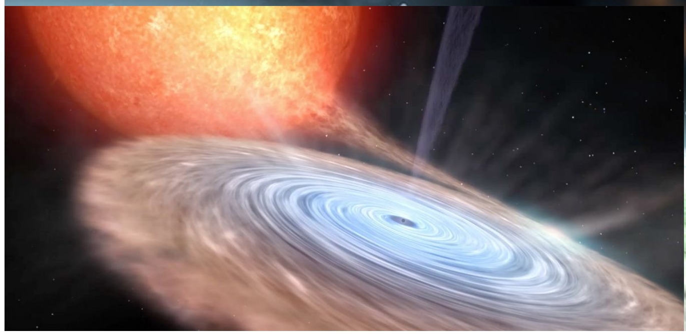
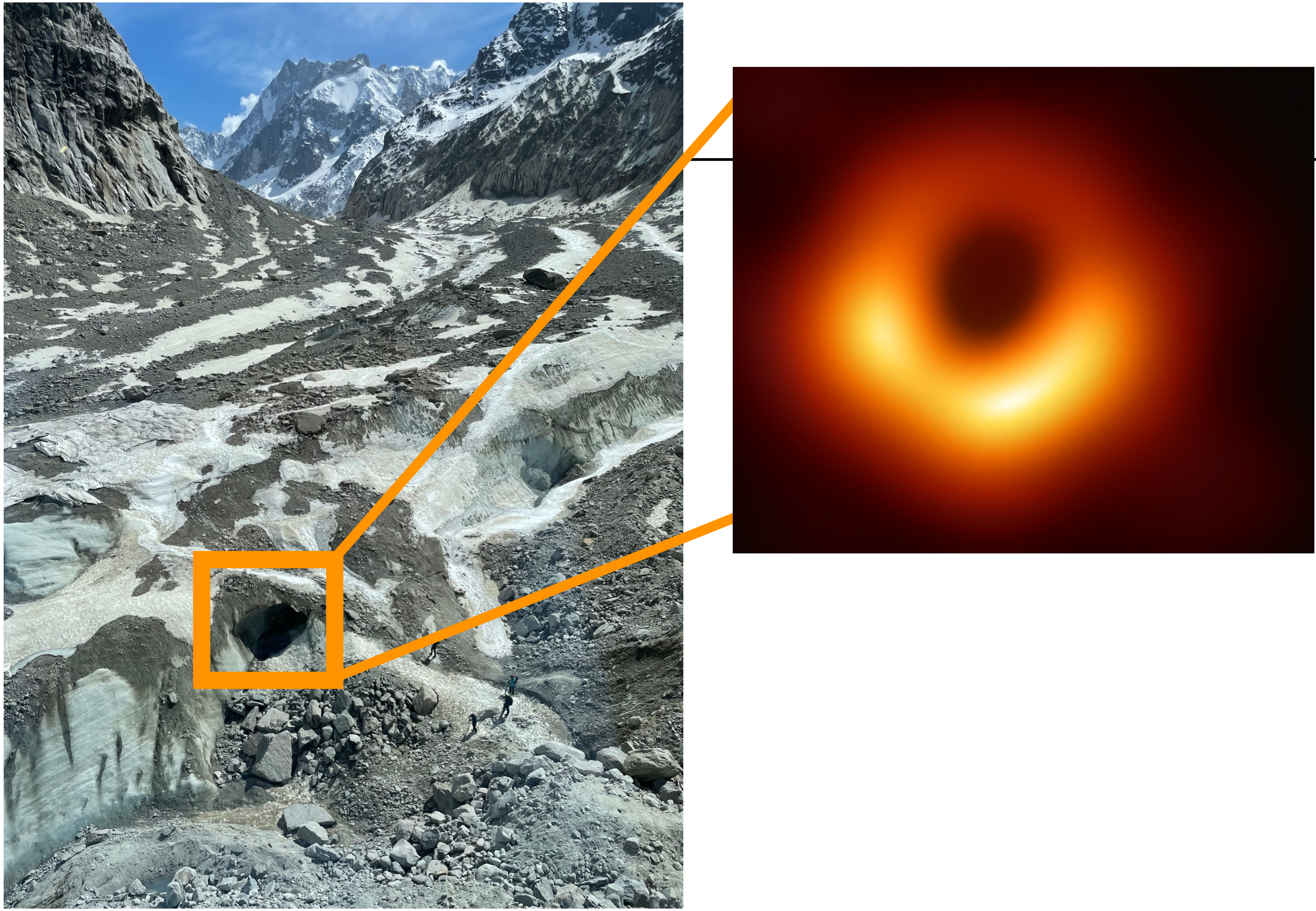
Relativistic magnetospheres: Insights from X-ray polarimetry

Alexandra Veledina
University of Turku, Finland
Nordita, Sweden

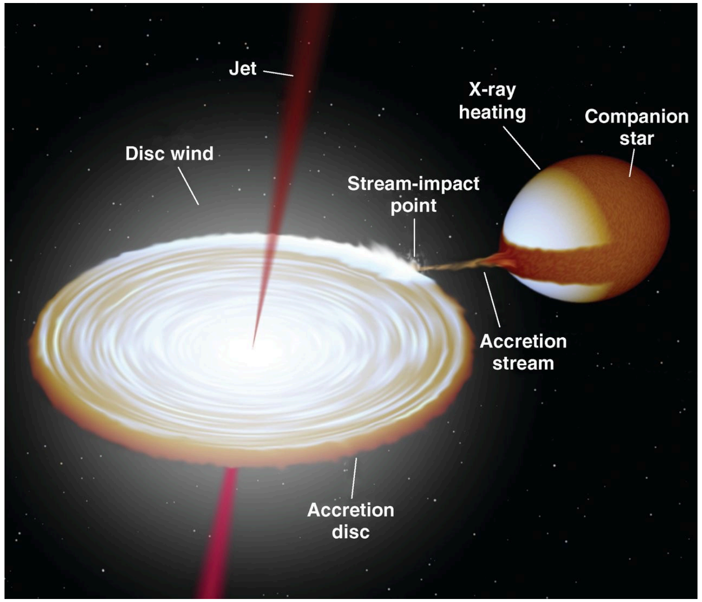


Les Houches, 10 April 2025

Big question: how the energy is dissipated?
How does the corona look like?

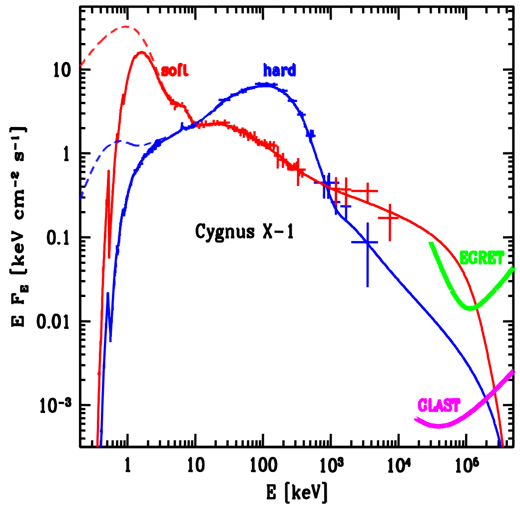


Accreting BH X-ray binaries



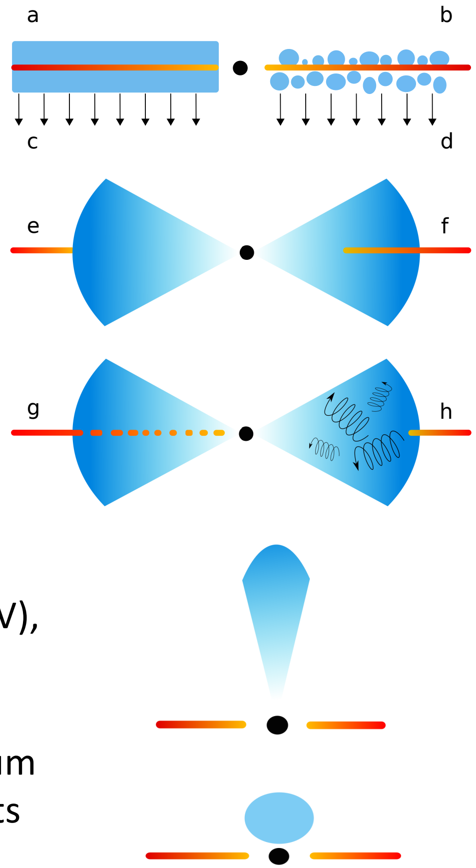
Why important?

- Spin measurements, BH formation, binary evolution
- How the energy is extracted and in which volume (compact/extended)
- High-energy gamma-ray sources

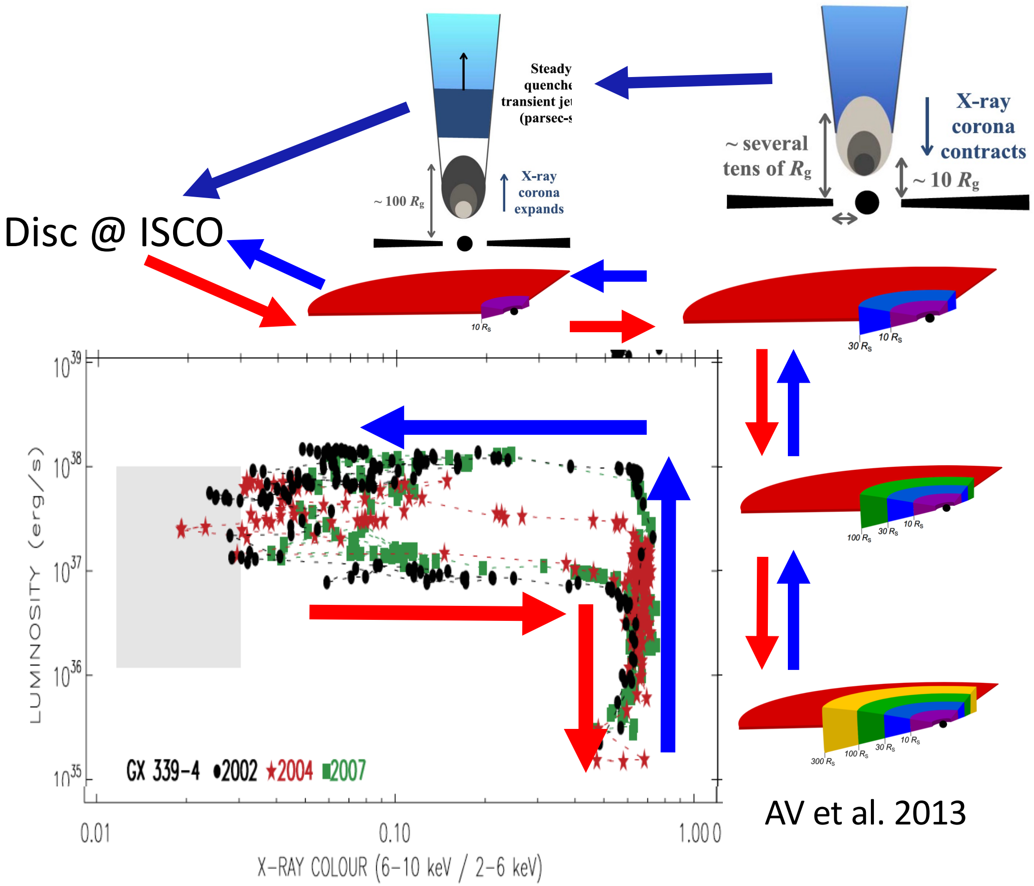


Zdziarski & Gierlinski, 2004

- Soft state - standard accretion disc (~ 1 keV), minor contribution from hot medium (corona), no jet
- Hard state - standard cold disc + hot medium 100 keV cut-off – Comptonization, radio jets
- Location of this medium is debated, so as radiative processes

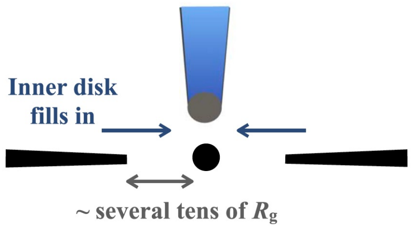


Geometry and states of LMXBs: spectra and timing



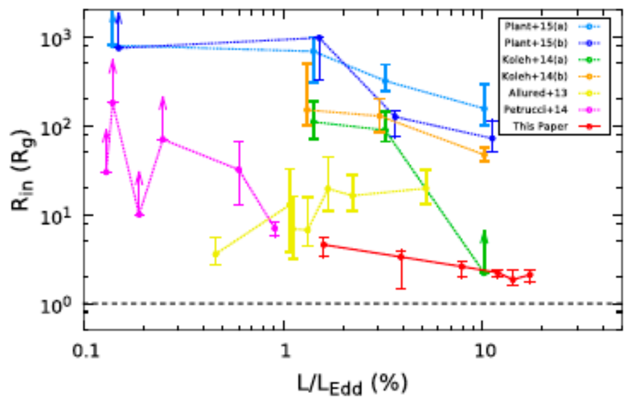
Munoz-Darias et al. 2013

AV et al. 2013



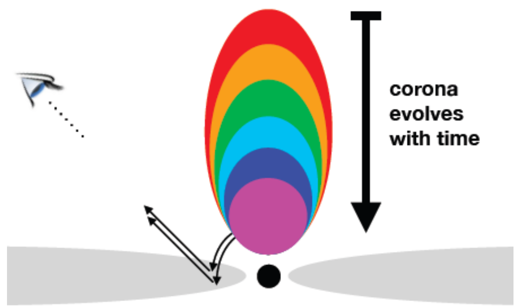
Wang et al. 2022

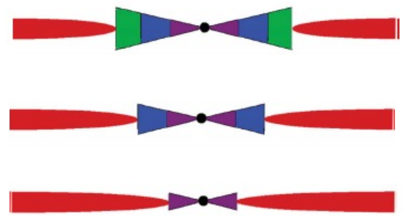
- Conventional tools of spectroscopy and timing probe the inner radius of the disc in the bright hard state and state transitions
- Inferred radii do not match even for the same data

