

X-RAY POLARIZATION IN ACTIVE GALACTIC NUCLEI

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X-RAY POLARIMETRY

Information on celestial (extra-solar) sources is mostly provided by studying the spatial, spectral, timing and **polarization** properties of the observed electromagnetic 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

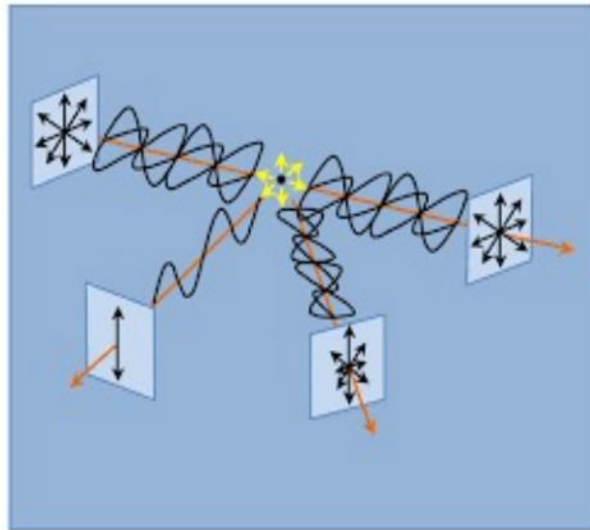
Our knowledge of the emission from a celestial source in any energy band is therefore incomplete without polarimetry. However, polarimetric information was basically missing in the X-ray band before IXPE!

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

X-RAY POLARIMETRY

Linear polarization defines an orientation on the sky and therefore probes source geometry (of the emitting matter, the radiation field, the magnetic field, the space-time, ...)

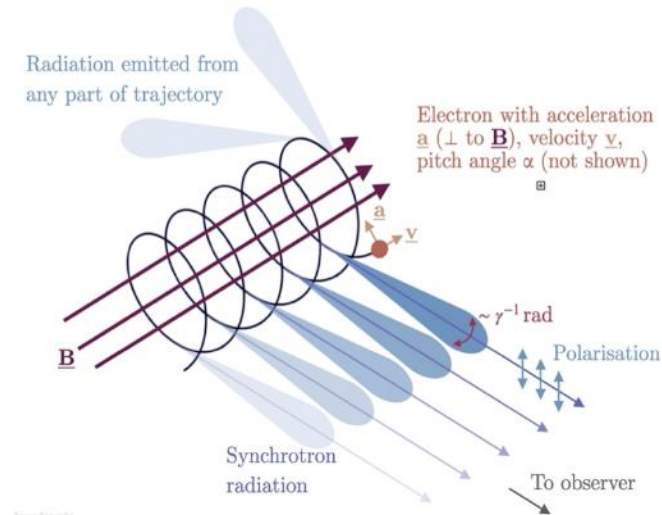
Scattering / reflection



EVPA perpendicular to scattering plane

(EV)PA = (electric vector) position angle / polarization angle

Synchrotron radiation



EVPA perpendicular to magnetic field lines

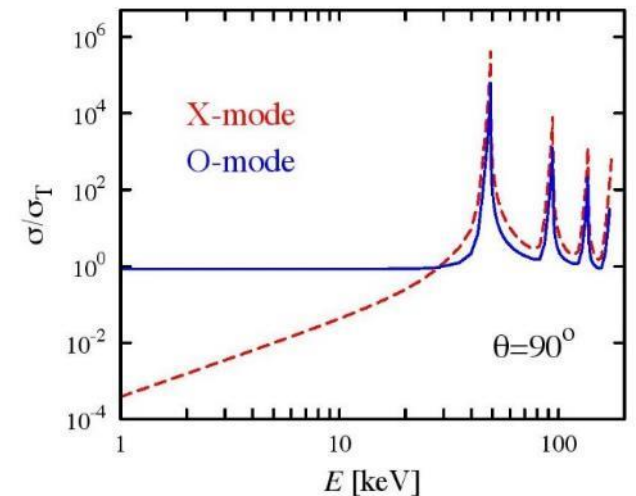
General relativity

$$\nabla_k f = 0$$



EVPA changes

Highly magnetized plasma



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

IXPE MISSION DESCRIPTION

- A **NASA/ASI** mission within 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
- **PI: *Phil Kaaret* (former PI, until May 2022: *Martin Weisskopf*)**



MARTIN CHARLES WEISSKOPF

(April 21, 1942 – May 2, 2026)

Rossi Prizes:

2004 with H. Tananbaum for the Chandra XRO

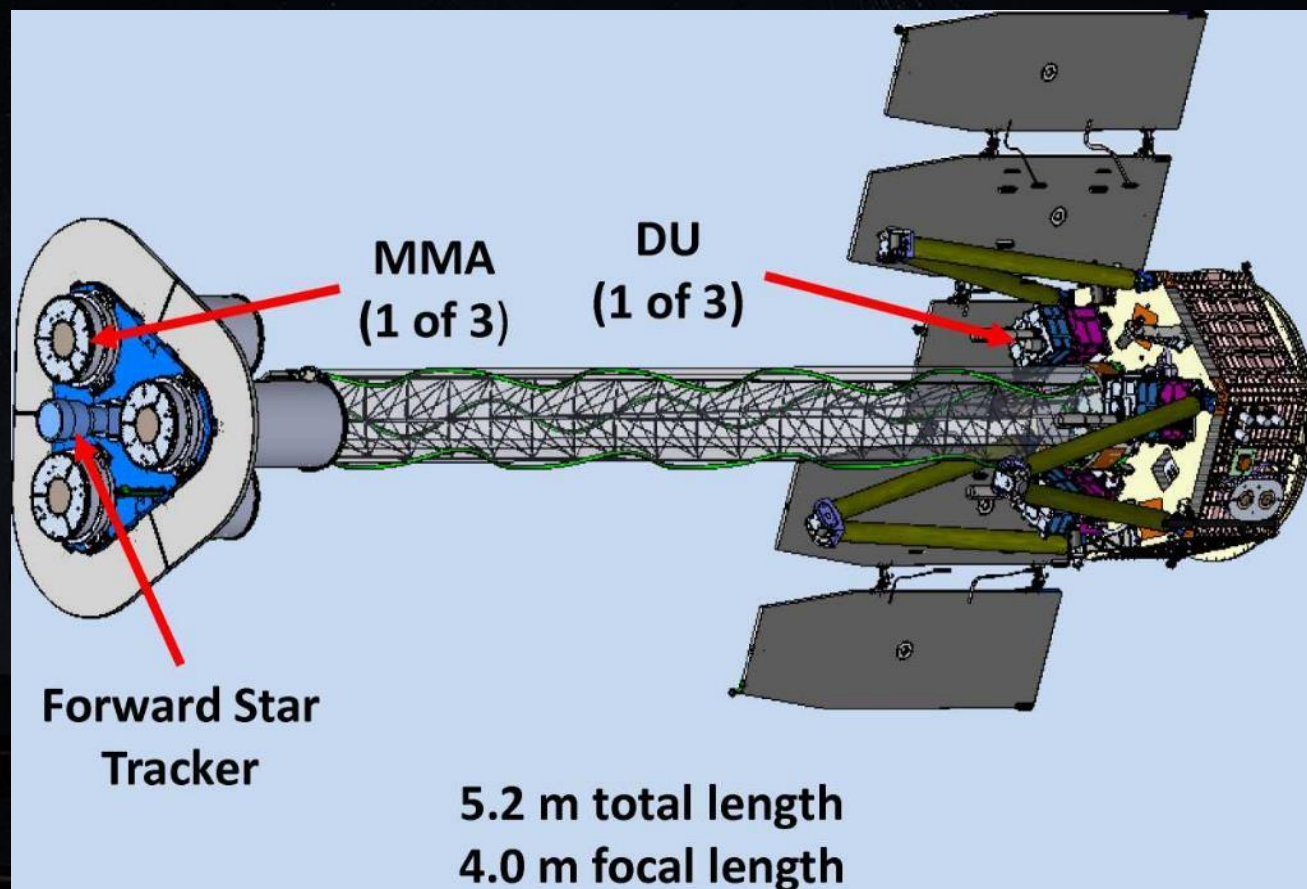
2024 with P. Soffitta and the IXPE team





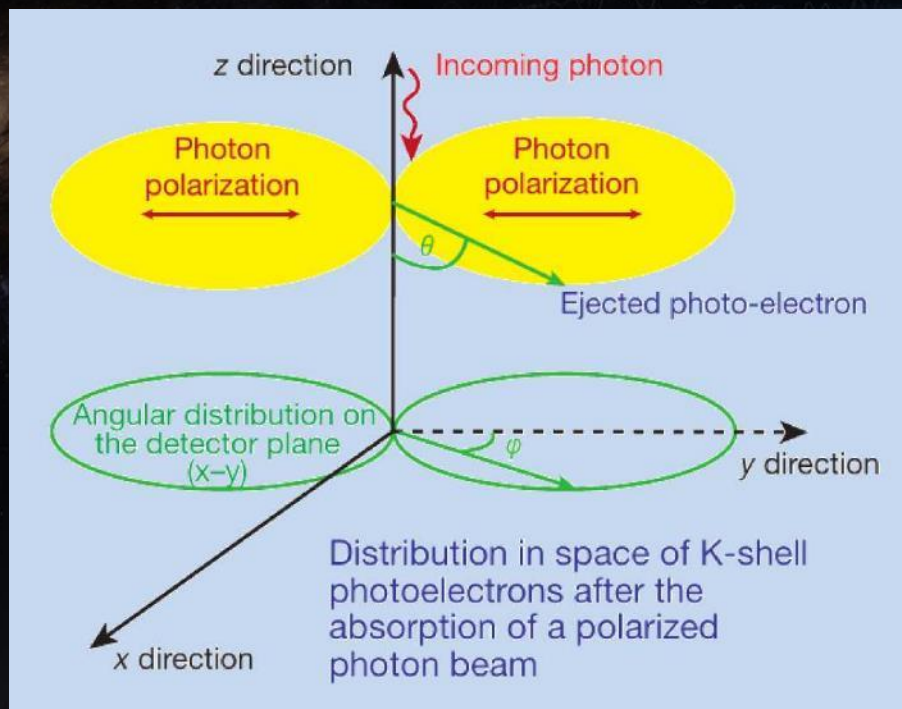
- ✓ 3 Telescopes
- ✓ 3 Detector Units (Gas Pixel Detectors)
- ✓ Energy range: 2-8 keV
- ✓ Angular resolution: 30" (HPD)
- ✓ FOV=13'
- ✓ Energy resolution: 0.57 keV @ 2 keV (FWHM)

