The Imaging X-ray Polarimetry Explorer

Results from the first year of observations

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https://ixpe.msfc.nasa.gov/partners_sci_team.html

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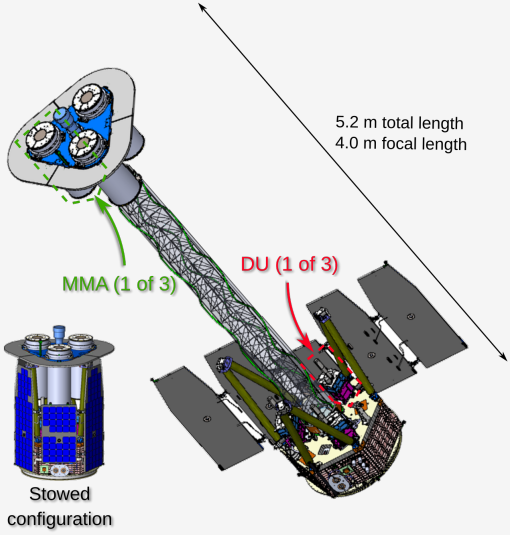
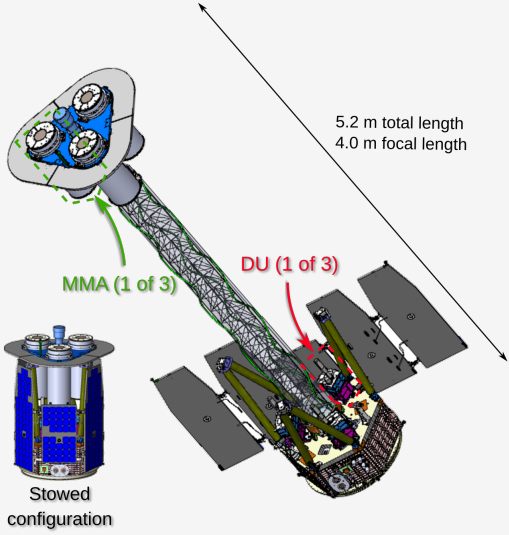
The Imaging X-ray Polarimetry Explorer

- NASA-ASI SMall EXplorer mission dedicated to (linear) X-ray imaging polarimetry
  - Energy range: 2–8 keV
  - Polarimetry: MDP>5.5% in 10 days for 10^{-11} cgs
    - + Imaging (< 30 arcsec)
    - + Timing ($\sim 10\mu s$)
    - + Spectroscopy (<20% at 5.9 keV)
- 3 identical telescopes
  - Grazing-incidence X-ray mirrors (3+1 spare)
  - Imaging X-ray photoelectric polarimeters based on GPD design (3+1 spare)
  - The two are separated by an extensible boom
- Mass at launch: 330 kg



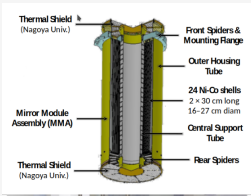
- Outstanding science:
  - polarimetry of tens of sources belonging to almost all astrophysical classes of sources
  - Insight in source modelling and fundamental physics
- Involved parties

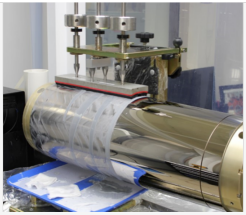
Marshall Space Flight Center PI team, project management, SE and S&MA oversight, mirror module fabrication, X-ray calibration, science operations, and data analysis and archiving	INAF, IAPS, INFN, OAC, OHB Italia Polarization-sensitive imaging detector systems
	LASP Mission operations
Detector system funding, ground station	ROMA TRE, Stanford University Scientific theory
	Nagoya University Thermal shields
Ball Spacecraft, payload structure, payload, observatory I&T	MIT Co-Investigator

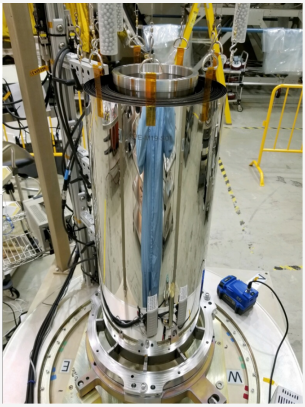


IXPE Mirrors

- Manufactured at NASA/MSFC with replica from mandrels technique
- Nickel-cobalt alloy shells, 24 shells/module
- Heritage from HERO, FOXSI and ART programs
- Contribution from Nagoya University (Japan) for thermal shields
- 4.0 m focal length
- Shell thickness: 178-254 μm
- Mass: 93 kg for three mirrors
- Measured total collecting area: 540 cm^2 at 3 keV
- Measured angular resolution $<$30 arcsec

