

The IXPE view on the accreting stellar-mass Black Holes: Measurement of Cyg X-1 X-ray polarization properties in its hard state

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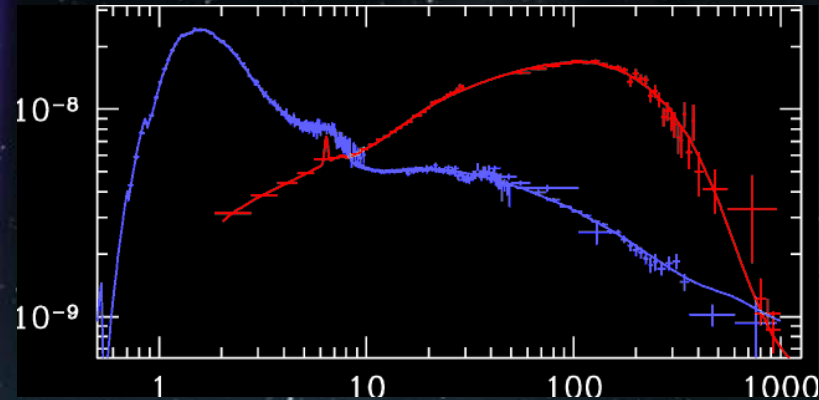
**Krawczynski, Muleri, Veledina, Rodriguez Caverro, Svoboda, Ingram, Matt,
Garcia, Loktev, Negro, Poutanen, Kitaguchi, Podgorný, Rankin, Zhang
on behalf of the whole IXPE team**

***RAGTIME, 24th Relativistic Astrophysics Group meeting
10-14/10/2022, Silesian University, Opava, Czech Republic***

Components:

- black hole
- star companion
- accretion disc
- corona
- winds
- jets

Done, Gierliński & Kubota (2007)



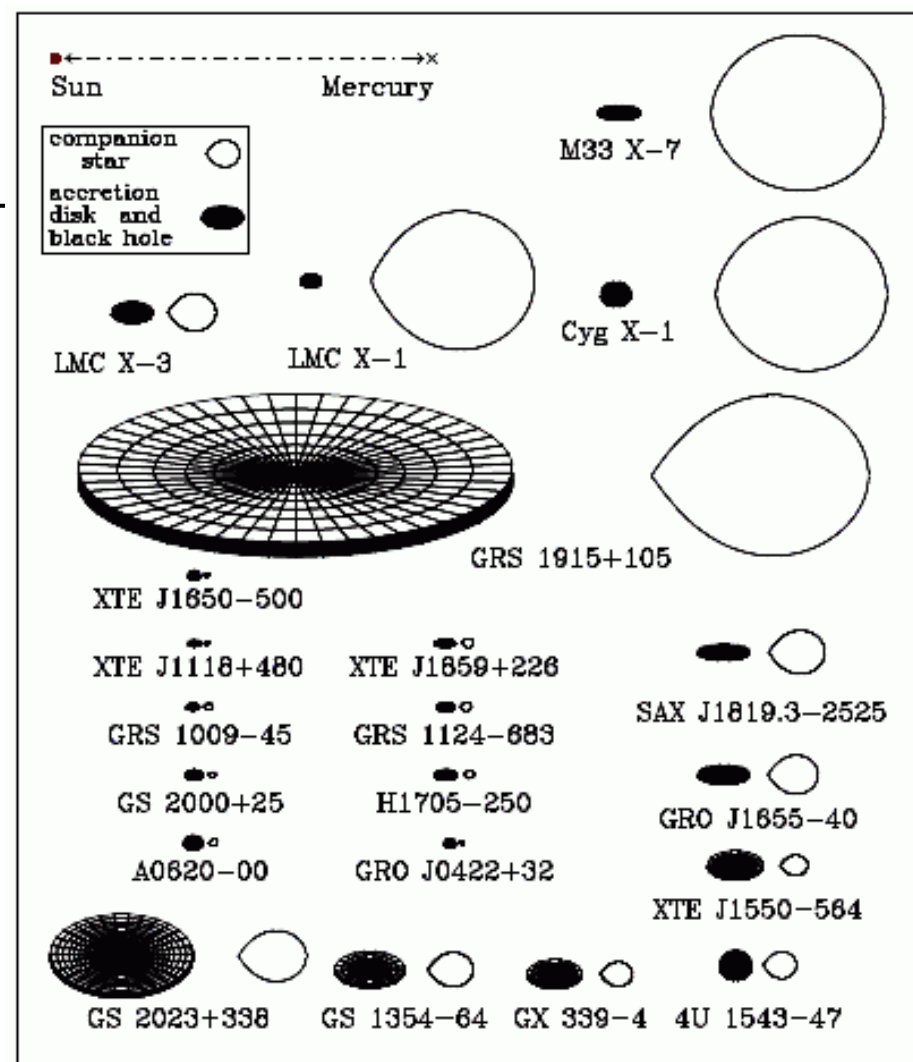
Spectral states:

- high/soft
- low/hard
- very high/steep power-law
- intermediate

XRB CENSUS

- Only about 10 sources are persistent
- From 77 transients only around 14 had at least 2 outbursts

McClintock, Narayan & Steiner (2014)



CYG X-1

Distance: $2.22^{+0.18}_{-0.17}$ kpc

Inclination: $27.1^\circ \pm 0.8^\circ$

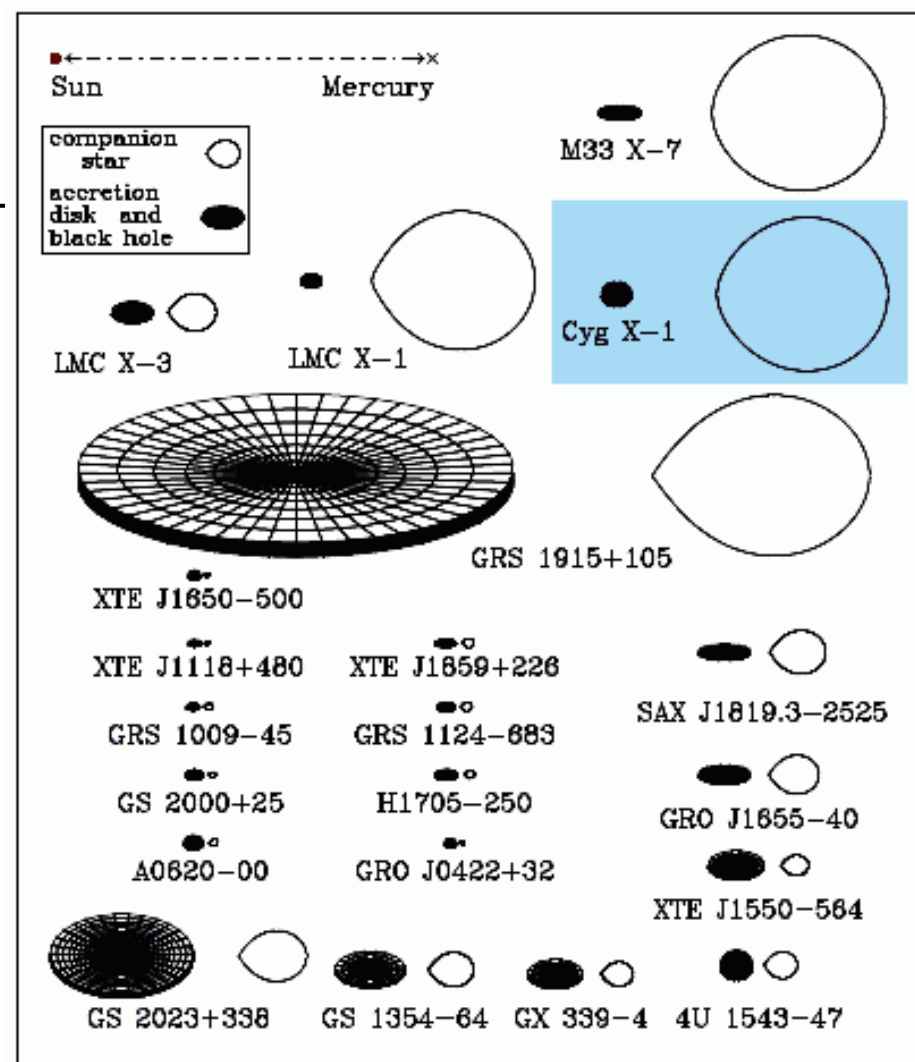
Companion mass: $40.6^{+7.7}_{-7.1} M_\odot$

