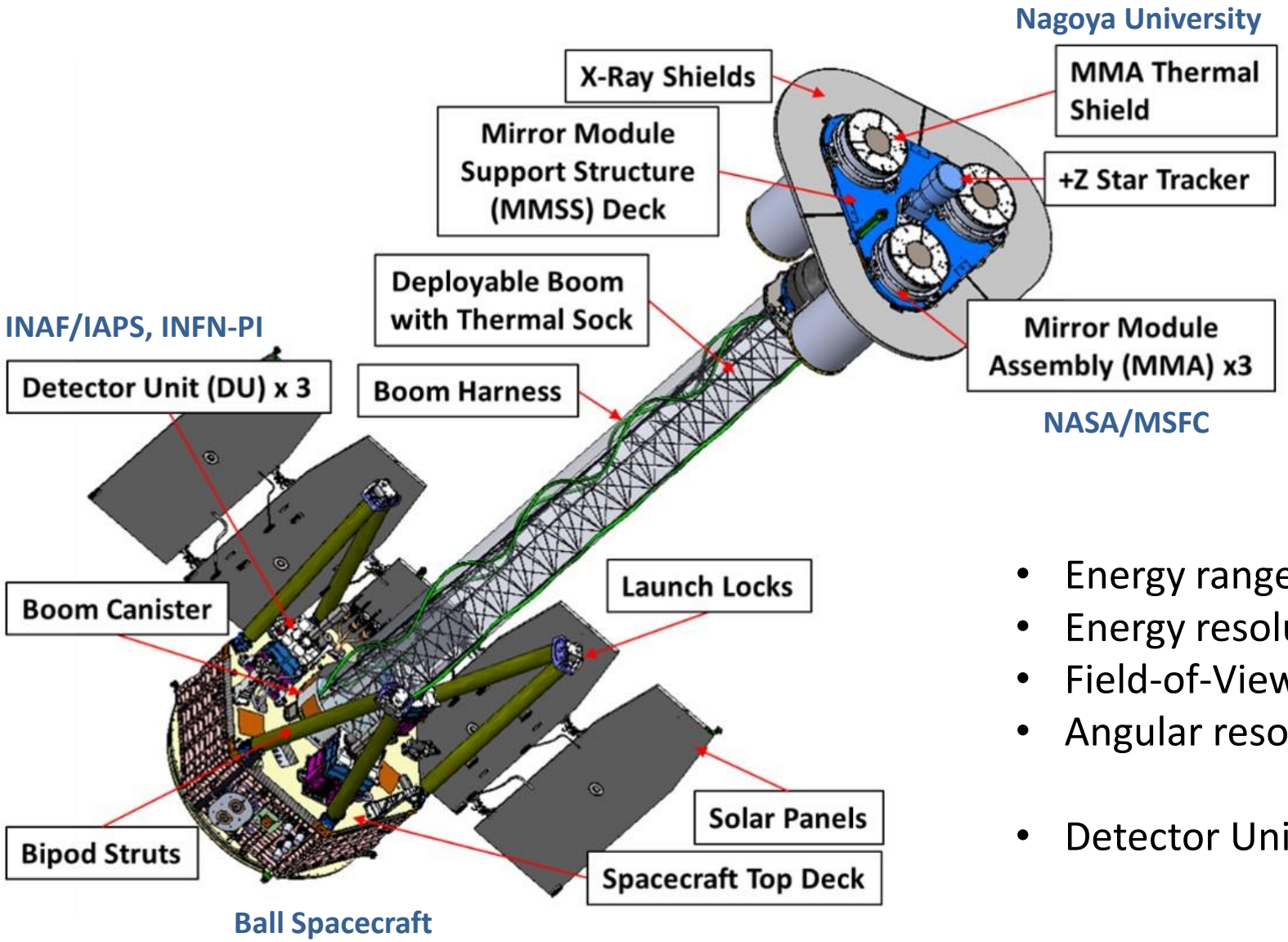
Imaging X-ray Polarimetry Explorer (IXPE) Mission Overview

Philip Kaaret
NASA/MSFC
on behalf of the IXPE Team

Imaging X-ray Polarimetry Explorer



- 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

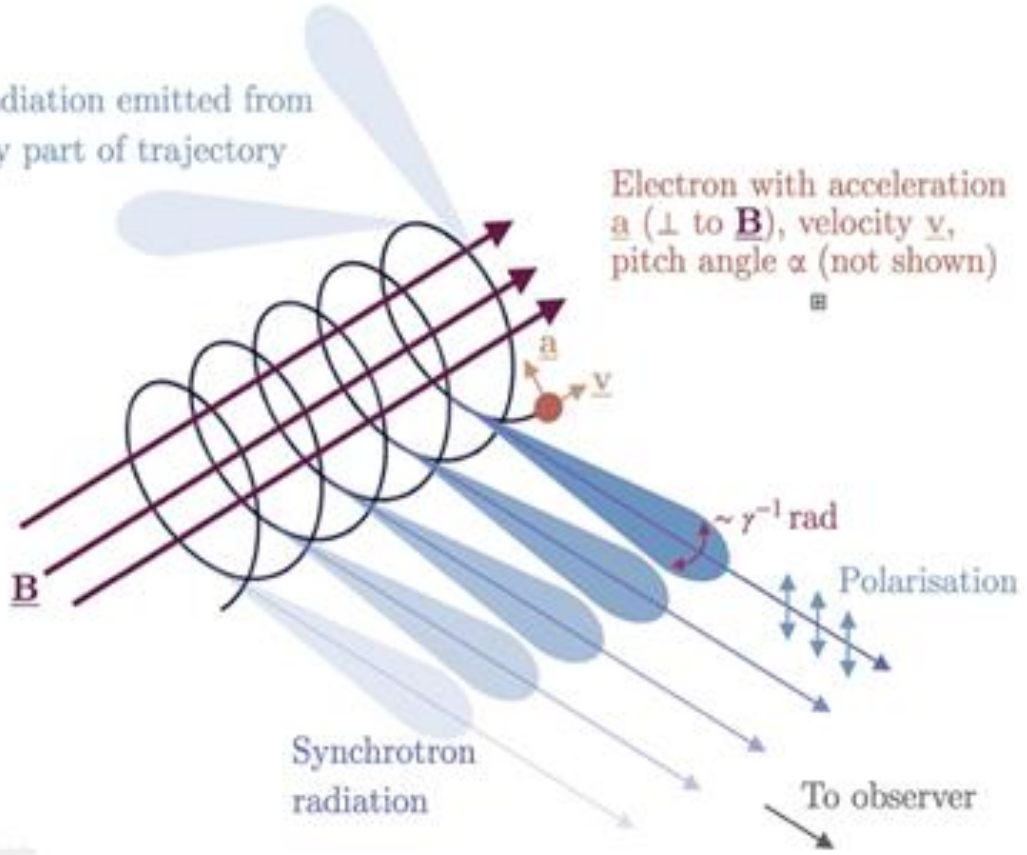
- Detector Unit = DU, numbered DU1, DU2, DU3

