IXPE
Imaging
X-Ray
Polarimetry
Explorer

The Imaging X-ray Polarimetry Explorer

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Presentation to Caltech

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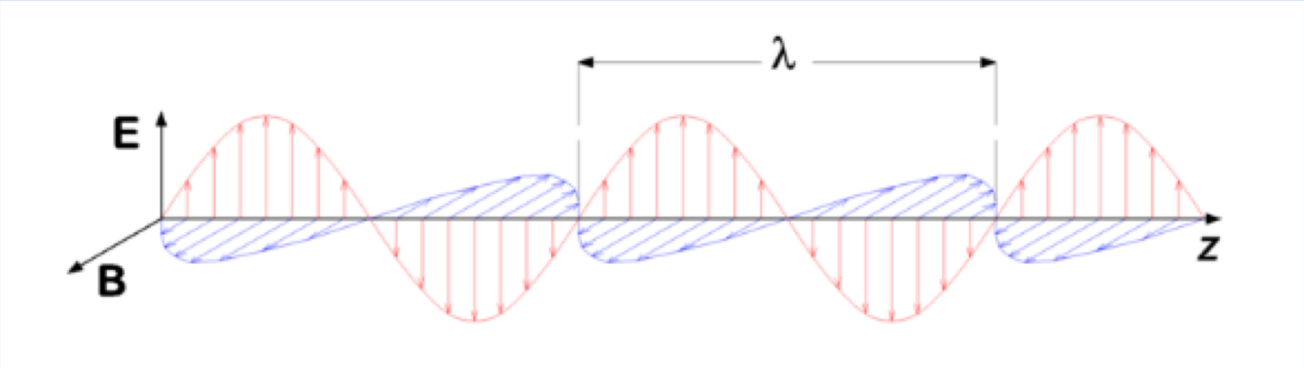
Brief Outline

- Polarimetry in the classical X-ray band (2-10 keV)
  - Sounding rocket experiments
  - OSO-8 crystal polarimeter
  - The Stellar X-ray Polarimeter on Spectrum-X
- IXPE
  - How it works
  - The science

POLARIZATION

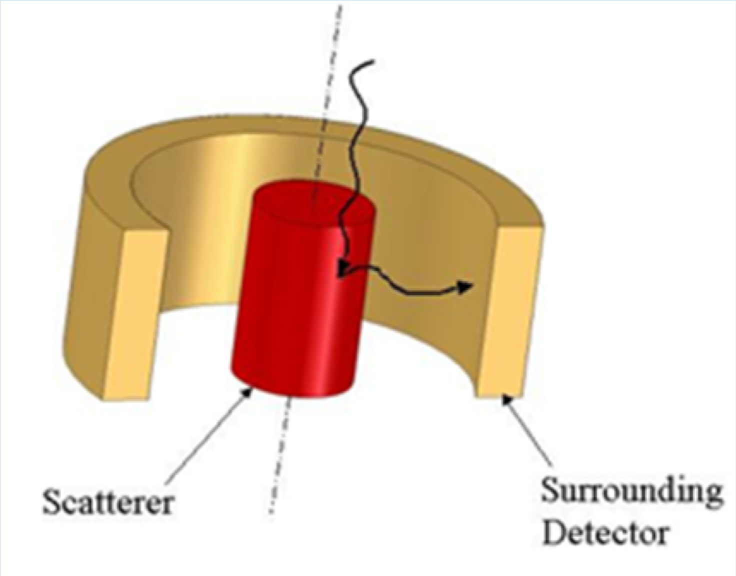
- **Polarization is a property of electro-magnetic waves connected with the direction of the electric and magnetic fields which are themselves transverse to the direction of propagation.**
- **It is the direction of the electric vector that determines the direction of the polarization**



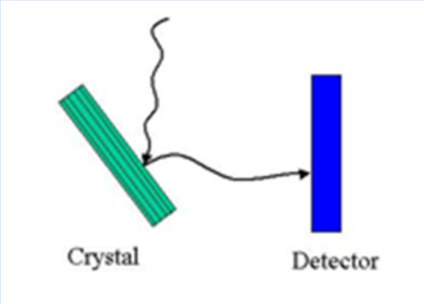
- **The degree of polarization and the "position angle on the sky" depend on the conditions under which the X-rays are produced**
- **Thus modeling of what we see must also predict the degree of polarization and the position angle**

HOW DOES ONE MEASURE X-RAY POLARIZATION?

- First devices were scattering polarimeters
  - The scattering material should be thick (deep) in order to effectively provide for interaction with all the incident photons.
  - The scattering material should be thin (narrow) in order to allow the scattered photon to easily escape.



- Bragg crystal polarimeters
  - Narrow band
  - Low efficiency



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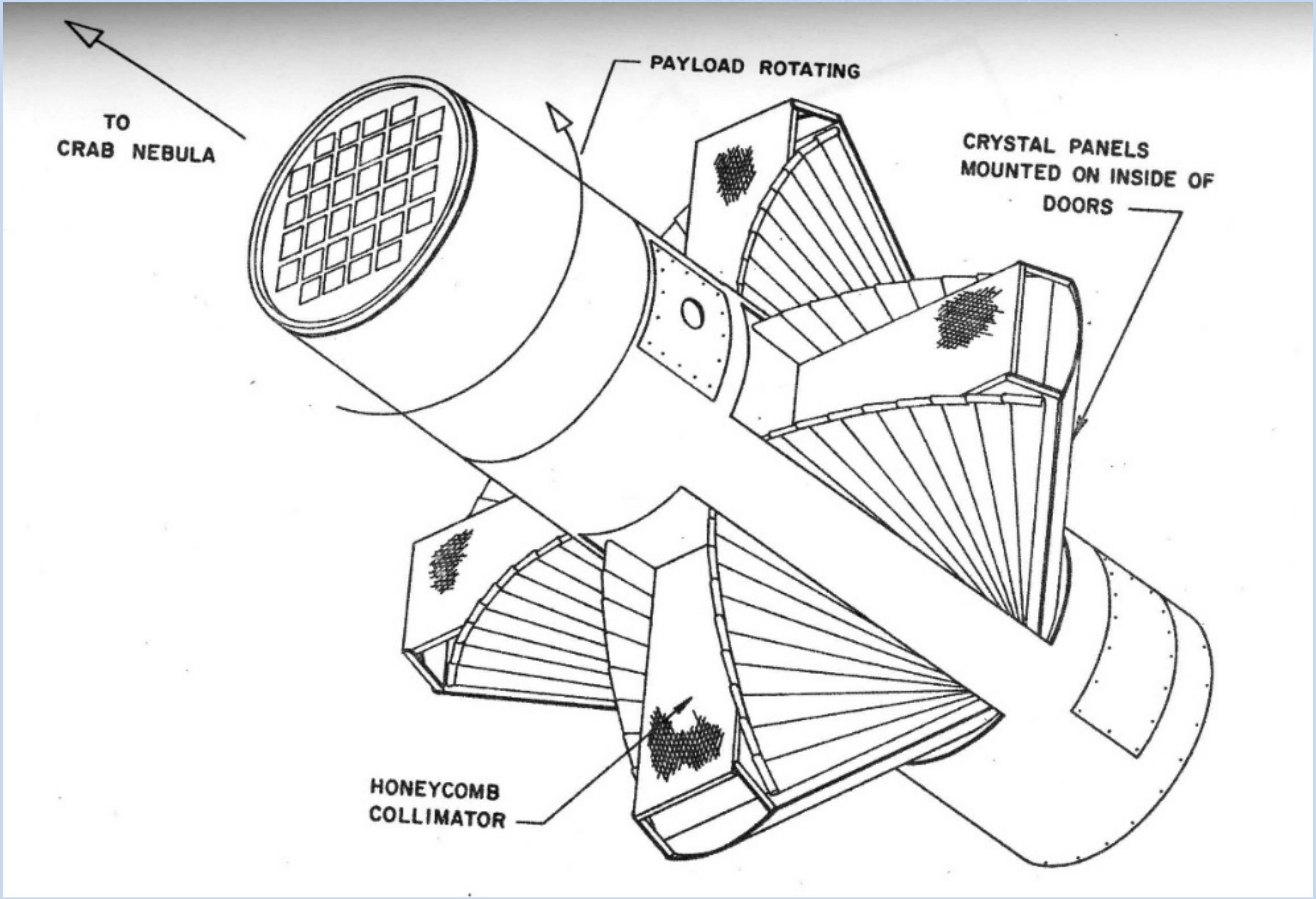
Rocket 17.09 (Aerobee 350) 1971