IXPE IN A NUTSHELL

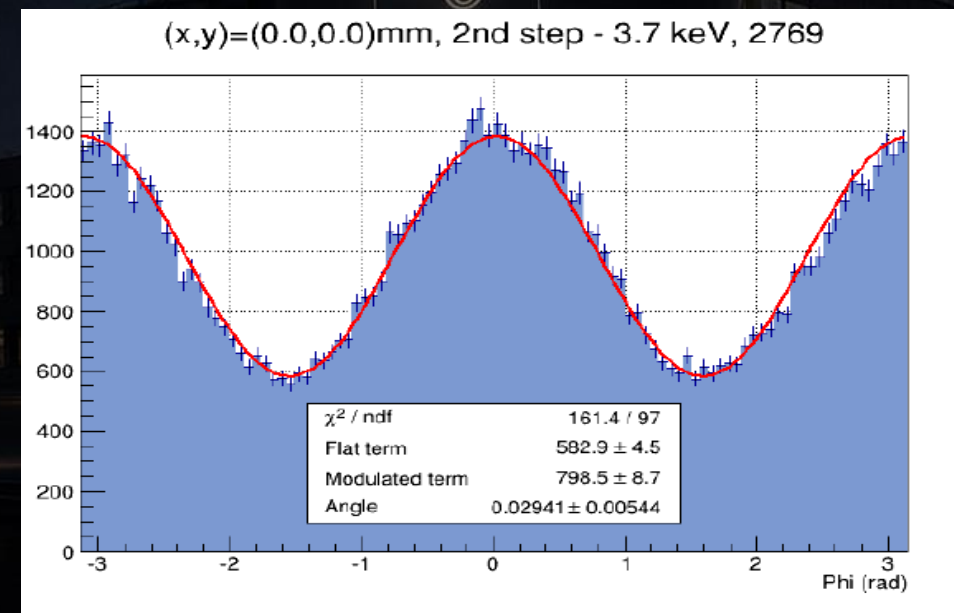
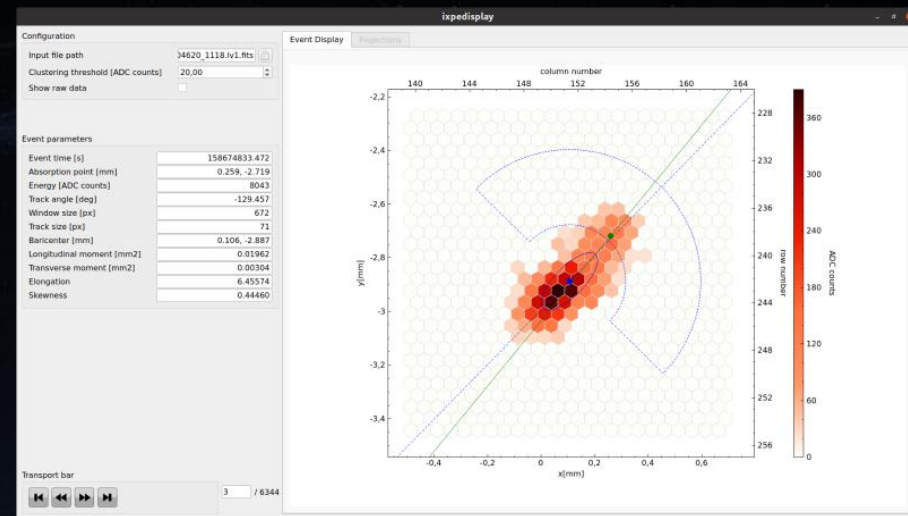


POLARIZATION DETECTION PRINCIPLE

Based on the photoelectric effect



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



IXPE OBSERVING PROGRAM

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

Extended mission approved; next NASA Senior Review expected in 2028

A General Observer Program now in place

Deadline for GO4 proposals: September 17, 2026

Joint programs with NuSTAR, Swift, XRISM, XMM-Newton (new!) and NSF/NRAO

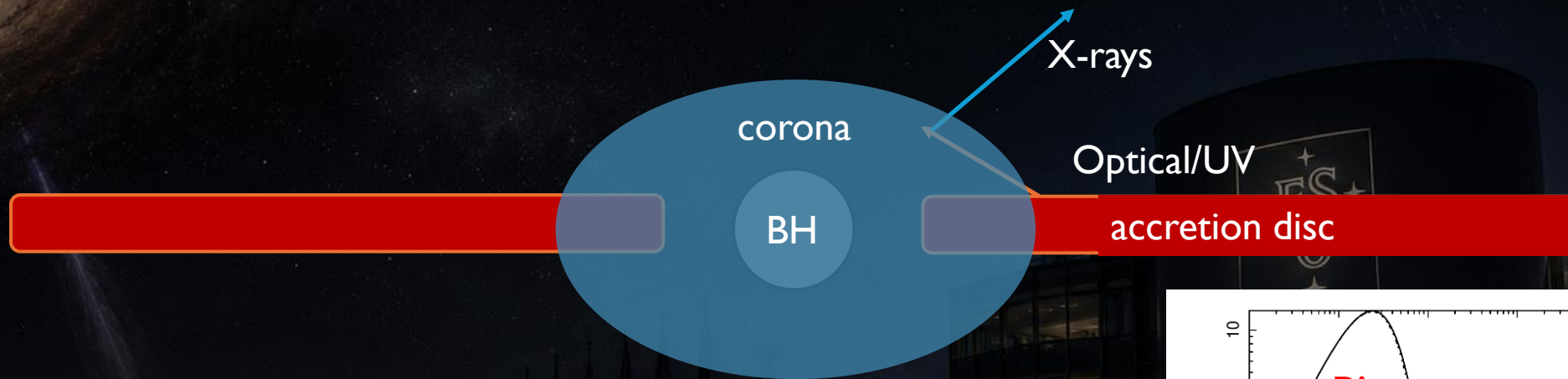
IXPE RESULTS: BASELINE PHASE

PWNe and isolated pulsars	Crab PWN,Vela PWN, MSH 15-52, PSR B0540-69, G21.5
SNR	Cas A,Tycho's, NE SN 1006, RCW 86, RX J1713.7-3946,Vela Jr.
Accreting stellar-BH	Cyg X-1, 4U 1630-472, Cyg X-3, LMC X-1, SS 433 Lobes, LMC X-3, 4U 1957+115, Swift J1727.8-1613
Accreting NS	Cen X-3, Her X-1, GSI826-67, Vela X-1, Cyg X-2, GX 301-2, X Persei, GX 9-9, 4U 1820, GRO J1008-57, XTE J1701-462, EXO 2030+375, LS V+44 17, GX 5-1, 4U 1624-49, Sco X-1, Cir X-1, GX13+1, SMC X-1, Swift J0243.6+6124
Magnetars	4U 0142+61, 1RXS J170849.0-400910, SGR 1806-20, 1E 2259+586
Radio-quiet AGN & 1 Sgr A*	MCG 5-23-16, Circinus Galaxy, NGC 4151, IC 4329 A, Sgr A* Complex, NGC 1068
Blazars & radio galaxies	Cen A, S5 0716+714, Mrk 421, BL Lac, 3C 454.3, 3C 273, 3C 279, Mrk 501, 1ES 1959+650, 1ES 0229+200, PG 1553+113, S4 0954+65

Positive detection in the majority of sources!

RADIO QUIET AGN

In AGN the primary X-ray emission is produced by Comptonization of UV/soft-X-ray disc photons by hot coronal electrons (Shapiro+76; Sunyaev & Titarchuk+80; Haardt & Maraschi+91)



