The Imaging X-ray Polarimetry Explorer

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OUTLINE

- A brief history of polarimetry in the classical X-ray band
  - Sounding rocket experiments
  - OSO-8 crystal polarimeter
  - The Stellar X-ray Polarimeter on Spektrum-X
- IXPE
  - Introduction
  - How it works
  - The science

IN THE BEGINNING

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

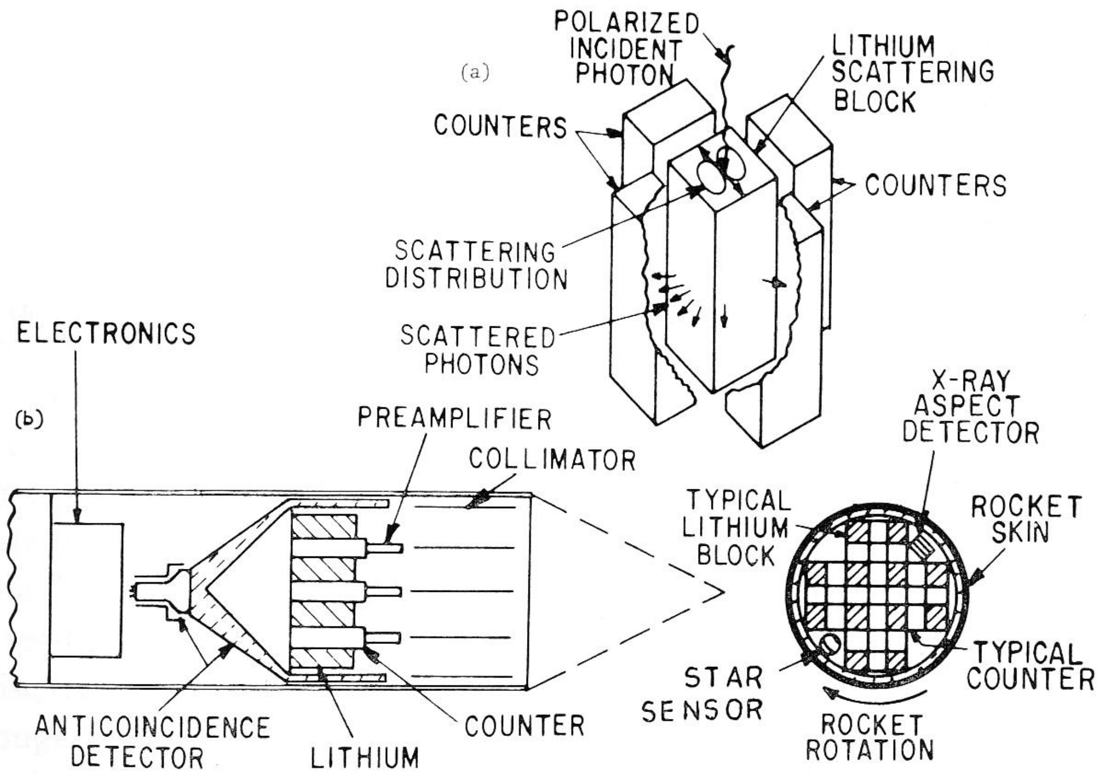
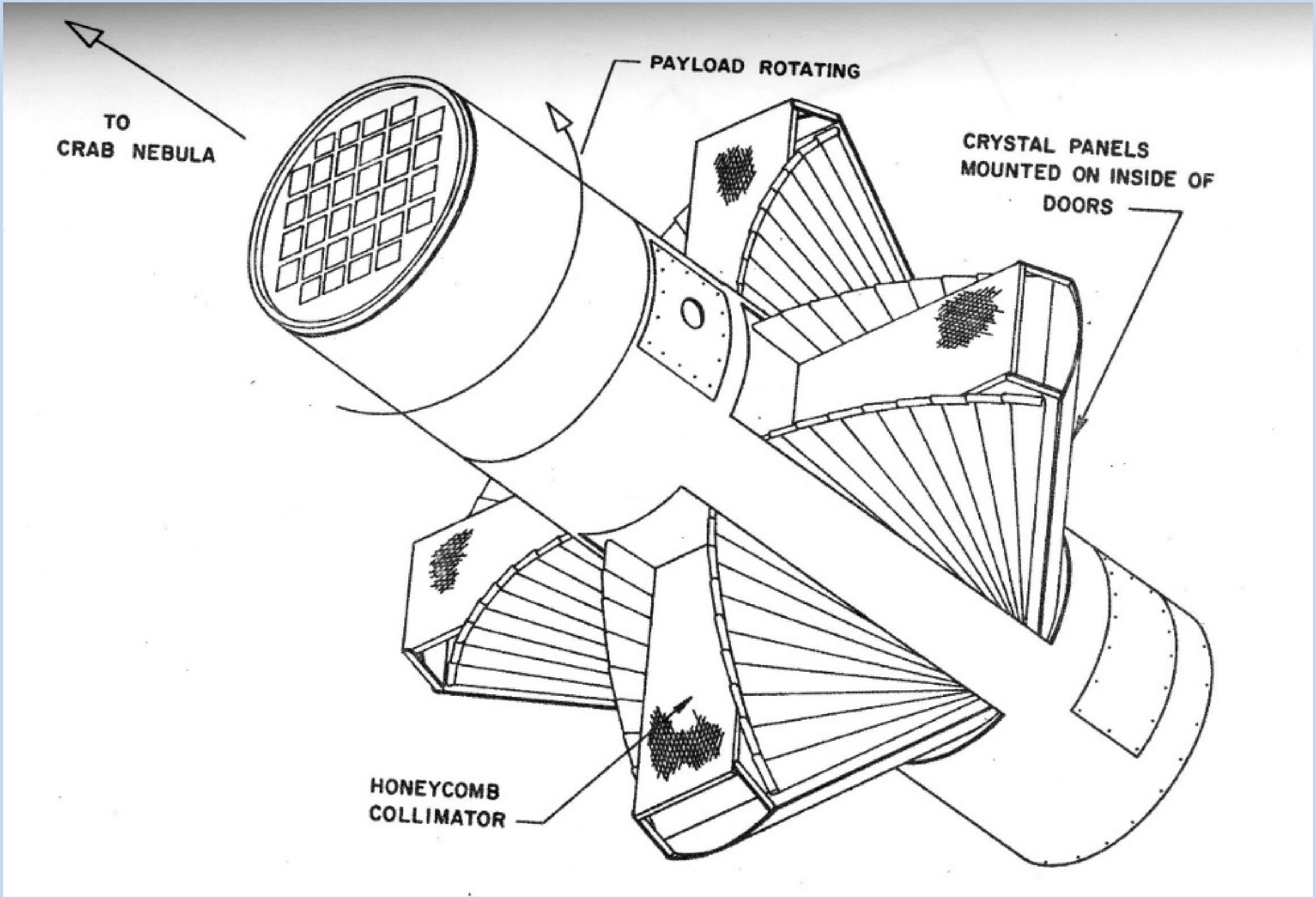


Fig. 1. (a) Schematic representation of the polarimeter concept. (b) Mounting of the polarimeter and ancillary equipment in the rocket.