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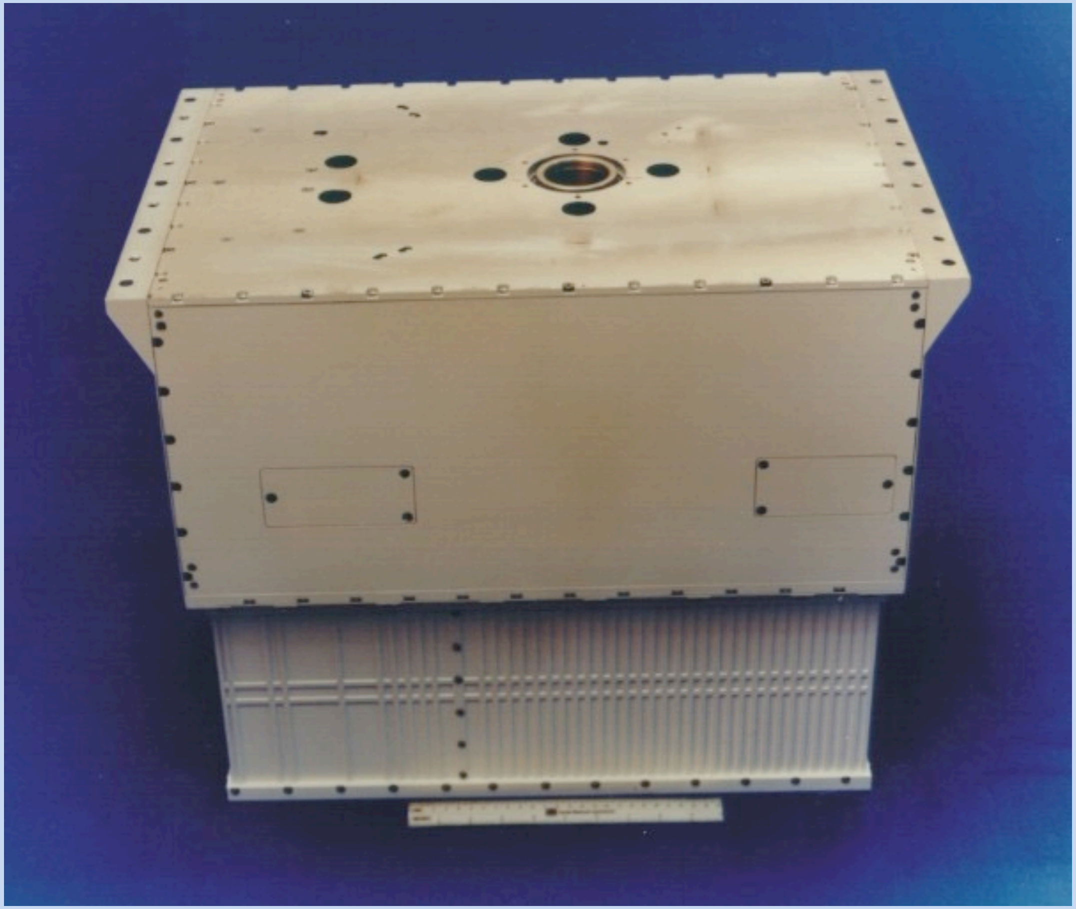
Rocket 17.09

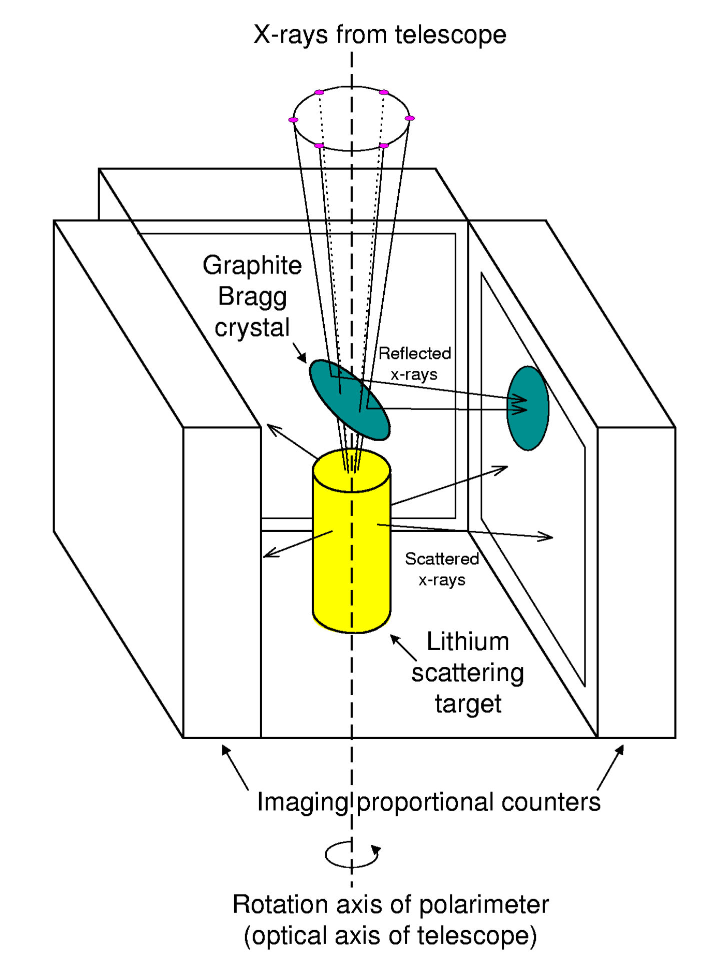
- Crab detection!
  - P = 15% ± 5%
  - ϕ = 156° ± 10°

Yes, I am the handsome one

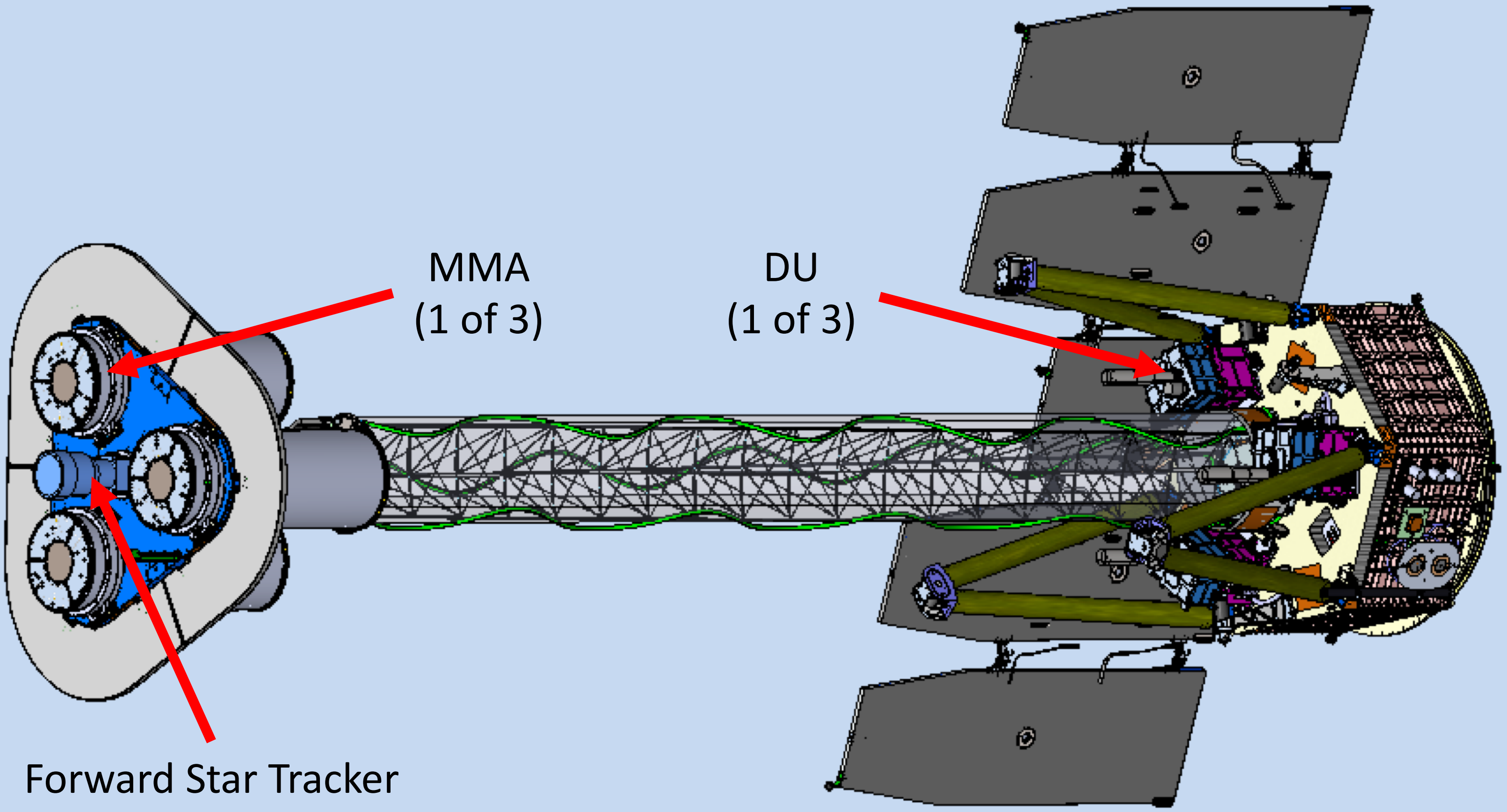
The Stellar X-ray Polarimeter (SXRP)

- **Planned to fly on the Russian Spectrum-X Gamma Mission in the early 1990s --- but was never launched**





IXPE DEPLOYED



5.2 m total length
4.0 m focal length

The IXPE Team

IXPE Imaging X-Ray Polarimetry Explorer

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, OAC, OHB Italia: Polarization-sensitive imaging detector systems
	CU, LASP: Mission operations
agenzia spaziale italiana: Detector system funding, ground station	Roma Tre Università degli Studi, Stanford University: Scientific theory
	McGill: Co-Investigator
Ball: Spacecraft, payload structure, payload, observatory I&T	MIT Massachusetts Institute of Technology: Co-Investigator

