

X-Ray Polarimetry of Astronomical Sources: Introducing a NASA Mission with a New Window on the X-ray Universe

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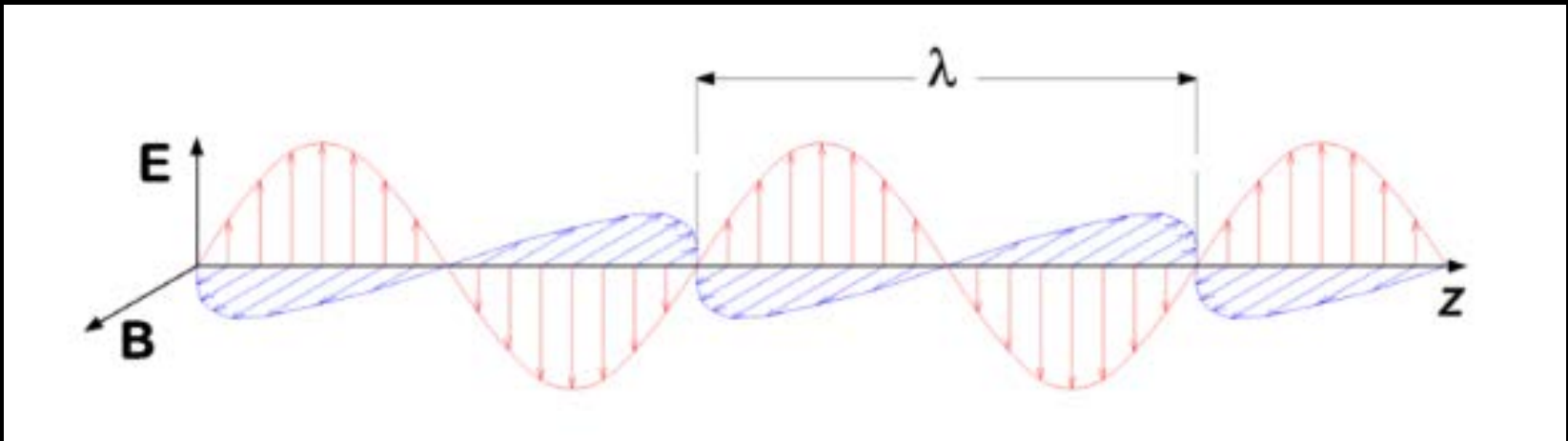
Wichita State , November 1, 2017

Outline

- A look to the past
 - Experimental techniques
- Electron tracking
- IXPE the mission
- IXPE 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 determine the direction of the polarization

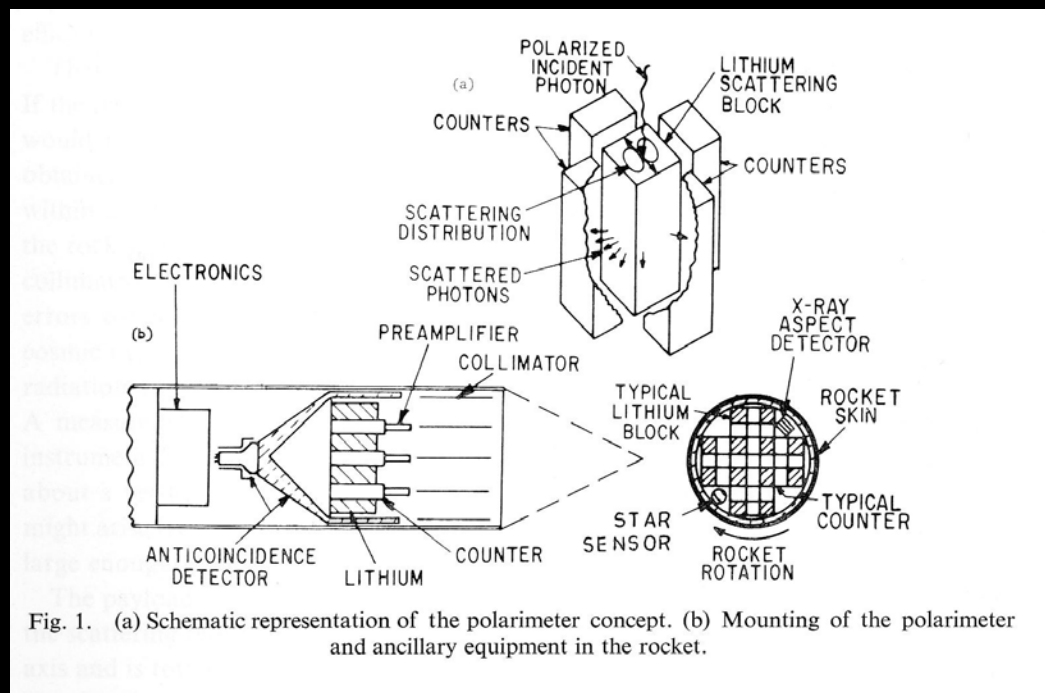


Why is polarization useful?

- 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

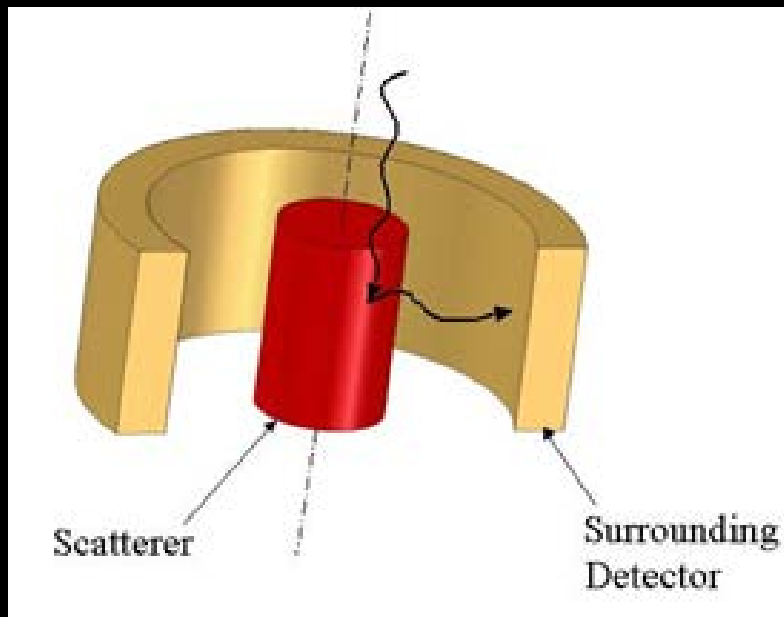


Scattering polarimeter

- Thomson cross-section approximates the angular dependence

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

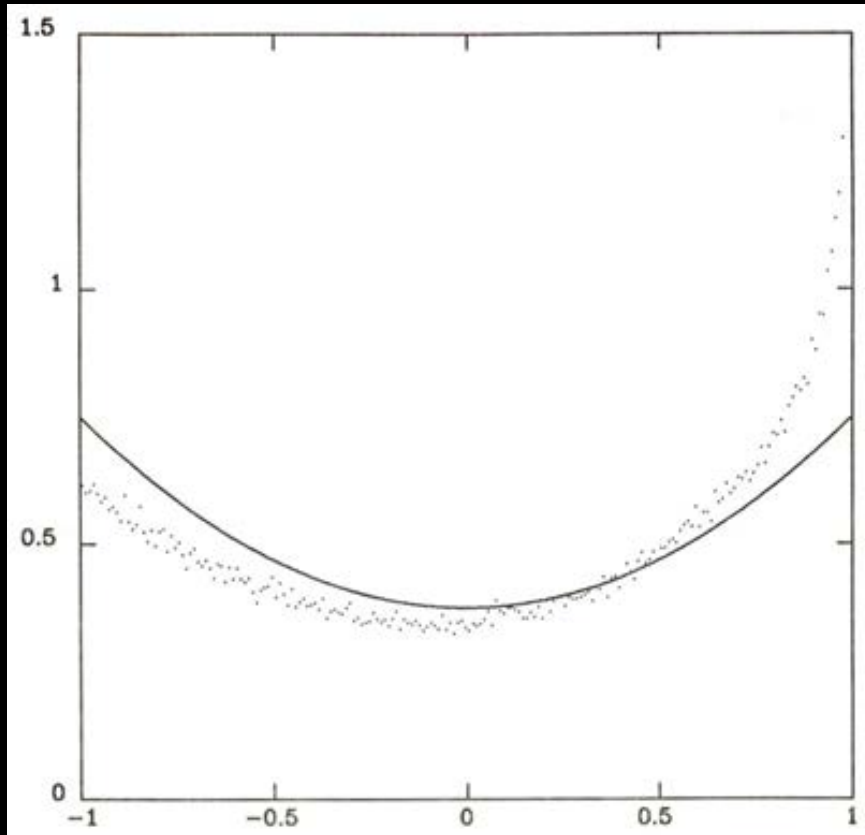
- From bound electrons one must account for both coherent and incoherent scattering and photoelectric absorption



