# An Overview of X-ray Polarimetry of Astronomical Sources

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# Outline

- A look to the past
    - Experimental techniques
- Electron tracking
- IXPE the mission
- IXPE the science

# Why is polarization useful?

- The degree of polarization and the “position angle” depend on the conditions under which the X-rays are produced
- Thus modeling of what we see must also predict the degree of polarization and the position angle

# In the beginning

- July 1968 – Lithium-block, “Thomson”-scattering polarimeter flown on an Aerobee -150 rocket
  - Target was the brightest X-ray source Sco X-1

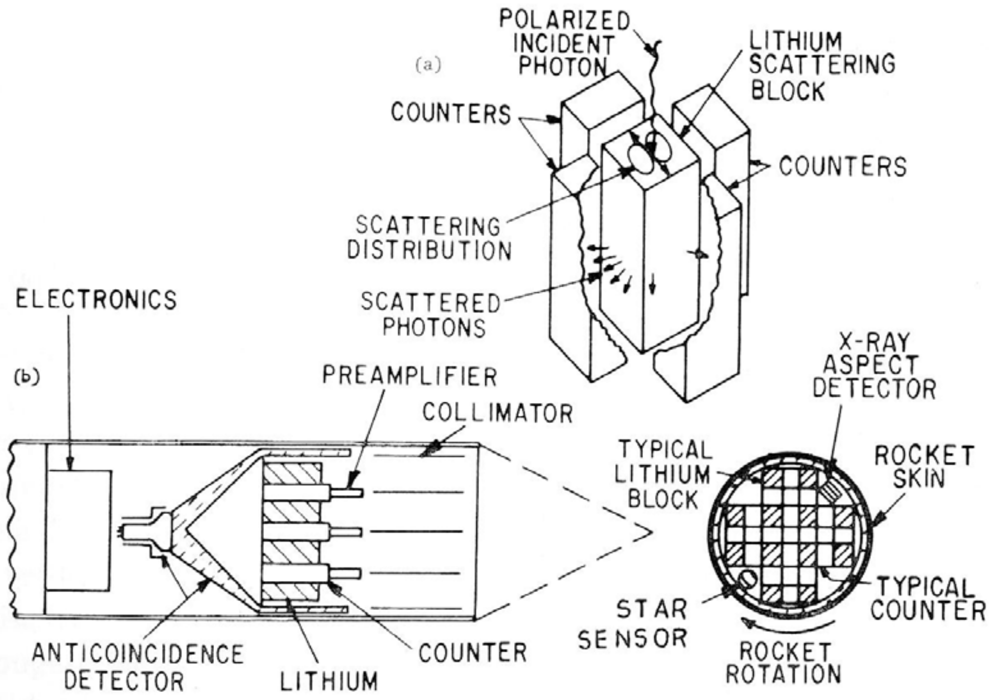



Fig. 1. (a) Schematic representation of the polarimeter concept. (b) Mounting of the polarimeter and ancillary equipment in the rocket.

# Scattering polarimeter

- Thomson cross-section approximates the angular dependence

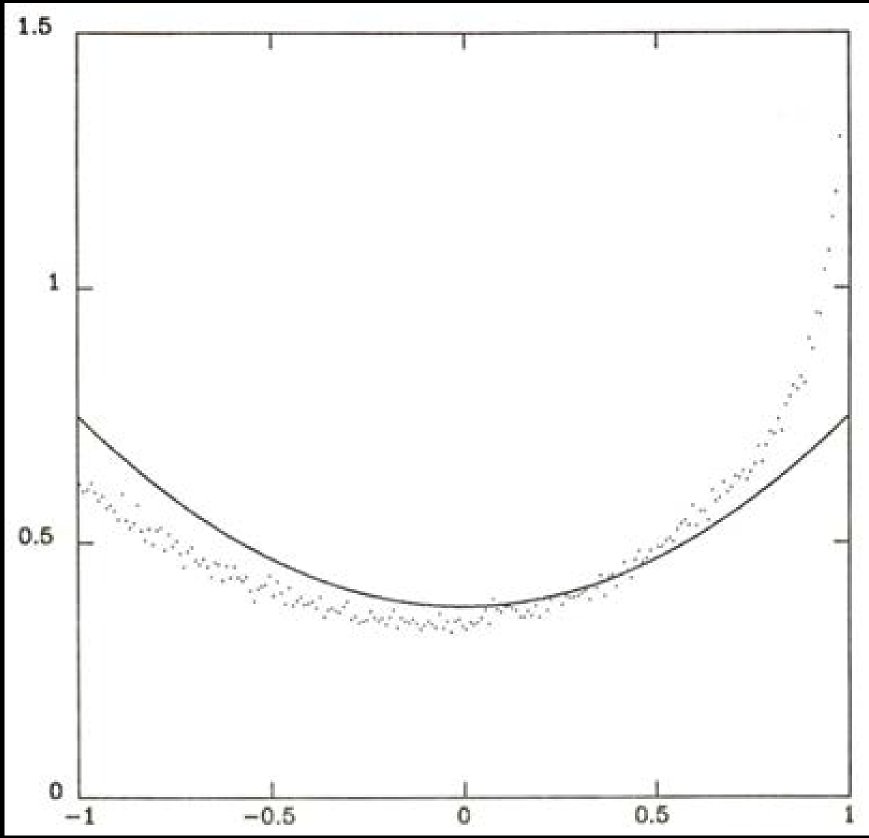
$$d\sigma / d\Omega = (e^2 / mc^2)^2 (\cos^2 \vartheta \cos^2 \varphi + \sin^2 \varphi)$$

- From bound electrons one must account for both coherent and incoherent scattering and photoelectric absorption

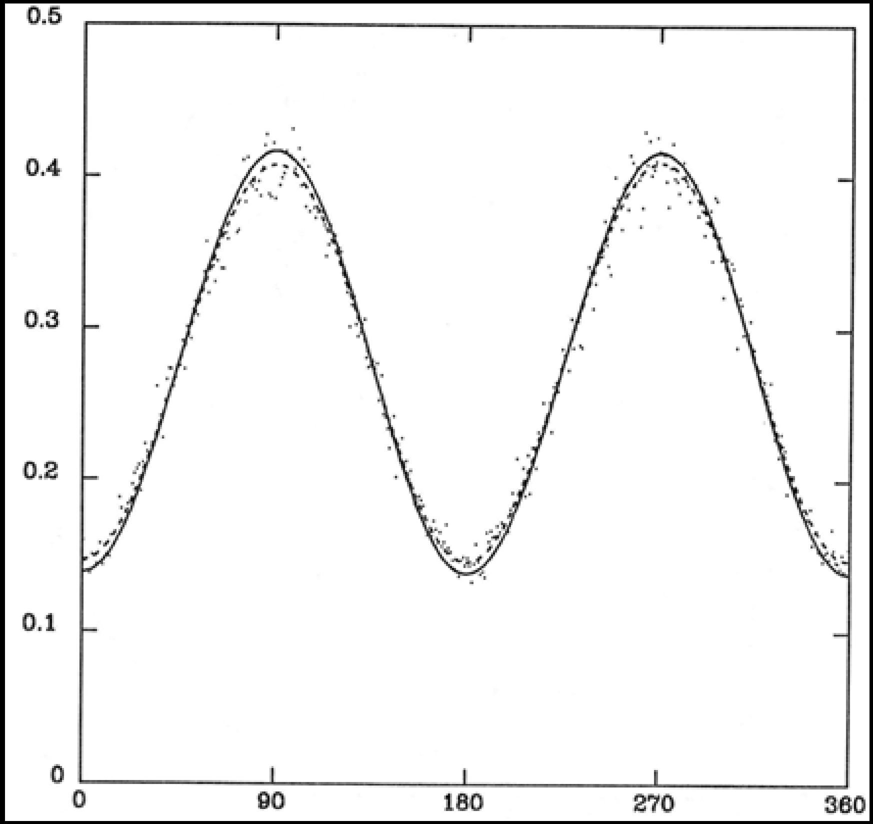
$$\frac{d\sigma_{\mathrm{coh}}}{d\Omega} = r_0^2 \langle \cos^2 \vartheta \cos^2 \varphi + \sin^2 \varphi \rangle |F|^2$$

$$\frac{d\sigma_{\mathrm{incoh}}}{d\Omega} = r_0^2 \langle \cos^2 \vartheta \cos^2 \varphi + \sin^2 \varphi \rangle I$$

# Thompson approximation




Cos (polar scattering angle)




Azimuthal scattering angle

# Considerations

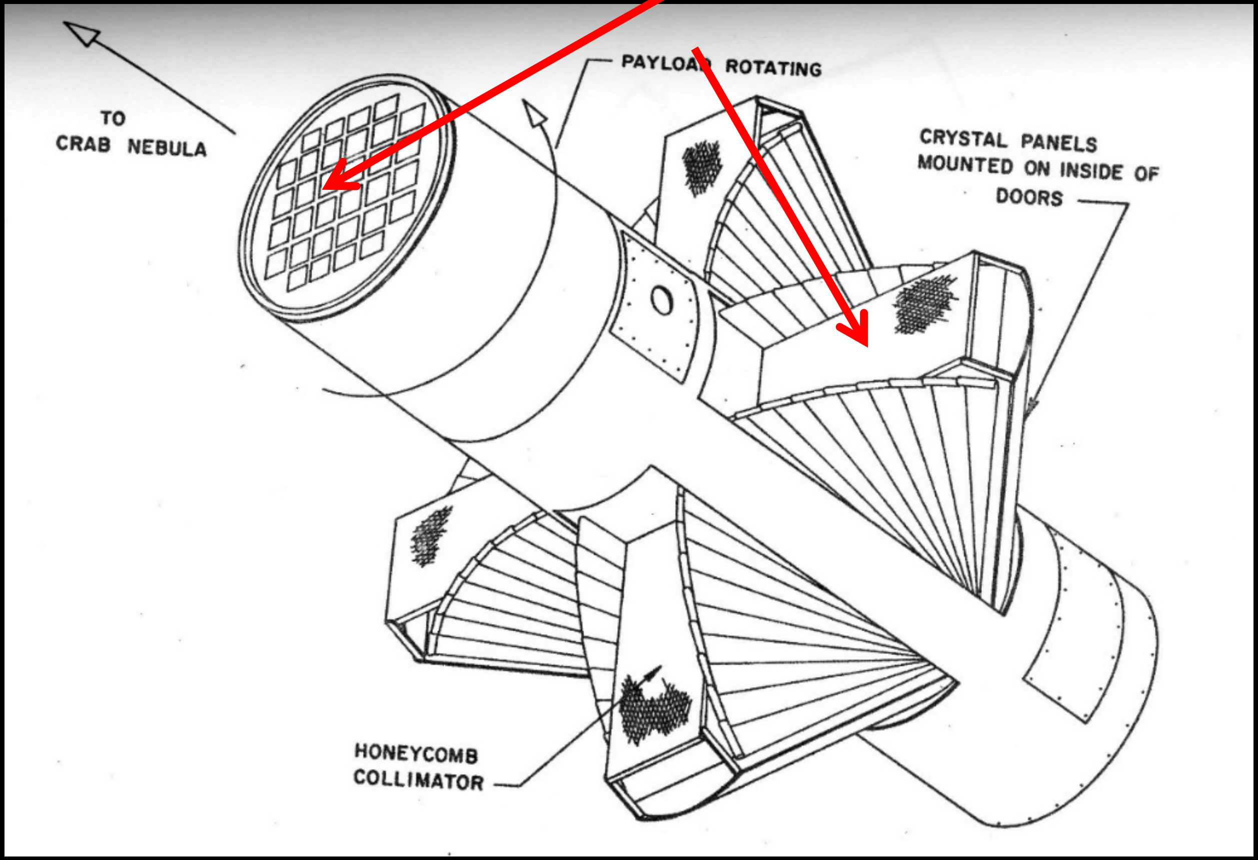
- Minimize the background
- Achieve as large a sensitivity to polarization as possible
  - Optimize the “MDP” at the 99% confidence level

