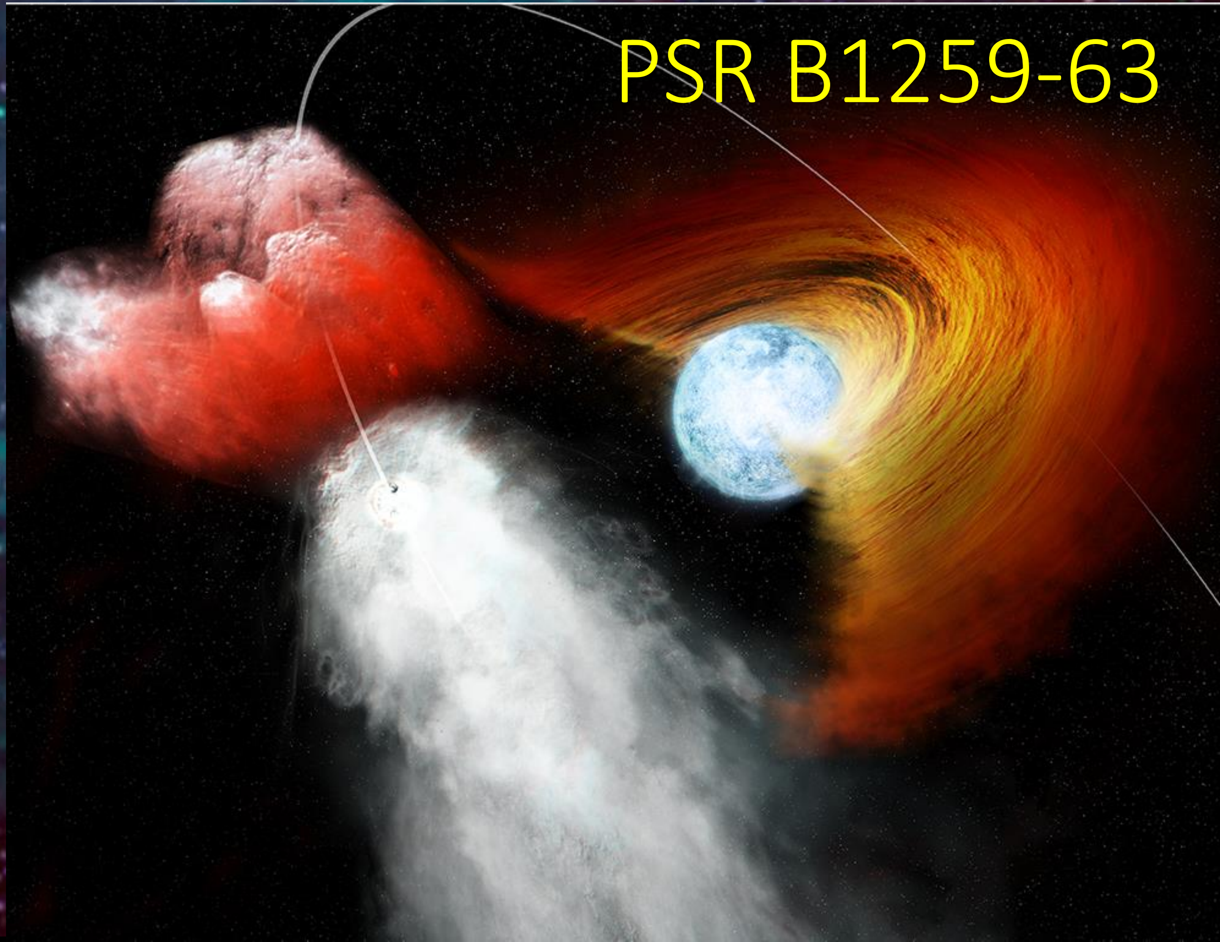
Results from the Imaging X-ray Polarimetry Explorer (IXPE) with a focus on gamma-ray binaries

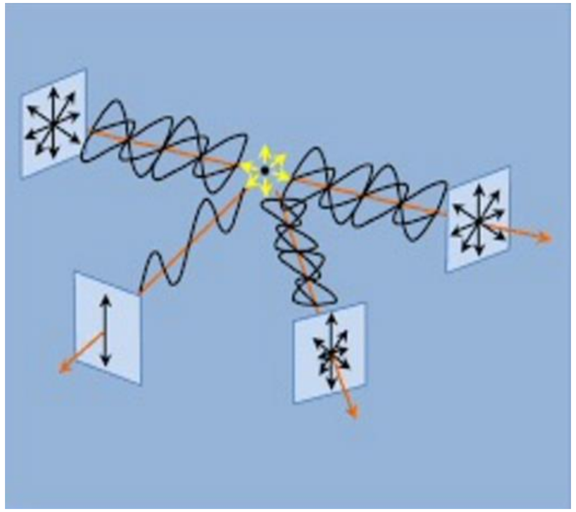
Philip Kaaret (NASA/Marshall Space Flight Center)



Polarization measures geometry

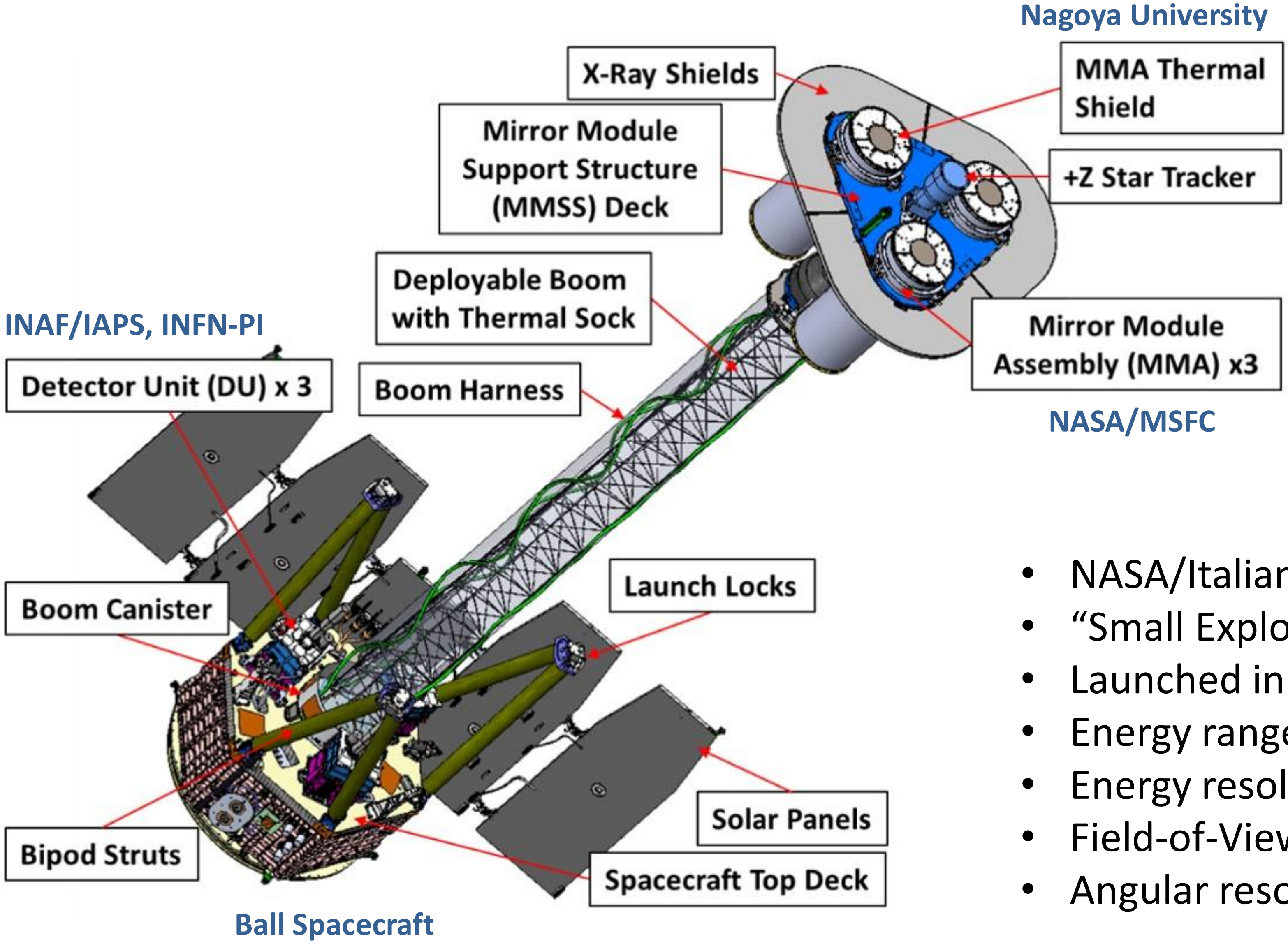
Polarization is a vector → measures geometry

Electric vector position angle = EVPA



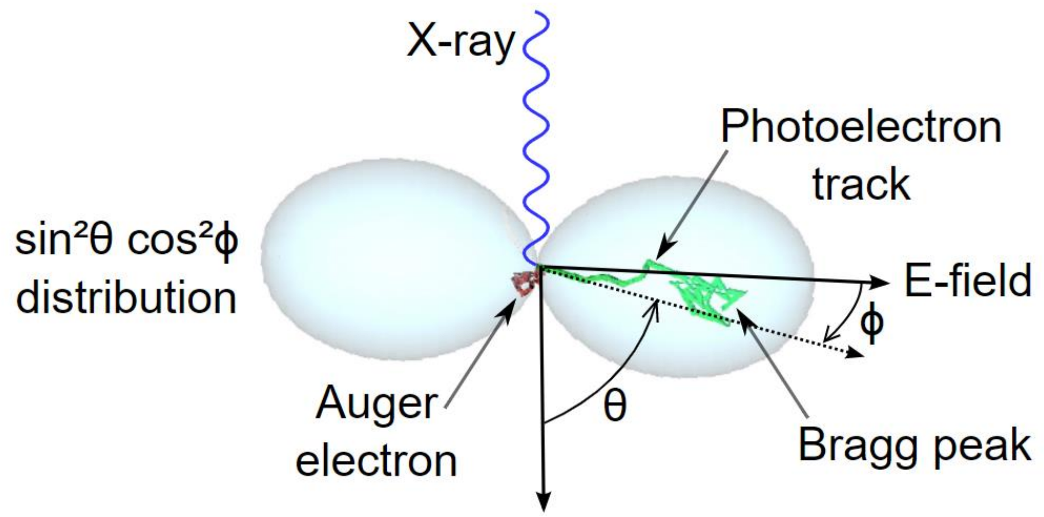
- Scattering/reflection →
  EVPA perpendicular to scattering plane
- Synchrotron radiation →
  EVPA perpendicular to magnetic field lines
- Strong magnetic fields →
  Opacity different parallel vs perpendicular to B
- Strong gravitational fields →
  EVPA parallel-transported along space-time geodesics

Imaging X-ray Polarimetry Explorer

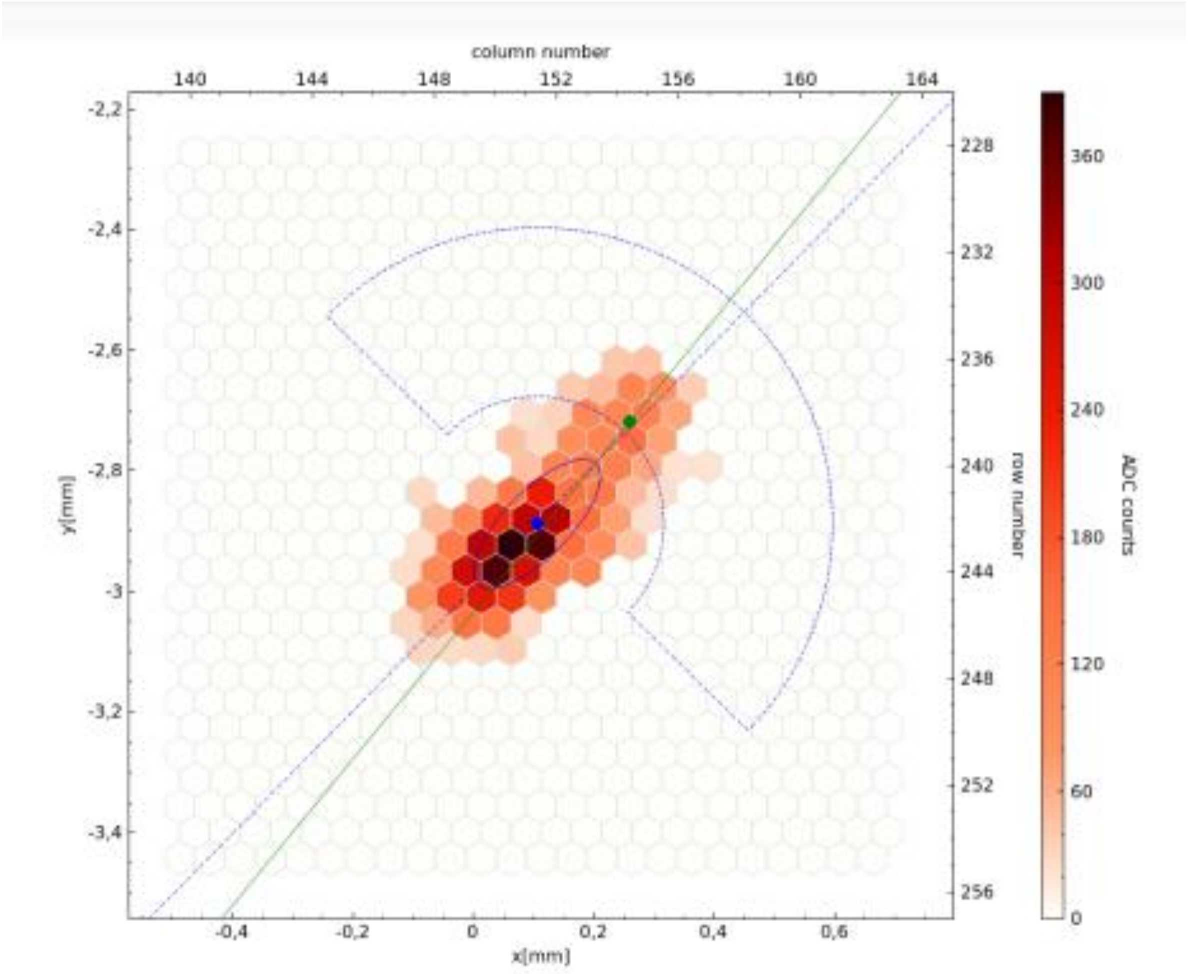


- NASA/Italian Space Agency mission
- "Small Explorer" ($188M)
- Launched in December 2021
- Energy range: 2–8 keV
- Energy resolution: 0.57 keV FWHM @ 2 keV ($\propto \sqrt{E}$)
- Field-of-View: 12.9′ diameter, useful 10′
- Angular resolution: 30″ HPD

X-ray polarization via the photoelectric effect



- IXPE uses the photoelectric effect to measure *linear* polarization, no sensitivity to circular polarization.
- Photoelectron ejected along photon E field.
- Key is to find photoelectron direction at interaction point.