Rocket 17.09 (Aerobee 350) 1971



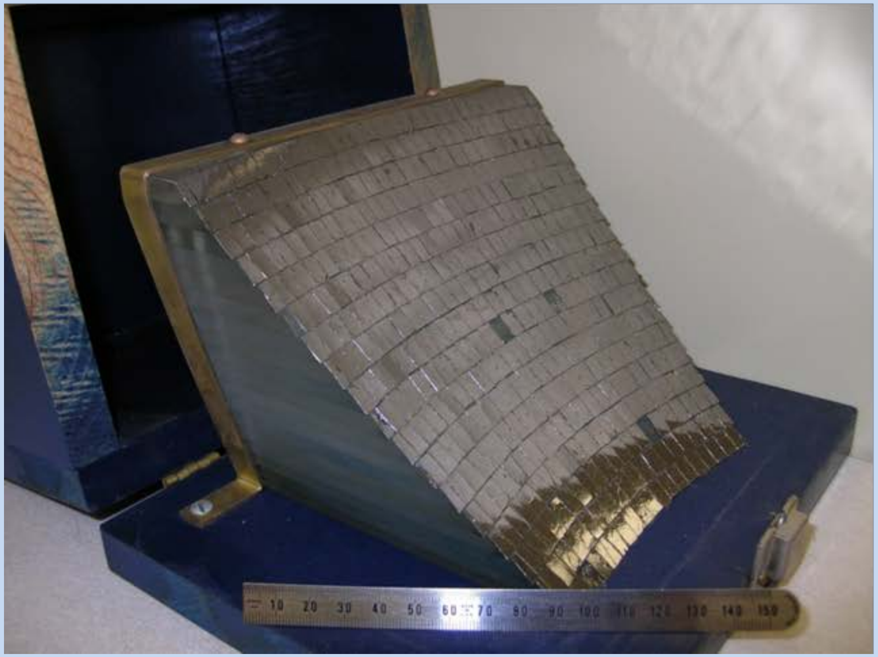
Rocket 17.09

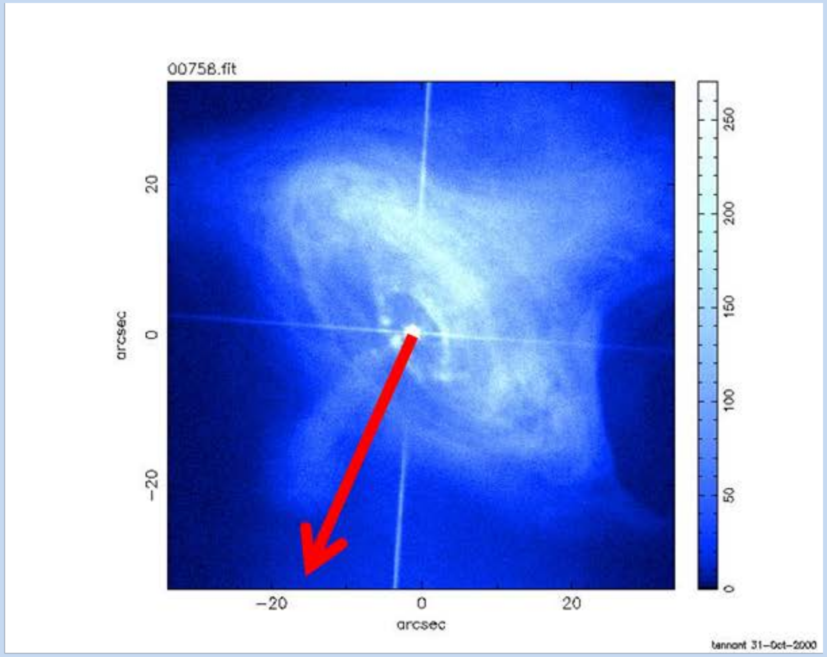
- Crab detection!
  - P = 15% ± 5%
  - $\phi = 156^\circ \pm 10^\circ$

Yes, I am the handsome one

CRYSTAL POLARIMETERS ON OSO-8

