The Imaging X-ray Polarimetry Explorer (IXPE)
(The prospects of X-ray polarization for accreting black hole science)

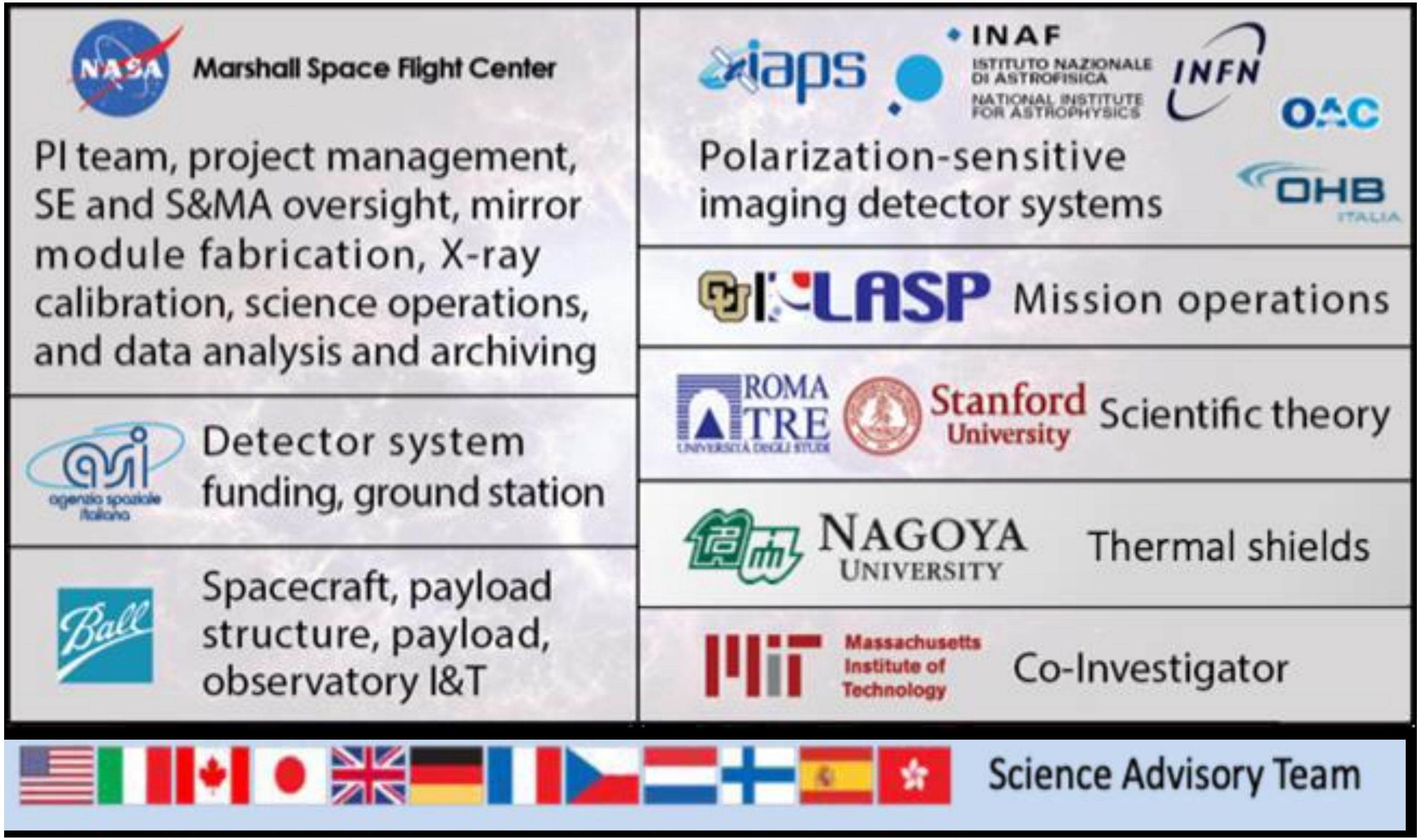
Giorgio Matt (Univ. Roma Tre)
on behalf of the IXPE Science Team

IXPE mission description

- A NASA + ASI mission in the NASA's Small Explorer Program (SMEX)
- Launch December 9, 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.

IXPE Team



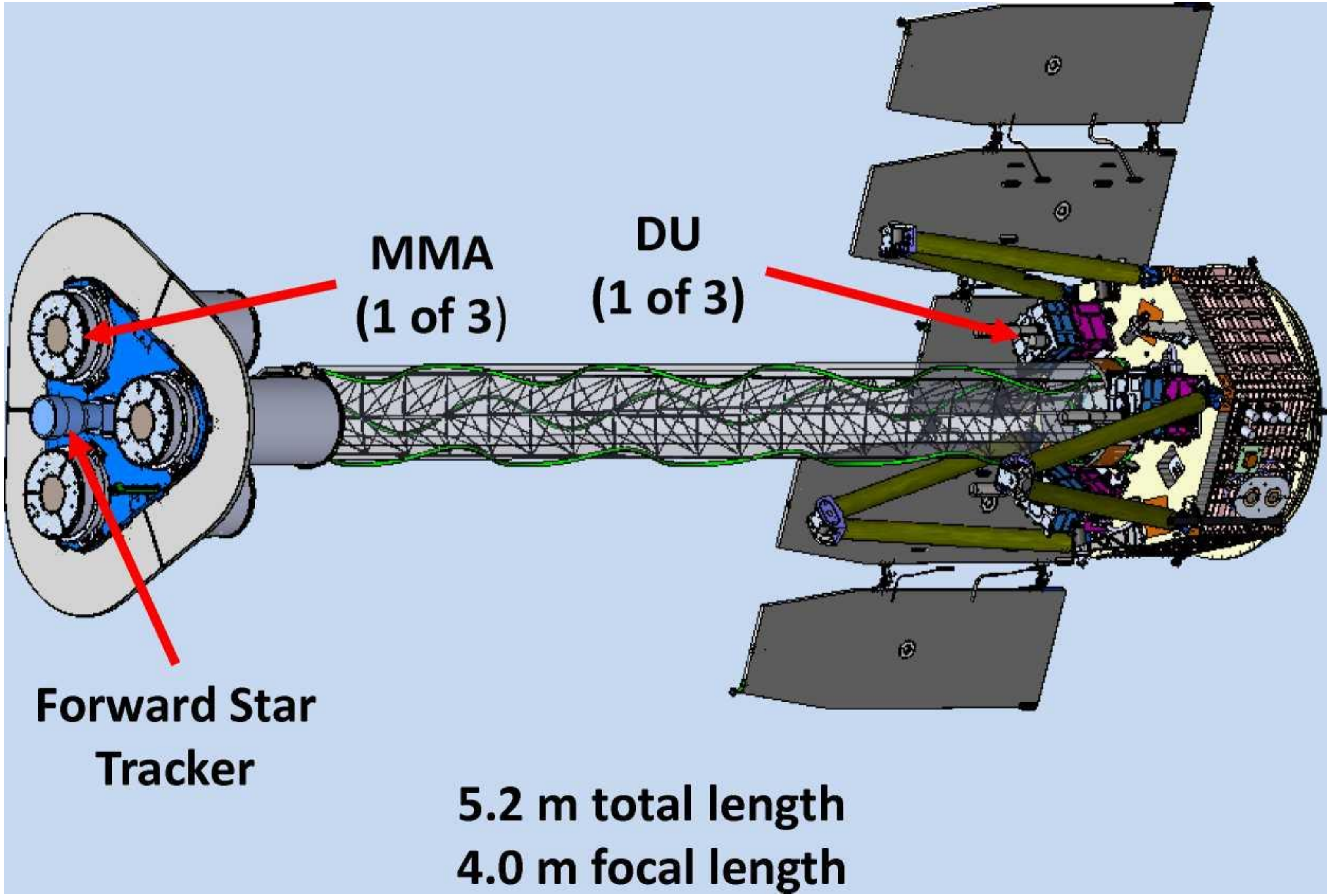
Principal Investigator: Martin Weisskopf (MSFC)

SAT currently comprises > 100 scientists from 12 countries

Launch (December 9, 2021)

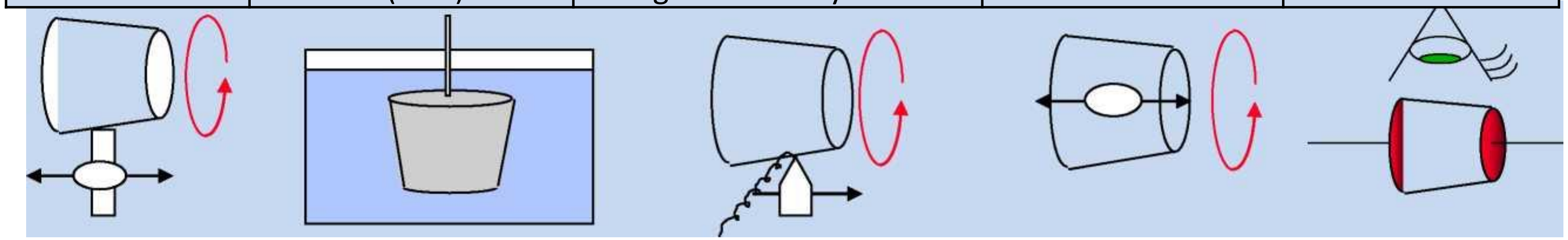
Equatorial Orbit 600 km altitude

IXPE deployed



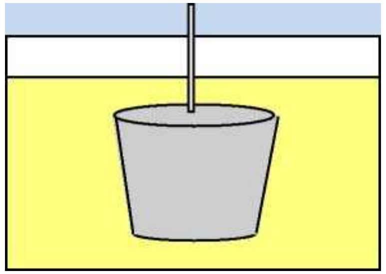
Mandrel fabrication

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

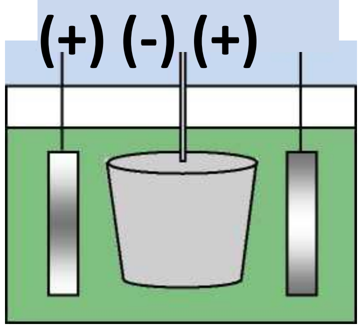


Mirror-shell forming

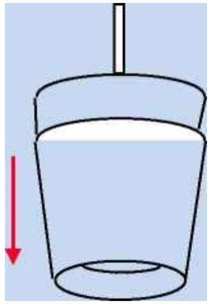
6. Passivate mandrel surface to reduce shell adhesion



7. Electroform Nickel/Cobalt shell onto mandrel

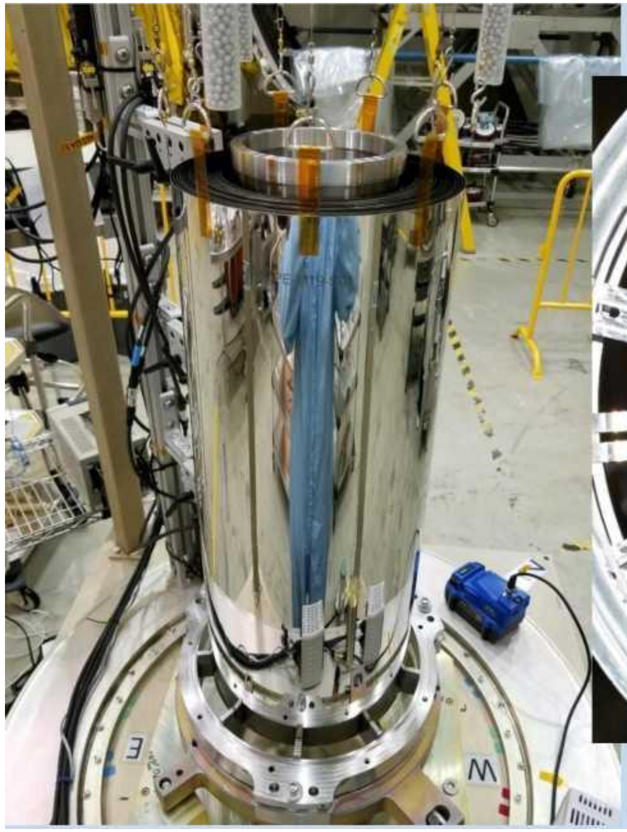


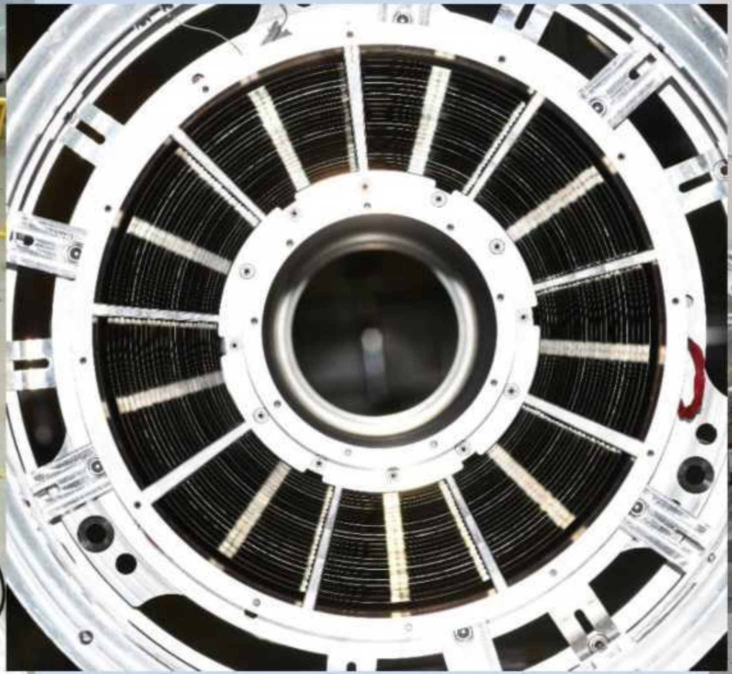
8. Separate shell from mandrel in chilled water