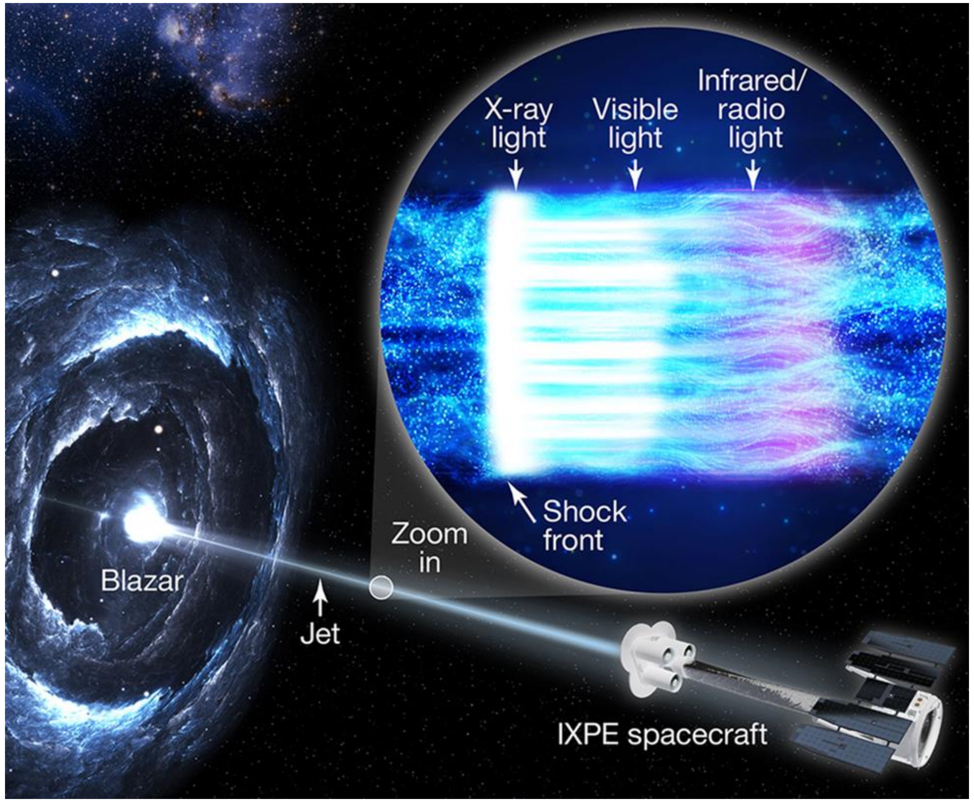


Photoelectron track from Cas A for 2.7-keV photon in DU1.

Science results

IXPE has made observations of:

- Blazars and radio galaxies
- Neutron-star low-mass X-ray binaries
- Accreting X-ray pulsars
- Accreting stellar-mass black holes
- Supernova remnants and pulsar wind nebulae
- Magnetars
- Radio-quiet active galactic nuclei
- Center of the Milky Way galaxy
- Gamma-ray burst (Brightest Of All Time)
- Accreting millisecond pulsar – new in GO phase
- Radio galaxy extended jet – new in GO phase



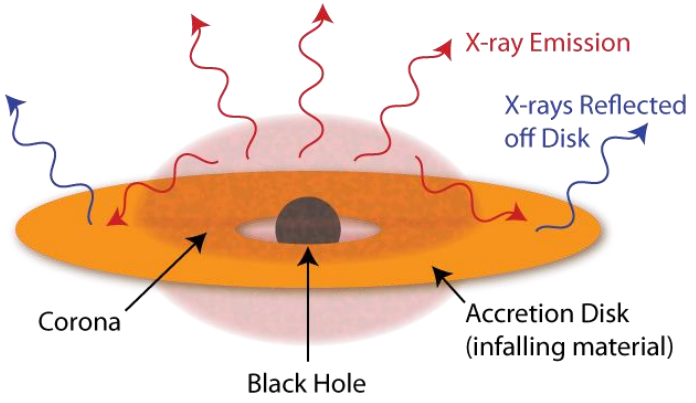
IXPE has opened a new window on the cosmos. New results on:
- magnetic field geometry in acceleration zones (blazars, supernova remnants and pulsar wind nebulae),
- accretion geometry near black holes (ruling out some commonly used models),
- behavior of matter in strong magnetic fields near neutron stars (magnetars, accreting puslars).

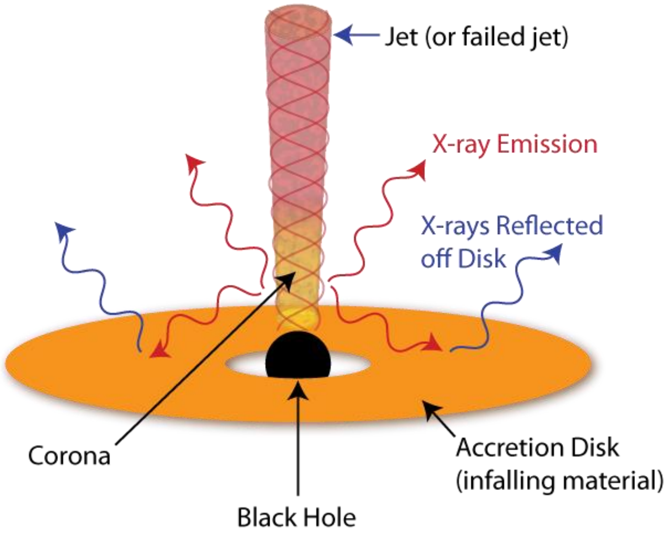
IXPE is making exciting discoveries that are reshaping our understanding of the energetic universe.

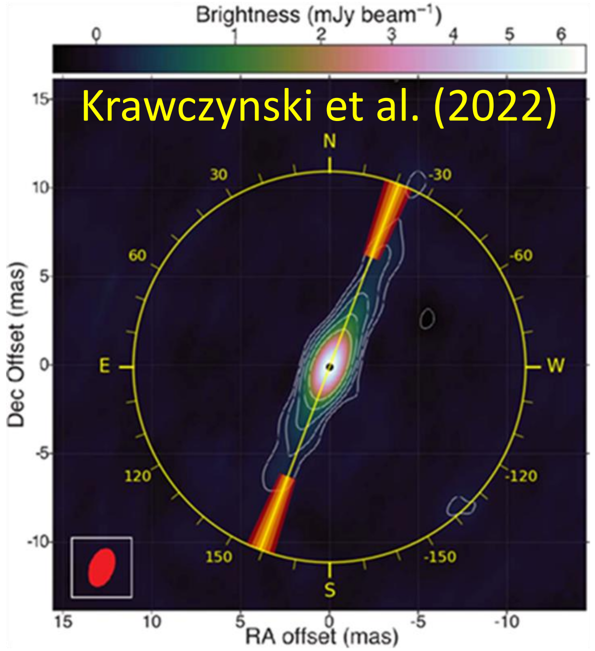
Corona geometry in accreting black holes

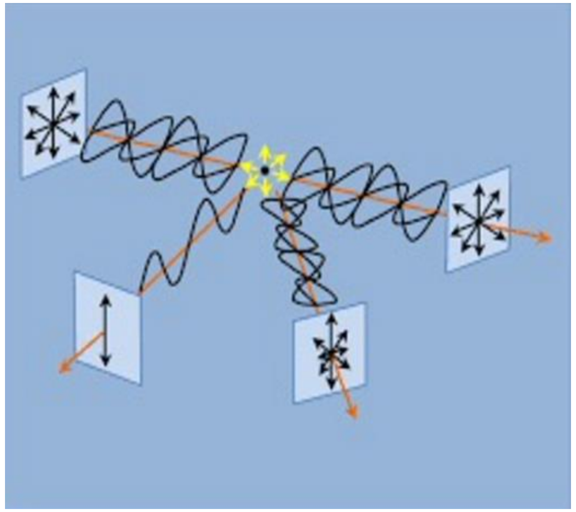
- Spectra of accreting black holes reveal two main components: disk and corona
- Decades of spectral and timing observations were unable to determine the geometry of the corona.
- First IXPE black hole (Cyg X-1) found polarization aligned with jet.

  → Corona is extended along disk.
- Excludes lamppost corona models - narrow column along the jet axis or two compact regions above/below BH.
- For more, see Juri Poutanen on March 26 and Henric Krawczynski on May 7





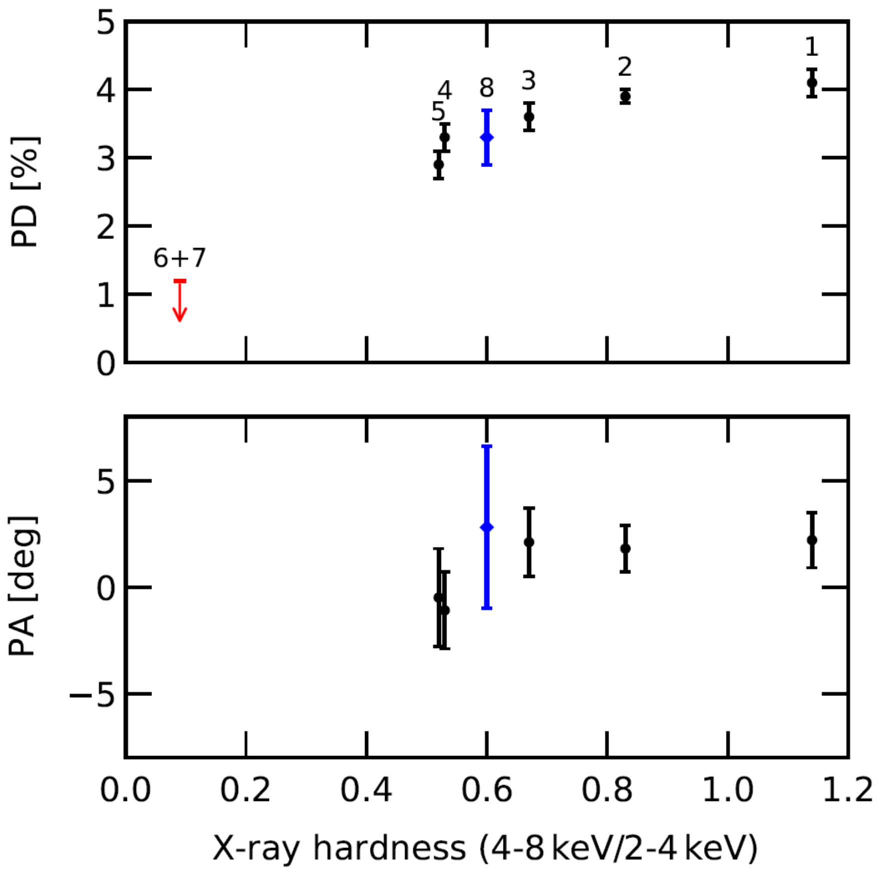


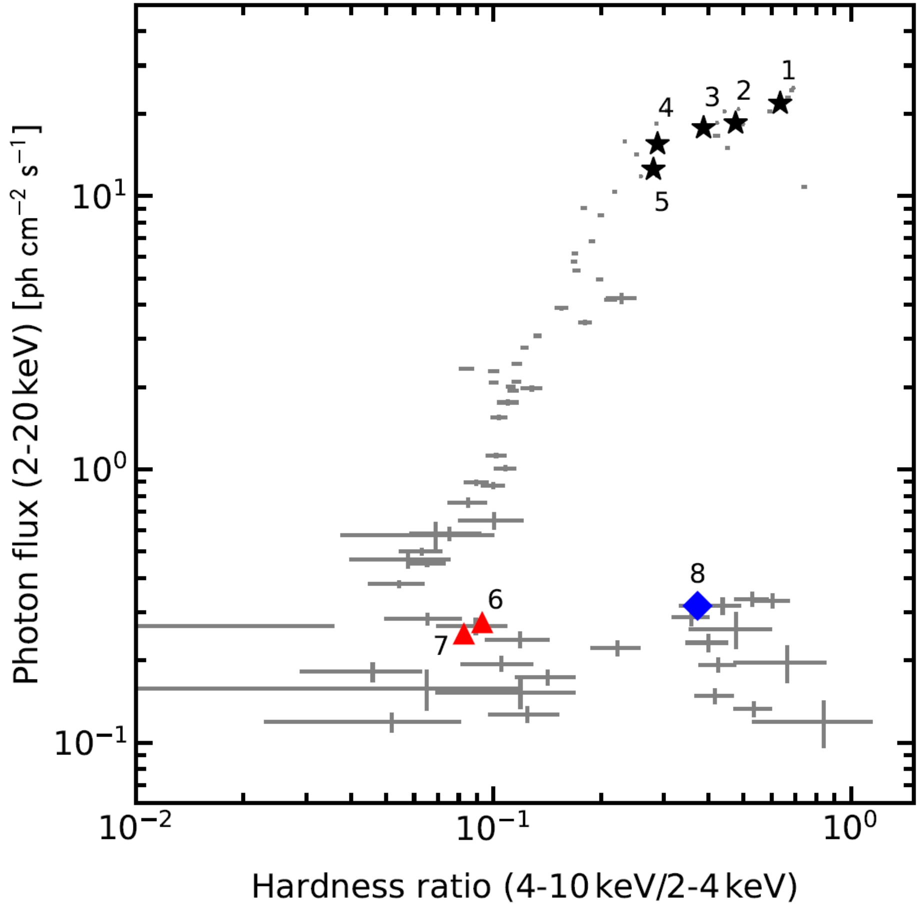


Black hole transient Swift J1727

IXPE observed Swift J1727.8-1613 eight times. Provided a comprehensive view of the transient outburst.

- Polarization unchanged between bright and low hard states, even with 100× change in flux.
- Can reproduce with existing models but requires fine tuning.
- Does this point to something fundamental?





Svoboda et al. 2024, Podgorný et al. 2024

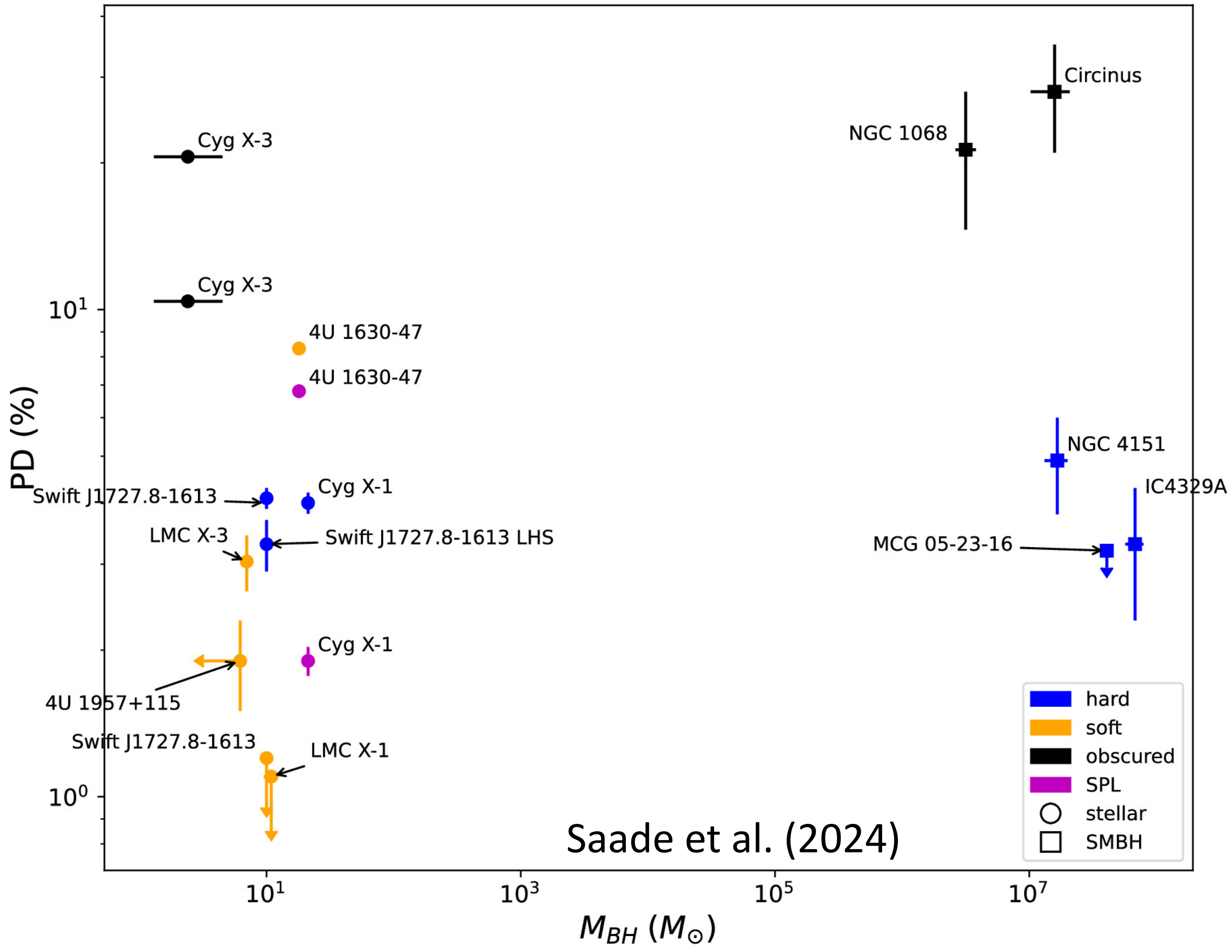
X-ray polarization of accreting black holes

- Saade et al. (2024) examined all IXPE measurements of accreting BH to date.

