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Imaging
X-Ray
Polarimetry
Explorer

Marshall Space Flight Center

agenzia spaziale italiana

The Imaging X-ray Polarimetry Explorer (IXPE)

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***IXPE* Principal Investigator**

NASA/MSFC

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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 observing time by a factor of 100 compared to only previous 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

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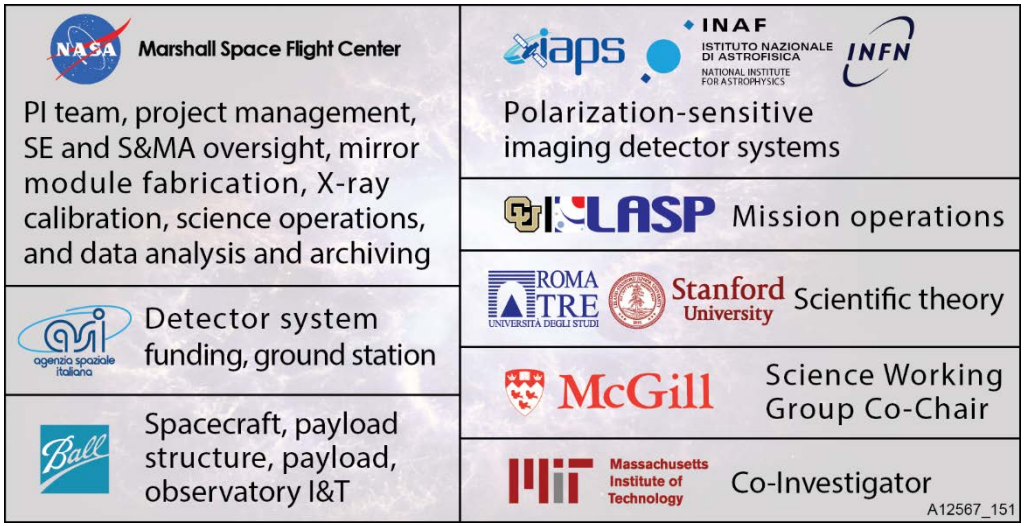
WHO IS INVOLVED?

Institutional Roles and Responsibilities



Science Advisory Team

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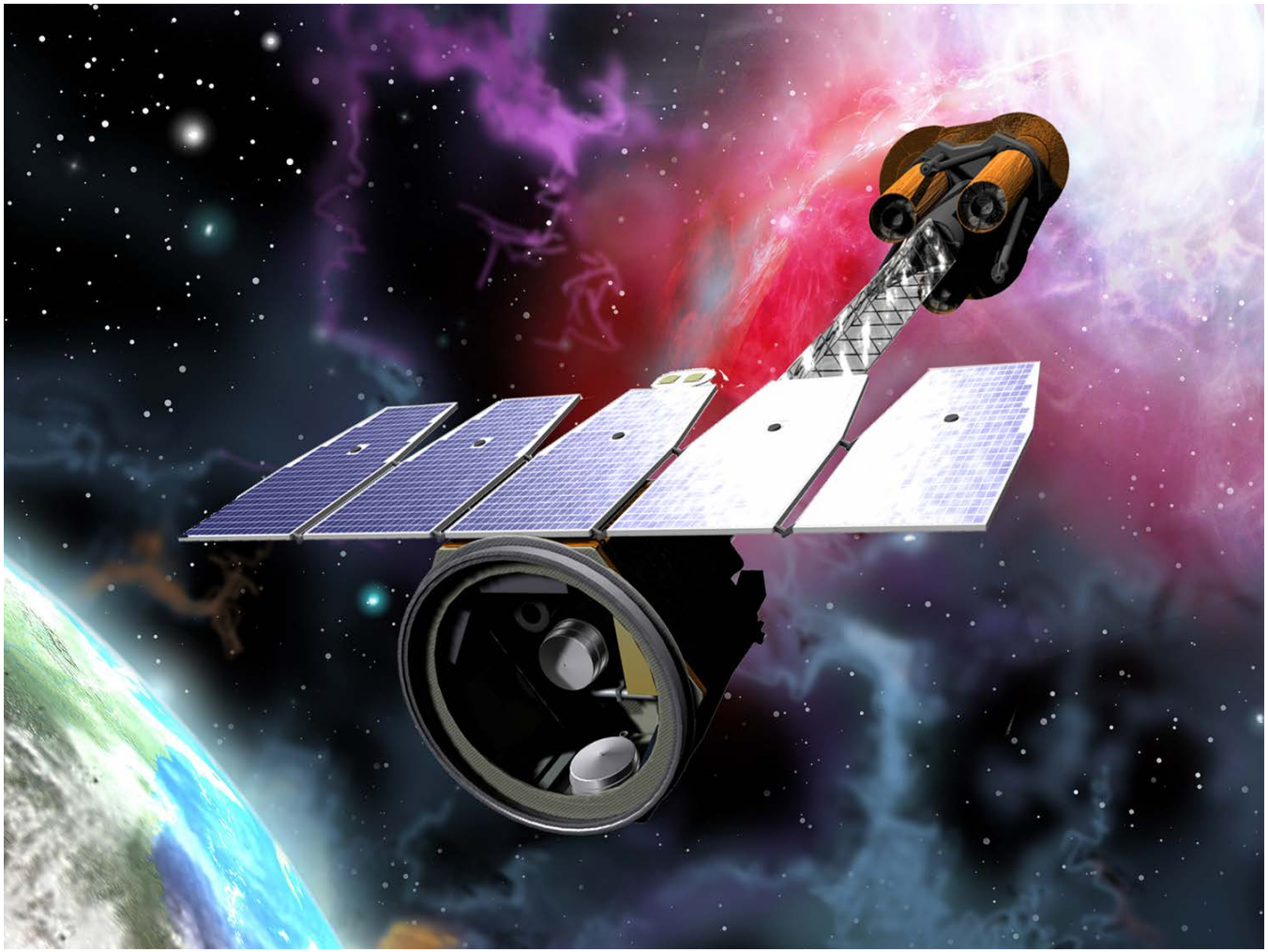
THREE SETS OF IDENTICAL X-RAY MIRROR MODULES AND IMAGING POLARIZATION SENSITIVE DETECTORS