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





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Imaging
X-Ray
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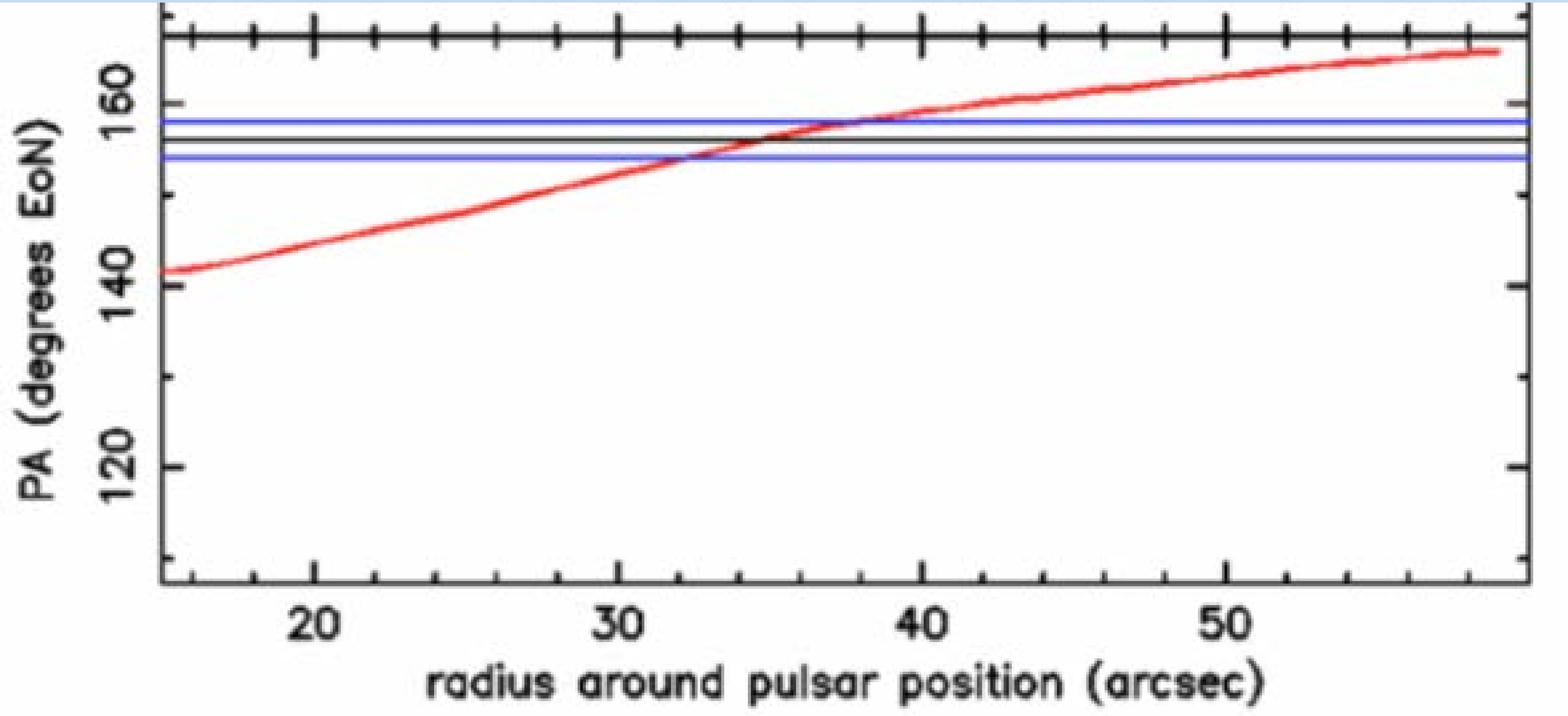
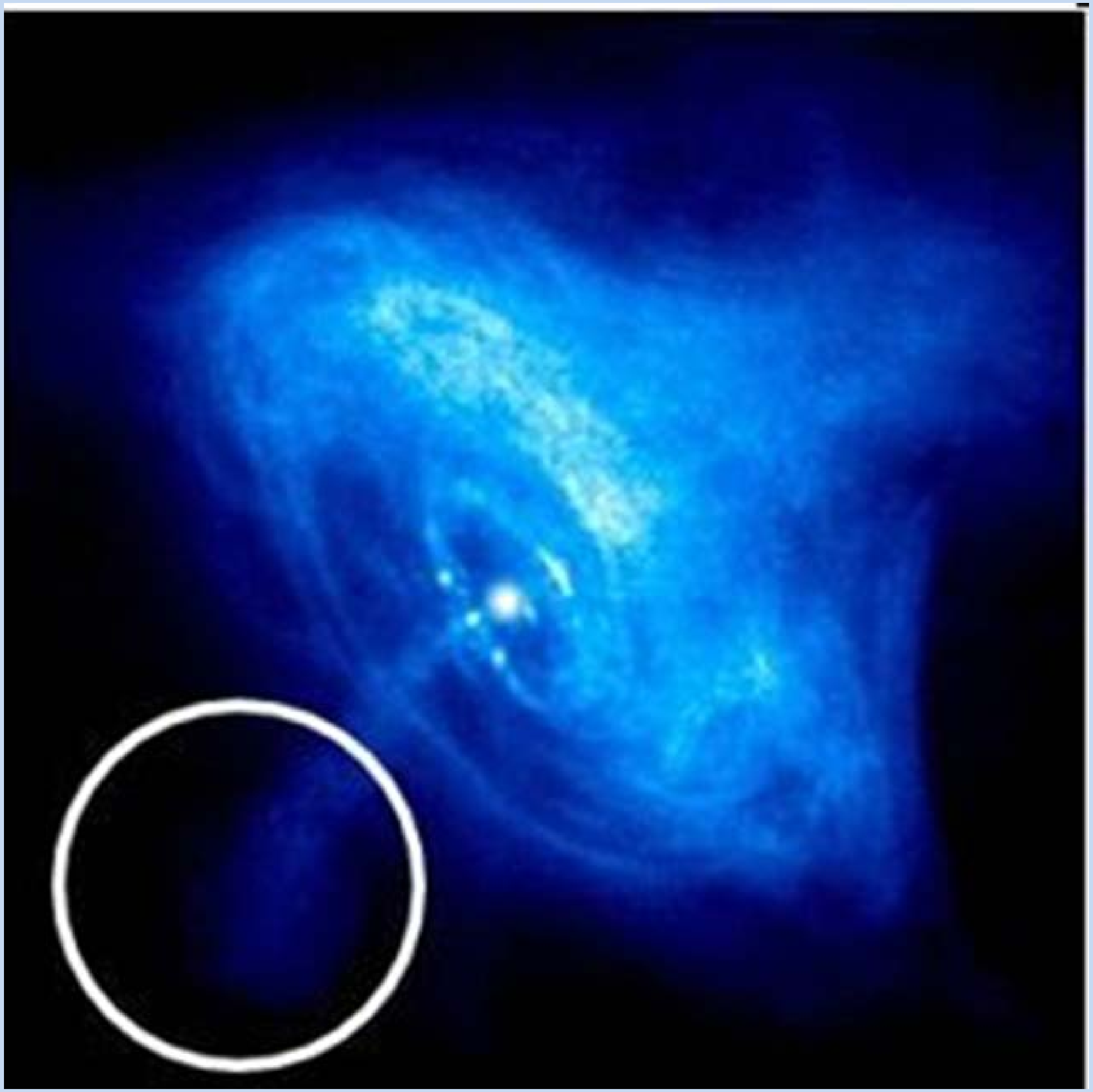
DID OSO-8 RESULT MAKE SENSE?