Polarization measures geometry

Polarization is a vector → measures geometry

Electric vector position angle = EVPA

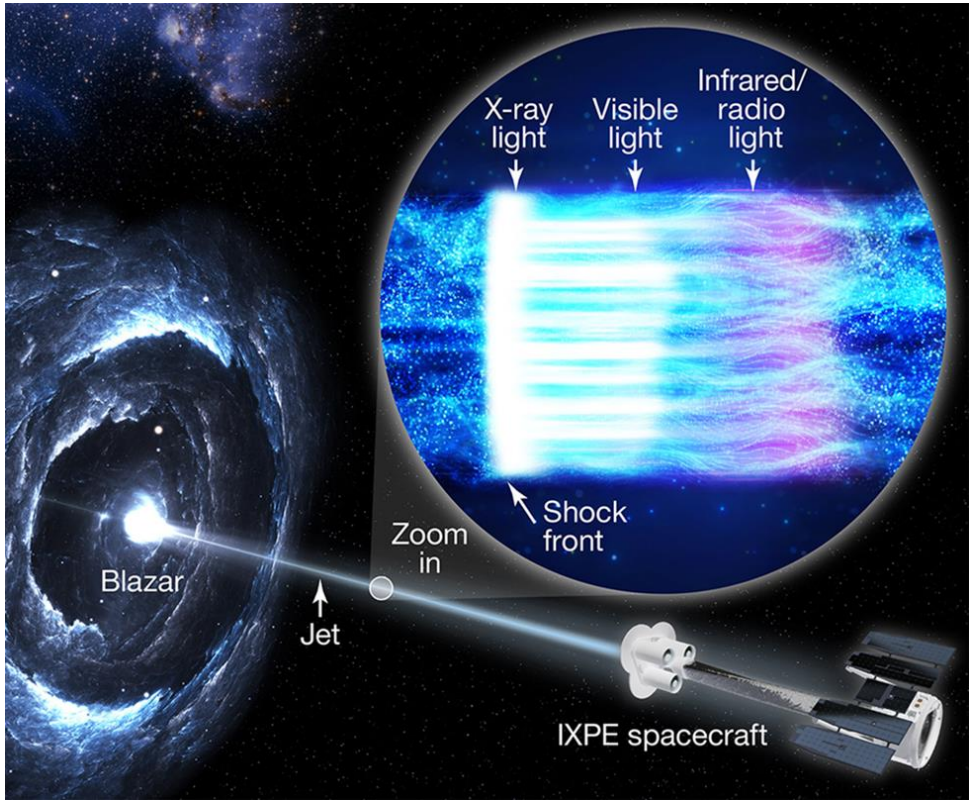
- Synchrotron radiation →
  EVPA perpendicular to magnetic field lines
- Scattering/reflection →
  EVPA perpendicular to scattering plane
- Strong magnetic fields →
  EVPA transported along magnetic field orientation
- Strong gravitational fields →
  EVPA parallel-transported along space-time geodesics



Science Results

IXPE has made observations of:

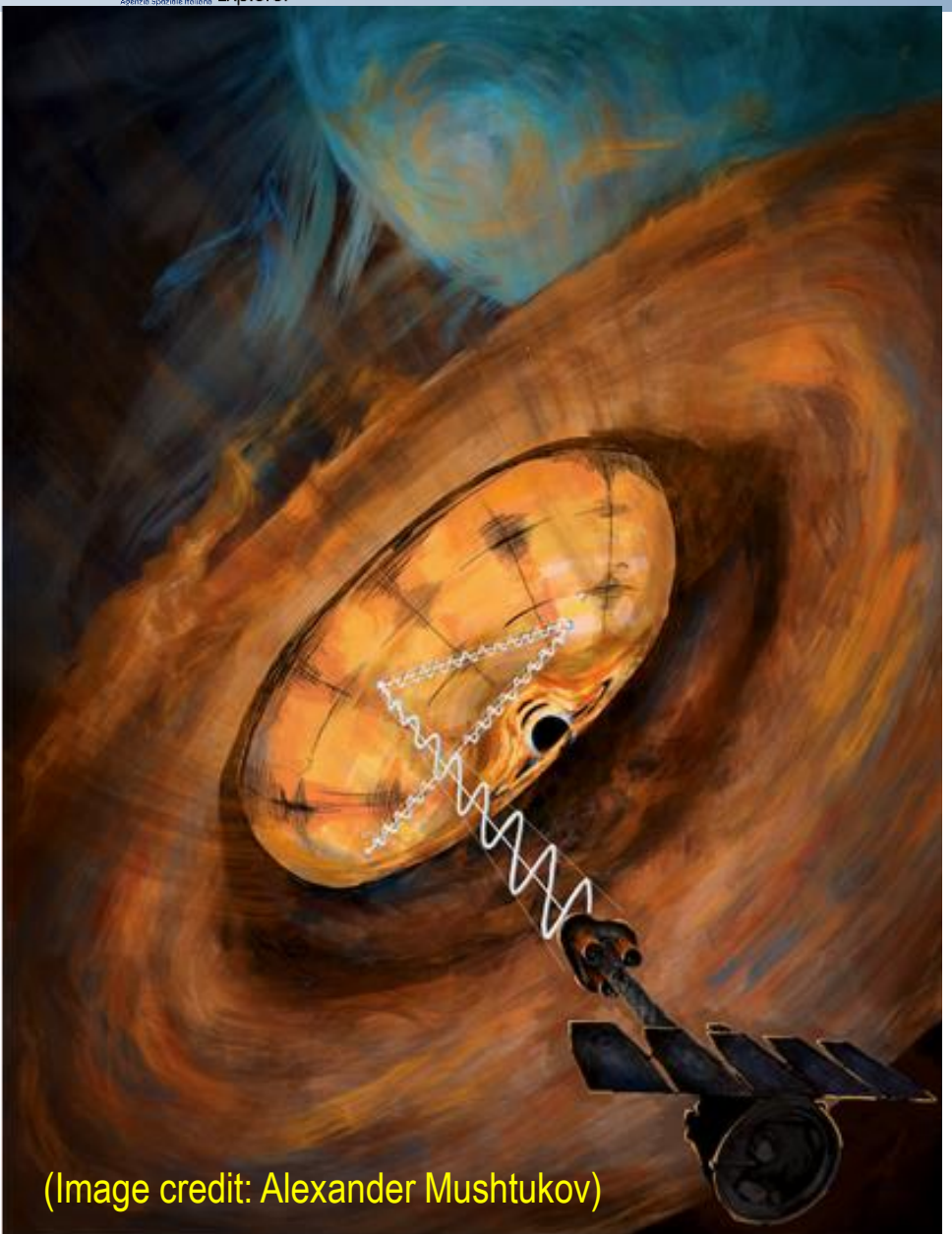
- Blazars and radio galaxies
- Neutron-star low-mass X-ray binaries
- Accreting X-ray pulsars
- Accreting stellar-mass black holes
- Supernova remnants and pulsar wind nebulae
- Magnetars
- Radio-quiet active galactic nuclei
- Center of the Milky Way galaxy
- Gamma-ray burst (Brightest Of All Time)
-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



