IXPE observations of blazars and stellar mass black holes

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CDY Black Hole Flare Workshop
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IXPE blazar observation

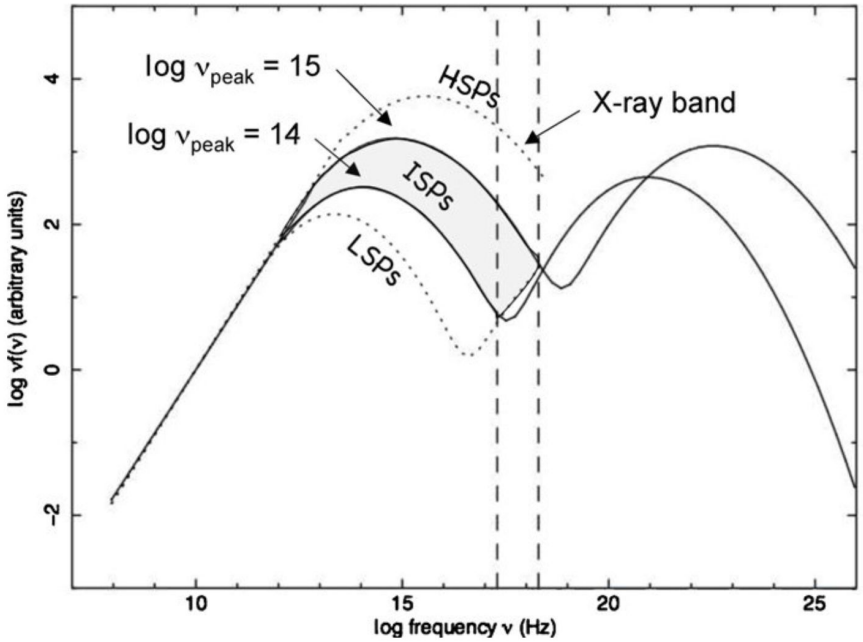
- Particle acceleration mechanism (reconnection, shock, turbulence) and geometry (single-zone vs multi-zone)

- Jet composition (leptonic vs hadronic)

(Image credit: NASA/JPL–Caltech/GSFC)

Blazar spectral types

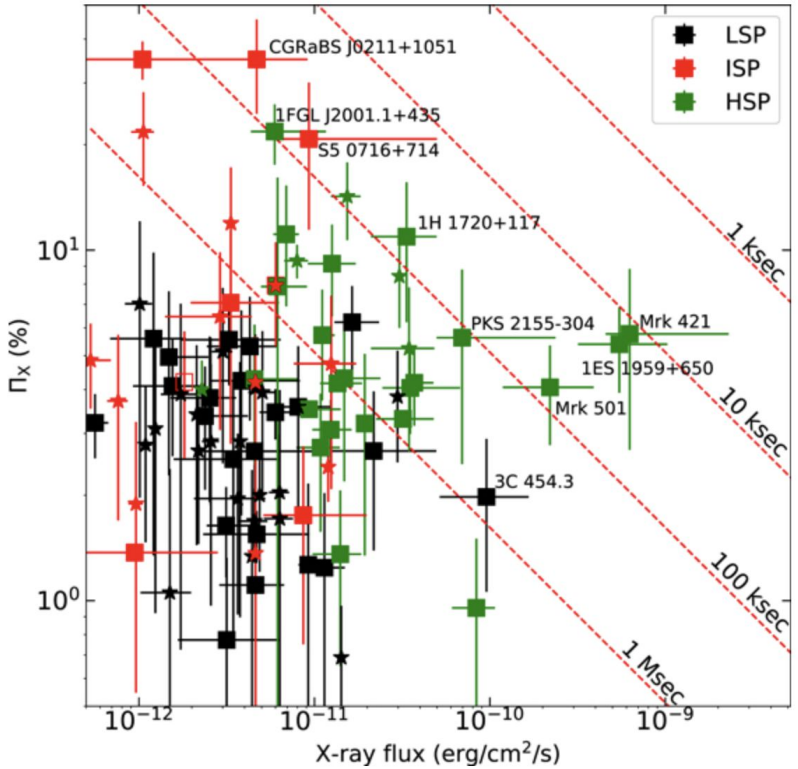
IXPE band (2 to 8 keV) covers different spectrum components for different types of blazars



Abdo+ 2010

Blazar spectral types

IXPE band (2 to 8 keV) covers different spectrum components for different types of blazars



