



X-ray Polarimetry of AGN: results from IXPE

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

- **A brief introduction to the Imaging X-ray Polarimetry Explorer (IXPE)**
- **IXPE results on RQ AGN:**

Unobscured AGN: the geometry of the hot corona

Compton-Thick AGN: the structure of the “torus”

- **A few words on RL AGN**

- **A brief introduction to the Imaging X-ray Polarimetry Explorer (IXPE)**

- **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**

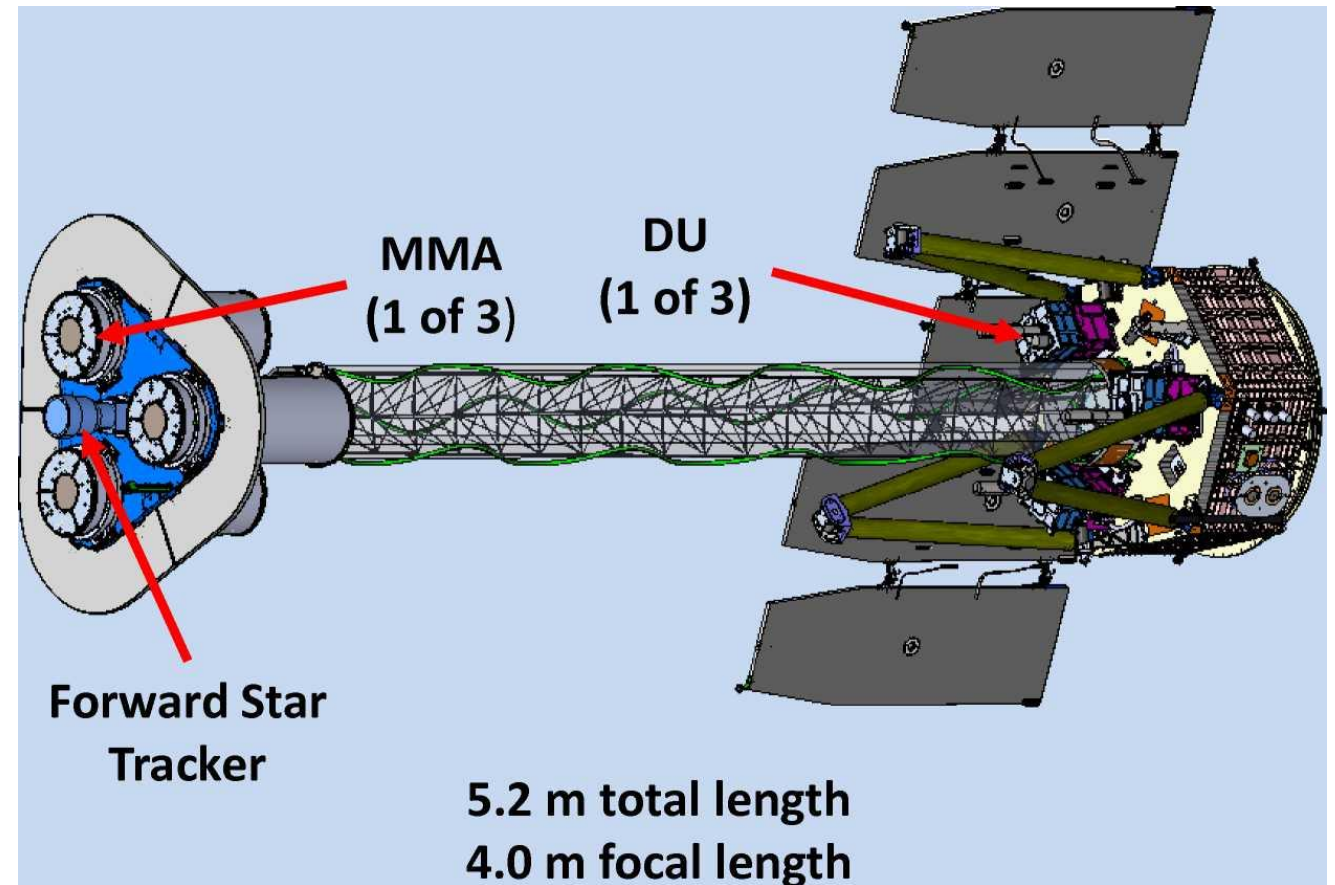
- A **NASA/ASI** mission within the NASA's Small Explorer Program (SMEX)
- Launched **December 9, 2021** on a Falcon 9 from KSC
- 600-km circular orbit at a nominal 0° inclination
- **2-year baseline mission, now extended with GO program**
- Point and stare (with dither) at pre-selected targets
- Malindi 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

 <p>Marshall Space Flight Center</p> <p>PI team, project management, SE and S&MA oversight, mirror module fabrication, X-ray calibration, science operations, and data analysis and archiving</p>	     <p>Polarization-sensitive imaging detector systems</p>
 <p>Detector system funding, ground station</p>	 <p>Mission operations</p>
 <p>Spacecraft, payload structure, payload, observatory I&T</p>	  <p>Scientific theory</p>
 <p>Science Advisory Team</p>	 <p>Thermal shields</p>  <p>Massachusetts Institute of Technology</p> <p>Co-Investigator</p>

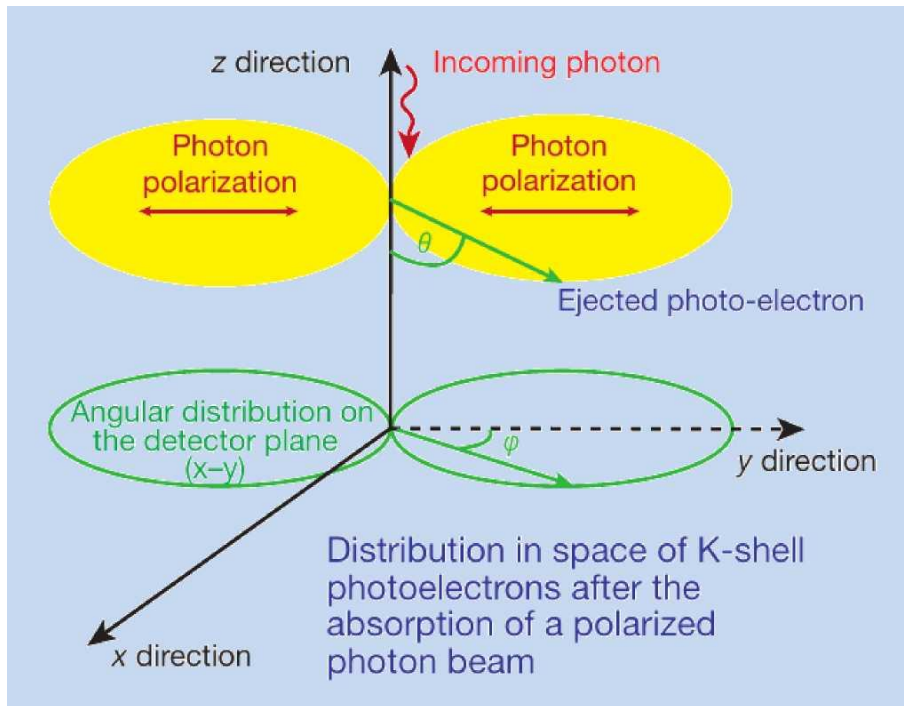
*PI: Phil Kaaret, MSFC
(formerly Martin Weisskopf)*

SAT currently comprises > 100 scientists from 12 countries

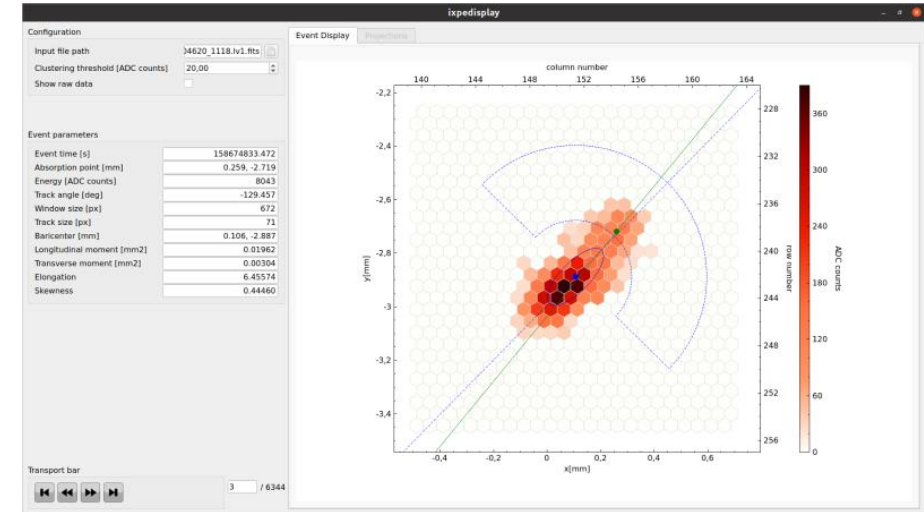
- *Energy range: 2-8 keV*
- *Spatial resolution: 30'' (FWHM)*
- *FOV=13'*
- *Energy resolution: 0.57 keV @ 2 keV (FWHM)*



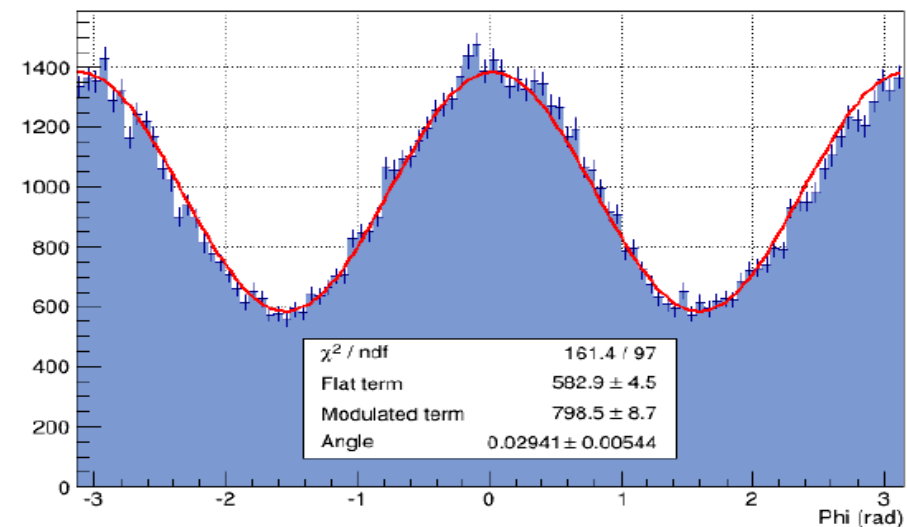
The detection principle is based on the photoelectric effect