Science Advisory Team

SAT currently comprises > 90 scientists from 12 countries

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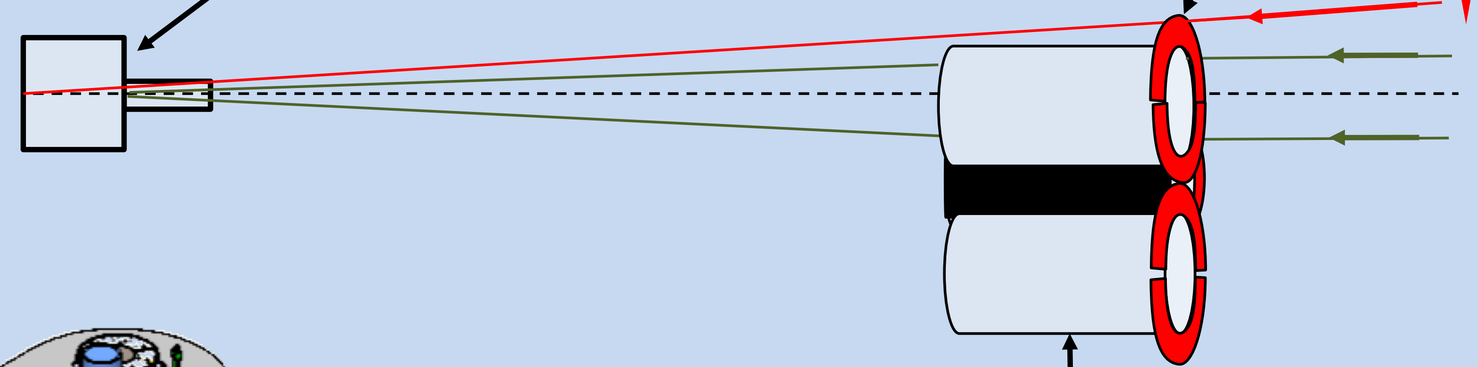
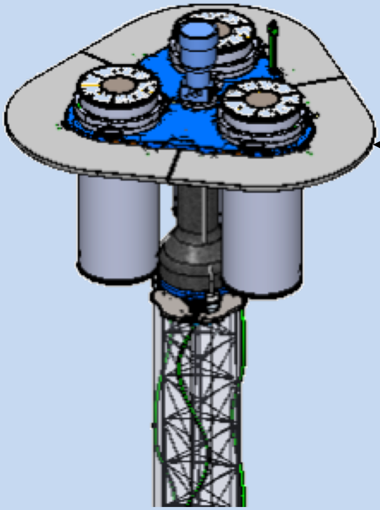
Mission Description

- Launch Fall 2021 on a Falcon 9 from KSC
- 600-km circular orbit at a nominal 0° inclination
- 2-year baseline mission, optional extension with GO program
- Point and stare (with dither) at pre-selected targets
- Malindi ground station - primary (Singapore - secondary)
- Mission Operations Center (MOC) at the University of Colorado, Laboratory for Atmospheric and Space Physics (LASP)
- Sciences Operations Center (SOC) at MSFC
- Data archiving at NASA's HEASARC
  - During the first 3 months of the mission, including one month of orbital checkout, all IXPE data shall be made publicly available at the HEASARC within 30 days of the end of an observation, which is defined as when data for 90% of the scheduled observation time are received by the MOC.
  - After the first 3 months of the mission, data shall be made available to the HEASARC within 1 week of the end of an observation, which is defined as when data for 90% of the scheduled observation time are received by the MOC.

Shield and Collimator Suppress Background





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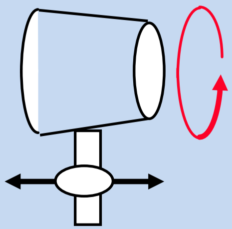
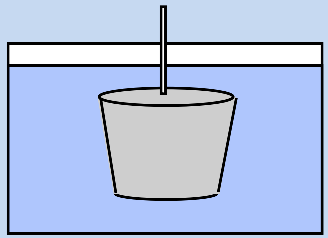
Mirror Production Process

Mandrel fabrication

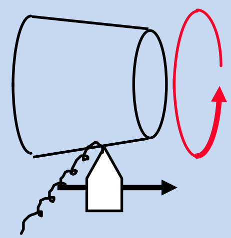
1. Machine mandrel from aluminum bar



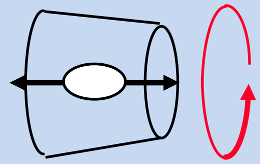
2. Coat mandrel with electroless nickel (Ni-P)



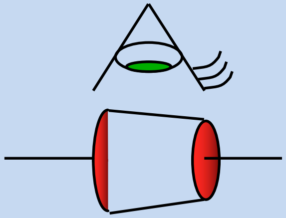
3. Diamond turn mandrel to sub-micron figure accuracy



4. Polish mandrel to 0.3-0.4 nm RMS

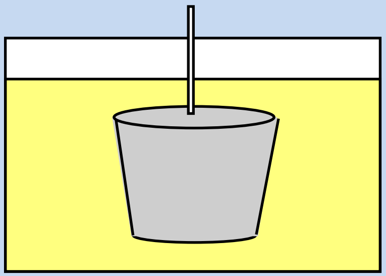


5. Conduct metrology on the mandrel

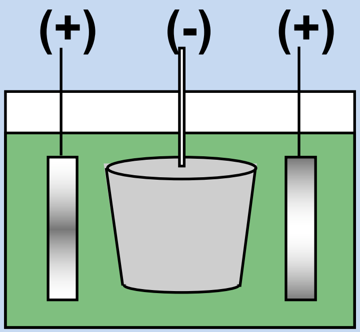


Mirror-shell forming

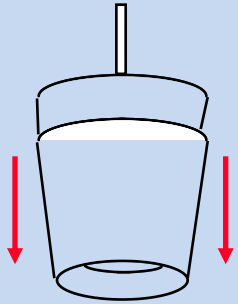
6. Passivate mandrel surface to reduce shell adhesion



7. Electroform Nickel/Cobalt shell onto mandrel



8. Separate shell from mandrel in chilled water



Ni/Co electroformed IXPE mirror shell

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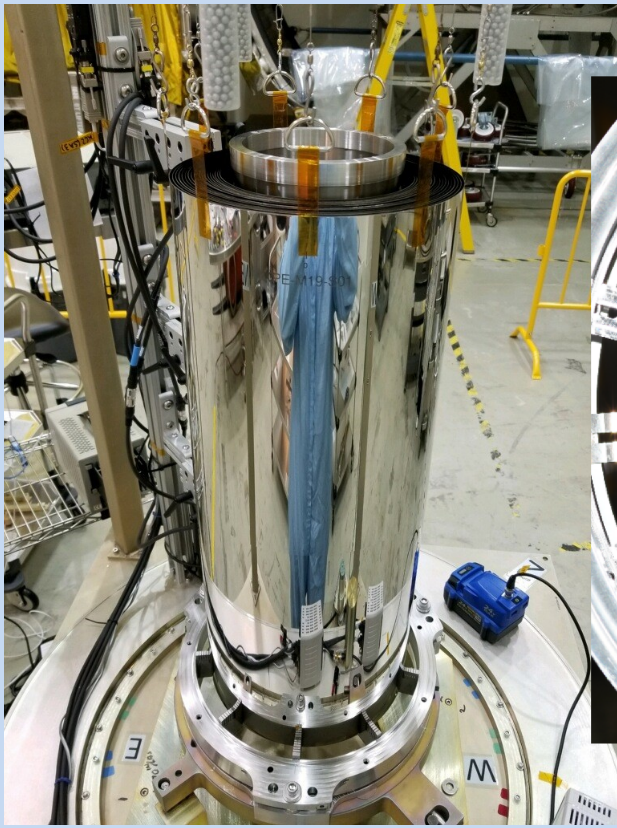
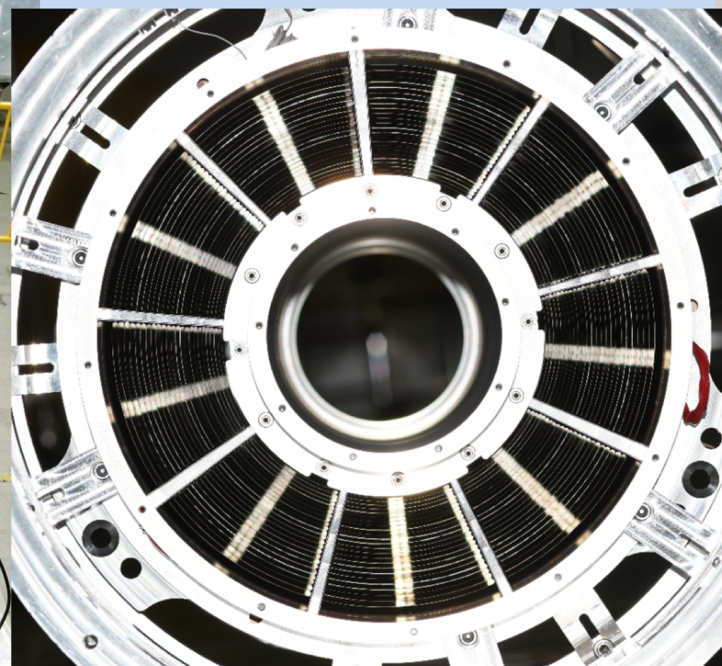
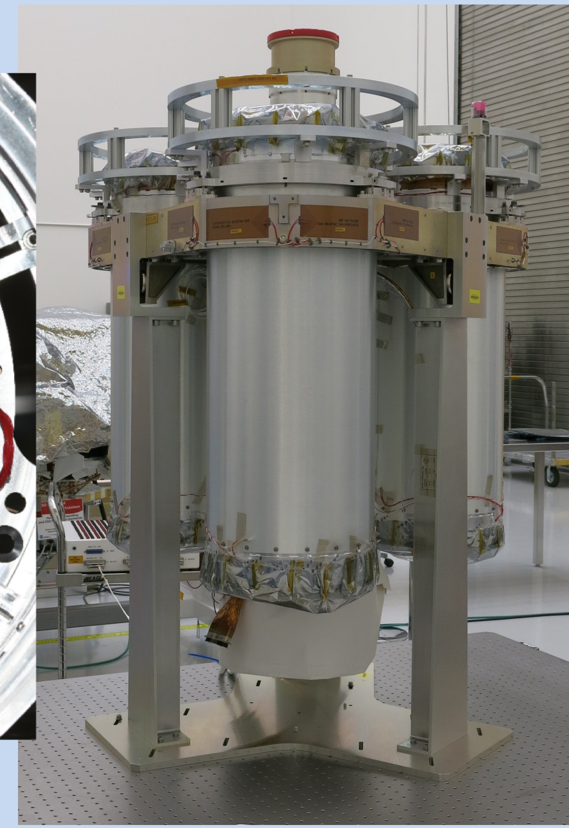
The Optics