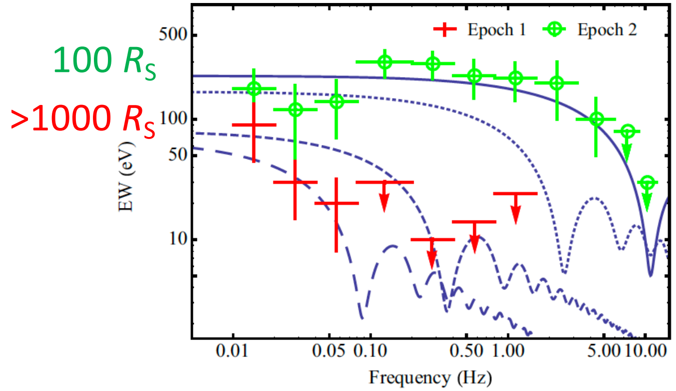


Garcia et al. 2015

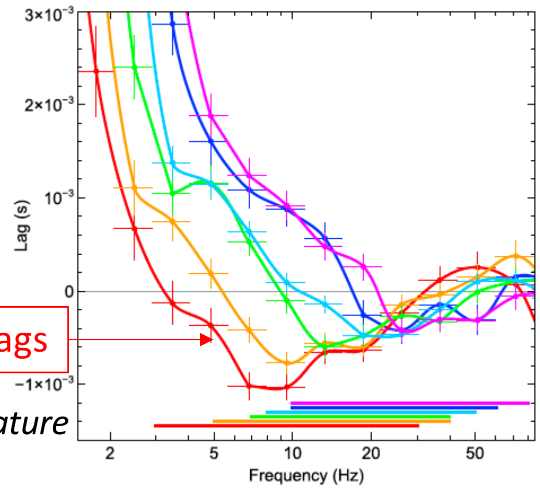
Geometry and states of LMXBs: spectra and timing



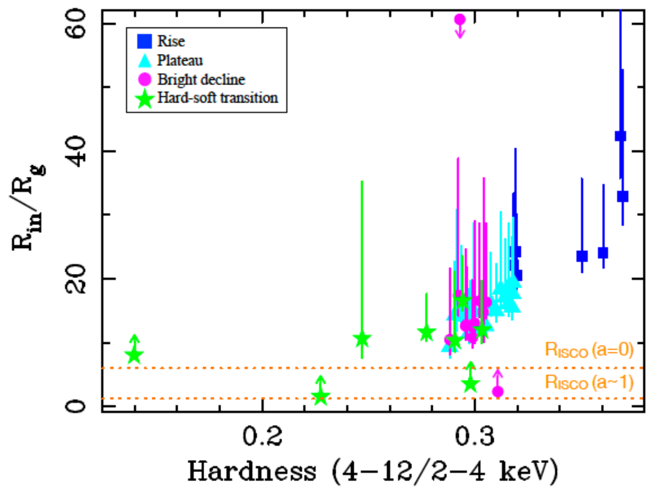




Reverberation lags



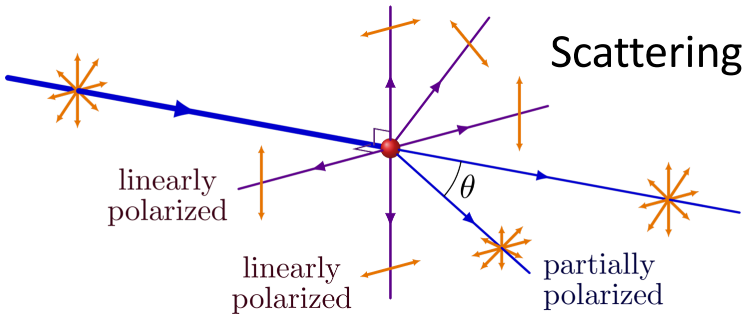
Kara et al. 2019, *Nature*
Buisson et al. 2019
Wang et al. 2021

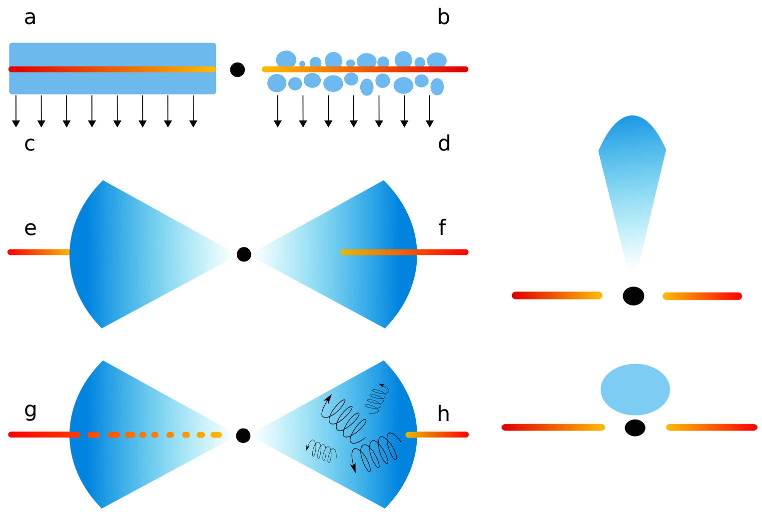


De Marco et al. 2021
Zdziarski et al. 2021
Axelsson & AV 2021

Hard state: polarization 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)

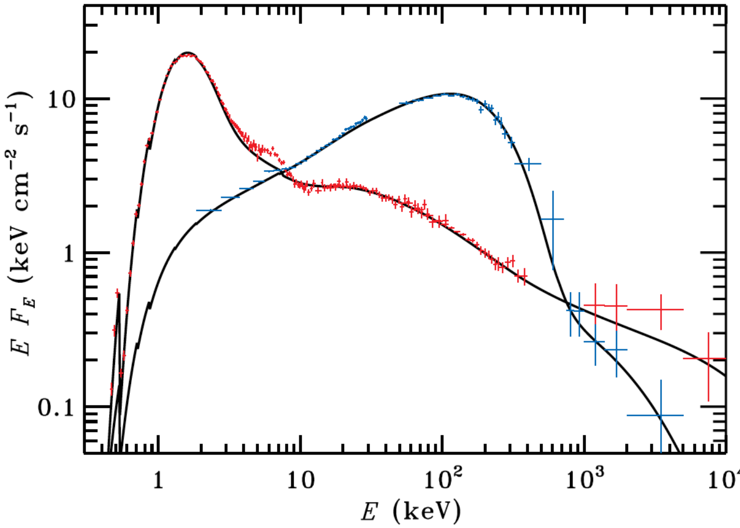


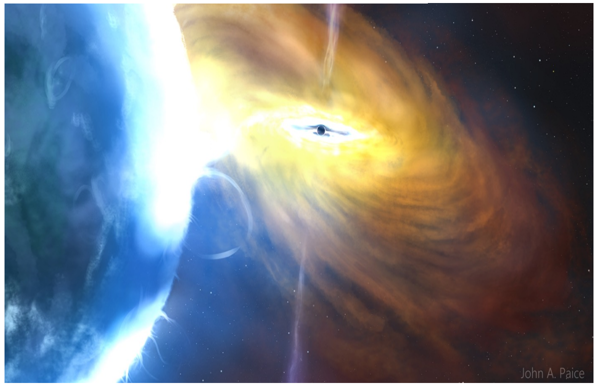


Cyg X-1: prototypical binary

- The first BH discovered in X-rays (1964)
- **Persistent**, bright high-mass X-ray binary
- Swings between hard and soft spectral state
- BH mass: $M_{\mathrm{BH}} = 21 \pm 2\ M_{\odot}$
- Orbital period: $P_{\mathrm{orb}} = 5.6^{d}$
- Distance: $D = 2.2 \pm 0.2$ kpc
- Binary inclination $i = 27.5° \pm 0.8°$

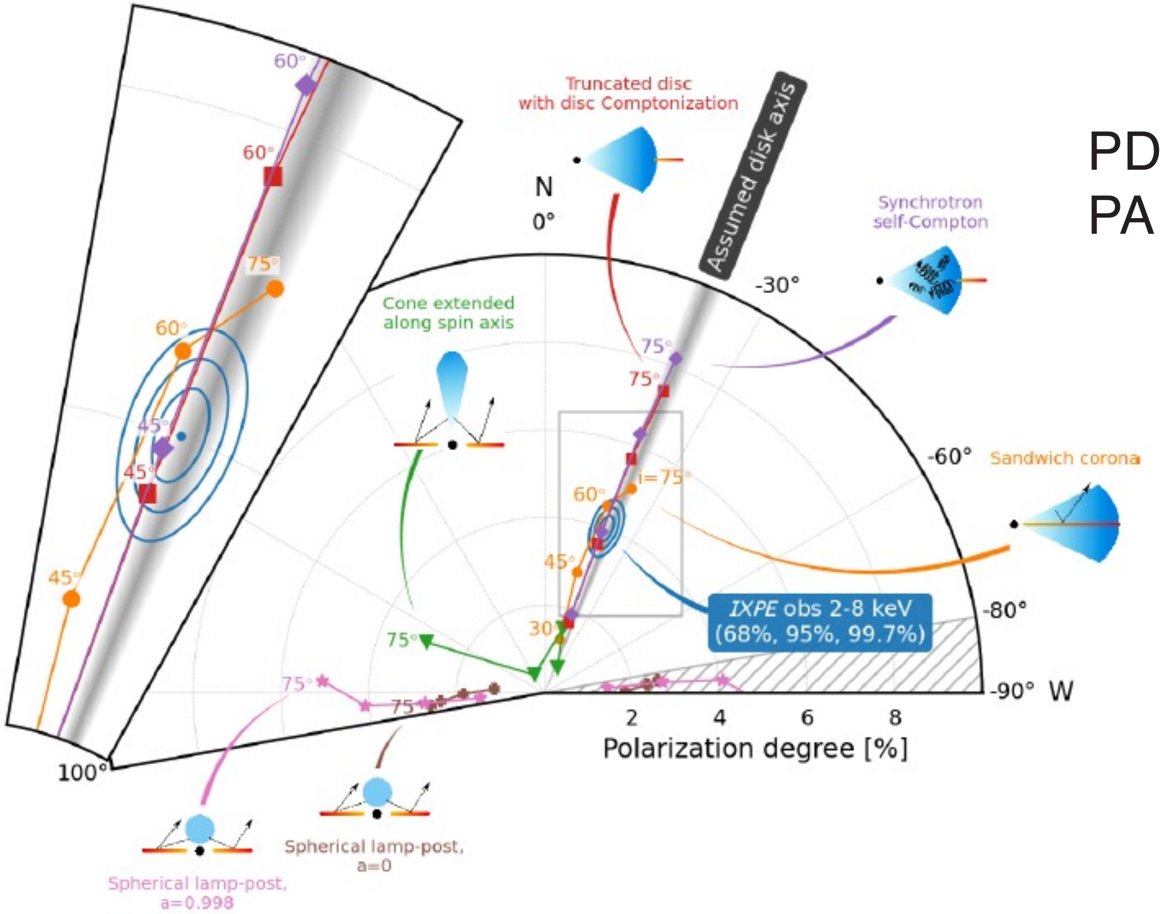
➡ expectations prior to *IXPE* observations: PD~1%



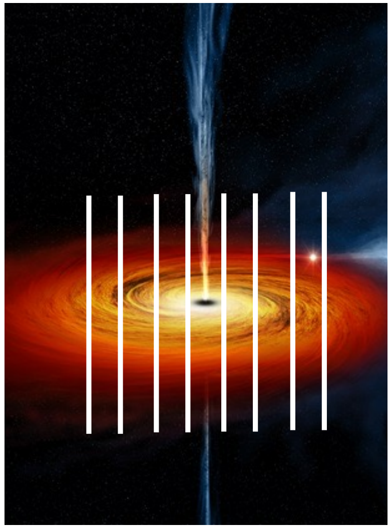


Bowyer et al. 1965
Brocksopp et al. 1999
Poutanen & Vurm 2009
Orocz et al. 2011
Miller-Jones et al. 2021, *Science*

IXPE observations of Cyg X-1



PD = 4.0 ± 0.2%
PA = -21° ± 1°

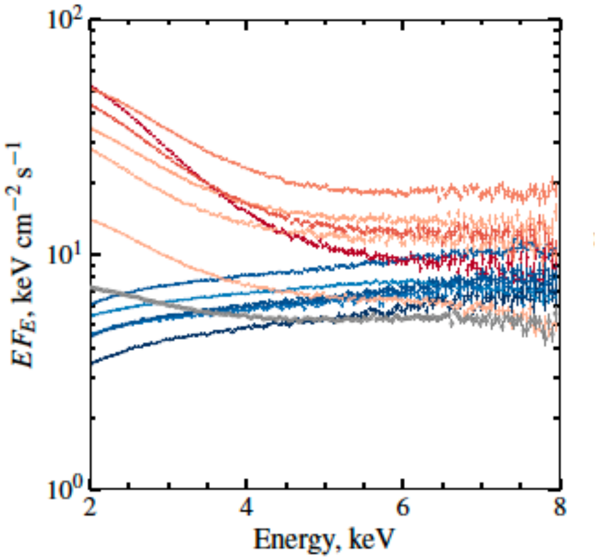


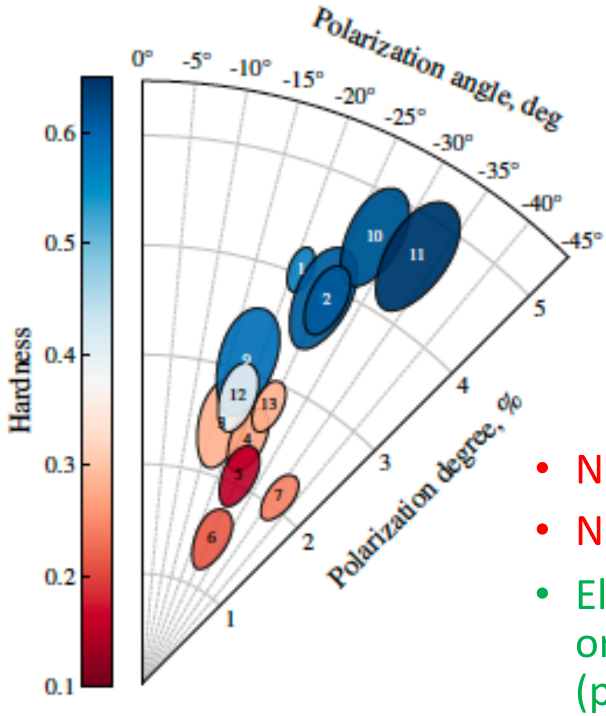
- Not cone-like
- Not spherical lamppost
- Elongated in the direction orthogonal to the jet (presumably, along the disc)
- Warp or windy accretion?