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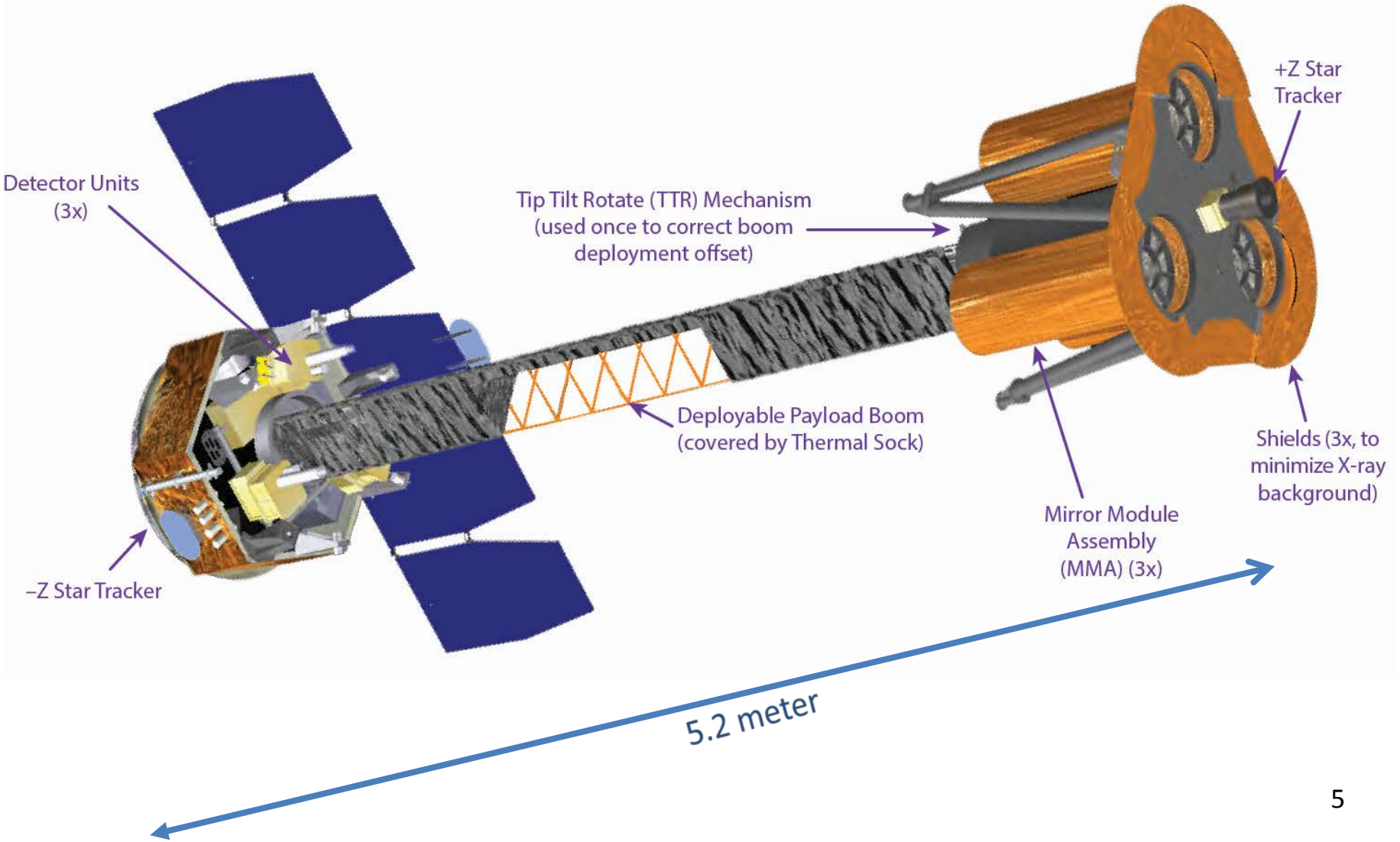
IXPE DEPLOYED



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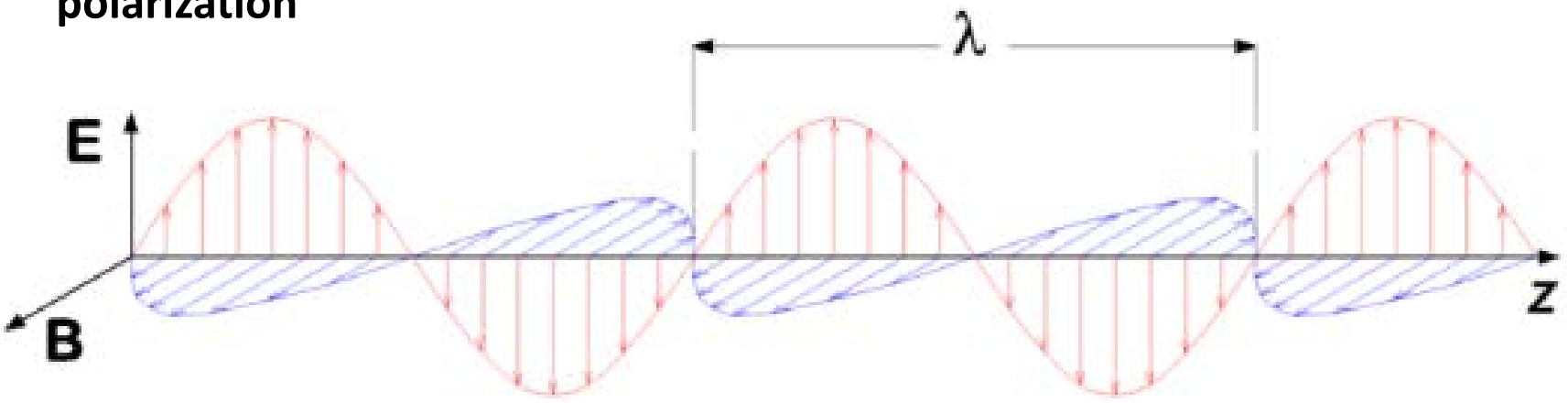
What is polarization?