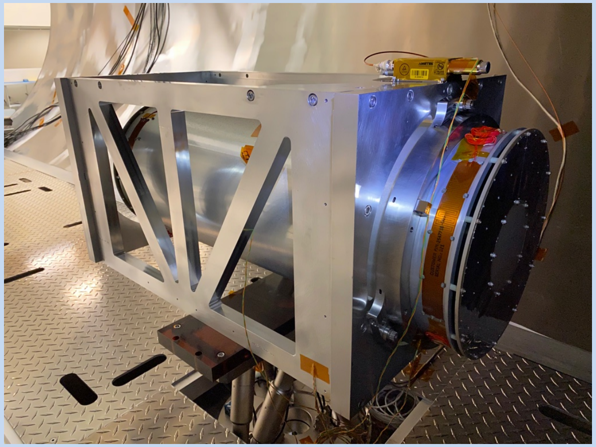


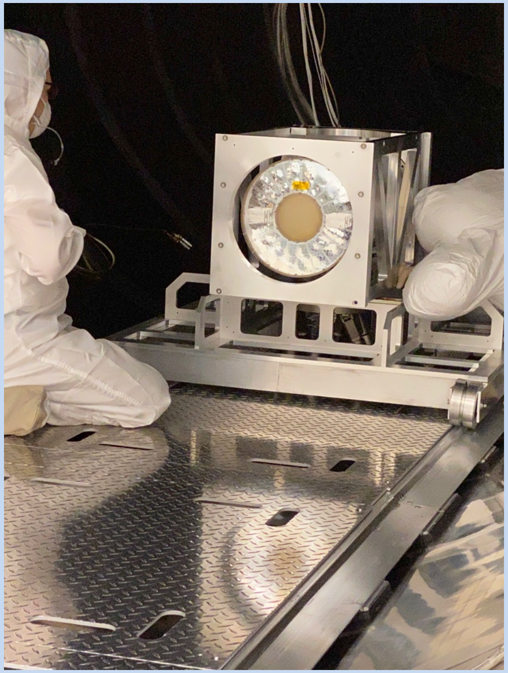


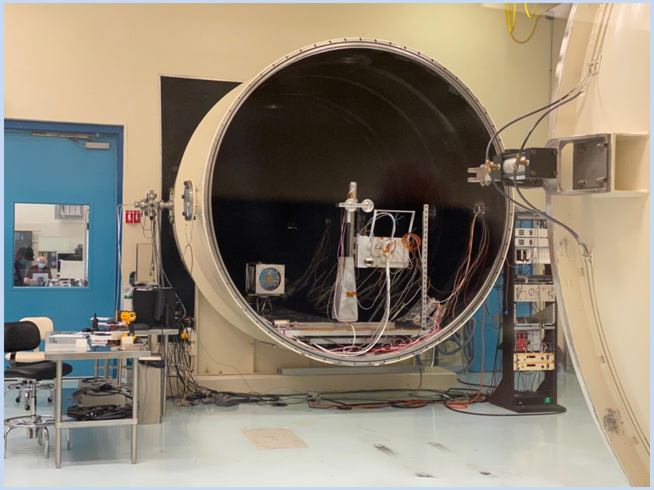


Stray Light Test Facility

- **X-ray calibration of the MMAs at MSFC's 100-m X-ray test facility**





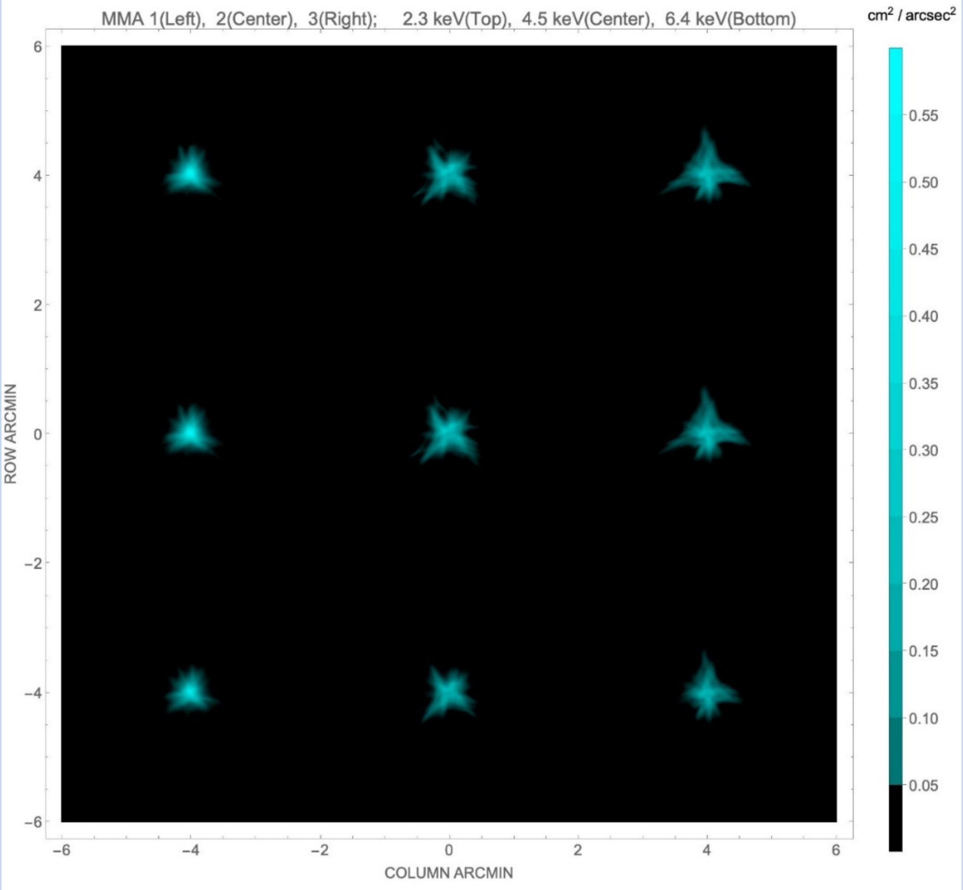


Angular Resolution

MMA	#1	#2	#3
6.4 keV	18.9″	24.8″	24.2″
4.5 keV	18.9″	25.0″	26.9″
2.3 keV	18.7″	24.5″	26.7″

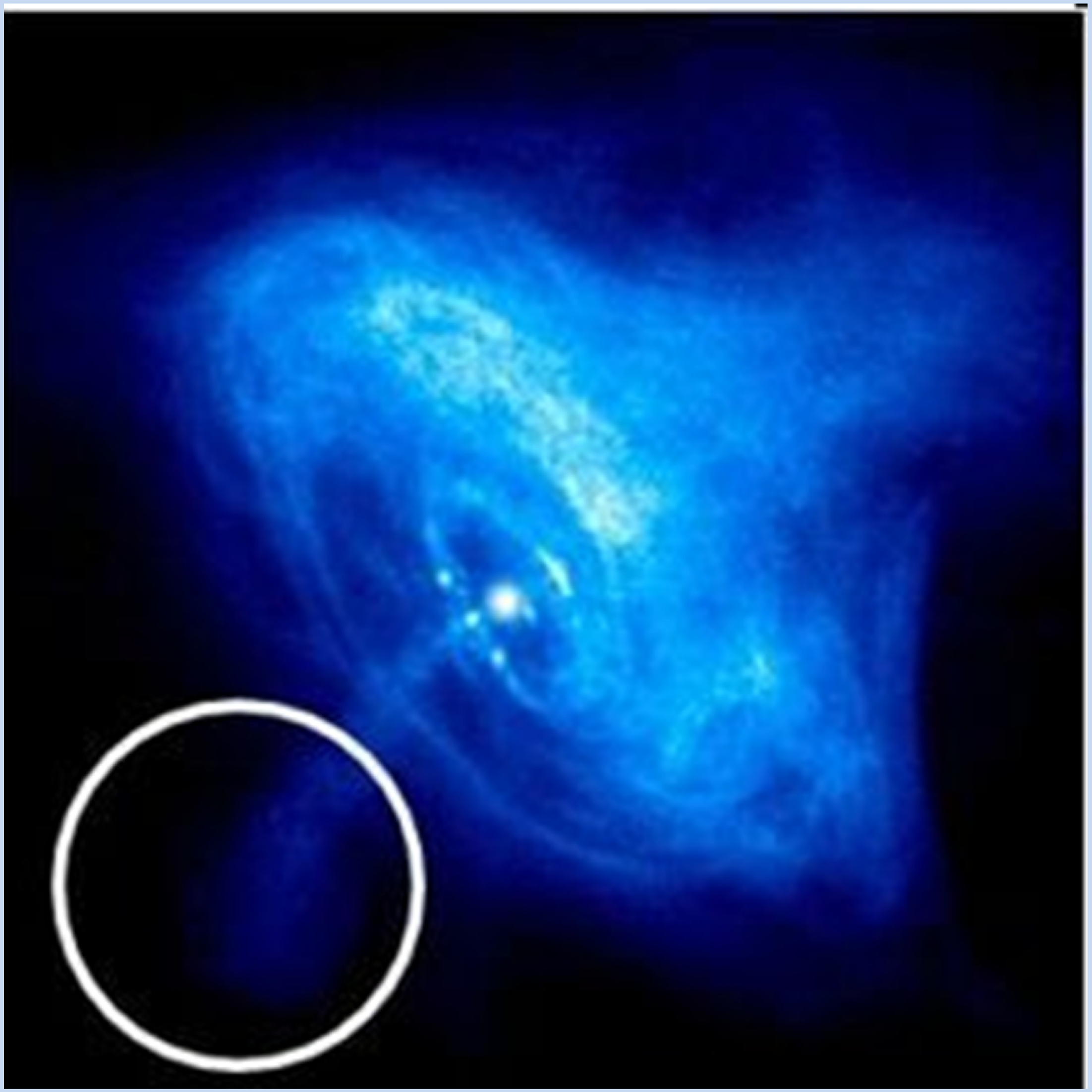
Values in the table are half-power diameters (HPDs) for the individual MMAs alone. These need to be adjusted for alignment errors, detector resolution, focus etc. to determine the on-orbit system-level resolution.