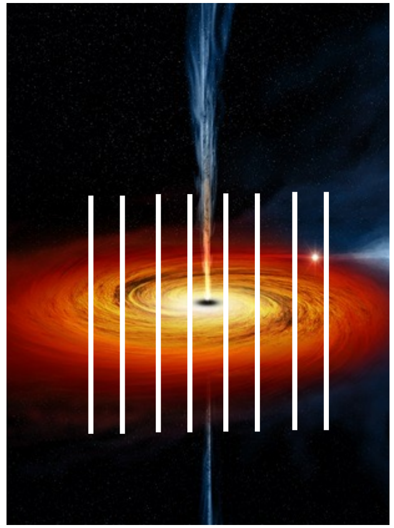
Krawczynski et al. 2022, *Science*
Poutanen, AV, Beloborodov 2023
Kravtsov et al. in prep.

IXPE
Imaging X-Ray Polarimetry Explorer

IXPE observations of Cyg X-1





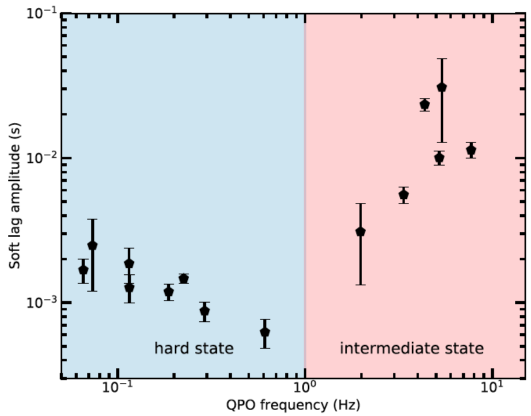


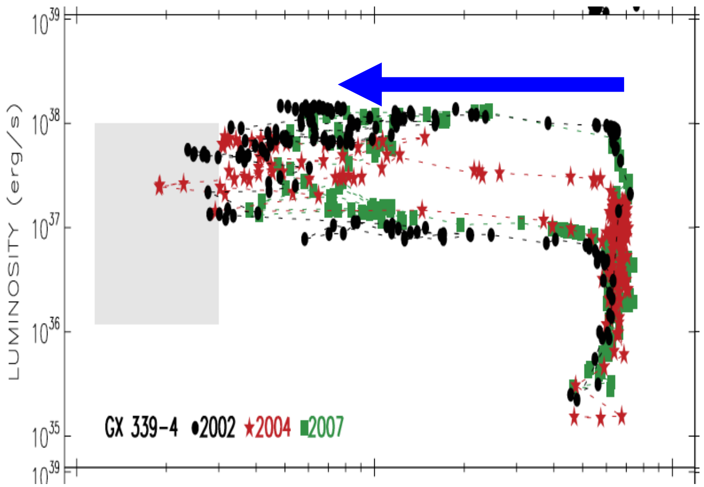
- Not cone-like
- Not spherical lamppost
- Elongated in the direction orthogonal to the jet (presumably, along the disc)
- Warp or windy accretion?

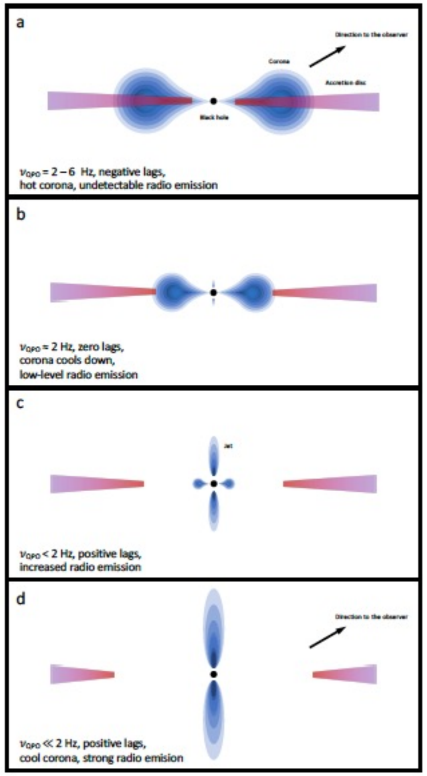
Krawczynski et al. 2022, *Science*
Poutanen, AV, Beloborodov 2023
Kravtsov et al. in prep.

Accretion geometry in LMXBs?

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



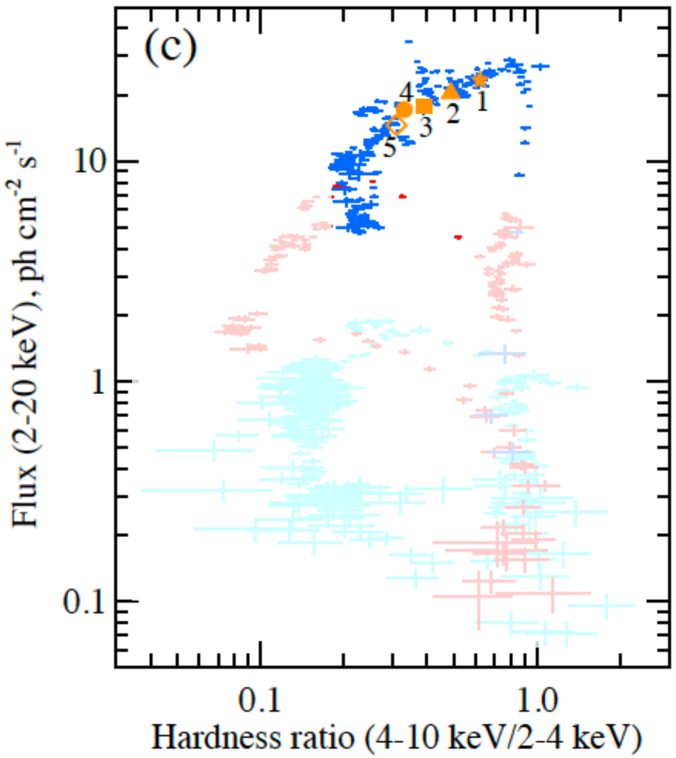


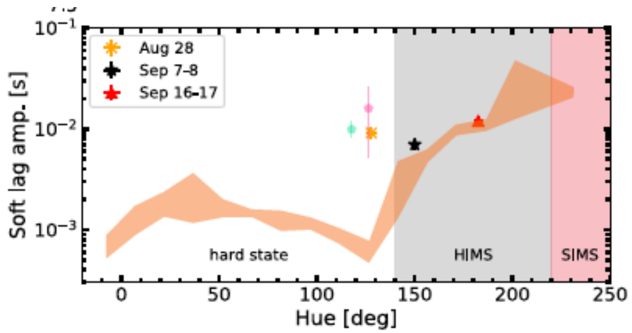


Hard state ⟷ **Soft state**

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

Exceptionally bright LMXB Swift J1727.8–1613



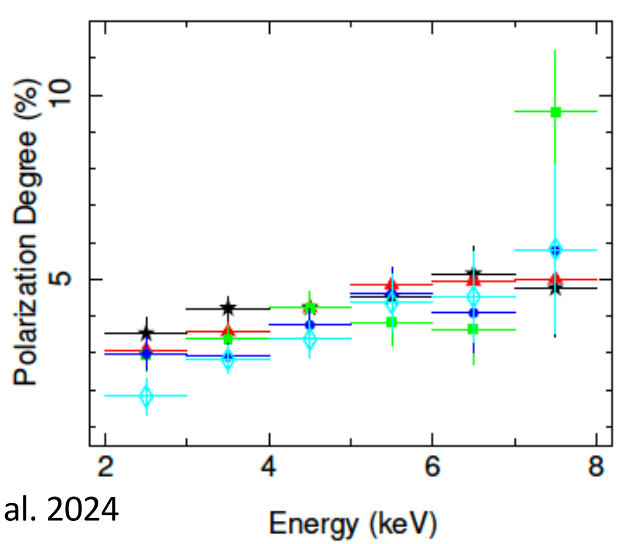


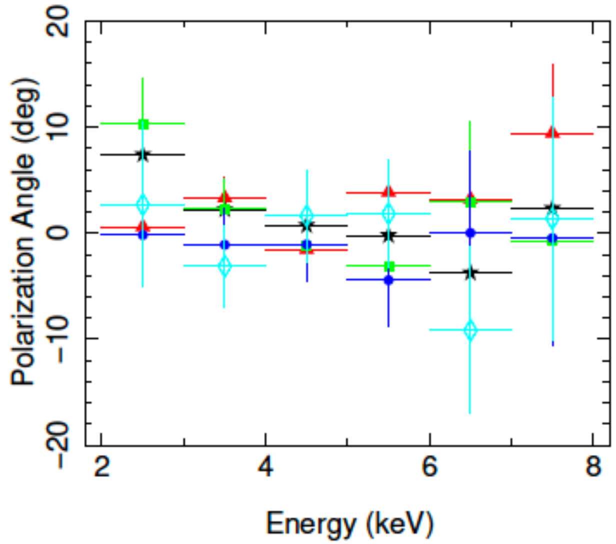
Hard state ⟷ **Soft state**

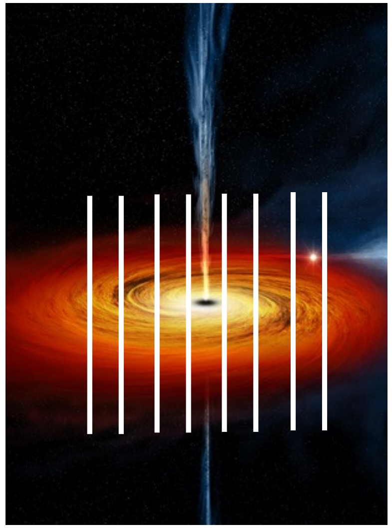
Exceptionally bright LMXB Swift J1727.8–1613

PD=4% → 3%

Polarization detection at about 20σ level





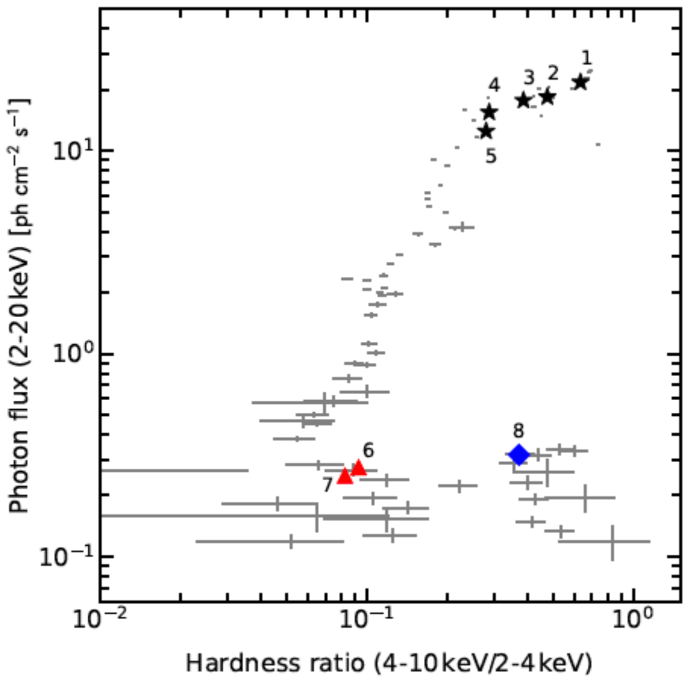


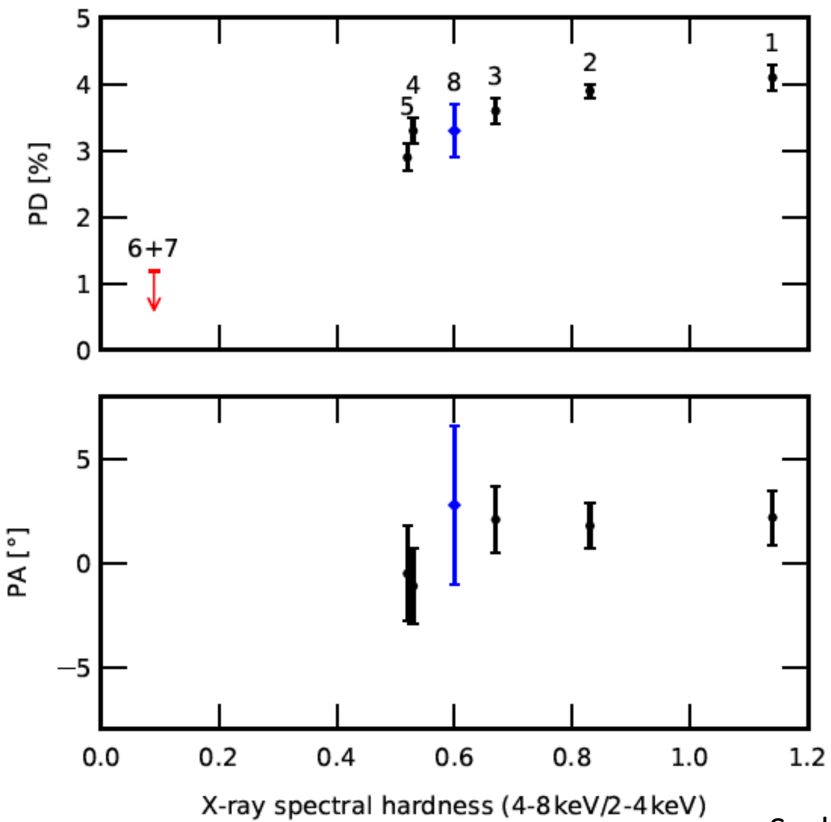
AV et al. 2023, Ingram et al. 2024

- Aligned with the sub-mm & optical polarization and 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