- Yes --- Compare to HST mapping (Moran, P., Shearer, A., Mignani, R.P., et al. 2013)
- IXPE detailed mapping is the next important step



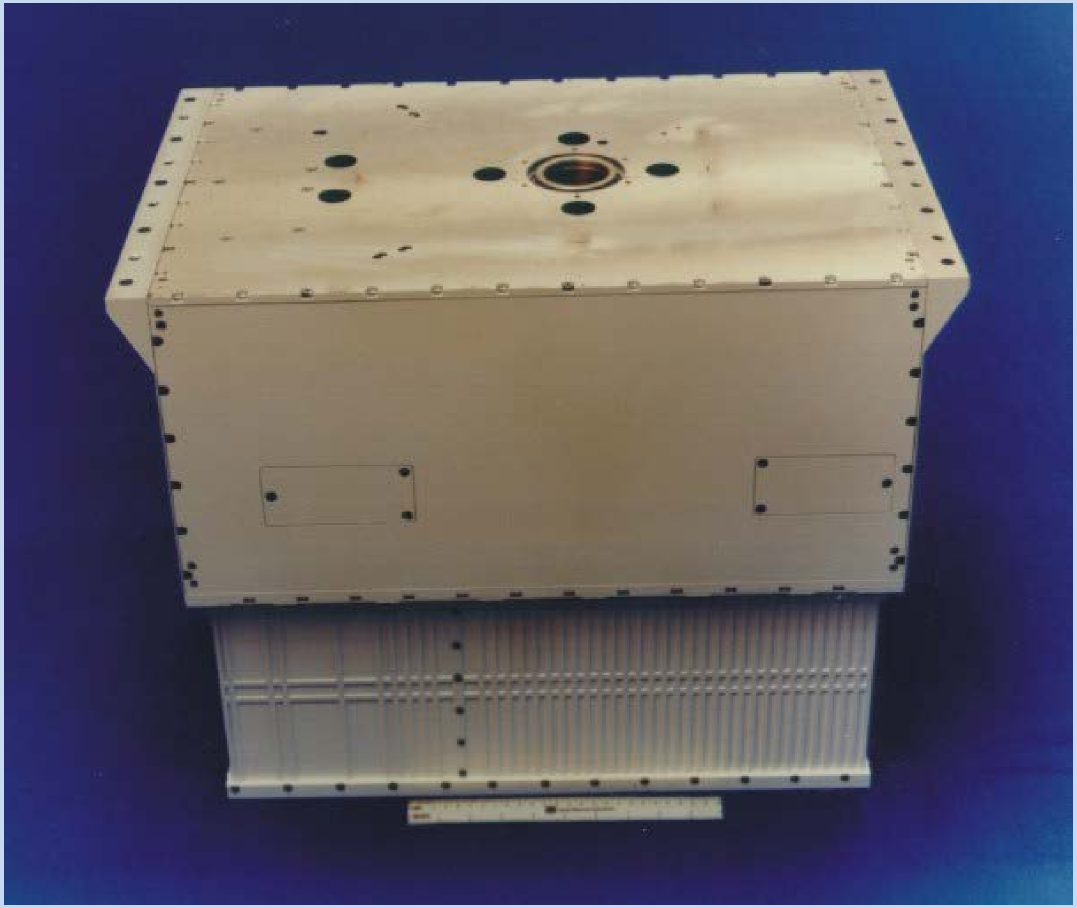
IMAGING POLARIMETRY

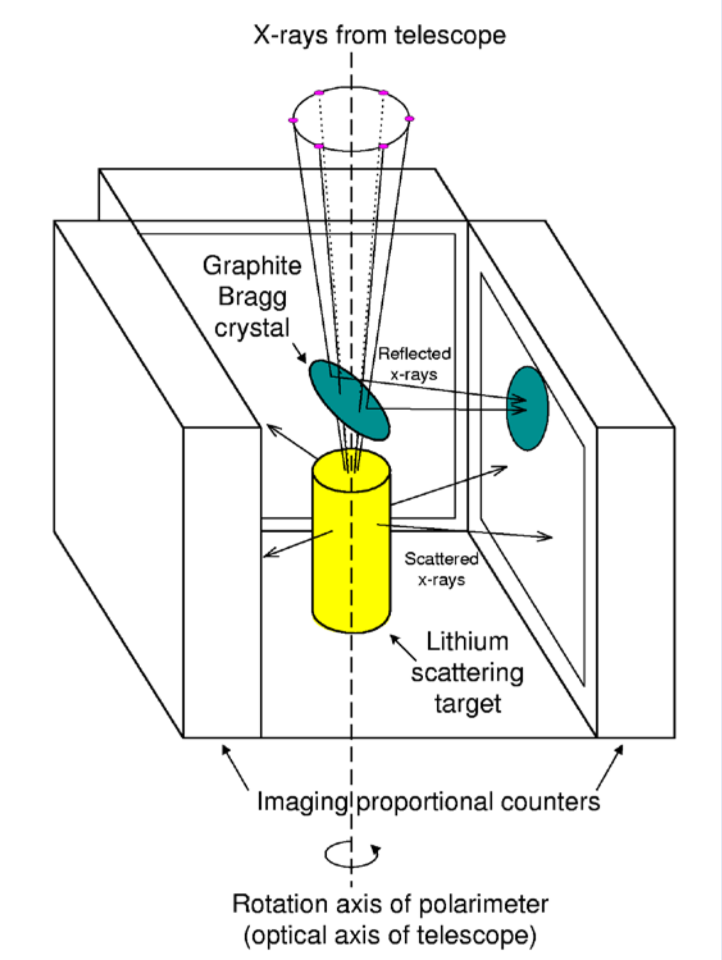
- **Chandra image with IXPE 30" half-power diameter**



The Stellar X-ray Polarimeter (SXRP)

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





THE IMAGING X–RAY POLARIMETRY EXPLORER

- **IXPE will accomplish, *for the first time,* high-sensitivity measurements of the polarization of X-rays coming to us from some of the most exciting types of astronomical objects — neutron stars and black holes**
- **IXPE will accomplish, *for the first time*, imaging X-ray polarization measurements from extended objects such as supernova remnants and at least one jet attached to super-massive black holes**
- **IXPE measurements are made possible by *new technology* advanced by our Italian partners**
- **IXPE measurements are astrophysically *unique,* adding two new dimensions to information space:**
  - **Polarization degree**
  - **Polarization angle**

The IXPE Team

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

Science Advisory Team

SAT currently comprises ~ 80 scientists from 12 countries

THE SCIENCE OBJECTIVES

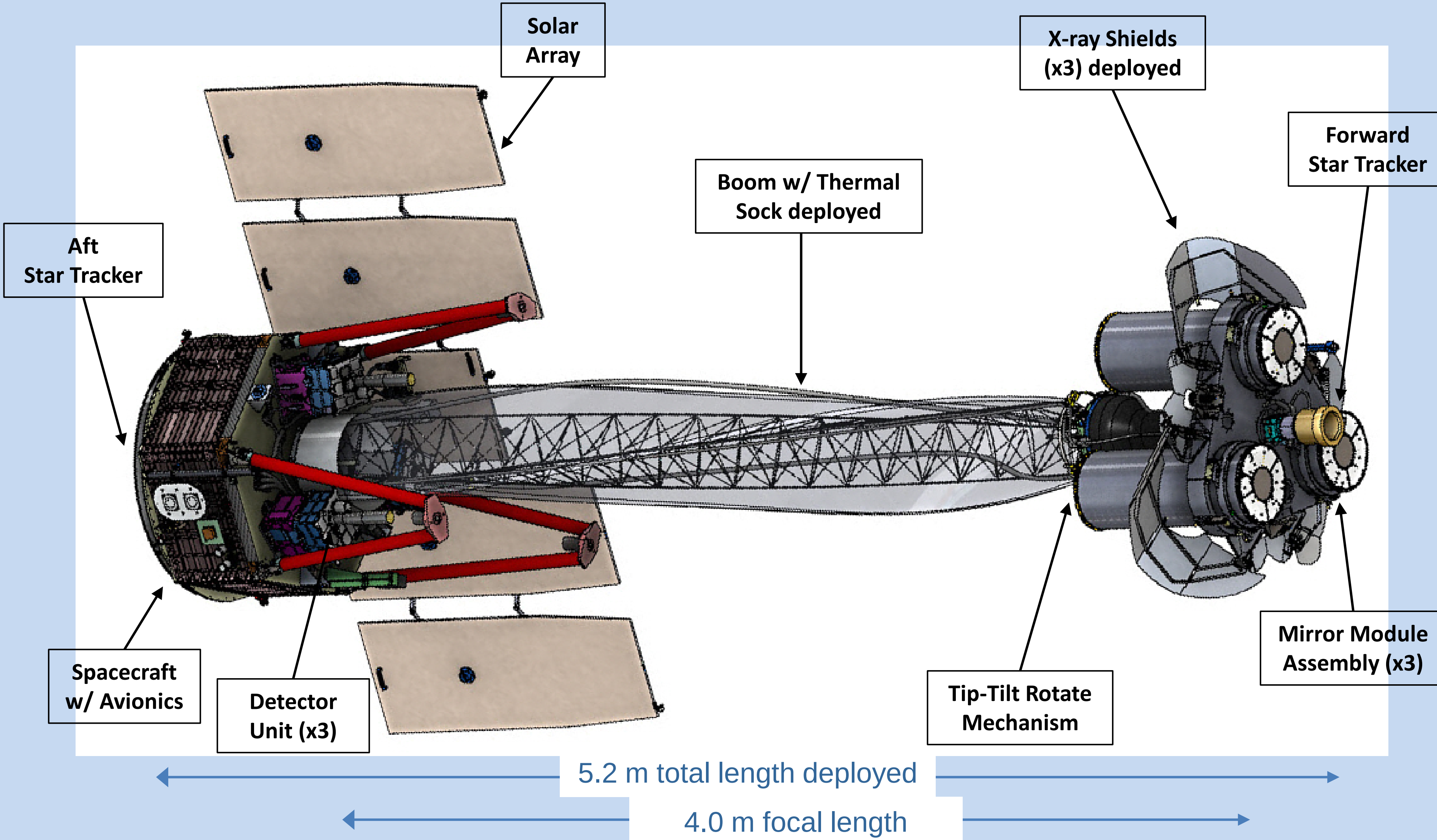
- **IXPE will study targets over a broad range of types of astronomical X-ray sources with emphasis on black holes and neutron stars**

- **IXPE will (some detailed examples on future slides):**
  - ***Constrain the radiation processes and detailed properties of different types of cosmic X-ray sources***
  - ***Investigate general relativistic and quantum effects in extreme environments***
  - ***Constrain the geometry of AGN and microquasars***
  - ***Establish the geometry and strength of the magnetic field in magnetars***
  - ***Constrain the geometry and origin of the X-radiation from radio pulsars***
  - ***Learn how particles are accelerated in Pulsar Wind Nebulae and in (shell-type) Supernova Remnants***

MISSION DESCRIPTION

- Launch April 2021
- 540-km circular orbit at 0° inclination
- 2-year baseline mission, 1 year extension (at least!)
- Point and stare at pre-selected targets
- Malindi ground station (Singapore backup)
- Mission Operations Center at the University of Colorado, Laboratory for Atmospheric and Space Physics
- Sciences Operations Center at MSFC
- Data archiving at NASA's HEASARC
  - No proprietary data