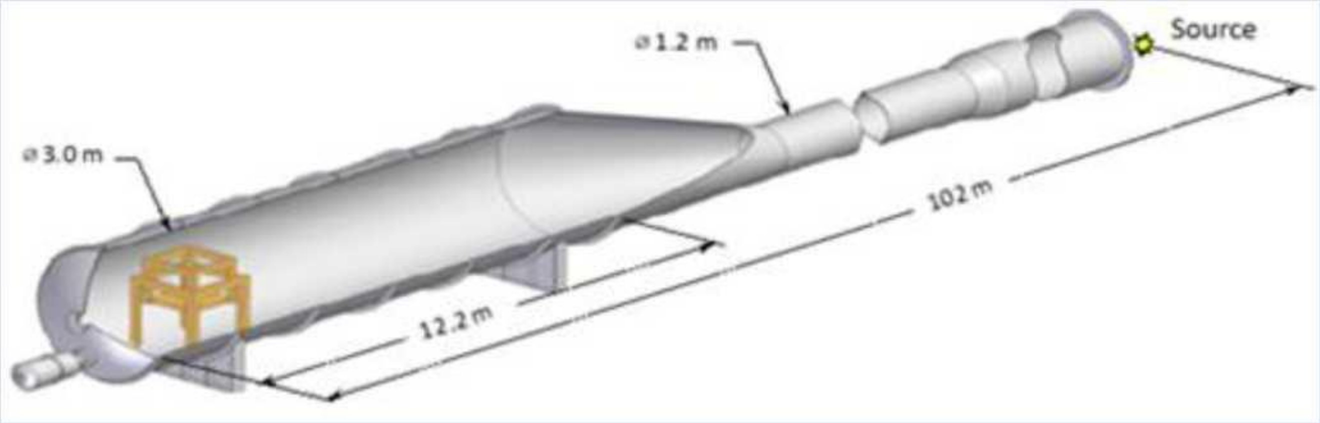
Ni/Co electroformed IXPE mirror shell

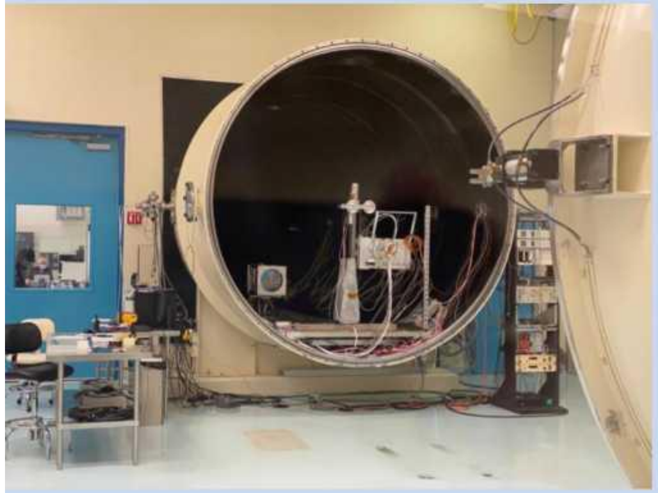
IXPE optics

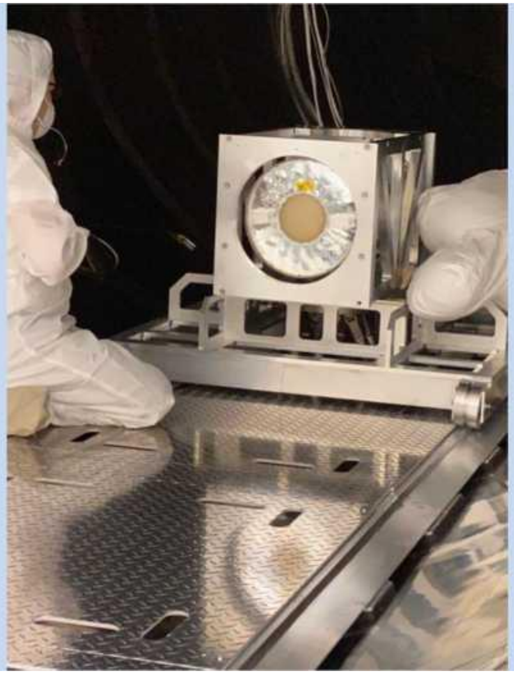


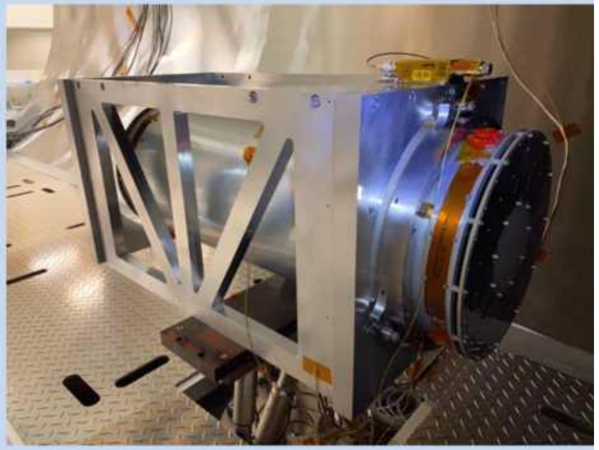


Calibration: MSFC Stray Light Test Facility





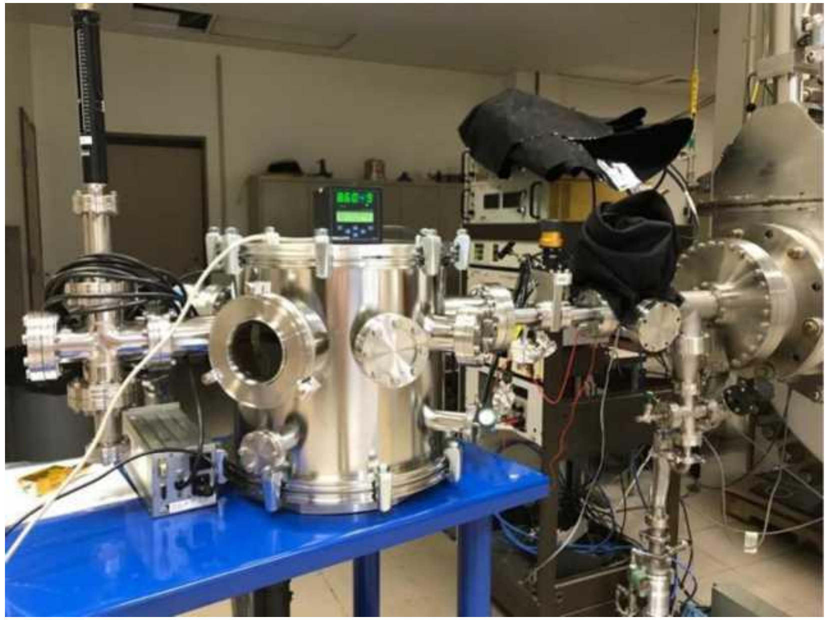




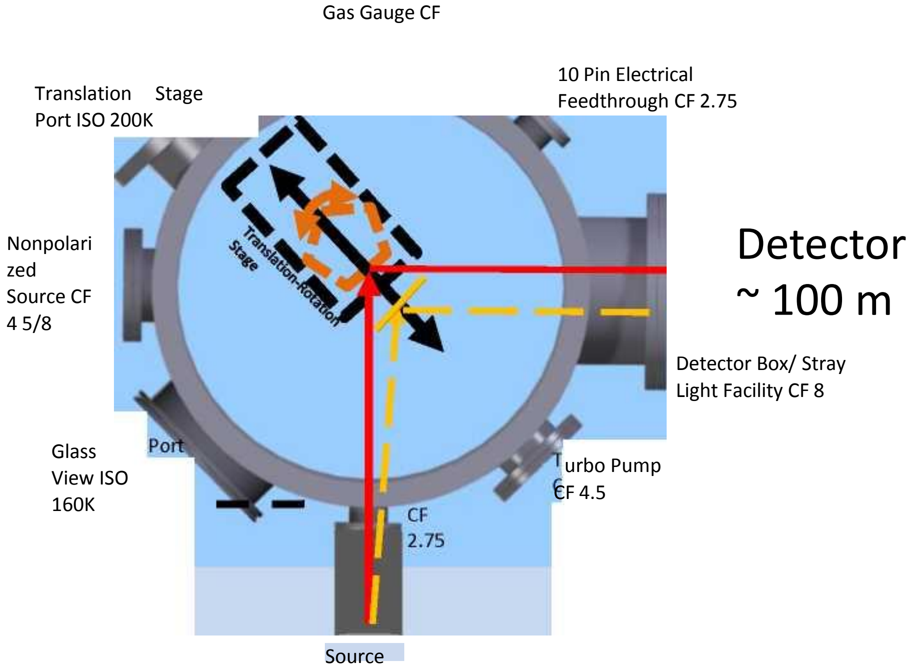
Polarized sources

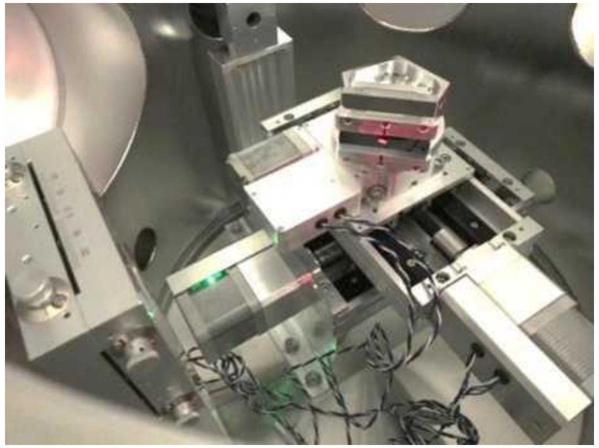
■ 3 Polarized Sources

- Crystal Box
  - Holds all X-ray sources
  - Holds crystals — needed for polarized source



Energy	X-ray Tube	Crystal	Polarization
2.7 keV	Rh	Ge(111)	> 99%
4.5 keV	Ti	Si(220)	> 99%
6.4 keV	Fe	Si(400)	> 99%



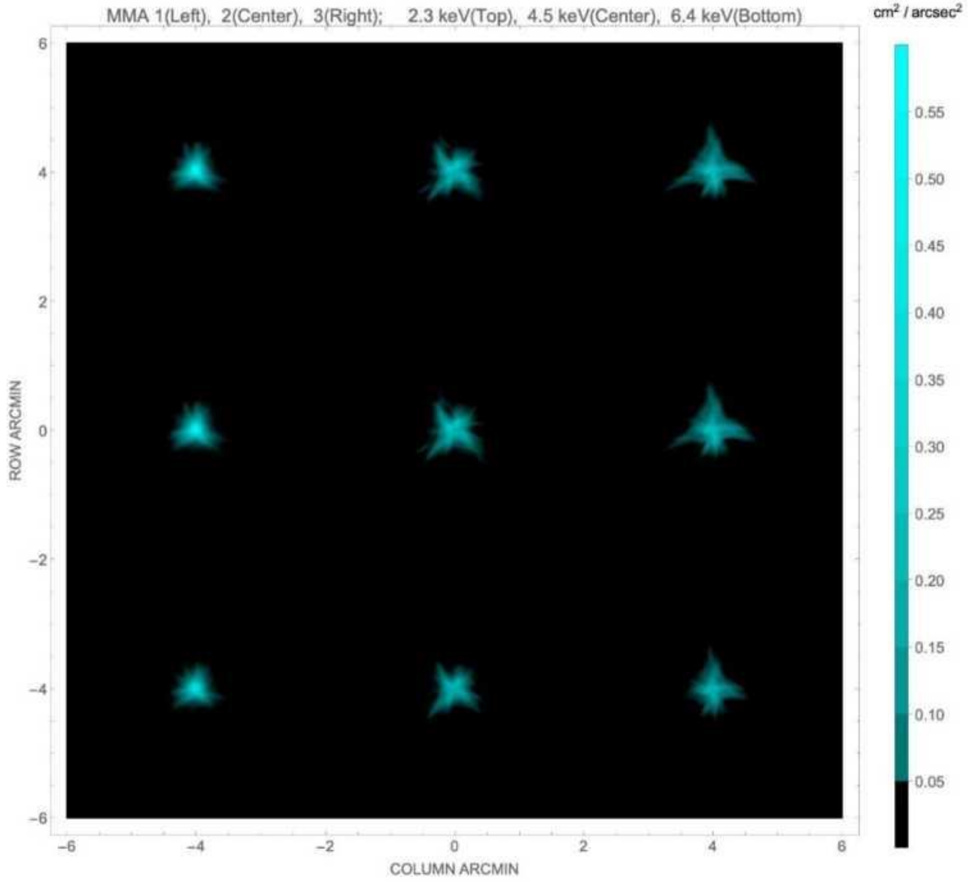


Interior of Crystal Box, showing stages and crystal being aligned

Angular resolution

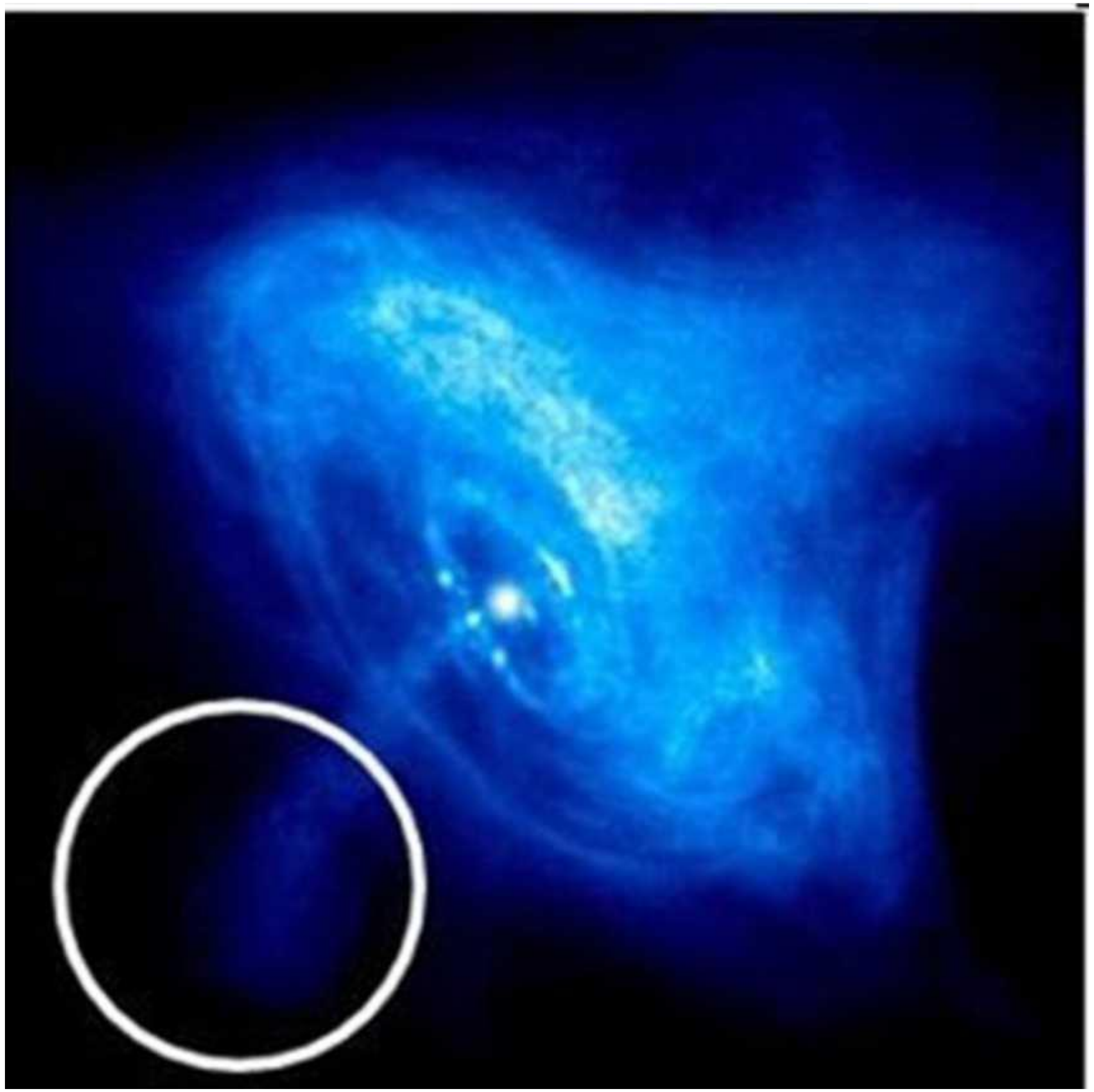
MMA	#1	#2	#3
6.4 keV	18.9"	24.8"	24.2"
4.5 keV	18.9"	25.0"	26.9"
2.3 keV	18.7"	24.5"	26.7"

