The Imaging X-ray Polarimetry Explorer (IXPE)

Martin C. Weisskopf, *IXPE* PI, MSFC
On behalf of the entire *IXPE* team

IXPE ACCOMPLISHES NEW SCIENCE WITH NEW CAPABILITIES

- **Opens a new window on the universe — imaging (30“) X-ray polarimetry**
  - Is the science driver that advances and impacts high-energy astrophysics
  - Increases information space and lifts modeling degeneracies
- **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 integration time by a factor of 100 compared to the OSO-8 experiment
  - Simultaneously provides imaging, spectral, timing, and polarization data
  - Is free of false-polarization systematic effects at less than a fraction of a percent
  - Enables meaningful polarization measurements for many sources of different classes

Marshall Space Flight Center

IXPE
Imaging X-Ray Polarimetry Explorer

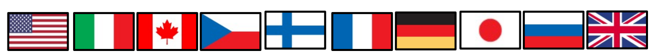
agenzia spaziale italiana

WHO IS INVOLVED?

Institutional Roles and Responsibilities

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
asi 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	Polarization-sensitive imaging detector systems
LASP	Mission operations
Roma Tre Università degli Studi; Stanford University	Scientific theory
McGill	Science Working Group Co-Chair
Massachusetts Institute of Technology	Co-Investigator