Exceptionally bright LMXB Swift J1727.8–1613

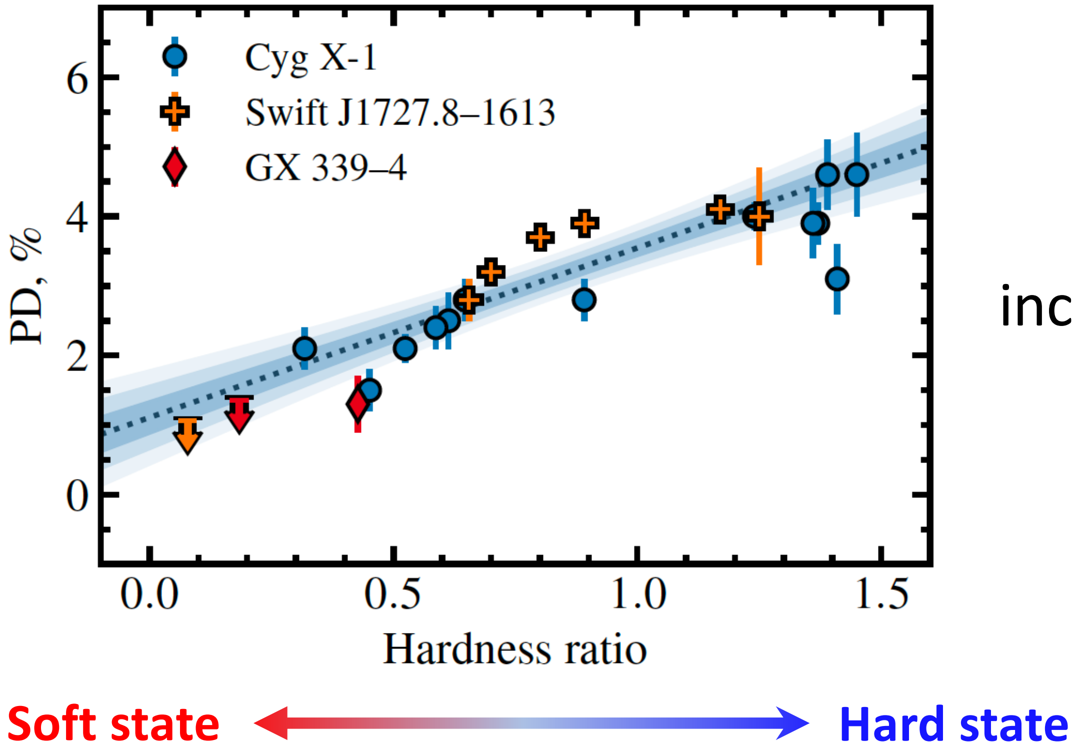
- Decaying hard state





Svoboda et al. 2024
Podgorny et al. 2024

Comparison between X-ray binaries

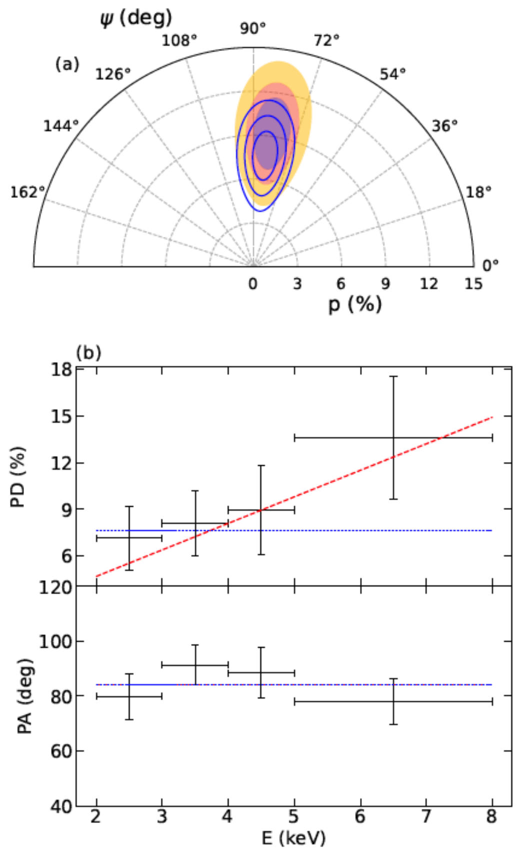


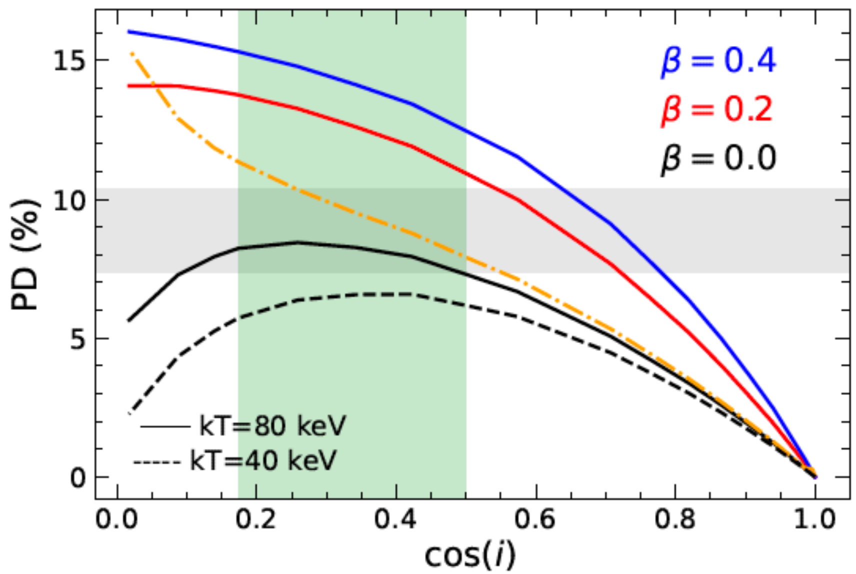
inclinations $i \approx 30° - 40°$

Kravtsov et al. in prep.

High-inclination source: IGR J17091−3624

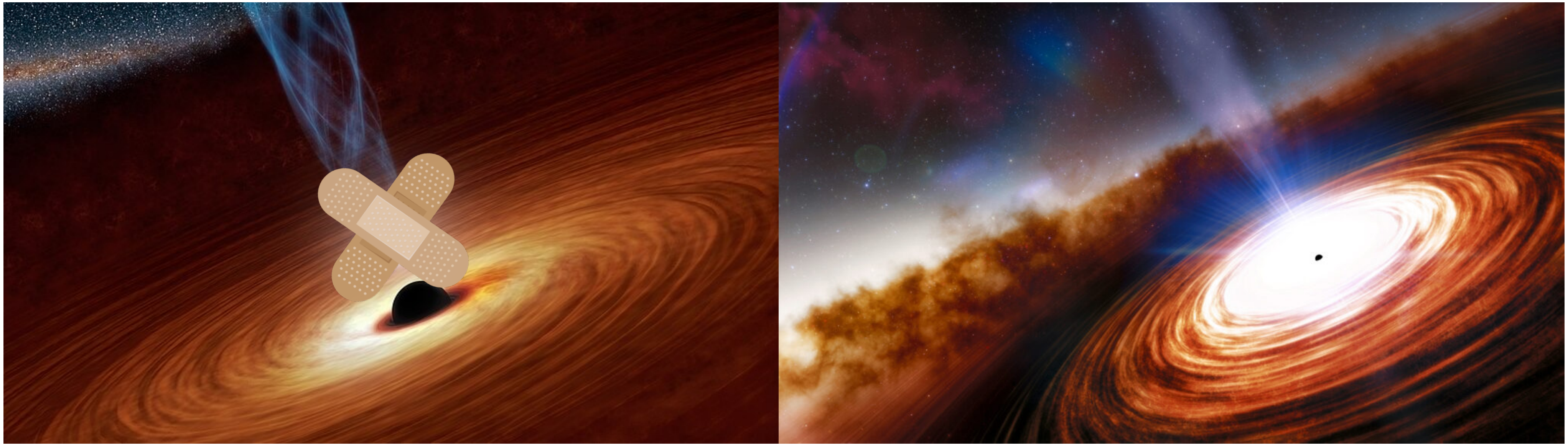
- Behaviour typical to hard-state XRB at high inclination: hard spectrum, QPOs, aperiodic dips
- High PD: 8-9%
- Aligned with optical *R* and *I* polarization





Ewing et al. 2025

Shape of corona in X-ray binaries



Results are consistent with extended (slab) corona

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

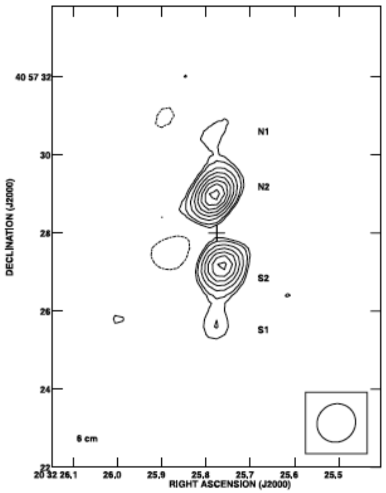
Astronomical puzzle Cyg X-3

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

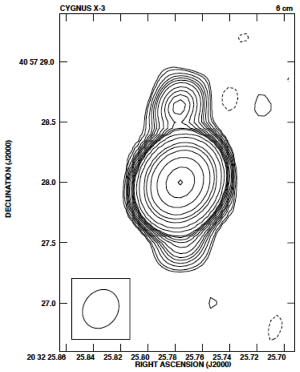
An Astronomical Puzzle Called Cygnus X-3

