scattering of the incident spectrum at jet-outflow interface. Challenge: small scattering fraction due to small solid angle
  - Sridhar et al. 2024: production of incident spectrum and polarization within the parabolic sheath. Challenge: too small optical depth and curved shape
- Large hot outflow:
  - Kylafis & Reig 2024: production of the incident emission in a broad, filled parabolic outflow. Challenge: curved shape of the photosphere







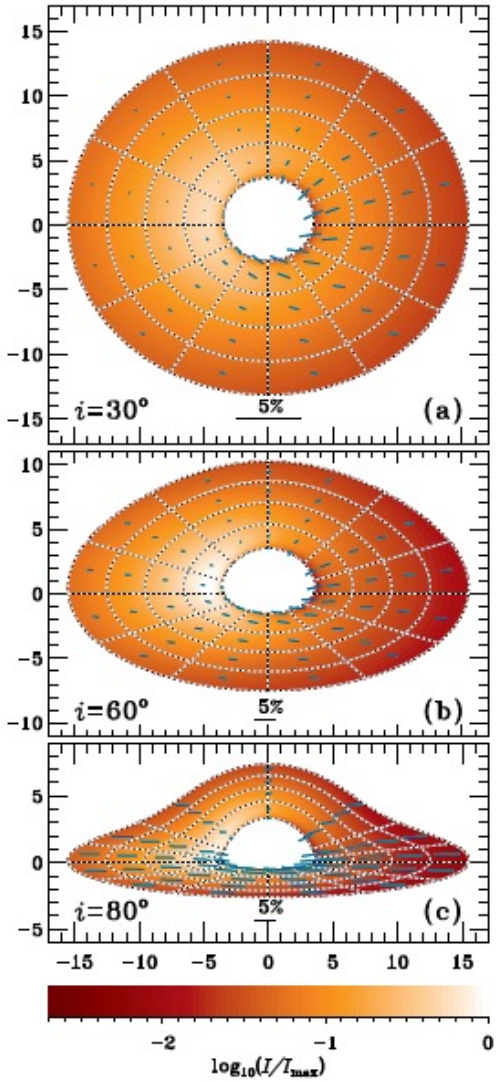
Soft state: expectations

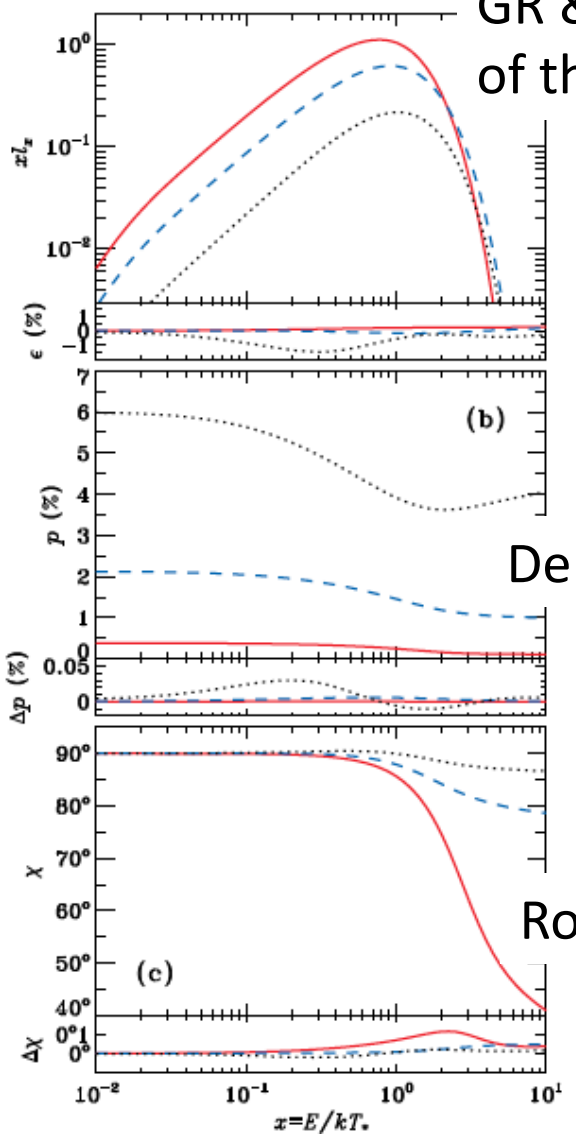
- Soft state:
  - Shakura & Sunyaev 1973, Novikov & Thorne 1973
  - Rees 1975: results of plane-parallel atmospheres (Chandrasekhar 1960, Sobolev 1963) for accretion discs with pure electron scattering, PA along the disc surface

$$\mathrm{PD} = 11.7\% \frac{1 - \cos i}{1 + 3.58 \cos i}$$

  - Loskutov & Sobolev 1979, 1980, Taverna et al. 2021: absorption effects
  - Stark & Connors 1977, Pineault 1980, Dovciak et al. 2008, Loktev et al. 2022, 2024: GR and SR effects
    - Depolarization
    - PA rotation
  - Schnittman & Krolik 2009, 2010: self-irradiation