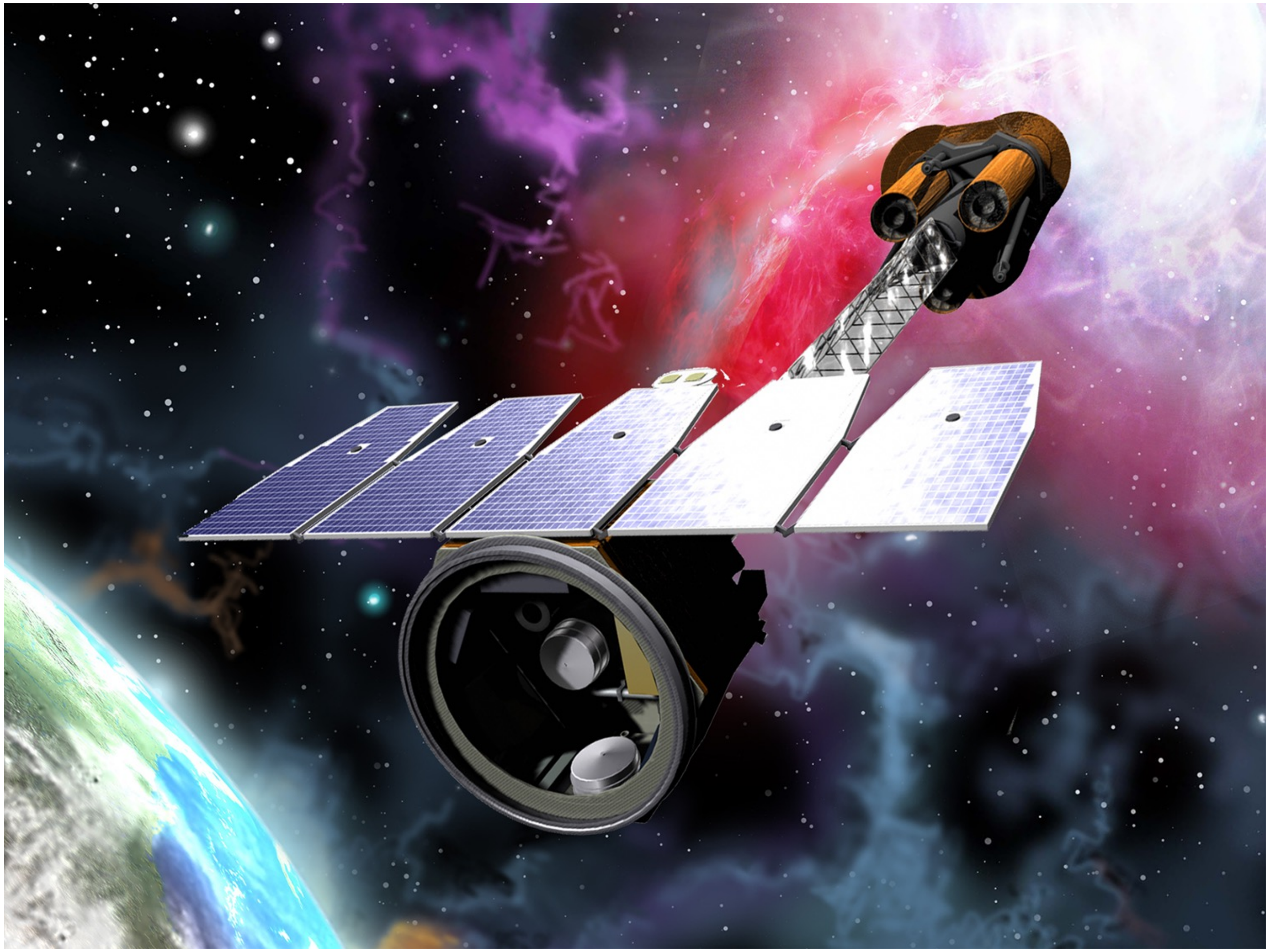
A12567_151


Science Advisory Team

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

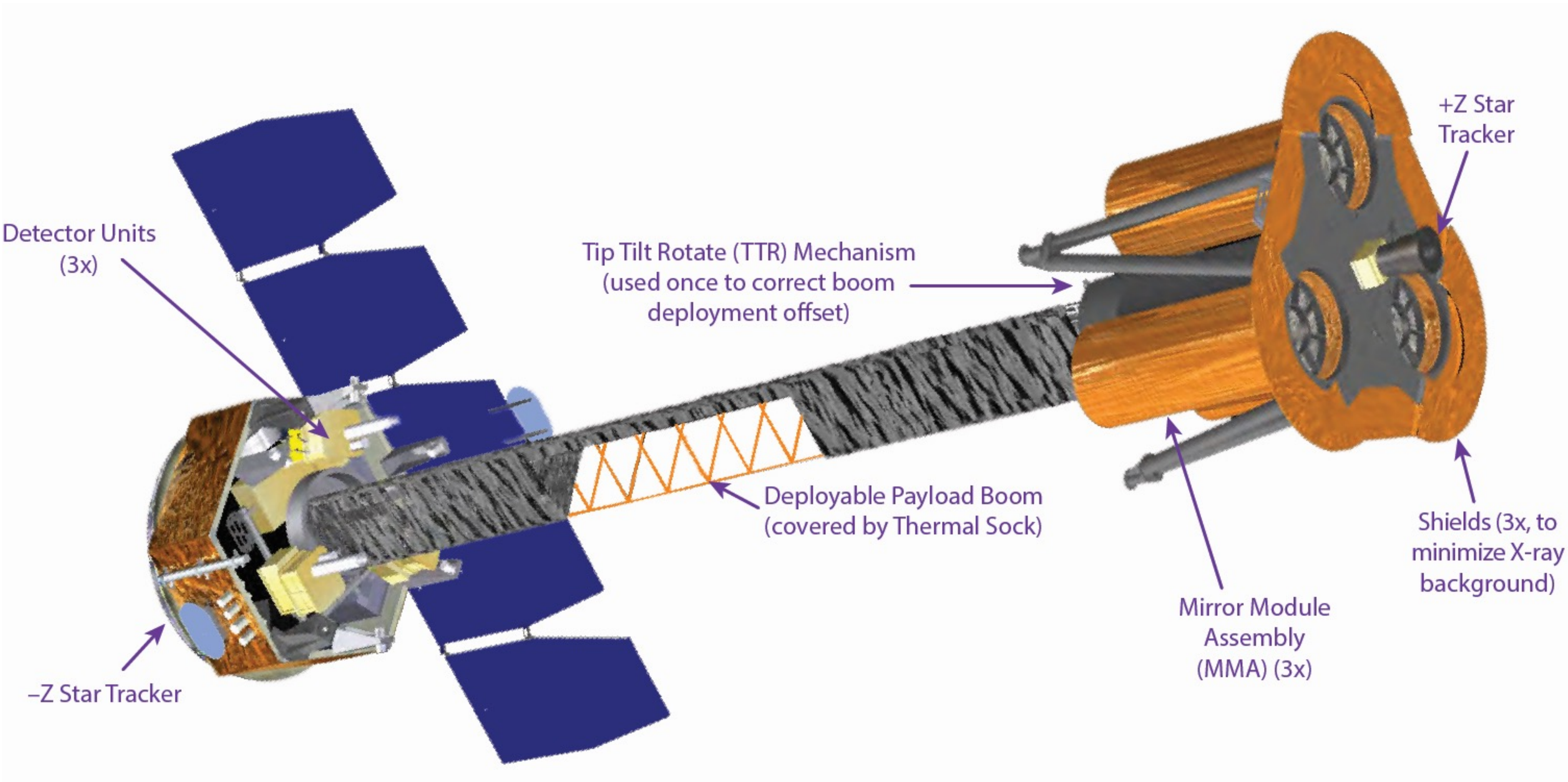
Collaborators: A. Brez, N. Bucciantini, E. Churazov, S. Citrano, E. Del Monte, N. Di Lalla, I. Donnarumma, M. Dovčiak, Y. Evangelista, S. Fabiani, R. Goosmann, S. Gunji, V. Karas, M. Kuss, A. Manfreda, F. Marin, M. Minuti, N. Omodei, L. Pacciani, G. Pavlov, M. Pesce-Rollins, P.-O. Petrucci, M. Pinchera, J. Poutanen, M. Razzano, A. Rubini, M. Salvati, C. Sgrò, F. Spada, G. Spandre, L. Stella, R. Sunyaev, R. Taverna, R. Turolla, K. Wu, S. Zane, D. Zanetti