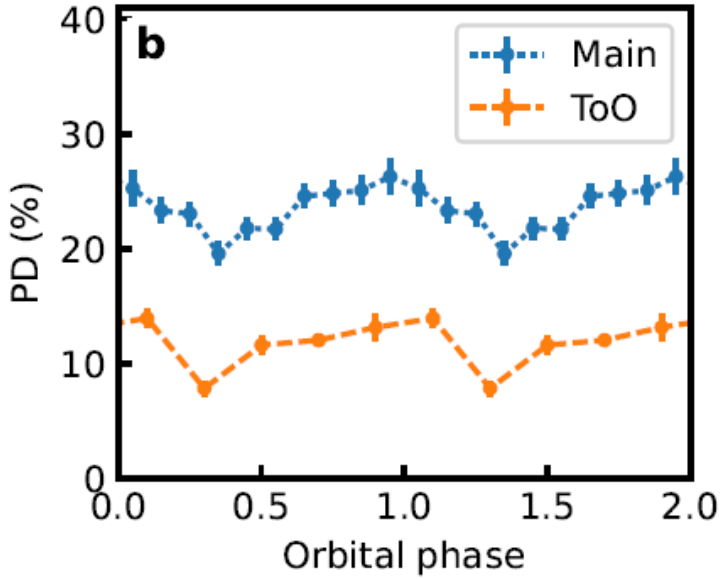
IXPE has opened a new window on the cosmos. New results on:
- magnetic field geometry in acceleration zones (blazars, supernova remnants and pulsar wind nebulae),
- accretion geometry near black holes (ruling out some commonly used models),
- behavior of matter in strong magnetic fields near neutron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

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

Cygnus X-3



Cyg X-3 is an X-ray binary
- Powerful jets - radio to γ-rays
- Wolf-Rayet companion
- Orbit 4.8 hours



High PD ≈ 20%.
- Emission 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 an Ultraluminous X-ray source (ULX)

Veledina+ (2024) in Nature Astronomy on June 21, 2024

Hercules X-1

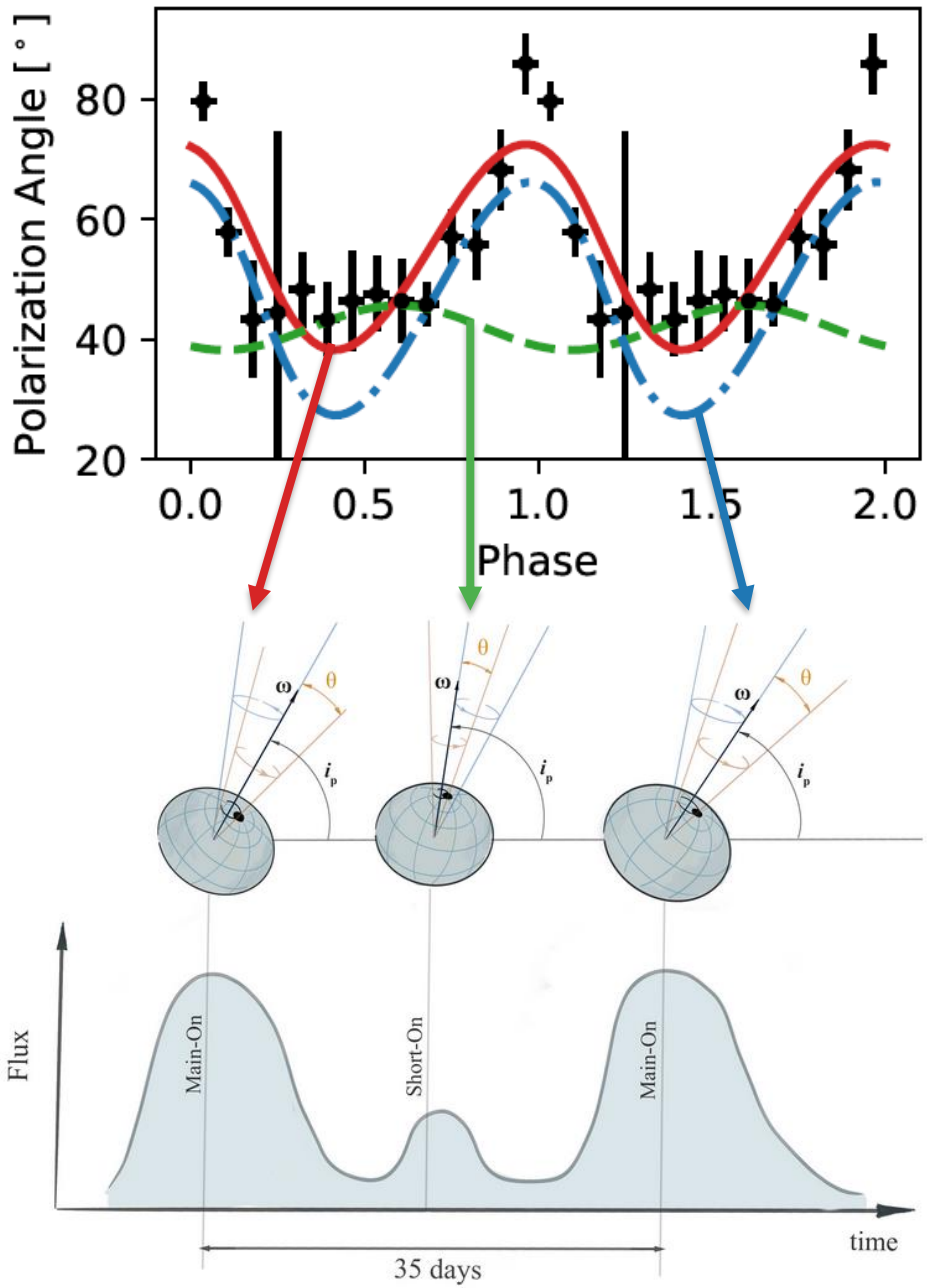
Her X-1 is an X-ray pulsar.

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

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

- Use Rotating Vector Model (RVM) 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.