Soft state: expectations





GR & SR: change of the spectral shape

Depolarization

Rotation of PA

$i = 80°$ ·····

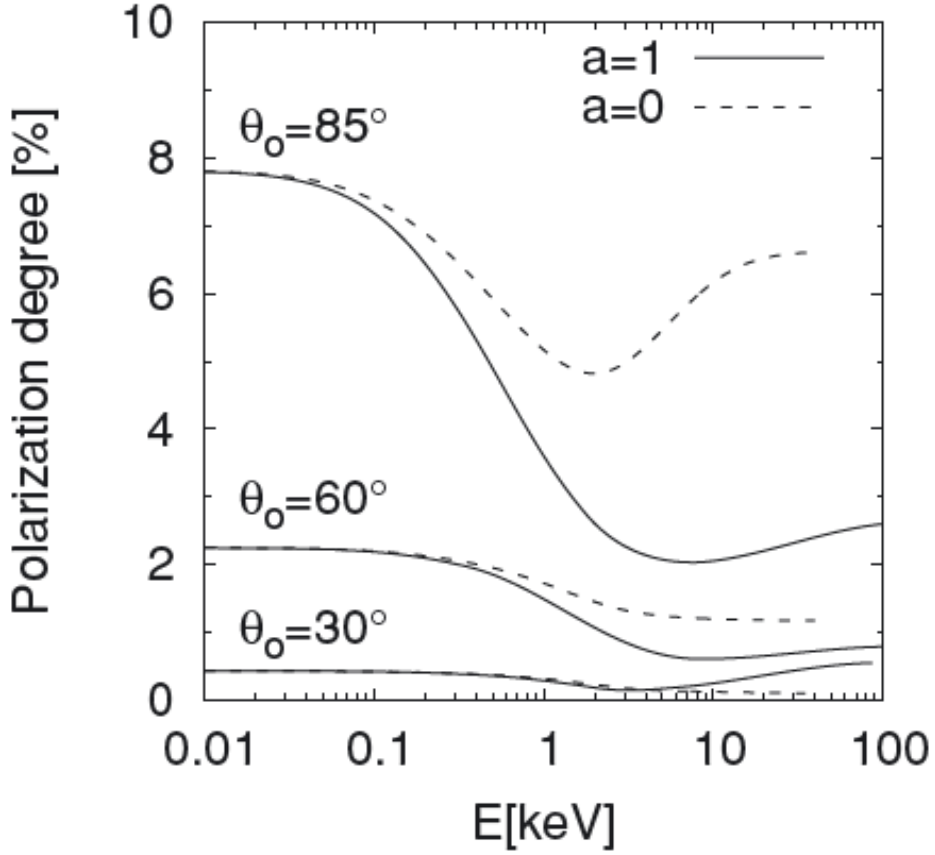
$60°$ - - - -

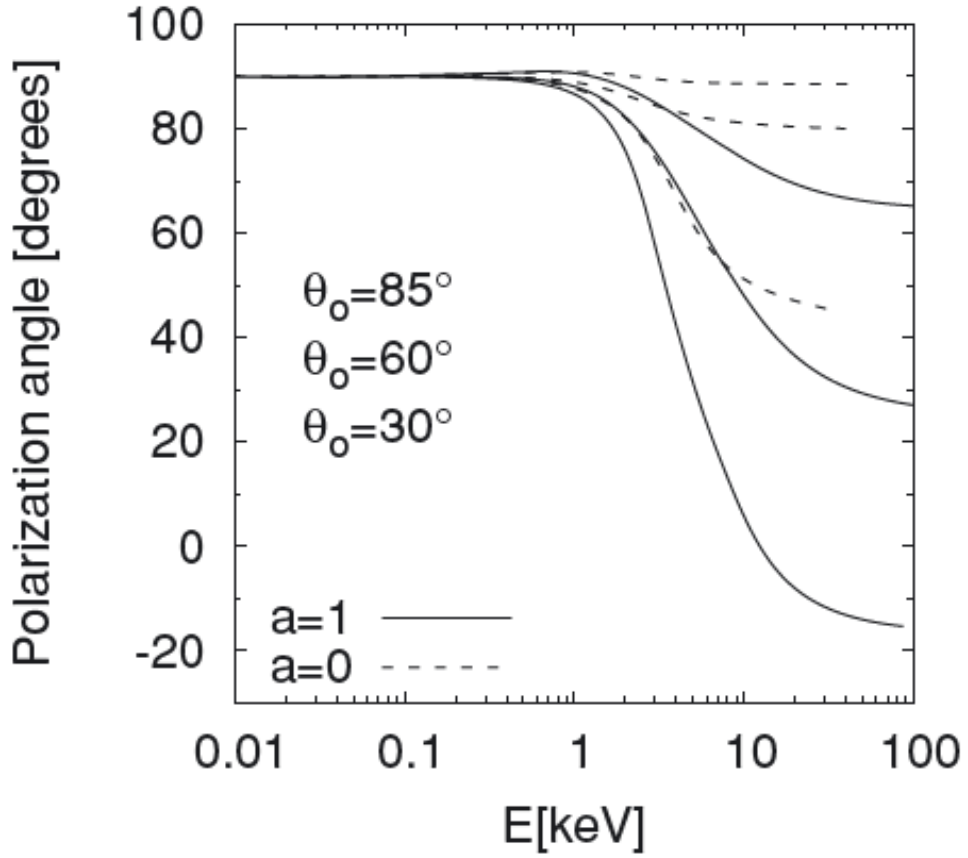
$30°$ ——

Analytical ray-tracing for spectra and polarization

Loktev, AV, Poutanen 2022

Extreme spin: severe PA rotation, depolarization

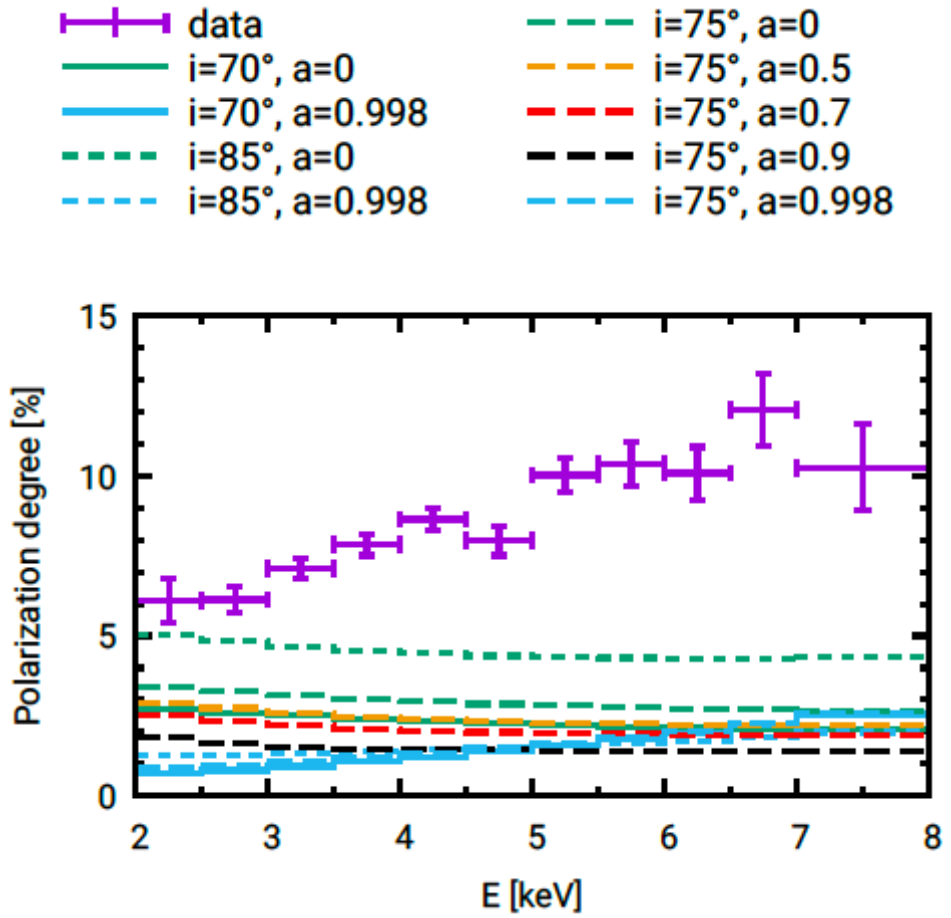




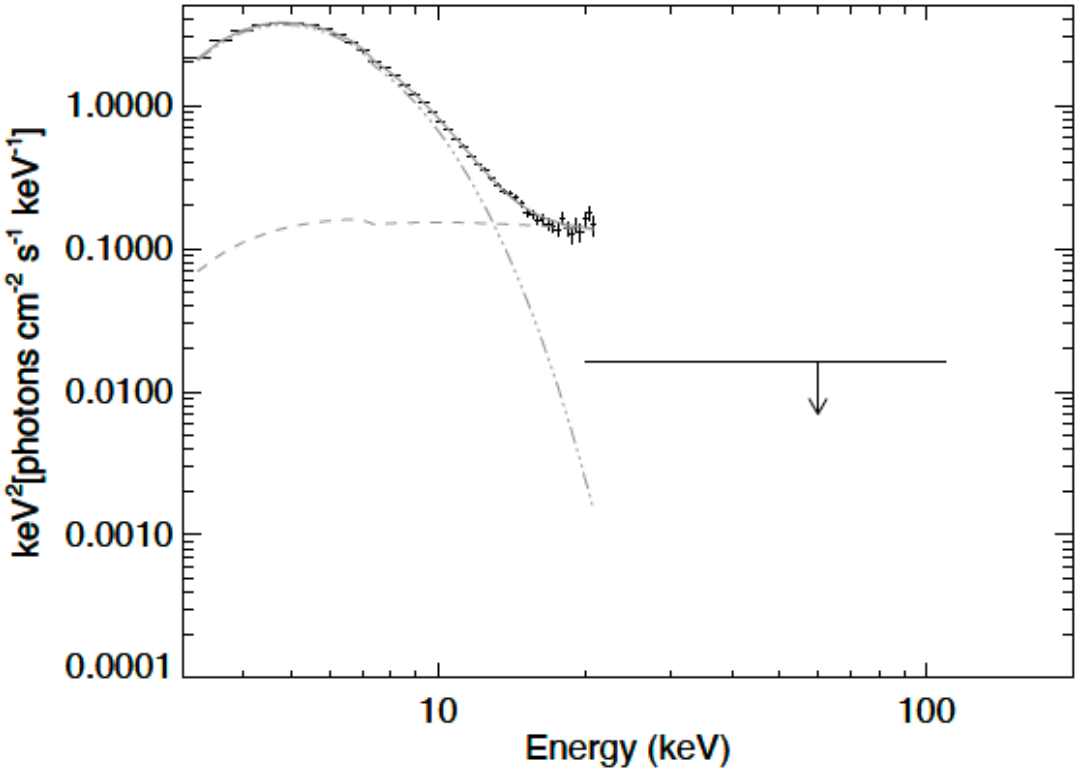
Dovciak et al. 2004, 2008
Loktev, AV et al. 2024