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



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

IXPE
Imaging X-Ray Polarimetry Explorer



IXPE
Imaging
X-Ray
Polarimetry
Explorer

The X-ray mirror modules

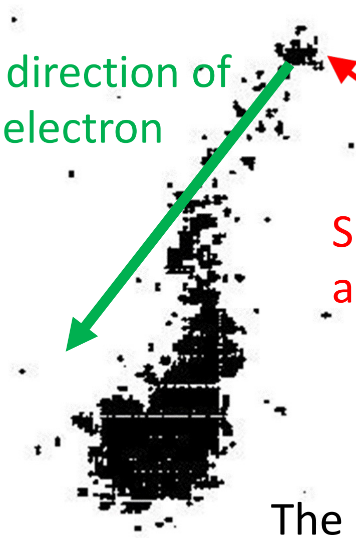
Parameter	Value
Number of mirror modules	3
Number of shells per mirror module	24
Focal length	4000 mm
Total shell length	600 mm
Range of shell diameters	162–272 mm
Range of shell thicknesses	0.16–0.26 mm
Shell material	Electroformed nickel–cobalt alloy
Effective area per mirror module	230 cm^2 (@ 2.3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

IXPE Imaging X-Ray Polarimetry Explorer

THE POLARIZATION SENSITIVE DETECTORS

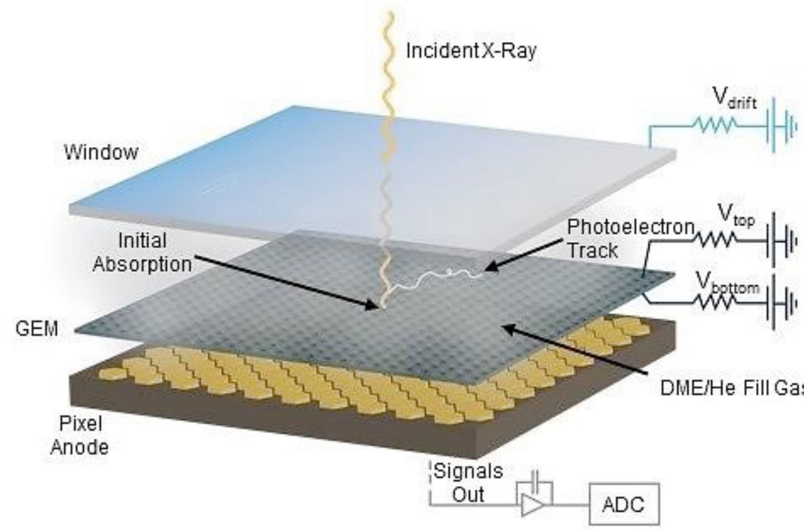
- **The initial direction of the K-shell photoelectron is determined by the electric vector**