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

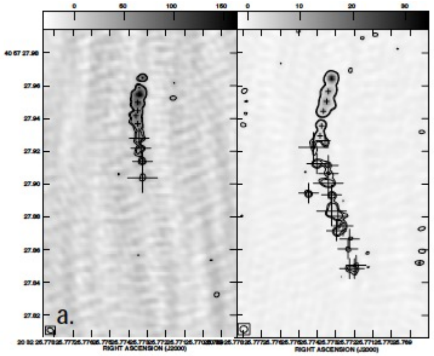
R. M. Hjellming



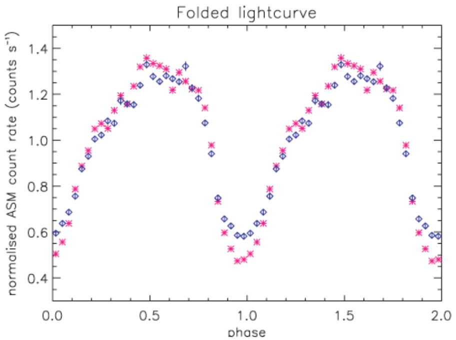
Marti et al. 2001



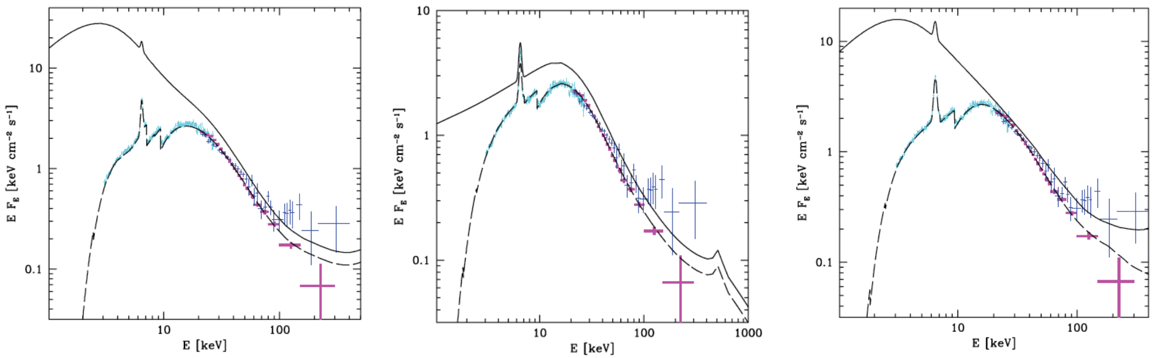
Molnar et al. 1988



Miodzuszewski et al. 2001



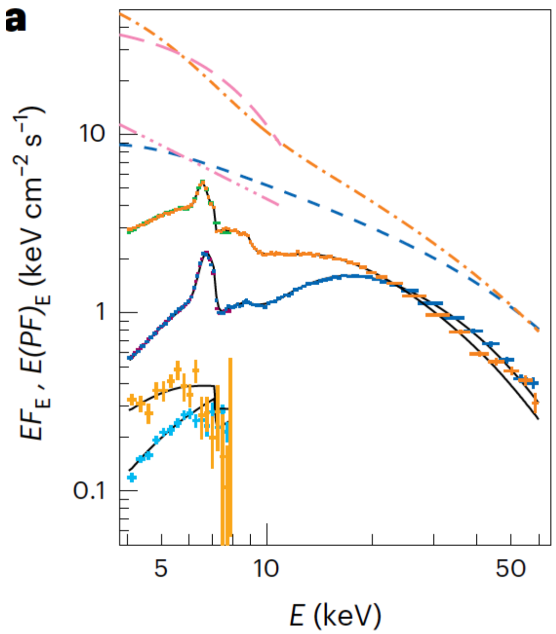
Orbital period: 4.8h

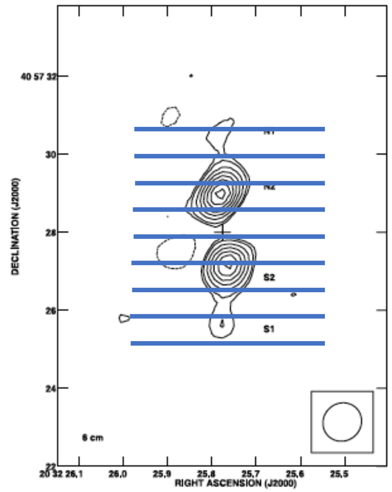


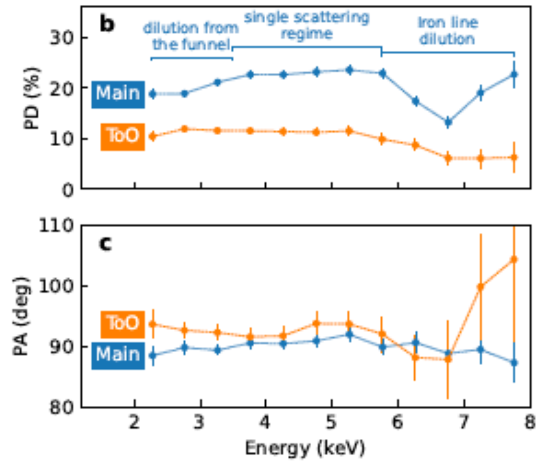
Hjalmarsdotter et al. 2009

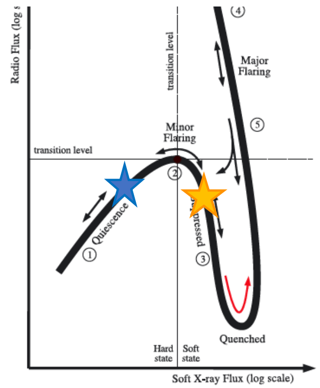
IXPE observations in 2022

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





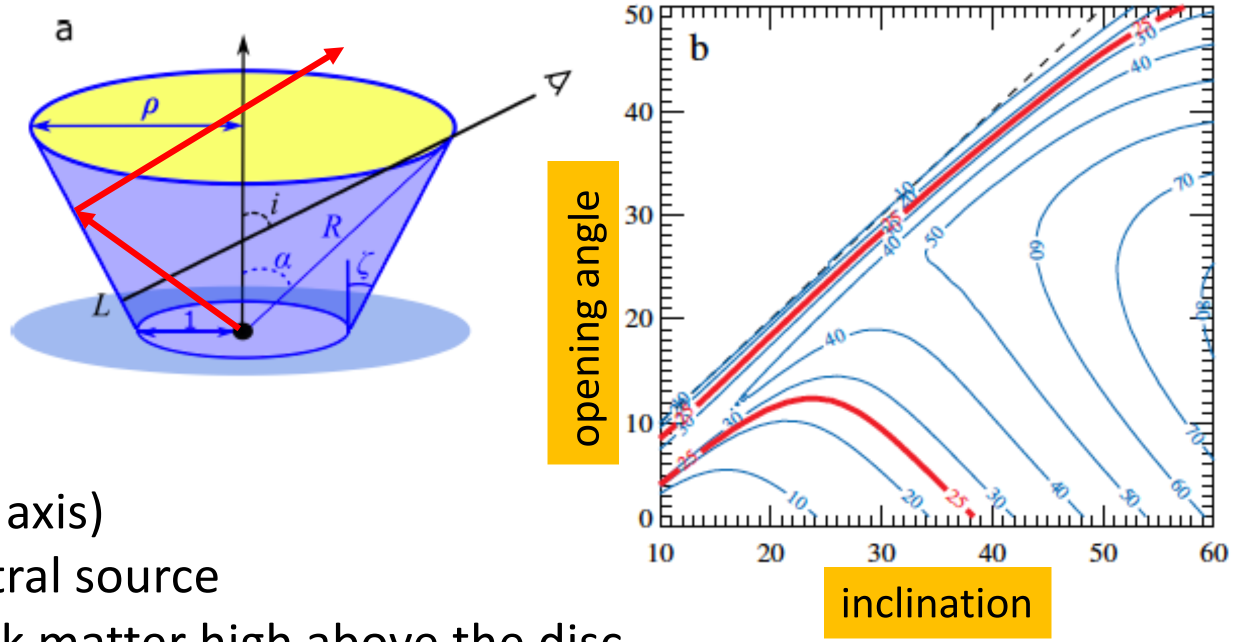




- **High polarization!**
- Polarization $\perp$ to the jet direction
- Constant PD/PA with energy -> single scattering
- Prominent orbital variability

AV et al. 2024, *Nature Astronomy*

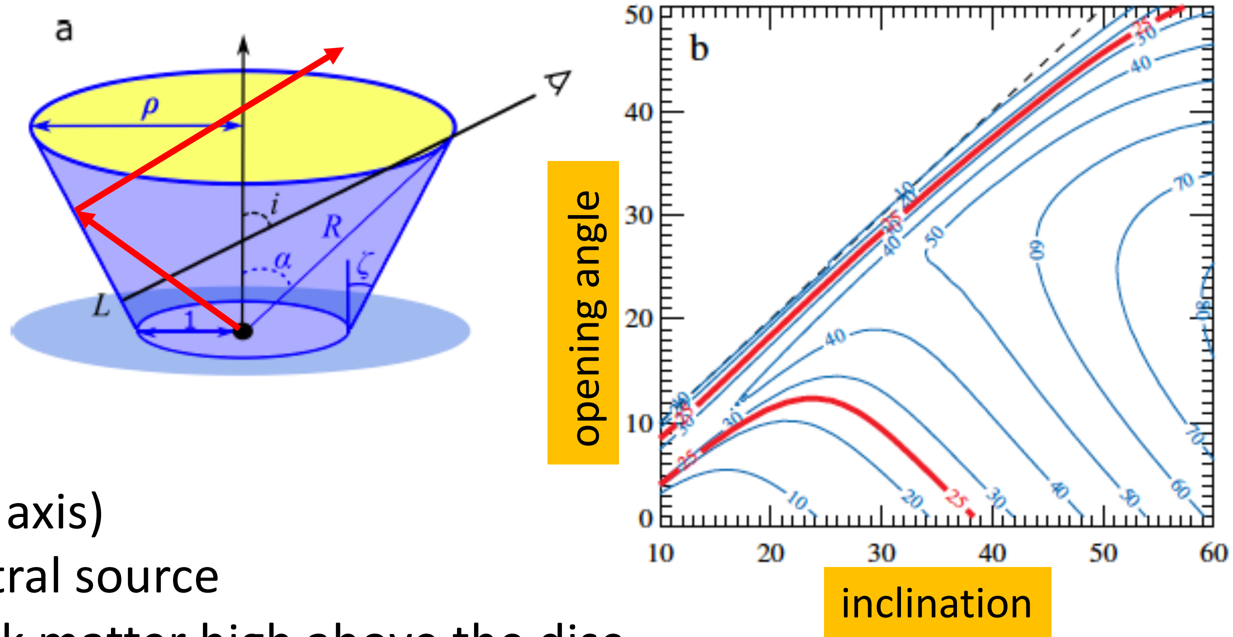
Astronomical puzzle Cyg X-3



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

AV et al. 2024, *Nature Astronomy*

Astronomical puzzle Cyg X-3



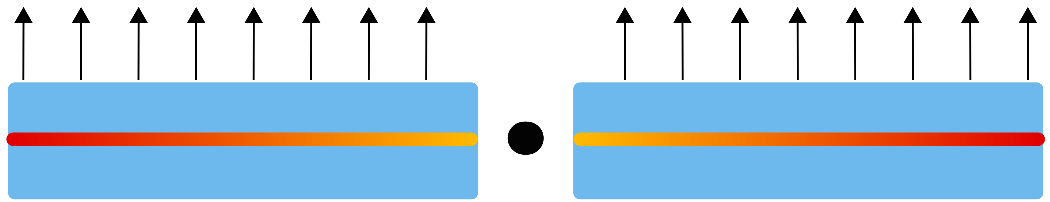
- Polarization $\perp$ jet (& binary axis)
- High PD: we do not see central source
- $i \approx 30^{o}$ hence optically thick matter high above the disc
- Apparent luminosity along the funnel: $L_{ULX} \geq 5{\times}10^{39}\mathrm{erg\ s}^{-1}$
- Bolometric luminosity: $> 3{\times}10^{39}\mathrm{erg\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

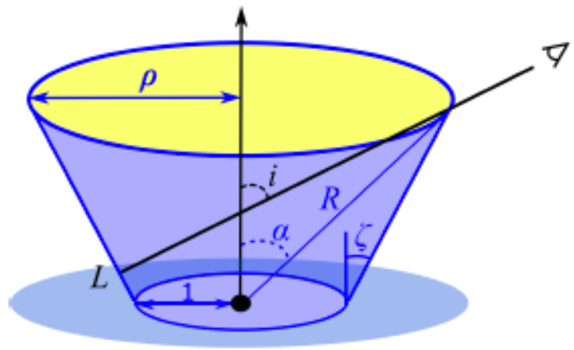
Super-Eddington accretion

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): envelope
- IGR J17091−3624 (Ewing et al. 2025)

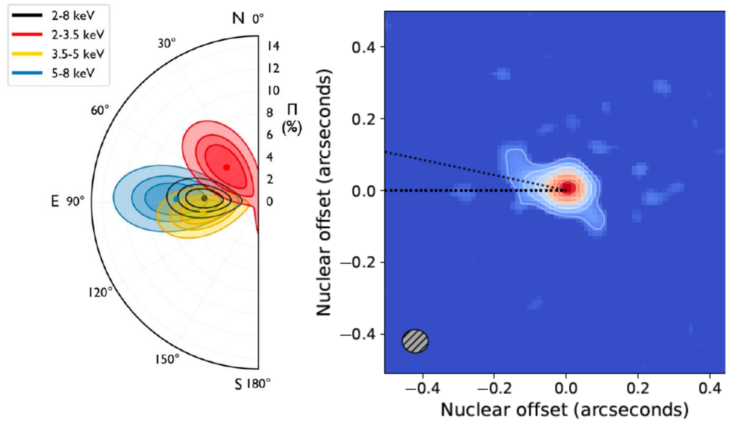




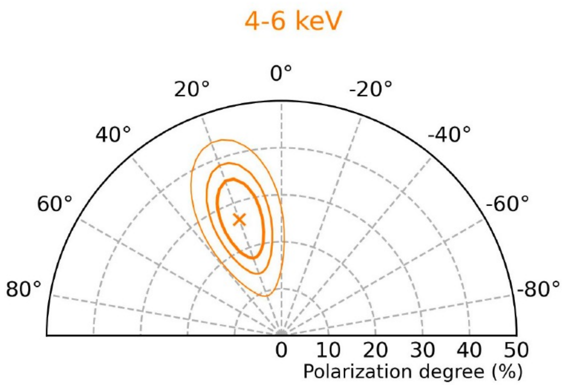
- PA=const: constraints on relativistic effects & magnetic fields
- High PD for sources at intermediate inclinations
- PD is the same for hard state at vastly different luminosities: puzzling

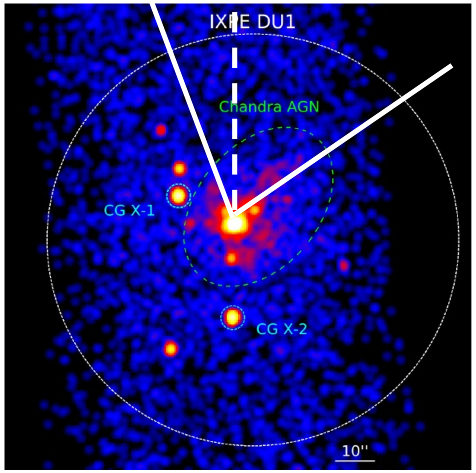
Links to Seyfert galaxies

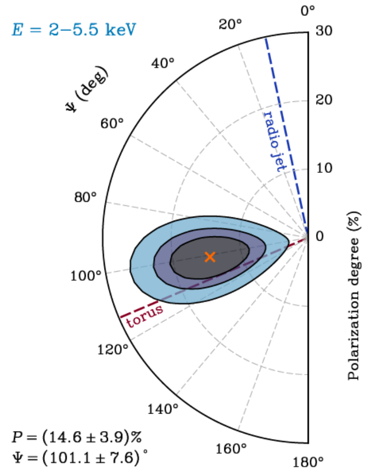
- Seyfert I:
  - IC 4329A (Ingram et al 2023)
  - NGC 4151 (Gianolli et al. 2023, 2024)
  - MGC 05-23-16 (Marinucci et al. 2022, Tagliacozzo et al. 2023)