Liodakis+ 2019

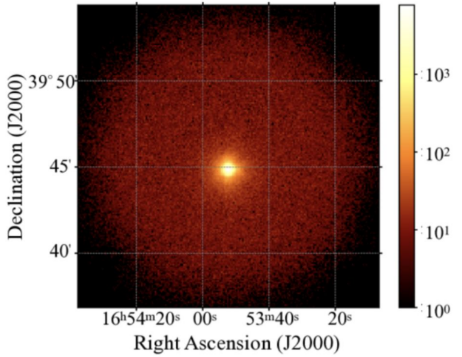
HSP: Mark 501

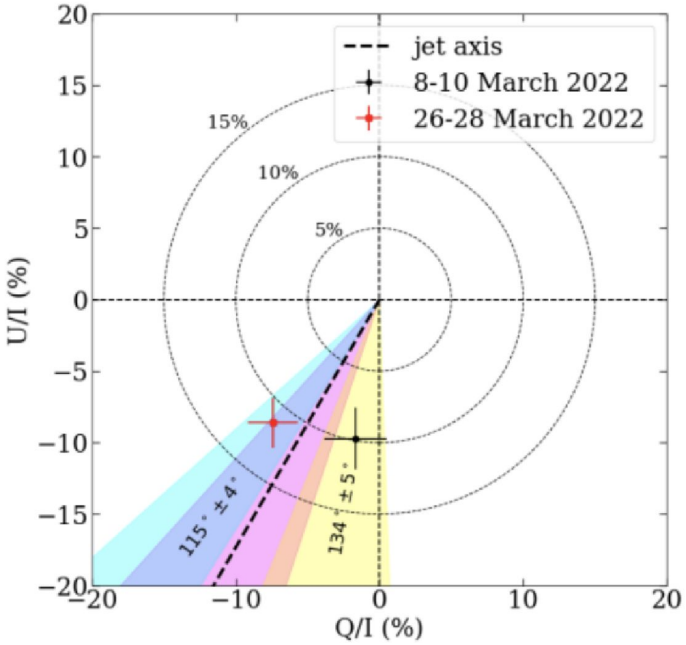
Liodakis+ 2022

8-10 March 2022 (100 ks)
PD = 11 ± 2 %
PA = 134 ± 6 deg

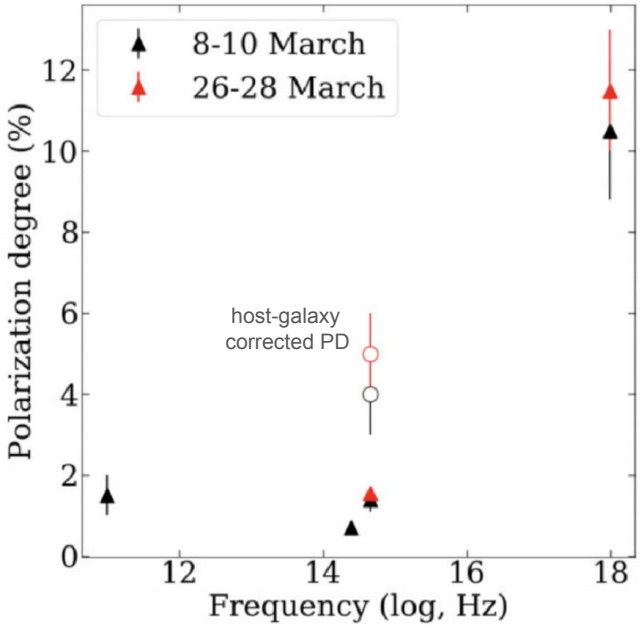
26-28 March 2022 (85 ks)
PD = 11 ± 2 %
PA = 115 ± 4 deg

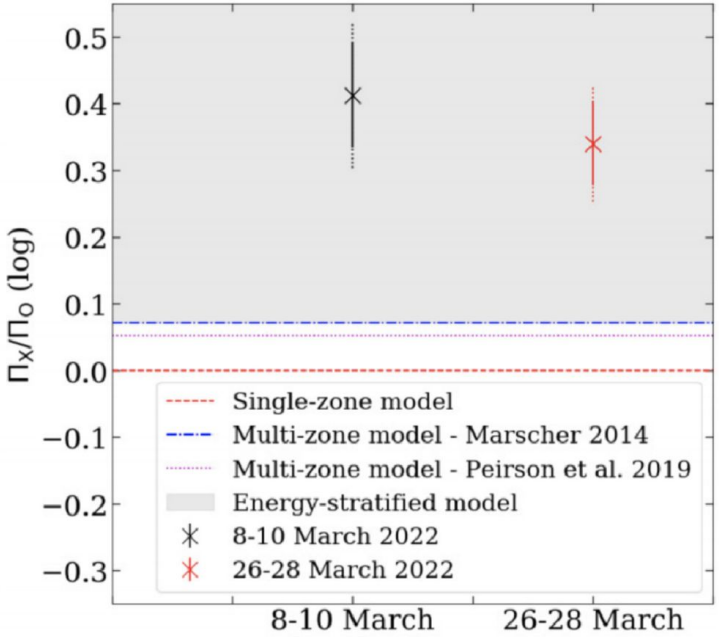
9-12 July 2022 (97 ks)
PD = 7 ± 2 %
PA = 135 ± 8 deg





HSP: Mark 501


8-10 March
26-28 March
host-galaxy
corrected PD
Polarization degree (%)
Frequency (log, Hz)
0
2
4
6
8
10
12
12
14
16
18


Π_X/Π_O (log)
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
Single-zone model
Multi-zone model - Marscher 2014
Multi-zone model - Peirson et al. 2019
Energy-stratified model
8-10 March 2022
26-28 March 2022
8-10 March
26-28 March

HSP: Mark 501

Model	Multiwavelength polarization	X-ray polarization variability†	X-ray polarization angle
Single-zone	constant*	slow	any
Multi-zone	mildly chromatic	high	any
Energy stratified (shock)	strongly chromatic	slow	along the jet axis
Magnetic reconnection (kink instability)	constant	moderate	perpendicular to jet axis
Observed	strongly chromatic	slow	along the jet axis

*There is a slight dependence on the slope of the emission spectrum.

†Slow variability = a few days to week, moderate variability = days, high variability $\leq$ 1 day.

