X-ray polarimetry observations (IXPE)

Manel Errando
Washington University in St Louis

Polarization measures geometry

Polarization is a vector → measures geometry

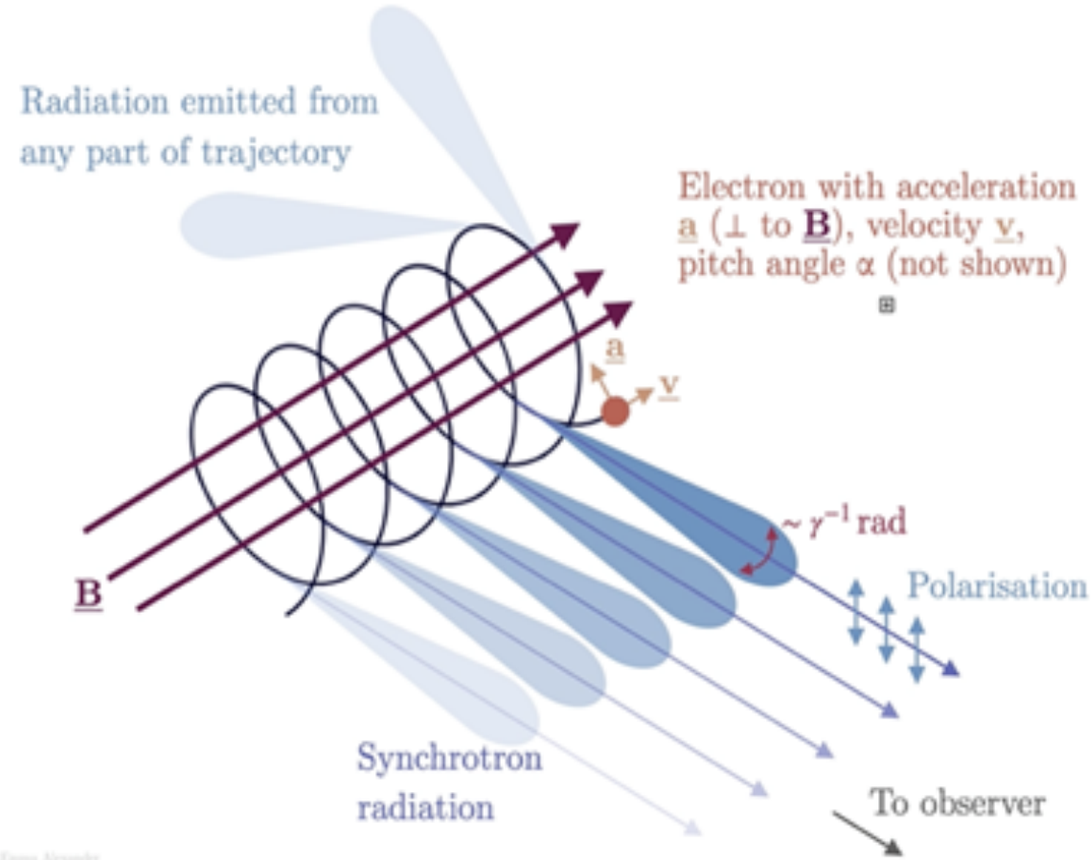
Electric vector position angle = EVPA

•Synchrotron radiation →
EVPA perpendicular to magnetic field lines

•Scattering/reflection →
EVPA perpendicular to scattering plane

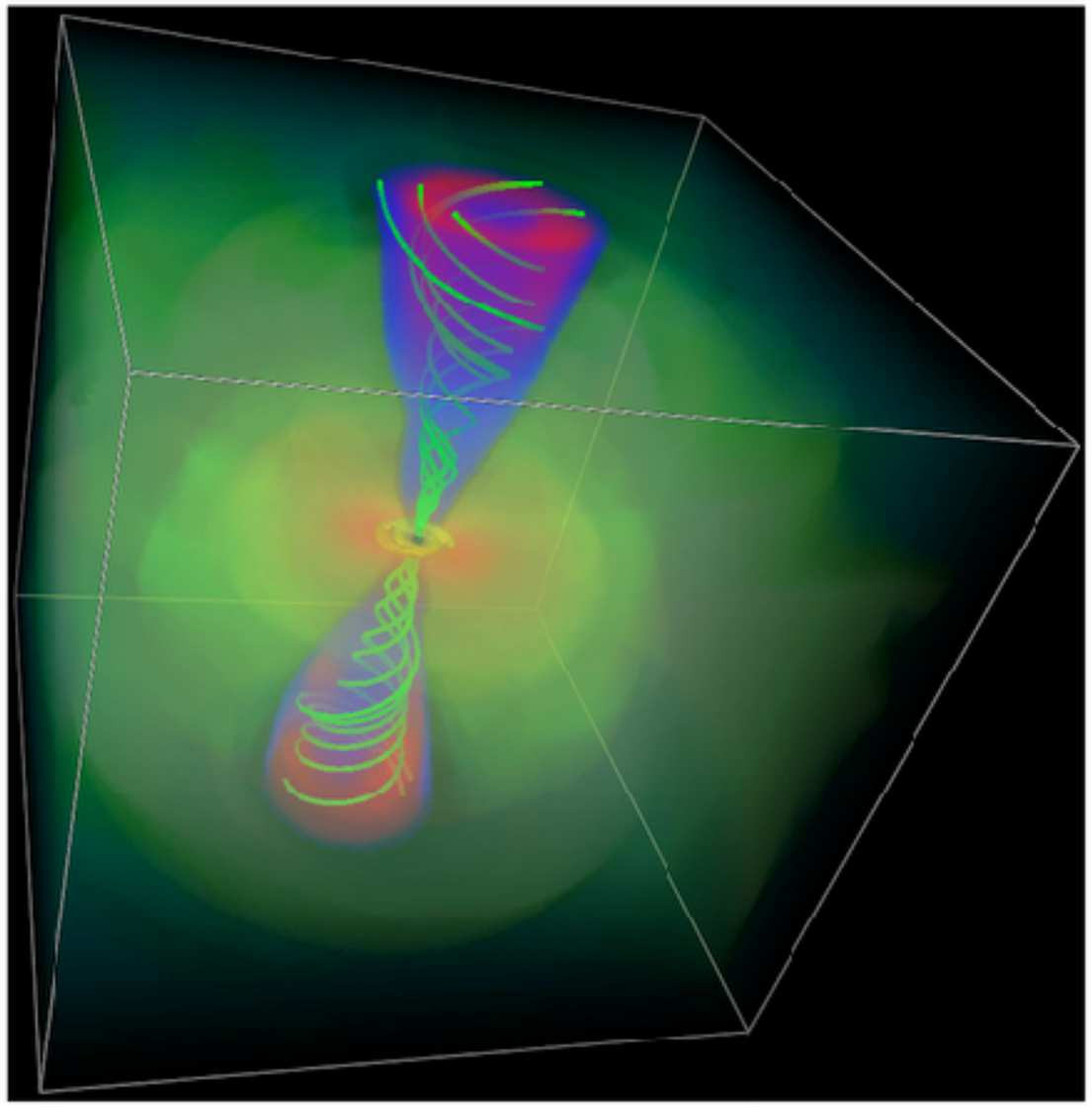
•Strong magnetic fields →
Opacity different parallel vs perpendicular to B
EVPA transported along B in strong B

•Strong gravitational fields →
EVPA parallel-transported along space-time geodesics