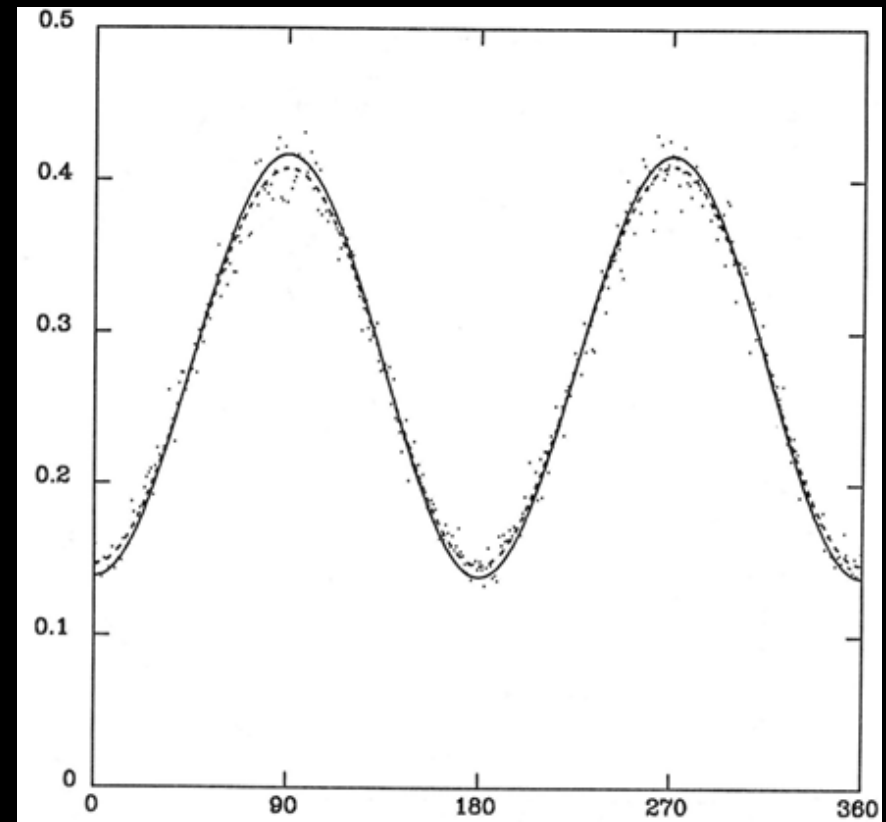
$$\frac{d\sigma_{\text{coh}}}{d\Omega} = r_0^2 \langle \cos^2 \vartheta \cos^2 \varphi + \sin^2 \varphi \rangle |F|^2$$

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

Thompson approximation



Cos (polar scattering angle)



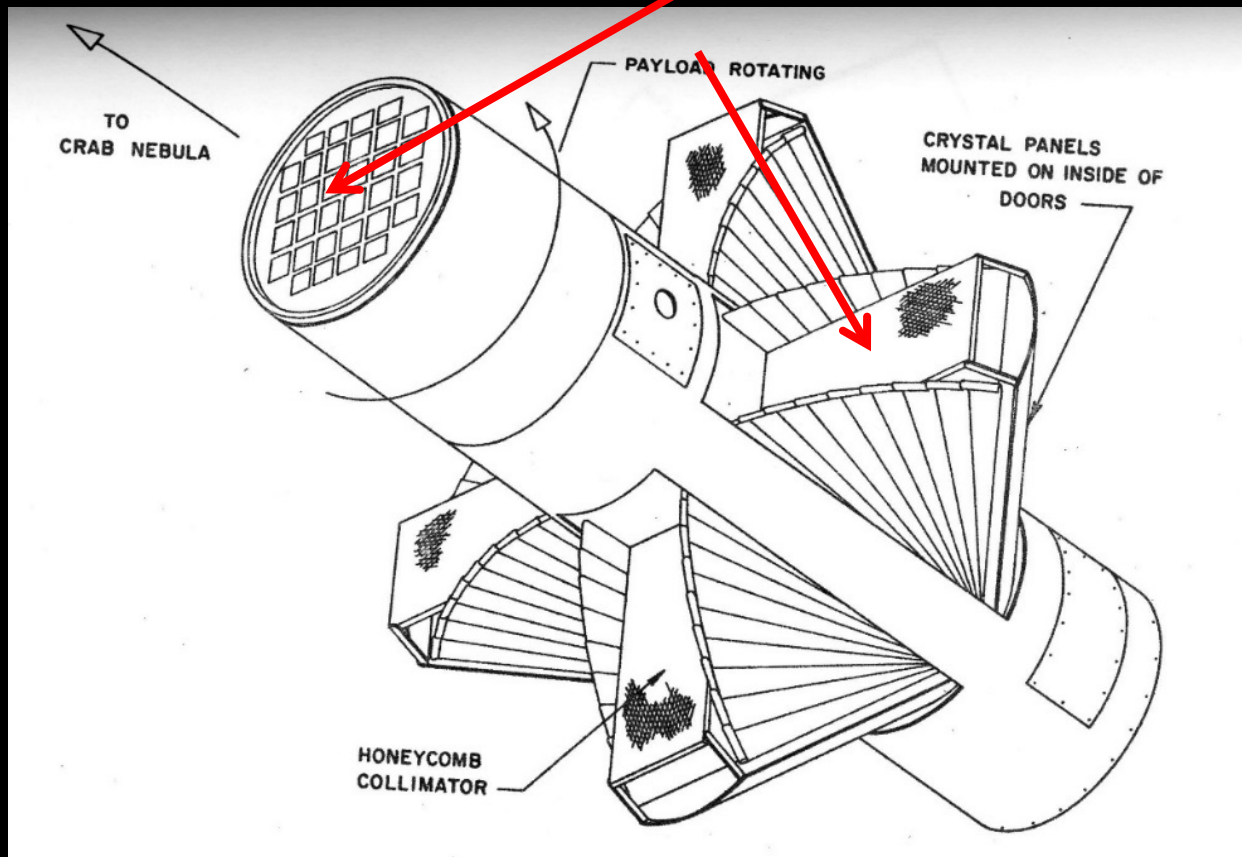
Azimuthal scattering angle

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

$$MDP_{99}(\%) = (4.29 \times 10^4 / M(\%)) \sqrt{(R_S + R_B)} / \sqrt{R_S^2 t}$$

- 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 $R_B = 0$

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

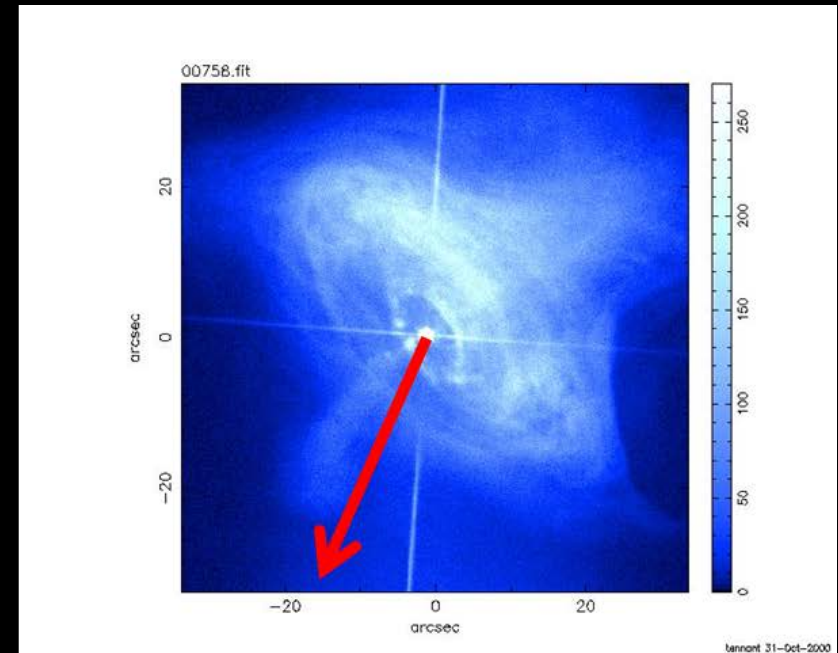
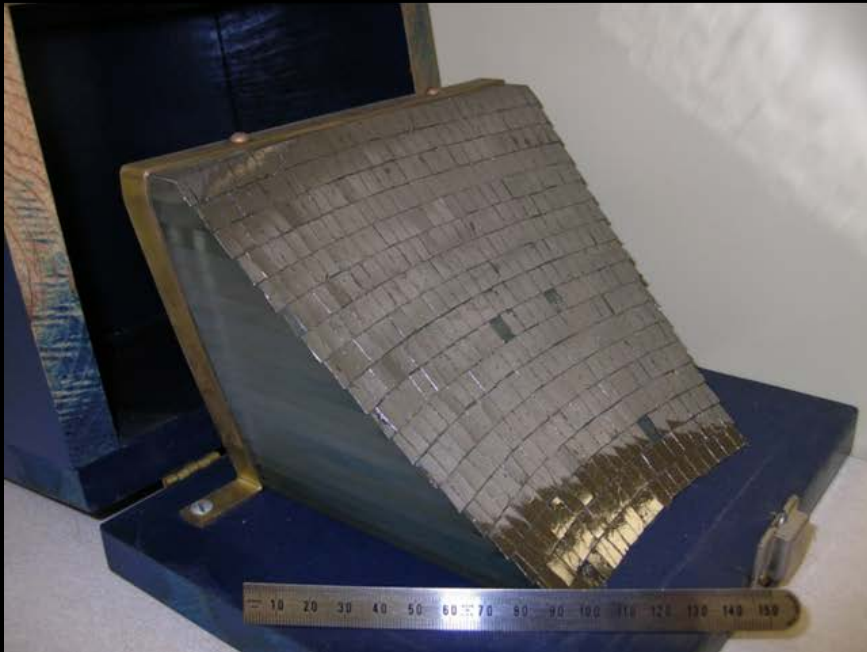


