X-ray polarimetric view of X-ray binaries

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NORDITA
The Nordic Institute for Theoretical Physics

Centre of Excellence neutronstars.fi

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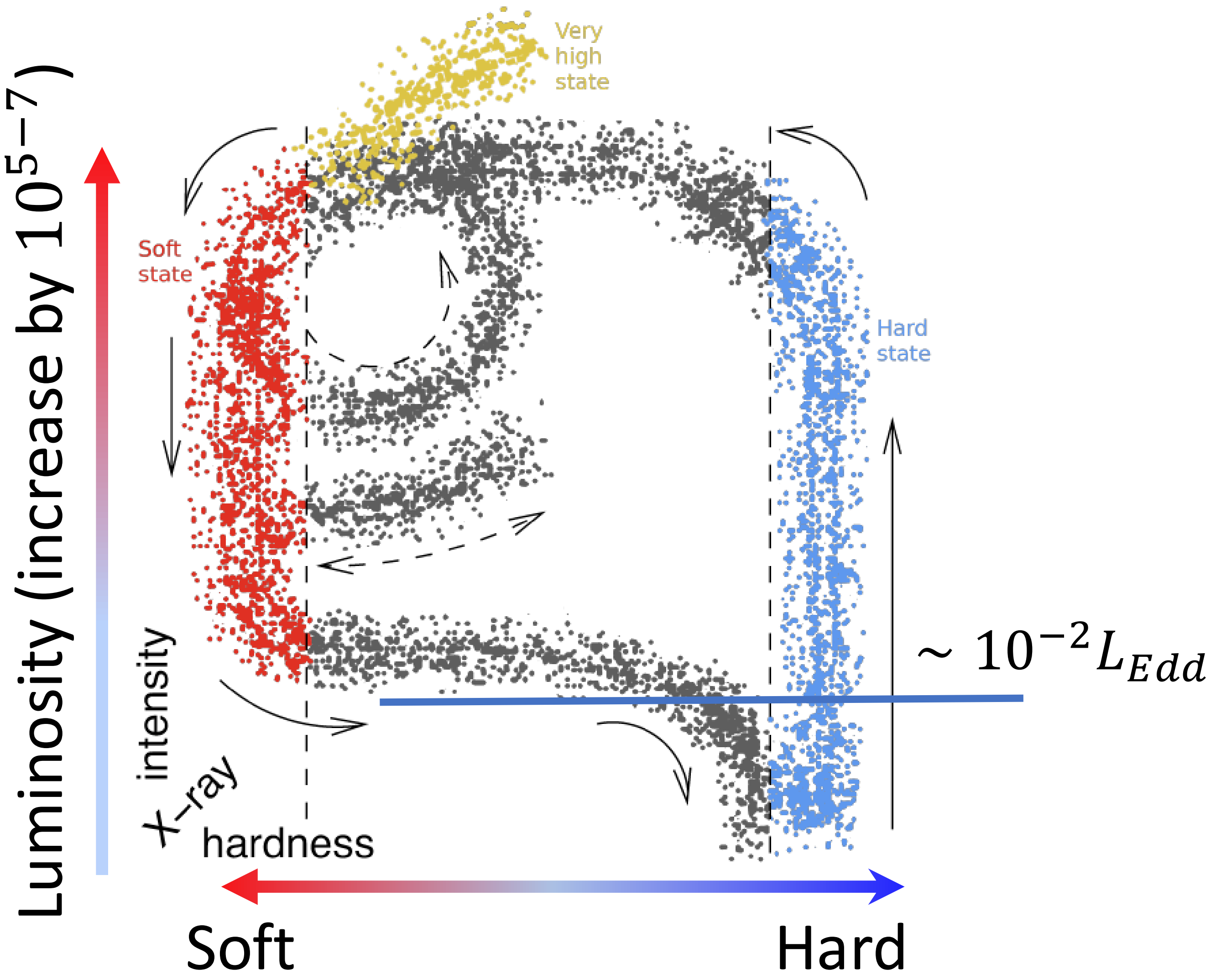
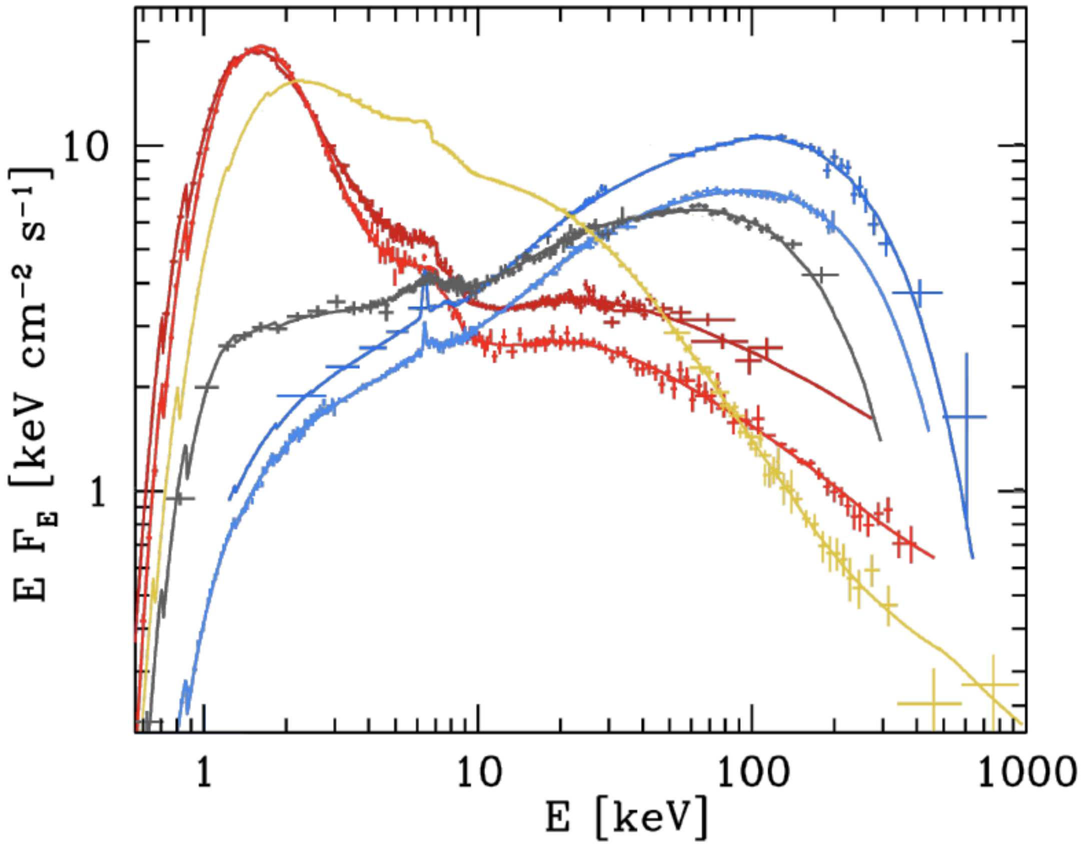
Many tones of accretion, Cefalu, 10 September 202

Spectral states of accreting black holes

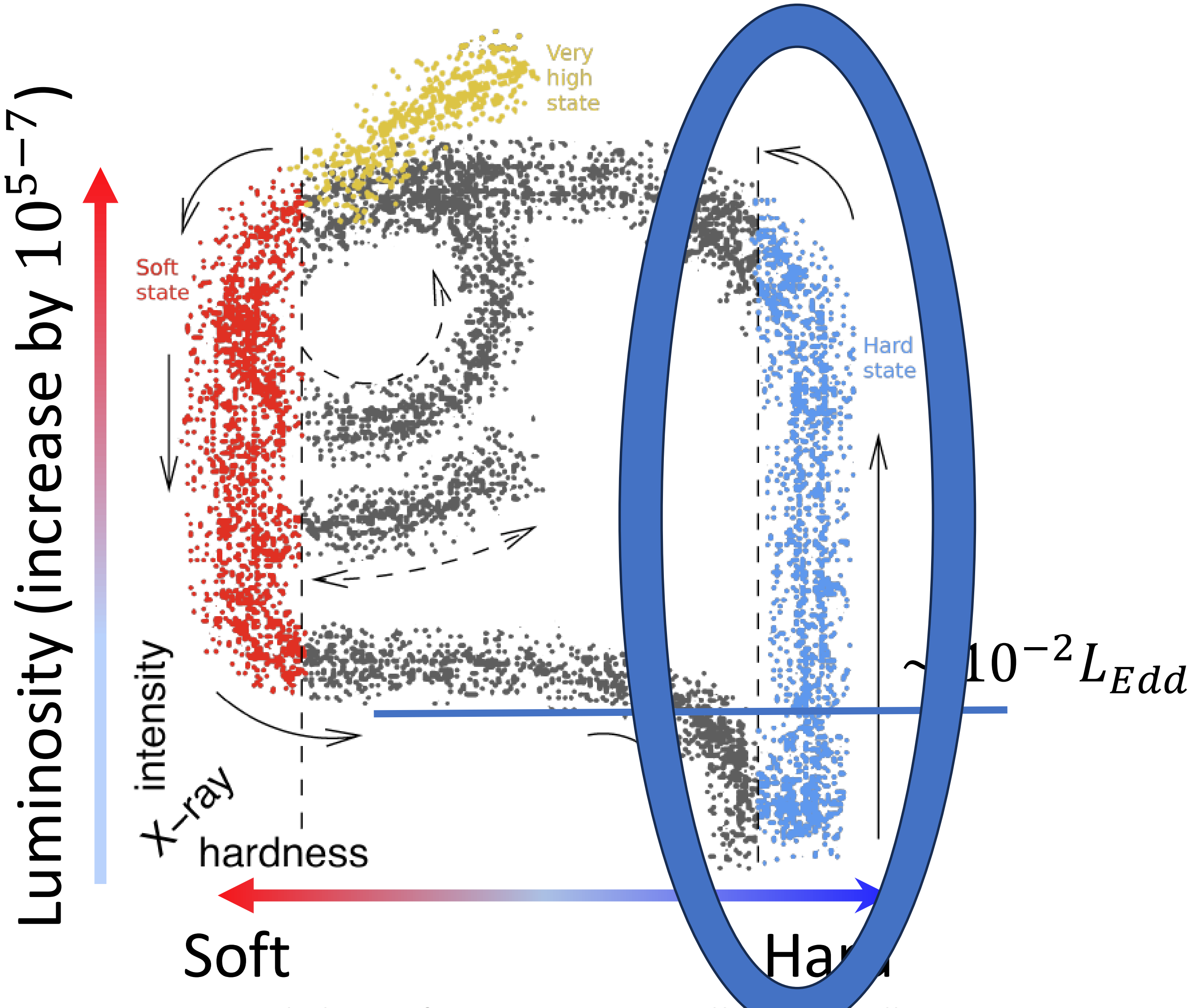


Original shape from: Fender, Belloni & Gallo 2004



Marcel … AV, arXiv:2606.19952

Spectral states of accreting black holes



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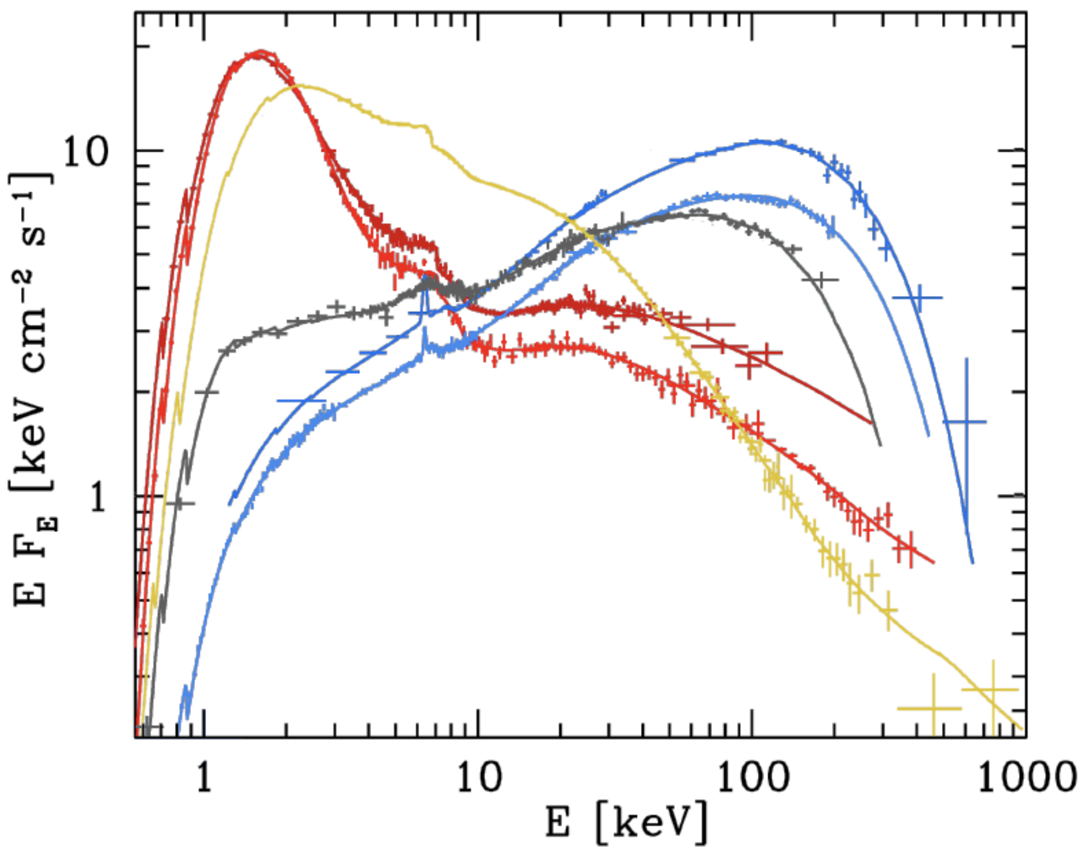


Marcel … AV, arXiv:2606.19952

Sombreros and lampposts:
The Geometry of Accretion onto Black Holes

ISSI Team led by A. Zdziarski (Poland) & T. Belloni (Italy)

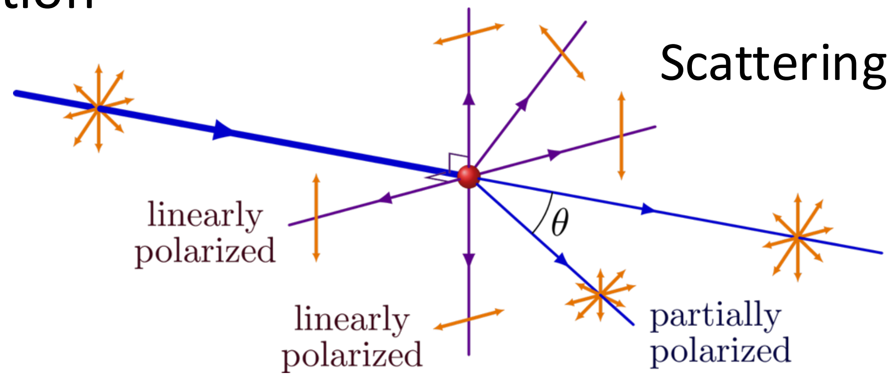
X-ray polarimetry: powerful but delicate tool

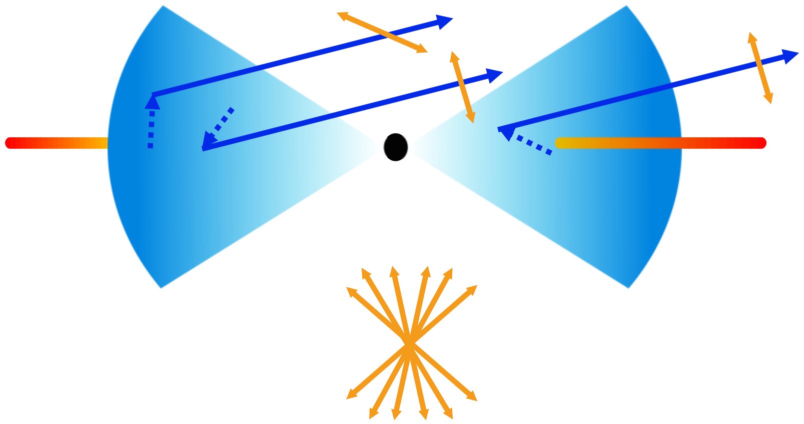
Thomson/Compton scattering in a slab corona: maximal polarization

PA aligned with disc axis (orthogonal to disc plane)

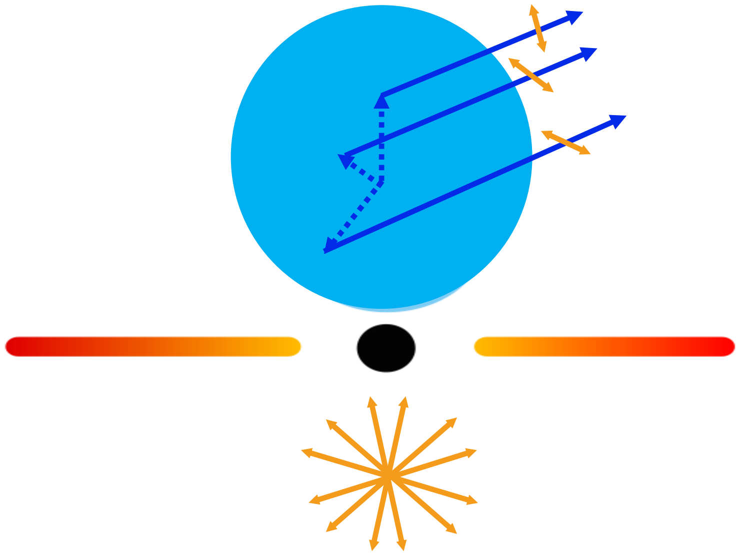
Lamppost corona: low polarization (spherical symmetry)