HSP: Mark

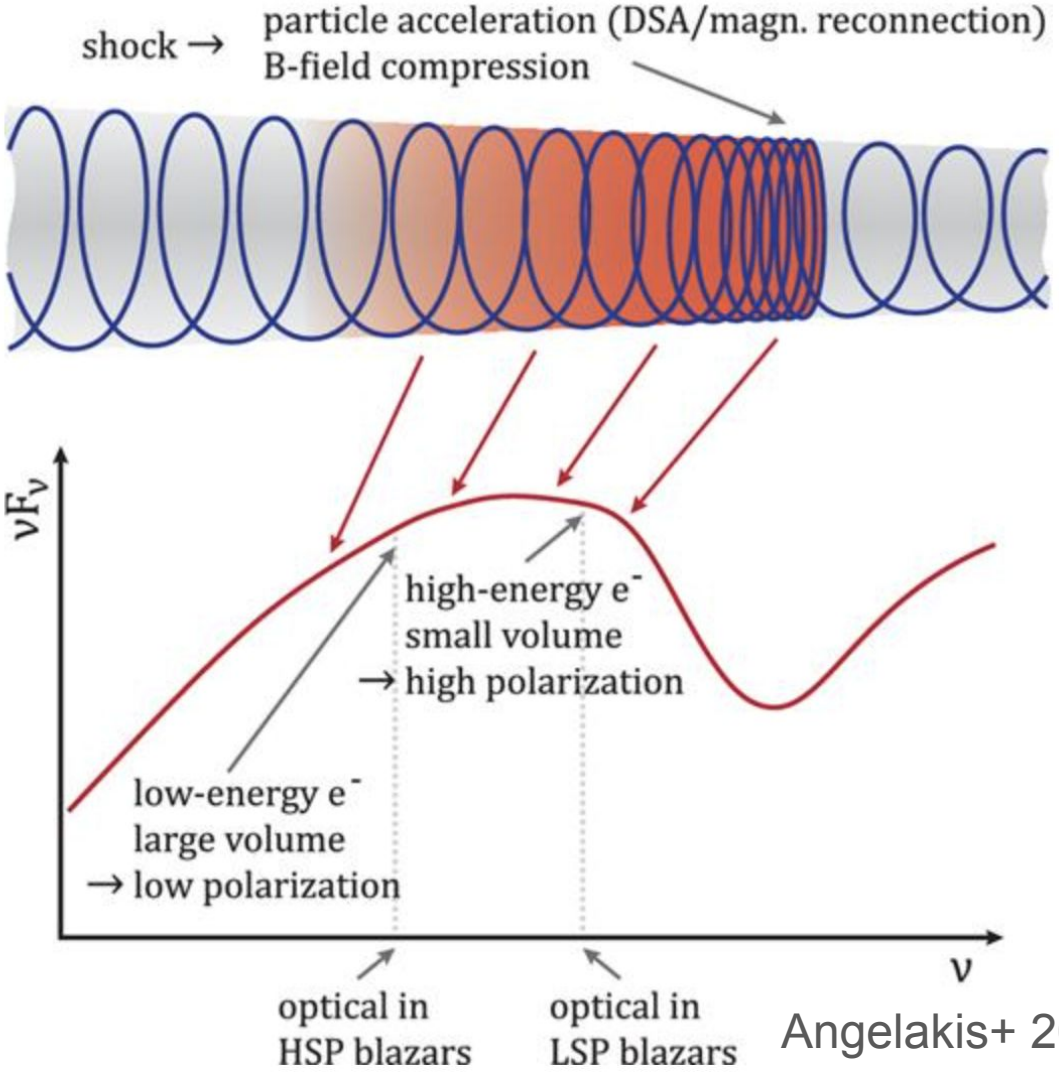
Model	ay polarization angle
Single-zon	any
Multi-zon	any
Energy strati (shock)	along the jet axis
Magnetic recon (kink instabi	erpendicular to jet axis
Observed	along the jet axis

*There is a slight

†Slow variability

day.

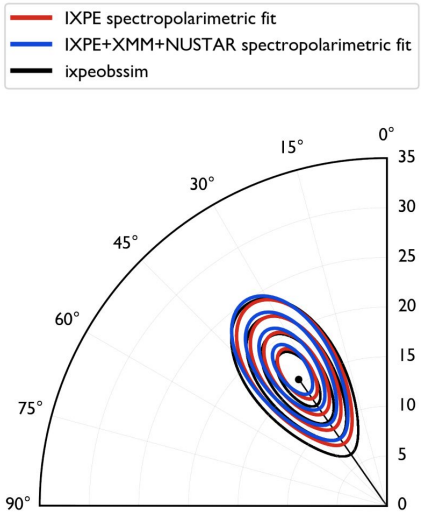
ı variability ≤ 1



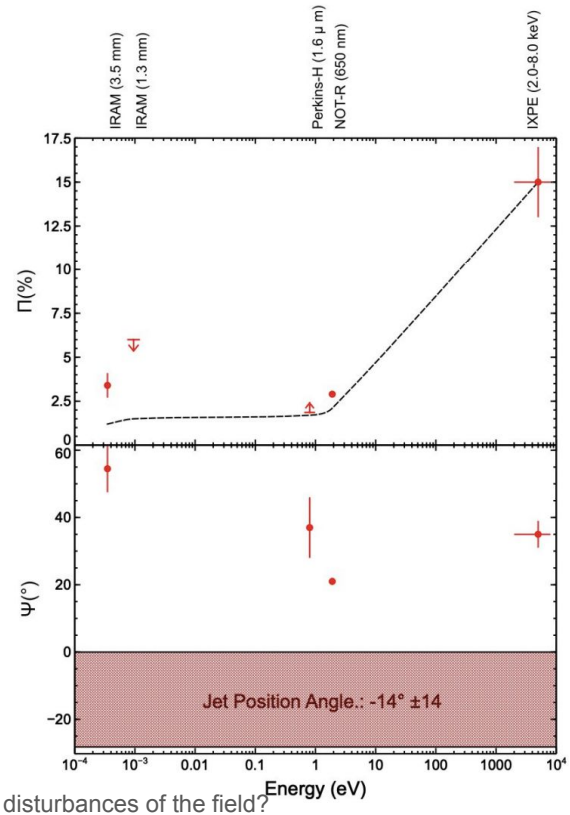
Angelakis+ 2016

HSP: Mark 421

4-6 May 2022 (97 ks)
PD = 15 ± 2 %
PA = 35 ± 4 deg



Di Gesu+ 2022



local disturbances of the field?

the degree of X-ray polarization is several times higher than at optical/infared/millimeter wavelengths

Steady x-ray polarization properties during flux increase

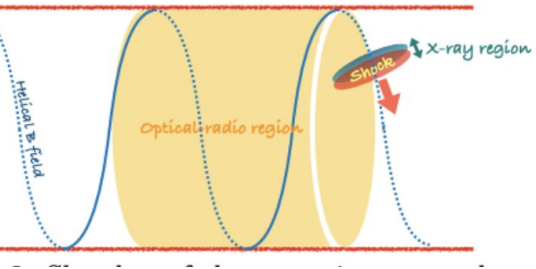
shock acceleration is the most likely particle acceleration mechanism in the jet