Polarization measures geometry

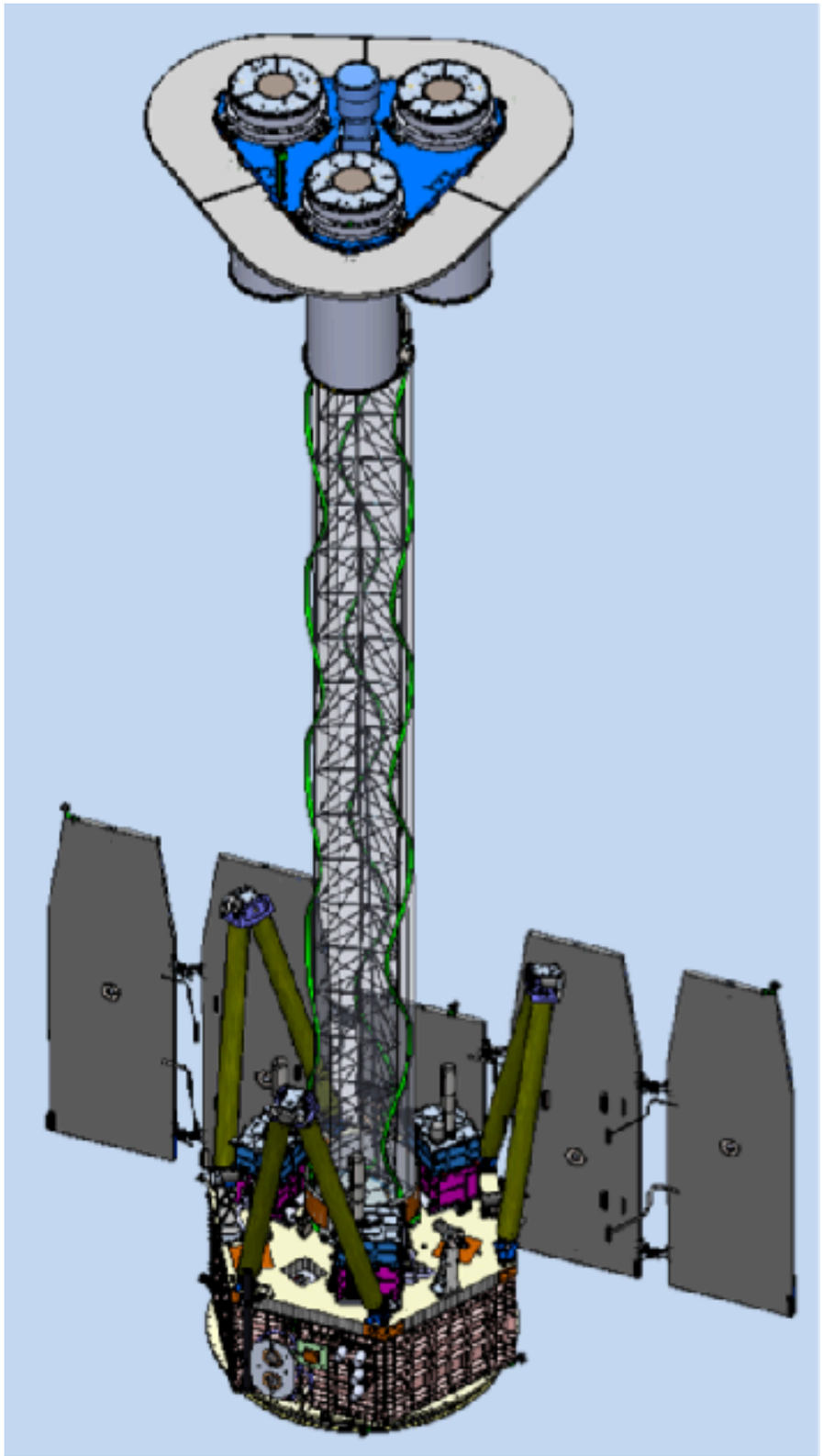
X-rays
Reveal skeleton



McKinney + Blandford 2009

X-ray polarization
Reveals magnetic field structure in astrophysical objects

IXPE status and operations

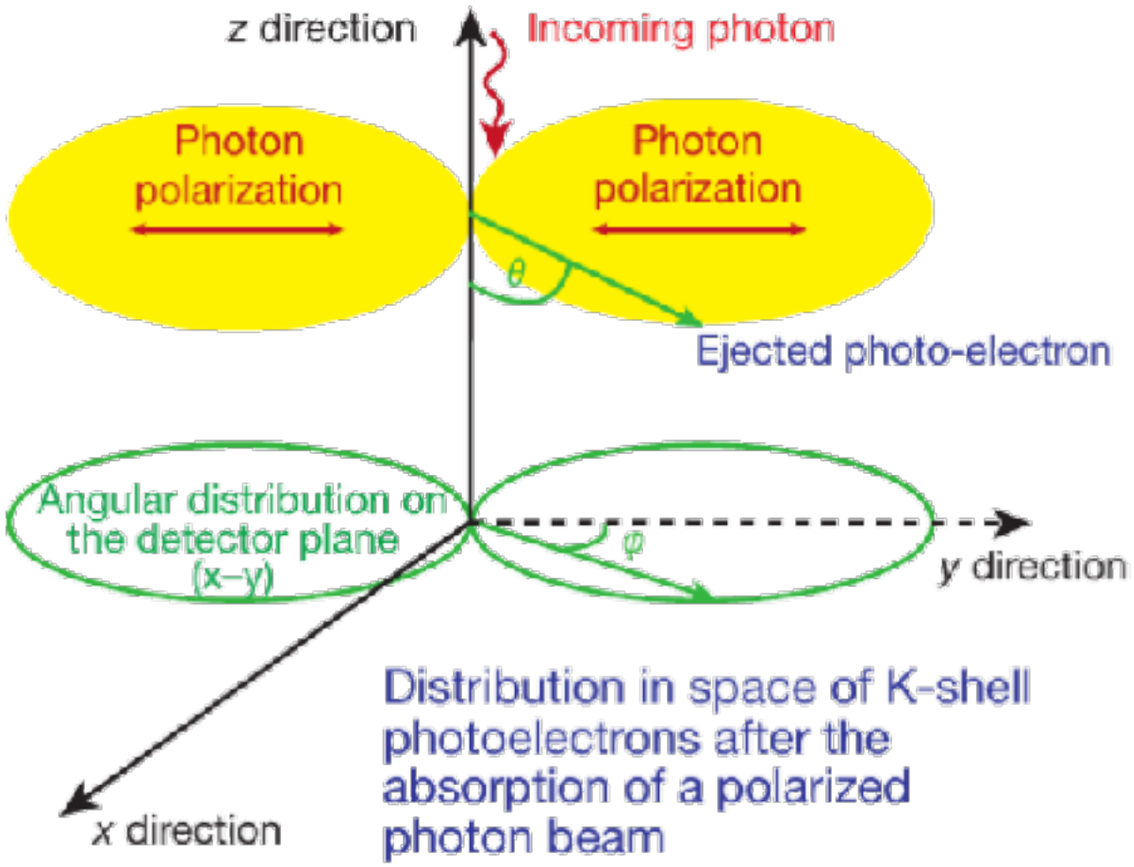


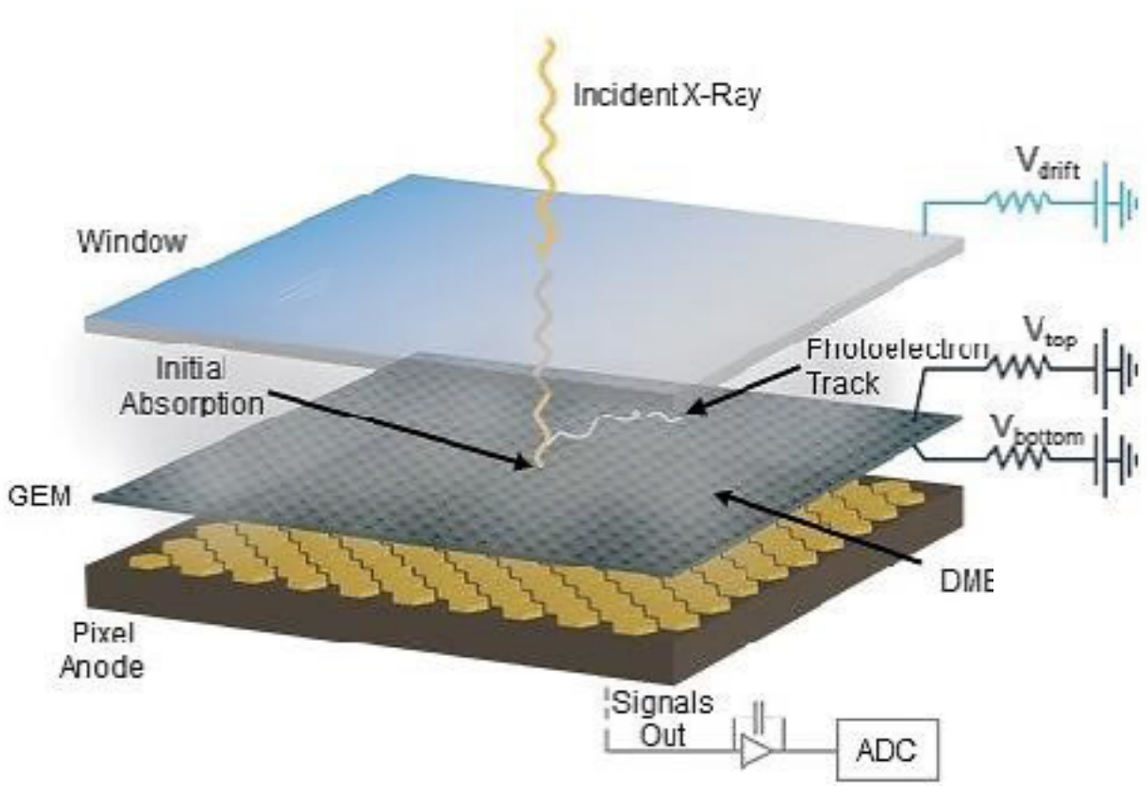
- Launched on Dec 9th 2021.
- Boom deployed on Dec 15.
- Commissioning and calibration finished successfully.
- Science operations started Jan 11 2022.
- Sensitive to X-ray polarization in the 2-8 keV band.
- First X-ray polarimeter in space in 40 years.

X-ray polarization via the photoelectric effect

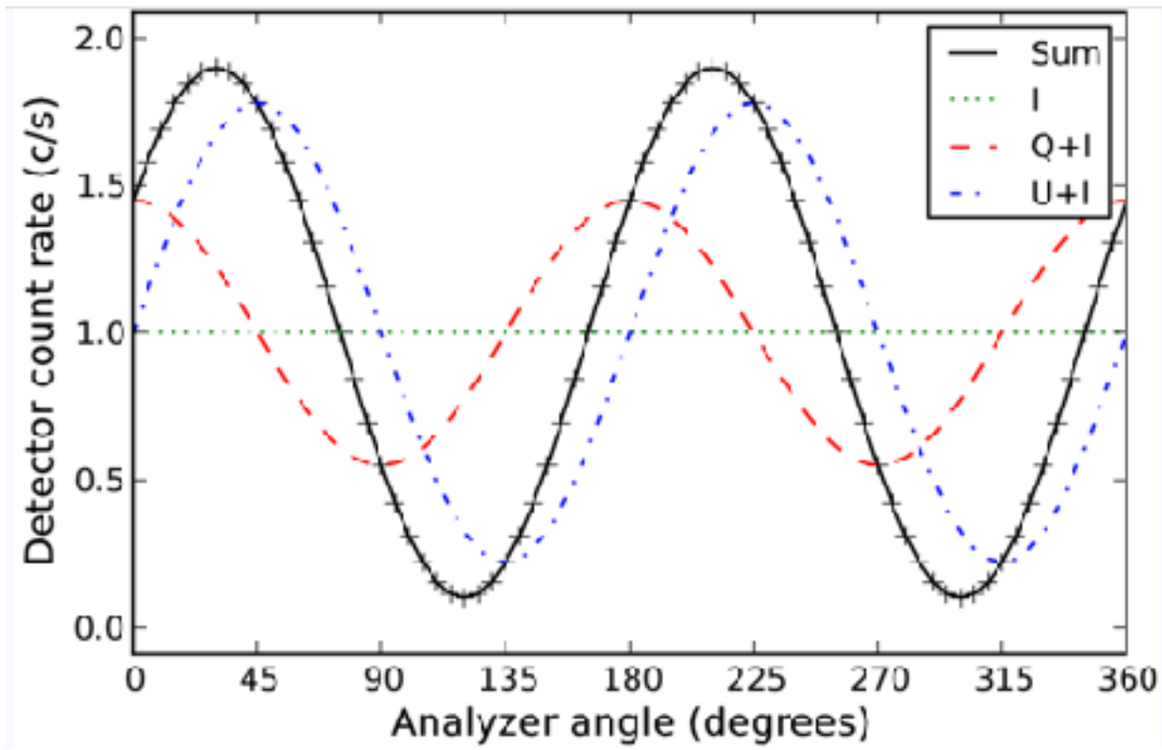
IXPE uses the photoelectric effect.

•Photoelectron ejected along photon E field.

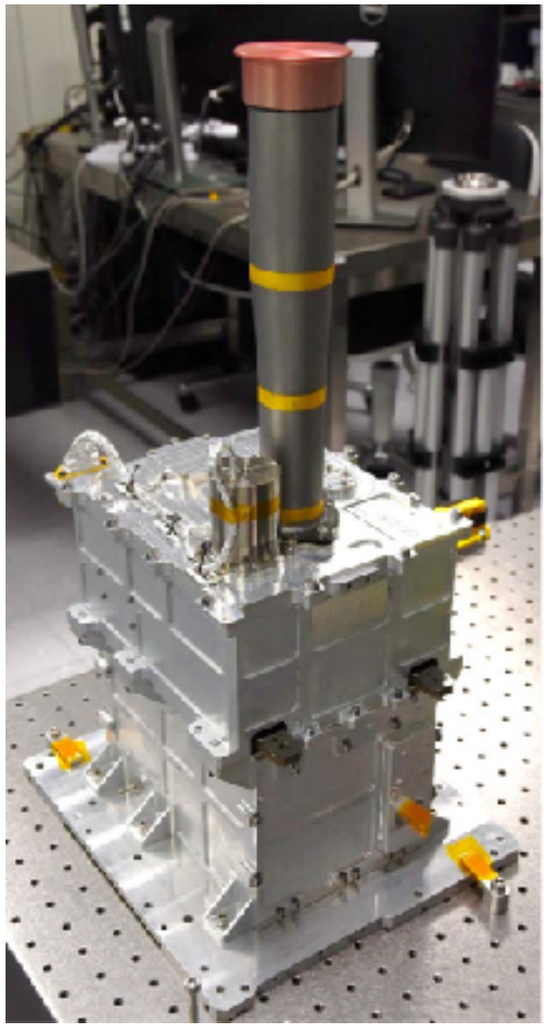




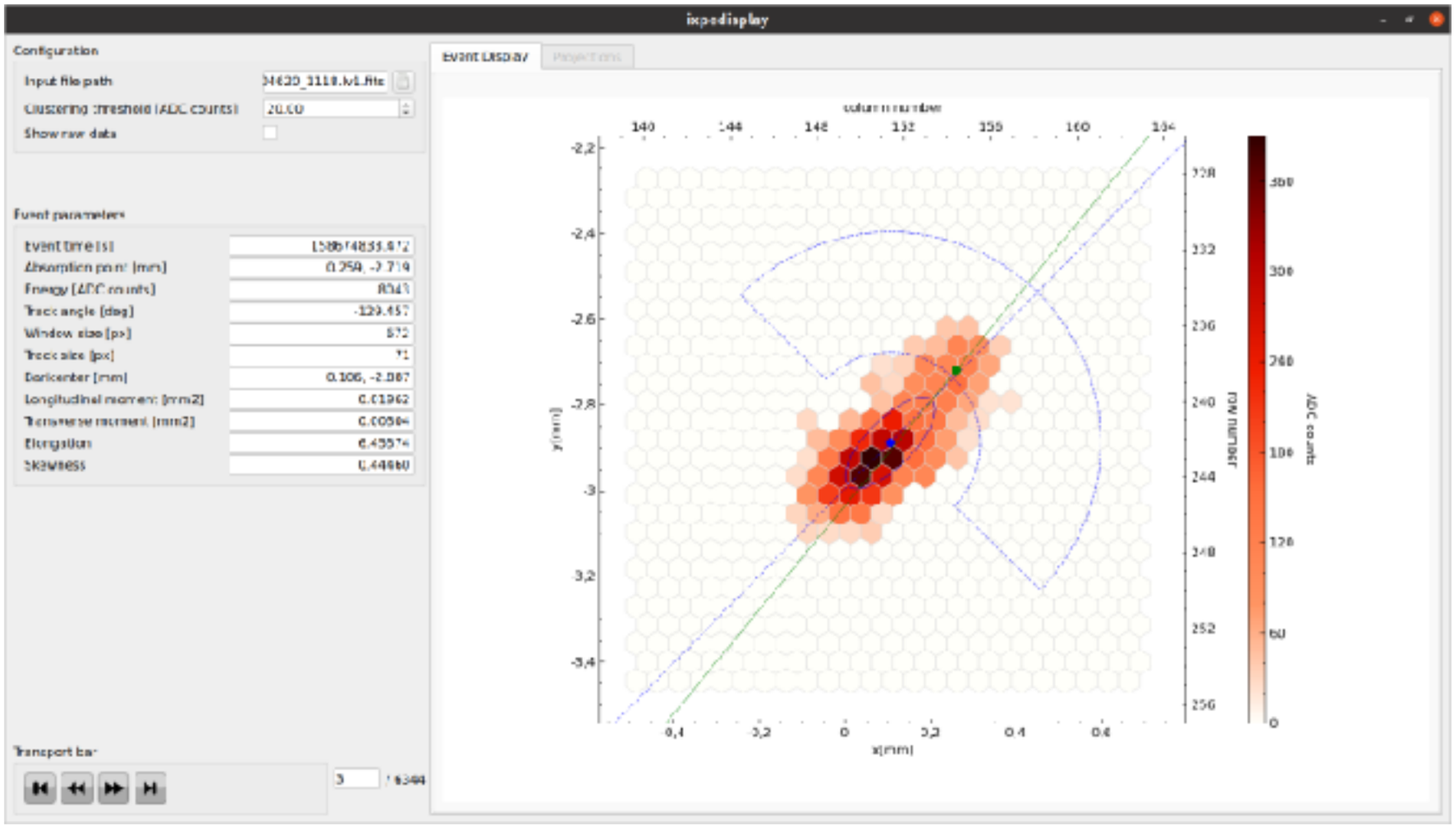
INAF/IAPS,
INFN-PI



X-ray polarization via the photoelectric effect



Detector Unit (DU) INAF/IAPS, INFN-PI



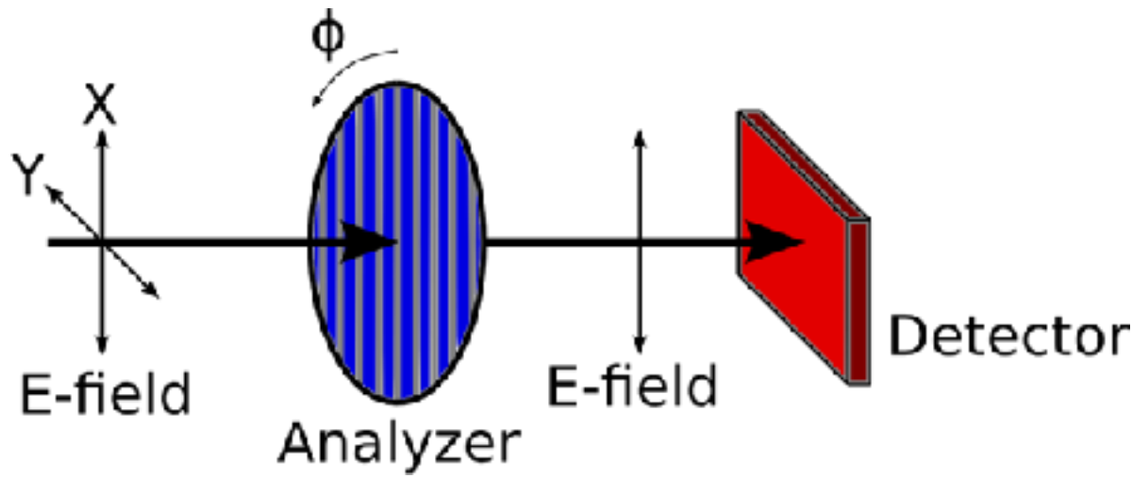
First photo-electron track obtained during IXPE science operations

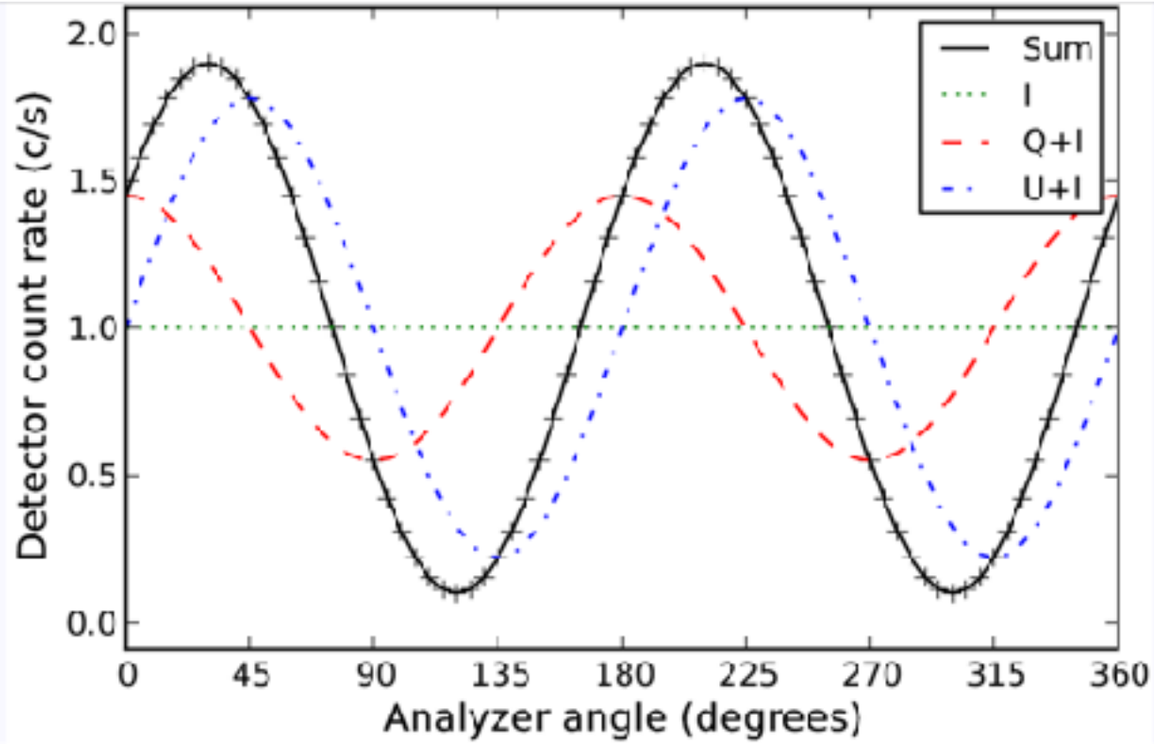
SNR Cas A, 2022 January 11, initiated by 2.7-keV photon in DU1.