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, analysis, and on-orbit performance the system-level performance is = 30" HPD

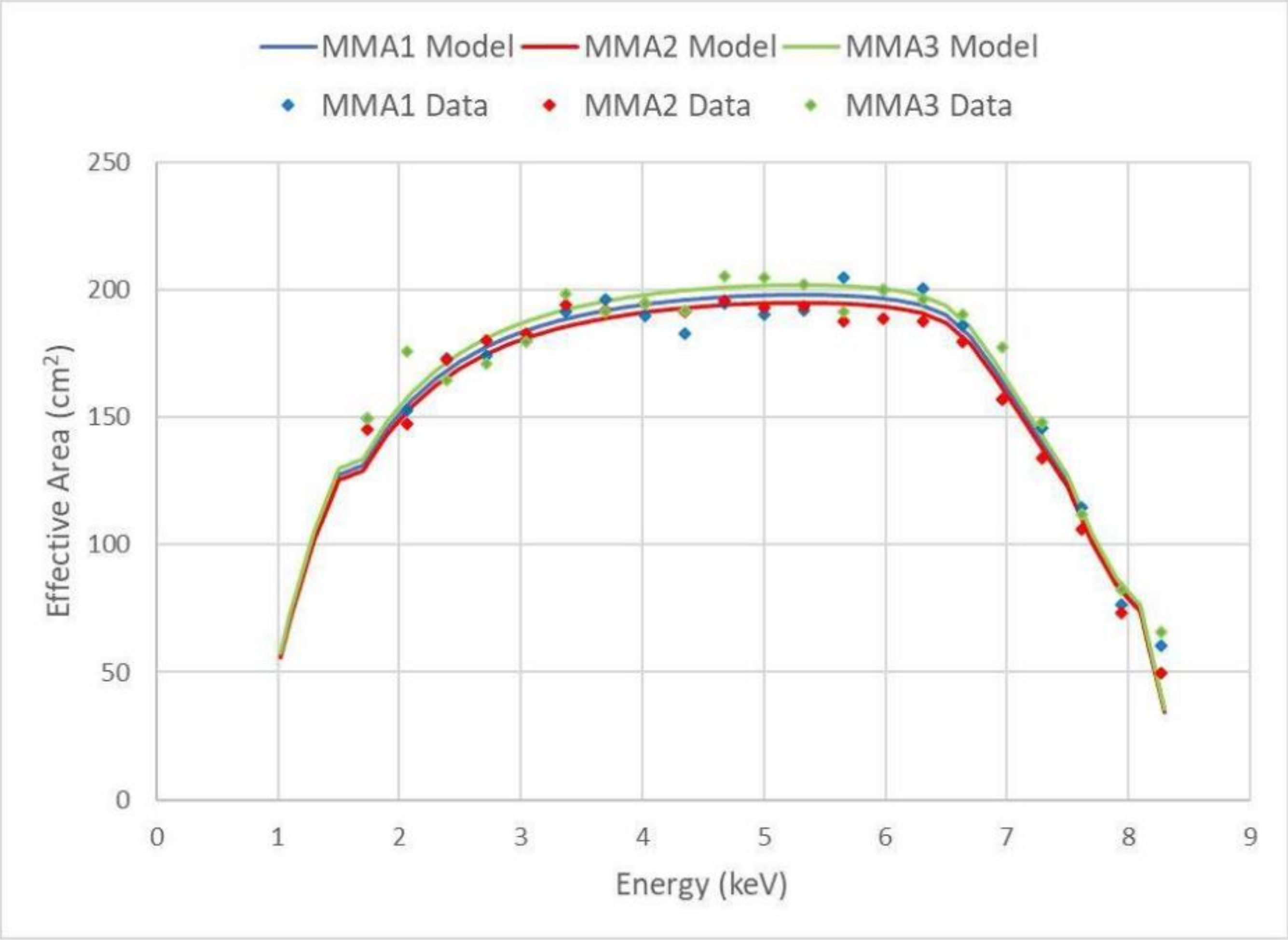
Imging polarimetry



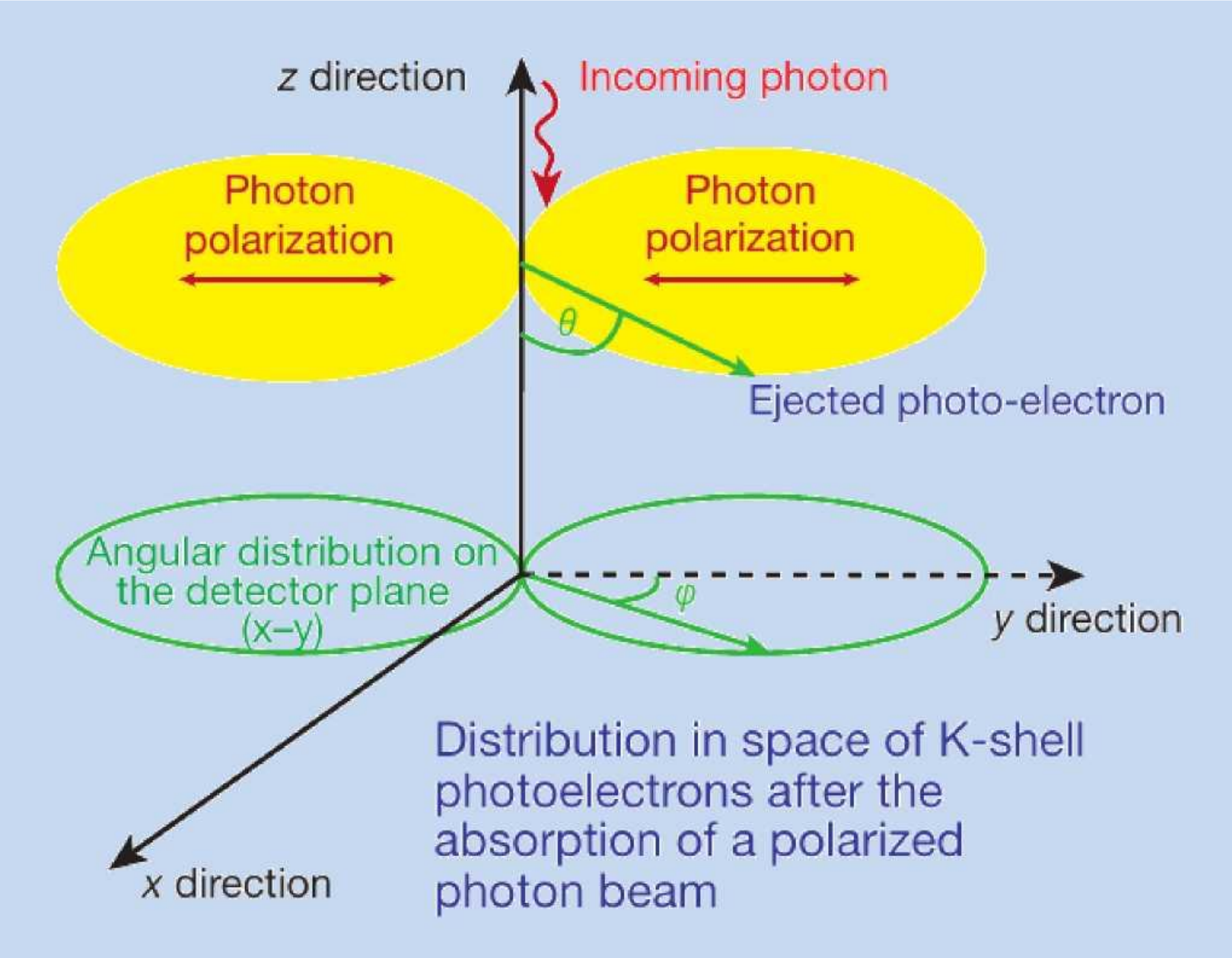
IXPE 30" half-power diameter on Chandra image

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 pm
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)	93.12 kg



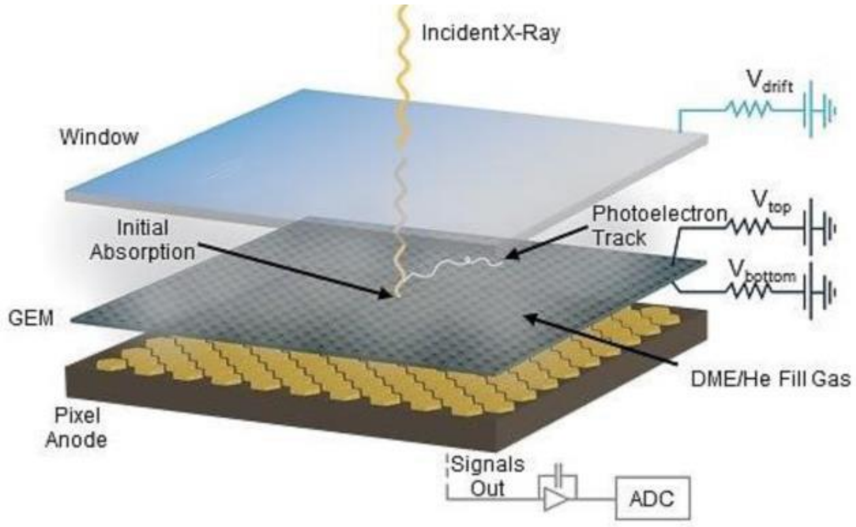
Polarization Detection Principle

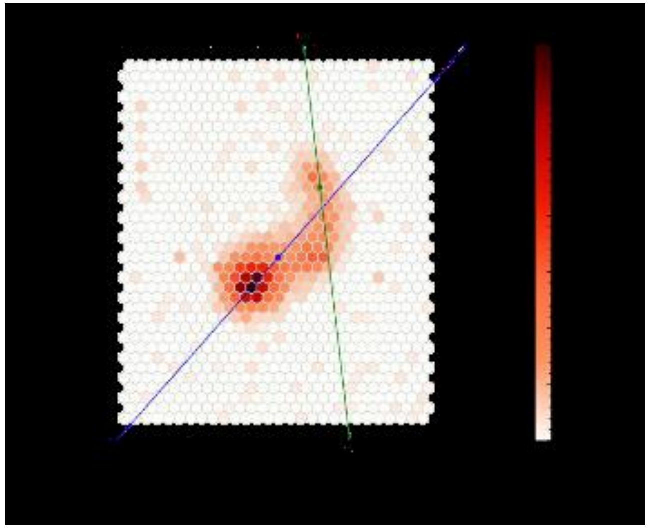


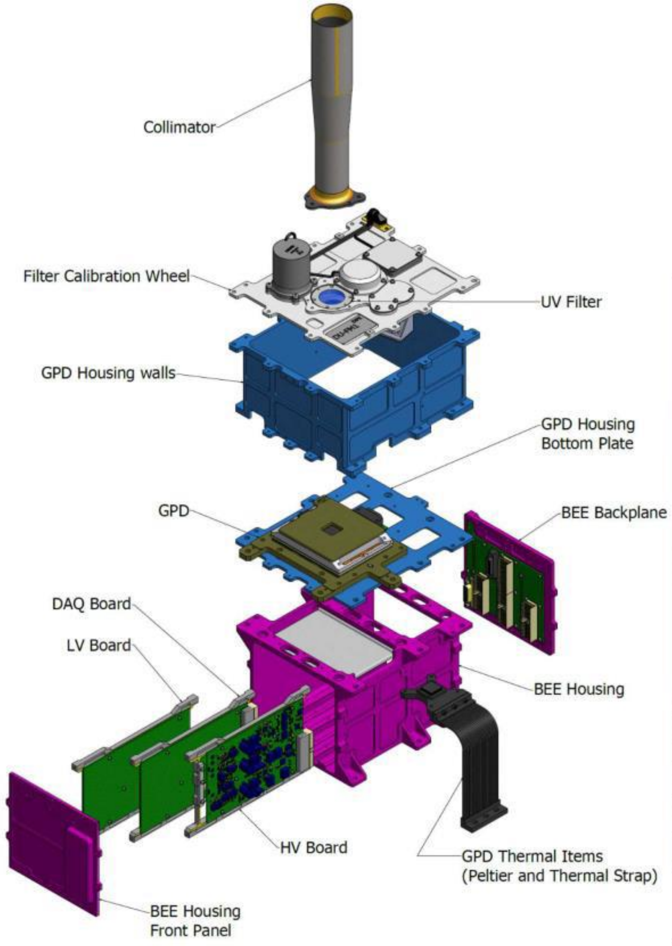
The detection principle is based on the photoelectric effect

$$\frac{\partial\sigma}{\partial\Omega} = r_0^2 \frac{Z^5}{137^4}\left(\frac{mc^2}{h\nu}\right)^{7/2} \frac{4\sqrt{2}\sin^2(\theta)\cos^2(\varphi)}{(1-\beta\cos(\theta))^4}$$