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



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



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

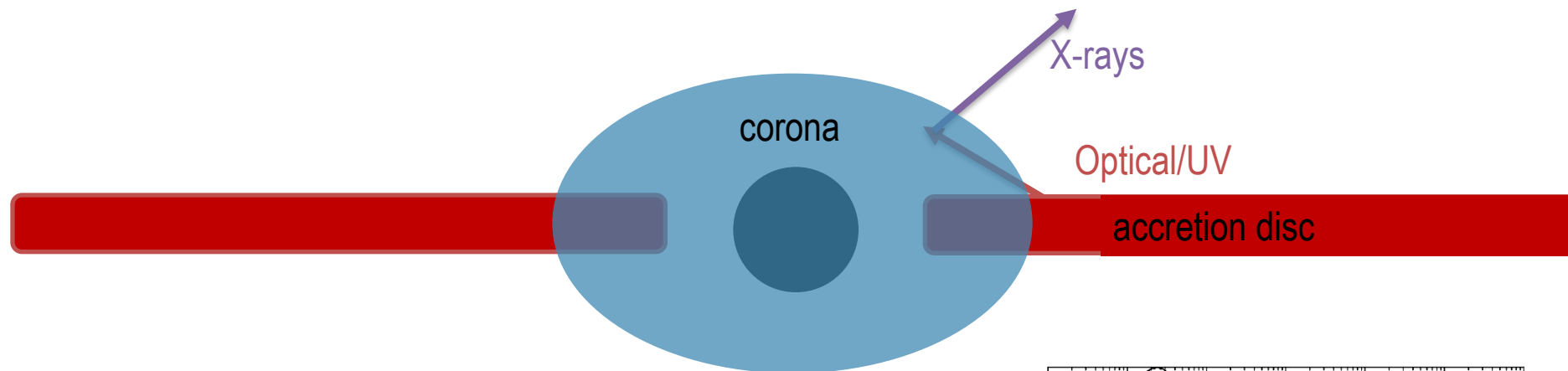
A General Observer Program issued in 2023. GO1 started February 1, 2024. Oversubscription larger than 6

GO2 started on February, 2025. Joint programs with NICER, NuSTAR and Swift

- **IXPE results on RQ AGN:**

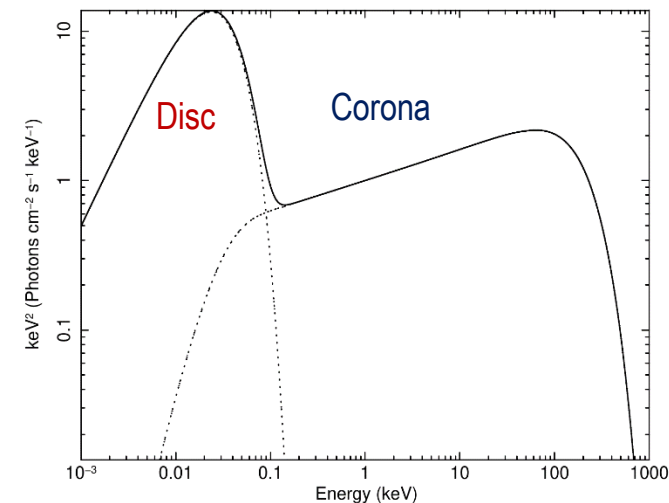
Unobscured AGN: the geometry of the hot corona

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 $F_E \sim E^{-\Gamma} \exp(-E_c/kT)$
 $\Gamma = \Gamma(kT, \tau)$, while E_c depends on kT

Temperature $kT \sim 10\text{-}100$ keV
 Thomson optical depth ~ 1

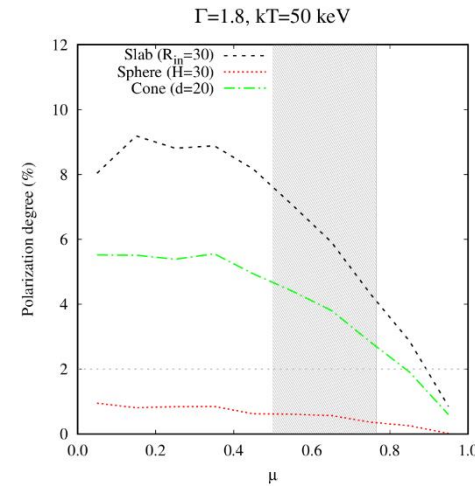
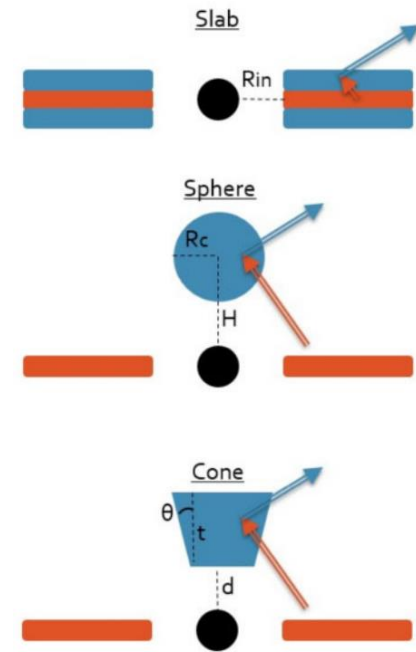


X-ray spectroscopy can constrain the physical parameters of the corona.

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.

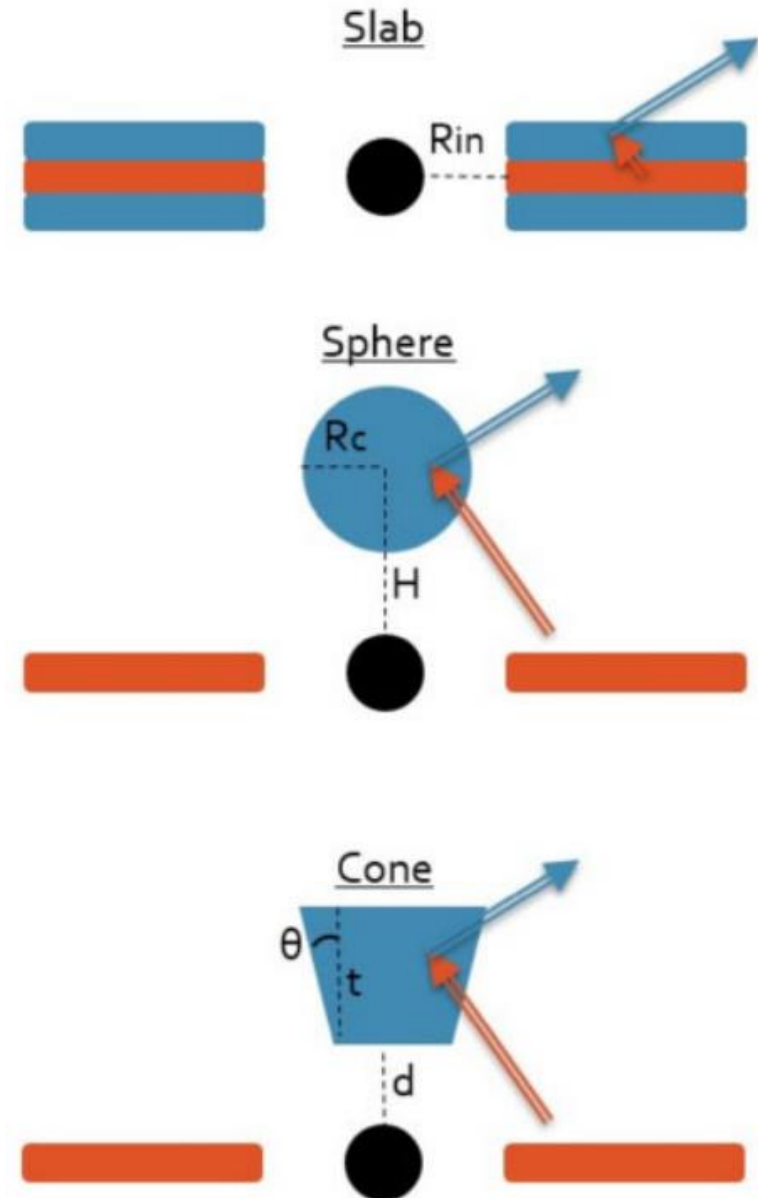
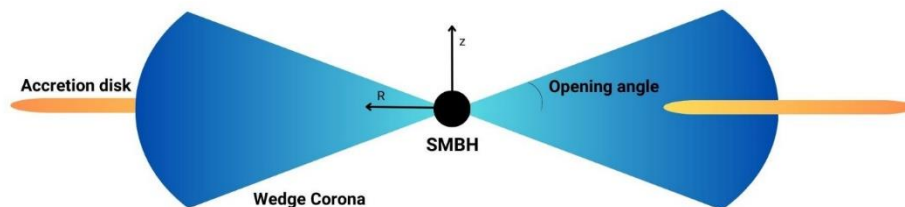
The coronal geometry is related to its physical origin.



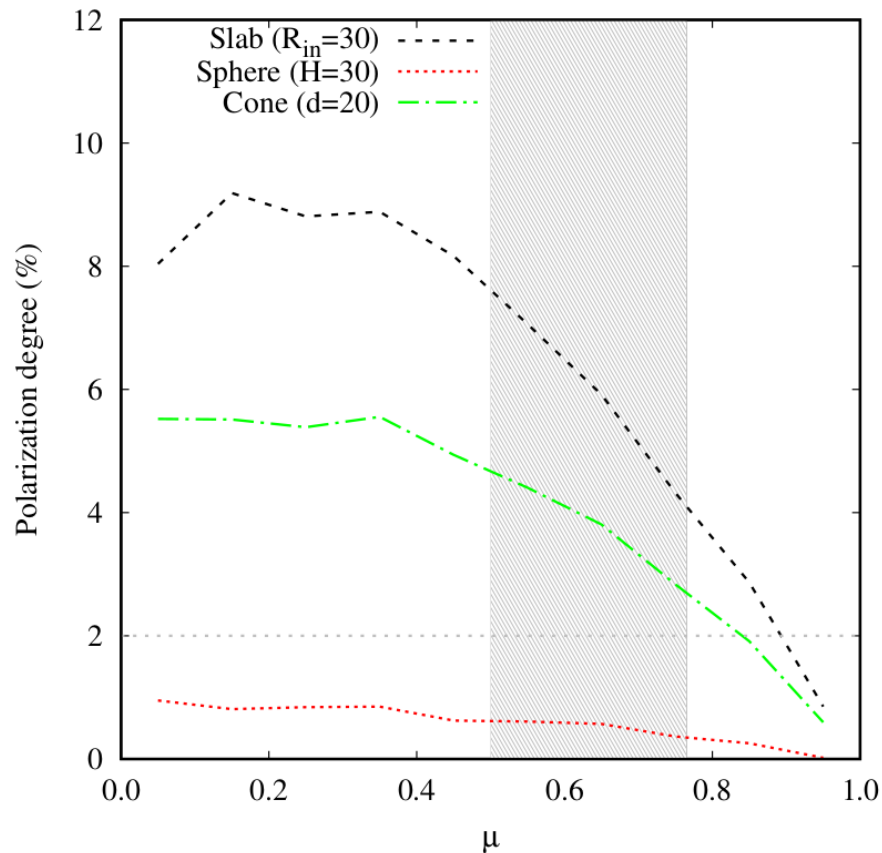
MonteCarlo simulations normally used to predict the polarization properties. Many codes available.

