Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
Roma Tre

The X-ray polarized sky: results from the Imaging X-ray Polarimetry Explorer (IXPE)

Giorgio Matt (Univ. Roma Tre)
on behalf of the IXPE Science Team

IXPE Imaging X-Ray Polarimetry Explorer

Plan of the talk

- **A brief introduction to X-ray polarimetry**
- **The Imaging X-ray Polarimetry Explorer (IXPE)**
- **Results from the first 2 years of operation ("baseline mission").**
  Warning: an inevitably incomplete and somewhat biased review!

More IXPE results elsewhere, and in particular in two special sessions:

- ***SS16 - Relativistic jets from AGN in the era of high energy polarimetry (today)***
- ***SS26 - Extended sources in the IXPE era (thursday)***

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X-ray polarimetry

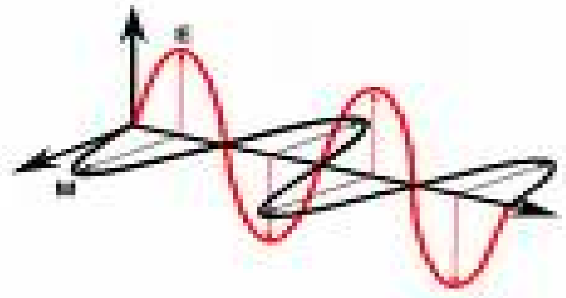
Information on celestial (extra-solar) sources are mostly provided by electromagnetic radiation.

They can be obtained by studying the spatial, spectral, timing and *polarization* properties of the observed radiation.

In particular, the polarization properties give us information on *geometry* (in a broad sense: geometry of the emitting matter but also of magnetic and gravitational fields, of space-time, etc.). The polarization degree depends on the level and type of symmetry of the system, the polarization angle indicates its orientation.

Our knowledge of the emission from a celestial source in any energy band is therefore incomplete without polarimetry.

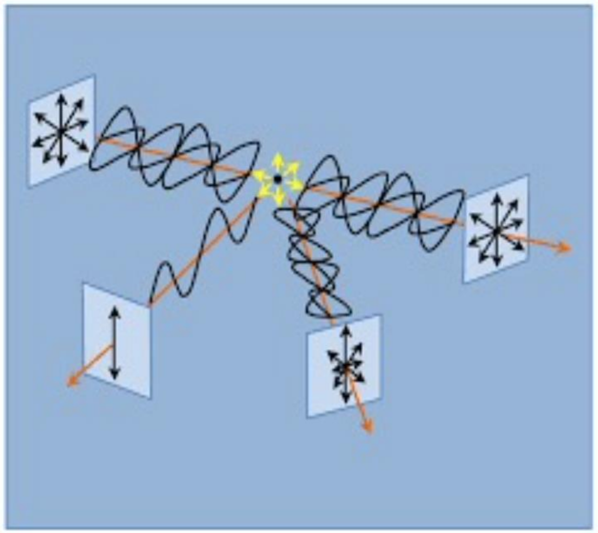
However, polarimetric information were basically missing in the X-ray band before IXPE!



X-ray polarimetry

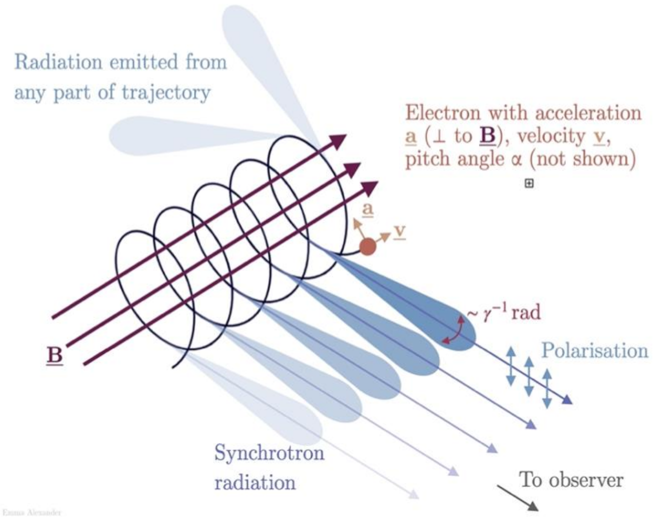
Polarization is a (pseudo) vector → measures geometry (of the emitting matter, the radiation field, the magnetic field, the space-time, …)

Scattering / reflection



EVPA perpendicular to scattering plane

Synchrotron radiation



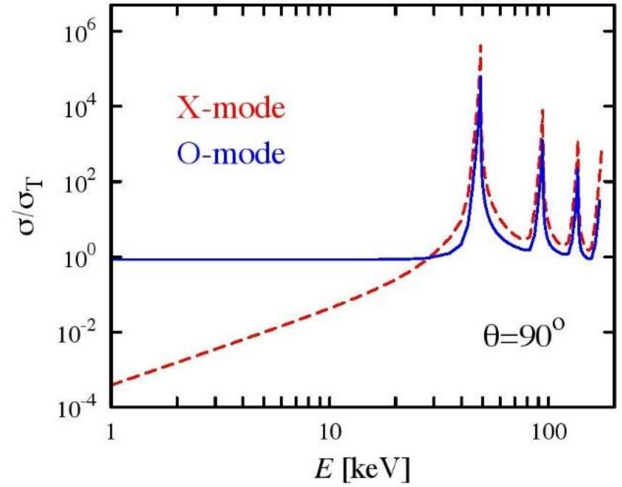
EVPA perpendicular to magnetic field lines

General relativity

$$\nabla_k f = 0$$

EVPA changes

Highly magnetized plasma



EVPA parallel or perpendicular to magnetic field lines depending on the dominant mode

EVPA = electric vector position angle

X-ray polarimetry

- Before IXPE, only one positive measurement (Crab Nebula: 19%) in the classic X-ray band, dating back to the 70s (OSO-8)
- No X-ray polarimeters onboard X-ray satellites after OSO-8, due to lack of sensitive enough detectors
- Now such detectors do exist, based on the photoelectric effect
- The Imaging X-ray Polarimetry Explorer (IXPE) was selected by NASA in 2017 in the framework of the SMEX program, and launched in December 2021
- IXPE is providing a wealth of diverse and often surprising results

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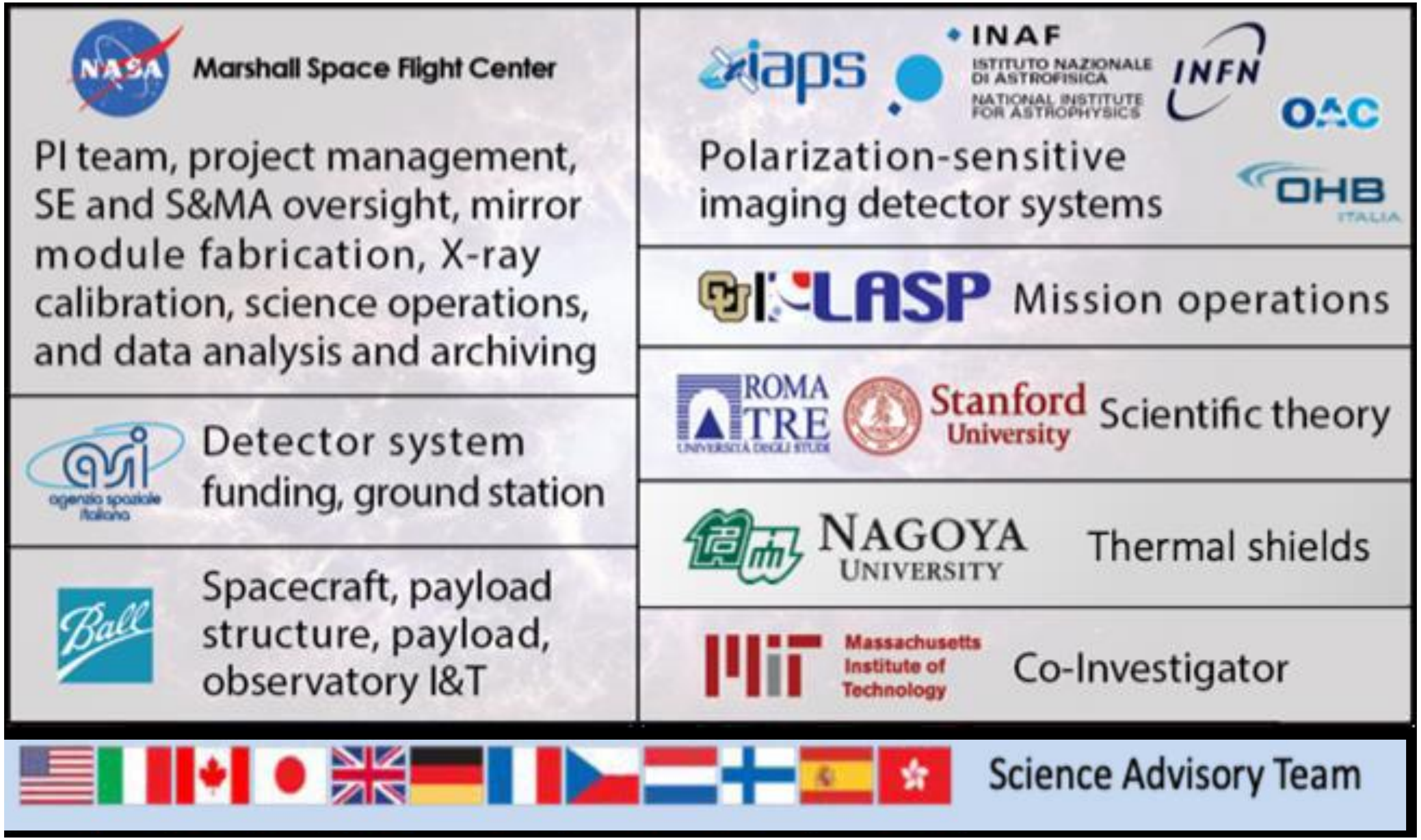
IXPE mission description

- A NASA/ASI mission within the NASA's Small Explorer Program (SMEX)
- Launched December 9, 2021 on a Falcon 9 from KSC
- 600-km circular orbit at a nominal 0° inclination
- 2-year baseline mission, now extended with GO program
- Point and stare (with dither) at pre-selected targets
- Malindi ground station - primary (Singapore - secondary)
- Mission Operations Center (MOC) at the University of Colorado, Laboratory for Atmospheric and Space Physics (LASP)
- Sciences Operations Center (SOC) at MSFC
- Data archiving at NASA's HEASARC – No proprietary rights, neither in the baseline phase nor in the present GO phase

IXPE Team



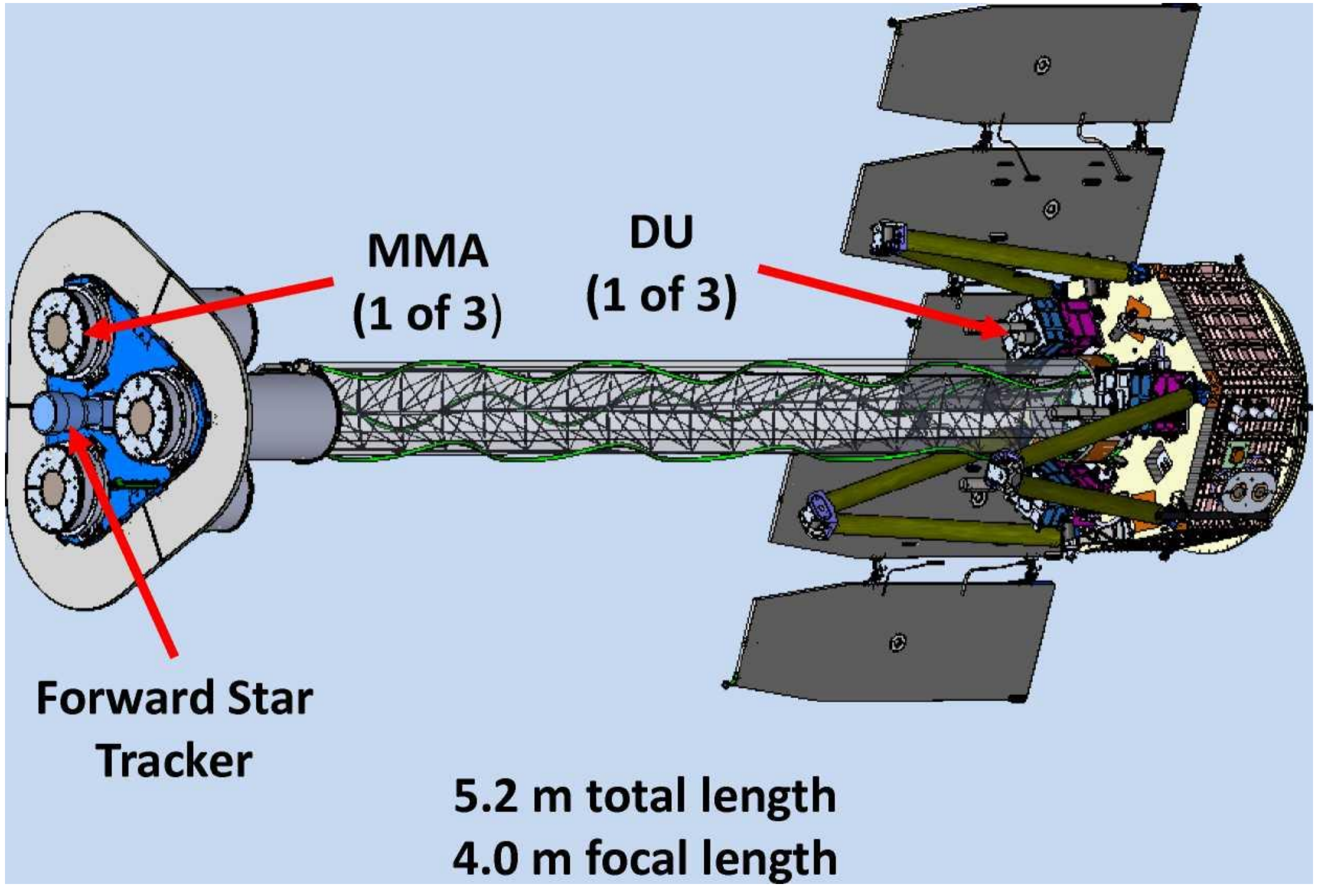
PI: Phil Kaaret, MSFC

(formerly Martin Weisskopf)