IXPE DEPLOYED



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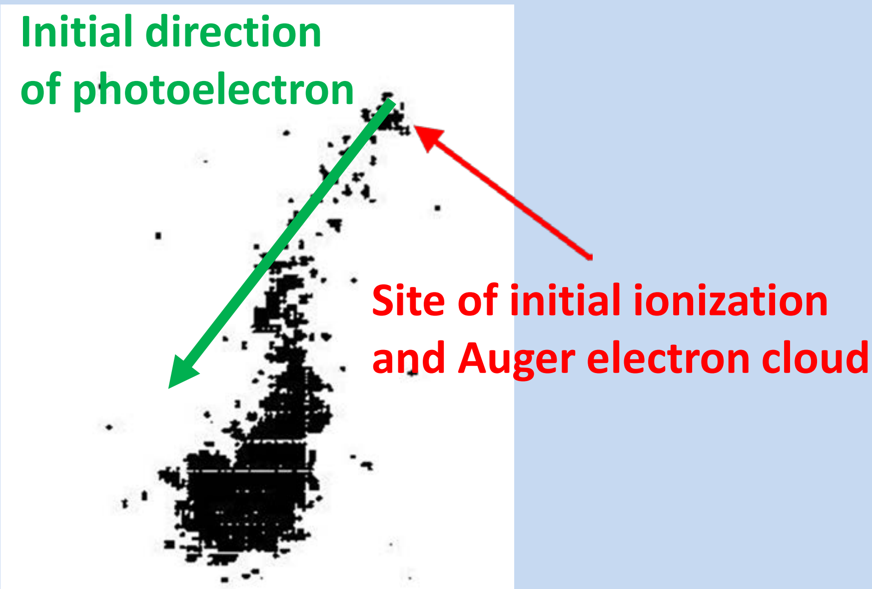
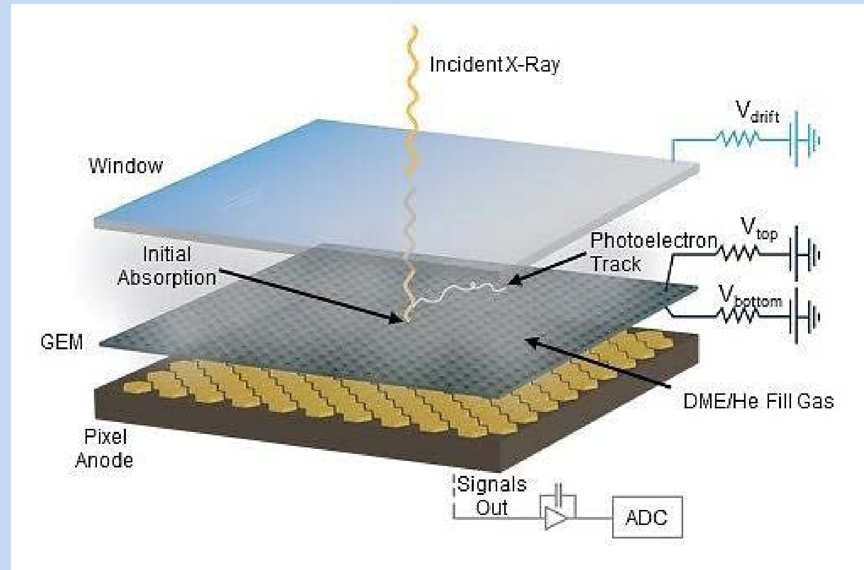
THE POLARIZATION-SENSITIVE DETECTORS

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





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

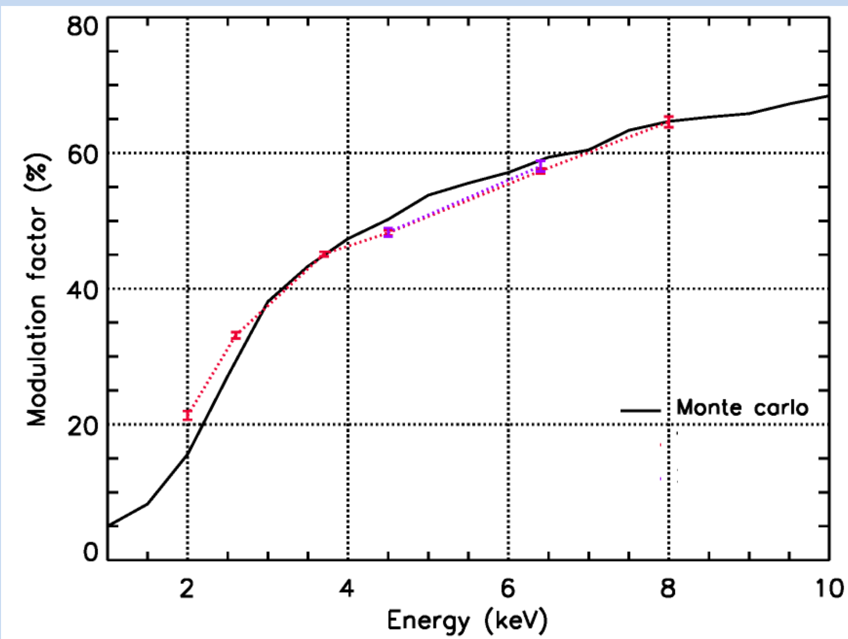
$$\frac{d\sigma}{d\Omega} = f(\zeta) r_0^2 Z^5 \alpha_0^4 \left(\frac{1}{\beta}\right)^{7/2} 4\sqrt{2}\sin^2\theta\cos^2\varphi\,, \text{ where } \beta \equiv \frac{E}{mc^2} = \frac{h\nu}{mc^2}$$

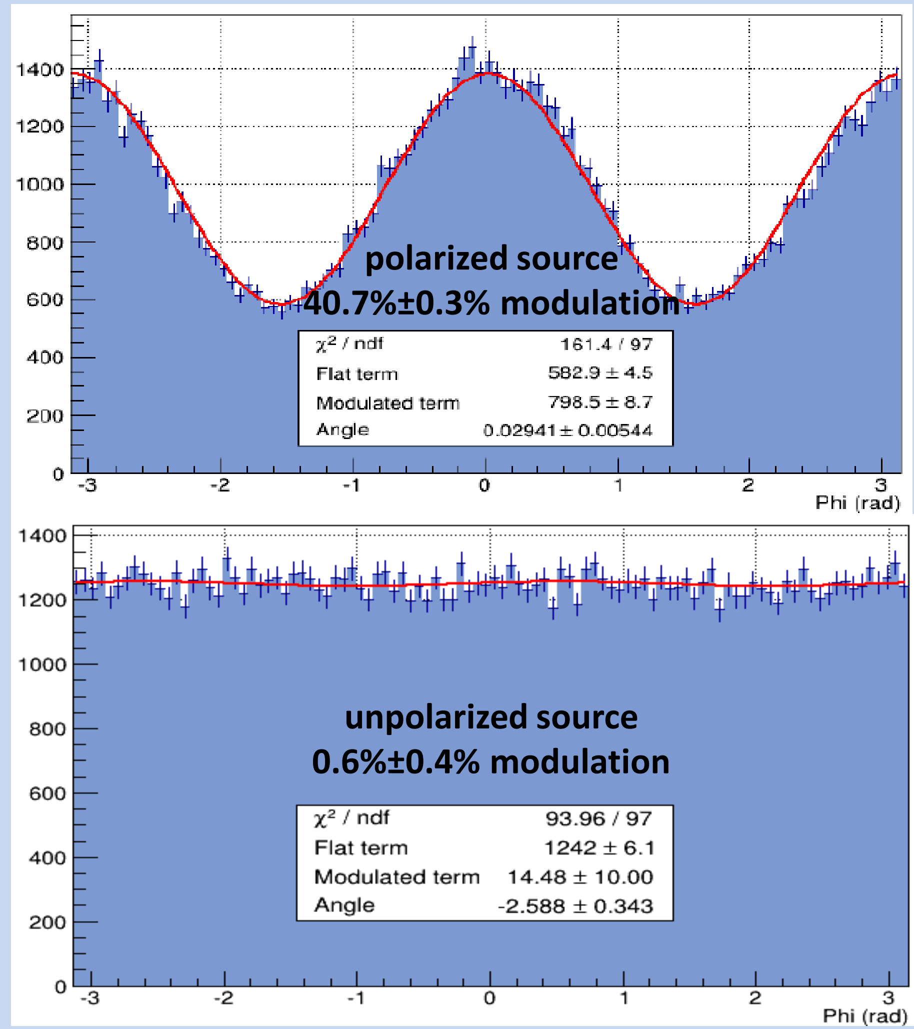
DETECTOR PROPERTIES

Parameter	Value
Sensitive area	15 mm × 15 mm (13 x 13 arcmin)
Fill gas and composition	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 ($\propto \sqrt{E}$)
Useful energy range	2 - 8 keV