$$MDP_{99}(\%) = (4.29x10^4 / M(\%))\sqrt{(R_S + R_B)} / \sqrt{R_S^2 t}$$

- *MDP* is the degree of polarization detected at the 99% confidence independent of the position angle
- *M* is the modulation from a 100% polarized beam with $R_B = 0$

# Rocket 17.09 (1971)

- Two instruments in one payload!
    - Lithium scattering polarimeter
    - 4 Bragg crystal polarimeters

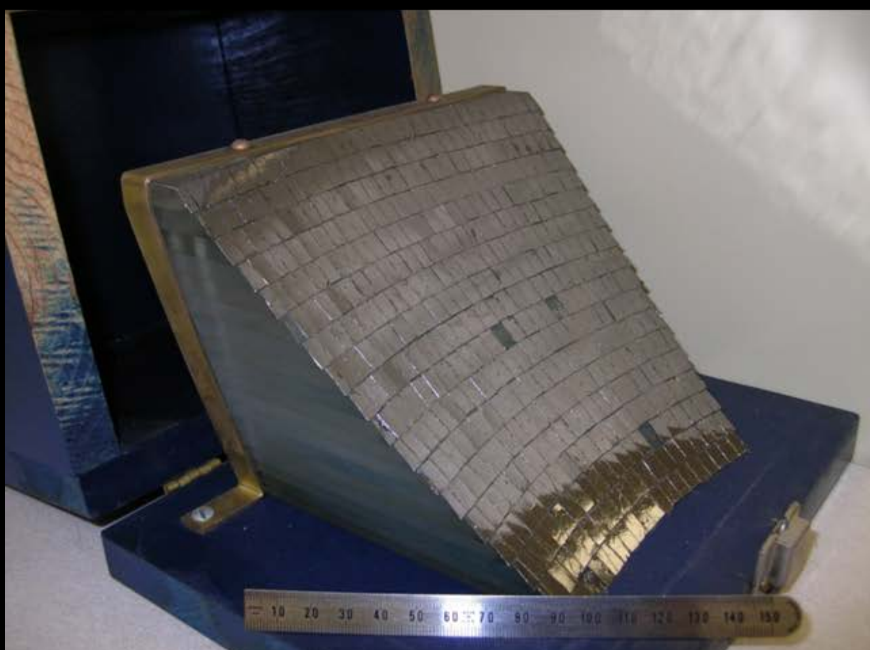


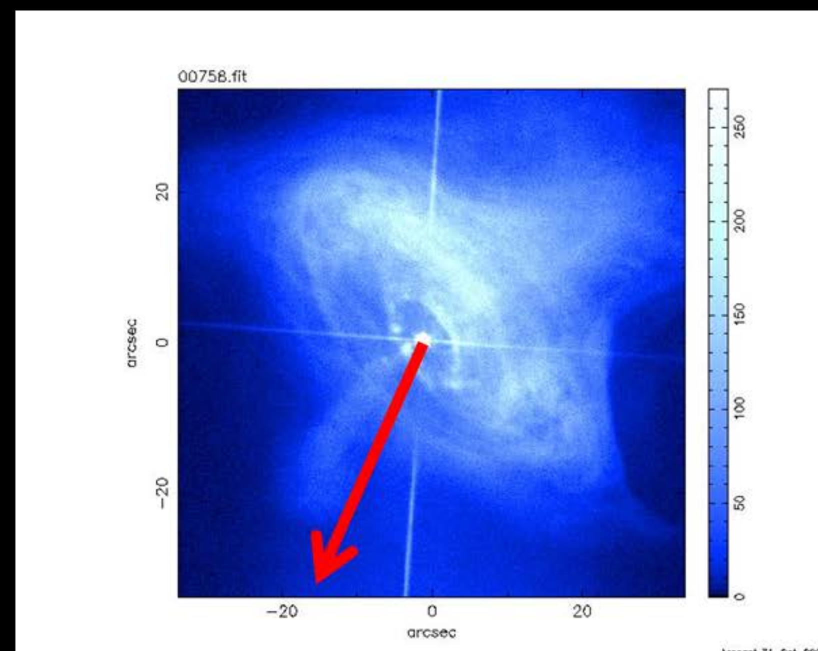
# Rocket 17.09

- 1971 Aerobee 350
  - Crab detection!
    - P = 15% ± 5%
    - $\varphi = 156 \pm 10^{\circ}$

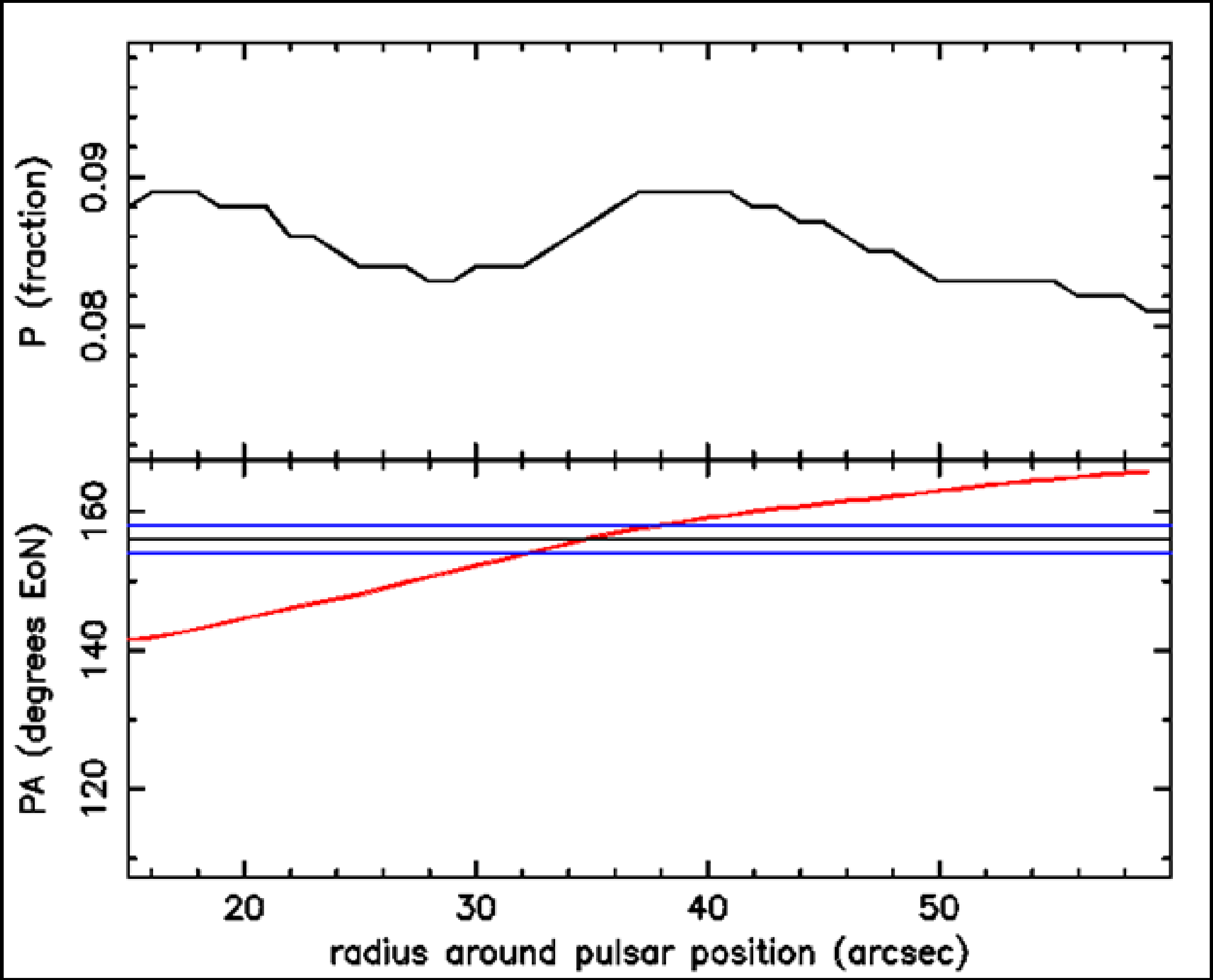
# Crystal polarimeters on OSO-8

- 1975 OSO-8 crystal polarimeter
- Precision measurement of integrated emission from the Crab Nebula polarization at 2.6 keV
  - P = 19% ± 1%
  - φ = 156 ± 2° (NNE)