SAT currently comprises > 100 scientists from 12 countries

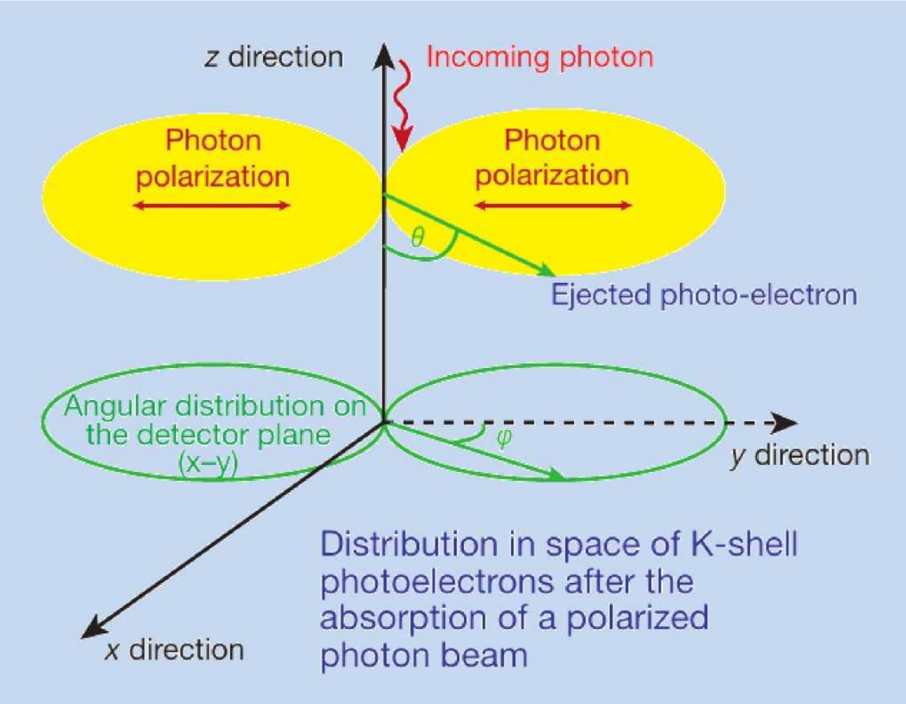
IXPE in a nutshell

- *Energy range: 2-8 keV*
- *Spatial resolution: 30'' (FWHM)*
- *FOV=13'*
- *Energy resolution: 0.57 keV @ 2 keV (FWHM)*

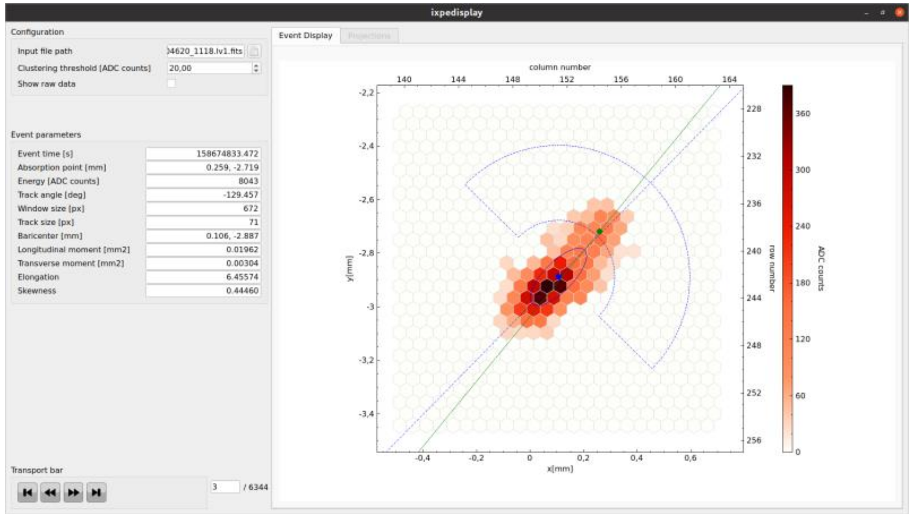


Polarization Detection Principle

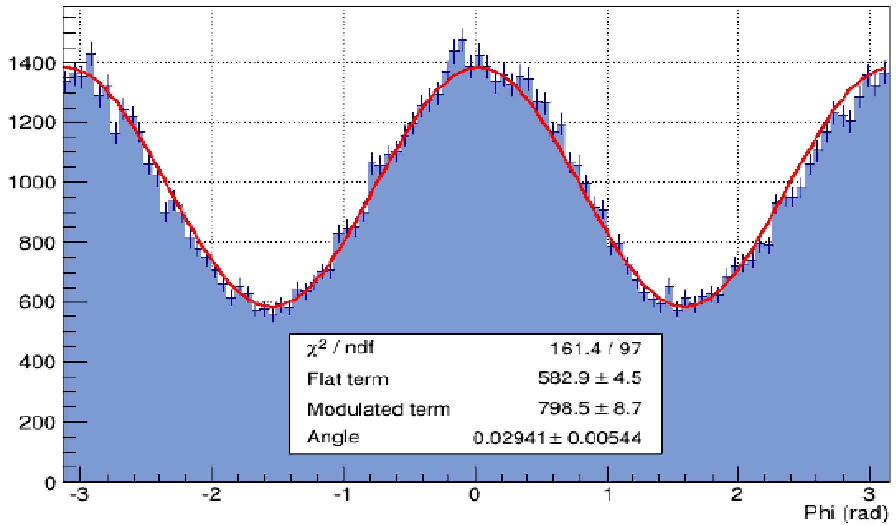
The detection principle is based on the photoelectric effect



$$\frac{\partial \sigma}{\partial \Omega} = r_0^2 \frac{Z^5}{137^4} \left(\frac{mc^2}{h\nu}\right)^{7/2} \frac{4\sqrt{2}\sin^2(\theta)\cos^2(\varphi)}{(1-\beta\cos(\theta))^4}$$



(x,y)=(0.0,0.0)mm, 2nd step - 3.7 keV, 2769



Observing Program

The IXPE baseline mission was funded for two years, and finished on January 31, 2024. Observation program defined by the IXPE team

A "bridge" extension till September 2025 granted by NASA, waiting for the standard call for mission extensions in 2025

A General Observer Program issued in 2023. GO1 started February 1, 2024. Oversubscription larger than 6

Deadline for GO2 proposals: August 29, 2024. Joint programs with NICER, NuSTAR and Swift

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IXPE Imaging X-Ray Polarimetry Explorer

Observing Program: Baseline Phase

5 PWNe and isolated pulsars	Crab PWN, Vela PWN, MSH 15-52, PSR B0540-69, G21.5
6 SNR	Cas A, Tycho's, NE SN 1006, RCW 86, RX J1713.7-3946, Vela Jr.
11 Accreting stellar-BH	Cyg X-1, 4U 1630-472, Cyg X-3, LMC X-1, 4U 1957-115, SS 433 Lobes, LMC X-3, SWIFT J1727.8-1613, 4U 1957+115, Swift J0243.6+6124, Swift J1727.8-1613
19 Accreting NS	Cen X-3, Her X-1, GS1826-67, Vela X-1, Cyg X-2, GX 301-2, X Persei, GX 9-9, 4U 1820, GRO J1008-57, XTE 1701-46, EXO 2030+375, LS V+44 17, GX 5-1, 4U 1624-49, Sco X-1, Cir X-1, GX13+1, SMC X-1
4 Magnetars	4U 0142+61, 1RXS J170849, SGR 1806-20, 1E 2259+586
5 Radio-quiet AGN & 1 Sgr A*	MCG 5-23-16, Circinus Galaxy, NGC 4151, IC 4329 A Sgr A* Complex, NGC 1068
15 Blazars & radio galaxies	Cen A, S5-0716-714, 1ES 19-59-650, Mrk 421, BL Lac, 3C 454, 3C 273, 3C 279, Mrk 501,1ES 1959-650, BL-Lac, 1ES 0229-200, PG 1553 -113, S4 0954+65, 1E 2259+586,

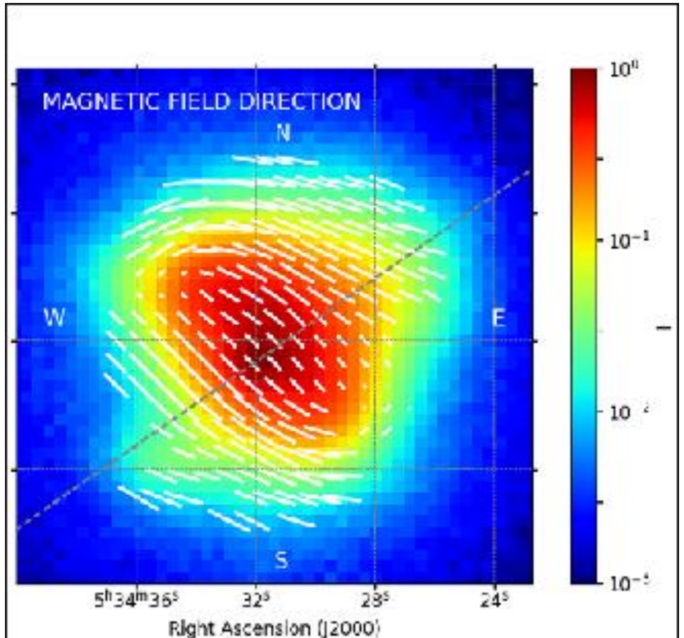
Some sources have been revisited
Mrk 421, Mrk 501, BL Lac, Vela X1, Her X-1, MCG 5-23-16, Crab, MSH 15-52, Cyg X-1, Sgr A (complex), Swift J1727, …

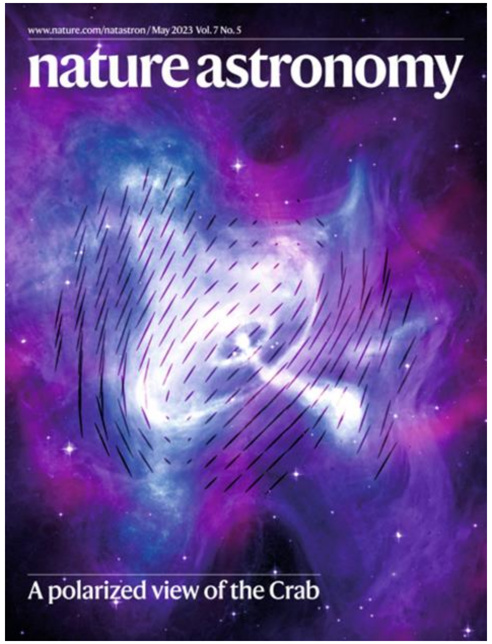
Positive detection in the majority of sources!

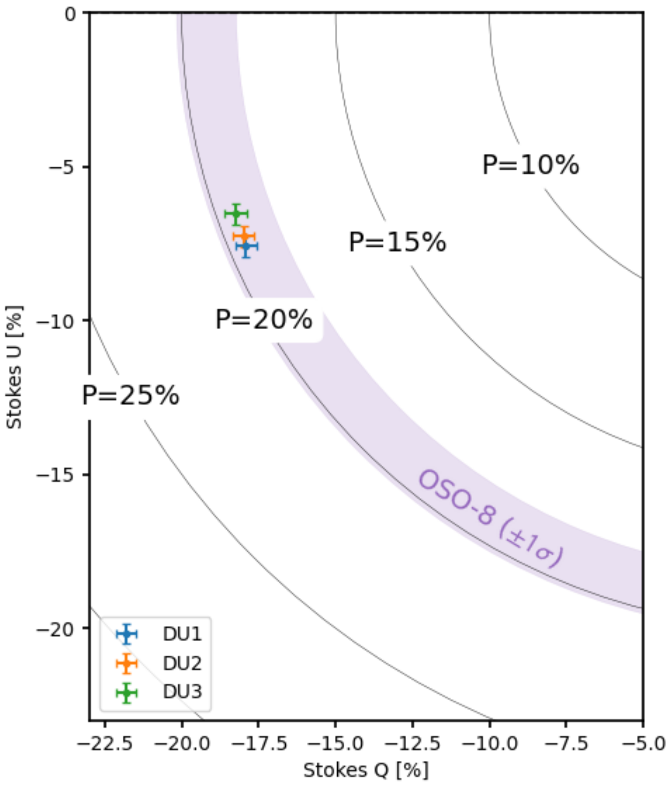
Pulsar Wind Nebulae

IXPE observations of PWN (Crab, Vela) confirmed they are highly polarized (very high in certain regions, close to the synchrotron limit) *(Bucciantini et al. 2022, Xei et al. 2002).*

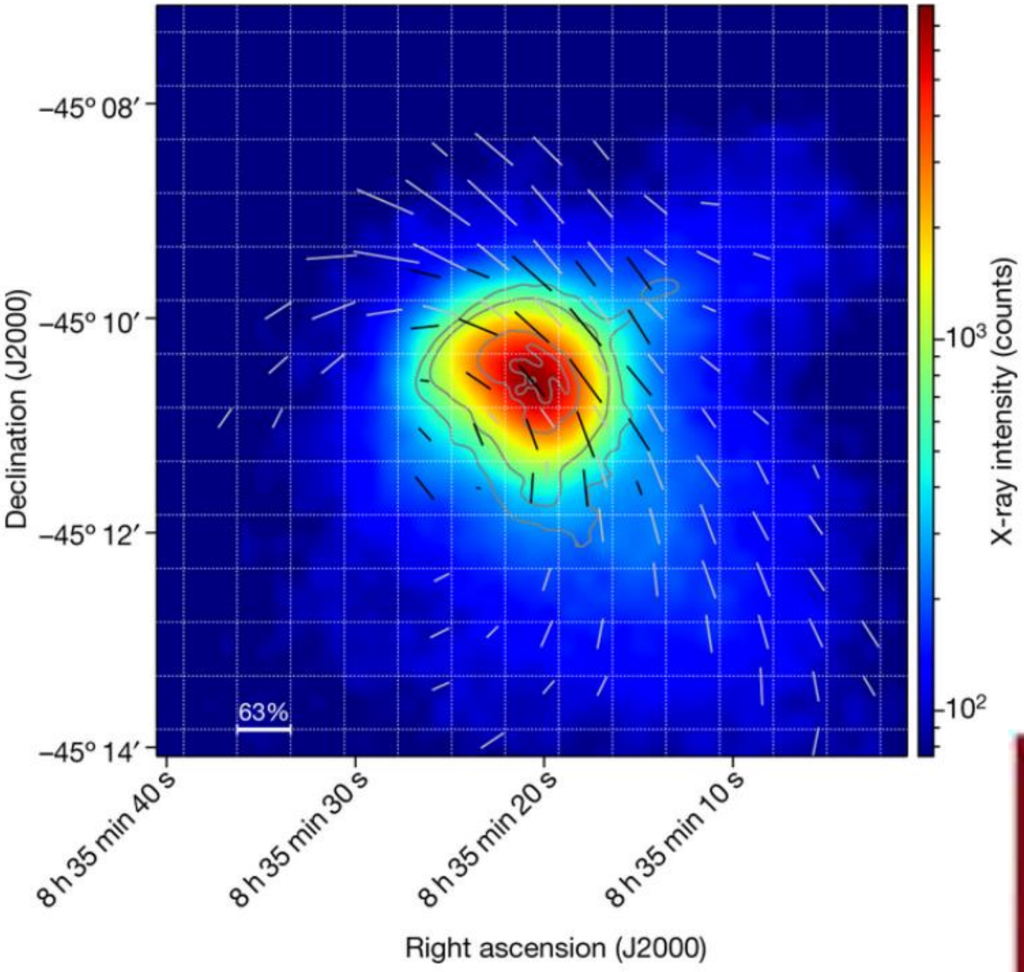
Crab result consistent with OS0-8, when integrated over the entire nebula. However, polarization map shows a complex pattern, not surprisingly given the Chandra image







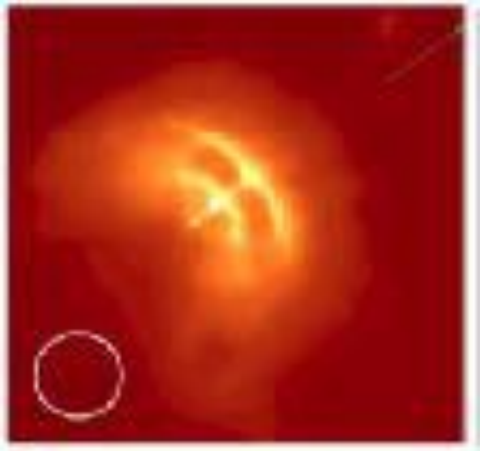
The Vela PWN



Average polarization of 45%, larger than 60% is some, small regions → close to the Synchrotron limit!