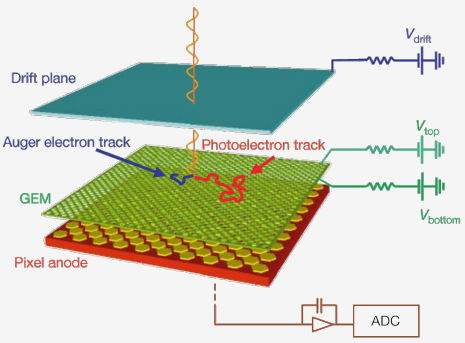


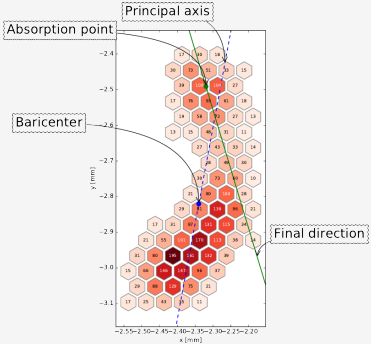


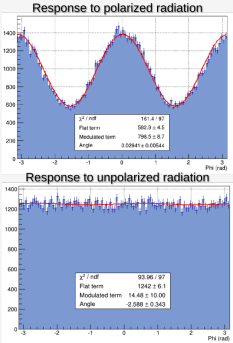


The Gas Pixel Detector

- Developed by INFN-Pisa and INAF-IAPS since 2001
- Photons are absorbed in a gas mixture
- Primary ionization is multiplied with a Gas Electron Multiplier (GEM) and eventually collected on the top layer of a dedicated ASIC
- Polarization is derived from direction of the photoelectron
- All the characteristics of the photons are measured contemporaneously and photon by photon

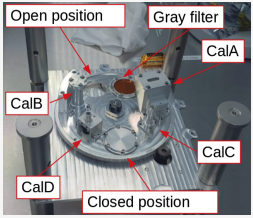


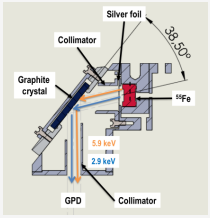


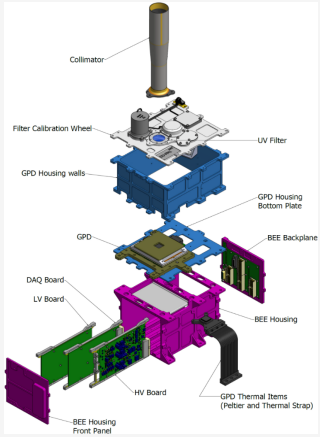


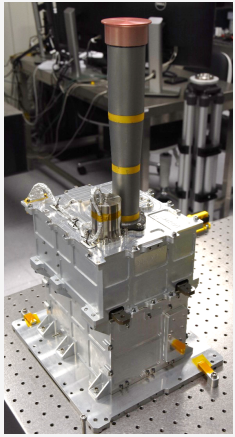
The Instrument on-board IXPE

- The GPD is hosted inside the Detector Unit
- The Back-End Electronics which powers and controls the GPD
- A filter and calibration wheel
  - 1 polarized at two energies (3.0 and 5.9 keV)
  - 3 not polarized (5.9 and 1.7 keV)
  - All powered by ^{55}Fe
  - Filters for special observations









Launch...

9th December, 2021 from LC 39A in the “NASA Kennedy Space Center”

... and separation!