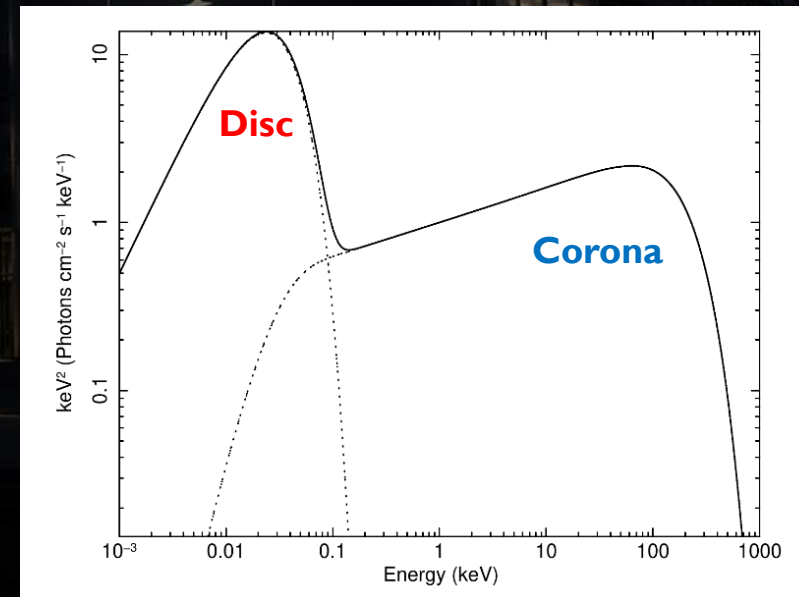
Cutoff power law

Γ depends on τ and kT

E_c depends on kT

Temperature $kT \sim 10 - 100$ keV

Thomson optical depth $\tau \sim 1$

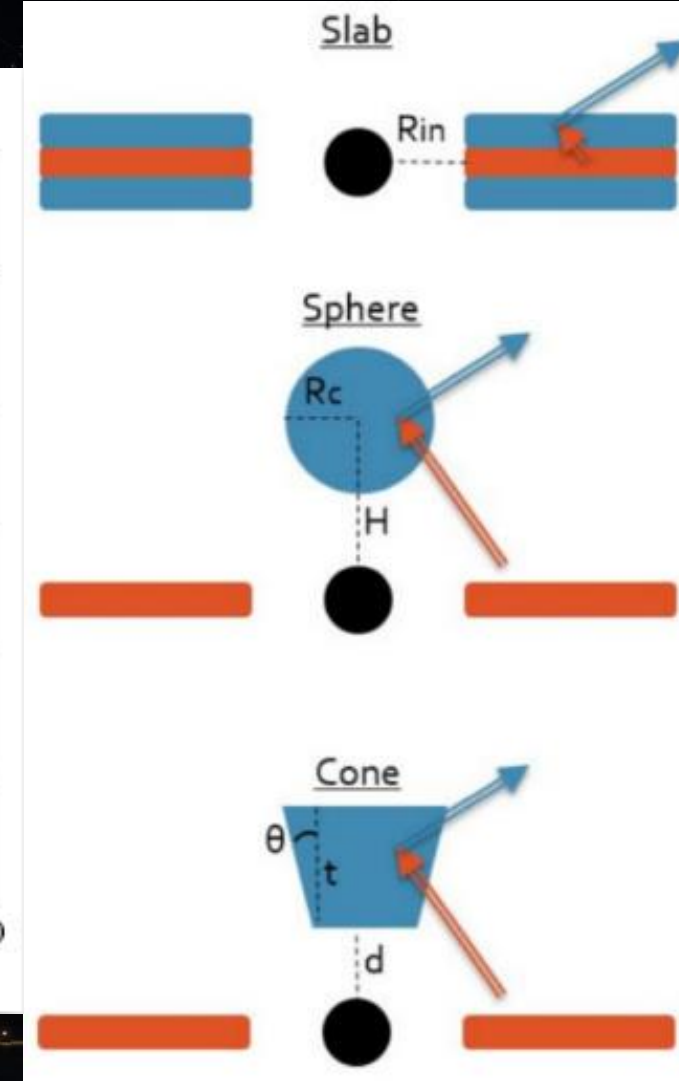
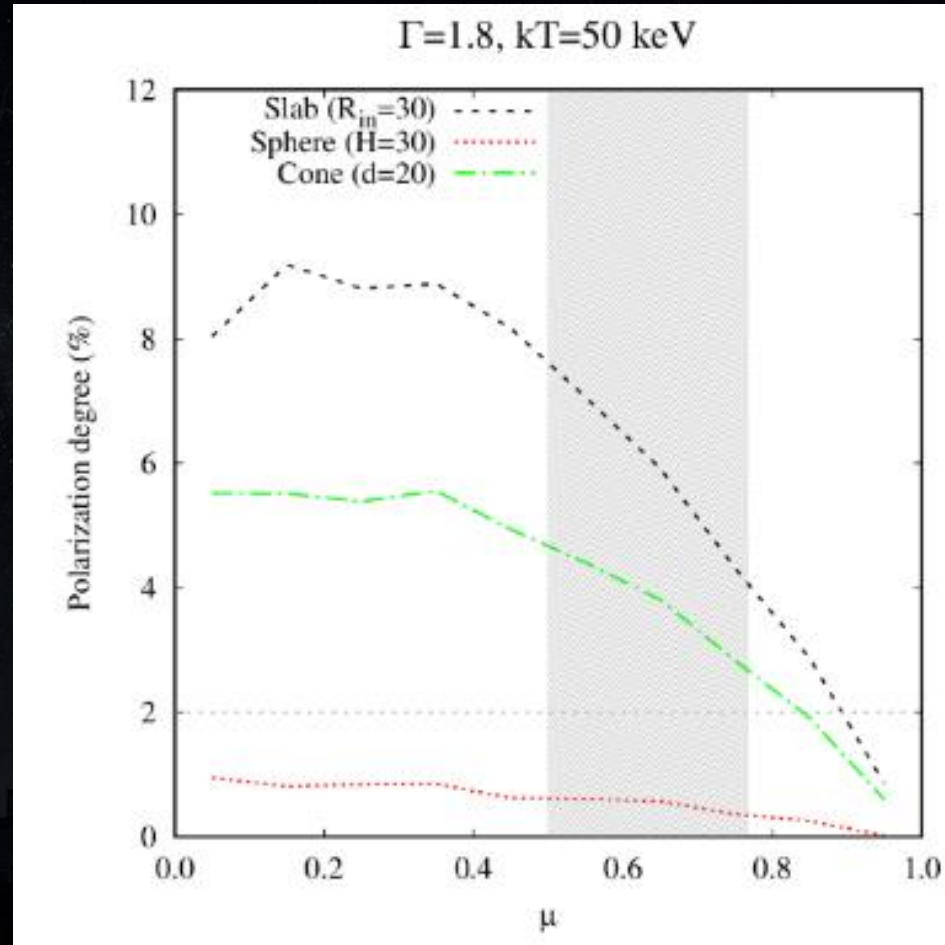


RADIO QUIET AGN

X-ray spectroscopy can constrain the physical parameters of the corona, but 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 spherical symmetry

The coronal geometry is related to its physical origin



RADIO QUIET AGN

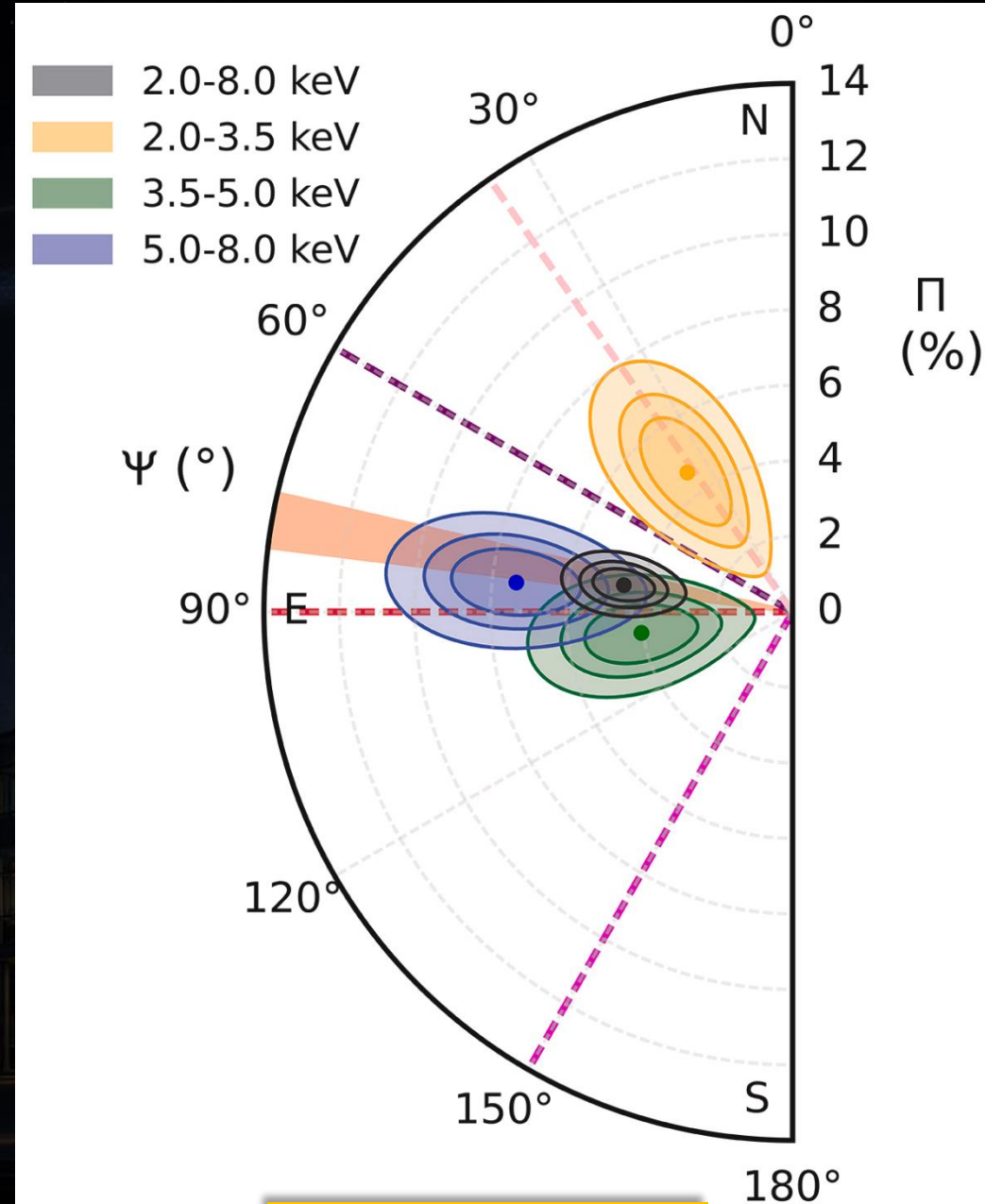
NGC 4151 Two IXPE observations
(Gianolli+23,+24) yield consistent results:

$$PD = 4.5 \pm 0.9\% - PA = 81^\circ \pm 6^\circ$$

Above ~ 4 keV, $PD \sim 6 - 7\%$ and the PA is aligned with the radio jet, as in the BH XRB Cyg X-1, favouring a radially extended **slab/wedge corona**

Below ~ 4 keV, a significant PA rotation reveals an additional polarized component, likely scattered emission

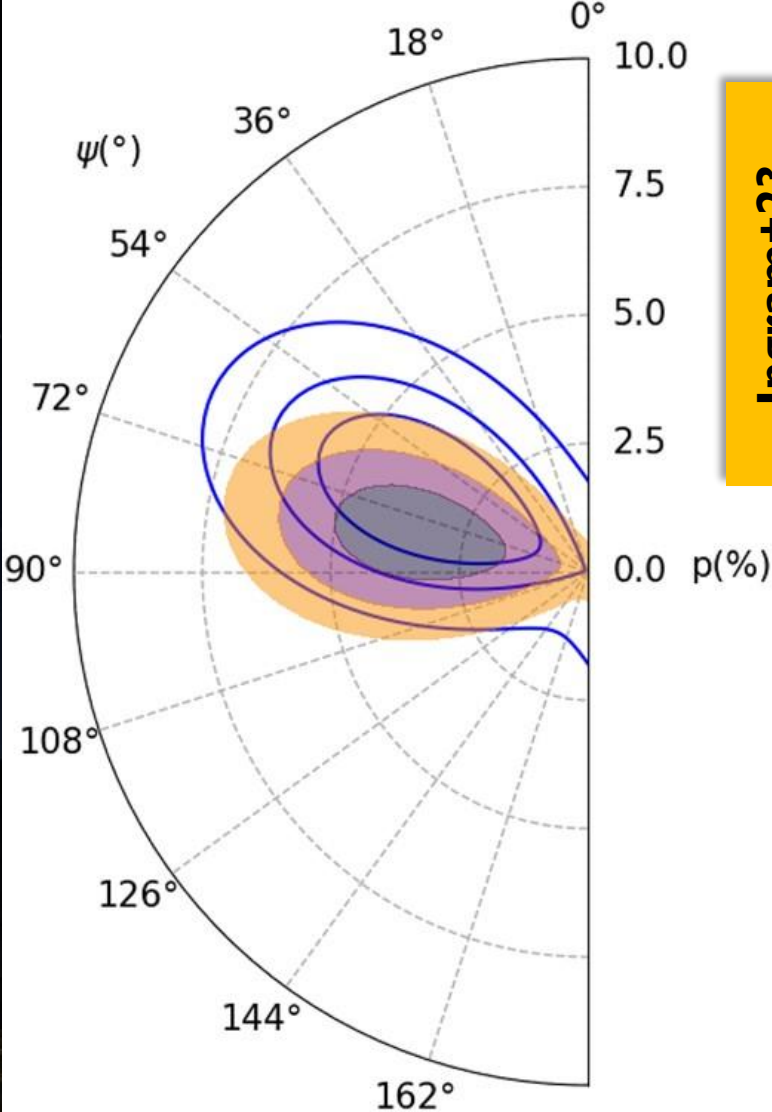
Caveat: The same data can also be reproduced by relativistic disk reflection from a compact lamp-post corona (Kammoun+26)