Period: 5.6 day

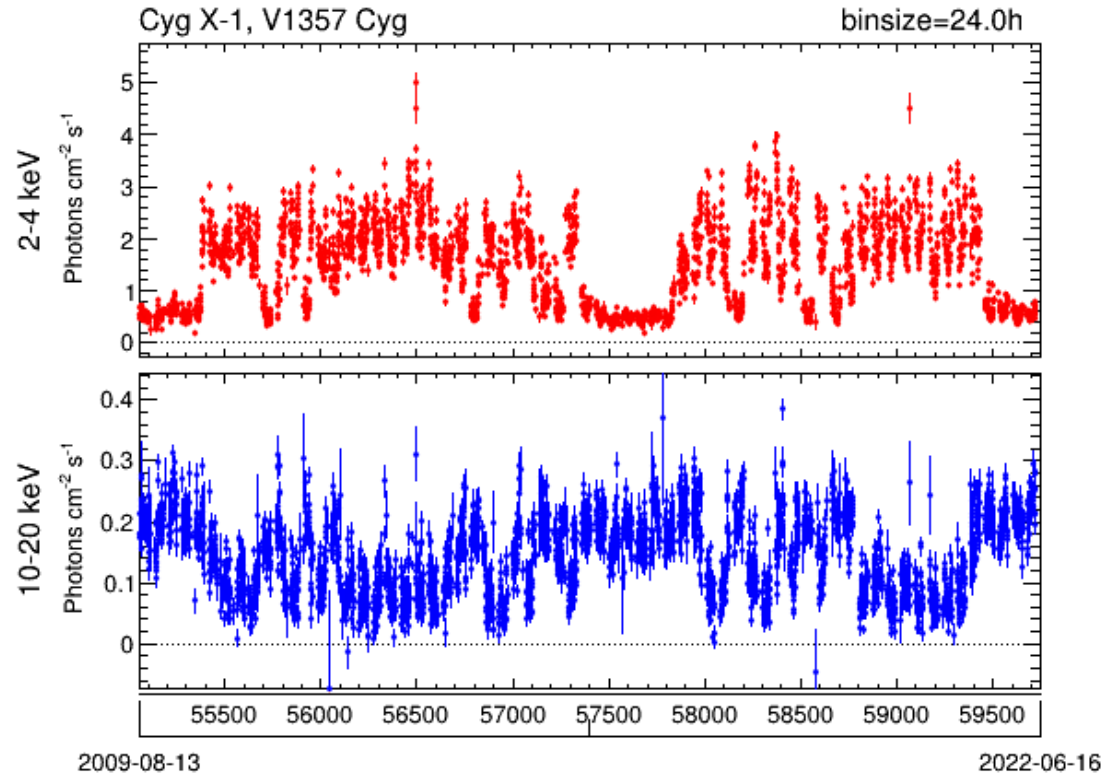
BH Mass: $21.2 \pm 2.2 M_\odot$

BH spin: $\gtrsim 0.92$

McClintock, Narayan & Steiner (2014)



- one of the brightest X-ray sources on the sky
- long-term hard state



Cyg X-1 MAXI light curve

OBSERVATIONAL CAMPAIGN

- **Observations:**

- **IXPE:** 242 ksec (15-21/5)
- NuSTAR: 42 ksec (18-21/5)
- NICER: 87 ksec (15-21/5)
- SWIFT: 54 ksec (15-20/5)
- INTEGRAL: 196 ksec (15-20/5)
- ART-XC: 171 ksec (15-19/5)
- optical telescopes with polarimetry (DIPol-2, RoboPol)

- **Additional ToO**

- to check variability of polarization
- IXPE: 100 ksec (20-21/6)
- NuSTAR: 40 ksec
- NICER: 40 ksec

- **High energy polarization (15-80 keV)**

- XL-Calibur: 168 ksec

IXPE - NASA and ASI mission

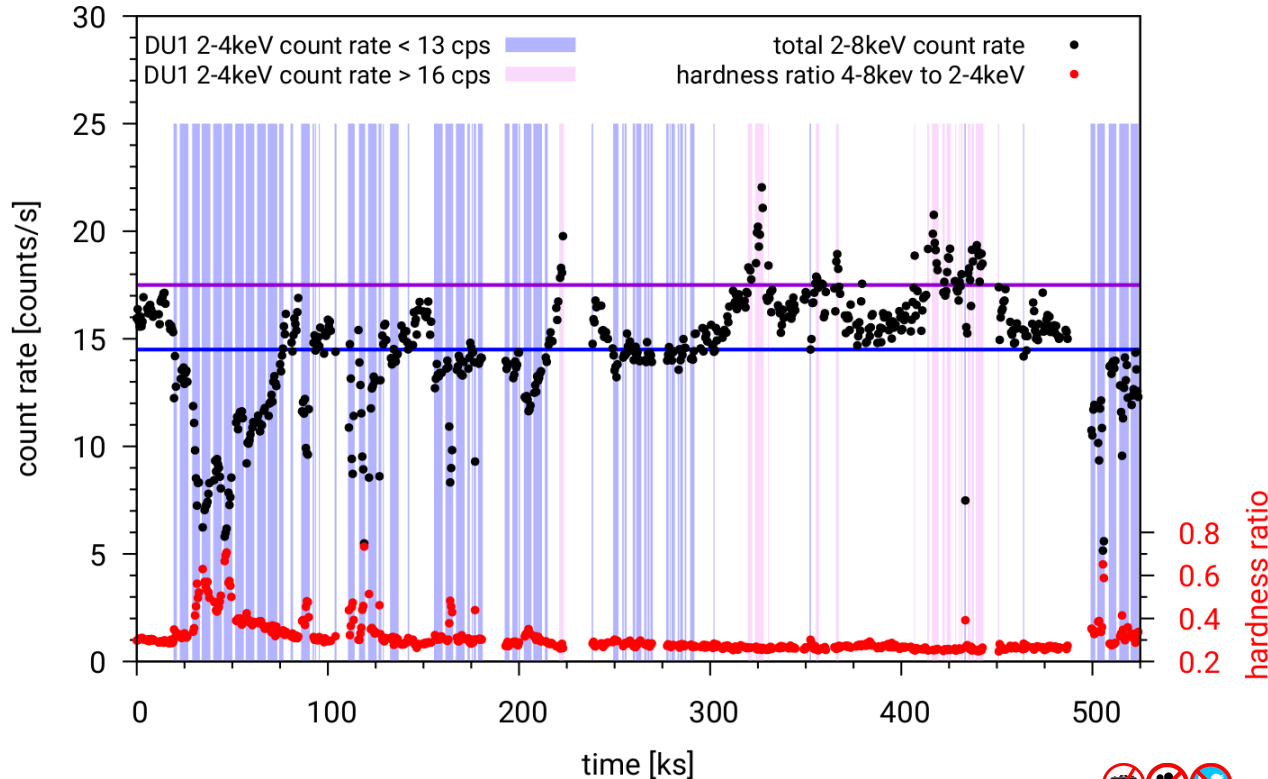
- SMEX-14, ~200 million USD (8 years ago)
- Selected on 3rd January 2017 (5 years ago)
- Launched on 9th December 2021

IXPE data sheet

- 3 mirror modules + 3 gas pixel detectors
- imaging and polarization capabilities
- effective area: 525 cm² (3–6 keV)
- angular resolution: 28 arcsec
- field of view: 12.9 arcmin square
- energy resolution: 0.57 keV @ 2 keV
- useful energy range: 2 - 8 keV



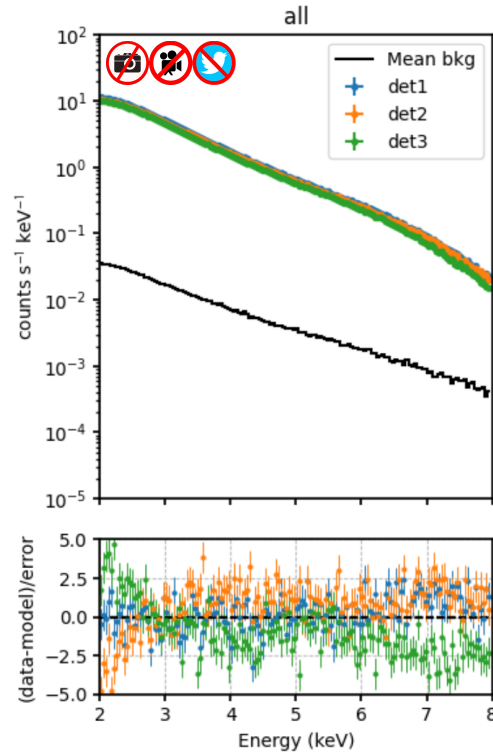
IXPE LIGHT-CURVE



- High variability
- Mean IXPE Flux:
 $5.2 \times 10^{-9} \text{ ergs cm}^{-2} \text{ s}^{-1}$
 217 mCrab