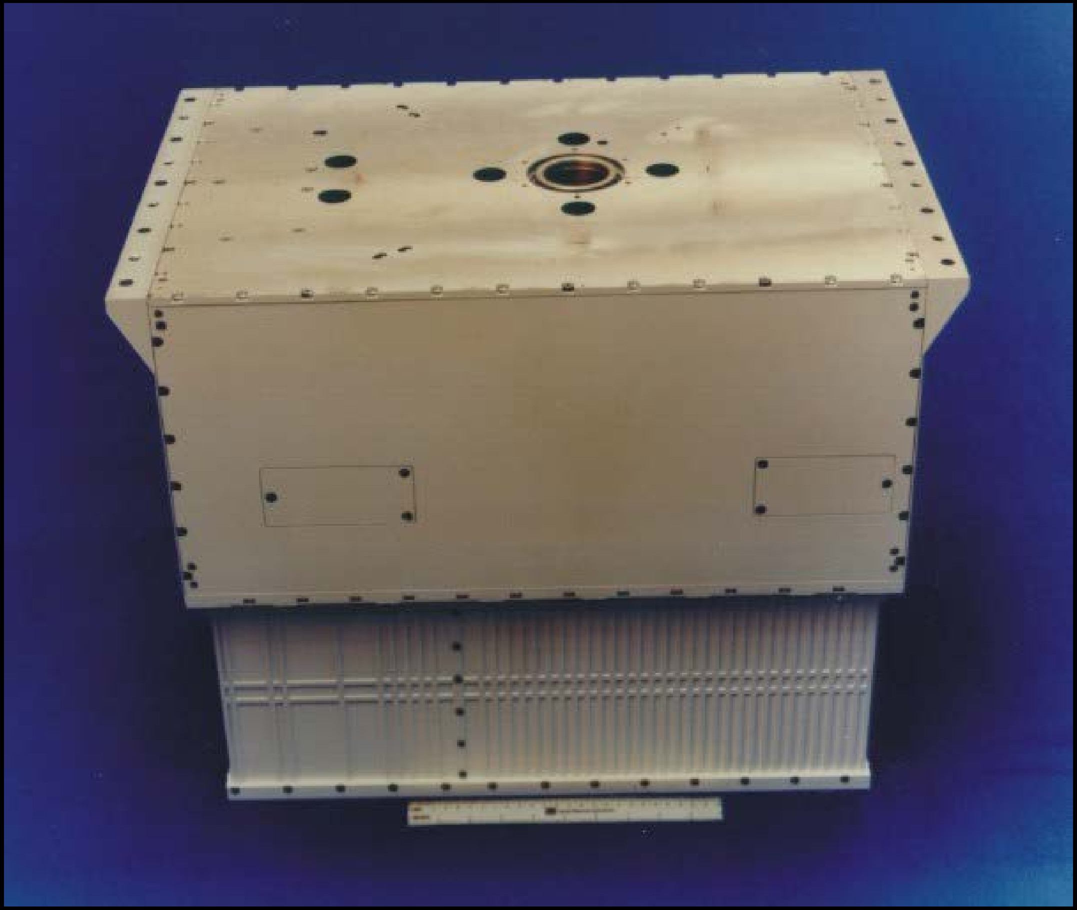
# Compare to detailed optical results

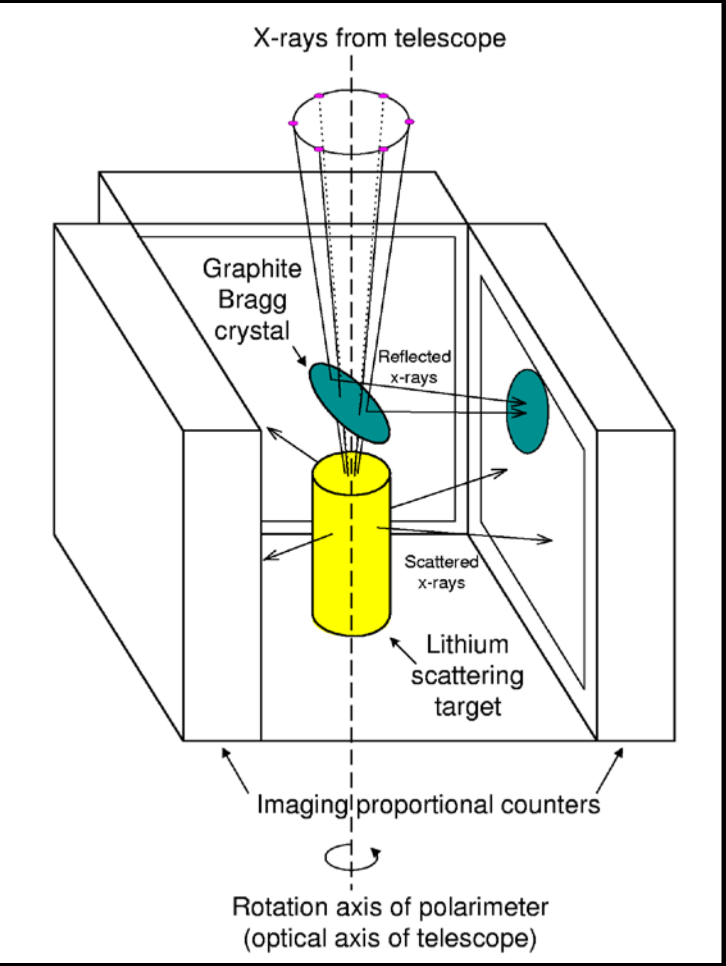



Moran, P., Shearer, A., Mignani, R.P., et al. (2013)

# Next came the Stellar X-ray Polarimeter (SXRP)

- Planned to fly on the Russian Spectrum-X Gamma Mission in the early 1990s






- Soviet Union Collapsed --- never launched

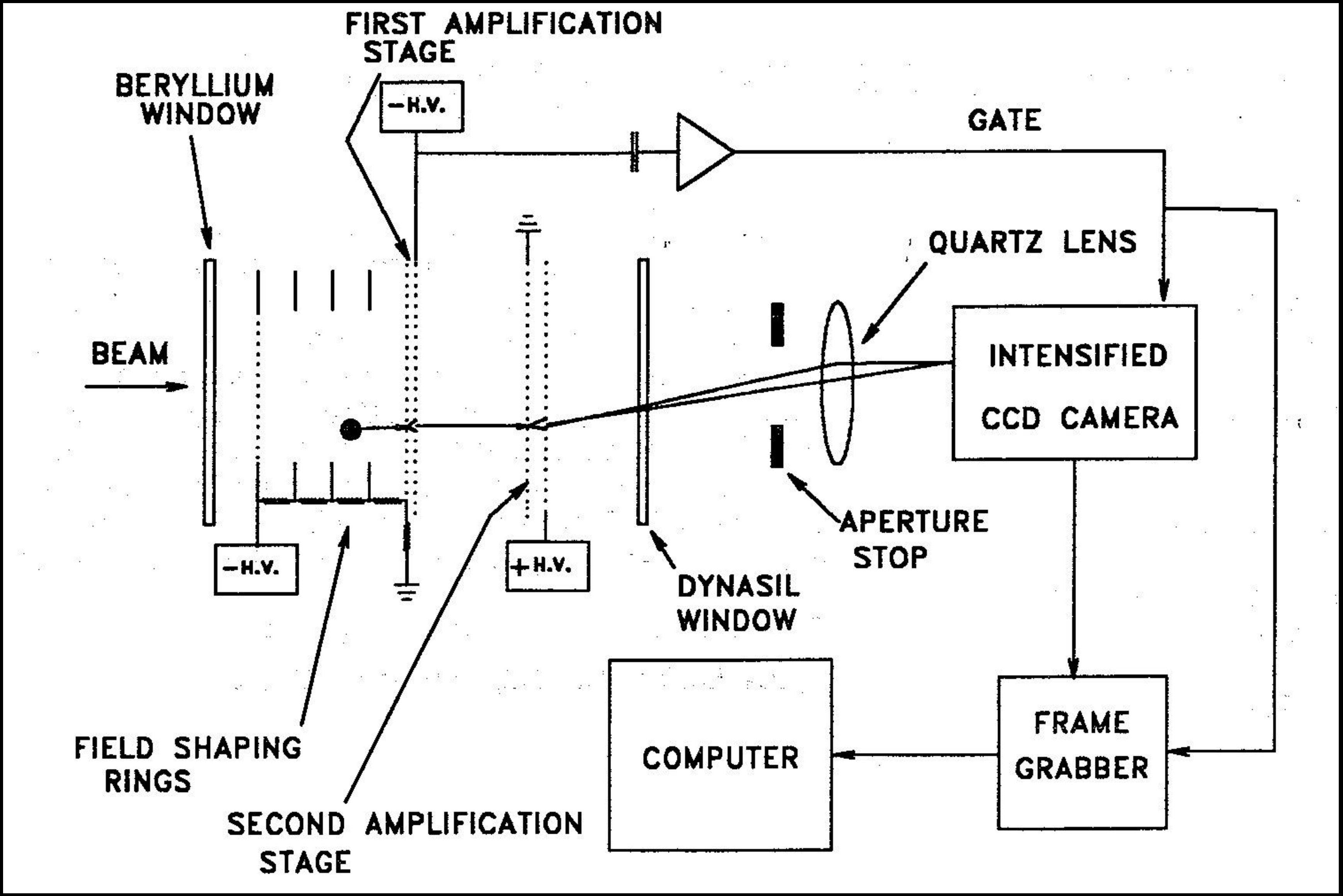
# Breakthrough --- electron-tracking polarimeters

- The direction of the *initial* K-shell photoelectron is determined by the electric vector and the direction of the incoming photon

$$\frac{d\sigma}{d\Omega} = f(\zeta) r_0^2 Z^5 \alpha_0^4 \left( \frac{mc^2}{h\nu} \right)^{7/2} 4\sqrt{2} \sin^2\theta \cos^2\varphi$$

- Optical Imaging Chamber
  - Austin & Ramsey 1992
- Pixelated Gas Multiplication
  - Costa et al. 2001
- Time Projection Chamber
  - Black et al. 2007

# Electron tracking




Austin and Ramsey (1992)