- **Based upon X-ray calibration and analysis, the system-level performance is 28″ HPD**



Imaging polarimetry

- **IXPE 30" half-power diameter on Chandra image**



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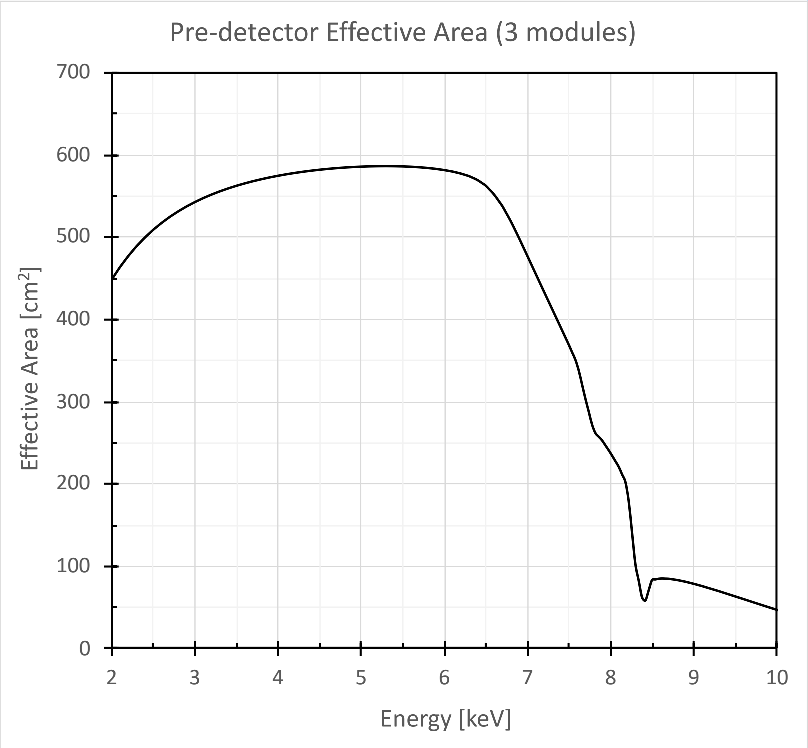
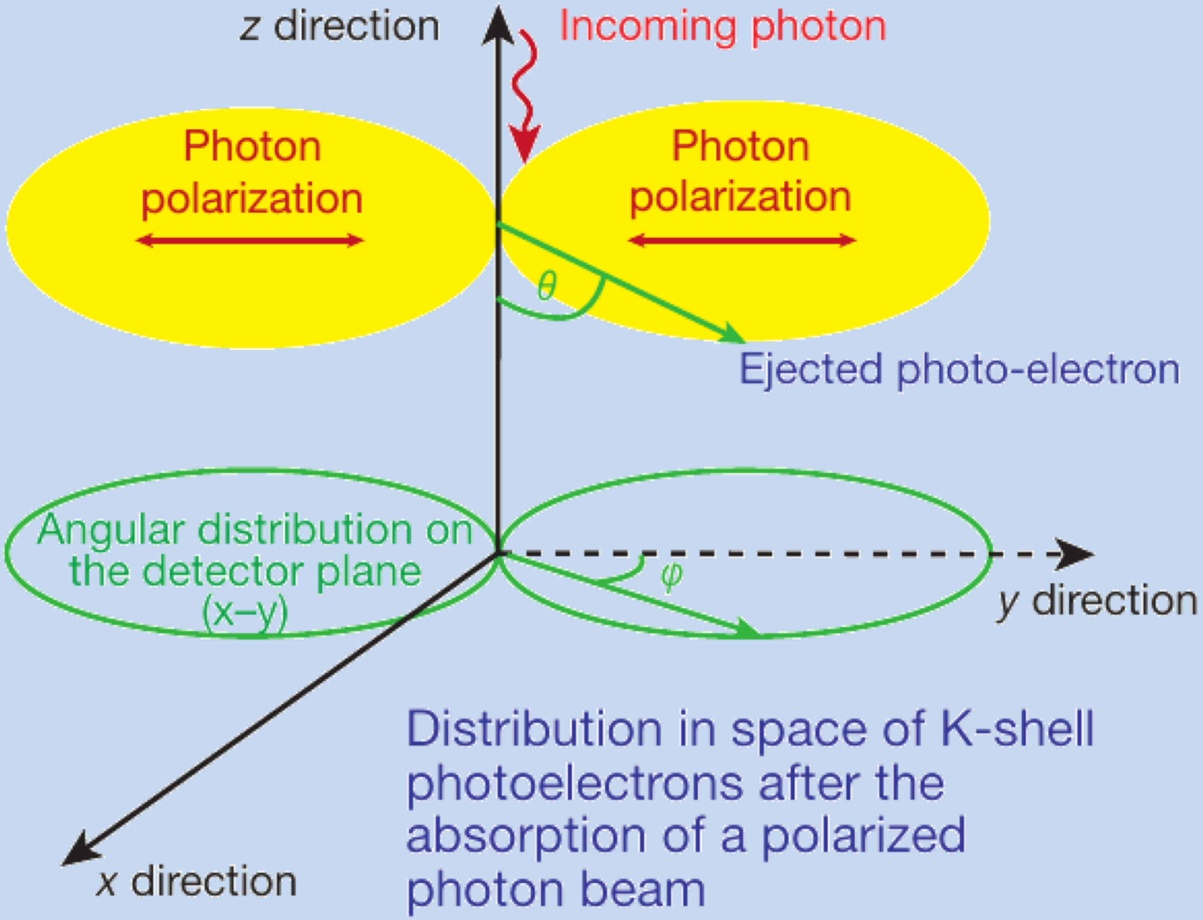
Mirror Module Assembly Properties

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)	95 kg with contingency



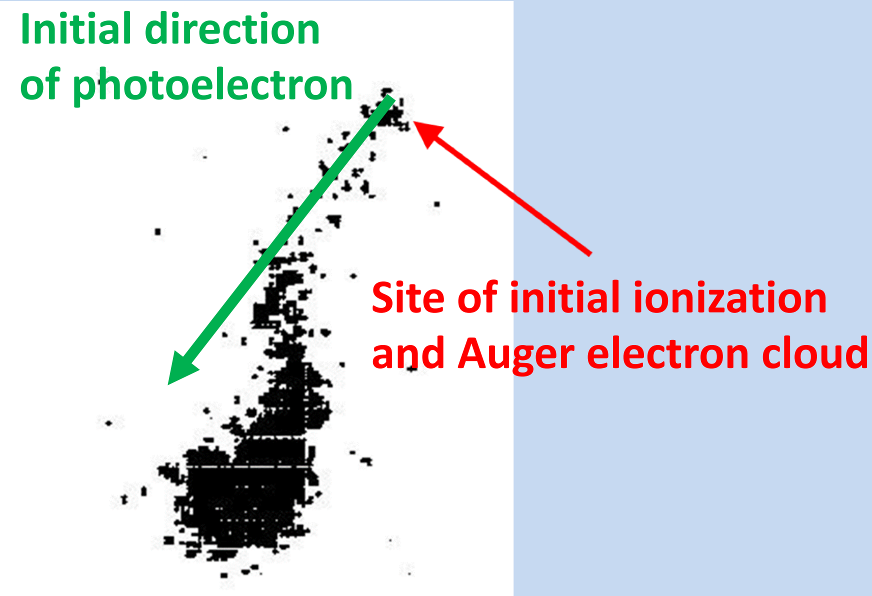
Detection Principle

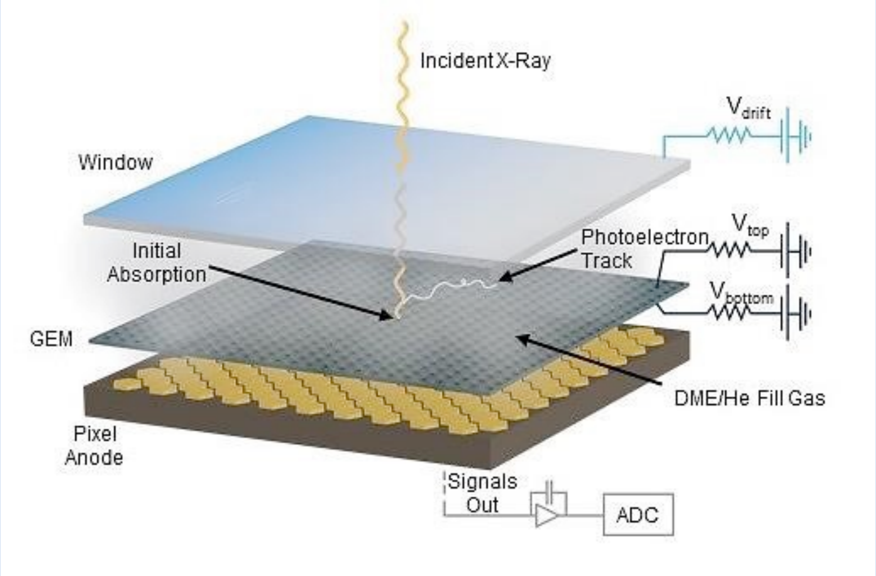
- **The detection principle is based on the photoelectric effect**



The Polarization-Sensitive Detectors

- **The initial direction of the K-shell photoelectron is determined by the orientation of the incident photon's electric vector**





The distribution of the photoelectron initial directions determines the degree of polarization and the position angle

