IXPE
Imaging
X-Ray
Polarimetry
Explorer

IXPE Science Highlights

(an incomplete and biased selection)

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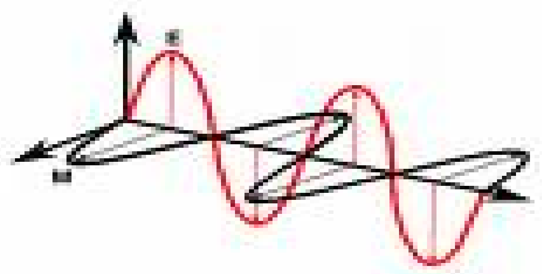
X-ray polarimetry

- Polarimetry may provide unique information - mostly on geometry of: emitting matter, magnetic field, space time, .., - not obtainable with other techniques
- The polarization degree (PD) depends on the level and type of symmetry of the system, the polarization angle (PA) indicates its orientation.
- Even if PD may depend on some uncontrolled parameters (e.g. system's inclination), PA is often equally – if no more – important
- IXPE has shown that significant polarization in X-rays is common. Often results have exceeded expectations. Do not be (too much) restrained by theoretical predictions!
- Upper limits may convey important scientific information



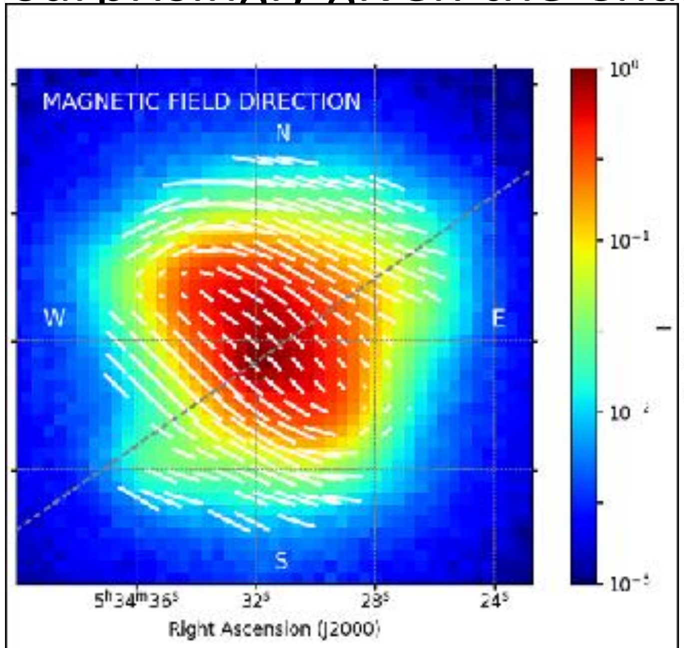
Things to consider before proposing

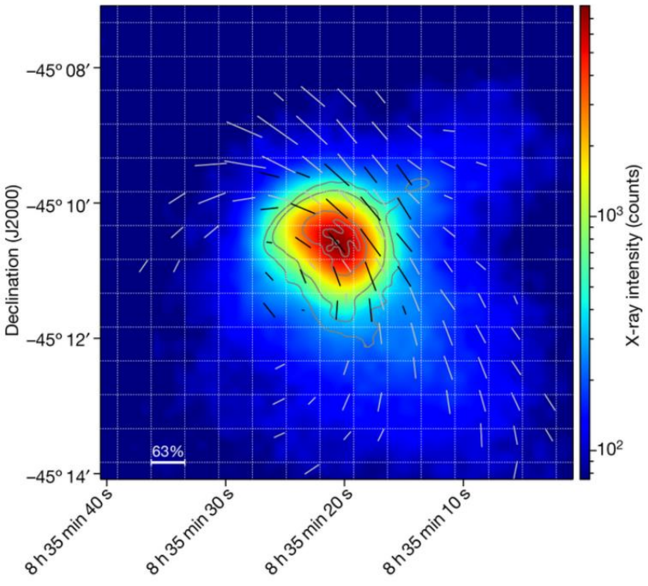
- Polarimetry requires a lot of photons → bright sources and/or long exposures
- Time, energy, spatial variations may be an issue: if PA changes, PD is reduced (need for long exposure times even for bright sources like some X-ray pulsars)
- IXPE energy band is relatively narrow. (Simultaneous) observations by other X-ray facilities may help significantly in the spectral decomposition
- Repointing time is a few days. Not good for fast transients. But good enough for many other classes of variable/transient sources, as amply demonstrated by several very important results on e.g. accreting BHs and NSs in outburst.

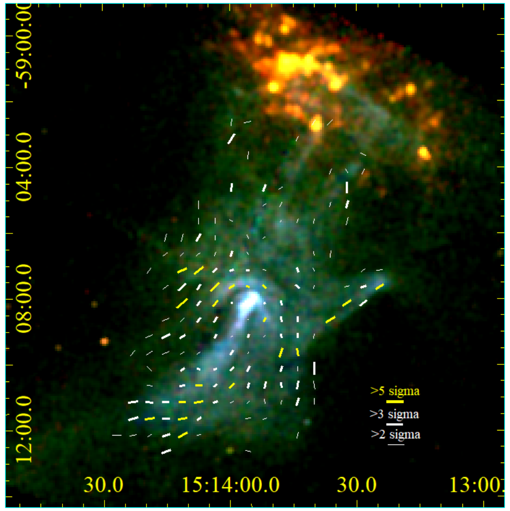
Pulsar Wind Nebulae

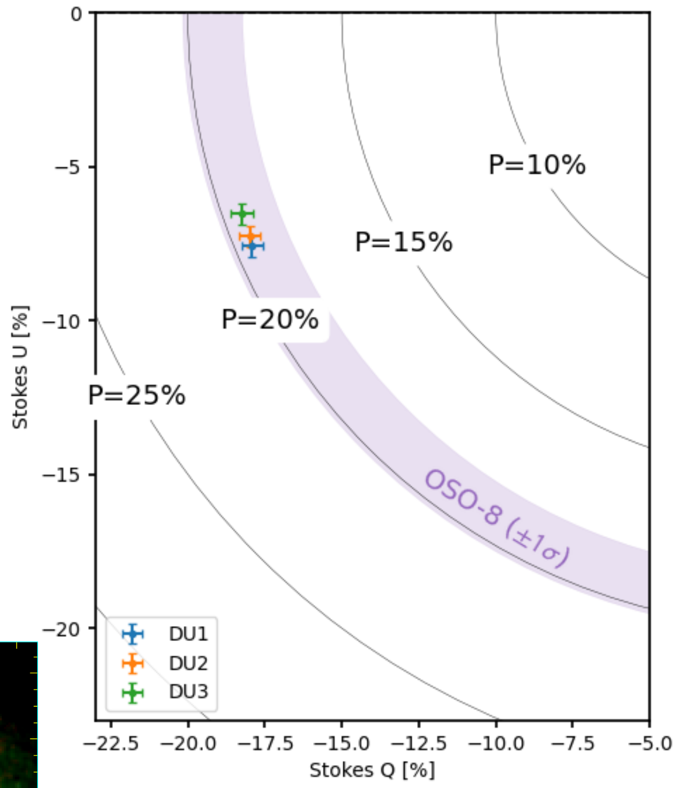
IXPE observations of PWN (Crab, Vela) confirmed they are highly polarized (very high in certain regions, PD>50%, close to the synchrotron limit) *(Bucciantini et al. 2022, Xei et al. 2022, Romani et al. 2023).*

Crab result consistent with OS0-8, when integrated over the entire nebula. However, polarization map shows a complex pattern, not surprisingly given the Chandra image







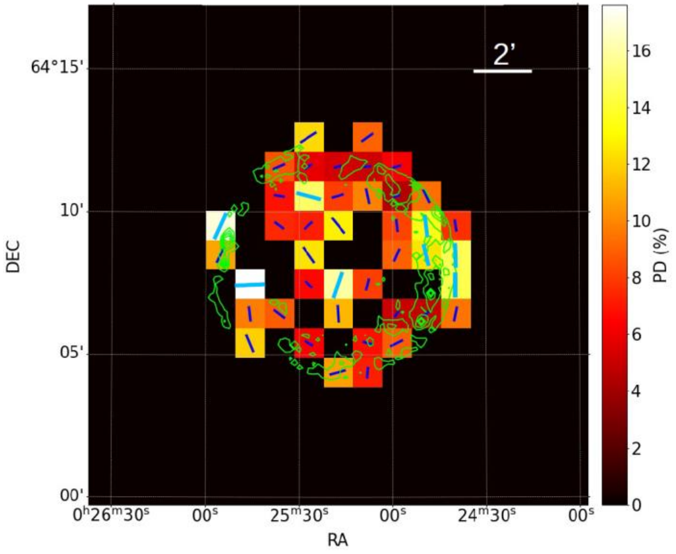


SuperNova Remnants

SNR overall less polarized than PWN (not surprisingly, as emission is mostly thermal).

Cas A *(Vink et al. 2022),* Tycho *(Ferrazzoli et al. 2023)* and SN 1006 *(Zhou et al. 2023)* all show radial magnetic fields near particle acceleration sites.

- Cas A has PD = (4.5±1.0)% near forward shock.
- Tycho has PD = (12±2)% in rim. Tycho has factor 2 variations, (23±4)% in the west.
- SN 1006 has an average synchrotron PD = (22±4)%



Different level of turbulence! Why?

The magnetic field is, however, tangential in the NW rims of the older remnants RX J1713.7–3946 *(Ferrazzoli et al. 2024)* and Vela Jr *(Prokhorov et al. 2025)*

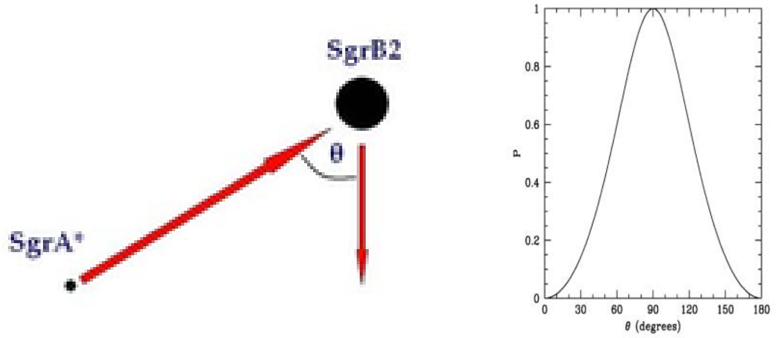
Tycho (Ferrazzoli et al. 2023)

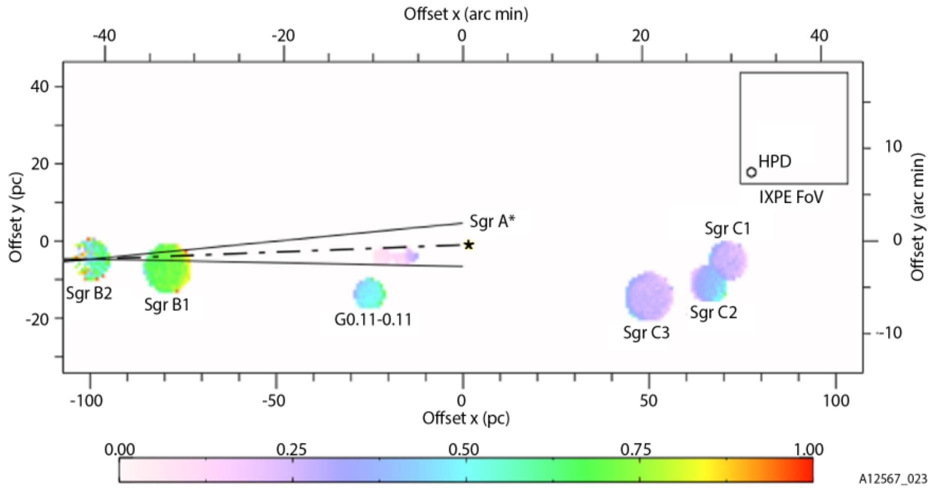
Sagittarius A*

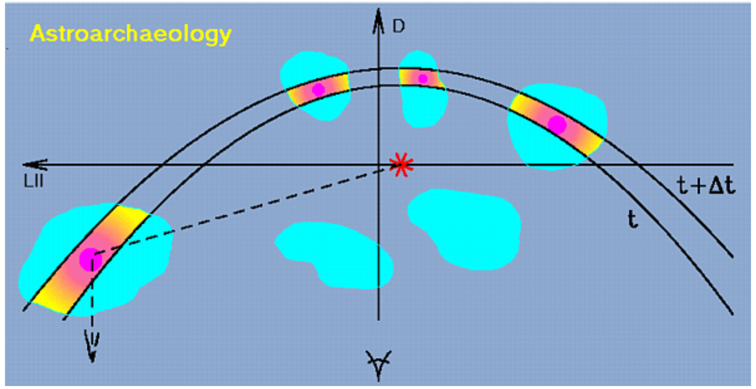
Galactic Center molecular clouds (MC) are bright X-ray sources.
Their X-ray spectra indicate reflection from external sources