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



Initial direction of photoelectron

Site of initial ionization and Auger electron cloud



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

IXPE
Imaging
X-Ray
Polarimetry
Explorer

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 ($\propto \sqrt{E}$)

POLARIZATION SENSITIVITY

- **For point sources, sensitivity is described in terms of the Minimal Detectable Polarization (MDP)**
  - The MDP depends upon source count rate (R_S), background count rate (R_B), exposure time Δt, and the count-weighted modulation factor <μ>
    - The modulation factor μ is the fractional amplitude in the histogram of initial photoelectron directions for a 100%-polarized source
    - For *IXPE*, R_B is negligible; thus the MDP is inversely proportional to <μ> $(R_S\,\Delta t)^{1/2}$
  - MDP_{99} is the degree of polarization (independent of the position angle) that has only a 1% chance of being a statistical fluke

$$\mathrm{MDP}_{99} = \sqrt{-2\ln(1-\mathrm{CL})}\,\sqrt{2}\,\frac{\sqrt{C_S + C_B}}{C_S\langle\mu\rangle} \xrightarrow{\mathrm{CL}=0.99} 3.035\sqrt{2}\,\frac{\sqrt{C_S + C_B}}{C_S\langle\mu\rangle} \xrightarrow{C_S \gg C_B} \frac{4.292}{\sqrt{C_S}\,\langle\mu\rangle}.$$

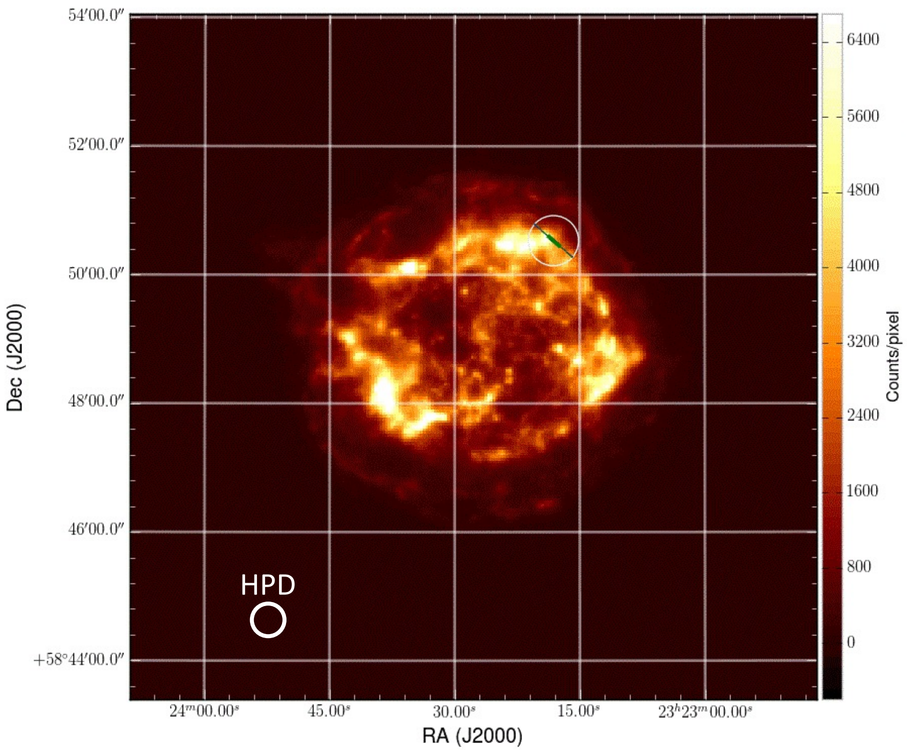
For *IXPE*,

$$\mathrm{MDP}_{99} \approx 4.5\% \Big/ \sqrt{\left[\frac{F_{2-8}}{10^{-11}\,\mathrm{erg\ cm^{-2}\,s^{-1}}}\right]\left[\frac{\Delta t}{10\ \mathrm{day}}\right]}$$