High polarization suggests B less turbulent than expected.

Polarization consistent with radio, but X-rays sample regions closer to the site of acceleration.

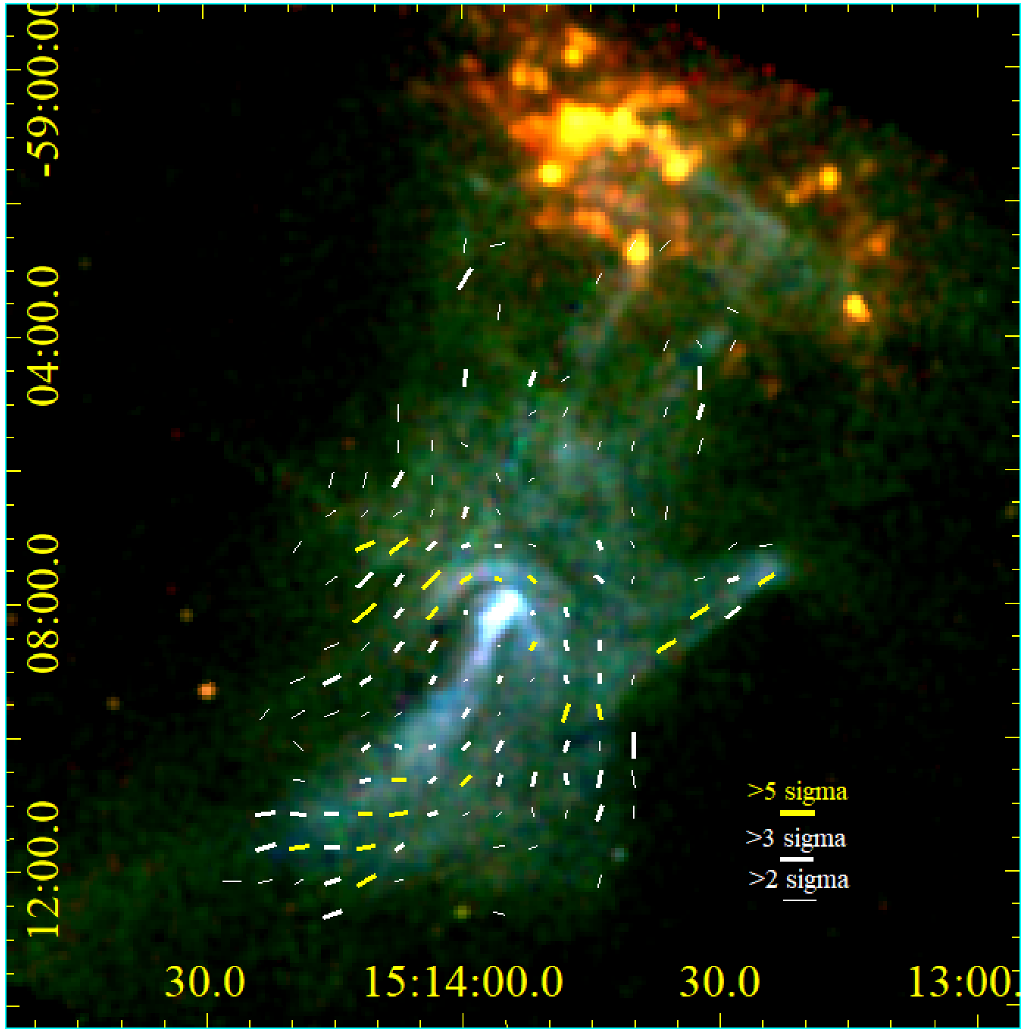


(Xie et al. 2022)

PWN: MSH 15-52 (Cosmic Hand)

Highly significant polarization in arcs and at the end the jet, with PD>70% *(Romani et al. 2023)*

Smaller polarization at the base of the jet, indicating a more complex magnetic field.



SuperNova Remnants

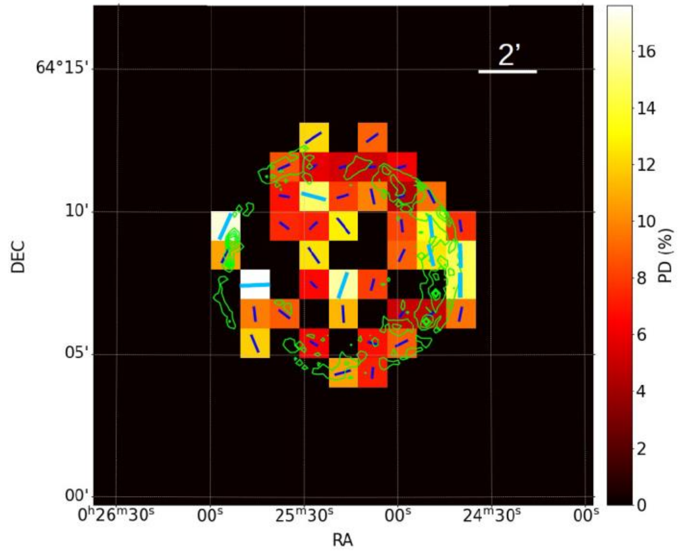
SNR overall less polarized than PWN (not surprisingly, as emission is mostly thermal).

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 rim of SNR RX J1713.7–3946 *(Ferrazzoli et al. 2024)*



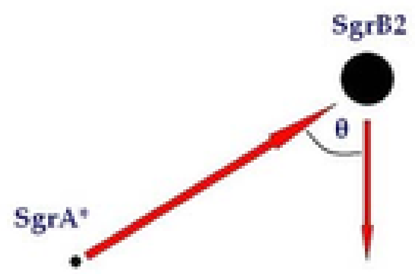
Tycho (Ferrazzoli et al. 2023)

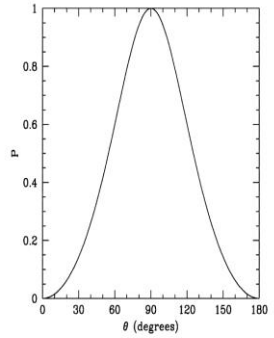
Sagittarius A*

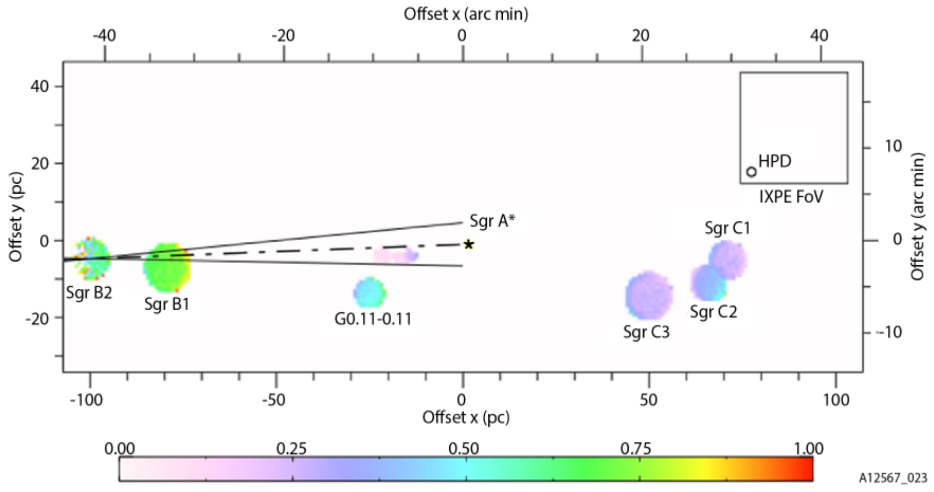
Galactic Center molecular clouds (MC) are bright X-ray sources.
Their X-ray spectra indicate reflection from external sources

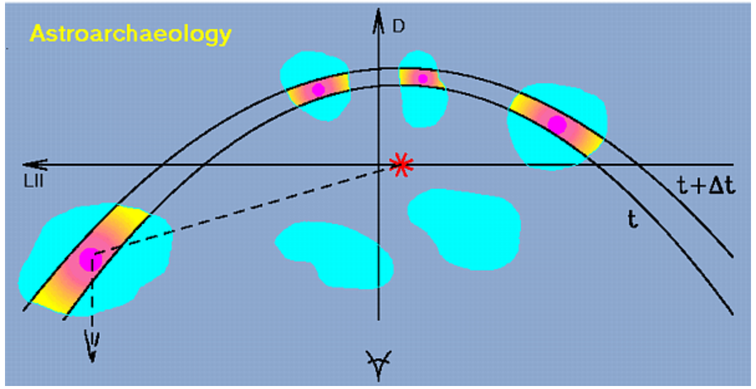
Are they reflecting X-rays from Sgr A* ?
If so, Sgr A* X-ray luminosity was 10^6 larger a few hundred years ago

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

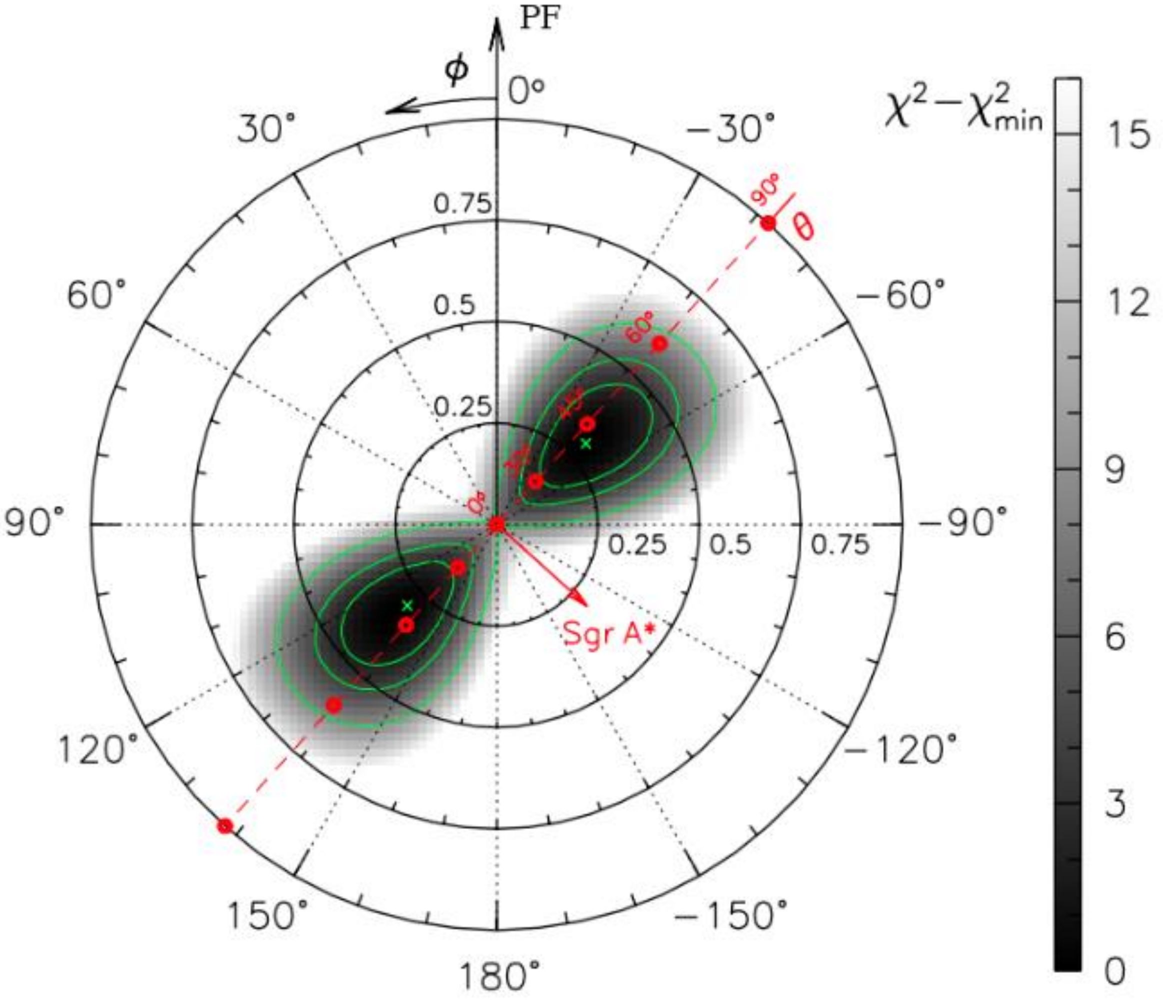








Sagittarius A*



2.7σ result. Polarization angle consistent with Sgr A* as the origin of the illuminating radiation *(Marin et al. 2023)*

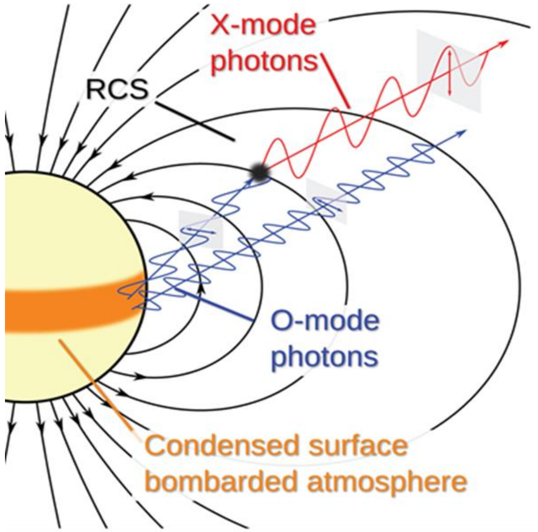
From the polarization degree, two solutions for the age of the burst: ~30 or ~200 years ago. Second solution much more probable.