Gianolli+24

RADIO QUIET AGN

IC 4329A (Ingram+23)	$PD = 3.3 \pm 1.1\%$ PA aligned with the radio axis	Supports a radially extended , possibly outflowing corona
MCG–05-23-16 (Marin+26)	$PD < 2.5\%$ (99%, three obs)	Consistent with an equatorial corona if the inclination is low
NGC 2110 (Pal+25)	$PD < 7.6\%$ (99%)	Very low-flux state; no useful constraint on coronal geometry



The IXPE radio-quiet, Compton-thin AGN sample is still expanding:
NGC 3227, NGC5506, IES 1927+654, Ark 564, Fairall 51, and MCG–6-30-15
have already been observed

COMPTON-THICK AGN

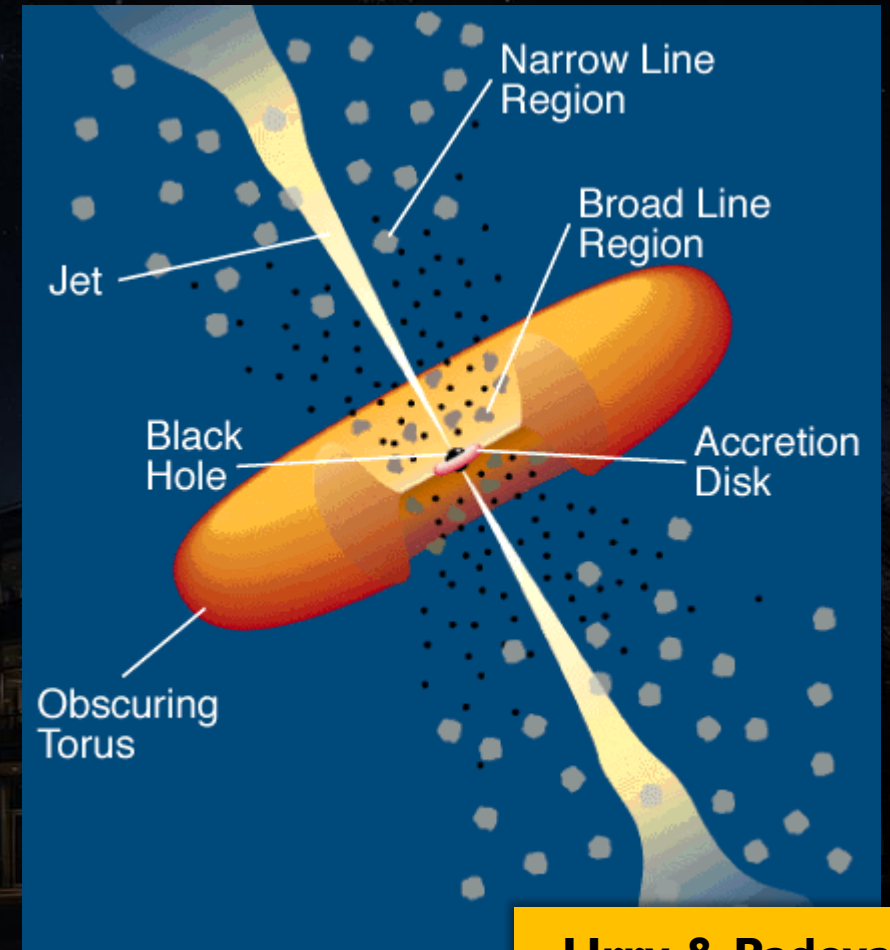
X-ray emission is dominated by **reflection**, so it should be **highly polarized**

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 also scatters (and polarizes) the primary emission

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



Urry & Padovani

COMPTON-THICK AGN

Ursini+23

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

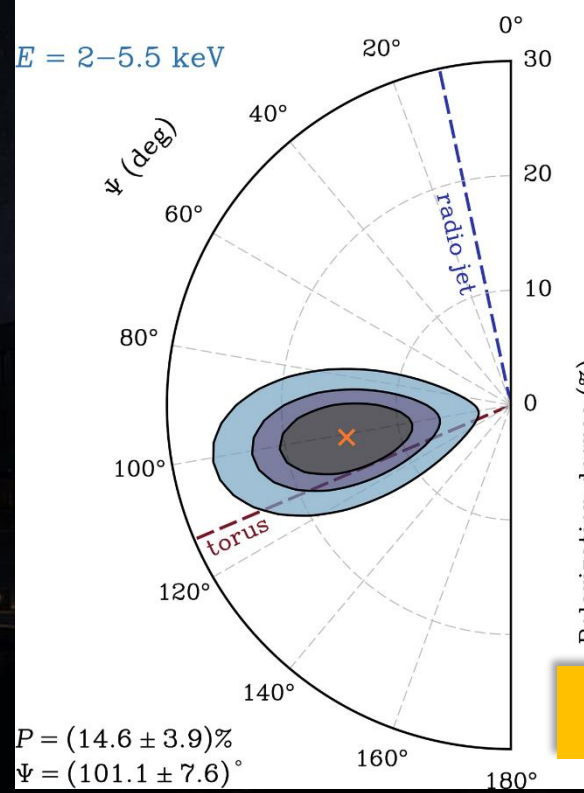
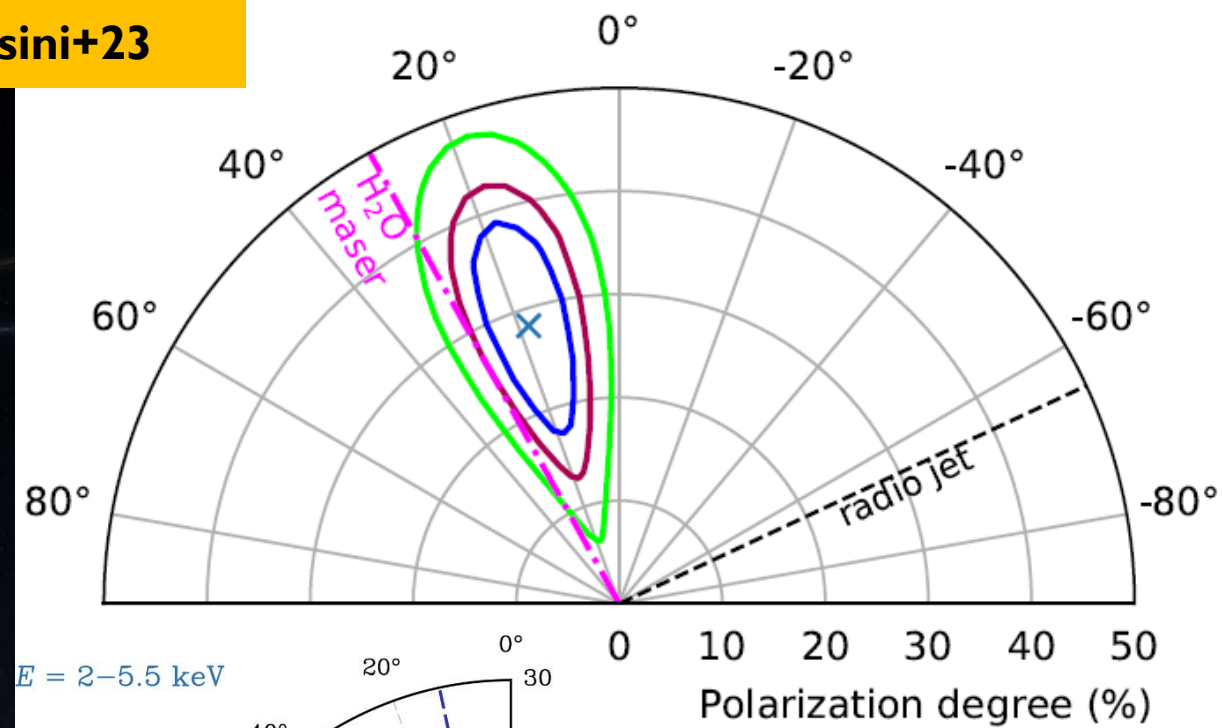
Spectro-polarimetric analysis for **Circinus** shows for the cold reflector:

$$PD = 28 \pm 7\%$$

PA = $18^\circ \pm 5^\circ$, perpendicular to radio jet

AGN Unification Model confirmed!