Key is to find photoelectron direction at interaction point.

Stokes parameters and MDP

- Work in Stokes parameters
  - Independent, gaussian errors
  - Simply additive
  - No coordinate singularity at $\Pi = 0$
- Compute Stokes parameters (q_i, u_i) for each X-ray from initial direction of photoelectron
- Do spectropolarimetry (in Xspec) using spectra in Stokes I, Q, and U and 'modulation response'.





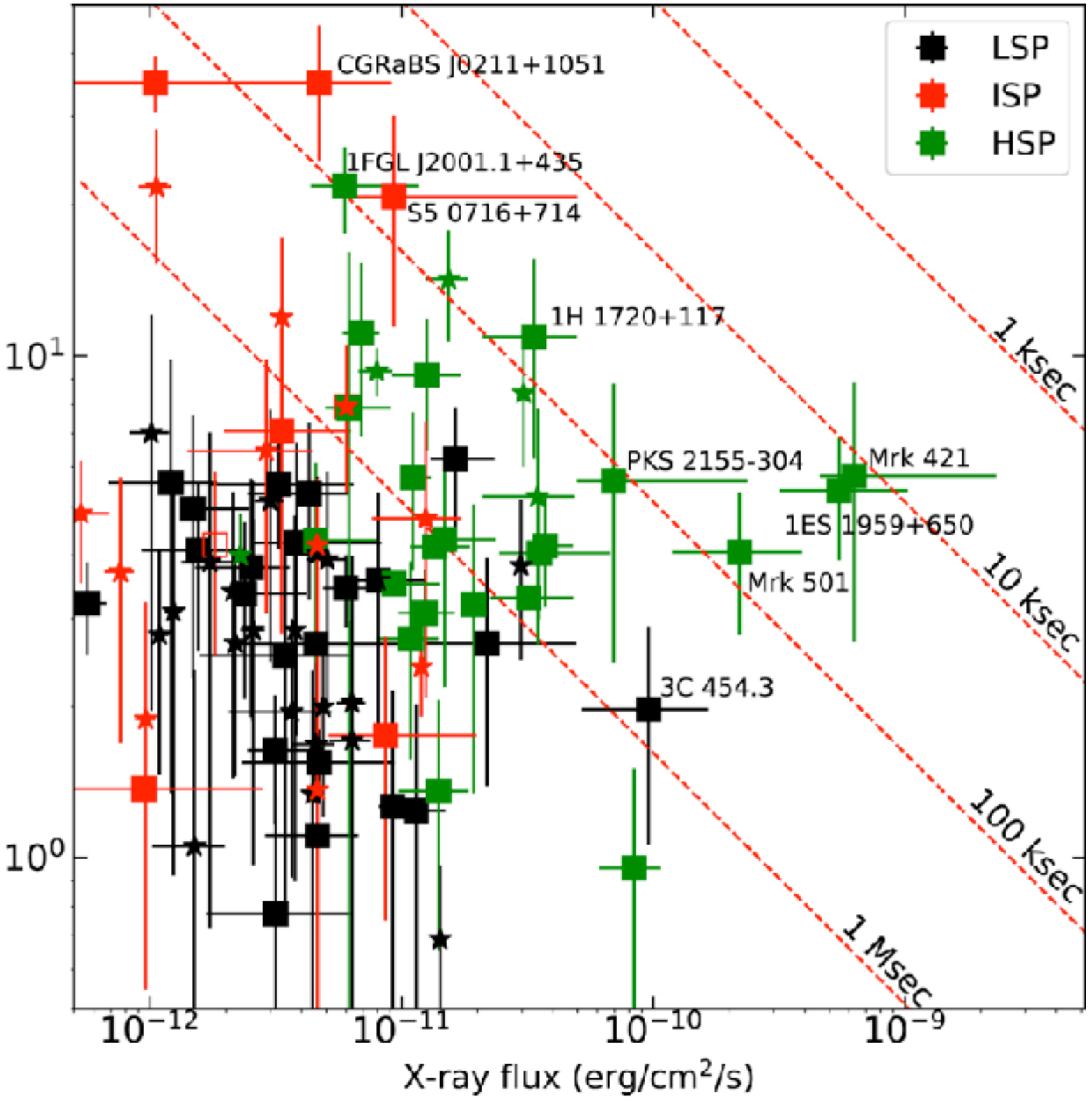
•Minimum Detectable Polarization (MDP)

$$MDP99 = \frac{4.29}{\mu\, s}\sqrt{\frac{s+b}{T}}$$

where μ = modulation factor, *s* = source rate, *b* = background rate, *T* = exposure time.

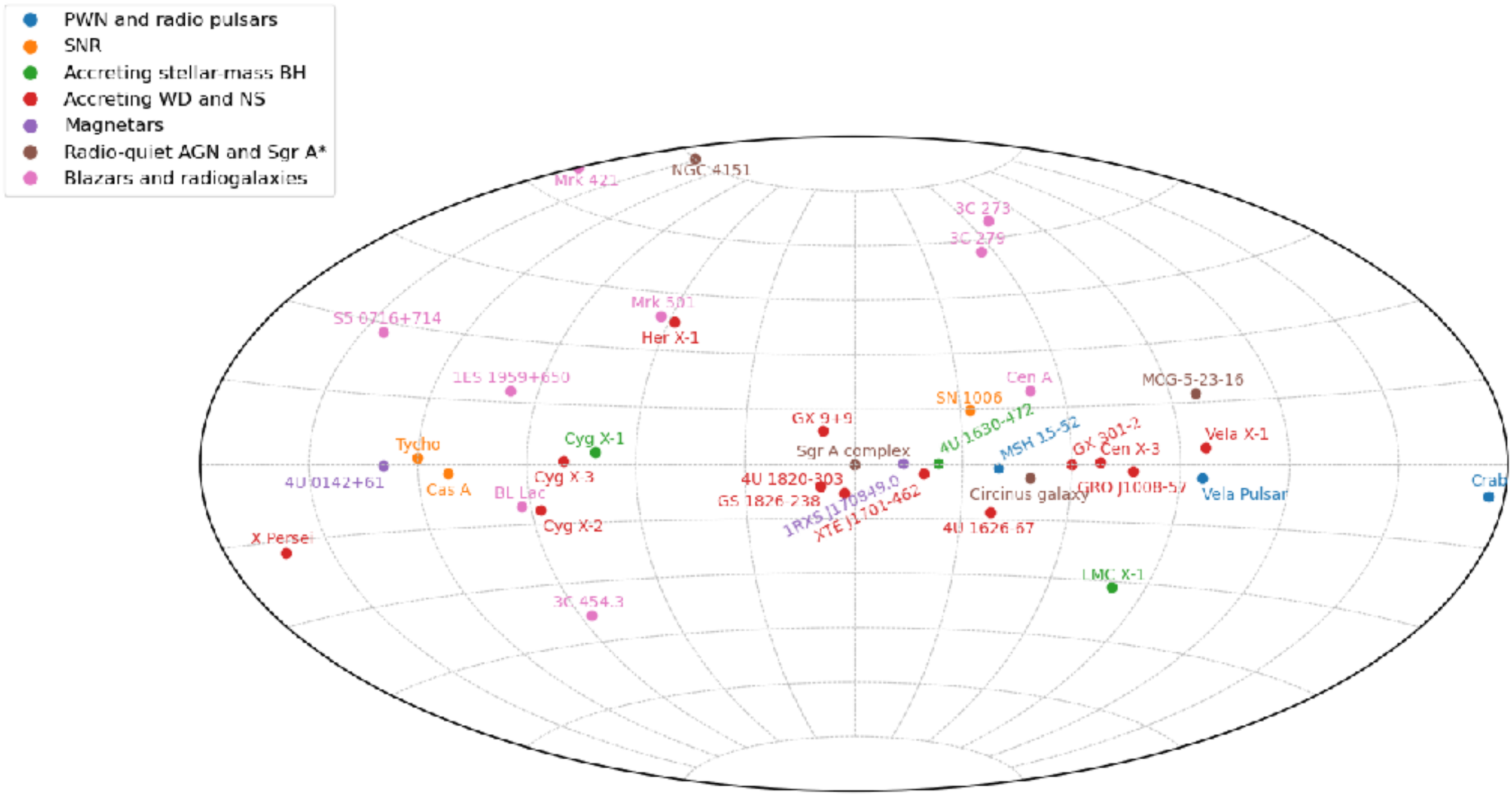
For MDP = 2% with μ = 0.4 and *b* = 0, need 3×10^5 X-rays.

IXPE capabilities

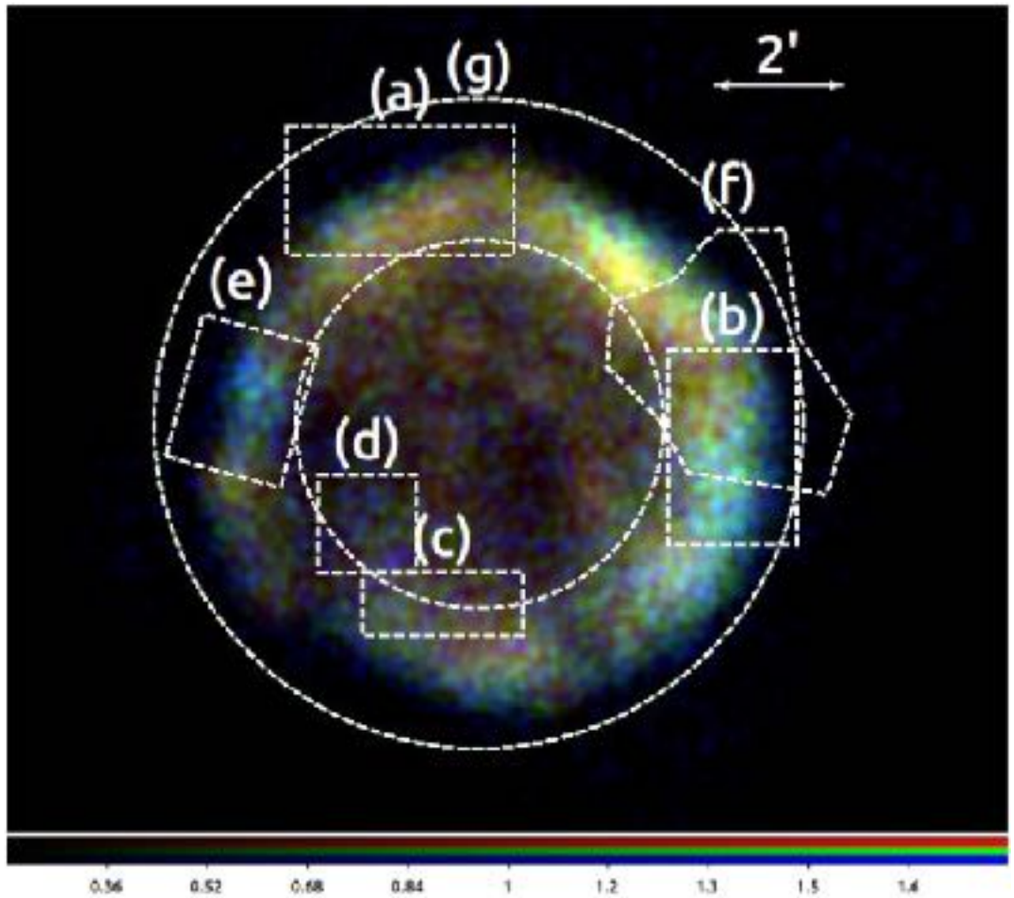


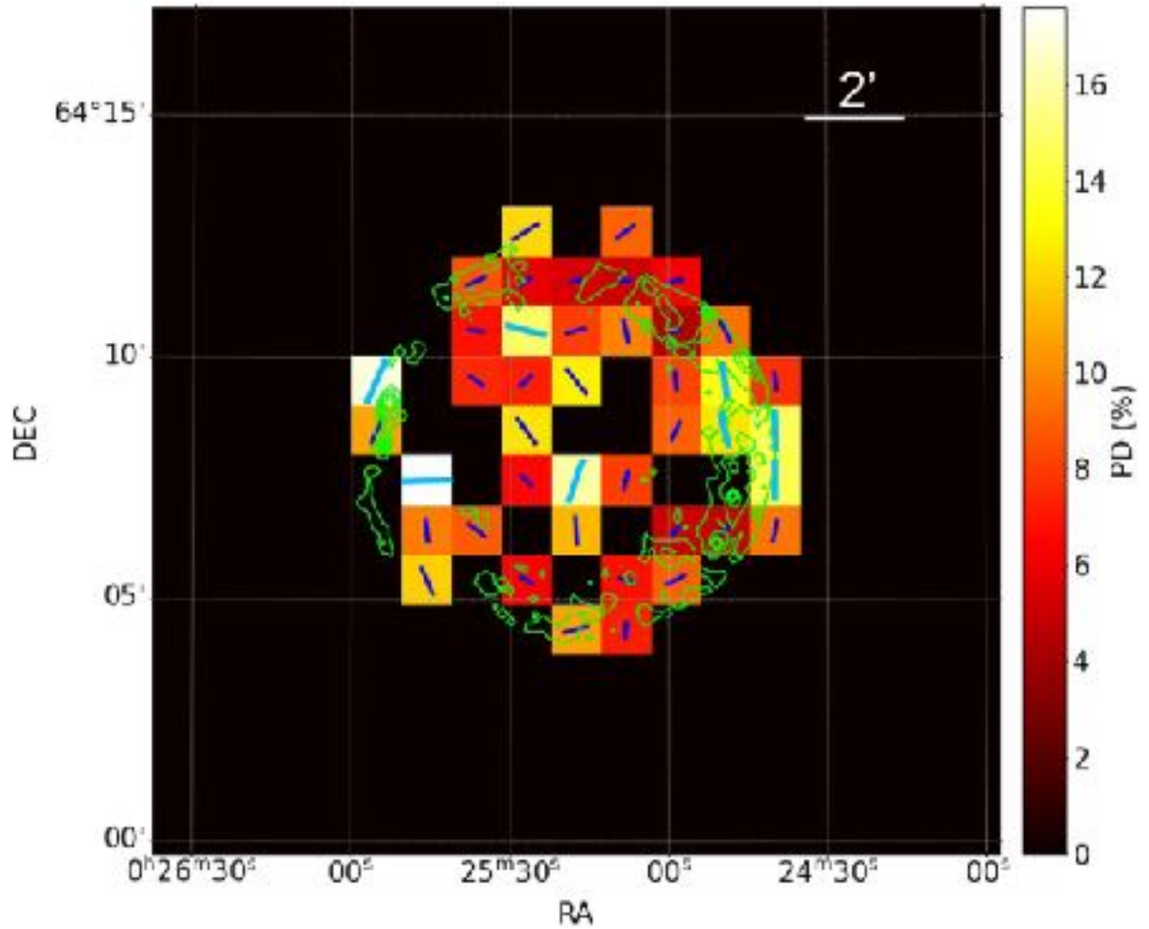
Liodakis+ 2019

IXPE targets to date



Tycho supernova remnant





- Radial, relatively well-ordered magnetic field gives rise to polarization ~10% and reproduces the measured EVPA.