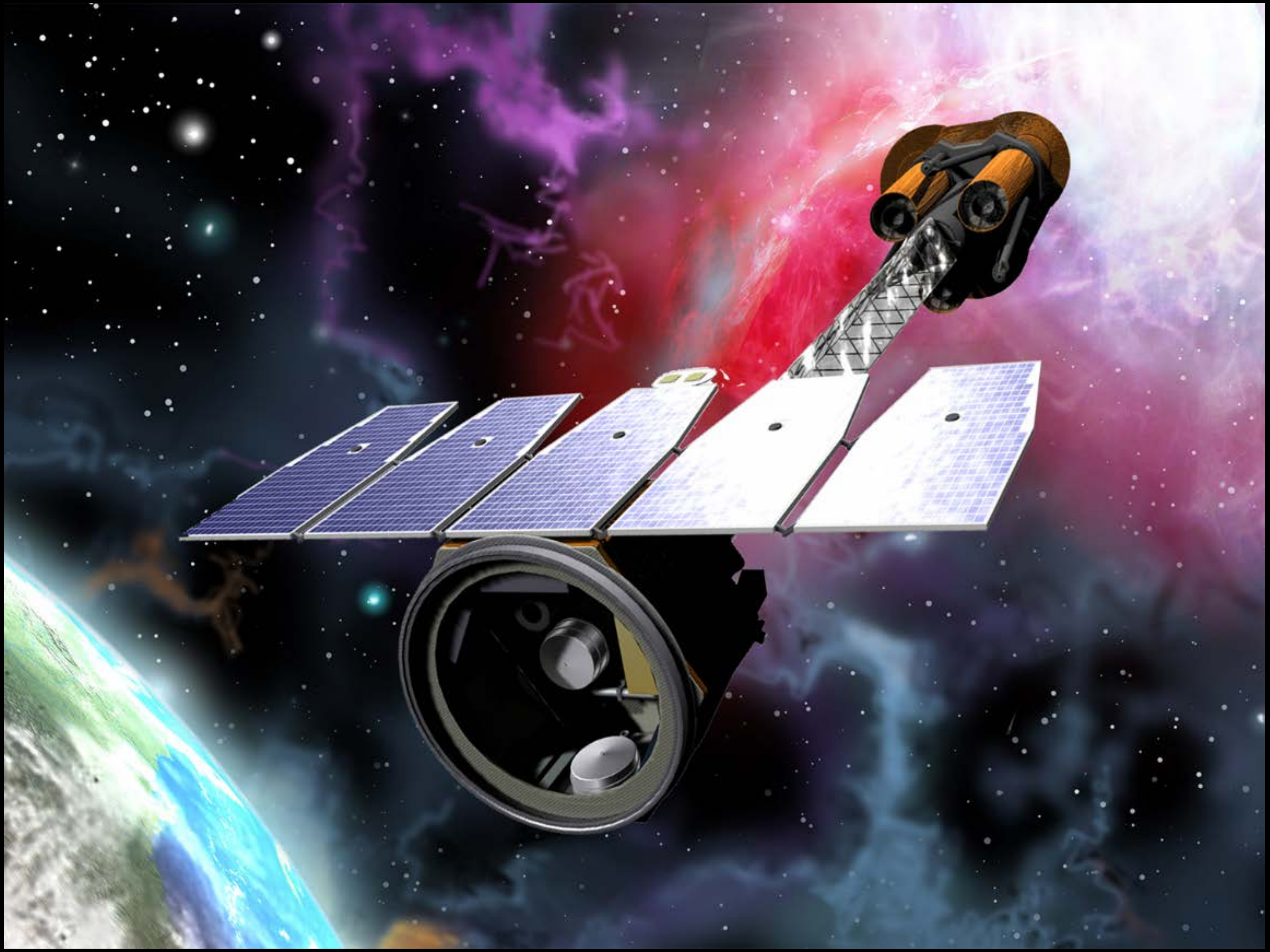
# Electron tracking

Site of initial ionization and Auger electron cloud produced by a 54 keV photon in a mixture of argon (90%), methane (5%), and trimethylamine (5%) at two atmospheres

Austin and Ramsey (1992)

# Imaging X-ray Polarimetry Explorer (IXPE)

- Three sets of identical X-ray mirror modules and imaging, polarization-sensitive detectors



# IXPE new science with new capabilities

- Opens a new window on the universe — imaging (30“) X-ray polarimetry
- Addresses key questions, providing new scientific results and constraints
  - What is the spin of a black hole?
  - What are the geometry and magnetic-field strength in magnetars?
  - Was our Galactic Center an Active Galactic Nucleus in the recent past?
  - What is the magnetic field structure in synchrotron X-ray sources?
  - What are the geometries and origins of X-rays from pulsars (isolated and accreting)?
- Provides powerful and unique capabilities
  - Reduces observing time by a factor of 100 compared to OSO-8
  - Simultaneously provides imaging, spectral, timing, and polarization data
  - Is free of false-polarization systematic effects at less than 0.3%
  - Enables meaningful polarization measurements for many sources of different classes

# Institutions and countries involved

| | |
|---|---|
| NASA 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 | IAPS, INAF (Istituto Nazionale di Astrofisica, National Institute for Astrophysics), INFN: Polarization-sensitive imaging detector systems |
| | CU, LASP: Mission operations |
| ASI (agenzia spaziale italiana): Detector system funding, ground station | Roma Tre (Università degli Studi), Stanford University: Scientific theory |
| | McGill: Science Working Group Co-Chair |
| Ball: Spacecraft, payload structure, payload, observatory I&T | MIT (Massachusetts Institute of Technology): Co-Investigator |

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## Co-Investigators

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## Collaborators

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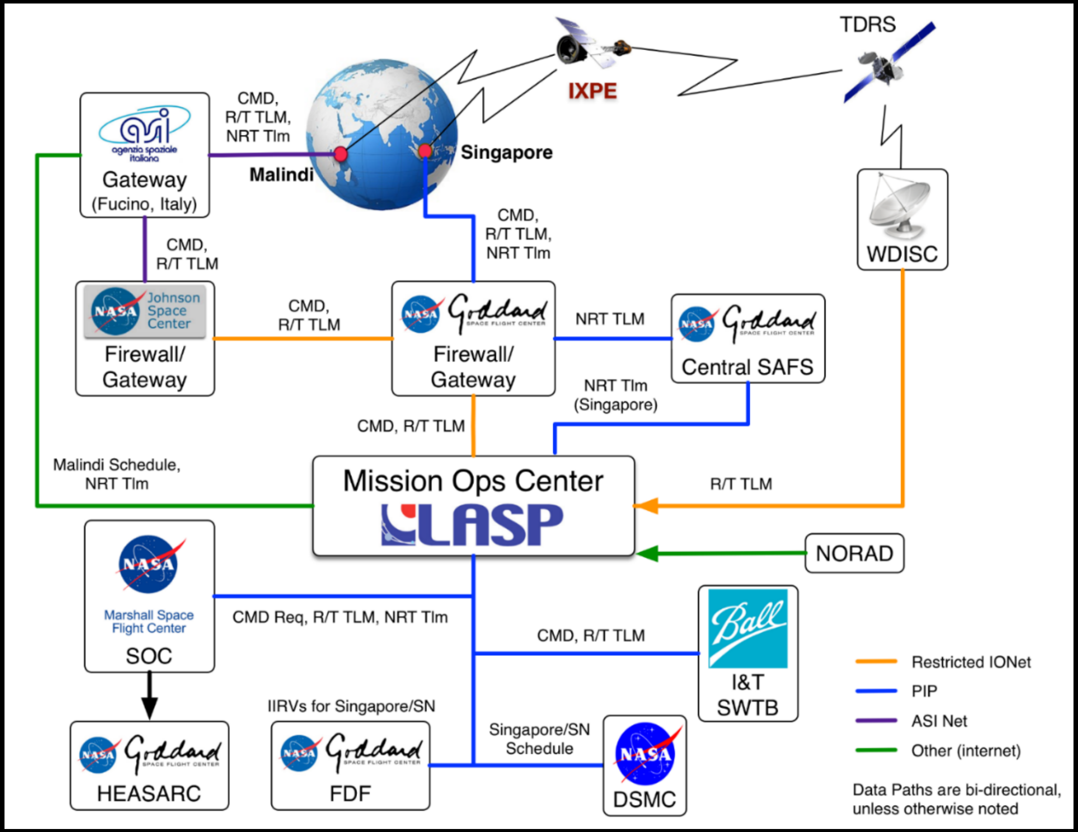
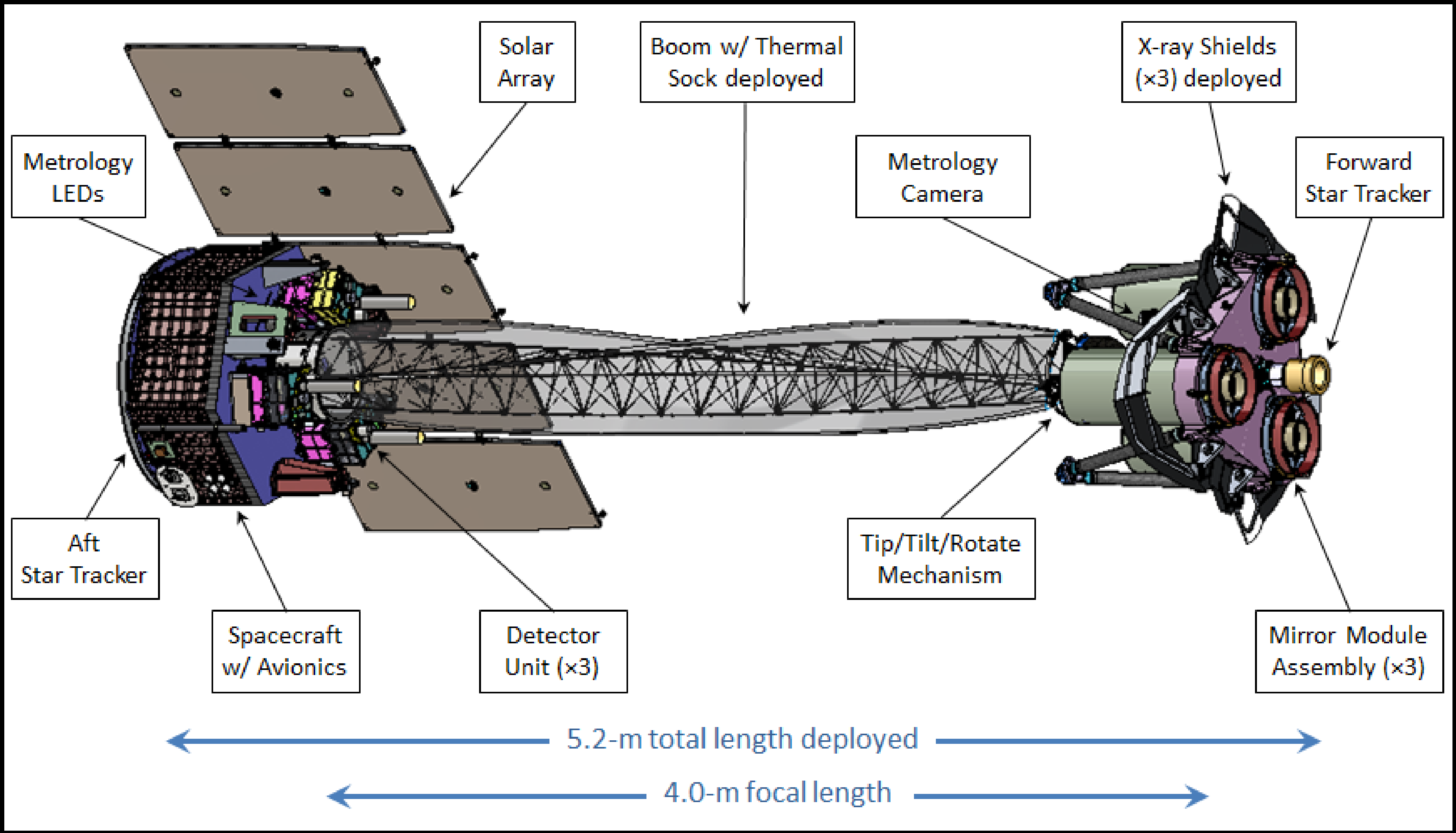
# IXPE mission overview