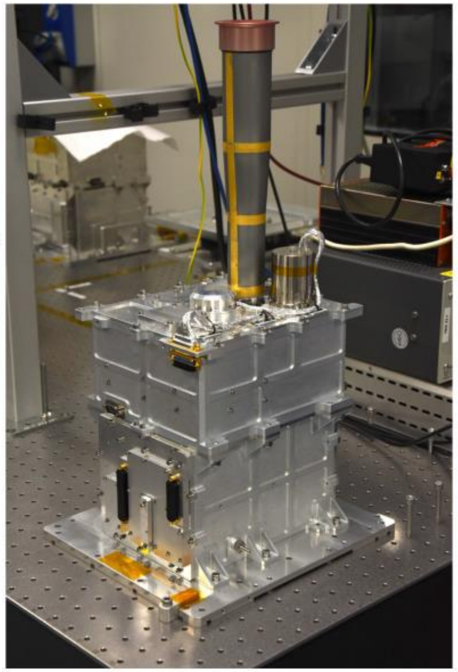
Polarization Detection Principle





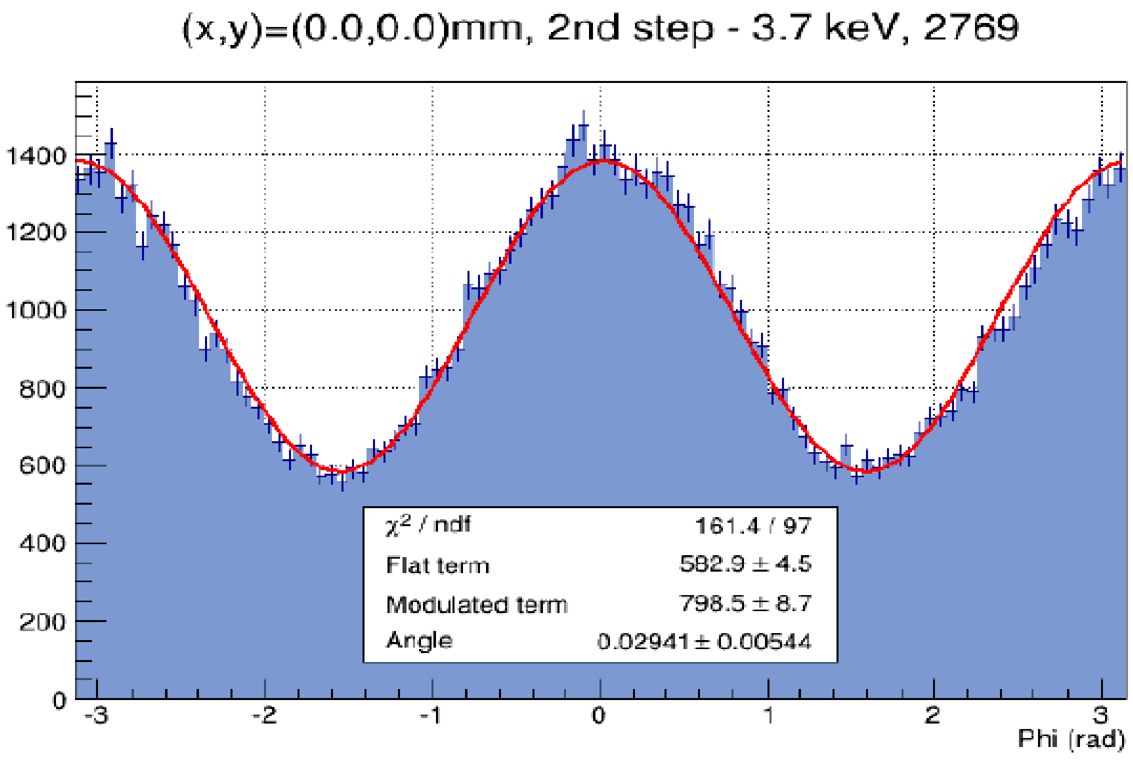


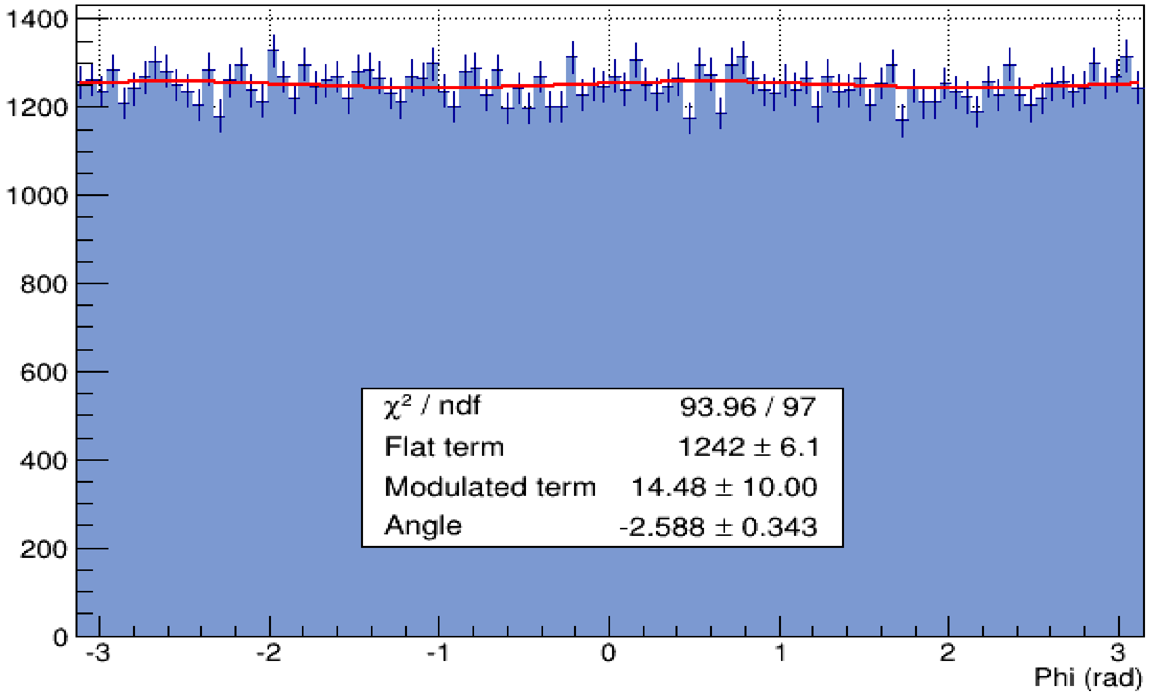
(a)


(b)

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

Modulation factor



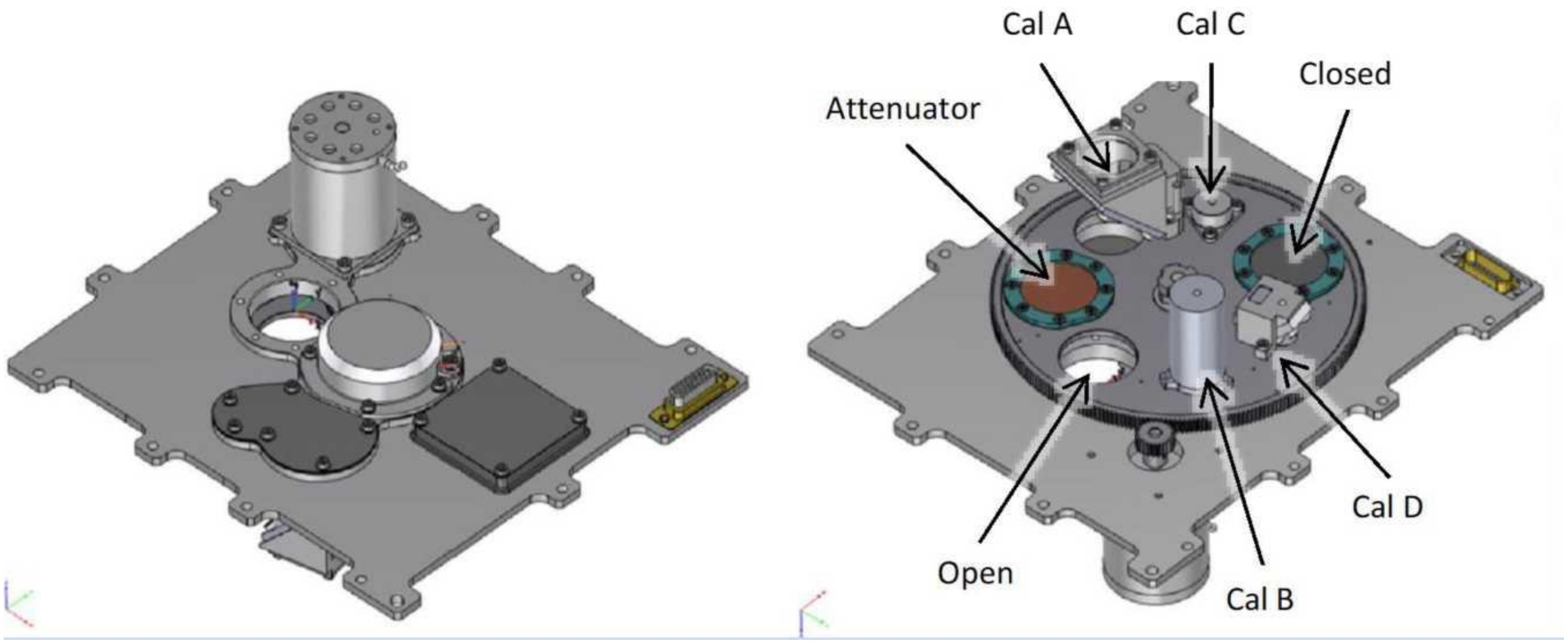


Bellazzini et al. 2012

Detector properties

Parameter	Value
Sensitive area	15 mm x 15 mm (13 x 13 arcmin)
Fill gas and composition	DME @ 0.8 atmosphere
Detector window	50-pm thick beryllium
Absorption and drift region depth	10 mm
GEM (gas electron multiplier)	copper-plated 50-pm liquid-crystal polymer
GEM hole pitch	50 pm triangular lattice
Number ASIC readout pixels	300 x 352
ASIC pixelated anode	Hexagonal @ 50-pm pitch
Spatial resolution (FWHM)	< 123 pm (6.4 arcsec) @ 2 keV
Energy resolution (FWHM)	0.57 keV @ 2 keV (a VE)
Useful energy range	2 - 8 keV

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-La fluorescence) and 5.89-keV (Mn-Ka)**
- **Cal B - unpolarized 5.89-keV spot**
- **Cal C - unpolarized 5.89-keV flood**
- **Cal D - unpolarized 1.74-keV (Si-Ka fluorescence) flood**