- 1971 Aerobee 350
 - Crab detection!
 - $P = 15\% \pm 5\%$
 - $\phi = 156 \pm 10^\circ$

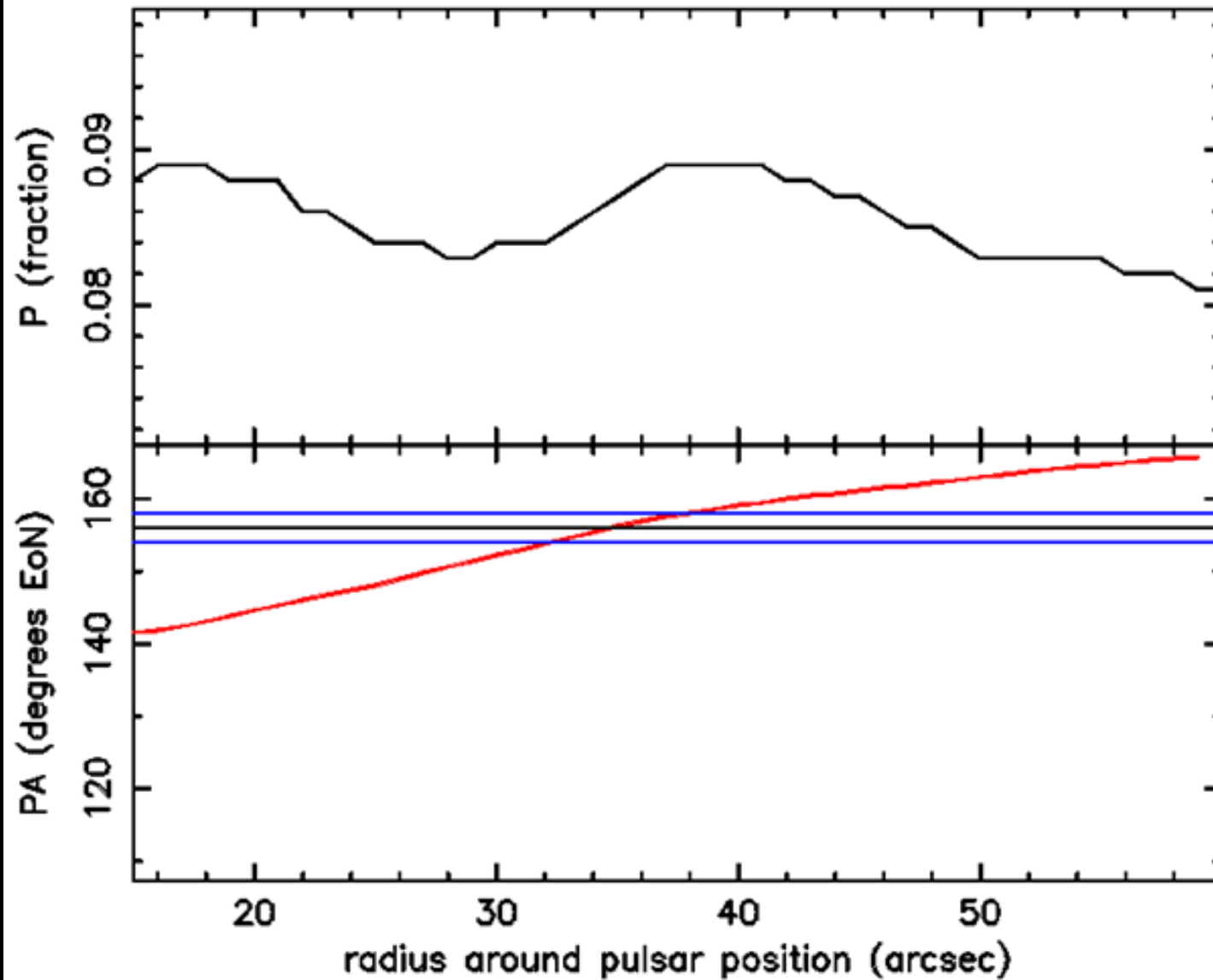


Crystal polarimeters on OSO-8

- 1975 OSO-8 crystal polarimeter
- Precision measurement of integrated emission from the Crab Nebula polarization at 2.6 keV
 - $P = 19\% \pm 1\%$
 - $\phi = 156 \pm 2^\circ$ (NNE)

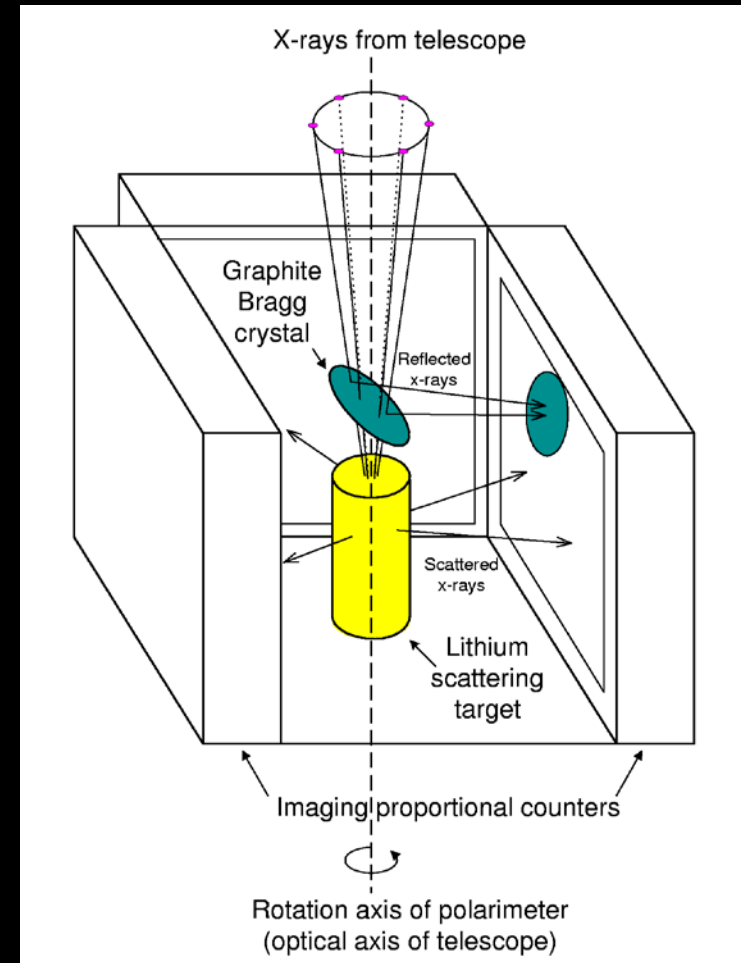


Compare to detailed optical results



Next came the Stellar X-ray Polarimeter (SXP)

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



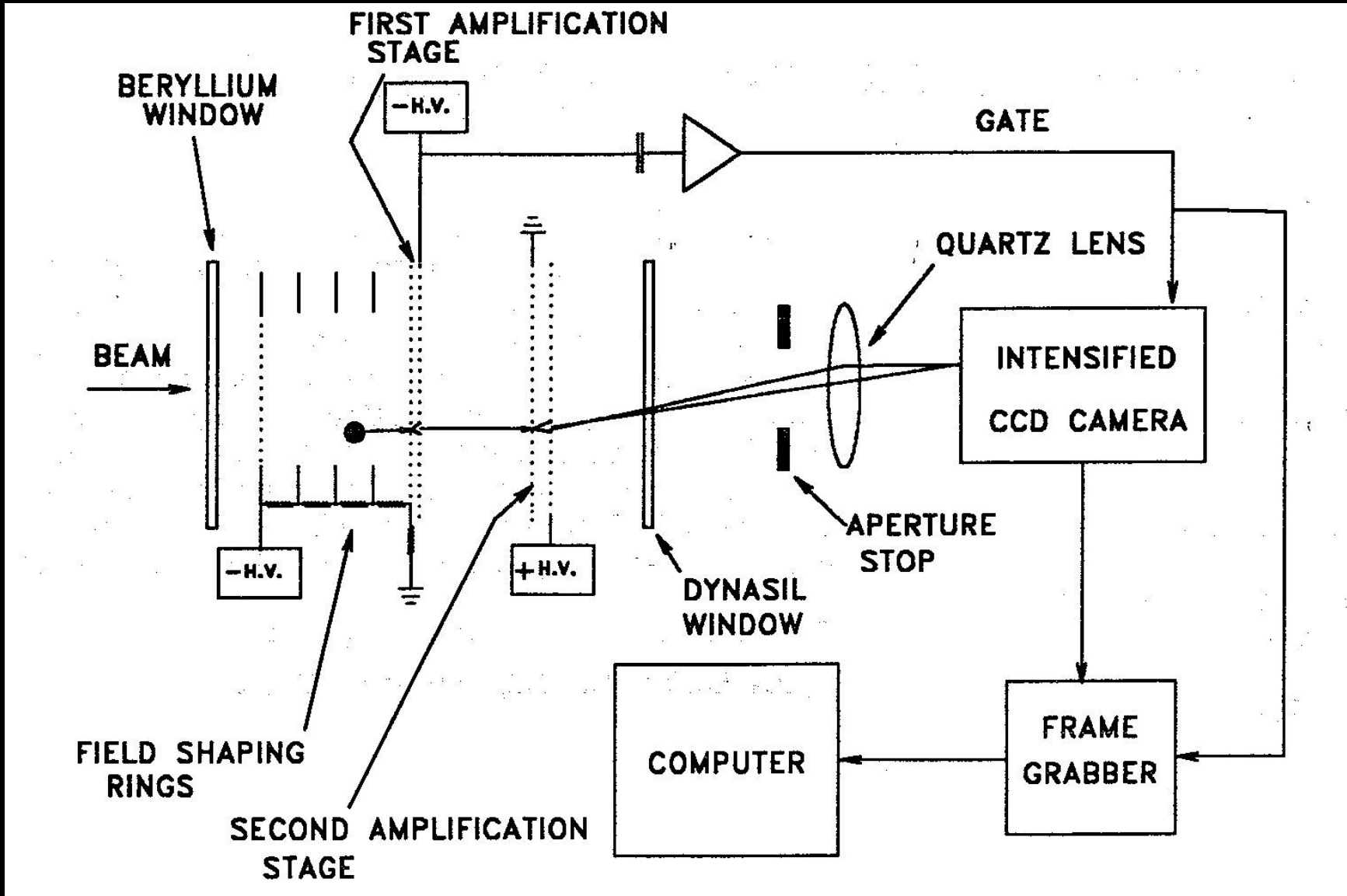
- Soviet Union Collapsed --- never launched