Are they reflecting X-rays from Sgr A* ?
If so, Sgr A* X-ray luminosity was 10^6 larger a few hundred years ago

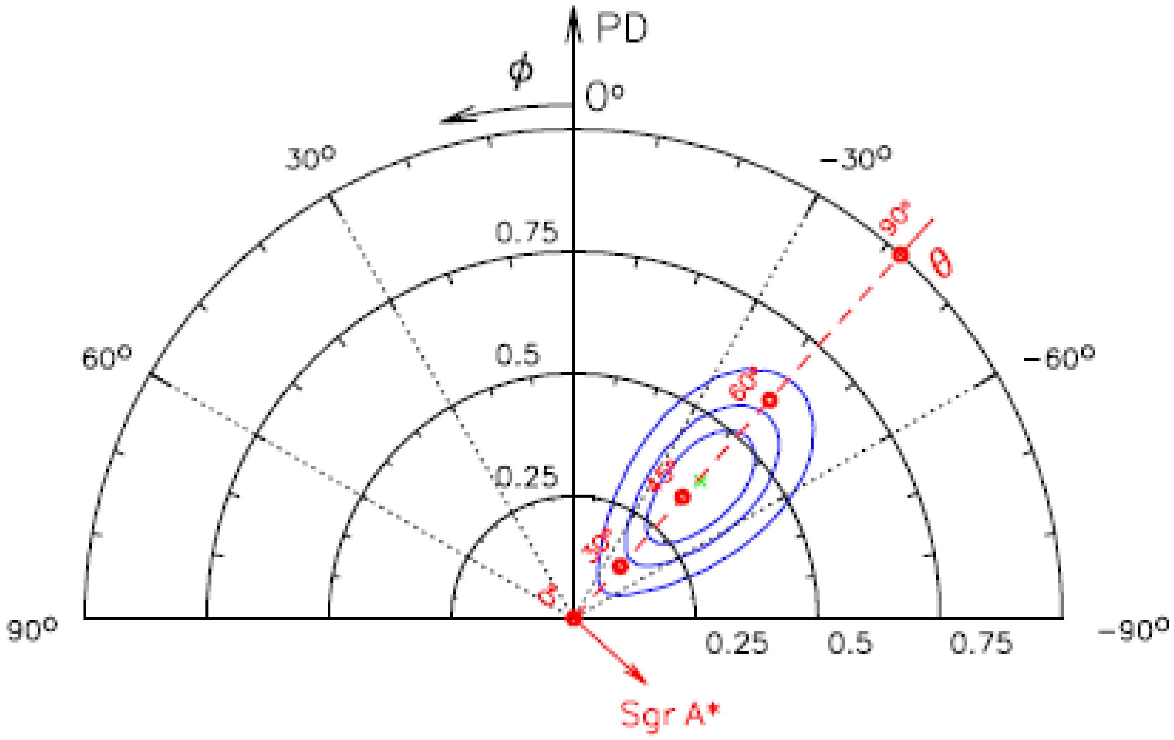
In this case, X-rays should be *highly polarized* perpendicular to plane of reflection and indicates the direction back to Sgr A*







Sagittarius A*

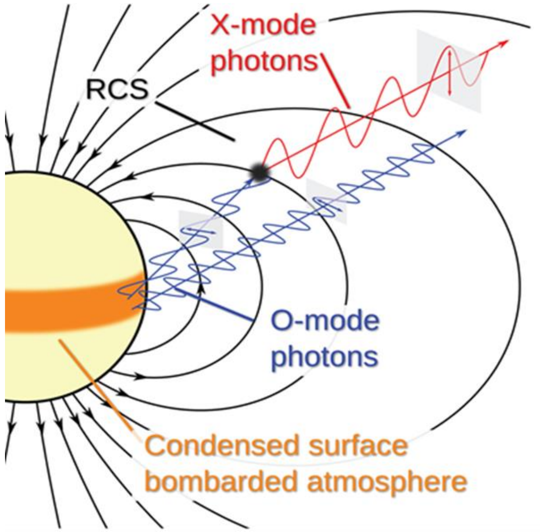


2.7σ result. Polarization angle consistent with Sgr A* as the origin of the illuminating radiation *(Marin et al. 2023).* A second observation confirmed the result with a ~4σ confidence level (plus further complications: multiple flares, multiple sources? *Khabibullin et al. 2026*)

From the polarization degree, two solutions for the age of the burst: ~30 or ~200 years ago. Second solution much more probable.

Magnetars

Taverna et al. 2022



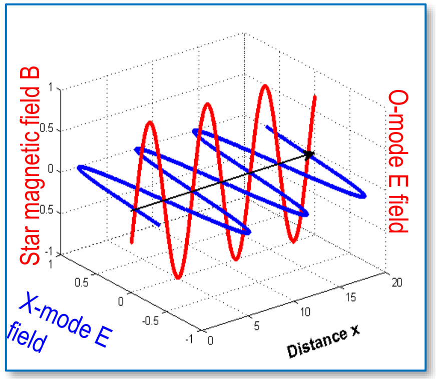
- **Anomalous X-ray Pulsars and Soft-gamma ray repeaters**
  - $B_{sd} \approx 10^{14} - 10^{15}$ G
  - $L_{X,\text{persist}} \approx 10^{33} - 10^{35}$ erg s^{-1} (typically $< \dot{E}_{\text{rot}}$)
  - Bursting activity (short bursts – intermediate/giant flares)
  - (At least) two components (thermal and PL) spectra

  - **Powered by their own magnetic energy**

Two modes, with very different opacities

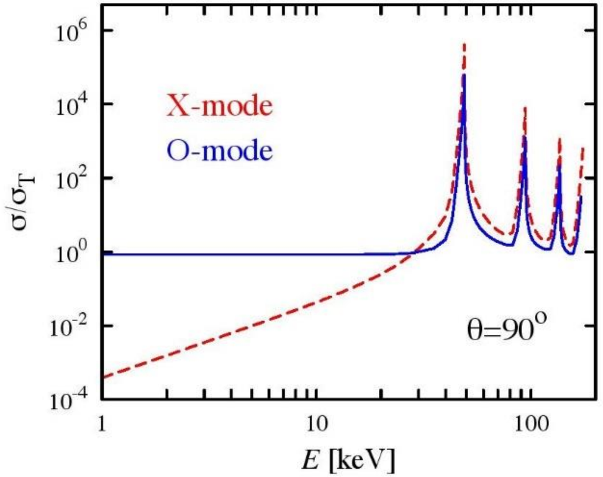
- Ordinary mode: E field parallel to the k-B plane
- Extraordinary mode: E field perpendicular to the k-B plane

The X-mode from deeper, hotter layers



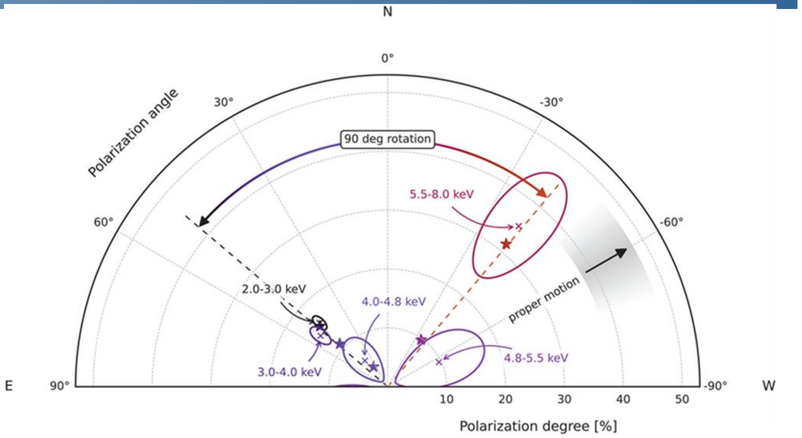
O-mode:

X-mode:

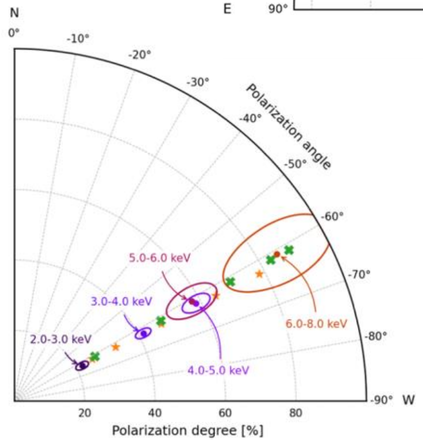


Magnetars

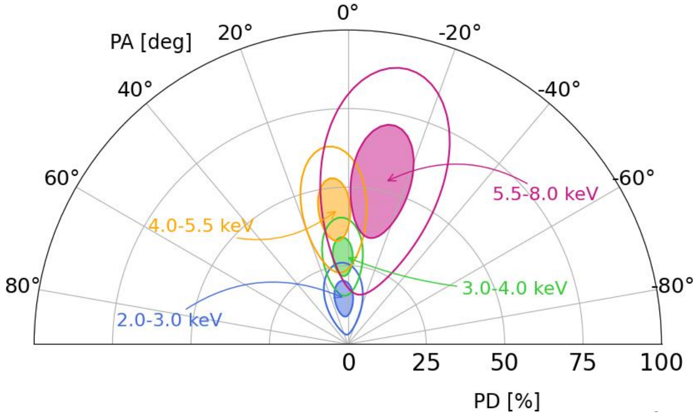
4U0142+61 shows PA swing of 90° (top) *(Taverna et al. 2022).* Two different modes dominate in the two components (Thermal + Resonant Compton Scattering). Low polarization indicates a condensed surface.



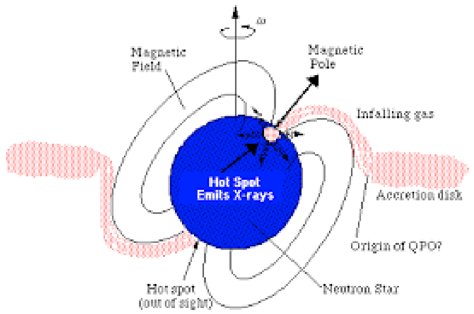
1RXS J170849.0-400910 has constant PA *(Zane et al. 2023).* The same mode is dominating in the two spectral components (both thermal). Pulse-phase-resolved data indicate condensed surface, plus a hotter cup covered by a gaseous atmosphere.