Includes systems:

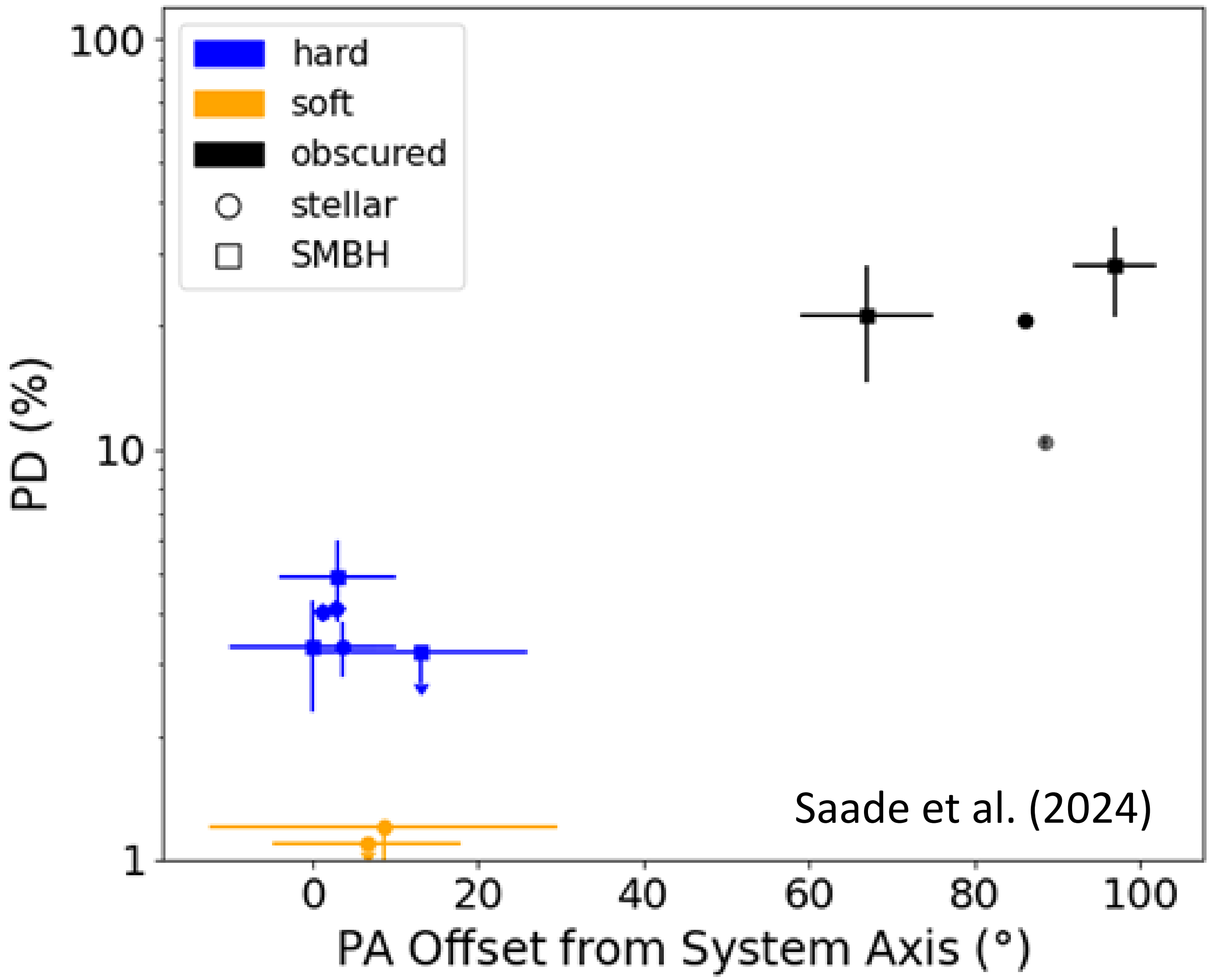
- View of inner disk blocked (obscured)
- X-rays dominated by corona (hard state)
- X-rays dominated by disk (soft state)

➢ No strong dependence on BH mass.



X-ray polarization of accreting black holes

- Measured offset of polarization angle (PA) from symmetry axis.
- Polarization degree (PD) is large (10s of %) when offset is near 90°.
- PD is moderate (few %) for hard state systems and offset ≈ 0° implies corona is extended along disk.
- Results support the idea that stellar and supermassive black holes share a common coronal geometry.
- Alignment of polarization angle with symmetry axis in hard state systems implies corona is extended along disk.
- Large polarizations for obscured systems support the AGN unification hypothesis.



Magnetic field in X-ray pulsars

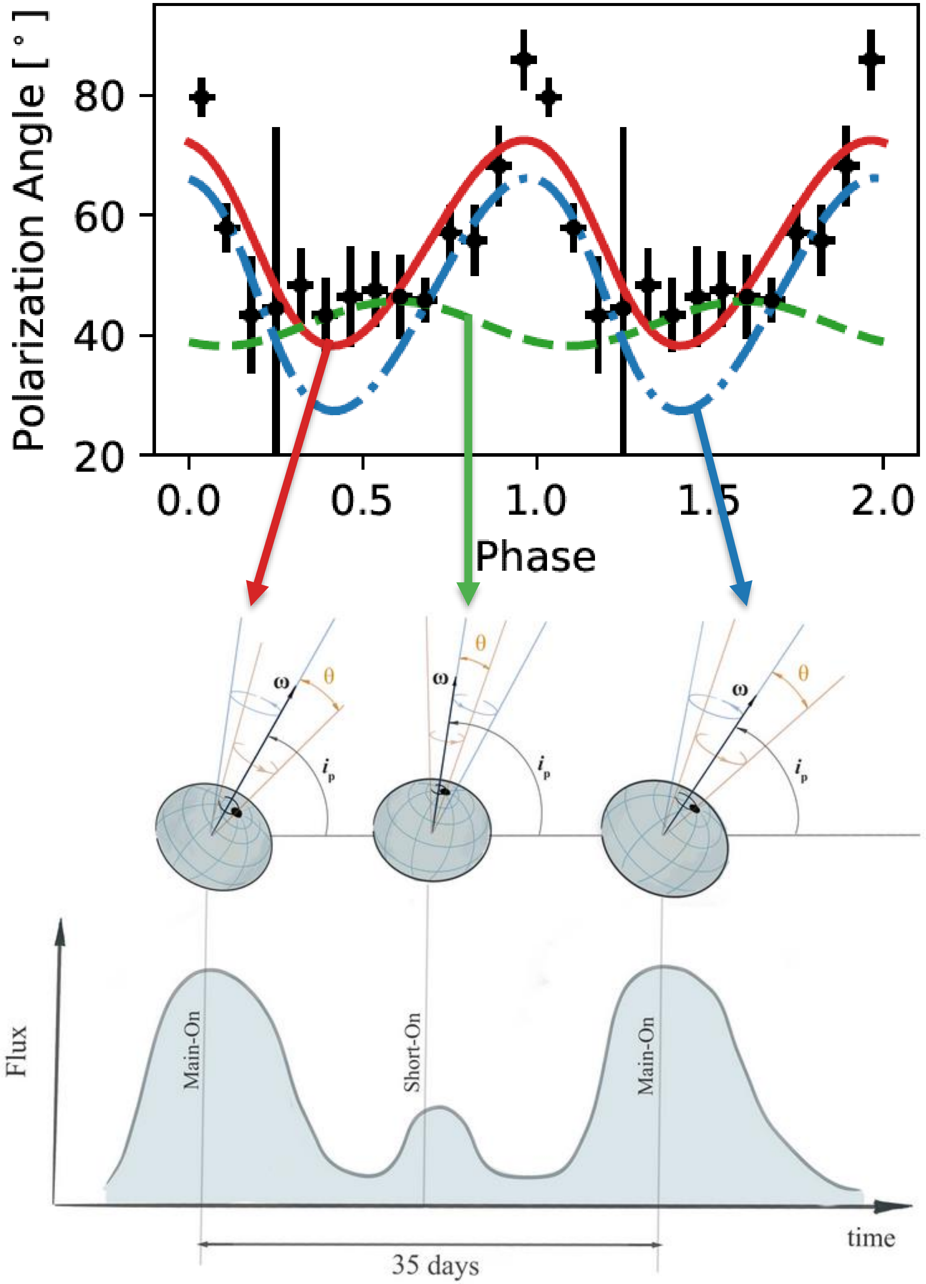
Her X-1 is an X-ray pulsar.

- Spin period 1.2 seconds
- Orbital period 1.7 days
- **Stable, superorbital period of 35 days.**

Superorbital period is likely precession.
Question: precession of disk or neutron star?

- Use Rotating Vector Model to measure geometry of magnetic field/NS rotation axis.
- **Find free precession of the neutron star crust sets the 35-day-period.**
- Further observations will probe the interior of the neutron star and the coupling between the crust and the superfluid.

Heyl et al. (2024) Nature Astronomy



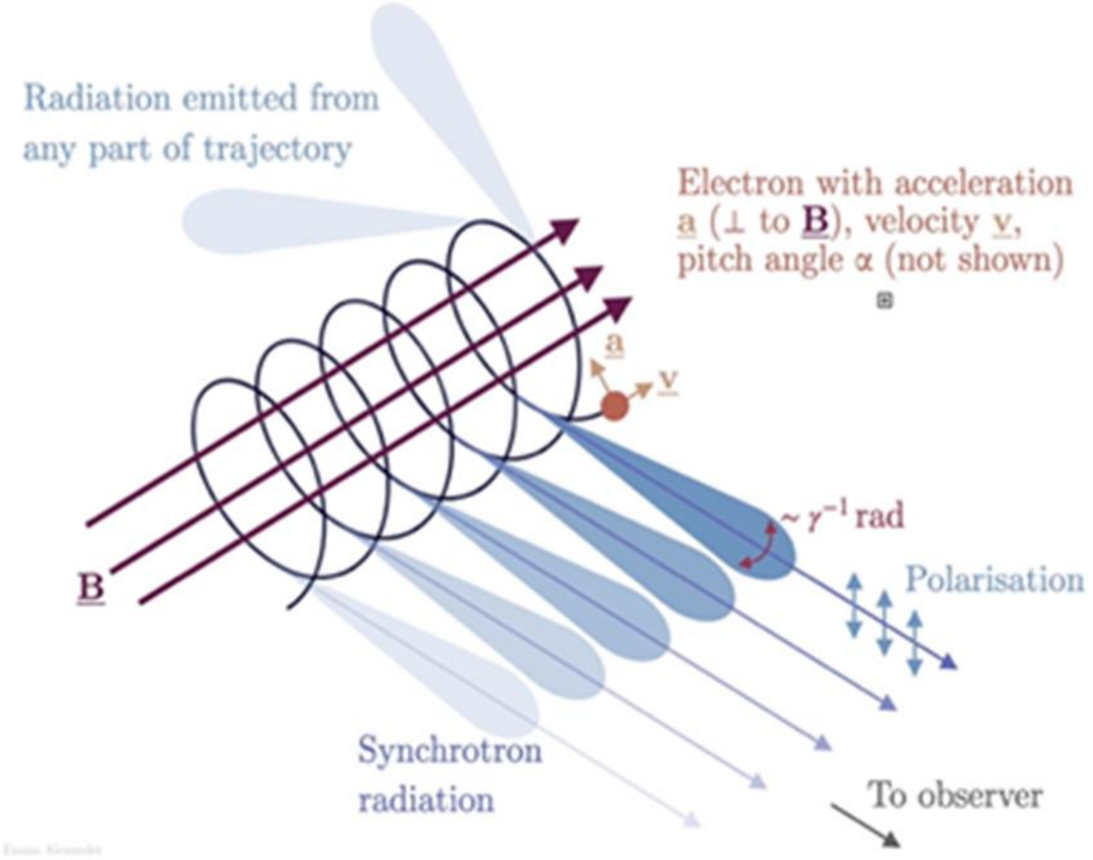
(Credit: Alexander Mushtukov)

Non-thermal particle acceleration

X-rays via synchrotron radiation of energetic particles

Polarization indicates direction and level of order of magnetic field

- Supernova remnants – see Jacco Vink on March 12
- Blazar jets – see Alan Marscher on June 18
- Pulsar wind nebulae
- TeV binaries



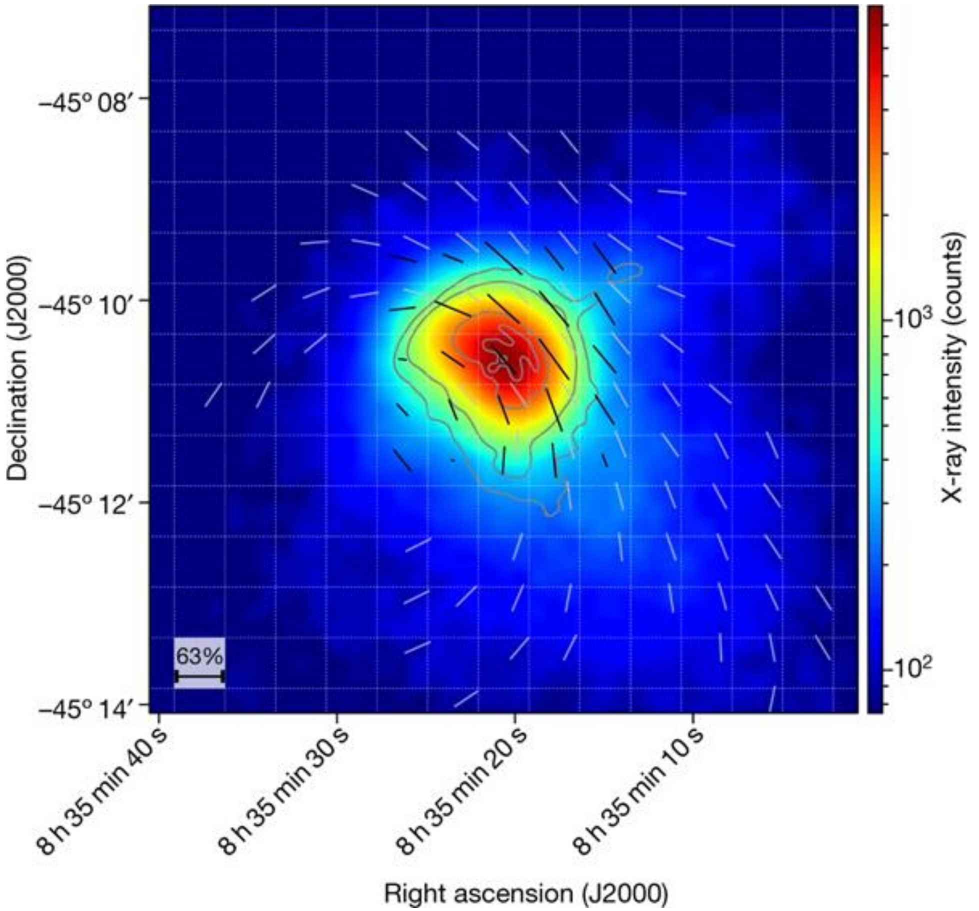
X-ray polarization in pulsar wind nebulae

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).