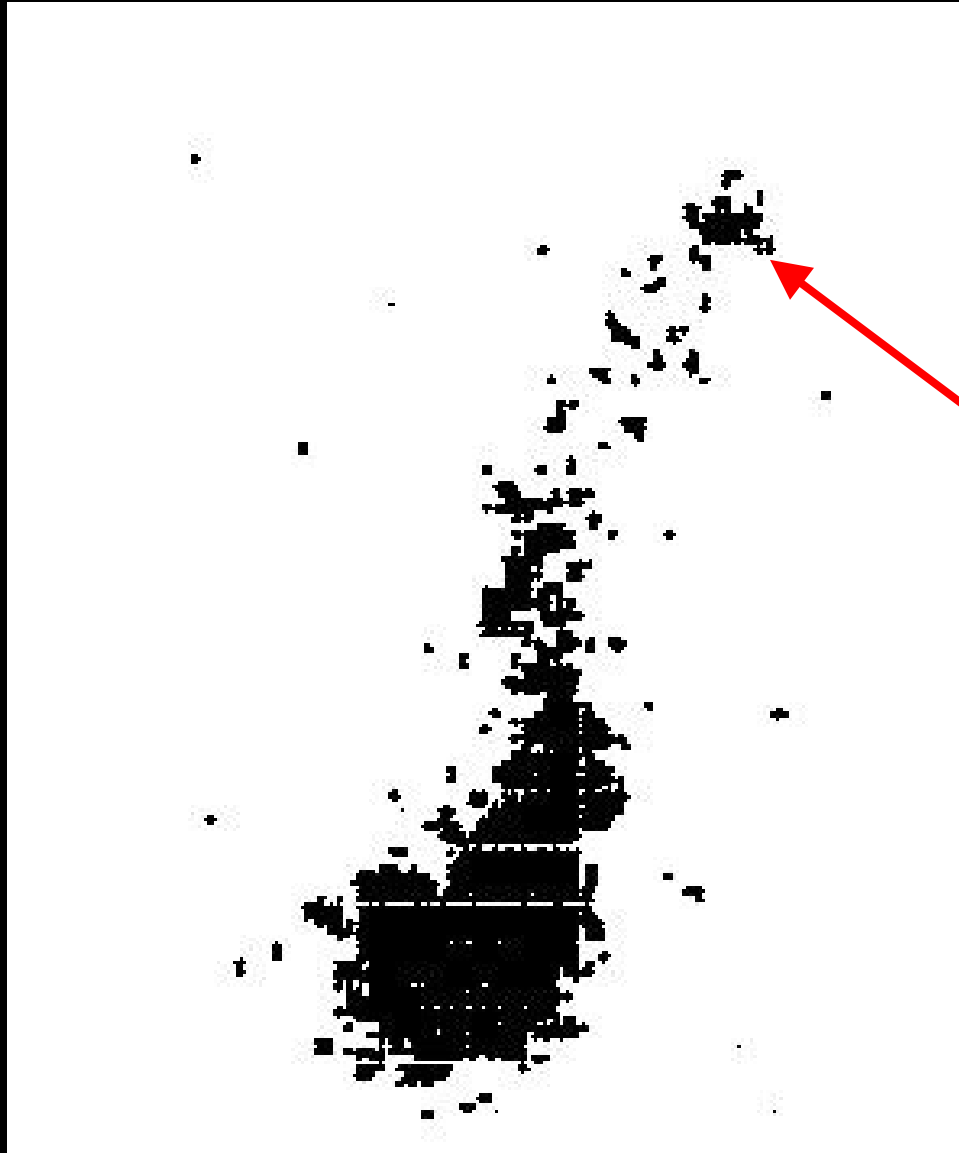
- The direction of the *initial* K-shell photoelectron is determined by the electric vector and the direction of the incoming photon

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

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

Electron tracking





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

- 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



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



Detector system funding, ground station



Spacecraft, payload structure, payload, observatory I&T



INAF

ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS



Polarization-sensitive imaging detector systems



Mission operations



Stanford University

Scientific theory



McGill

Science Working Group Co-Chair



Massachusetts Institute of Technology

Co-Investigator

A12567_151



Co-Investigators

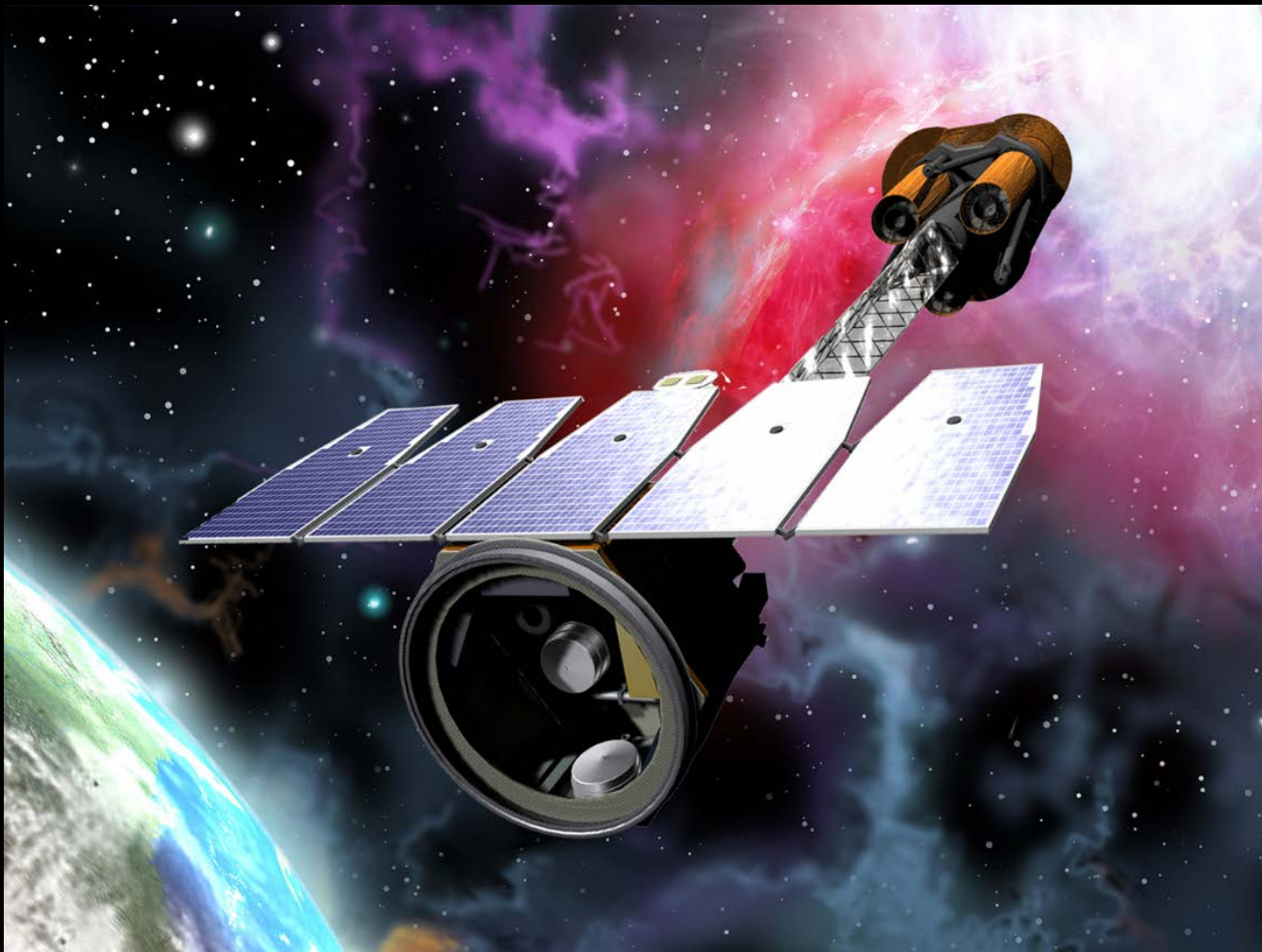
Luca Baldini, Ronaldo Bellazzini, Enrico Costa,
Ronald Elsner, Victoria Kaspi, Jeffery Kolodziejczak,
Luca Latronico, Herman Marshall, Giorgio Matt,
Fabio Muleri, Stephen L. O'Dell, Brian D. Ramsey,
Roger W. Romani, Paolo Soffitta, Allyn Tennant