We performed numerical simulations of the expected coronal polarization with the Monte-Carlo radiative transfer code MONK (Zhang et al. 2019), which includes also special and general relativistic effects. Pure thermal plasma assumed (Maxwell-Jüttner distribution)

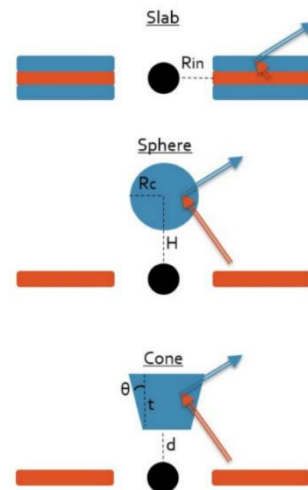
We explored different configurations and physical parameters of the disc/corona/BH system: e.g. a **slab**, a **wedge**, a **spherical lamppost**, an **outflowing ($v=0.3 c$) cone** (Ursini et al. 2022, Tagliacozzo et al. 2023, 2025)



$\Gamma=1.8, kT=50 \text{ keV}$



MCG-5-23-16



Polarization from **slab** and **wedge** geometries much higher than for **spherical lamppost** geometries.

Intermediate values for the **conical** geometry

Polarization either parallel or perpendicular to the accretion disc

The exact values depends on the temperature and optical depth \rightarrow need for good spectroscopic simultaneous observations

To study the geometry of the hot corona in AGN, three bright Compton-thin Seyfert galaxies have been observed by IXPE during baseline mission

MCG-05-23-16 May/November 2022 (Marinucci et al. 2022, Tagliacozzo et al. 2023)

$M_{\text{BH}} = 2 \times 10^7 M_{\text{sun}}$ (Ponti et al. 2012)

IXPE: 486 ks+642 ks

XMM-Newton: 58 ks/none -- NuSTAR: 83 ks/85ks

NGC 4151 December 2022 and April-May 2024 (Gianolli et al. 2023)

$M_{\text{BH}} = 4.6 \times 10^7 M_{\text{sun}}$ (Bentz et al. 2006)

IXPE: 632 ks

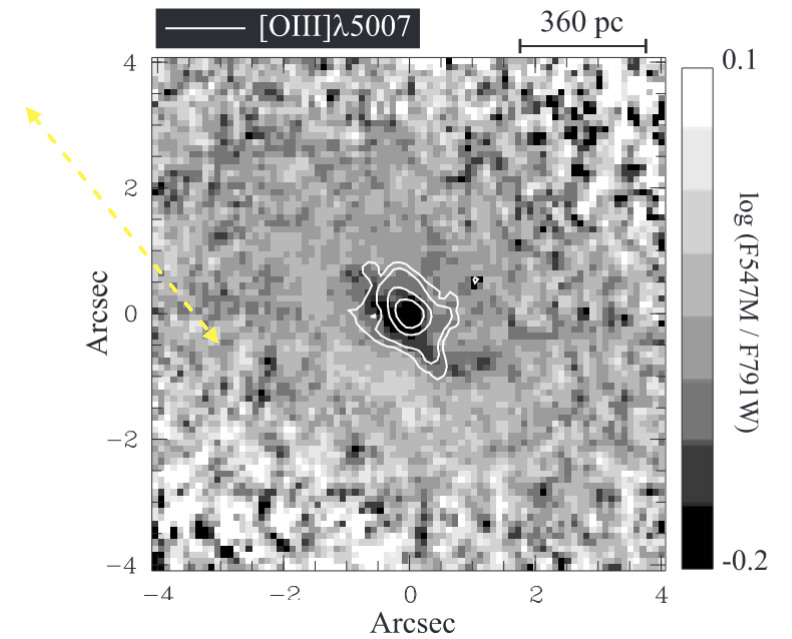
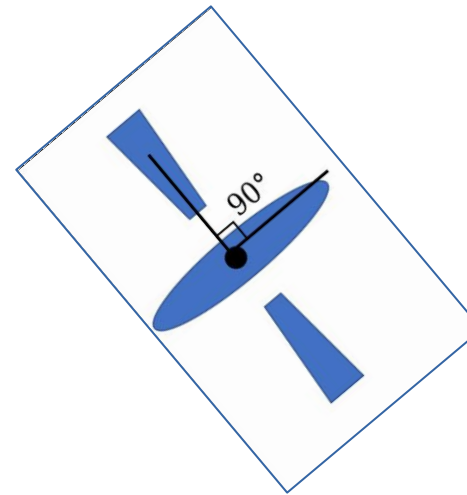
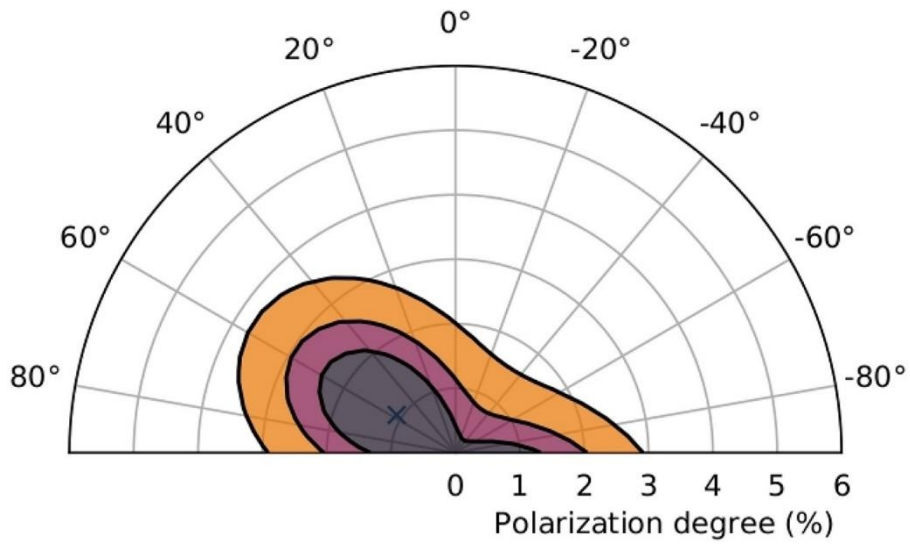
XMM-Newton: 33 ks -- NuSTAR: 97 ks

IC 4329A January 2023 (Ingram et al. 2023)

$M_{\text{BH}} = 7 \times 10^7 M_{\text{sun}}$ (Bentz et al. 2023)

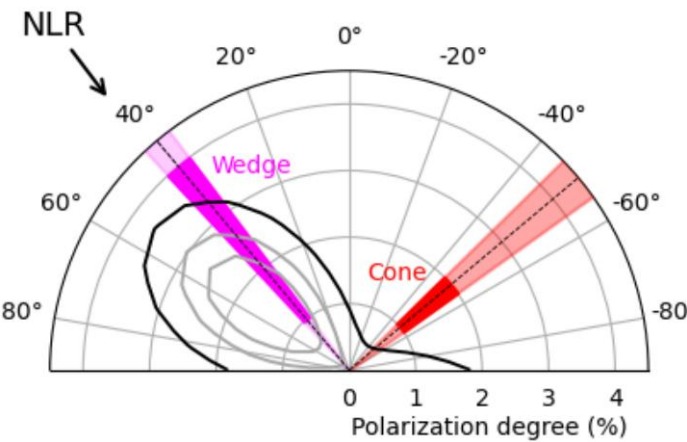
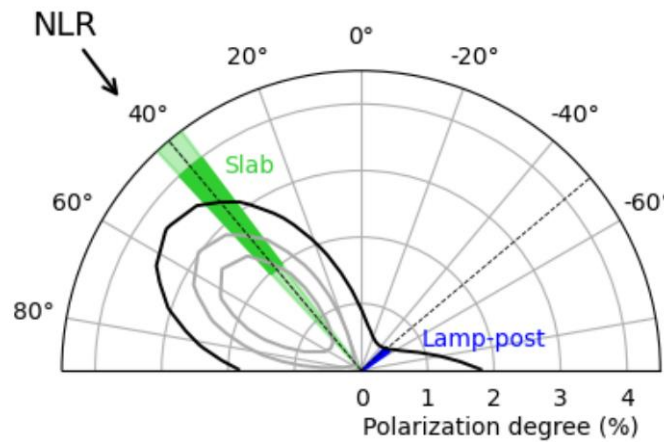
IXPE: 458 ks

XMM-Newton: 62 ks -- NuSTAR: 82 ks



Tagliacozzo et al. 2023

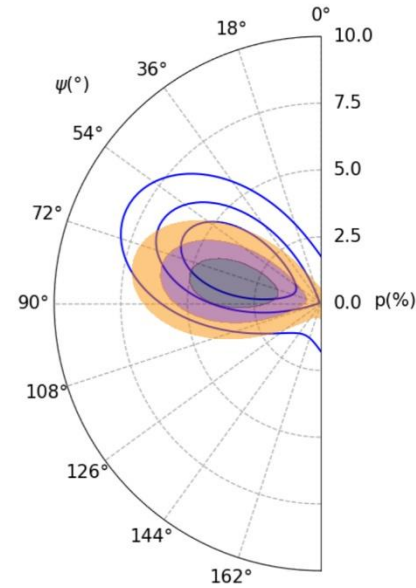
Ferruitt et al. 2000



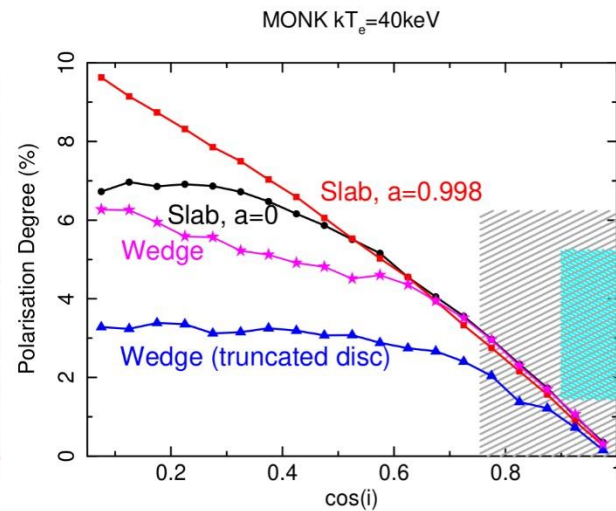
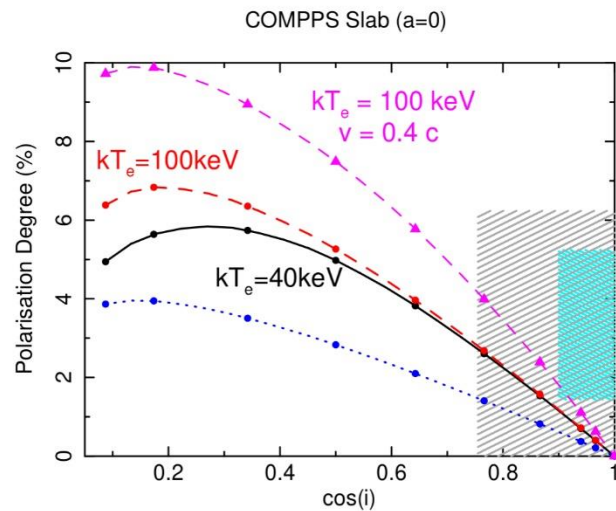
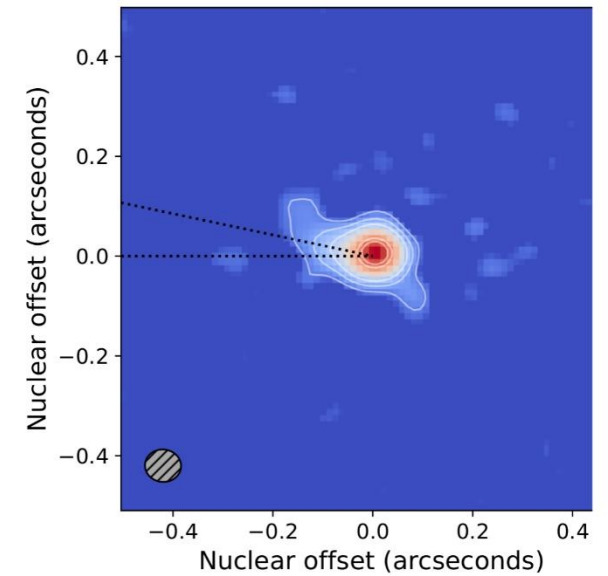
P < 3.2 %