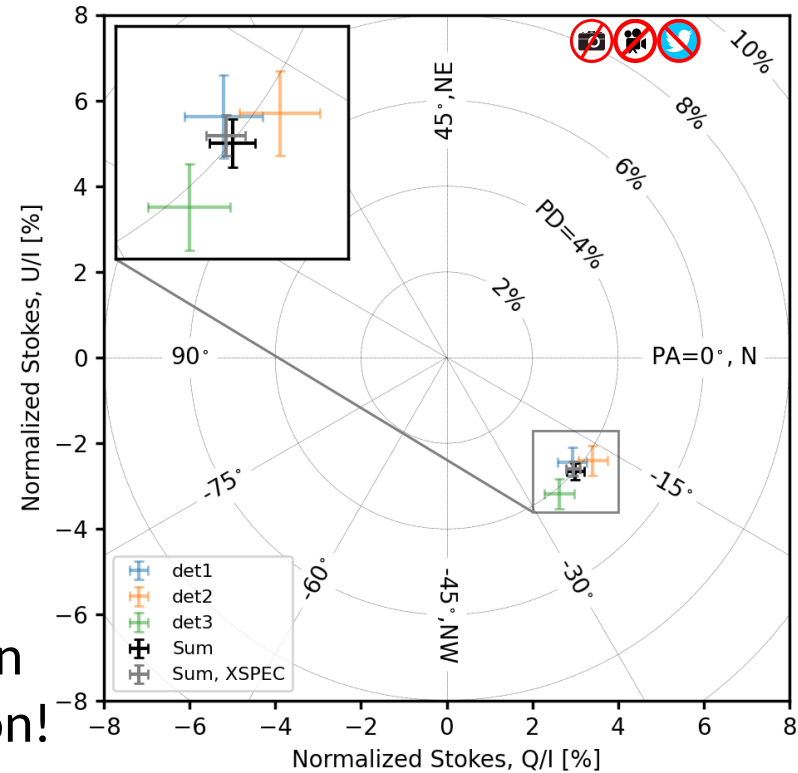


NORMALIZED STOKES PARAMETERS



Background is 2 orders of magnitudes lower than the signal

2-8 keV:
>20 sigma detection of linear polarization!

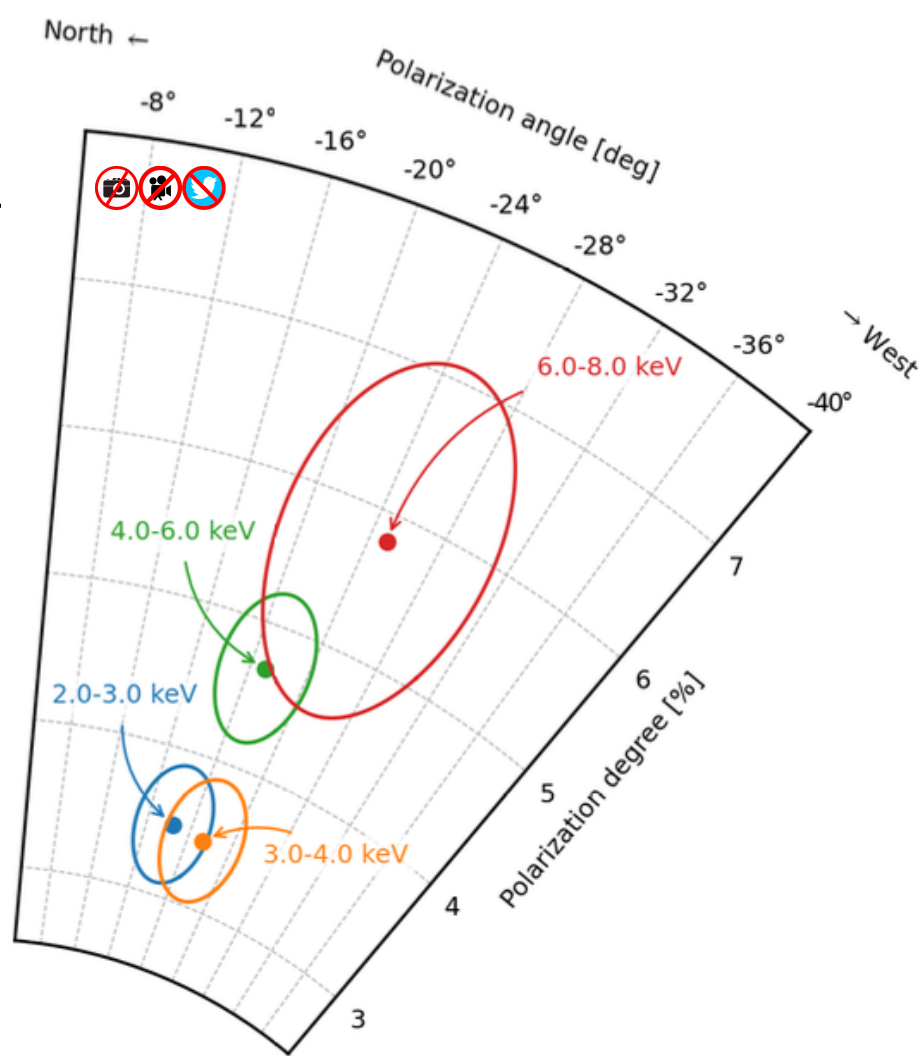


POLARIZATION DEGREE & ANGLE

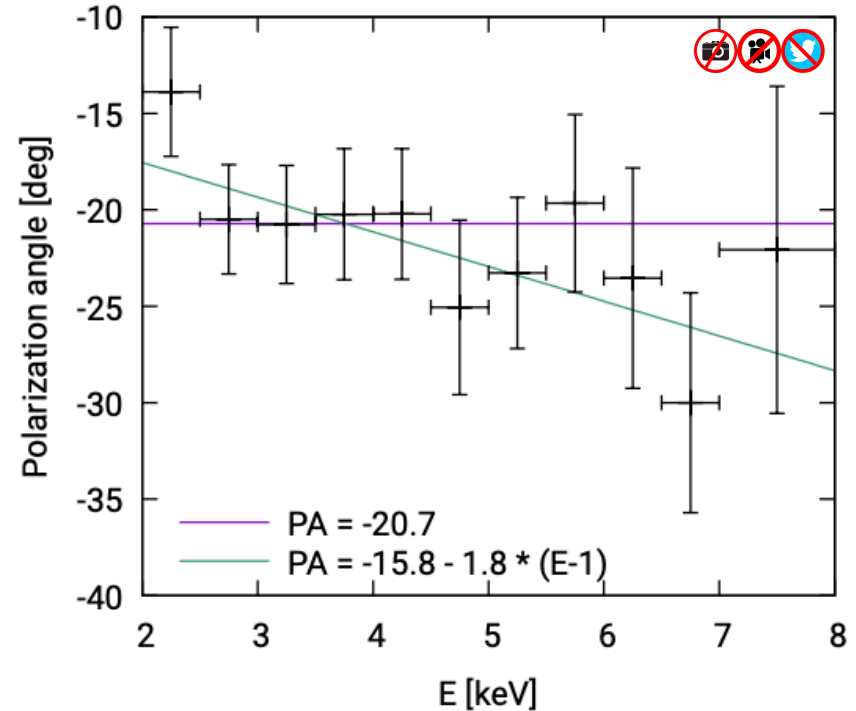
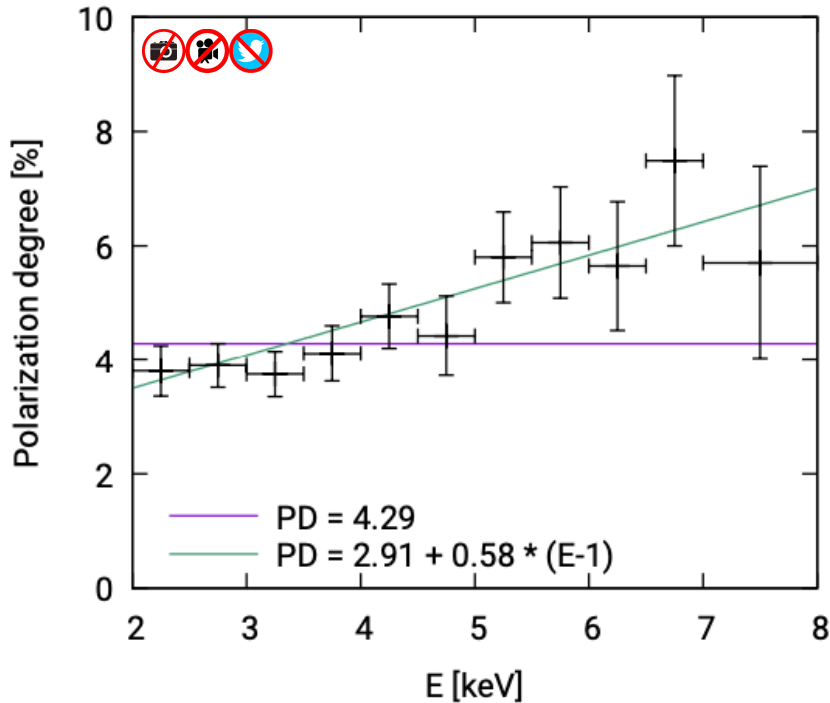
2-8 keV:

$$PD = (4.0 \pm 0.2) \%$$

$$PA = (-21 \pm 1) \text{ deg}$$



POLARIZATION DEGREE & ANGLE

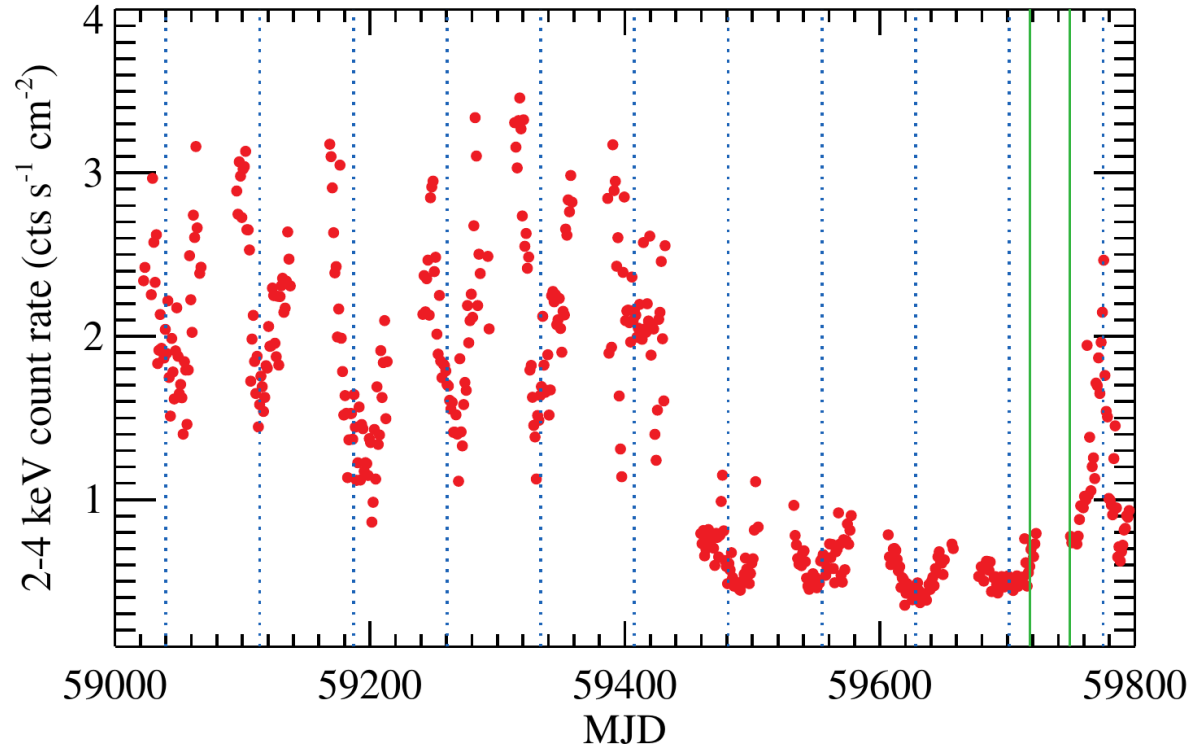


No highly significant energy dependence of pol. properties.

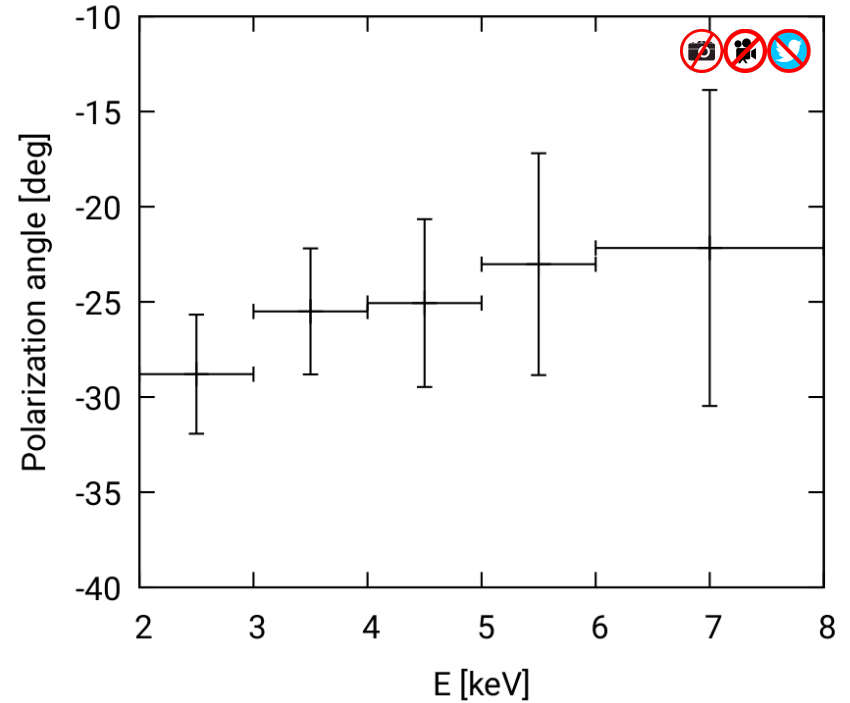
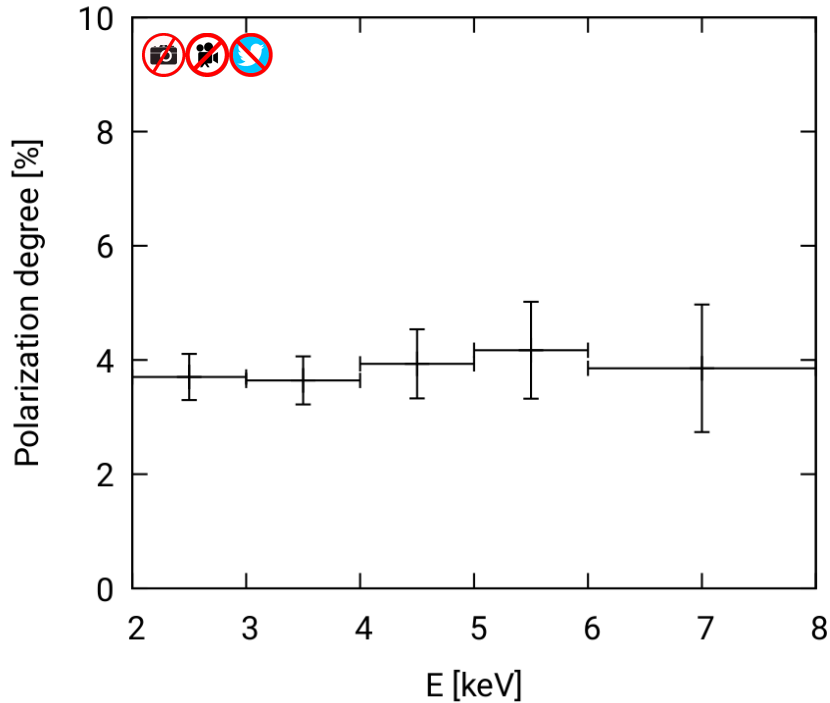
SUPERORBITAL VARIABILITY

Superorbital precession of the inner accretion disc?

- different X-ray, optical and radio instruments indicate the presence of a superorbital periodicity (Poutanen, Zdziarski & Ibragimov 2008) – **73.5 days**
- precession of the accretion disc?
- we have performed IXPE observation 1 month later to test this scenario