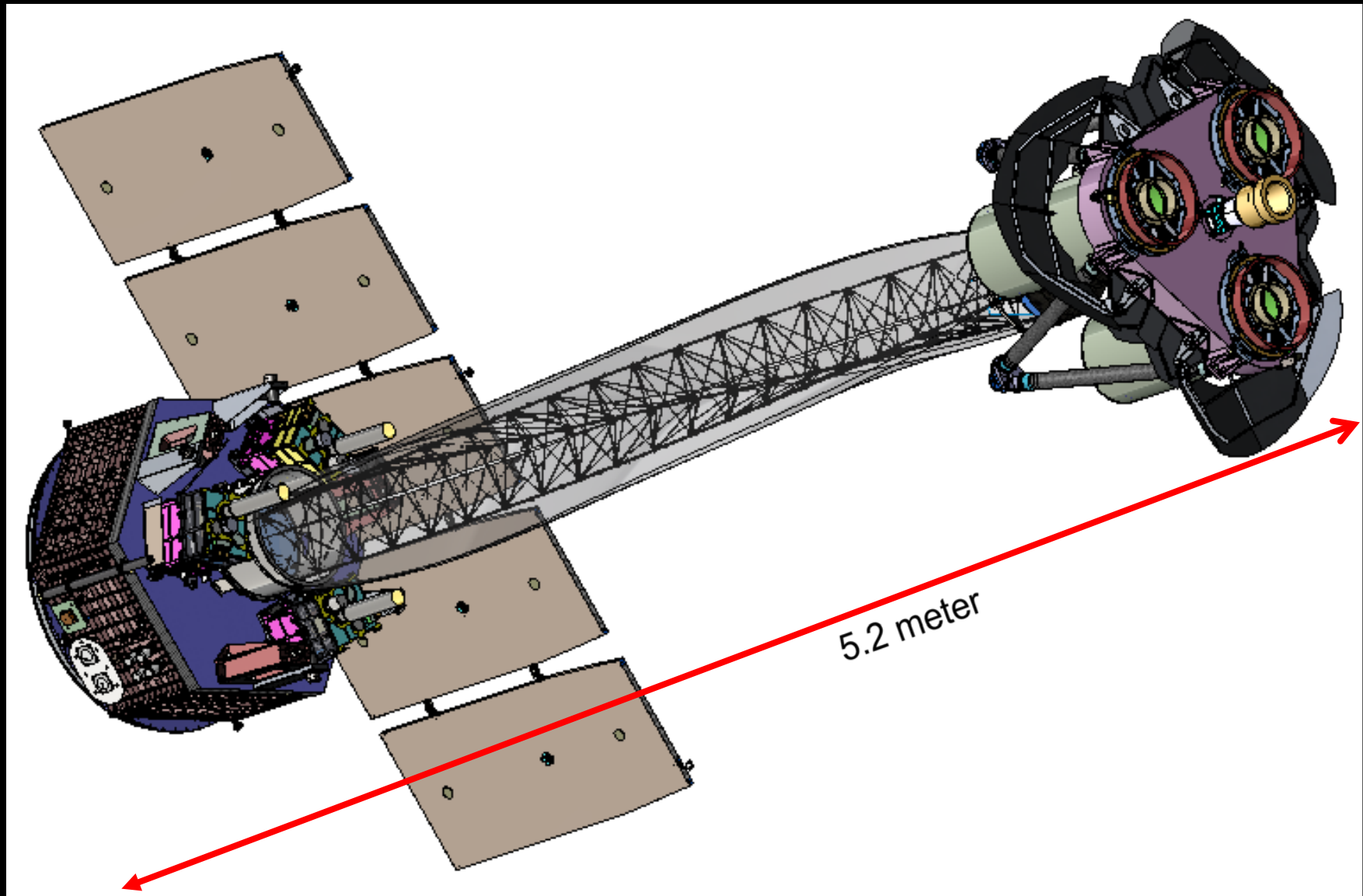
Collaborators

W. Baumgartner, A. Brez, N. Bucciantini, E. Churazov, S. Citrano, E. Del
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M. Pesce-Rollins, P.-O. Petrucci, M. Pinchera,
J. Poutanen, M. Razzano, A. Rubini, M. Salvati, C. Sgrò,
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R. Turolla, K. Wu, S. Zane, D. Zanetti

Imaging X-ray Polarimetry Explorer (IXPE)

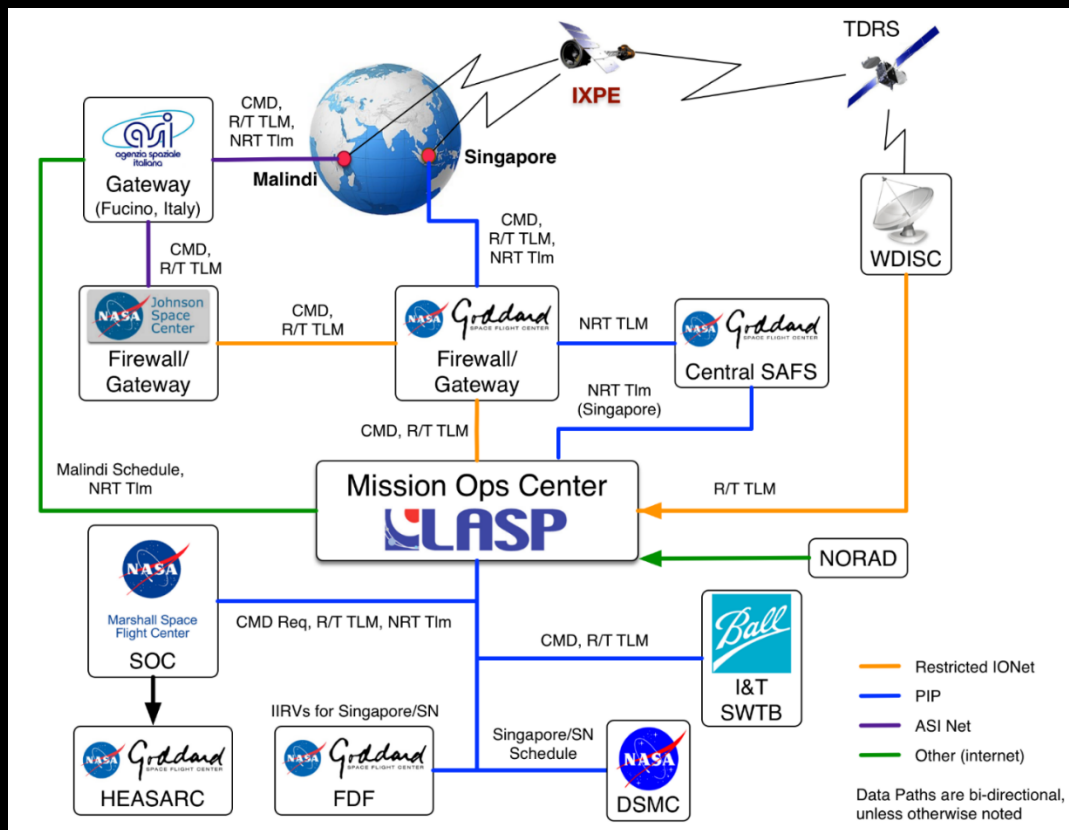
- Three sets of identical X-ray mirror modules and imaging, polarization-sensitive detectors





IXPE mission overview

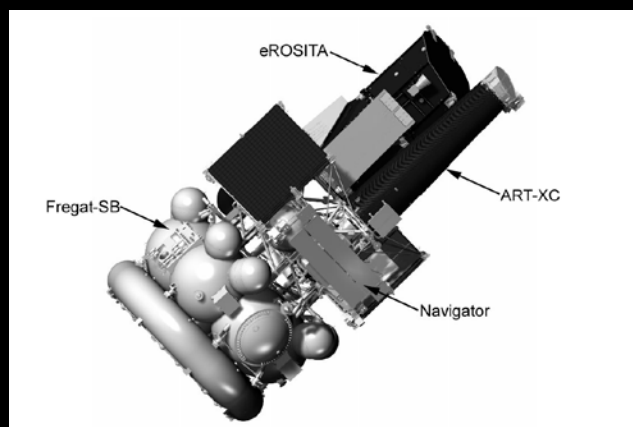
- Pegasus XL launch from Kwajalein
- Launch ready by early 2021
- 540-km circular orbit at 0° inclination
- 2-year baseline mission, 1 year extension
- Point-and-stare at known targets
- Malindi ground station (Singapore Backup)
- Mission Operations Center at CU/LASP
- Science Operations Center at MSFC