Cone-like corona: similar to slab, but PA orthogonal to disc axis

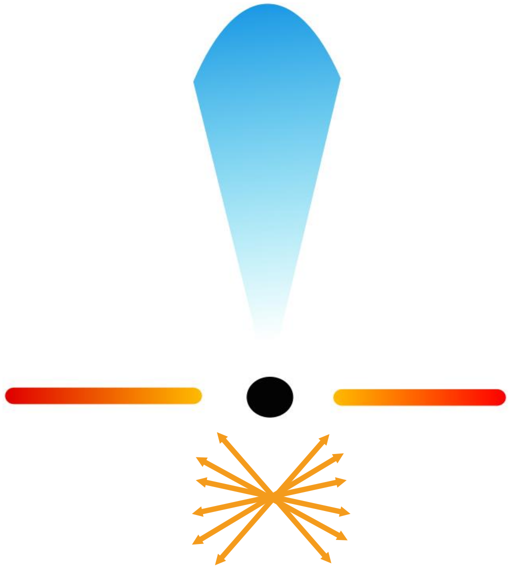




Sunyaev & Titarchuk 1985
Poutanen & Svensson 1996



Dovciak et al. 2004, 2008
Schnittman & Krolik 2010

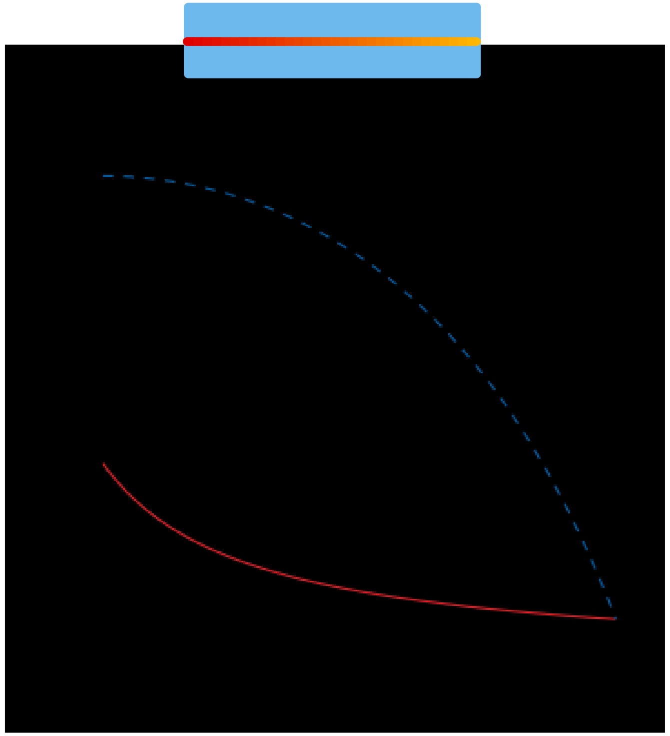


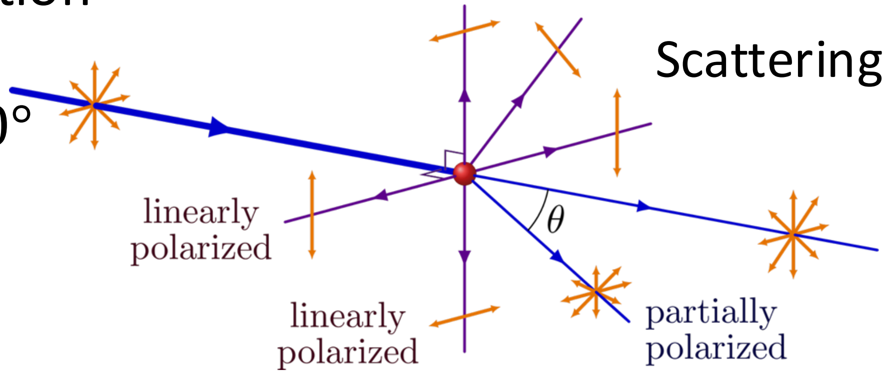
Krawczynski & Beheshtipour 2022

X-ray polarimetry: powerful but delicate tool

Thomson/Compton scattering in a slab corona: maximal polarization

- PD depends on the inclination and energy
- **Up to** ~15% for highest energies, ~7% in IXPE band for $i \sim 80°$





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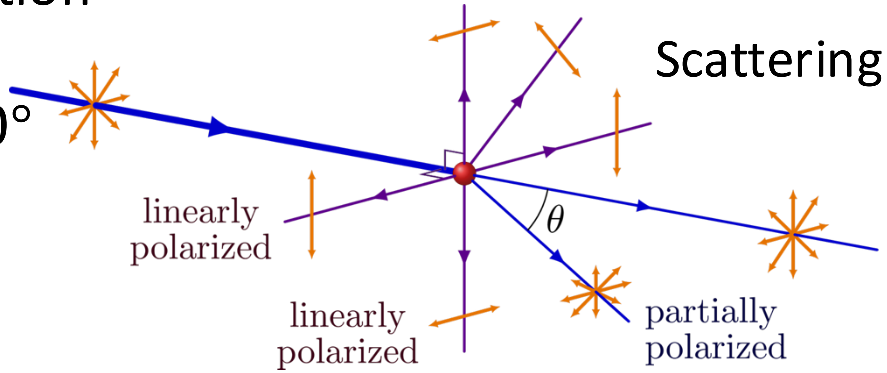
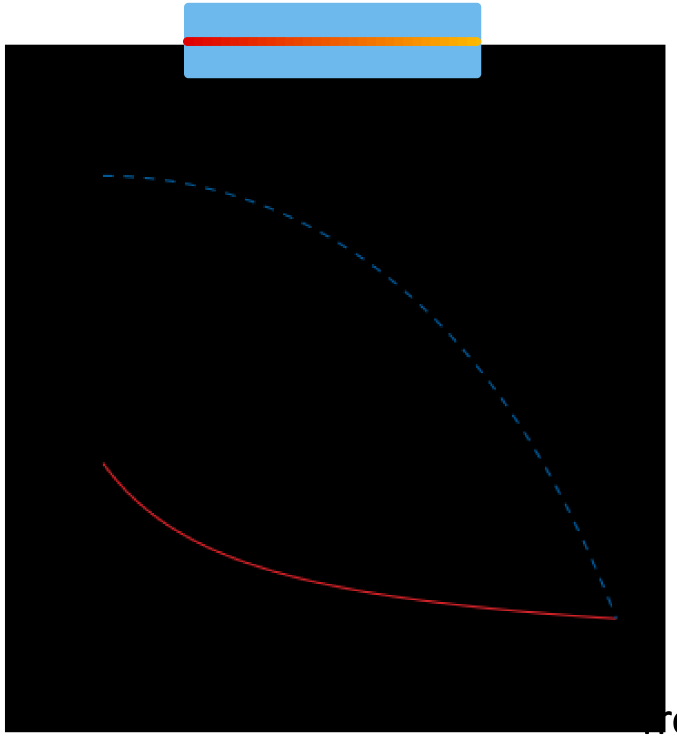
X-ray polarimetry: powerful but delicate tool

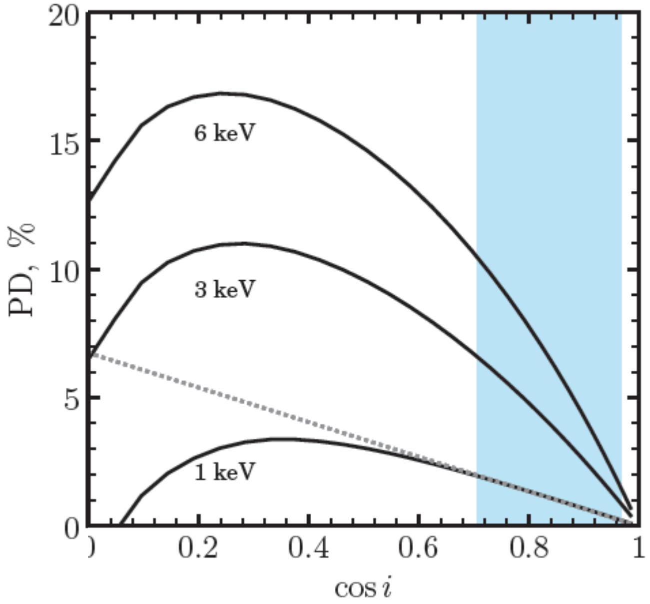
Thomson/Compton scattering in a slab corona: maximal polarization

- PD depends on the inclination and energy
- **Up to** ~15% for highest energies, ~7% in IXPE band for i~80°

Scattering





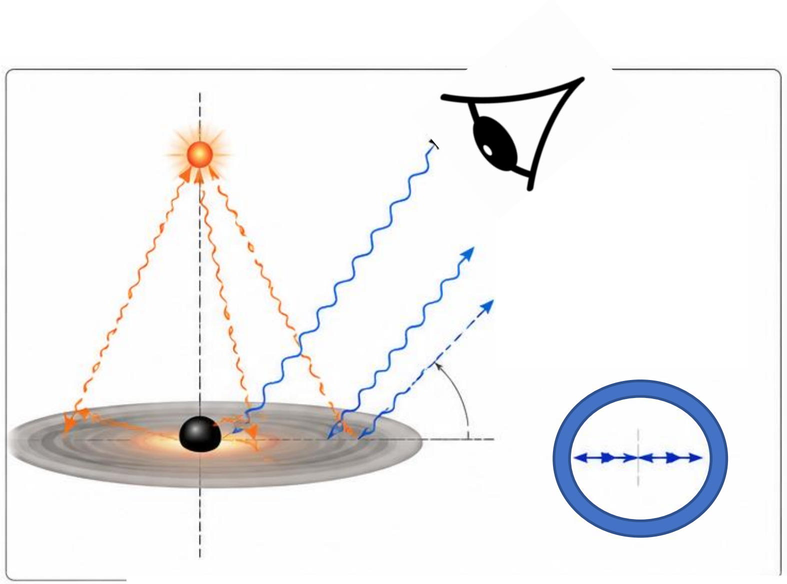


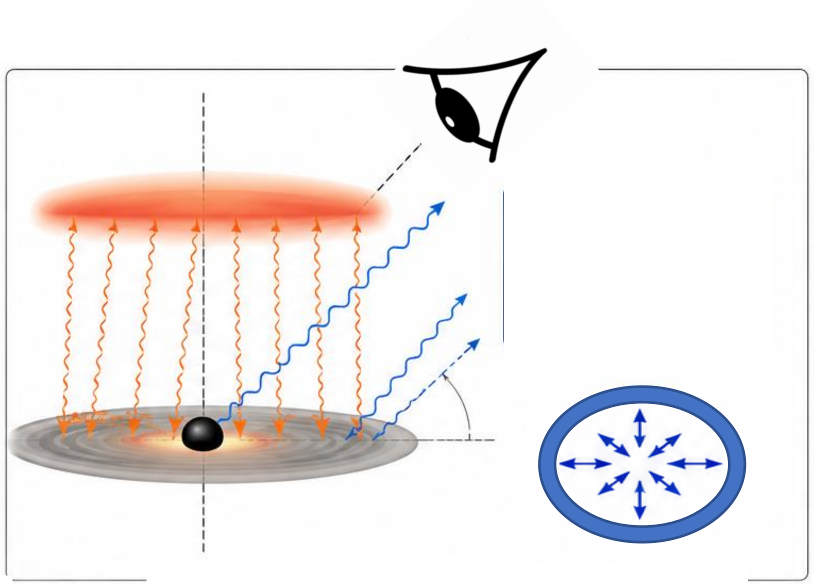
rom Bocharova, AV, Poutanen et al. in prep.

Sunyaev & Titarchuk 1985
Poutanen & Svensson 1996

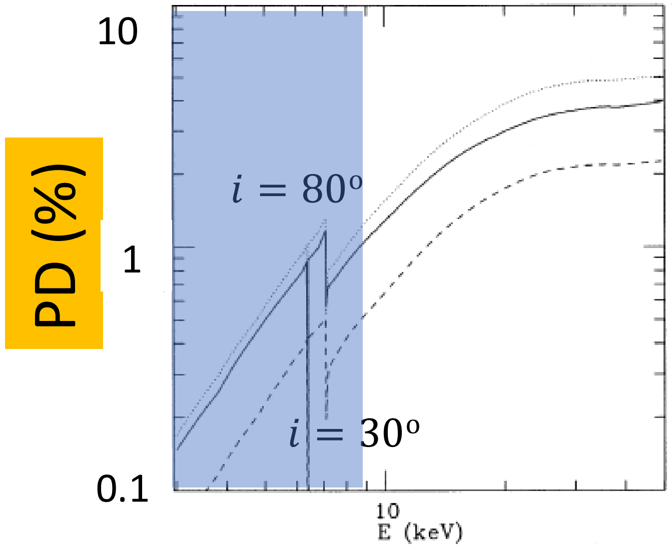
X-ray polarimetry: powerful but delicate tool

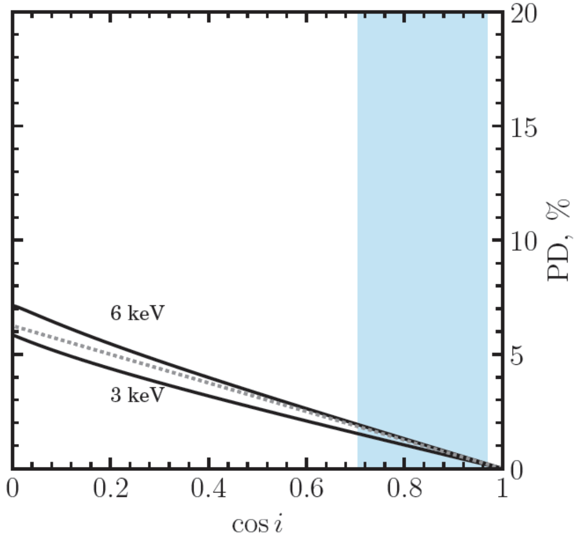
Reflection





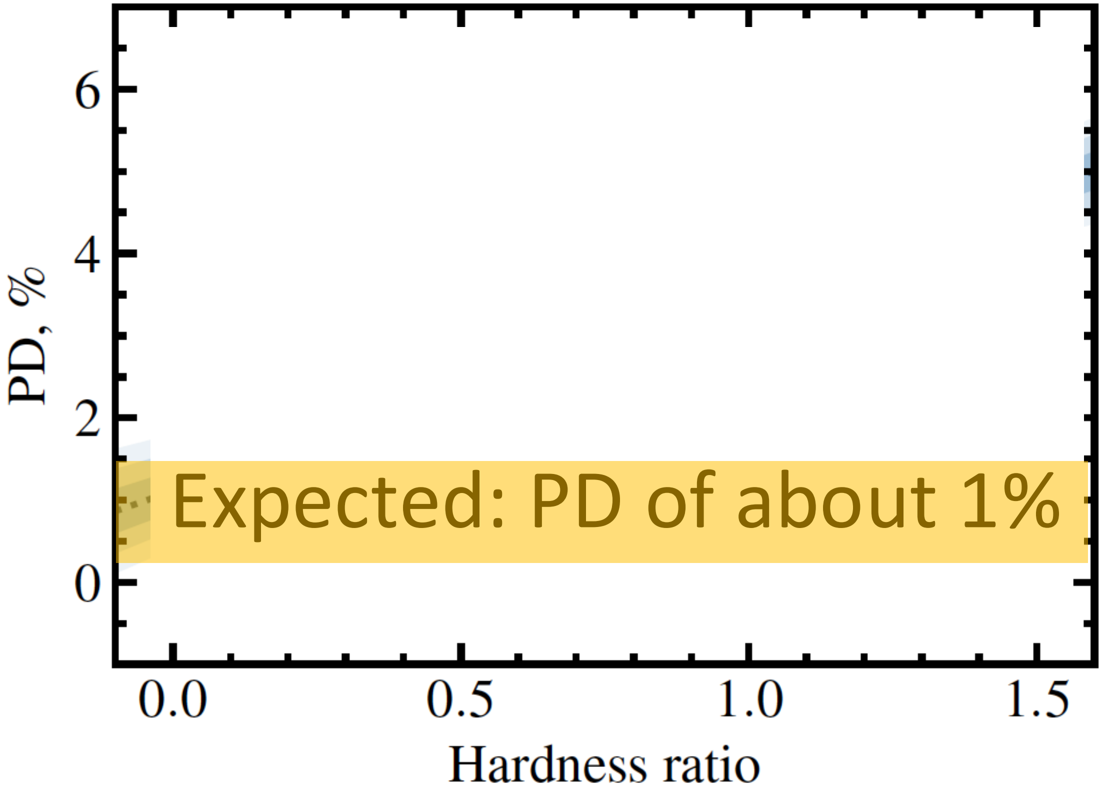
- Parallel or orthogonal to disk axis
- PD depends on the location of the incident source and its shape; total polarization is below 10%.