→ expectations prior to *IXPE* observations: PD<6%

Soft-state of 4U 1630-47 with IXPE: surprise #4

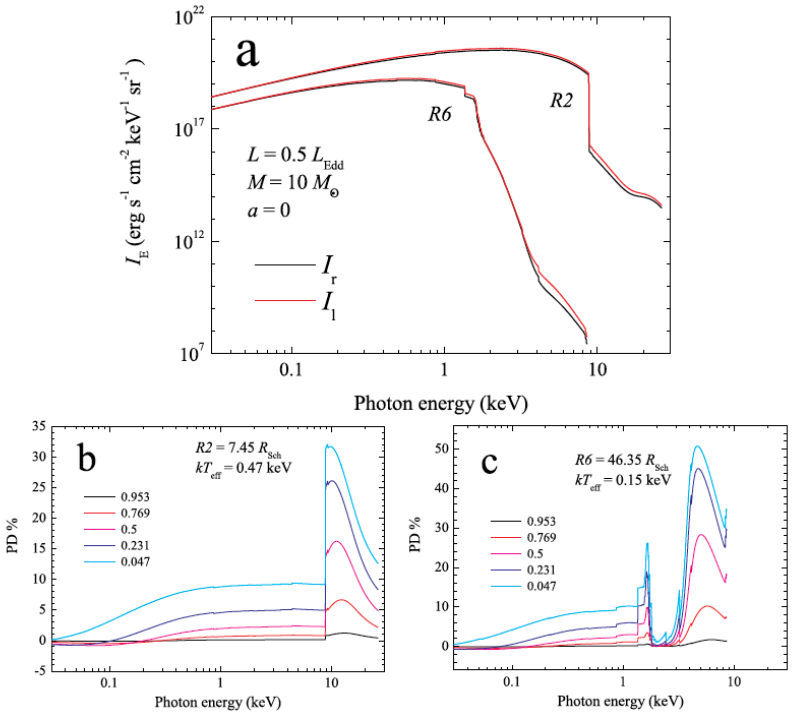


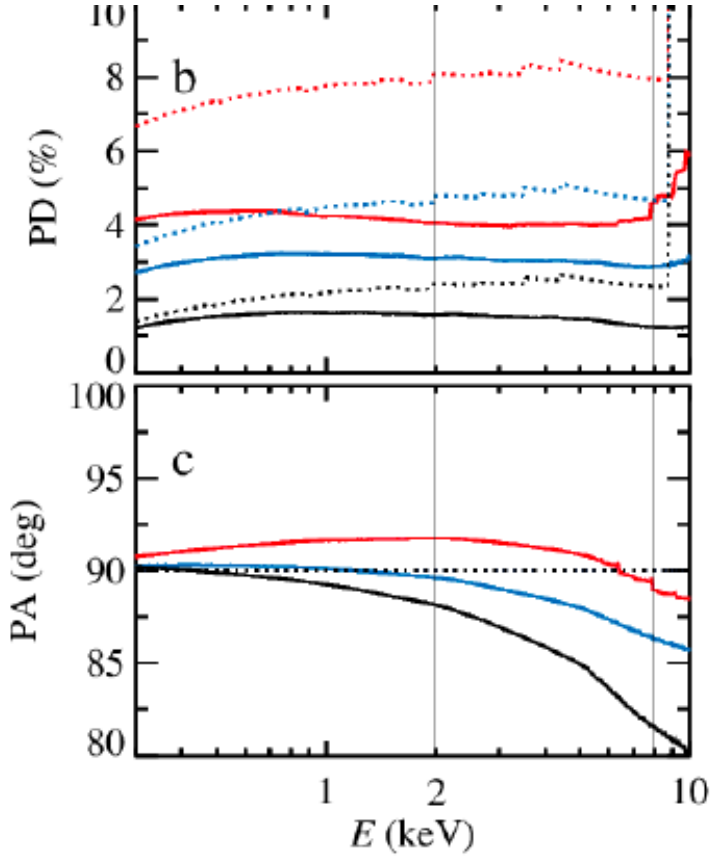
- Too low PD (especially for the high spins)