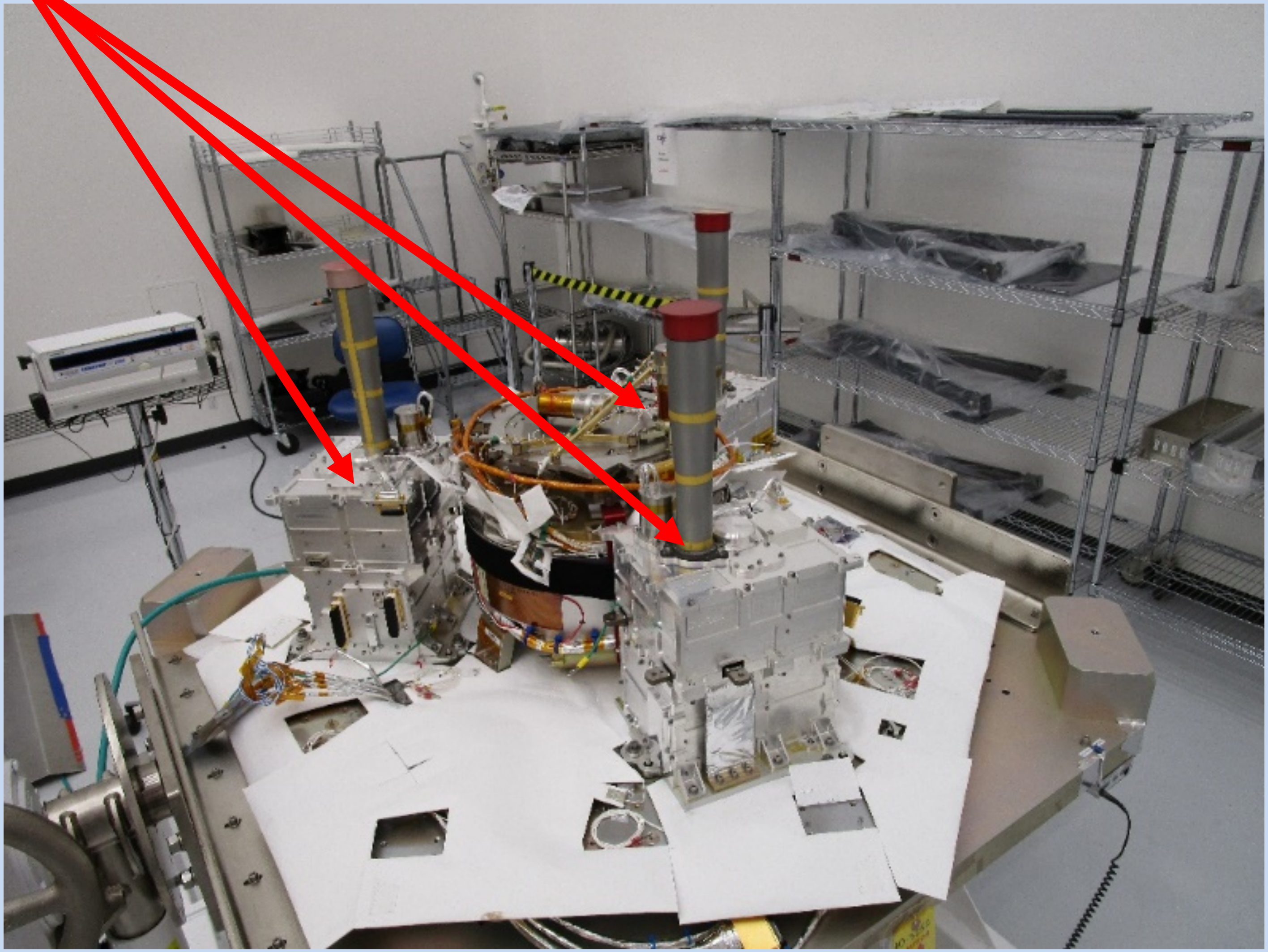
$$\frac{d\sigma}{d\Omega} = f(\zeta) r_0^2 Z^5 \alpha_0^4 \left(\frac{1}{\beta}\right)^{7/2} 4\sqrt{2}\sin^2\theta\cos^2\varphi\,, \text{ where } \beta \equiv \frac{E}{mc^2} = \frac{h\nu}{mc^2}$$

Detector Properties

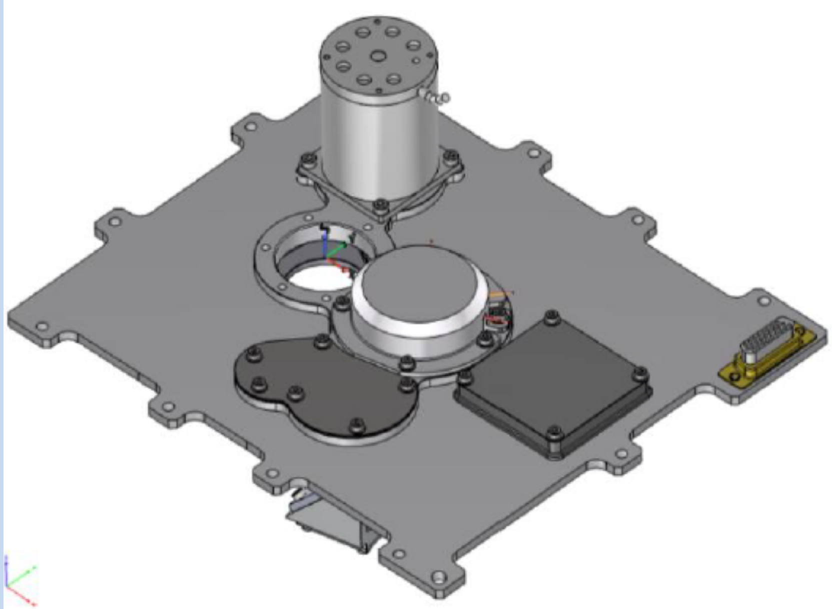
Parameter	Value
Sensitive area	15 mm × 15 mm (13 x 13 arcmin)
Fill gas and composition	DME @ 0.8 atmosphere
Detector window	50-µm thick beryllium
Absorption and drift region depth	10 mm
GEM (gas electron multiplier)	copper-plated 50-µm liquid-crystal polymer
GEM hole pitch	50 µm triangular lattice
Number 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)	0.57 keV @ 2 keV ($\propto \sqrt{E}$)
Useful energy range	2 - 8 keV