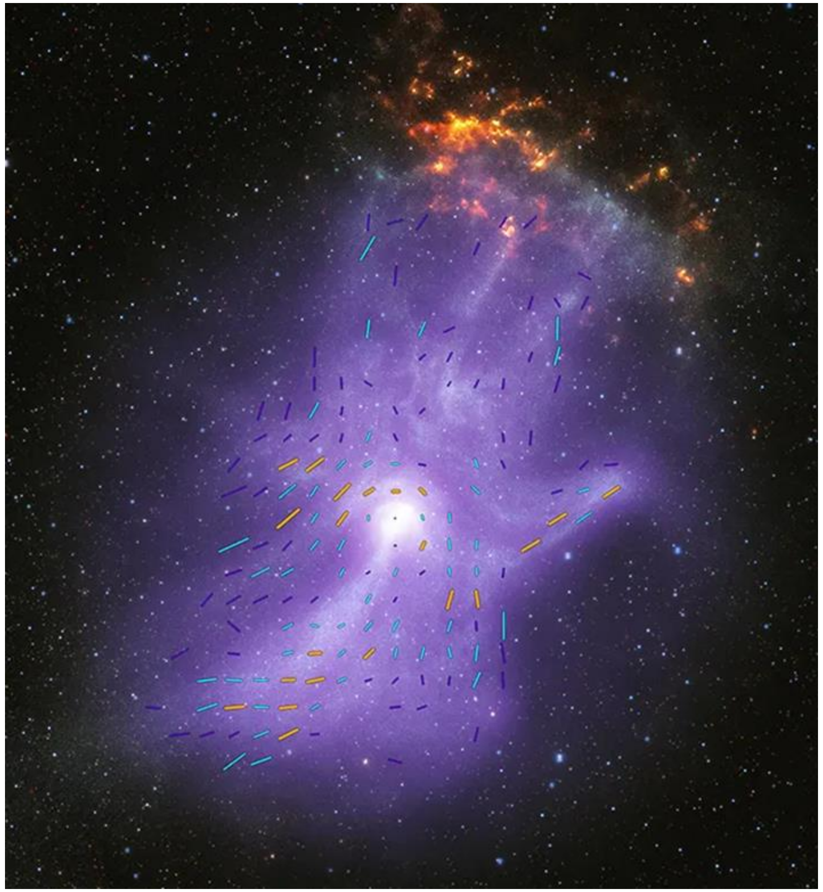
➢ Highly uniform magnetic field and acceleration with little or no turbulence.
➢ Evidence against turbulence-driven diffusive shock acceleration.
➢ Other processes, such as magnetic reconnection, may power this PWN.

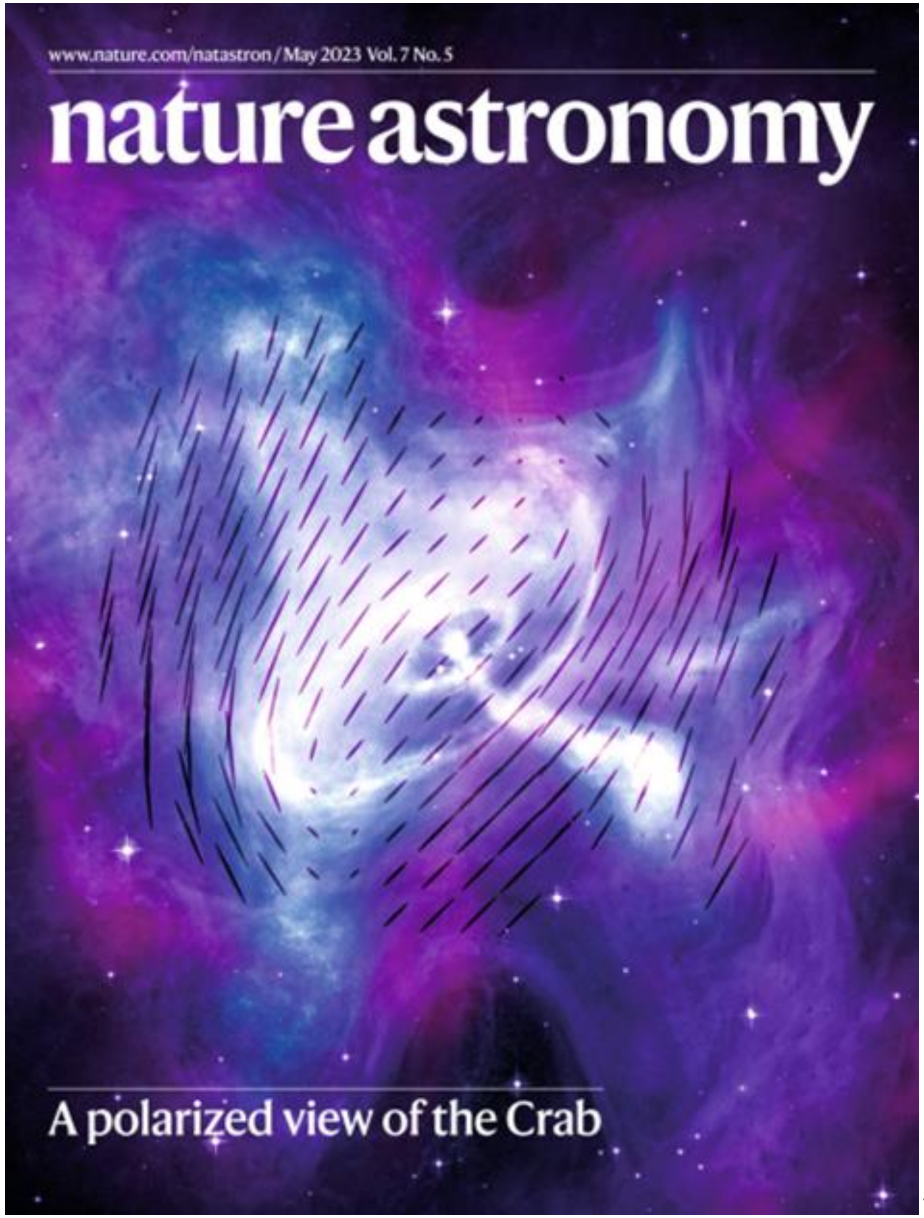


Colors are 2–8 keV intensity. Bars show magnetic field direction from X-ray (black) or radio (silver) with length proportional to PD. Xie et al. (2022), Nature

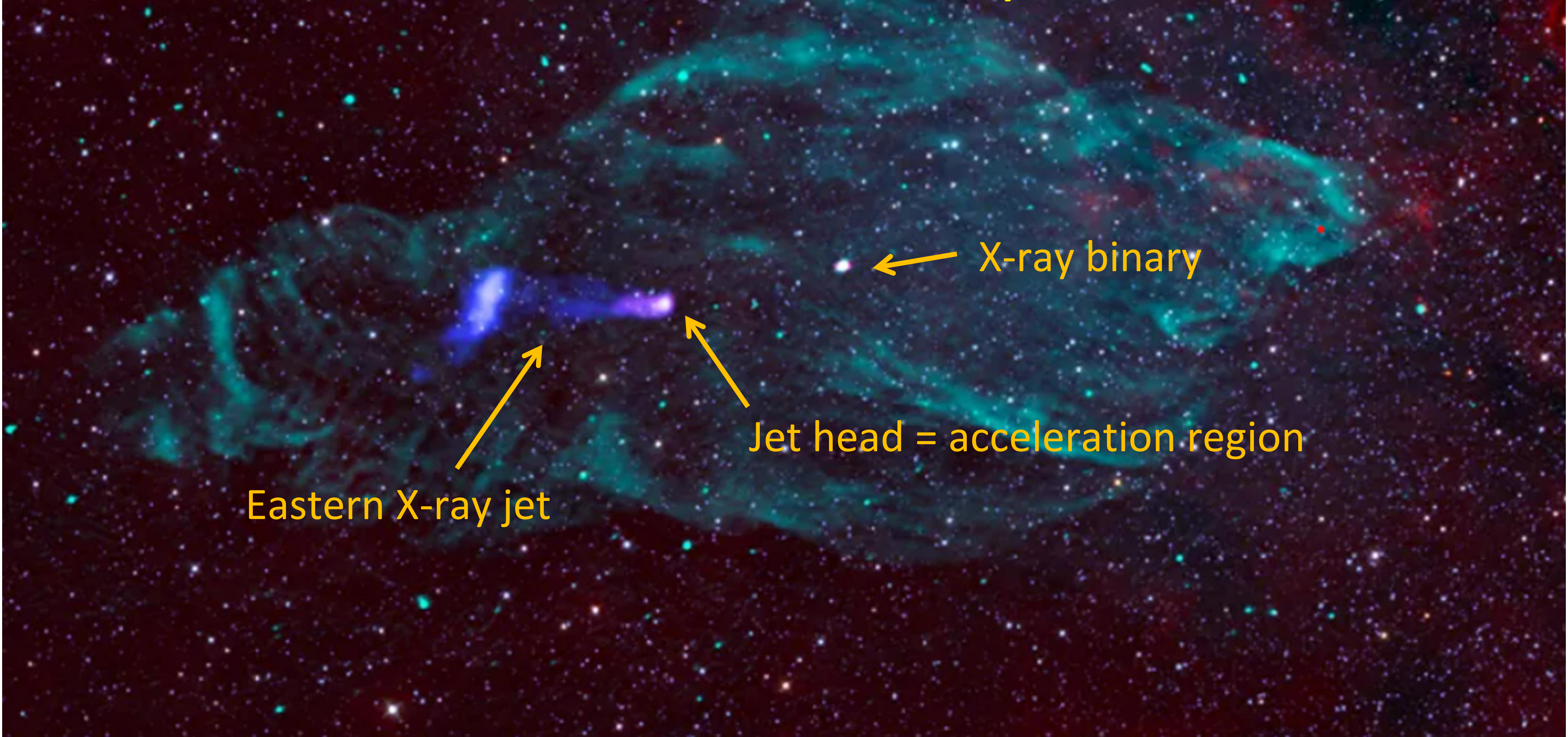
X-ray polarization in pulsar wind nebulae

- Crab nebula shows lower similar properties, but lower polarization (Bucciantini et al. 2023, Nature Astronomy).
- "Cosmic Hand" or MSH15−5 2 shows polarization ≥ 70% in arcs near pulsar and end of jet (Romani et al. 2023)





The eastern lobe of the microquasar SS 433



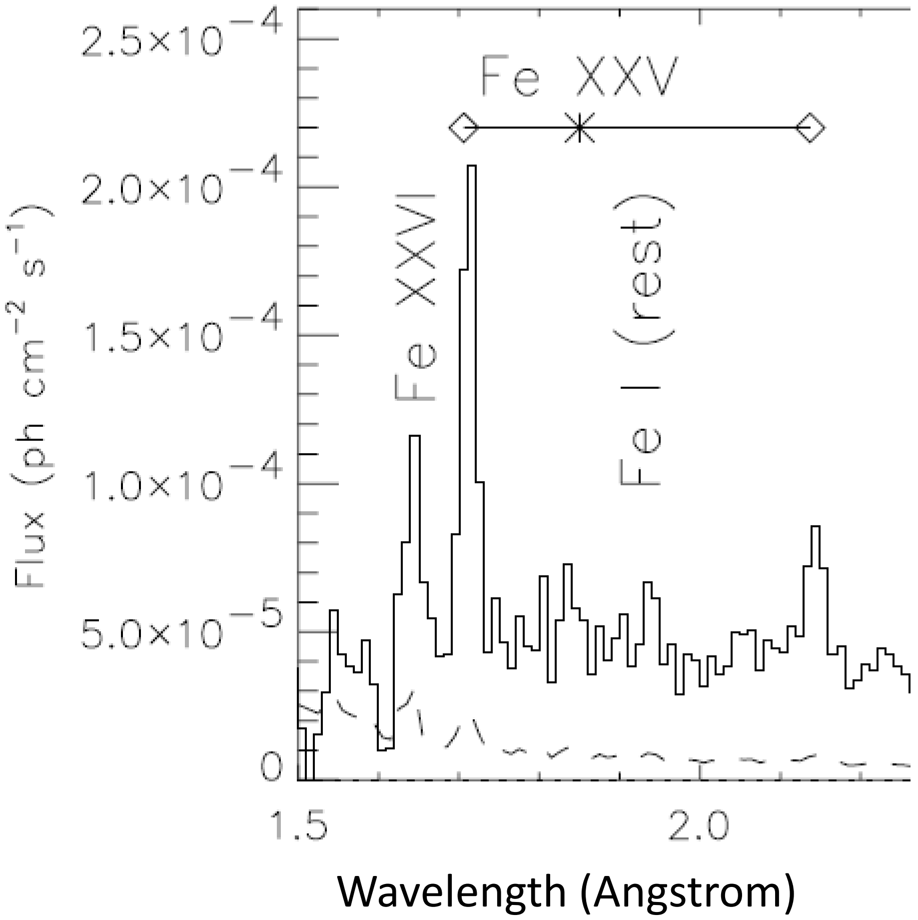
SS 433 in X-rays/UV

- Luminosity ≈ 3×10^{35} erg/s (2-10 keV)

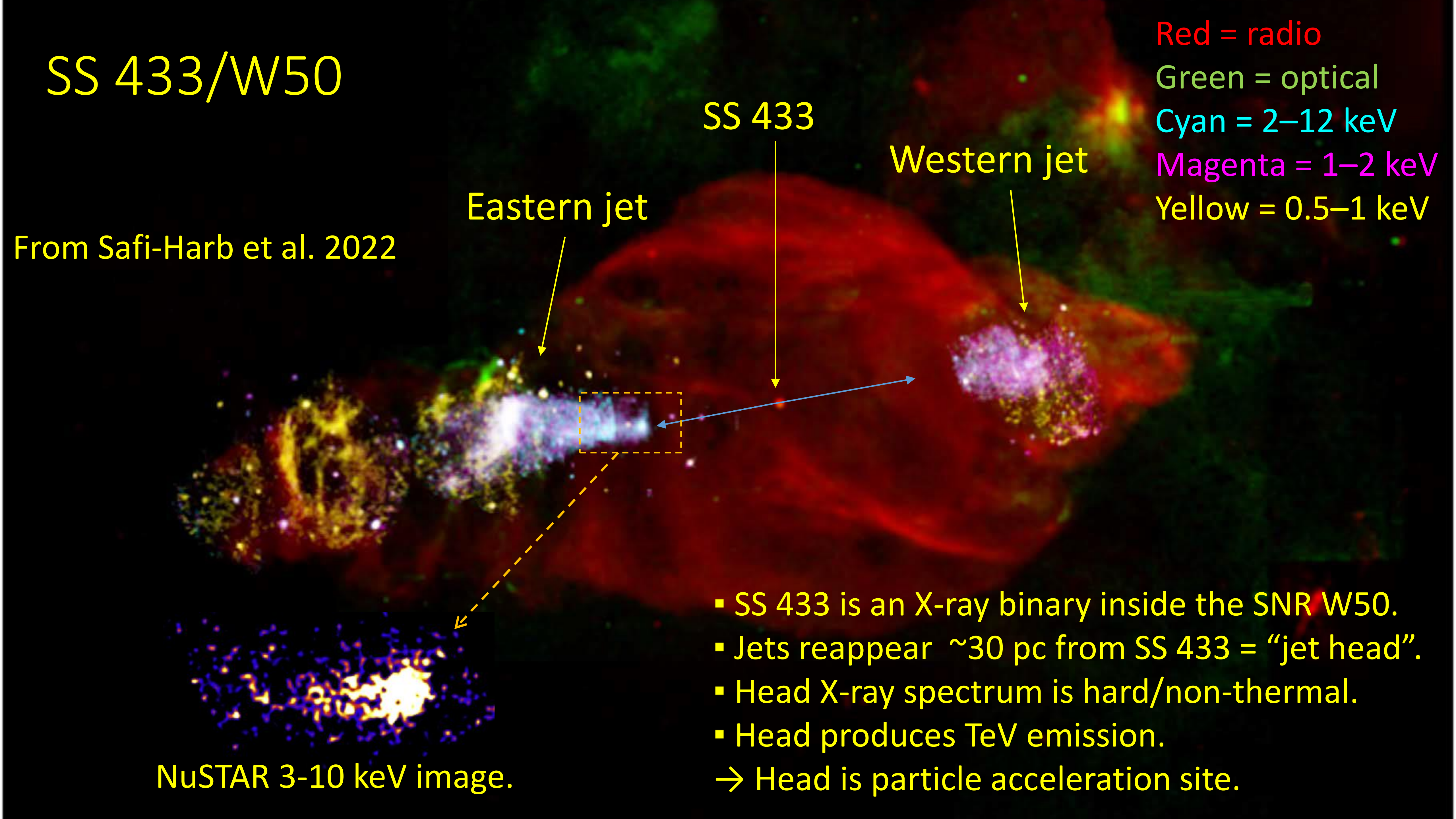
- X-ray spectra show blue- and red-shifted lines
- Speed slightly larger than in optical.
- Temperatures in jet 5×10^{6} K to 10^{8} K.
- Jet kinetic power is large
  ≈ 3×10^{38} erg/s (Marshall et al. 2002)
  ≈ 6×10^{39} erg/s (Fabrika 2004)

- Far-UV luminosity ≈ 10^{40} erg/s from nearby photo-ionized gas (Fabrika & Sholukhova 2008)

- Binary is a likely an ultraluminous X-ray source (ULX) with X-ray beam pointed away from us and accreting at super-Eddington rates.