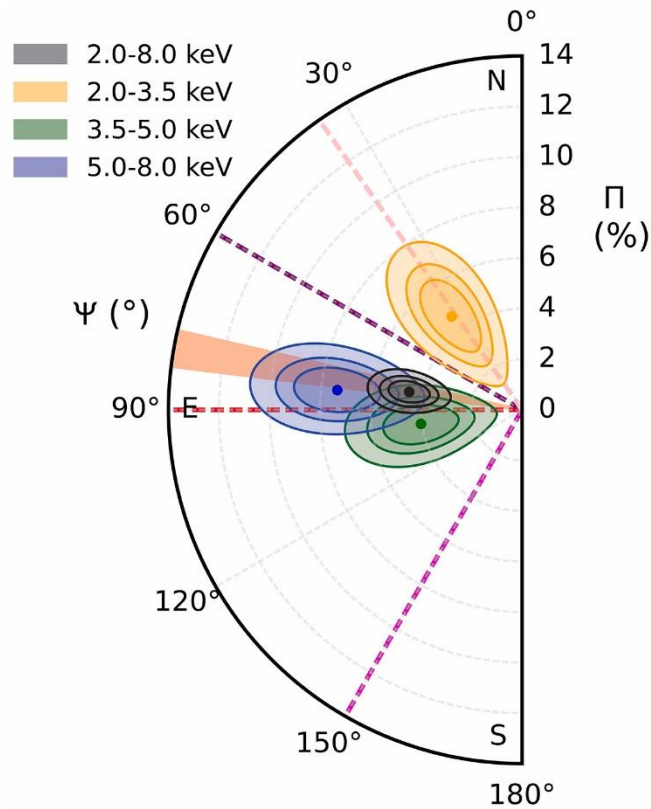
Strictly speaking, an upper limit.
 However, a 2.97σ result with $P=3.3\%$

Ingram et al. 2023



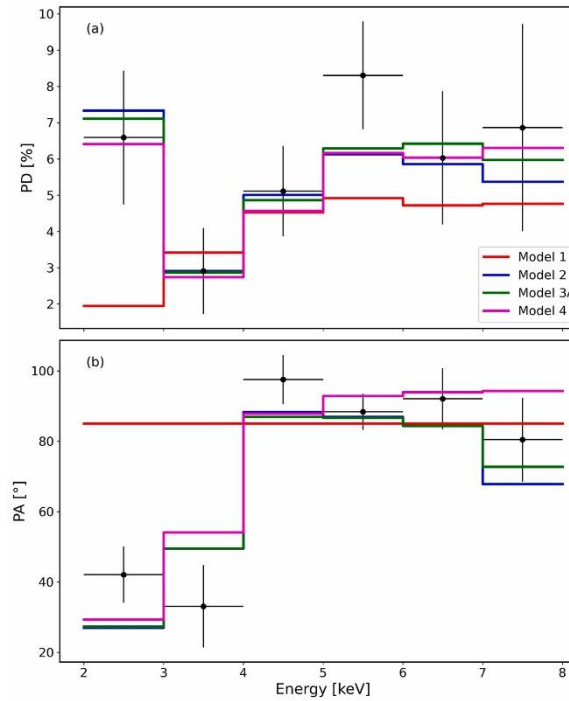
ALMA image at 100 GHz



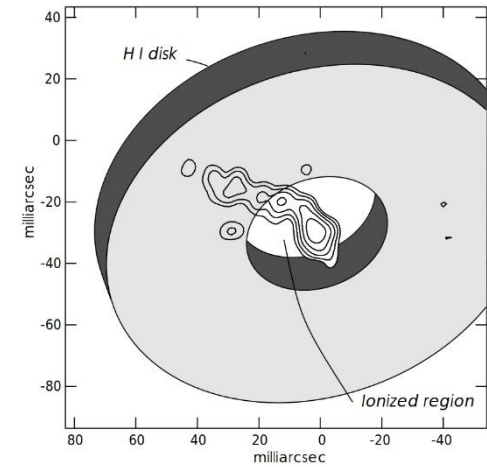


Gianolli et al. 2023, 2024

$P=4.5\pm 0.9\%$ in the 2-8 keV range

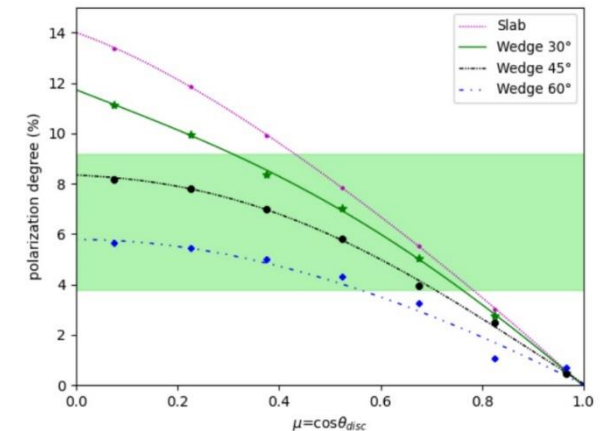


The polarization degree and angle disfavours the lamppost geometry for the hot corona.



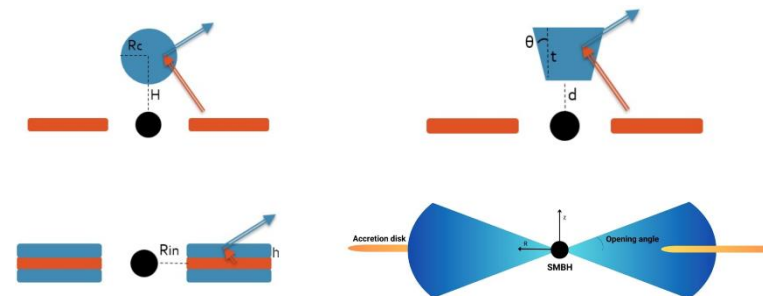
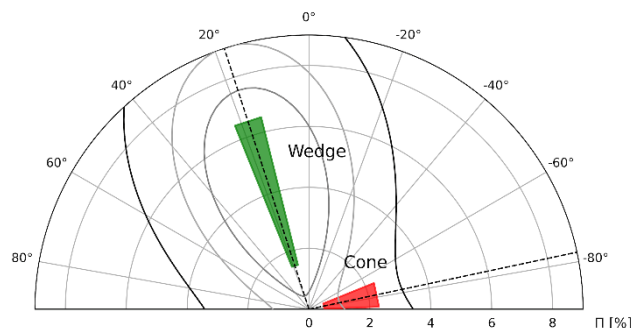
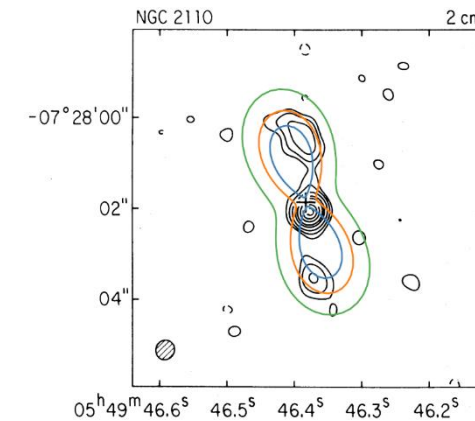
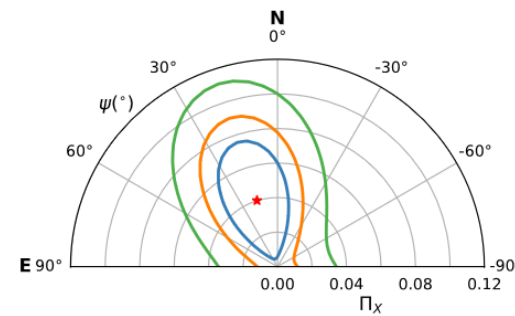
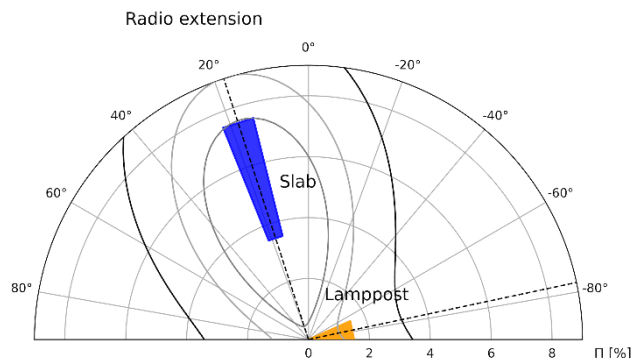
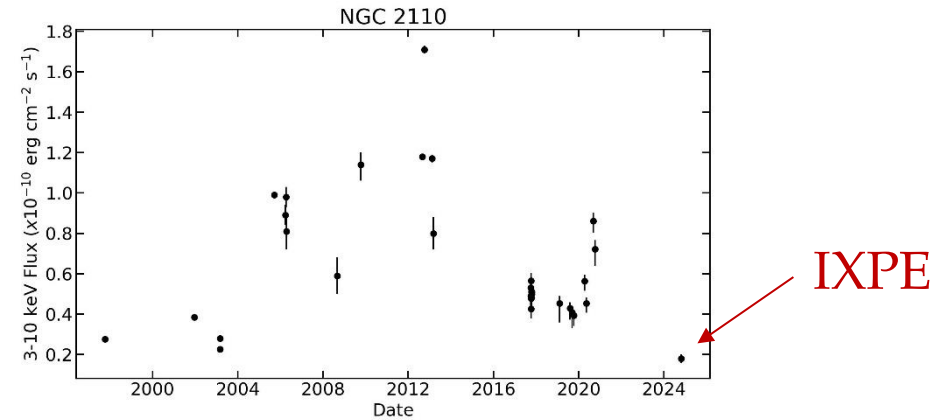
Ulvestad et al. 1998

The measured Ψ is in the direction of the radio emission (P.A. $\sim 83^\circ$: Wilson & Ulvestad 1982, Harrison et al. 1986, Pedlar et al. 1993)



Observed in GO1 for 550 ks
 (Chakraborty et al. 2025, Pal et al. 2025).