- **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**



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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**

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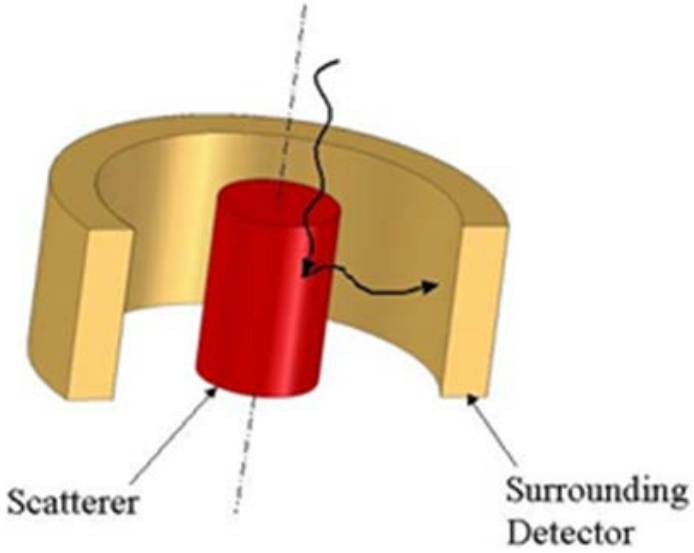
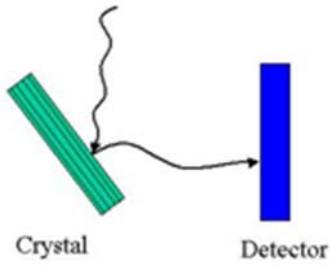
How do you measure X-ray polarization?

- Several techniques used prior to IXPE

- 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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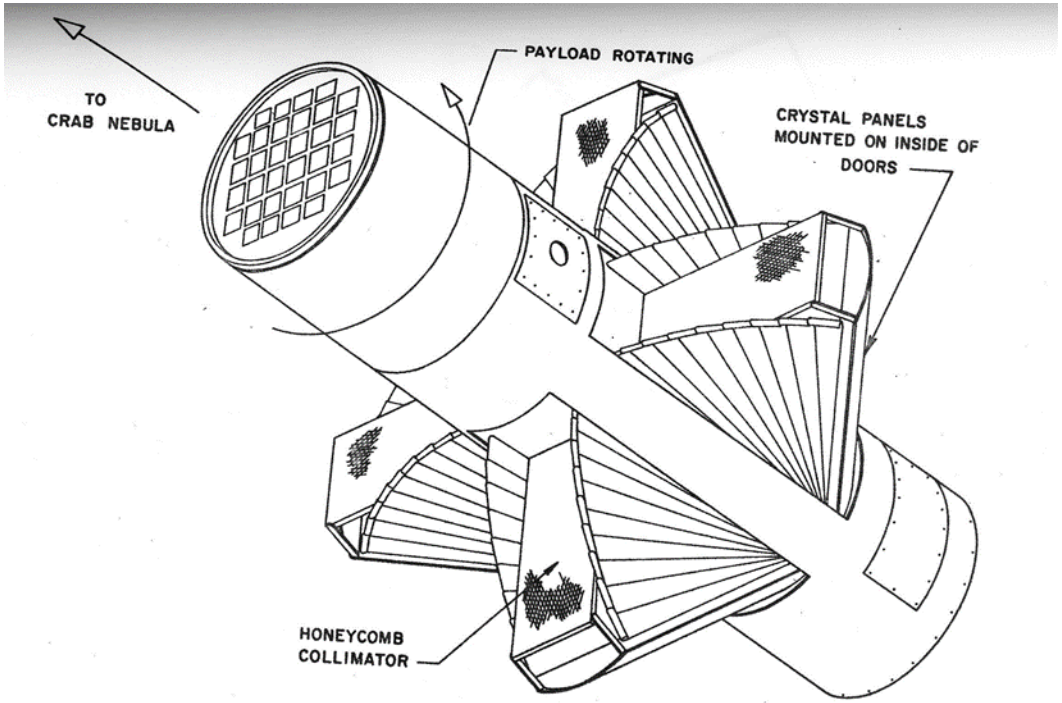
1971 Rocket 17.09

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



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SOUNDING ROCKET ERA
FIRST MEASUREMENT!