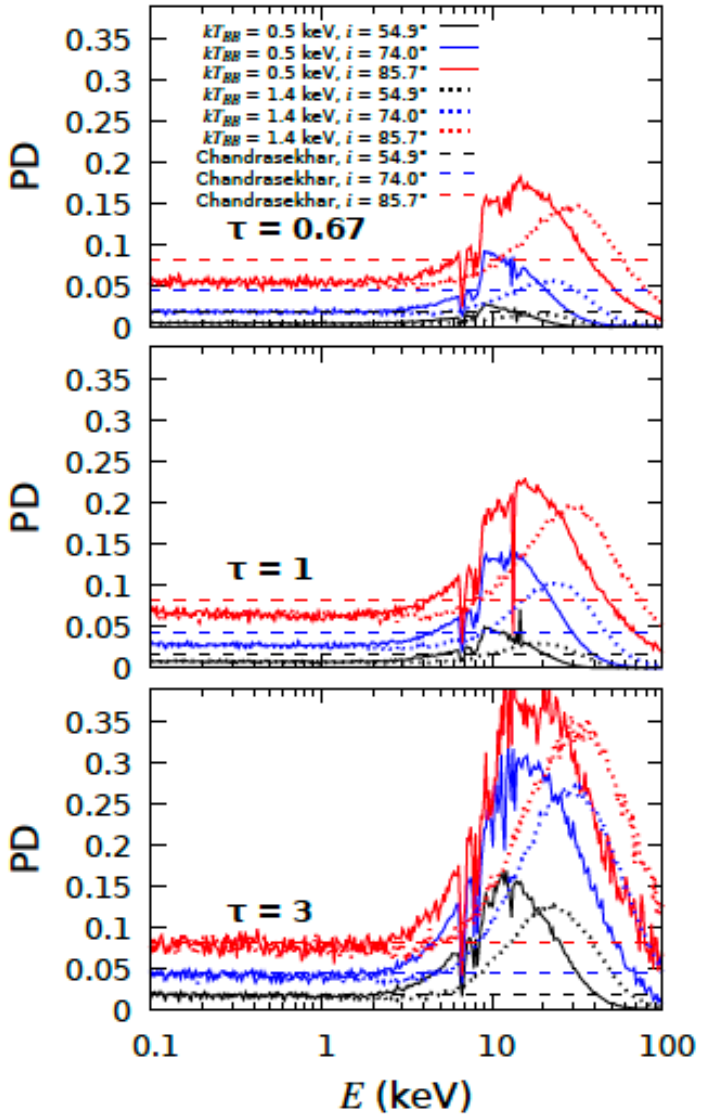


Ratheesh … AV et al. 2024

IXPE soft-state observations: 4U 1630-47

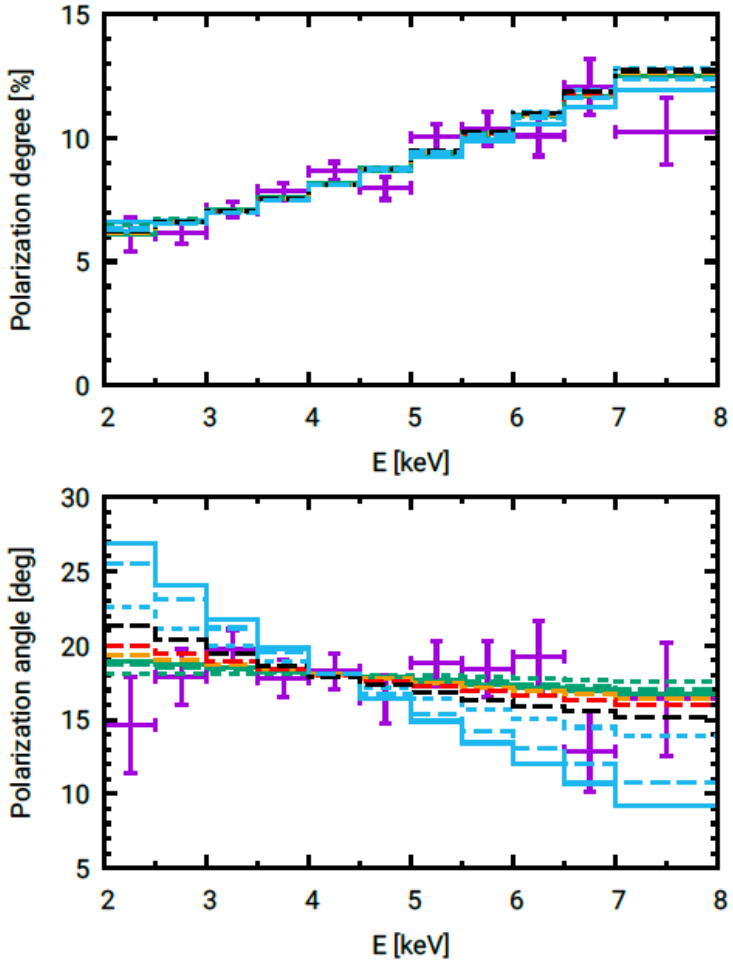




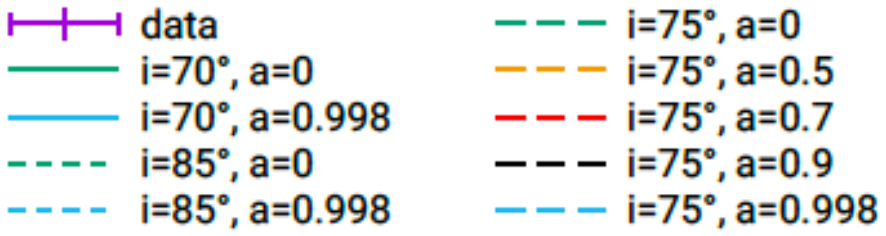


Ratheesh … AV et al. 2024

IXPE soft-state observations: 4U 1630-47

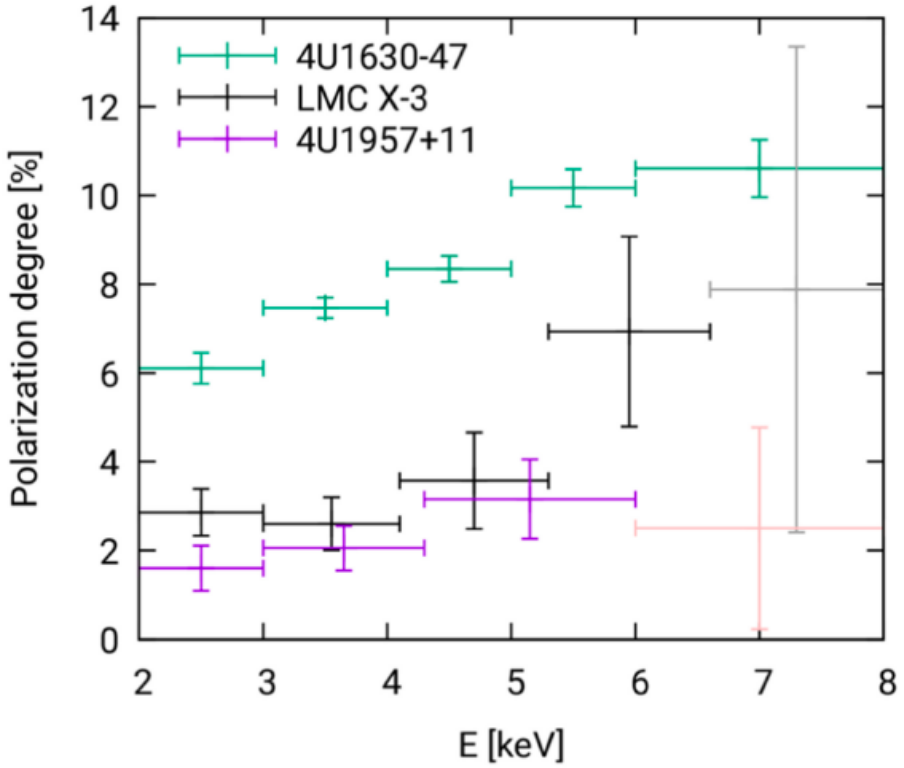


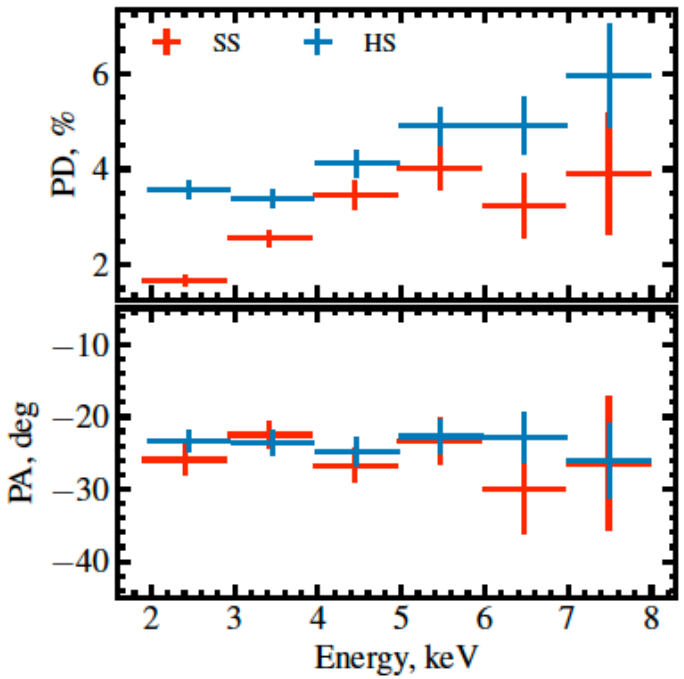
- Adding outflow $v/c = 0.5$ and absorption for slab of the optical depth $\tau = 7$
- PA: constraints on the spin (a<0.7)

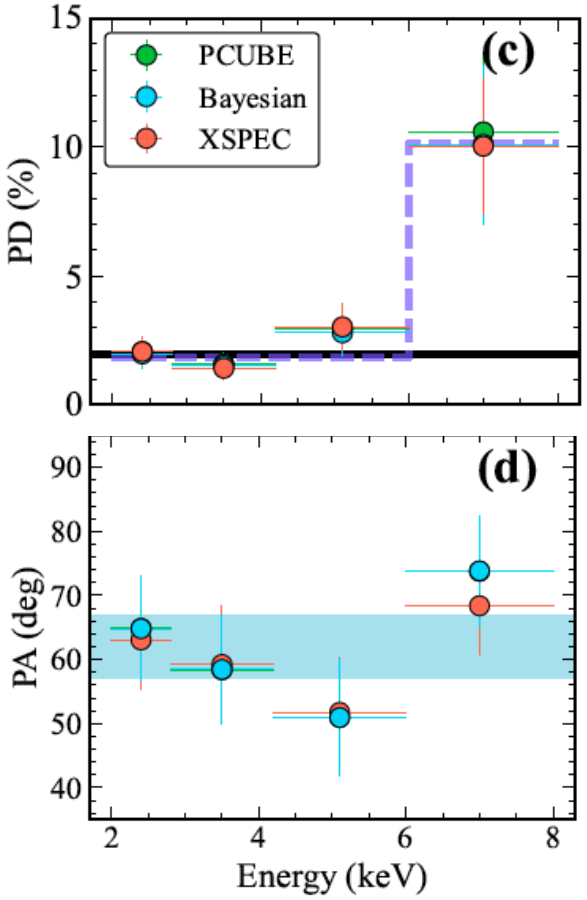


Ratheesh … AV et al. 2024

Other soft-state sources





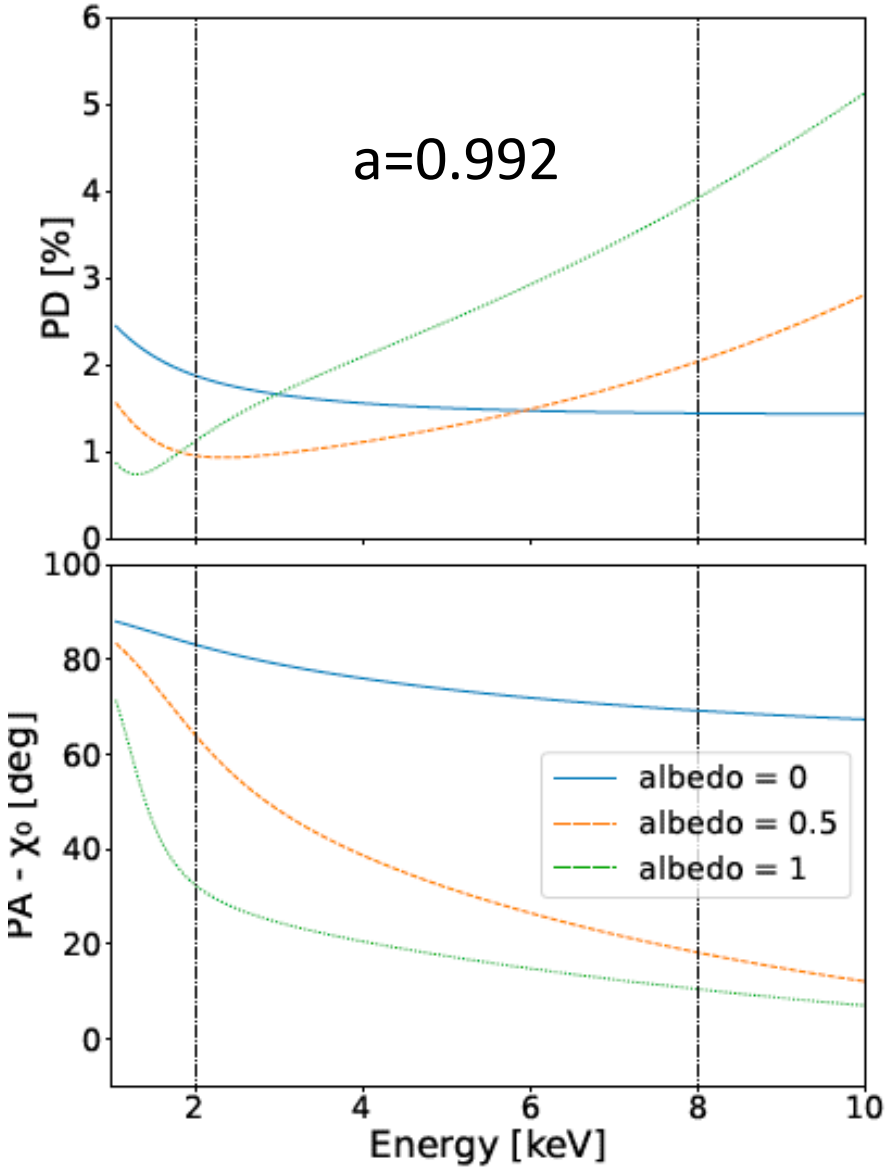


Svoboda … AV et al. 2024
Marra… AV et al. 2024
Steiner … AV et al. 2024
Kravtsov, Bocharova, AV et al. 2025
Zhao et al. 2026

Other soft-state sources: returning radiation (?)