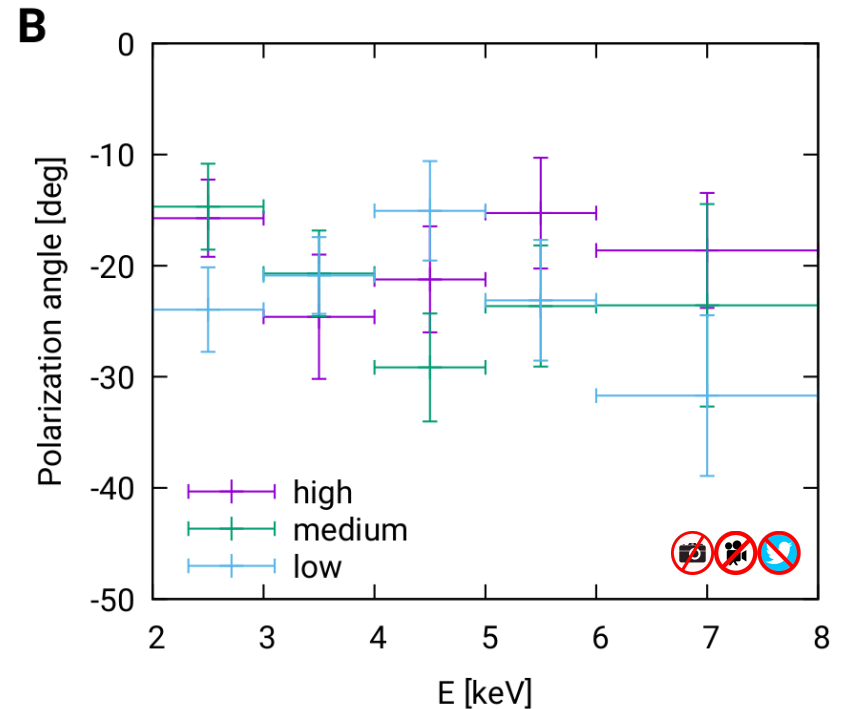
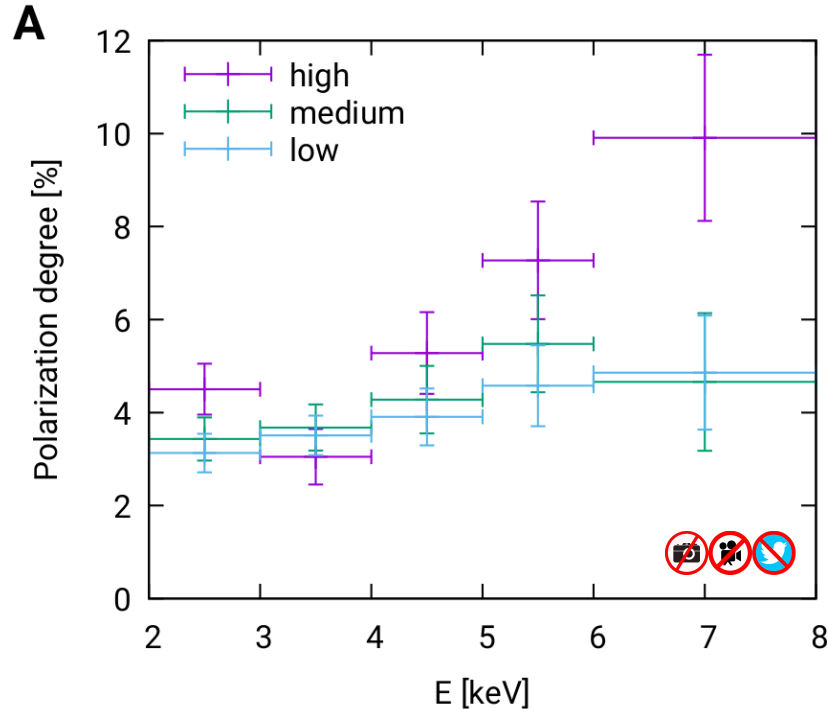


POLARIZATION DEGREE & ANGLE



Polarization properties of ToO

FLUX DEPENDENCE

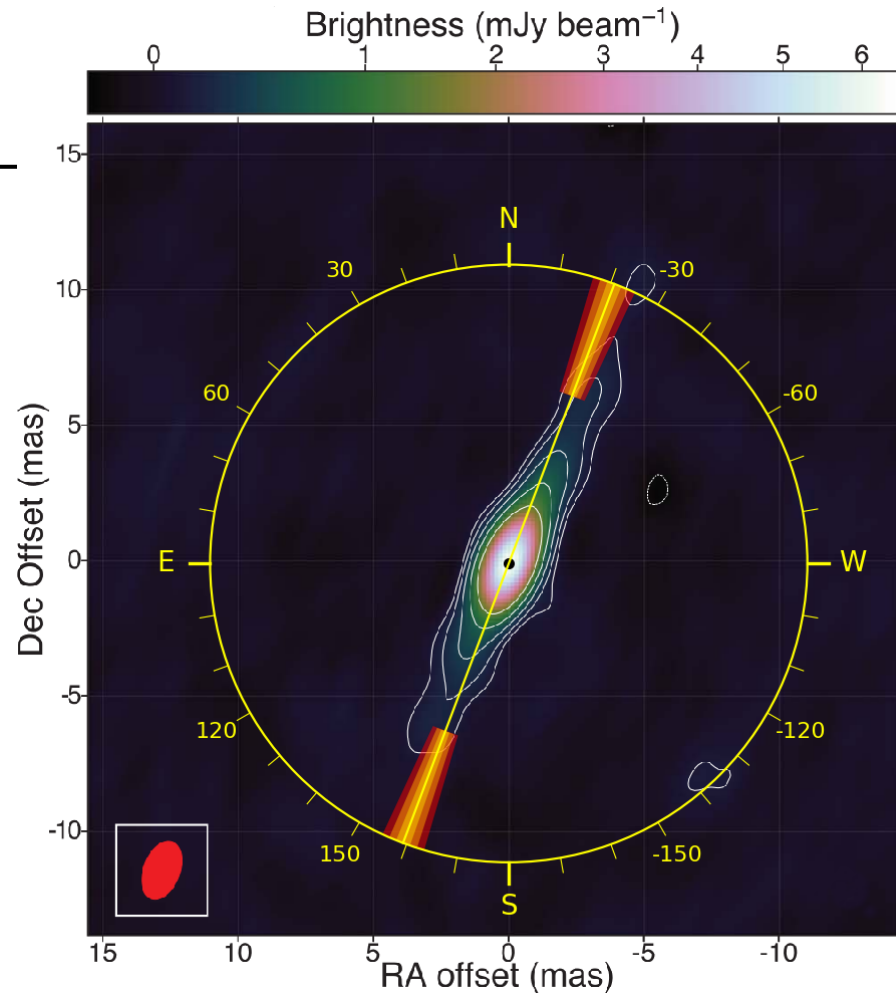


Polarization degree in 2-8keV band slightly increases with the flux:
 $(3.63 \pm 0.30)\%$, $(3.87 \pm 0.34)\%$, $(5.03 \pm 0.41)\%$

ALIGNMENT WITH RADIO JET

The figure shows radio jet.
Figure axes extend 10 billion km.

IXPE emission probes 600 km region,
more than 7 magnitudes smaller region!

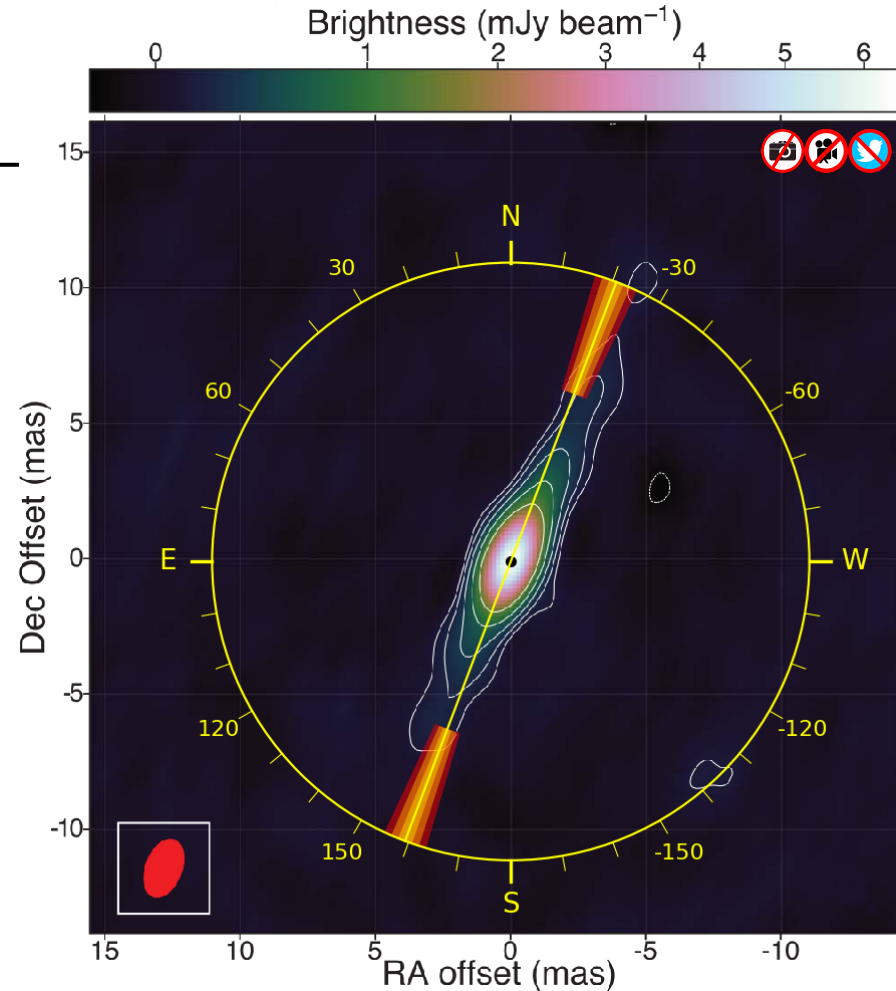


ALIGNMENT WITH RADIO JET

If polarization is perpendicular to inner accretion flow than the jet is perpendicular to inner accretion disc