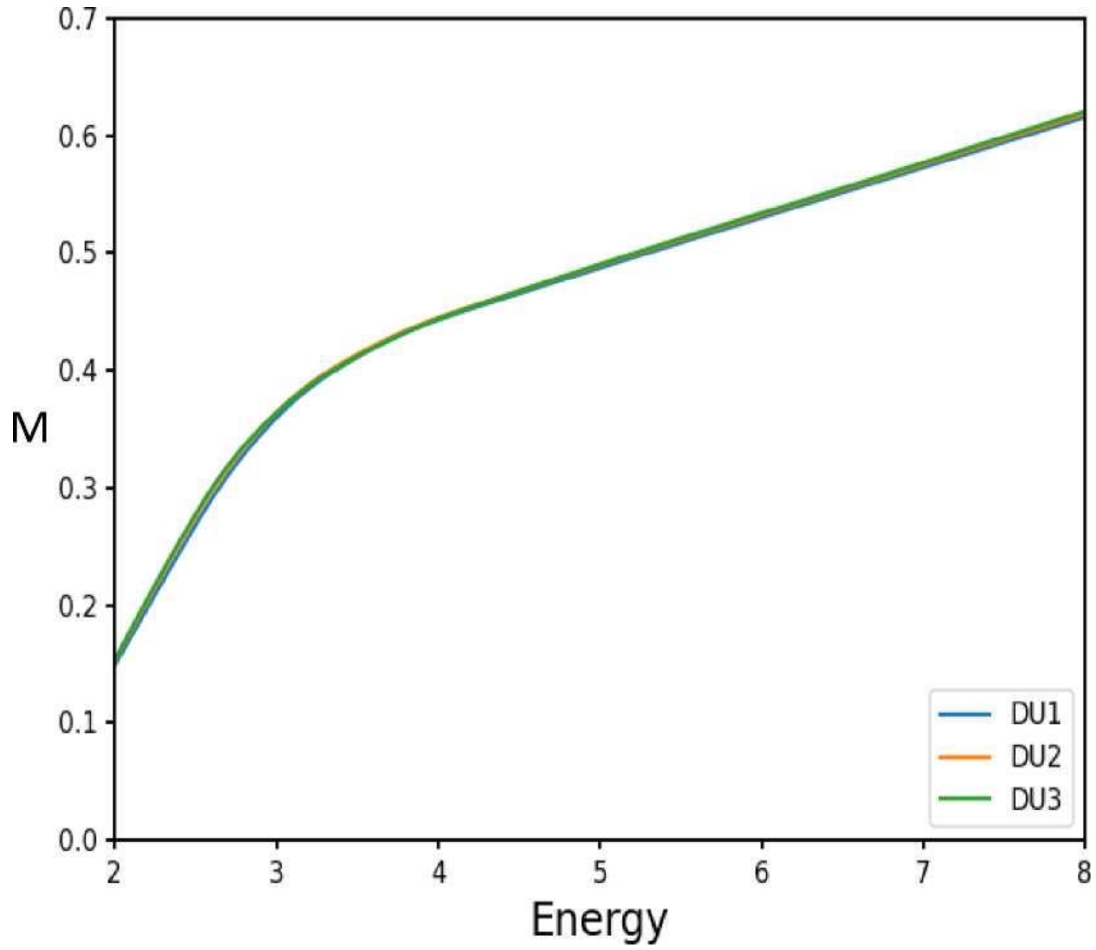
IXPE Imaging X-Ray Polarimetry Explorer

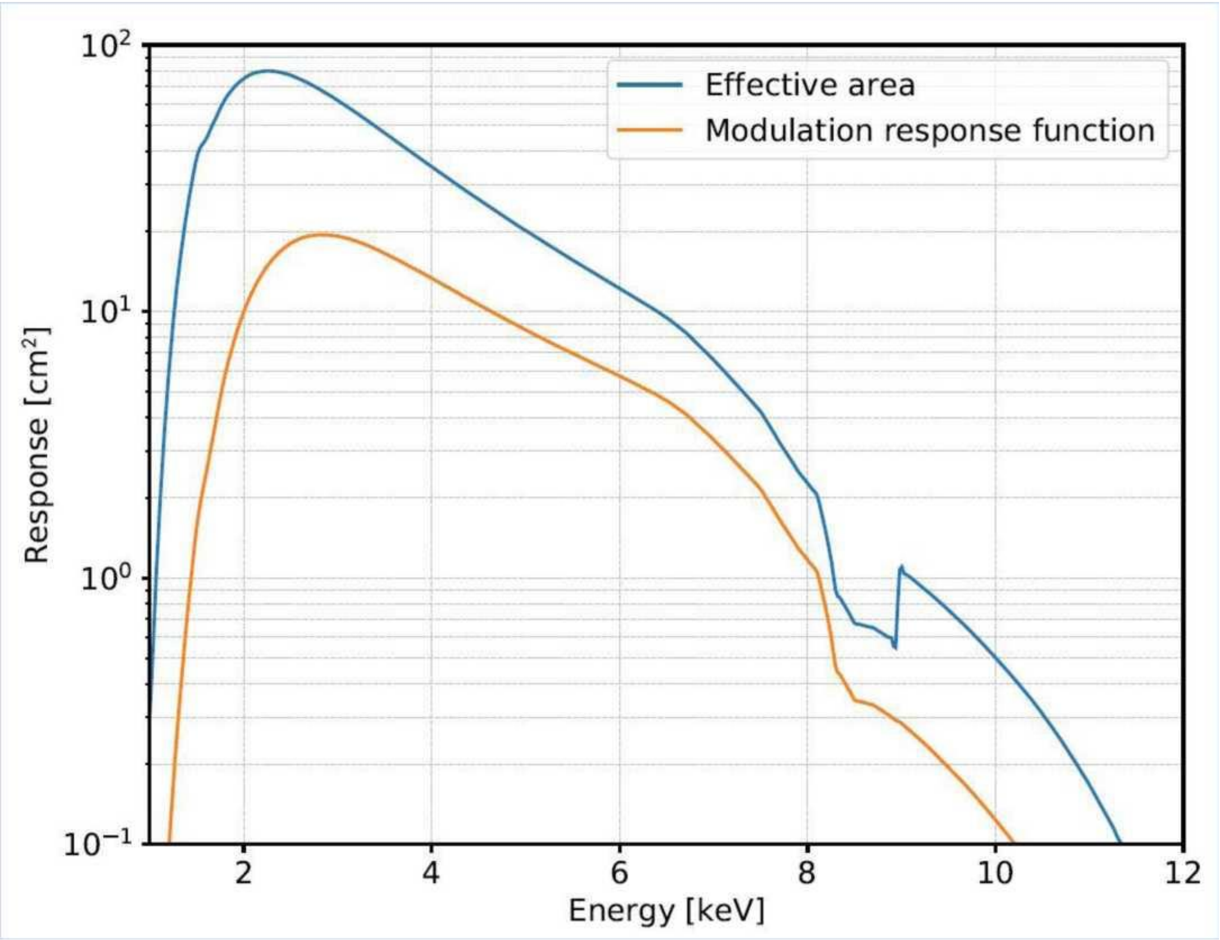
The Minimum Dectable Polarization (MDP)

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

- 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

Modulation factor



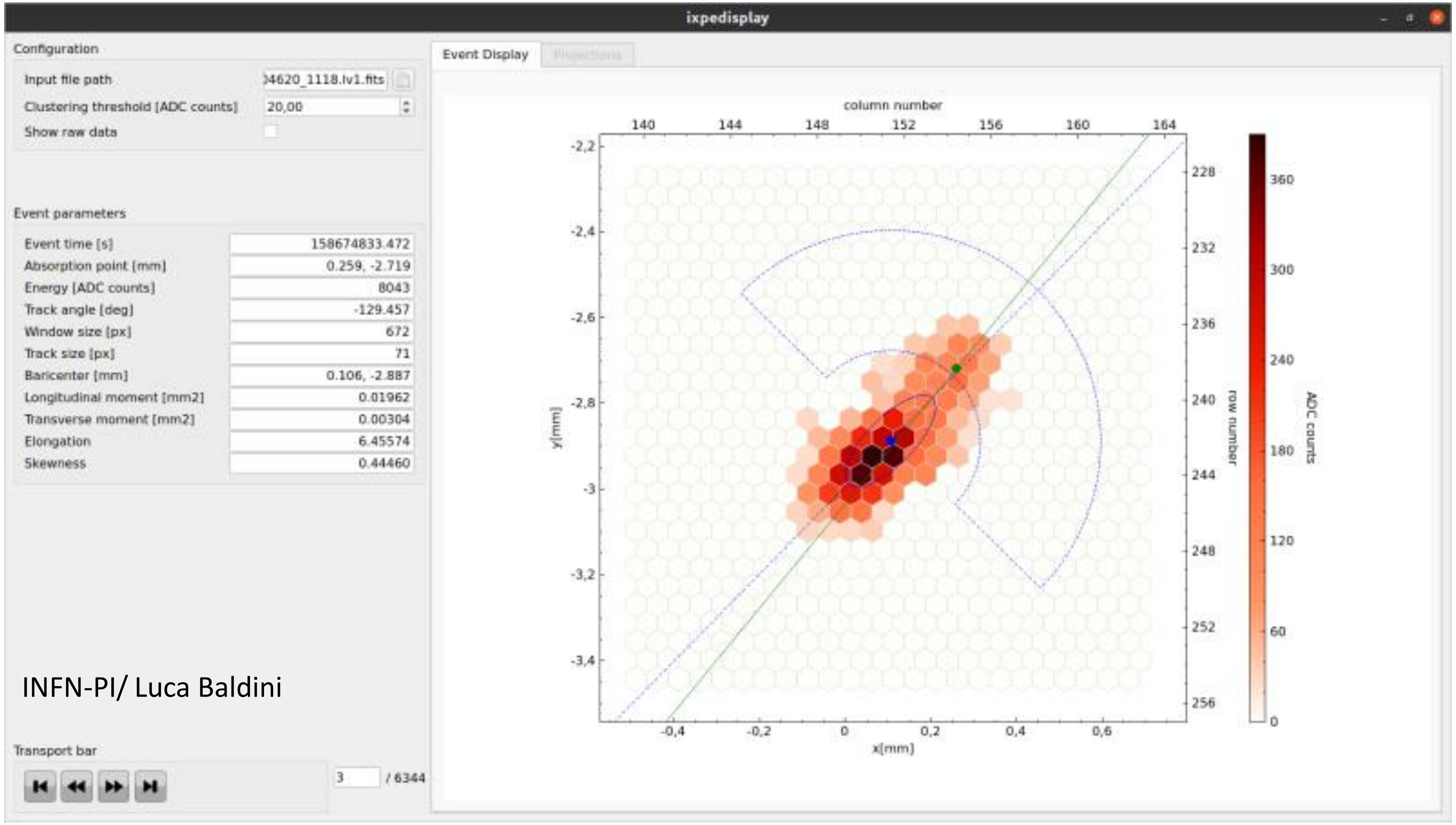


IXPE in operation: commissioning (~1 month)

- **Solar panels deployed**
- **Boom deployed**
- **All spacecraft functions activated and verified**
- **Polarization-sensitive detectors activated and used to view onboard polarized and unpolarized calibration sources**
- **Final telescope (optics + detector) alignments checked and adjusted viewing various X-ray sources**

First photon track

- **First photo-electron track obtained during IXPE science operations (SNR Cas A observation)**
  - Recorded 2022 January 11 by Detector Unit DU1, initiated by a photon with 2.7-keV estimated energy



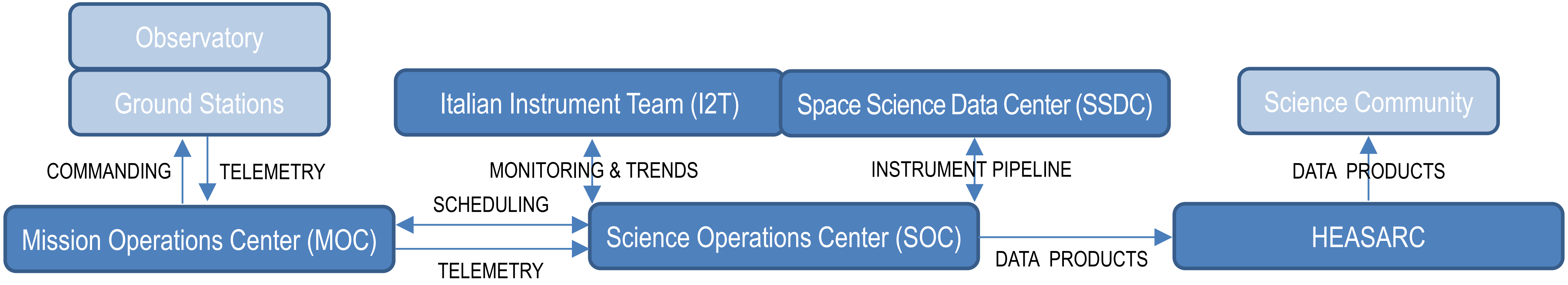
INFN-PI/ Luca Baldini

Science operations concept

- **Observatory**
  - Three x-ray mirror assemblies oriented parallel to axis of forward star tracker
  - Three x-ray detector units, each positioned near the focus of an x-ray mirror assembly using TTR mechanism
    - Polarization-sensitive Gas Pixel Detector at core of each detector unit
    - Detector units clocked at 120° to reduce systematic effects
    - Filter calibration wheel with 4 calibration sources, open, closed, and attenuated positions
  - Three-axis stabilized pointing, with most observations dithered
  - Fixed solar panels facing perpendicular to primary axis of Observatory
    - Power considerations require solar arrays point within 25° of sun, limiting Observatory's field of regard
- **Orbit**
  - 600-km-altitude circular orbit (96.6-minute period)
  - Nearly equatorial orbit
  - Primary ground station at Malindi (ASI); secondary, at Singapore (KSAT on NASA's NSN)
- **Point and stare approach**
  - Remain pointed toward target until observation segment is complete
  - Simultaneously observe astrophysical target on all 3 detector units when target is not occulted by the earth
  - Observe 1 calibration source on 1 detector unit when astrophysical target is occulted by the earth
  - Ramp down detector high voltage when passing through South Atlantic Anomaly (11.7 minutes)
  - Slew to next astrophysical target at completion of an observation segment

Science operations interfaces

- **MOC – SOC**
  - Schedule observations with MOC, at U Colorado's Laboratory for Atmospheric and Space Physics (LASP)
  - Ingest and aggregate science and engineering telemetry from the MOC
- **SOC – ASI Organizations**
  - Transmit low-level data products to Instrument Team; receive recommendations for adjustments
  - Collaborate with ASI's Space Science Data Center (SSDC) to develop and maintain the Instrument Pipeline and CalDB at the SOC
- **SOC – HEASARC**
  - Archive science data products at NASA's HEASARC for public access to IXPE data and tools
  - Test HEASoft tools provided by the HEASARC for analysis of IXPE data

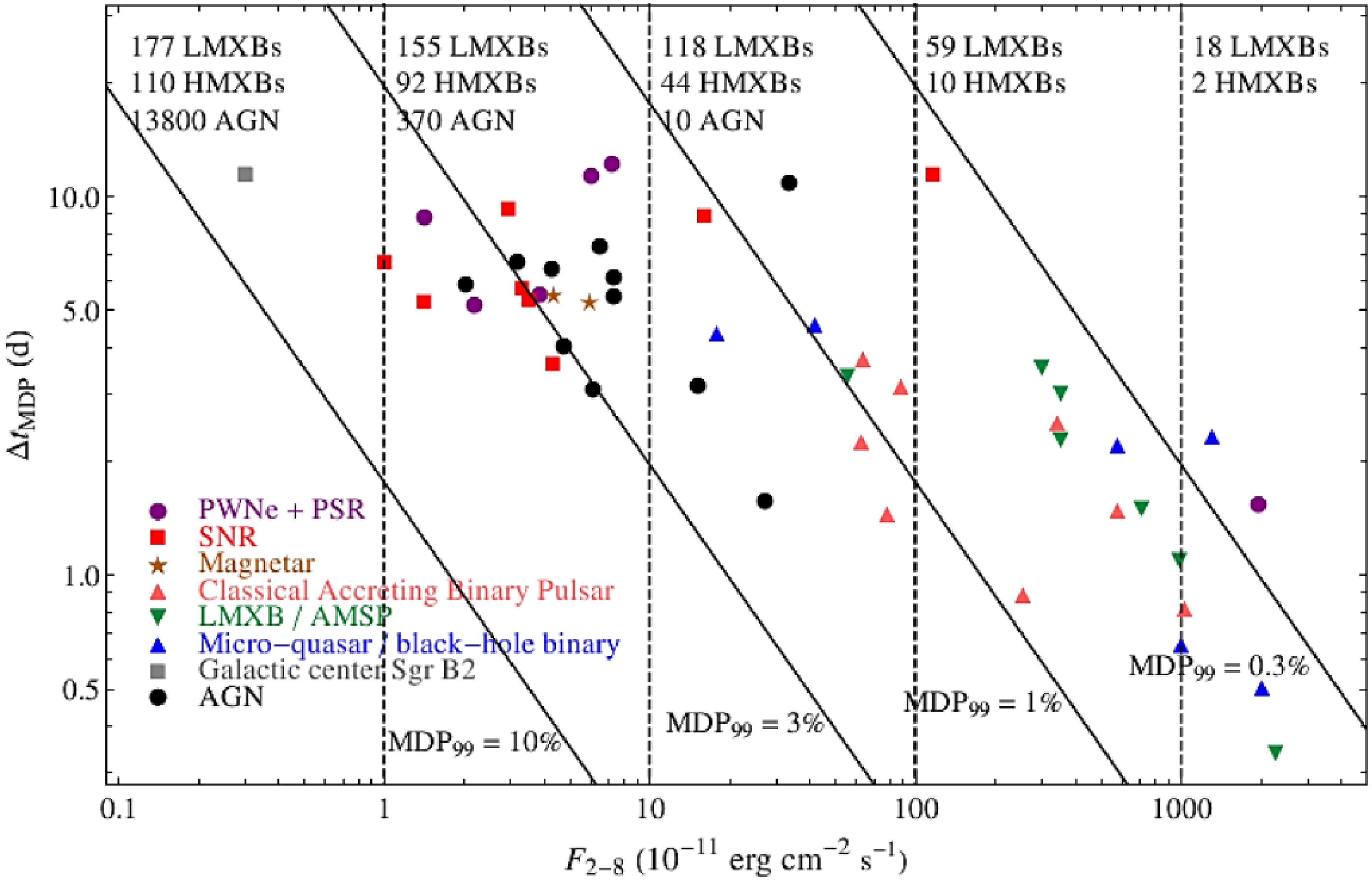


Science Operations Center (SOC)

- **Science Mission Planning**
  - Develop long-term observing plan
    - For baseline 2-year mission, based upon recommendations by IXPE's Science Advisory Team
    - For extended mission (if approved), dependent upon HEASARC administered General Observer program
  - Interact with the Mission Operations Center (MOC) on a weekly basis to schedule observations
  - Rework schedule when needed to accommodate targets of opportunity
- **Science Data Processing**
  - Ingest and aggregate telemetered IXPE science and engineering data from the MOC
  - Run these data through the SOC pipeline to generate science data products
    - Provide low-level data products to the Instrument Team for monitoring and trends analysis
    - Generate Level-1 data products, including electron track images and event lists in detector coordinates
    - Generate Level-2 data products, including event lists in sky coordinates for detailed scientific analysis
  - Maintain a Calibration Database (CalDB), which is needed for detailed scientific analysis
- **Science Data Archiving**
  - Provide IXPE CalDB to the High-Energy Astrophysics Science Archive Research Center (HEASARC)
  - For each observation, transmit science data products to the HEASARC within 1 week of end of observation
  - Test HEASoft tools provided by the HEASARC for analysis of IXPE data (HEASoft 6.30 now available)

The SOC is responsible for executing the observing program and processing the data.