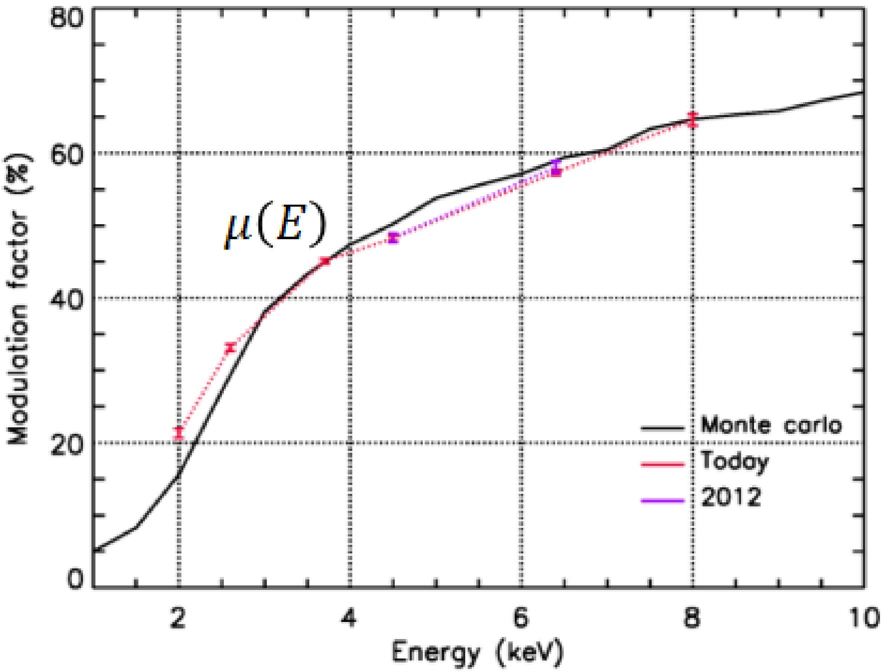
- Pegasus XL launch from Kwajalein
- Launch ready by early 2021
- 540-km circular orbit at 0° inclination
- 2-year baseline mission, 1 year extension
- Point-and-stare at known targets
- Malindi ground station (Singapore Backup)
- Mission Operations Center at CU/LASP
- Science Operations Center at MSFC

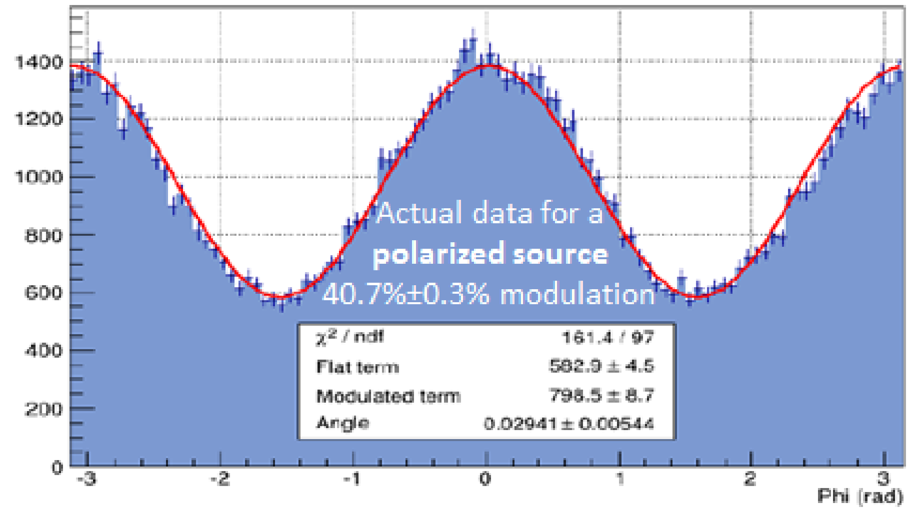


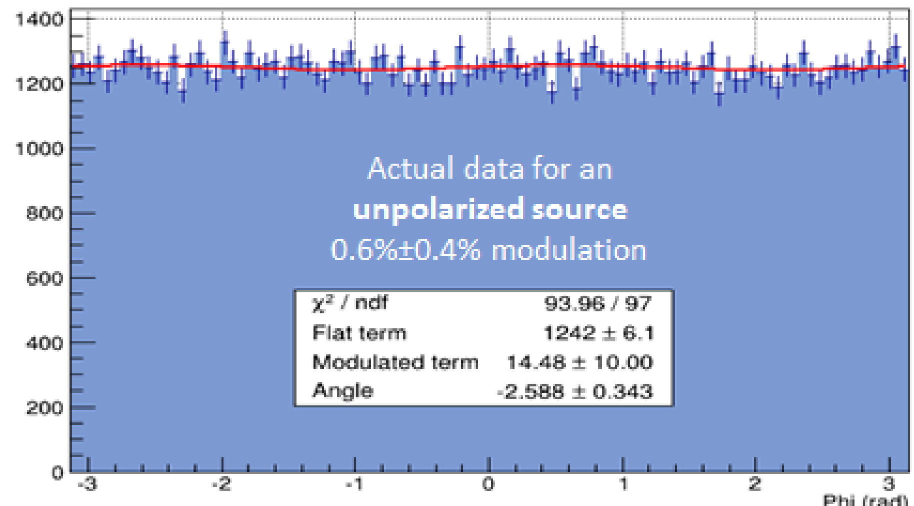
# IXPE deployed



- **Polarization degree**
  - $\Pi = \text{Modulation}/\mu(E)$



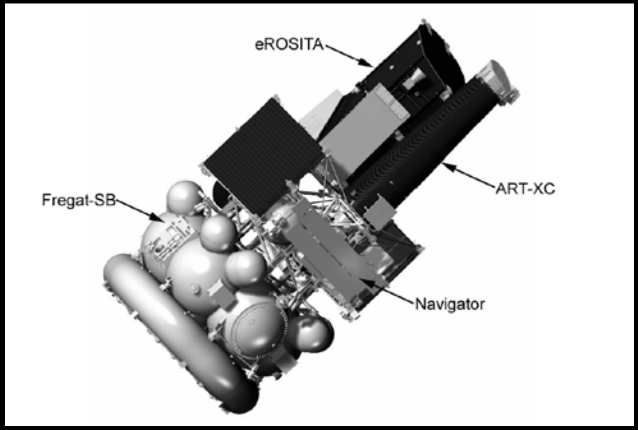



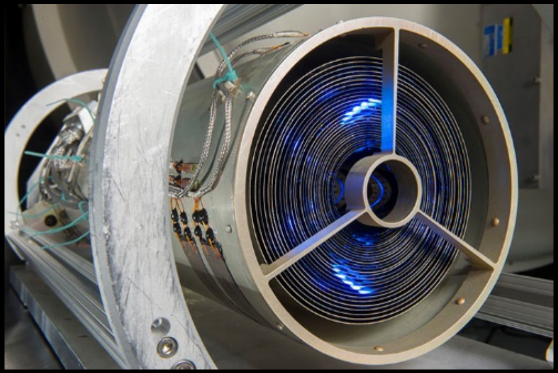
# Electroformed X-ray optics @ MSFC

**ART-XC (satellite)**
8 Modules, 28 shells, qualified and delivered for flight in 2018

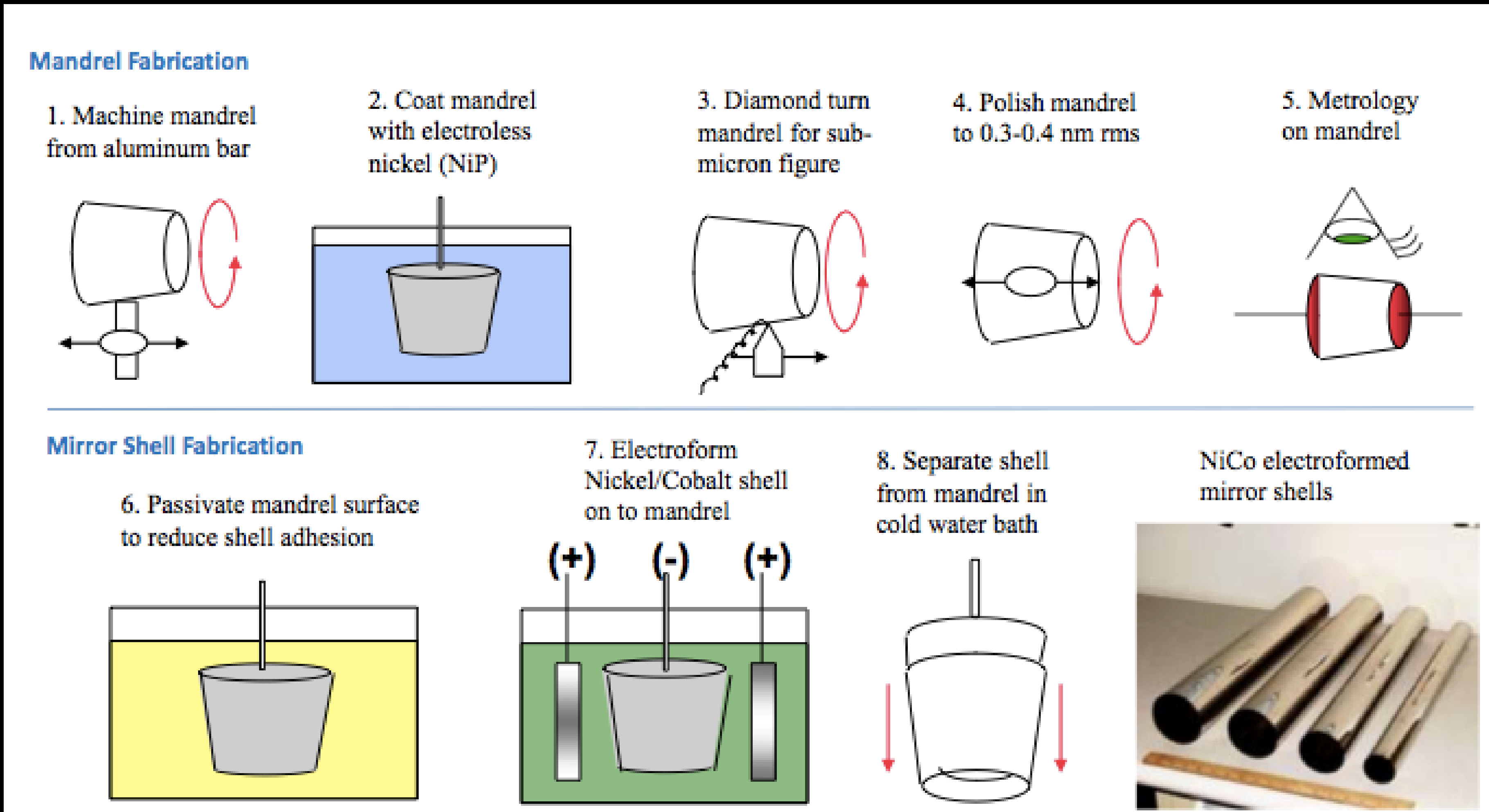
**FOXSI (rocket)**
7 Modules, 7/10 shells, flown in 2012 & 2014