Hyle et al. (2024) Nature Astronomy on June 18, 2024

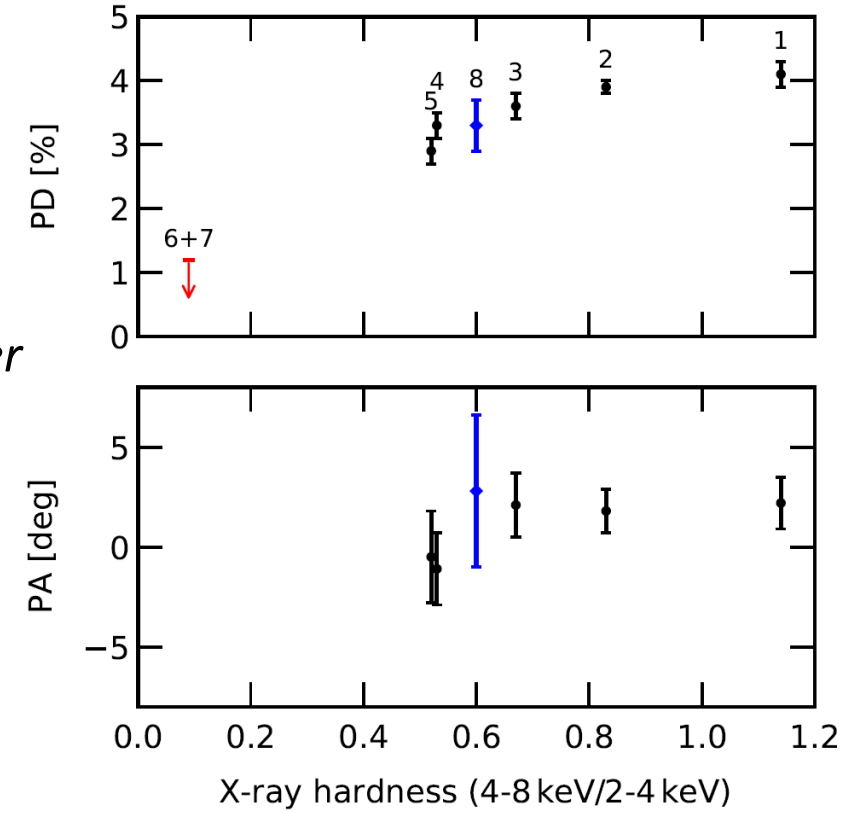


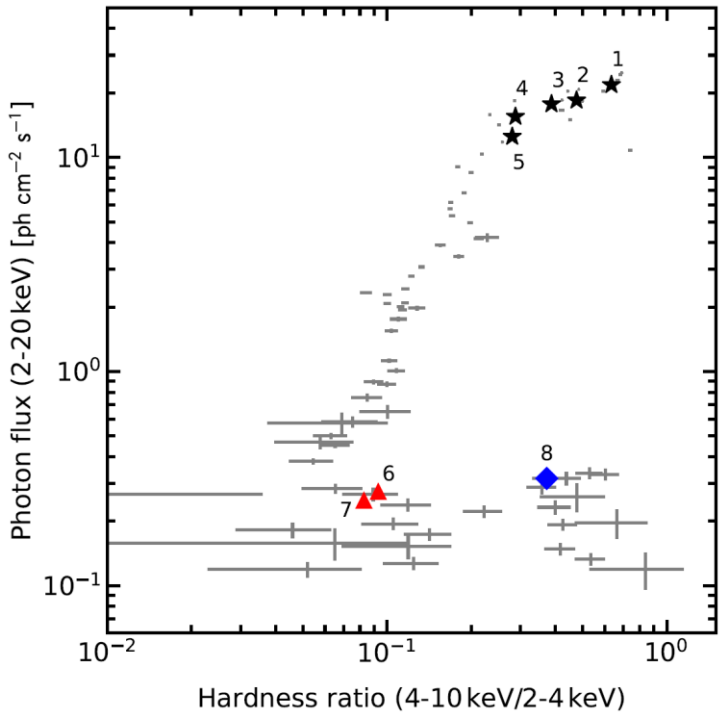
(Credit: Alexander Mushtukov)

Accreting Stellar Mass Black Holes

For Cyg X-1 in hard state, IXPE found

- Polarization degree = 4.0±0.2 %
- PD increases with energy.
- Polarization angle parallel to jet
- ➢ Corona is parallel to disk.
- ➢ *Excludes lamppost corona and other vertically extended geometries.* (Krawczynski+ 2022)





- In Swift J1727.8-1613, polarization is unchanged between bright and low hard states, even with 100× change in flux.

Svoboda et al. 2024, Podgorný et al. 2024

- Also, PD decreases in soft state.

Pulsars and Pulsar Wind Nebulae

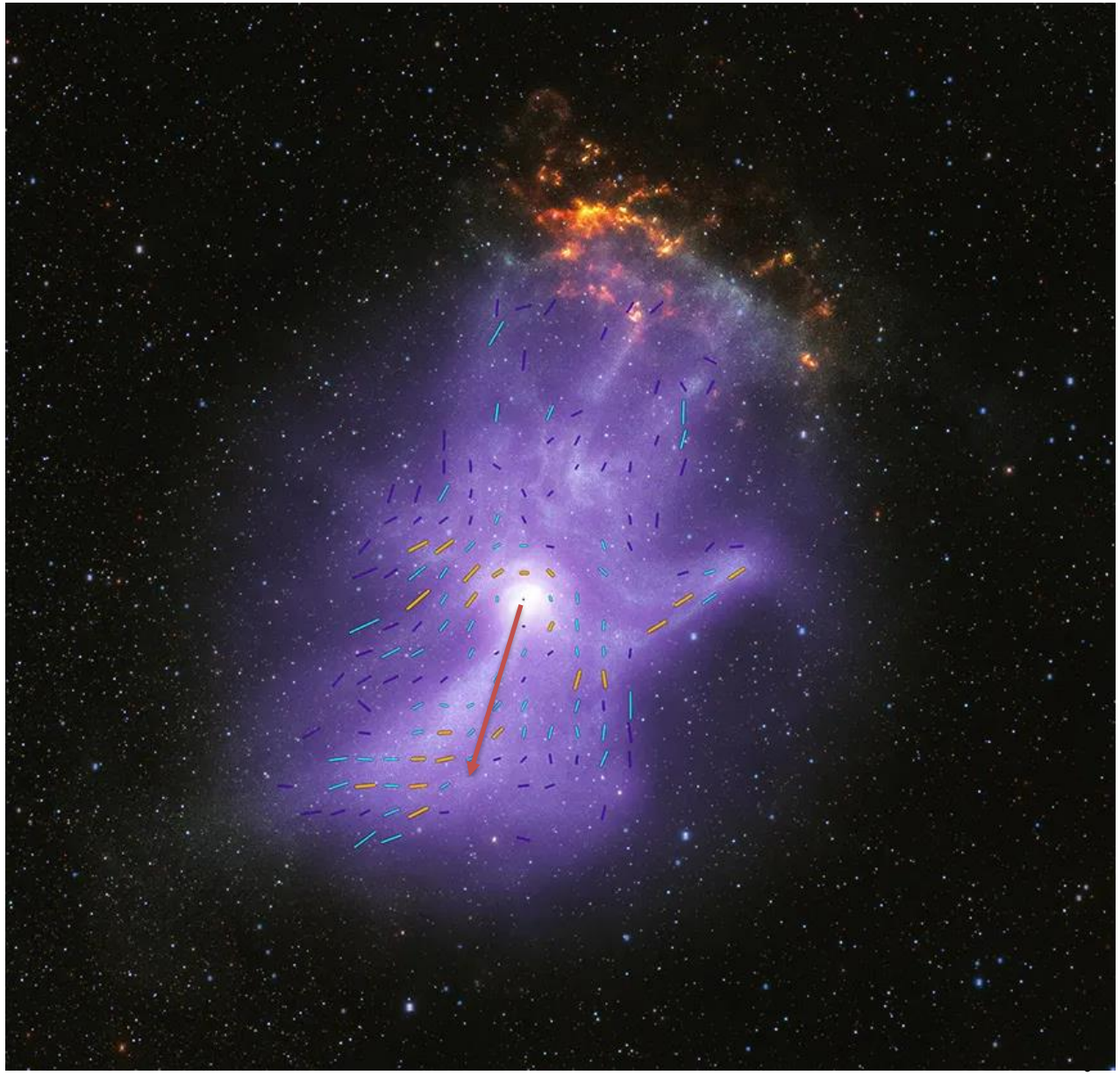
"Cosmic Hand" MSH15−5 *2*

- PD ≥ 70% in arcs near pulsar and end of jet
- PD is close to limit for synchrotron
- ➢ Uniform magnetic field - little or no turbulence
- ➢ Acceleration may be due to magnetic reconnection
- Similar results are seen for Crab and Vela.