Electroformed X-ray optics @ MSFC

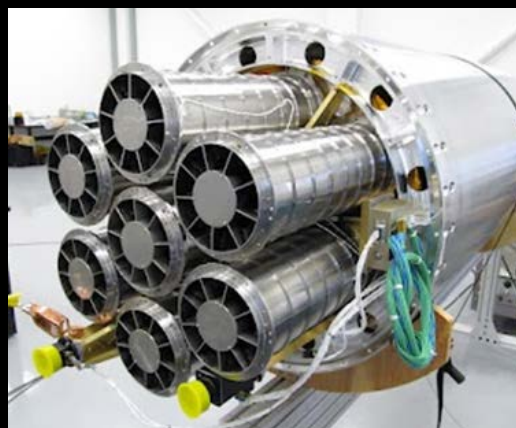
ART-XC (satellite)

8 Modules, 28 shells,
qualified and delivered
for flight in 2018



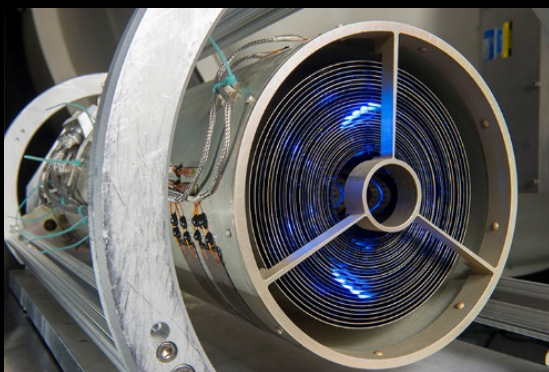
FOXSI (rocket)

7 Modules, 7/10
shells,
flown in 2012 & 2014



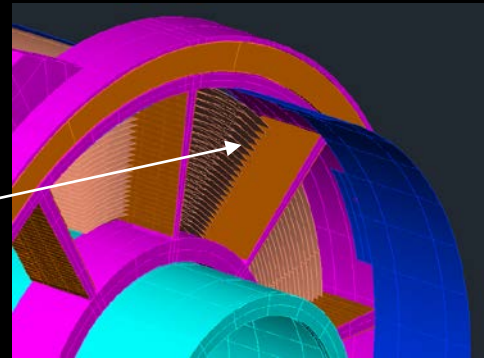
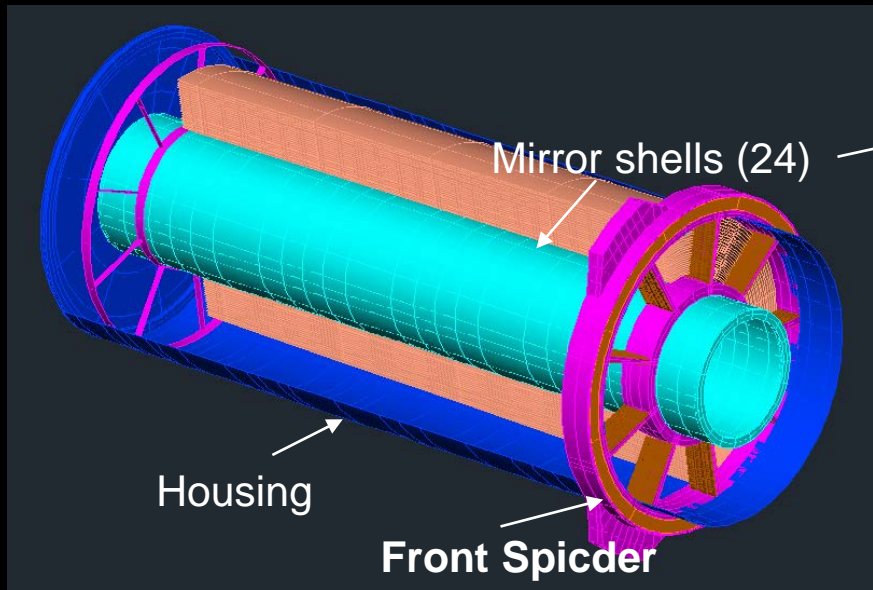
HERO/HEROES (balloon)