It also constrains torus geometry: opening angle $\sim 45 - 55$ deg



Qualitatively similar results for **NGC 1068**

Marin+24

RADIO QUIET AGN: THE EMERGING PICTURE

MGC-05-23-16 (combined)

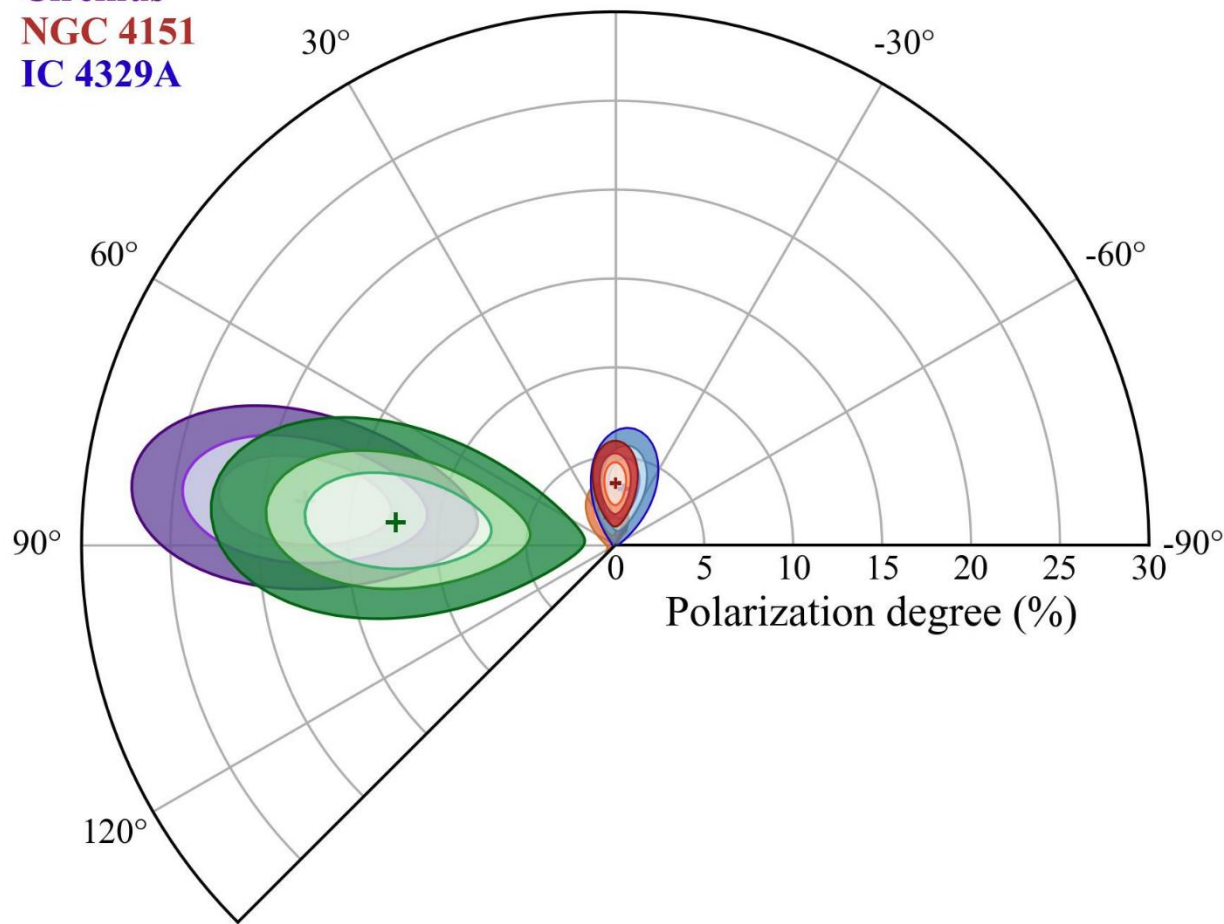
NGC 1068

Circinus

NGC 4151

IC 4329A

$\psi_X - \psi_R$
0°



Two distinct polarization regimes emerge:

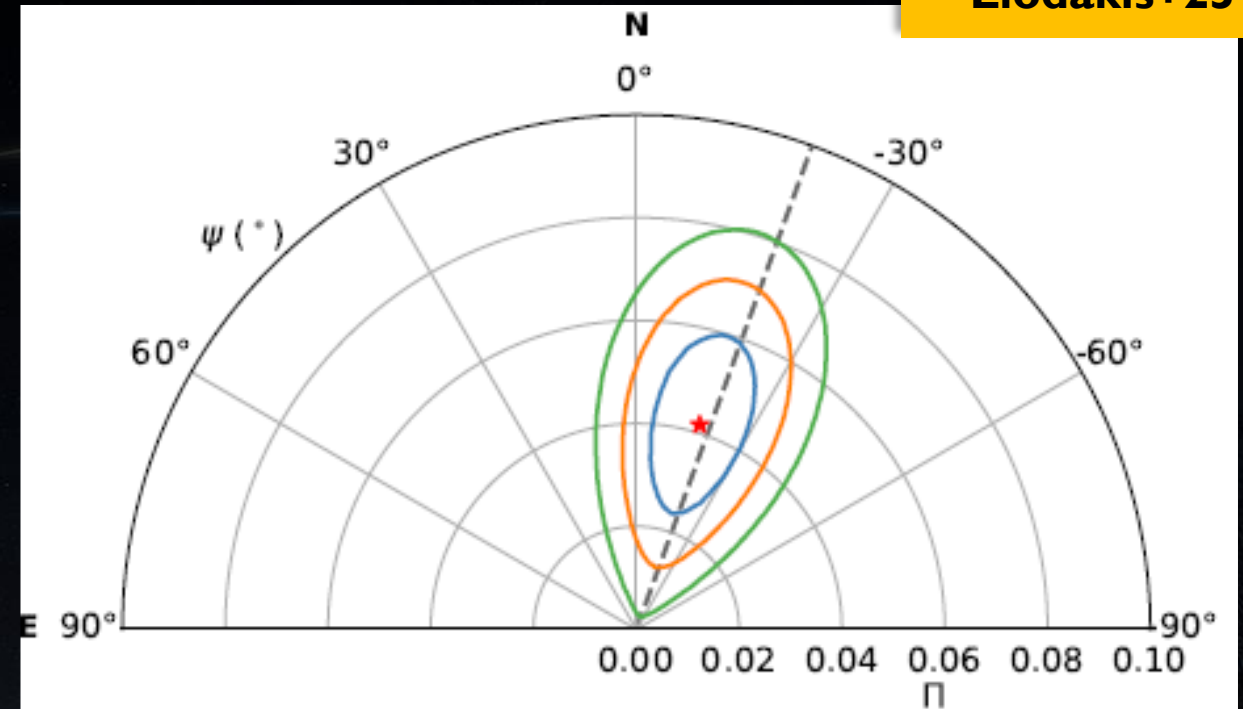
Unobscured AGN: few-percent PD and X-ray PA parallel to the radio axis (when measured), tracing the direct coronal emission and favouring radially extended coronae

Compton-thick AGN: much higher PD and X-ray PA perpendicular to the radio axis, as expected when the nucleus is hidden and reprocessed emission dominates
X-ray polarimetry separates direct coronal emission from reprocessed radiation

RADIO GALAXIES

Liodakis+25

While only an upper limit of $\sim 8\%$ for the PD of Centaurus A could be found (Ehlert+22), 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 radio galaxy **3C84** (a.k.a. NGC 1275)

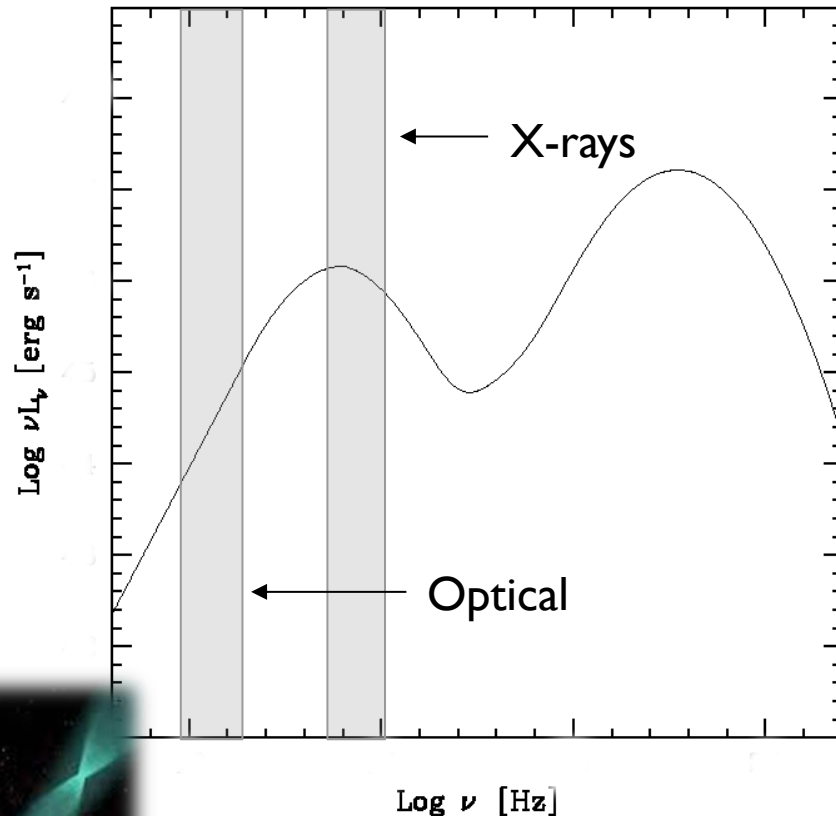


$PD = 4.2 \pm 1.3 \%$, PA aligned with the radio jet

The PA favors a jet origin over polar/torus scattering; the multiwavelength behavior points to Compton emission, likely SSC

BLAZARS

High Synchrotron Peaked



Blazars are obvious targets for X-ray polarimetry

High-synchrotron-peak blazars, whose X-ray emission in the IXPE band is synchrotron-dominated, like Mrk 501 (*Liodakis+22*) and Mrk 421 (*Di Gesu+22*) are **significantly polarized**

Multifrequency observations permit to discriminate among models

Low- and intermediate-synchrotron-peaked blazars, whose emission in the IXPE band is generally inverse-Compton-dominated, are instead **much less polarized**, and only upper limits are found (e.g. BL Lac, *Middei+22*, *Agudo+25*)

