First Science Results from the Imaging X-ray Polarimetry Explorer (IXPE)

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NASA/MSFC
on behalf of the IXPE Team

Outline:
- **X-ray polarimetry**
- **IXPE mission**
- **Science results**
- **Future of IXPE**

IXPE Contributors

Mission Partners

Science Advisory Team

Acknowledgements

- Martin C. Weisskopf, IXPE PI Emeritus
- Brian Ramsey, IXPE PI Emeritus
- Steve O’Dell, IXPE PI

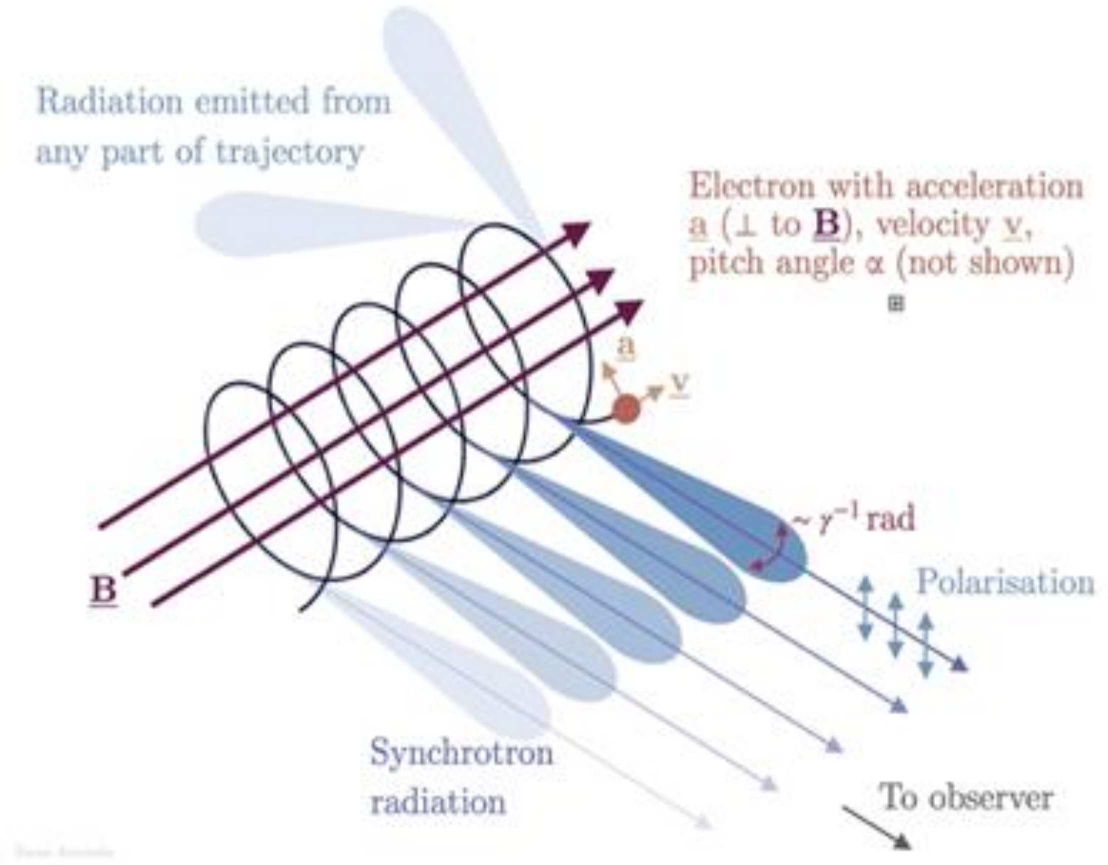
- Slides from: Michela Negro, Ilaria Caiazzo, Steve O’Dell, Elisabetta Cavazzuti, Roger Romani, Henric Krawczynski, Roberto Turolla

Polarization measures geometry

Polarization is a vector → measures geometry

Electric vector position angle = EVPA

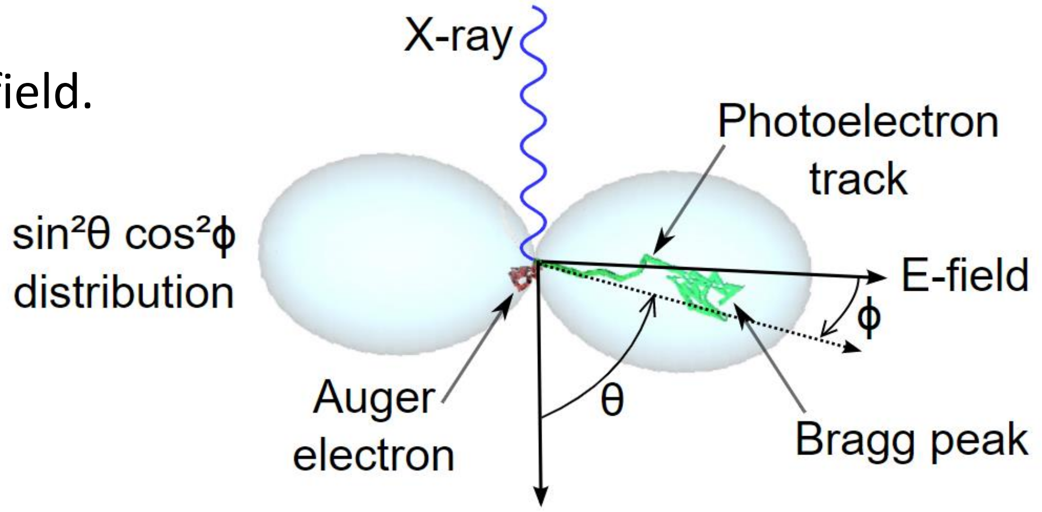
- Synchrotron radiation →
  EVPA perpendicular to magnetic field lines
- Scattering/reflection →
  EVPA perpendicular to scattering plane
- Strong magnetic fields →
  Opacity different parallel vs perpendicular to B
  EVPA transported along B in strong B
- Strong gravitational fields →
  EVPA parallel-transported along space-time geodesics

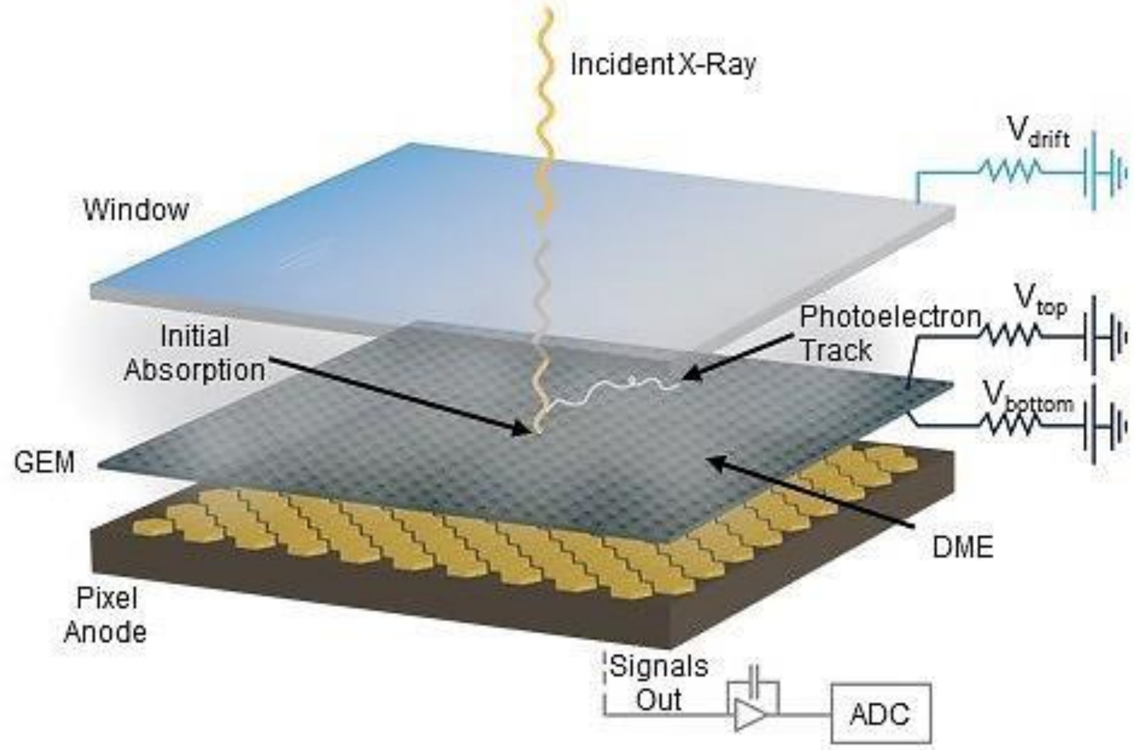


X-ray polarization via the photoelectric effect

IXPE uses the photoelectric effect.

- Photoelectron ejected along photon E field.





IXPE uses 'gas pixel detector' (GPD).

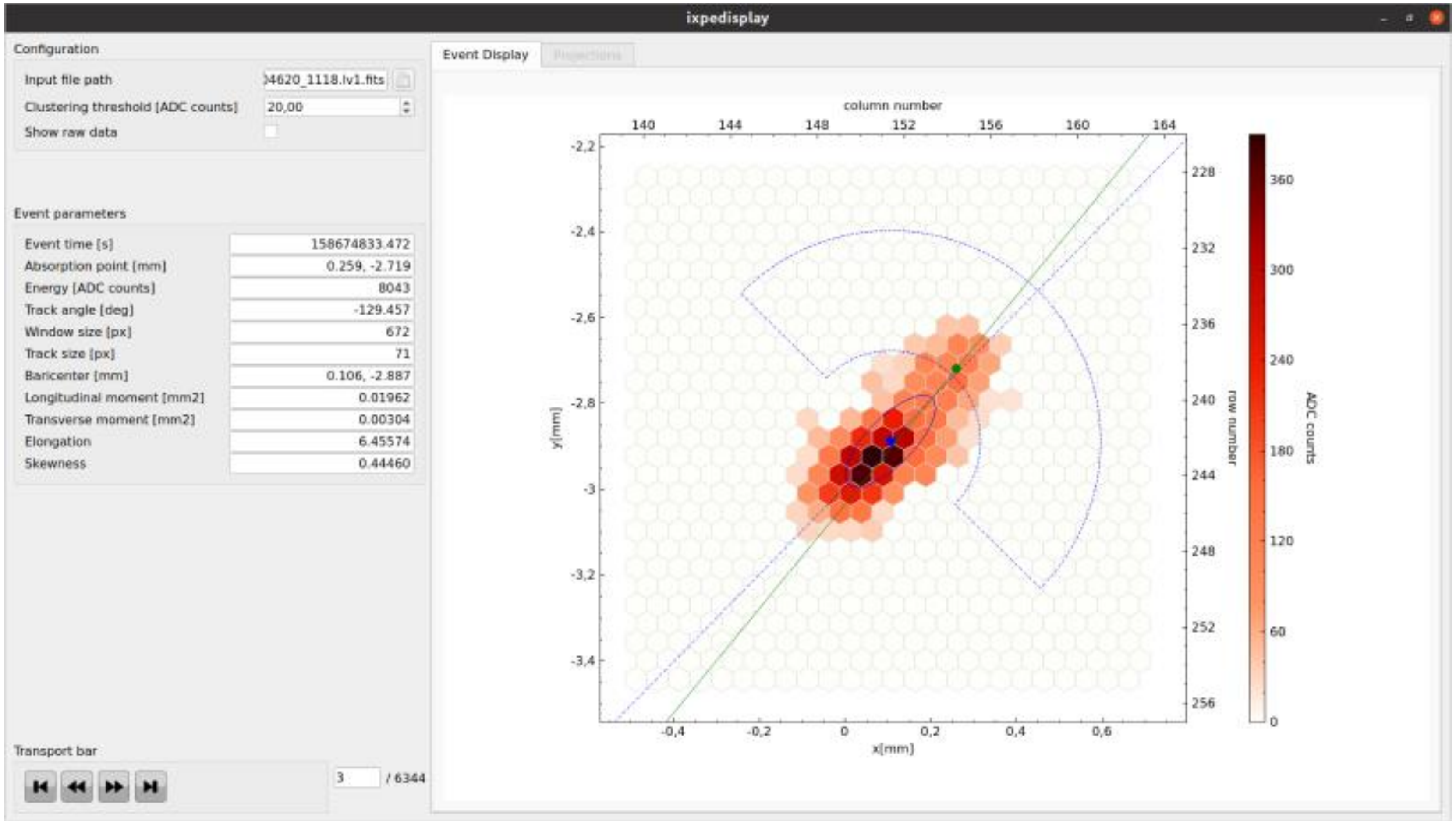
- Photoelectron liberates electrons in gas (DME),
- multiplied in gas electron multiplier (GEM),
- imaged with 105k hexagonal pixels 50µm.

- Concept from Costa et al. (2001)
- Extensive development of readout in Italy.

