IXPE
Imaging
X-Ray
Polarimetry
Explorer

Calibration of the Imaging X-ray Polarimetry Explorer (IXPE)

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Italian Instrument Team (I2T): IAPS/INFN

23 April 2023

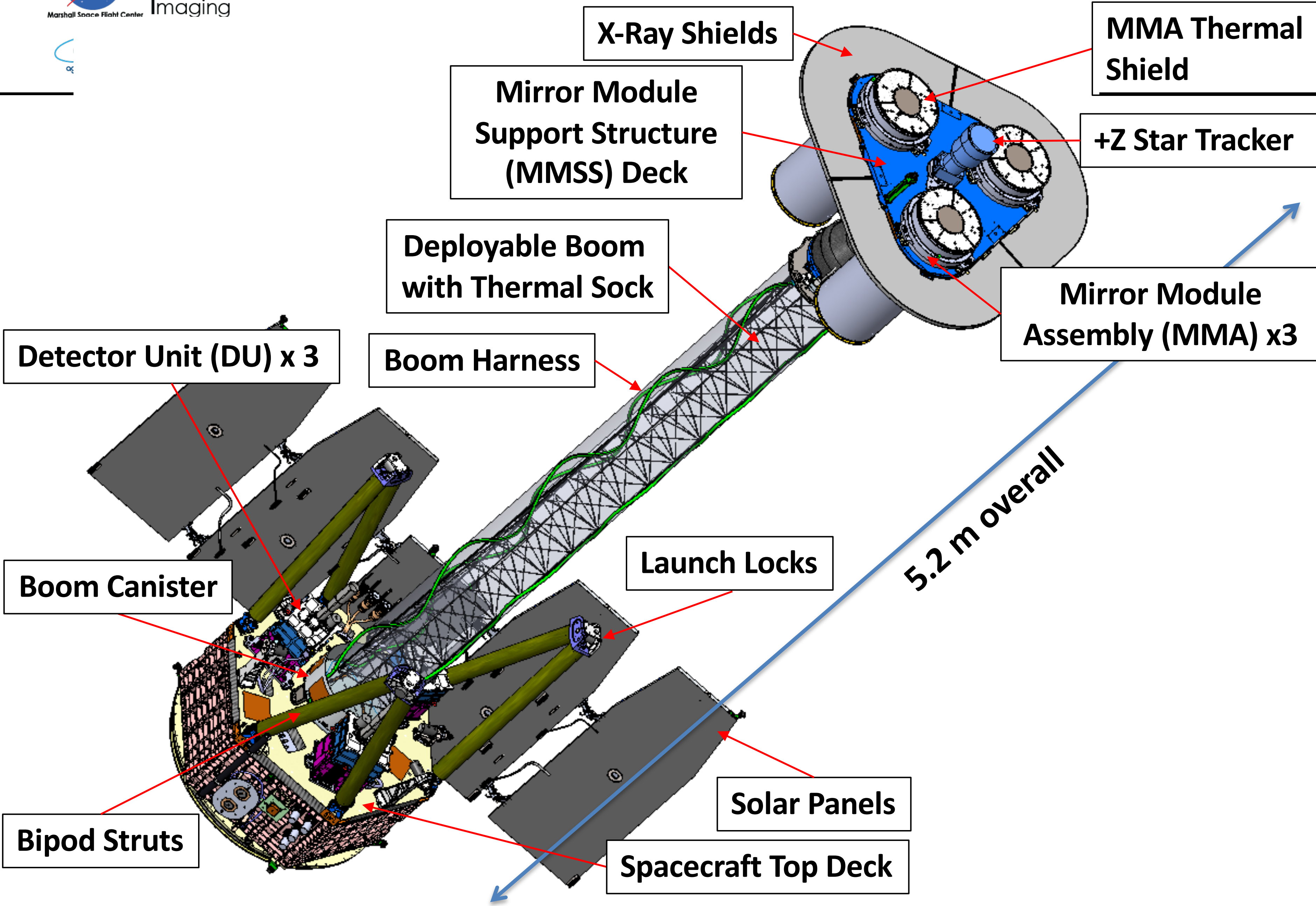
The IXPE Team

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

Science Advisory Team

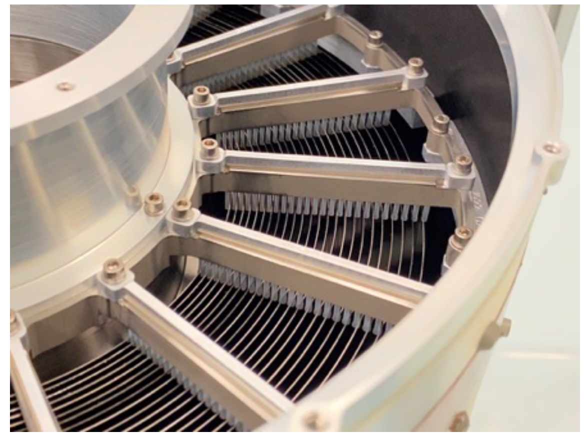
SAT currently comprises > 90 scientists from 12 countries

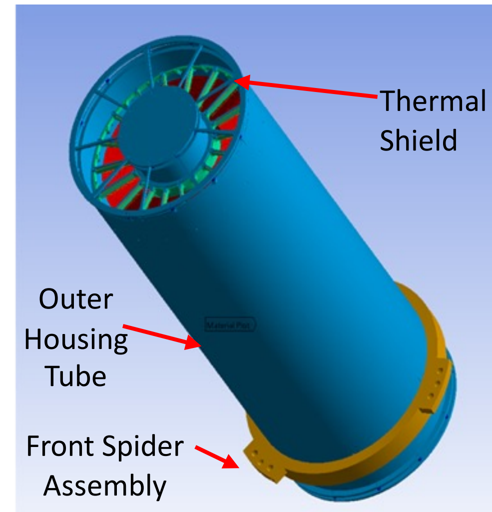
IXPE
Imaging

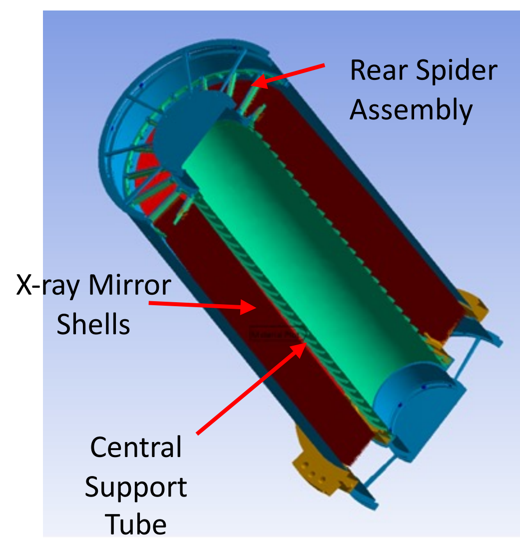


The Mirror Module Assemblies (MMAs)

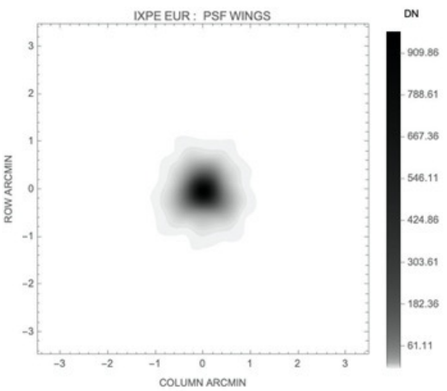
Parameter	Value
Number of mirror modules	3
Number of shells per mirror module	24
MMA Mass	93 kg (three together)
Focal length	4 m
Total shell length	600 mm
Range of shell diameters	162–272 mm
Range of shell thicknesses	0.16–0.25 mm
Shell material	Electroformed nickel–cobalt alloy
Effective area per mirror module	163 cm^2 (@ 2.3 keV); >192 cm^2 (3–6 keV)
Angular resolution (HPD)	~25 arcsec (MMA alone)
Field of view (detector limited)	12.9 arcmin square