DETECTOR PERFORMANCE

- **The modulation factor is the variation in the position angle for a 100%-polarized beam**

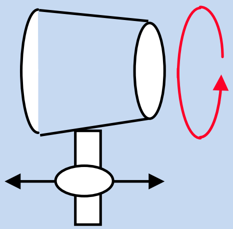




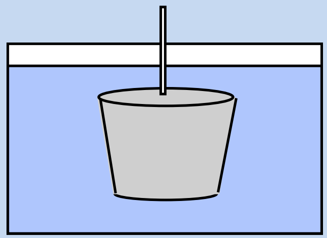
MIRROR PRODUCTION PROCESS

Mandrel fabrication

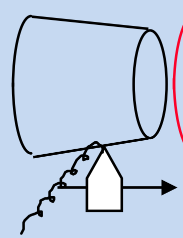
1. Machine mandrel from aluminum bar



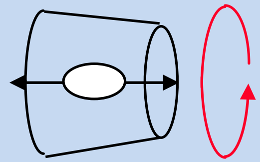
2. Coat mandrel with electroless nickel (Ni-P)



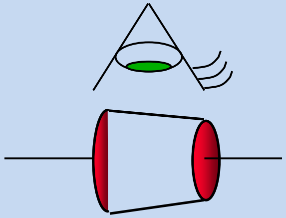
3. Diamond turn mandrel to sub-micron figure accuracy



4. Polish mandrel to 0.3-0.4 nm RMS

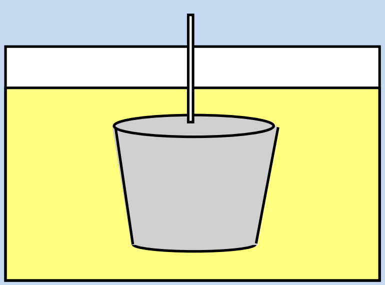


5. Conduct metrology on the mandrel

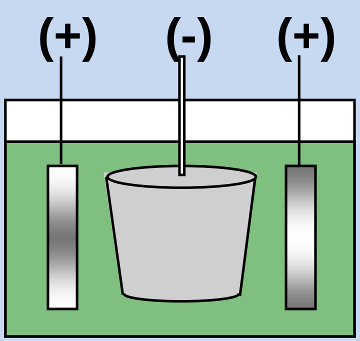


Mirror-shell forming

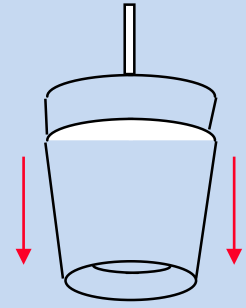
6. Passivate mandrel surface to reduce shell adhesion



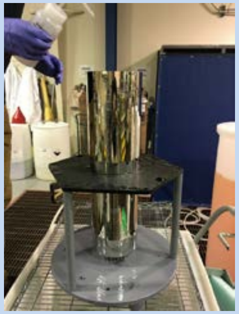
7. Electroform Nickel/Cobalt shell onto mandrel



8. Separate shell from mandrel in chilled water

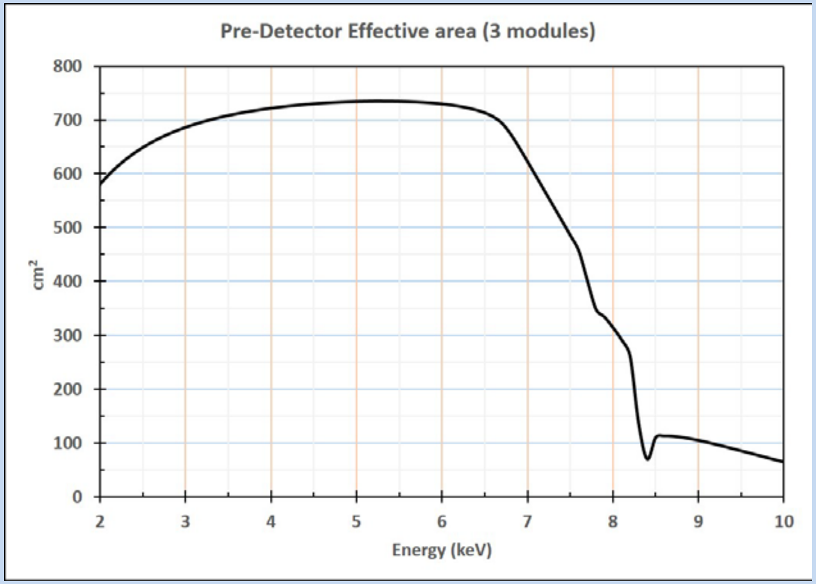


Ni/Co electroformed IXPE mirror shell



MIRROR MODULE ASSEMBLY

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, 260 µm
Shell material	Nickel cobalt alloy
Effective area per module	210 cm^2 (2.3 keV) > 230 cm^2 (3-6 keV)
Angular resolution	≤ 25 arcsec HPD
Detector limited FOV	12.9 arcmin
Focal length	4 m
Mass (3 assemblies)	95 kg with contingency



MMA – Engineering Unit

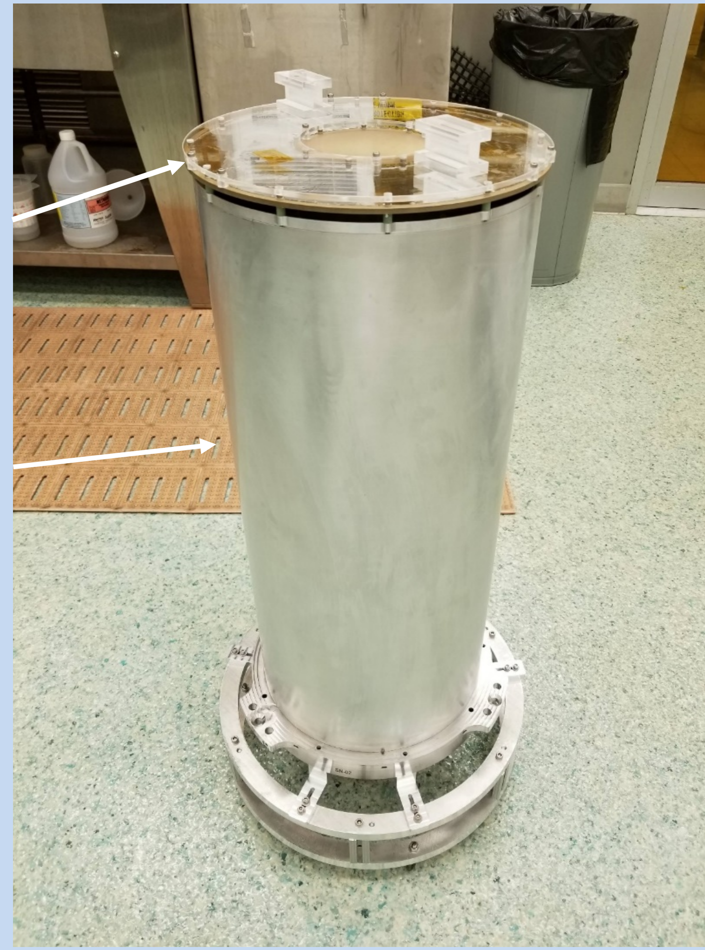
Inner shells (3)