**HERO/HEROES (balloon)**
8 Modules, 13/14 shells, latest flight in 2013



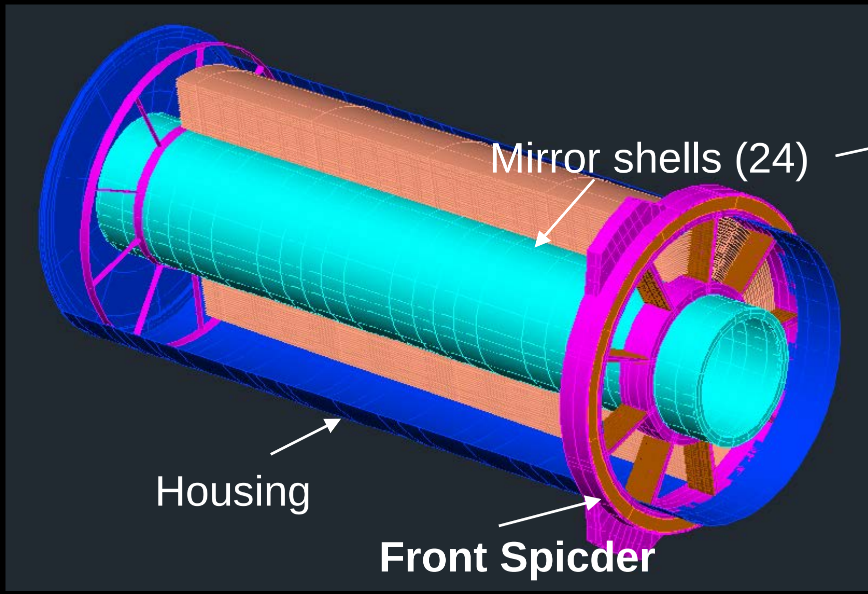



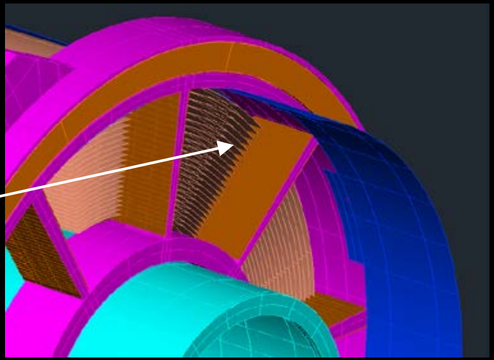
# Replication Process



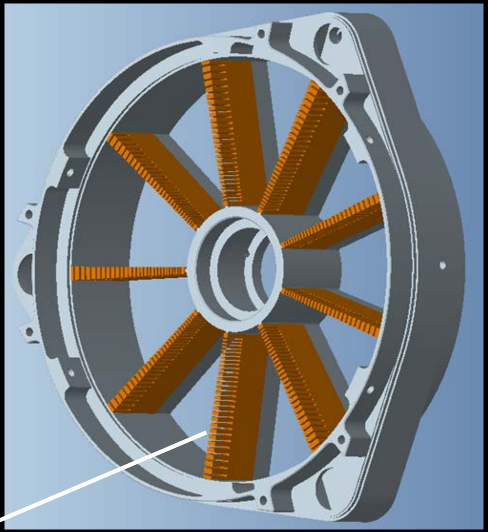
# Mirror Module Assembly

## IXPE Mirror Module Assembly



Front Spider



Shell Mounting Comb

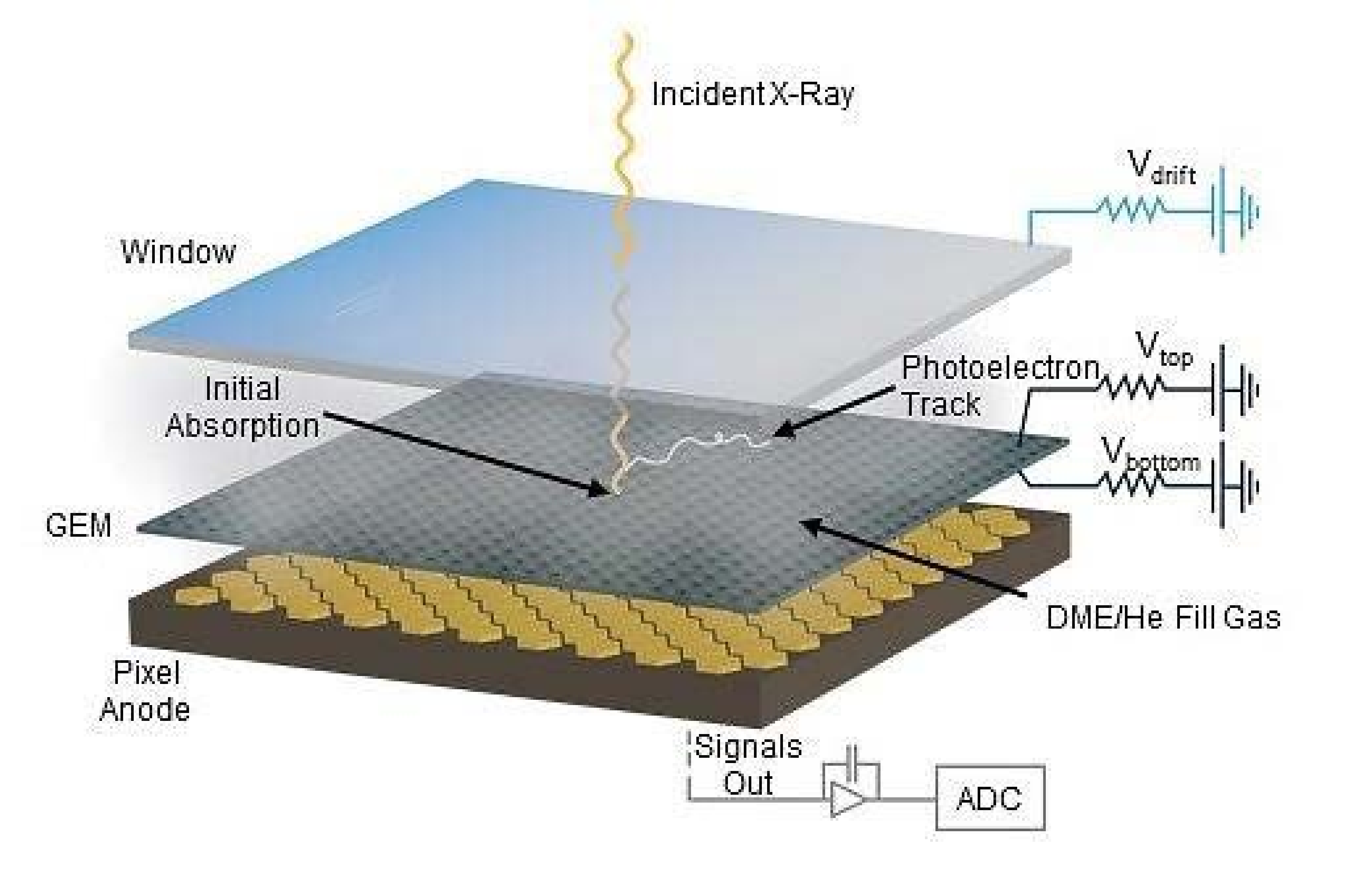
### Design approach

- Uses a single rigid spider to support the 24 nested shells and attach module to structure
- Light-weight housing mainly for thermal control
- Limit (rear) spider does not support mirror shells but limits their vibrations during launch
- Mounting combs provide shell attachment points

# The X-ray mirror modules

| Parameter | Value |
|---|---|
| Number of mirror modules | 3 |
| Number of shells per mirror module | 24 |
| Focal length | 4000 mm |
| Total shell length | 600 mm |
| Range of shell diameters | 162–272 mm |
| Range of shell thicknesses | 0.16–0.26 mm |
| Shell material | Electroformed nickel–cobalt alloy |
| Effective area per mirror module | 230 $cm^2$ (@ 2.3 keV); >240 $cm^2$ (3–6 keV) |
| Angular resolution (HPD) | ≤ 25 arcsec |
| Field of view (detector limited) | 12.9 arcmin square |

# The IXPE detectors



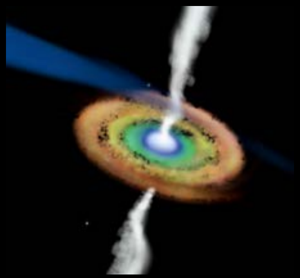

E. Costa et al. 2001, Bellazzini 2006, Bellazzini 2007

# The polarization sensitive detectors

| Parameter | Value |
|---|---|
| Sensitive area | 15 mm × 15 mm |
| Fill gas and composition | He/DME (20/80) @ 1 atm |
| Detector window | 50-µm thick beryllium |
| Absorption and drift region depth | 10 mm |
| GEM (gas electron multiplier) | copper-plated 50-µm liquid-crystal polymer |
| GEM hole pitch | 50 µm triangular lattice |
| Number ASIC readout pixels | 300 × 352 |
| ASIC pixelated anode | Hexagonal @ 50-µm pitch |
| Spatial resolution (FWHM) | ≤ 123 µm (6.4 arcsec) @ 2 keV |
| Energy resolution (FWHM) | 0.54 keV @ 2 keV ($\propto \sqrt{E}$) |