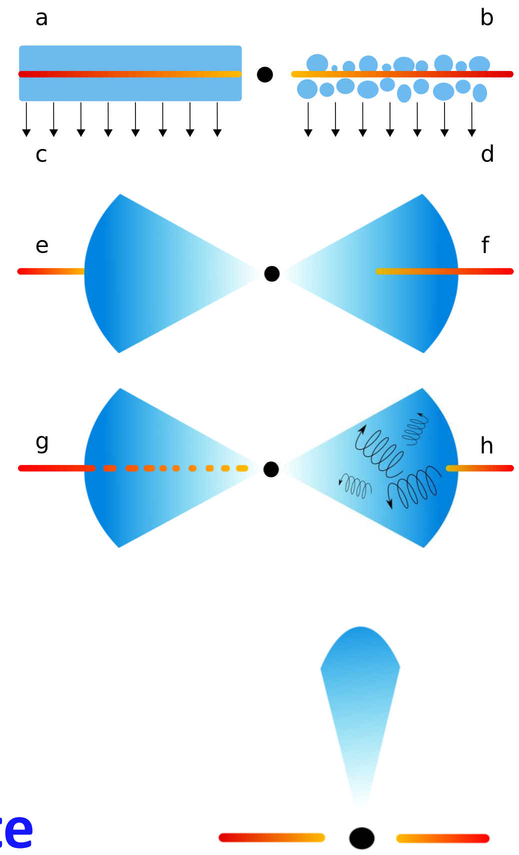




Matt et al. 1993; Poutanen et al. 1996; Dovciak et al. 2011; Podgorny et al. 2023

X-ray polarimetry: first results on accretion geometry in X-ray binaries





Soft state ⟷ **Hard state**

inclinations $i \approx 30° - 40°$

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

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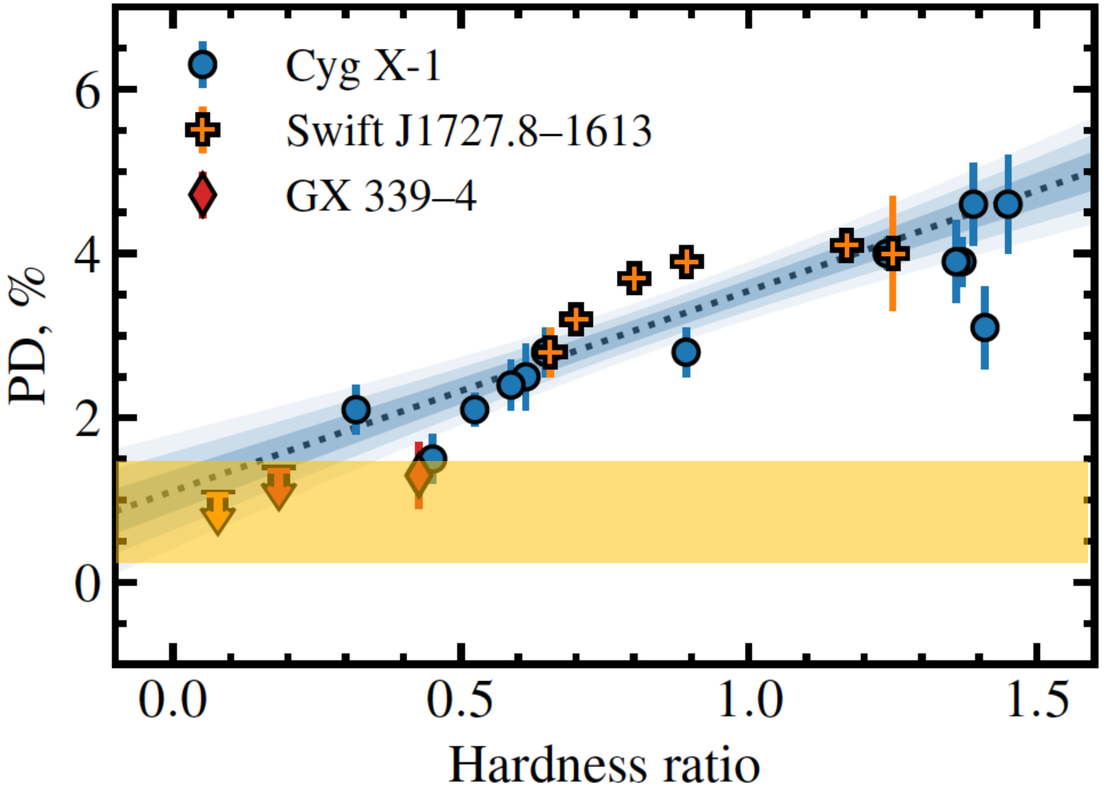
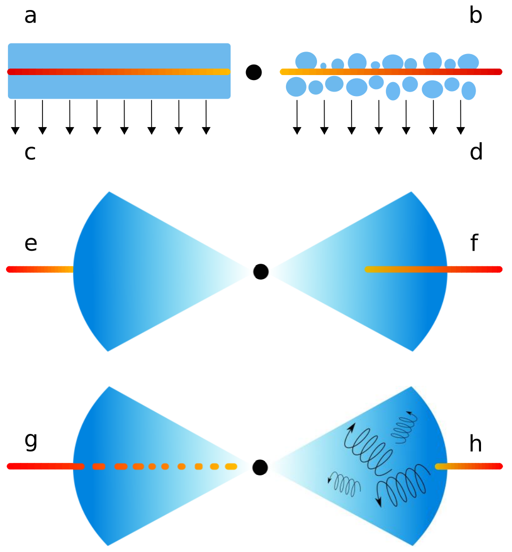
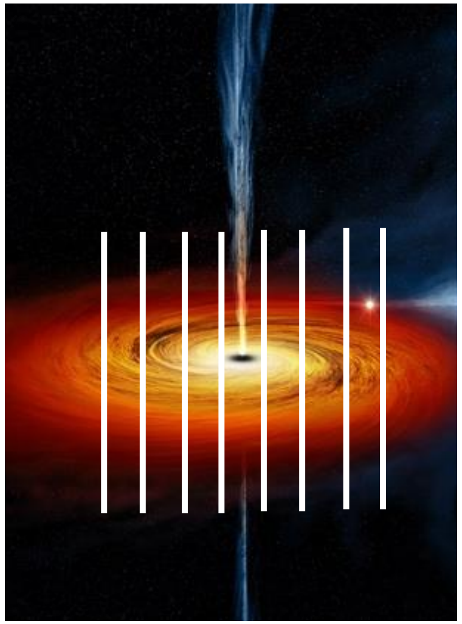






Soft state ⟵⟶ **Hard state**

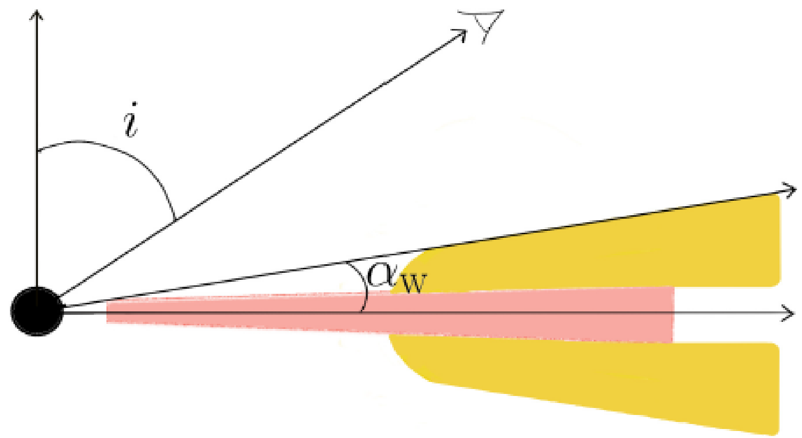
inclinations $i \approx 30° - 40°$

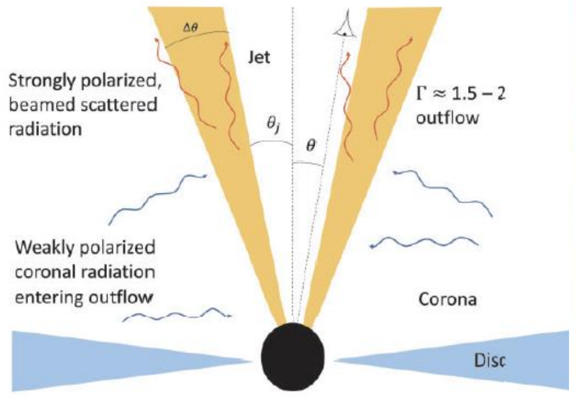
- Not cone-like
- Not spherical lamppost
- Elongated in the direction orthogonal to the jet (presumably, along the disc)
- Warp/outflow/wind?...

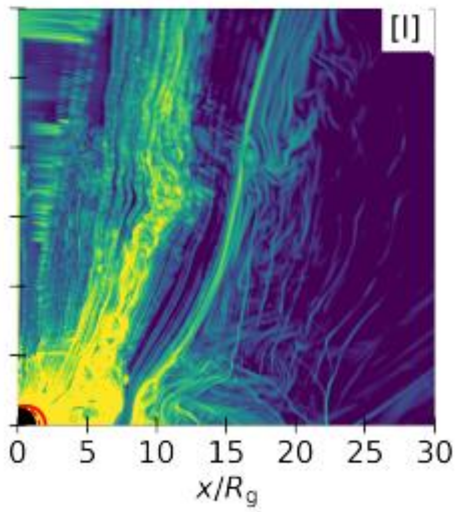
Krawczynski…AV, et al. 2022, *Science*; AV et al. 2023; Ingram…AV et al. 2024; Podgorny…AV et al. 2024; Kravtsov, AV et al. 2025

Additional effects and alternative scenarios

- Outflow:
  - Poutanen, AV, Beloborodov 2023: aberration effects lead to higher PD at the low inclination
- Wind:
  - Nitindala, AV, Poutanen 2024: single scattering in the outer wind; only boost of corona polarization, need to have right profile/optical depth (Ryota et al. 2024)
- 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







An astronomical puzzle called Cygnus X-3

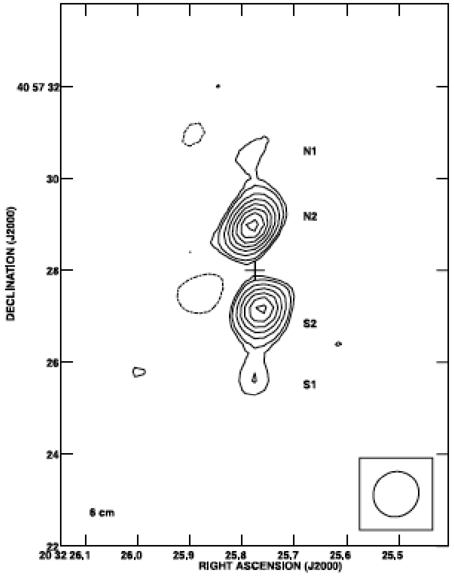
- Radio counterpart (Braes & Miley 1972), sometimes the brightest radio XRB (detected fluxes as high as 20 Jy, Corbel et al. 2013)

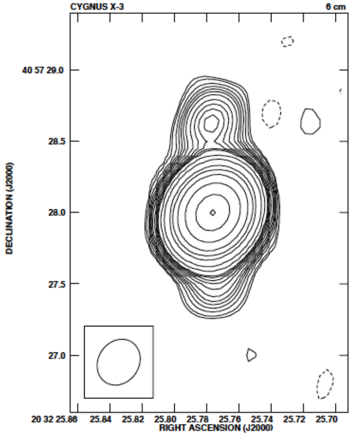
An Astronomical Puzzle Called Cygnus X-3

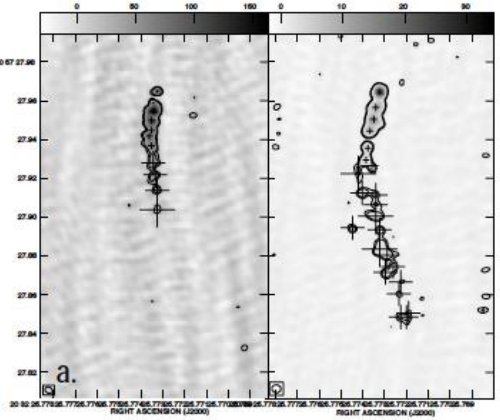
The early history of an x-ray, infrared, cosmic ray, and radio emitting star system.

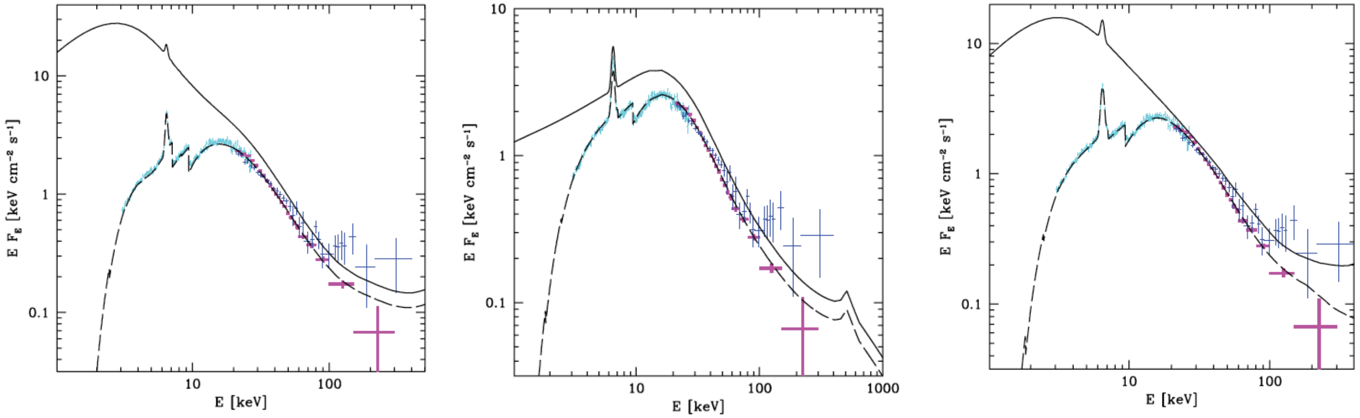
R. M. Hjellming

Orbital period: 4.8h
Inclination: 29.5°
Luminosity - ???







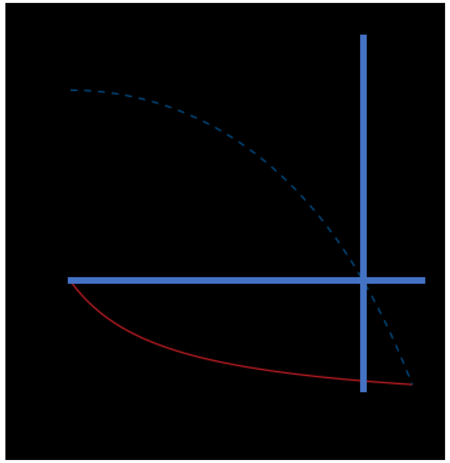


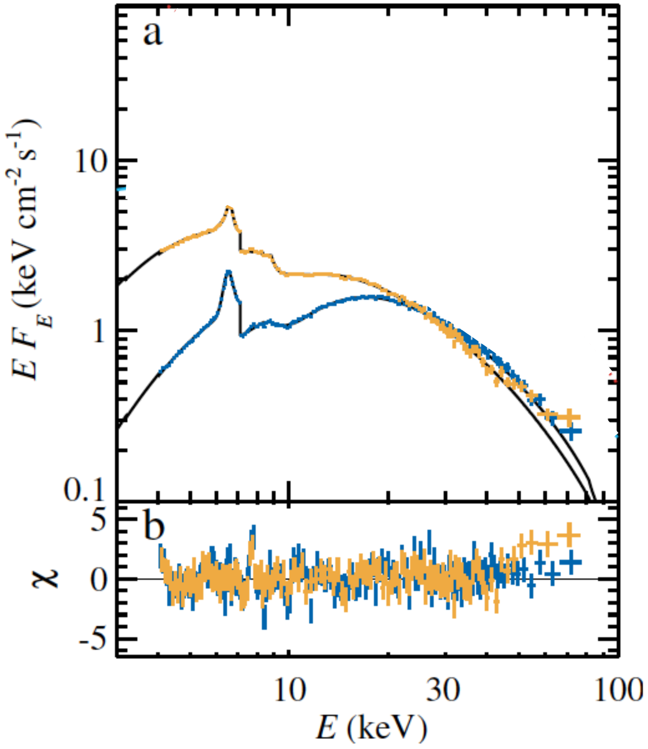
Hjalmarsdotter et al. 2009

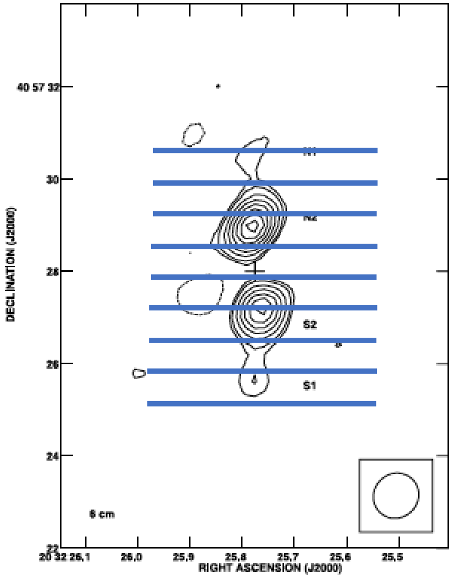
First observations in 2022: hard & intermediate state

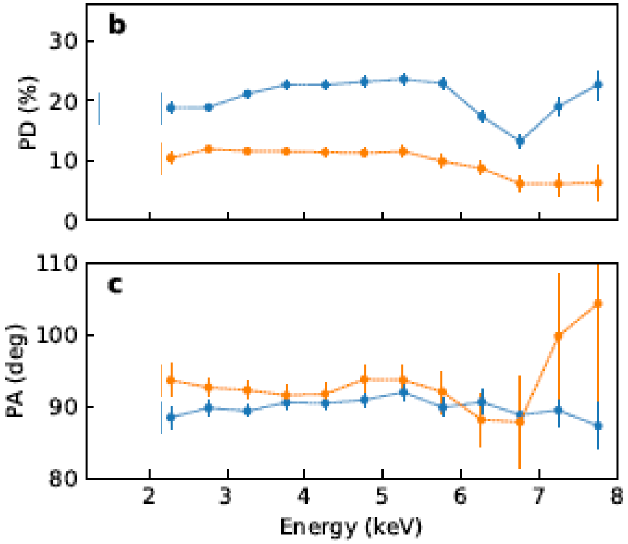
- Hard state

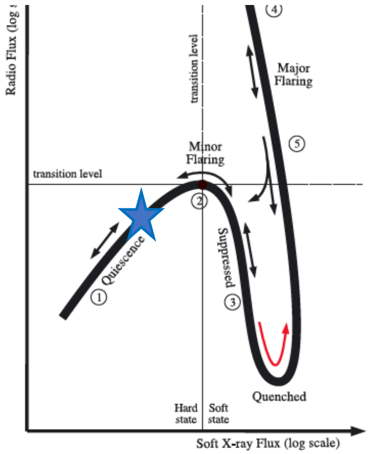
PD = 20.6 +/- 0.3 %
PA = 90.1 +/- 0.4º











- **High polarization!**
- Polarization ⊥ to the jet direction -> incoming photons | | jet
- Constant PD/PA with energy -> single scattering
- Stable over years (Mikusinkova, AV et al. 2026)

AV et al. 2024, *Nature Astronomy*

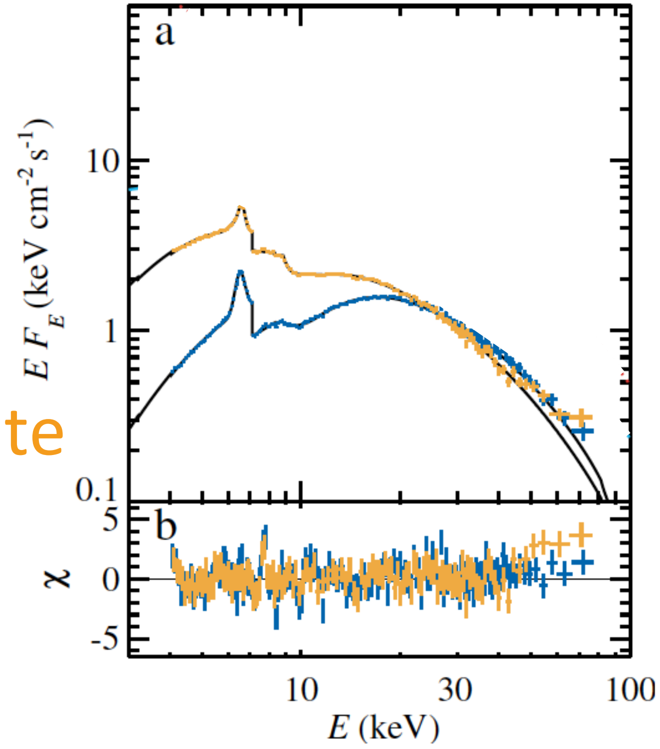
First observations in 2022: hard & intermediate state