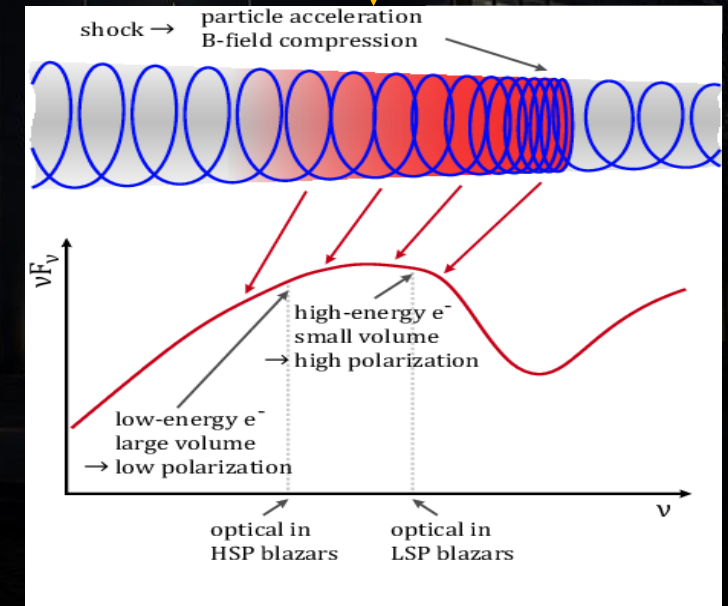
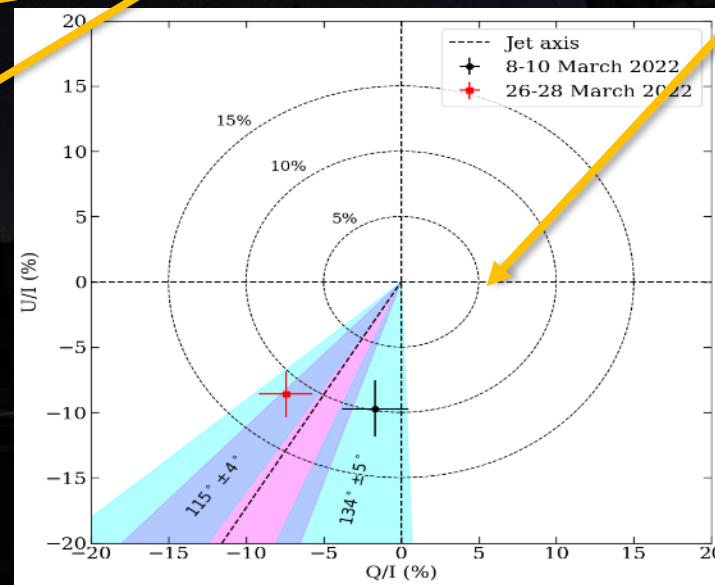
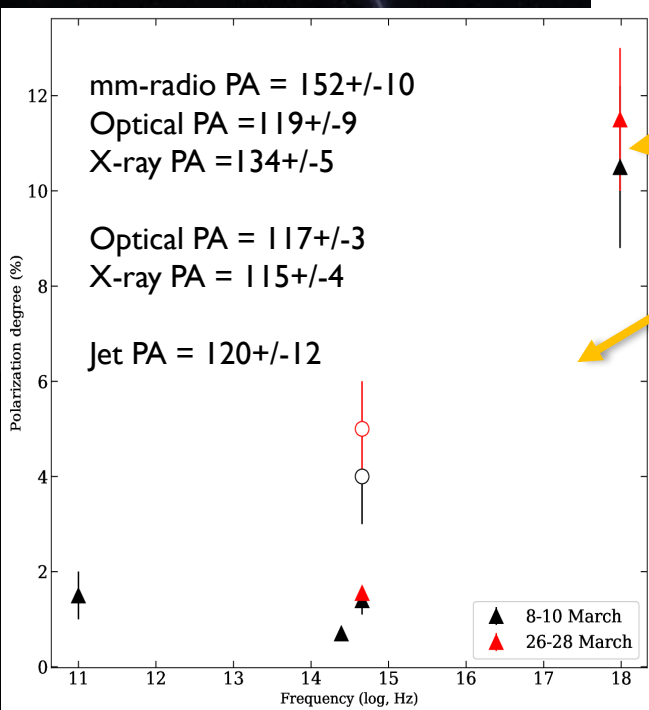
But, again, multifrequency observations allow us to discriminate among models

BLAZARS

Mrk 501: an energy-stratified shock scenario is favored by its multiwavelength polarization properties

Lioudakis+22

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

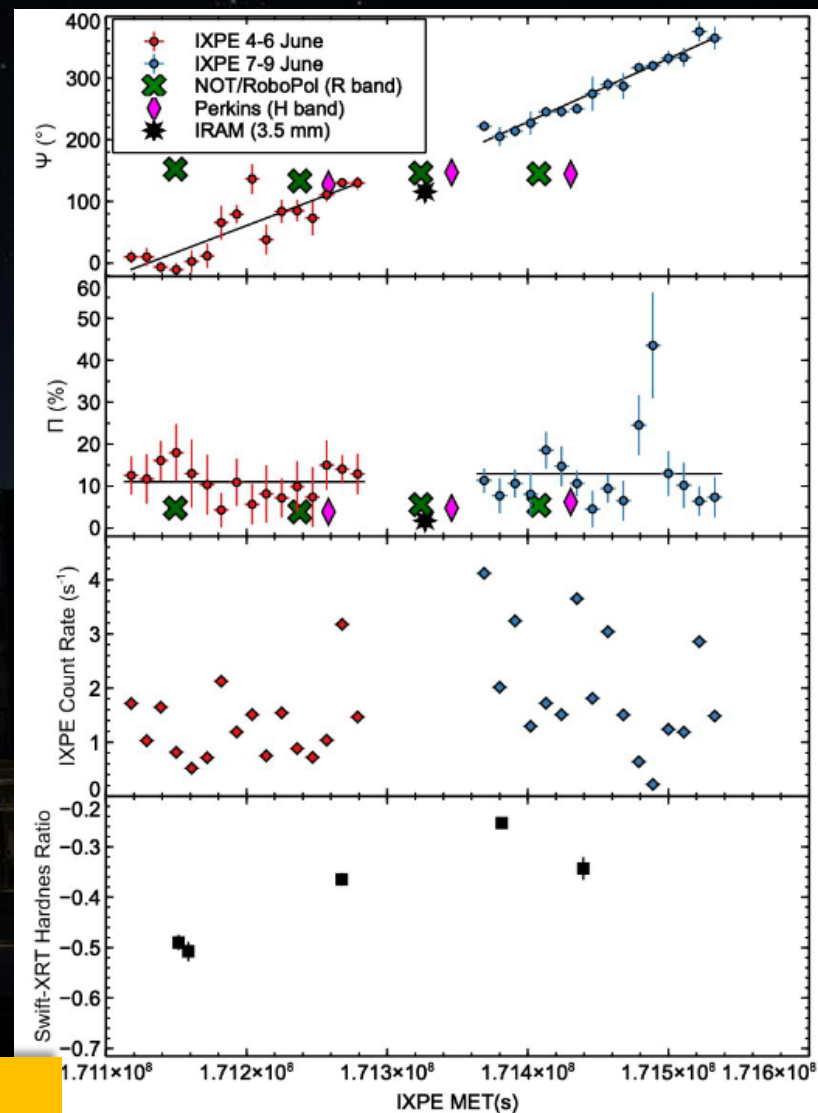
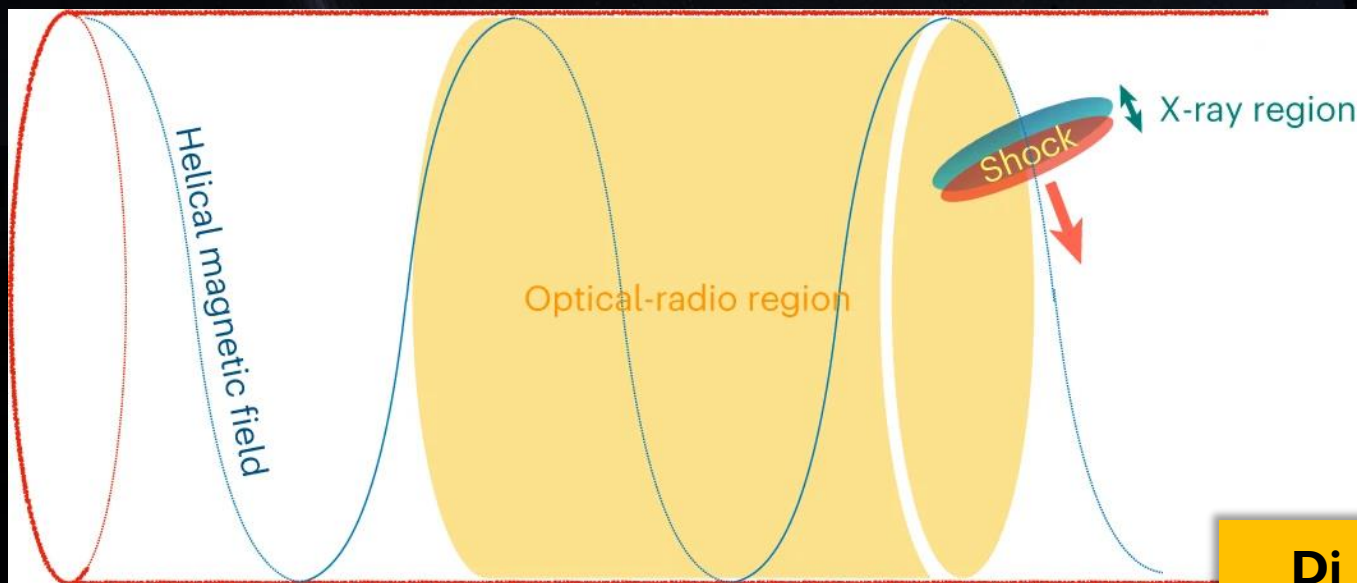


BLAZARS

Mrk 421: Very similar results, and very similar conclusions (Di Gesu+22)...