misaligned or curved jet
or jet not related to disc



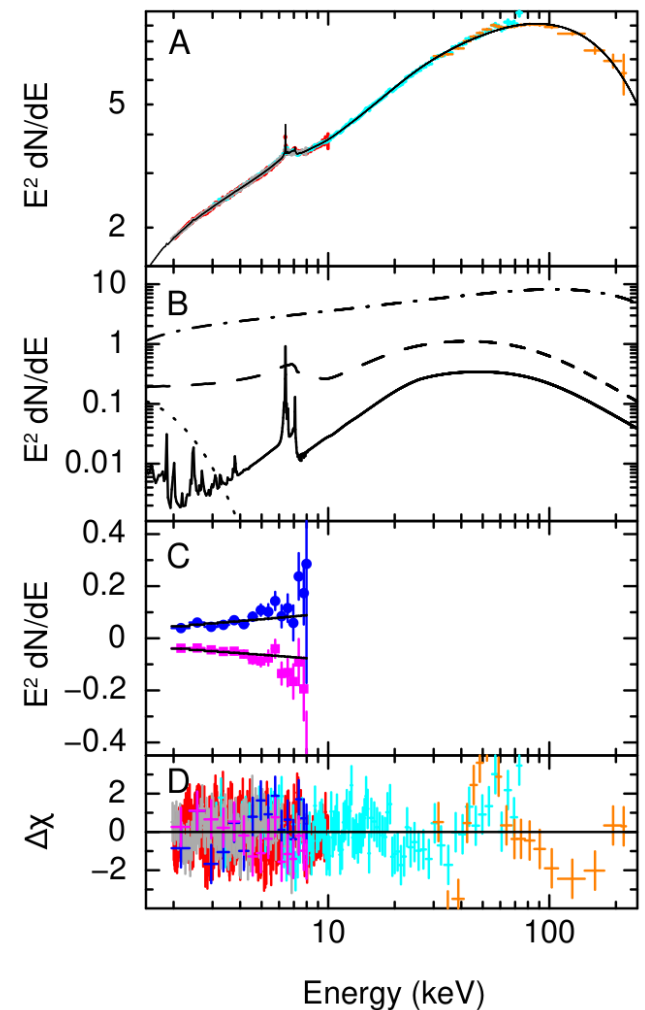
SPECTRO-POLARIMETRIC FIT

IXPE + NuSTAR + NICER + INTEGRAL in 2-250 keV

Spectral components:

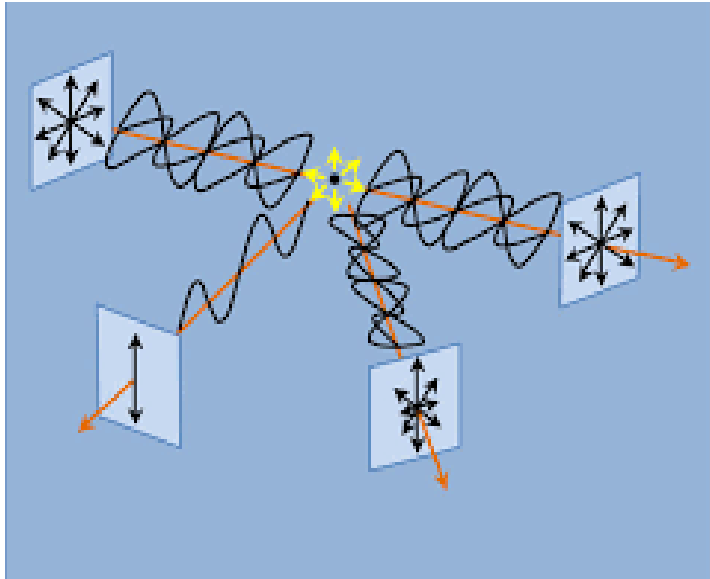
- cross-calibration (mbpo)
- Galactic absorption (tbabs)
- thermal emission (diskbb, < 1%) - unpol.
- Comptonization (nthcomp, 90%) - pol.
- relativistic reflection (relxillcp, 10%) - unpol.
- Distant reflection (xillvercp, <1%) - unpol.

$$PD = 3.63 \pm 0.26\% \quad PA = -20.5 \pm 2.1 \quad \chi^2/dof = 2380.4/2415.$$



ORIGIN OF POLARIZATION

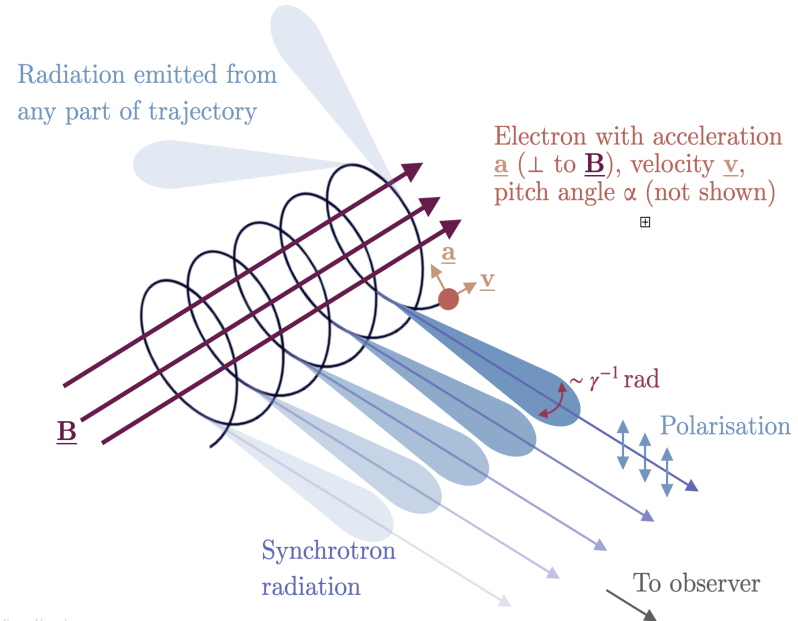
Scattering-Polarization



<http://sites.sinauer.com/animalcommunication2e/chapter05.02.html>

Synchrotron-Polarization

+ GR



Emma Alexander

https://en.wikipedia.org/wiki/Synchrotron_radiation#/media/File:Emmaalexander_synchrotron.png

SCATTERING & CORONA GEOMETRY

- **Slab sandwich corona**

- consistent PD and PA but for incl. > 65 deg
- but Haardt & Maraschi (1991)

- **Spherical corona**

- low polarization degree (Schnittman & Krolik 2010)

- **Hot inner accretion flow (truncated disc)**

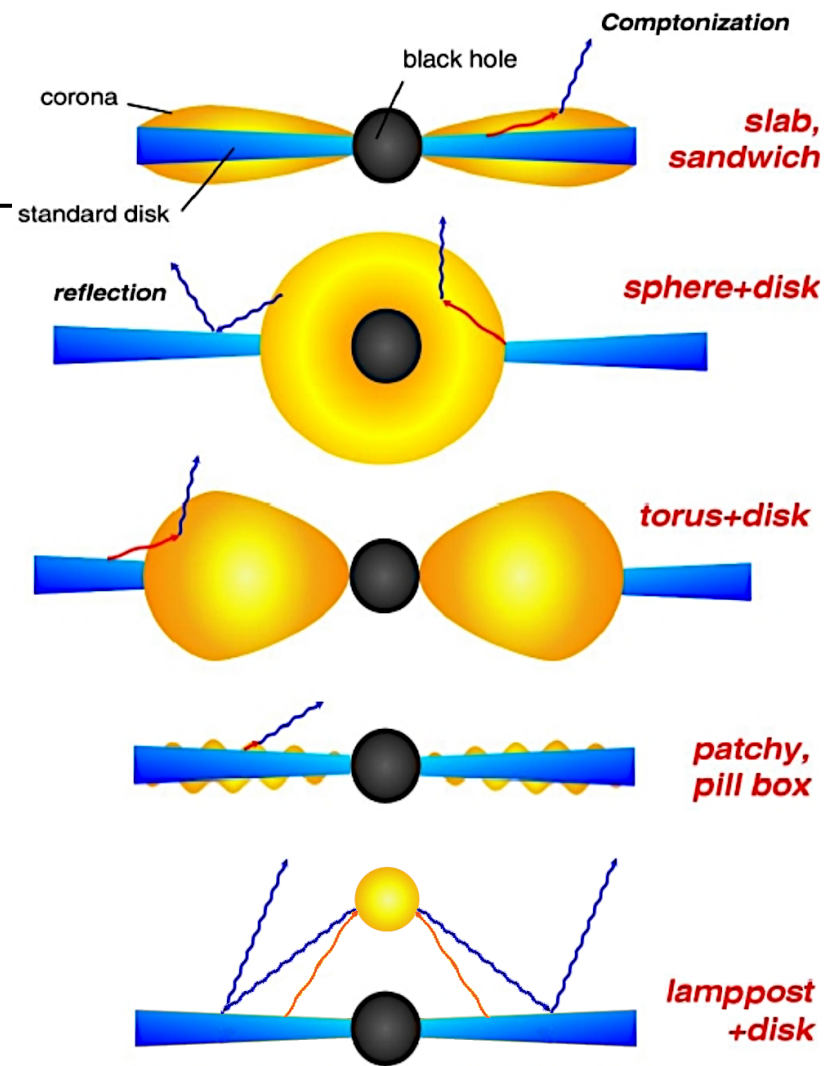
- consistent PD and PA but for incl. > 45 deg
- internal synchrotron seed photons