1E 1841-045 has also a constant PA *(Rigoselli et al. 2025, Younes et al. 2025).* Spectropolarimetrc analysis suggests a soft thermal component (PD≈25%), an intermediate resonant Compton scattering (PD≈30%) and a hard tail with PD≈65%, probably of Synchrotron origin

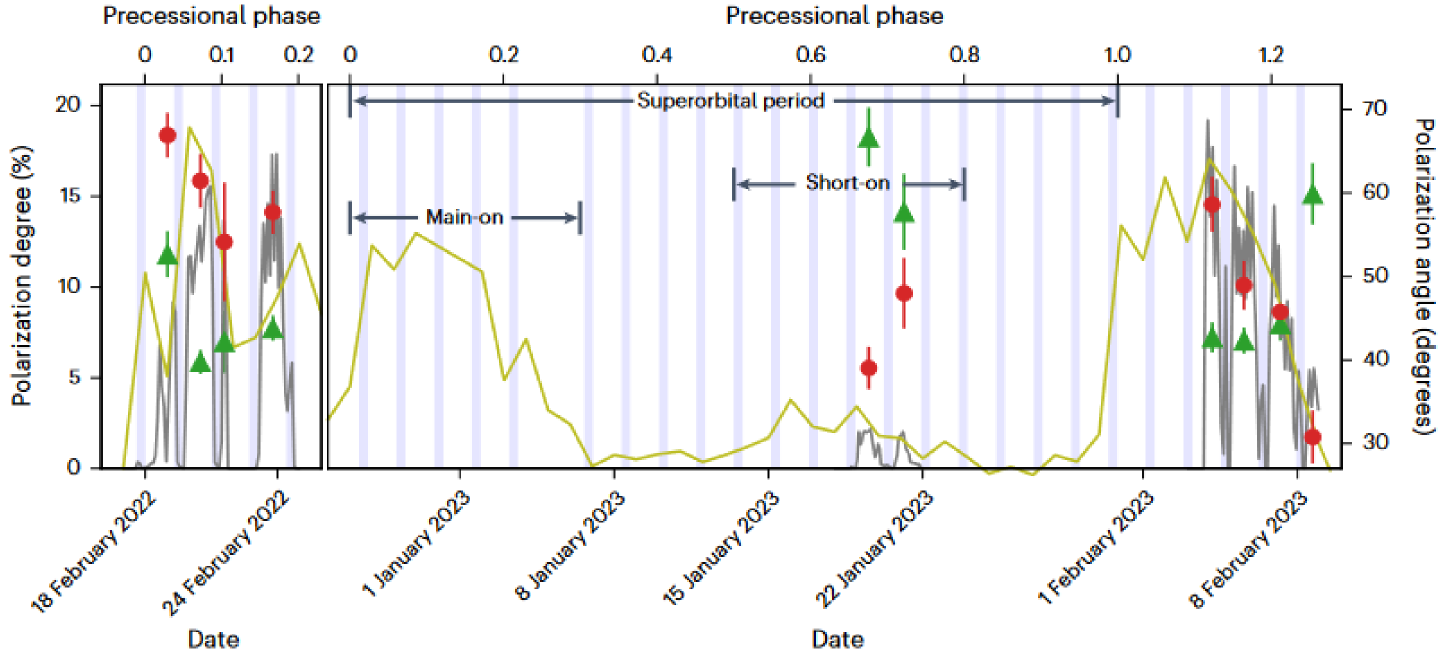


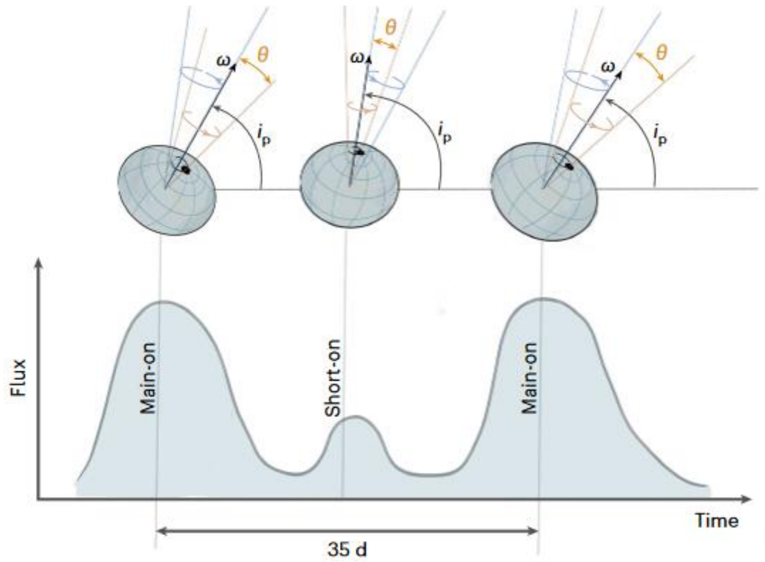
Accreting NS – X-ray Pulsars



Phase dependent polarization observed in many X-ray pulsars, even if with polarization degrees less than predicted by old (probably too simple) models. Important geometrical parameters can be inferred.

In Her X-1, a 35d superorbital period is observed, explained as a precession of either the neutron star or the accretion disc. IXPE results suggest that the crust of the neutron star is indeed precessing, probably exciting the precession and warping of the disc (Heyl et al. 2024)



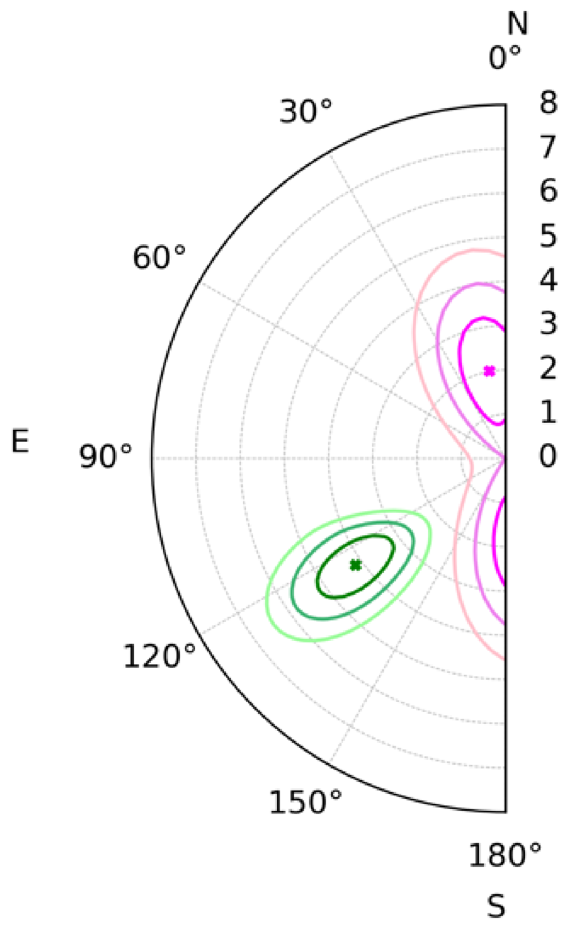


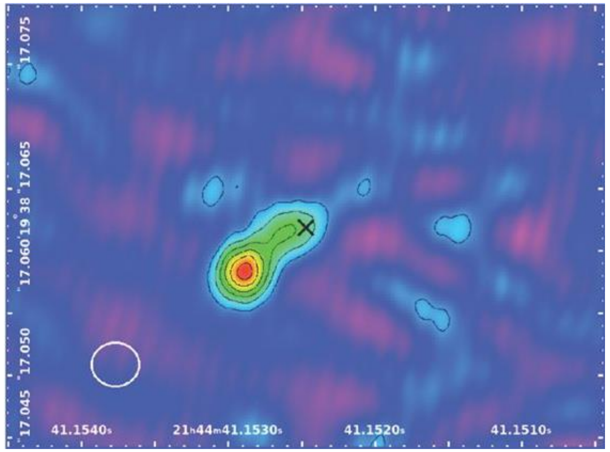
Weakly Magnetized Accreting NS

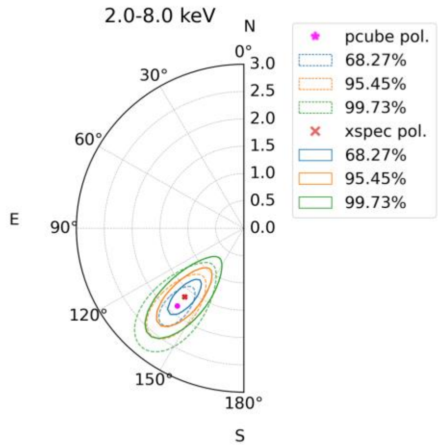
Non-pulsating accreting NS were expected to have low polarization.

Surprisingly, many of them show significant (and sometimes large) polarization, often increasing with energy, and depending on the observed branch in the color-color diagram.

Many sources observed, population studies.







Cyg X-2 (Farinelli et al. 2023)

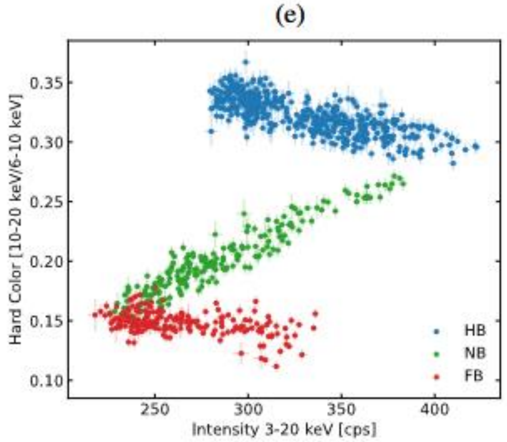
Weakly Magnetized Accreting NS

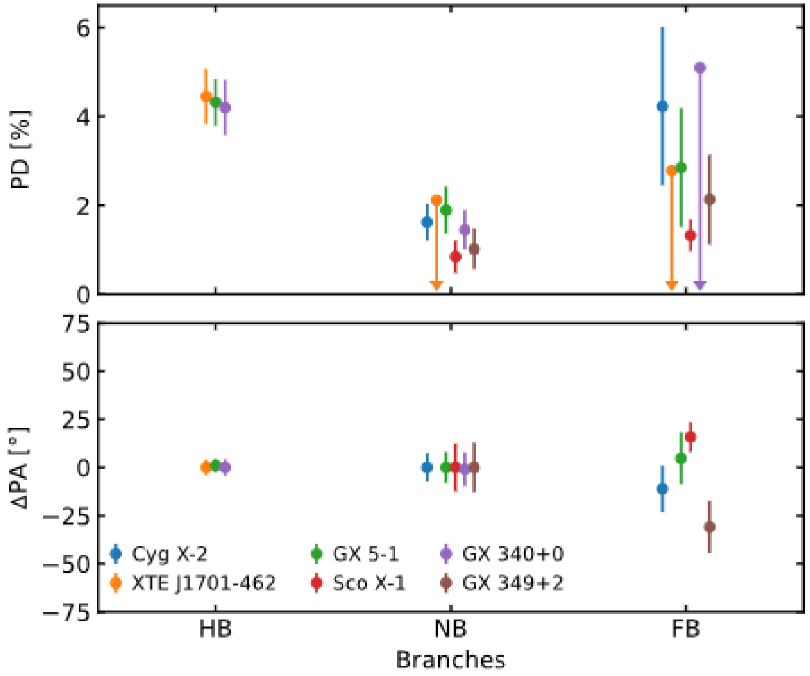
In Z-sources, PD is higher in HB.

Polarization mostly from Comptonization, but reflection likely plays an important role

In some sources rotation of PA with energy and/or time → breaking of axial symmetry!

Extreme polarization during eclipses (up to ≈30% in the serendipitous source AX J1745.6-2901, *Mikusincova et al. 2026*). Wind scattering (e.g. *Nitindala et al. 2025*)?