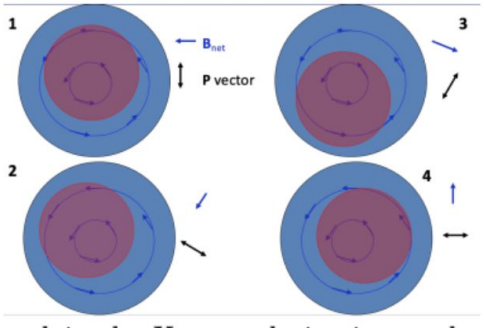
HSP: Mark 421

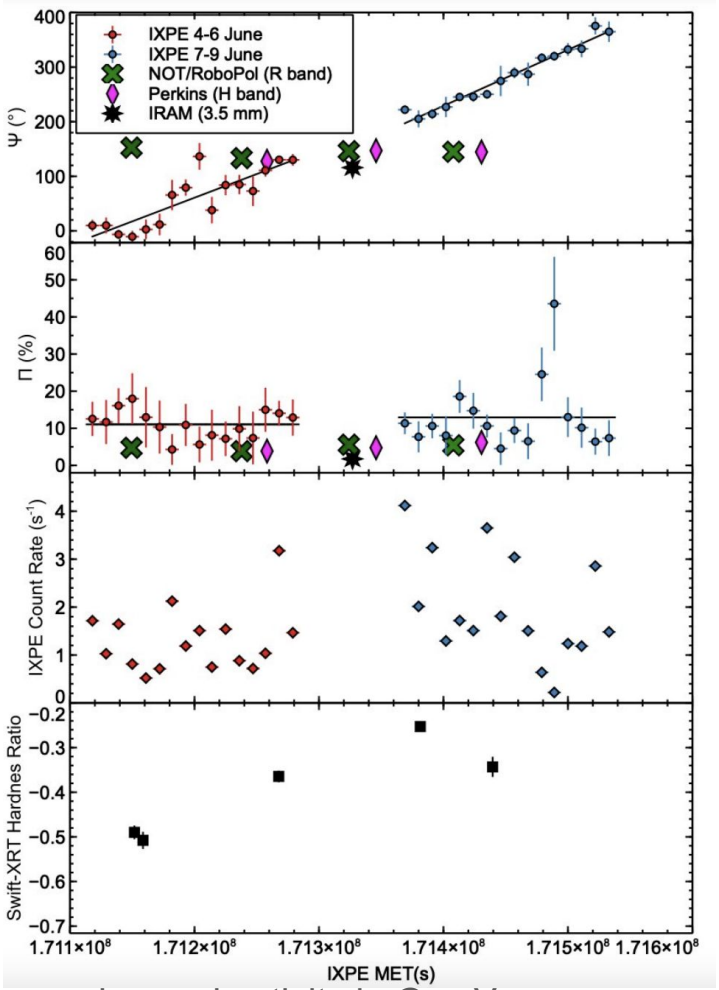
Di Gesu+ 2023

4-6 June 2022, 7-9 June 2022:
Low PD~4% → X-ray PA rotation

a magnetosonic shock propagates along helical magnetic field lines



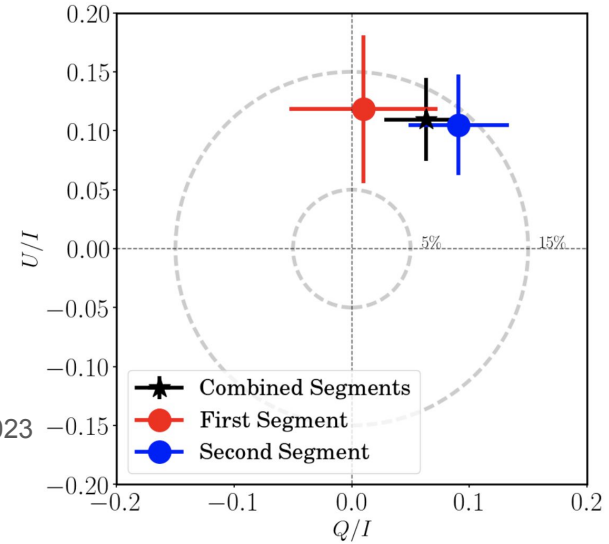




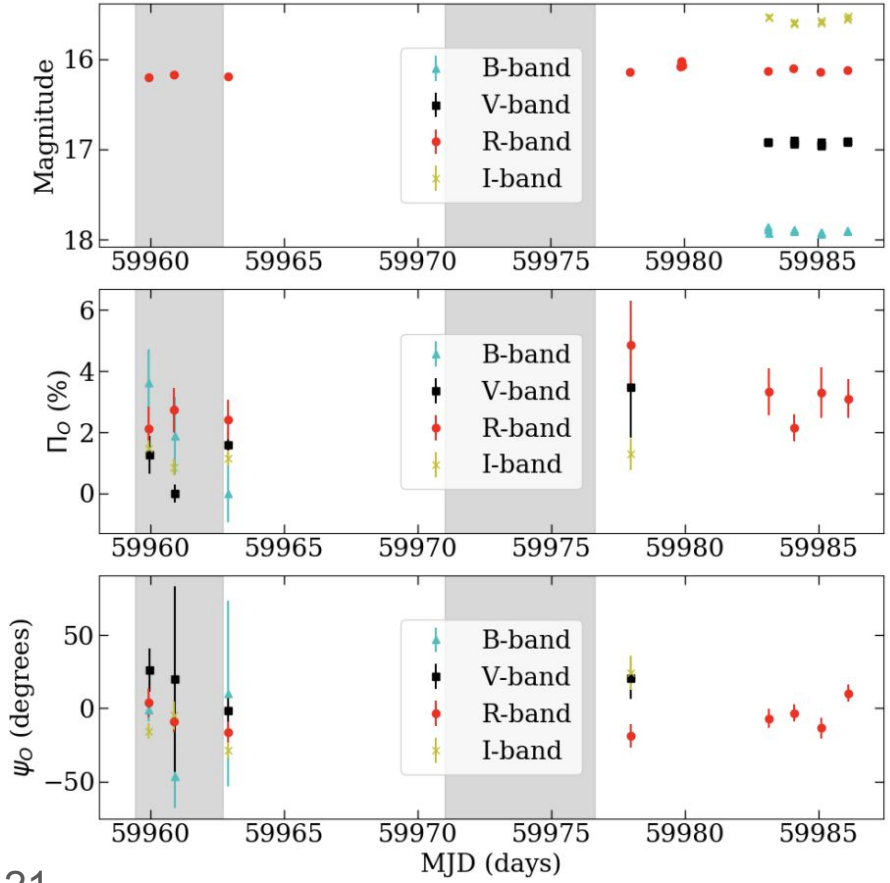
Reconnection: optical PD~X-ray PD
Turbulence: irregular PA rotation