- a>0.96 (4U 1957+11)
- a>0.96 (Cyg X-1)
- a>0.991 (GRS 1739-278)

- But: albedo=1 should be assumed to get substantial flux from the returning component (which is highly polarized).
- Given that a big fraction of returning photons hit outer parts of the disc, this assumption raises concerns

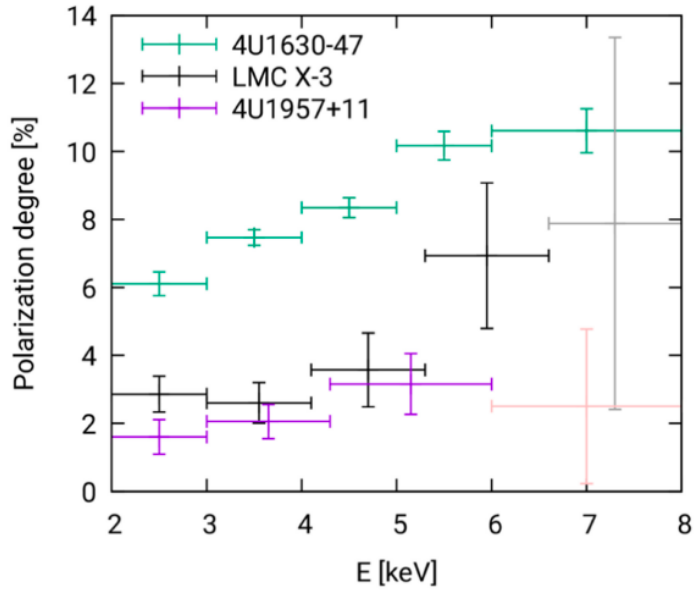


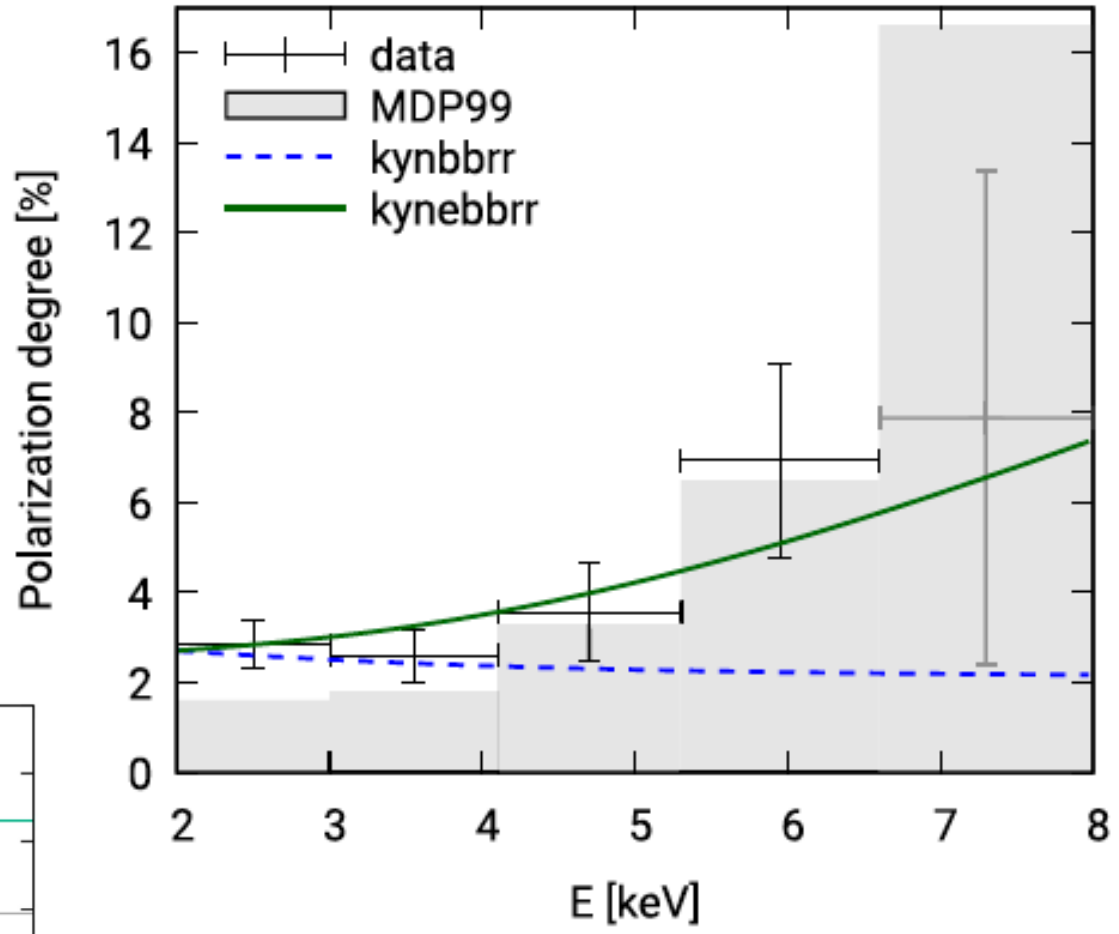
Marra … AV et al. 2024

Other soft-state sources: returning radiation (?)

- a<0.7 (LMC X-3)

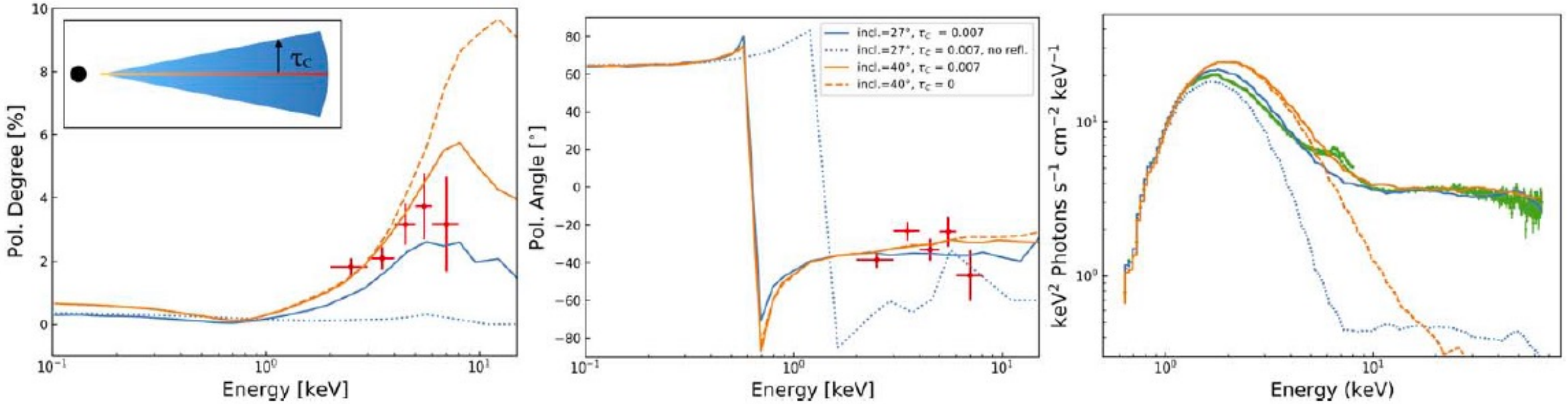
- More complex case, fit with returning radiation: blue dashed lines
- But: similarity with 4U1915+11





Svoboda … AV et al. 2024

Cyg X-1 soft-state polarization: reflection/returning radiation

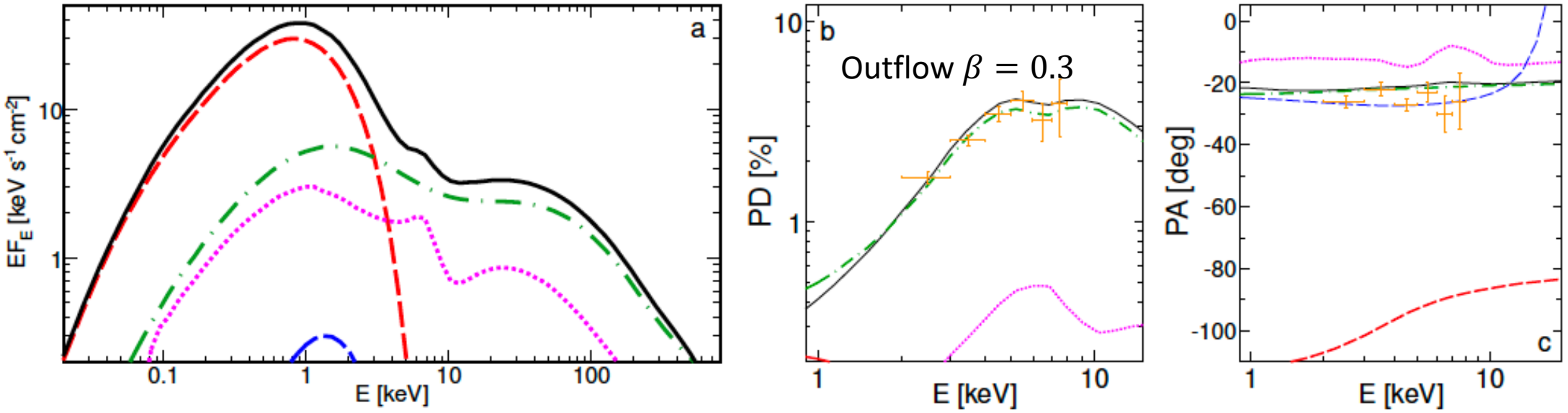


a>0.96

$\lambda = 1$

Steiner… AV et al. 2024

Cyg X-1 soft-state polarization: reflection/returning radiation?