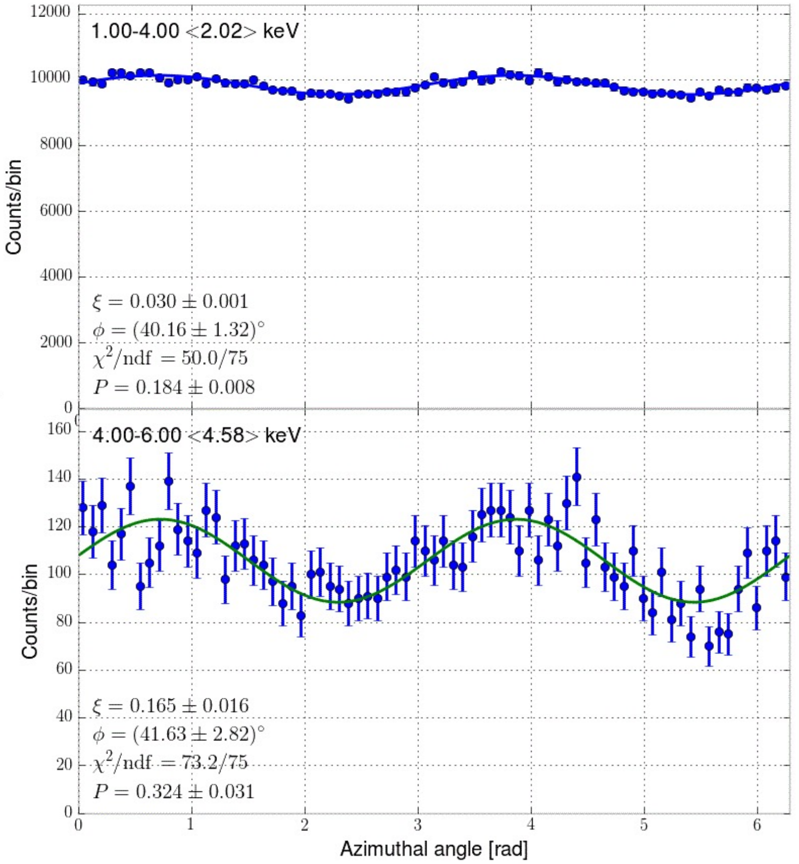
MAP MAGNETIC FIELD OF SYNCHROTRON SOURCES TO PROBE SITES OF COSMIC-RAY ACCELERATION: CAS A

IXPE Imaging X-Ray Polarimetry Explorer

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

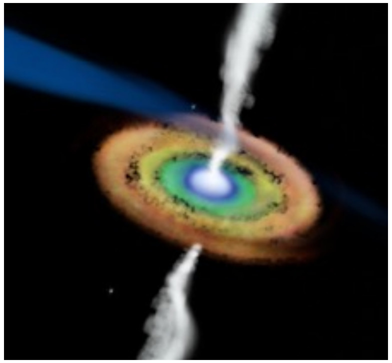


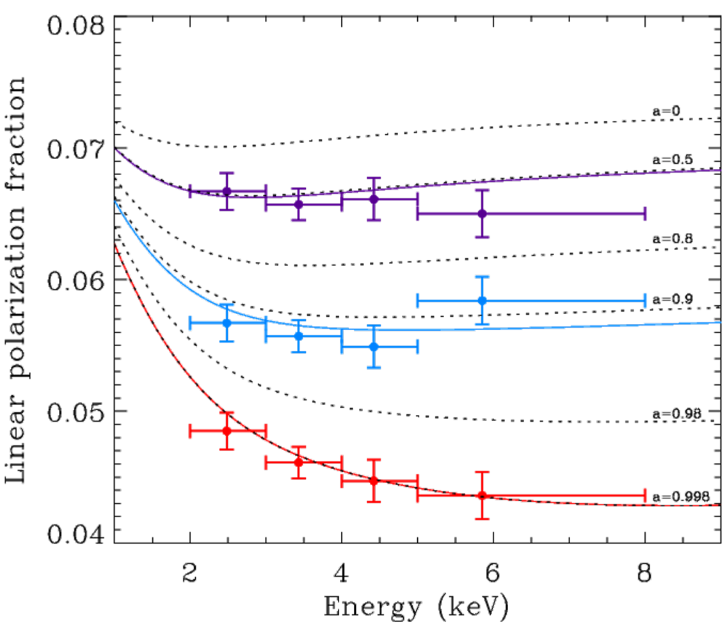
Cas A image at *IXPE* resolution (1.5-Ms)