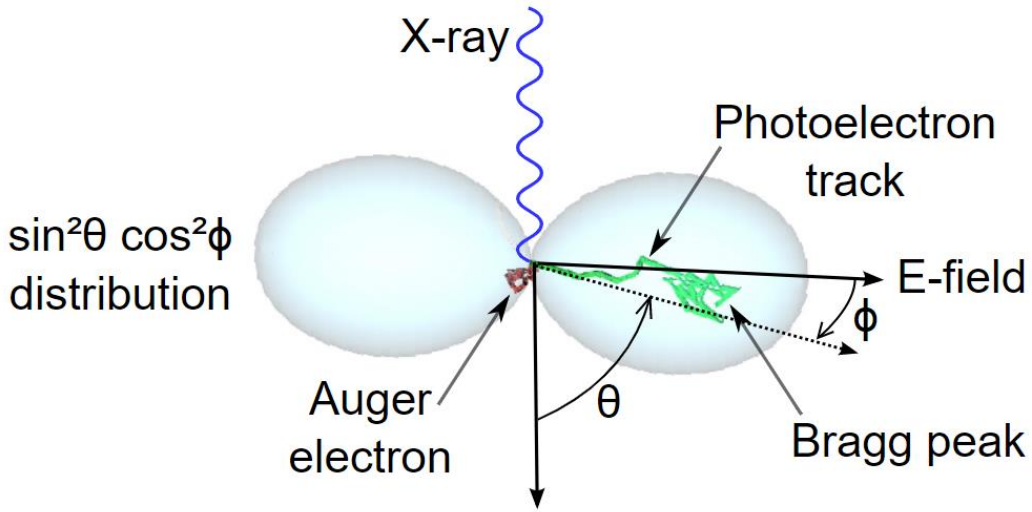
- Detection of polarization from pulsar
- ➢ Could help understand pulsation mechanism

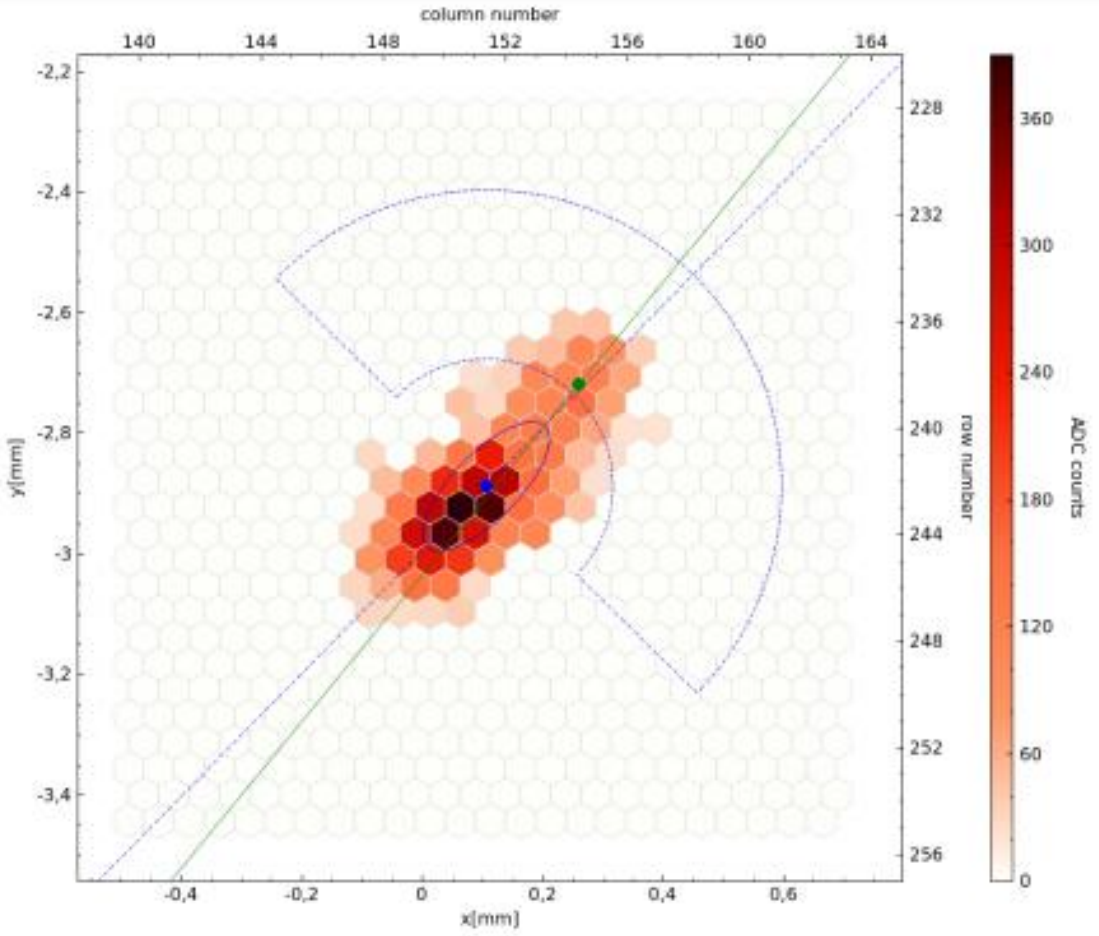
Purple = X-ray/ Red = IR
Bar direction is magnetic field, length is PD
orange > 5σ, blue > 3σ, black > 2σ
Red arrow shows jet direction

Romani et al. 2023



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.

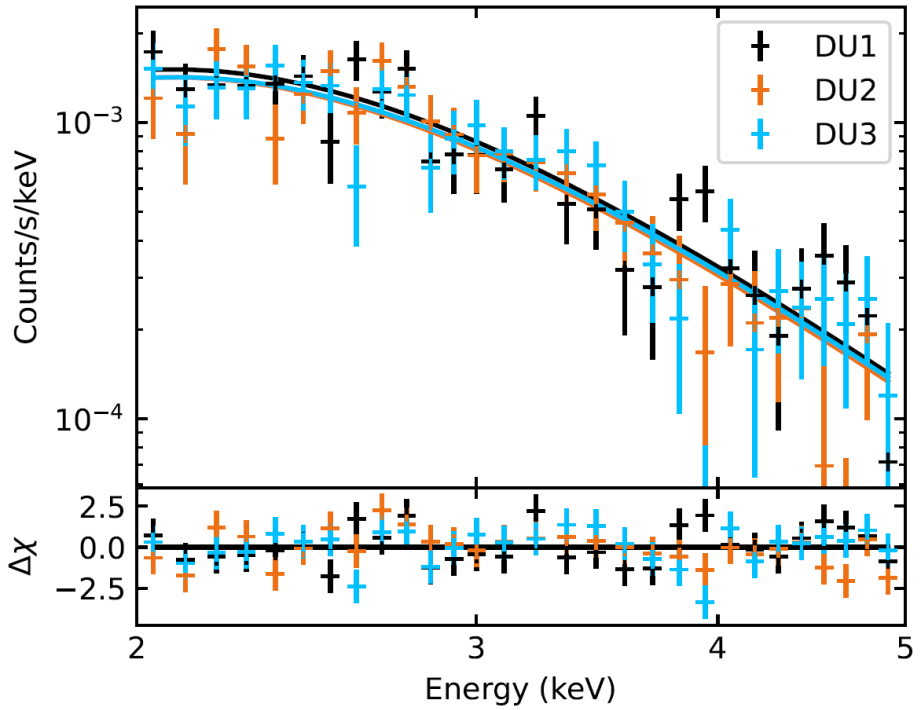
Photoelectron track from Cas A for 2.7-keV photon in DU1.