- **Patchy corona**

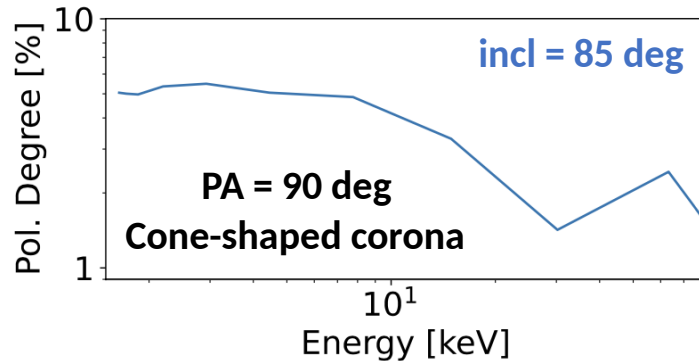
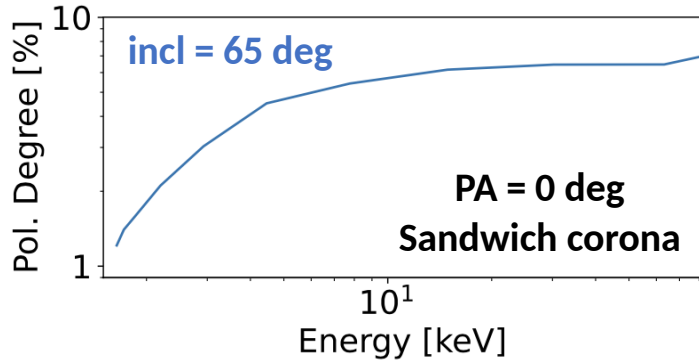
- low polarization degree (Schnittman & Krolik 2010)

- **Lamp-post corona (spherical, cone-shaped)**

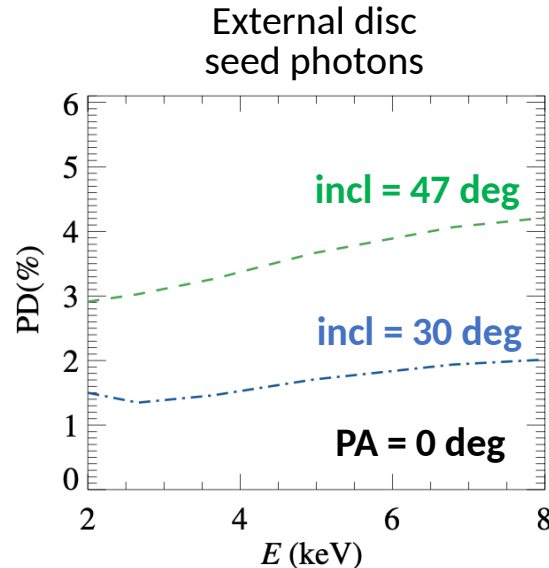
- low PD or horizontal PA or PD decreases with energy
- various heights, speeds and disc truncation tried



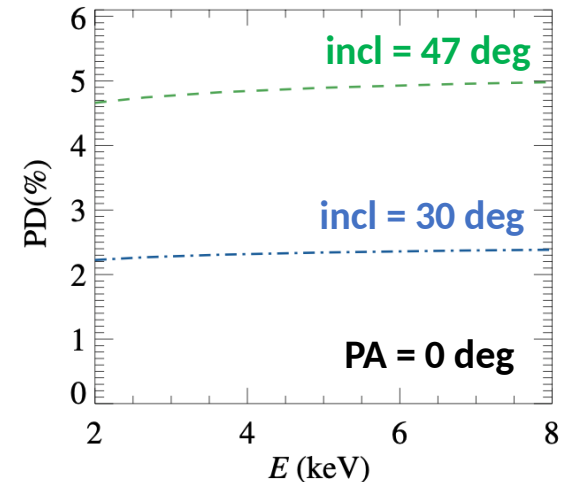
SCATTERING & CORONA GEOMETRY



Hot inner accretion flow



Internal synchrotron seed photons



HIGH INCLINATION OF INNER ACCRETION DISC?

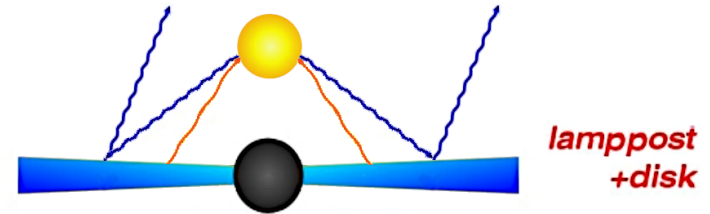
Higher inclination is needed

- **Bardeen and Petterson effect with highly spinning BH**
 - warping of the inner accretion disc into the BH equatorial plane (Bardeen, Petterson & Jacobus 1975)
 - some analyses of reflected Cyg X-1 spectra give high disc inclinations (Tomsick et al. 2014, Parker et al. 2015, Tomsick et al. 2018)
- **Outflowing corona** with mildly relativistic velocities (Poutanen et al. in prep.)

CAN REFLECTION DOMINATE POLARIZATION?

- **Reflection**

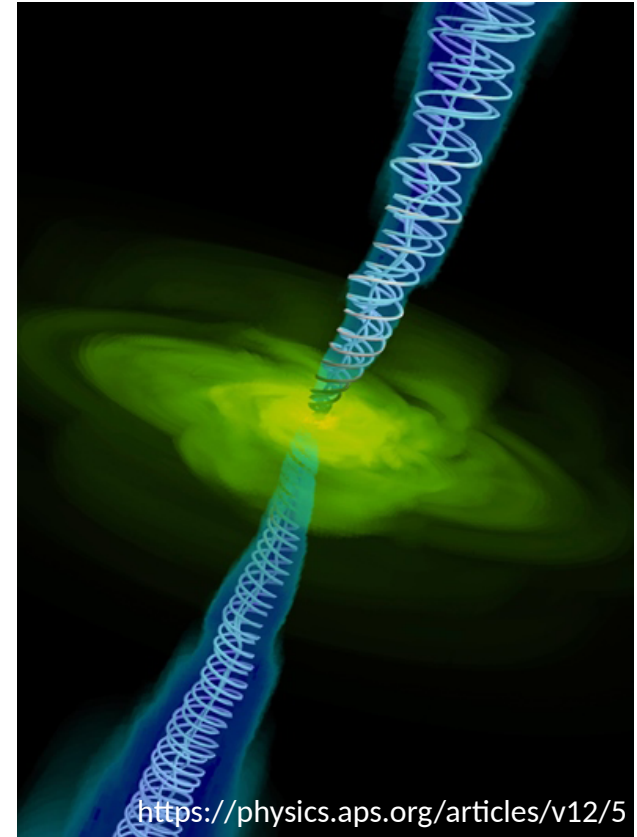
- contributes by 10%
- to dominate, it would have to be polarized at $> 40\%$ level
- reflection is polarized $< 40\%$
(Dovciak et al. 2011, Podgorny et al. in prep.)



Polarization is dominated by the power-law component!