INAF/IAPS, INFN-PI

X-ray polarization via the photoelectric effect

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

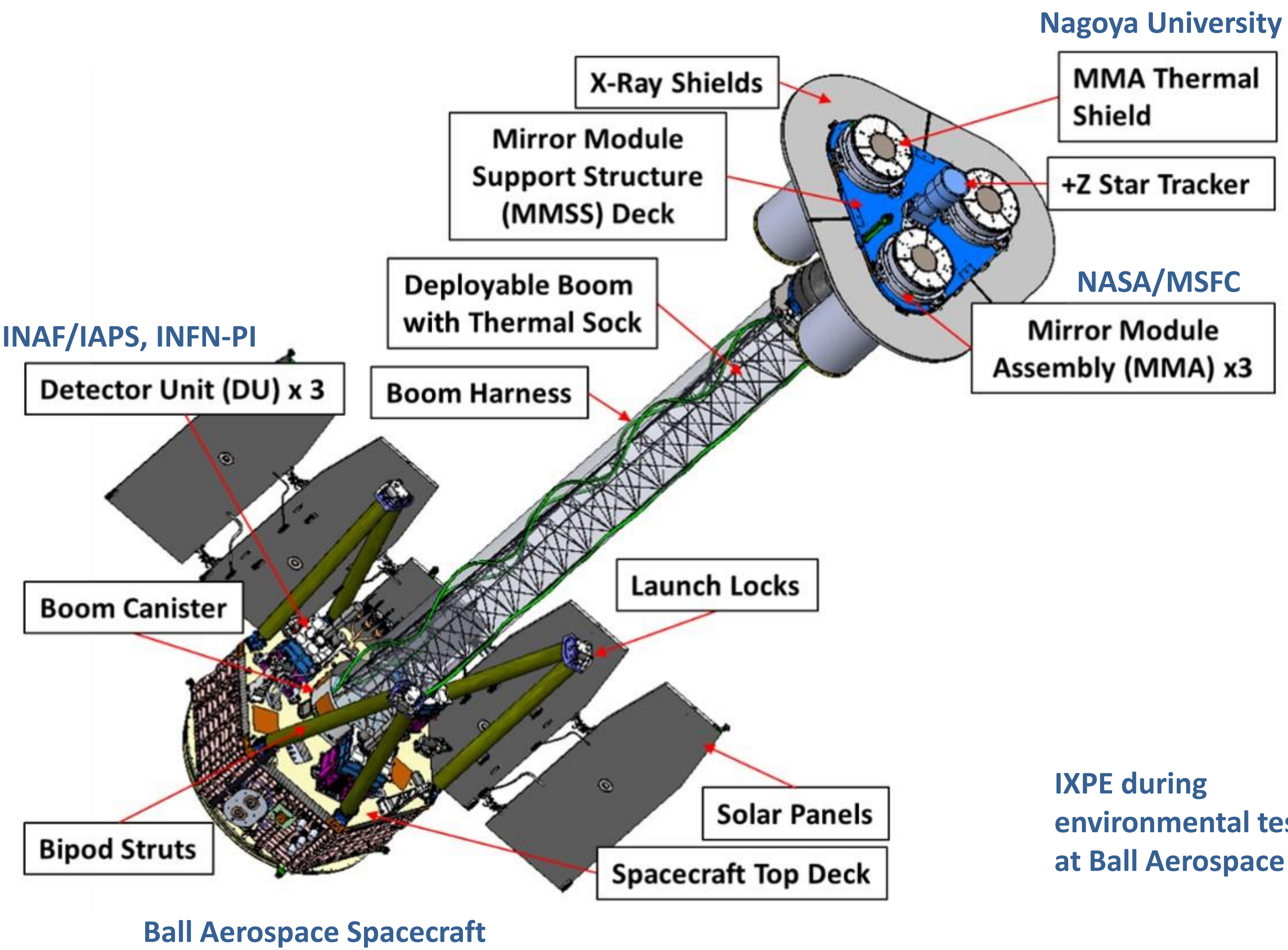


First photo-electron track obtained during IXPE science operations SNR Cas A, 2022 January 11, initiated by 2.7-keV photon in DU1.

Key is to find photoelectron direction at interaction point.

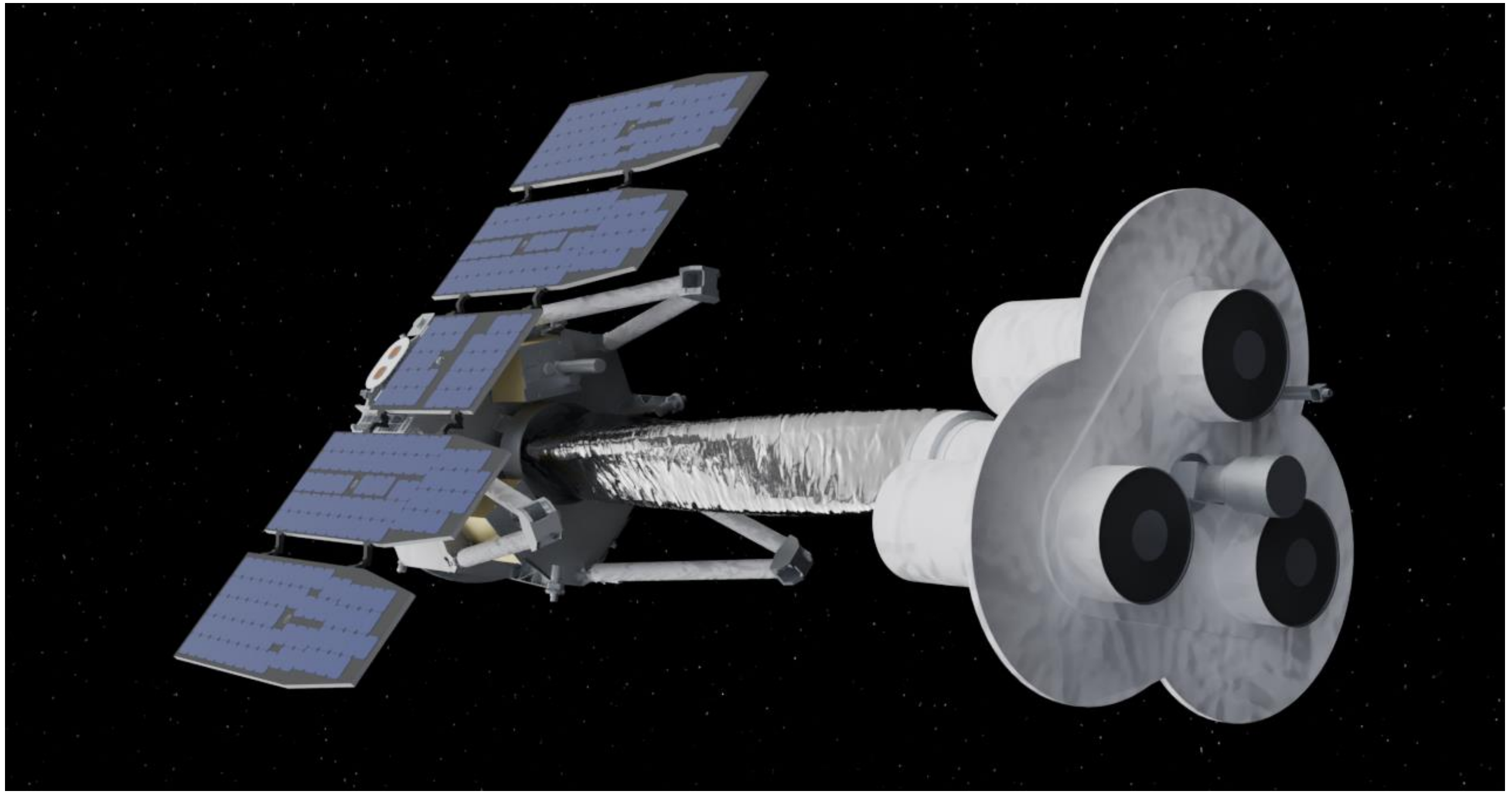
Imaging X-ray Polarimetry Explorer

IXPE Imaging X-Ray Polarimetry Explorer



IXPE during environmental testing at Ball Aerospace

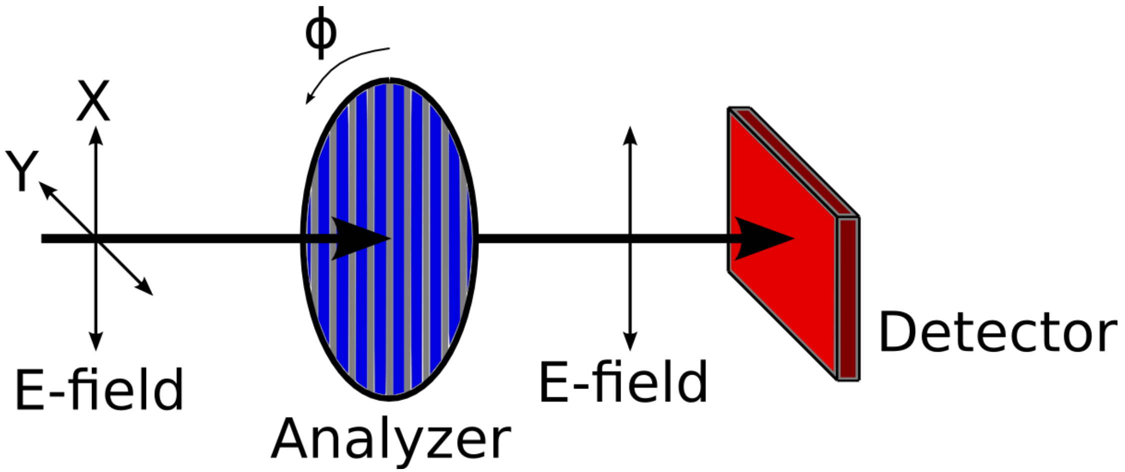
Launch and Operations

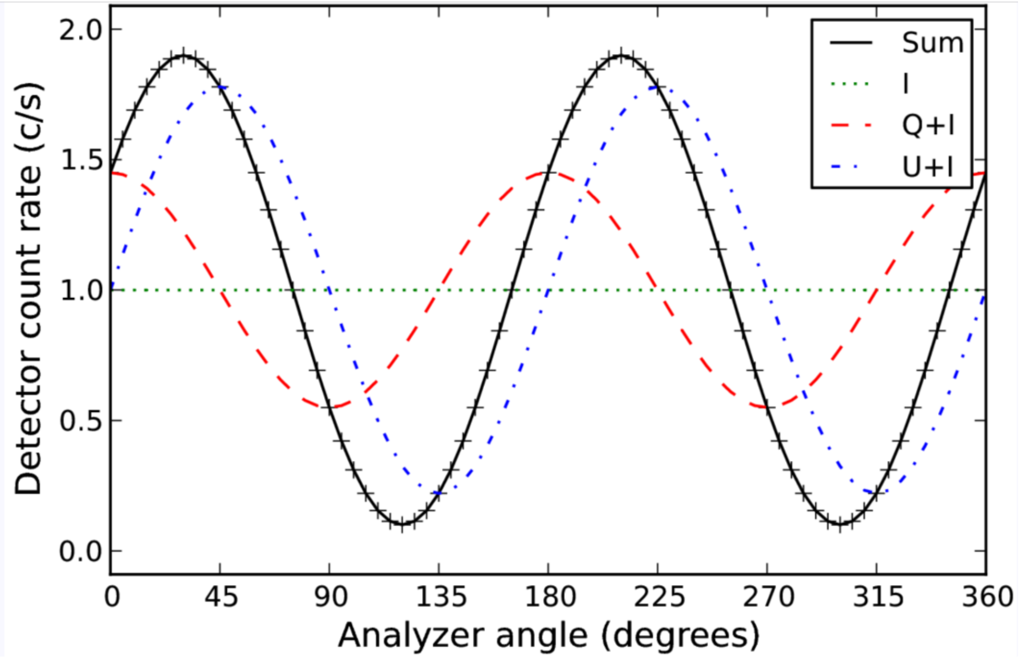


Launch: 2021 December 9 (06:00 UTC), on Falcon 9 from KSC LC-39A
Orbit: Near-equatorial, circular at 600-km altitude
Ground stations: Malindi (ASI) primary, Singapore (KSAT on NASA's NSN)
Operations: MOC at LASP (CU Boulder), SOC at MSFC (Huntsville)
Science operations: started 2022 January 11, after 1-month commissioning

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 observations to date by class

Class	Targets	Obs	Total (ks)	%	Avg (ks)	Min (ks)	Max (ks)
RQ AGN | Sgr A	5	6	4085	16.6%	681	470	1000
PWN	4	7	3738	15.2%	534	100	953
Blazar | Radio Galaxies	11	23	3637	14.8%	158	50	414
Stellar BH	5	10	3430	14.0%	343	24	943
X-ray pulsar	9	15	3227	13.1%	215	85	300
SNR	3	5	3063	12.5%	613	222	1000
Magnetar	3	3	2649	10.8%	883	770	987
NS LMXB	6	9	653	2.7%	73	10*	100
GRB	1	1	100	0.4%	100	100	100

As of 2023/05/12

* Truncated due to TOO

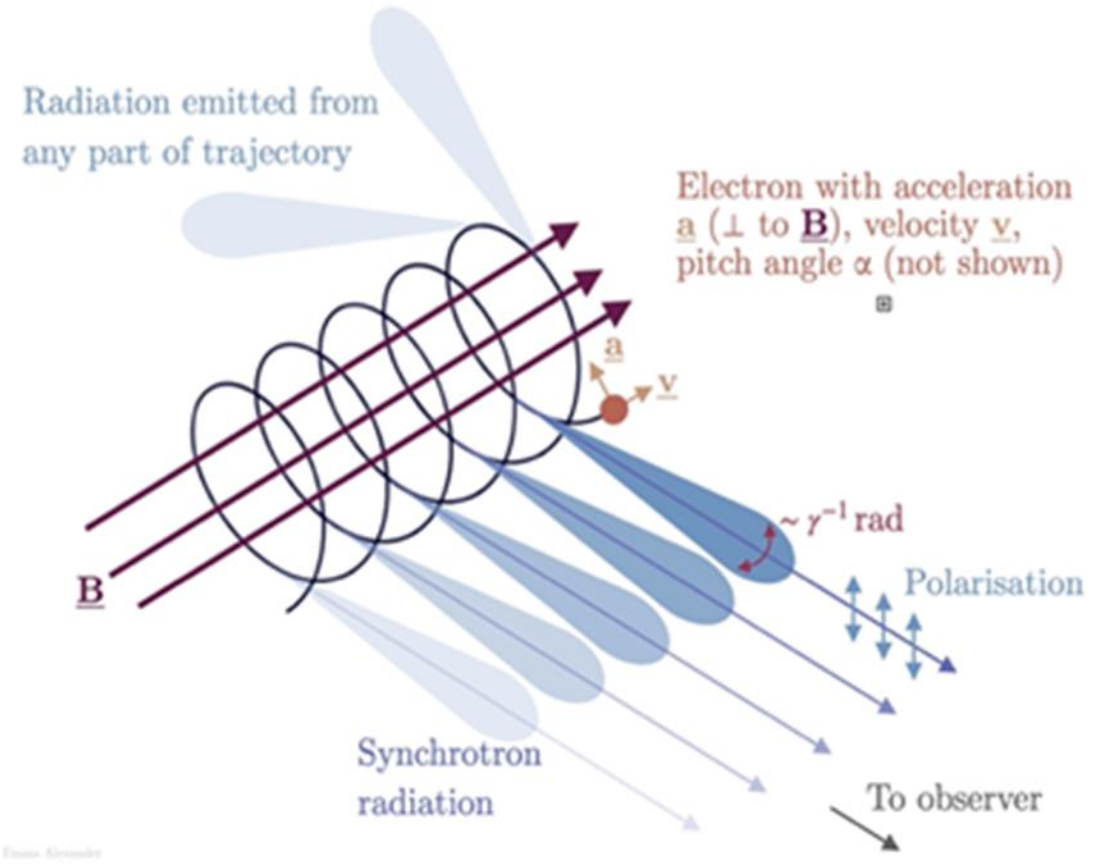
Selected IXPE science results

- Blazar jets
- Pulsar wind nebulae
- Supernova remnants

- Radio-quiet active galactic nuclei
- Echoes of Sgr A*
- Accreting stellar-mass black holes
- Accreting neutron stars (low B)