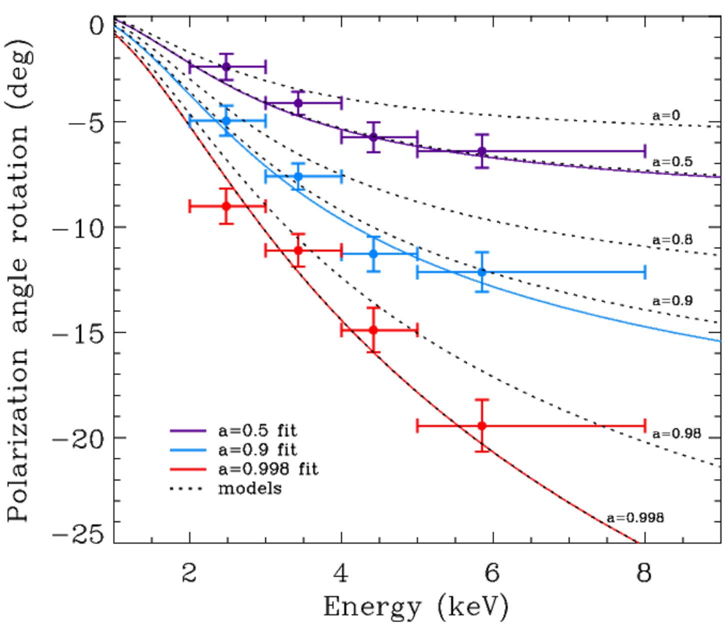


MEASURE BLACK-HOLE SPIN FROM POLARIZATION ROTATION IN TWISTED SPACE-TIME: GRX1915+105

- **For a micro-quasar 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 constrain GRX1915+105 model
    - a = 0.50±0.04; 0.900±0.008; 0.99800±0.00003 (200-ks observation)