no enhanced activity in Gev ɣ-ray

Extreme HSP: 1ES 0229+200



Ehlert+ 2023



Spectropolarimetric fitting→ PD = 17.9 ± 2.8%

Similar X-ray polarization degree to Mrk 501 and Mrk 421

Have trouble fitting the SED with single zone SSC model

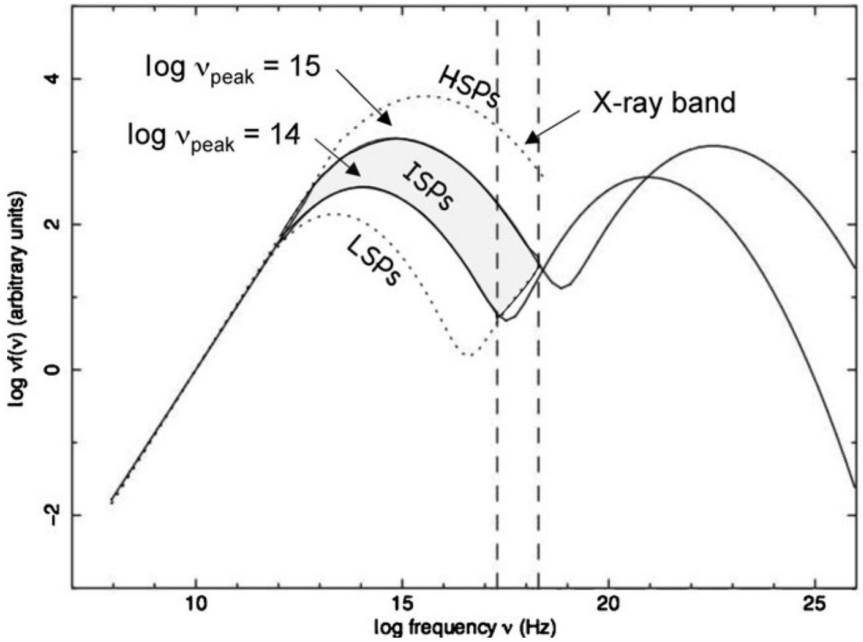
LSP and ISP

IXPE samples the rising part of the second peak

Provide us information of the origin of the second peak:

Leptonic: $\Pi_{SSC}/\Pi_{Sy} \approx 0.3$

Hadronic: PD similar to the first peak



Abdo+ 2010

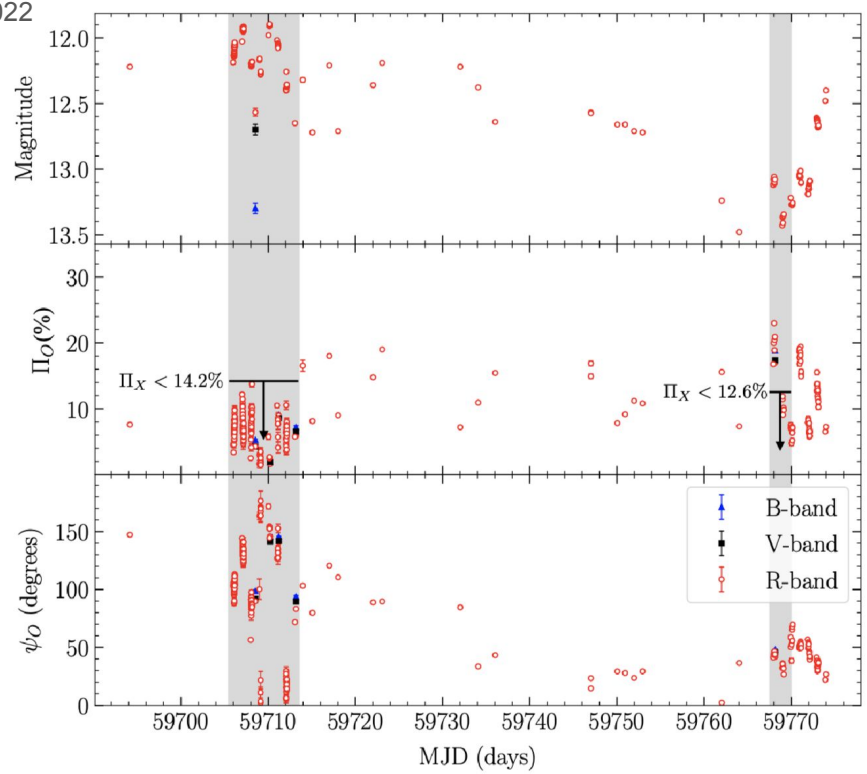
LSP: BI Lac

May,2022 (390 ks); July, 2022 (116 ks)

Upper limits for observation 1 (<14.2%) and observation 2 (<12.6%). PA is not constrained

Optical polarization degree is greater than the X-ray polarization degree for observation 2 → leptonic picture?