SYNCHROTRON MAGNETIC FIELD STRUCTURE

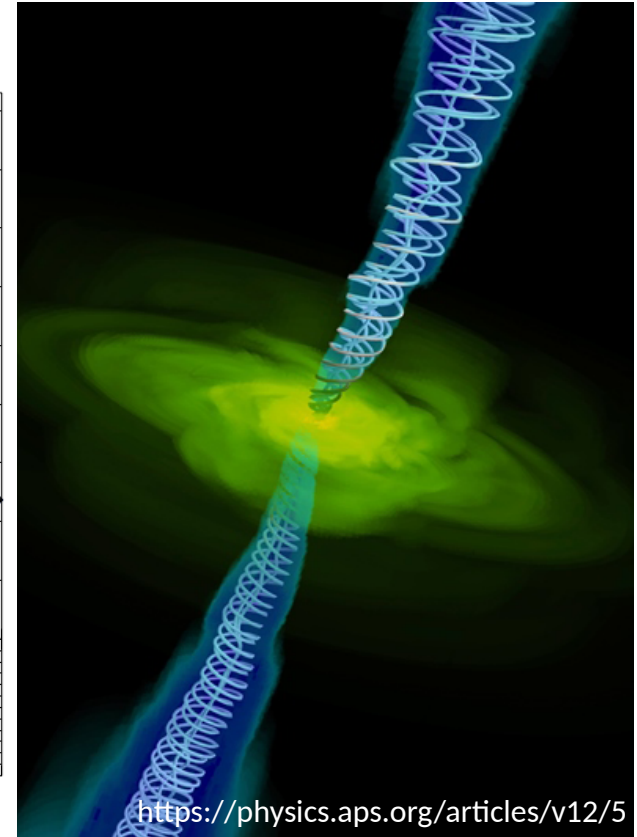
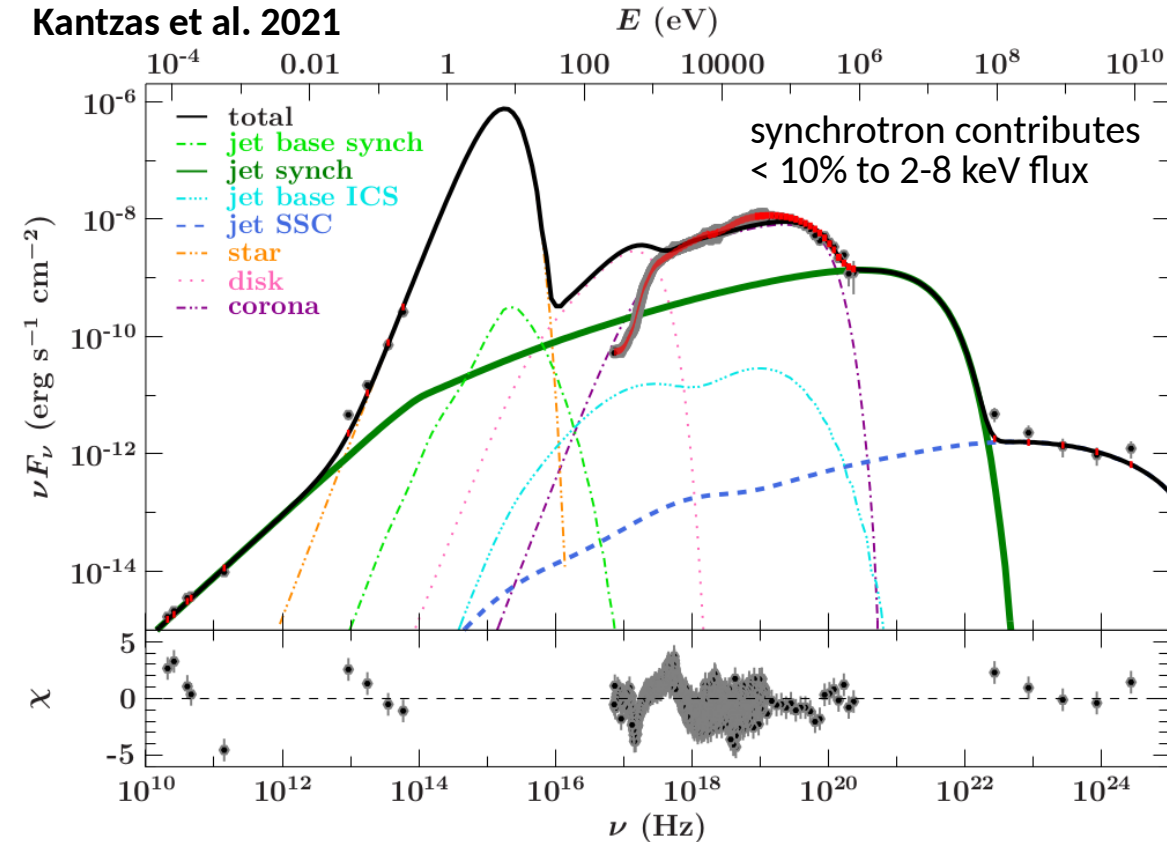
**Could synchrotron jet emission explain
the polarization properties?**



<https://physics.aps.org/articles/v12/5>

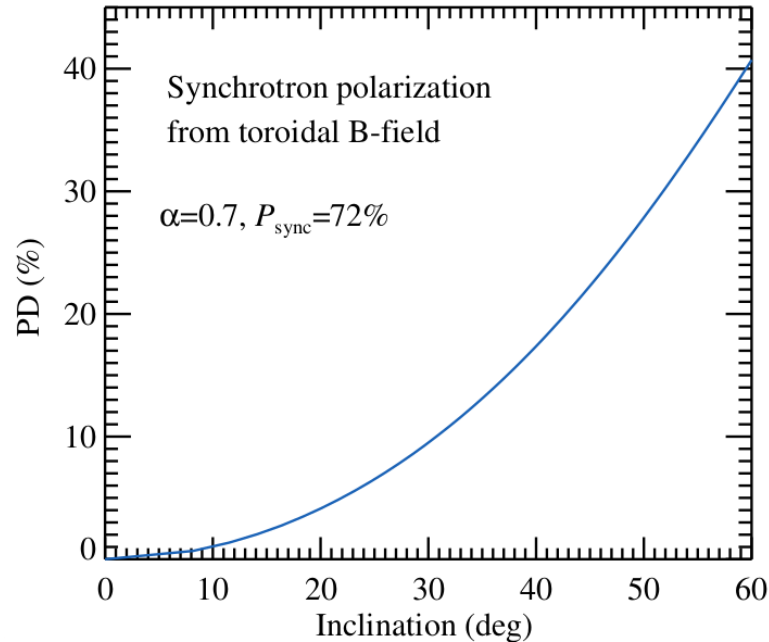
SYNCHROTRON MAGNETIC FIELD STRUCTURE

Kantzas et al. 2021

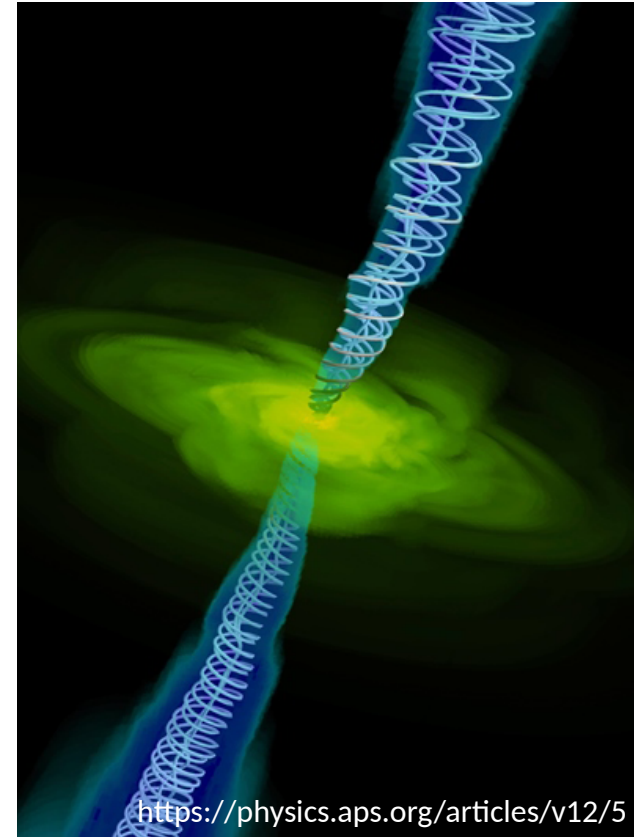


SYNCHROTRON MAGNETIC FIELD STRUCTURE

- PA parallel with jet \rightarrow toroidal magnetic field
- PD \ll than the theoretical maximum for unidirectional magnetic field (Lyutikov, Pariev & Gabuzda 2005)



- synchrotron requires yet again large inclination angle



- **Deeper analysis of Cyg X-1 data from observational campaign (timing)**
- **Other bright persistent sources in hard state (e.g. Cyg X-3)**
- **Bright persistent sources in soft state
(e.g. LMC X-1, 4U1957+115, LMC X-3, Cyg X-1, GRS1915+105)**
- **GRS 1915+105 in obscured state**
- **Outburst of transient source - 4U1630-47
(e.g. GX 339-4, GRO 1655-40)**
- **Other interesting sources (e.g. SS433, ...)**

- **IXPE observed currently the brightest persistent XRB Cyg X-1 in its hard state**
- **IXPE detected unexpectedly high PD in 2-8 keV band: $4.0 \pm 0.2 \%$
with PA parallel with radio jet**
- **corona seems to be extended in disc plane**
- **Comptonization models: $\text{incl} > 45 \text{ deg}$; Synchrotron models: $\text{incl} > 60 \text{ deg}$**
- **warped inner disc misaligned with orbital axis (Bardeen Petterson effect)**
- **or corona is outflowing with mildly relativistic velocities**