IXPE Targets



Exposures are long, but IXPE can do ~50-100 Sources/year

Year-1 Targets

- **OBJECTIVE 1: Active Galactic Nuclei (AGN)**
  - Obtain polarimetry of RQ AGN to constrain the geometry of the emitting regions, and of Blazars and RG to study jet emission

- **OBJECTIVE 2: Microquasars**
  - Obtain spectral polarimetry of microquasars to constrain the value of the black-hole spin parameter (if in soft state), or constrain the geometry of the corona (if in hard state)

- **OBJECTIVE 3: Radio Pulsars and Pulsar-Wind Nebulae (PWNe)**
  - Obtain polarimetric imaging of the Crab to constrain the magnetic-field geometry of the nebula and the phase-dependent polarization of the pulsar

- **OBJECTIVE 4: Supernova Remnants (SNR)**
  - Obtain spectral polarimetric imaging of Supernova Remnants (SNR) to constrain the magnetic-field structure of the X-ray emitting regions

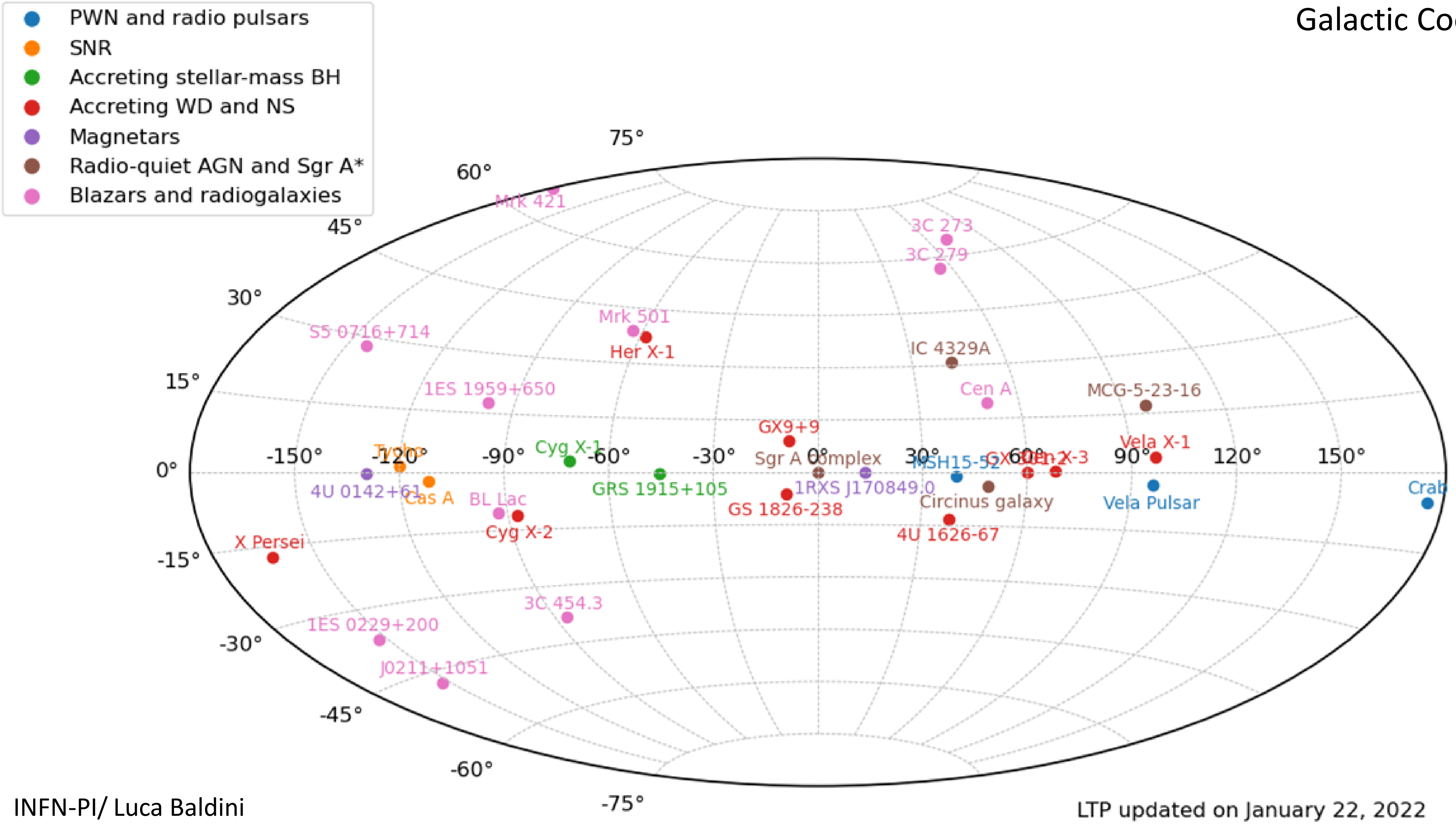
- **OBJECTIVE 5: Magnetars**
  - Obtain phase-dependent polarimetry of one magnetars to constrain the effects of vacuum polarization (birefringence in a strong magnetic field)

- **OBJECTIVE 6: Accreting X-ray Pulsars**
  - Obtain phase-dependent polarimetry of accreting X-ray pulsars (high-magnetic-field binaries) to constrain models and geometries for the pulsing emission. Obtain polarimetry of non pulsating accreting NS to constrain the geometry of the system

IXPE Imaging X-Ray Polarimetry Explorer

Year-1 targets

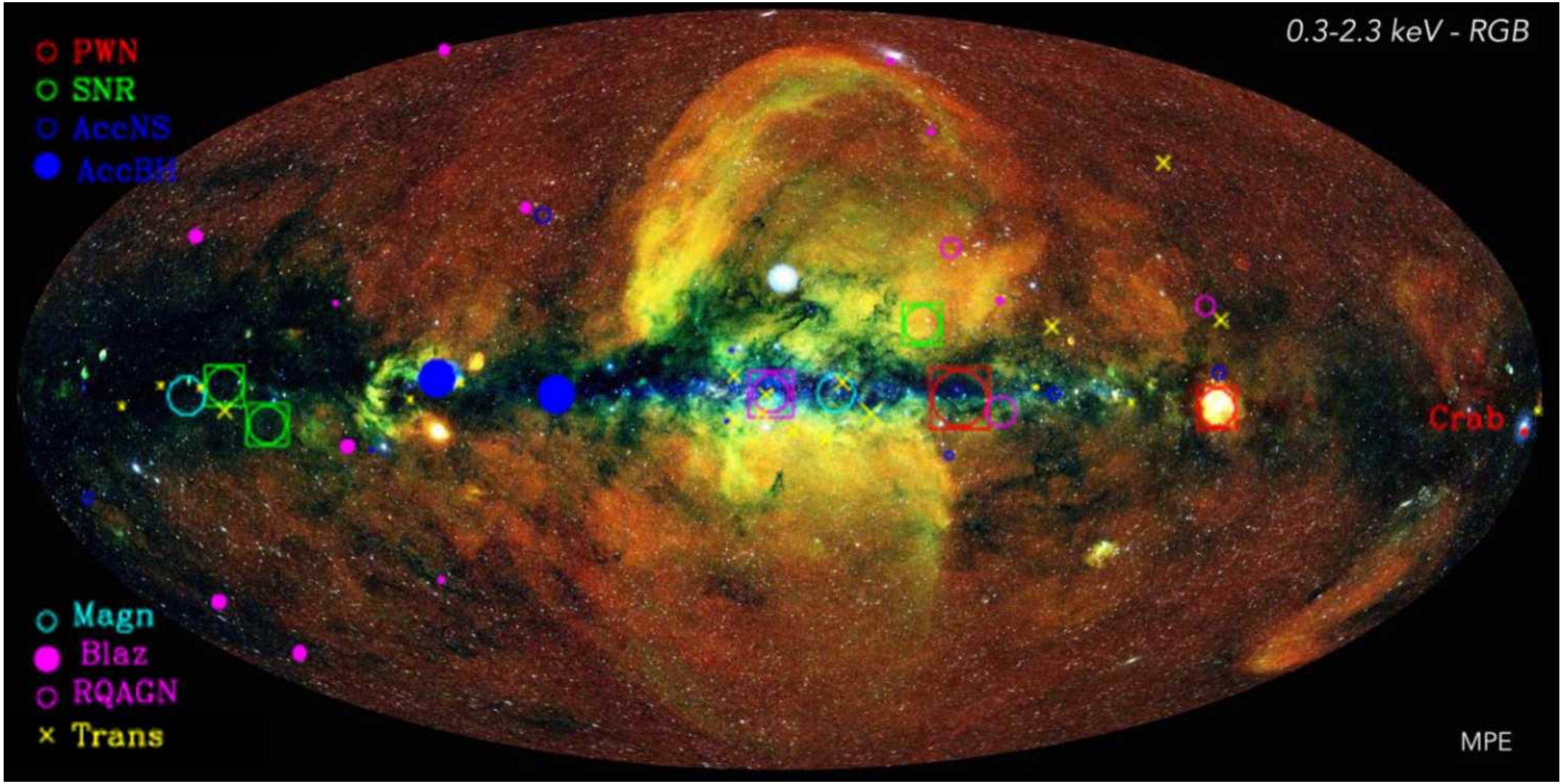
Galactic Coordinates



INFN-PI/ Luca Baldini

LTP updated on January 22, 2022

Year-1 targets



Notes: Dot size ~t_{exp} **Dots in squares - polarization images of extended target**

Execution of observing plan so far

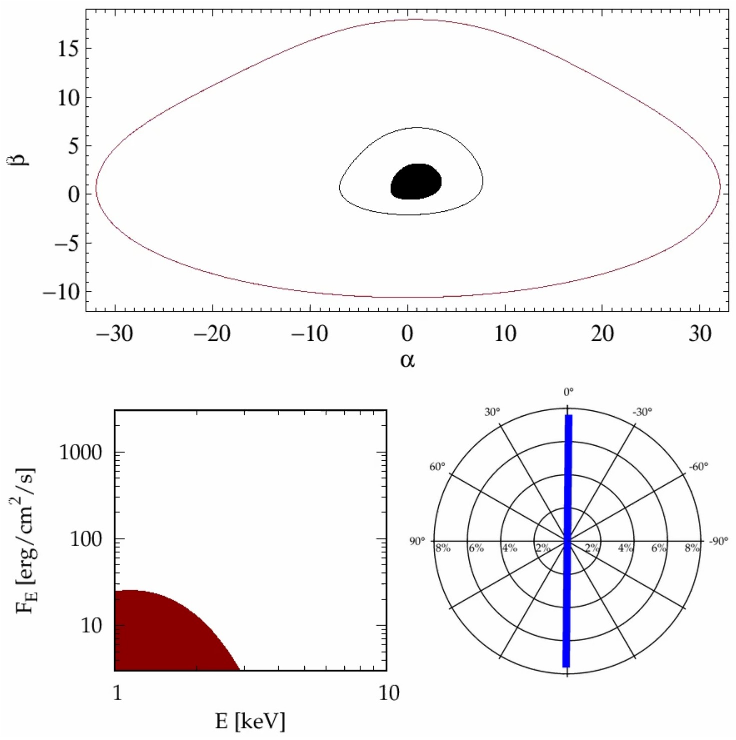
Name	TWG	Exposure [d]	Start	Stop
Cas A	SNR	11.57	01-11	01-29
Cen X-3	Acc NS (P)	1.16	01-29	01-31
4U 0142+61 (1 of 2)	Magnetar	6.94	01-31	02-14
Cen A	Blazar | RG	1.16	02-15	02-17
Her X-1 (1 of 2)	Acc NS (P)	2.31	02-17	02-21
Crab (1 of 2)	PWN	0.58	02-21	02-22
Her X-1 (2 of 2)	Acc NS (P)	1.16	02-22	02-24
4U 0142+61 (2 of 2)	Magnetar	1.97	02-24	02-27
Sgr A Complex (1 of 2)	RQ AGN | Sgr A	4.05	02-27	03-06
Crab (2 of 2)	PWN	0.58	03-07	03-08
Mrk 501	Blazar | RG	1.16	03-08	03-10
Sgr A Complex (2 of 2)	RQ AGN | Sgr A	7.52	03-10	03-23
4U 1626-67	Acc NS (P)	2.31	03-23	03-26
Mrk 501	Blazar | RG	1.16	03-26	03-28
GS 1826-238	Acc NS (NP)	1.16	03-28	03-31

X-ray Polarimetry and black holes

- **The spin of the black hole in accreting stellar-mass BH**
- **The geometry of the hot corona in accreting BH**
- **Reflection in heavily obscured AGN and GBH**
- **The structure of the magnetic field in blazars**
- **Astroarcheology of the Galactic Centre**

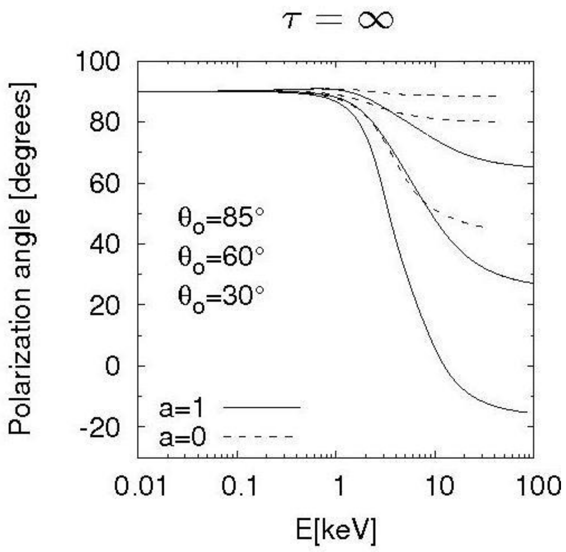
The spin of the black hole

- **For an accreting Galactic BH in the soft state**
  - Scattering polarizes the thermal disk emission (Chandrasekhar 1960; Taverna et al. 2021)
  - Polarization angle rotates due to GR effects
    - Polarization rotation is greatest for emission from inner disk
    - Inner disk is hotter, producing higher energy X-rays