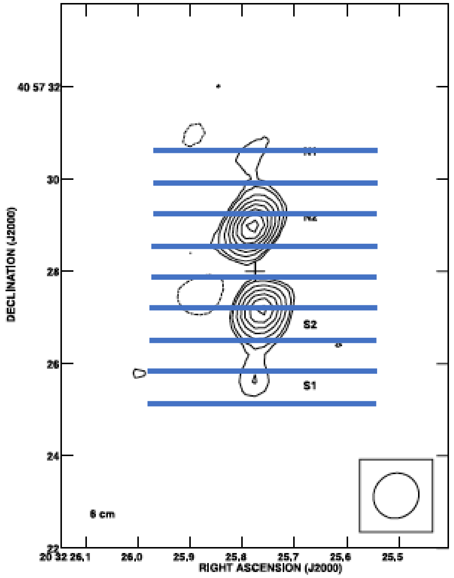
- Hard state

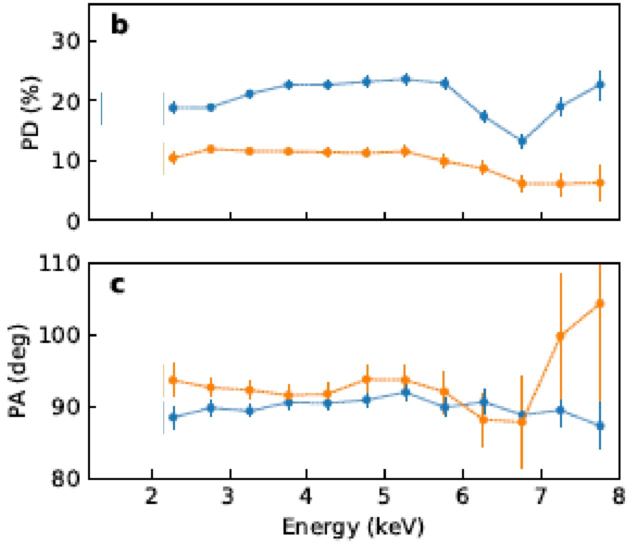
PD = 20.6 +/- 0.3 %
PA = 90.1 +/- 0.4º

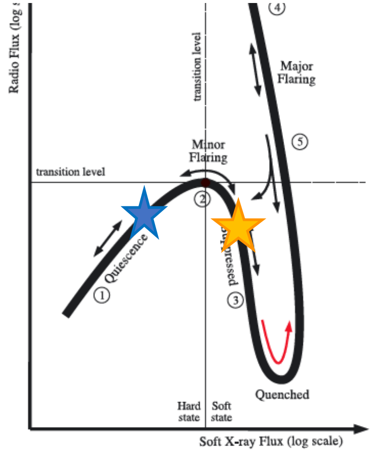
- Intermediate state

PD = 10.0 +/- 0.5 %
PA = 90.6 +/- 1.2º









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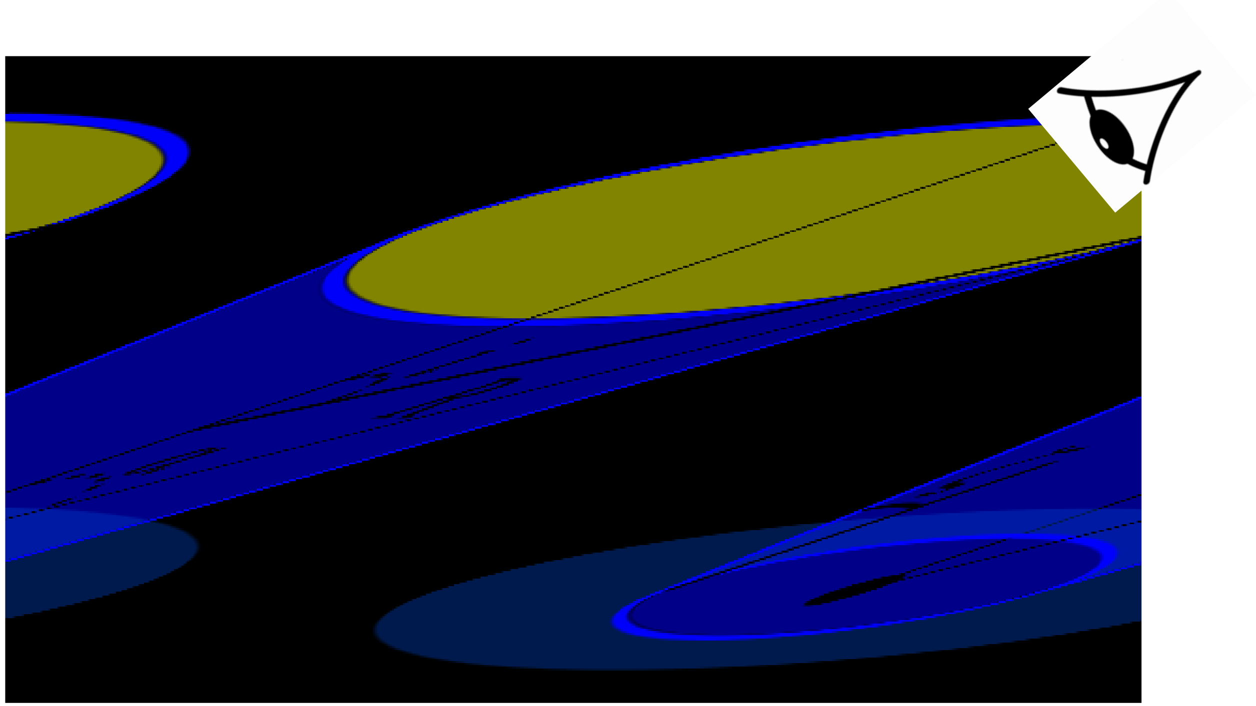
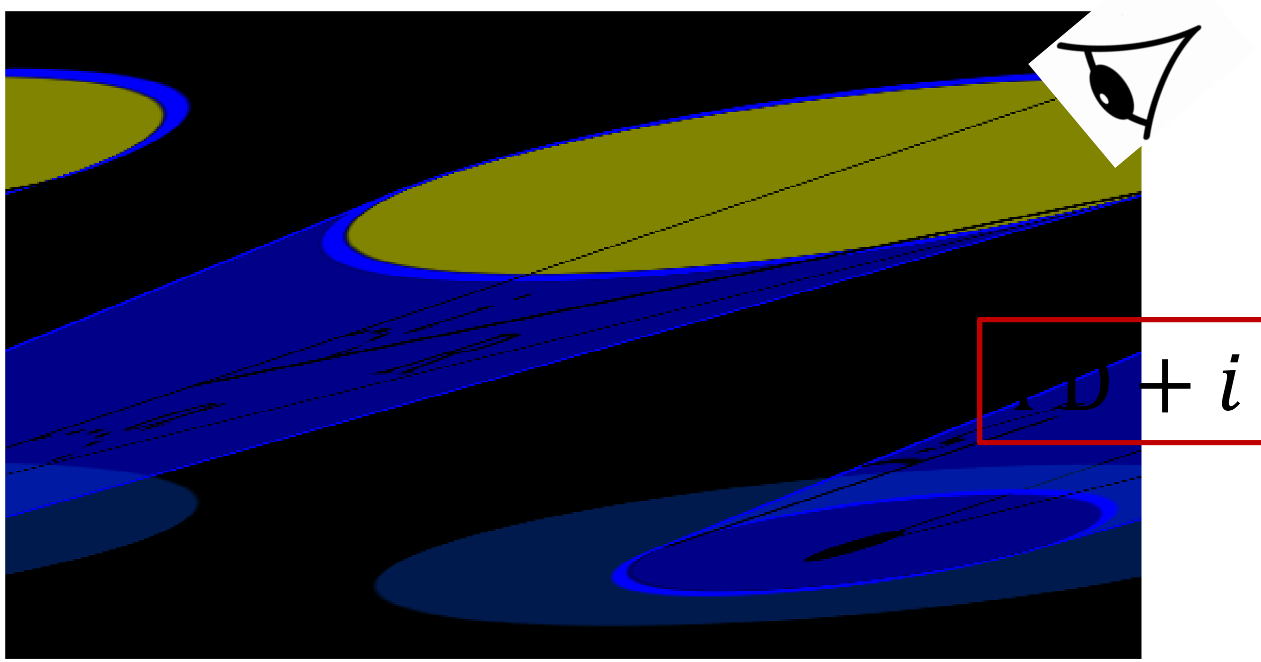
Obscured Galactic source: geometry

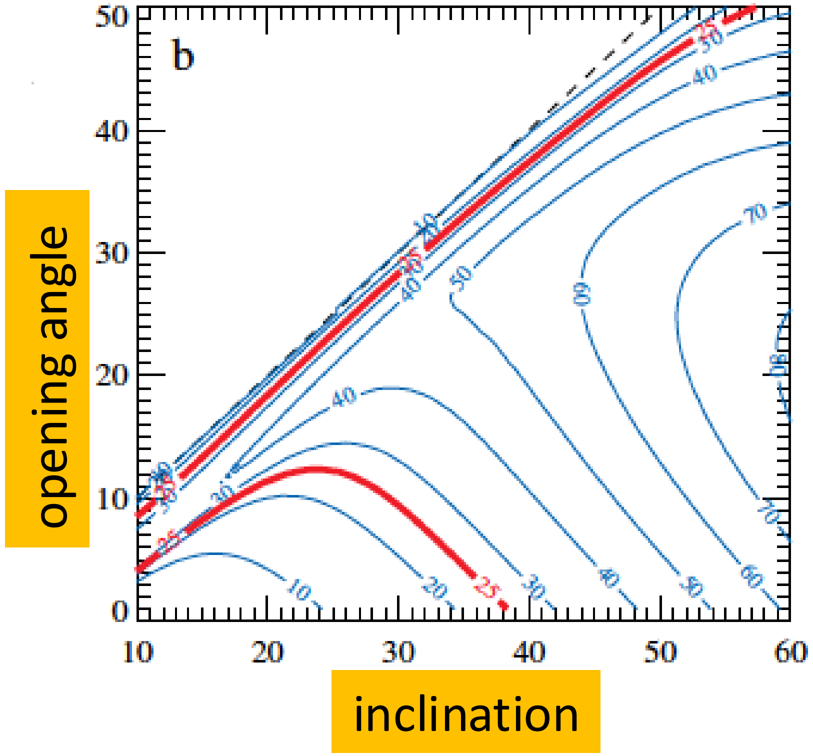


- High polarization we don't see the incident source

Obscured Galactic source: geometry



$+ i = \alpha$

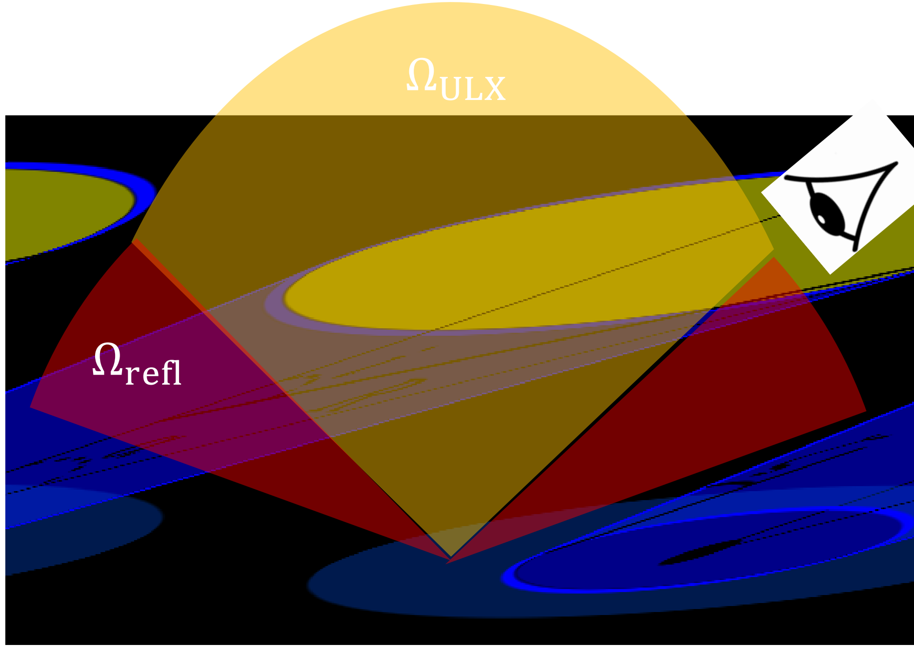


- High polarization we don’t see the incident source
- Opening angle estimate

Obscured Galactic ULX: on-axis apparent L

- Luminosity estimates: simple case when the intrinsic X-ray source is isotropic, the luminosity escaping in a given solid angle is: $L_\Omega \propto \Omega$

$$L_{ULX} \geq 5 \times 10^{39} \mathrm{erg\ s^{-1}}$$



- Bolometric luminosity from modelling

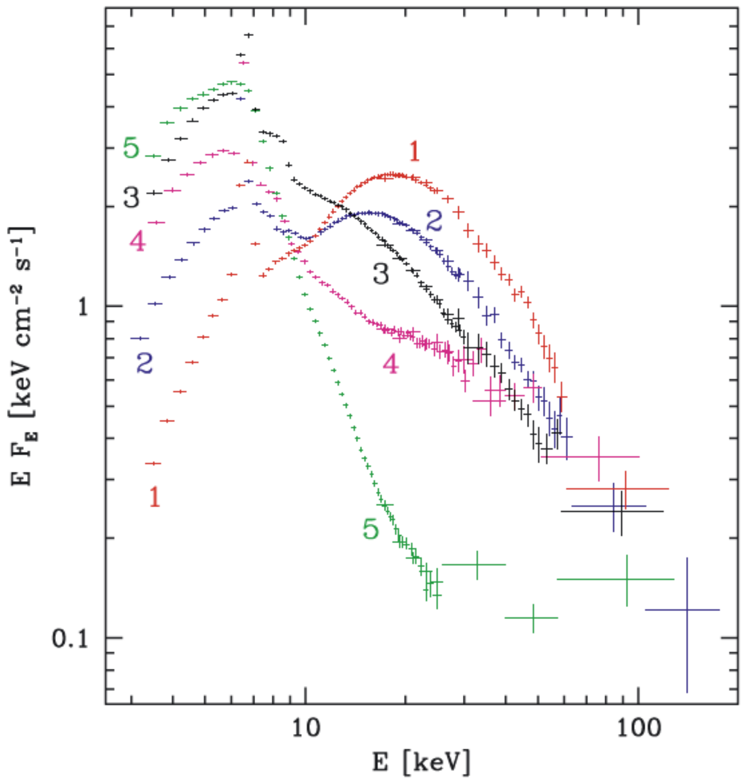
$$L_{\mathrm{X,bol}} = \frac{4\pi D^2 f_{\mathrm{bol}} F_{\mathrm{unabs}}}{a} \left(1 + \frac{\Omega_{\mathrm{ULX}}}{\Omega_{\mathrm{refl}}}\right) > 3 \times 10^{38} \left(1 + \frac{1 - \cos\zeta}{\Omega_{\mathrm{refl}}/2\pi}\right) \mathrm{erg\ s^{-1}}$$

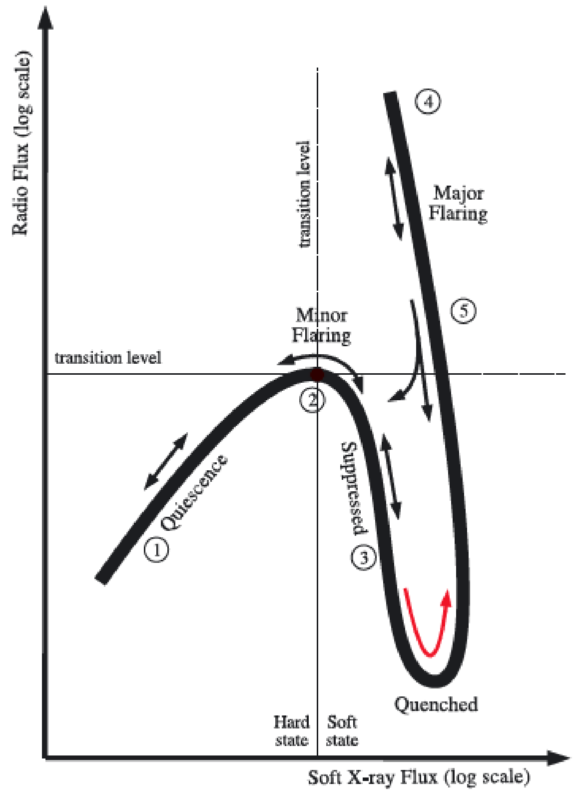
- Can be above $3 \times 10^{39} \mathrm{erg\ s^{-1}}$ for the funnel opening angle 15°

→ **Super-Eddington accretion**

Obscured Galactic ULX: softer states

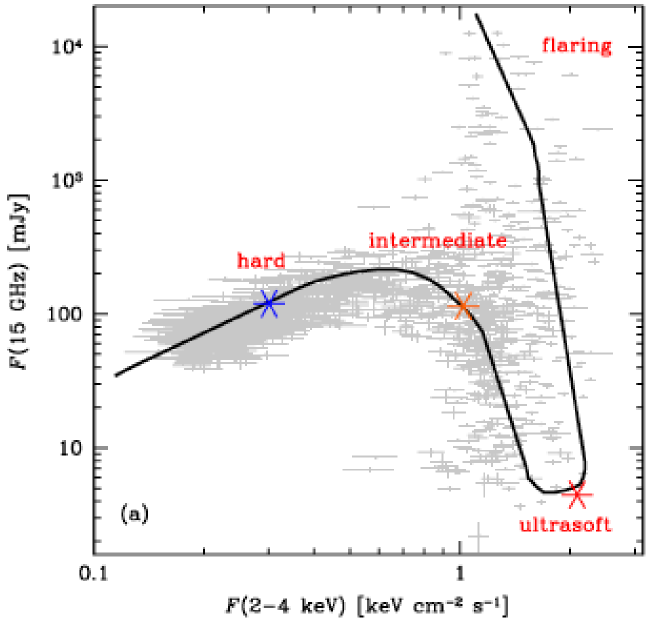
Hard
Intermediate
Very high
Ultrasoft
Soft non-thermal