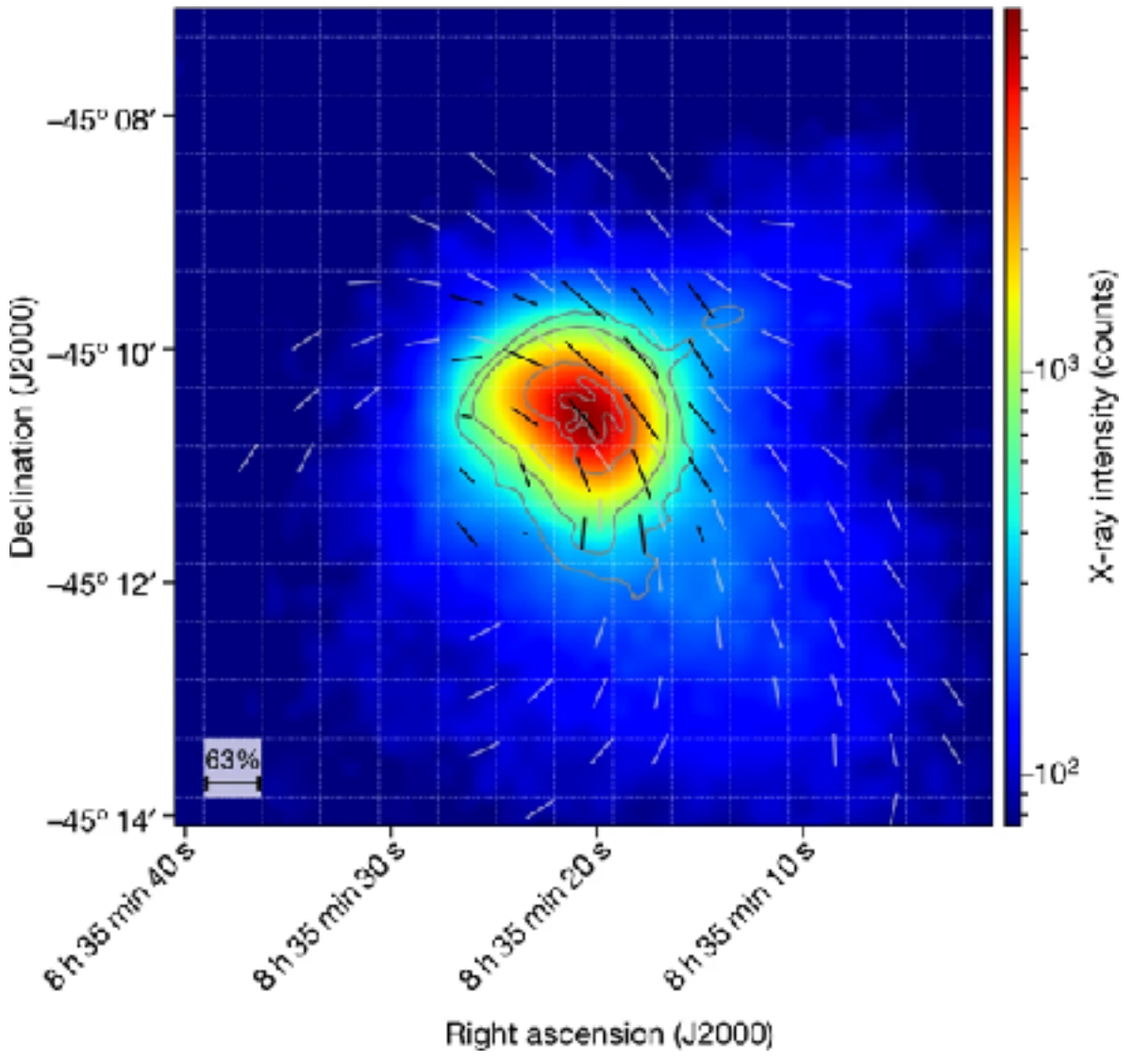
X-ray polarization from the Vela pulsar wind nebula

How are particles accelerated in pulsar wind nebulae?

- Vela PWN has average PD ~ 45%
- Some regions have PD ≥ 60%

- PD is close to theoretical limit for polarization of synchrotron emission (~75% for Vela).

➢ Highly uniform magnetic field and acceleration with little or no turbulence.
➢ Evidence against turbulence-driven diffusive shock acceleration.
➢ Other processes, such as magnetic reconnection, may power this PWN.



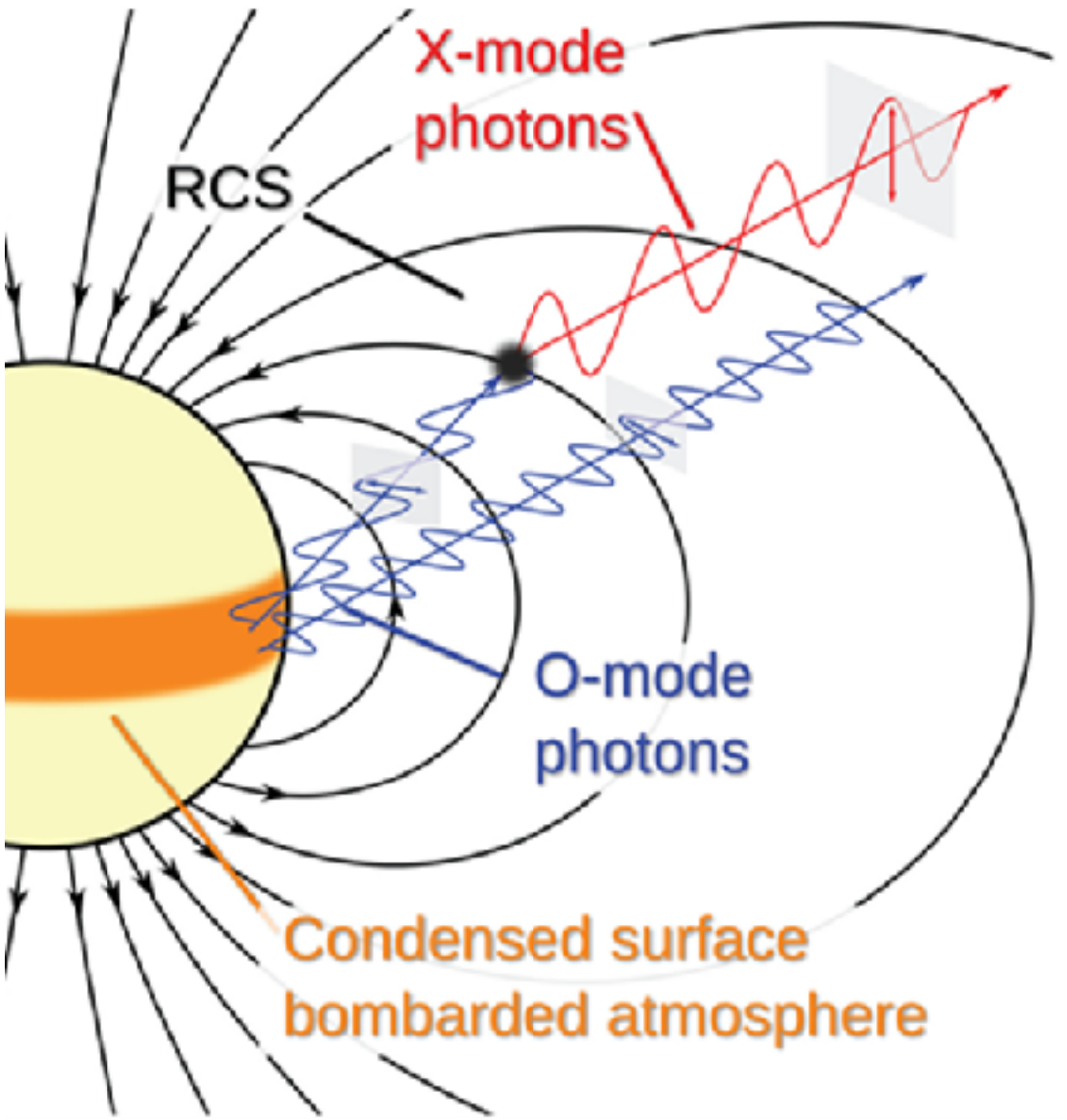
Colors are 2–8 keV intensity. Bars show magnetic field direction from X-ray (black) or radio (silver) with length proportional to PD. Xie et al. 2022, Nature 612, 658

Magnetars

Photons polarized by magnetic field

- What is the state of the matter at the magnetized neutron star surface?
- Do high magnetic fields cause vacuum birefringence?

Figure shows thermal radiation from NS equatorial belt reprocessed by resonant Compton scattering (RCS) in the magnetosphere (Taverna et al. 2022).

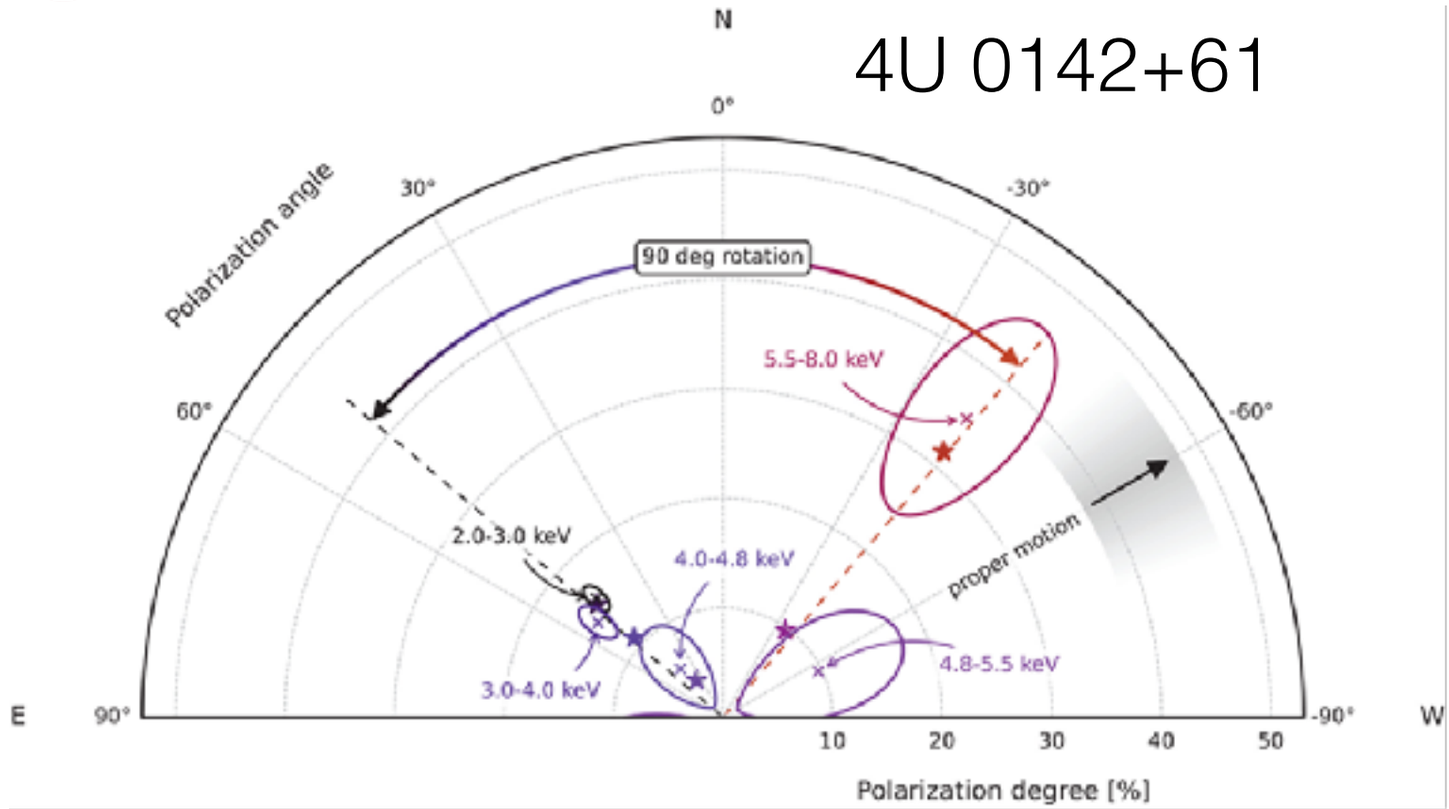


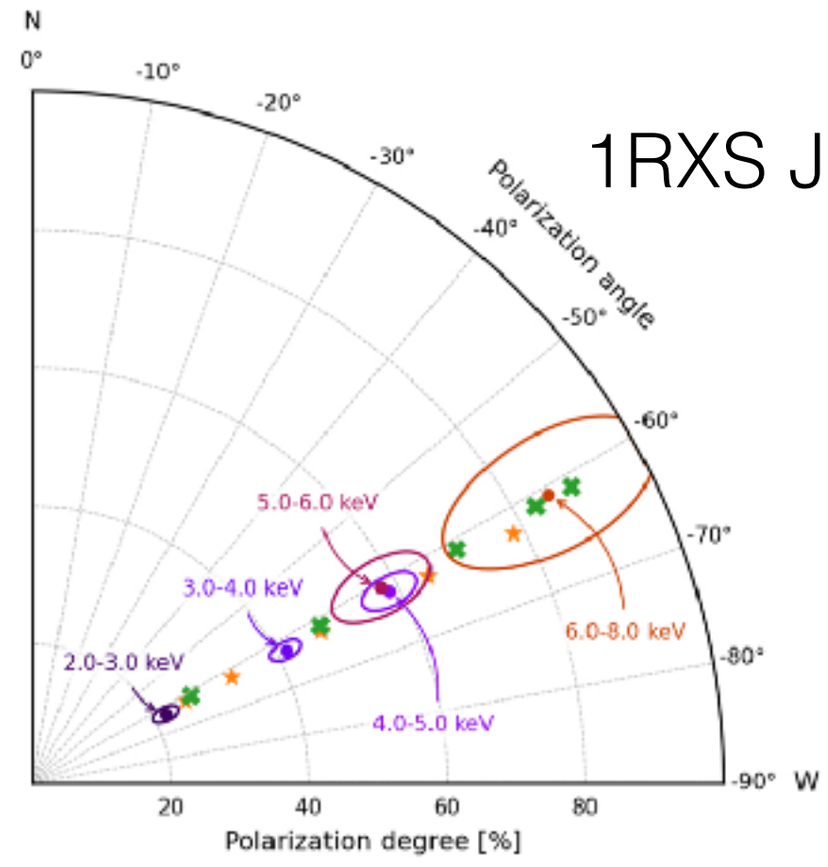
Magnetars

- 4U0142+61 shows PA swing of 90° (top)
- 1RXS J170849.0-400910 has constant PA
- Both have high PD.