- **1968 Aerobee 150**
  - **Lithium**
  - **Sco X-1 upper limit**
- **1969 Aerobee 150**
  - **Lithium**
  - **Crab upper limit**
- **1971 Aerobee 350**
  - **Lithium & Crystal**
  - **Crab detection!**
  - **P = 15% ± 5%**
  - **ϕ = 156° ± 10°**

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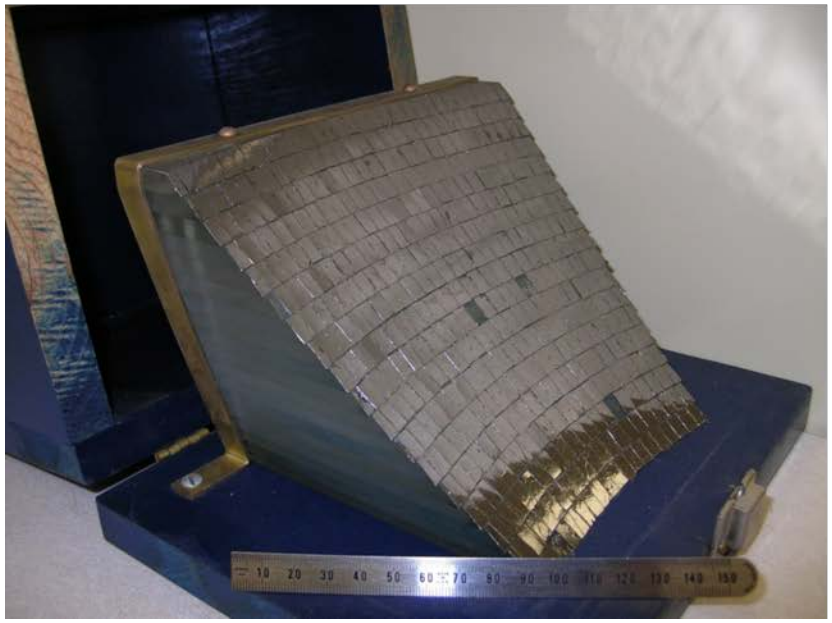
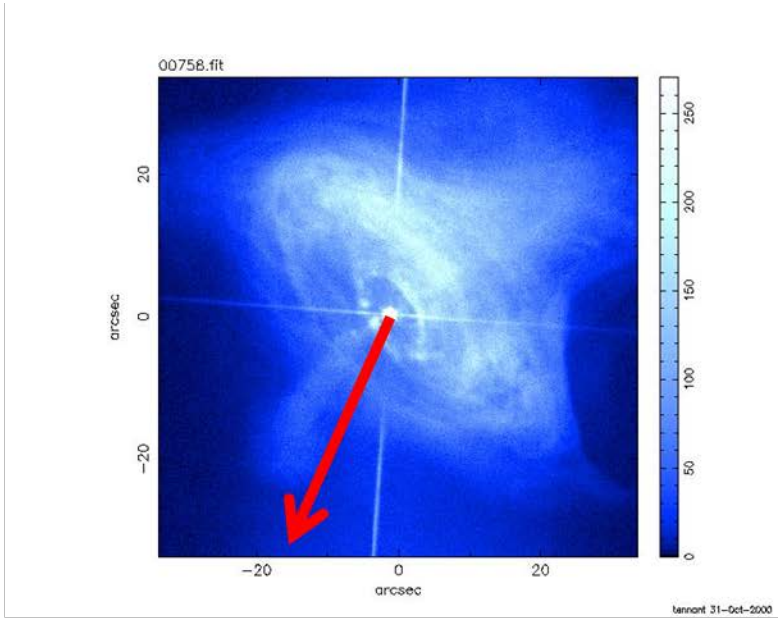
Next step crystal polarimeters on OSO-8

- **(1975) experiments were somewhat promising**
  - **1975 OSO-8 crystal polarimeter**
  - **Precision measurement of integrated Crab Nebula polarization at 2.6 keV**
  - **P = 19% ± 1%**
  - **ϕ = 156° ± 2° (NNE) agrees with optical**





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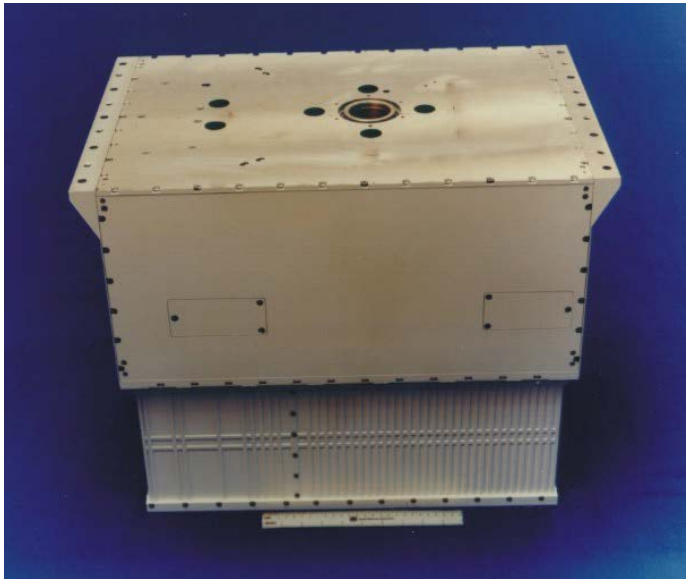
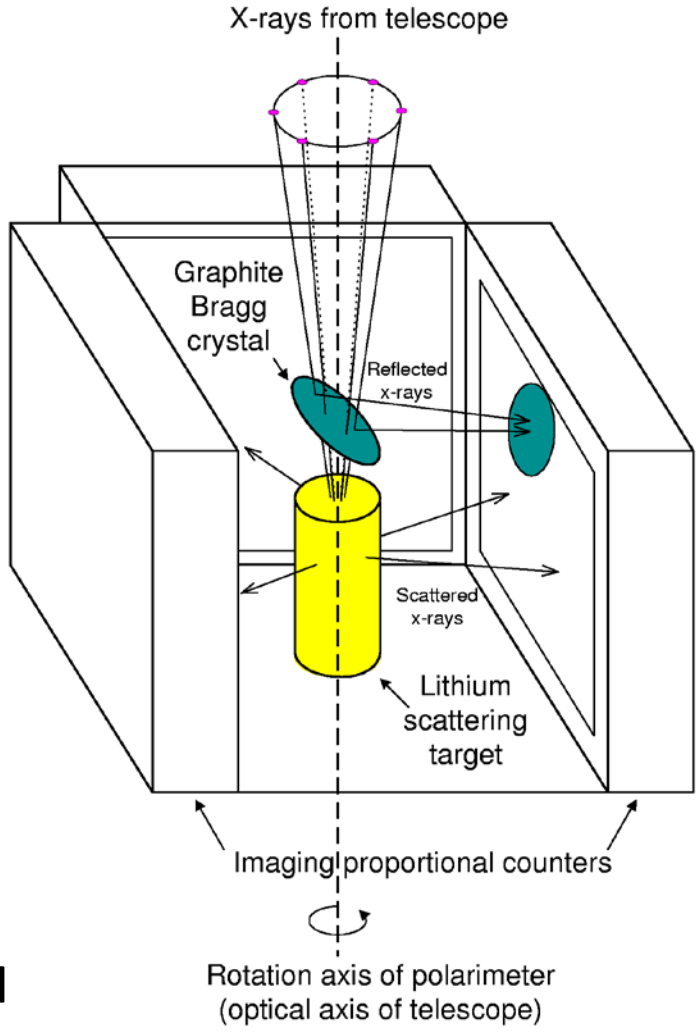
Along came the Stellar X-ray Polarimeter to fly on the Russian Spectrum-X Gamma Mission in the early 1990s