Magnetars

Taverna et al. 2022

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

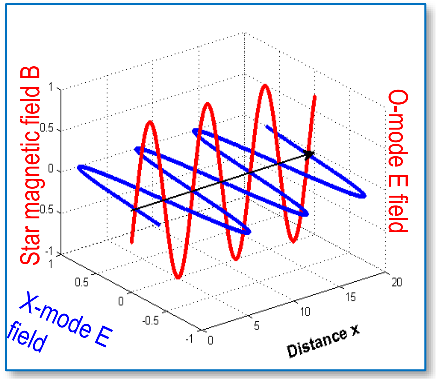
  - **Powered by their own magnetic energy**



Two modes, with very different opacities

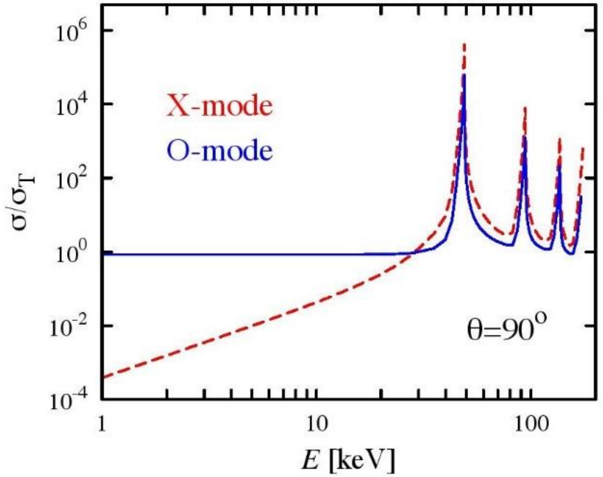
- Ordinary mode: E field parallel to the k-B plane
- Extraordinary mode: E field perpendicular to the k-B plane

The X-mode from deeper, hotter layers



O-mode:

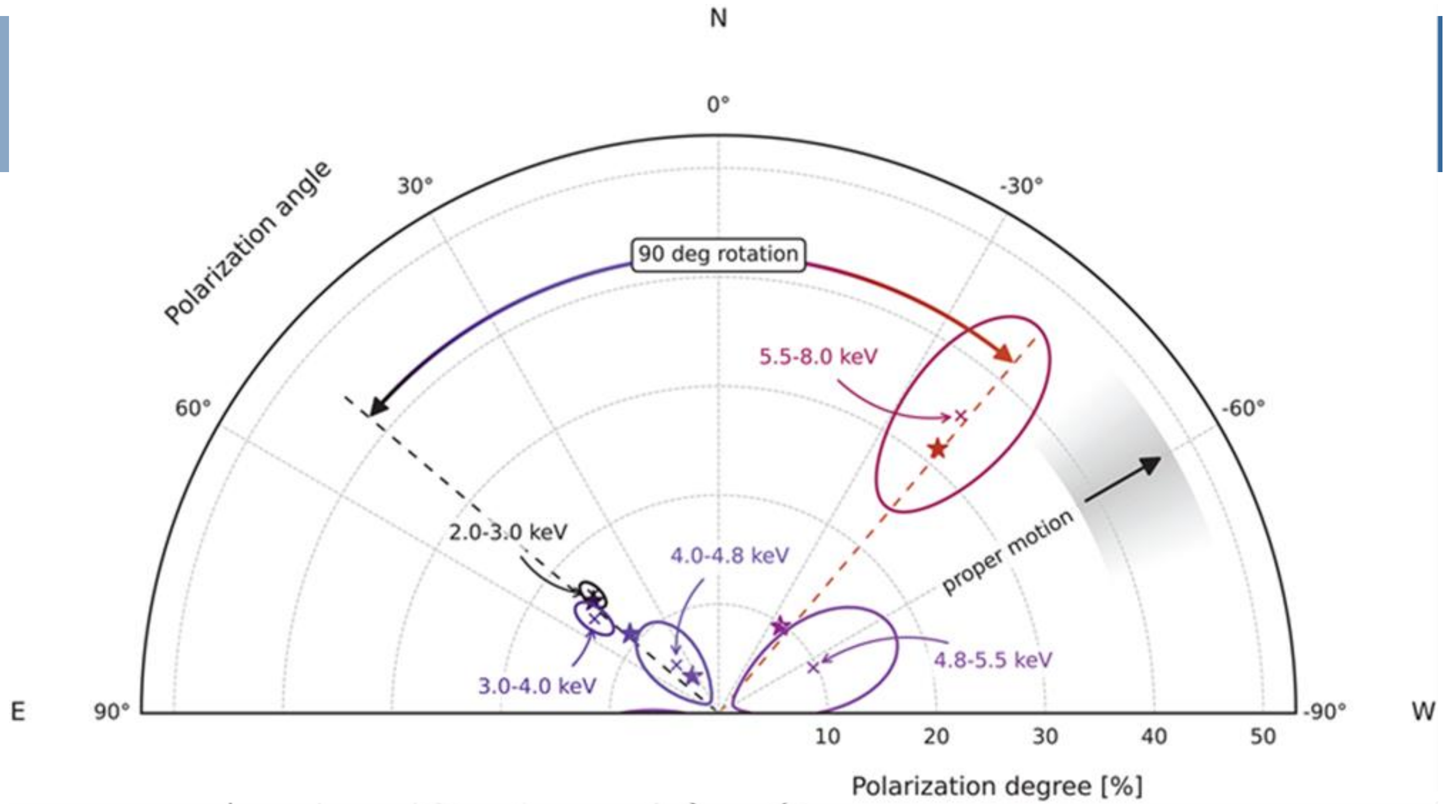
X-mode:

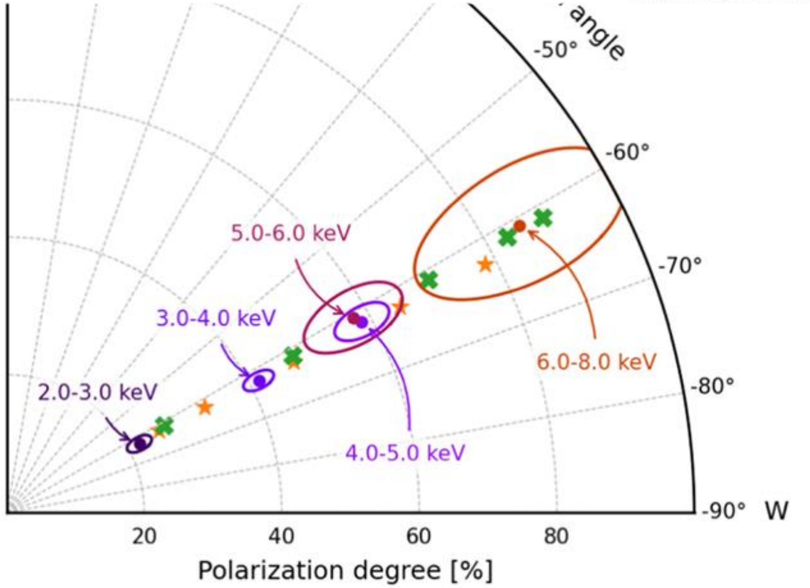


Magnetars

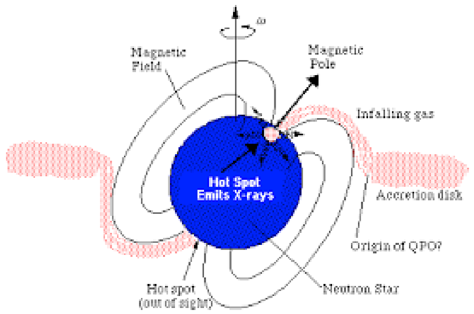
4U0142+61 shows PA swing of 90° (top) *(Taverna et al. 2022).* Two different modes dominate in the two components (Thermal + Resonant Compton Scattering). Low polarization indicates a condensed surface.

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.



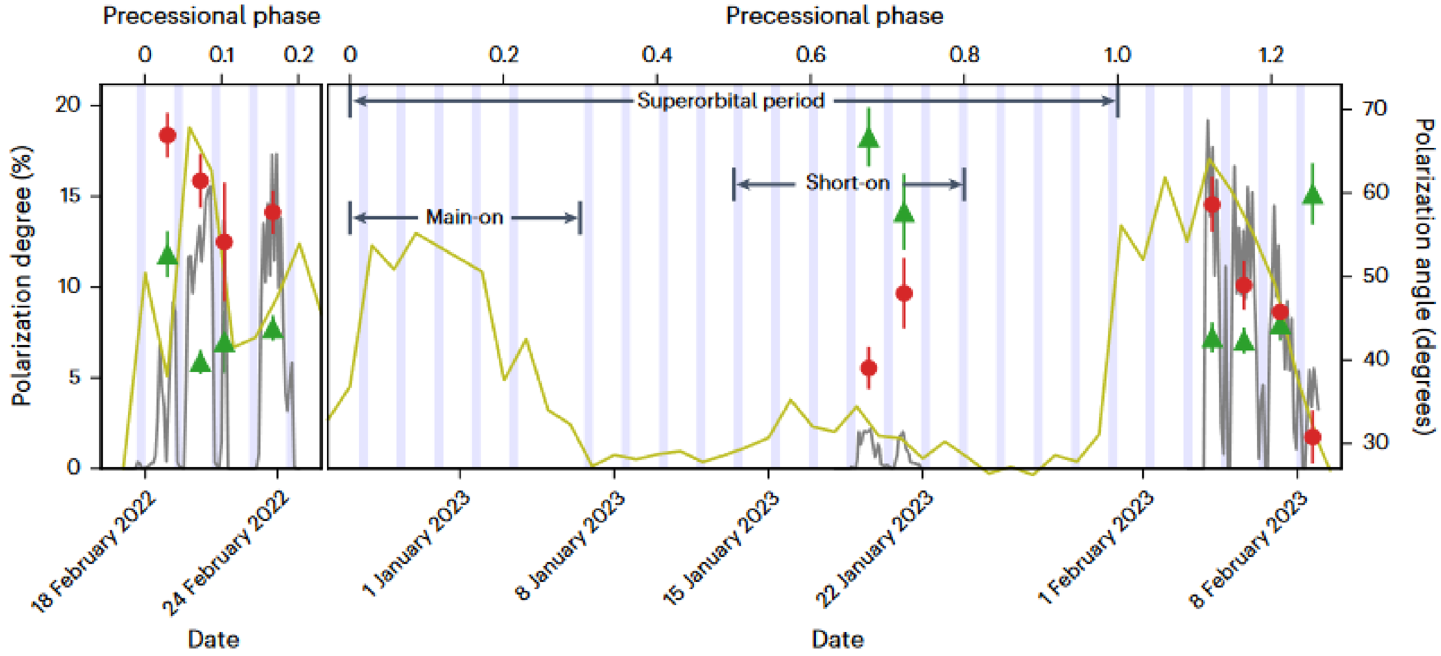


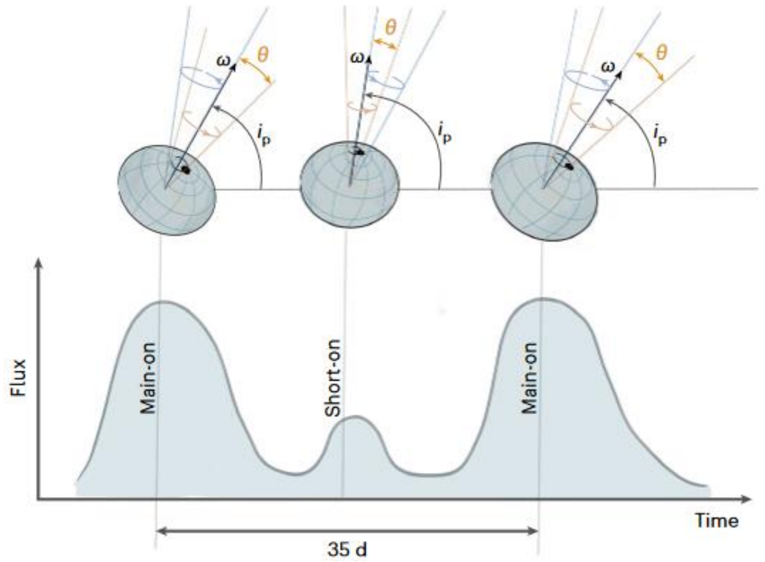
Accreting NS – X-ray Pulsars



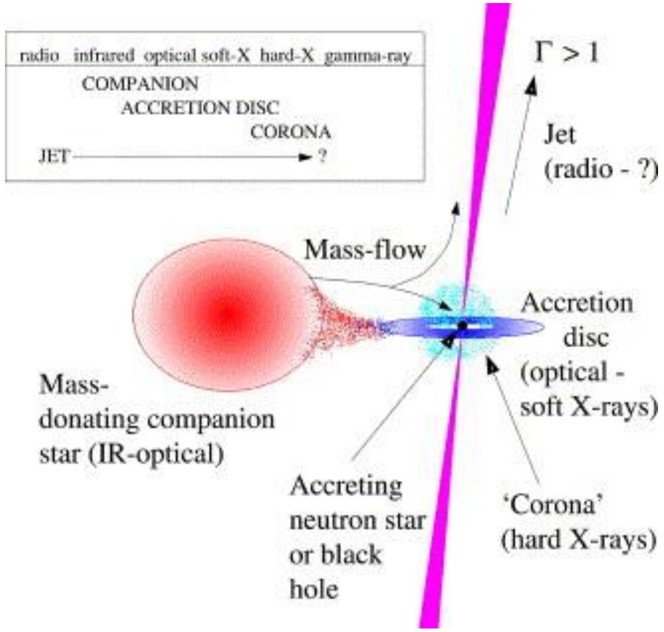
Phase dependent polarization observed in many X-ray pulsars, even if with polarization degrees less than predicted by old (probably too simple) models. Important geometrical parameters can be inferred.

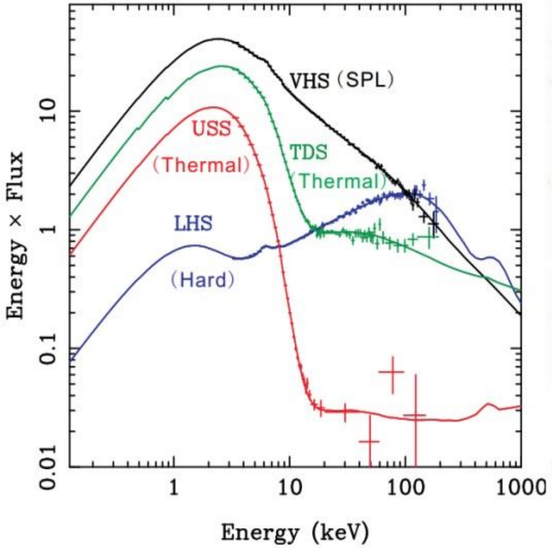
In Her X-1, a 35d superorbital period is observed, explained as a precession of either the neutron star or the accretion disc. IXPE results suggest that the crust of the neutron star is indeed precessing, probably exciting the precession and warping of the disc (Heyl et al. 2024)

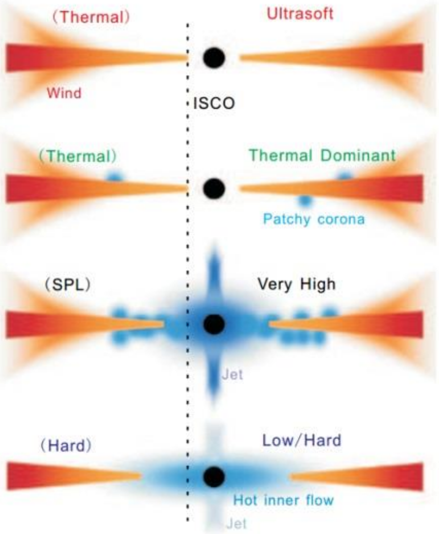




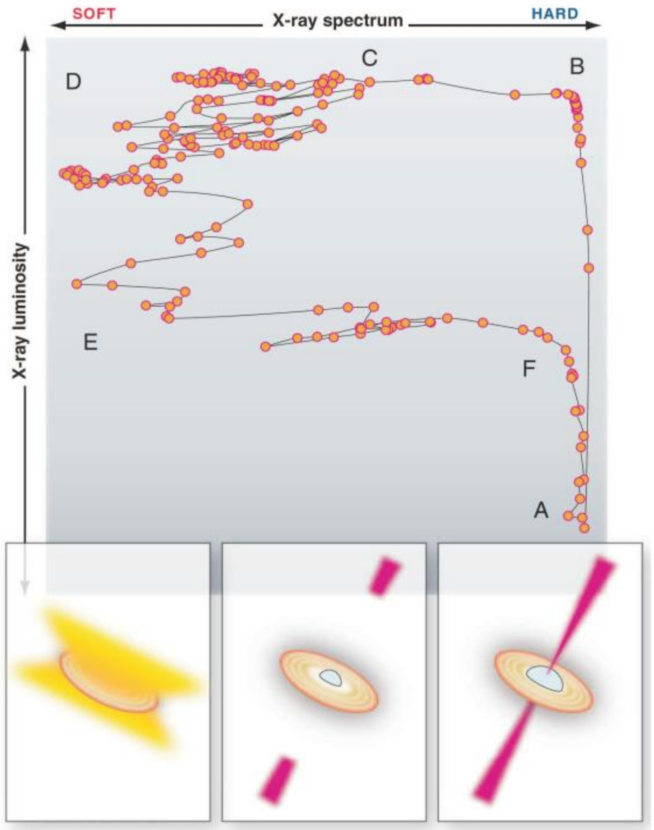
Accreting Stellar-mass BH (“microquasars”)