In-flight operations

- Three-axis stabilized pointing, with most observations dithered
- Fixed solar panels facing perpendicular ± 25 deg to primary axis of Observatory
- Point and stare: Remain pointed toward target until observation segment is complete
  - ➥ Simultaneously observe astrophysical target on all 3 detector units when target is not occulted by the earth
  - ➥ Observe 1 calibration source on 1 detector unit when astrophysical target is occulted by the earth
  - ➥ Ramp down detector high voltage when passing through South Atlantic Anomaly (11.7 minutes)
- Slew to next astrophysical target at completion of an observation segment
- Data downloaded at MOC at the U Colorado's/LASP, and forwared to the SOC at NASA/MSFC
- Public archive at HEASARC (data available in one week)
  - ➥ Analysis tools part of HEASoft
  - ➥ ... or IXPE team's tool ixpeobssim

First scientific results (a selection of)

Year 1 observations

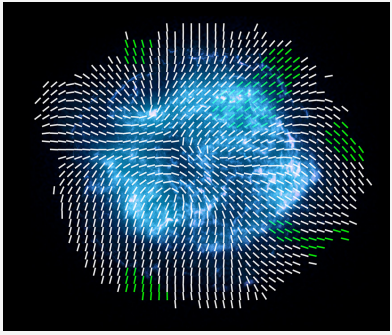
- 40 observations, including 4 TOOs, in ~ 1 year
- 15 "prominent" detections ($> 6\sigma$), > 27 "meaningful" detections
- Galactic and Extragalactic sources, belonging to different classes

4 PWNe and isolated pulsars	Crab PWN, Vela PWN, MSH 15-52, PSR B0540-69
3 SNR	Cas A, Tycho, SN 1006 NE
4 Accreting stellar-BH	Cyg X-1, 4U 1630-472, Cyg X-3, LMC X-1
12 Accreting NS & WD	Cen X-3, Her X-1, GS1826-67, Vela X-1, Cyg X-2, GX 301-2, Xpersei, GX 9-9, 4U 1820-303, GRO J1008-57, XTE 1701-46, LSV +44 17
2 Magnetars	4U 0142+61, 1RXS J170849
Radio-quiet AGN & Sgr A*	MCG 5-23-16, Circinus Galaxy, Sgr A* Complex, NGC4151, IC4329A
11 Blazars & radio galaxies	Cen A, S5-0716-714, 1ES 1959-650, Mrk 421, Bl Lac, 3C 454, 3C 273, 3C 279, Mrk 501, PG1553+113, 1ES 0229+200
Others	GRB 221009A

Polarization samples the magnetic field topology close to the acceleration site

Cas A

- Average polarization $\sim 1.8 \pm 0.3\%$, assuming radial symmetry Vink et al. [2022]
  - Polarization of only the synchrotron component $\lesssim 5\%$
  - Lower than radio (5-10%)
- Tentative detection also in single regions
- Magnetic field largely turbulent
  - Radial average direction
  - Expected to be re-oriented within 10^{17} cm from the shock

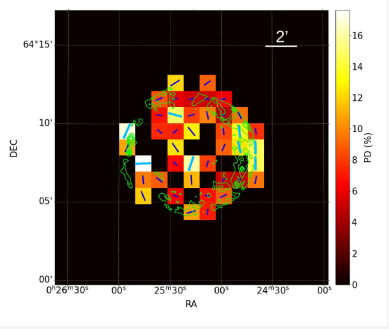


Vink et al. [2022]
Chandra: NASA/CXC/SAO;
IXPE: NASA/MSFC/J. Vink et al.

Polarization samples the magnetic field topology close to the acceleration site

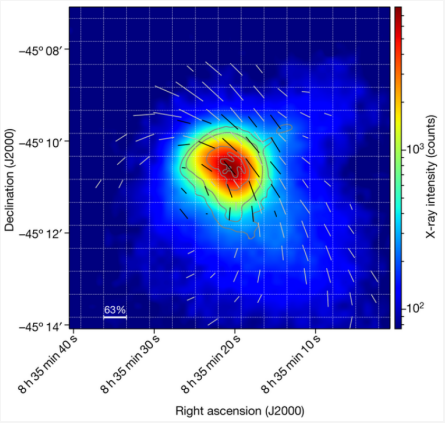
Tycho

- Polarization is much higher for Tycho
  - Up to ∼23% for the synchrotron component
  - Higher than radio, which is similar to Cas A
- Detection is a few regions
- Magnetic field has a similar radial profile
  - more ordered or longer scale for turbulence
- Effect on particles acceleration?