Mass Simulators

Front Spider

Thermal Shields

Outer Housing



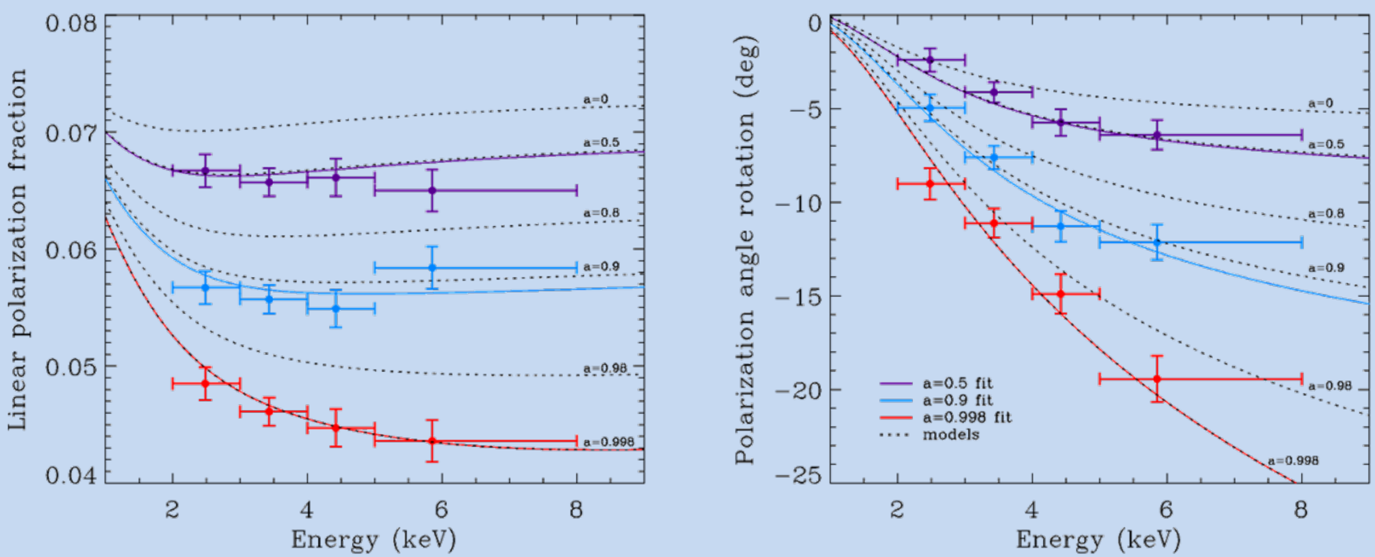
Measured angular resolution 20 arcsec @ 2.3 and 4.5 keV

MICROQUASARS

▪ Microquasars

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

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)



RADIO PULSARS

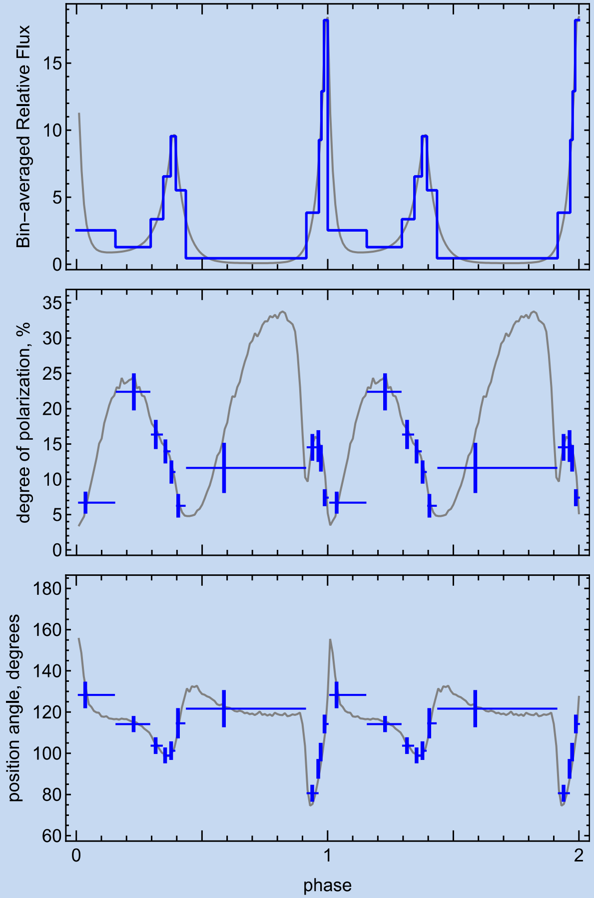
- Radio Pulsars
  - Perform X-ray phase-resolved polarimetry to test models for a radio pulsar's X-ray emission, which are distinct from those for its radio emission
  - Grey is optical, blue is IXPE

Emission geometry and processes are still unsettled.

- Competing models predict differing polarization behavior with pulse phase.

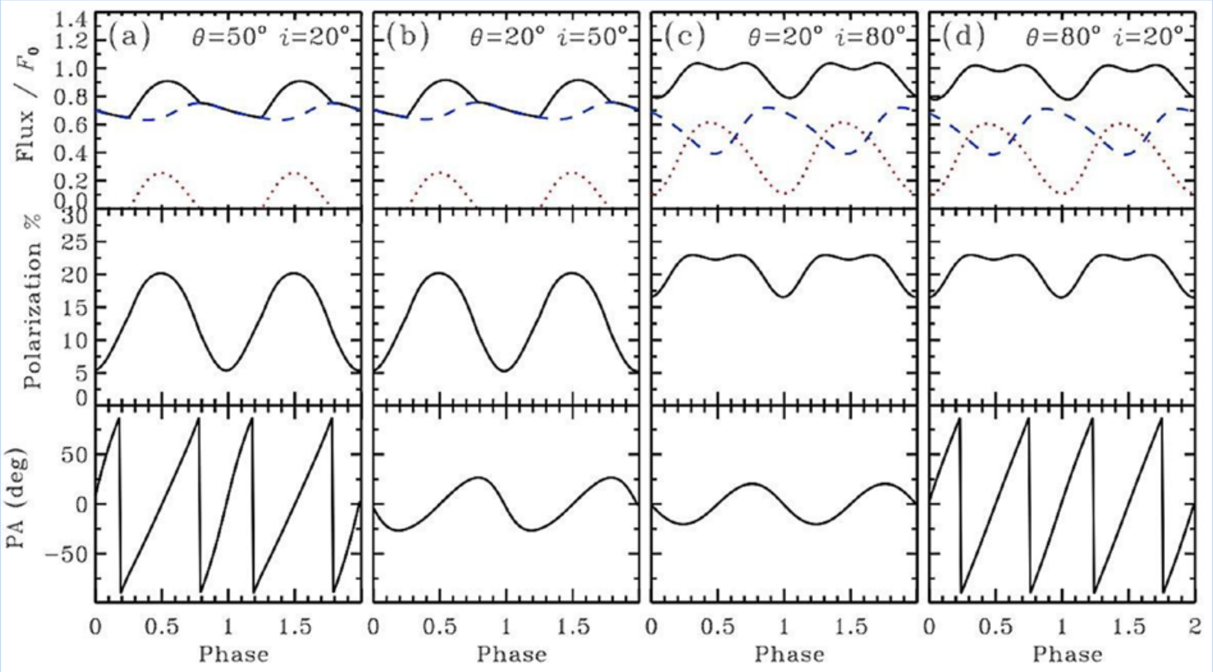
X-rays provide clean probe of geometry.

- 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.