- Seyfert II:
  - Circinus galaxy (Ursini et al. 2023)
  - NGC 1068 (Marin et al. 2024)







Soft state: expectations

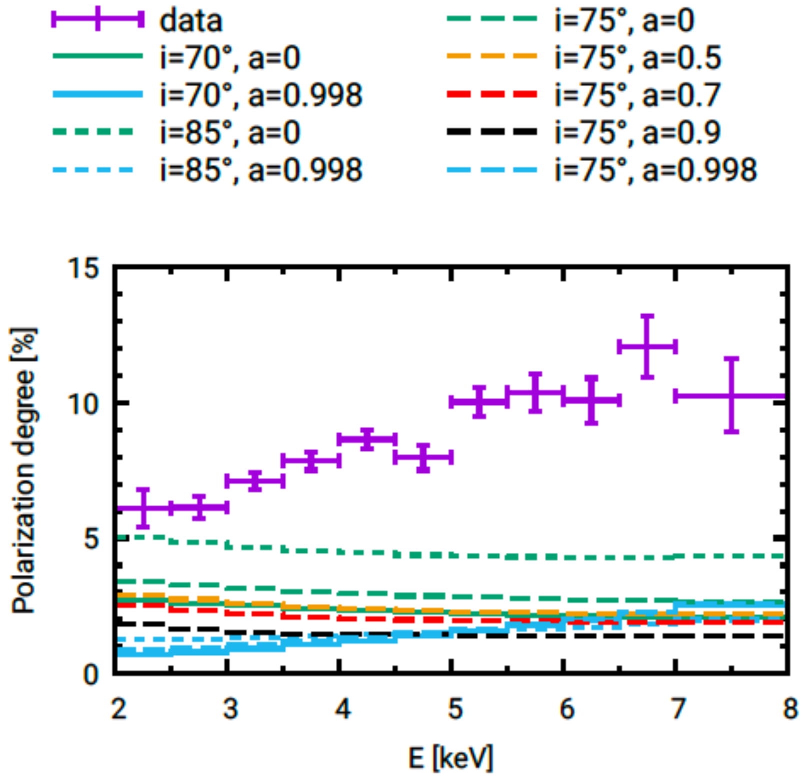
- Soft state:
  - Shakura & Sunyaev 1973, Novikov & Thorne 1973
  - Rees 1975: results of plane-parallel atmospheres (Chandrasekhar 1960, Sobolev 1963) for accretion discs with pure electron scattering

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

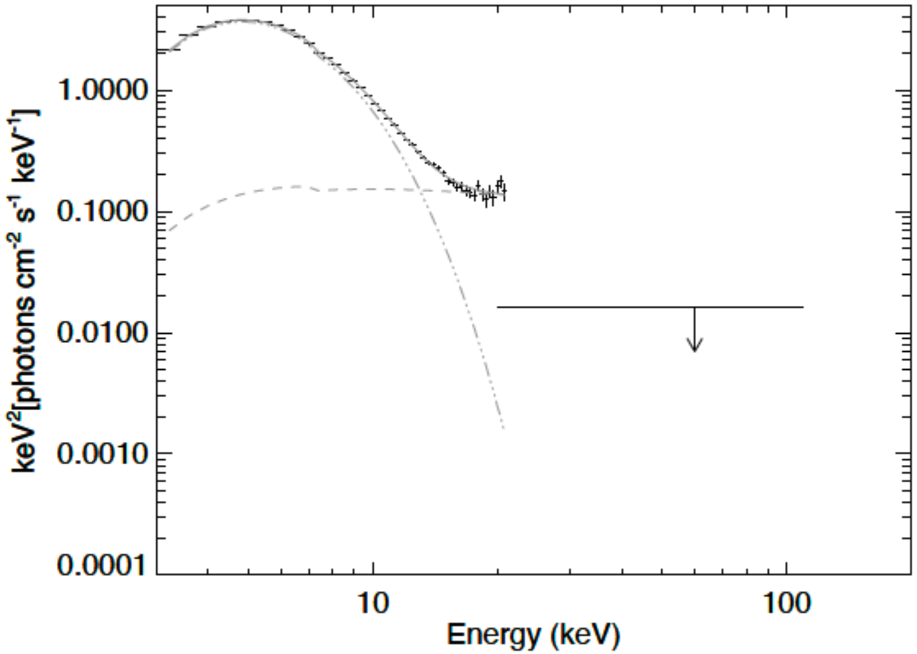
  - Loskutov & Sobolev 1980, Taverna et al. 2021: absorption effects
  - Stark & Connors 1977, Pineault 1980, Loktev et al. 2022, 2024: GR and SR effects
    - Depolarization
    - PA rotation
  - Schnittman & Krolik 2009, 2010: self-irradiation

$\Rightarrow$ expectations prior to *IXPE* observations: PD$<$6%

The first soft-state source: 4U 1630-47

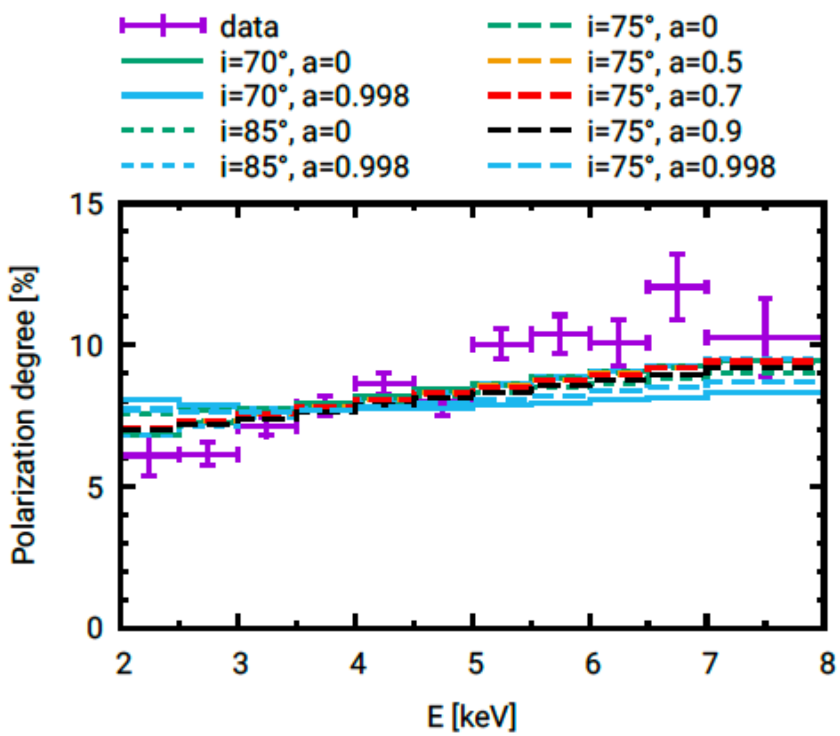


- Too low PD (especially for the high spins)



Ratheesh et al. 2024

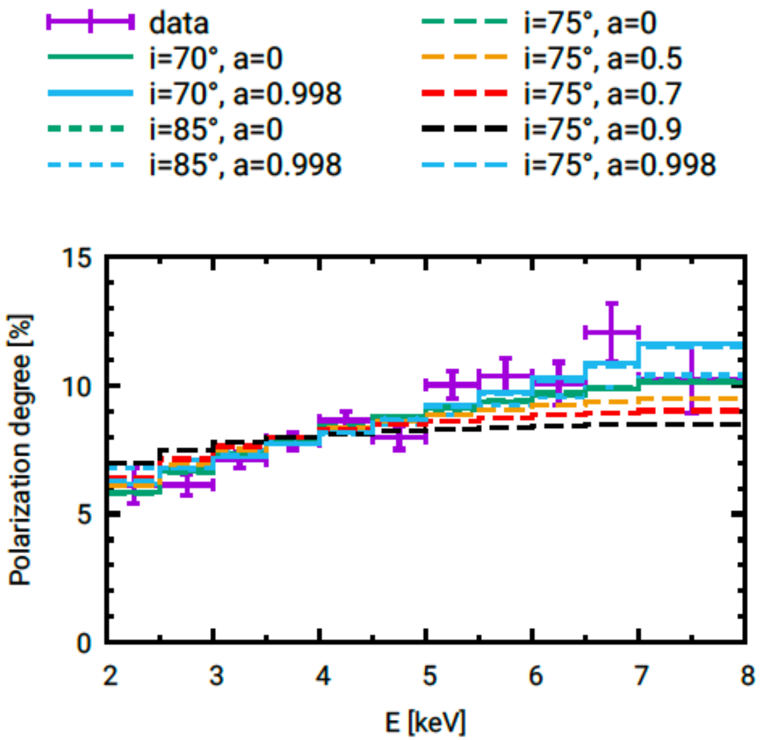
The first soft-state source: 4U 1630-47



- Adding outflow: lower PD, no energy dependence

Ratheesh et al. 2024

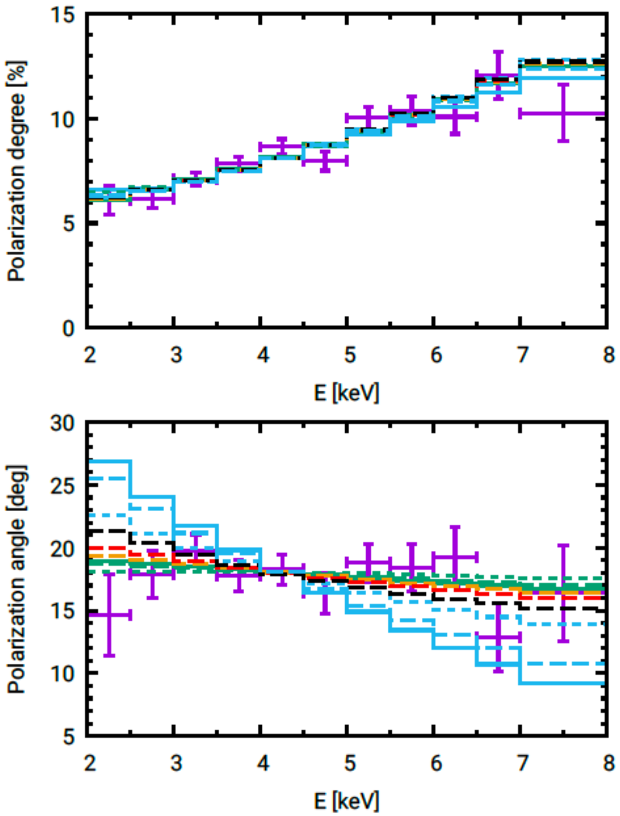
The first soft-state source: 4U 1630-47



- Adding self-irradiation (but albedo larger than 1)

Ratheesh et al. 2024

The first soft-state source: 4U 1630-47



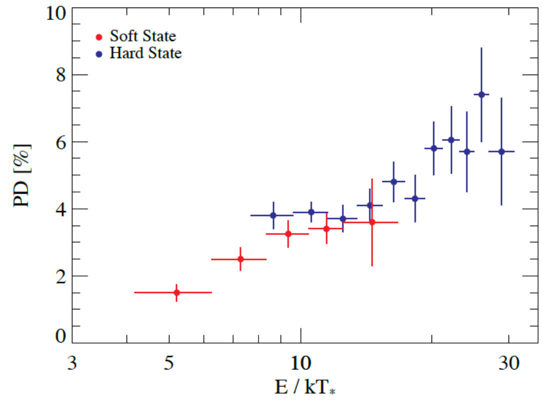
- Adding outflow $v/c = 0.5$ and absorption for slab of the optical depth $\tau = 7$
- PA: constraints on the spin (a<0.7)

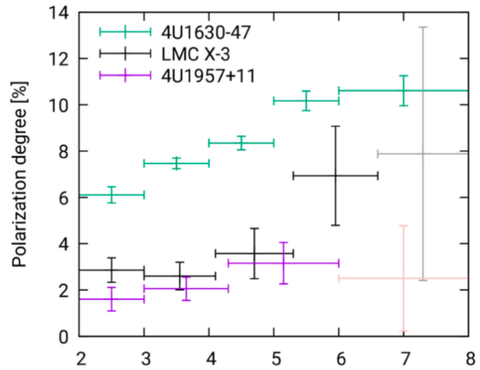
Ratheesh et al. 2024

IXPE
Imaging X-Ray Polarimetry Explorer

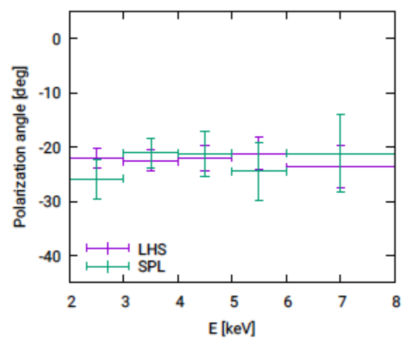
Soft-state sources

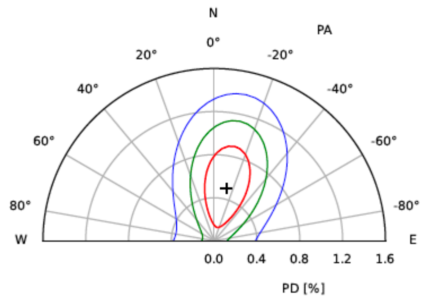
- LMC X-1 (Podgorny et al. 2023) – upper limits
- Swift J1727.8-1613 (Svoboda et al. 2024) – upper limits
- LMC X-3 (Svoboda et al. 2024)
- 4U 1957+11 (Marra et al. 2024)
- Cyg X-1 (Steiner et al. 2024)
- Swift J151857.0-572147 (Mondal et al. 2024)
- 4U 1630-47 (Ratheesh et al. 2024)
- GX 339-4 (Mastroserio et al. 2024)