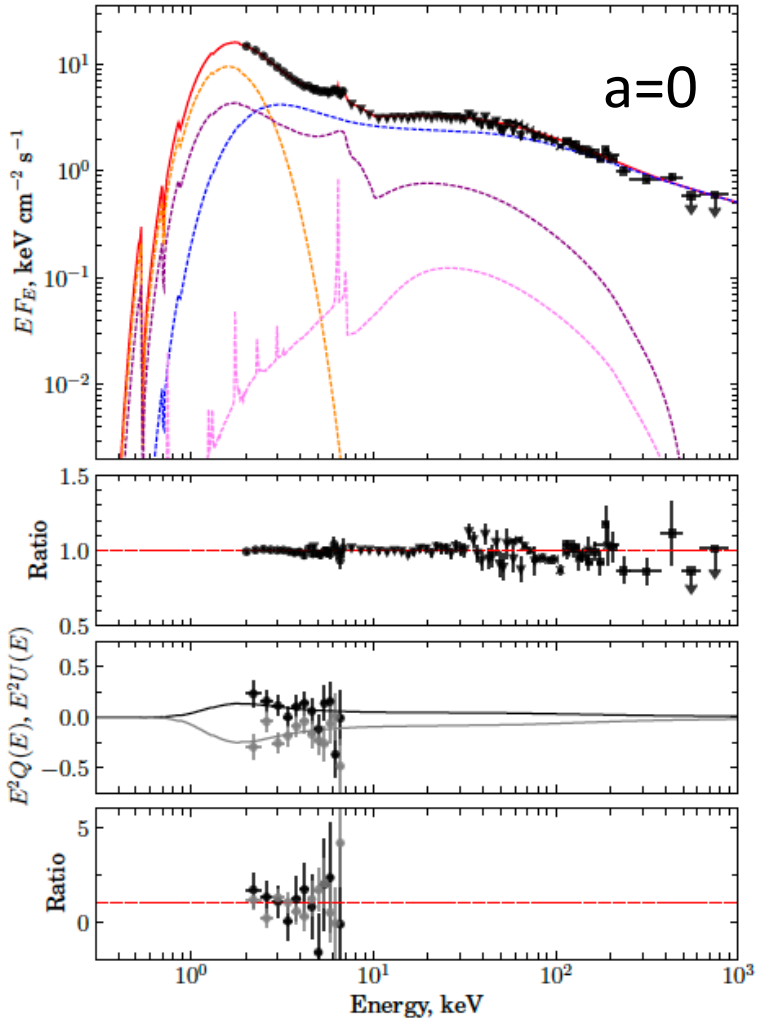


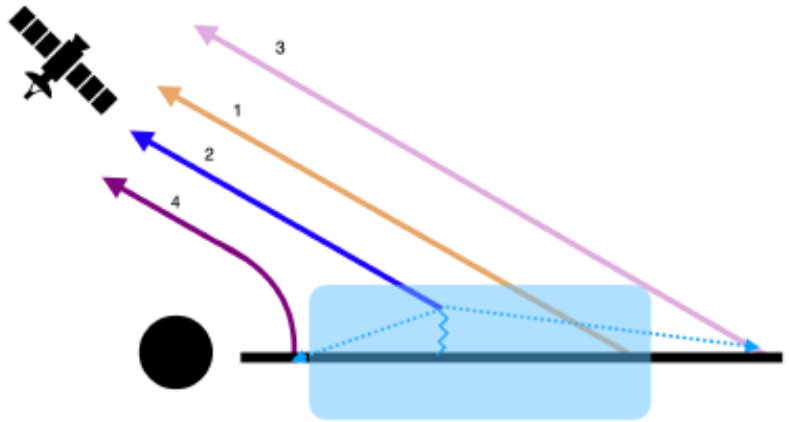
a=0

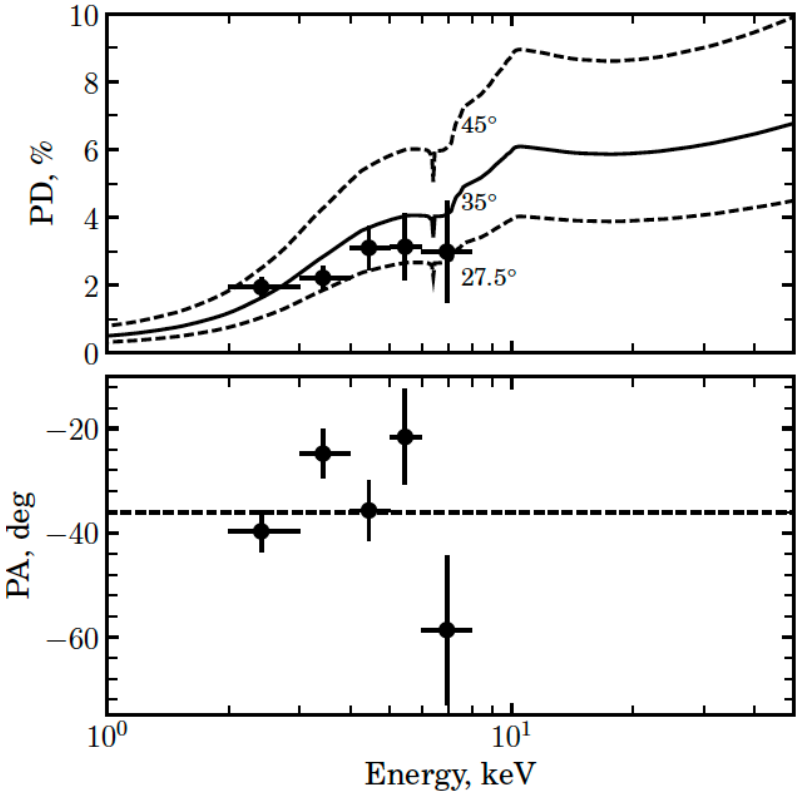
$\log\xi \approx 4$

Niedzwiecki… AV et al. 2026

Cyg X-1 soft-state polarization: hybrid corona





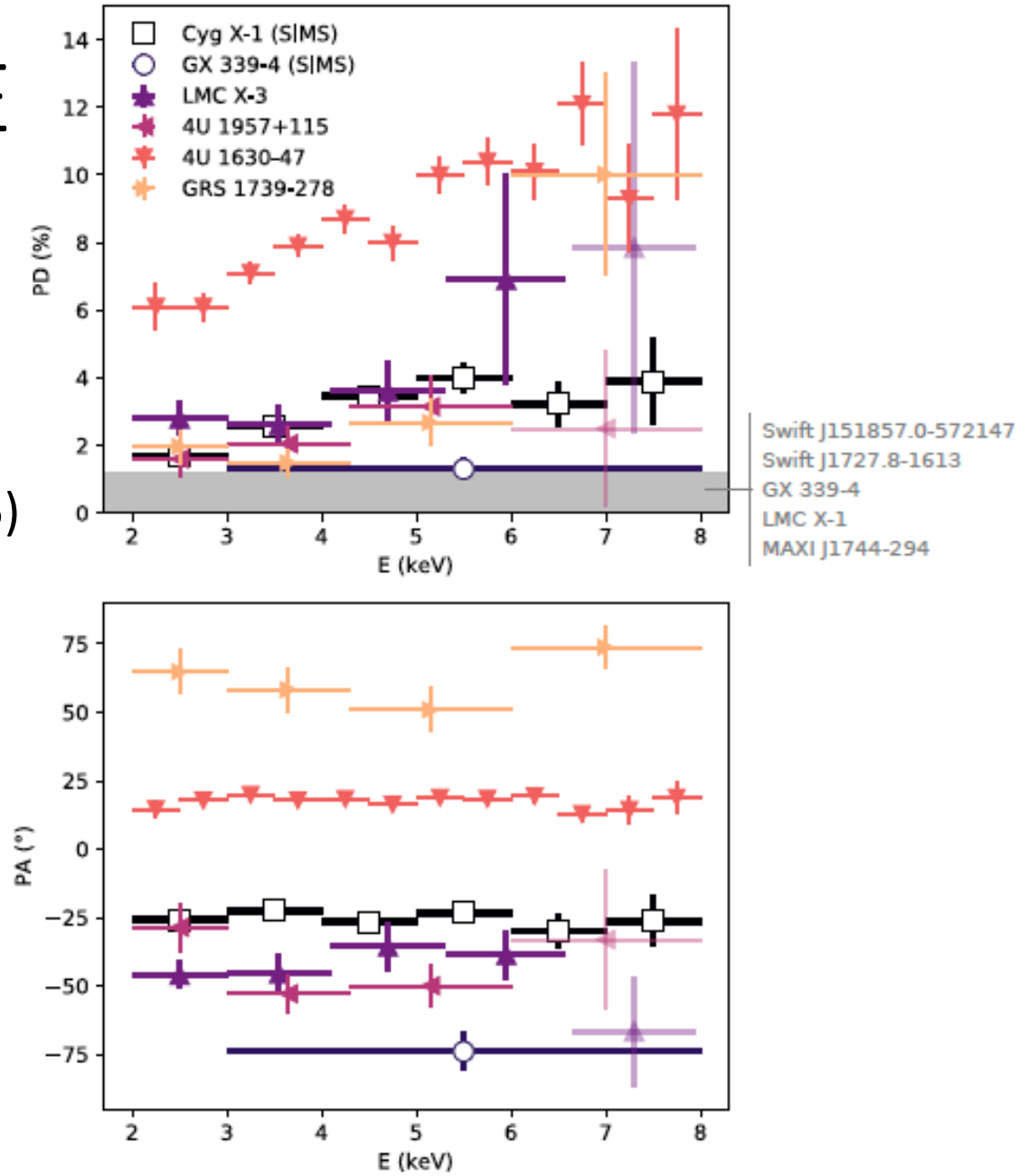


$kT_e \approx 12$ keV, $\tau \approx 1.4$, $p \approx 3.2$, $\gamma_{min} \approx 1.19$, $T_{in} \approx 0.4$ keV

Bocharova, AV et al.