IXPE analysis can be done in Xspec

Spectrum = counts in energy bins.

For each X-ray find: 1

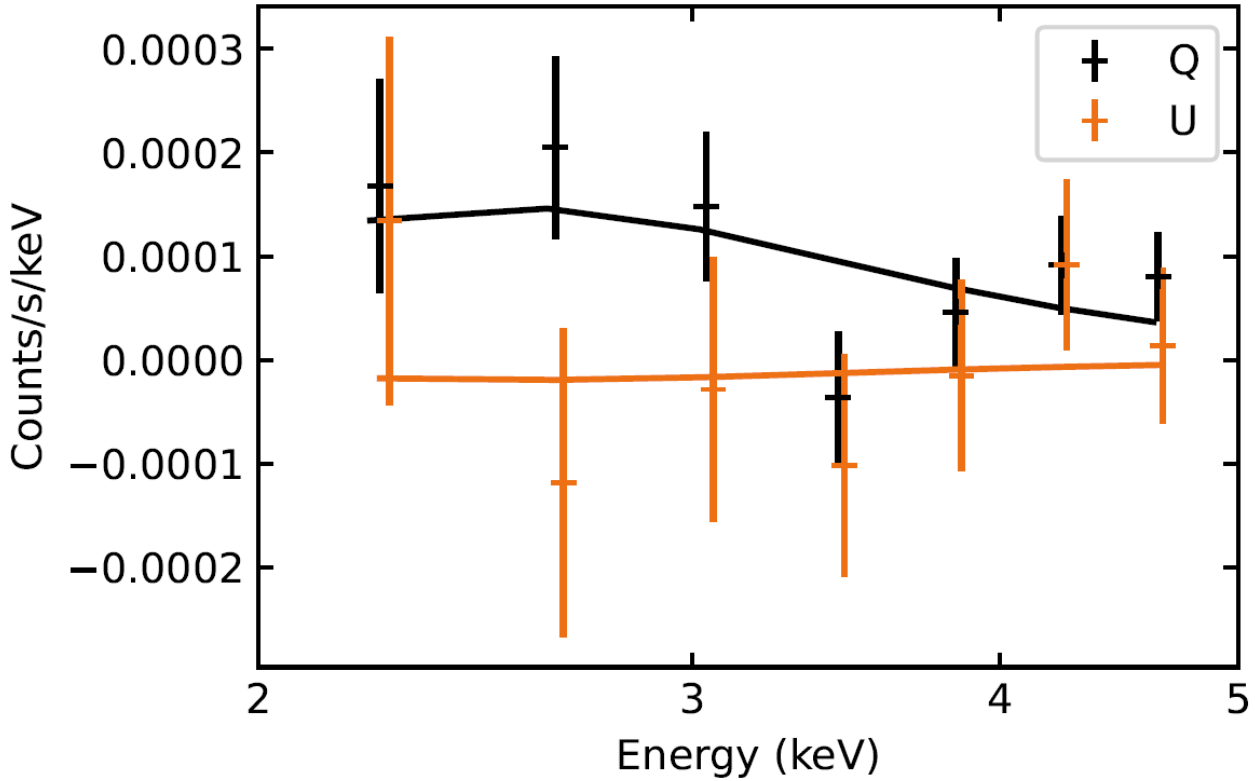
Make sums in energy bins:



Spectropolarimetry uses sums of q_i, u_i in energy bins.

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

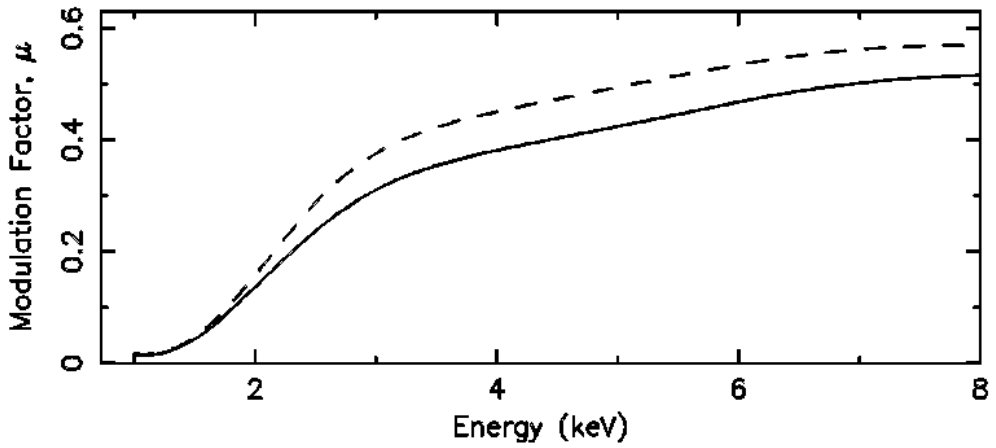
Make sums in energy bins:

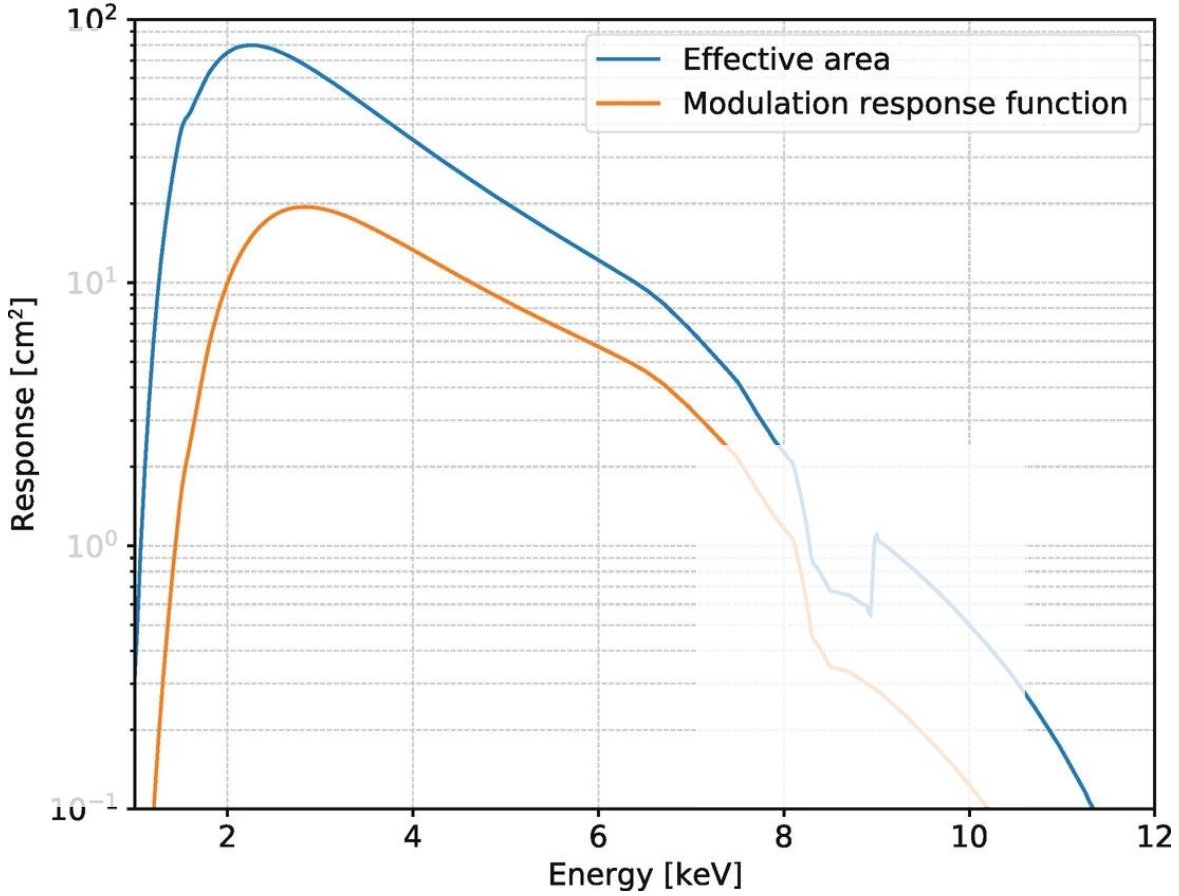


Have three spectra: Stokes I, Stokes Q, Stokes U.

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.

General Observer Program

GO Cycle 1 Proposals were due on October 18, 2023

- 135 proposals - 121 regular, 14 theory, 6 large
- 103 Ms of IXPE time requested, oversubscription ≈ 6
- ToO were very highly oversubscribed, by a factor ≈ 9

- 99 distinct targets, includes source classes beyond prime mission:
  tidal disruption events, white dwarfs, galaxy clusters, recurrent nova

- GO observations started on 2024-02-03T12 UTC
- Will conduct 15 Ms of GO observations
- Many observations of 500-1000 ks, one large program for 2 Ms

- Review panel chairs commented that accepted proposals were of very high quality and that there were 2-3 years of scientifically important observations.

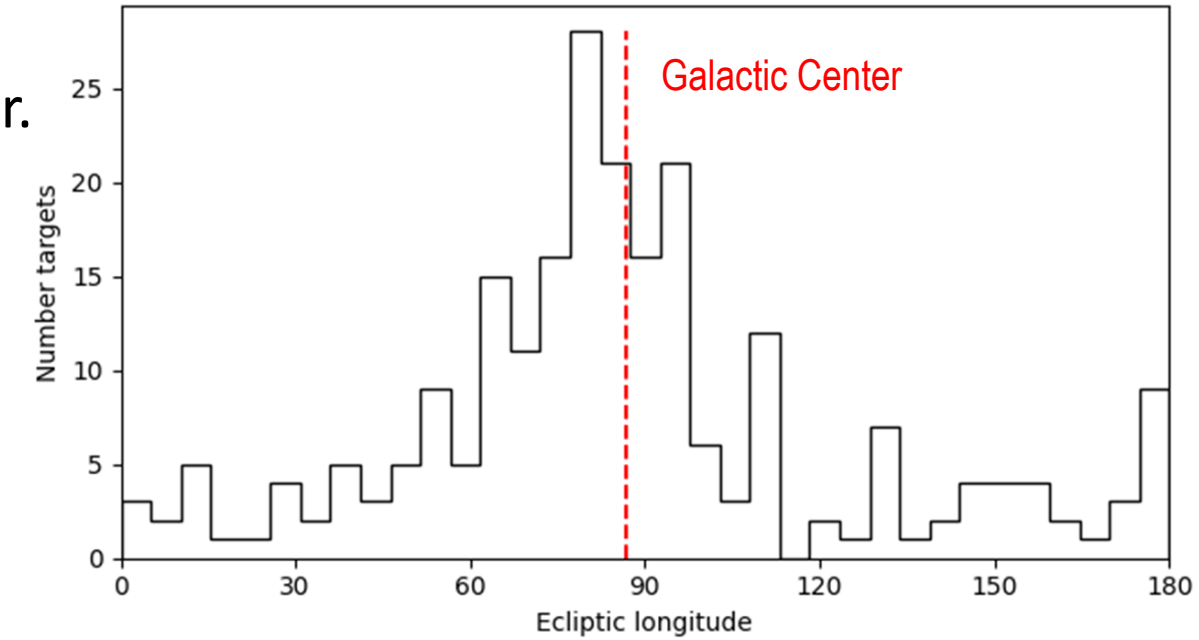
➢ If your proposal was declined, then edit and resubmit!

IXPE GO Cycle 2

- **Deadline for IXPE GO cycle 2 is August 29, 2024.**
- Notice of Intent is **not** requested for this cycle.
- Continuing joint program with NICER, adding joint programs with NuSTAR and Swift.
- Swift GO cycle 21, due on 9/26/2024, will award IXPE time (200 ks, one medium ToO).
- ToOs with unspecified coordinates are allowed.

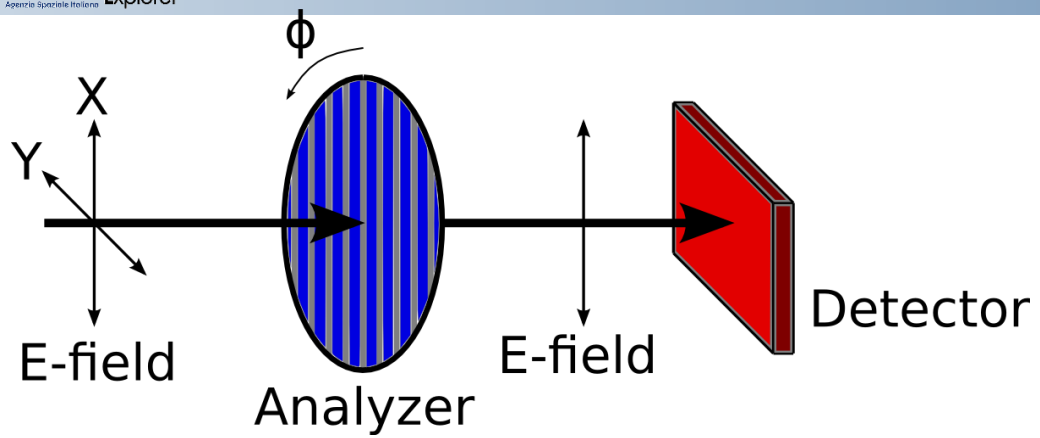
- IXPE targets cluster towards the Galactic center.
- Please propose targets away from GC.
- Best are targets within 34° of an ecliptic pole.

- Can observe 1 Crab source for ~75 ksec.
- Then need ~7 days to get data to ground.