- Magnetars
- Accretion powered pulsars

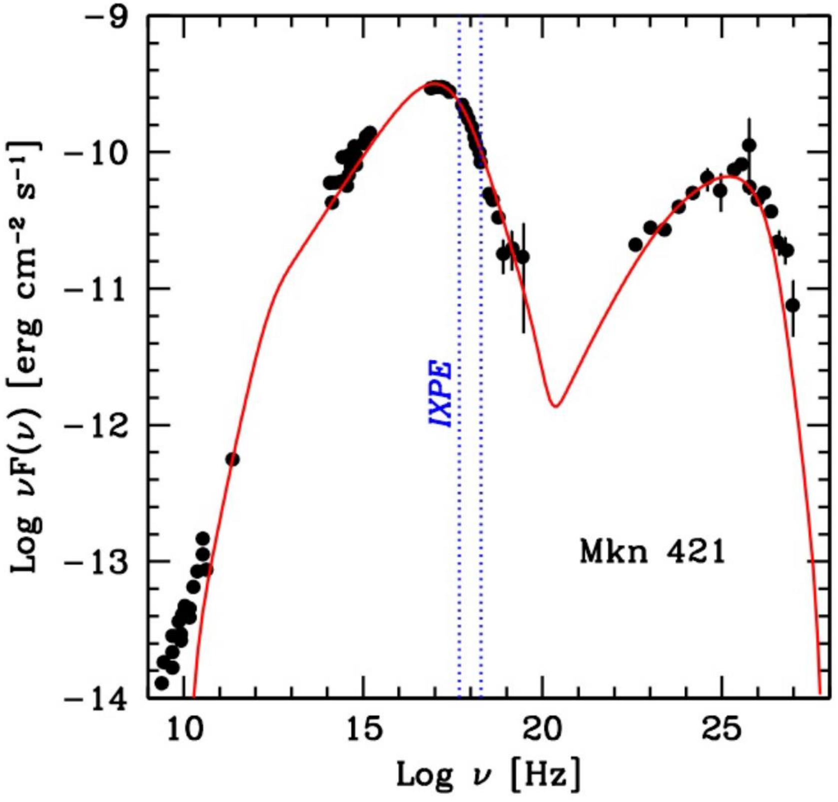
Emission in first group is via synchrotron radiation



Particle acceleration in blazar jets

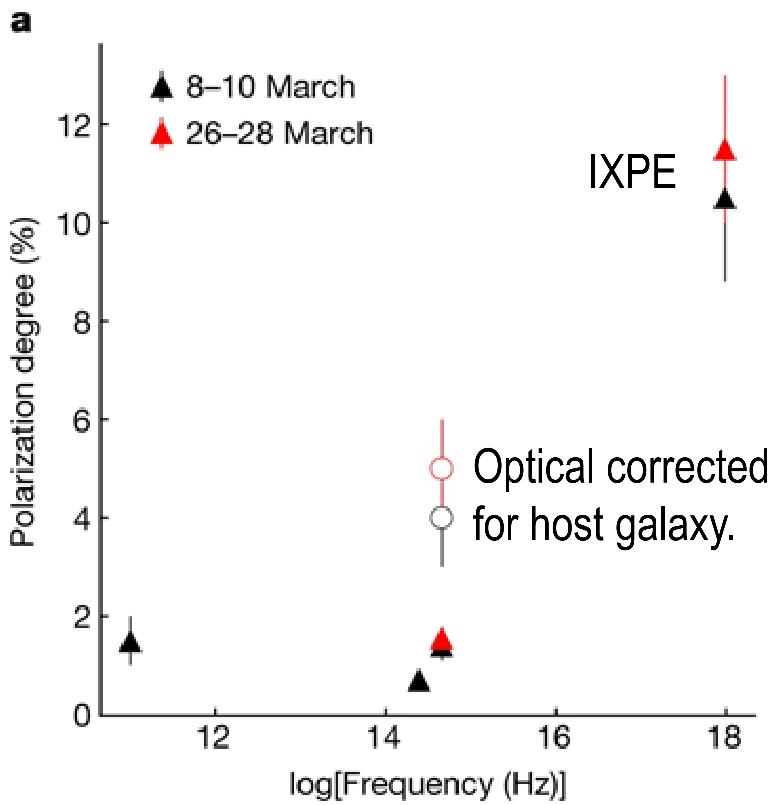
How are particles accelerated in blazar jets?

- 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.

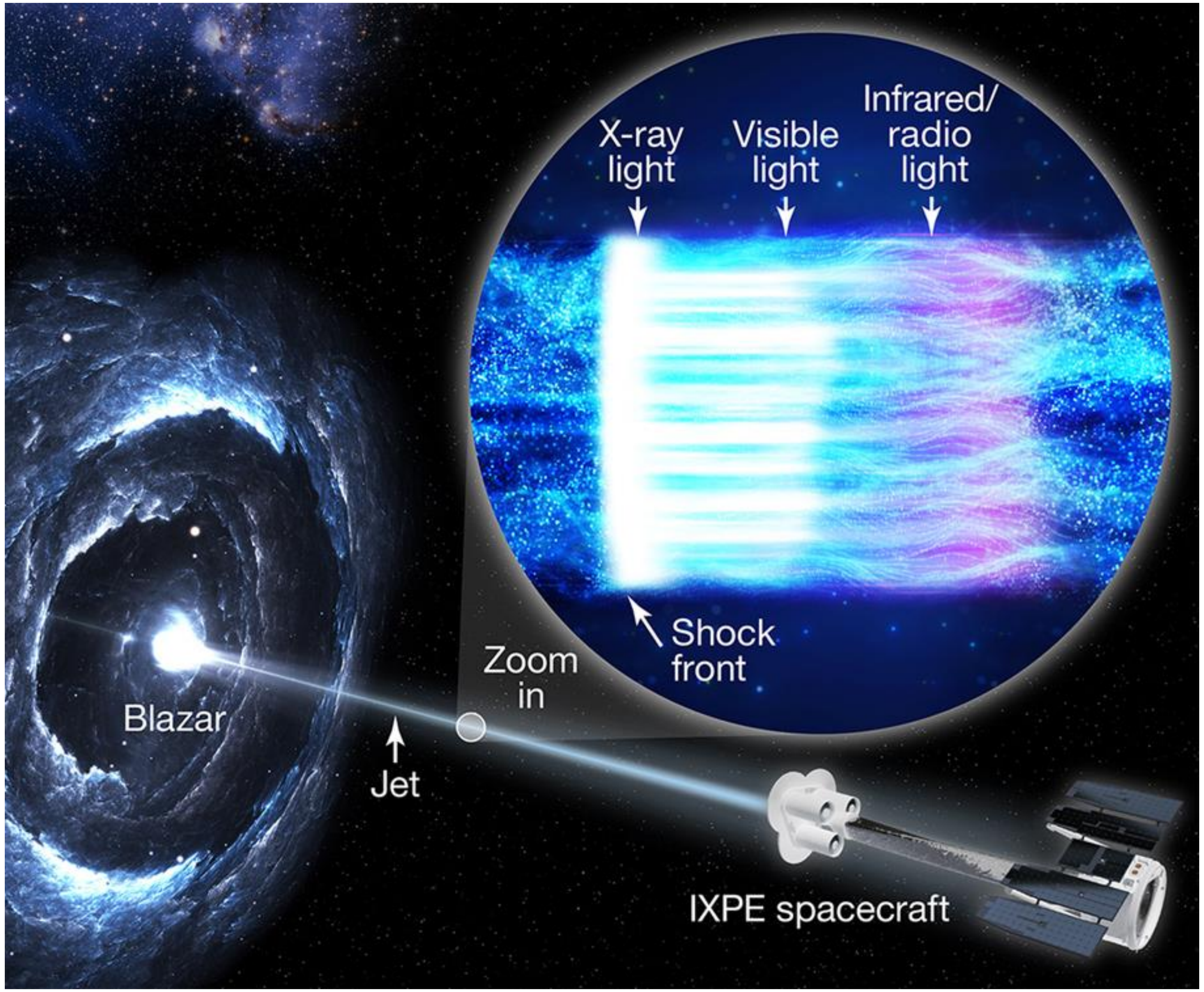


Liodakis, I. et al. Nature 611, 677–681 (2022)

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.



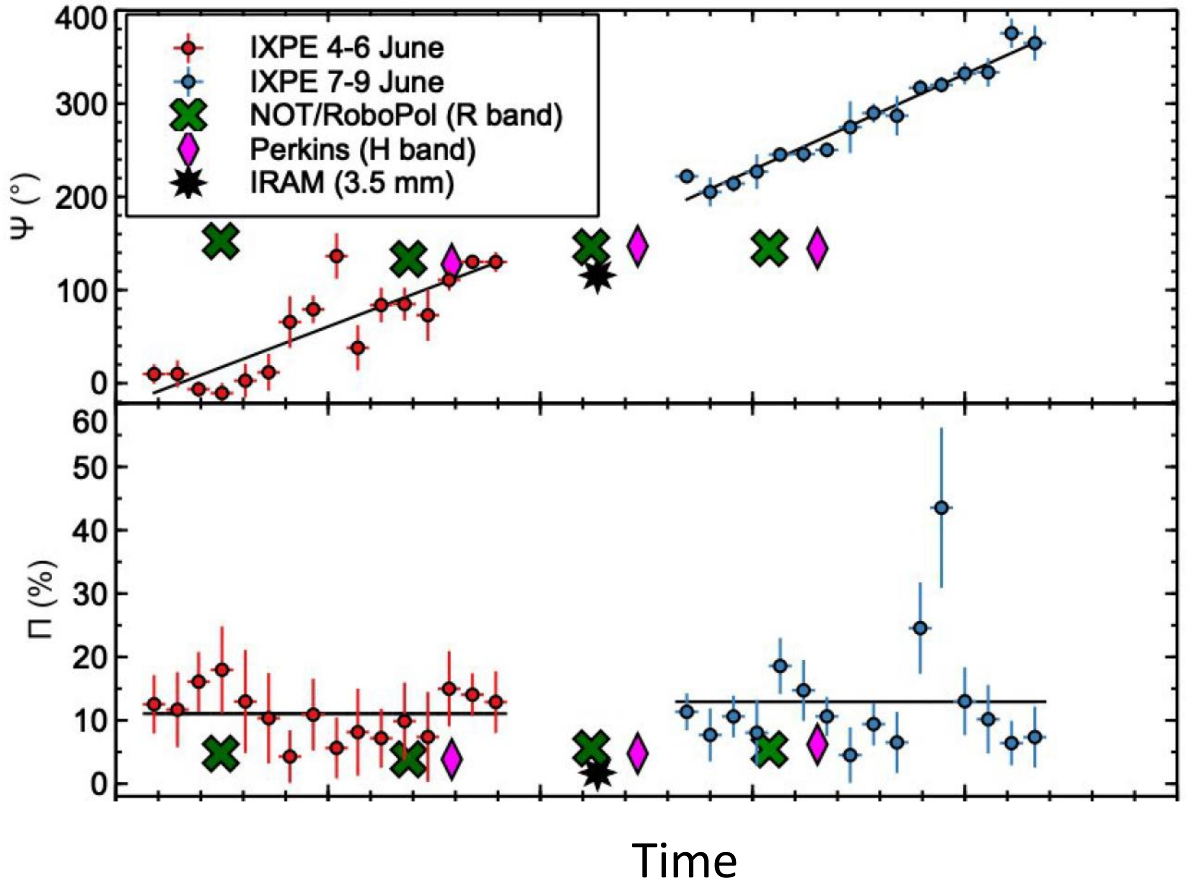
Particle acceleration in blazar jets

How are particles accelerated in blazar jets?

For Mrk 421, IXPE found:

- No X-ray polarization in time-averaged data.
- EVPA rotation by > 360° over 5 days.
- X-ray PD ≈ 10%.
- No EVPA rotation at optical/IR/radio.

➢ Helical magnetic structure in the jet, illuminated in X-rays by a localized shock propagating along the helix.



Di Gesu et al., Nature Astronomy to appear

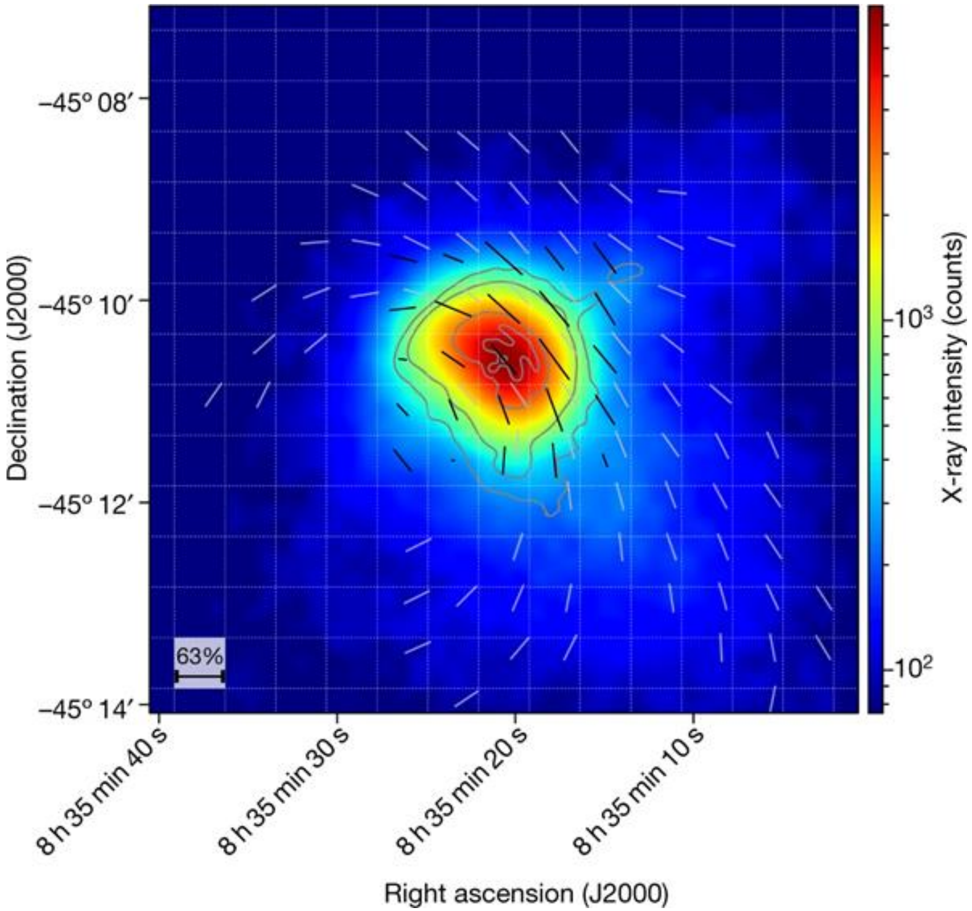
X-ray polarization from the Vela pulsar wind nebula