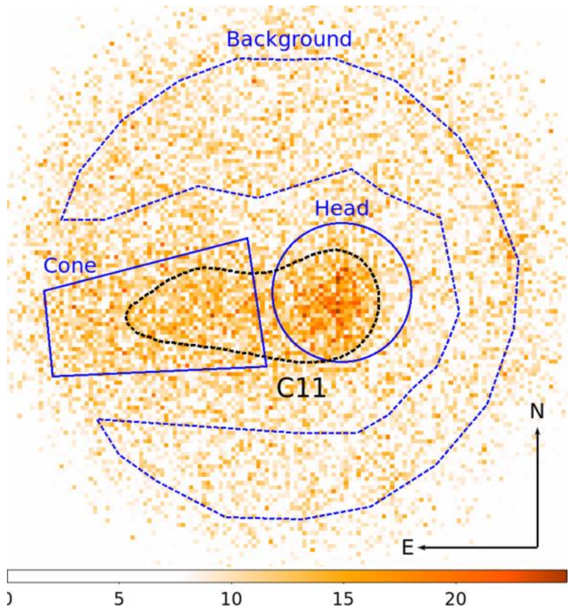


Marshall et al. 2002


SS 433/W50
From Safi-Harb et al. 2022
Red = radio
Green = optical
Cyan = 2–12 keV
Magenta = 1–2 keV
Yellow = 0.5–1 keV
SS 433
Eastern jet
Western jet
NuSTAR 3-10 keV image.
▪ SS 433 is an X-ray binary inside the SNR W50.
▪ Jets reappear ~30 pc from SS 433 = “jet head”.
▪ Head X-ray spectrum is hard/non-thermal.
▪ Head produces TeV emission.
→ Head is particle acceleration site.

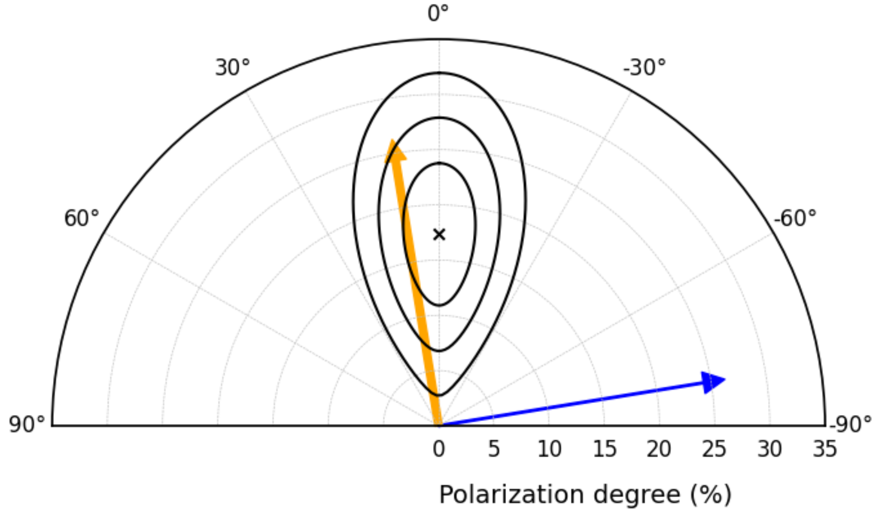
X-ray polarization of the Head

- Imaging X-ray Polarimetry Explorer (IXPE) observed head of eastern jet
- 99.9756% confidence detection
- Polarization degree (PD) = 17.3% ± 4.3%
- Polarization angle (PA) = -0.2° ± 7.0°
- After correction for background
  PD = 52% ± 14%, PA = -3.7° ± 7.8°



- For synchrotron, B field is perpendicular to PA
- ➢ **Magnetic field is parallel to flow**

- Maximum PD = 70% for synchrotron with Γ = 1.57
- ➢ **Magnetic field is well ordered**



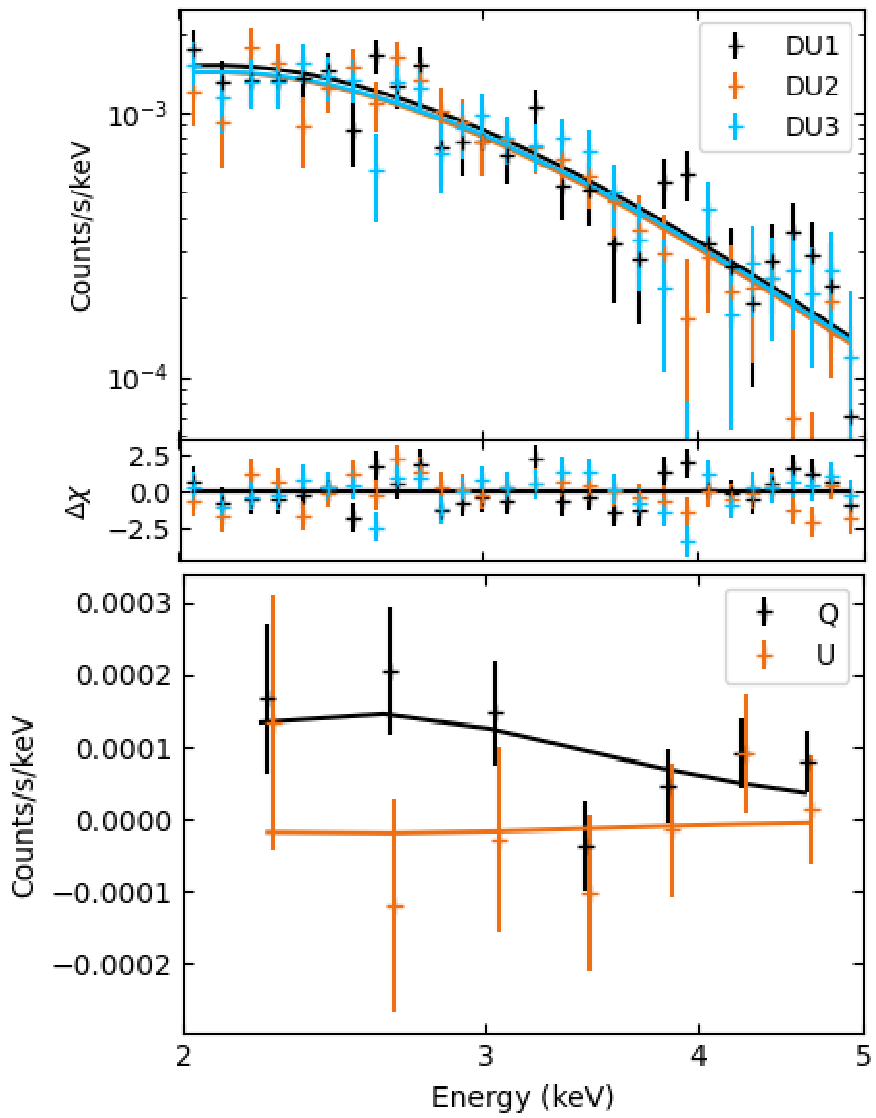
Blue arrow = direction to SS 433.
Orange arrow is perpendicular.

IXPE results

- Perform Xspec analysis.
- Model = cons*tbabs*polconst*powerlaw

- Fixed $N_H = 1.18\times10^{22}$ cm^{-2} from ‘Cone’ region
- χ^2/dof = 137.0/123
- Photon index Γ = 1.57 ± 0.14, consistent with Safi-Harb
- Flux = 5.8×10^{-13} erg cm^{-2} s^{-1} in 2–5 keV band.
- Luminosity = 1.3×10^{34} erg s^{-1} in 0.3–30 keV band.

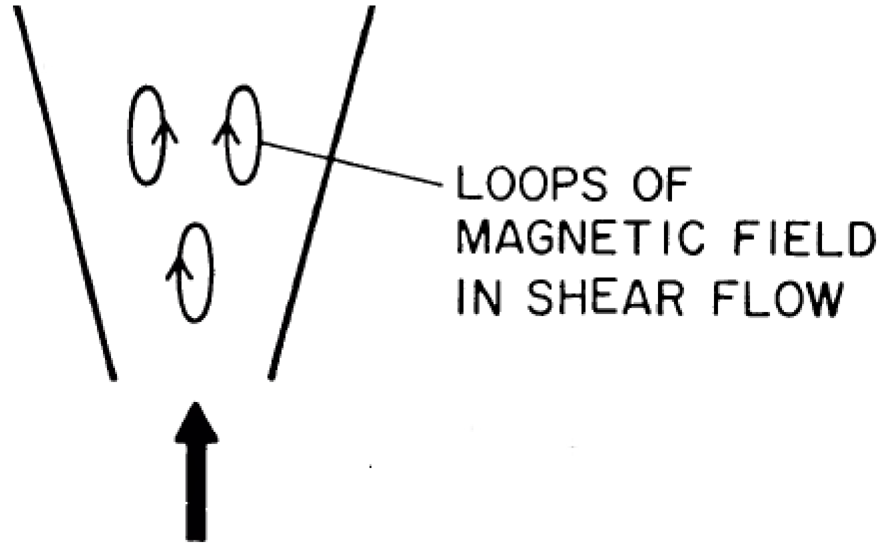
	PD	PA
Xspec	52% ± 14%	-3.7° ± 7.8°
Pcube	62% ± 15%	2.8° ± 7.0°
Joint	38% to 77%	-12° to +10°



Top: Intensity spectra.
Bottom: Stokes Q and U. Points shifted by ±20 eV.
Color of model matched data.

How to make B parallel to flow?

- **Alignment due to velocity shear.**
- At sub-parsec scales, SS 433 radio polarization indicates B-field parallel to motion of individual knots (Miller-Jones et al. 2008; Blundell et al. 2018).
- Magnetic field parallel to flow seen in FR II radio galaxies (Bridle+ 1984; Potash+ 1980) and young, shell-type SNR (Vink 2022).



From Blandford 1983

➢ Particle acceleration likely due to reconnection.

➢ Shock acceleration at shear interfaces or at leading edge of head also suggested.

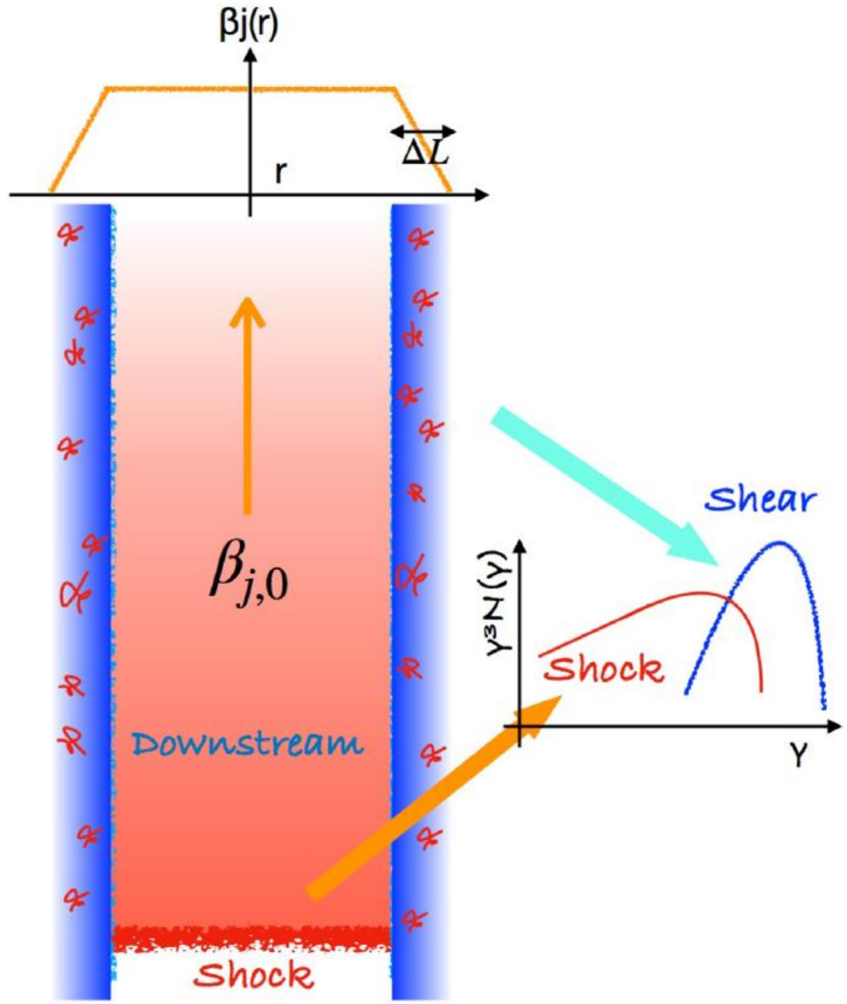
How to accelerate particles?

- Equipartition magnetic field ≈ 10 μG.
- Gyroradius << transverse diameter of C11 is 3 pc.
- Bulk Lorentz factor = 1.036 for v = 0.26 *c*
- For jet density of 0.05 cm^{-3} (Panferov 2017), Alfven Mach number ≈ 900, magnetization σ = 2×10^{-4}.

1) Shock at leading edge, synchrotron cooling downstream.
   Bright region in 10-20 keV could be acceleration region.
   Magnetic field aligned downstream of acceleration.