... but in another observation of this source a **continuous rotation of the polarization angle** by more than 360 degrees in 5 days is detected

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



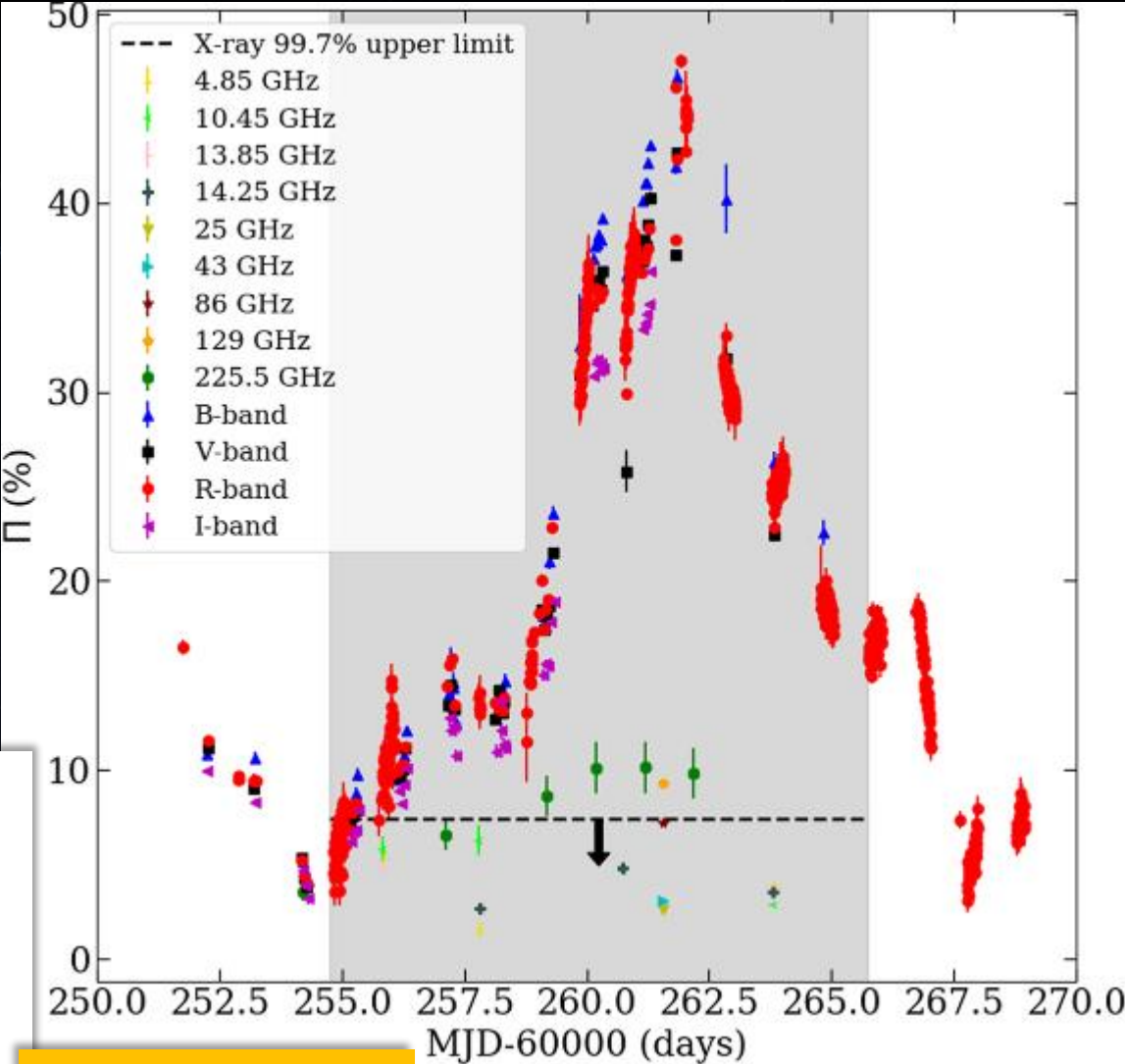
Di Gesu+23

BLAZARS

During an extraordinary event in which the optical linear polarization of **BL Lac** reached a PD of 47.5%, IXPE measured $PD_X < 7.4\%$

The strong optical-to-X-ray polarization contrast rules out hadronic models and strongly favors a **leptonic scenario**, in which the X-rays are produced by inverse-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)	$\leq 0.3 \times \Pi_O$	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



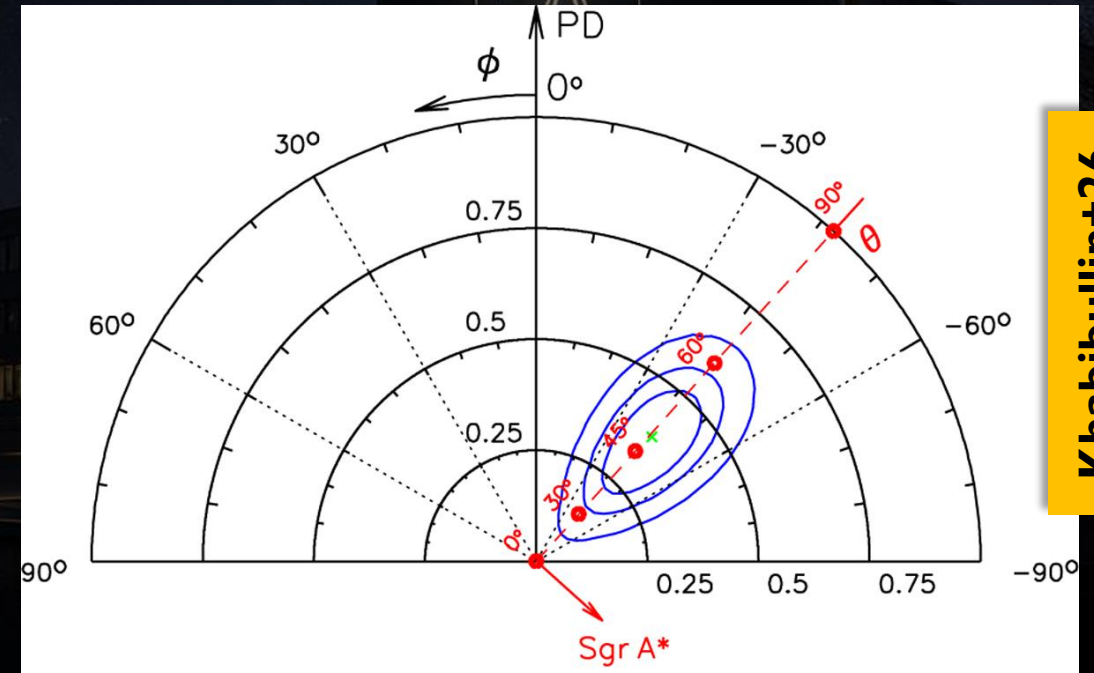
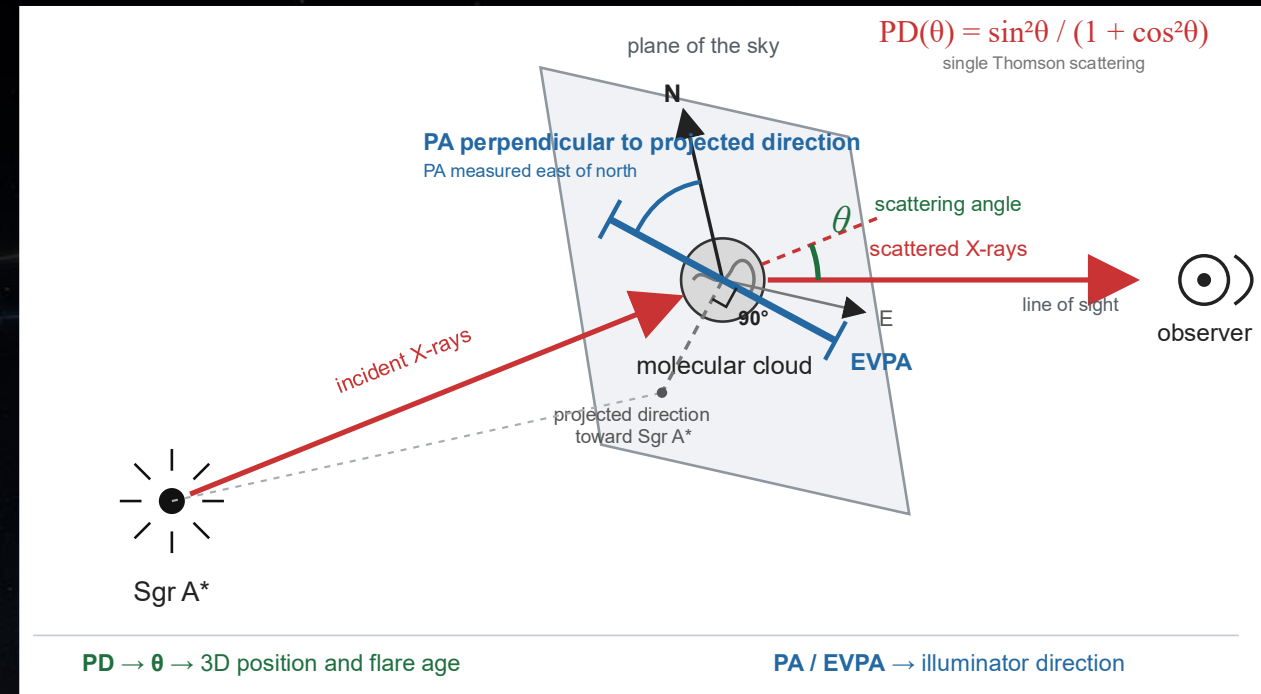
Agudo+25

SAGITTARIUS A*

Dense molecular clouds around the Galactic Centre preserve X-ray echoes of past energetic flares (Marin+23, Khabibullin+26)