Soft-state sources with IXPE

- LMC X-1 (Podgorny…AV et al. 2023)
- Swift J1727.8-1613 (Svoboda…AV et al. 2024b)
- LMC X-3 (Svoboda…AV et al. 2024a)
- 4U 1957+11 (Marra…AV et al. 2024)
- Cyg X-1 (Steiner… AV et al. 2024, Kravtsov … AV 2025)
- Swift J151857.0-572147 (Ling et al. 2024)
- 4U 1630-47 (Ratheesh … AV et al. 2024)
- GX 339-4 (Mastroserio et al. 2024)
- GRS 1739-278 (Zhao et al. 2026)



- PA=const: constraints on relativistic effects
- PD increasing with energy: challenging

Marcel … AV, arXiv:2606.19952

Soft-state sources with IXPE

- LMC X-1 (Podgorny…AV et al. 2023)
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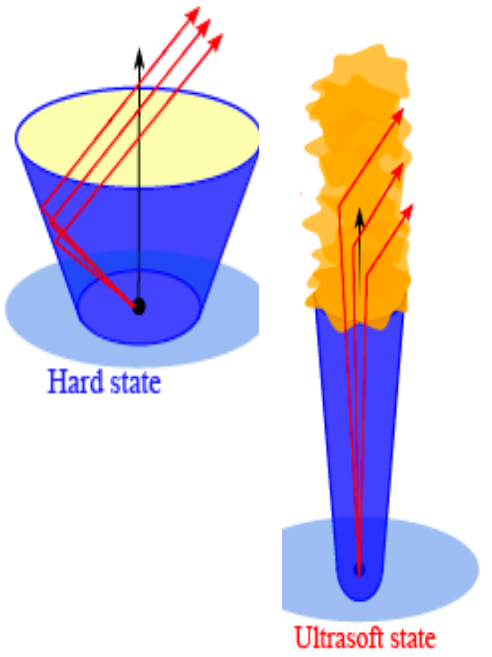
- 4U 1957+11 (Marra…AV et al. 2024)
- Cyg X-1 (Steiner… AV et al. 2024, Kravtsov … AV 2025)
- Swift J151857.0-572147 (Ling et al. 2024)
- 4U 1630-47 (Ratheesh … AV et al. 2024)
- GX 339-4 (Mastroserio et al. 2024)
- GRS 1739-278 (Zhao et al. 2026)
- Cyg X-3: PD = 11.9%±0.5%, orthogonal to the jet → funnel again!



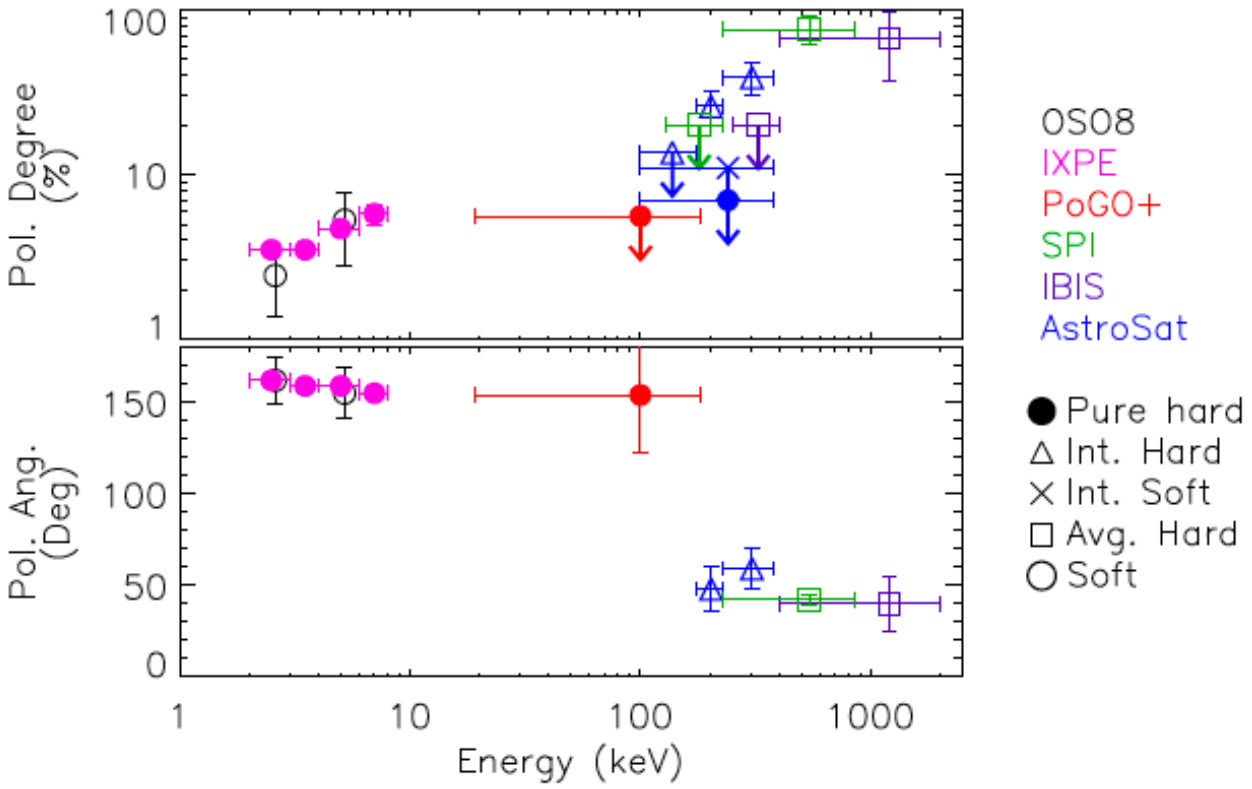
AV et al. 2024

- PA=const: constraints on relativistic effects
- PD increasing with energy: challenging

Summary

- Hard-state sources: corona extended in the direction orthogonal to the jet axis (presumably, along the disk plane)
- Unique nature of Cyg X-3
- Soft-state sources: puzzling PA=const, implications for self-irradiation or a more complex spectral decomposition (warm or hybrid corona)
- In many soft-state cases statistics is poor – eXTP!