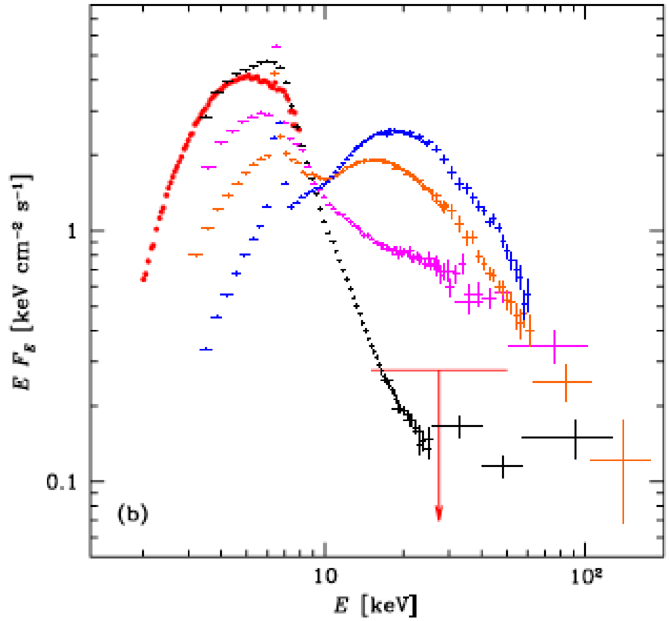




Szostek et al. 2008

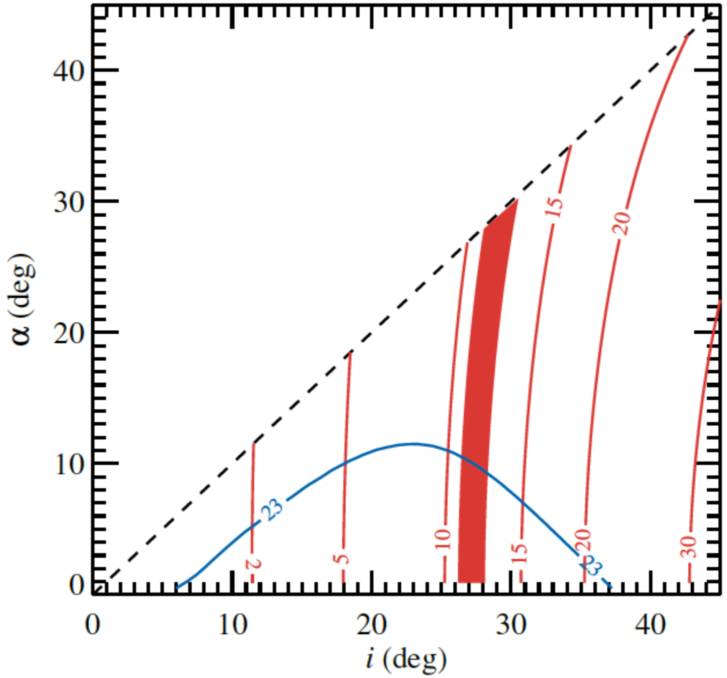
Obscured Galactic ULX: softer states



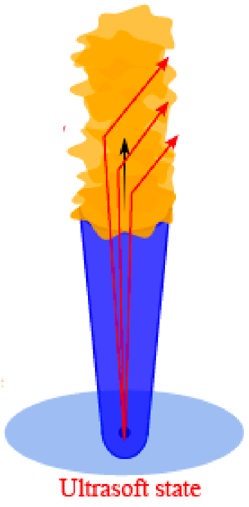


PD = 11.9 +/- 0.5 %

PA = 94º +/- 1º



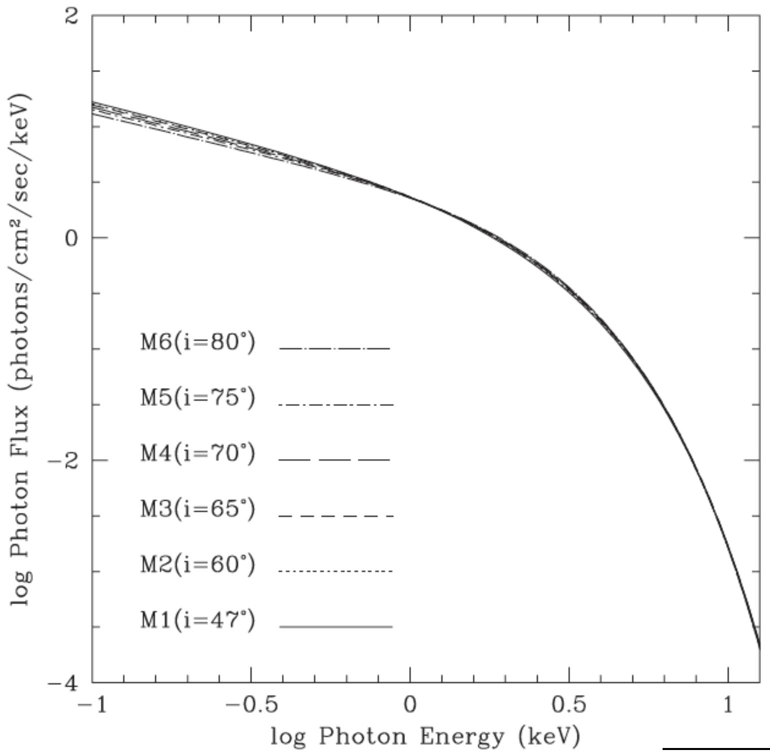
$26° < i < 28°$

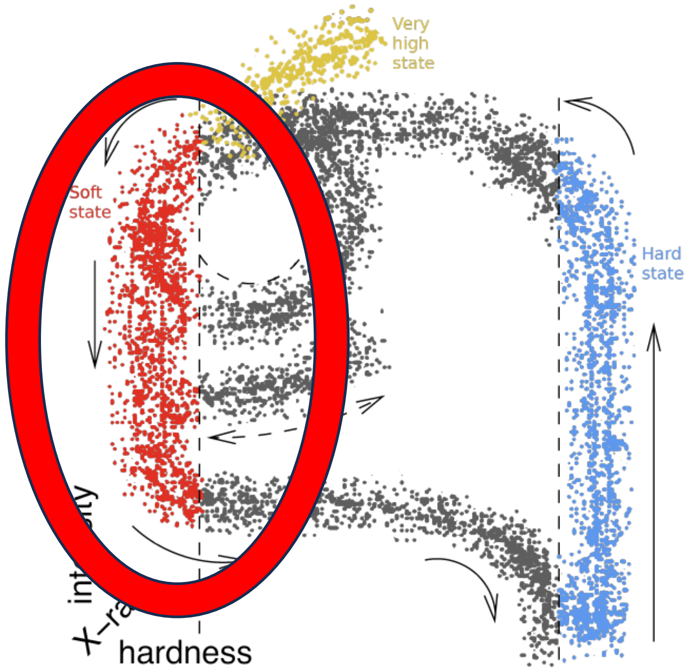


Ultrasoft and intermediate states: scattering from the medium inside/above the funnel

AV et al. 2024, A&A, 688, L27

Polarization of the soft-state sources





Model	a_*	i_{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

Li, Narayan & McClintock 2009

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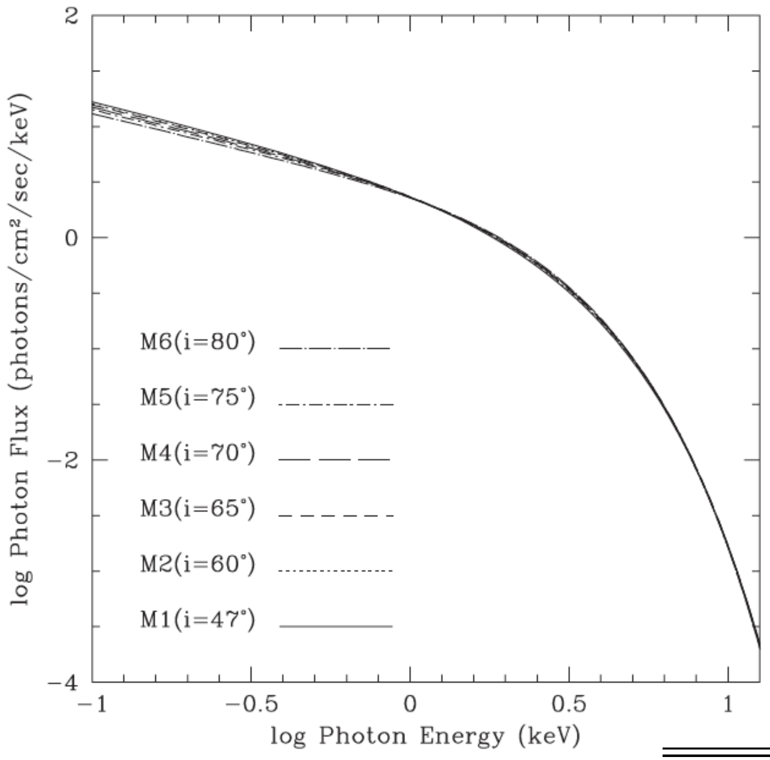
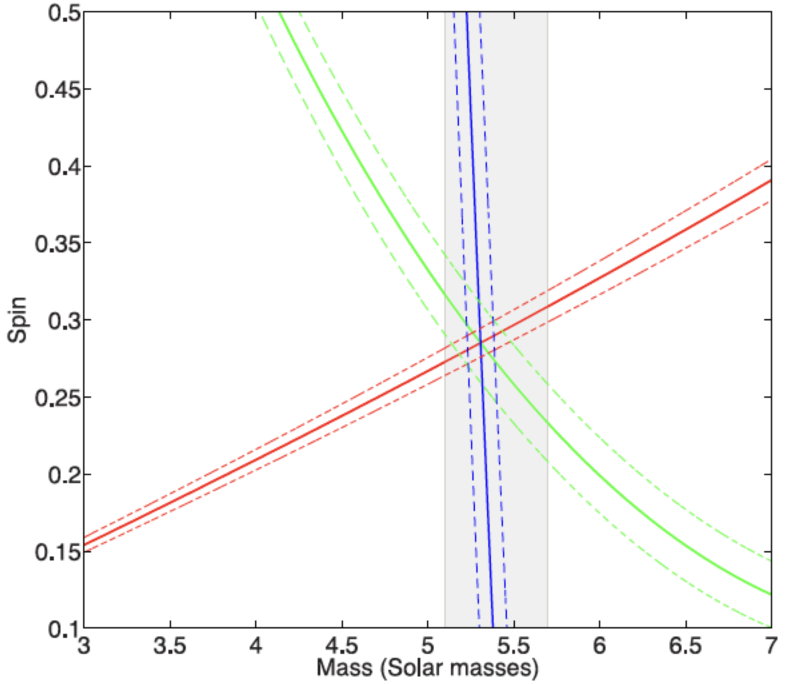


GRO J1655–40



Motta et al. 2024

Li, Narayan & McClintock 2009

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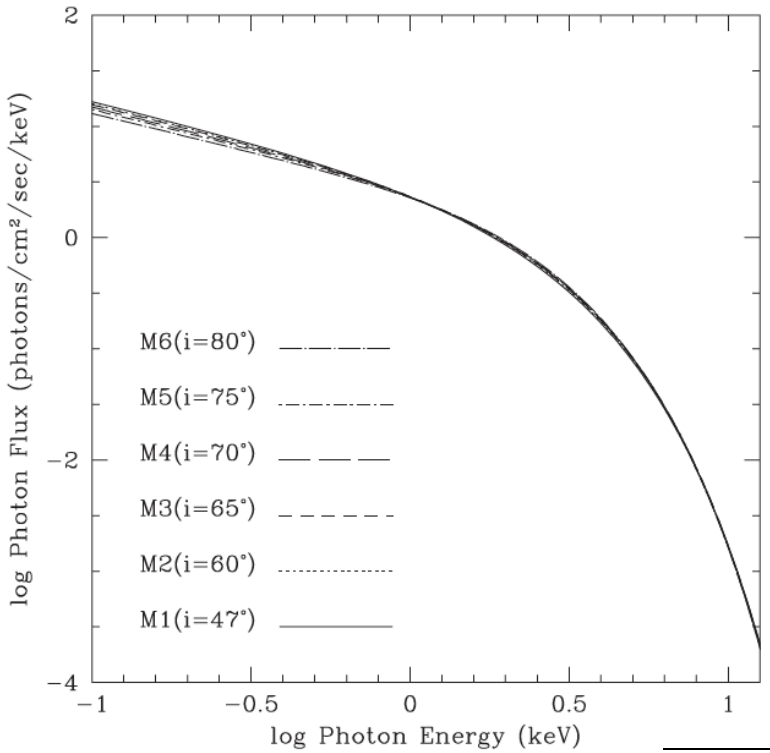

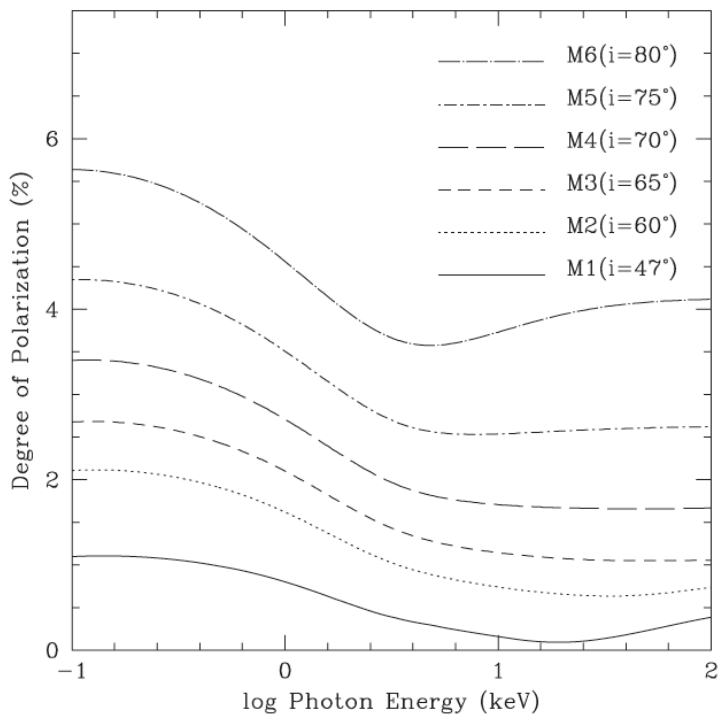

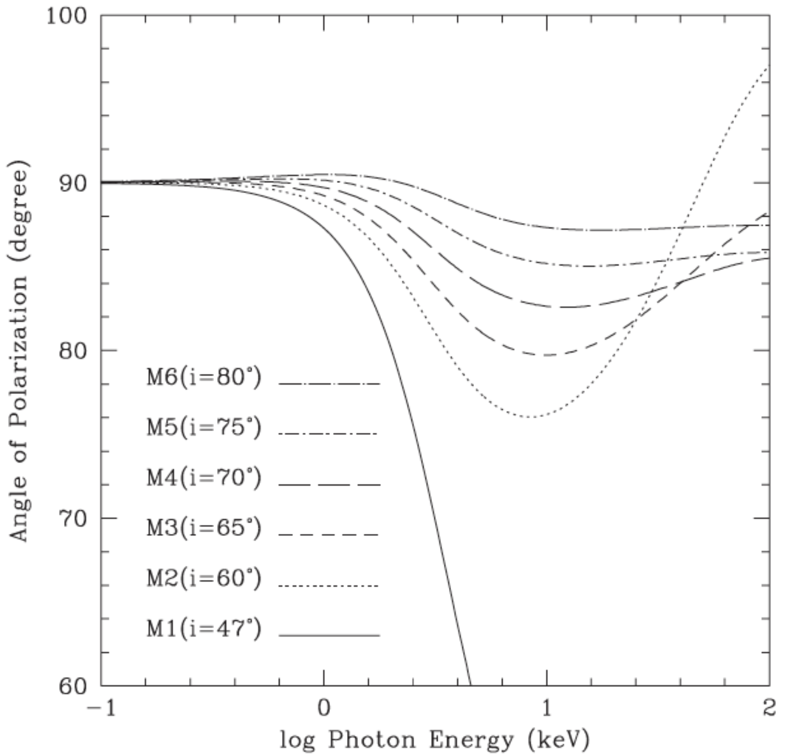

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Li, Narayan & McClintock 2009

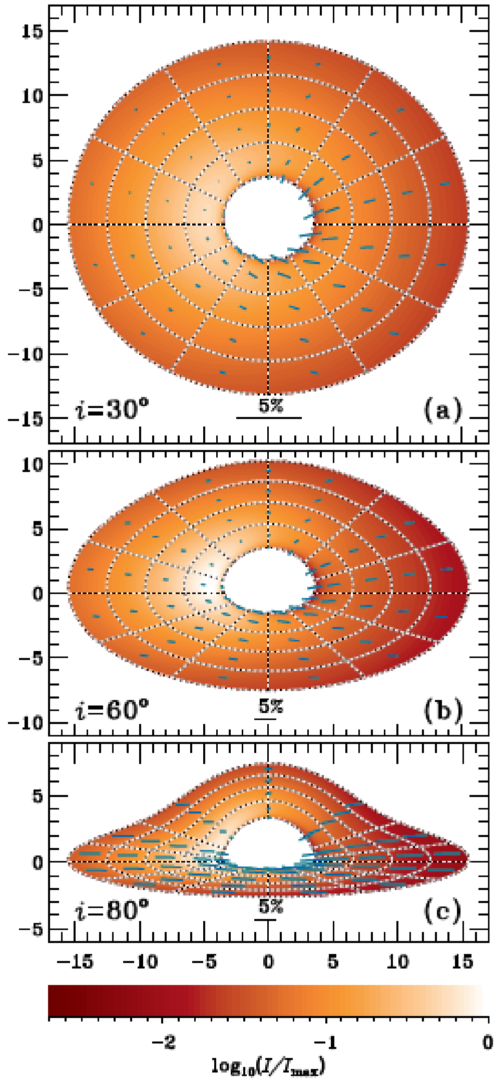
Soft state: expectations

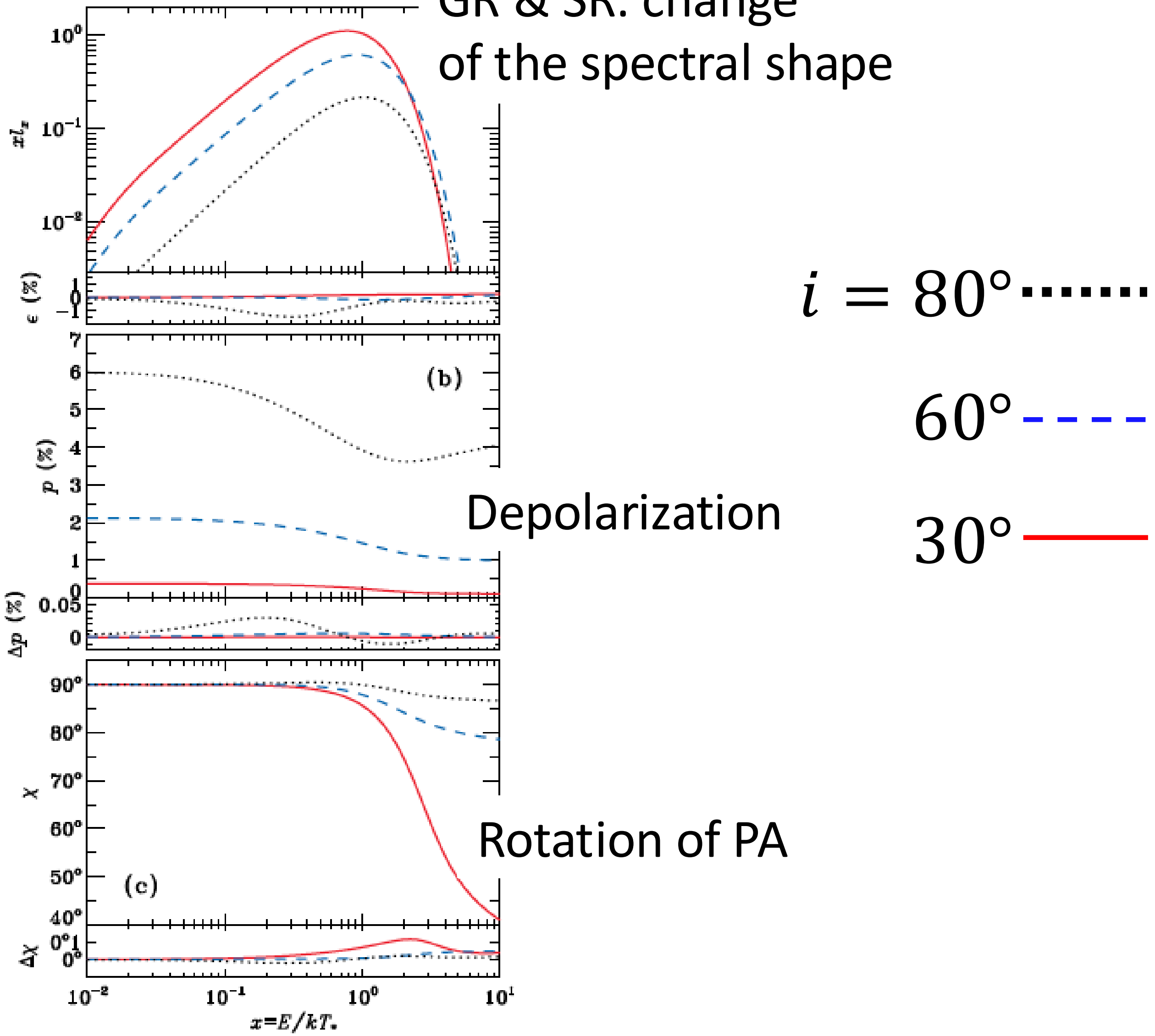
- Soft state:
  - Shakura & Sunyaev 1973, Novikov & Thorne 1973
  - Rees 1975: results of plane-parallel atmospheres (Chandrasekhar 1960, Sobolev 1963) for accretion discs with pure electron scattering, PA along the disc surface