Courtesy: Michal Dovciak

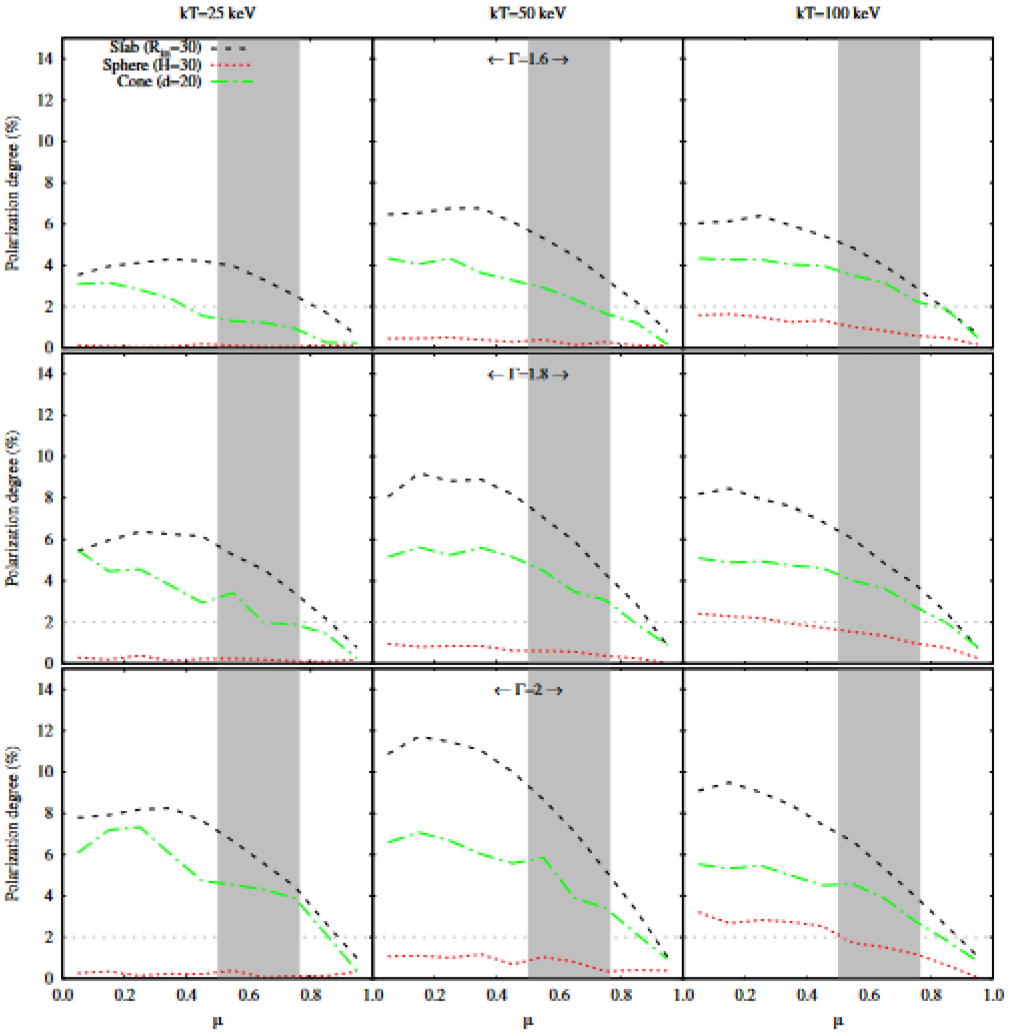
→ Rotation of the polarization angle with energy



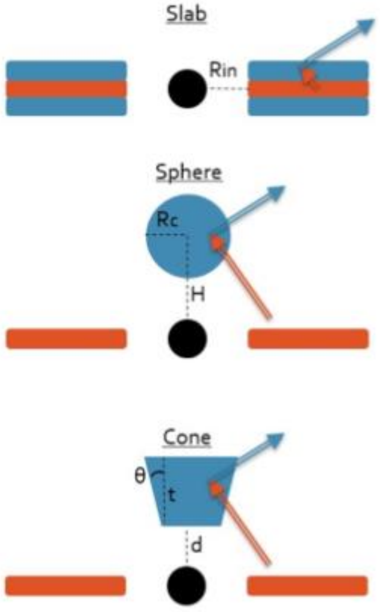
Dovciak et al. (2008); see also Taverna et al. 2020

IXPE Imaging X-Ray Polarimetry Explorer

The geometry of the hot corona



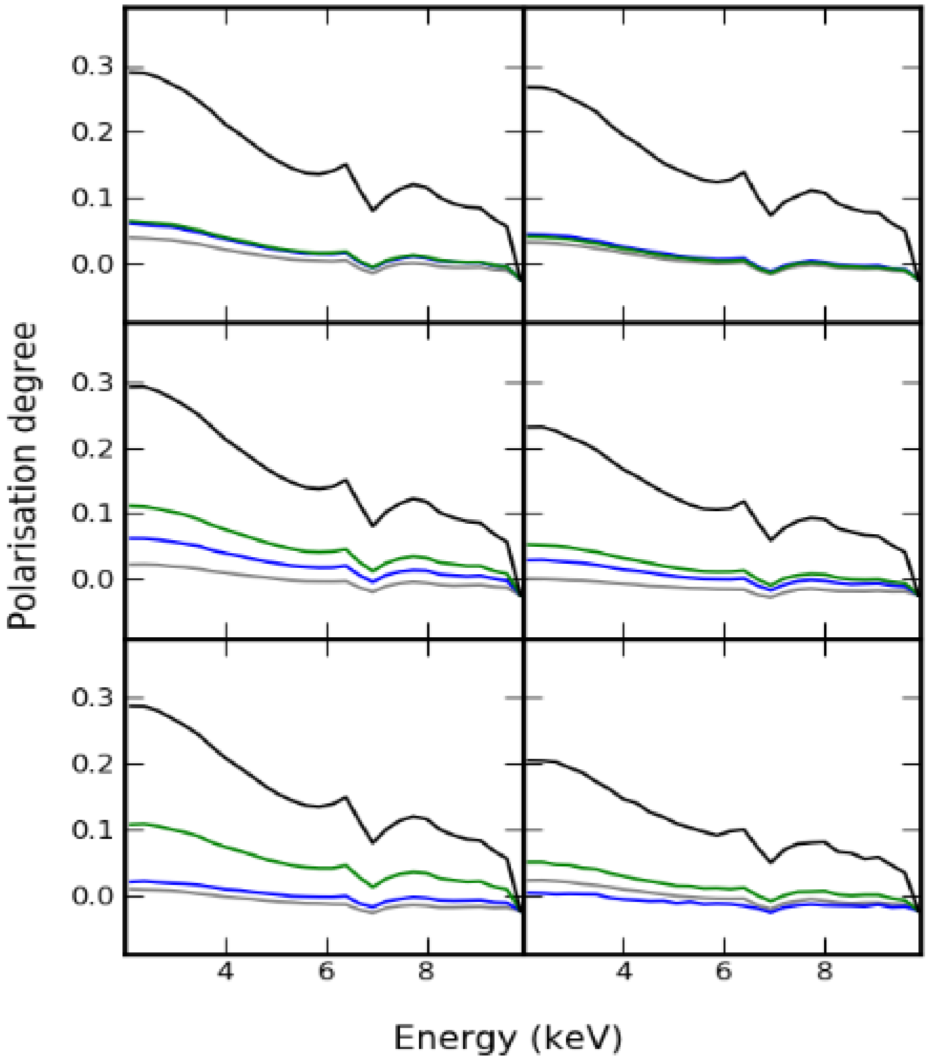
Ursini et al. (2022)



The geometry of the hot corona is unknown. Emission is expected to be polarized if the corona OR the radiation field are not spherical (Schnittman & Krolik 2010, Behestipour et al. 2017, Tamborra et al. 2018)

MONK code (Zhang et al. 2019) applied to GBH (Zhang et al. 2022), AGN (Ursini et al. 2022) and weakly magnetized NS (Gnarini et al., in prep.)

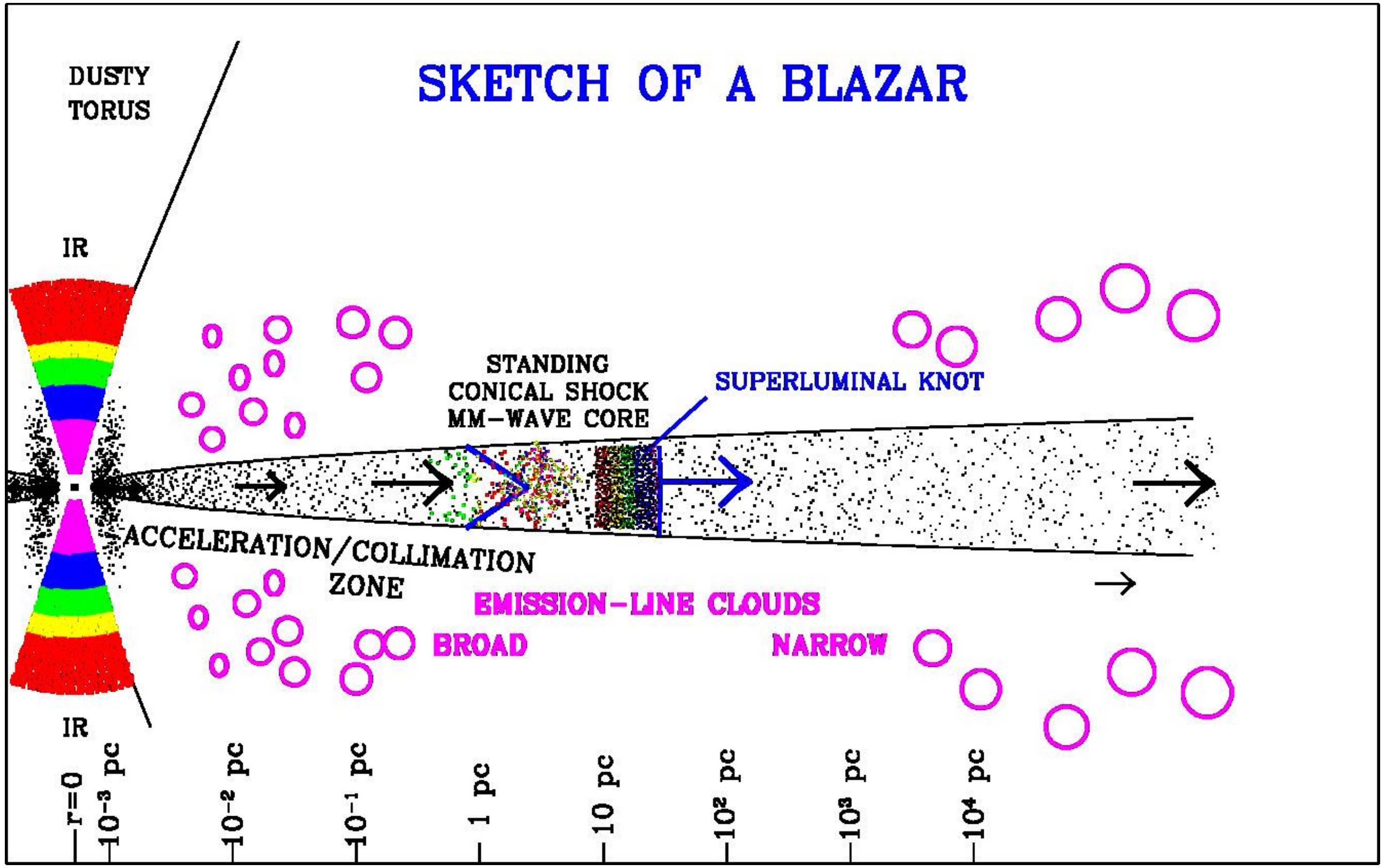
Reflection in heavily obscured AGN and GBH



Ratheesh et al. (2021)

- In Compton-Thick AGN, X-ray emission is dominated by reflection
- The same is true in a few GBH, most notably GRS 1915+105 (since 2018)
- Reflected emission is expected to be highly polarized

Blazars



Courtesy: Alan Marsher

Synchrotron (high-synchrotron-peak BL Lac objects & sometimes intermediate-synchrotron-peak BL Lacs)

Degree of polarization P = [(α+1)/(α+5/3)] x (magnetic field disorder factor)

(α = energy index)

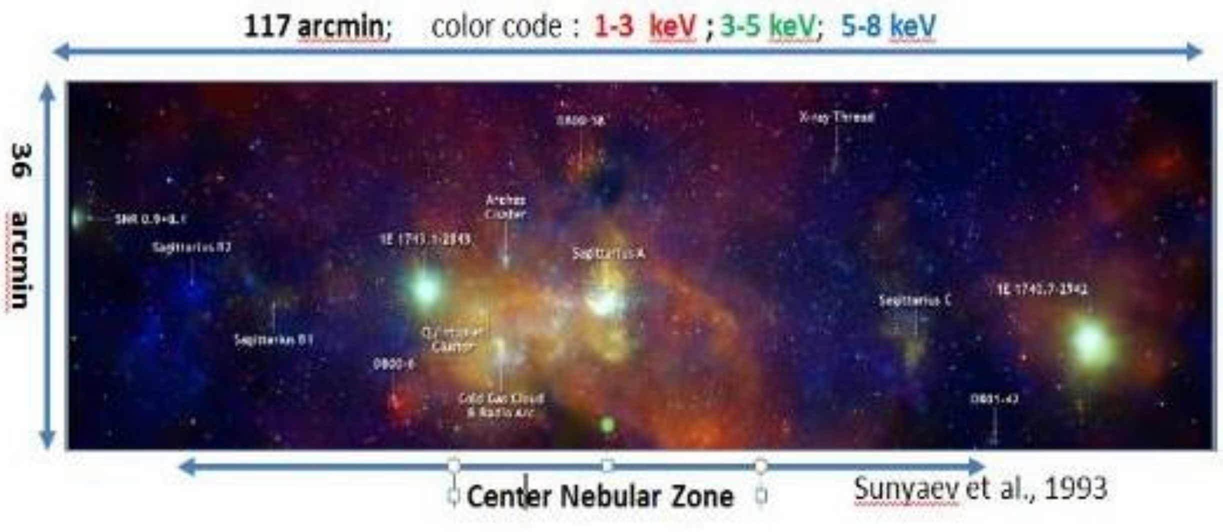
Position angle: ⊥ mean magnetic field direction projected on sky