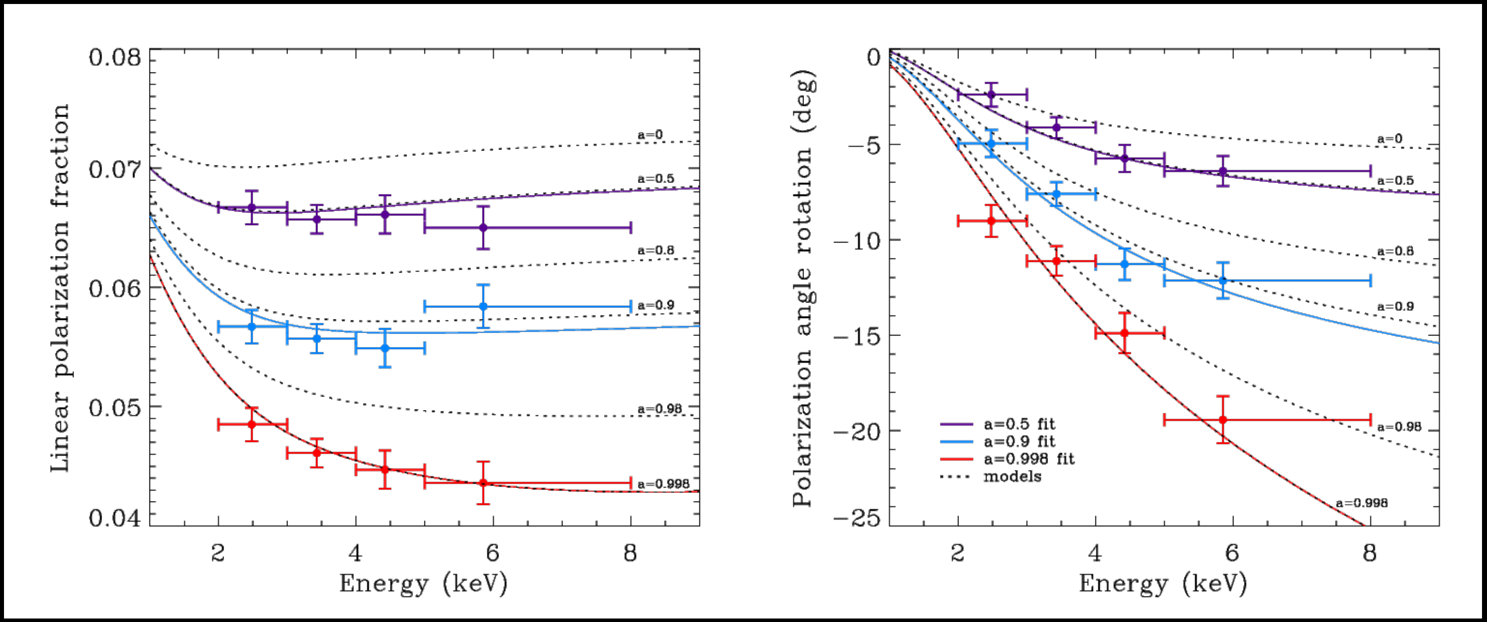
# Measure black-hole spin in twisted space-time

- For a micro-quasar GRX1915+105 in an accretion dominated state
  - Scattering polarizes the thermal disk emission
  - Polarization rotation is greatest for emission from inner disk
    - Inner disk is hotter, producing higher energy X-rays
  - Priors on disk orientation also constrain model

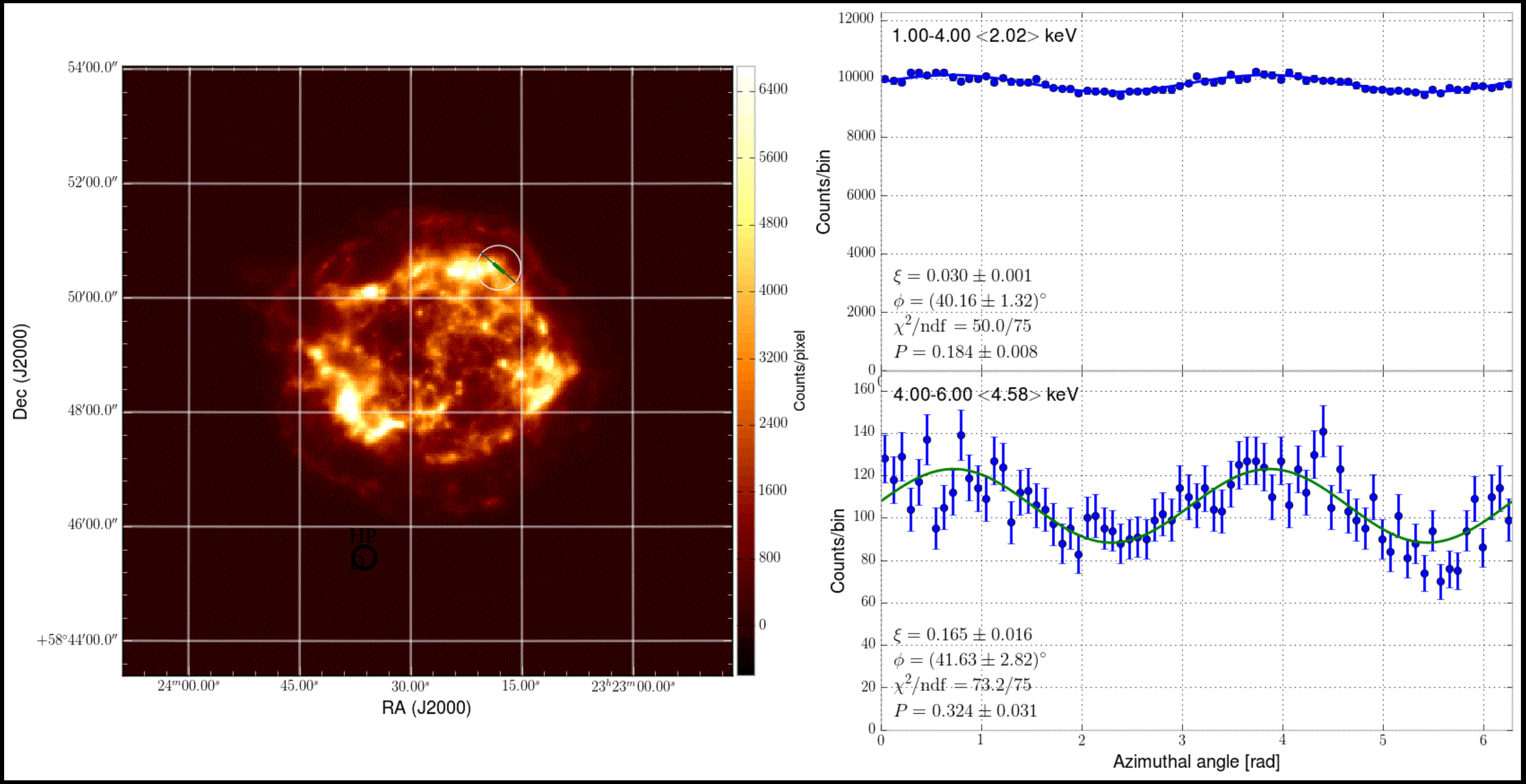


a = 0.50±0.04; 0.900±0.008; 0.99800±0.00003

(200-ks observation)



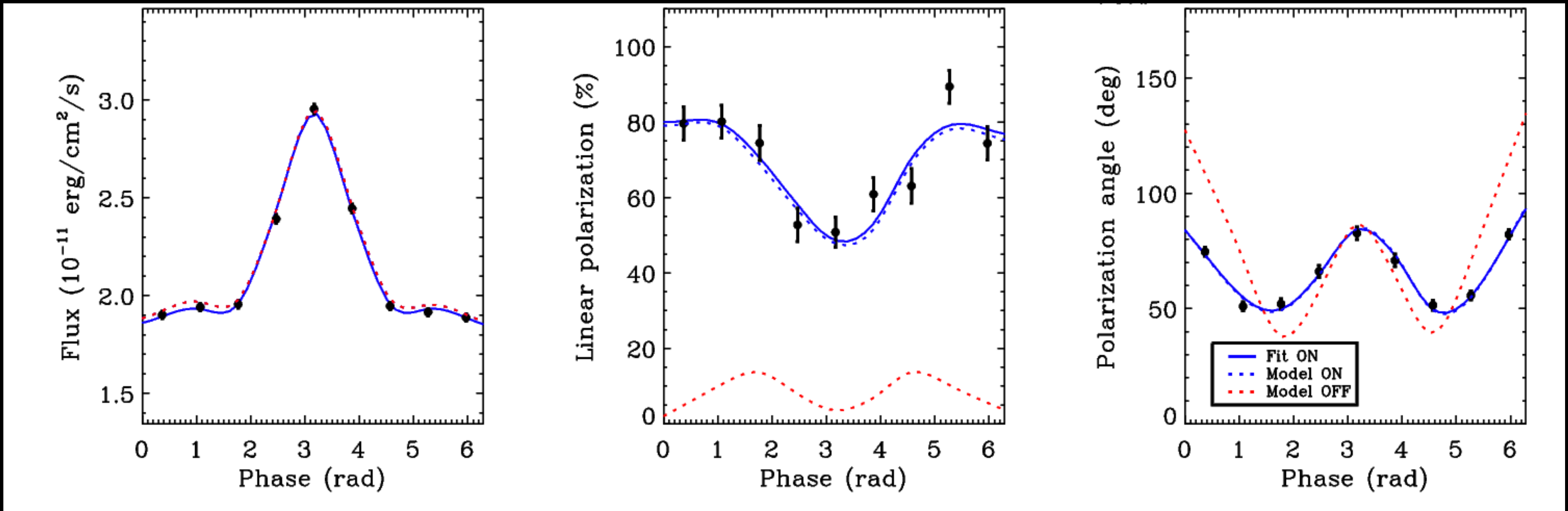
- Probe sites of cosmic-ray acceleration: Cas A
  - Lines and thermal continuum dominate 1-4 keV
  - Non-thermal emission dominates 4-6 keV