- **Soviet Union Collapsed --- never launched**

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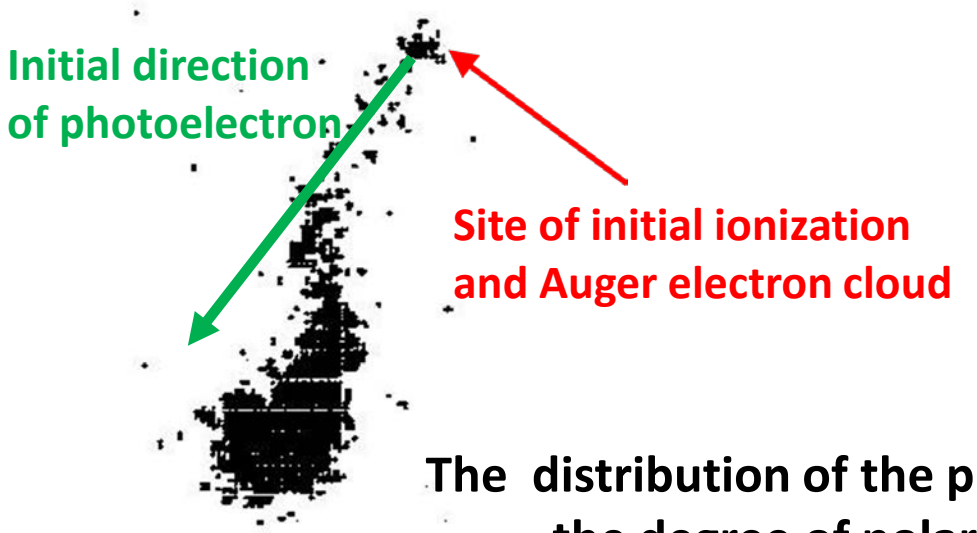
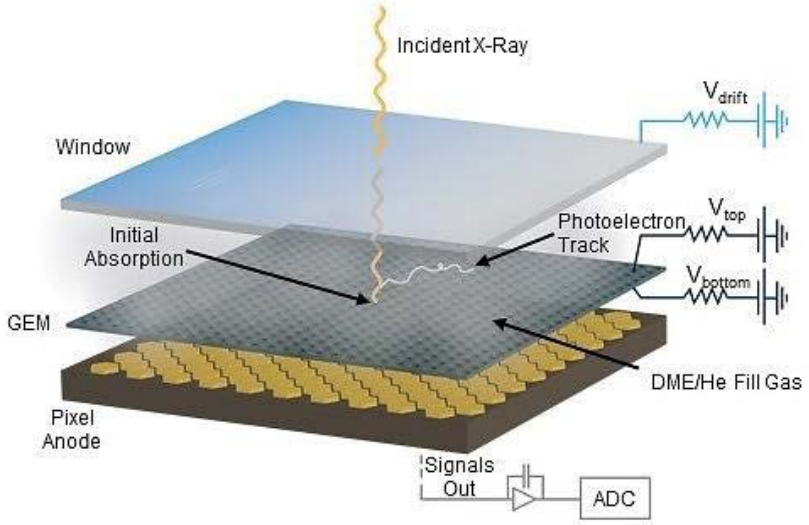
BREAKTHROUGH --- IXPE POLARIZATION-SENSITIVE DETECTORS 10 TIMES MORE SENSITIVE THAN OSO-8