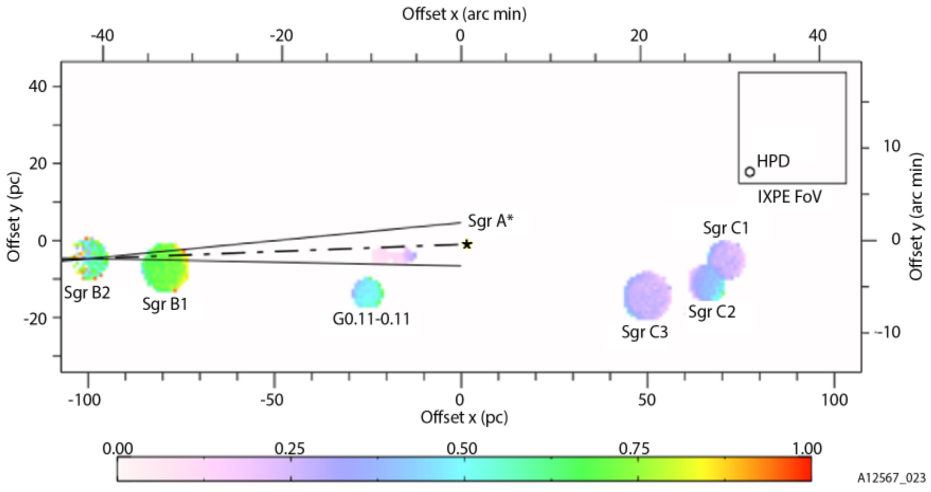
External Compton Scattering of unpolarized seed photons: no polarization expected

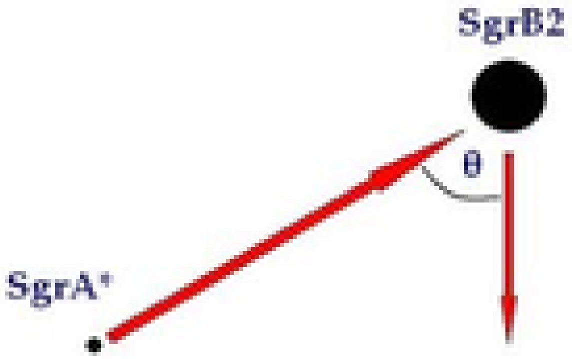
Synchrotron self-Compton: ~ 0.4±0.2 times the corresponding synchrotron polarization, same position angle (Krawczynski 2012)

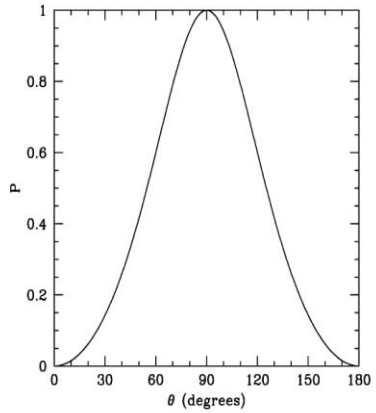
Astroarcheology of the Galactic Center

- **Galactic Center molecular clouds (MC) are known X-ray sources**
  - Are MCs reflecting X-rays from Sgr A* ? (supermassive black hole in the GC)
    - 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

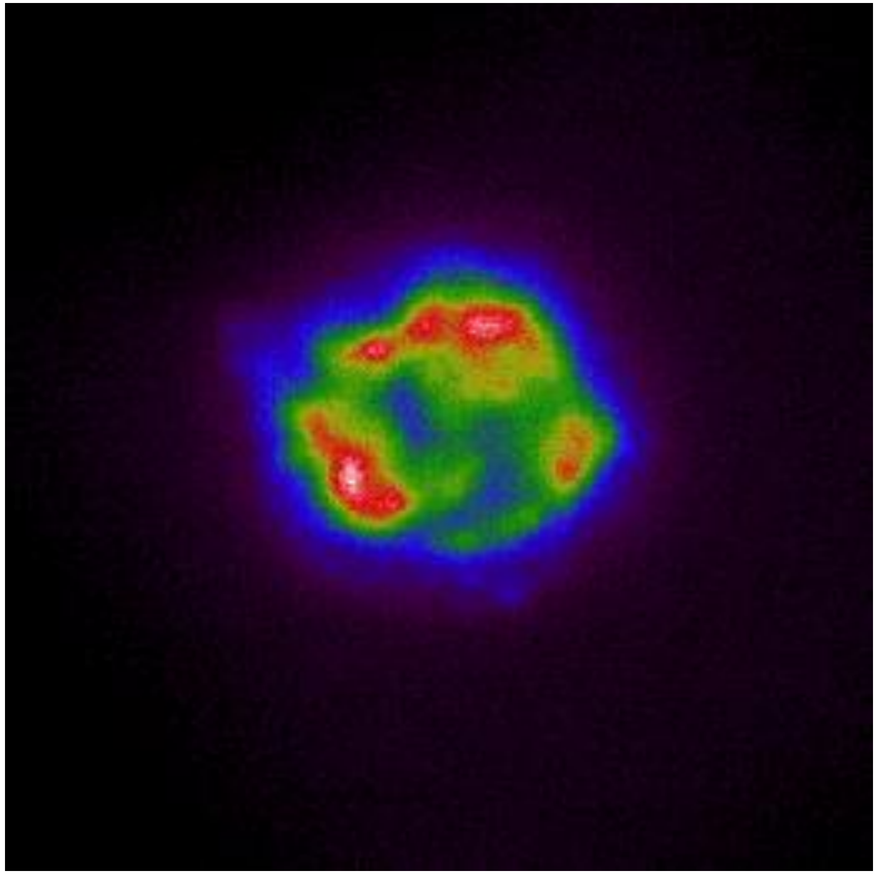


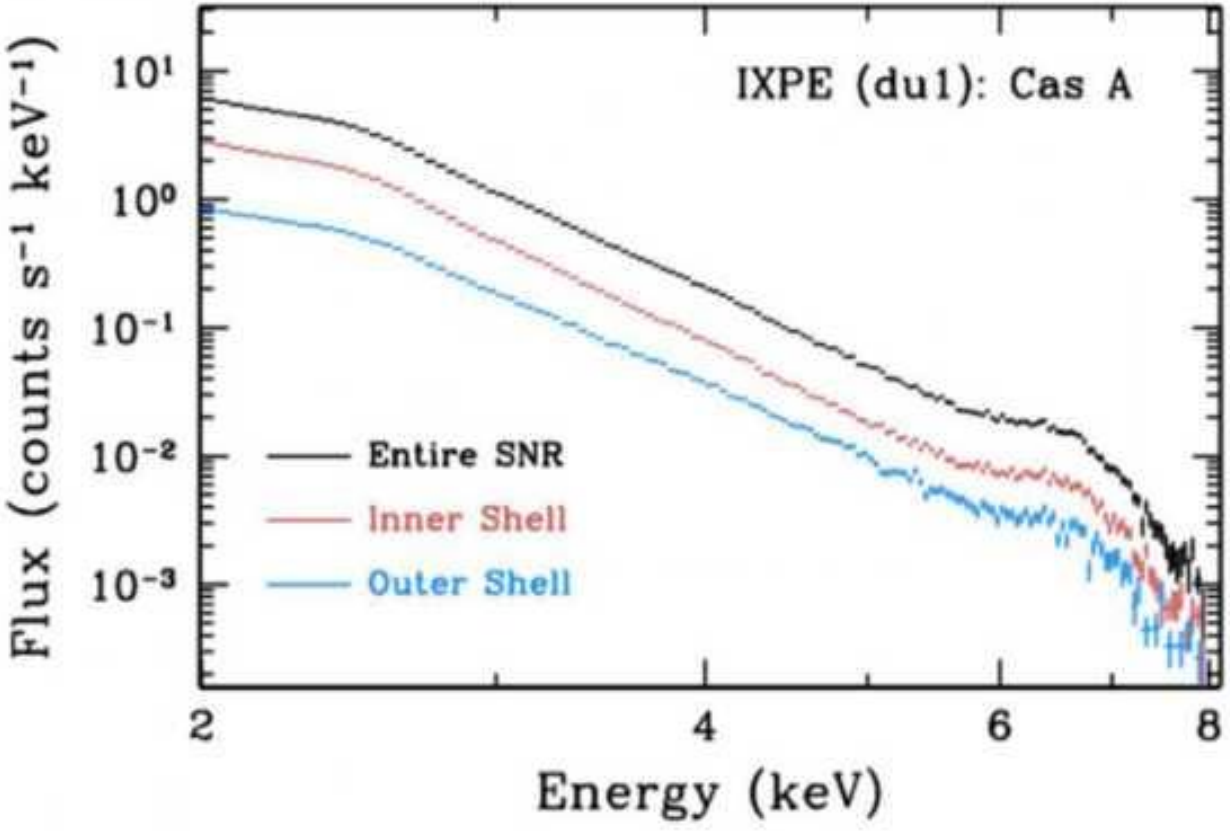






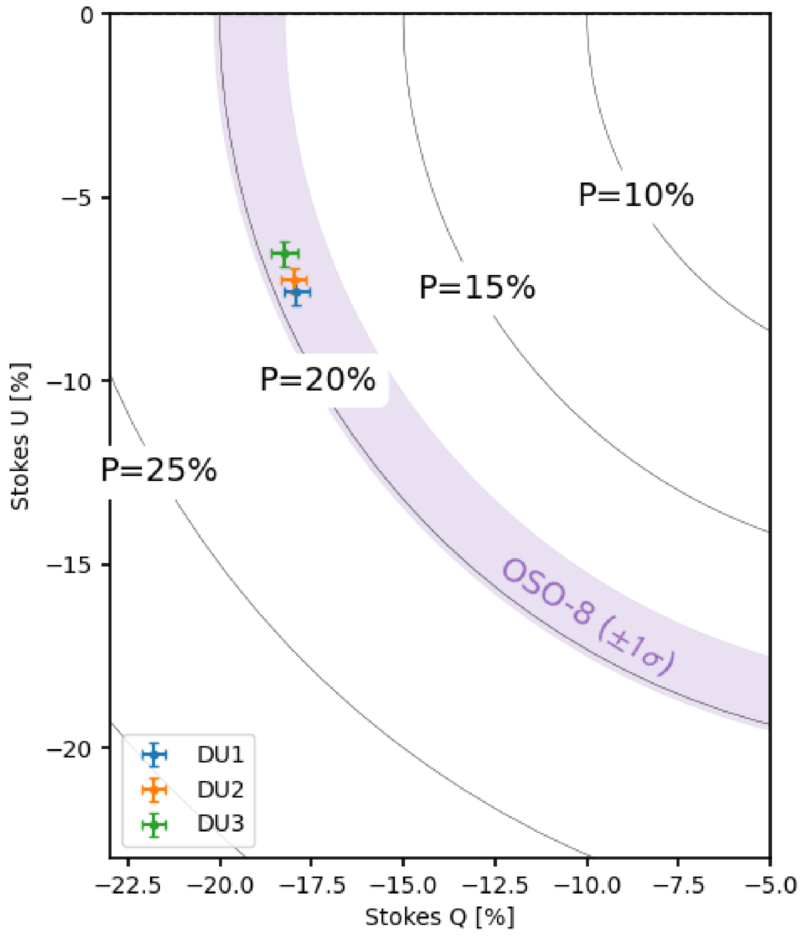
First science image and spectra (Cas A)





Quick-look polarization results

- **Low-level data products monitored by Italian Instrument Team (I2T)**
  - Lack spacecraft data needed for aspect determination
  - Allow polarization measurements averaged over position and time
  - May currently have fewer events than the final Level-2 data products
- **Secure detection (> 10 sigma) of average polarization in 3 of first 6 sources**
  - 4U0142+61 (Magnetar)
  - Her X-1 (X-ray Pulsar)
  - Crab (PWN)
    - Measure 19.45±0.21% polarization averaged over source and phase
    - Polarization degree comparable to OSO-8 and PolarLight results but much better precision

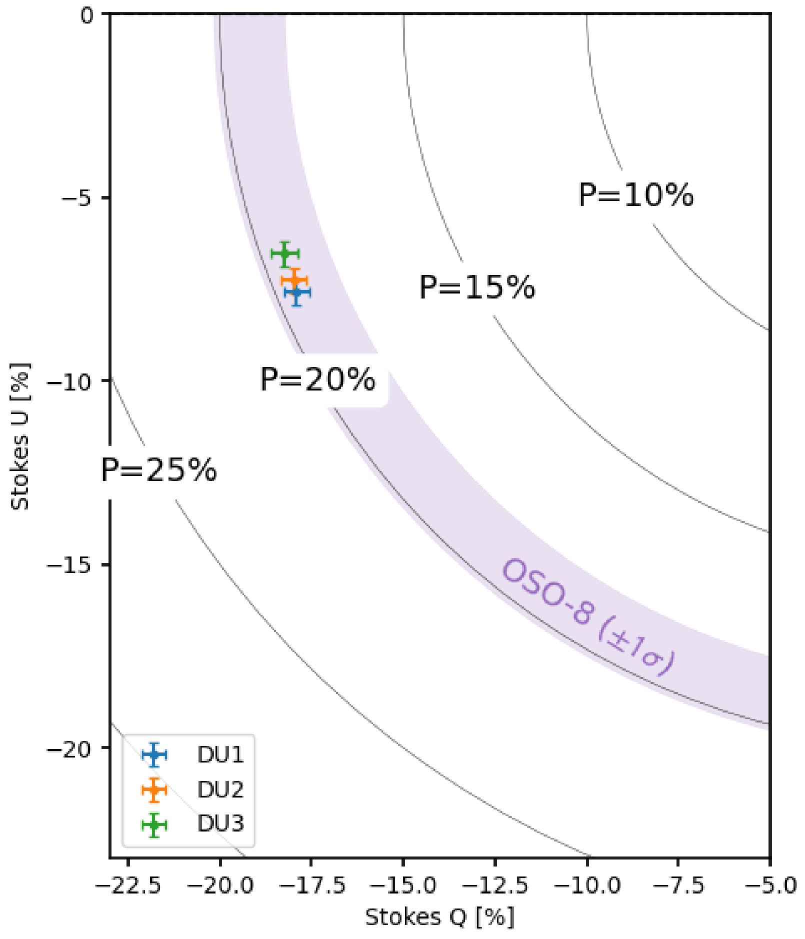


INAF-IAPS/ Fabio Muleri

IXPE Imaging X-Ray Polarimetry Explorer

Quick-look polarization results

- **Low-level data products monitored by Italian Instrument Team (I2T)**
  - Lack spacecraft data needed for aspect determination
  - Allow polarization measurements averaged over position and time
  - May currently have fewer events than the final Level-2 data products
- **Secure detection (> 10 sigma) of average polarization in 3 of first 6 sources**
  - 4U0142+61 (Magnetar)
  - Her X-1 (X-ray Pulsar)
  - Crab (PWN)
    - Measure 19.45±0.21% polarization averaged over source and phase
    - Polarization degree comparable to OSO-8 and PolarLight results but much better precision



INAF-IAPS/ Fabio Muleri

IXPE is functioning nominally and has begun measuring the polarization of cosmic x-ray sources.

Thank you for attention, and stay tuned!!