Done et al. 2007



Fender & Belloni 2012

Cyg X-1

Cyg X-1 observed in hard state (coronal emission) (Krawczynski et al. 2022)

Polarization degree (2-8 keV): 4.01+/-0.20

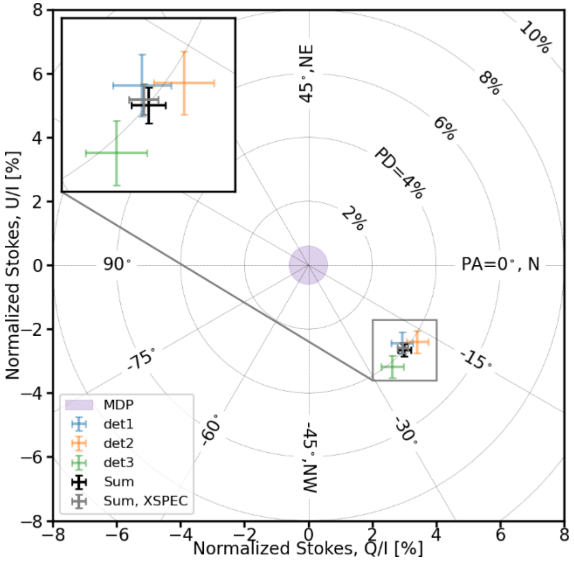
Larger than expected given the ≈30° orbital inclination

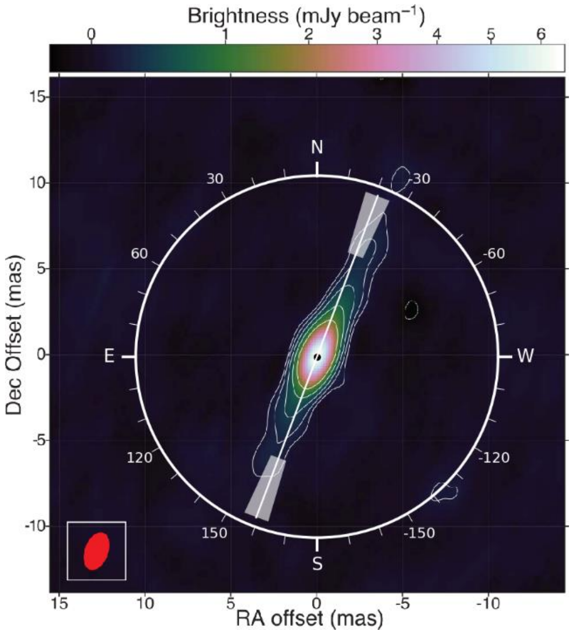
- Misalignement between the inner accretion flow and the orbital plane?
- Relativistic outflow of the corona? (Poutanen et al. 2023)

Polarization angle parallel to the radio jet

Flattish configuration of the emitting region

Observational evidence of link between disc and jet



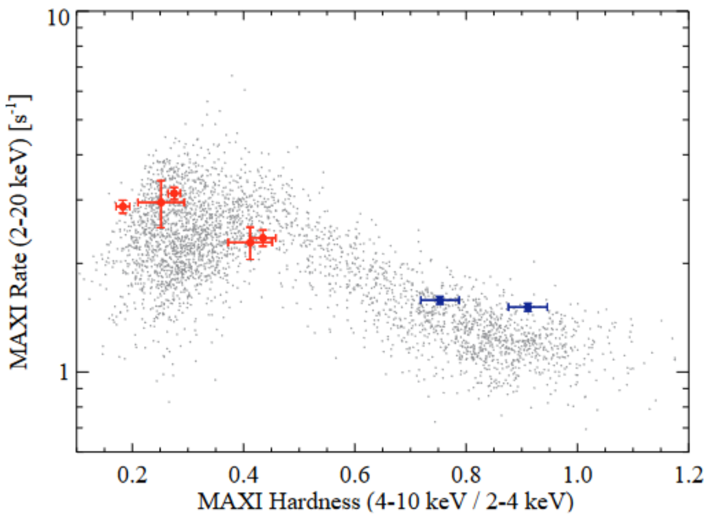


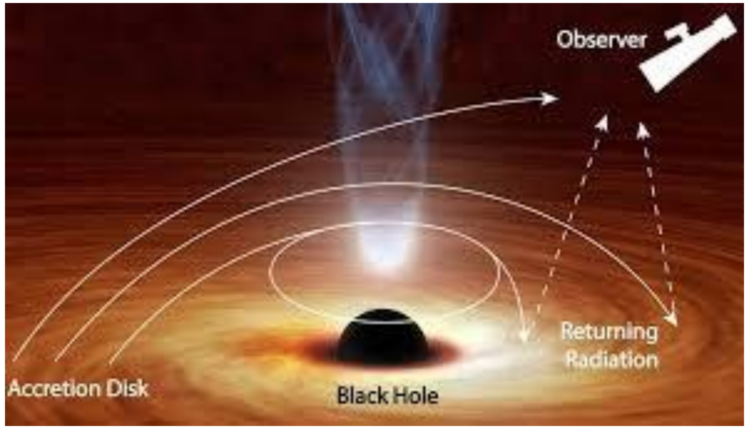
Cyg X-1 observed in soft state (accretion disc thermal emission) (Steiner et al. 2024)

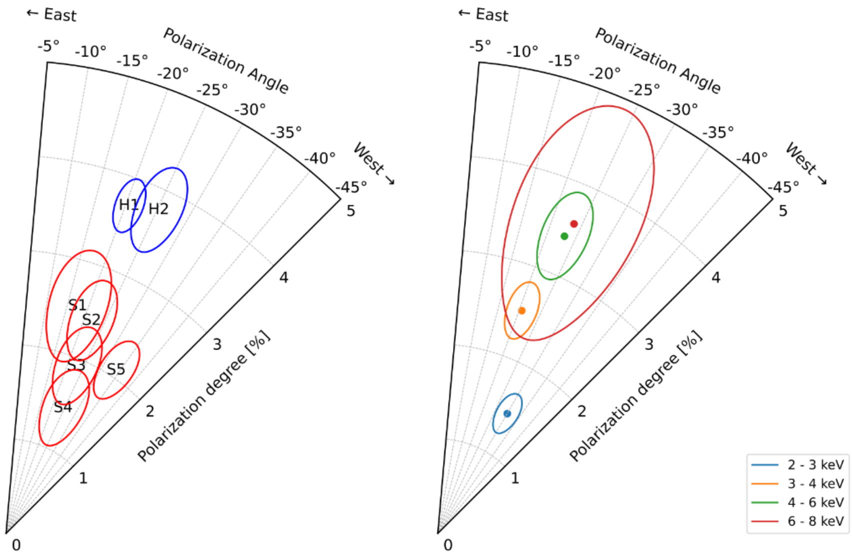
Polarization degree (2-8 keV): 1.99+/-0.13

Polarization angle still parallel to the radio jet (contrary to expectations for disc polarization)

Best explained by Gravitational lensing effects (''returning radiation''). If so, spin should be high (≥ 0.96)







Other microquasars

Cyg X-3 (hard state): P≈10-20% (time) !!

Source clearly obscured. Reflection from the wind (*Veledina et al. 2024*)

4U 1630-47 (transient, soft state): P=6-10% (energy)

Results inconsistent with standard, thin accretion disc models (*Rawat et al. 2023, Ratheesh et al. 2024*)

LMC X-1 (soft state): P<1.1%

Low inclination (**Podgorny et al. 2023**)

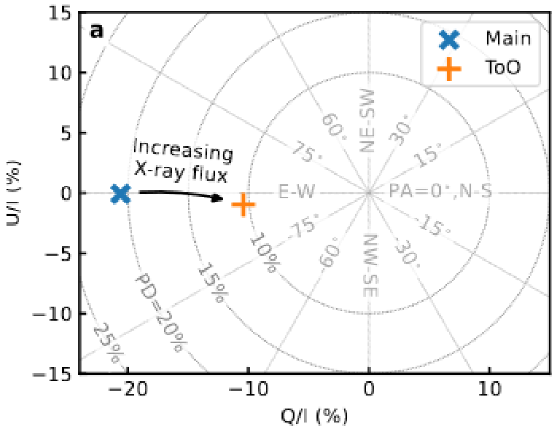
LMC X-3 (soft state): P ≈3%

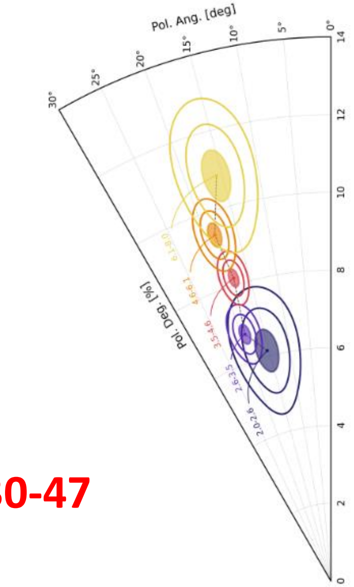
Low BH spin (*Svoboda et al. 2023, Majmuder et al. 2024*)

4U 1957+115 (soft state): P ≈2%

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

Cyg X-3





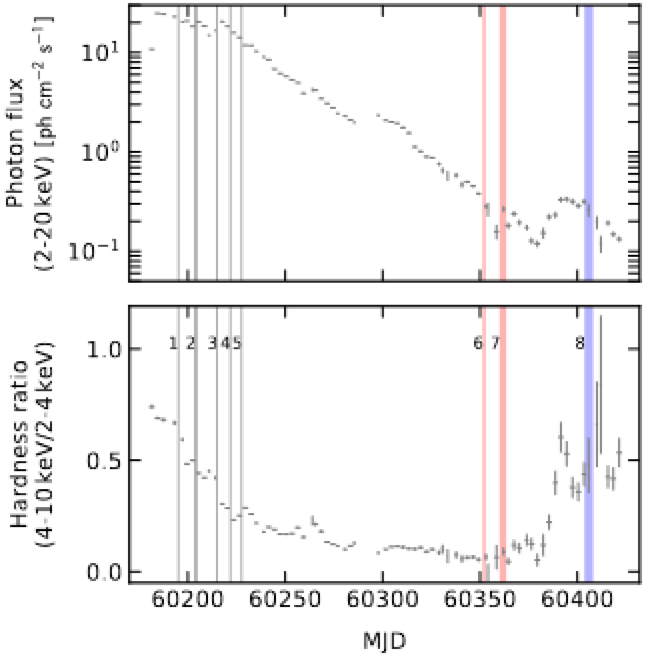
4U 1630-47

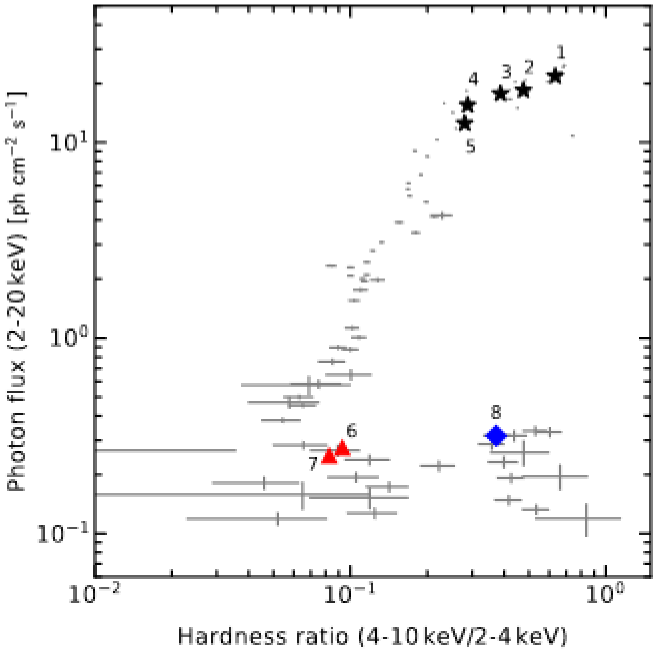
Swift J1217.8-1613

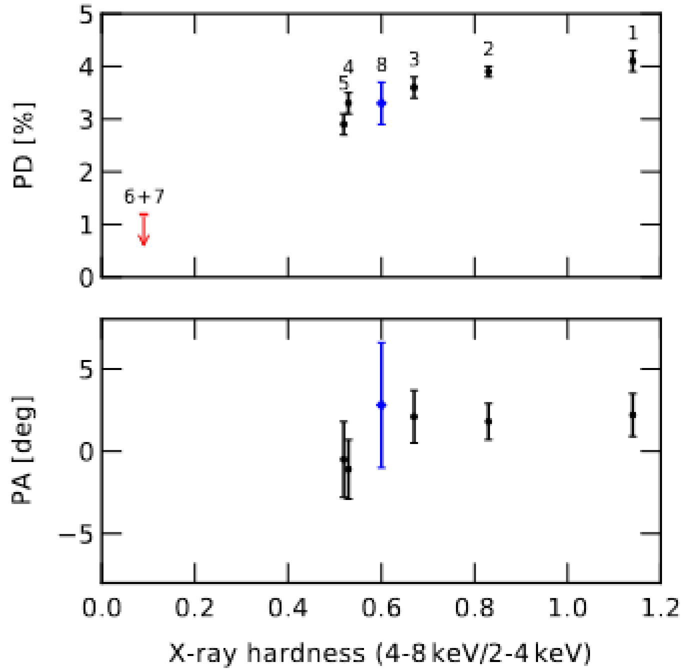
A new transient, very bright microquasar which started its outburst in August 2023

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



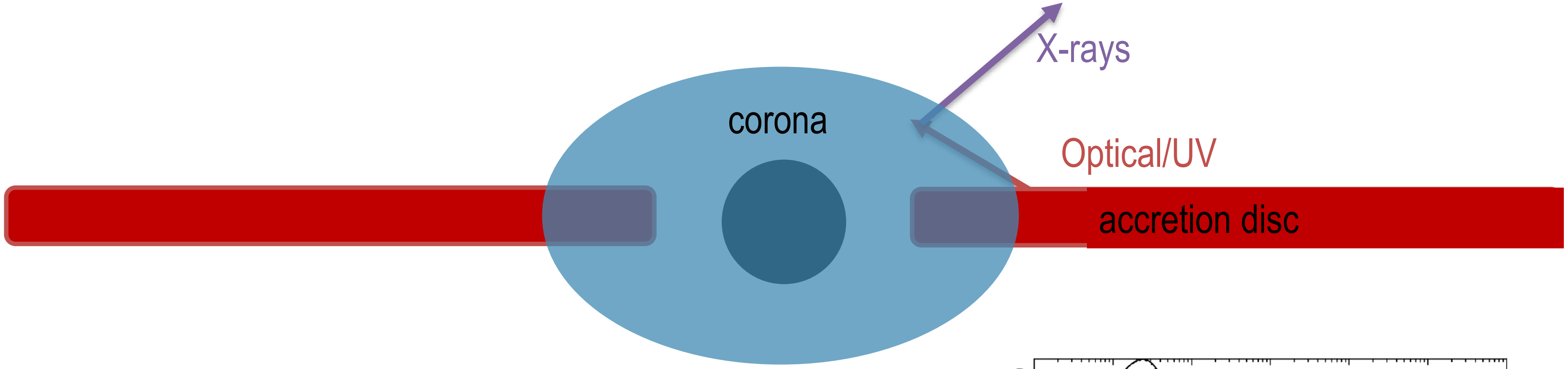




(Podgorný et al. 2024)