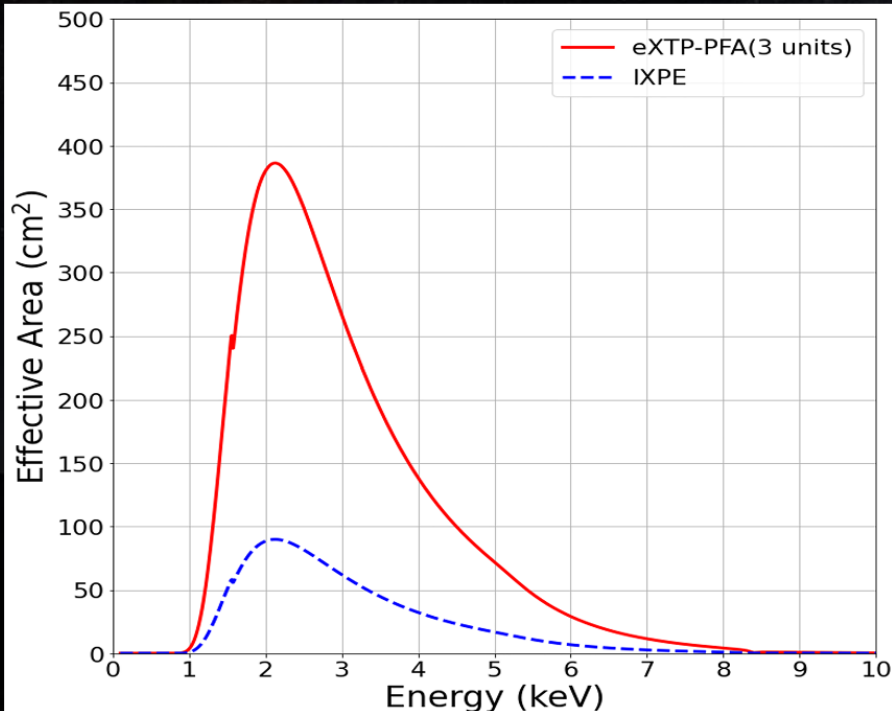
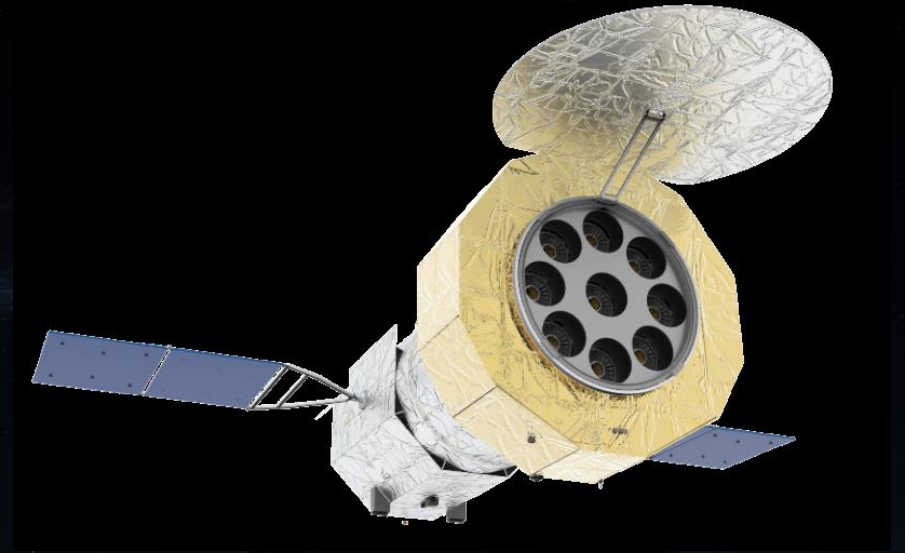
For the extended Sgr A complex, the PA points back to Sgr A*, while the PD constrains the 3D scattering geometry and dates the flare to 190 ± 25 years ago

The flare was short ($\Delta t < 1.5$ yr) and powerful ($L_X > 10^{39}$ erg s⁻¹), implying that **Sgr A* briefly reached an AGN-like luminosity**, although multiple flares or illuminating sources may complicate the reconstruction



BEYOND IXPE: eXTP

The enhanced X-ray Timing and Polarimetry mission (eXTP) is a Chinese-led mission, approved for launch in **2030** (Zhang et al. 2025)



The payload includes CCD-like cameras for spectroscopy and timing, and **3 polarimeters**

The polarimeters are very similar to the IXPE ones, but the **total effective area is about 4 times larger**

Similar scientific objectives, but reachable with shorter exposure times → short-term variable objects, population studies, simultaneous high-quality spectroscopy and polarimetry

BEYOND IXPE: EXPO

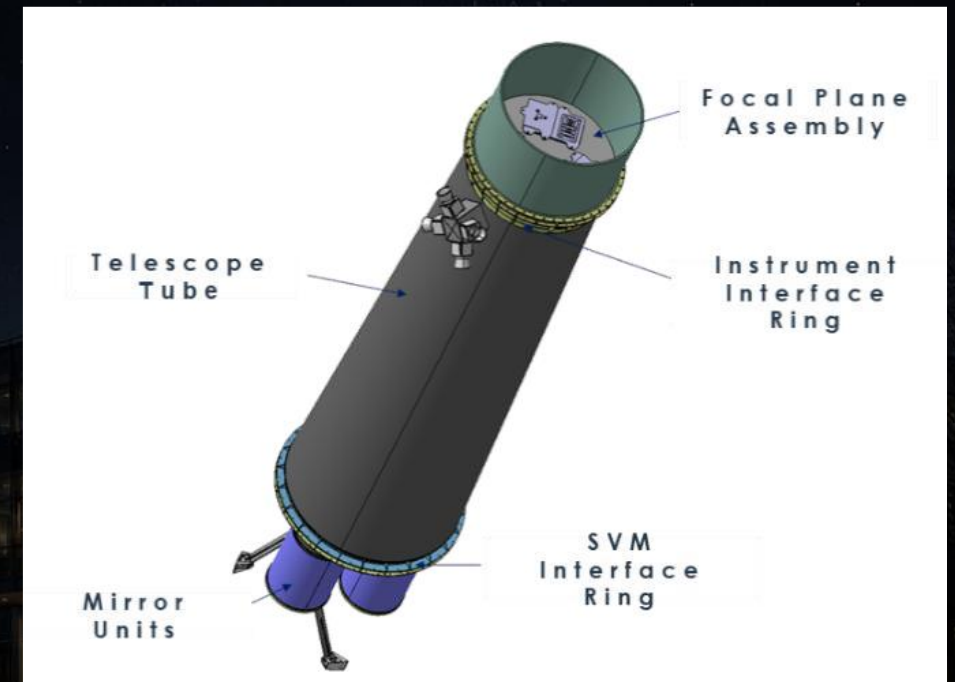
The Enhanced X-ray Polarimetry Observatory (EXPO) is one of the 10 missions which passed the Step-I selection for the ESA M8 program (PI: Paolo Soffitta)

Next steps:

Nov. 2026 - 10 → 5 (Phase 0)

Nov. 2027 - 5 → 3 (Phase A)

June 2030 - Final selection



Expected launch of the selected mission in 2041

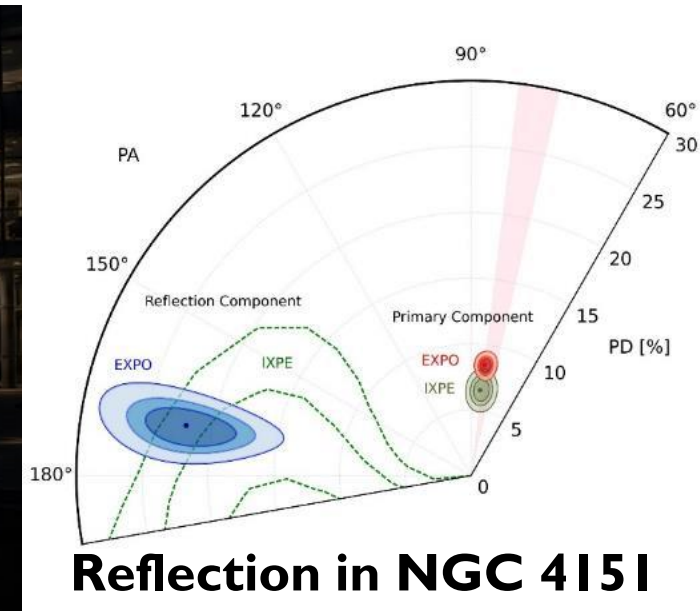
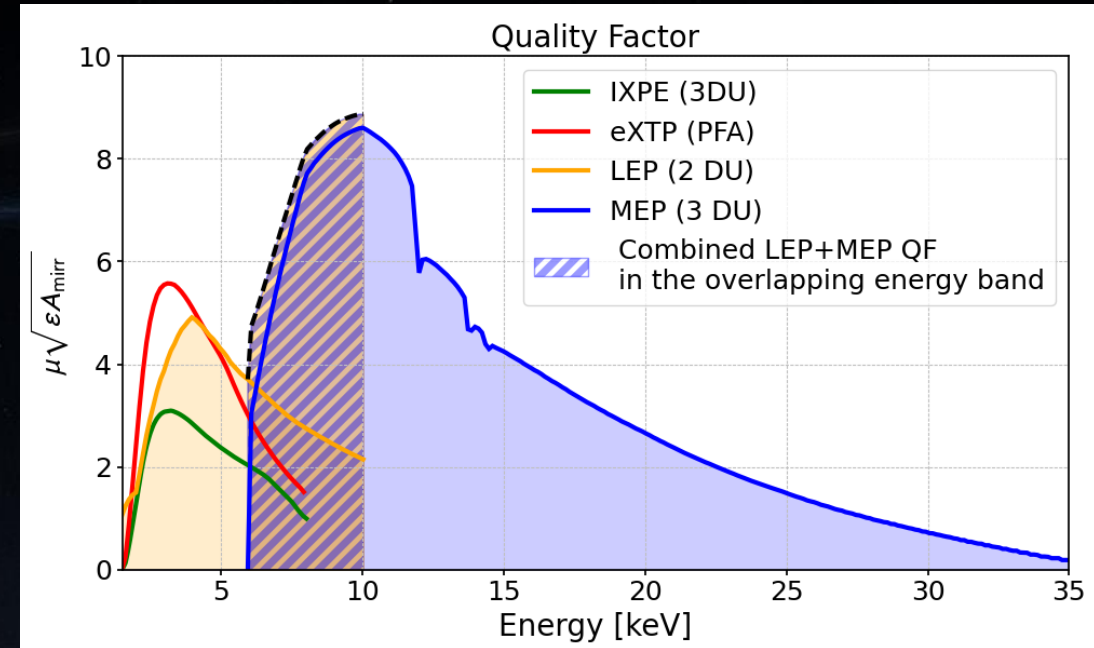
BEYOND IXPE: EXPO

The payload includes:

- 2 Low Energy Polarimeters (2-10 keV)
- 3 Medium Energy Polarimeters (6-35 keV)
- 1 Spectrometer (CCD-like, 0.5-35 keV)
- 1 Wide Field Monitor (1/6 of the sky, 4-150 keV)

The effective area is comparable to that of eXTP in the same energy range

With respect to IXPE, a broader energy range and a much faster repointing capability



TAKE-AWAY MESSAGES

- ✓ IXPE has (re-)opened the X-ray polarimetric window
- ✓ In Compton-thin RQ AGN, polarization constrains coronal geometry
- ✓ in Compton-thick AGN, it traces the reprocessing geometry and supports the unification model
 - ✓ In jetted AGN, multiwavelength polarization discriminates between synchrotron shocks and Compton-dominated emission
- ✓ Scattering polarization reveals otherwise hidden geometry and past activity, as shown for Sgr A*
- ✓ eXTP and EXPO will provide broader energy coverage, higher sensitivity and faster response to transients