Gnarini et al. (2025)

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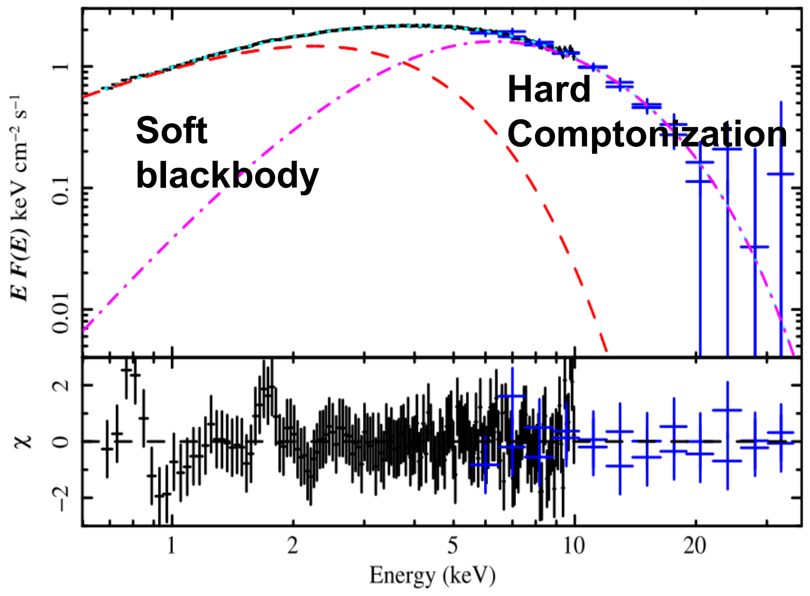
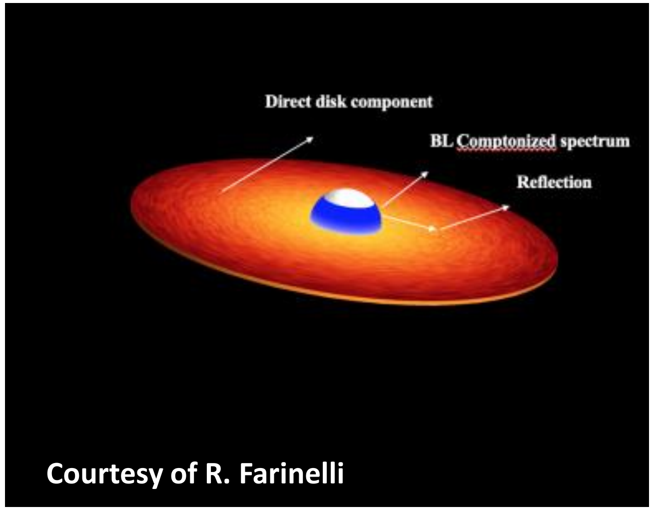


Capitanio et al. 2023



Courtesy of R. Farinelli

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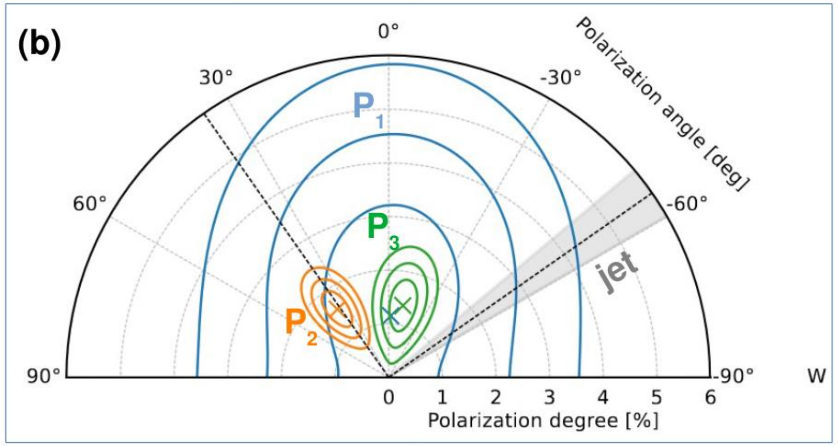
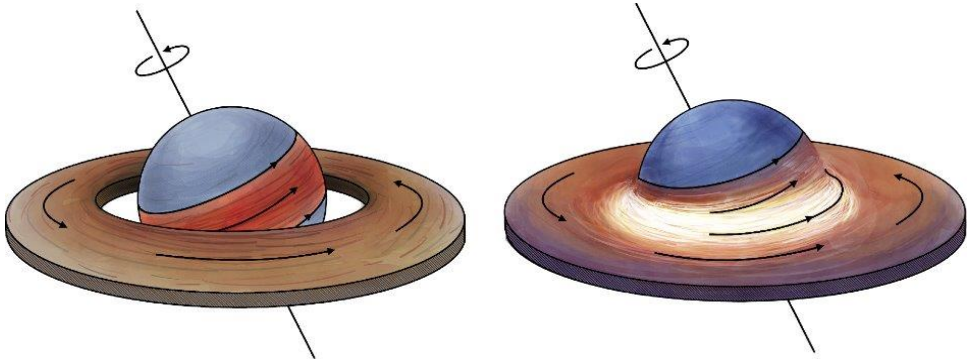




Circinus X-1 (Rankin et al. 2024)

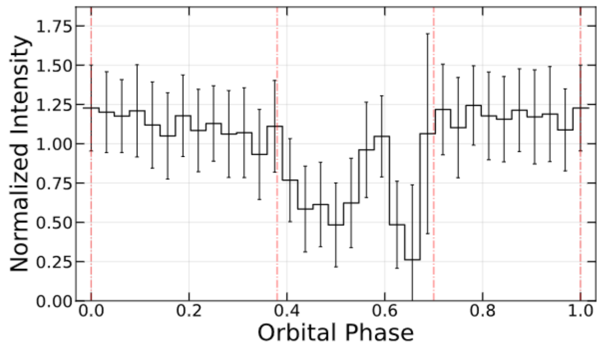
Weakly Magnetized Accreting NS

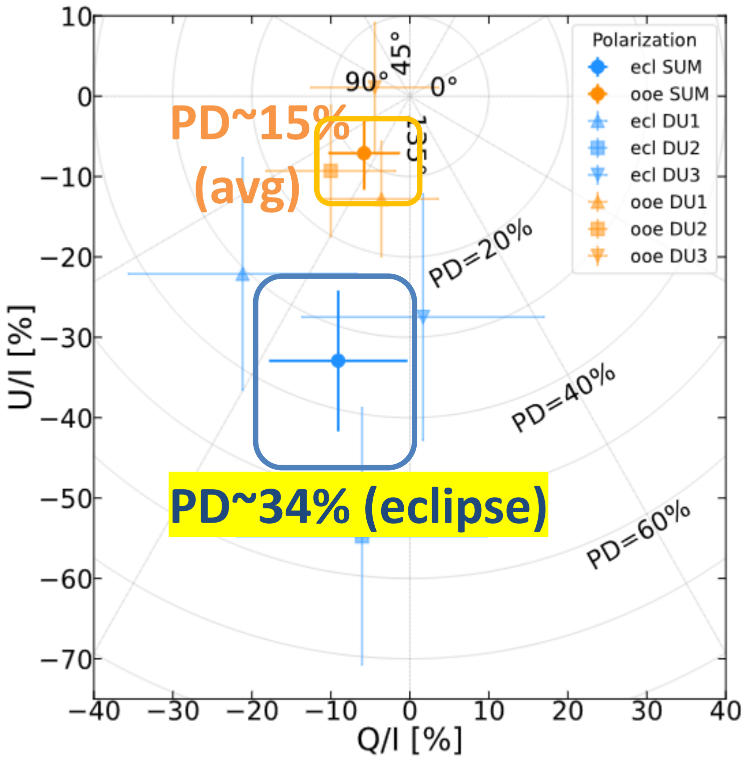
In Z-sources, PD is higher in HB.

Polarization mostly from Comptonization, but reflection likely plays an important role

In some sources rotation of PA with energy and/or time → breaking of axial symmetry!

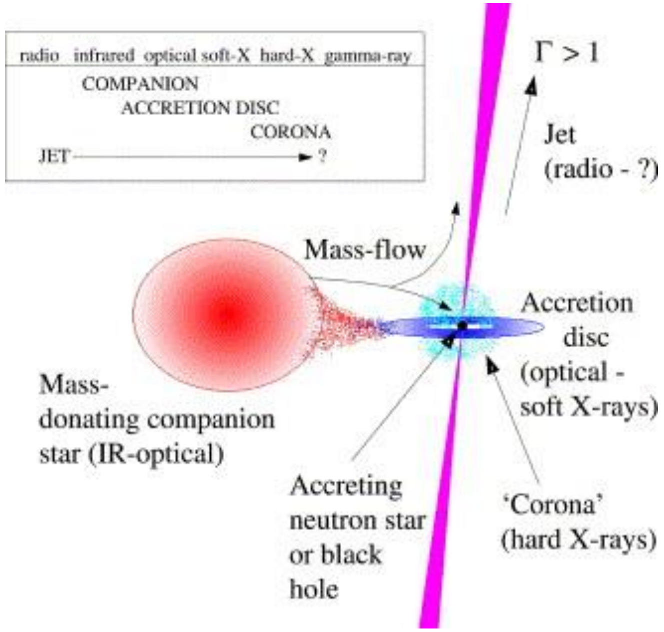
Extreme polarization during eclipses (up to ≈30% in the serendipitous source AX J1745.6-2901, *Mikusincova et al. 2026*). Wind scattering (e.g. *Nitindala et al. 2025*)?

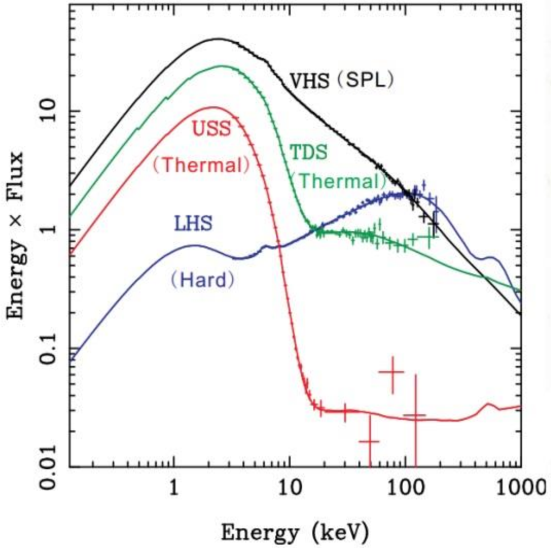


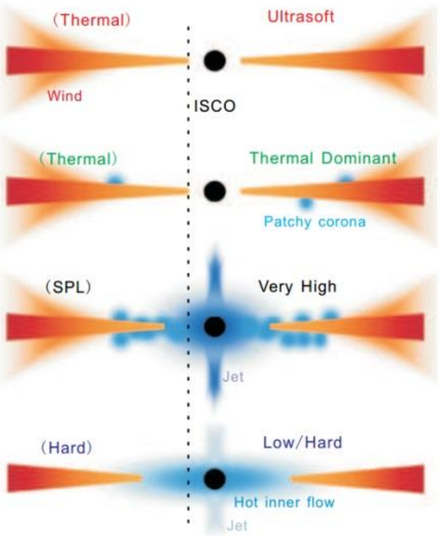


AX J1745.6-290 (Mikusincova et al. 2026)