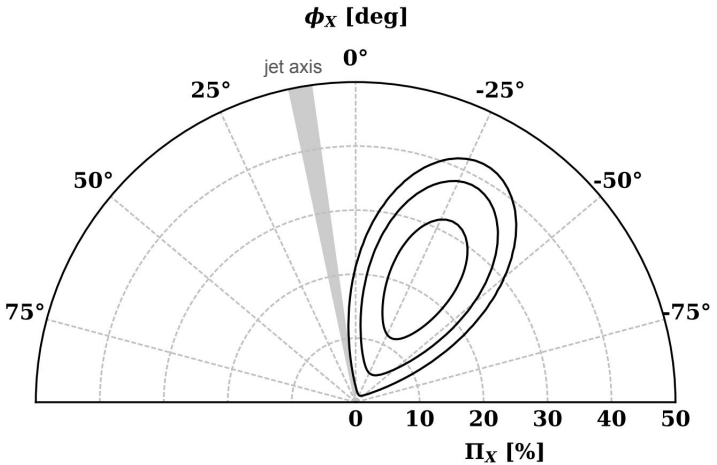
Middei+ 2022

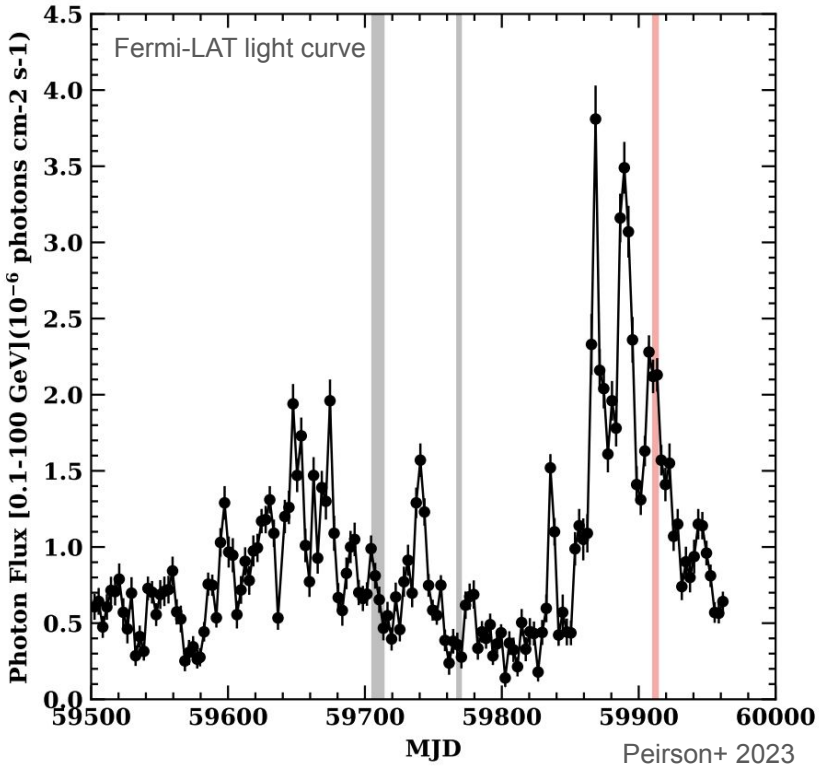


LSP/ISP: Bl Lac

Outburst in observation 3 (Nov.27-30,2022), the SED was boosted to ISP

X-ray PD: 21.7% (2-4 keV, first ~100ks), Optical: 13%





In consistent with leptonic picture, upper limit cannot rule out hadronic scenario

LSP and ISP

Marshall 2023

3C 273, 3C 279, 3C 454.3, S5 0716+714

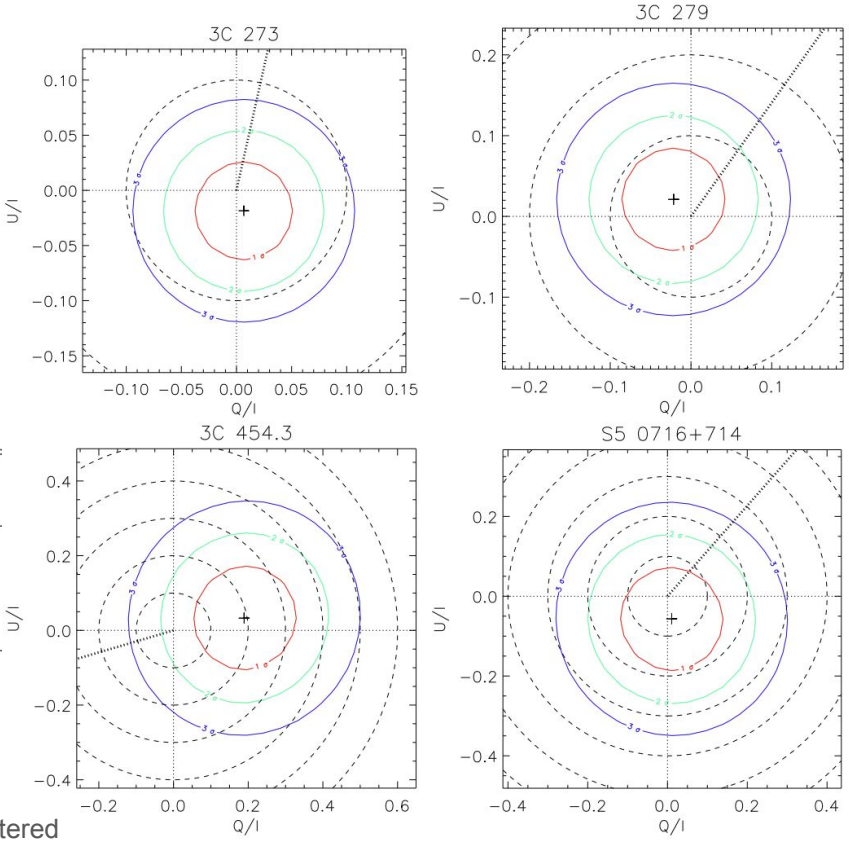
Non detection at 3σ level

Table 1. Summary of IXPE Observations

Source	Instrument	Observation ID	MJD range	Exposure (ks)[a]	Π_X[b]
3C 273	IXPE	01005901	59732.37 - 59734.45	95.28	< 9.0%
3C 279	IXPE	01005701	59743.02 - 59748.85	264.42	< 12.7%
3C 454.3	IXPE	01005401	59730.19 - 59732.34	98.12	< 28%
S5 0716+714	IXPE	01005301	59669.43 - 59674.80	358.68	< 26%

[a] Average of exposures for the three detector units.

[b] 99% confidence limits using the unbinned, event-based likelihood method (§ 2.1).

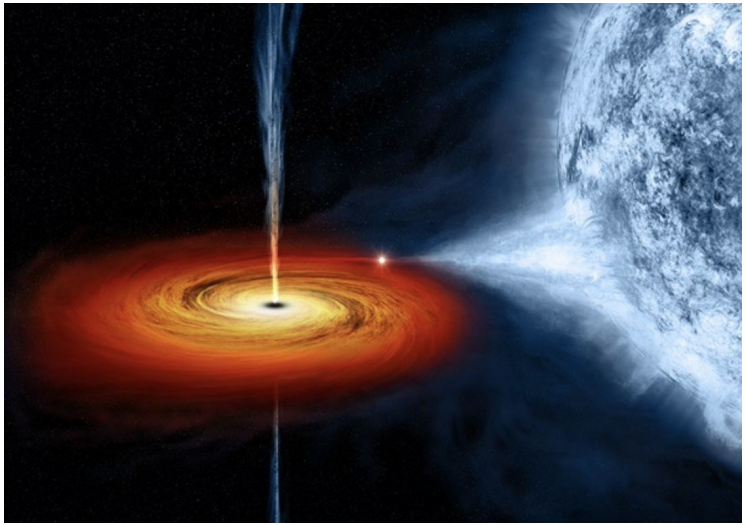


favor models where the X-ray band is dominated by unpolarized photons upscattered by relativistic electrons

hadronic models are not completely eliminated

IXPE stellar mass black hole observation

- Probes the innermost accretion flow
- Constrain the geometry (disk inclination, corona) and black hole spin