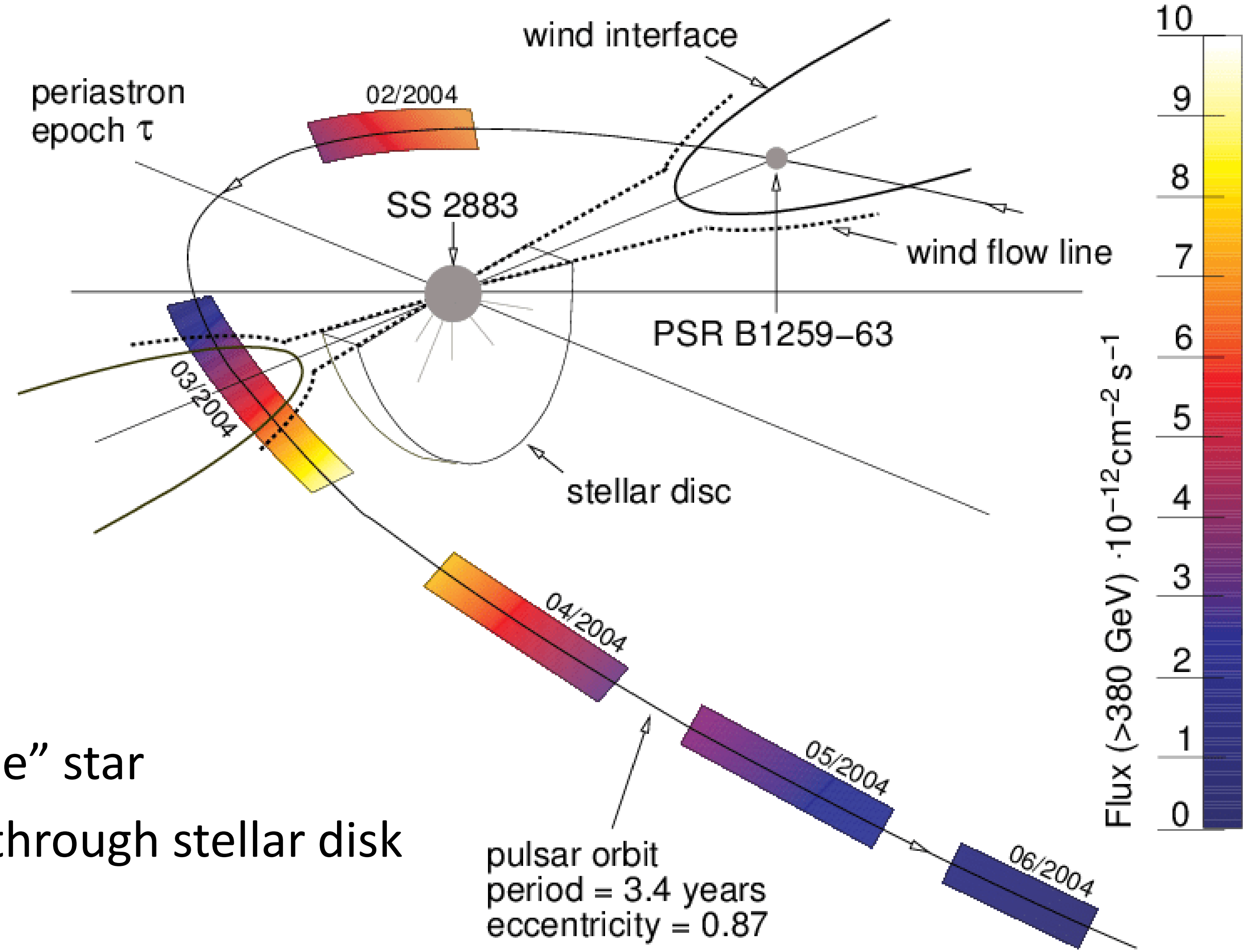
2) Acceleration at shear interfaces.
   Proposed for FR II radio galaxies (Stawarz+2002; Rieger+ 2004)
   Could have extended acceleration region.

3) Magnetic field reconnection at loops or more complex structures (Romanova+1992; Aulanier+ 2006).
   Need continual reconnection events to produce power-law.
   Could have extended acceleration region.



Tavecchio 2021 – Particles are accelerated at shock front (red at bottom), some diffuse into sheared flow (blue) and are accelerated further through turbulence (red squiggles).

PSR B1259-63

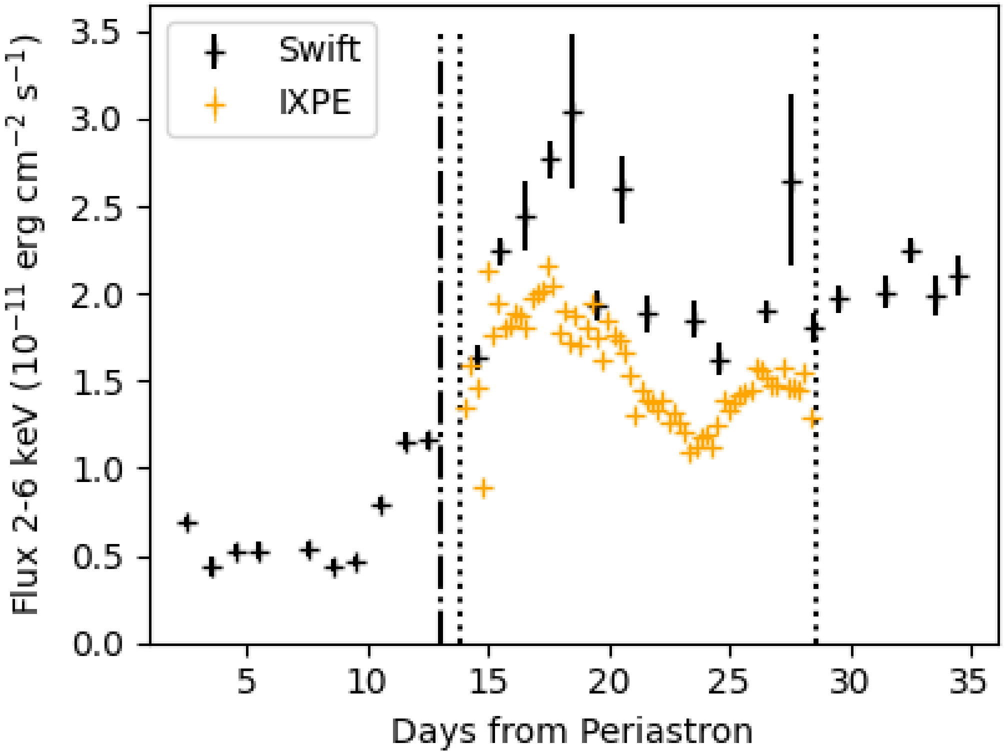


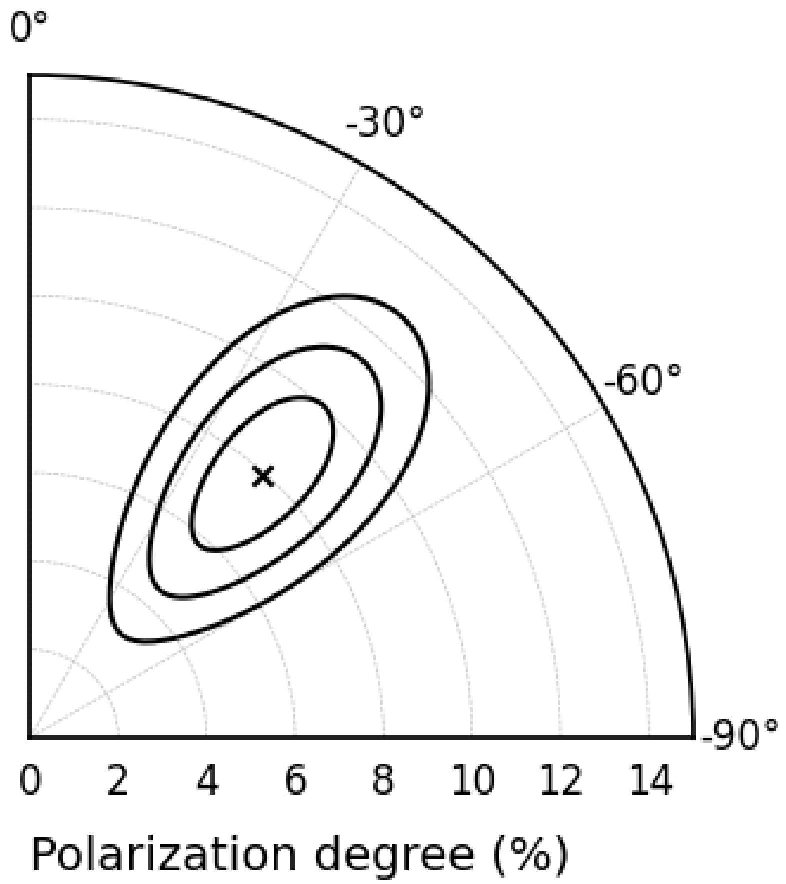
- Young, energetic pulsar orbiting “Be” star
- TeV emission after pulsar plunges through stellar disk
- Synchrotron X-rays up to 200 keV
- Acceleration at pulsar wind termination shock

From Aharonian et al. 2005

X-ray polarization

- IXPE observed after disk crossing
- 5.3σ confidence detection
- Polarization degree (PD) = 8.3% ± 1.5%
- Polarization angle (PA) = -42° ± 5°
- After correction for background

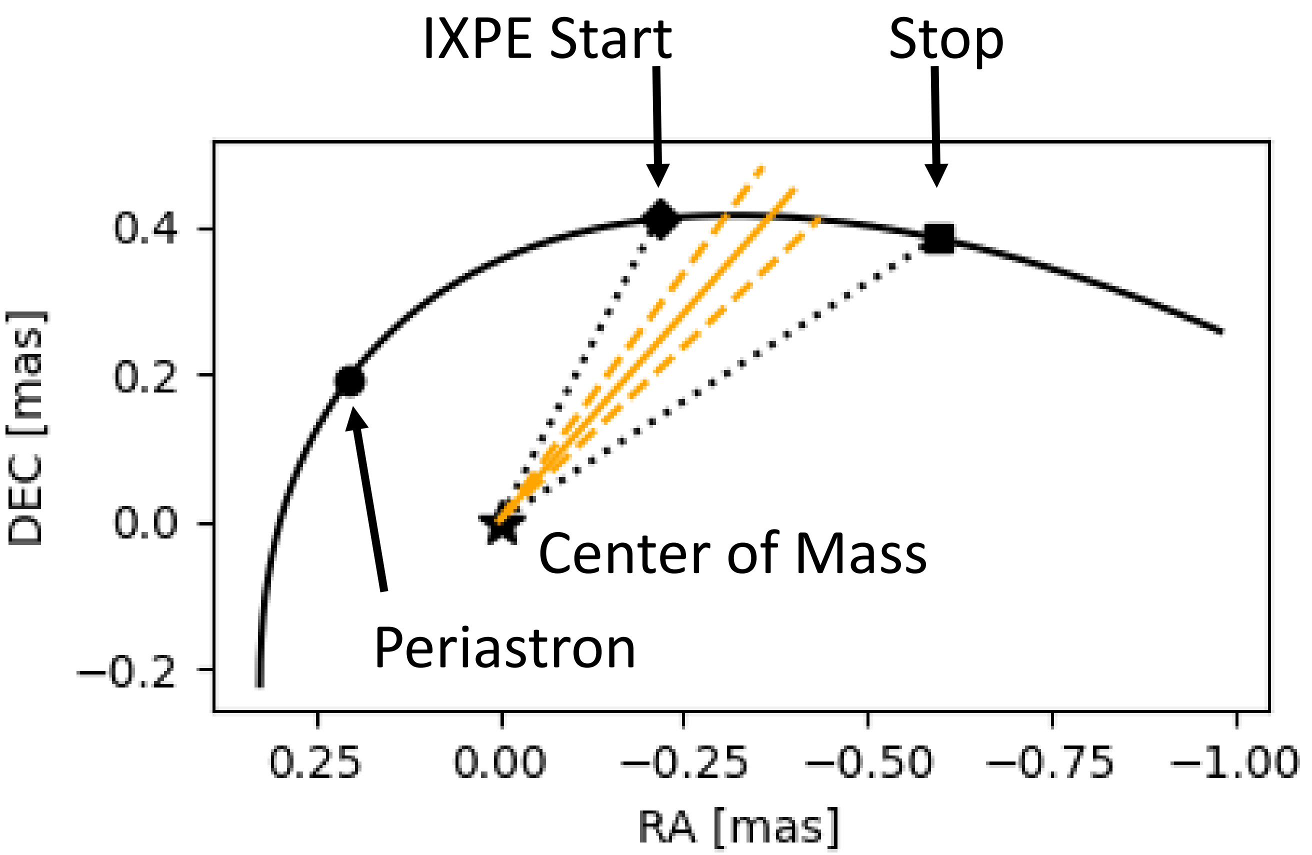


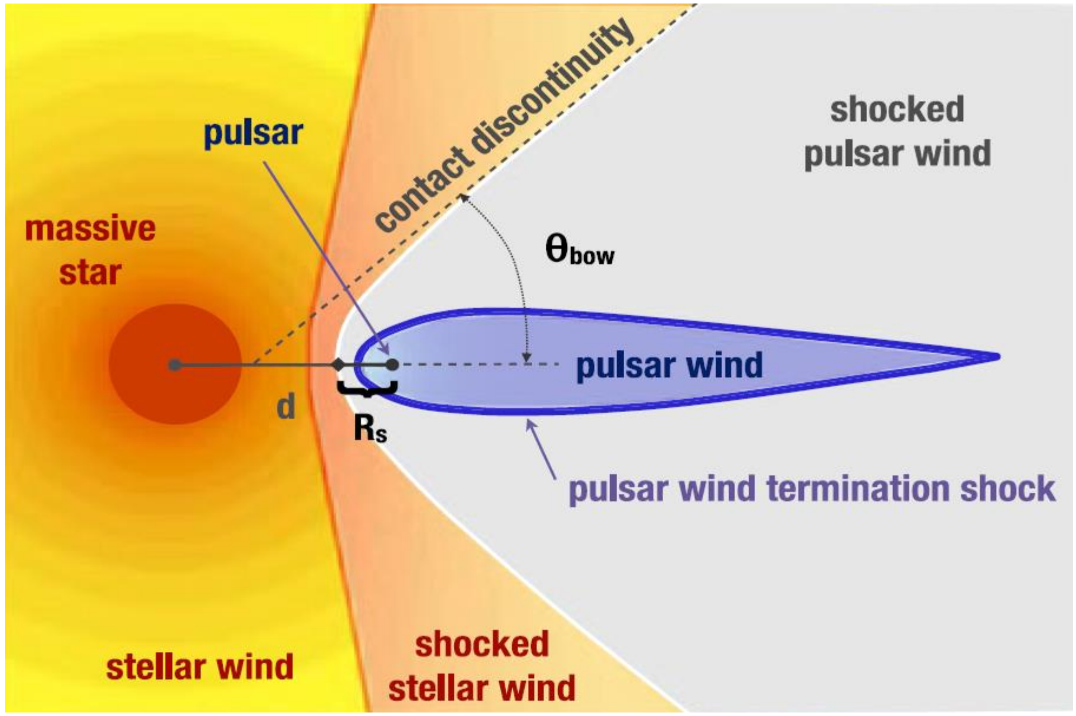


From Kaaret et al. 2024

Polarization versus orbit

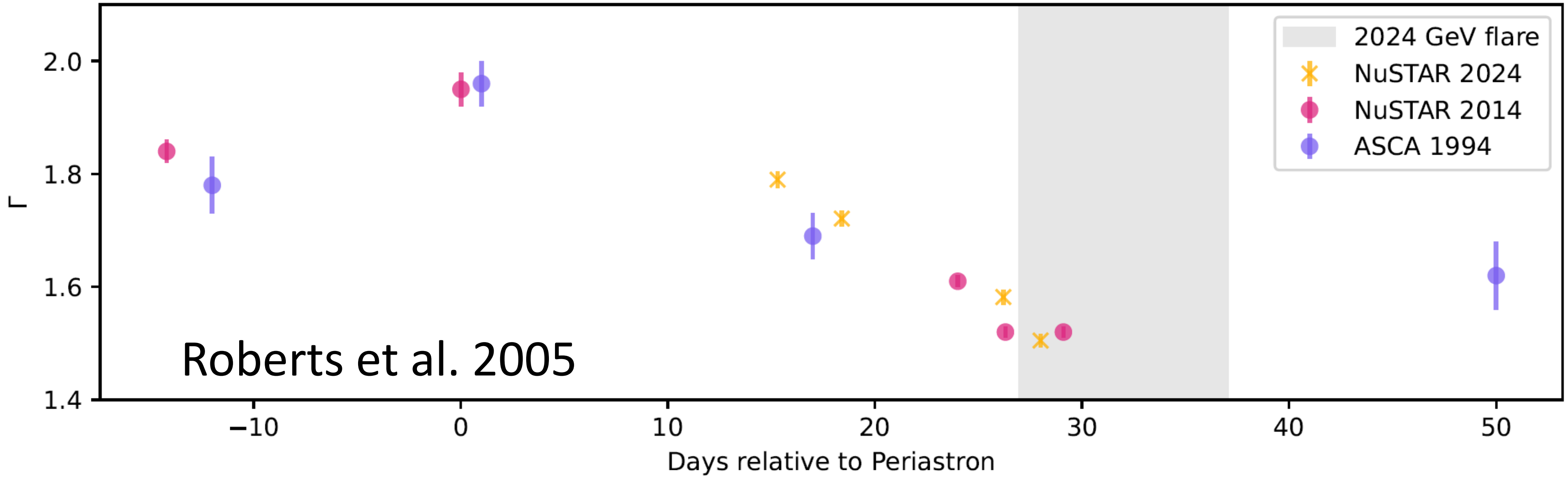
- Black curve is pulsar orbit
- Orange shows polarization
- PA is aligned with pulsar-star axis
- ➢ Magnetic field orthogonal to shock axis
- ➢ Acceleration in perpendicular shock





From Dubus 2013

Evolution of X-ray spectrum



We obtained NuSTAR observations covering the IXPE observation.