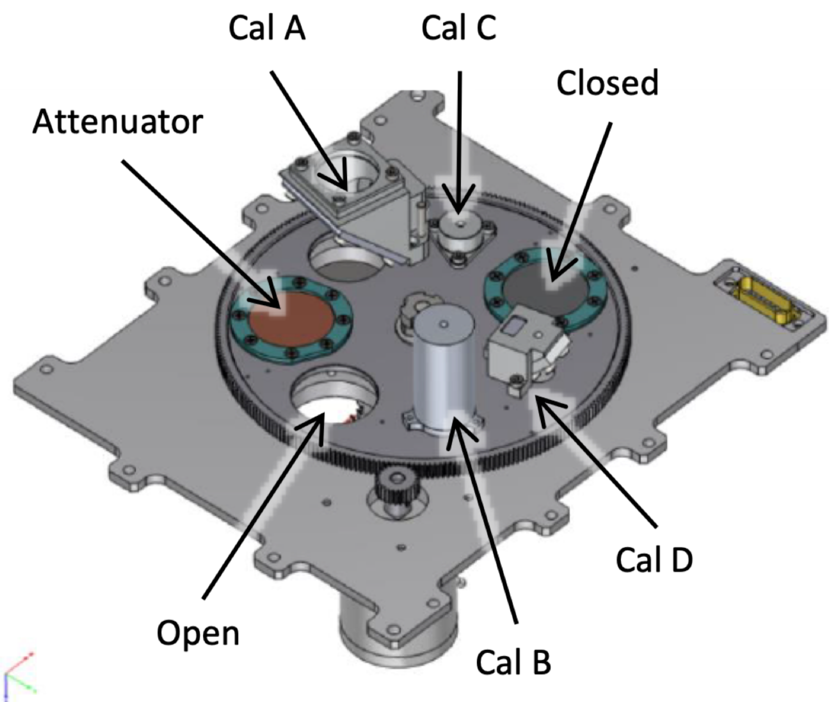
The Detectors

- **The Detector Units (DUs) mounted to the spacecraft top deck at Ball**



Filter Calibration Wheel Assembly



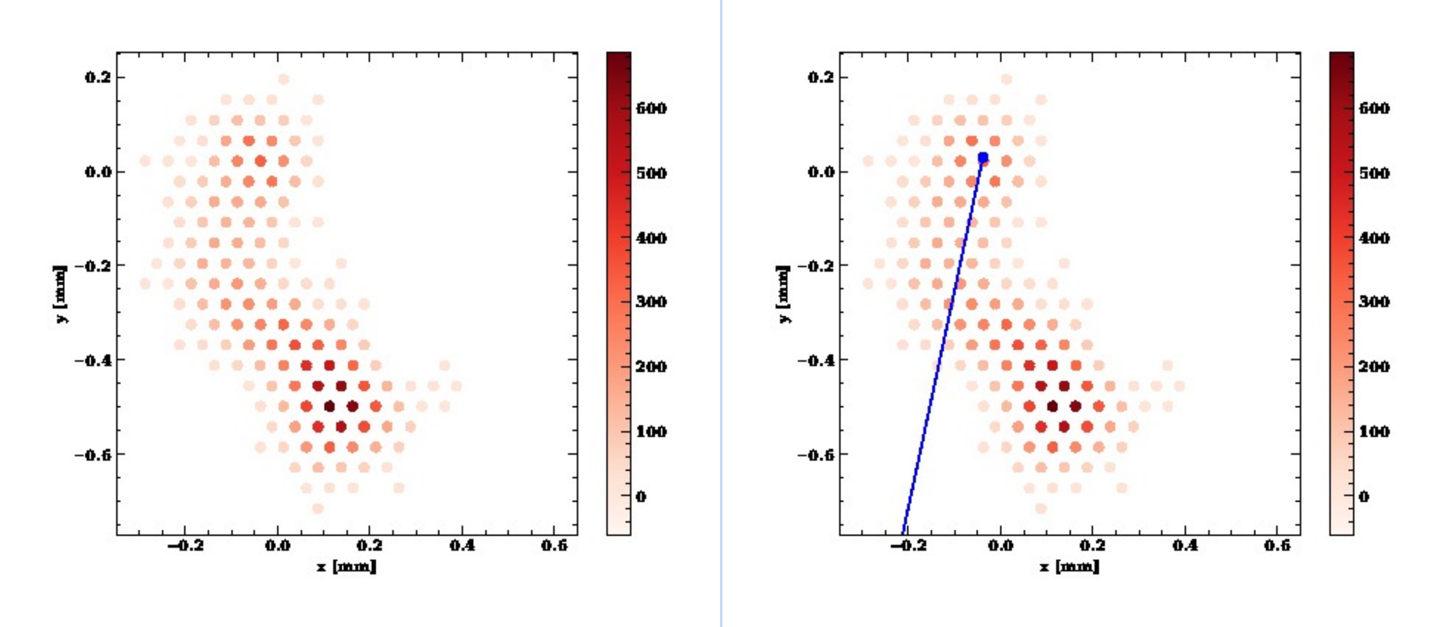


Filter and Calibration Wheel (FCW), providing open, attenuator, and closed positions, plus four ^{55}Fe-powered calibration sources:

- Cal A – Bragg-reflected polarized 2.98-keV (Ag-Lα fluorescence) and 5.89-keV (Mn-Kα)
- Cal B – unpolarized 5.89-keV spot
- Cal C – unpolarized 5.89-keV flood
- Cal D – unpolarized 1.74-keV (Si-Kα fluorescence) flood

Analysis Based upon Neural Networks

- **Baseline moments analysis is a simple, effective, long-studied and well-understood method of extracting information from ionization tracks made by a photo-electron in the detector gas**
- **Machine Learning (neural-network) techniques can extract more information from each track**
  - **Improves position-angle (PA) measurements, especially at high energy**
  - **Computes statistical and reconstruction errors for each event**
  - **Mildly improves estimates of the energy and conversion point of each event**



The Minimum Detectable Polarization (MDP)

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

- R_S is the observed source counting rate
- R_B is the observed background counting rate
- t is the integration time
- M is the modulation factor, i.e. the amplitude of the variation of the ensemble of position angles for a 100% polarized source
- The power of the neural-network analysis for an ensemble of events in the case of IXPE, is as if we were flying 4 rather than 3 optics/detector combinations!

Radio Pulsars

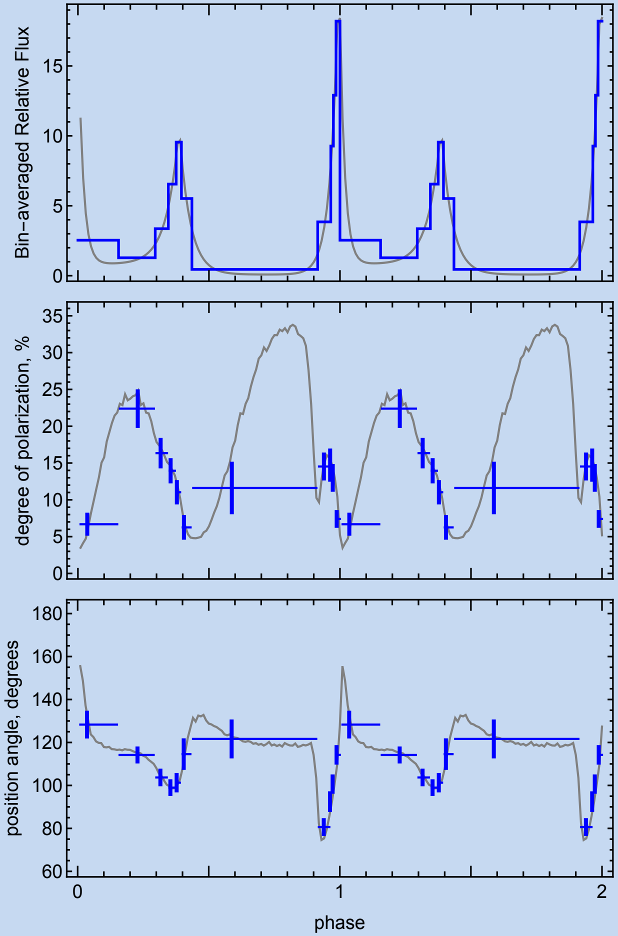
- **Radio Pulsars**
  - **Perform X-ray phase-resolved polarimetry to test models for a radio pulsar's X-ray emission**
  - **Grey is optical, blue is IXPE**

Emission geometry and processes are still unsettled.

- **Competing models predict differing polarization behavior with pulse phase.**

X-rays provide clean probe of geometry.

- **Absorption likely more prevalent in visible band.**
- **Radiation process entirely different in radio band.**
  - **Recently discovered *no* pulse phase-dependent variation in polarization degree and position angle @ 1.4 GHz.**
- **140-ks observation gives ample statistics to track polarization degree and position angle.**



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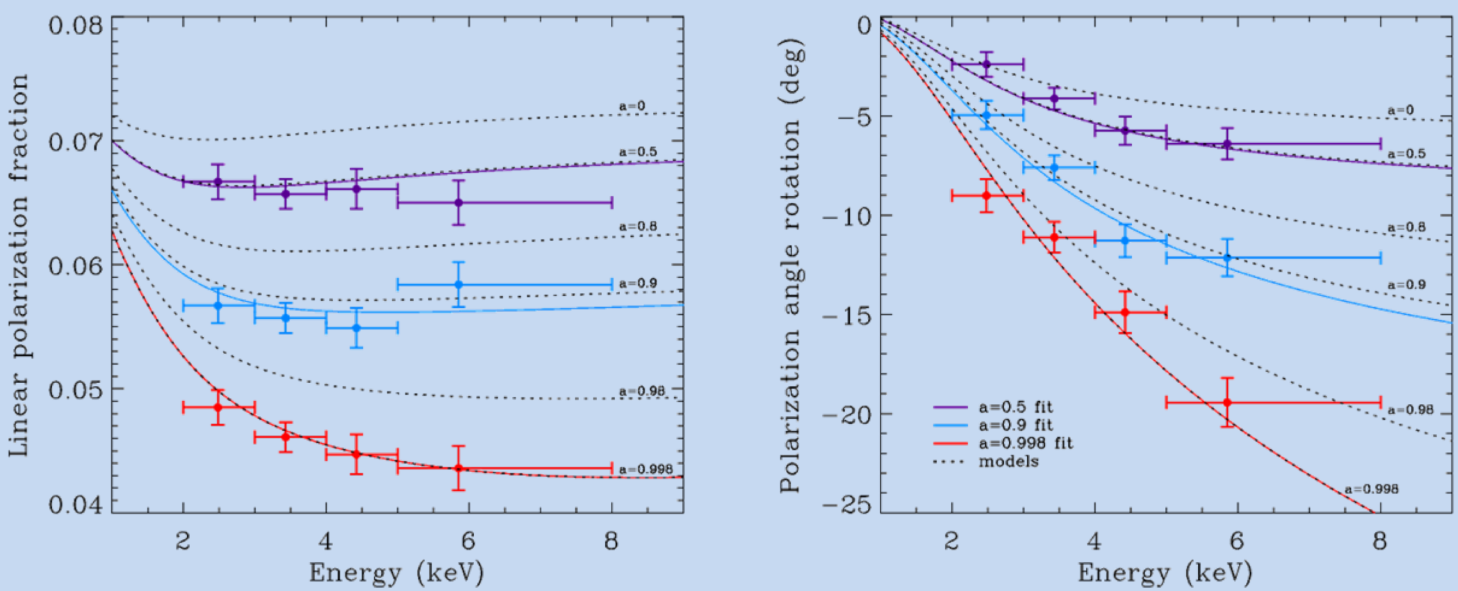
Microquasars

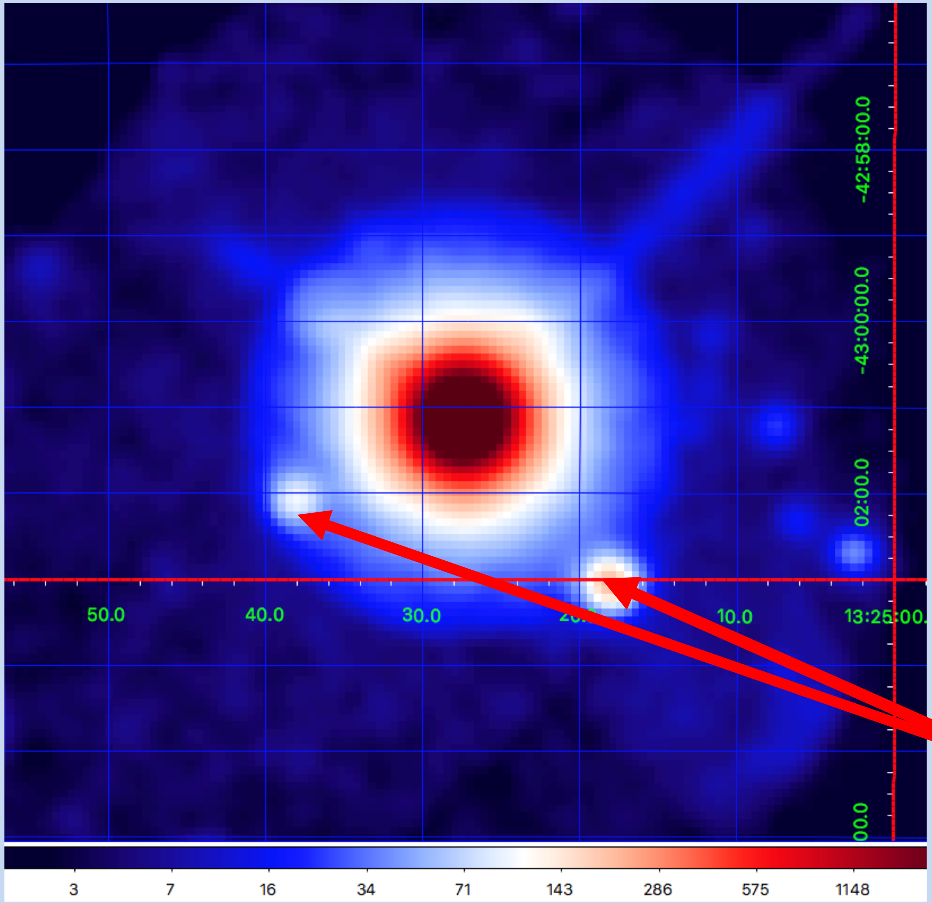
- ## Microquasars
  - **Perform X-ray spectral polarimetry on microquasars to use the position angle to help localize the emission site (accretion disk, corona, jet)**