NASA, M. Weisskopf

stellar mass BH spectral states

(High) soft state:

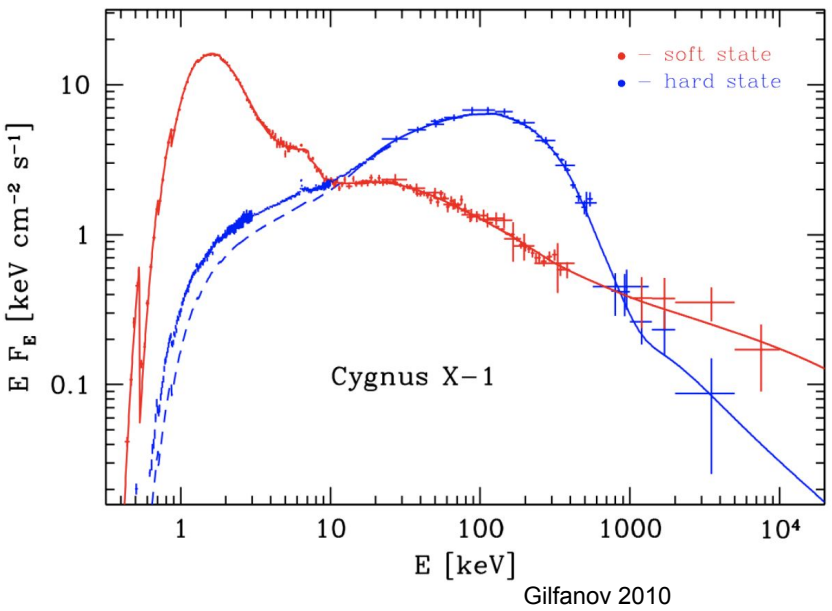
Dominated by thermal disk emission

Steep power law state:

Competing thermal and power-law emission

(Low) hard state:

Dominated by componized and reflected emission

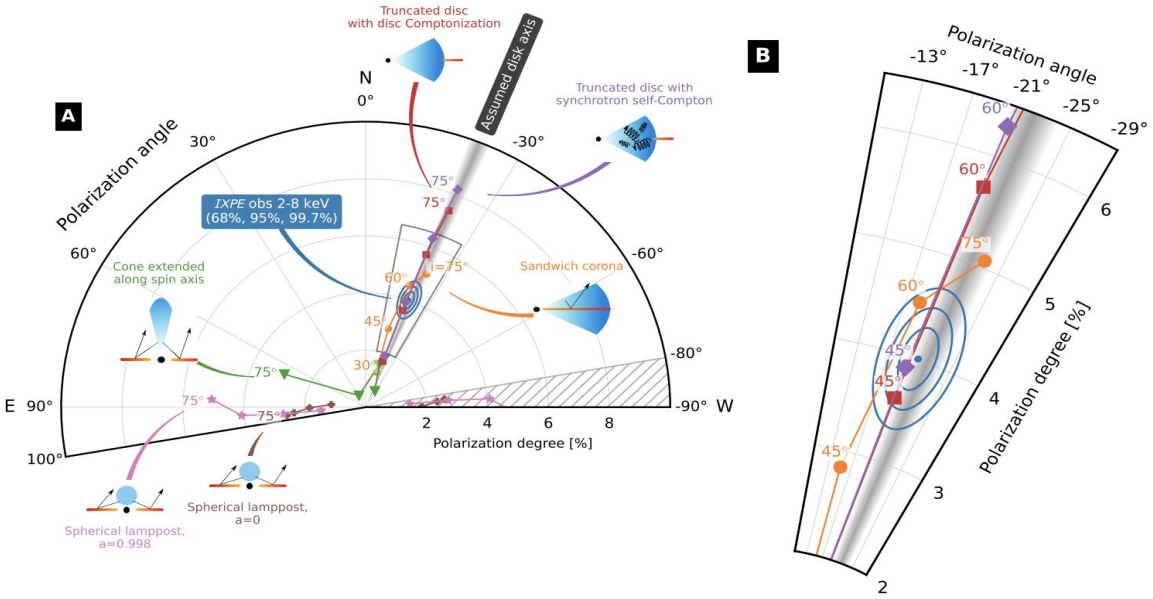


Gilfanov 2010

stellar mass BH: Cyg X-1

Hard state: PD~4% at PA~ -21 deg (Krawczynski+ 2022)

Soft state: similar polarization pattern with lower PD (2%) (Steiner+ in prep.)



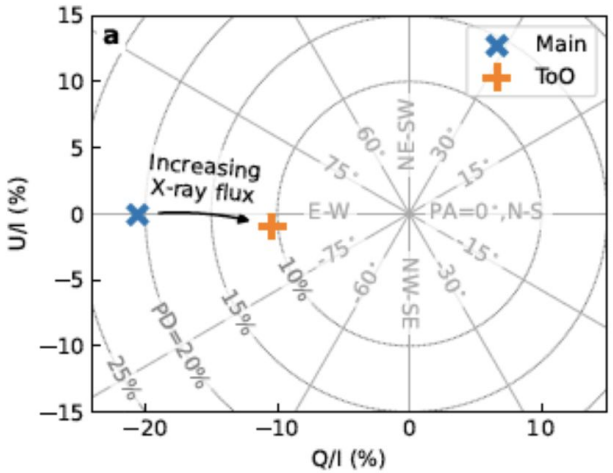
Hard state: polarization parallel to the jet, corona seems to be extended in plane of disk

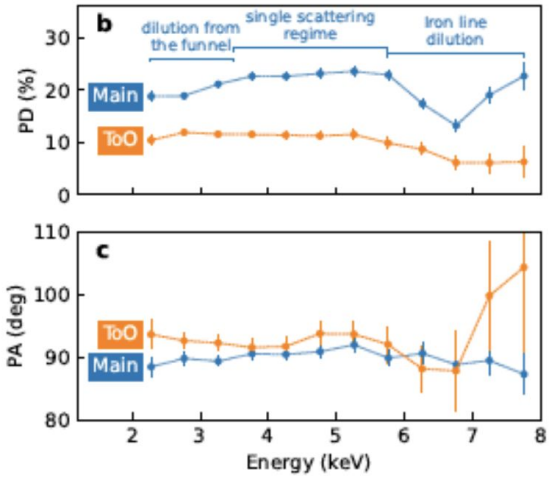
Comptonization models→inclination > 45 deg (orbital~27 deg)