Somewhat underexposed because found at a low flux level, so only an unconstraining upper limit could be found



- **IXPE results on RQ AGN:**

Compton-Thick AGN: the structure of the “torus”

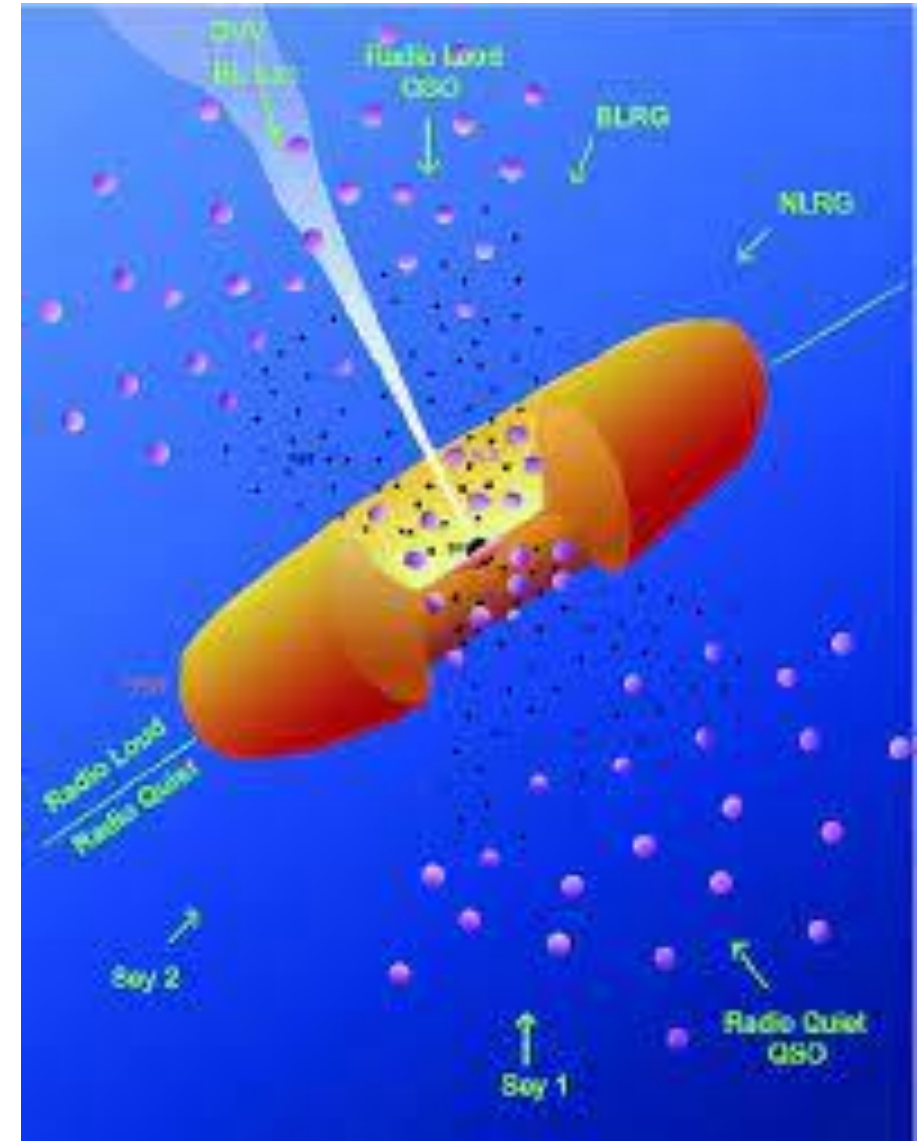
X-ray emission is dominated by reflection, so it should be highly polarized.

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.

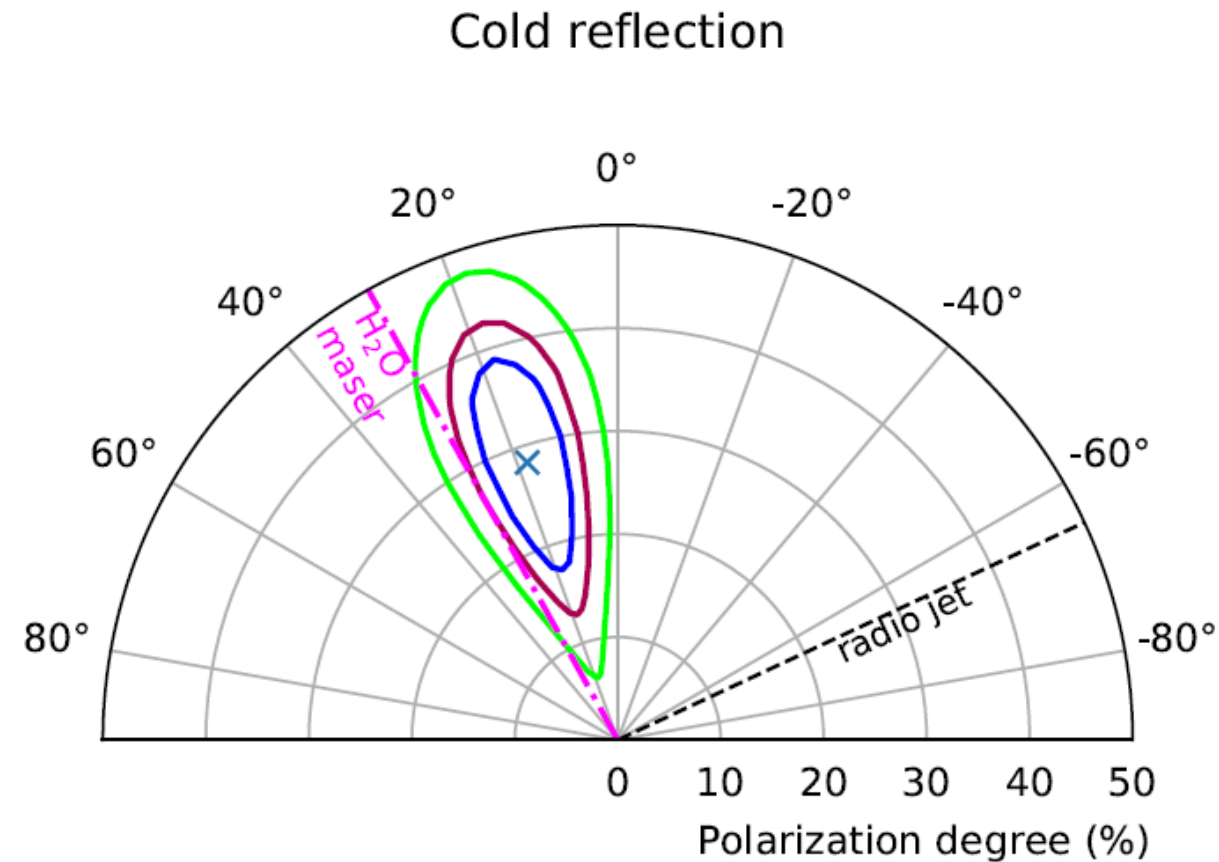
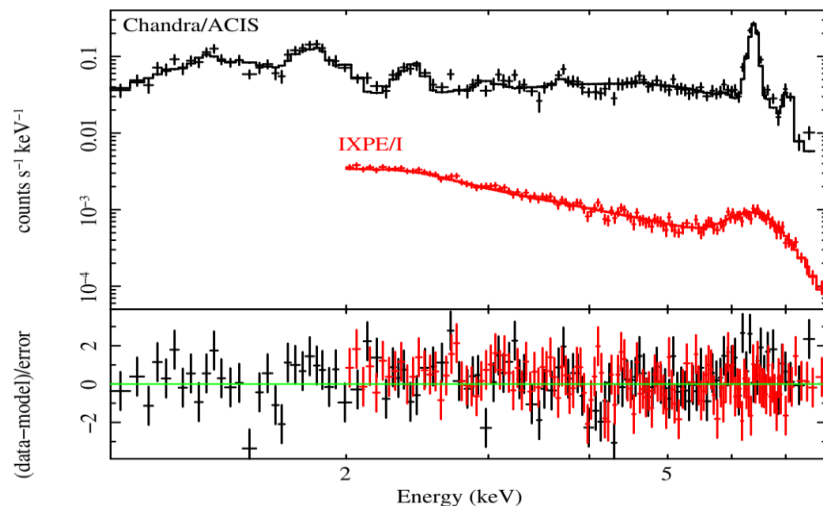
The ionization cone/NLR may also scatter (and polarize) the primary emission.

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



IXPE observed the Circinus Galaxy for about 800 ks, along with two Chandra snapshots to monitor the ULXs in Circinus.

A high polarization degree (about 30%) is found, perpendicular to the radio jet (and the ionization cone)

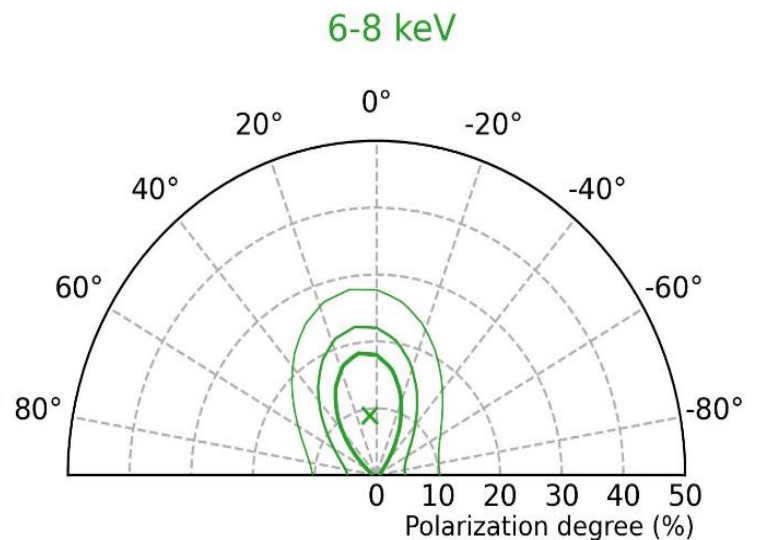
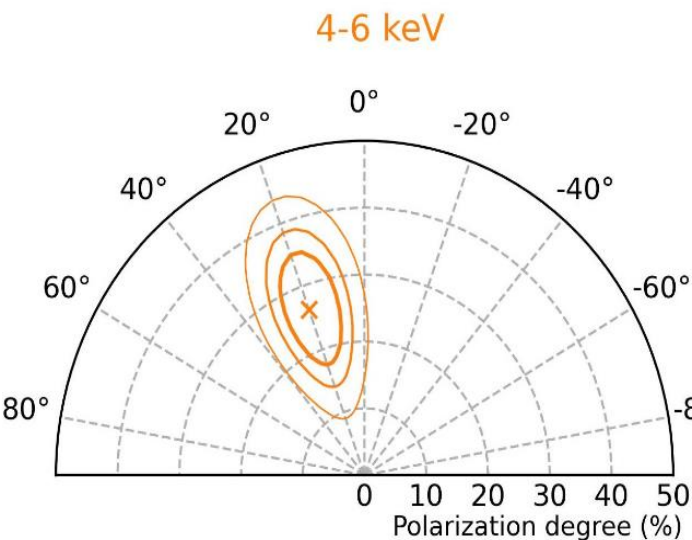
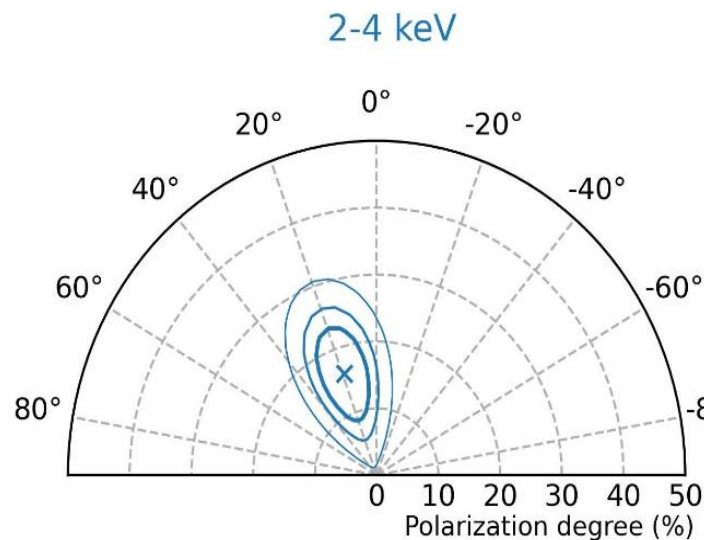