- Pulse-phase-resolved data indicate surface is a solid, condensed due to the high magnetic field, which supports an atmosphere only in locally heated patches

- PA rotation in 4U 0142+61 is consistent with vacuum birefringence but can be explained with other models since low energy Polarization Degree (PD) is low.

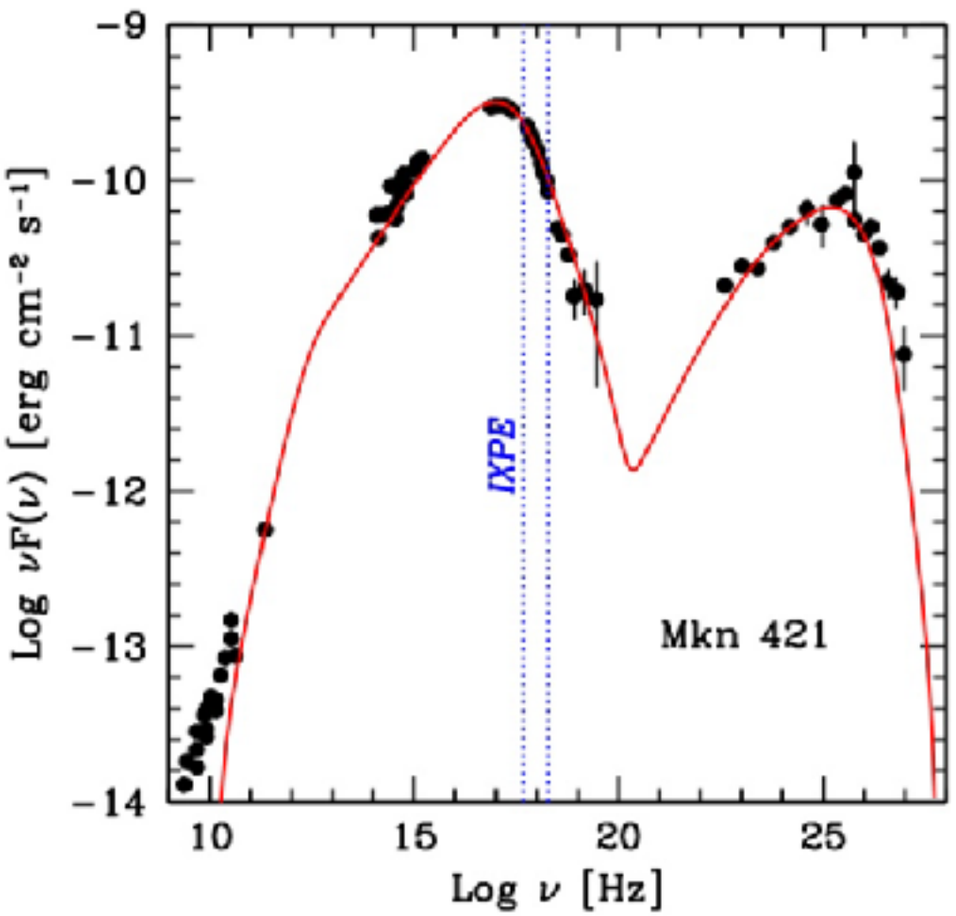




Particle acceleration in blazar jets

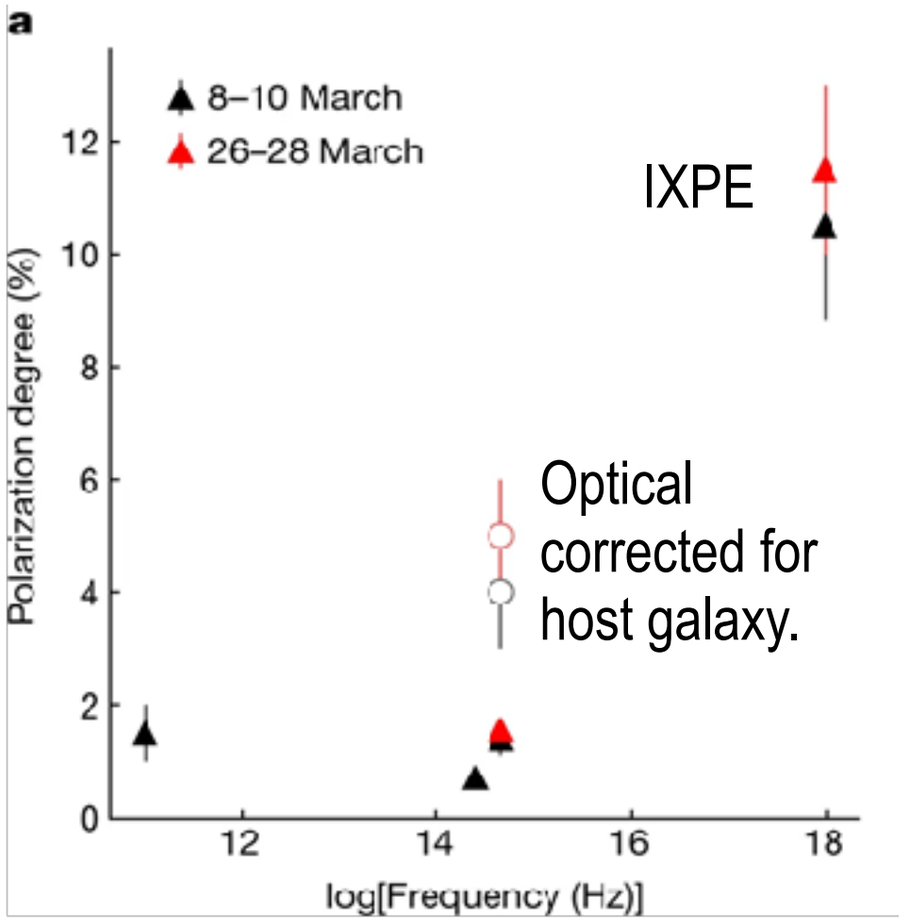
How are particles accelerated in blazar jets?

- In high synchrotron peak (HSP) blazars X-rays probe high energy particles that are near the acceleration site.



For Mrk 501, IXPE found:

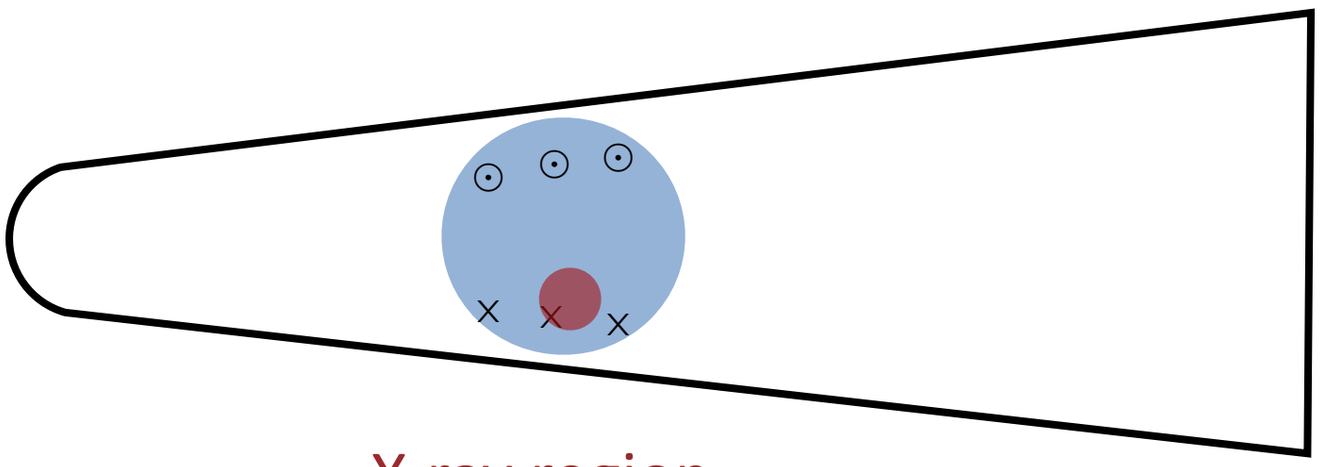
- X-ray PD = 10% ± 2%, which is 2× > optical PD
- X-ray EVPA is parallel to radio jet.



Liodakis, I. et al. Nature 611, 677–681 (2022)

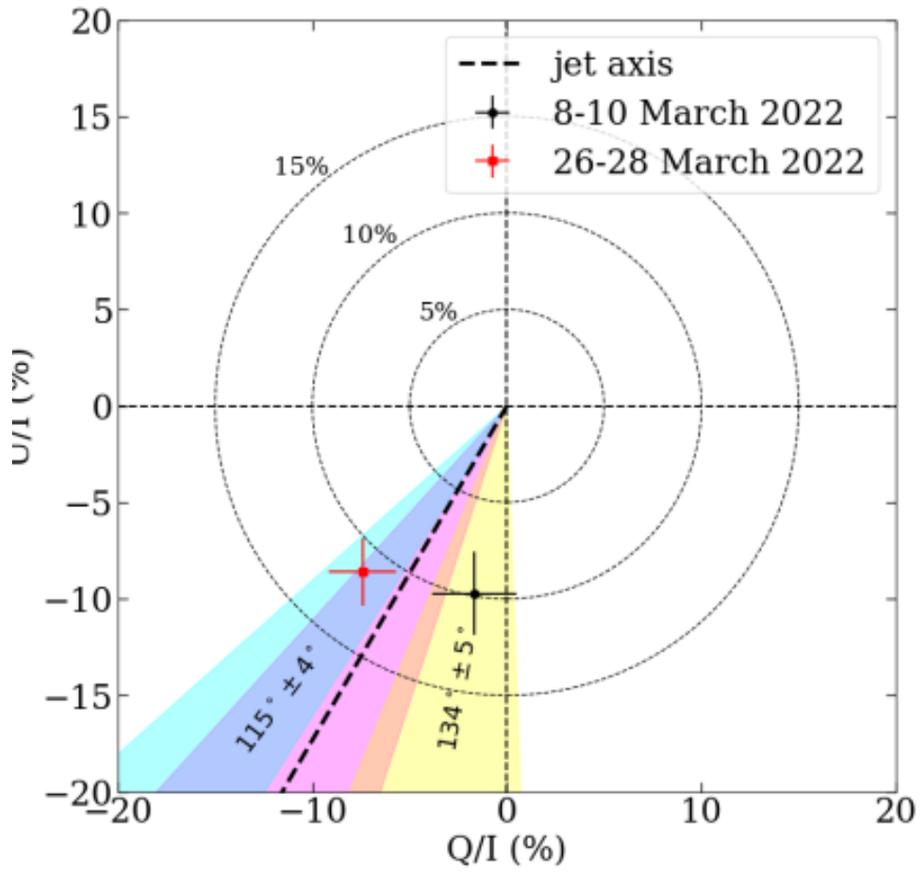
First blazar observation: Mrk 501

- X-ray polarization 11% ± 2%
- Optical polarization 4% ± 1%



X-ray region

Optical region



Liodakis, et al. (2022) Nature, 611, 677

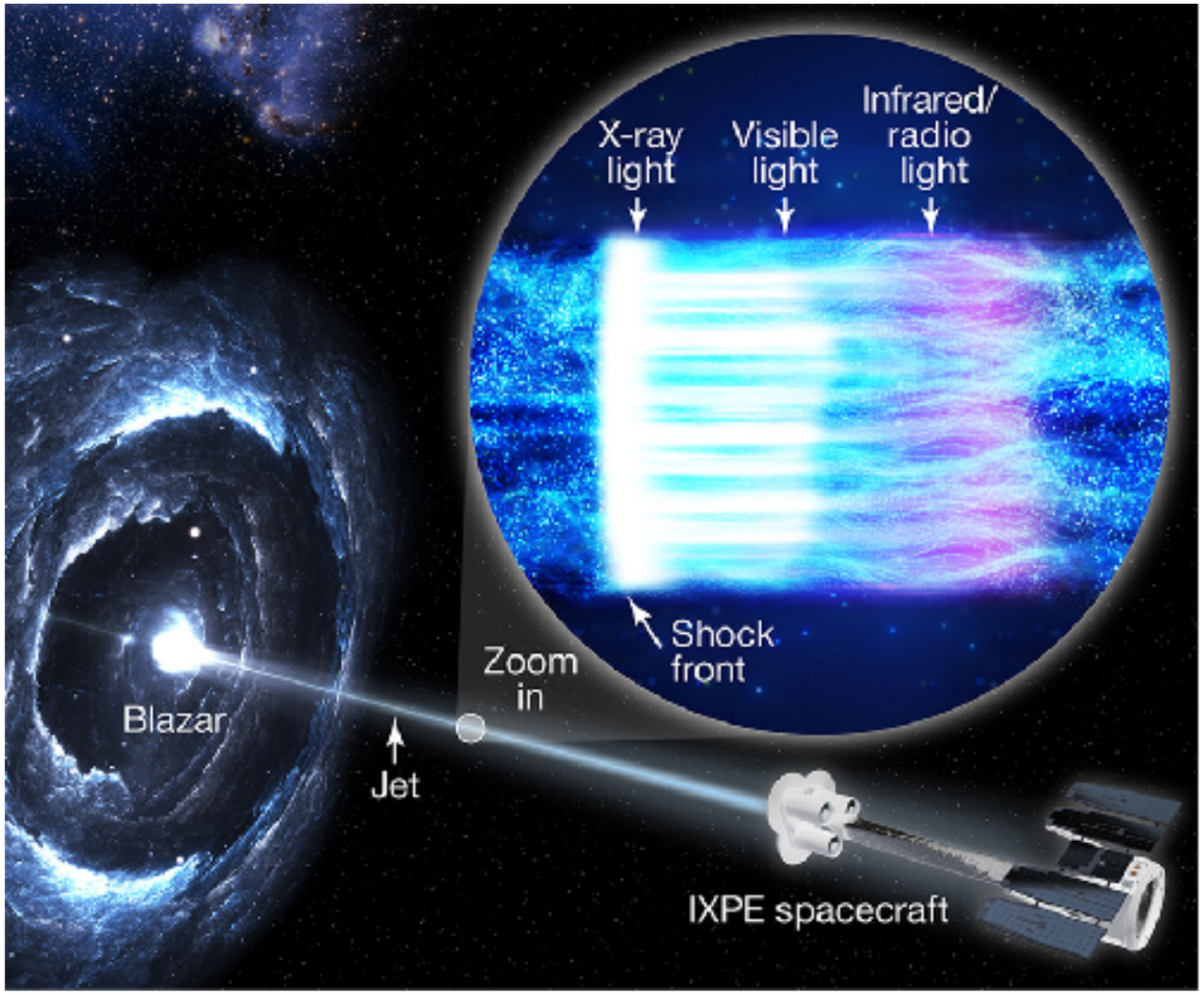
The X-ray emitting region in relativistic jets is more compact than the that at longer wavelengths. The highest-energy particles occupy a small volume and radiate quickly.