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

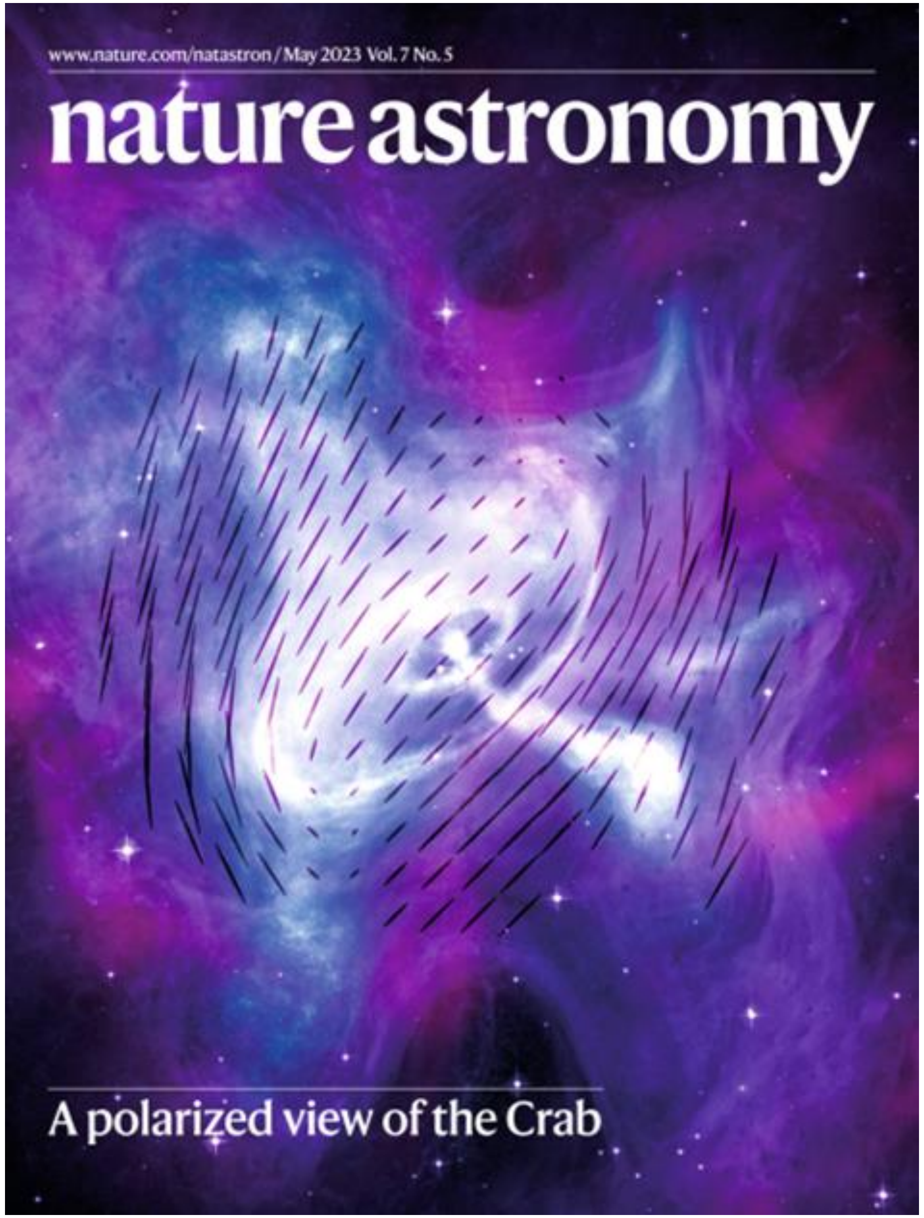
X-ray polarization from the Crab pulsar wind nebula

Nature Astronomy, May 2023, has three IXPE articles:

- “Simultaneous space and phase resolved X-ray polarimetry of the Crab pulsar and nebula” by Bucciantini et al.

- “A space-borne X-ray imaging polarimeter” by Weisskopf et al.

- “Revealing the magnetic field geometry in the Milky Way’s most efficient particle accelerator” - Research briefing on Crab paper.

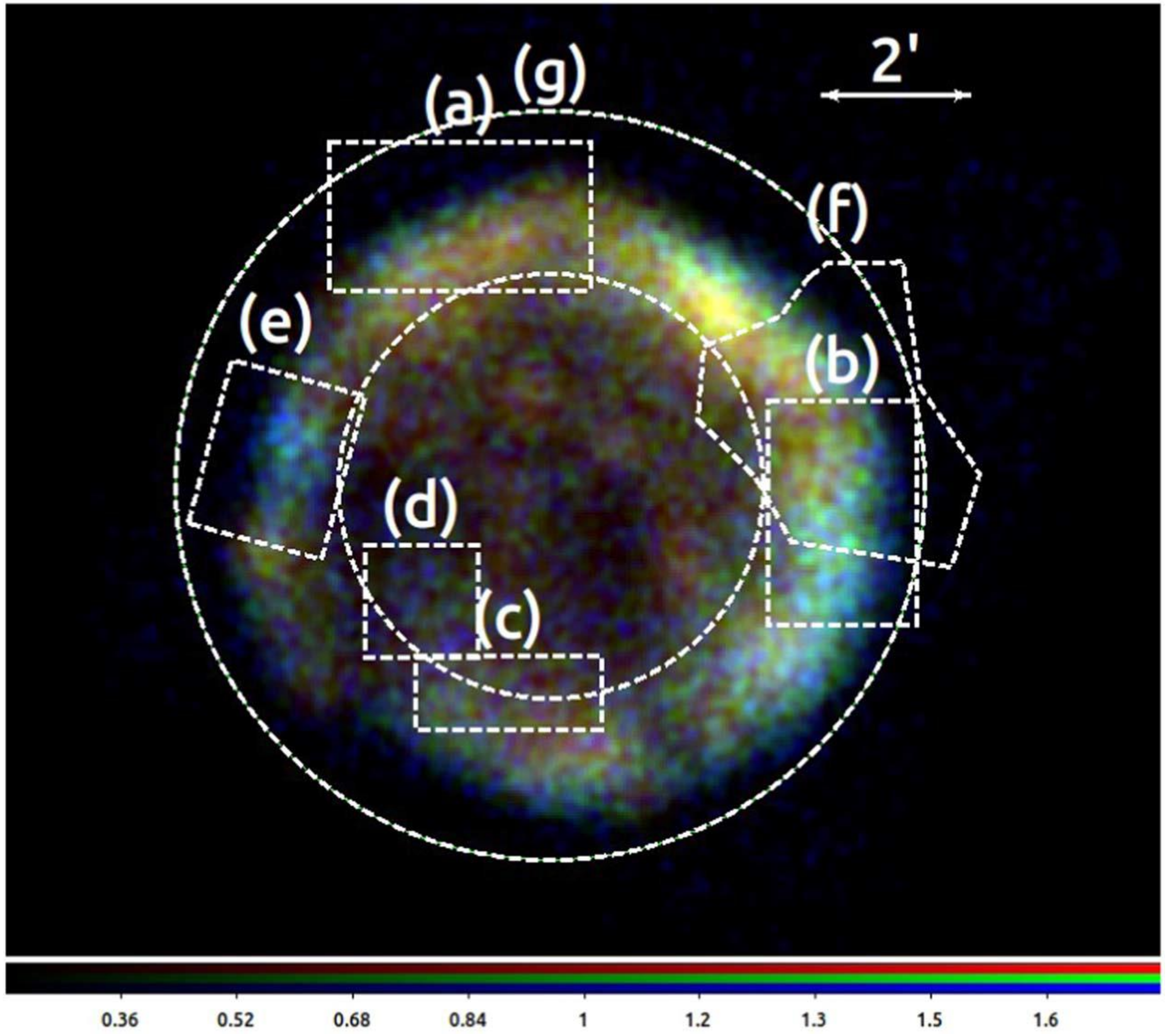


Polarization of filaments in SNR shells

What is the magnetic field geometry in SNR shells?

- Do analysis in pixels or assuming circular symmetry.
- Correct for thermal emission, PD are quoted for synchrotron component.

- Both Tycho and Cas A show magnetic fields are radial near the shock.
- 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.
- ➢ Compatible with turbulence produced by an anisotropic cascade of a radial magnetic field near the shock.

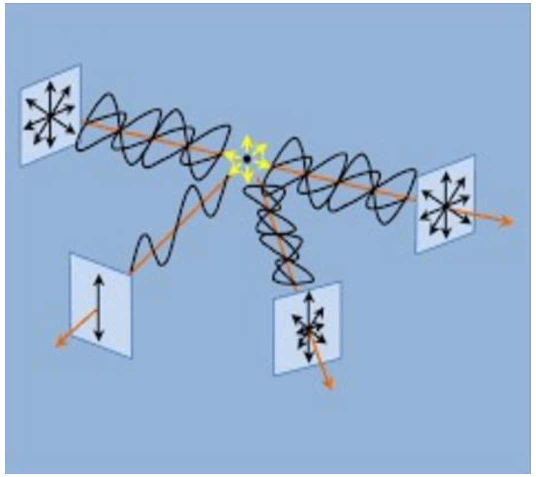


Tycho SNR (Ferrazzoli et al. 2023)

Radio quiet AGN

Is the reflection component in AGN spectra reflected?

Scattering/reflection →
EVPA perpendicular to scattering plane
Scattering through 90° produce high PD

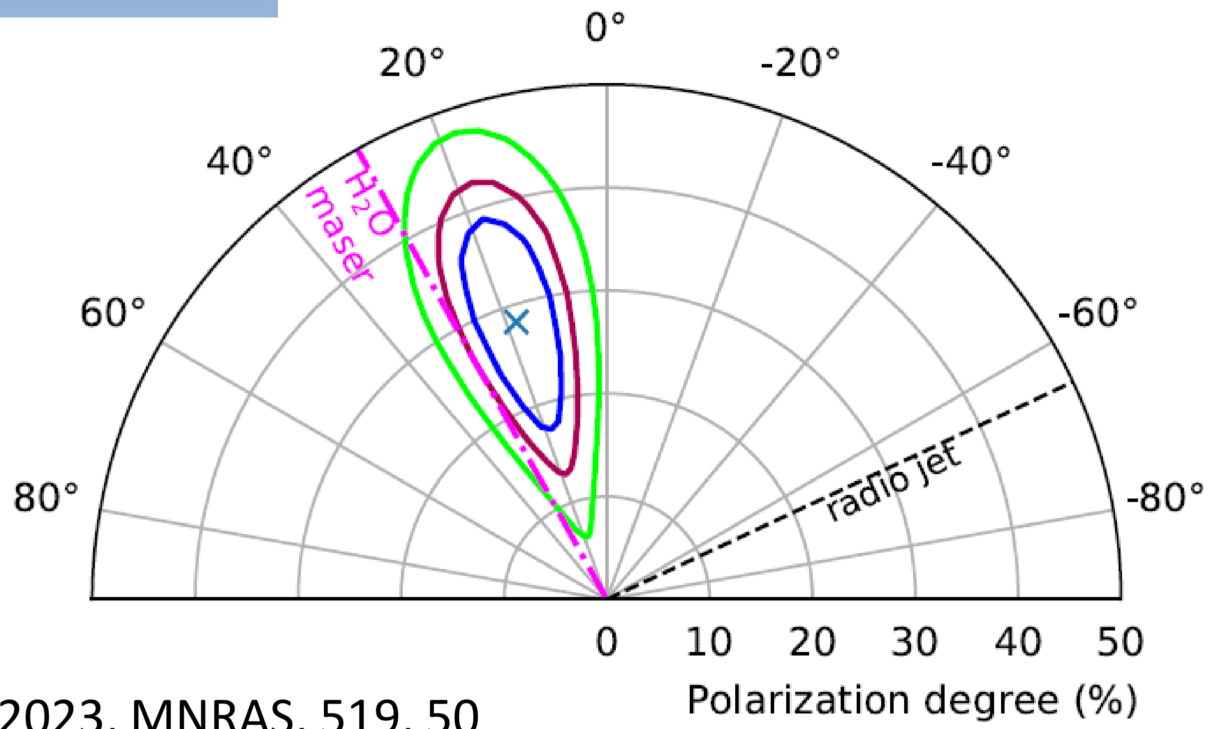


Spectropolarimetric analysis for Circinus galaxy shows cold reflector which dominates hard X-ray emission has:

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

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

Cold reflection



Ursini et al. 2023, MNRAS, 519, 50

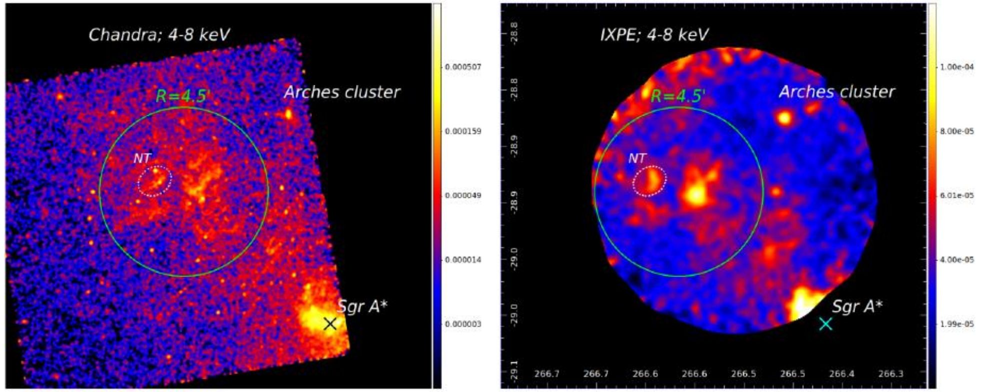
Past activity of Sgr A*

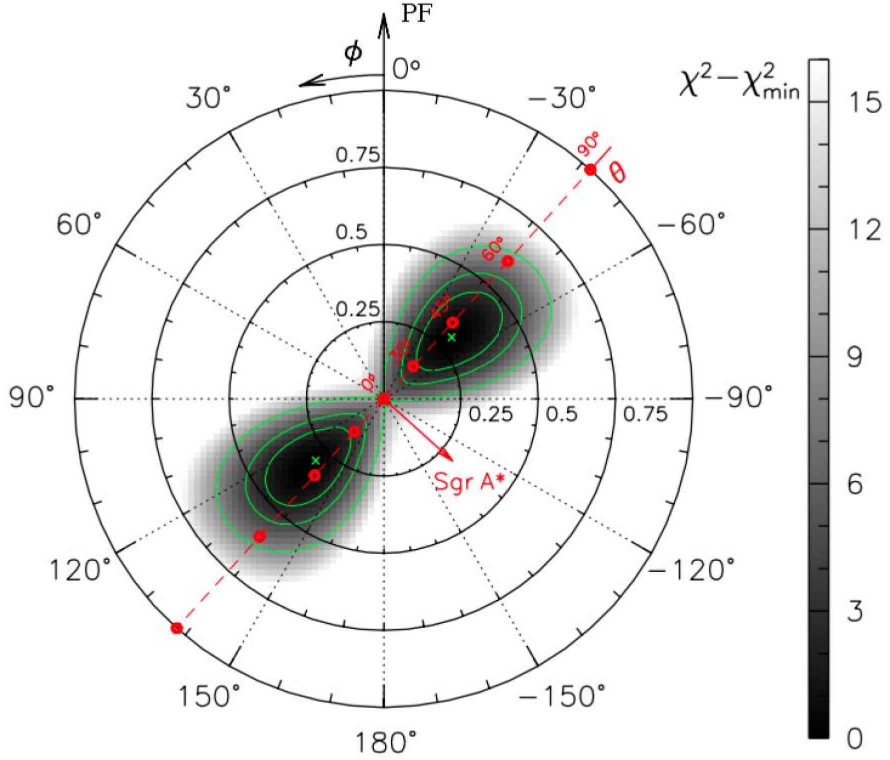
Does X-ray emission from molecular clouds near the Galactic center indicate past activity of Sgr A*?