Soft state: similar polarization patterns

stellar mass BH: Cyg X-3

Hard state + intermediate state : PD~20%. PD~10% (Veledina+ 2023)

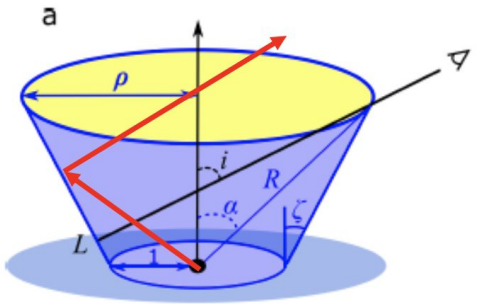




Polarization perpendicular to the jet

Obscured ultra luminous center source

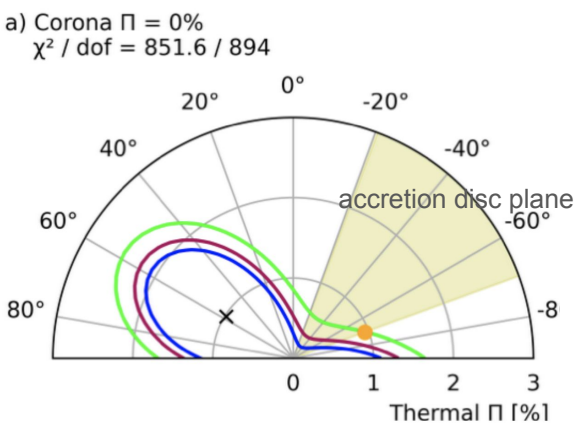
Reflection from compton thick wind

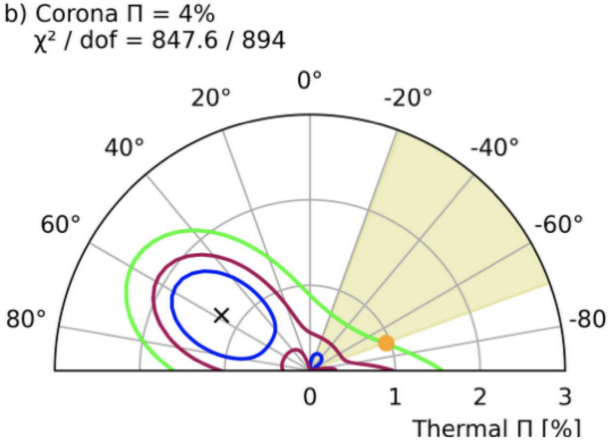


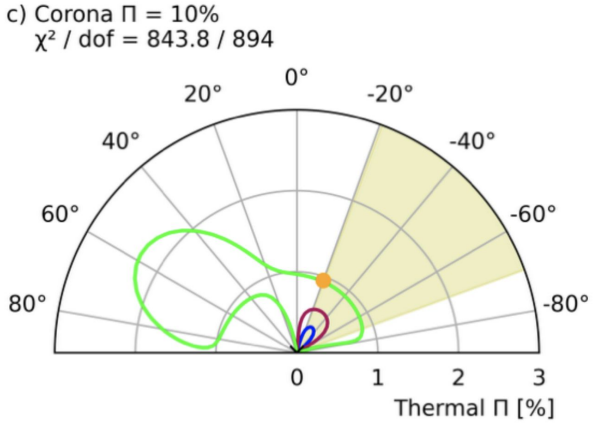
stellar mass BH: LMC X-1

Soft state: PD<2% Podgorny+ 2023

Assuming corona emission is perp to the thermal component with certain PD → upper limit of the thermal PD < 1%

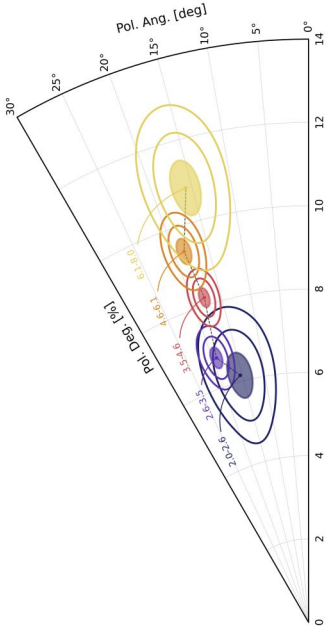


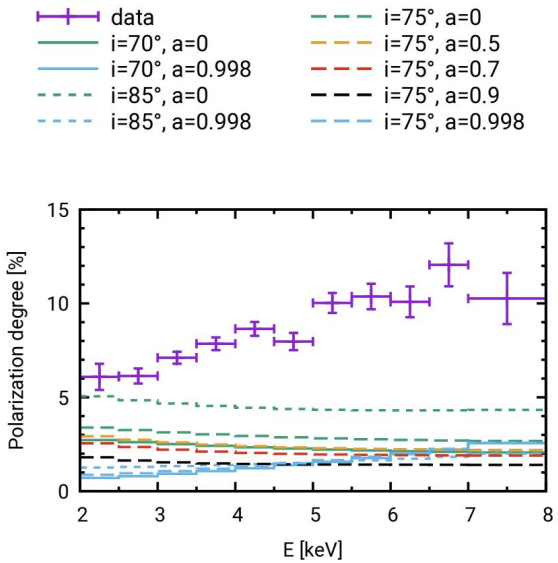




stellar mass BH: 4U 1630-47

Soft state: PD~8%, (Ratheesh+ 2023)





Soft state: very high PD~8%, increasing with energy

Vertically outflowing disc atmosphere?

Slim disk or thick disk?

Summary

Linear polarization or upper limit from blazars and stellar mass black holes have been observed by IXPE, providing insights into the field structure/geometry (cyg X-1 hard/soft states, cyg X-3)

Discrepancies between observations and theories (4U 16430-47 soft state)

More observations and detailed modelings are needed for exclusive conclusions