Radio Quiet AGN

In AGN the primary X-ray emission is due to Comptonization by electrons in a hot corona of the UV/soft X-ray disc photons (Shapiro et al. 1976; Sunyaev & Titarchuk 1980; Haardt & Maraschi 1991)

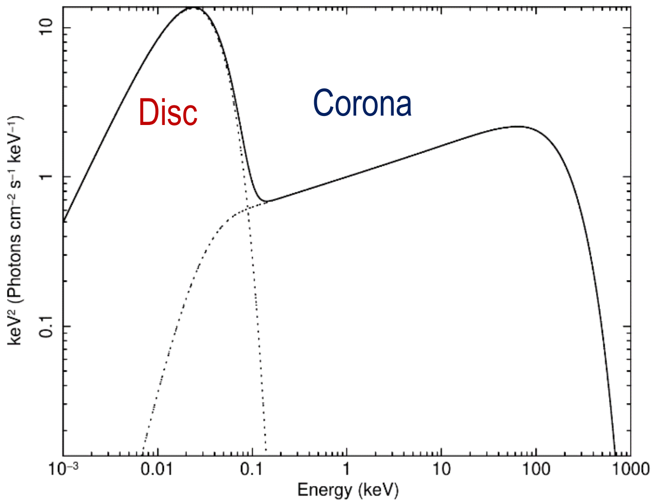


Cutoff power law $F_E \sim E^{-\Gamma} \exp(-Ec/kT)$

$\Gamma = \Gamma(kT,\tau)$, while Ec depends on kT

Temperature kT ~ 10-100 keV

Thomson optical depth ~ 1

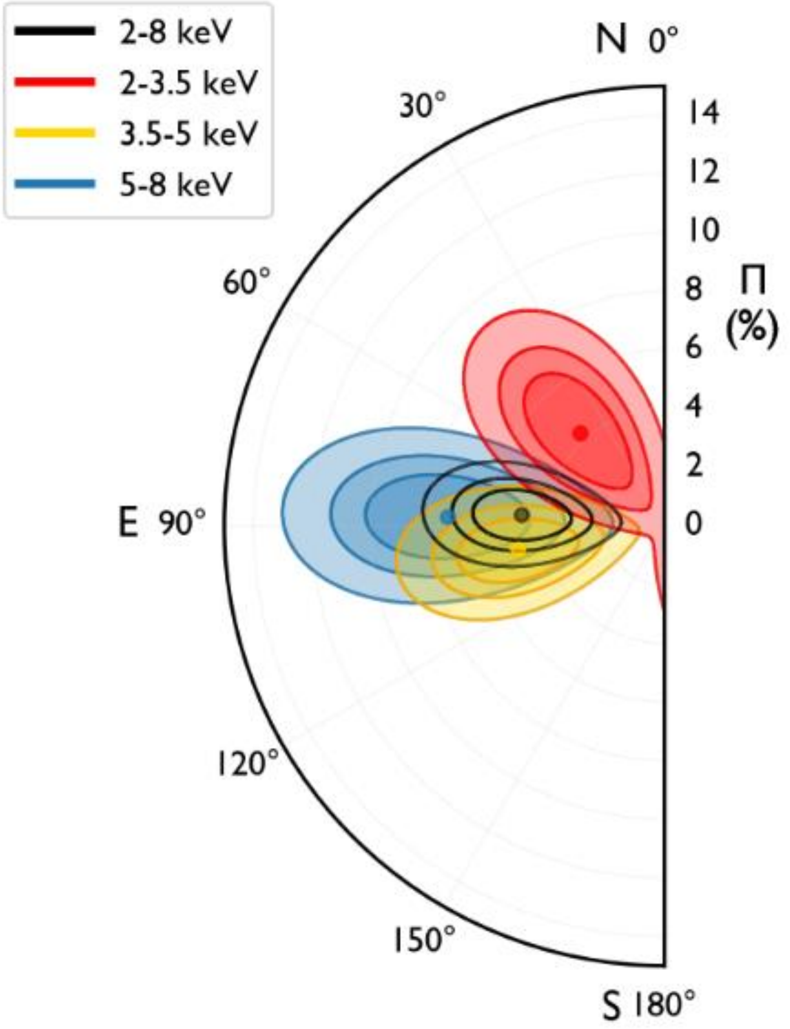


Radio Quiet AGN

Three unobscured RQ AGN have been observed so far:

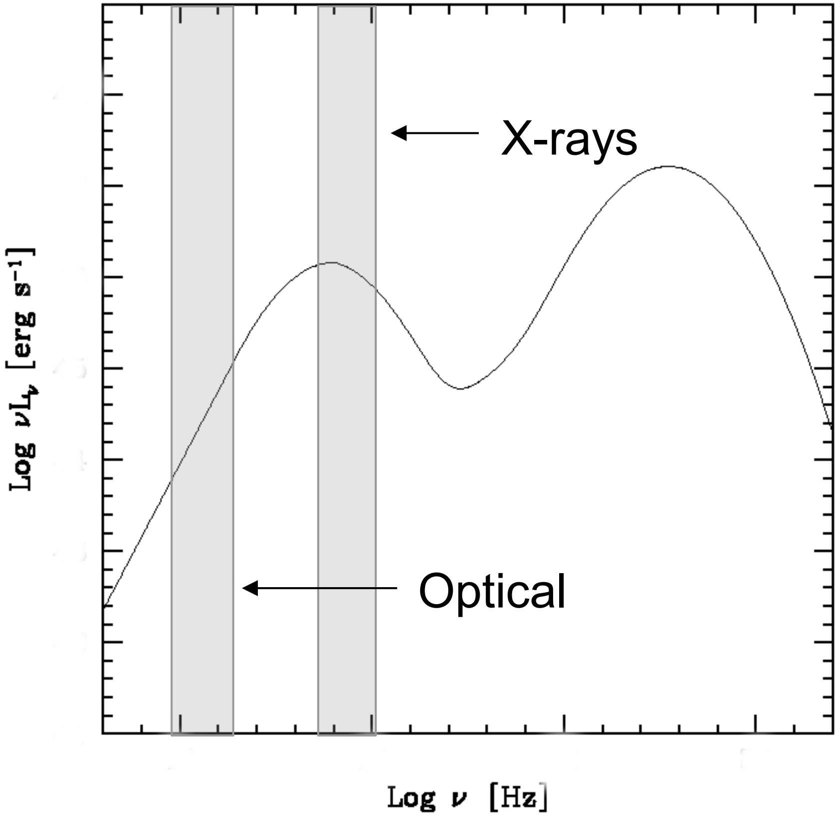
Positive detection in NGC 4151 (Gianolli et al. 2023). 2-8 keV PD=4.9±1.1%, aligned with the radio jet. Coronal polarization in between 4 to 8%, depending on the (poorly constrained) polarization of the reflection component. Slab or wedge preferred (as in Cyg X-1).

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



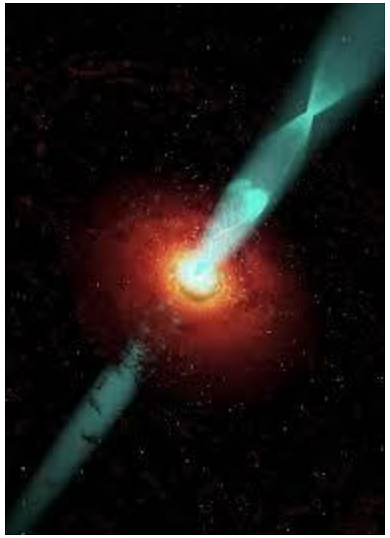
Blazars

High Synchrotron Peaked

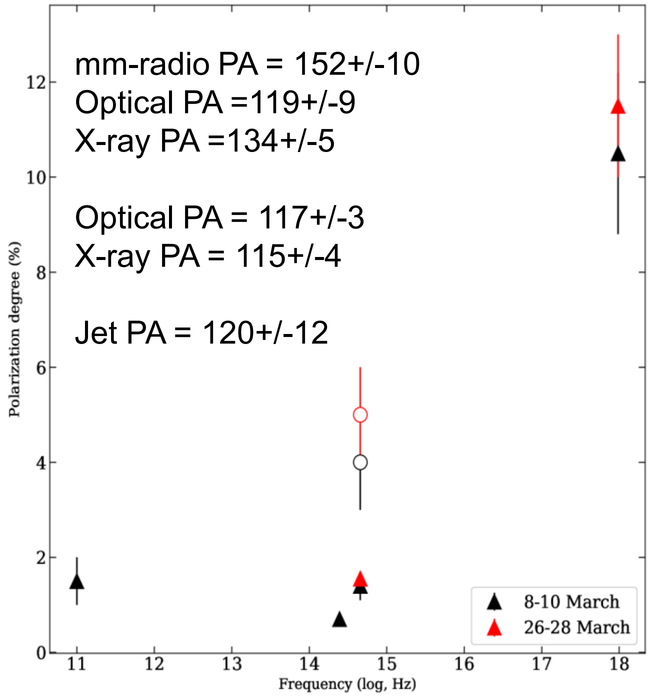


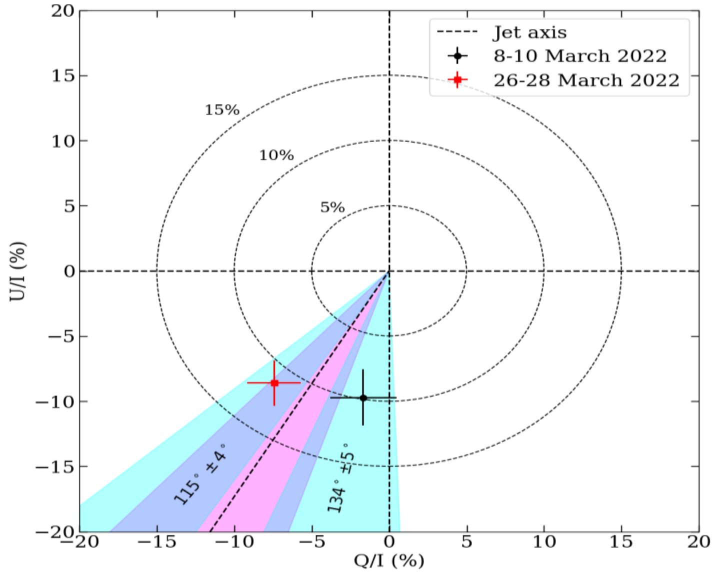
Blazars are promising sources for X-ray polarimetry. High Synchrotron Peak Blazars like Mrk 501 (*Liodakis et al. 2022*) and Mrk 421 (*Di Gesu et al. 2022*) are indeed significantly polarized. Multifrequency observations permit to discriminate among models.

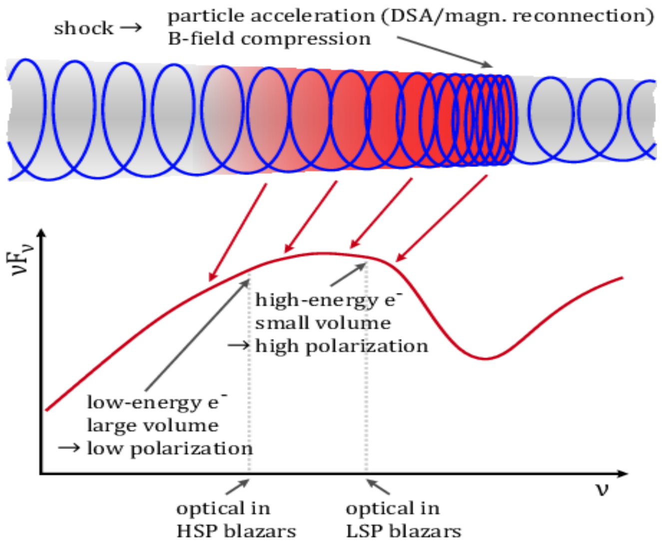
IC peak sources are instead much less polarized (e.g. Cen A, *Ehlert et al. 2022,* BL Lac*, Middei et al. 2022*).



Mrk 501





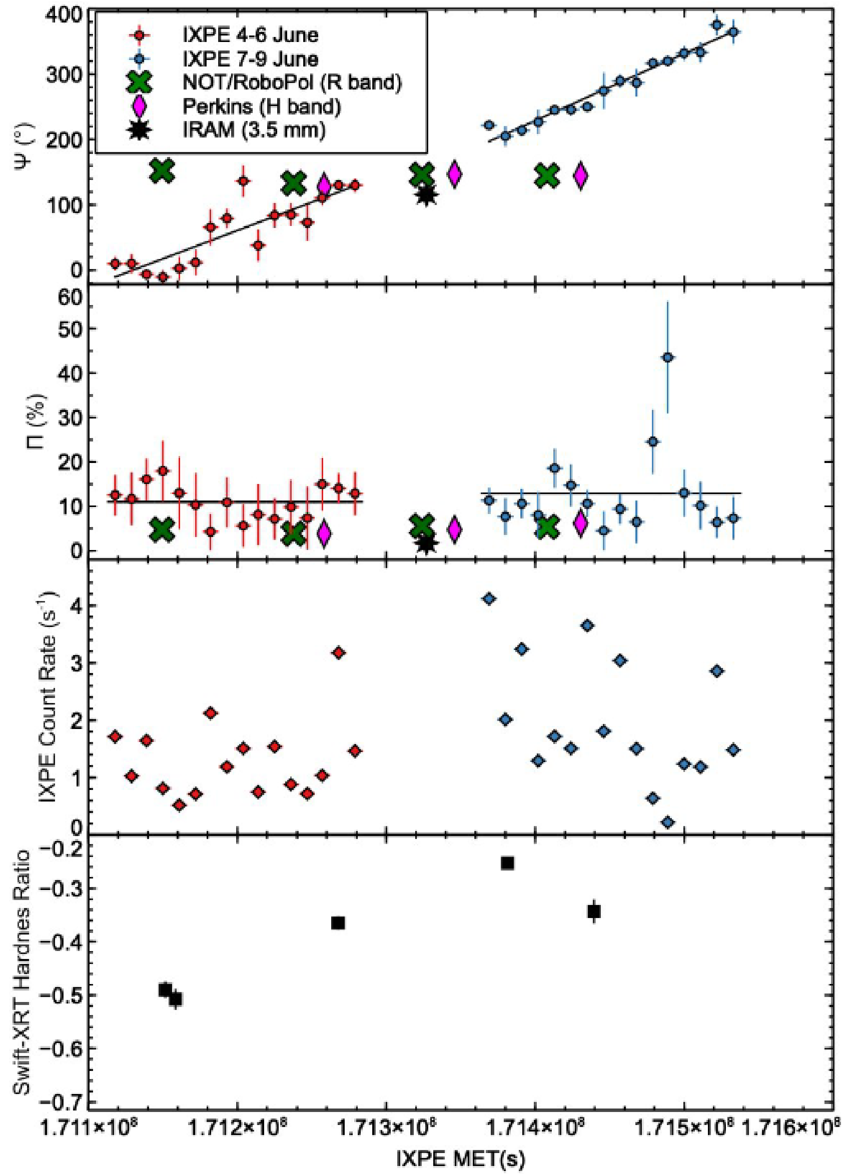


Model	Multiwavelength polarization	Variability†	Polarization angle
Single zone	constant*	moderate	any
Multizone	mildly chromatic	high	any
Energy stratified (shock)	strongly chromatic	slow	along the jet axis
Energy stratified (magnetic reconnection)	constant	moderate	perpendicular to jet axis
Observed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

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 2023). A localized shock propagating along a helical magnetic structure in the jet?