Particle acceleration in blazar jets

How are particles accelerated in blazar jets?

➢ Energy-stratified relativistic electron population.

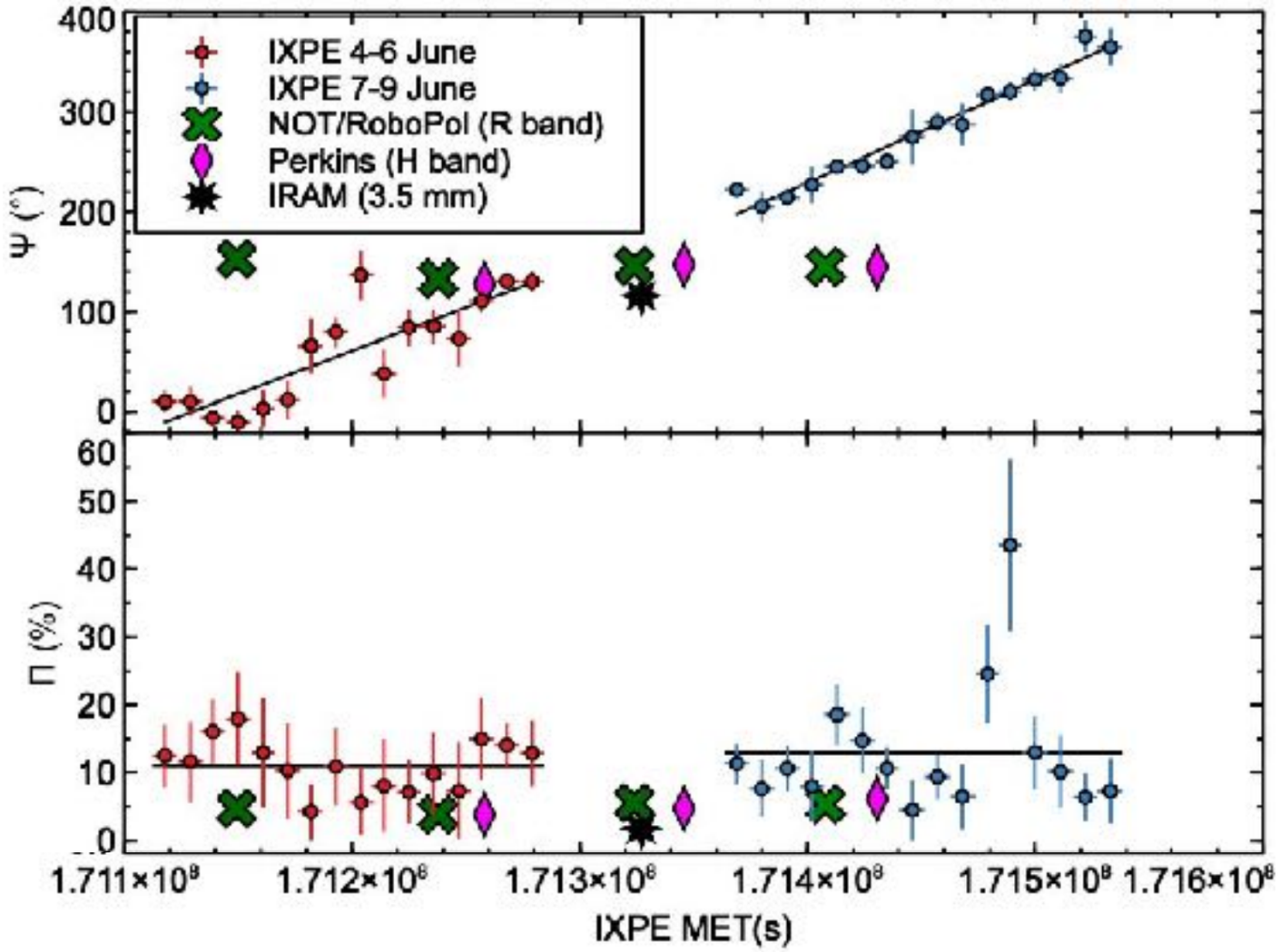
➢ Particles are accelerated by shock waves propagating along the jet and higher energy particles emit from more magnetically ordered regions closer to the acceleration site.

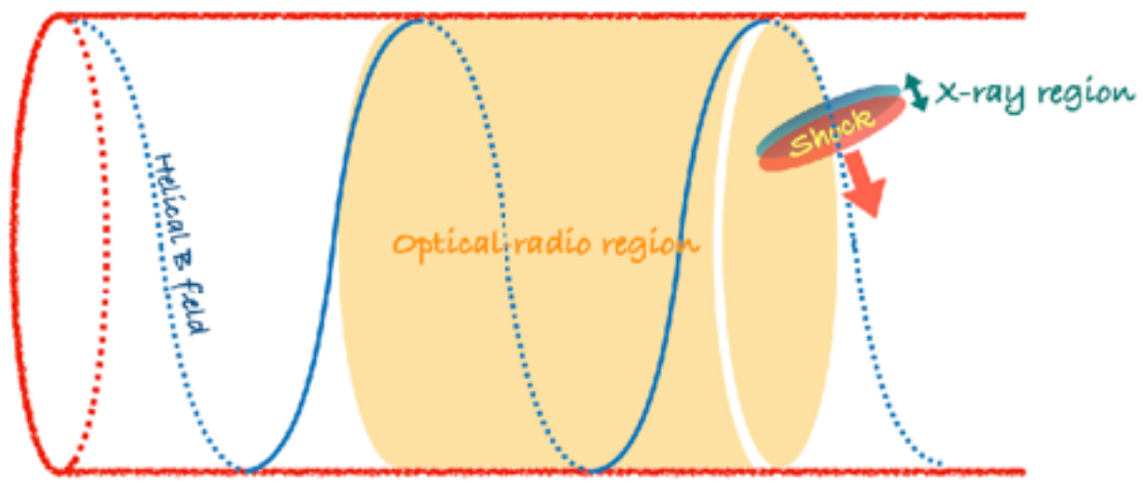


Polarization angle rotation: Mrk 421

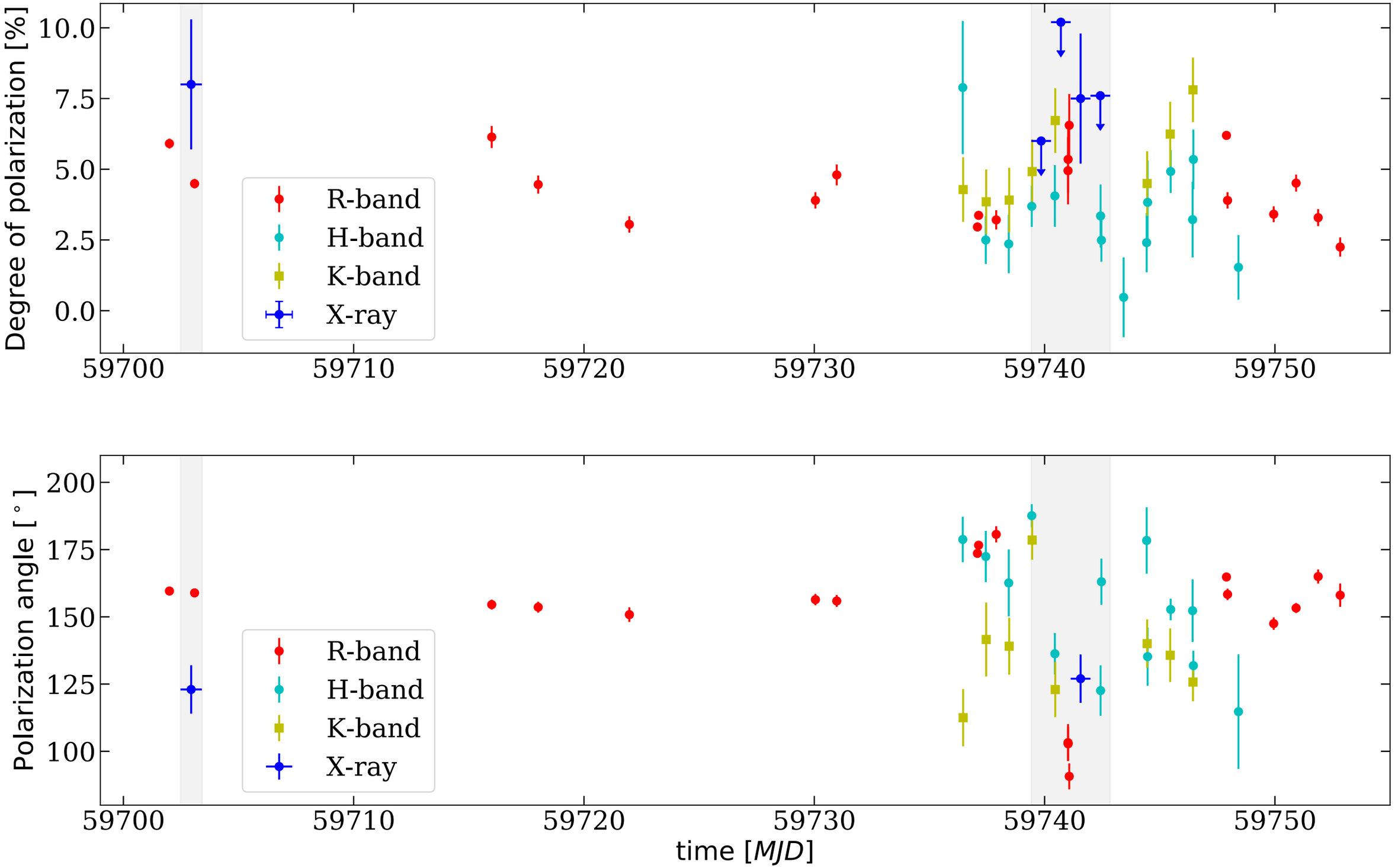
- Rotation of the X-ray polarization angle of ~85°/ day.
- Compatible with compact X-ray emitting region in helical motion around the jet spine.

Di Gesu, ME, et al. (2023) Nat. Astron.