Ferrazzoli et al. [2023]

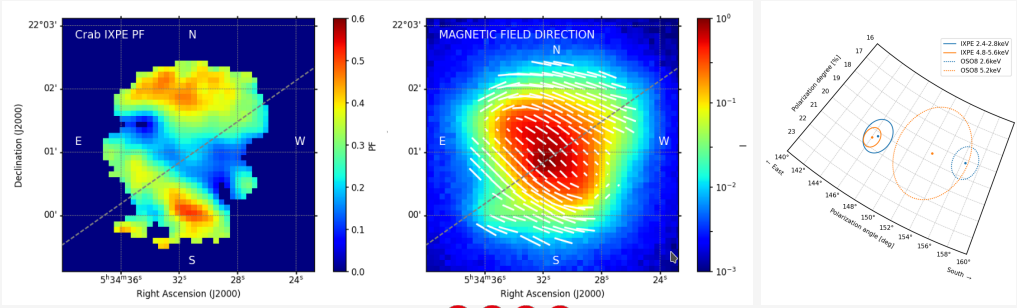
- Emission dominated by synchrotron
- Average polarization 45%, $\gtrsim$60% in small regions!
  - ➥ Close to the theoretical limit in a uniform magnetic field
  - ➥ Acceleration must occur in a very ordered environment
- Highly symmetric polarization angle pattern
- Polarization consistent with radio, but X-rays sample inner regions
- Polarization degree somehow increasing with energy
  - ➥ Expected as the nebula shrinks



[Fei et al., 2022, Nature]

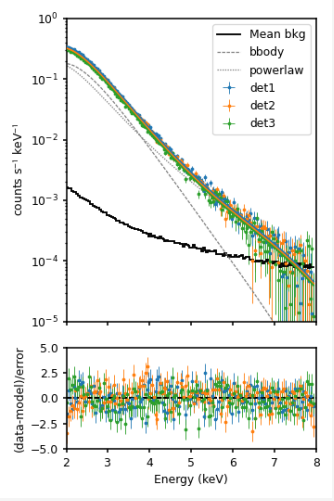
IXPE Pulsar Wind Nebulae: The Crab

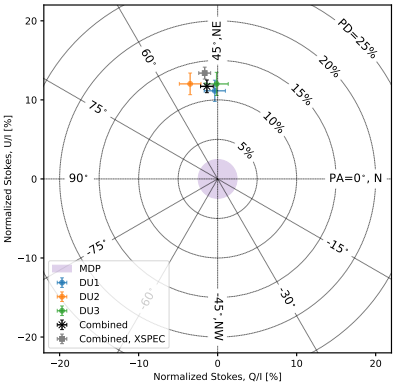
- The only known polarized source in the X-rays, ∼20% on average
- More complicated magnetic field pattern than Vela, but polarization degree still ∼45–50%
  - ➥ Not symmetric with respect to the axis of the intensity image
- Polarization changed since '70 (not surprisingly)
- Pulsar emission oddly low, $\lesssim 15\%$



[Bucciantini et al., 2022, accepted on Nature Astronomy]

- Belonging to the magnetar class
  - Emission powered from magnetic field, not rotation or accretion
- P$\sim$8.69 s, $\dot{P} = 2 \times 10^{-12}$ ss^{-1}; B$\sim 1.3 \times 10^{14}$ G
- (unabsorbed) Flux $\sim 7 \times 10^{-11}$ cgs
- Observed by IXPE for $\sim$840 ks in February 2022
- Spectrum shows two components
  - BBODY with kT 0.4 keV + POWERLAW with $\Gamma \sim 4$
  - Thermal photons and up-scattered by currents in the magnetosphere

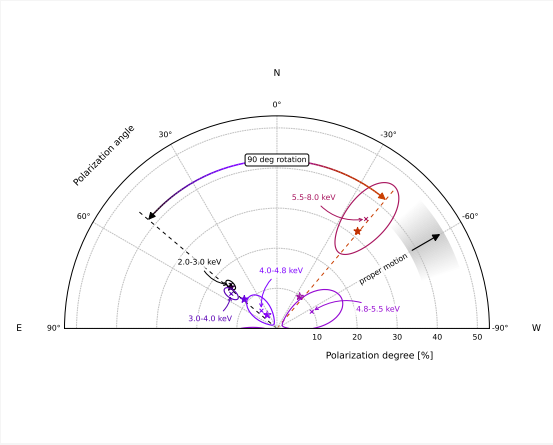




[Taverna et al., 2022, on Science]