Conclusions

IXPE has really (re-)opened a new observing window!

As expected, significant polarization is rather common in X-ray sources

Not surprisingly, most of the detections are related to strong Magnetic Fields (PWN, SNR, Magnetars, X-ray Pulsars, Blazars)

But scattering polarization is also very often detected! (e.g. coronal emission in X-ray binaries and AGN, reflection in obscured AGN, Sgr A*, …)

In many cases, results (even upper limits) are discriminating between competing models, or challenging popular ones

Summary on IXPE results

Pulsar Wind Nebulae: The magnetic field is very ordered even at large distances from the pulsar.

Supernova Remnants: The magnetic field is, in most cases, radially directed even in the vicinity of the shock.

Accreting stellar-mass Black Holes: A radially extended hot corona is favoured. Standard disc model does not work in at least one source.

Accreting Neutron Stars: The rotating vector model for X-ray pulsars works in X-rays. The degree of polarization is 5-6 times smaller than expected by simple models. Neutron star precession observed in Hercules X-1. Weakly magnetized accreting neutron stars typically polarized at a few percent level.

Magnetars: Different magnetars show different behavior on the polarization degree and angle. Evidence for condensed surfaces.

Galactic Center: Molecular clouds points to Sgr A* as origin of their reflected emission

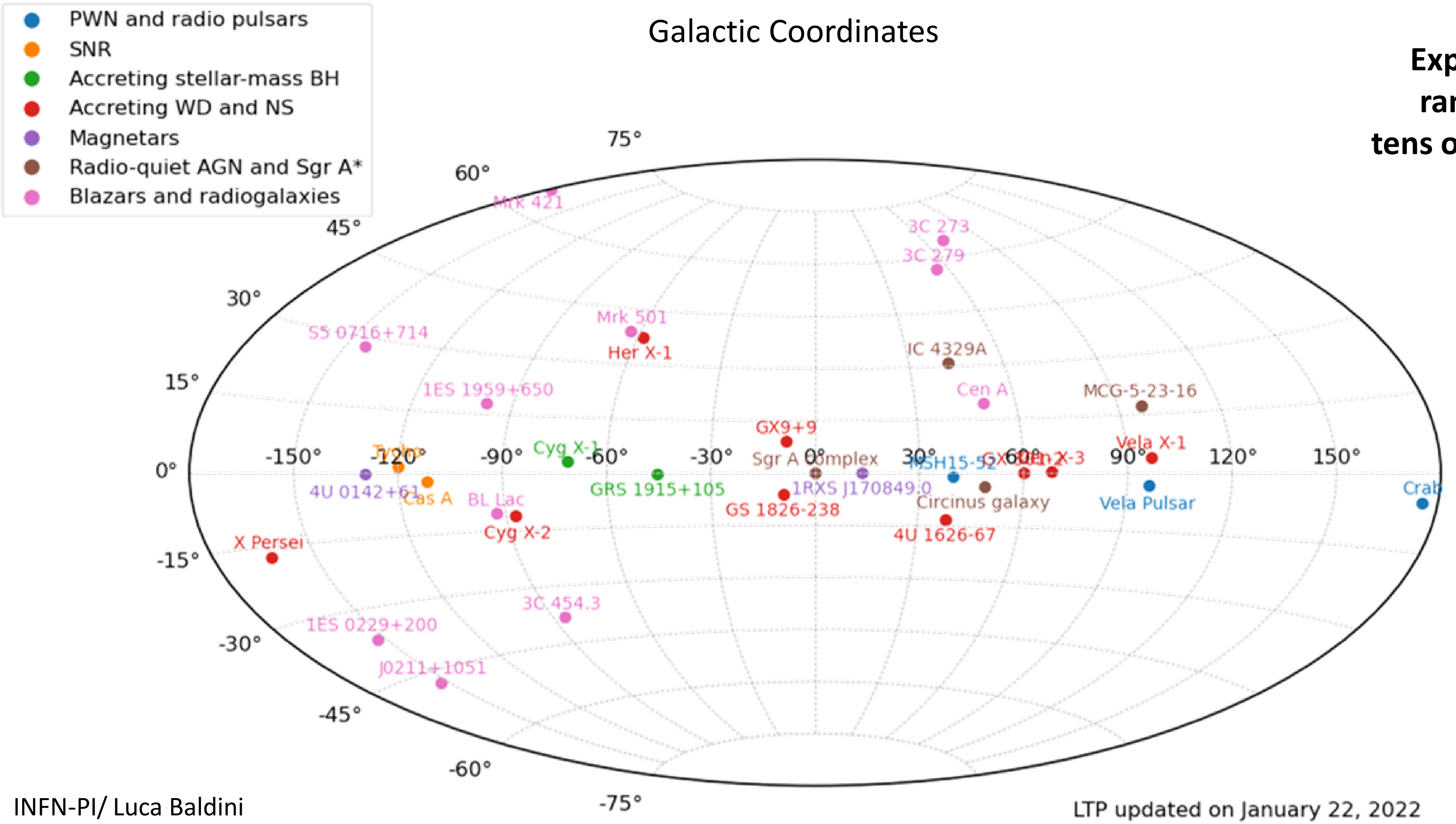
Radio-Quiet AGN: A radially extended hot corona is favoured. High polarization confirms obscuring torus in Compton-thick AGNs.

Blazars and Radio Galaxies: Energy stratified shock acceleration is confirmed. Fast rotation of the X-ray polarization vector is observed in some Synchrotron dominated blazars. Inverse Compton dominated blazars are much less polarized.

Thanks for your attention

Backup slides

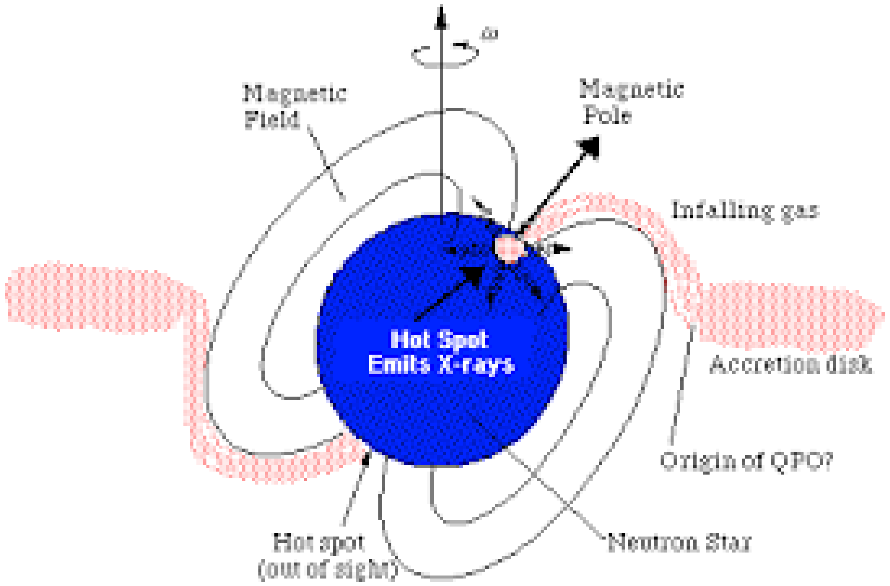
Year-1 targets

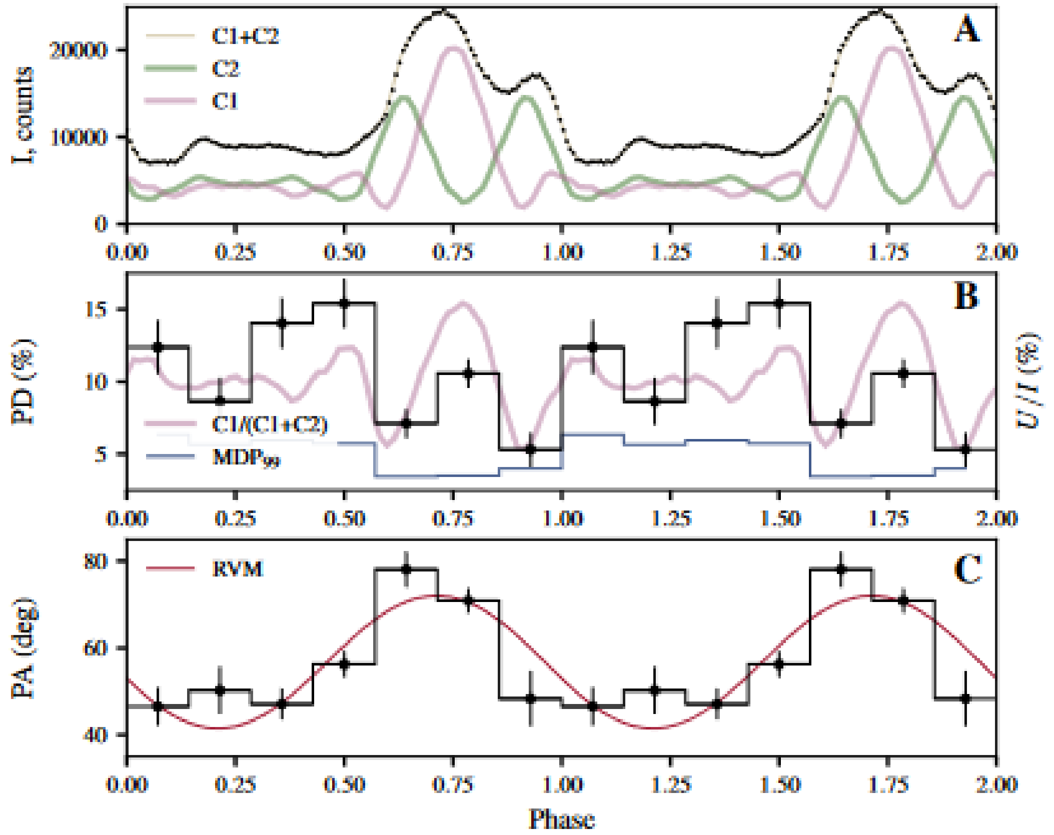


Exposure times ranging from tens of ks to ~1 Ms

INFN-PI/ Luca Baldini

Accreting NS – X-ray Pulsars





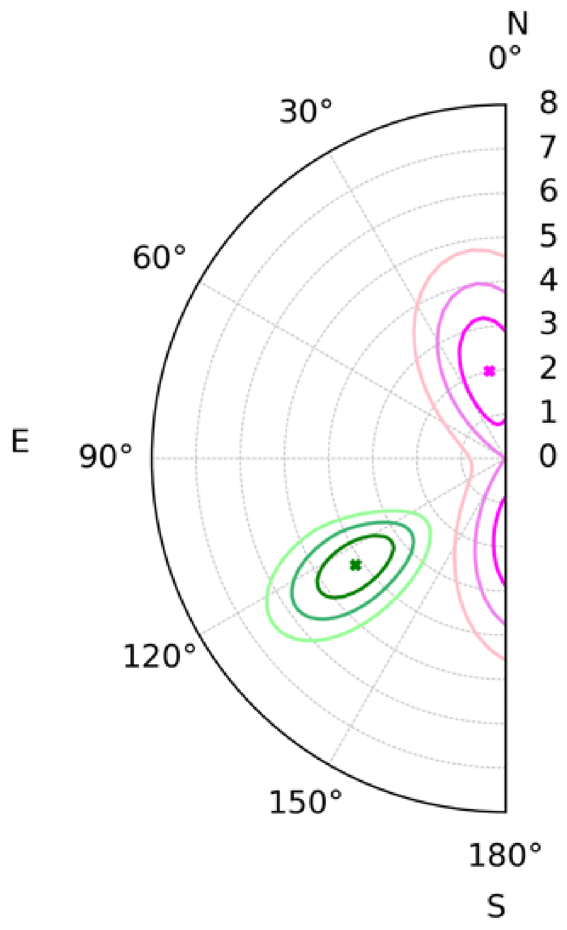
Doroshenko et al. 2022

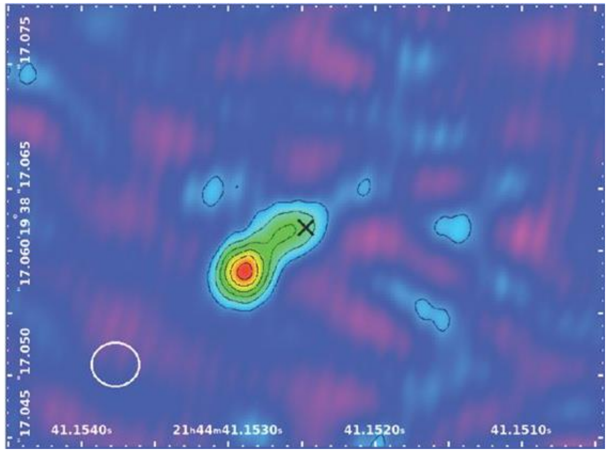
X-ray pulsars are predicted to be very highly polarized, while the polarization is lower than expected, but detected with very high significance in a number of sources, e.g. Her X-1 (*Doroshenko et al. 2022*), Cen X-3 (*Tsyganov et al. 2022*), Vela X-1 (*Poutanen et al. 2023*), GRO J1008-57 (*Tsyganov et al. 2023*) + X Persei (*Mushtukov et al. 2023*) + …

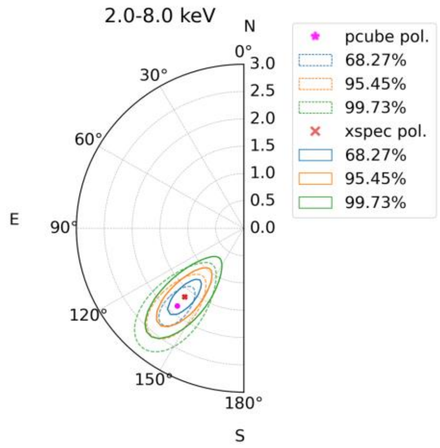
Weakly Magnetized Accreting NS

Not pulsating accreting NS were expected to be much less polarized (e.g. *Gnarini et al. 2022)*. IXPE is confirming this prediction, with a tight upper limit for GS 1826-238 (*Capitanio et al. 2023*) but a positive detection (PD of a few percent) for many others: Cyg X-2 *(Farinelli et al. 2023*), GX9+9 (*Ursini et al. 2023, Chatterjee et al. 2023*), XTEJ1701-462 (*Cocchi et al. 2023, Jayasurya et al. 2023*), 4U1820-303 (*di Marco et al. 2023*), GX 5-1 (*Fabiani et al. 2023*), Cir X-1 (*Rankin et al. 2024*), Sco X-1 (*La Monaca et al. 2024*), 4U1624 (*Saade et al. 2024*), GX13+1 (*Bobrikova et al 2024*)

e.g. Cyg X-2: PA of Comptonization component (green) is consistent with radio jet direction, suggesting emission from spreading/transition layer at the neutron star surface. Pink shows the disk emission.