- Some MC near GC show hard X-ray emission
- Absence of local sources suggests reflection of past hard X-ray flares.
- Polarization provides key test: expect PA to point back to GC, high PD

- IXPE finds PD = 31% ± 11%
- PA = 48° ± 11°

➢ PA is consistent with Sgr A* origin.
➢ PD implies that 200 years ago Sgr A* briefly has an X-ray luminosity comparable to a Seyfert galaxy.



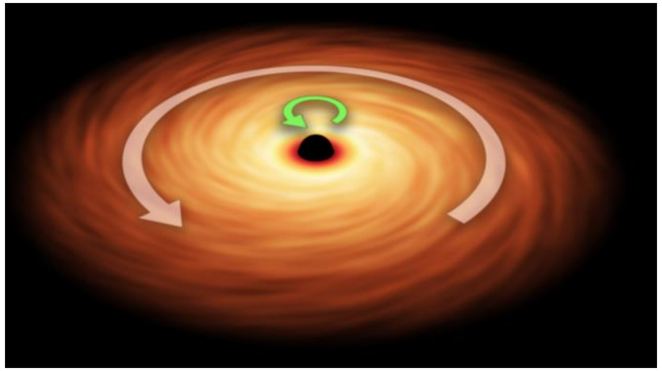


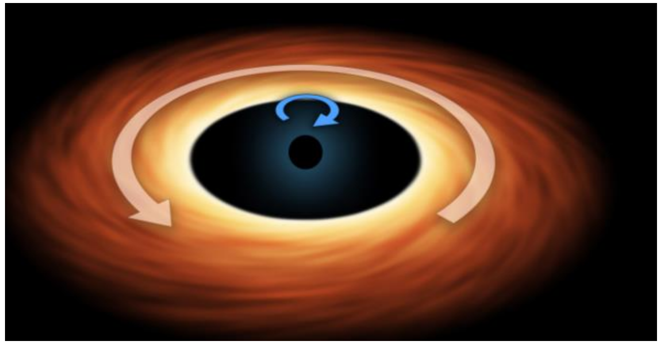
Marin et al., Nature to appear

Accreting Stellar Mass Black Holes

Expectations before IXPE Launch

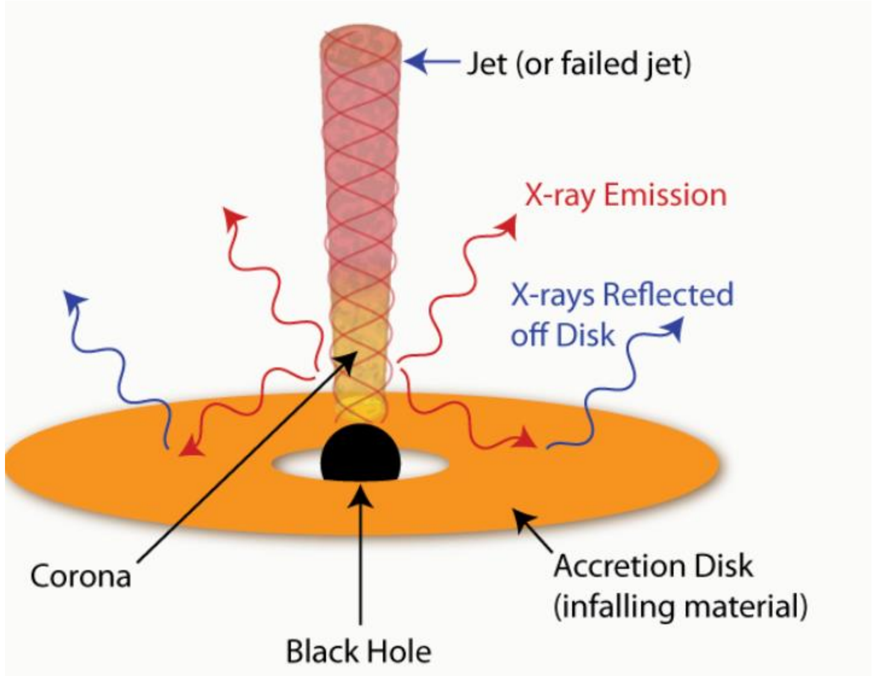
Thermal state





Temperature & Flux ⇒ area
Polarization ⇒ inclination & ISCO

Hard state

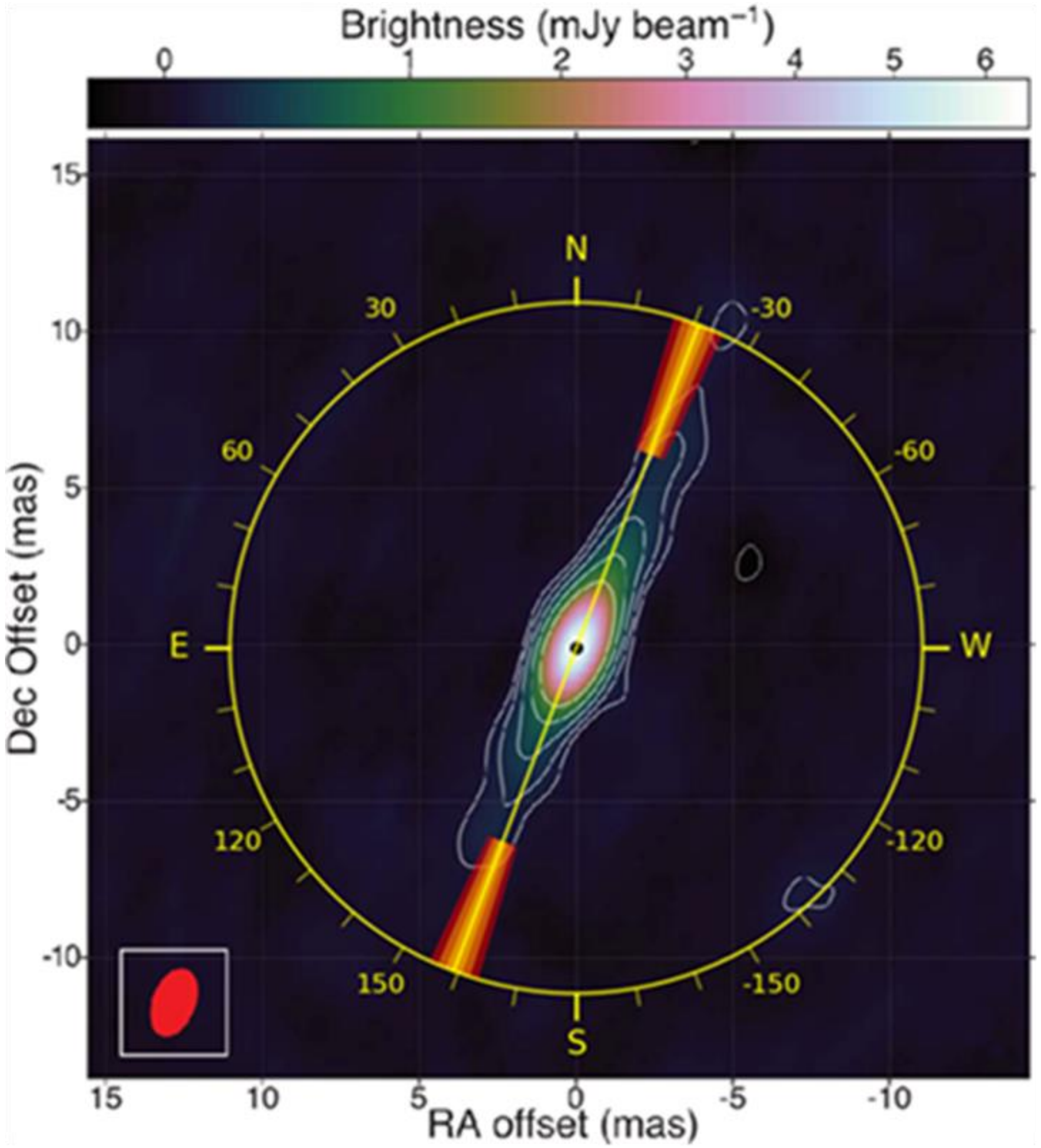


Shape of Fe K-alpha line ⇒ location of ISCO
Polarization ⇒ corona shape and location
Slides from Henric Krawczynski

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

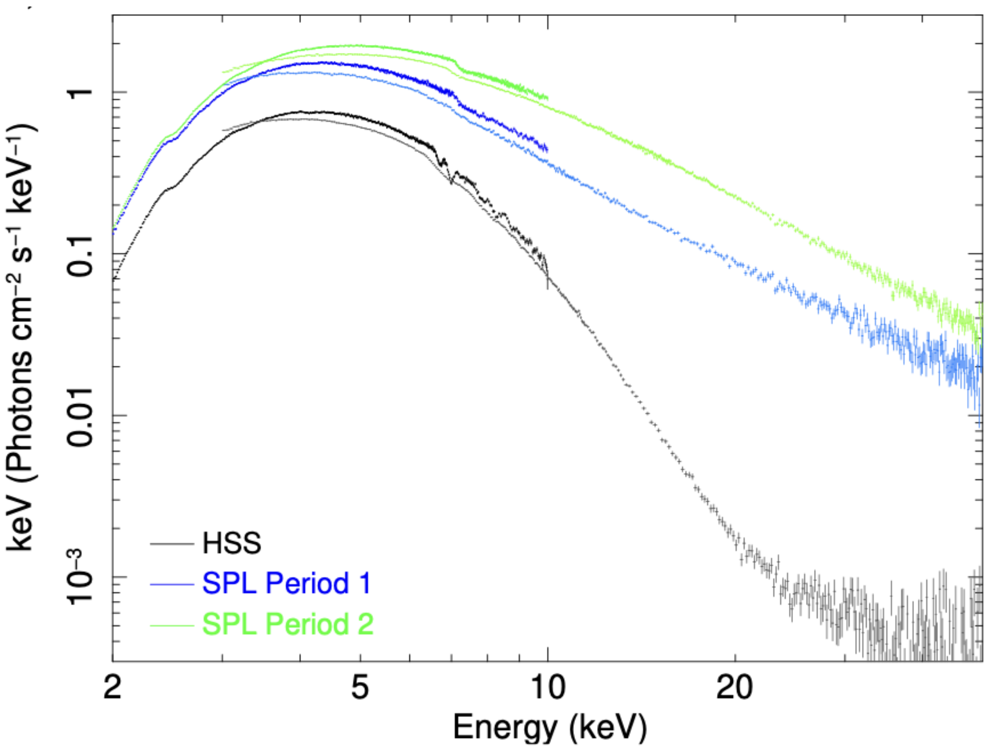
- ➢ Corona is parallel to disk.
- ➢ Excludes lamppost corona models - narrow column along the jet axis or two compact regions above/below BH

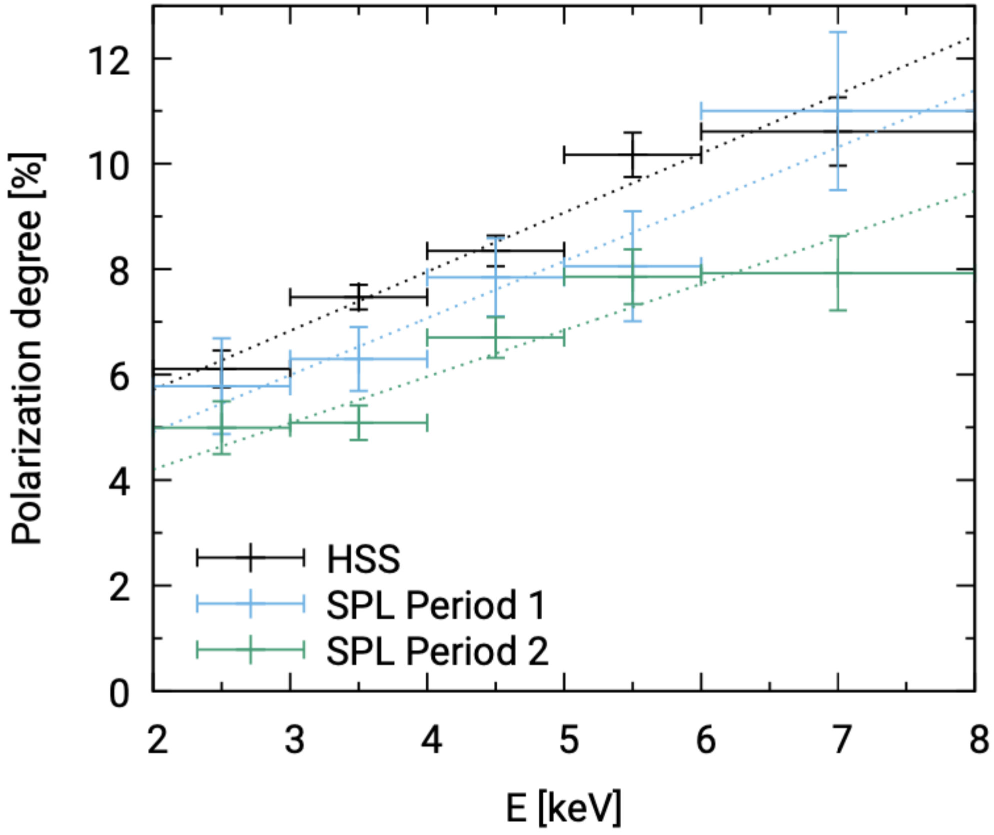
⇒ spin measurements relying on lamppost coronas need revision.