- Average polarization ∼12%, first detection since Crab Nebula!
  - Condensed surface and not an atmosphere
  - Evidence of vacuum birefringence induced by the magnetic field

IXPE observation of 4U 0142+61



- Average polarization $\sim$12%, first detection since Crab Nebula!
  - ➥ Condensed surface and not an atmosphere
  - ➥ Evidence of vacuum birefringence induced by the magnetic field
- Two components with polarization rotated of 90°
  - ➥ X (RCS at high energy) and O modes (emission from an equatorial belt?)
  - ➥ ... or the contrary and the kick velocity is really aligned with the spin axis

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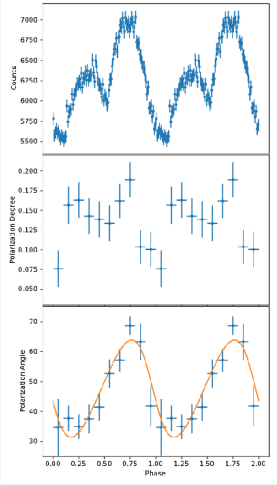

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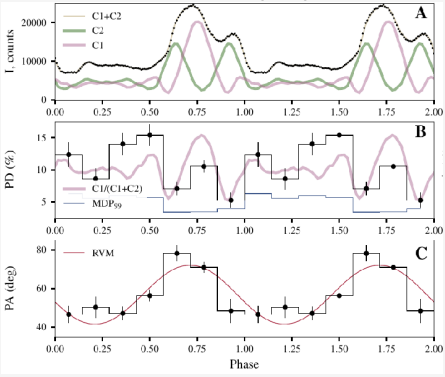
  - ➥ ... or the contrary and the kick velocity is really aligned with the spin axis
- Polarization varying with spin phase
  - ➥ Polarization angle *not* synchronized with flux
  - ➥ The usual suspect is again the birefringence of the vacuum
  - ➥ Geometry of the system in the Rotating Vector Model

The classical X-ray Pulsar Her X-1

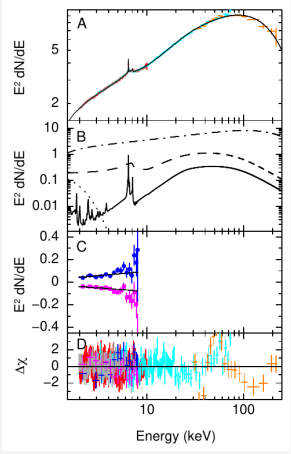
- Average polarization $\sim$8.6%
  - Much smaller than expected
  - Likely a combination of several mechanisms
- Polarization changing with the orbit and with the spin phase
- Polarization may be related to the component from one pole
- Simple polarization angle, as in 4U 0142+61
  - RVM allows to constrain magnetic axis and spin orientation
- Comparison with optical suggest tilted accretion disk, preceding at the superorbital period
- Similar picture for Cen X-3 [Tsygankov et al., 2022]

Polarization vs spin phase



[Doroshenko et al., 2022, on Nature Astronomy]

- Source caught in the **hard state**
- From the broad-band spectral modeling (IXPE, NICER, NuSTAR and INTEGRAL):
  - Corona emission largely dominates ($\sim$90%)
  - Contribution from reflection $\sim$ 10%
  - $\sim$ 1% from the disk



Krawczynski et al., 2022, on Science

The observation of Cyg X-1: the corona geometry

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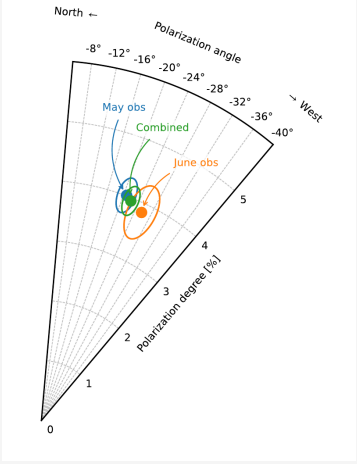
  - Contribution from reflection $\sim$ 10%
  - $\sim$ 1% from the disk
- X-ray polarization degree $\sim$4%
  - Some evidence that PD increases with energy and flux
- Constant during the orbit
  - No due to scattering on companion/winds