Cas A image at *IXPE* resolution (1.5-Ms)

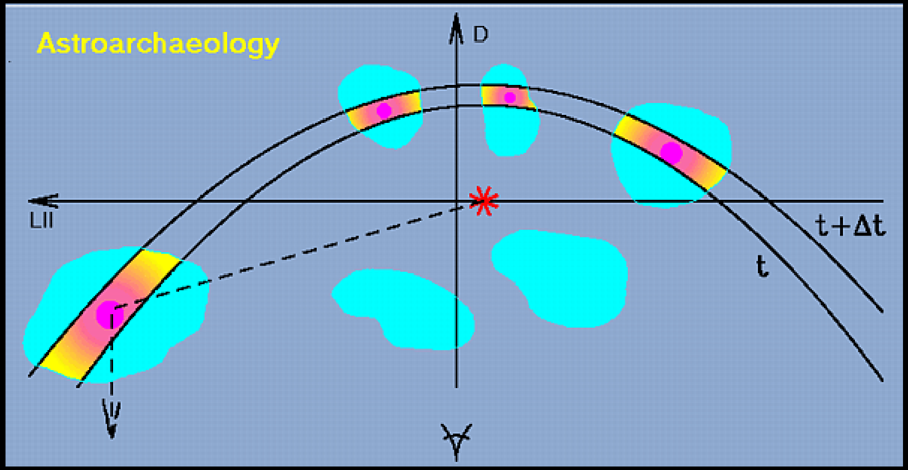
# Test quantum electrodynamics

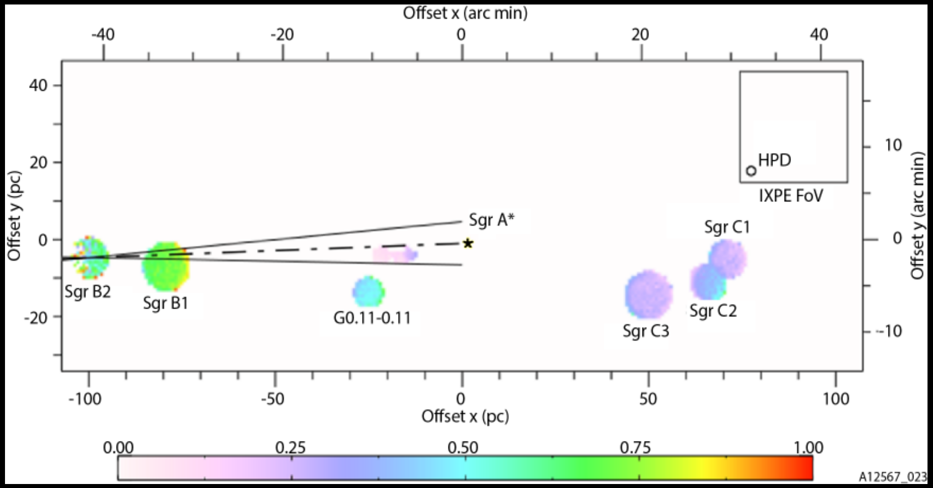
- Magnetar is a neutron star with magnetic field up to $10^{15}$ Gauss
  - Non-linear QED predicts magnetized-vacuum birefringence
    - Refractive indices of the two polarization modes differ from 1 and each other
    - Impacts polarization and position angle as functions of pulse phase
  - Example is the magnetar 1RXS J170849.0-400910, with an 11-s pulse period
    - Can easily exclude QED-off at better in 250-ks observation



# Was Sgr A* recently $10^6 \times$ more active?

- Galactic Center molecular clouds (MC) are known X-ray sources
  - If MCs reflect X-rays from Sgr A* (supermassive black hole in the Galactic center)
    - X-radiation would be *highly polarized* perpendicular to plane of reflection and indicates the direction back to Sgr A*
    - Sgr A* X-ray luminosity was $10^6$ larger ≈ 300 years ago

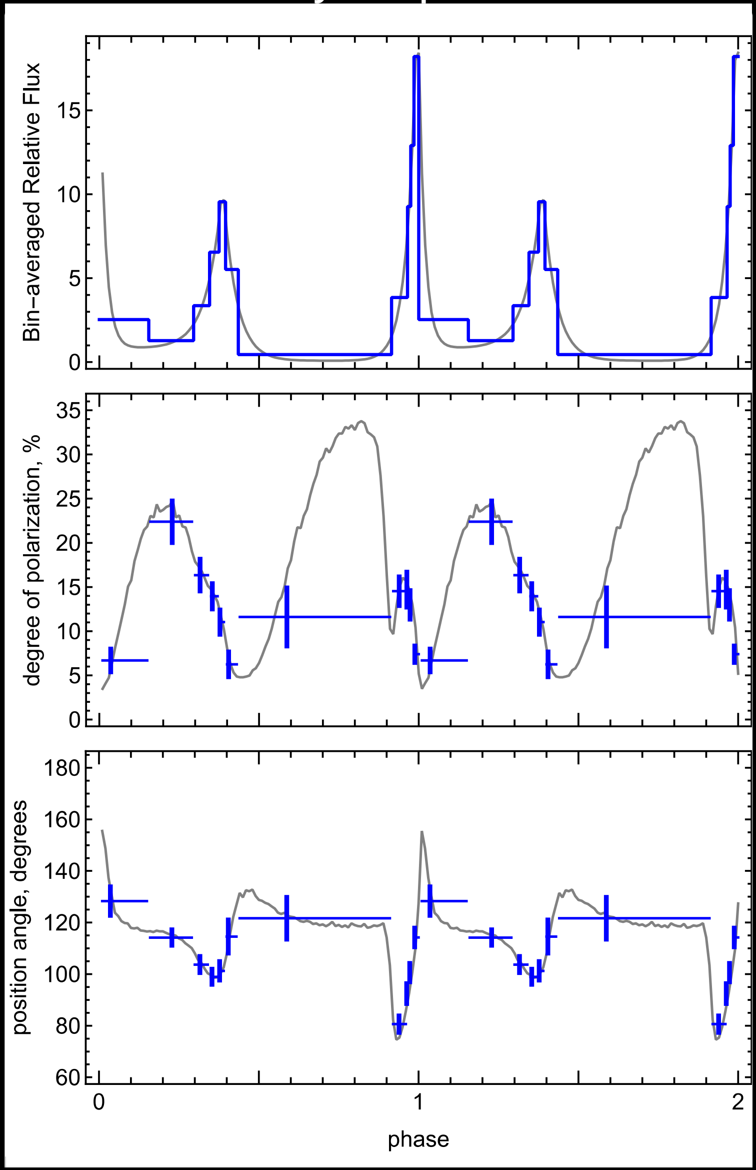


# Phase-resolved polarimetry: Crab Pulsar

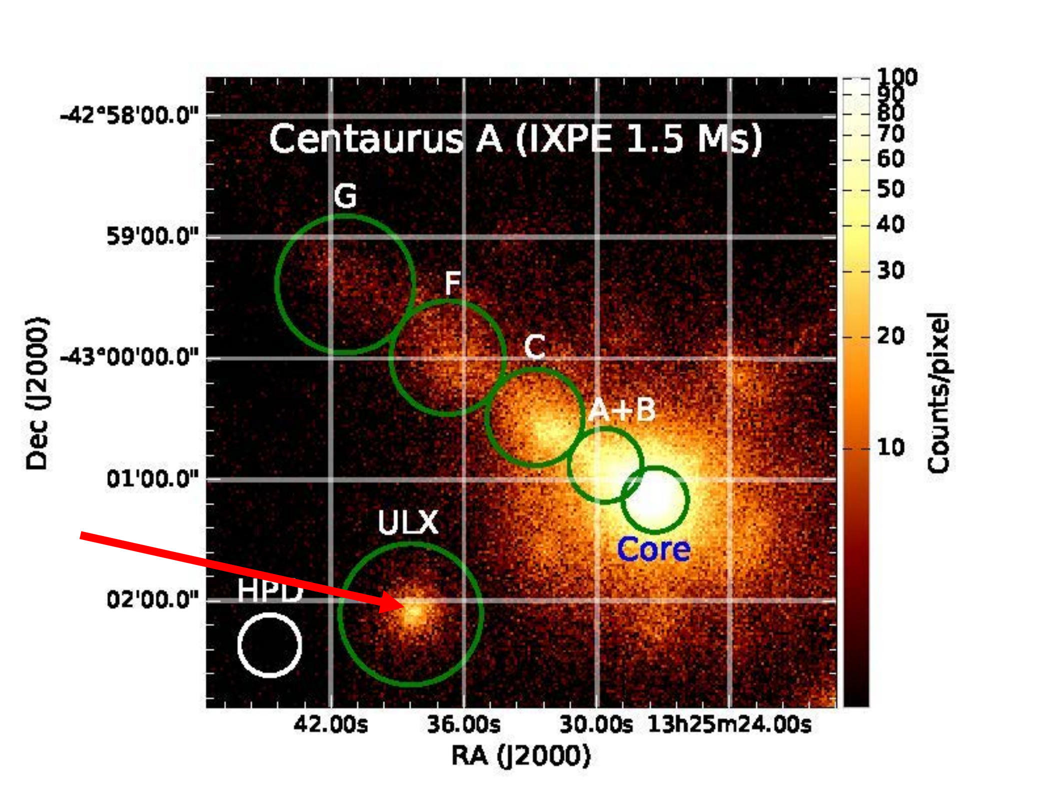
- Emission geometry and processes are unsettled
  - Competing models predict differing polarization behavior with pulse phase
- X-rays provide clean probe of geometry
  - process entirely different in radio band
  - We recently discovered no pulse phase-dependent variation in polarization degree  and position angle @ 1.4 GHz
  - Absorption likely more prevalent in visible band
- 140-ks observation gives ample statistics to track polarization degree and position angle

Grey = optical



# *IXPE* imaging of AGN

- Active galaxies are powered by supermassive BHs with jets
  - Radio polarization implies the magnetic field is aligned with jet
  - Different models for electron acceleration predict different dependence in X-rays
- Two Ultra Luminous X-ray sources (one to SW on detector but not visible in 6-arcmin-square displayed region)




| Region | $MDP_{99}$ |
|---|---|
| **Core** | **<7.0%** |
| **Jet** | **10.9%** |
| Knot A+B | 17.6% |
| Knot C | 16.5% |
| Knot F | 23.5% |
| Knot G | 30.9% |
| **ULX** | **14.8%** |

Includes effects of dilution by unpolarized diffuse emission

# Capturing the imagination