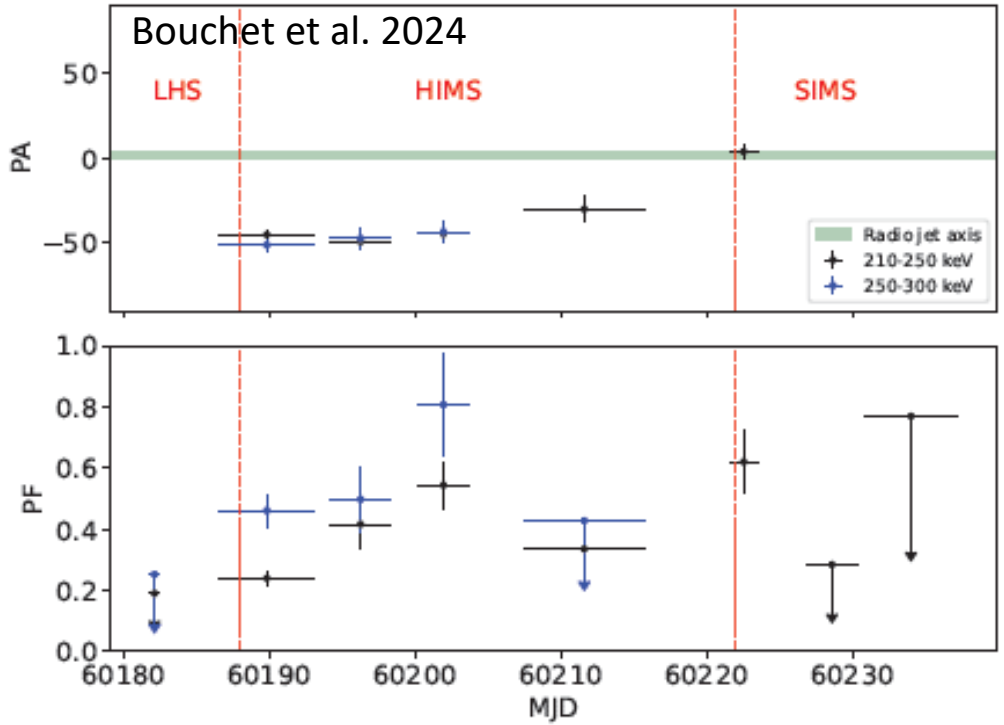
Comparison to INTEGRAL measurements

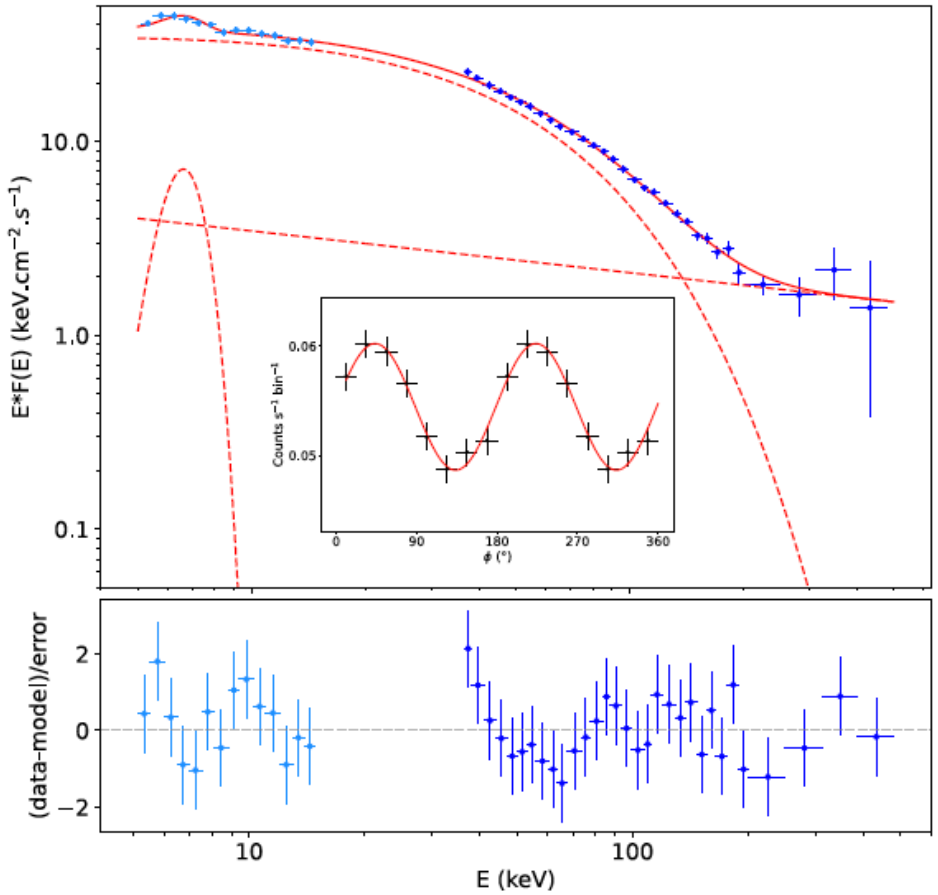


- INTEGRAL and AstroSAT give different PDs and in different states
- Both INTEGRAL and AstroSAT give PA that is different from IXPE PA and jet direction by 70^{o}

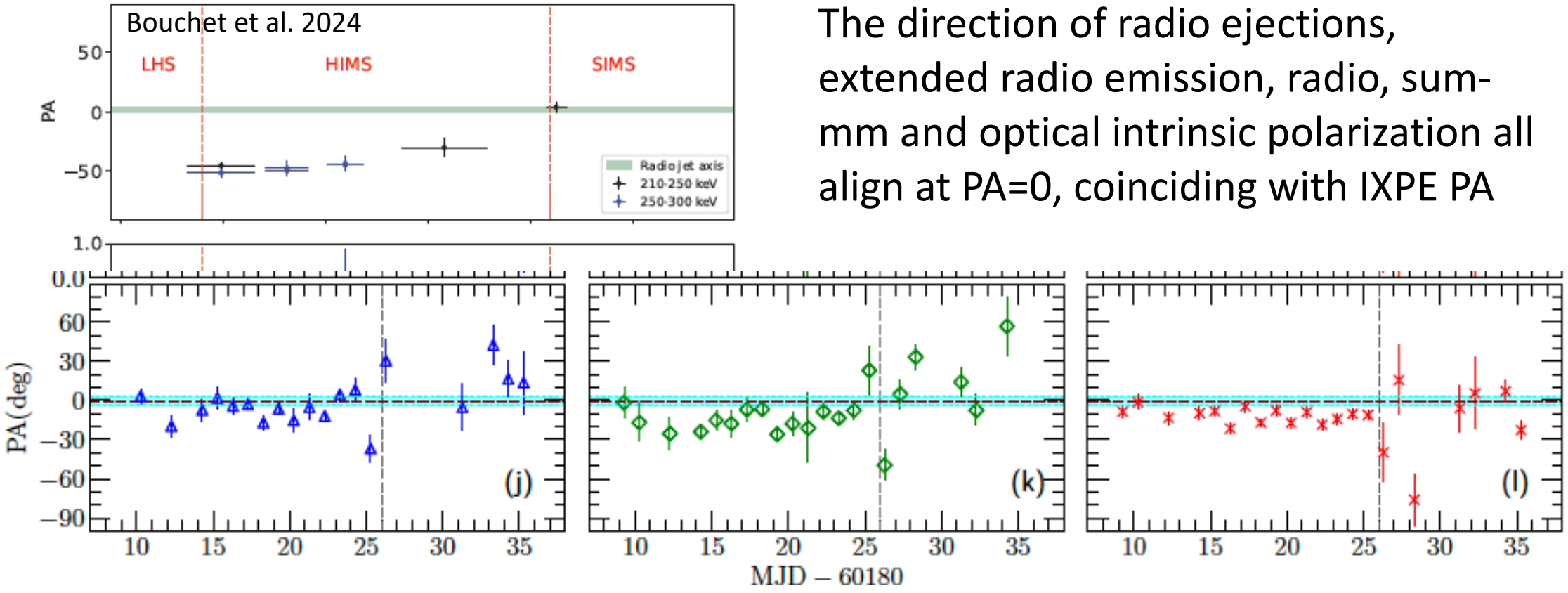
Laurent et al. 2011
Jourdain et al. 2012
Chattopadhyay et al. 2024

Comparison to INTEGRAL measurements





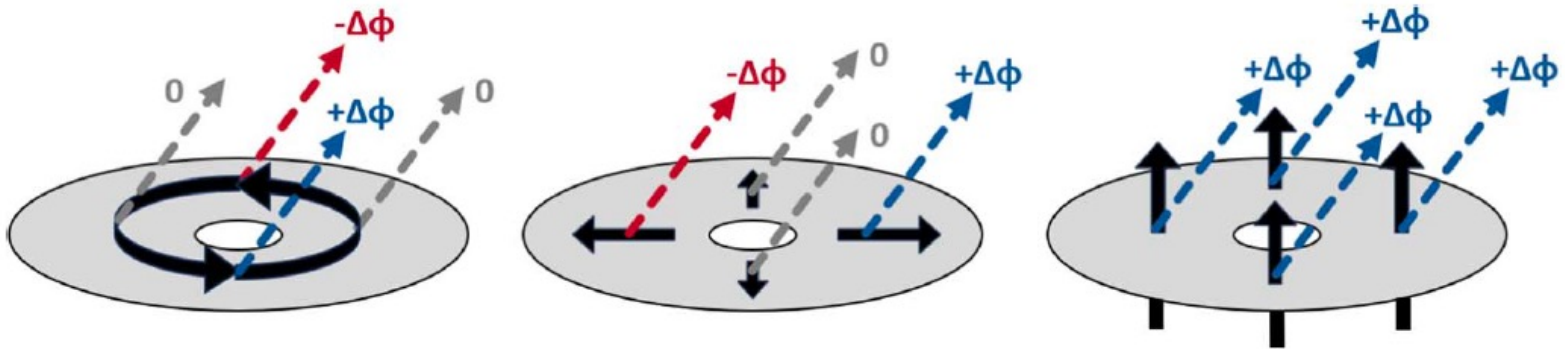
Comparison to INTEGRAL measurements

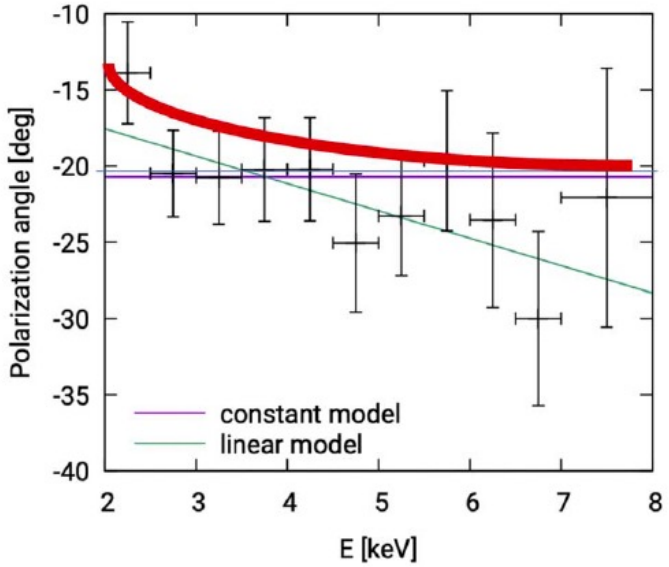


The direction of radio ejections, extended radio emission, radio, sum-mm and optical intrinsic polarization all align at PA=0, coinciding with IXPE PA

Nitindala, AV et al. 2026

Additional constraints: Faraday rotation





$B < 10^{6-8}$ G

Barnier & Done 2024
Krawczynski 2026