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

  - 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

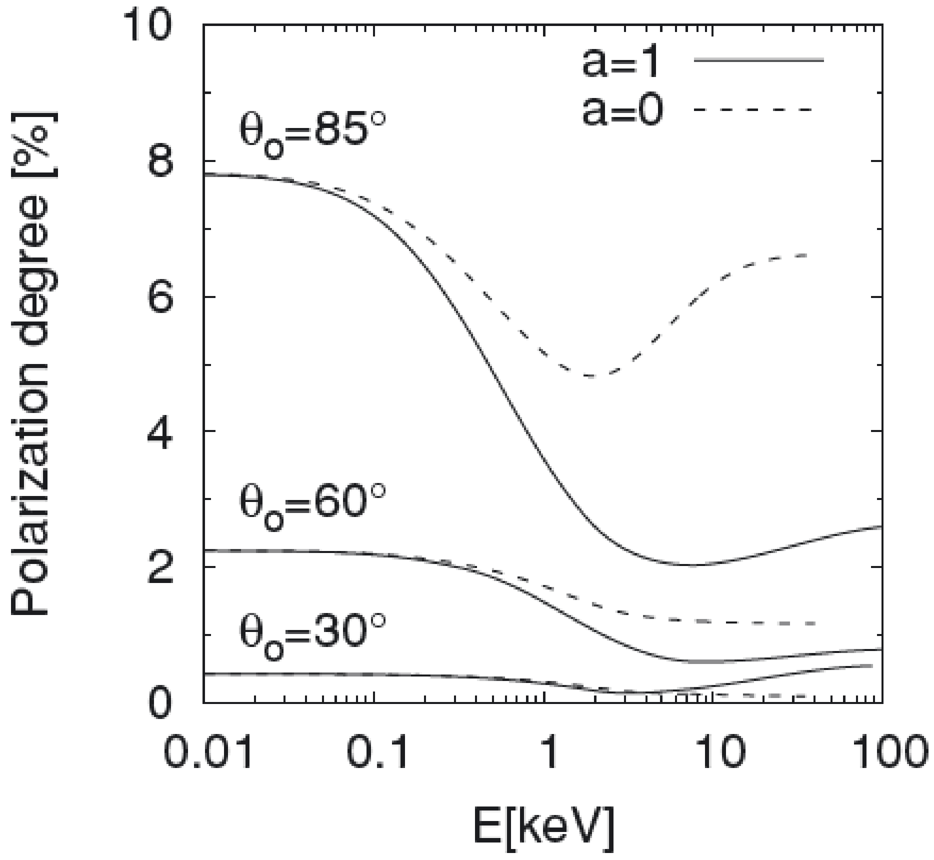


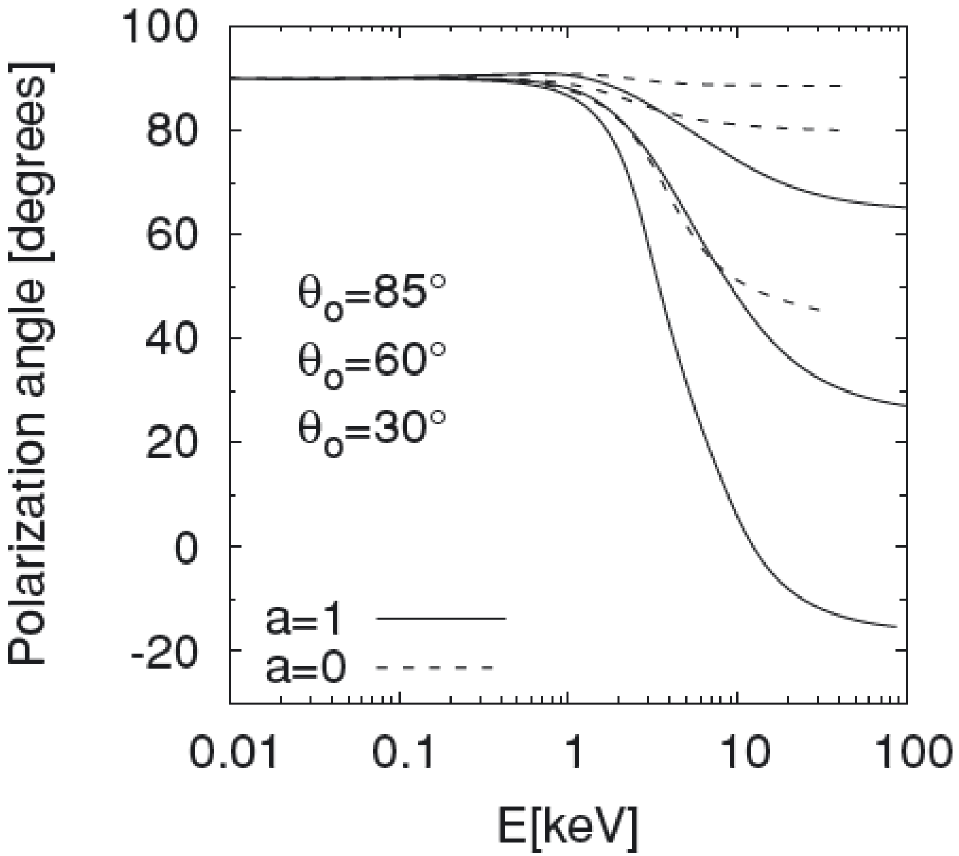


Analytical ray-tracing for spectra and polarization

Loktev, AV, Poutanen 2022

Very high spin: severe PA rotation, depolarization

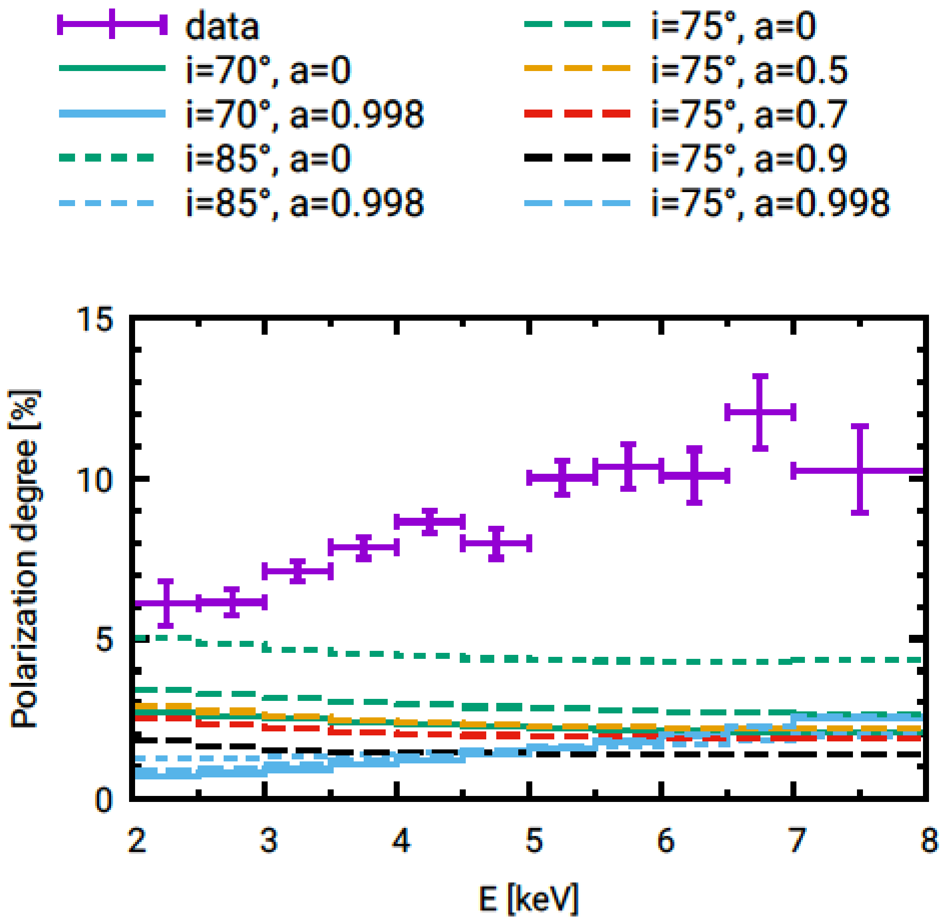




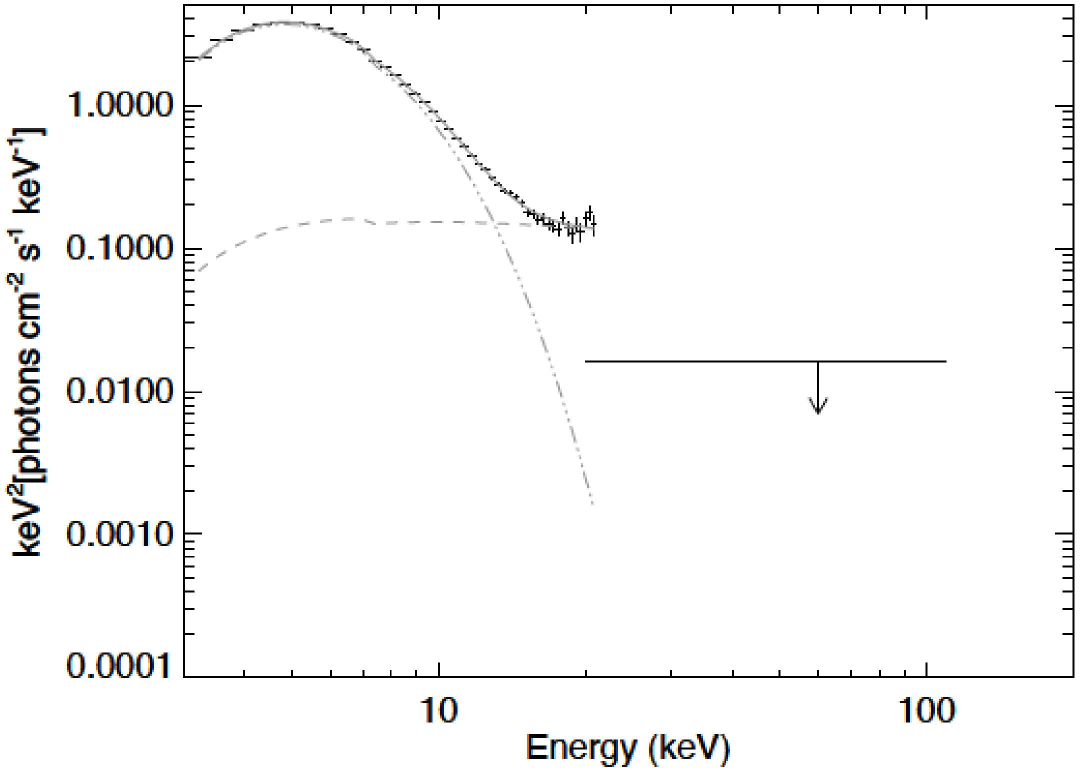
Dovciak et al. 2004, 2008
Loktev, AV et al. 2024

expectations prior to *IXPE*:
PD<6% and rotation of PA with energy

IXPE soft-state observations: 4U 1630-47

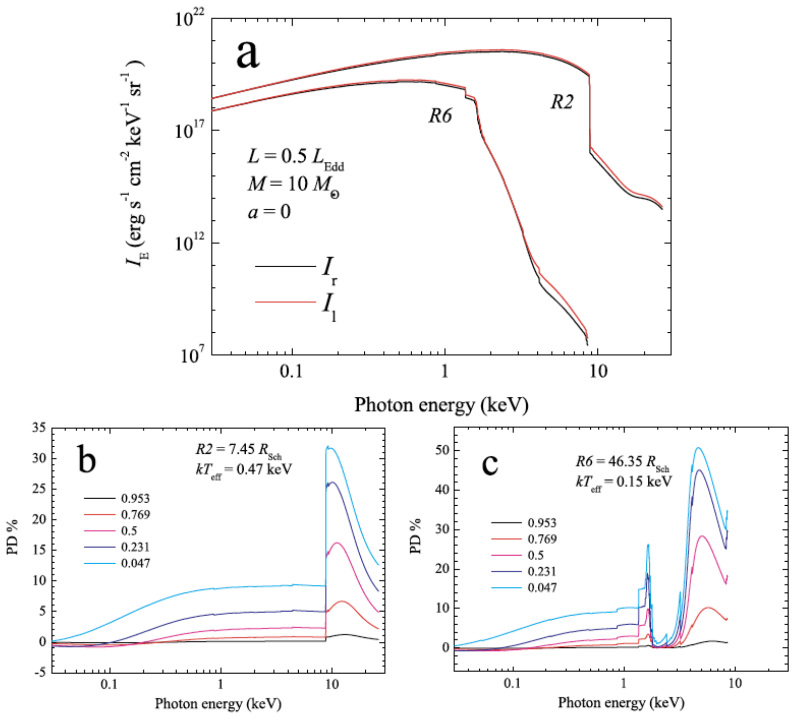


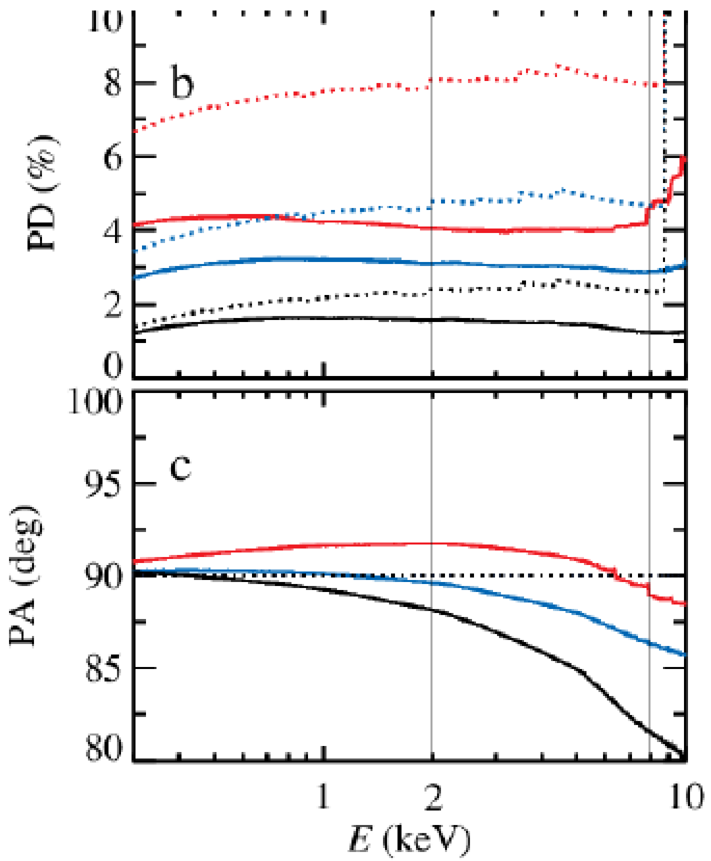
- Too low PD (especially for the high spins)