Science
Krawczynski+ 2022

Accreting Stellar Mass Black Holes

IXPE Results 4U1630-47





- Polarization higher than expected for standard thin disk scenario.
- Unexpected to find similar polarization in thermal and steep power law (SPL) states.
- ➢ Possible explanations: outflowing photosphere, slim disk.

Cyg X-3

What's going on in Cyg X-3?

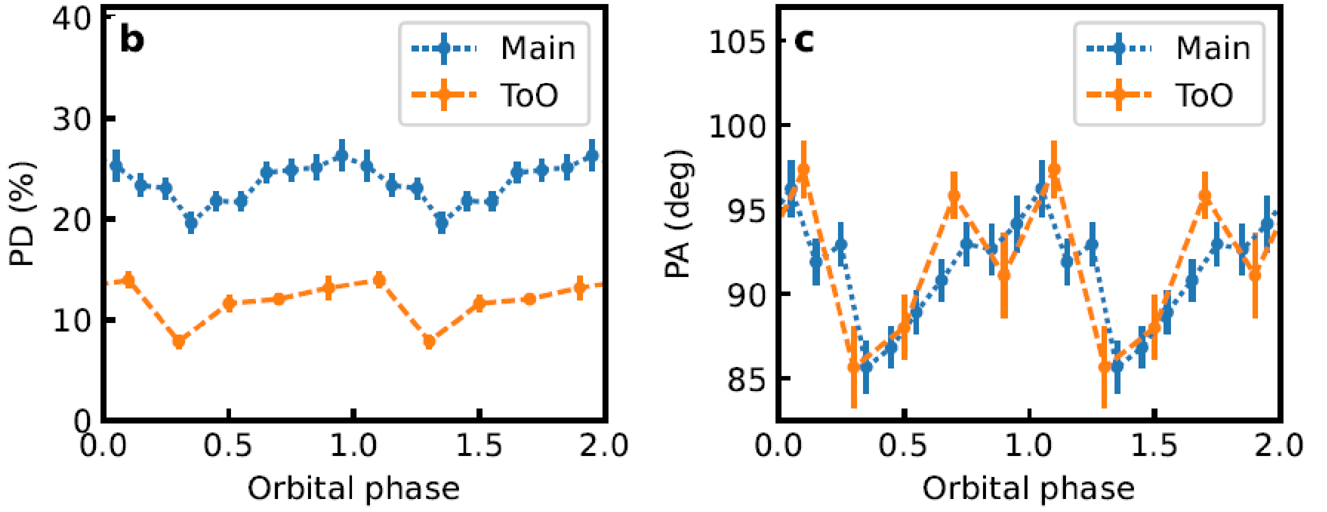
- High PD ≈ 20%.
- Suggests spectrum dominated by reflection.

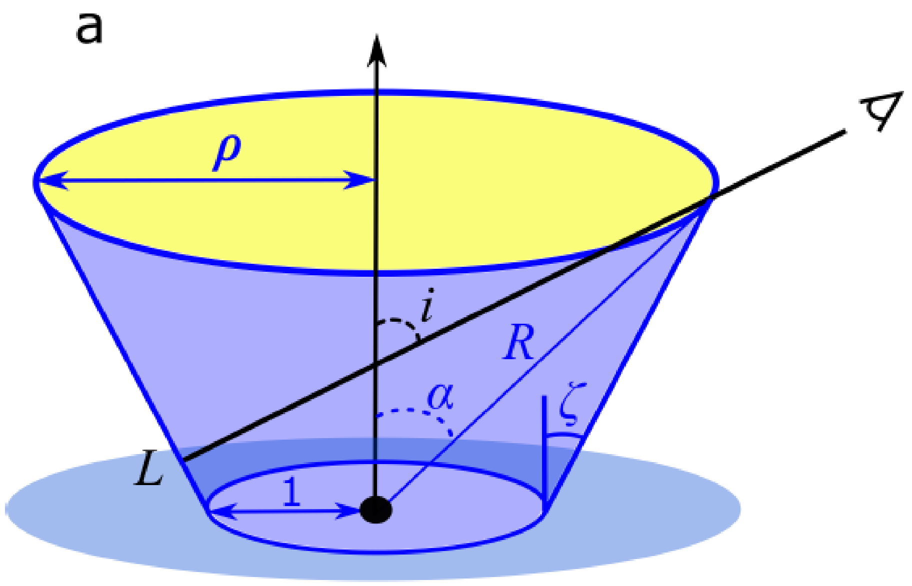
- Viewing radiation from inner surface of accretion funnel.
- Funnel opening angle ≤ 15°

- Apparent L > 5E39 erg/s if viewed down funnel

➢ Cyg X-3 is a ULX

- Intrinsic L may be super Eddington.





Neutron star low-mass X-ray binaries

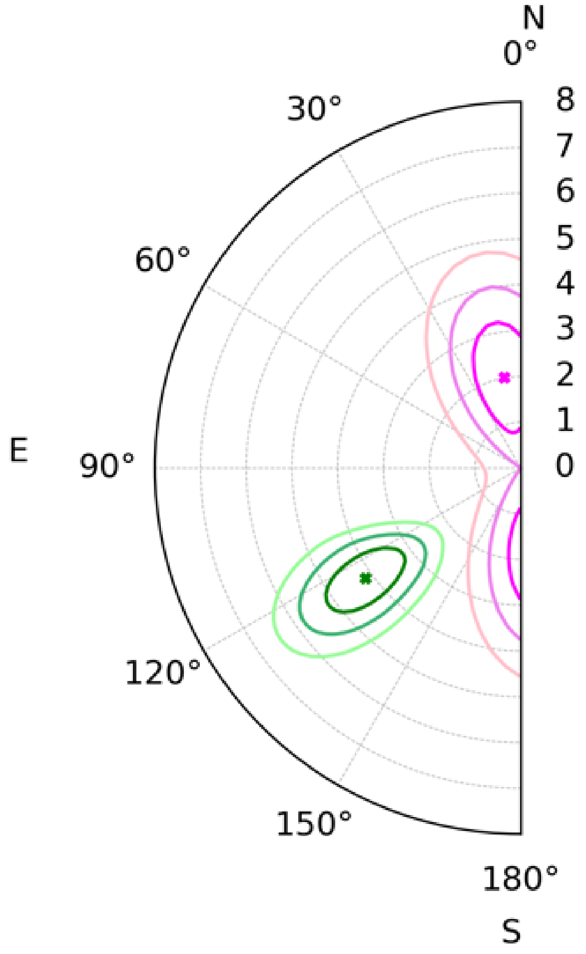
What is the geometry of the accretion flow?

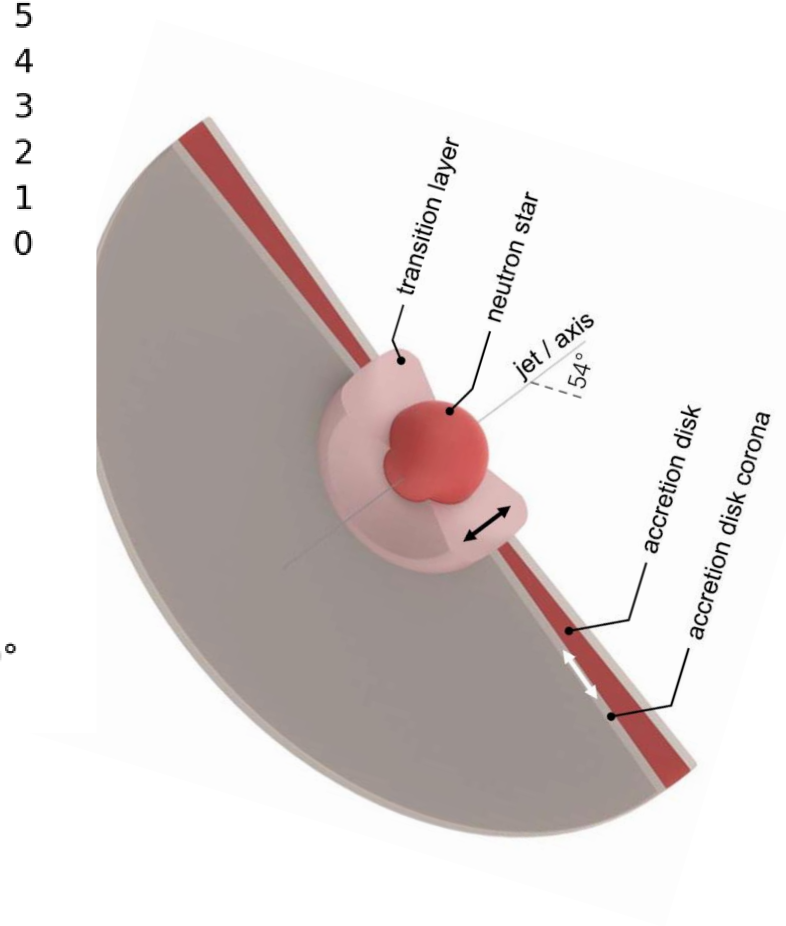
What are the origins of the emission components?

Cyg X-2:

- PA of Comptonization component (green) is consistent with radio jet direction (Farinelli et al. 2023)
- Suggests emission from spreading/transition layer at the neutron star surface.
- Pink shows the disk emission.

- Matches PolarLight results for Sco X-1
- Accretion geometry from Long et al. (2022)



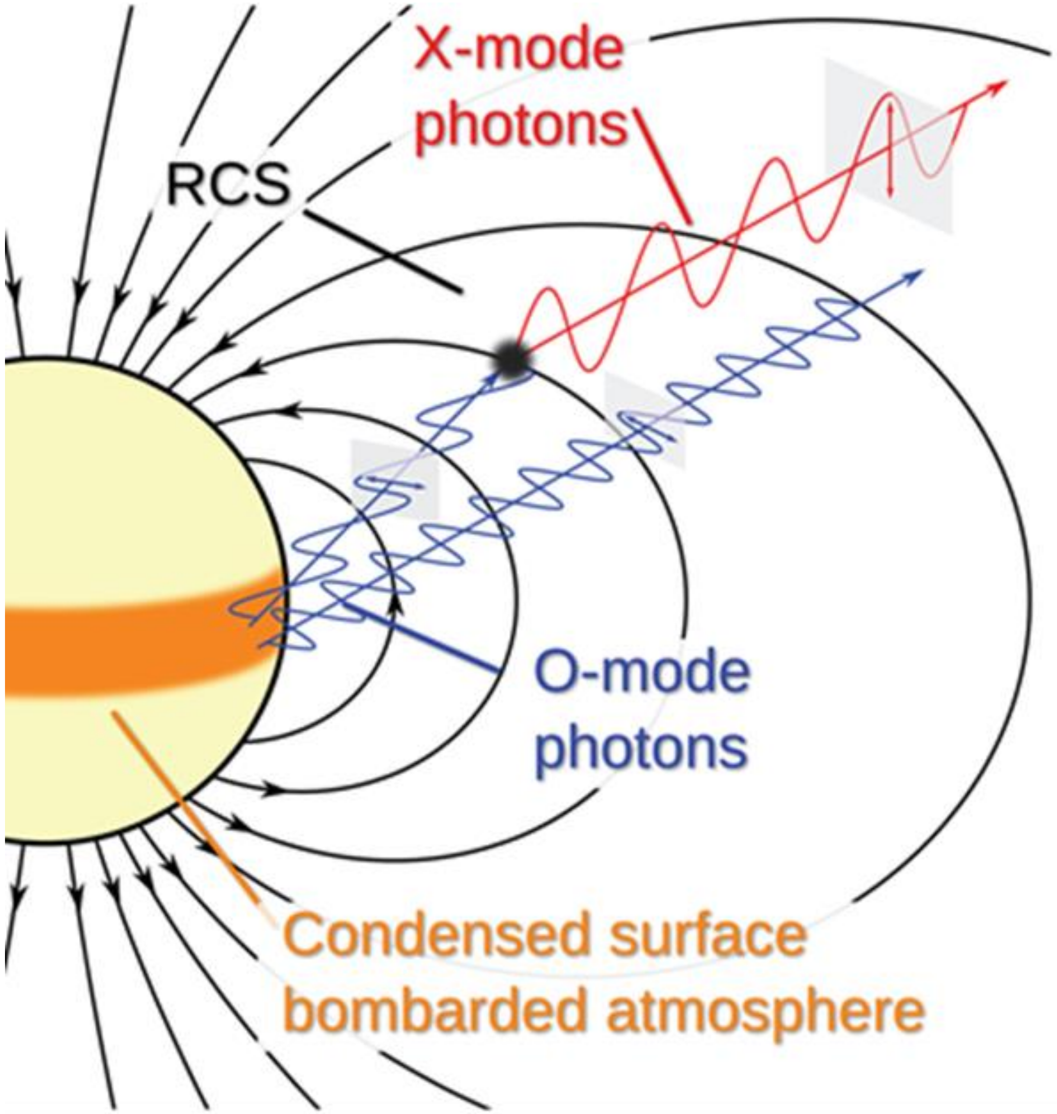


Magnetars

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).