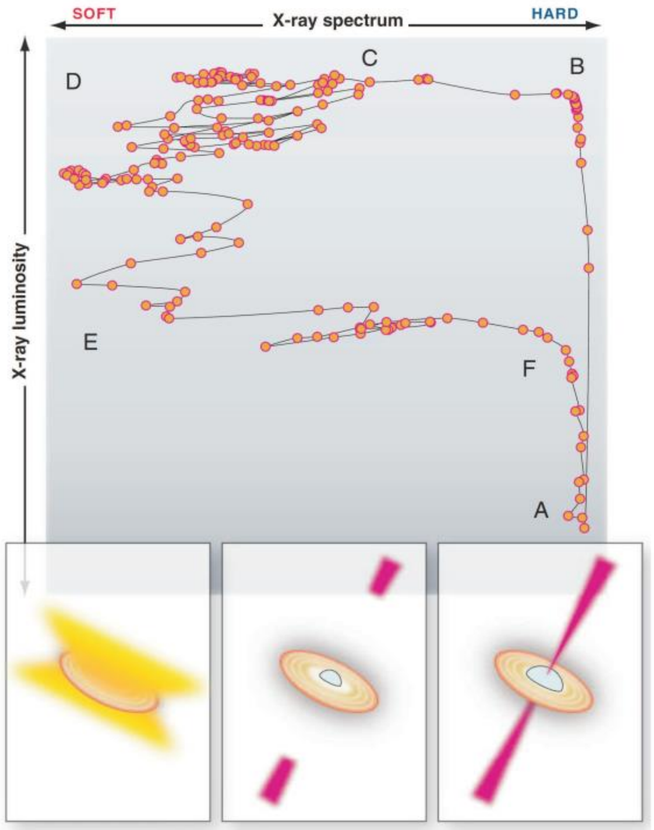
Accreting Stellar-mass BH (“microquasars”)







Done et al. 2007



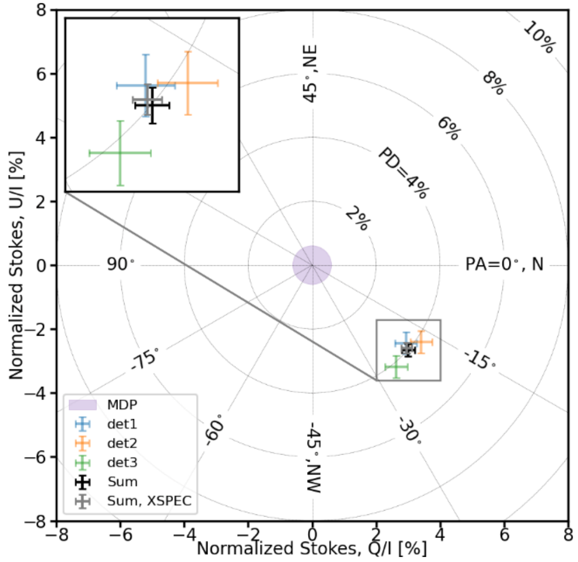
Fender & Belloni 2012

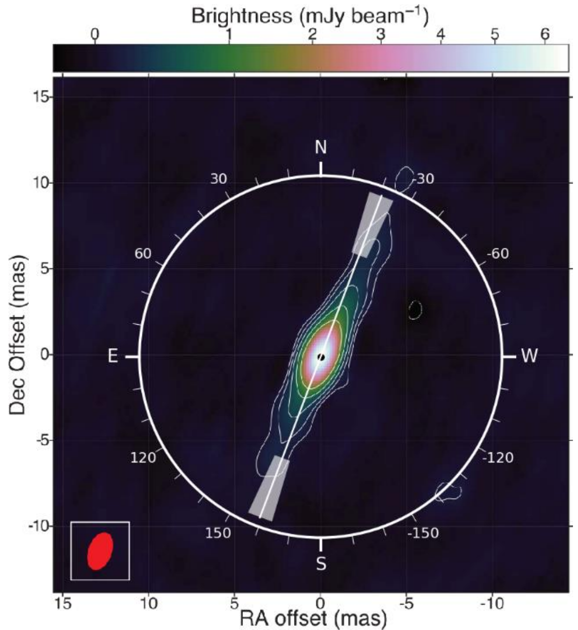
Accreting Stellar-mass BH

Several sources observed, both persistent and transient

Different states explored (sometimes in the same source). In hard state, significant polarization is usually observed (up to ≈9% in the highly inclined source IGR 17091-3624, *Ewing et al. 2025*). Polarization aligned with the radio jet, favouring radially extended coronae

In soft state, PD varies by less than 1% (LMC X-1, *Podgorny et al. 2023*) to a staggering 8-10% (4U 1630-47, *Ratheesh et al. 2024*)





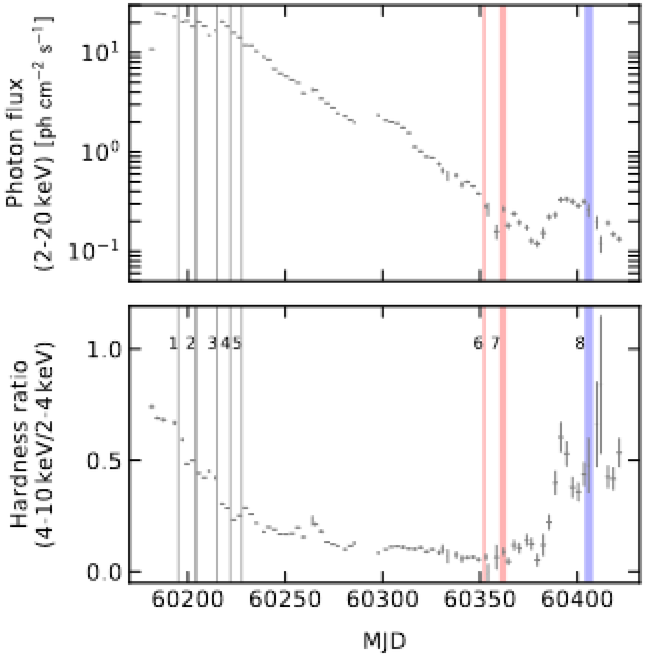
Cyg X-1 (Krawczynski et al. 2022)

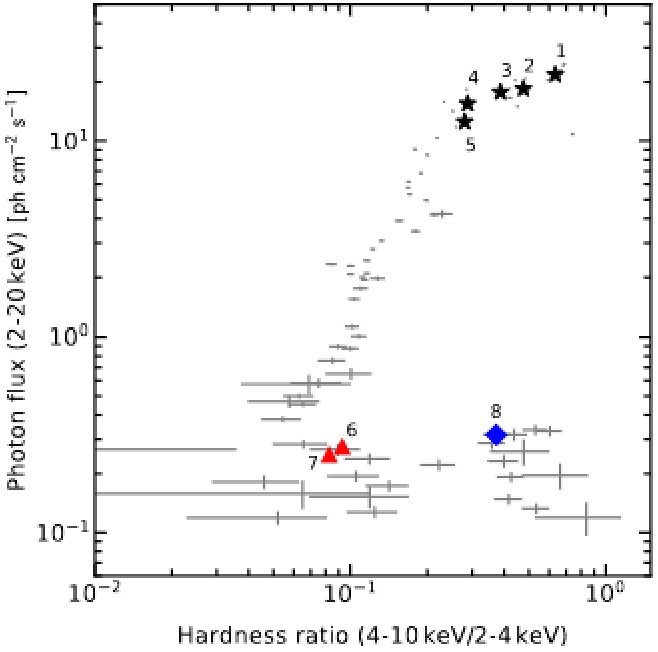
The importance of monitoring campaigns: Swift J1217.8-1613

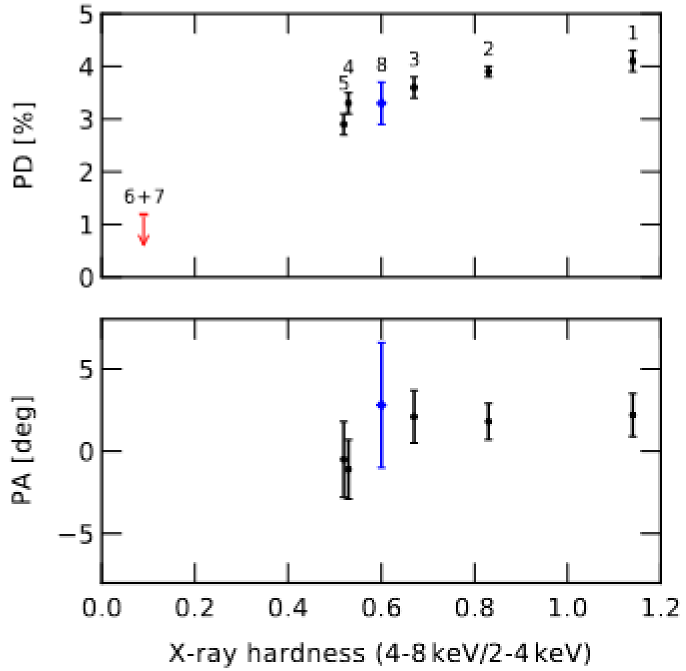
A new transient, very bright microquasar which started its outburst in August 2023

Observed in Hard and Intermediate States (September-October 2023, *Veledina et al. 2023, Ingram et al. 2024*), then becomes not visible by IXPE for a few months, and observed again In February-April 2024 in Soft State first (*Svoboda et al. 2024*), than back to Hard State (*Podgorný et al. 2024*)

Very similar to Cyg X-1 in hard state, very low polarization in soft state, same polarization when back to the hard state despite being two orders of magnitude fainter

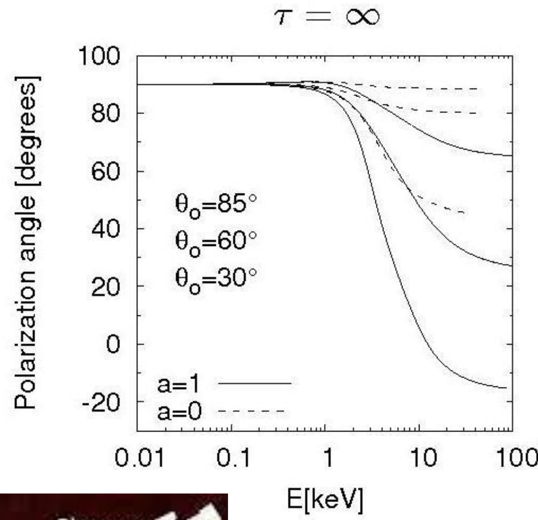






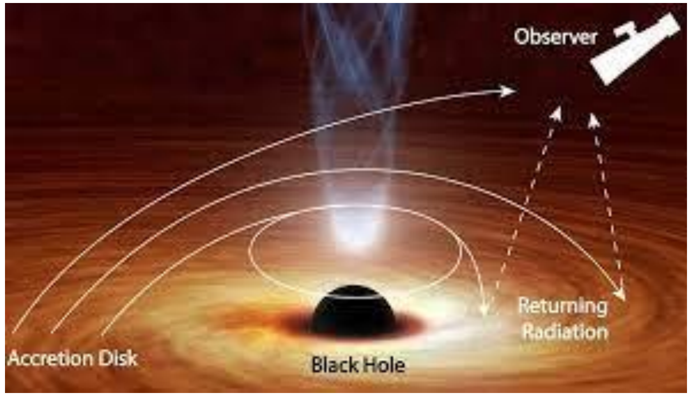
(Podgorný et al. 2024)

Black hole spin



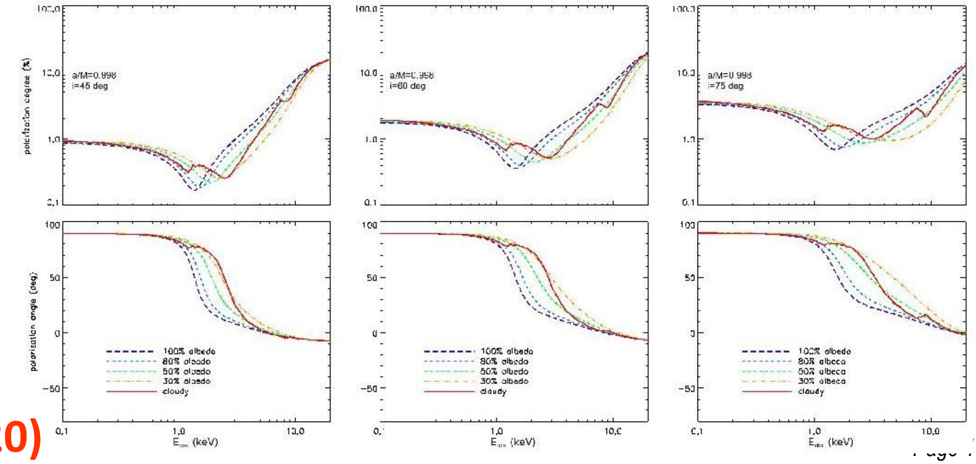
One of the main goal of IXPE is the measurement of BH spin via PA rotation with energy.