- Spectrum is well fitted with a simple powerlaw up 200 keV.
- Photon index evolves with time.
- Electron energy loss time scale shorter at periastron since stellar photon field is stronger.
- Hardest spectrum aligns with start of GeV flare.

- Polarization appears to weaken with time (99% confidence) suggests magnetic field becomes less ordered.

IXPE GO Cycle 3

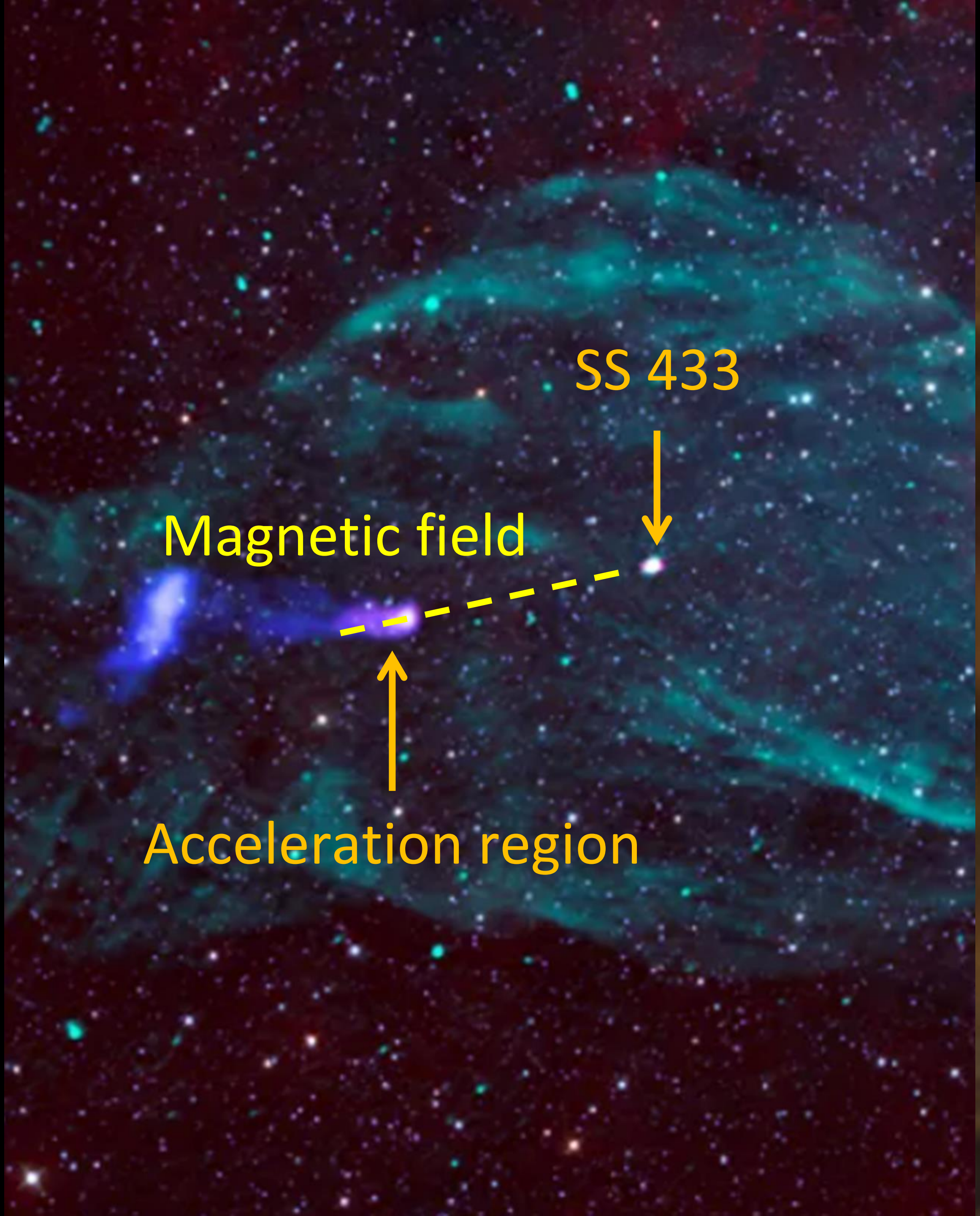
- **Deadline for IXPE GO cycle 3 is September 11, 2025.**

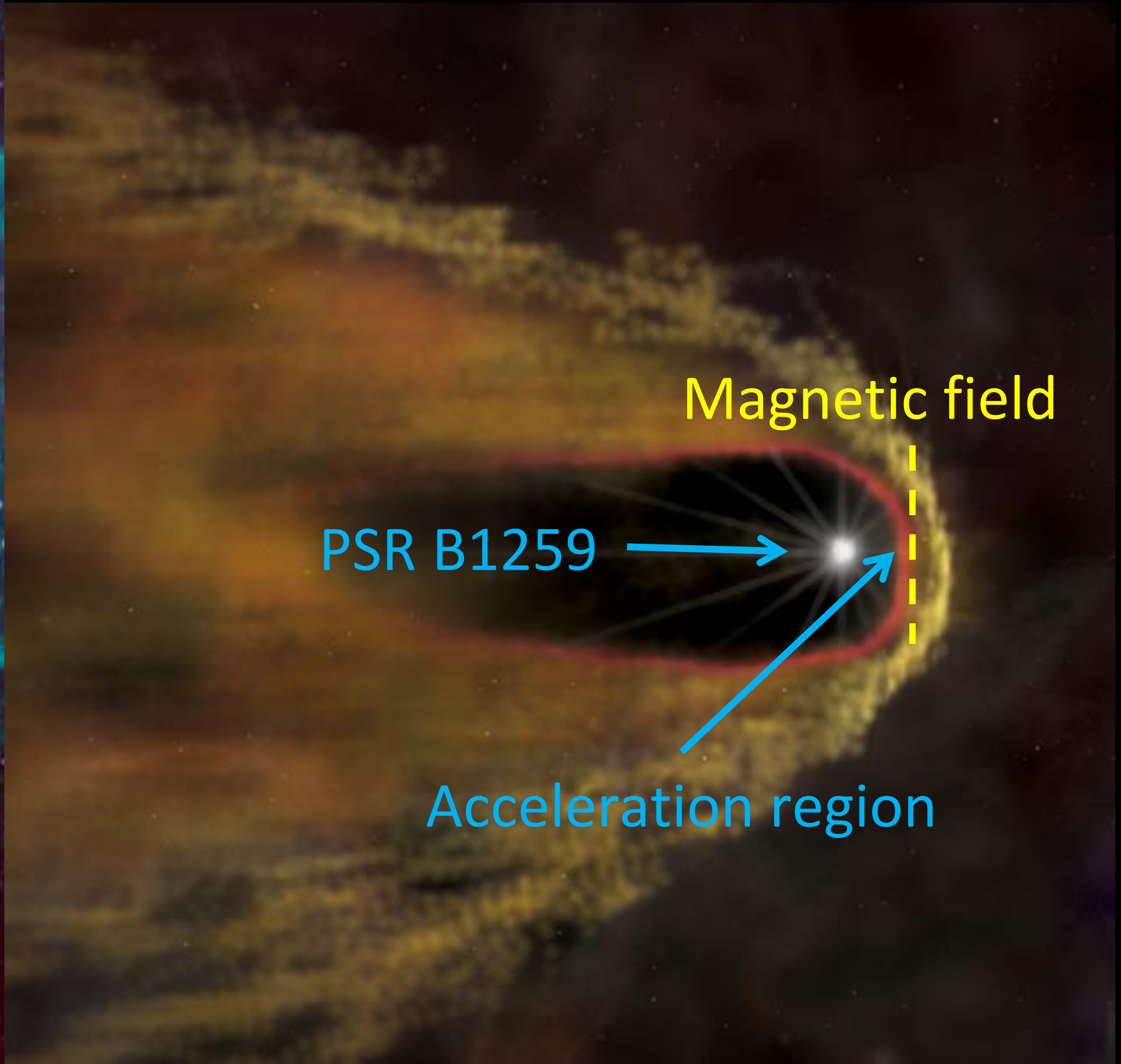
- Continuing joint program with NICER, NuSTAR, and Swift.
- Adding joint programs with XRISM and NRAO.
- **Please propose to the GO program**

- **You can analyze IXPE data**
- All IXPE data from prime mission and most data from the GO program are public.
- Tools for IXPE analysis are publicly available and familiar to those who do X-ray analysis.
- Start with the QuickStart Guide on the HEASARC IXPE pages.

Thank you from the IXPE team!

Conclusions

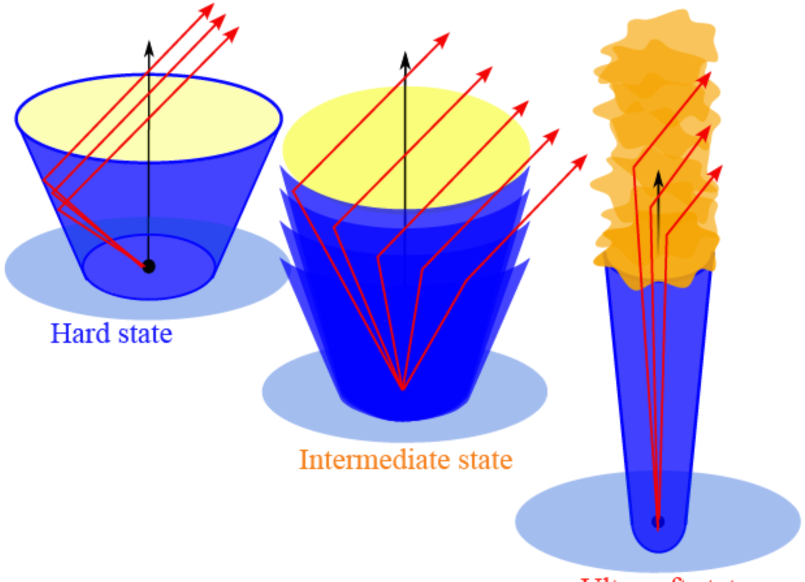




Enigmatic X-ray binary Cyg X-3

IXPE observed Cyg X-3 twice in the prime mission and once in Cycle 1, sampling three different spectral states.

- Polarization is high, suggesting scattered radiation.
- Orbital phase dependence of PD and PA changes with state.
- Interpret as accretion funnel that is filled to varying degrees in different states.
- Implies Cyg X-3 is an ultraluminous X-ray source, apparent luminosity > 5E39 erg/s if viewed down the funnel.