Ursini et al. 2023

The spectro-polarimetric analysis shows for the cold reflector:

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

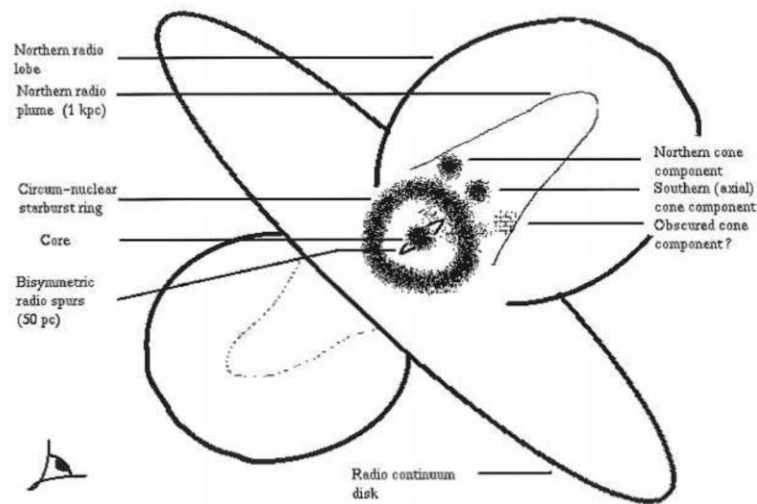
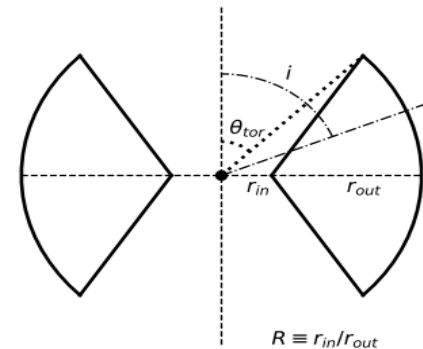
Energy	P.D. (%)	P.A. (deg)
2–8 keV	17.6 ± 3.2	16.9 ± 5.3
2–4 keV	16.0 ± 4.9	19.1 ± 8.9
4–6 keV	26.3 ± 5.7	20.2 ± 7.5
2–6 keV	20.0 ± 3.8	19.1 ± 5.5
6–8 keV	< 24.5	-



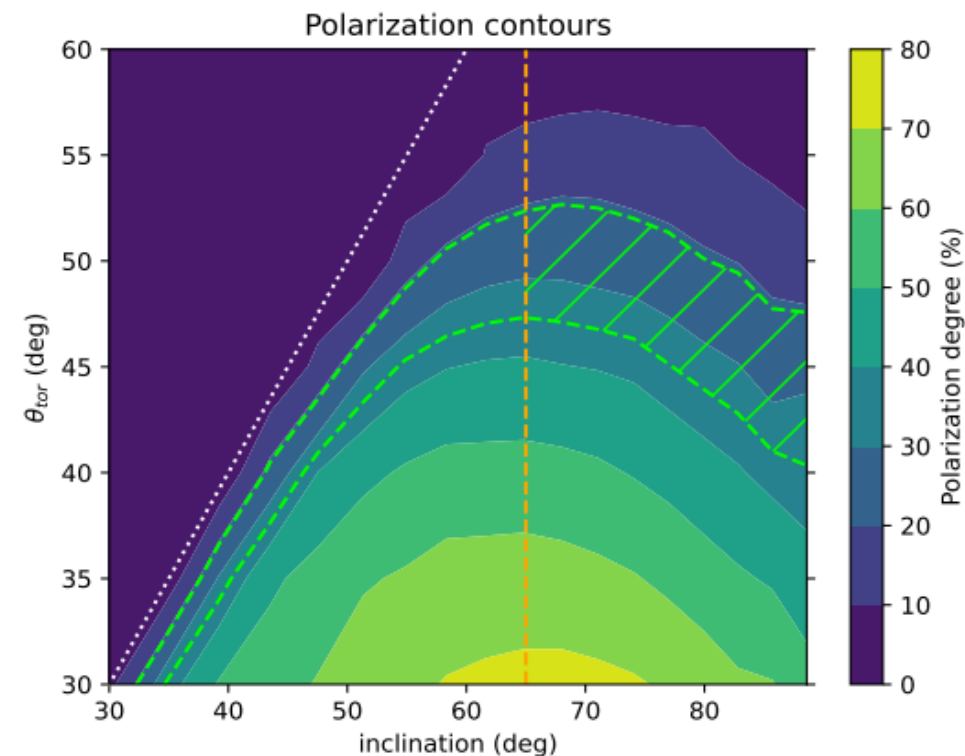
Ursini et al. 2023

Ursini et al. 2023

Also constrains torus geometry: opening angle likely in the 45-55 deg range, if an inclination of 65 deg is assumed (slightly lower values for higher inclinations).



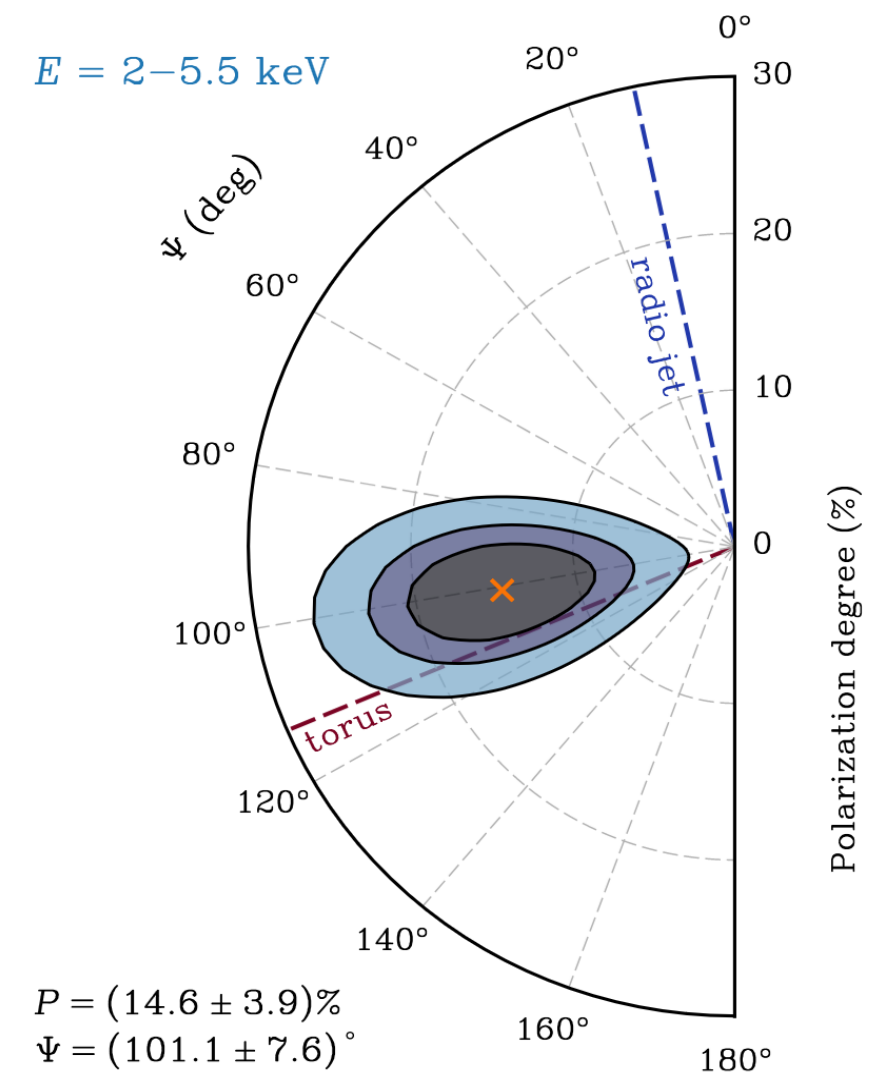
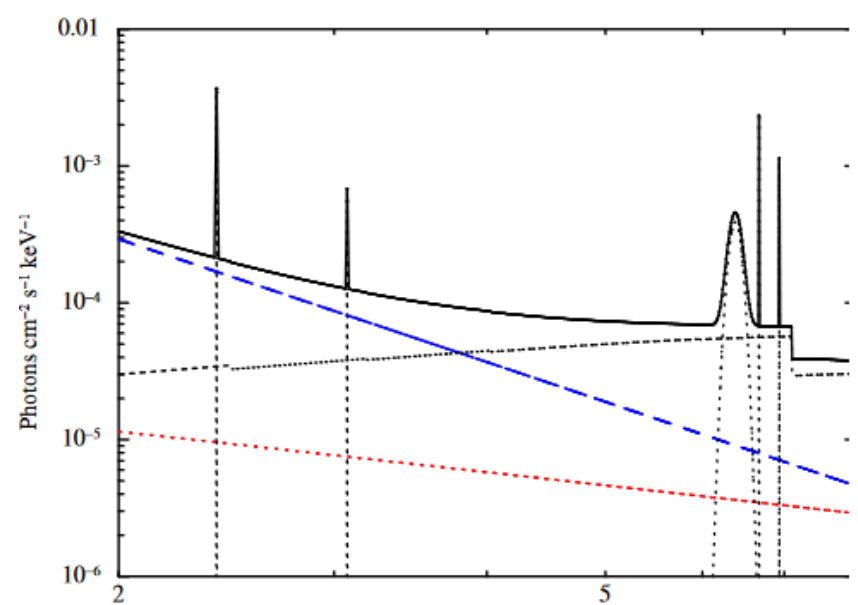
Elmoultie et al. 2008



IXPE observed NGC 1068 for about 1200 ks, along with two Chandra snapshots to monitor the ULXs.