8 Modules, 13/14 shells,
latest flight in 2013

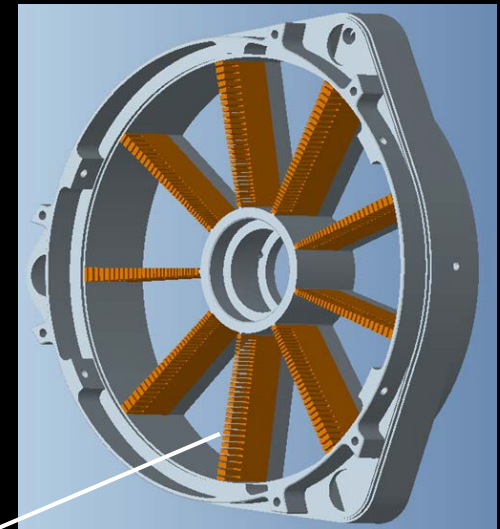


Mirror Module Assembly

IXPE Mirror Module Assembly



Front Spider



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

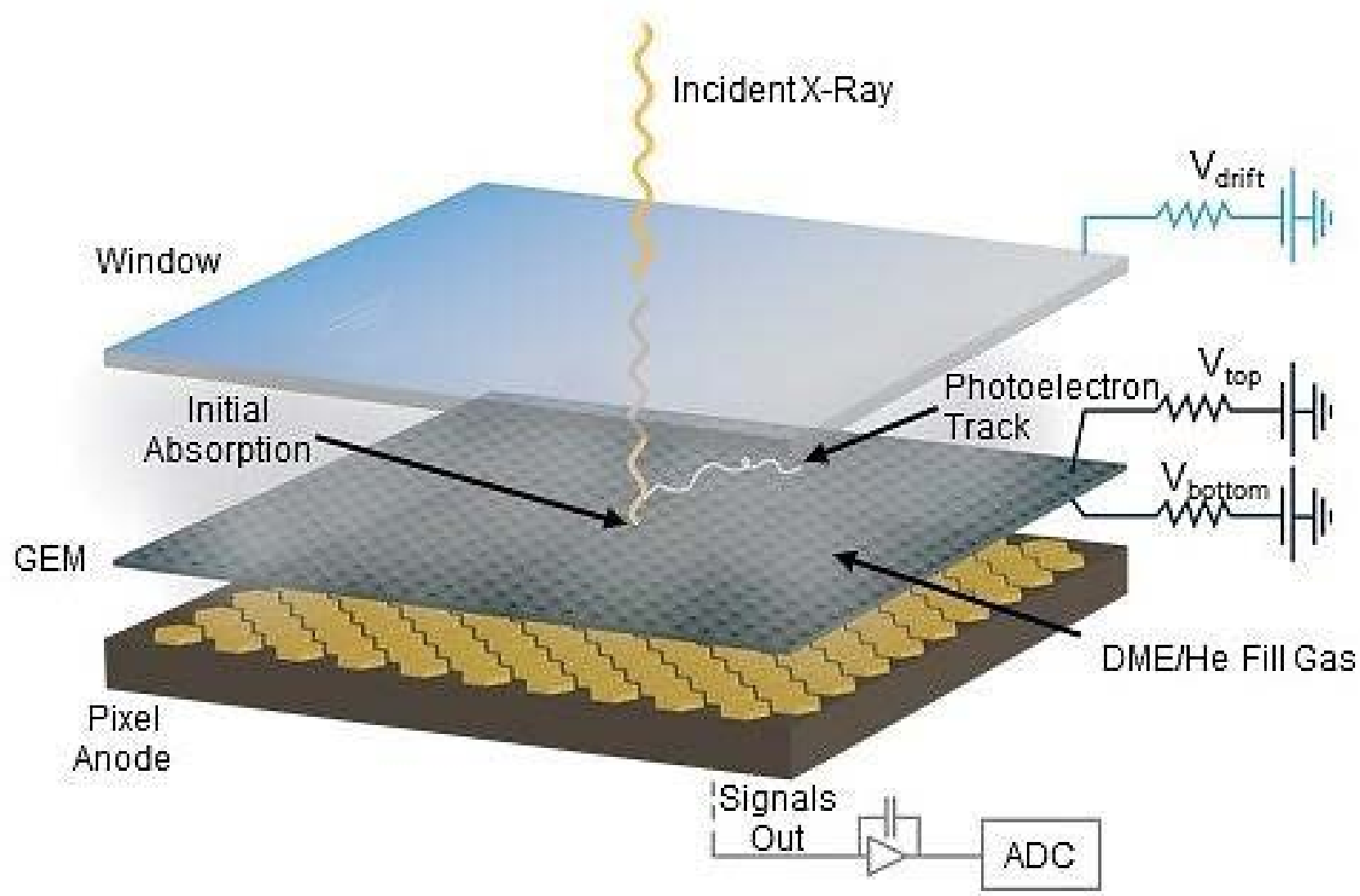
Shell Mounting Comb



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

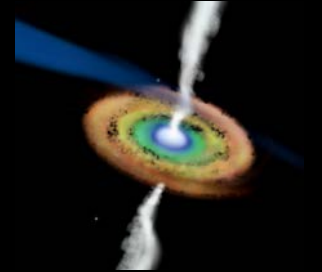


The polarization sensitive detectors

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

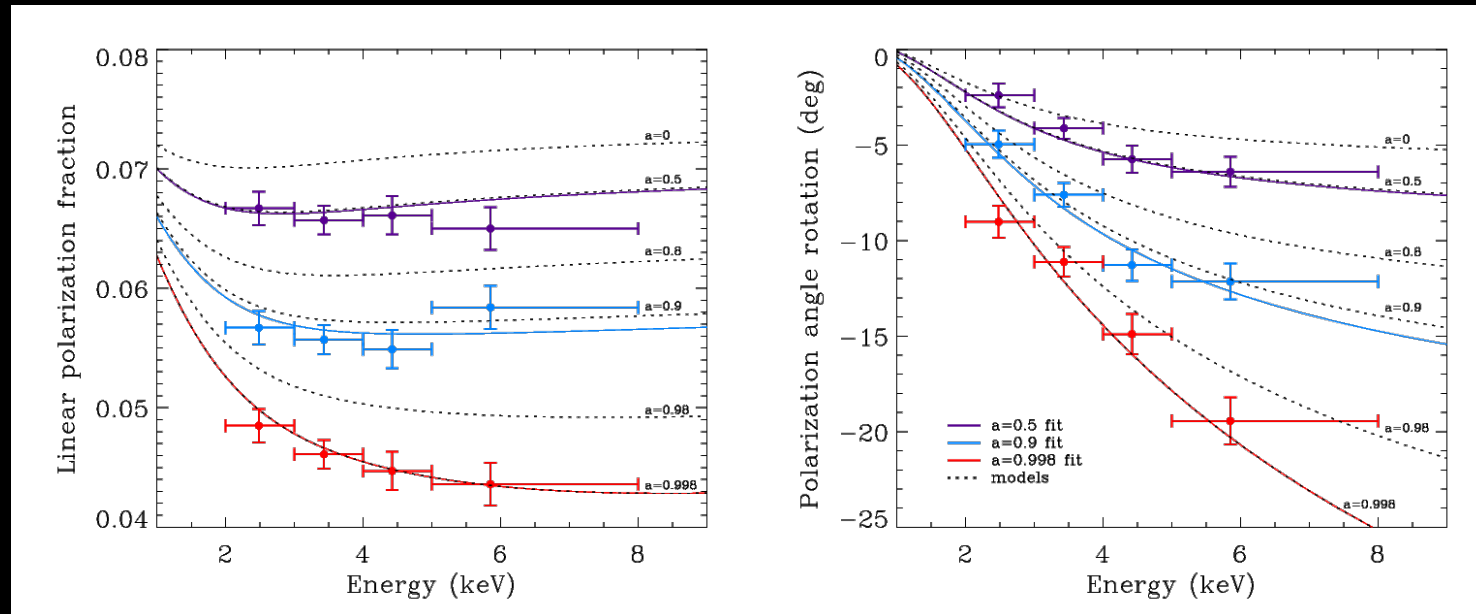
Measure black-hole spin in twisted space-time

- 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



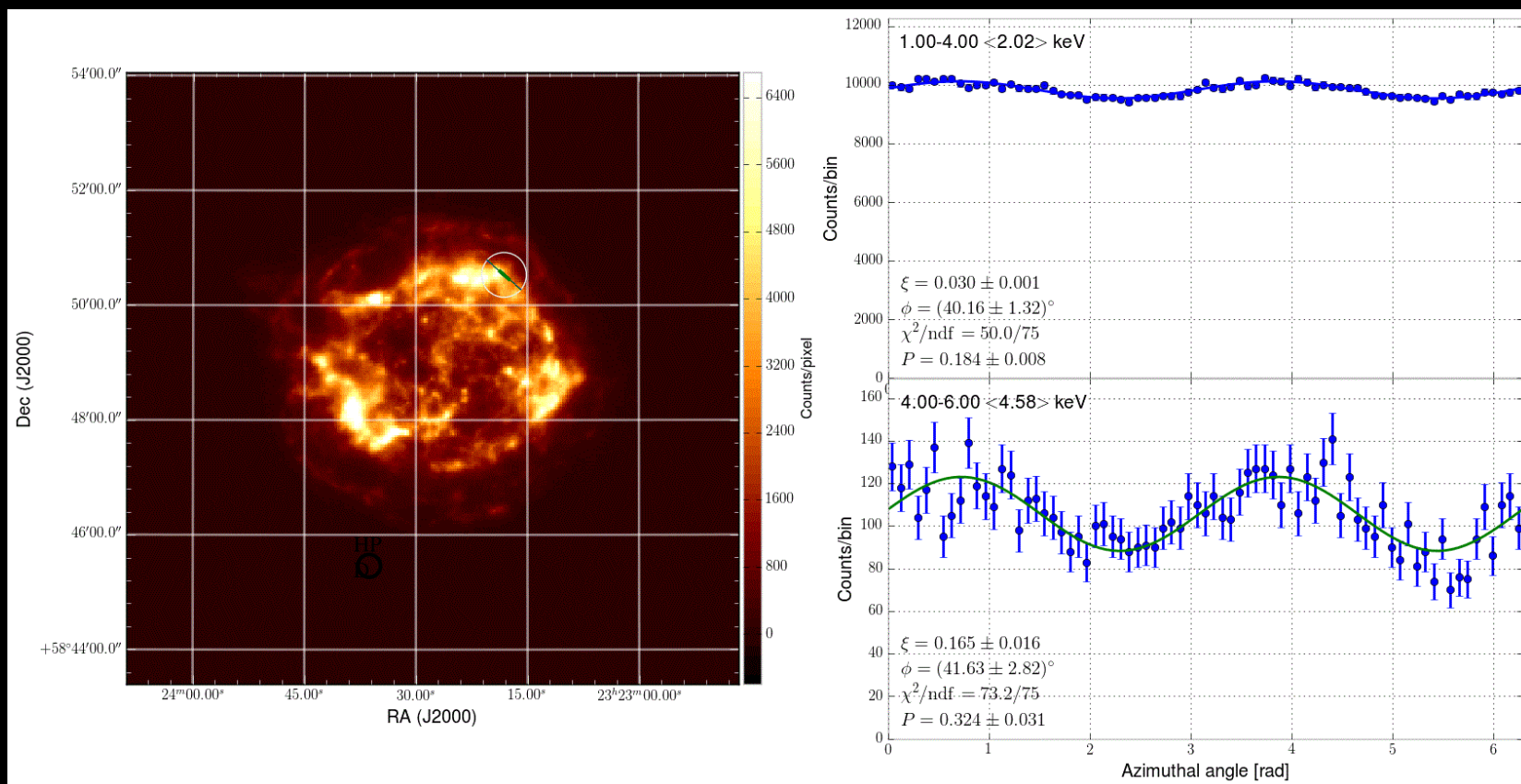
$$a = 0.50 \pm 0.04; 0.900 \pm 0.008; 0.99800 \pm 0.00003$$

(200-ks observation)



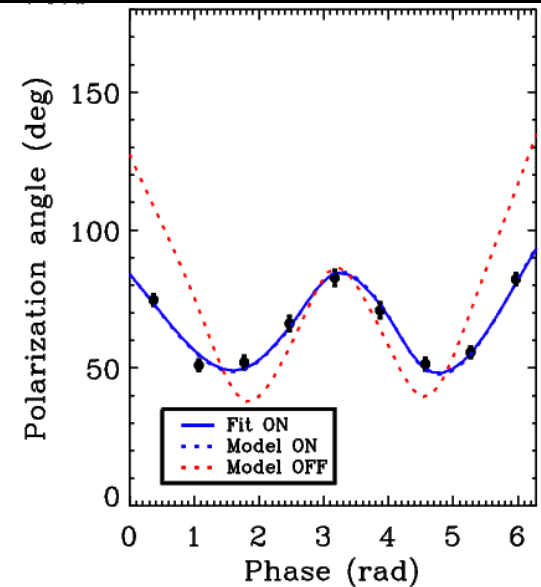
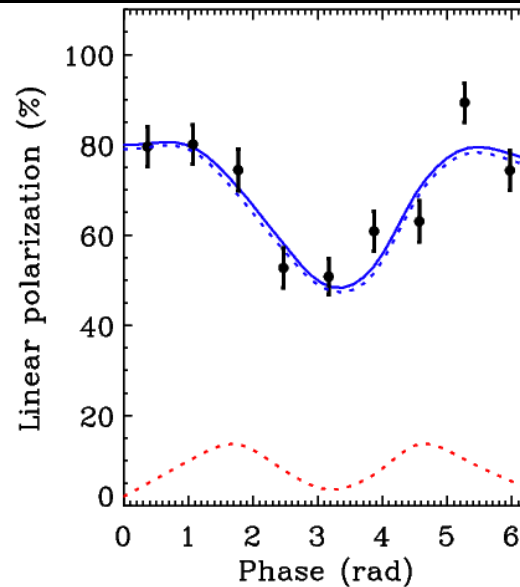
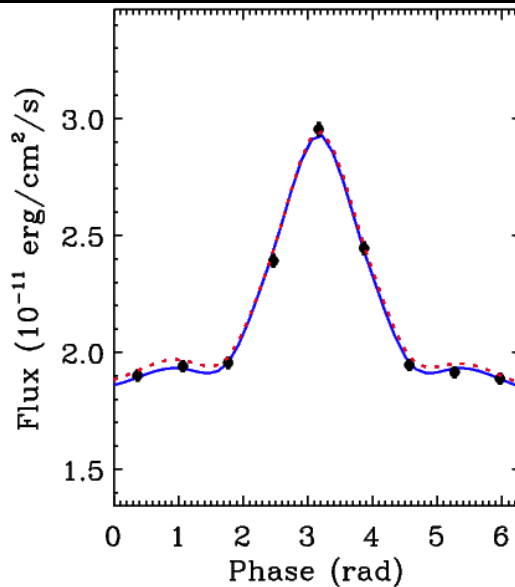
Map magnetic field of synchrotron sources