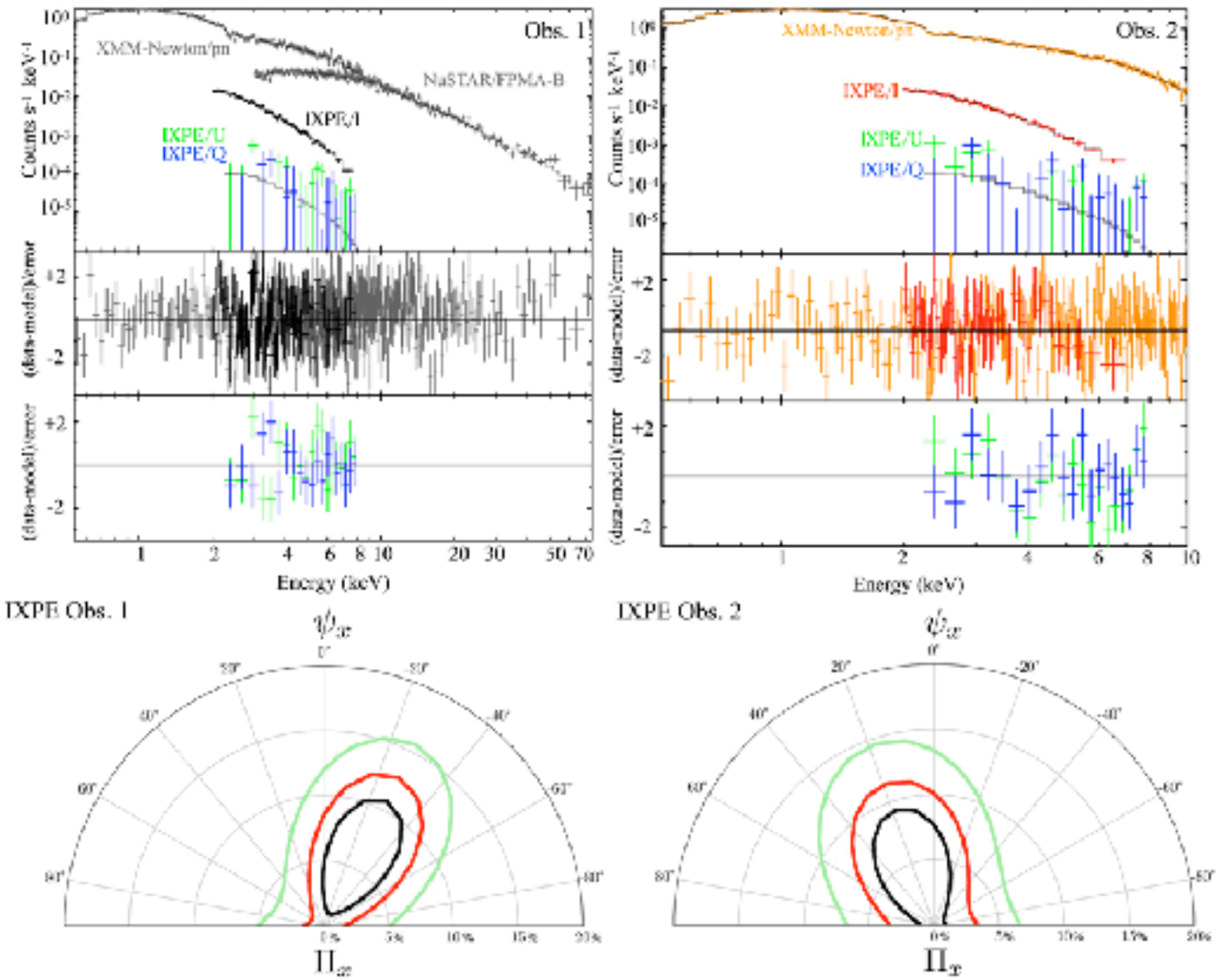


Turbulence in the jet: 1ES 1959+650

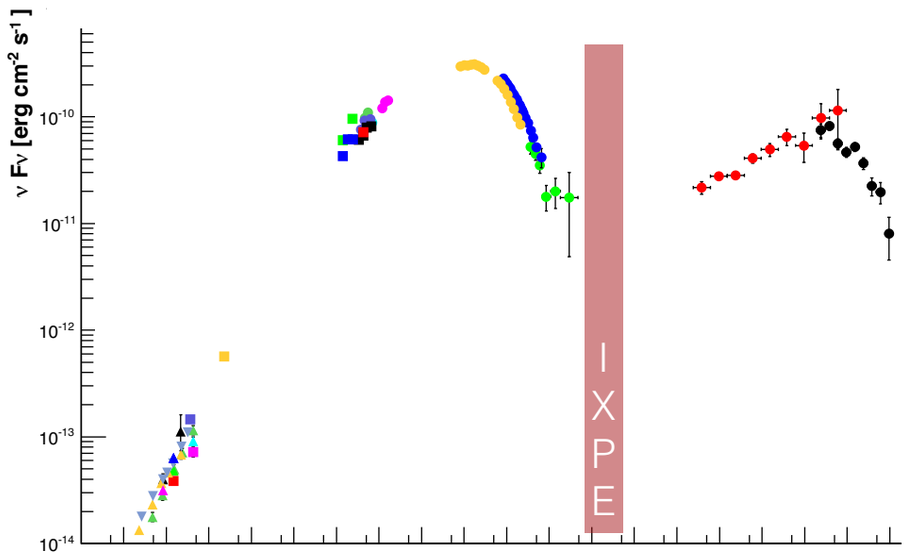


ME et al. (2023) ApJ, in prep

Observations of a low frequency peaked blazar: BL Lac



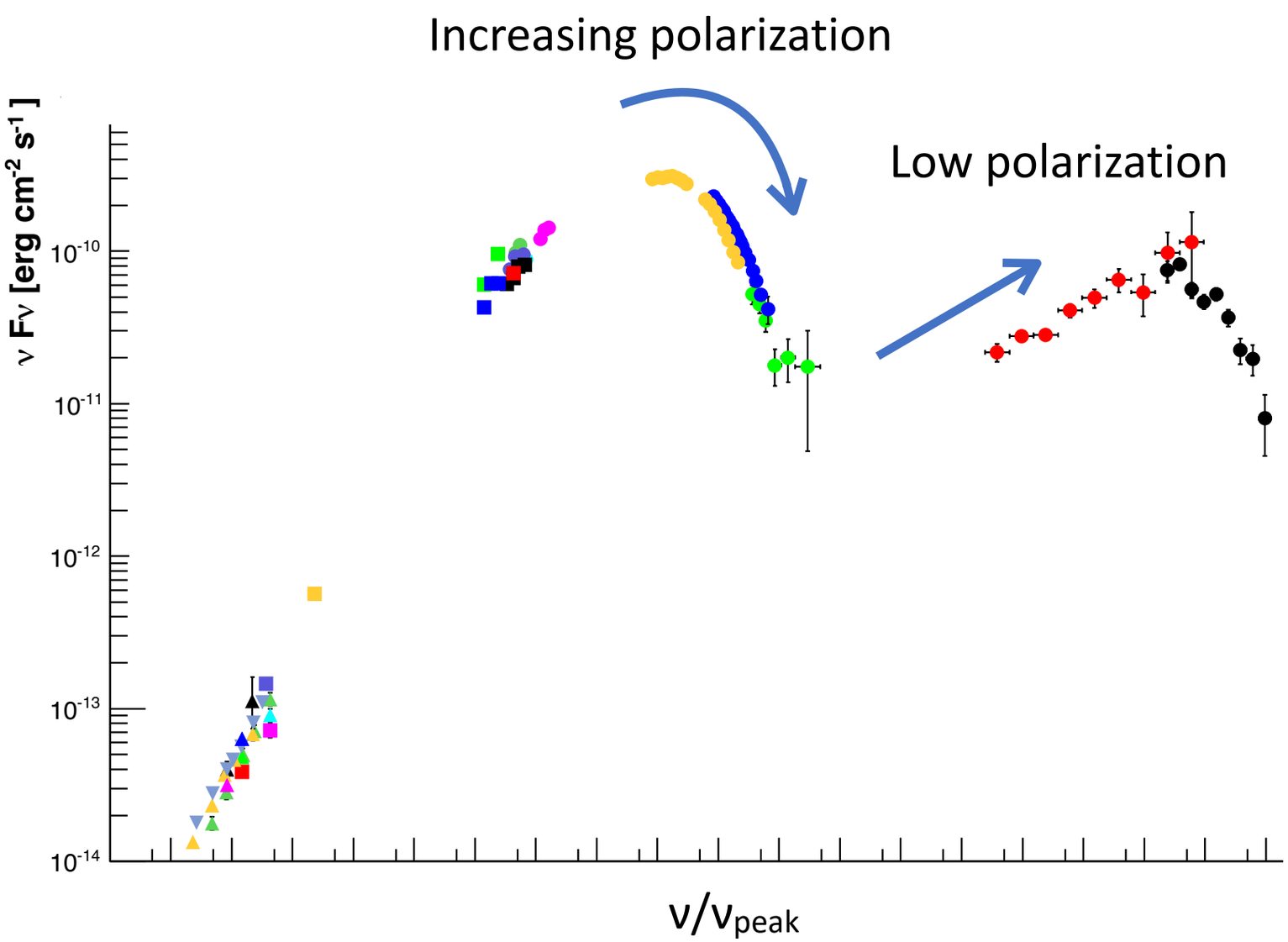
Middei et al. (IXPE) 2023



Upper limit $\Pi_X < 12.6\%$

Summary, blazar jets

Increasing polarization → Ordered B → More compact region



More often than not:
EVPA is aligned with the jet direction
X-ray polarization is higher than optical polarization

Summary

- IXPE can detect
  - X-ray polarization in bright X-ray sources.
  - For very bright sources, energy dependence of the polarization degree and angle can be measures. Time-resolved analysis also possible.
- Energy range is limited to 2-8 keV.
- Data is publicly available and easy to analyze.
- Guest Observer program to start in 2024. Proposals due ~ October 2024.
- No observations of a strong flare yet.

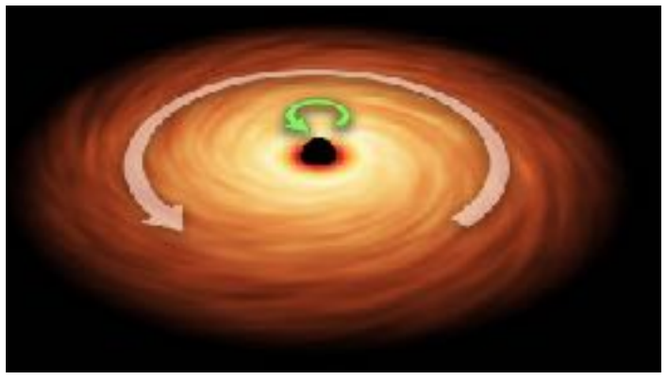
Summary

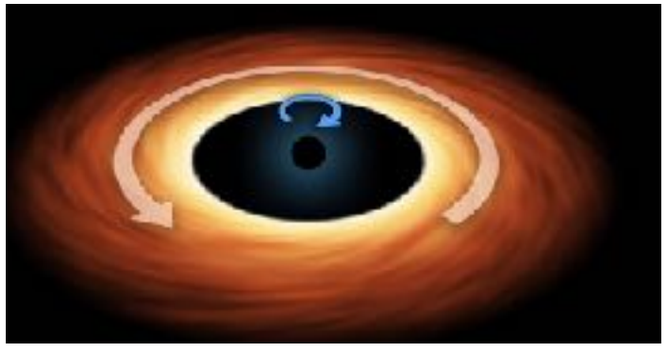
- Polarization observations of blazars are telling us about the geometry and structural makeup of the radiation zone.
- Link to particle acceleration mechanism is not yet established.
- Theoretical models that have clear predictions of the polarization angle with respect to the object geometry and/or the chromatic dependence of polarization (radio, optical, X-rays) can be tested against current observations.
- Polarization-dependent radiation transport (relevant for high B fields) may change the observed polarization.

Accreting Stellar Mass Black Holes

Expectations before IXPE Launch

Thermal state

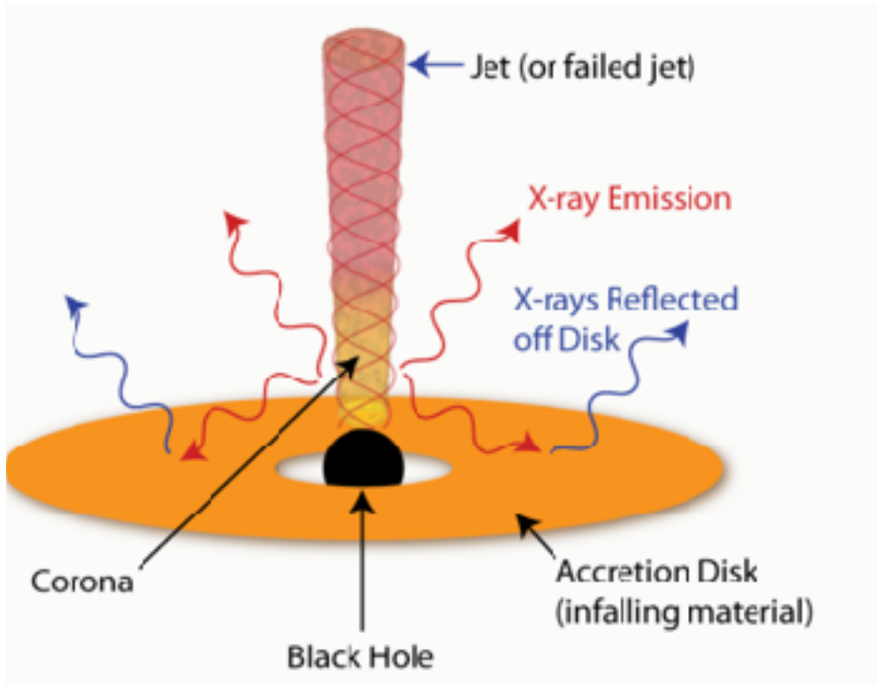




Temperature & Flux ⇒ area

Polarization ⇒ inclination & ISCO

Hard state



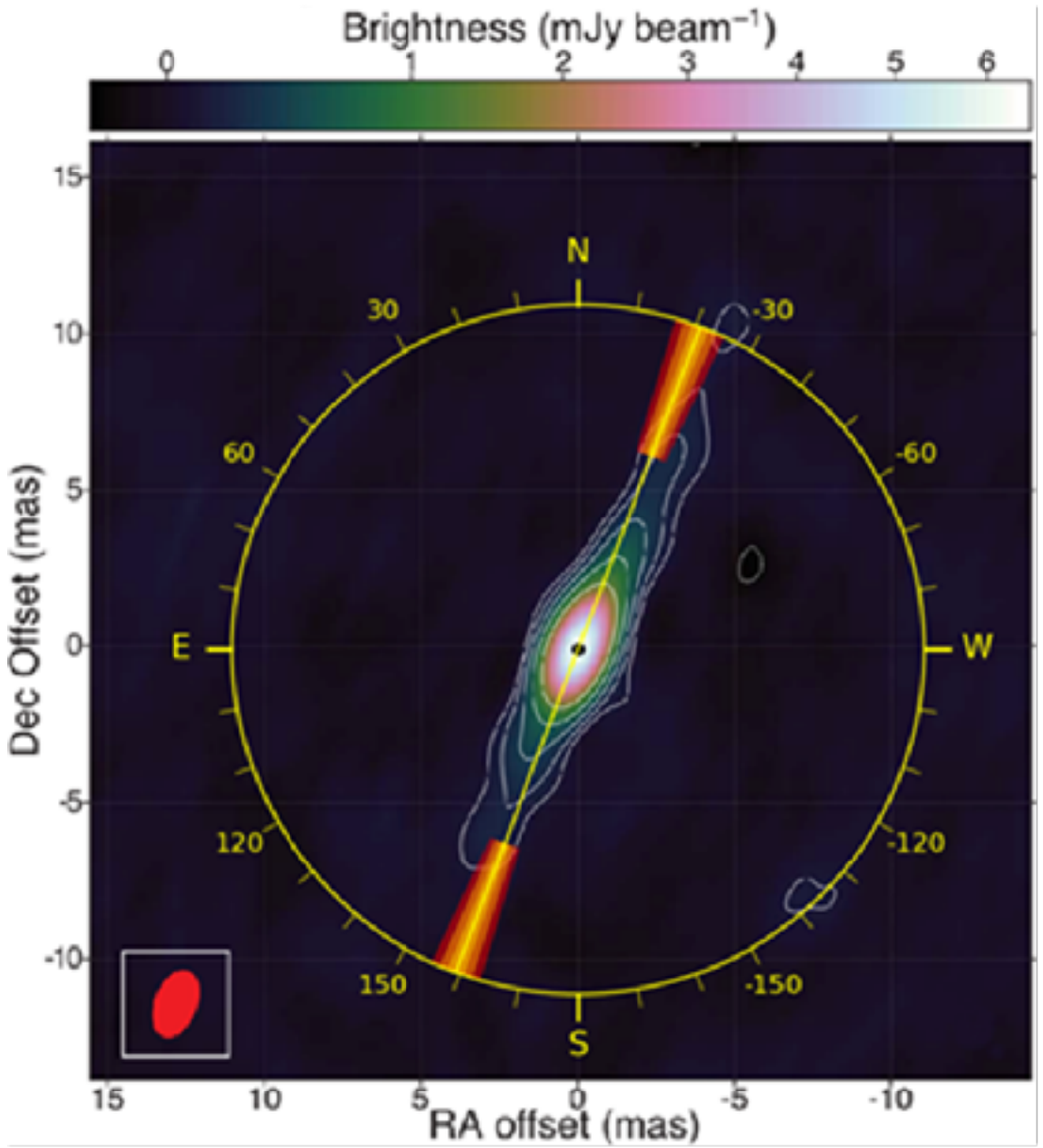
Shape of Fe K-alpha line ⇒ location of ISCO

Polarization ⇒ corona shape and location

Pre-launch expectations: *IXPE* provides additional handles on system parameters and independent spin measurements.