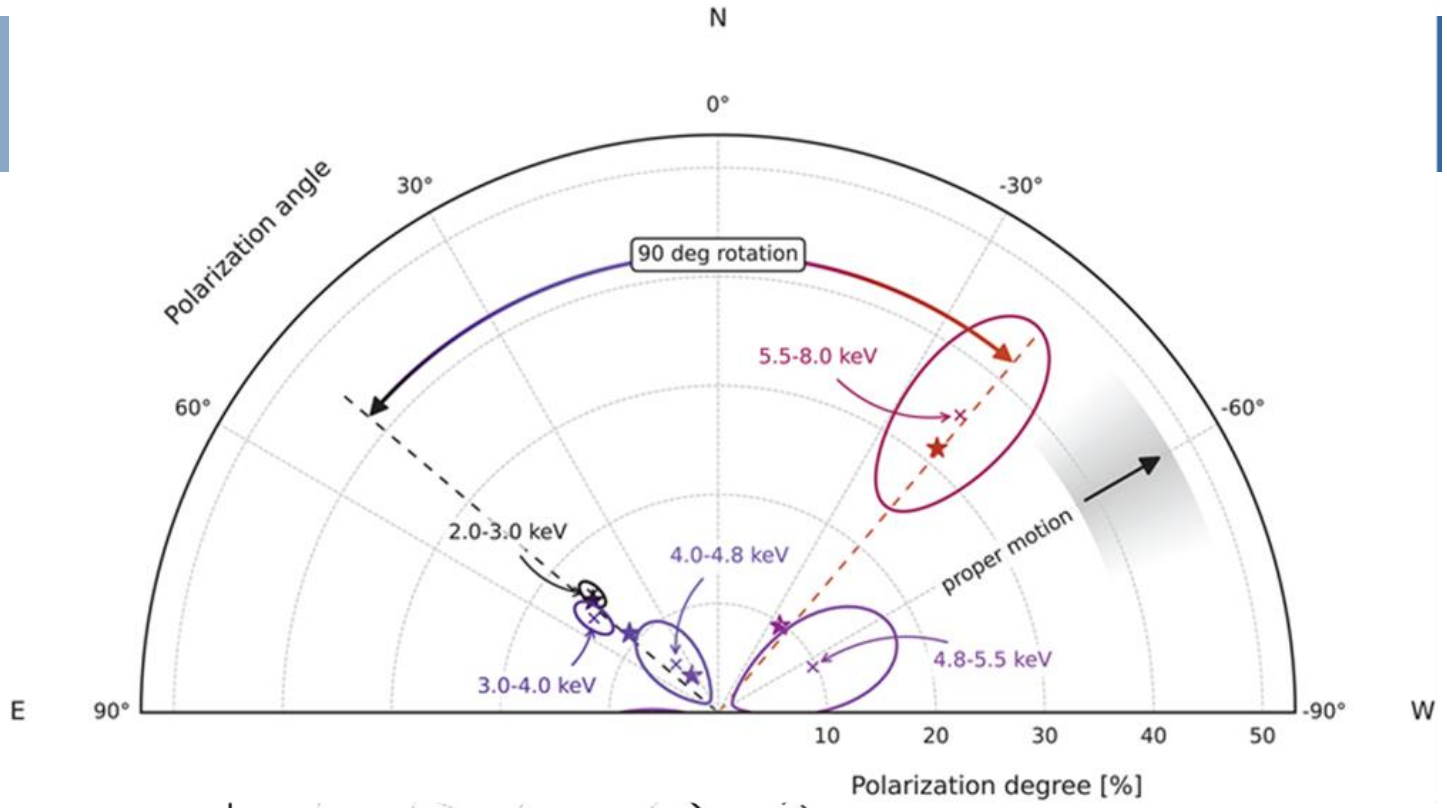


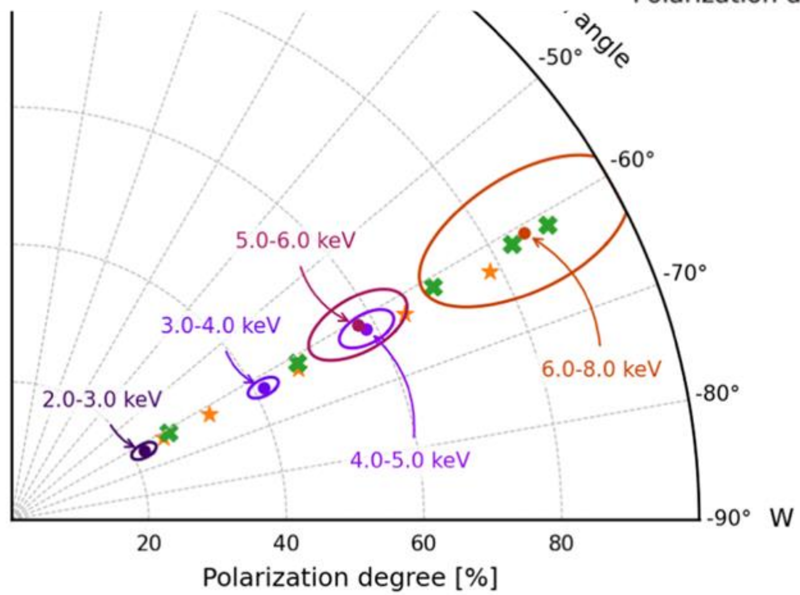
Magnetars

- 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 4U0142 is consistent with vacuum birefringence but can be explained with other models since low energy Polarization Degree (PD) is low.





X-ray pulsars

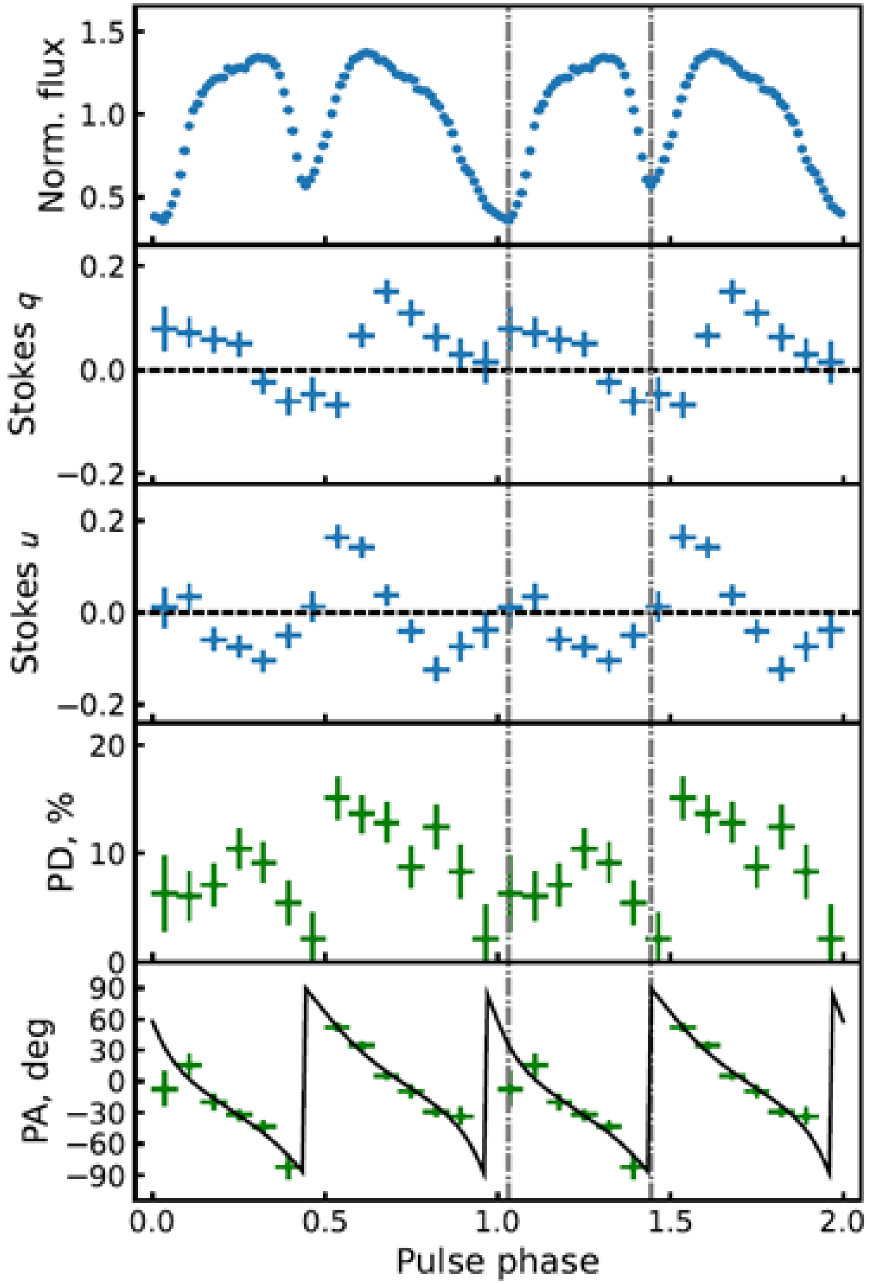
How are the neutron star magnetic fields oriented?

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.



All IXPE data are public

- HEASOFT analysis tools and documentation (including quick start guide) at GSFC GOF
  https://heasarc.gsfc.nasa.gov/docs/ixpe/analysis/

- Alternate package is ixpeobssim
- simulation and analysis framework specifically developed for IXPE by Italian team.
- Link under GOF ‘Contributed IXPE Software’ page

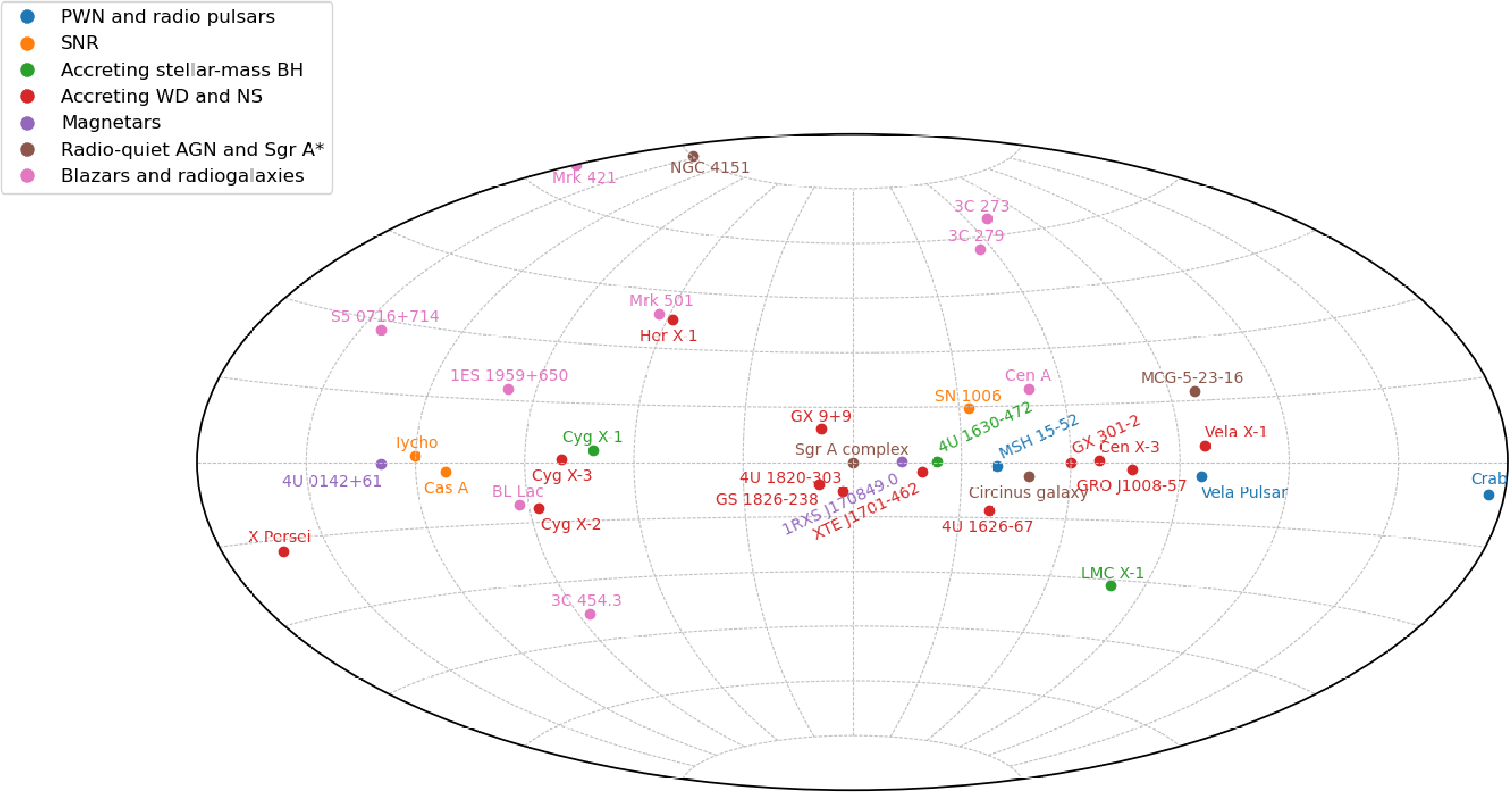
- Much of the analysis can be done in Xspec.

General Observer Program

- **Mission extension beyond 2-year baseline**
  - Mission Success Progress Review (MSPR) by independent panel
  - APD Director approved 20-month mission extension on 5 June 2023
- **General Observer Program**
  - Call for GO proposals released on 8 June 8 2023
  - Will have a theory component (~15% of funding)
  - Asking for NOI's to estimate number of proposals, categories (by 18 Sept 2023)
  - GO proposals due 18 October 2023
  - GO observations to begin in February 2024
- **Responsibilities**
  - General Observer Facility (GOF) at GSFC to administer IXPE General Observer Program
  - IXPE Mission Partners execute and process observations, archive to HEASARC
- **NASA policy: No exclusive-use period (can request 6 months exclusive use)**


IXPE has produced outstanding science and will continue to do so via a rich GO program.