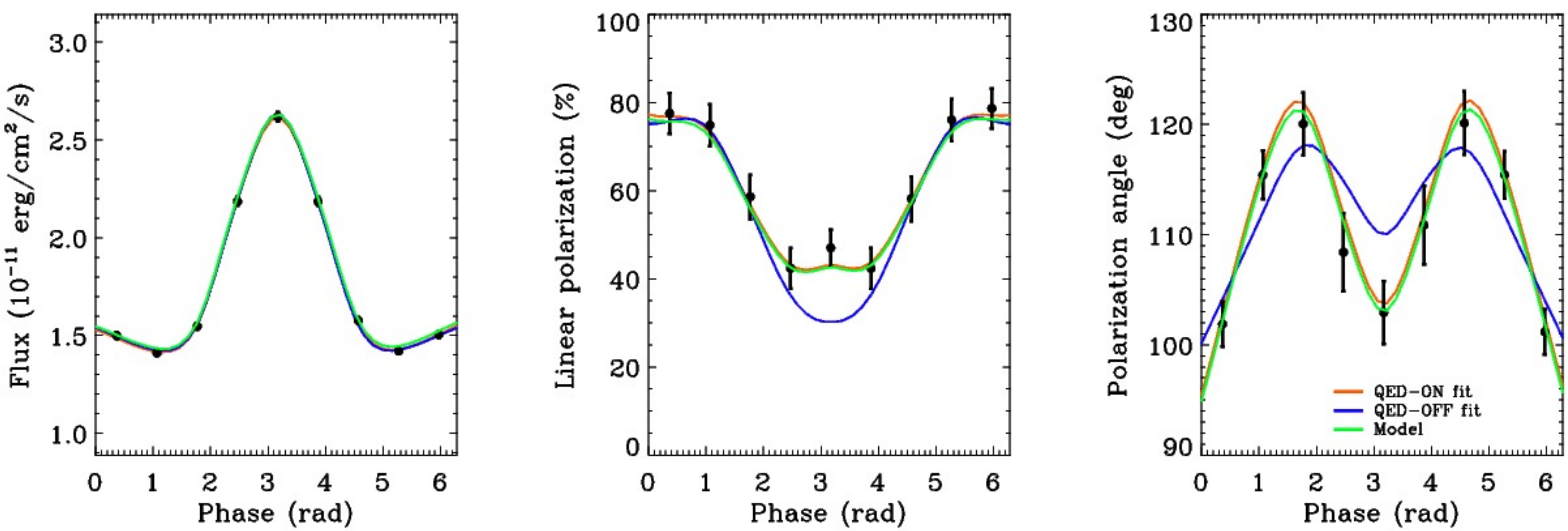






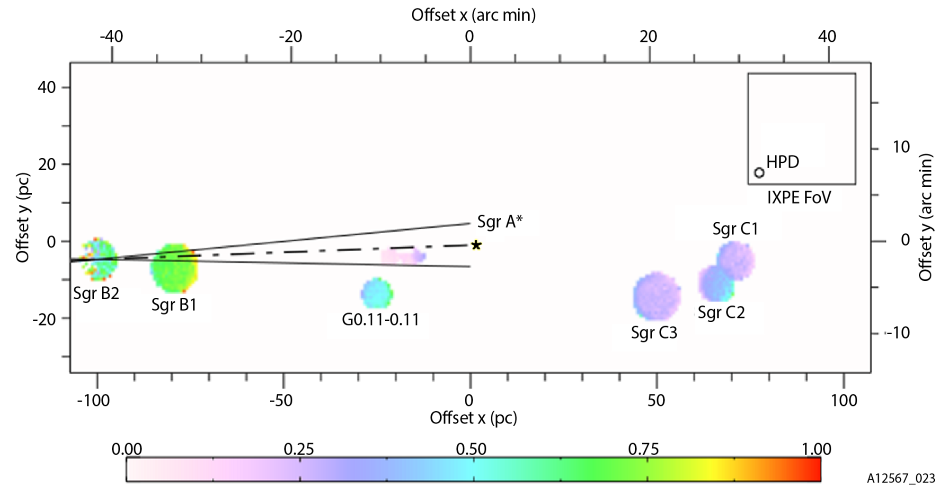
TEST QUANTUM ELECTRODYNAMICS (QED) IN ULTRA-STRONG MAGNETIC FIELDS

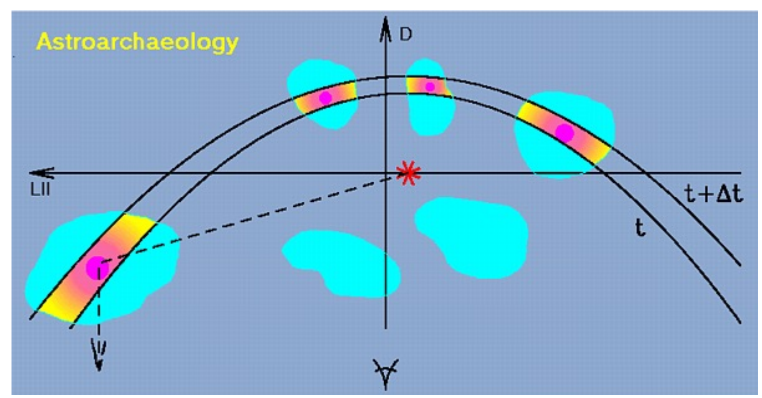
- **Magnetar is a neutron star with magnetic field up to 10^{15} Gauss**
  - Non-linear QED predicts magnetized-vacuum birefringence
    - Refractive indices of the two polarization modes differ from 1 and from each other
    - Impacts polarization and position angle as functions of pulse phase, but not the flux
  - Example is the magnetar 1RXS J170849.0-400910, with an 11-s pulse period
    - Can exclude QED-off at better than 99.9% confidence 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
  - If not, still a discovery