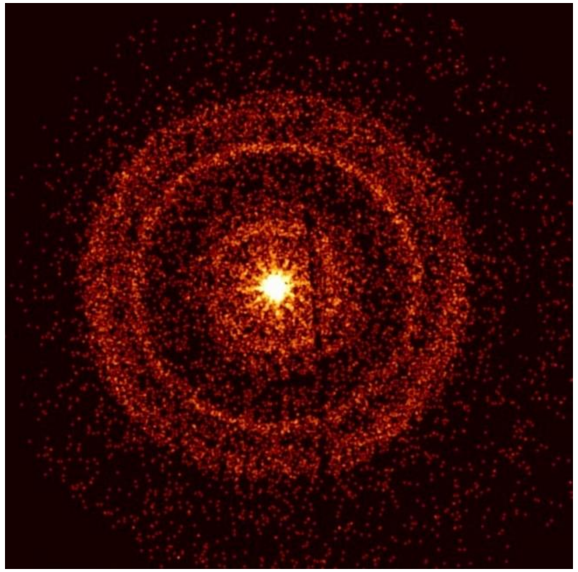


Farinelli et al. 2023

GRB 221009A

We did not plan to follow-up on GRBs, because of the relatively slow reaction time (2-3 days).

However, GRB 221009A (the ‘BOAT’ GRB) was so exceptional in terms of brightness, that we decided to observe it.



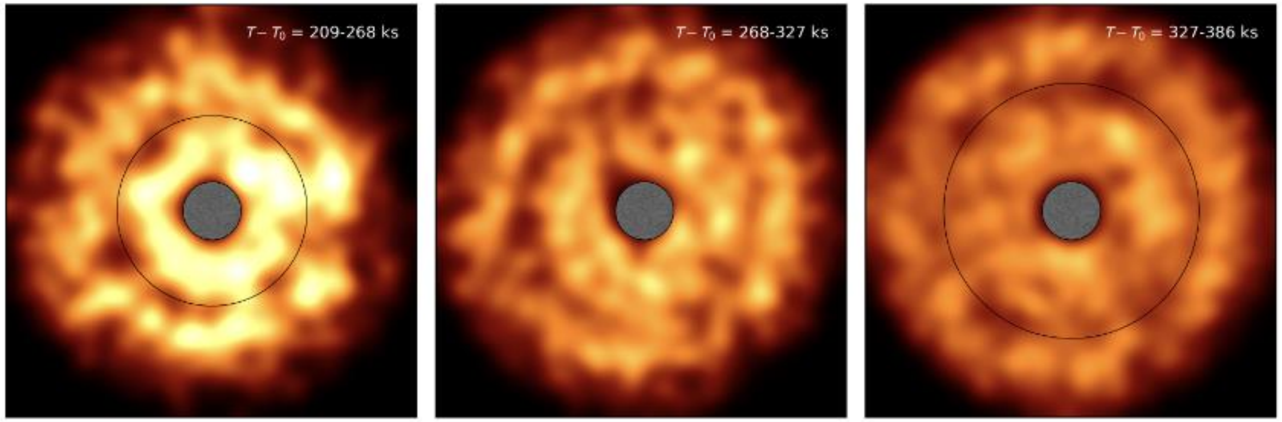
Swift/XRT image

P<13.8% (99% c.l.)

(Negro et al. 2023)

Dust rings also observed →

polarization of the prompt emission (<55%)



Time evolution of dust rings as seen by IXPE

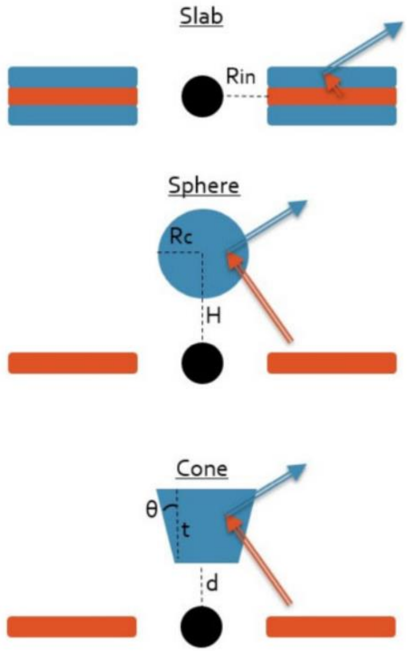
Radio Quiet AGN

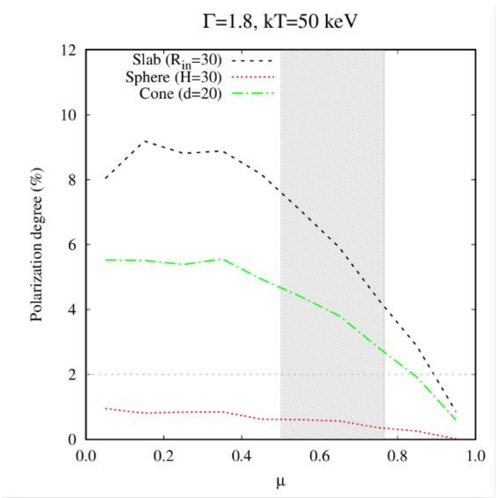
X-ray spectroscopy can constrain the physical parameters of the corona.

However, it is almost insensitive to its shape and location.

Polarimetry, on the contrary, is very sensitive to the geometry of the corona, and can measure deviations from a spherical symmetry.

The coronal geometry is related to its physical origin.

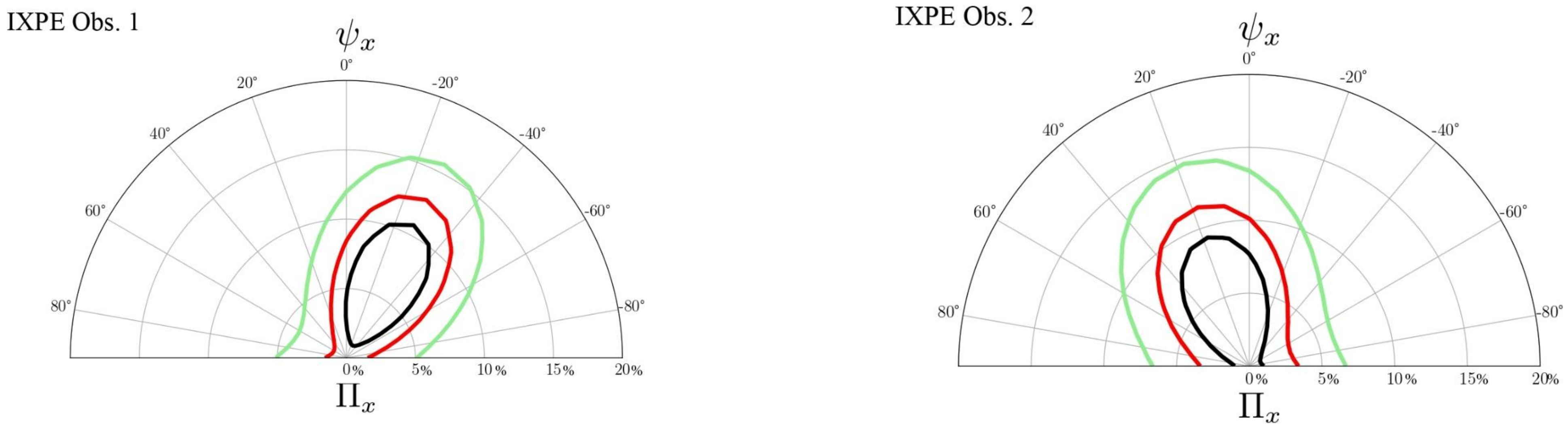




BL Lac

In the LSP BL Lac X-ray emission is no longer dominated by electron Synchrotron. The source was pretty faint when observed by IXPE, and only an u.l. of 12.6% (99% c.l.) to the polarization degree could be obtained (*Middei et al. 2022*).

Hadronic models disfavoured in this source!



But polarization detected later on during an outburst (*Peirson et al 2023*) → Synchrotron emission likely extending to the IXPE band

Compton-thick AGN

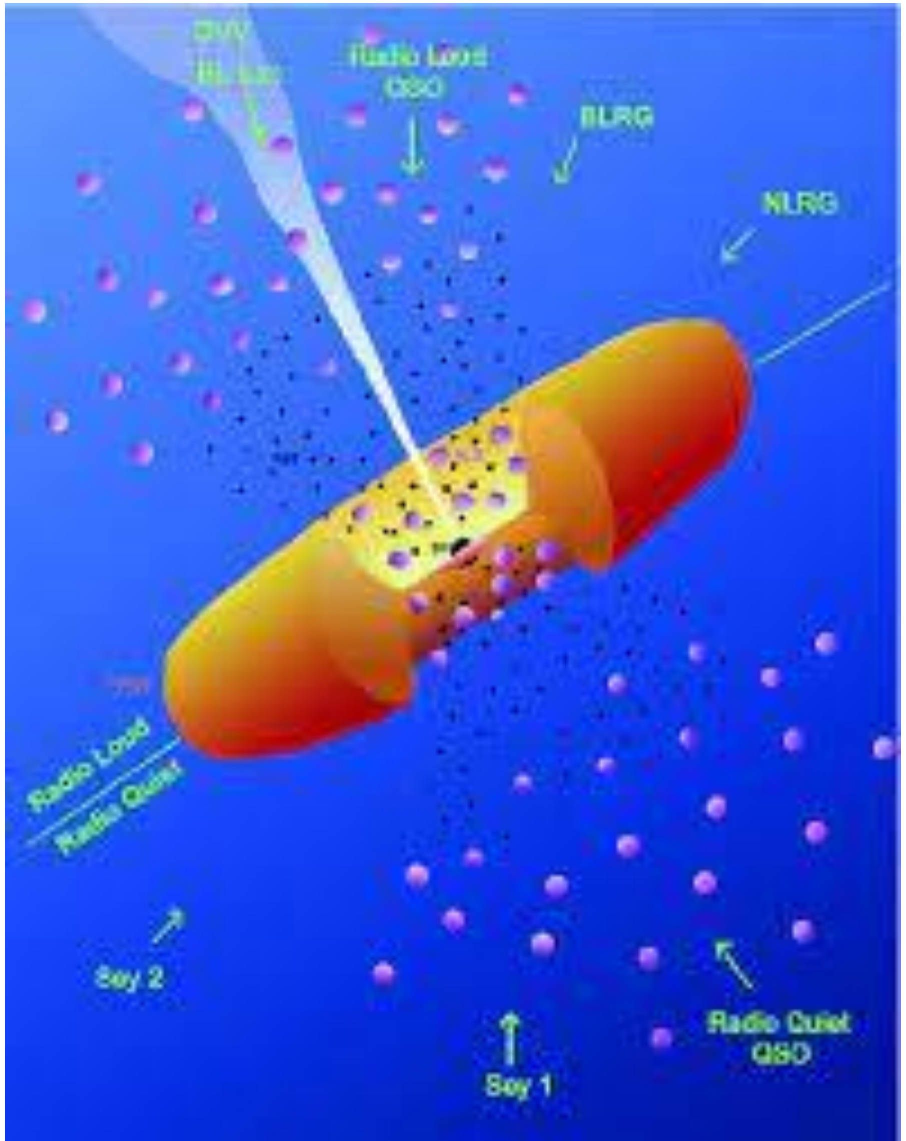
X-ray emission is dominated by reflection, so it should be highly polarized.

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

The polarization vector is expected to be orthogonal to the torus axis.

The ionization cone/NLR may also scatter (and polarize) the primary emission.

Polarization vectors from ionization cone and torus are the same, if coaligned.



Compton-thick AGN: the Circinus Galaxy

In Compton-thick AGN the X-ray emission is dominated by cold reflection from the "torus" (the nucleus being obscured)

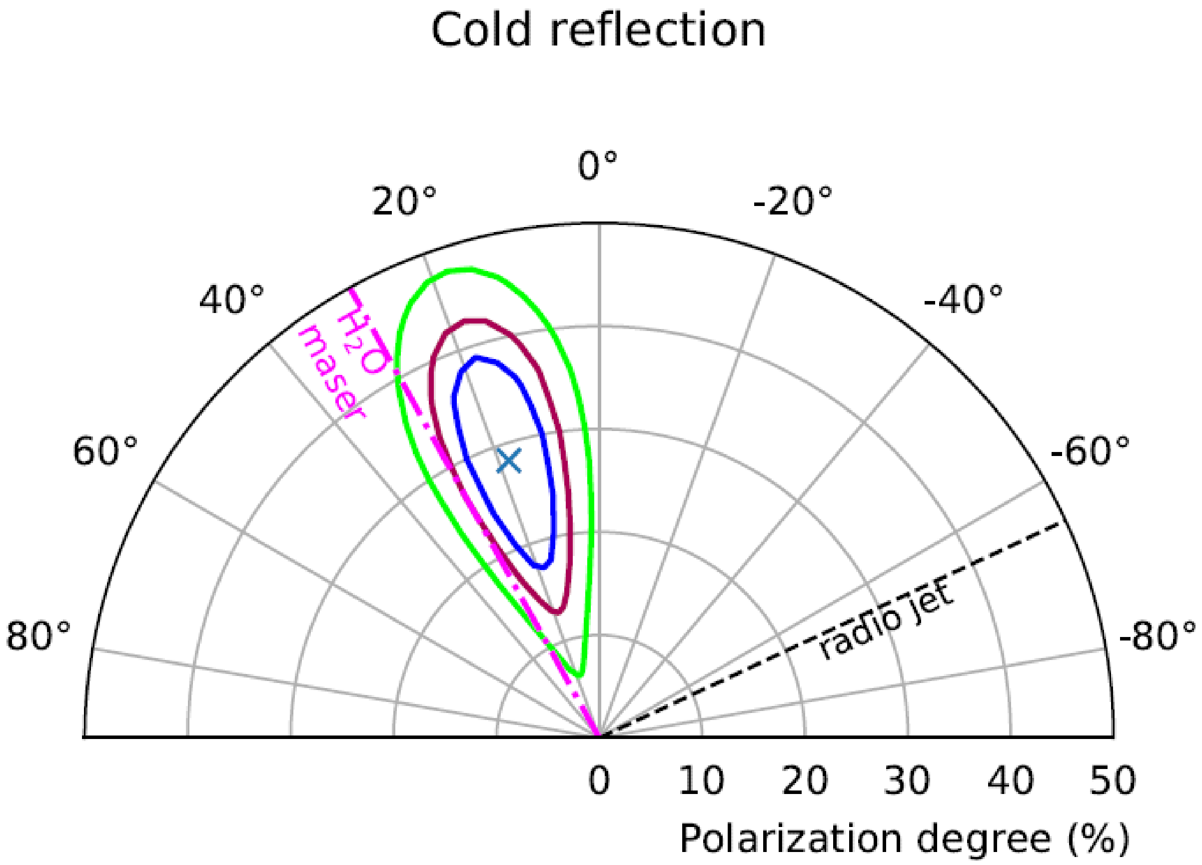
Spectro-polarimetric analysis for Circinus galaxy shows for the cold reflector:

- PD = 28% ± 7%
- PA = 18° ± 5°, perpendicular to radio jet

Confirms AGN Unification Model.

Also constrains torus geometry (opening angle likely in the 45-55 deg range (*Ursini et al. 2023*).

Qualitatively similar results for NGC 1068 (*Marin et al. 2024*)



Ursini et al. 2023

General Observer Program

GO Cycle 1 Proposals were due on October 18, 2023

- 135 proposals - 121 regular, 14 theory, 6 large
- 103 Ms of IXPE time requested, oversubscription > 6
- Over 1400 co-Is (174 institutions, 30 countries)
- 48 proposals part of student theses

- 99 distinct targets, includes source classes beyond prime mission:
- tidal disruption events, white dwarfs, galaxy clusters, recurrent nova

- Approved 39 proposals: 31 regular, 1 large, 7 theory
- Regular in categories A (13), ToO (8), and C (10)
- ToO were very highly oversubscribed, by a factor of 9
- GO observations started on 2024-02-03T12 UTC
- Will conduct 15 Ms of GO observations, including one large program for 2 Ms