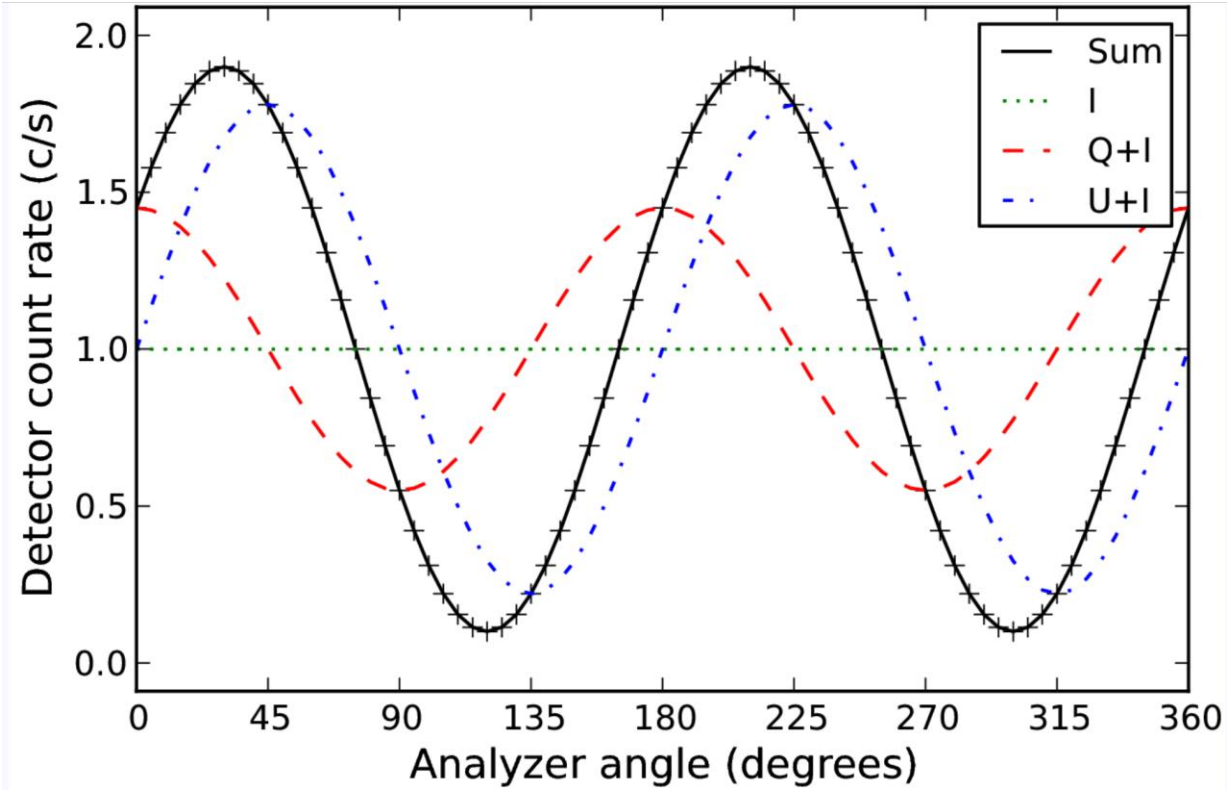



The IXPE General Observer program
is producing outstanding science.
We counting on you to propose
observations that will enhance IXPE's
scientific impact.

Measuring polarization using Stokes parameters



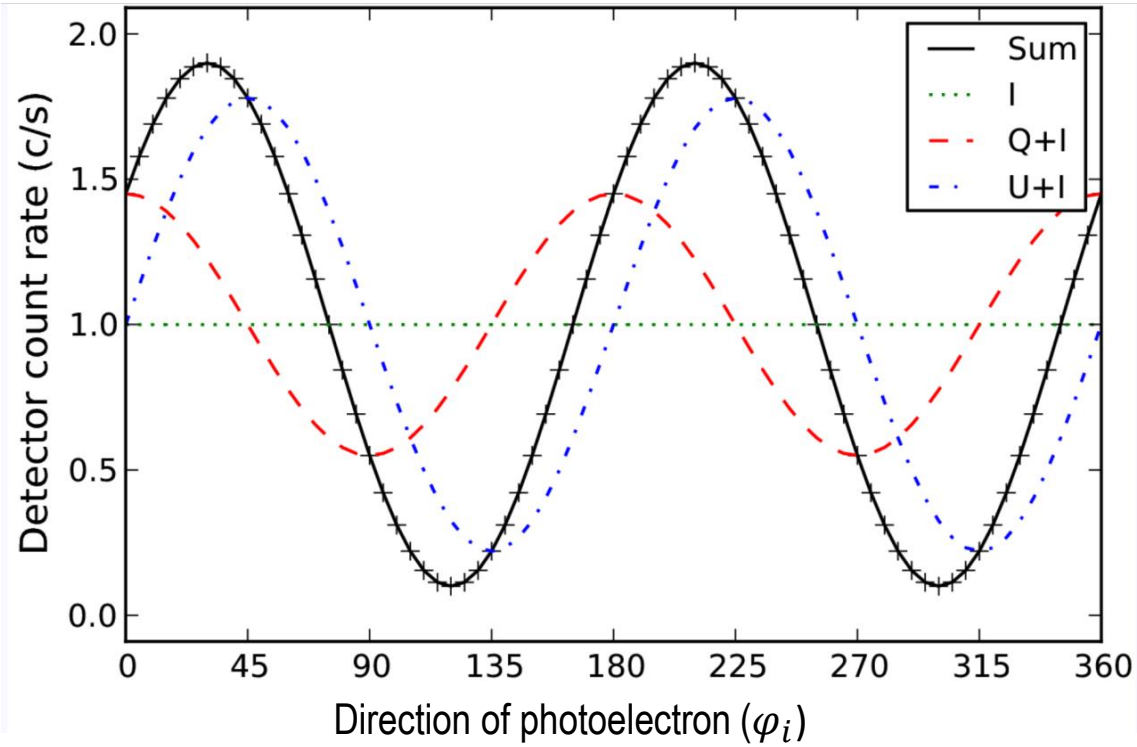
- Measure polarization by rotating analyzer and finding rate versus angle.
- Angle of peak rate gives polarization angle.
- Amplitude of modulation gives polarization degree (PD).
- Need to take into account polarization sensitivity.
- Use “modulation factor” = μ = modulation for 100% polarized beam.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

Measuring polarization using Stokes parameters



- Work in Stokes parameters
  - Independent, gaussian errors
  - Simply additive
- Compute Stokes parameters (q_i, u_i) from initial direction of photoelectron (φ_i) for each event i

$$q_i = 2\cos(\varphi_i) \quad u_i = 2\sin(\varphi_i)$$

- Make sums of q_i, u_i, intensity (Q, U, I)
- Find polarization degree (PD) and position angle (PA)

$$\mathrm{PD} = \sqrt{(Q/I)^2 + (U/I)^2}$$
$$\mathrm{PA} = (1/2)\tan^{-1}(U/Q)$$

- Can do this in bins (energy, time, phase, …)

Calibration Updates

- IXPE calibration had issue in 6-8 keV band, now solved with adjustment of mirror surface density and Ni:Co ratio in fits to ground calibration data.

- Now include time-dependence of gas pressure in DUs
- Reduces difference in normalization of DUs.

- Working on correction for charging of gas electron multipliers that affects spectra for bright sources.

- Neural network approaches to X-ray image analysis can improve polarization sensitivity. Currently manpower limited for implementation.