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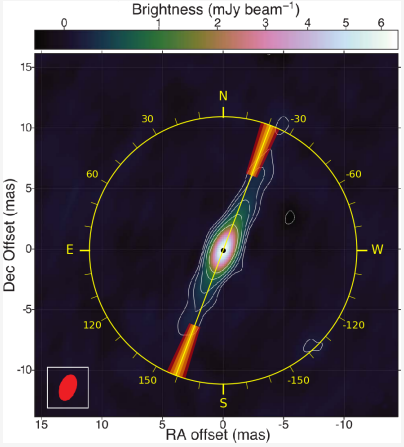
- X-ray polarization degree $\sim$4%
  - Some evidence that PD increases with energy and flux
- Constant during the orbit
  - No due to scattering on companion/winds
- Polarization angle parallel to the radio jet
  - Confirmation that jets are orthogonal to inner accretion flow
- Observation constrains the corona geometry



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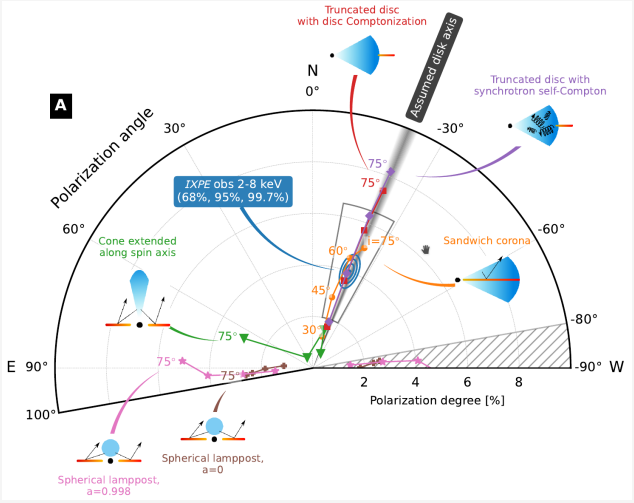
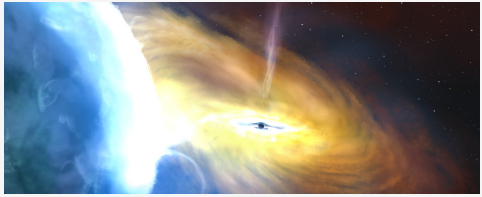
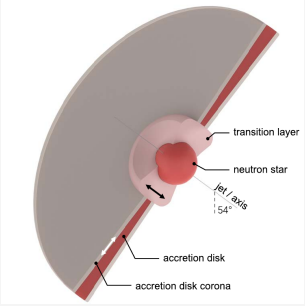


- Laterally-extended corona favored respect to lamp-post scenarios
- Inclination must be larger than 27°
  - ➥ BH spin and orbit axes misaligned
  - ➥ Superobital precession excluded by ToO observation
- Jet contribution $< 5\%$ in flux, $<0.4\%$ to the observed PD
  - ➥ $\vec{B}$ should be along the jet

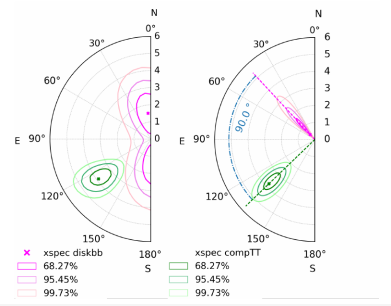


Credit: John A. Paice

- Joint IXPE+NICER+INTEGRAL observation
- Polarization detected at high significance, $1.85 \pm 0.29\%$
  - ➥ Angle aligned with the jet
- Typical state with a large contribution from the corona in the IXPE band
- Favour a corona in the spreading layer
  - ➥ Support PolarLight results



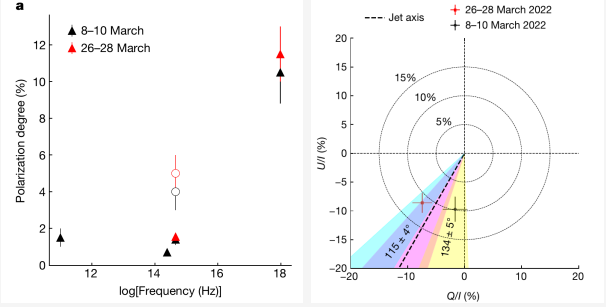
[Long et al., 2022]