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

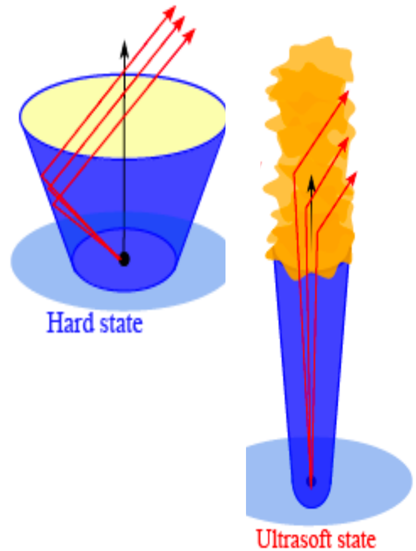




Swift J1727.8-1613

Soft-state sources

- LMC X-1 (Podgorny et al. 2023) – upper limits
- Swift J1727.8-1613 (Svoboda et al. 2024) – upper limits
- LMC X-3 (Svoboda et al. 2023)
- 4U 1957+11 (Marra et al. 2023)
- Cyg X-1 (Steiner et al. 2024)
- Swift J151857.0-572147 (Mondal et al. 2024)
- 4U 1630-47 (Ratheesh et al. 2024)
- GX 339-4 (Mastroserio et al. 2024)
- Cyg X-3: PD = 11.9%$\pm$0.5%, orthogonal to the jet → envelope

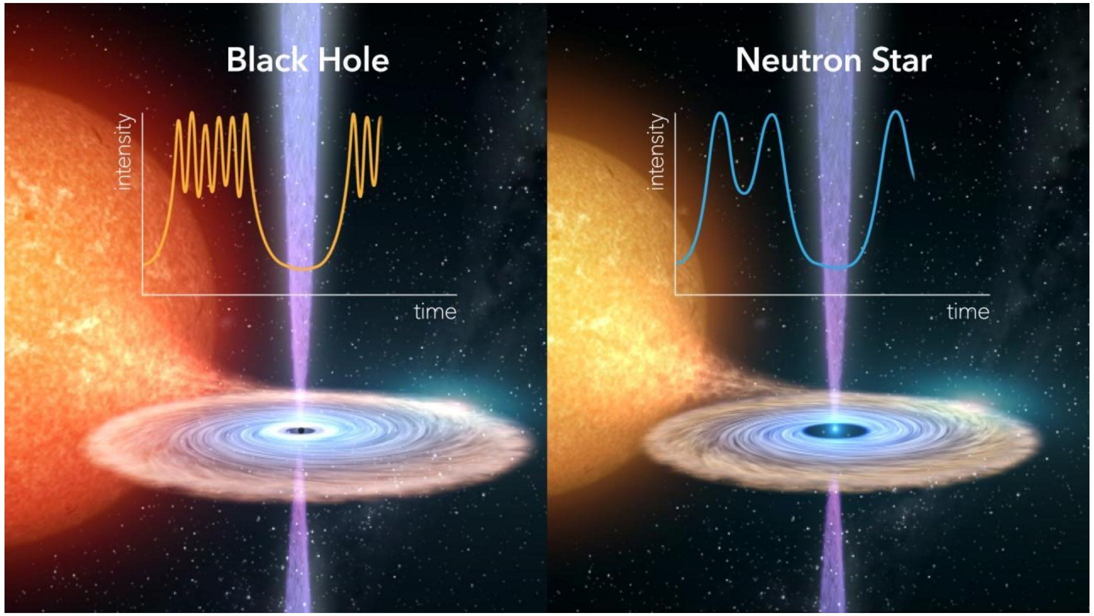


AV et al. 2024

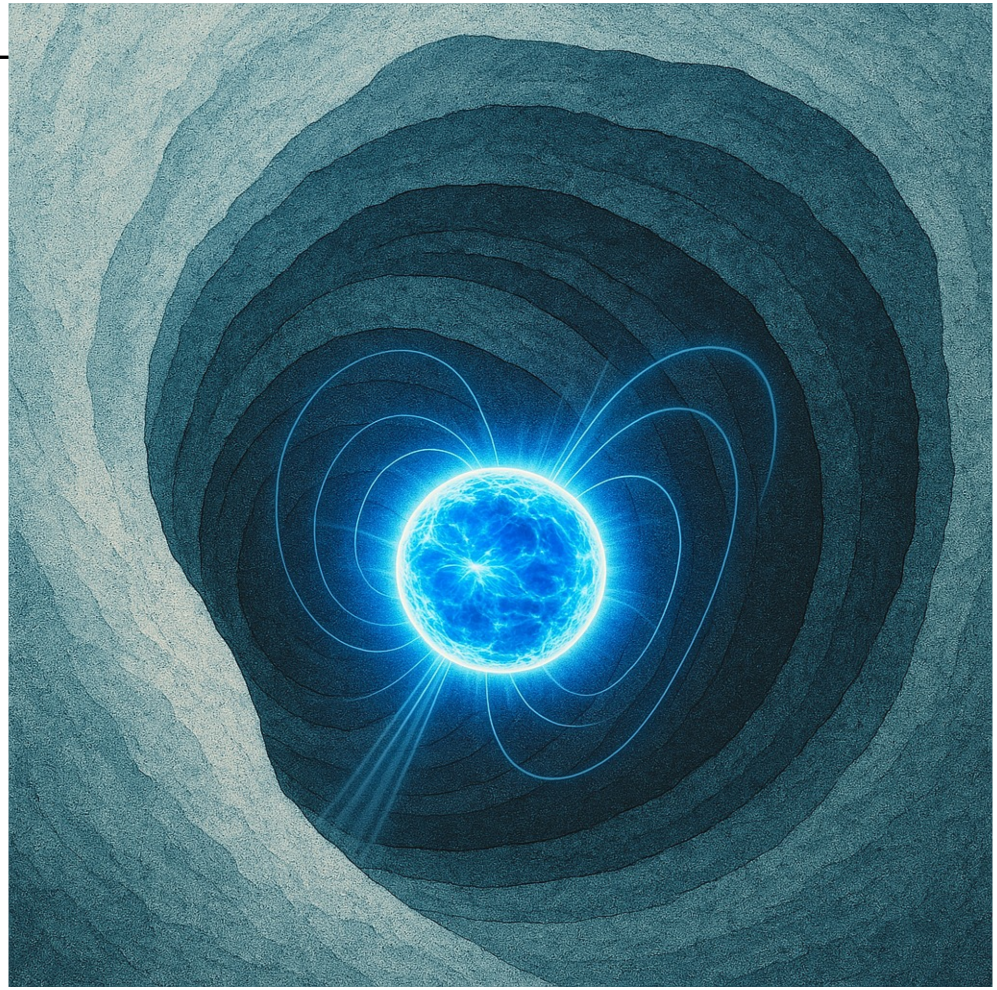
- PA=const: constraints on relativistic effects
- PD increasing with energy: puzzling

IXPE
Imaging X-Ray Polarimetry Explorer

Neutron stars: similarities

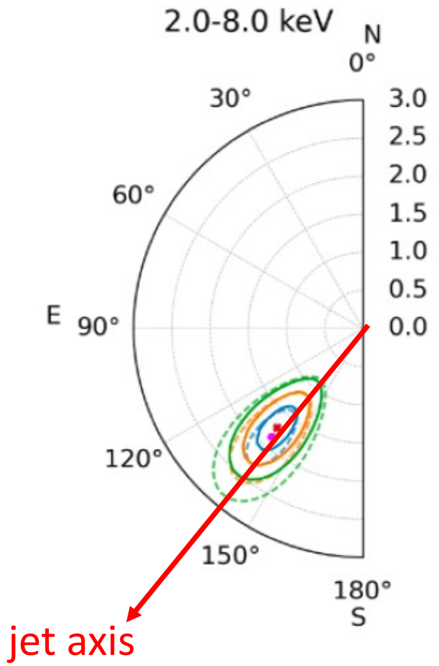


Credit: Vincentelli et al. 2024



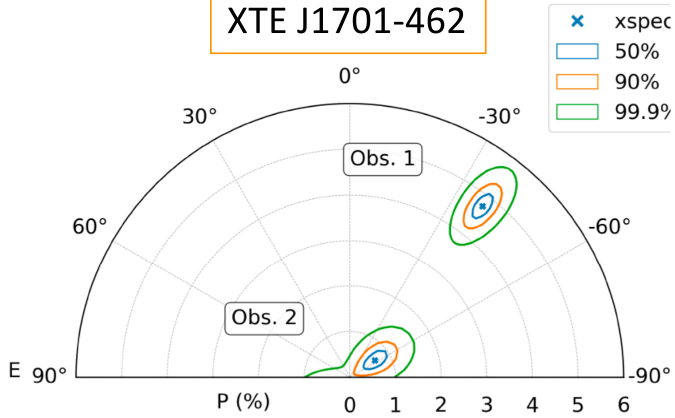
Accreting weakly-magnetised NSs: likewise high PD

Cyg X-2



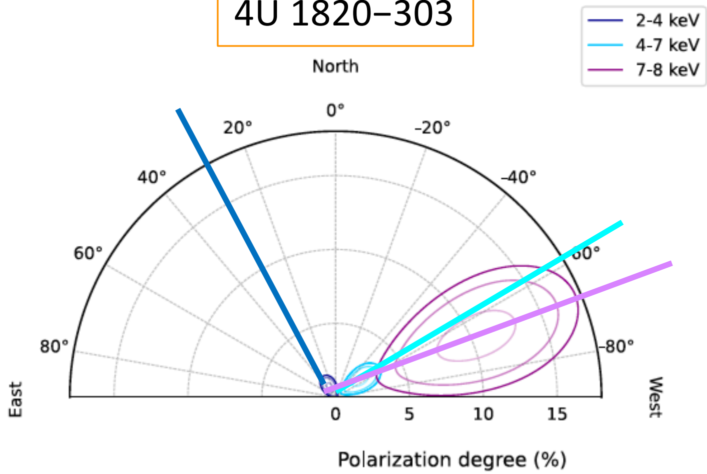
Polarization along jet axis

XTE J1701-462



PD changes substantially

4U 1820−303

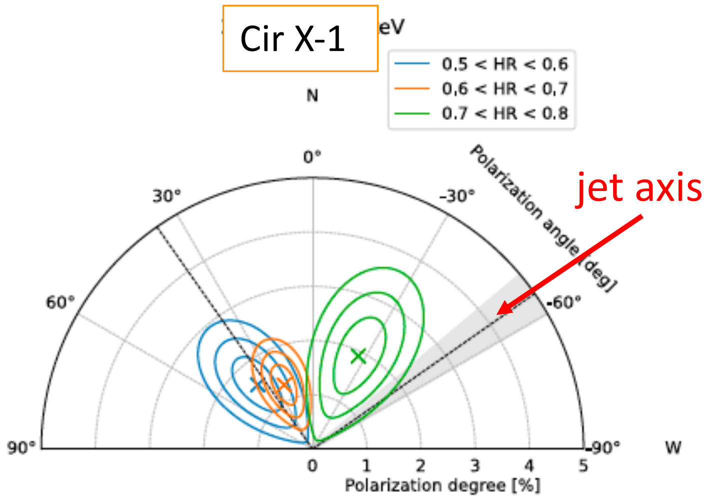


PA switch by **nearly** 90°
across energy bend

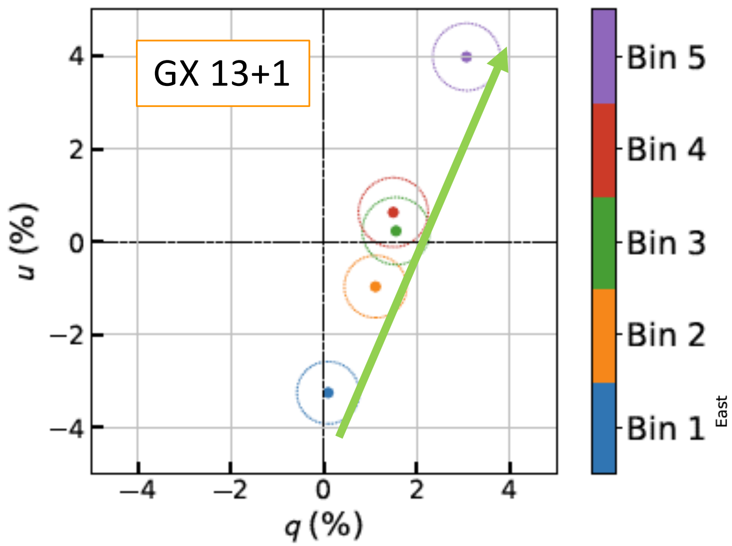
PD between 1% to 10%(!!)