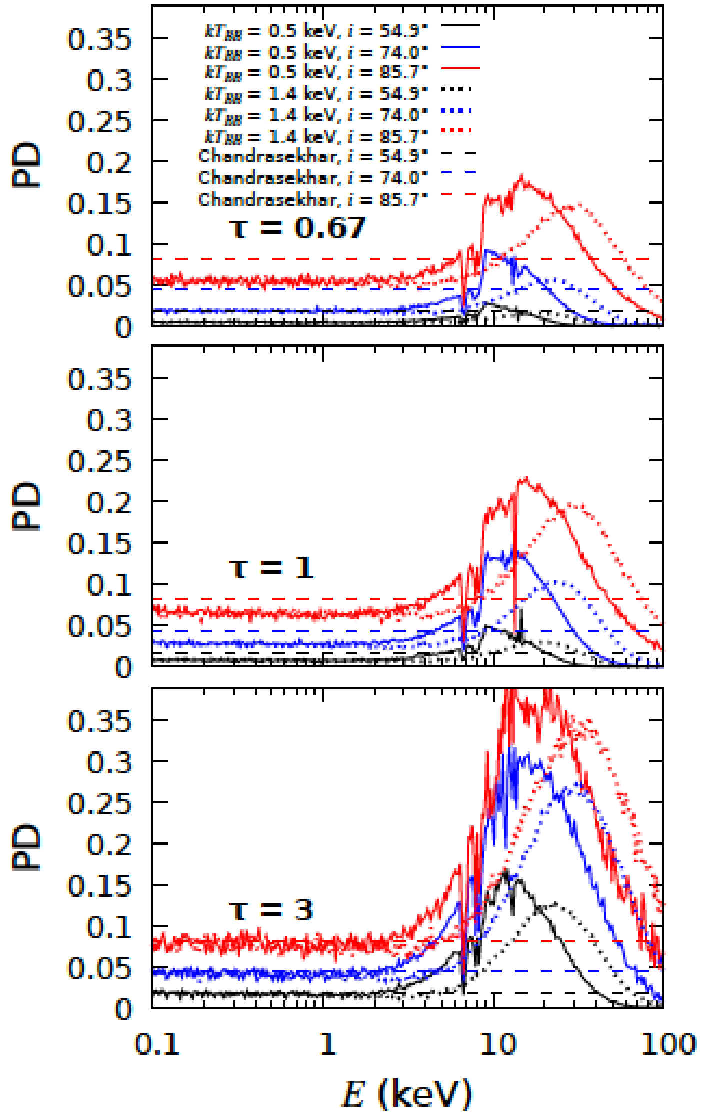


Ratheesh … AV et al. 2024

IXPE soft-state observations: 4U 1630-47

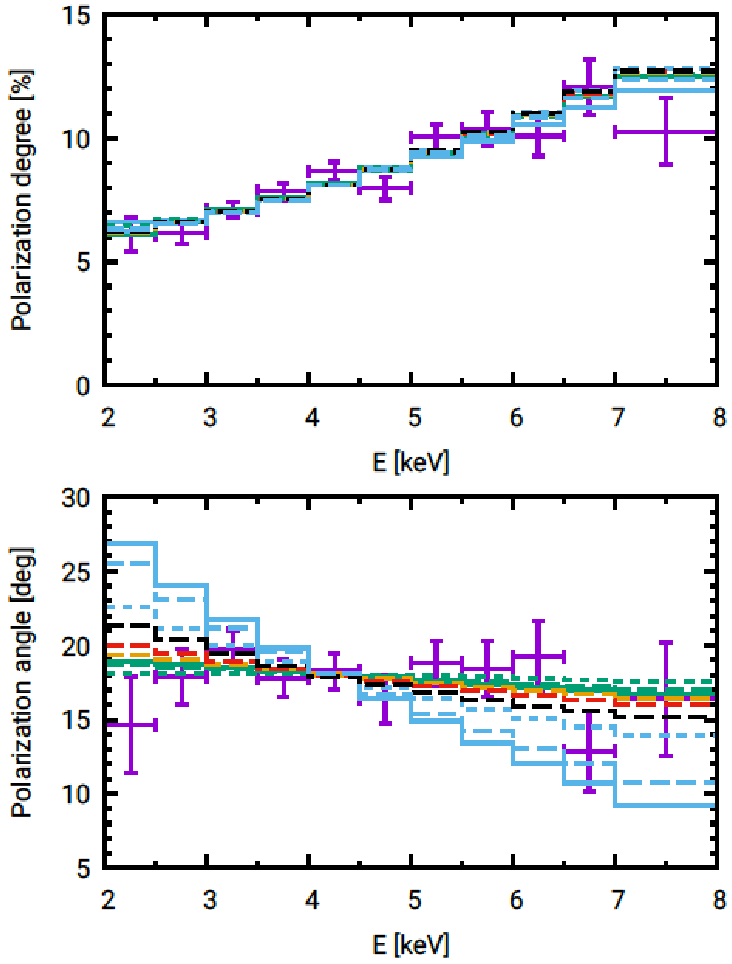




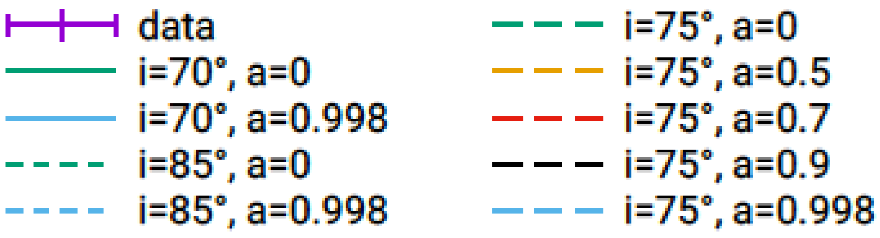


Ratheesh … AV et al. 2024

IXPE soft-state observations: 4U 1630-47

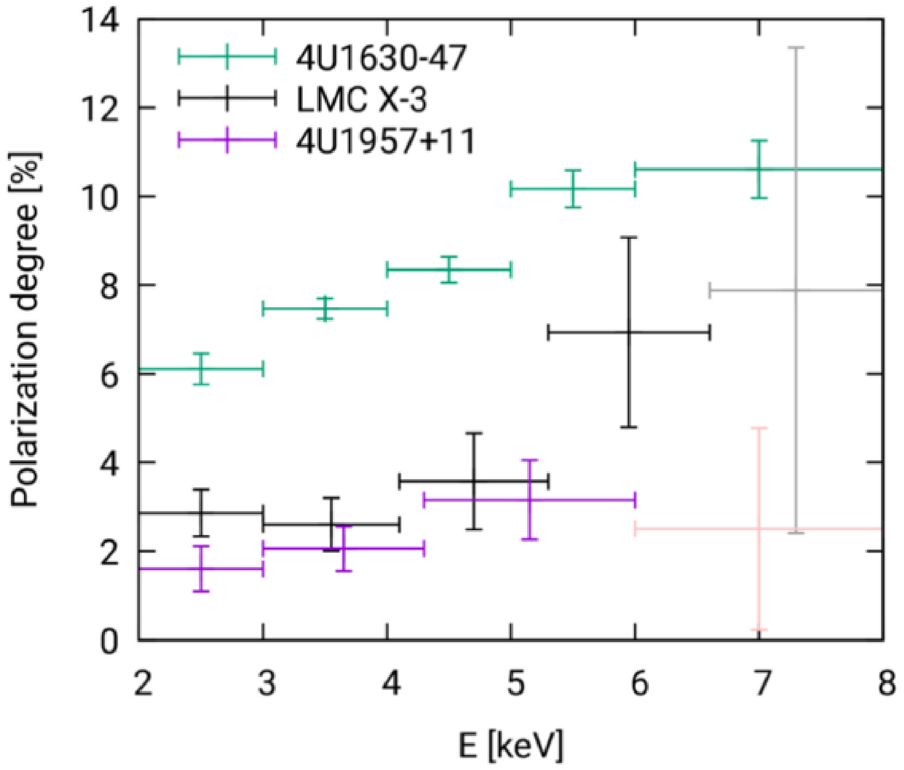


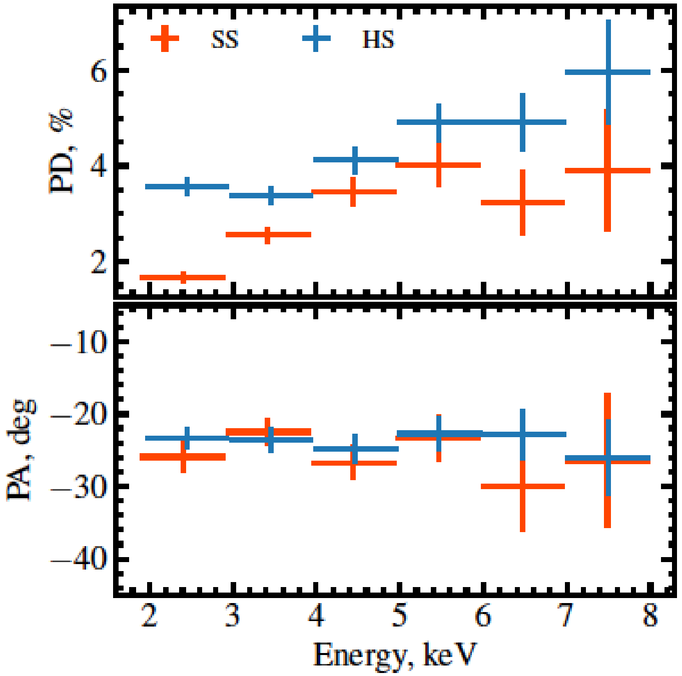
- Adding outflow $v/c = 0.5$ and absorption for slab of the optical depth $\tau = 7$
- PA: constraints on the spin (a<0.7)

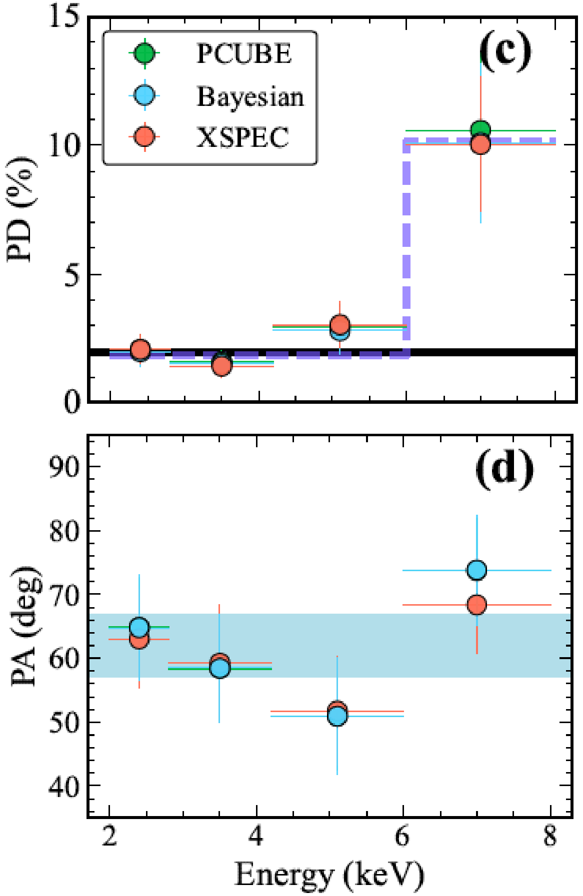


Ratheesh … AV et al. 2024

Other soft-state sources





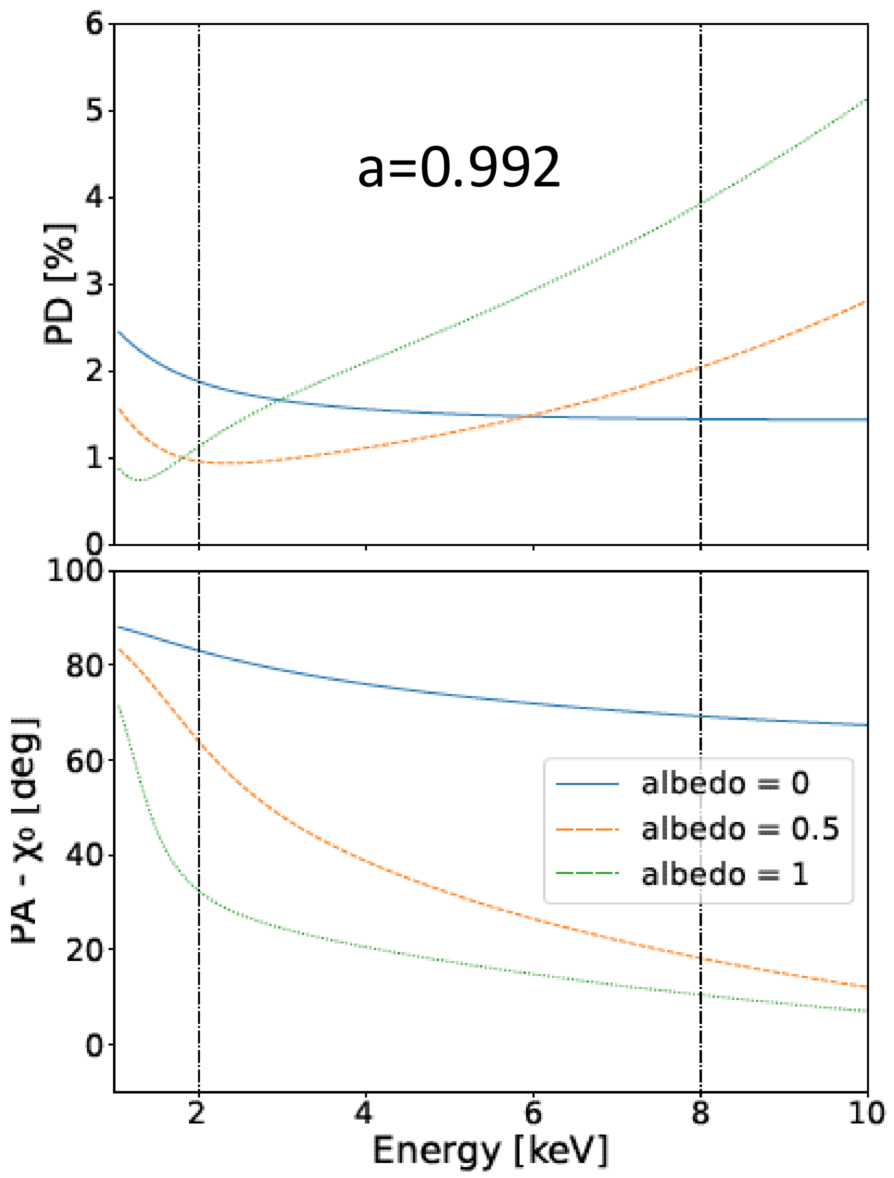


Svoboda … AV et al. 2024
Marra… AV et al. 2024
Steiner … AV et al. 2024
Kravtsov, Bocharova, AV et al. 2025
Zhao et al. 2026

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

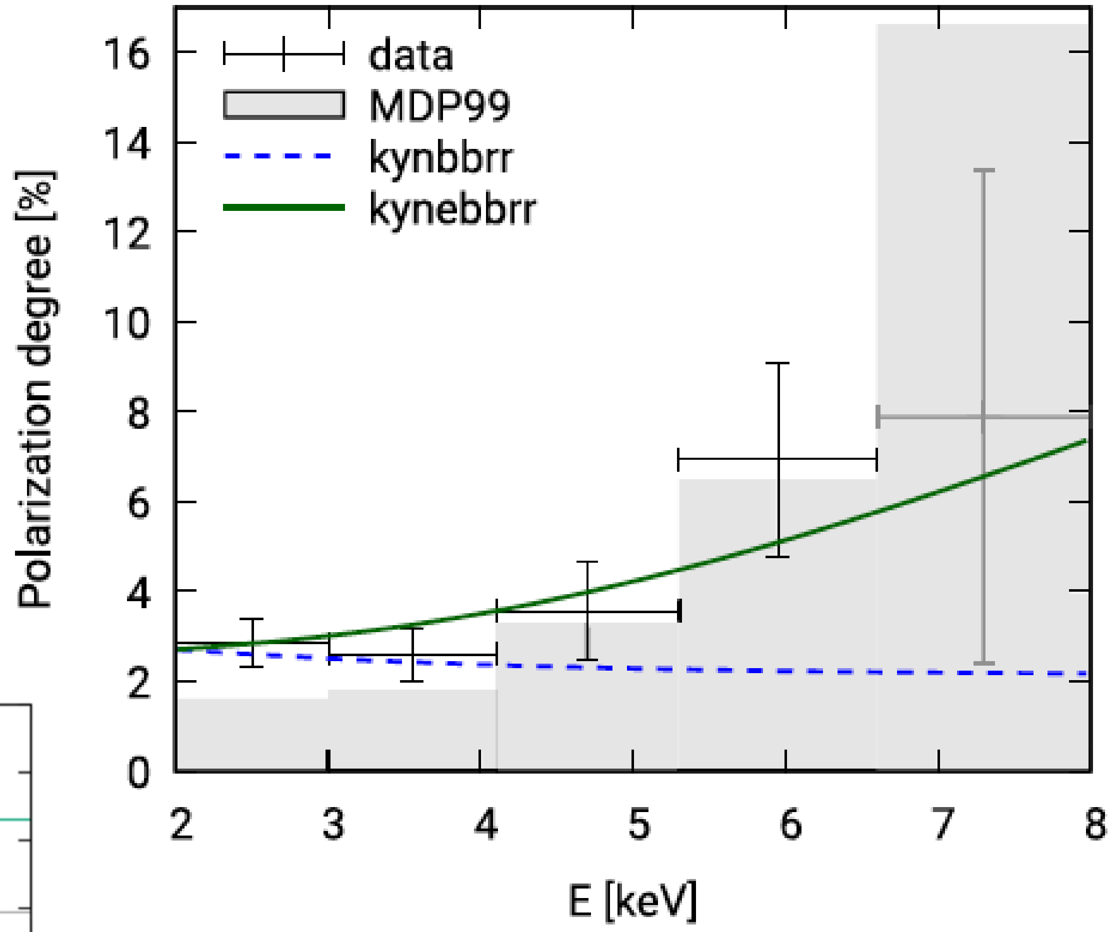


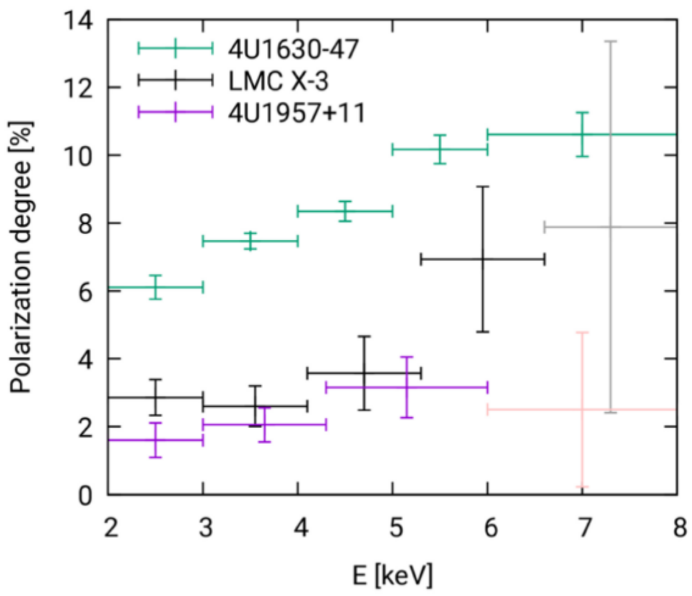
Marra … AV et al. 2024

Other soft-state sources: returning radiation (?)