But these calculations do not include the "returning radiation" (*Cunningham 1976*), i.e. disc photons which illuminate the disc itself. *Schnittman & Krolik (2009)* included this effect in their calculations, assuming a perfect disc reflectivity (100% albedo, i.e. no absorption). *Taverna et al. (2020)* re-calculated the effect with a more realistic albedo.



The effect strongly increases with spin (because ISCO gets closer to the BH horizon)!

→ Energy dependent polarization



Taverna et al. (2020)

Black hole spin

By combining X-ray polarimetry and broad band spectroscopy:

LMC X-3: P ≈3%

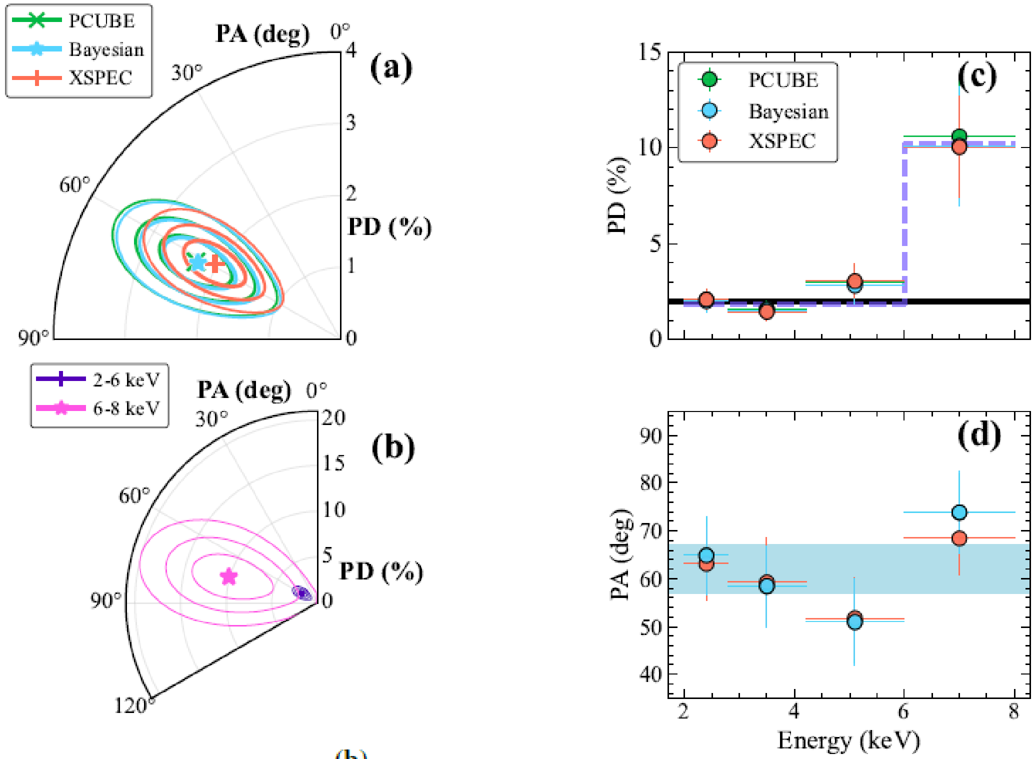
Low BH spin (*Svoboda et al. 2023, Majmuder et al. 2024*)

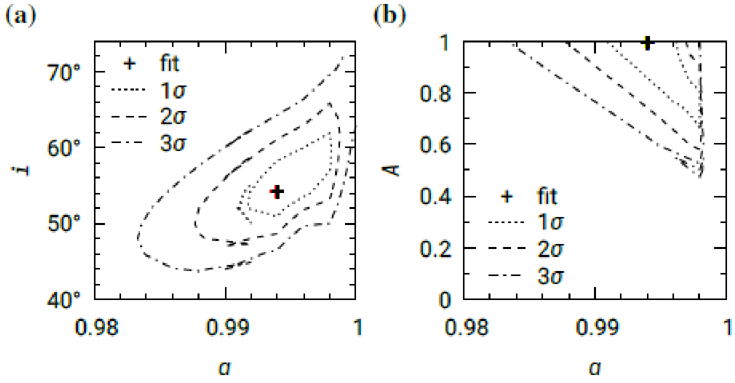
4U 1957+115: P ≈2%

High BH spin (*Marra et al. 2024, Kushwawa et al. 2024*)

GRS 1739-278: P ≈2.3%

High BH spin (*Zhao et al. 2025)*





GRS 1739-278 (Zhao et al. 2025)

Radio Quiet AGN

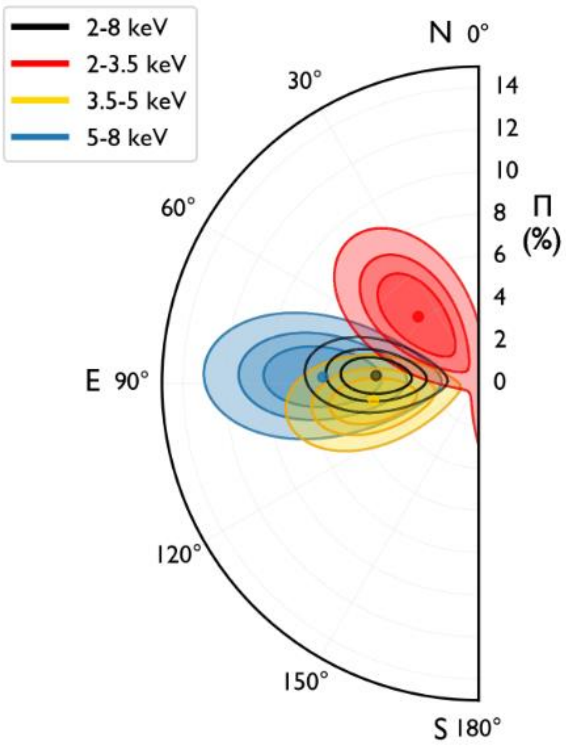
X-ray emission due to Comptonization in a hot corona (similar to accreting stellar mass BHs in hard state).

Positive detection in NGC 4151 (*Gianolli et al. 2023*). 2-8 keV PD=4.9±1.1%, aligned with the radio jet. Coronal polarization in between 4 to 8%, depending on the (poorly constrained) polarization of the reflection component. Radially extended corona (as for accreting stellar-mass BHs in hard state).

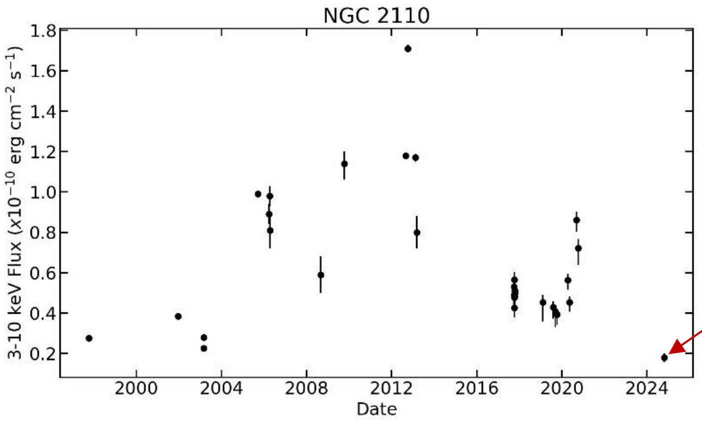
A marginal (2.97σ) detection (PD=3.3%) for IC4329A (*Ingram et al. 2023*), only an upper limit (PD<3.2%) for MCG-5-23-16 (PD <2.5%, *Marin et al. 2026*).

NGC 2110 was caught in a very low flux state, unfortunately (*Chakraborty et al. 2025, Pal et al. 2025)*

Other sources (NGC 3227, Ark 564, MCG-6-30-15) recently observed (or to be observed soon)



NGC 4151 (Gianolli et al. 2023)



NGC 2110 (Chraborty et al. 2023)

IXPE

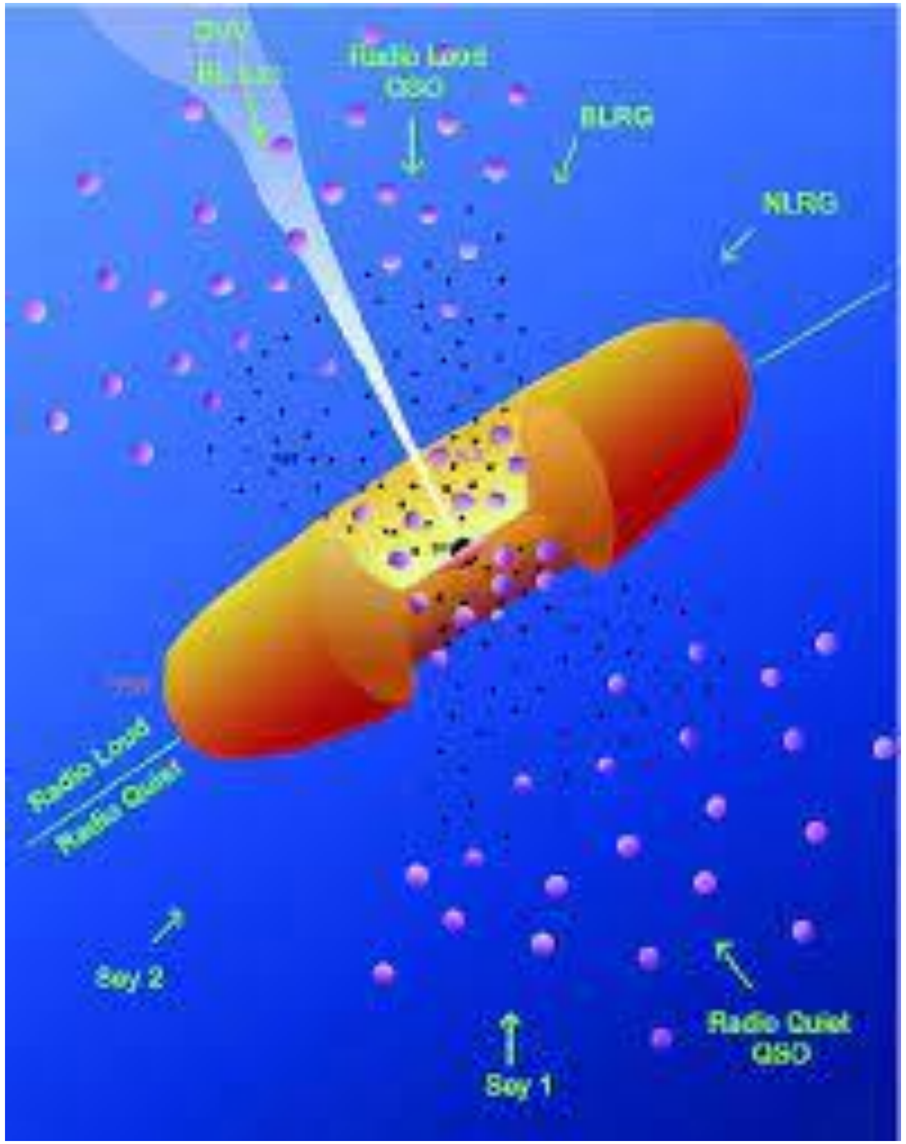
Compton-thick AGN

X-ray emission is dominated by reflection, so it should be highly polarized.