Veledina et al. 2024

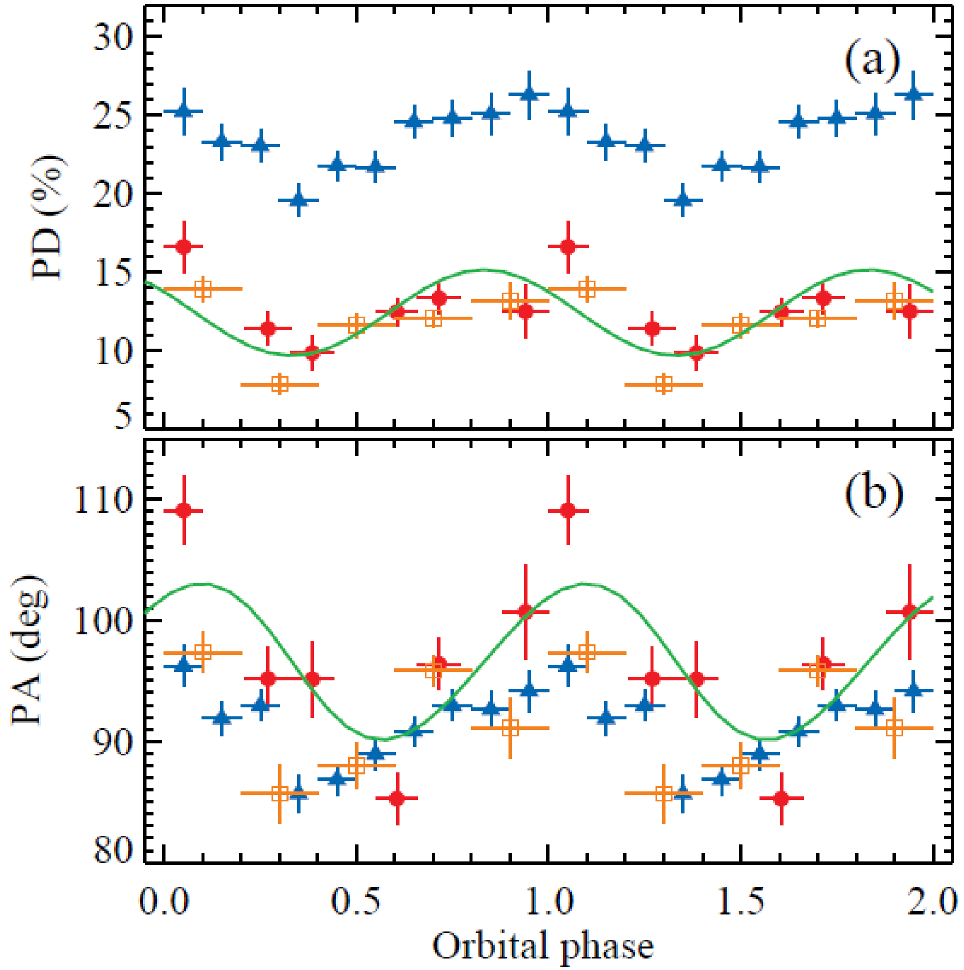
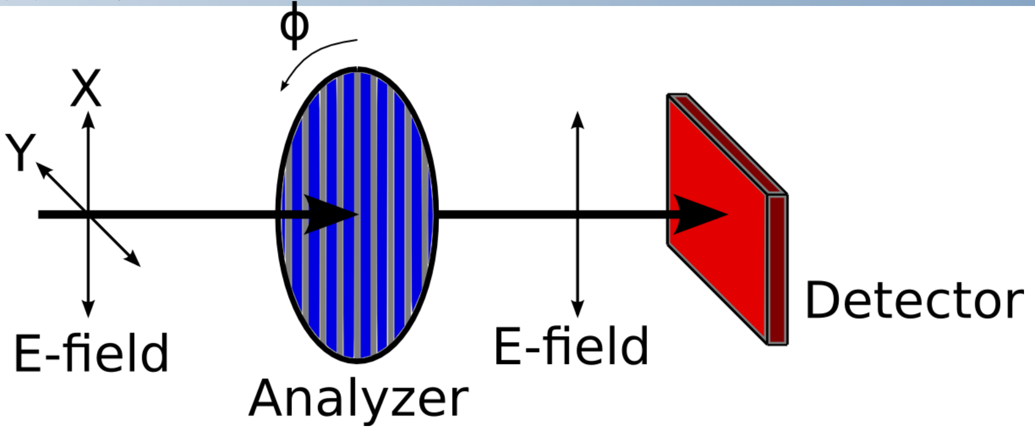
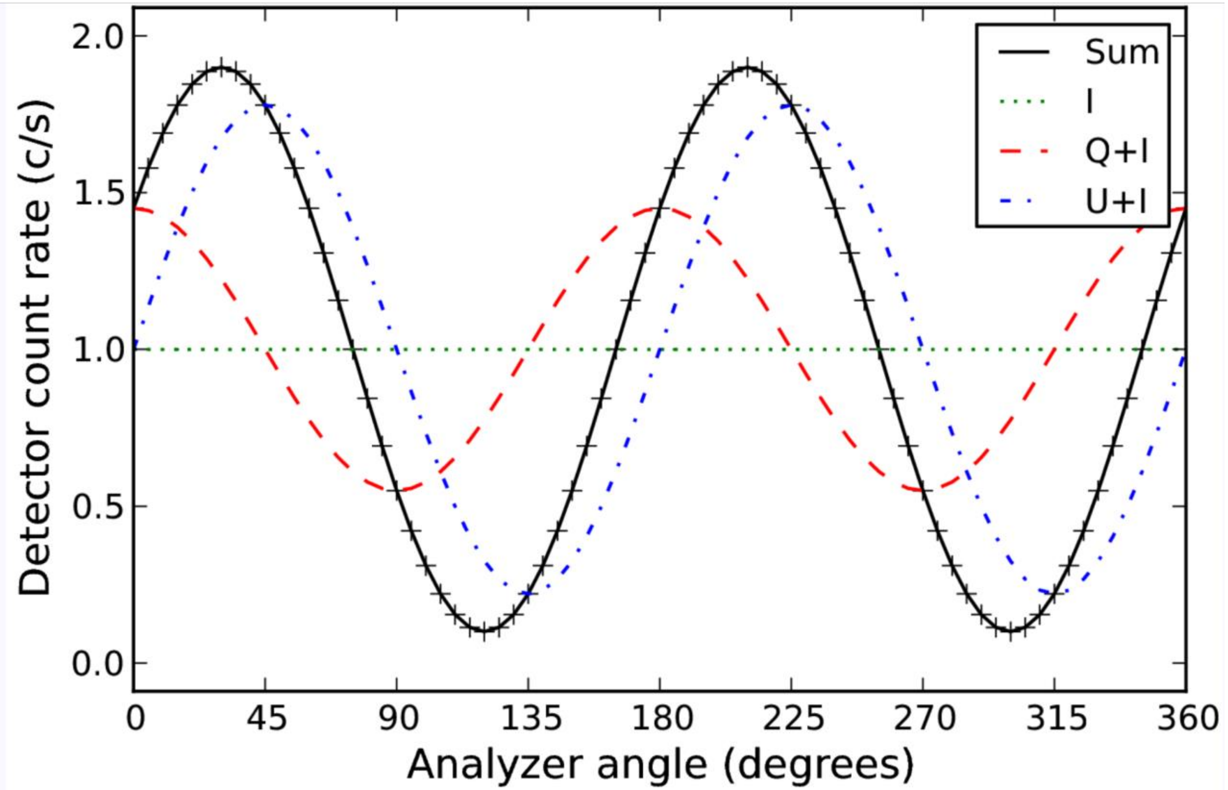


Fig. 4. Orbital phase dependence of the PD and PA from the hard state (blue triangles), the intermediate state (orange open squares), and ultra-soft state (red circles). The green lines show the best-fit rotating vector model (Appendix C) to the ultrasoft-state data.

Measuring polarization using Stokes parameters



- Measure polarization by rotating analyzer and finding rate versus angle.
- Angle of peak rate gives polarization angle.
- Amplitude of modulation gives polarization degree (PD).
- Need to take into account polarization sensitivity.
- Use “modulation factor” = μ = modulation for 100% polarized beam.
- PD = modulation/μ
- **For IXPE, measure ϕ instead of rotating analyzer.**



Direction of photoelectron (φ_i)

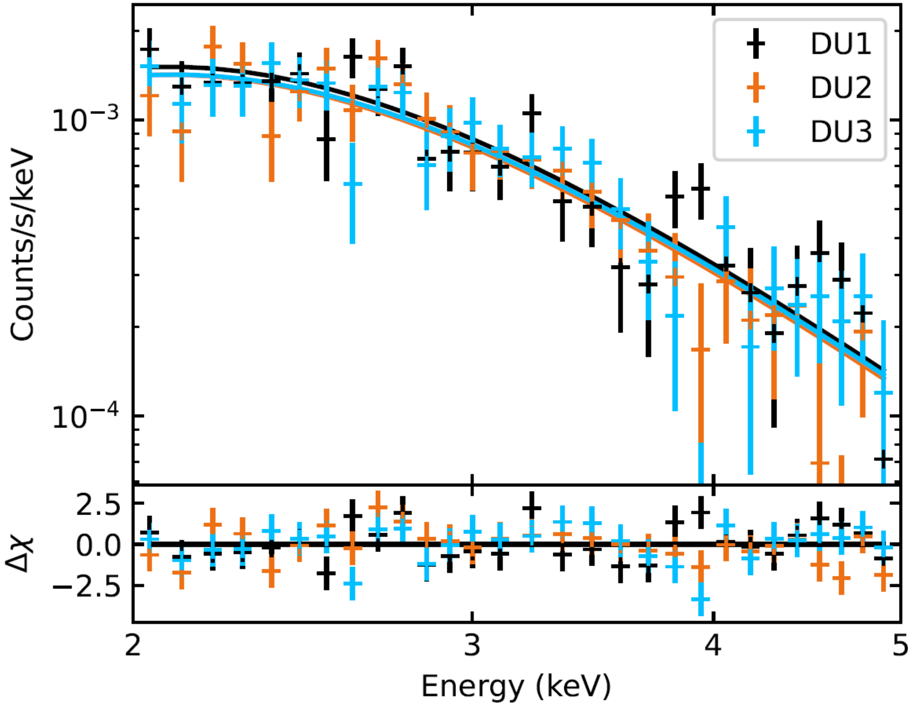
- Stokes parameters are the amplitudes of the constant (I), cosine (Q), and sine (U) components.

IXPE analysis can be done in Xspec

Spectrum = counts in energy bins.

For each X-ray find: 1

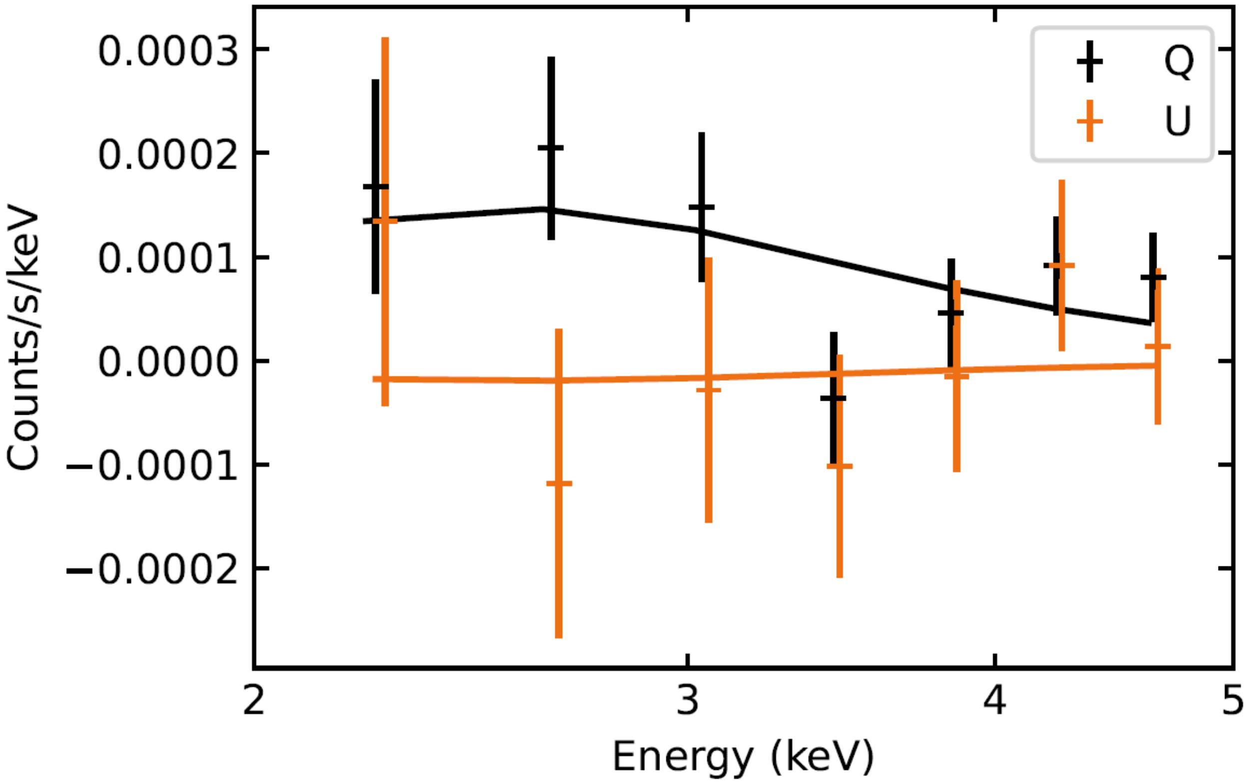
Make sums in energy bins:



Spectropolarimetry uses sums of q_i, u_i in energy bins.

For each X-ray find: $q_i = 2\cos(2\varphi_i)$ and $u_i = 2\sin(2\varphi_i)$

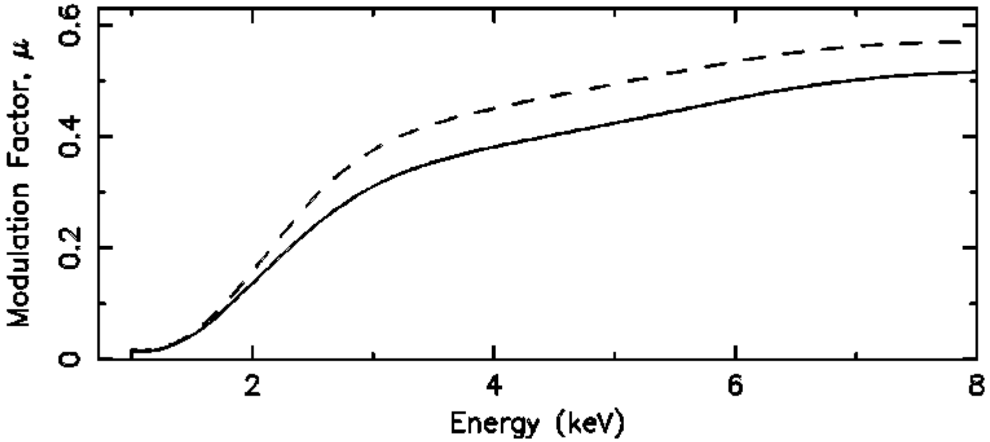
Make sums in energy bins:

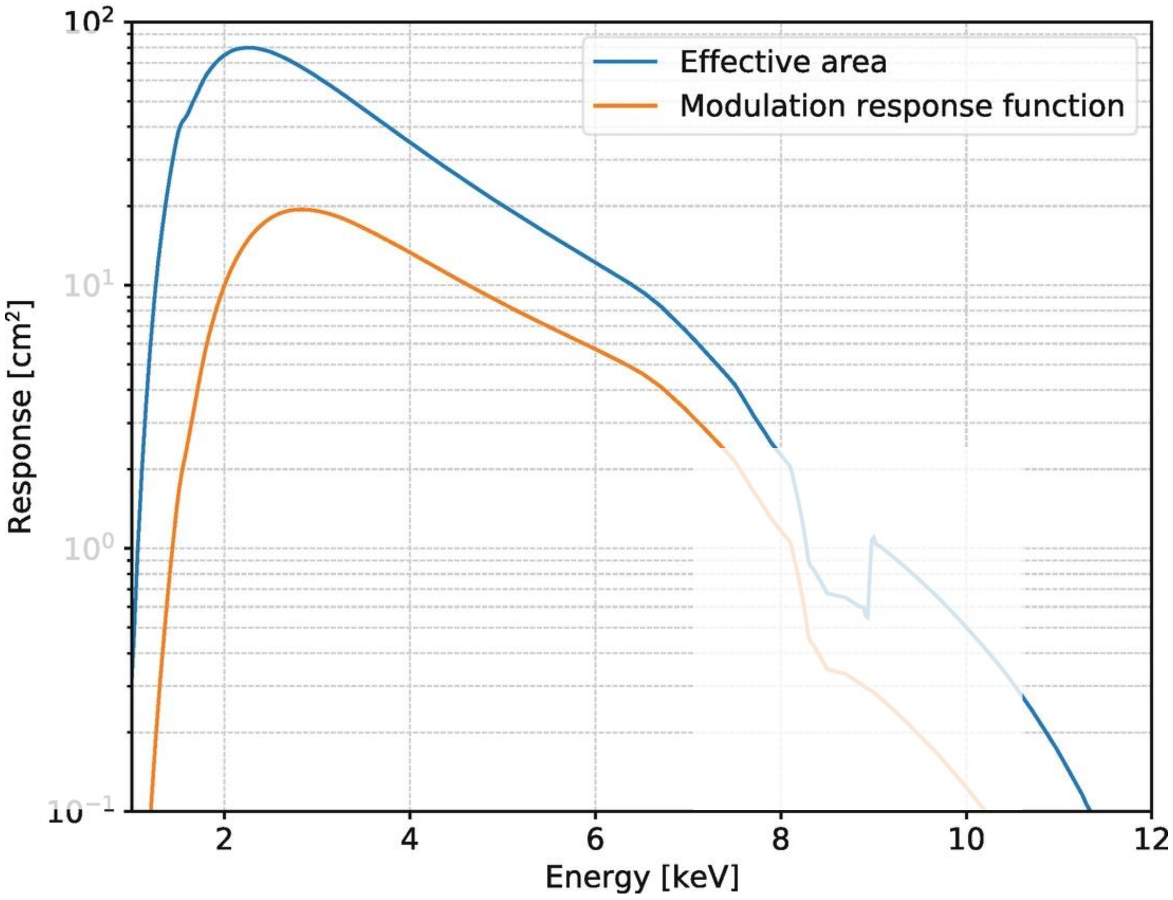


Have three spectra: Stokes I, Stokes Q, Stokes U.

Measuring polarization using Stokes parameters

- To do spectral fitting, one uses the response matrix and auxiliary response file, which is the effective area versus energy.
- Need to take into account the polarization response (μ).
- Use the ‘modulation response’.





- Steven Ehlert will talk more on Stokes parameters and the statistics of polarimetry.
- Doug Swartz will talk more on IXPE analysis using HEASoft and calibration updates.