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



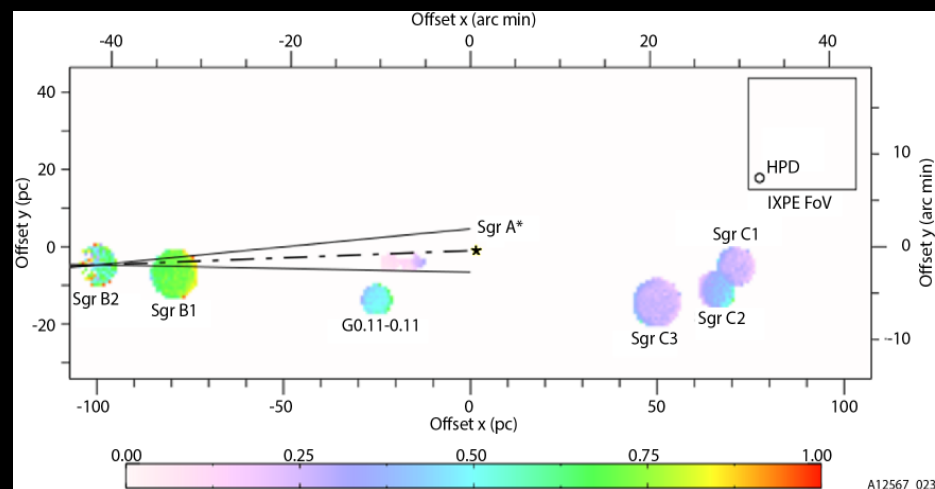
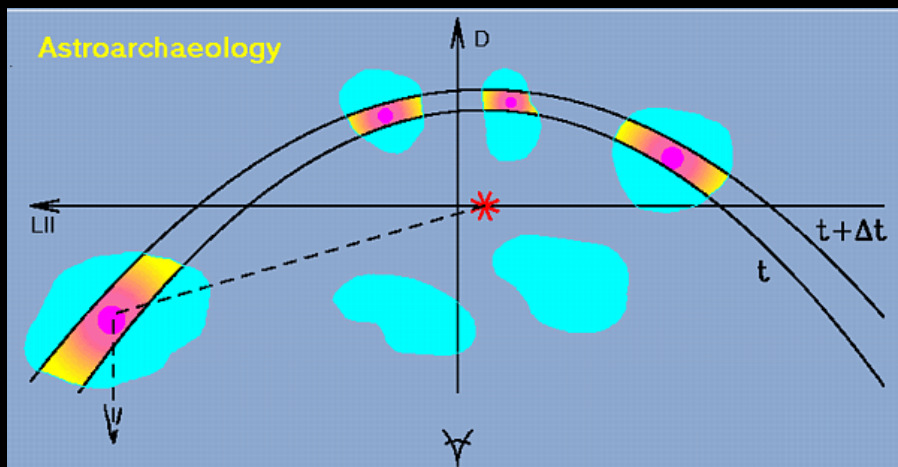
Cas A image at IXPE resolution (1.5-Ms)

- 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



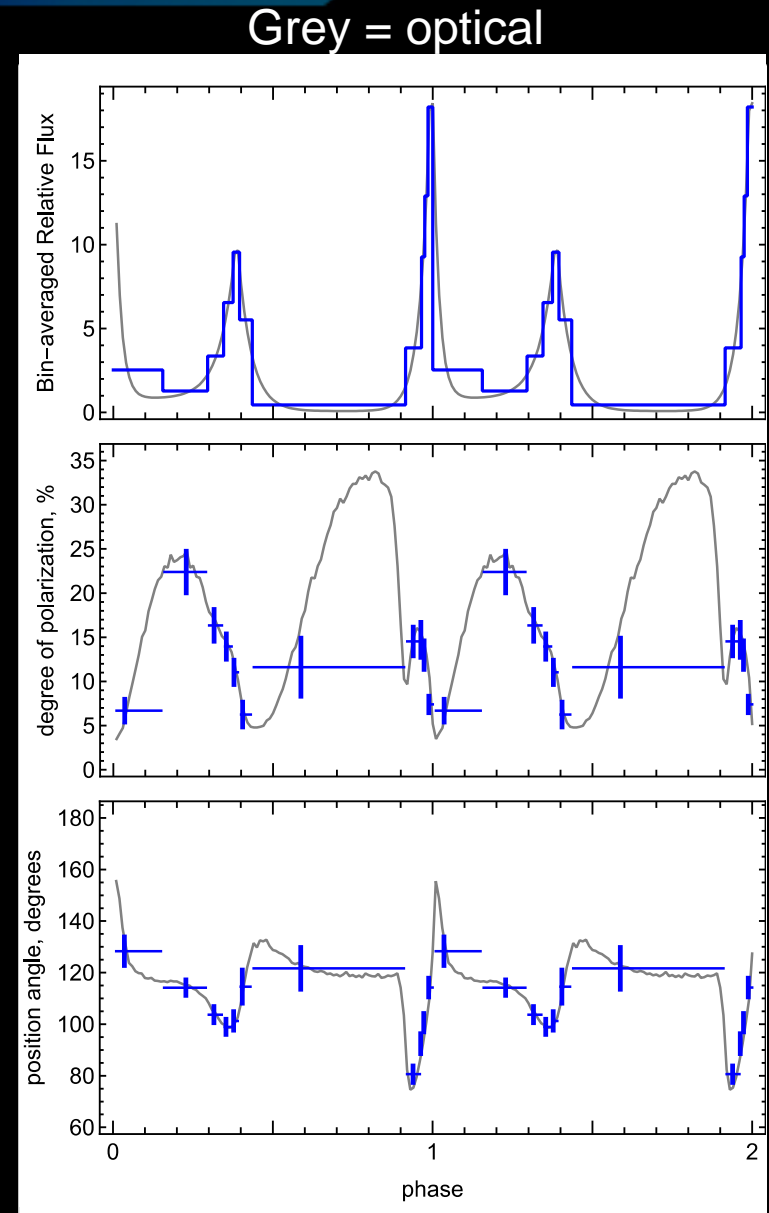
Was Sgr A* recently $10^6 \times$ more active?

- 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 \approx 300 years ago



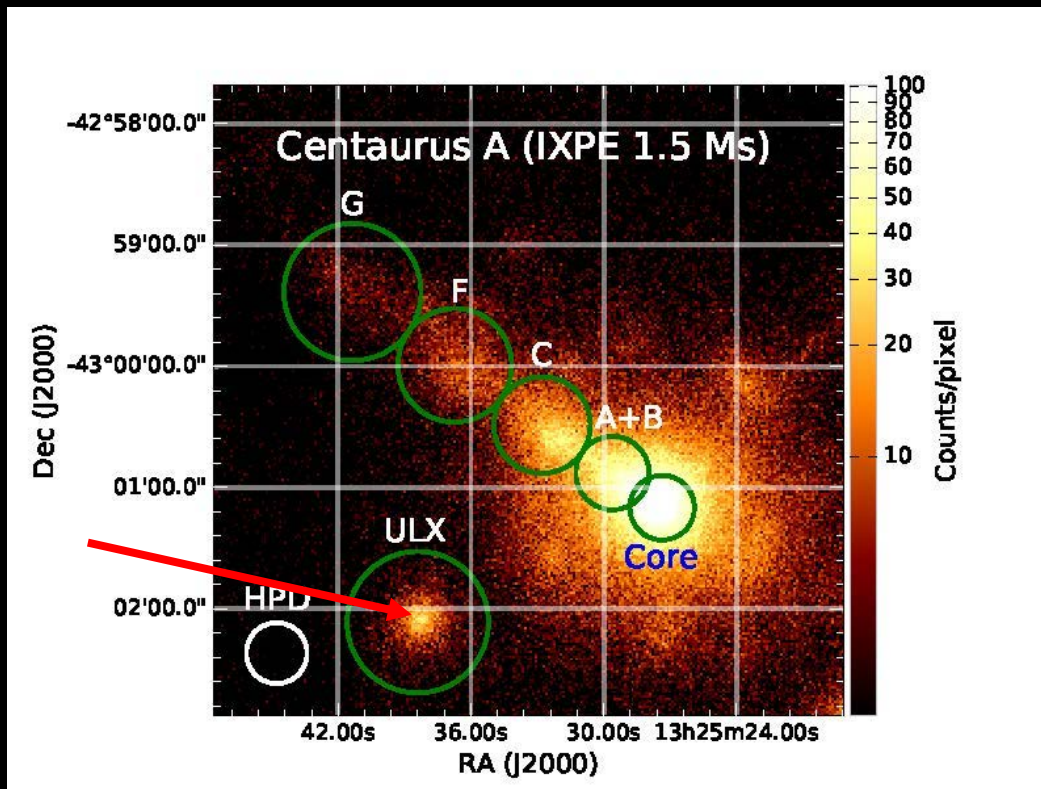
Phase-resolved polarimetry: Crab Pulsar

- 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



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