Farinelli et al. 2022
Cocchi et al. 2023
Di Marco et al. 2023

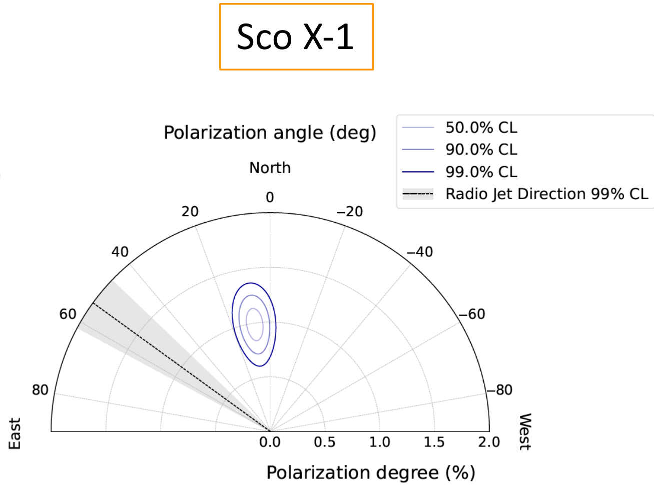
Accreting weakly-magnetised NSs: changes of PA



PA difference: ~60°



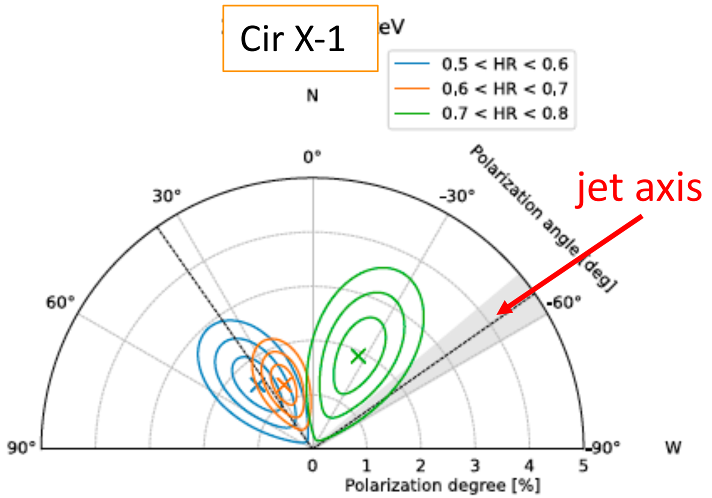
PA **rotation**: ~70°



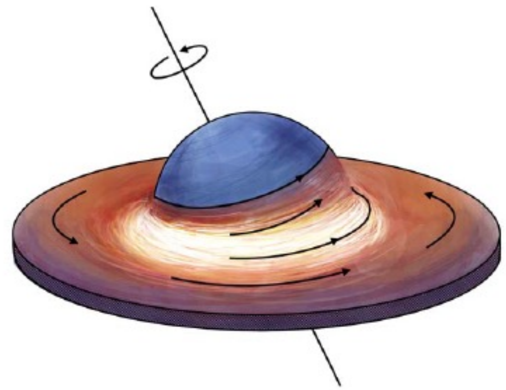
PA different from jet axis by ~45°

La Monaca et al. 2023
Rankin et al. 2023
Bobrikova et al. 2024 x2

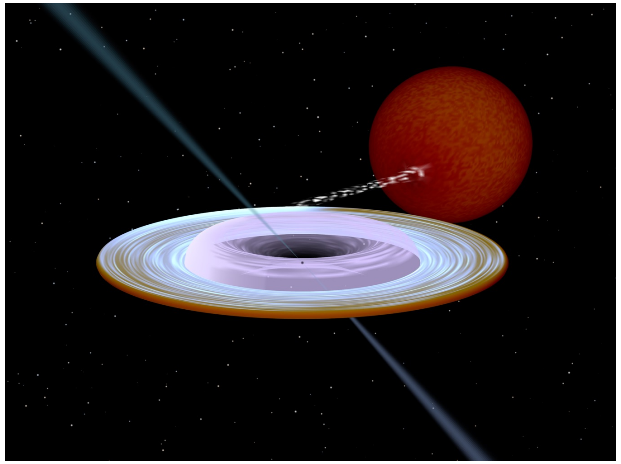
NSs and BHs: misalignment



PA difference: ~60°



NS spin – orbit misalignment?

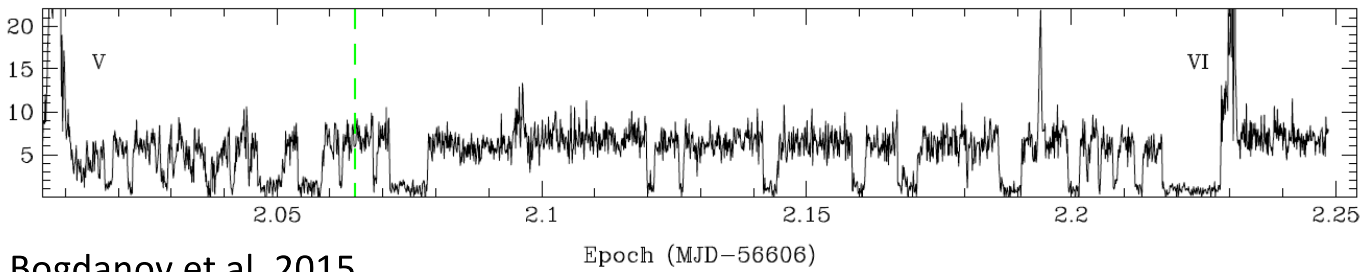


BH spin – orbit misalignment in MAXI J1820 (optical polarimetry)

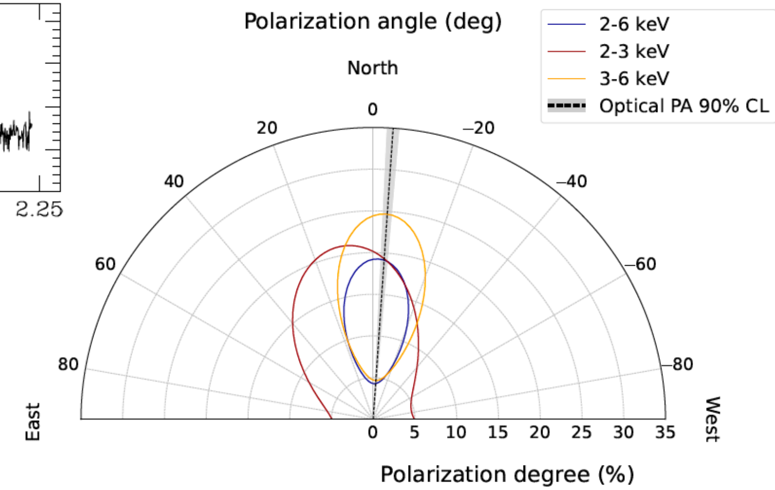
Rankin et al. 2023
Poutanen, AV et al. 2022, *Science*

Neutron star at low accretion rate: PSR J1023+0038

Transitional millisecond pulsar: properties of accreting NS and radio pulsar



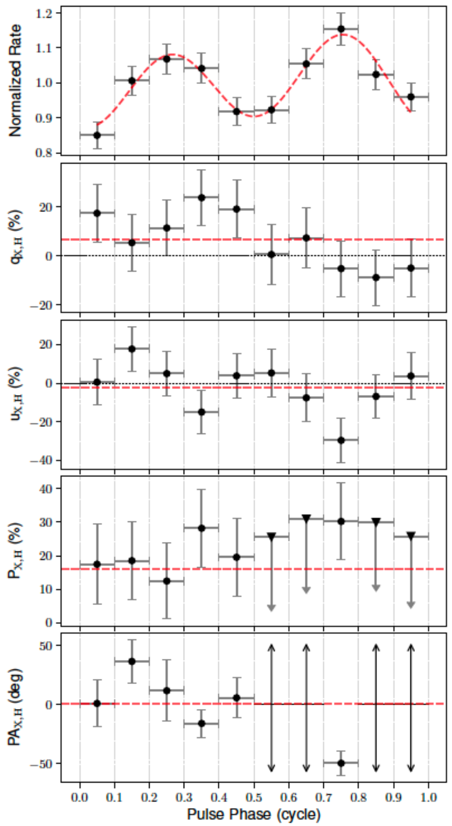
Bogdanov et al. 2015



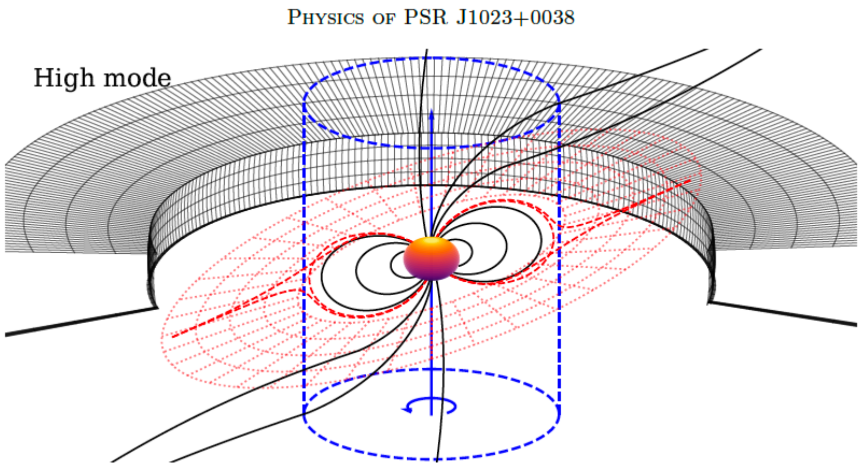
- Low accretion rate: 10^{-6} to 10^{-5} L_{Edd}
- Swings between two stable low/high modes, sometimes bright flares

Baglio et al. 2024

Neutron star at low accretion rate: PSR J1023+0038



Baglio et al. 2024

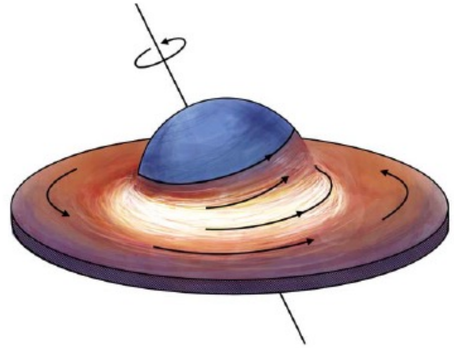


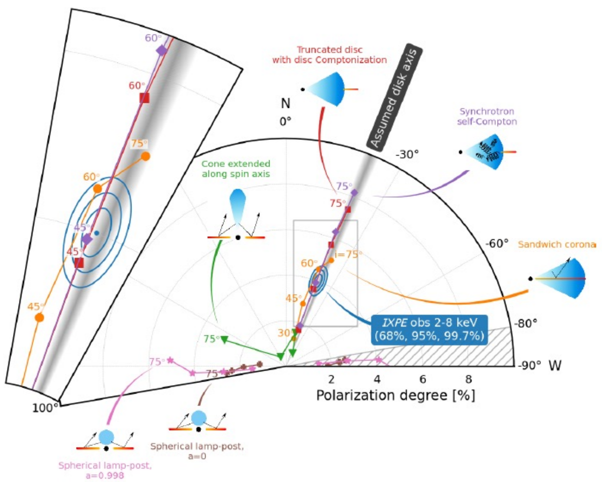
AV, Nättilä, Beloborodov 2019

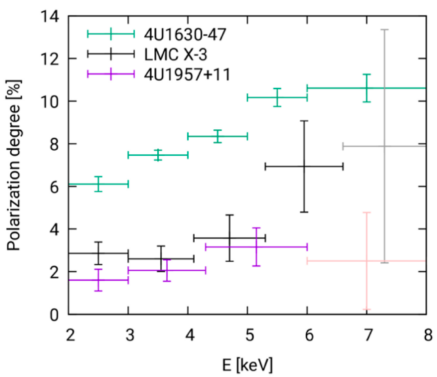
- Constant PA across the pulsation period: constraints on the B-field direction at the emission location

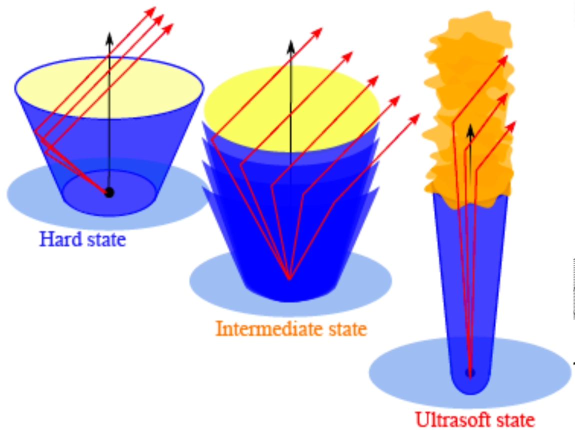
Summary

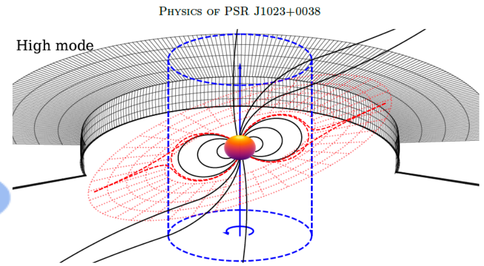
- Hard state sources: PA || jet, slab-like corona: warp(?)/outflow/wind
- Soft-state sources: questions to accretion disc structure
- Cyg X-3 and ULX connection
- NSs and rotation of PA: misalignment with the orbital axis
- Transitional ms pulsar: *B* field orientation











Thanks!