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





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

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

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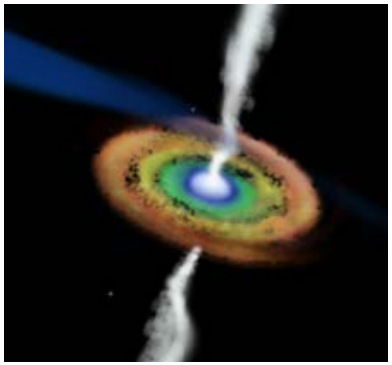
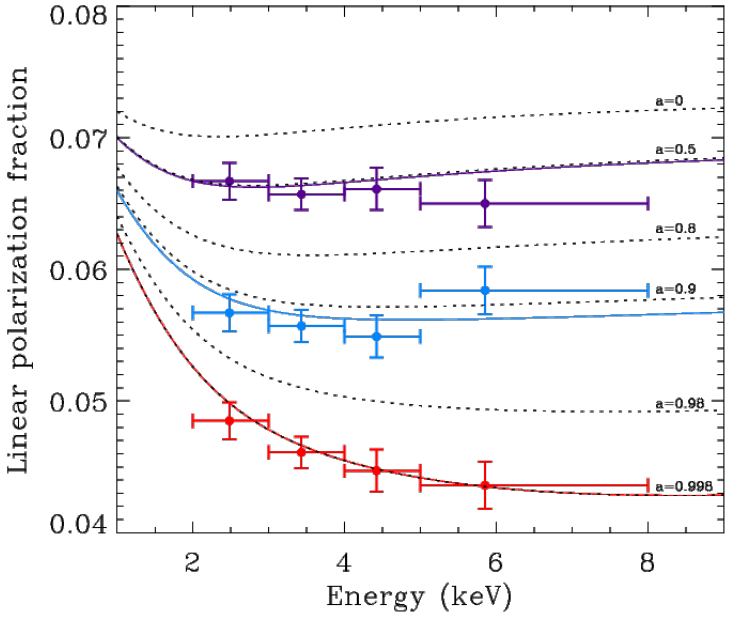
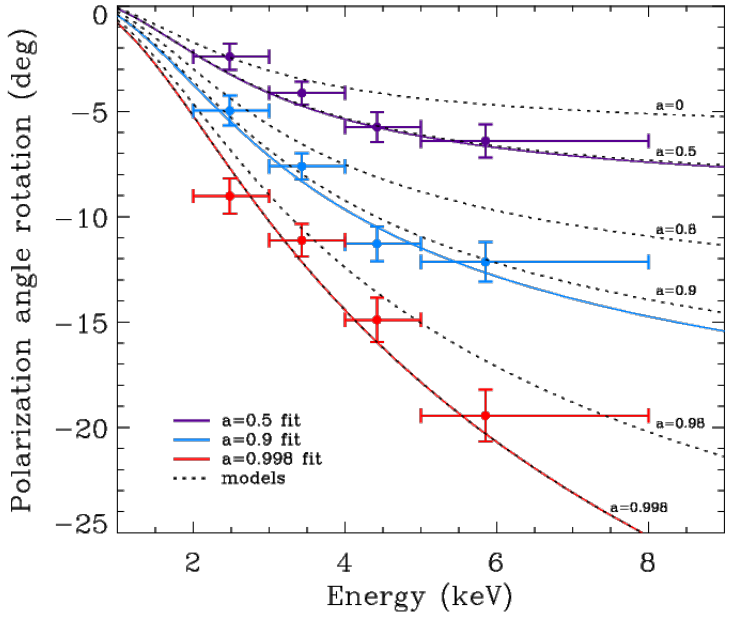
MEASURE BLACK-HOLE SPIN FROM POLARIZATION ROTATION IN TWISTED SPACE-TIME: GRX1915+105

- **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)**







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

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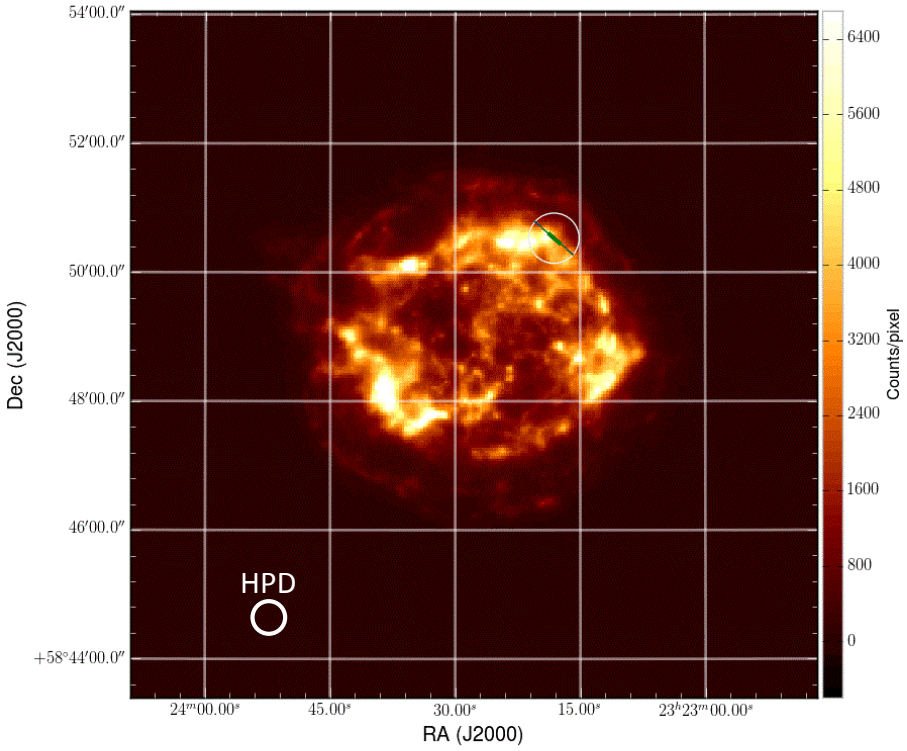
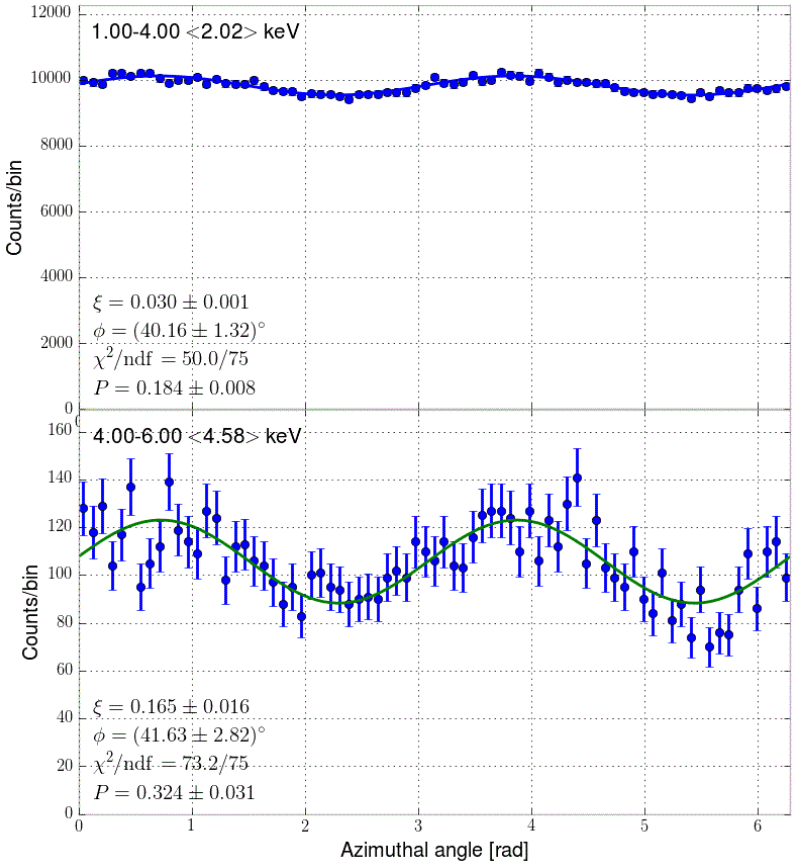
- **Lines and thermal continuum dominate 1-4 keV**
- **Non-thermal emission dominates 4-6 keV**