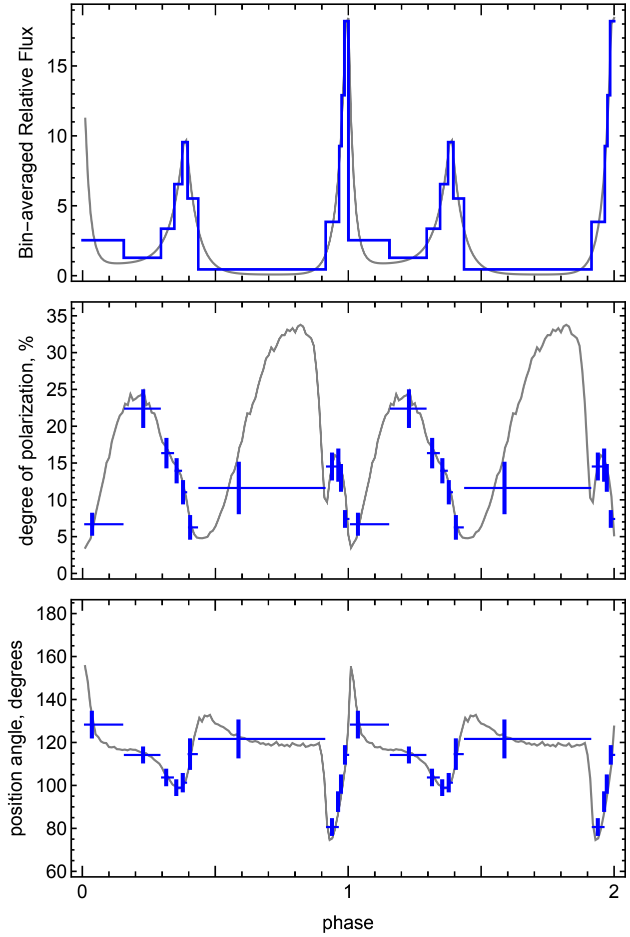


PROBE EMITTING REGIONS OF PULSARS THROUGH PHASE-RESOLVED POLARIMETRY: CRAB PULSAR

IXPE Imaging X-Ray Polarimetry Explorer

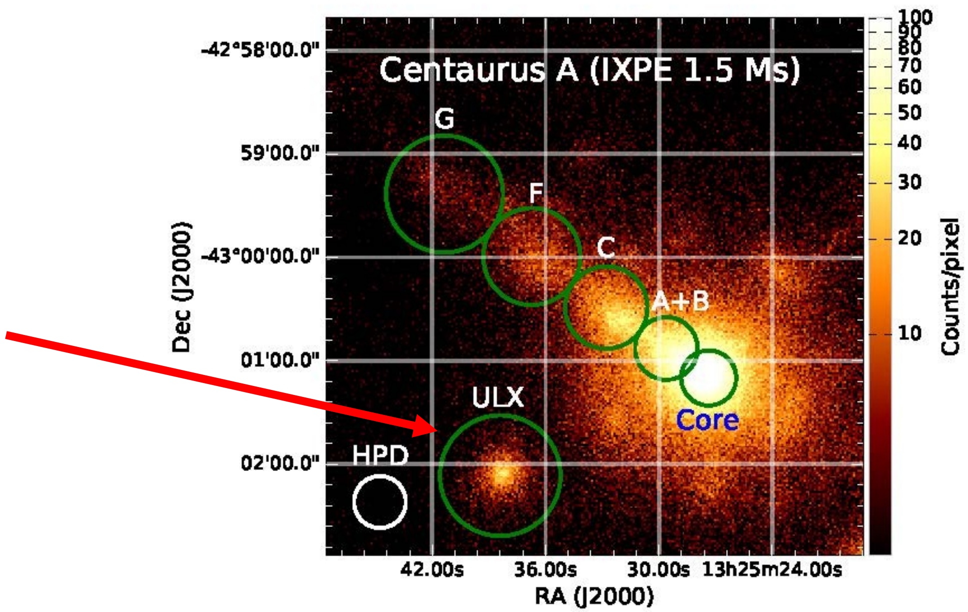
- **Emission geometry and processes are unsettled**
  - Competing models predict differing polarization behavior with pulse phase
- **X-rays provide cleaner probe of geometry**
  - Absorption likely more prevalent in visible band
  - Radiation process entirely different in radio band
    - Recently discovered 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**

Grey = optical



IXPE IMAGING ALSO AVOIDS CONFUSION AND PROVIDES SERENDIPITOUS BENEFITS

- **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
- **Imaging Cen A allows isolating other sources in the field**
  - 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

IXPE
Imaging X-Ray Polarimetry Explorer

CAPTURING THE PUBLIC'S IMAGINATION