Polarization degree from the torus depends on the geometry of the system (inclination angle, torus opening angle)

High polarization (PD≈20-30%) detected in both the Circinus Galaxy and NGC 1068, the two brightest Compton-thick Seyfert galaxies. The polarization angle is perpendicular to the radio jet/ionization cone

Polarimetric results fully consistent with reflection from a Compton-thick torus, as expected



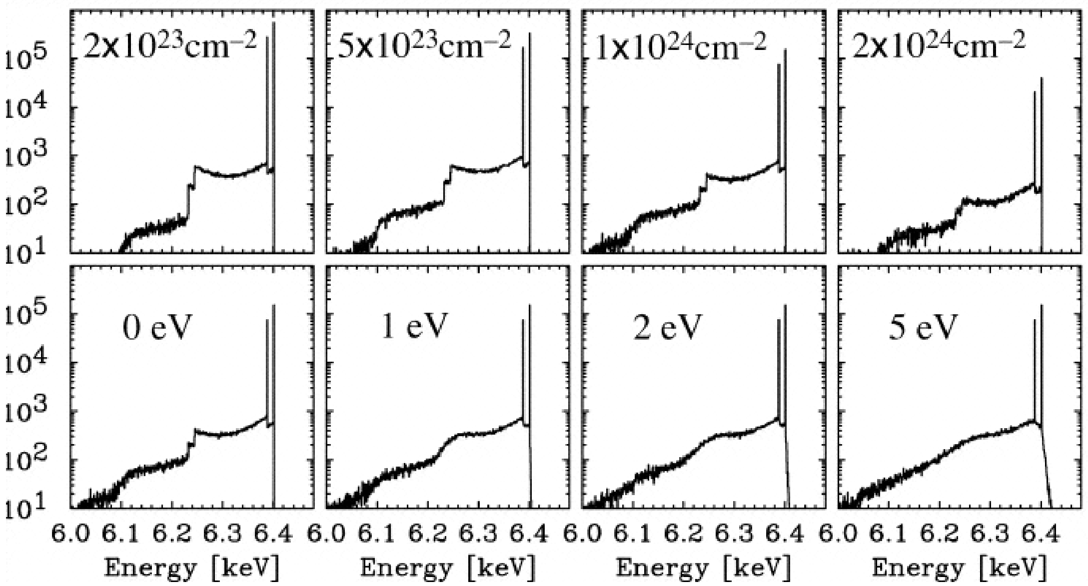
NGC 1068: synergy with XRISM

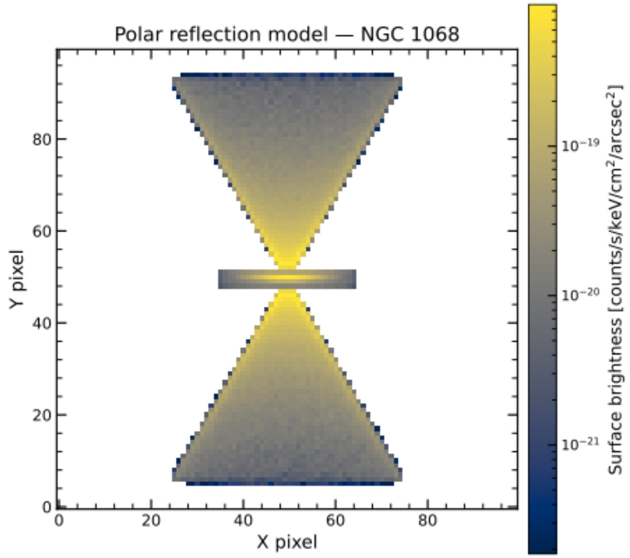
BUT

XRISM observation of the ratio between the Compton shoulder and the core of the iron line in NGC 1068 indicates that the bulk of the reflection is from Compton-thin matter (*Bianchi et al. 2026*).

But reflection from Compton-thin torus produces *parallel* polarization (SKIRT simulations, *Vander Meulen et al. 2024*).

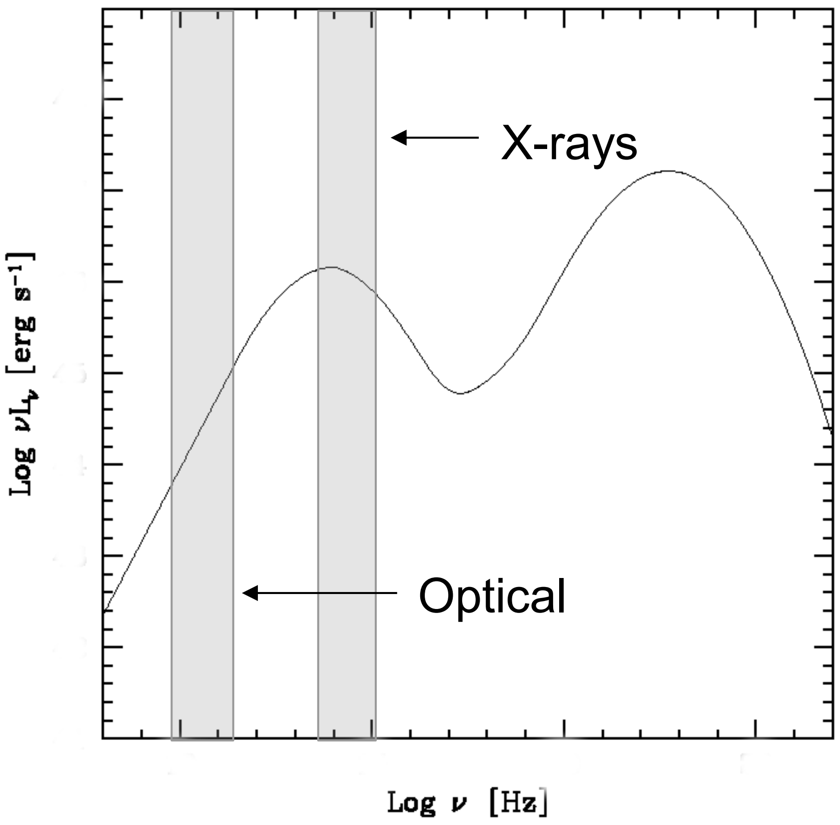
A geometry like this one? (*Vander Meulen et al., in prep.)*



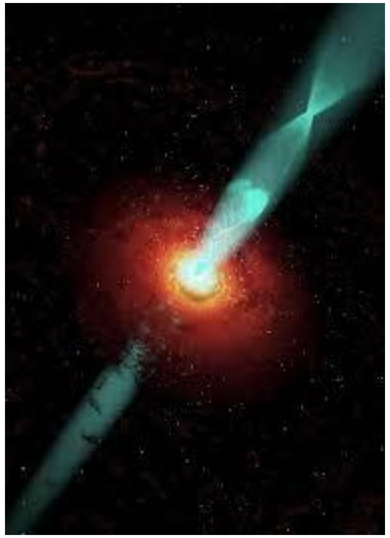


Blazars

High Synchrotron Peaked

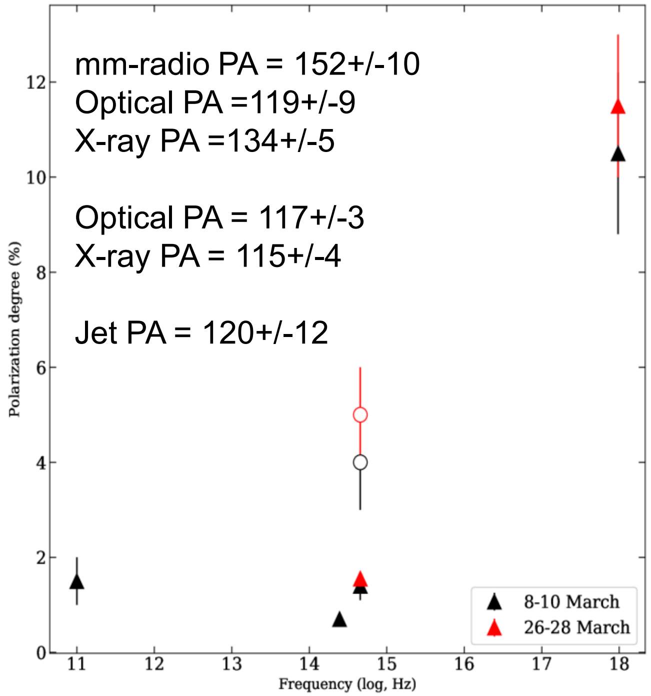


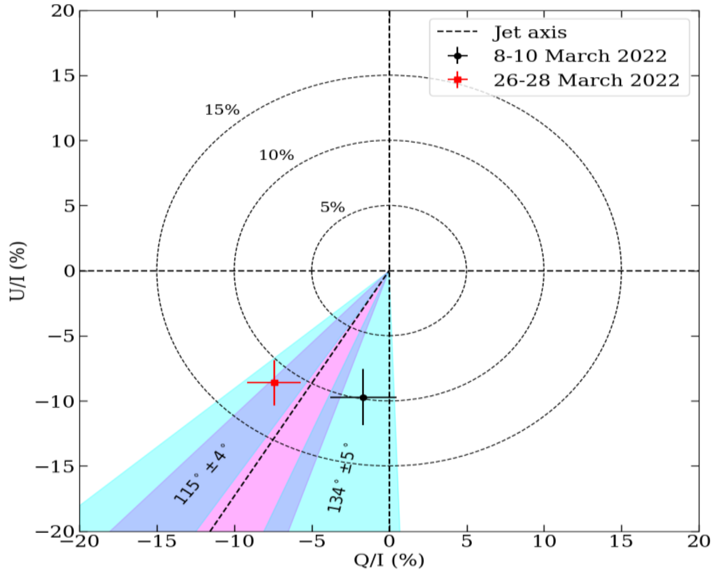
Blazars are obvious sources for X-ray polarimetry. High Synchrotron Peak Blazars like Mrk 501 (*Liodakis et al. 2022*) and Mrk 421 (*Di Gesu et al. 2022*) are indeed significantly polarized. Multifrequency observations permit to discriminate among models.

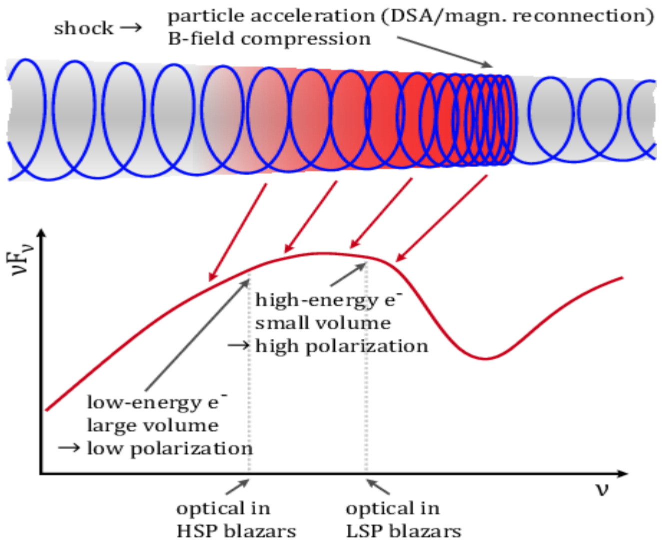


IC peak sources are instead much less polarized (e.g. Cen A, *Ehlert et al. 2022,* BL Lac*, Middei et al. 2022*).