For a micro-quasar in an accretion-dominated state, scattering polarizes the disk emission.
Polarization rotation versus energy is greatest for emission from inner disk.
– Inner disk is hotter, producing higher energy X-rays.
Disk orientation from other experiments used to constrain GRX1915+105 model.
a = 0.50±0.04; 0.900±0.008; 0.99800±0.00003 (200-ks observation)



Active Galaxies: CEN A

- **Active galaxies are powered by supermassive BHs with jets**
  - **Radio polarization implies the magnetic field is aligned with jet**
  - **Different electron-acceleration models predict different dependence in X-rays**



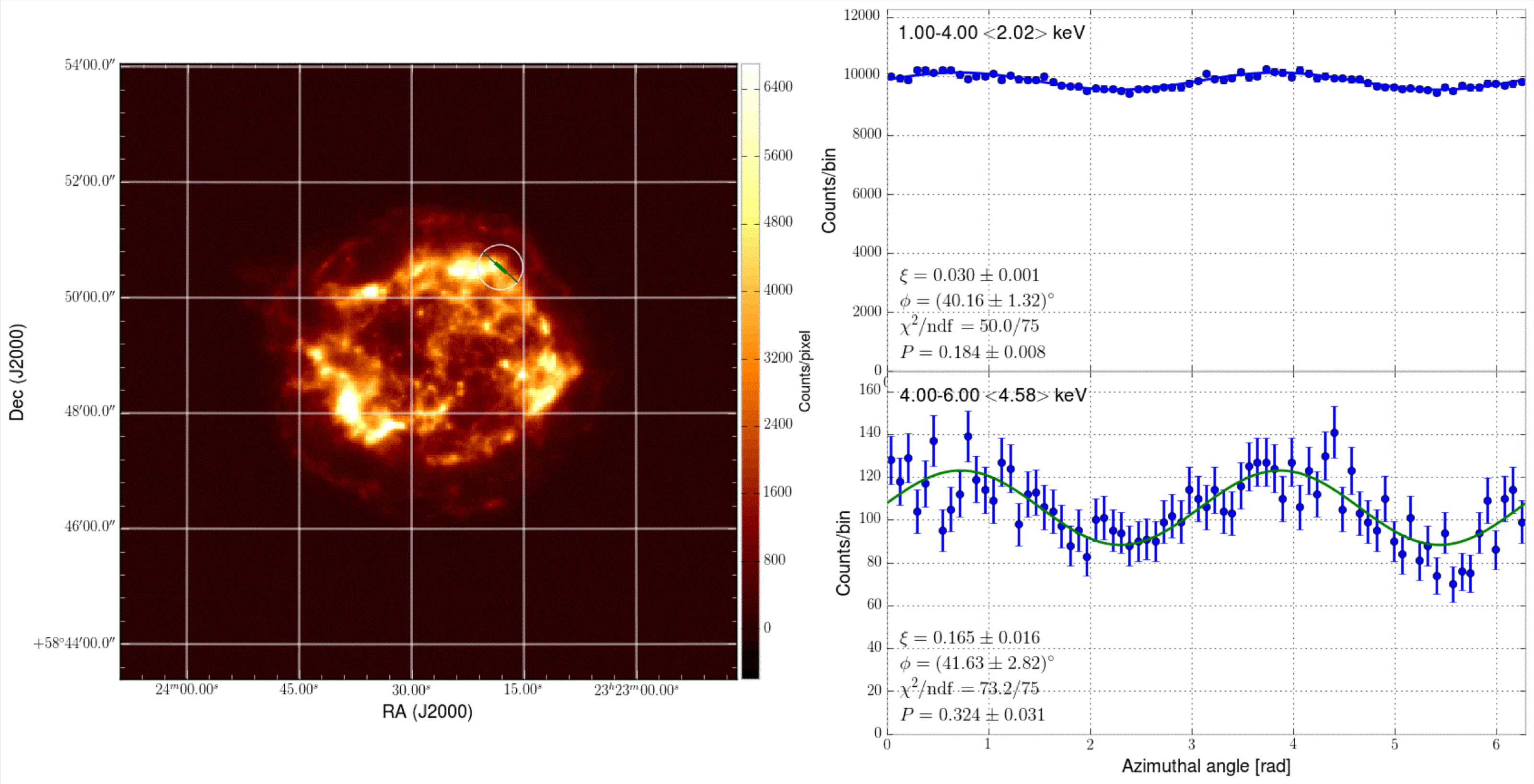
Region	MDP_{99}
Core	1.4%
Knots C+F+G	21%
ULXs	25% 15%

ULX sources

Supernova Remnants

- **Supernova Remnants (SNR – e.g. CAS-A)**
  - **Use X-ray polarmimetric imaging to examine the magnetic-field topology in the X-ray emitting regions of (shell-type) SNR, which are candidate sites for cosmic-ray acceleration (Entire image measured simultaneously)**

Lines and thermal continuum dominate 1-4 keV.
Non-thermal emission dominates 4-6 keV.



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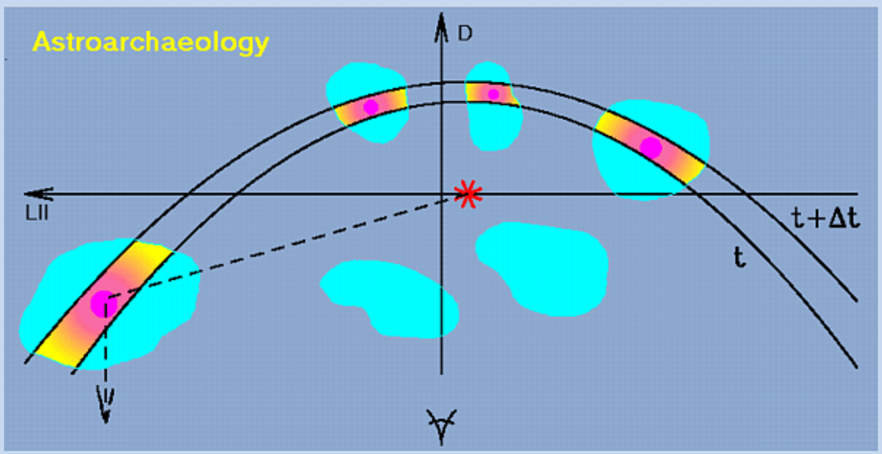
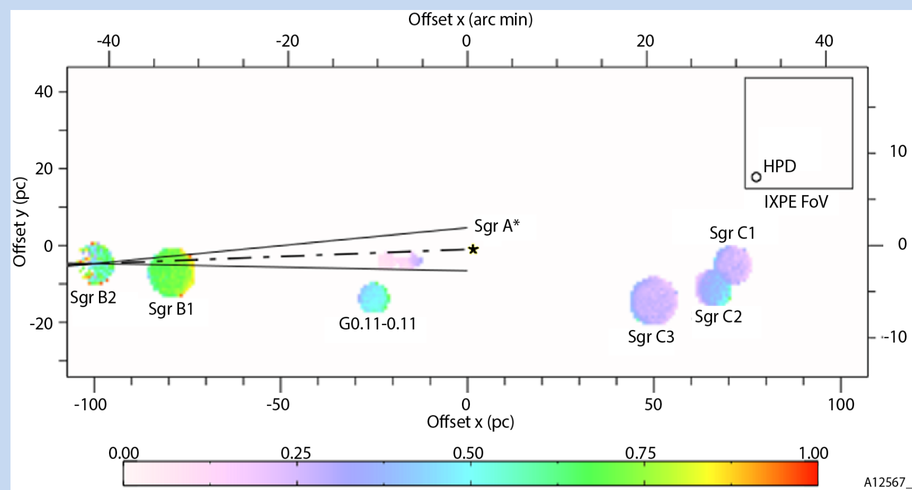
Was SGR A recently 10^6 × more active?*

- **Galactic Center molecular clouds (MC) are known X-ray sources**
  - **If the MCs reflect X-rays from Sgr A*, the X-radiation would be highly polarized perpendicular to plane of reflection and indicate the direction back to Sgr A***
    - **If true, Sgr A* X-ray luminosity was 10^6 larger ≈ 300 years ago**
    - **If not, still a discovery**





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Test QED

- **Study magnetars (pulsing neutron stars with magnetic fields up to 10^{15} Gauss)**
  - **Non-linear QED predicts magnetized-vacuum birefringence**
    - **Refractive indices of the two polarization modes differ from 1 and from each other**
    - **Impacts polarization and position angle as functions of pulse phase, but not the flux**
    - **Example is 1RXS J170849.0-400910, with an 11-s pulse period**
    - **Can exclude QED-off at better than 99.9% confidence in 250-ks observation**