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

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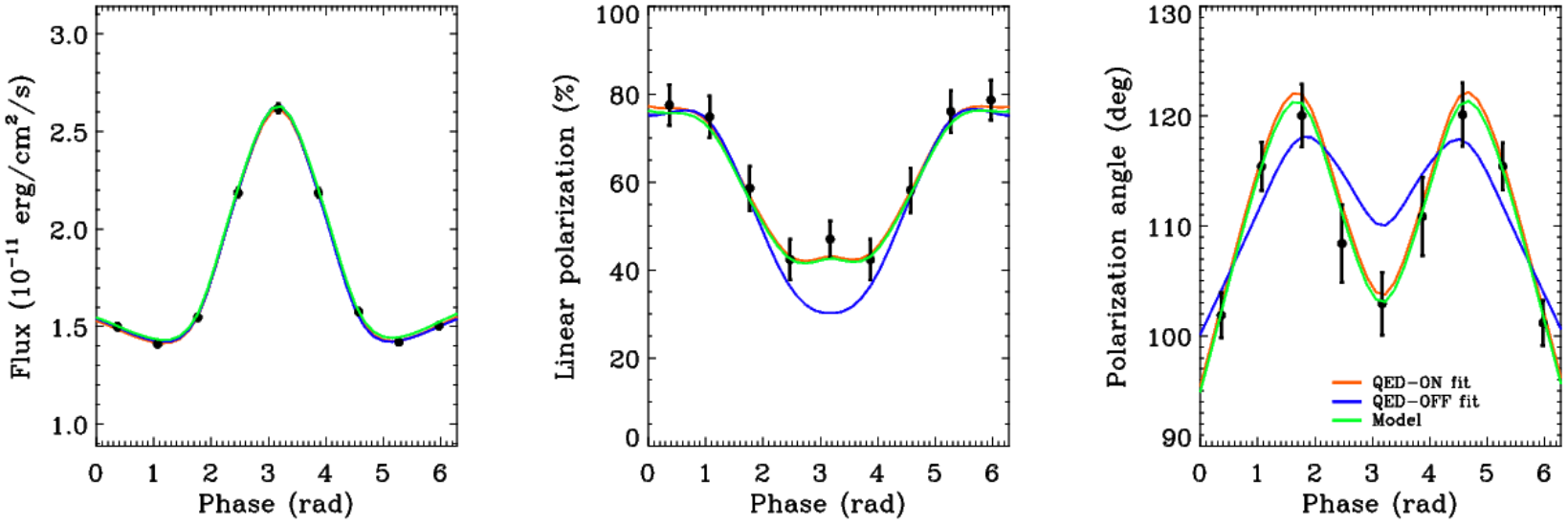
TEST QUANTUM ELECTRODYNAMICS (QED) IN ULTRA-STRONG MAGNETIC FIELDS