Accreting Stellar Mass Black Holes

Cyg X-1



- High PD = 4.0±0.2 %
- PS increases with energy.
- PA parallel to jet

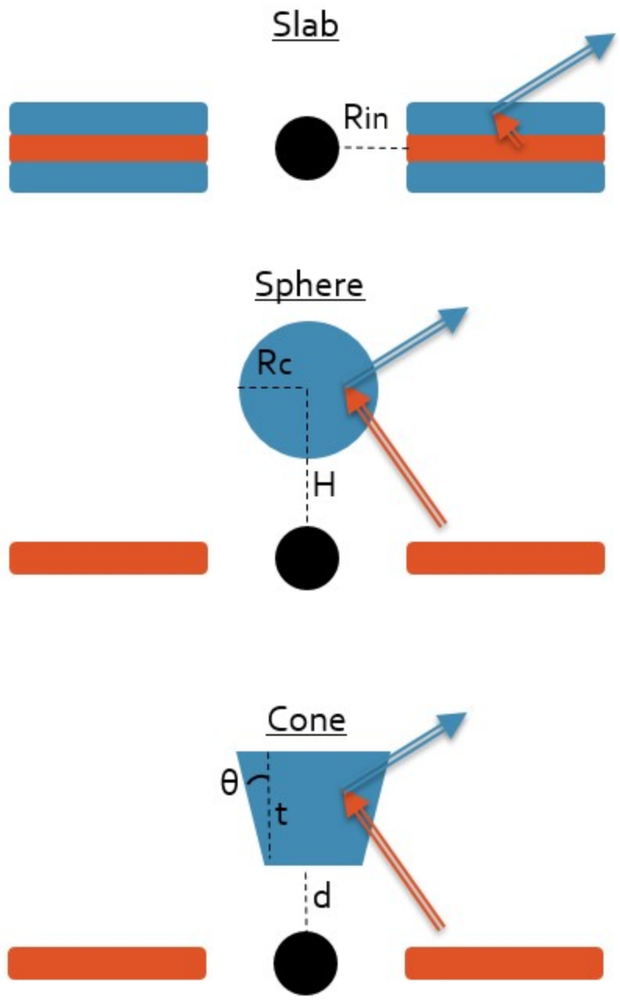
➢ Corona is parallel to disk.

➢ In tension with lamppost corona models -narrow column along the jet axis or two compact regions above/ below BH

Science
Krawczynski+ 2022

⇒ spin measurements relying on lamppost coronas need revision.

Origins of polarized radiation - Reflection

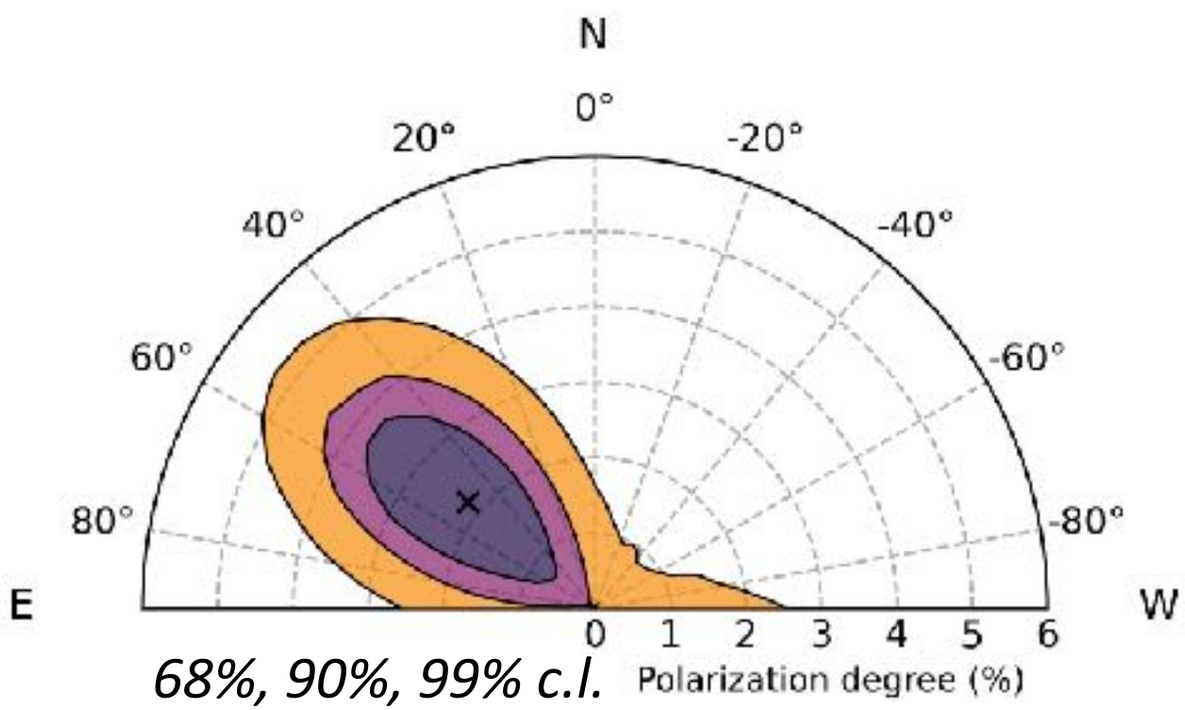


Ursini et at. 2022

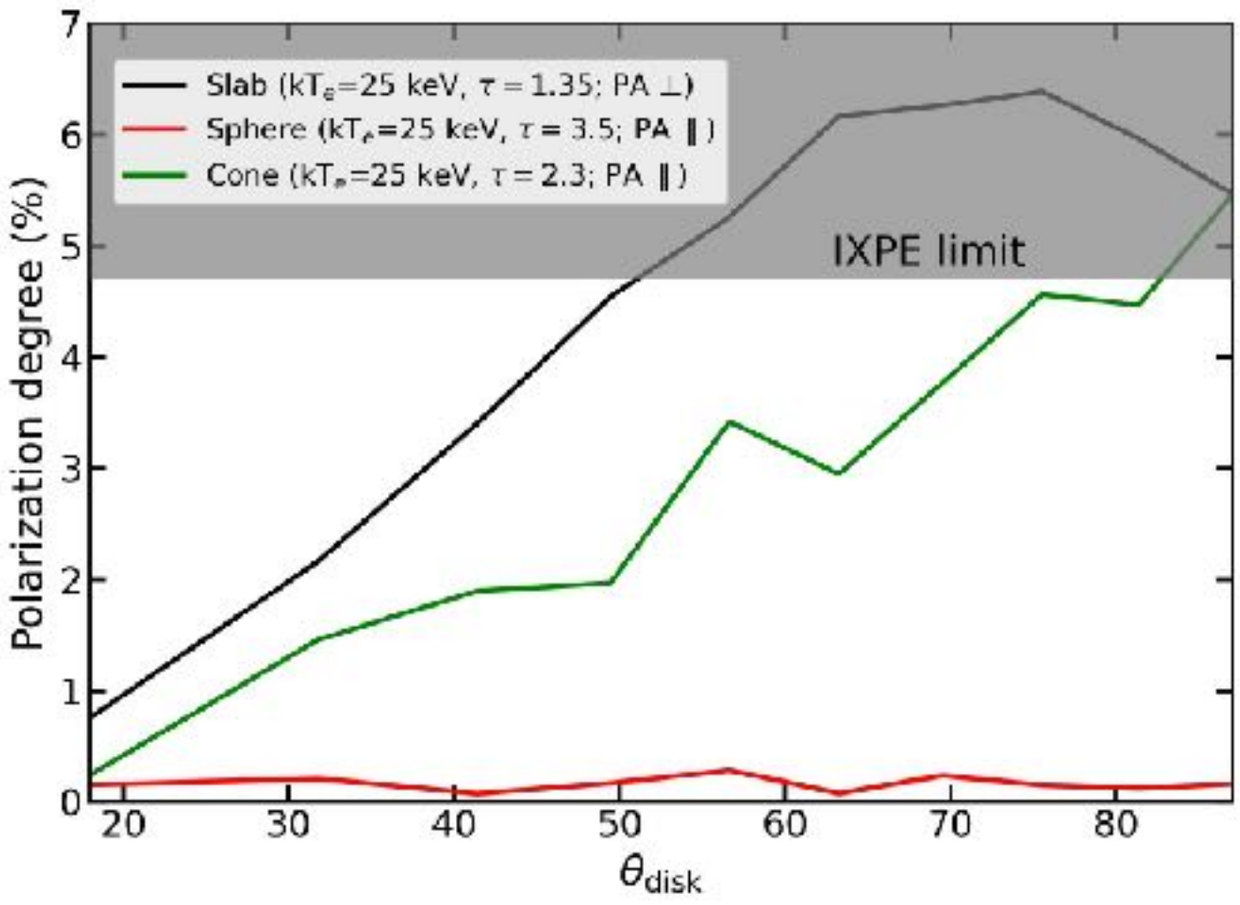
A radio quiet AGN: Seyfert 2 galaxy MCG-05-23-16

500 ks IXPE observation

Marinucci et al. (IXPE) 2022

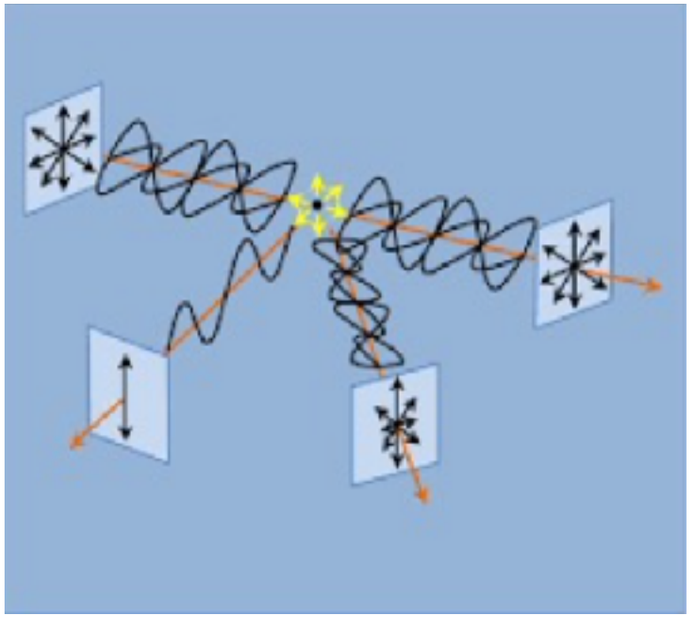


68%, 90%, 99% c.l.



Radio quiet AGN

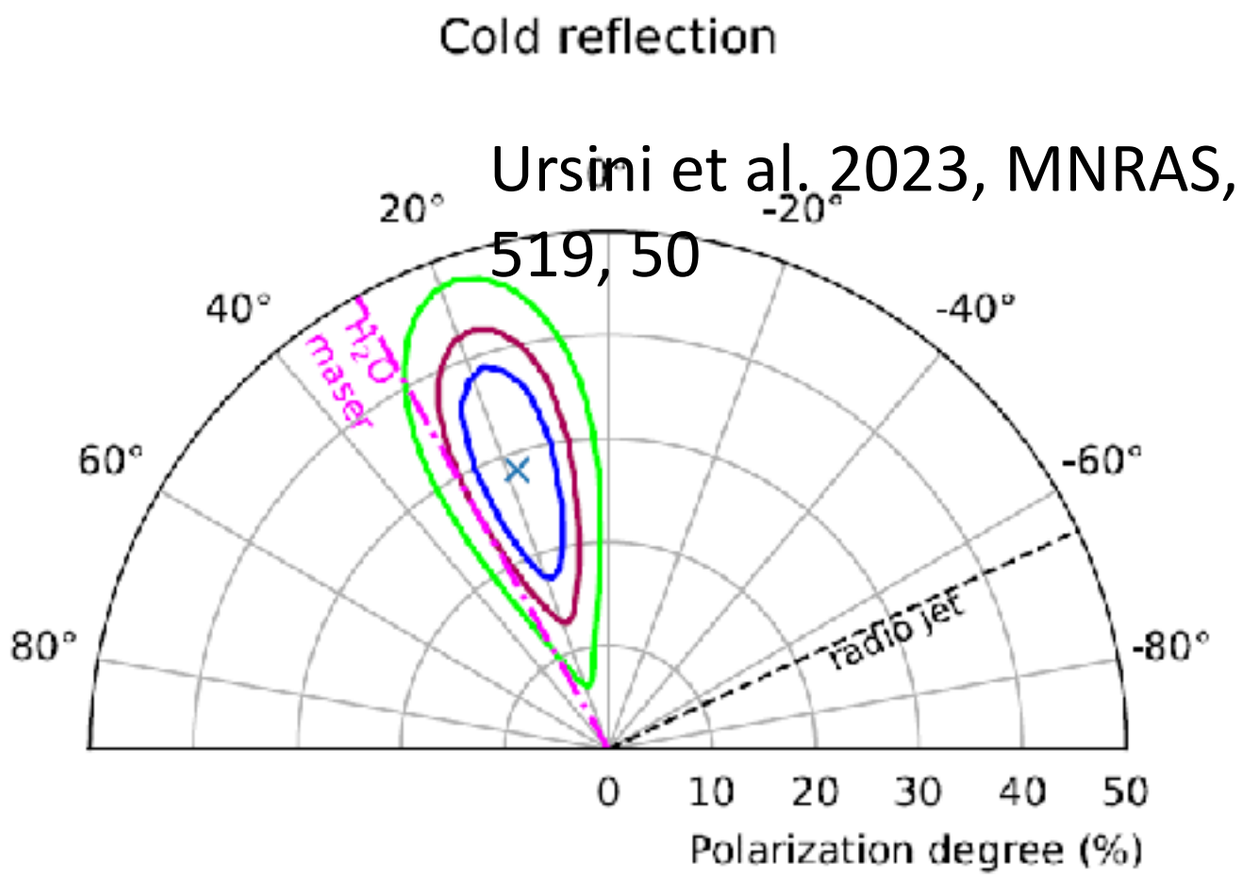
Is the reflection component in AGN spectra reflected?
Scattering/reflection →
EVPA perpendicular to scattering plane
Scattering through 90° produce high PD



Spectropolarimetric analysis for Circinus galaxy shows cold reflector which dominates hard X-ray emission has:

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

➢ Confirms AGN Unification Model.
➢ Also constrains torus geometry.



Ursini et al. 2023, MNRAS, 519, 50

X-ray pulsars

How are the neutron star magnetic fields oriented?

How is the radiation produced?

- Pre-IXPE expected high PD ≈ 60%-80%.
- Found PD of 5% to ~10%.
- Fits of rotating vector model (RVM) to PA versus pulse-phase enable measurement of pulsar inclination, spin axis position angle, and magnetic obliquity.
- Figure shows GRO J1008-57 (Tsygankov et al. 2023).

➢ Low PD to mode conversion in transition region between the upper hot layer and cooler underlying atmosphere.

➢ GRO J1008−57 and X Persei are nearly orthogonal rotators.