Millisecond Pulsars

- Figure shows the phase dependence of flux, polarization degree, and position angle for an accreting millisecond with two hot spots and a 3.3-ms period
- Assumes a NS radius, R = 2.5 Rg, and different combinations of angles, I, between the rotation axis and line of sight and θ between the rotation and magnetic axes.
- In favorable cases, IXPE phase-resolved polarimetry allows measurement of geometry-dependent position-angle variations, which flux measurements alone cannot accomplish.



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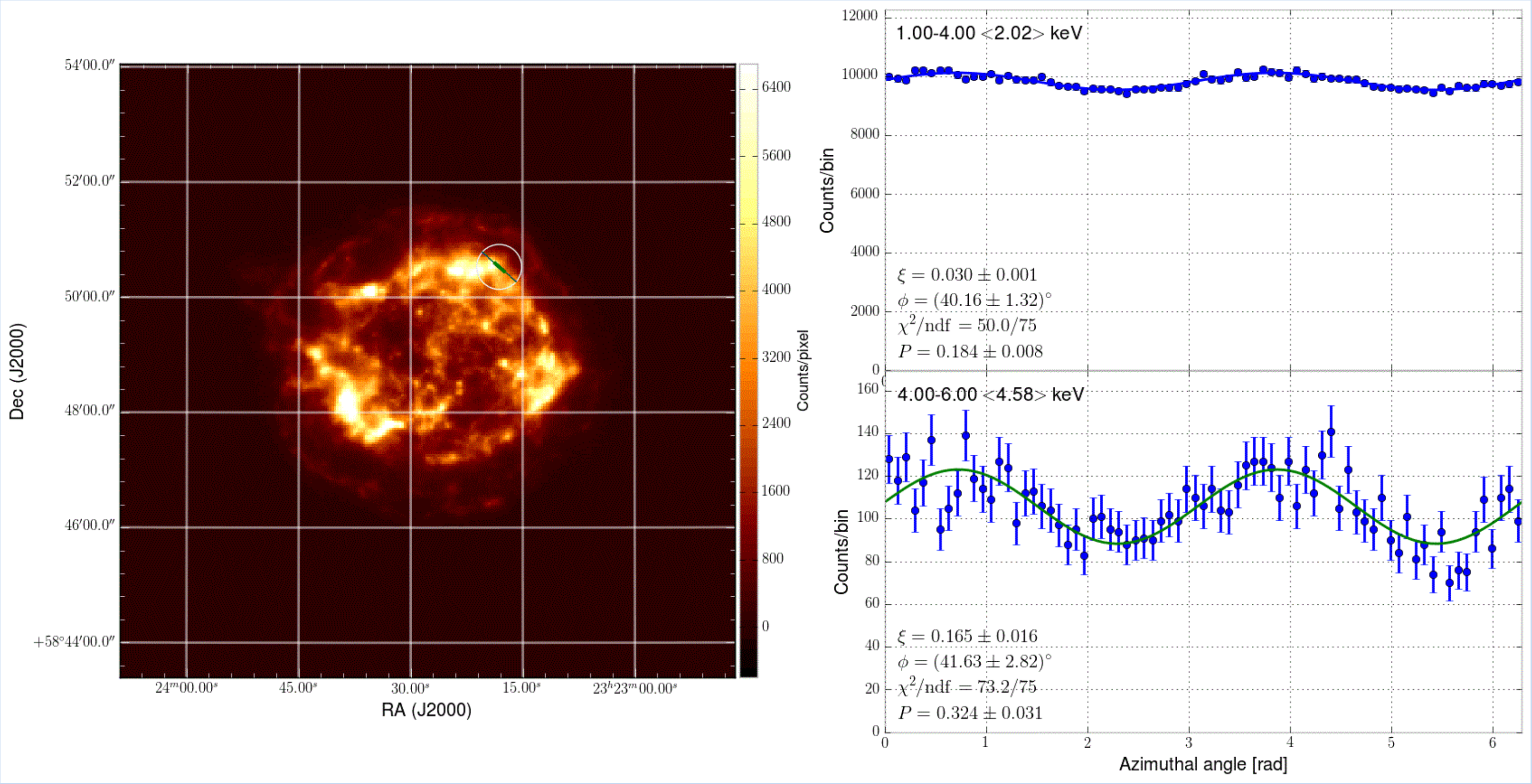
Supernova Remnants

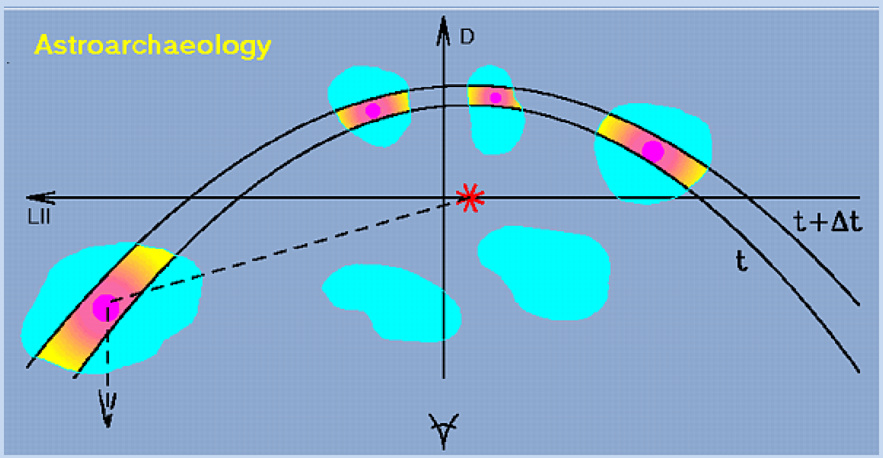
- **Supernova Remnants (SNR – e.g. CAS-A)**
  - **Use X-ray polarmimetric imaging to examine the magnetic-field topology in the X-ray emitting regions of (shell-type) SNR, which are candidate sites for cosmic-ray acceleration (Entire image measured simultaneously)**

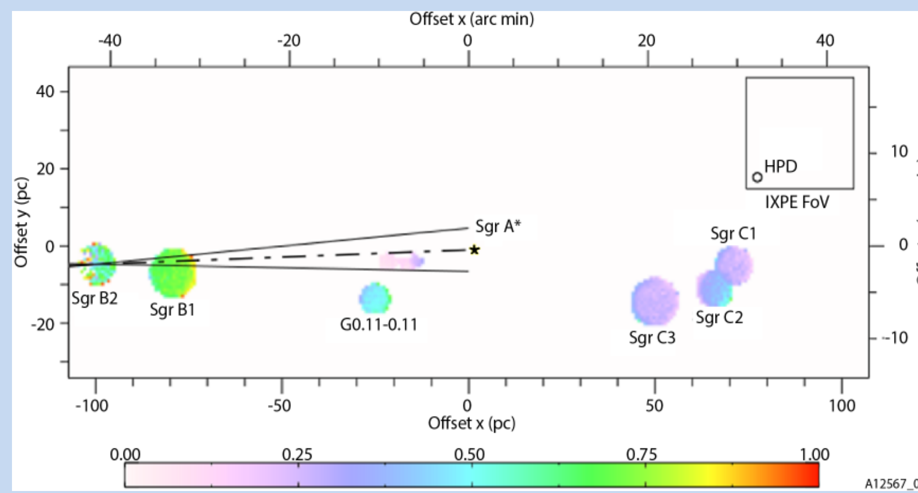
Lines and thermal continuum dominate 1-4 keV.
Non-thermal emission dominates 4-6 keV.



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 indicates the direction back to Sgr A***
    - **If true implied Sgr A* X-ray luminosity was 106 larger ≈ 300 years ago**
    - **If not, still a discovery**





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**