[Farinelli et al. 2022]

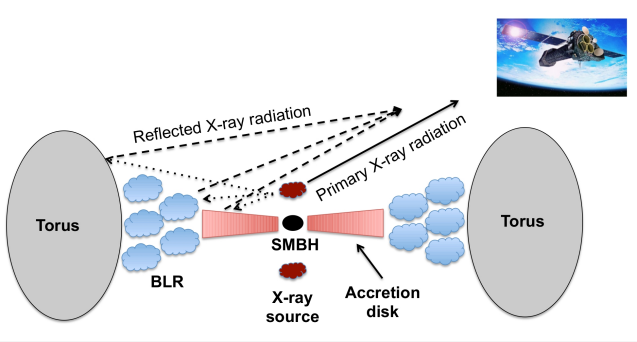
Blazars: Mrk 501 & Mrk 421

- X-rays probe acceleration sites on shorter spatial scales
- Measured polarization twice that of contemporaneous optical and mm observations, $\sim 10\%$
- Angle aligned with the jet at all wavelengths
- No variability
- Points to shock acceleration in a quite ordered magnetic field more than magnetic reconnection
- Similar picture for Mrk 421 [Di Gesu et al., 2022]

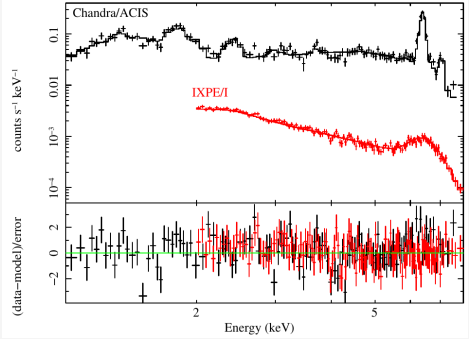


[Liodakis et al., 2022, on Nature]

- Reprocessed radiation, not direct one which is obscured by a dust torus



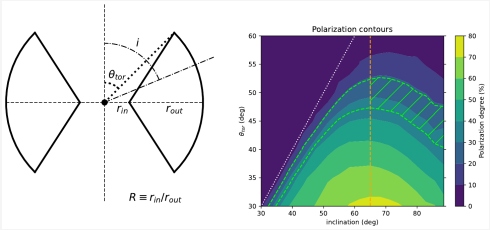
Credits: Ricci 2011, PhD thesis

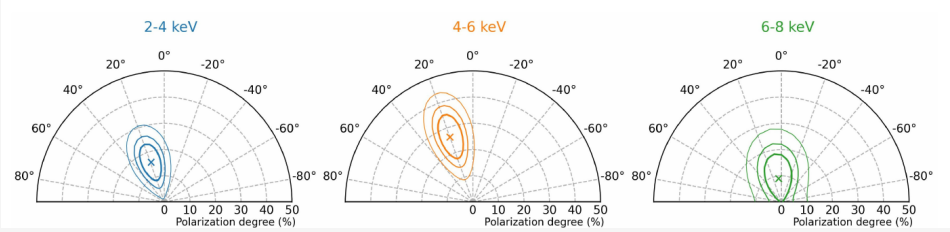


[Ursini et al., 2022]

Compton-thick AGNs: Circinus Galaxy

- High polarization, $\sim 25\%$
  - ➥ Orthogonal to the jet
- Confirmation of the Unification Model
- Constrain on inclination and torus aperture
  - ➥ 45-55 deg opening angle





[Ursini et al., 2022]

Conclusions

- Polarimetry is providing a new view in the X-ray sky
- Two-third of the observed sources shows a polarization useful for constraining models
- Objects belonging to different classes:
  - Supernovae Remnants, Pulsar Wind Nebulae
  - Isolated neutron stars
  - Binary systems with either neutron stars and black holes
  - Blazars
  - Active Galactic Nuclei
- Magnetic field the main player, but also scattering at work!
- Discoveries are ahead of modeling

- IXPE data are already public
- A Guest Observing Program will (likely) begin in January 2024

Bibliography I

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