- **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**



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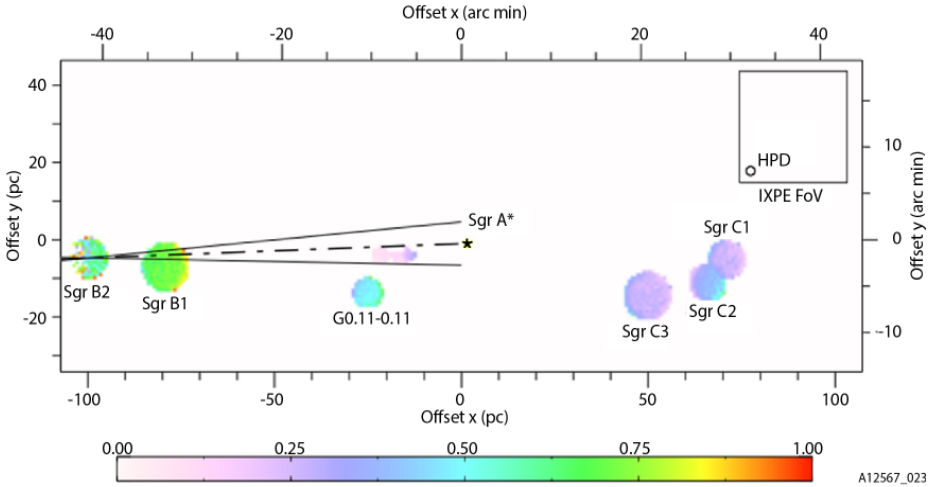
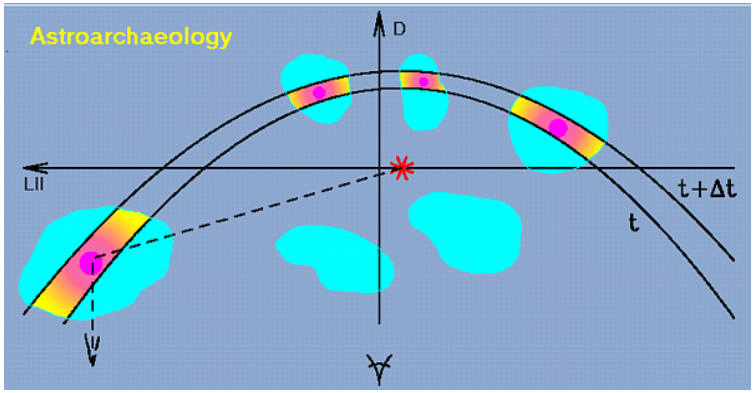
WAS SGR A* RECENTLY 10^6 × MORE ACTIVE?

- **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**





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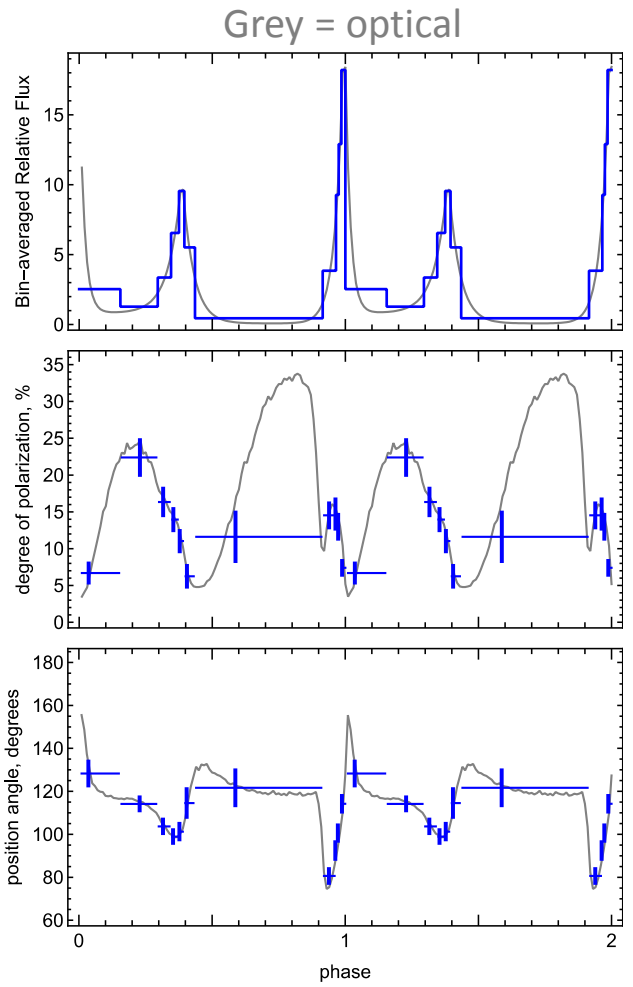
PROBE EMITTING REGIONS OF PULSARS THROUGH PHASE-RESOLVED POLARIMETRY: CRAB PULSAR

- **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**



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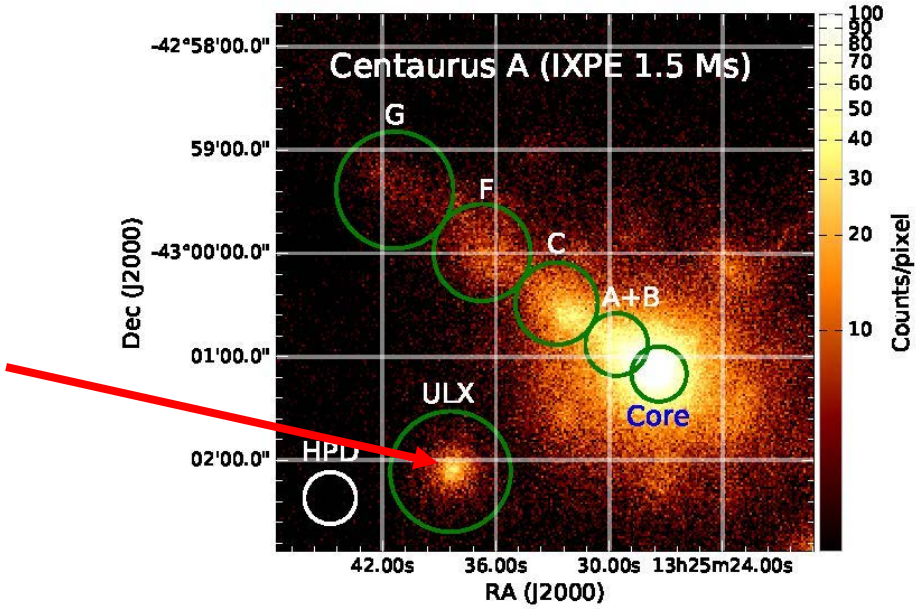
IXPE IMAGING ALSO AVOIDS CONFUSION AND PROVIDES SERENDIPITOUS BENEFITS

- **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

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CAPTURING THE IMAGINATION