A polarization degree of about 15% is found in the 2-5.5 keV range, again perpendicular to the radio jet.

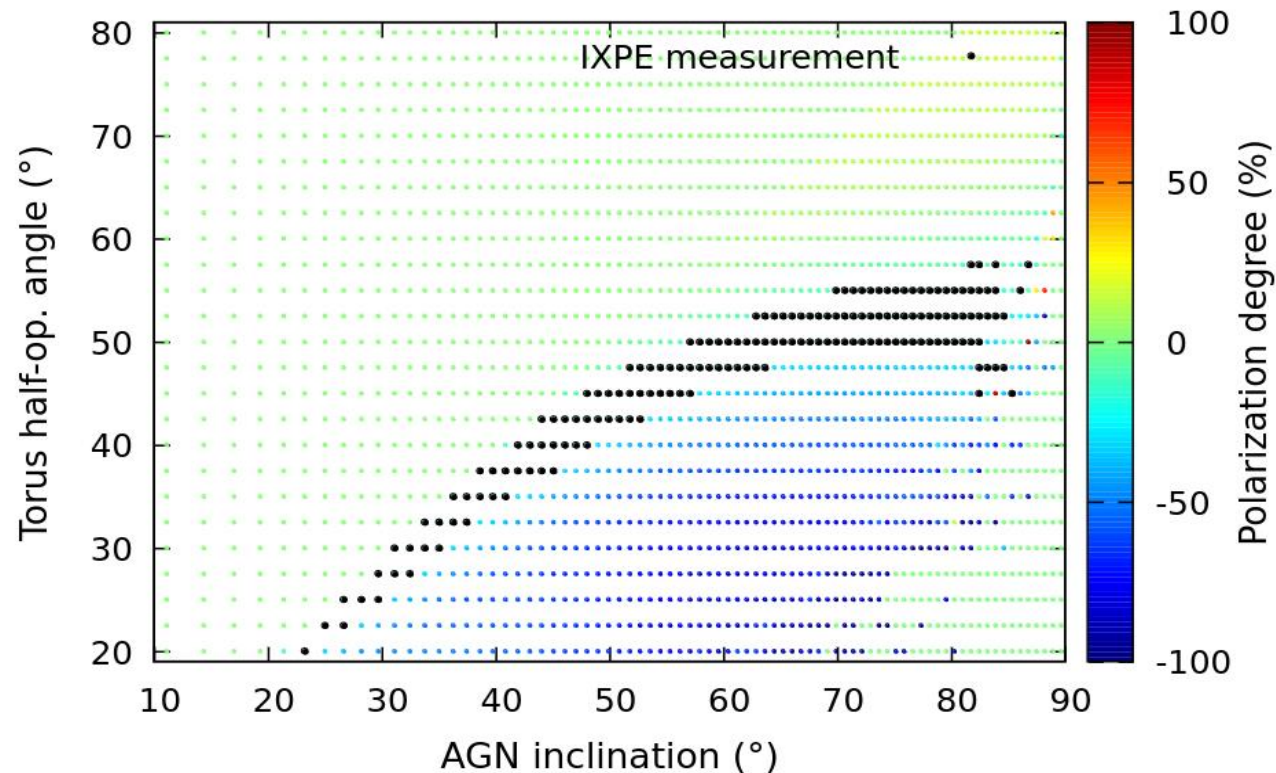
Torus is less dominant in the IXPE band than in Circinus



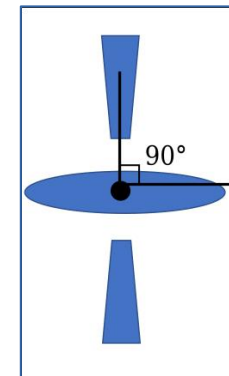
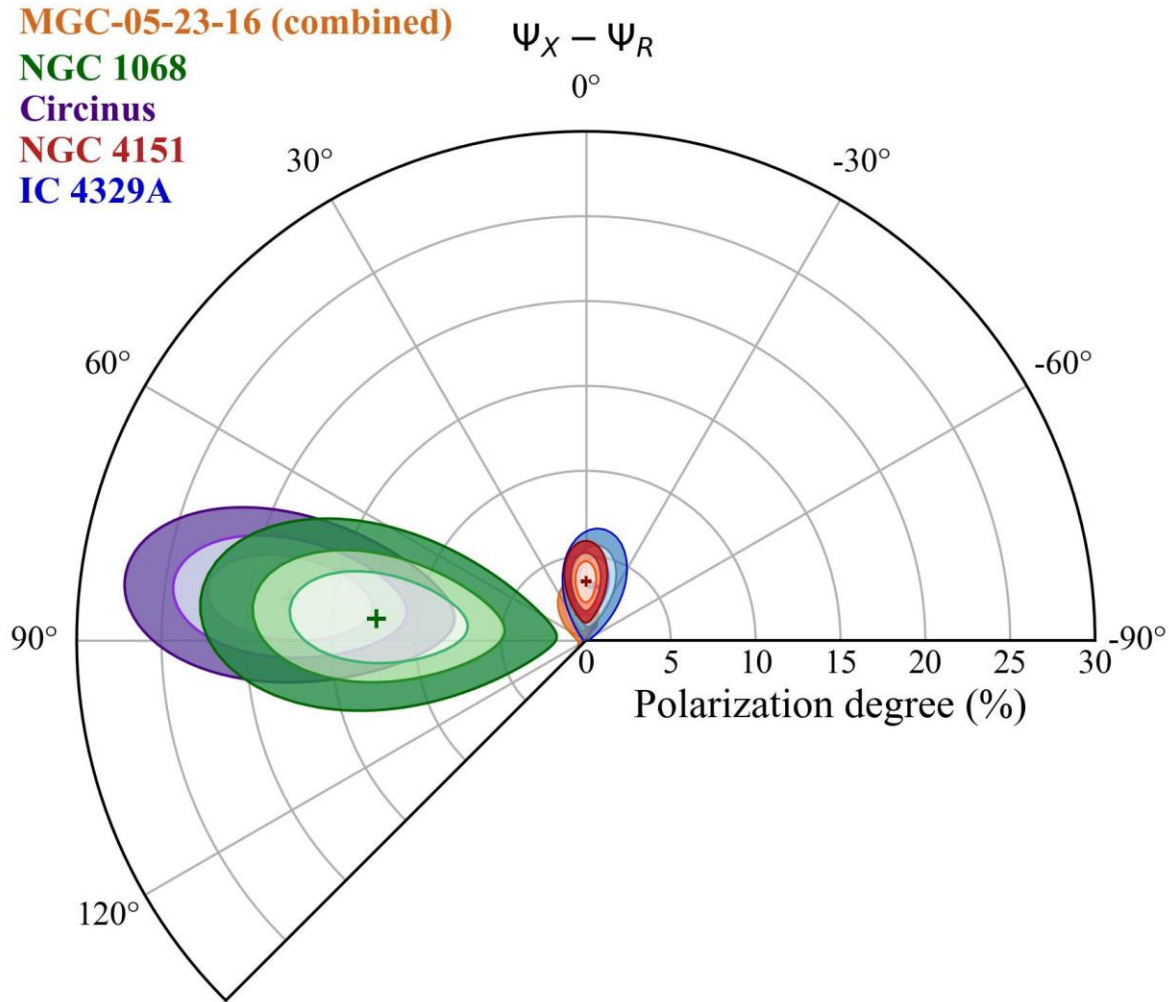
Marin et al. 2024

The spectropolarimetric analysis indicates a torus polarization degree of about 20%

Numerical simulations with STOKES suggest a half opening angle of 50-55 deg



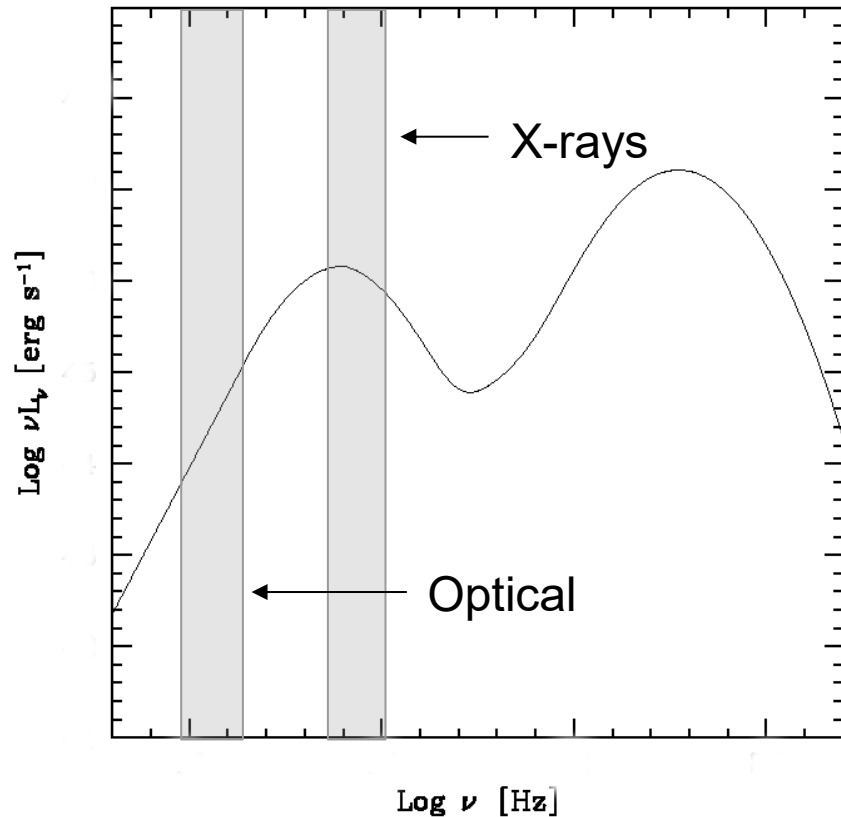
Marin et al. 2024



Courtesy: Andrea Marinucci

- **A few words on RL AGN**
(ask Riccardo Middei if you want to know more!)