IXPE targets to date



Circinus galaxy

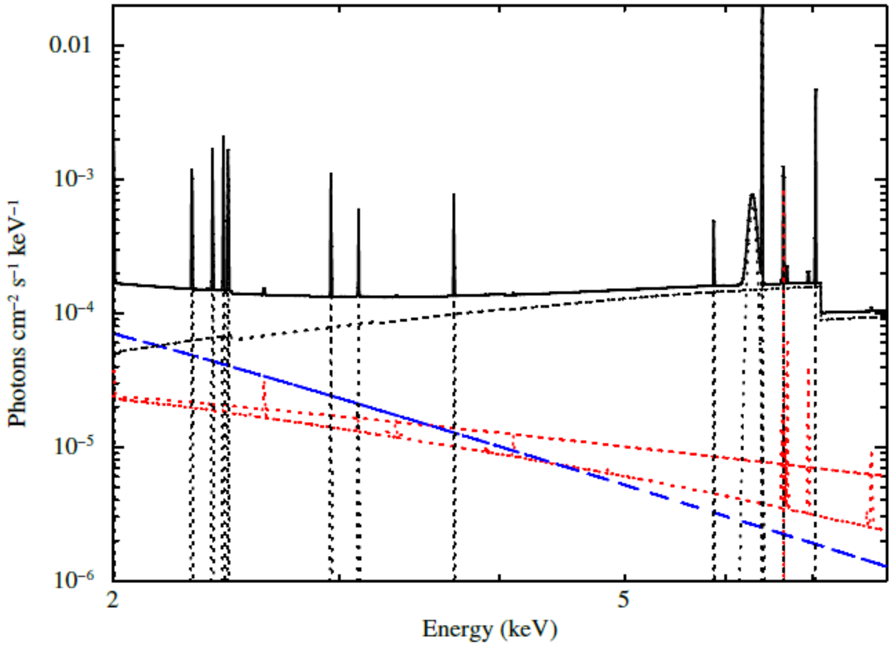


Figure 4. Best-fitting total model (black solid line) in the 2–8 keV band, together with the contribution of various components: cold reflection (black dotted line), warm reflection (blue dashed line), ULXs (red dotted lines).

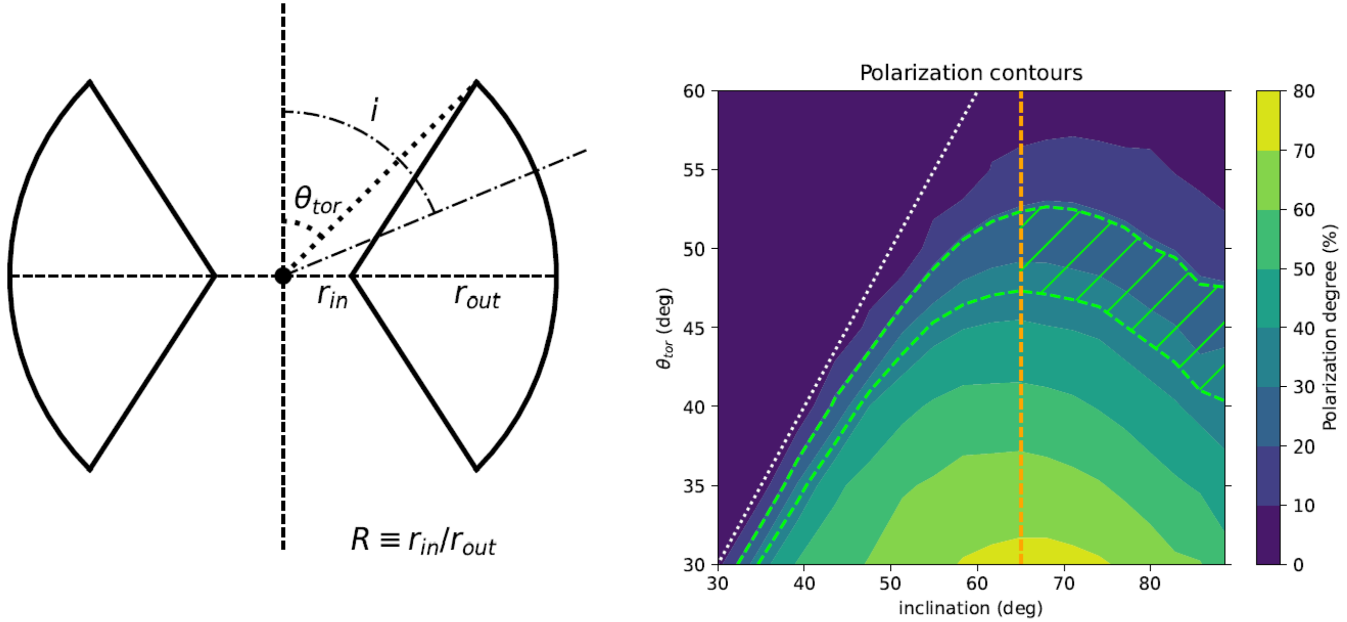
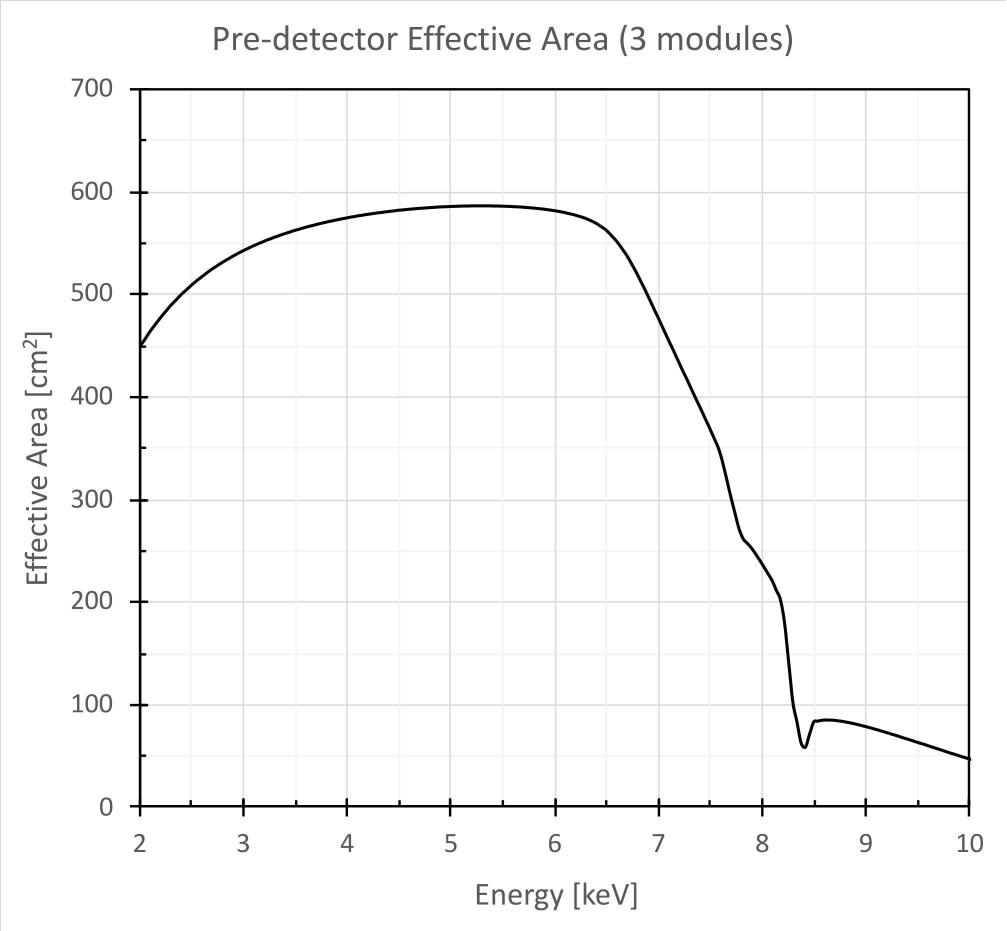


Figure 6. *Left panel:* Sketch of the torus geometry assumed for polarimetric modelling. The torus opening angle θ_{tor} and the observer inclination i are both measured from the symmetry axis. *Right panel:* Contour plots of the constant polarization degree calculated for scattering off a torus, on the $\theta_{tor} - i$ plane. The white dotted line corresponds to the equality $\theta_{tor} = i$; the condition for the obscuration of the central source is $\theta_{tor} < i$. The green dashed curves enclose the 68 per cent confidence level region on the measured polarization for the cold reflector in the Circinus galaxy. The orange dashed line marks the inclination of the host galaxy, likely a lower limit to the torus inclination (as discussed in the text). The green hatches mark the region of the parameter space consistent with all the observational constraints.

Mirror Module Assembly Properties

Property	Value
Number of modules	3
Mirror shells per module	24
Inner, outer shell diameter	162, 272 mm
Total shell length	600 mm
Inner, outer shell thickness	180, 250 µm
Shell material	Nickel cobalt alloy
Effective area per module	163 cm^2 (2.3 keV) ~ 192 cm^2 (3-6 keV)
Angular resolution	≤ 27 arcsec HPD
Detector limited FOV	12.9 arcmin
Focal length	4 m
Mass (3 assemblies)	93.12 kg



Stokes parameters

- **Work in Stokes parameters**
  - Independent, gaussian errors
  - Simply additive
  - No coordinate singularity at $\Pi = 0$
- **Compute modulation Stokes parameters (q_i, u_i) from initial direction of photoelectron**
  - Uses event reconstruction to determine φ_i for each event i

$$q = \langle q_i \rangle;\; q_i = \langle (2\cos(2\varphi_i) - q_i^{sm})/\mu_i \rangle = \langle q_i/\mu_i \rangle$$
$$u = \langle u_i \rangle;\; u_i = \langle (2\sin(2\varphi_i) - u_i^{sm})/\mu_i \rangle = \langle u_i/\mu_i \rangle$$

- **Each event is described by a time t_i; PI energy E_i; coordinates x_i, y_i; and Stokes q_i, u_i**
- **Obtain polarization degree and position angle from Stokes parameters**

$$\Pi = \sqrt{Q^2 + U^2}/I = \sqrt{q^2 + u^2}$$
$$\psi = \frac{1}{2}\tan^{-1}\left(\frac{U}{Q}\right) = \frac{1}{2}\tan^{-1}\left(\frac{u}{q}\right)$$

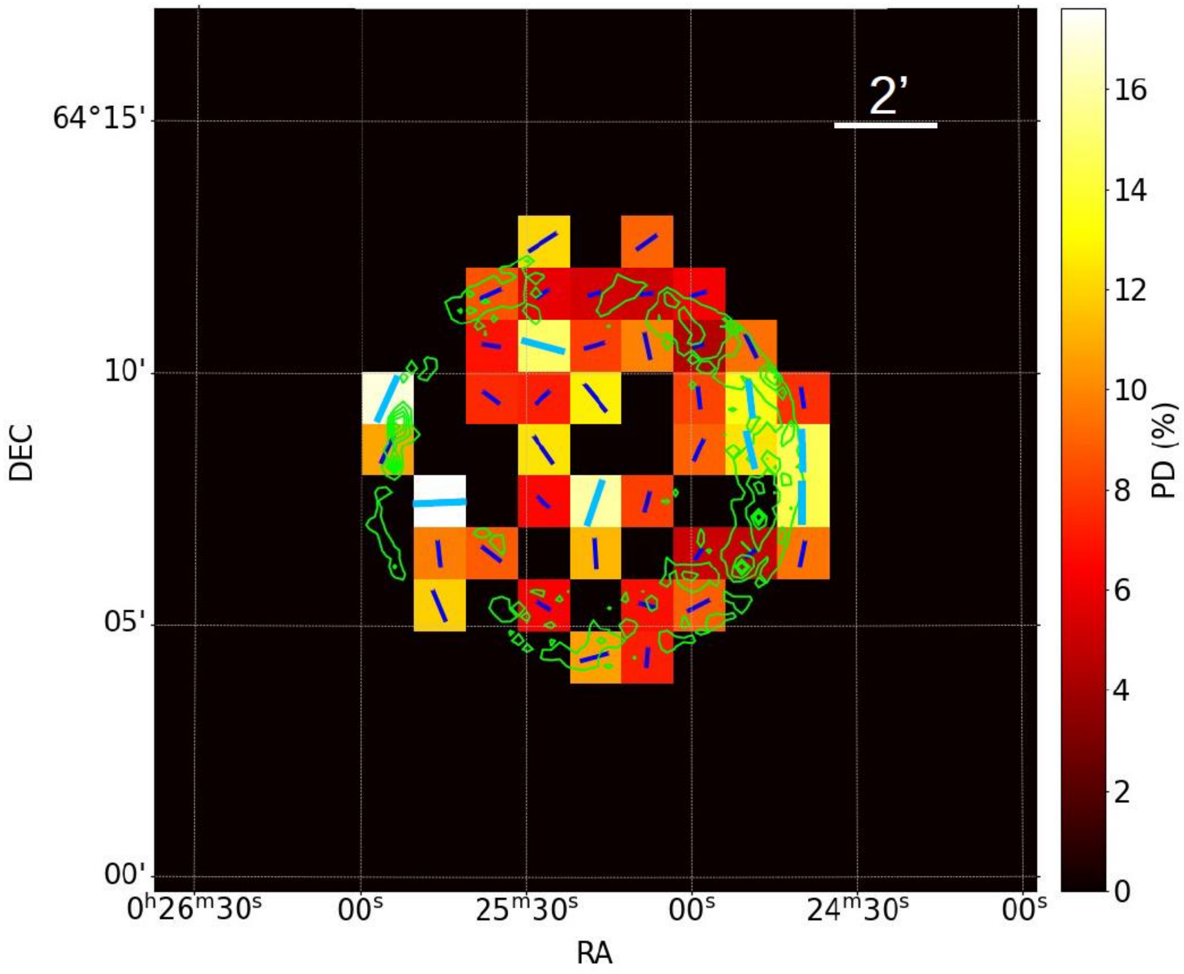
$$q = \Pi\ \cos(2\psi)$$
$$u = \Pi\ \sin(2\psi)$$

Polarization of filaments in SNR shells

What is the magnetic field geometry in SNR shells?

- Do analysis in pixels and assuming circular symmetry.
- Correct for thermal emission, PD are quoted for synchrotron component.

- Both Tycho and Cas A show magnetic fields are radial near the shock.
- 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.
- ➢ Compatible with turbulence produced by an anisotropic cascade of a radial magnetic field near the shock.



Tycho SNR
Ferrazzoli et al. 2023

Particle acceleration in blazar jets

Table 1 Summary of model properties. We find increasing Π towards higher frequencies, no significant variability during the 2-3 day long *IXPE* observations, and rough alignment of ψ with the jet axis from radio to X-rays. Therefore, a shock-accelerated, energy-stratified electron population model satisfies all our multiwavelength polarization observations.

Model	Multiwavelength polarization	X-ray polarization variability†	X-ray polarization angle
Single-zone	constant*	slow	any
Multi-zone	mildly chromatic	high	any
Energy stratified (shock)	strongly chromatic	slow	along the jet axis
Magnetic reconnection (kink instability)	constant	moderate	perpendicular to jet axis
Observed	strongly chromatic	slow	along the jet axis

* There is a slight dependence on the slope of the emission spectrum.
† Slow variability = a few days to week, moderate variability = days, high variability $\leq$ 1 day.