Mrk 501







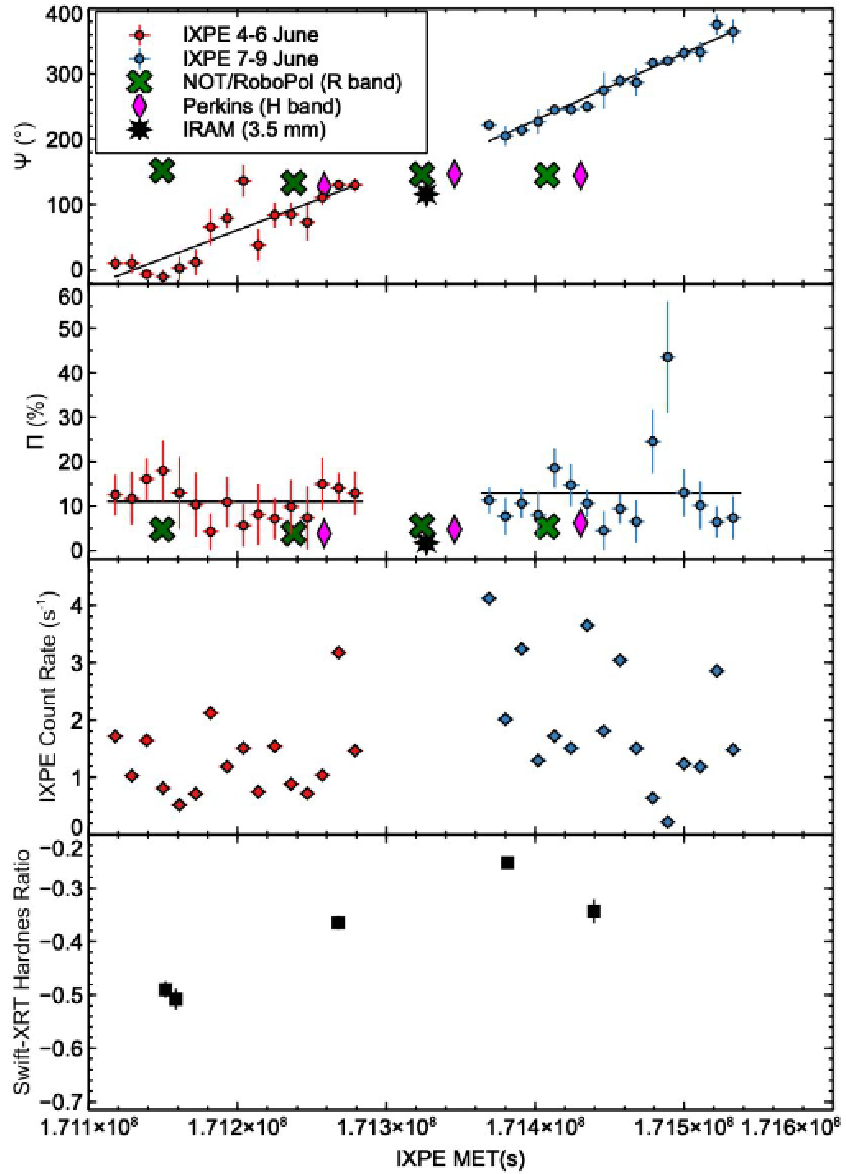
Model	Multiwavelength polarization	Variability†	Polarization angle
Single zone	constant*	moderate	any
Multizone	mildly chromatic	high	any
Energy stratified (shock)	strongly chromatic	slow	along the jet axis
Energy stratified (magnetic reconnection)	constant	moderate	perpendicular to jet axis
Observed	strongly chromatic	slow	along the jet axis

Liodakis et al. (2022)

Mrk 421

Very similar results, and very similar conclusions, for Mrk 421 (*di Gesu et al. 2022*) …

… but in another observation of this source a continuous rotation of the polarization angle by more than 360 degrees in 5 days is detected (*di Gesu et al. 2023*). A localized shock propagating along a helical magnetic structure in the jet?



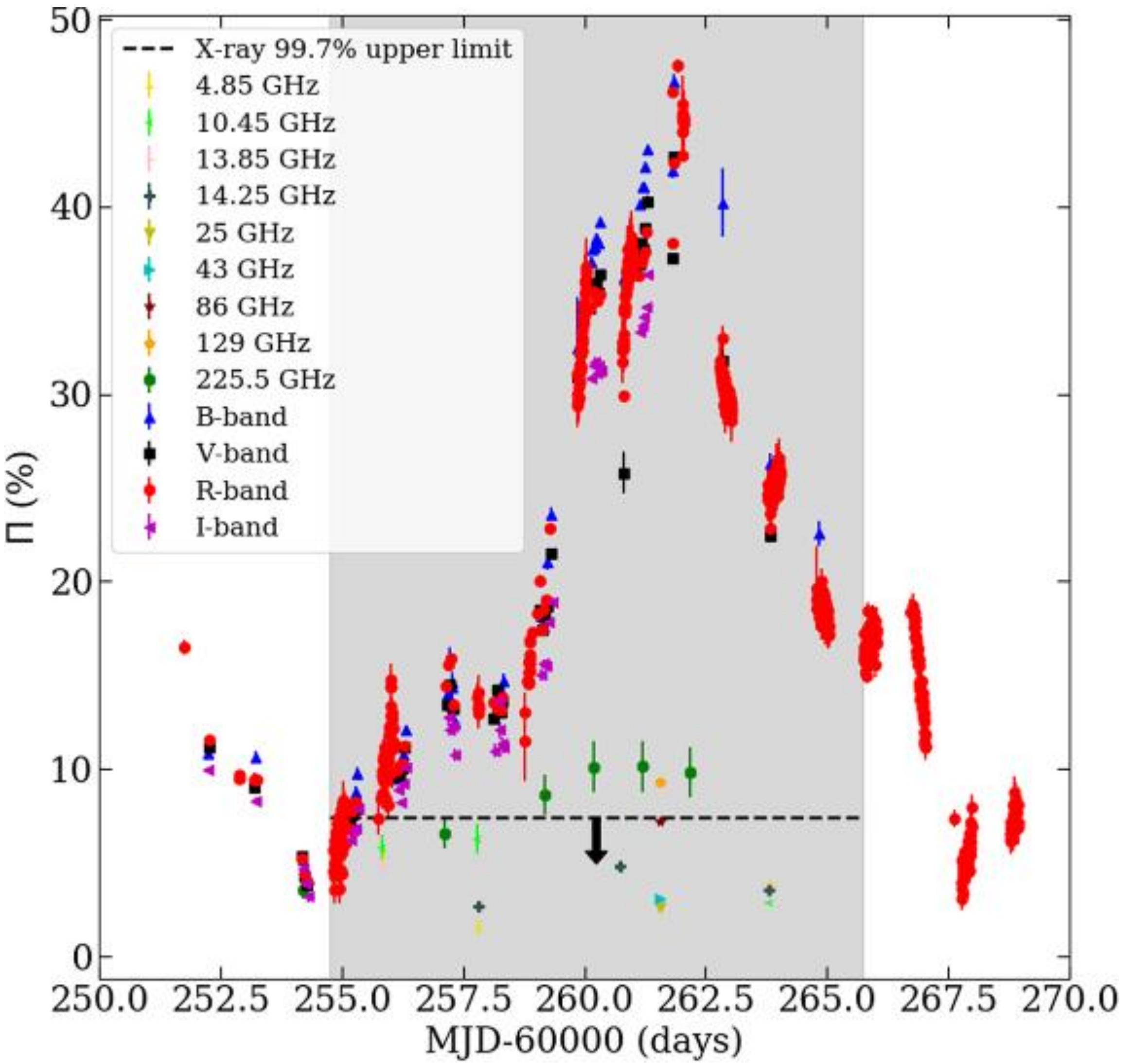
BL Lac

BL Lac was reobserved in Nov 23 during a multifrequency campaign, and caught an extraordinary event in which the optical linear polarization reached a PD of 47.5% *(Agudo et al. 2025)*

Even if only an upper limit could be obtained from IXPE data, the optical-to-X-rays ratio of polarization degrees is very constraining, strongly favouring a leptonic scenario (Compton scattering)

Table 1
Summary of the Multiwavelength Polarization Expectations for Different X-Ray Emission Scenarios Outlined in the Text

Model	X-Ray Polarization Degree	X-Ray Polarization Variability
Single-zone leptonic (EC)	Unpolarized	...
Single-zone leptonic (SSC)	$0.5 \times \Pi_O$	Similar to optical
Energy-stratified/multizone leptonic (SSC)	$\leqslant 0.3 \times \Pi_O$	Similar to millimeter
Single-zone hadronic	$\approx \Pi_O$	Less variable than optical
Energy-stratified/multizone hadronic (flare)	$\approx \Pi_O$	Less variable than optical
Energy-stratified/multizone hadronic (nonflare)	$\approx \Pi_{mm}$	Similar to millimeter

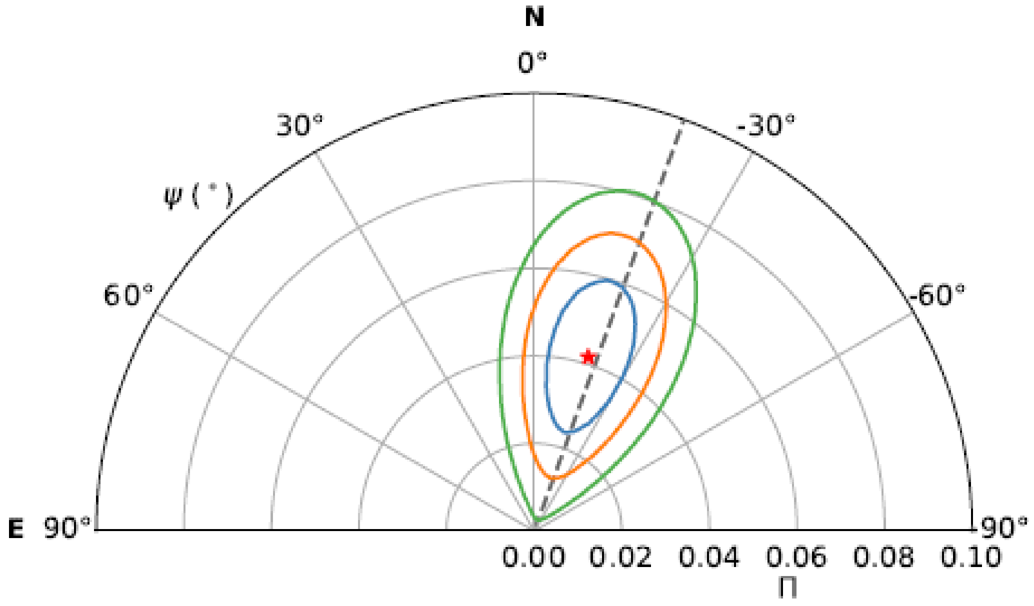


Agudo et al. (2025)

Radio galaxies

While only an upper limit of ≈ 8% for the PD of Centaurus A could be found (*Ehlert et al. 2022*), a very long (large program) observation of the Perseus Cluster (2.2 Ms) allowed a detection of the polarization of the core of the central galaxy, the radiogalaxy 3C84 (a.k.a. NGC 1275) (*Liodakis et al. 2025*)

Compton scattering (likely SSC) detected at last!



Liodakis et al.(2025)

PD=4.2±1.3 %, aligned with the radio jet

What next?

Pre-launch goals not yet achieved (but worth keep pushing, hoping for more collaborative objects):

BH spin via PA rotation
Vacuum birefringence in Magnetars
Neutron Star EoS in accreting millisecond pulsars

Other possible goals:

Accreting WD (first encouraging result in EX Hydrae)
Geometry of hot corona in Narrow Line Seyfert 1s (first results inconclusive)
(Jetted) Tidal Disruption Events
Full monitoring of more accreting BH and NS
More LSP Blazars to confirm leptonic models

… and of course any new, bright idea from you !!

A few final words of wisdom

In variable sources, it may be worth looking to different states/flux levels/phase, so reobserving a source may be a good idea

Many important IXPE results came out of DDT observations. Don't hesitate to make a request, if there is a good science case and the event was unanticipated. *But many transient events can be anticipated and should be proposed as ToO in the GO program*

Don't be shy! Ask the needed exposure time (with a bit of margin)

Take full advantage of the joint programs with NuSTAR, Swift, XRISM, XMM-Newton (new!) and NSF/NRAO

Thanks for your attention