High Synchrotron Peaked

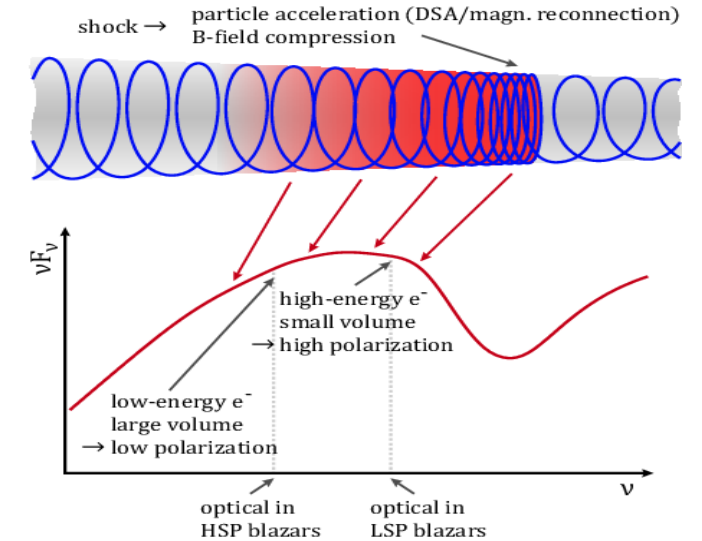
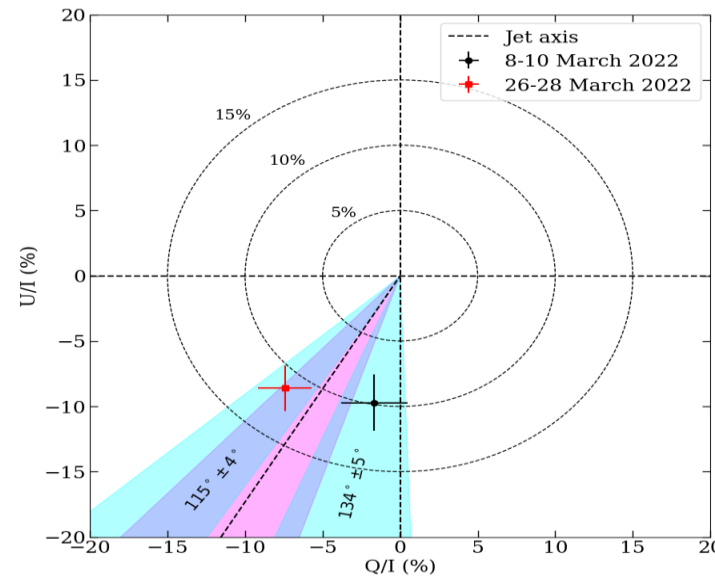
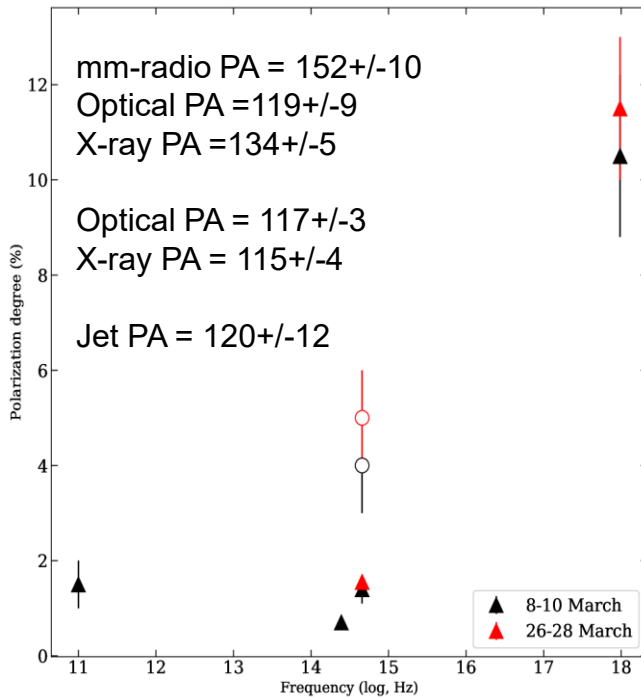


Blazars are promising sources for X-ray polarimetry.

High Synchrotron Peak Blazars like e.g. Mrk 501 (*Liodakis et al. 2022*) and Mrk 421 (*Di Gesu et al. 2022*) are indeed significantly polarized. Multifrequency observations permit to constrain models.

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

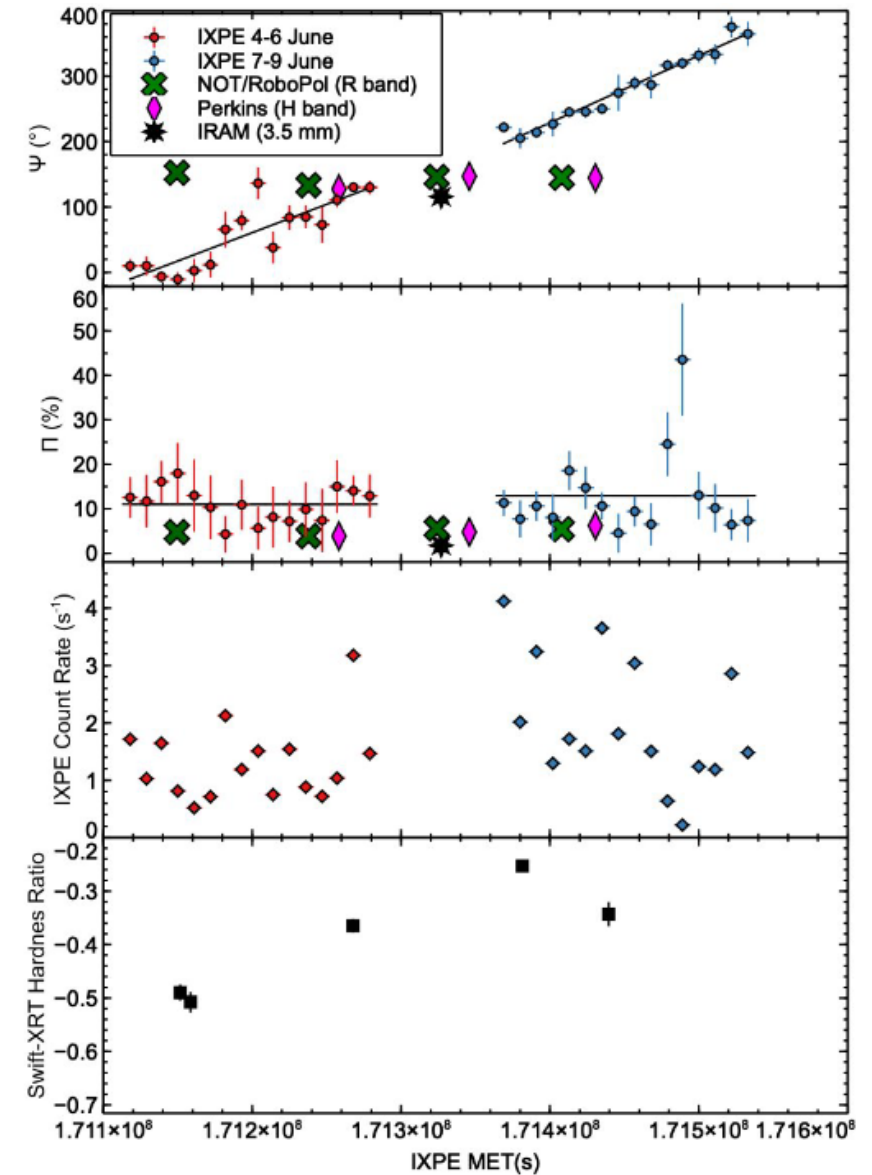




Model	Multiwavelength polarization	Variability [†]	Polarization angle
Single zone	constant*	moderate	any
Multizone	mildly chromatic	high	any
Energy stratified (shock)	strongly chromatic	slow	along the jet axis
Energy stratified (magnetic reconnection)	constant	moderate	perpendicular to jet axis
Observed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

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?

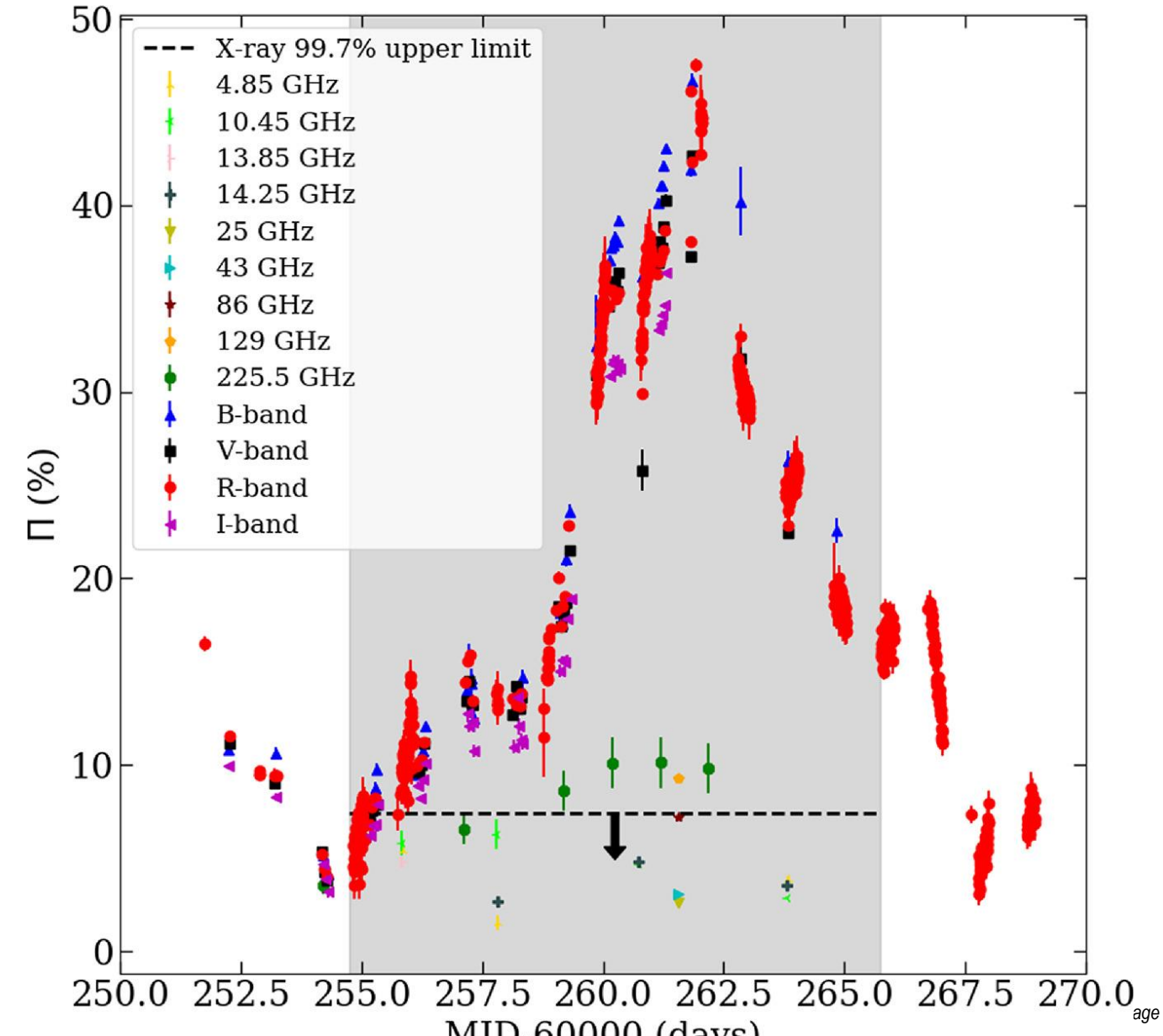


Multifrequency obs. of **BL Lac**
 provide the strongest evidence
 yet in favour of leptonic models
 (Agudo et al. 2025)

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



Thanks for your attention