- a<0.7 (LMC X-3)

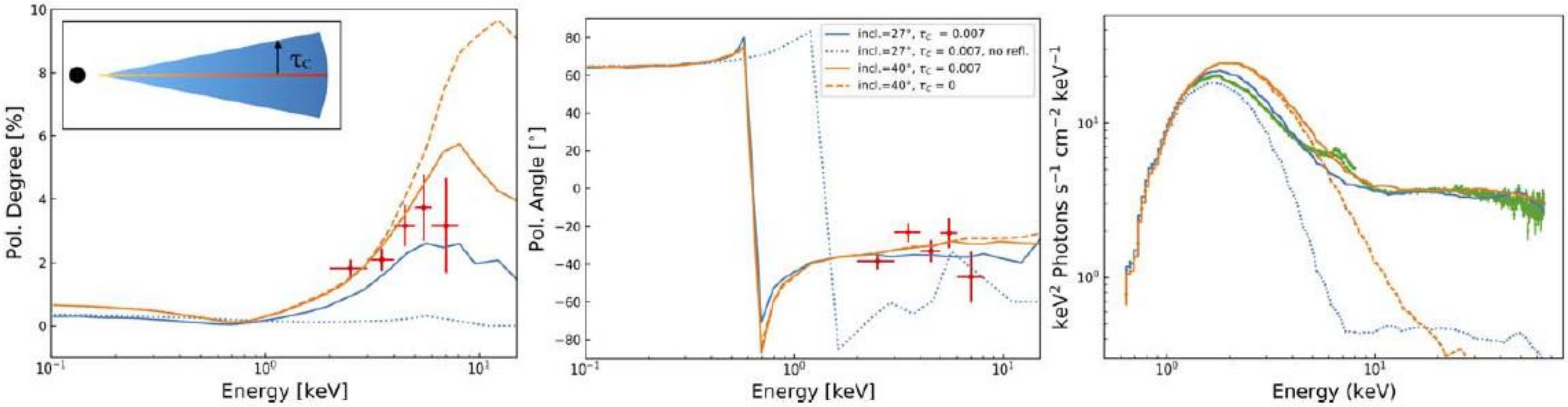
- More complex case, fit with returning radiation: blue dashed lines
- But: similarity with 4U1915+11





Svoboda … AV et al. 2024

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

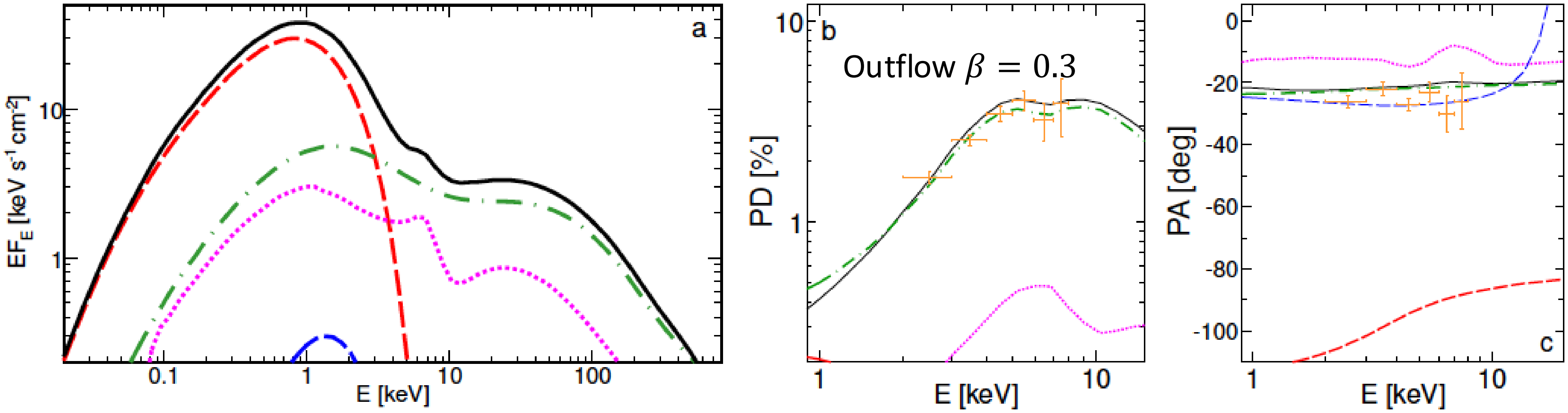


a>0.96

$\lambda = 1$

Steiner… AV et al. 2024

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

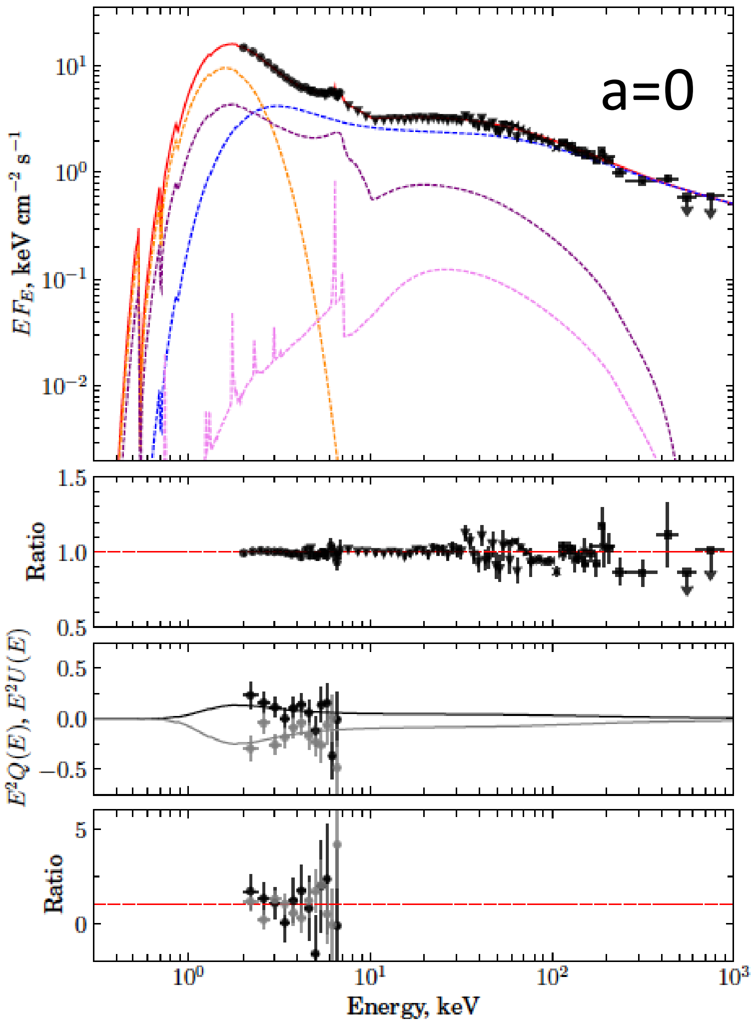


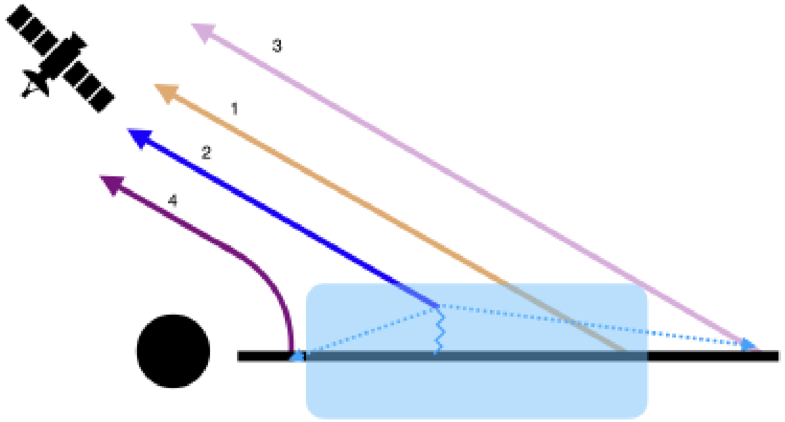
a=0

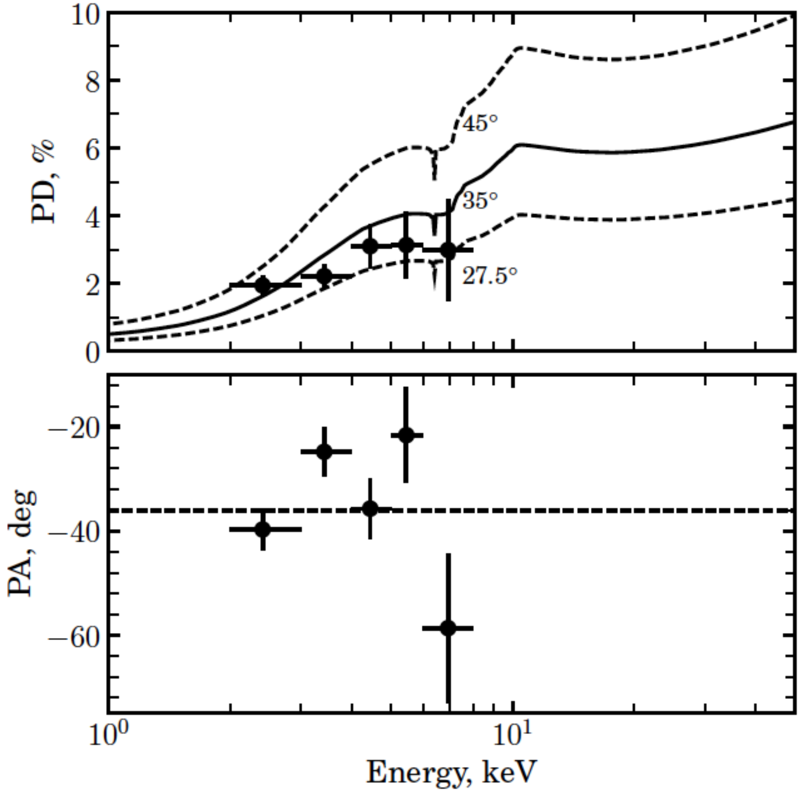
$\log\xi \approx 4$

Niedzwiecki… AV et al. 2026

Cyg X-1 soft-state polarization: hybrid corona





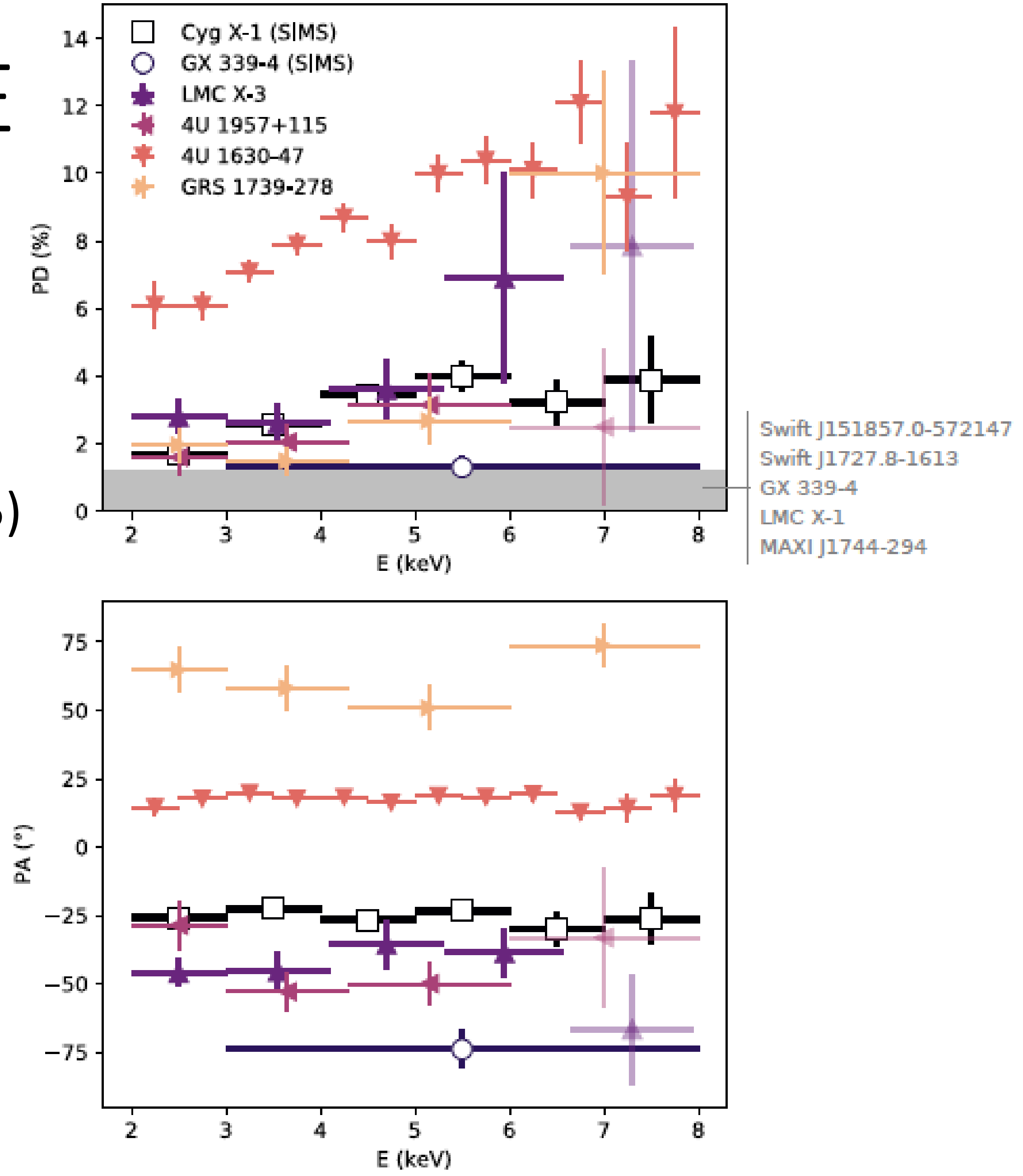


$kT_e \approx 12$ keV, $\tau \approx 1.4$, $p \approx 3.2$, $\gamma_{min} \approx 1.19$, $T_{in} \approx 0.4$ keV

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

Accretion disks:
the first 50 years

May 2023

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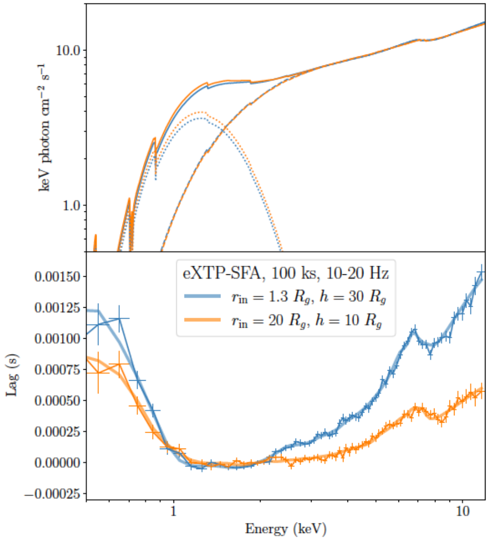
Omer Blaes (UC Santa Barbara, USA)

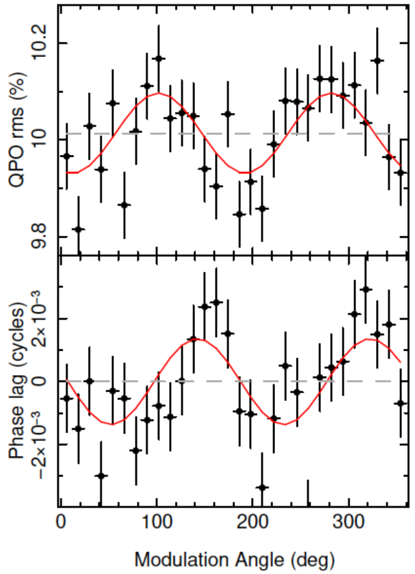
Christian Knigge (University of Southampton, UK)

Chris Done (Durham University, UK)

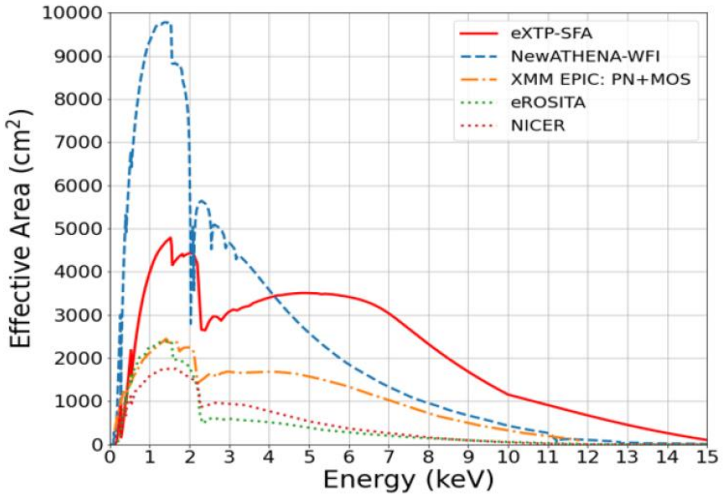
- *Omer Blaes et al. “Non-Stationary Discs and Instabilities”, 2025, SSRv, 221, 120*
- *Chris Fragile et al. “Tilted, Warped, and Eccentric Disks”, 2026, SSRv, 222, 25*
- *Simone Scaringi et al. “Accreting White Dwarfs: An Unreview”, 2026, SSRv, 222, 32*
- *Teo Munoz-Darias et al. “Accretion Disc Winds in X-ray Binaries”, 2026, SSRv, 222, 39*
- *Cristina Baglio et al. “Accreting Neutron Stars”*
- *Greg Marcel et al. “Accreting stellar-mass black holes”, arXiv:2606.19952*
- *Shane Davis et al. “The Central Engine of Accreting Supermassive Black Holes”*
- *Matthew Middleton et al. “Super-critical accretion onto stellar mass black holes and neutron stars: a short review”*

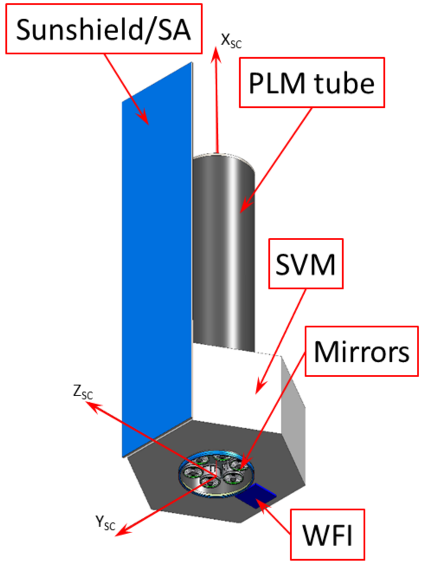
Next step: polarimetry-timing





Zhang et al. 2025
Bu…AV et al. 2025
Zhou…AV et al. 202





Soffita…AV et al. 2026