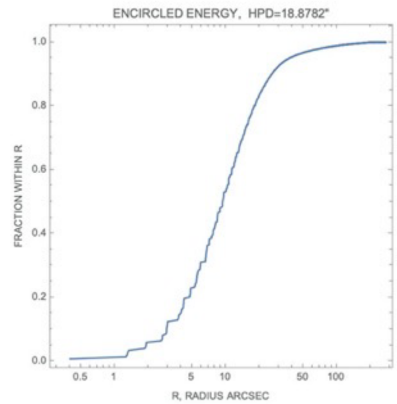




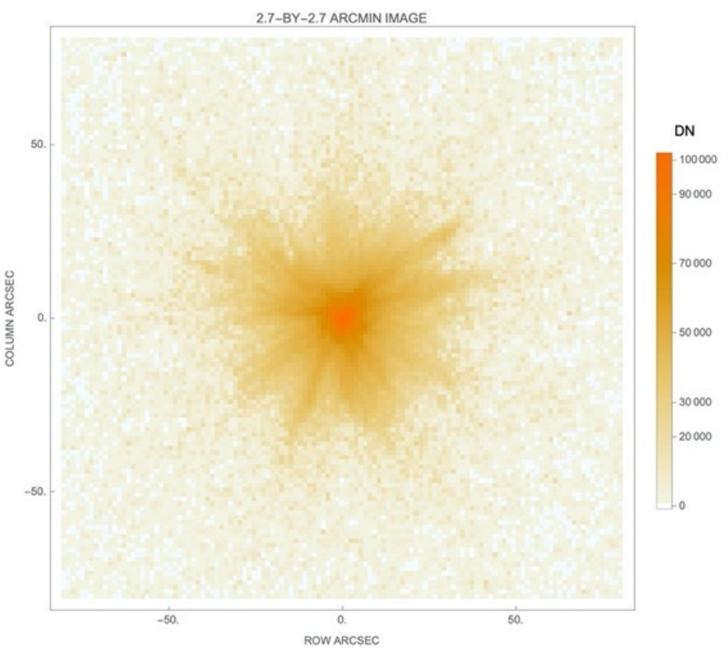


MMA ANGULAR RESOLUTION

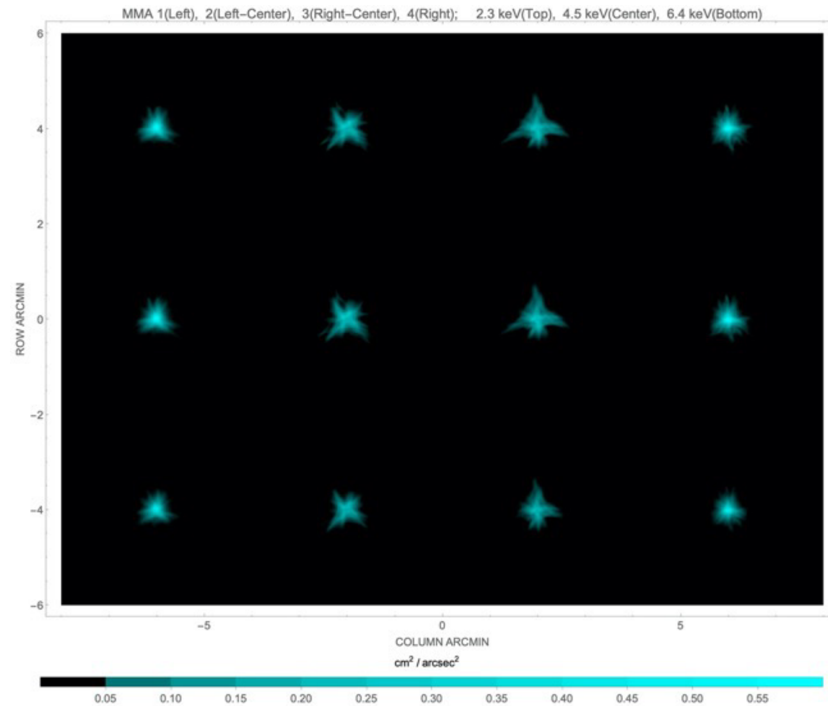




MMA1 PSF: HPD = 19.0”



Composite Image of: 4 MMA PSFs at 3 energies



IXPE MMA Angular Resolutions: HPD [arcsec]

	MMA1	MMA2	MMA3	MMA4
2.3 keV	19.0	25.0	27.6	20.0
4.5 keV	19.9	26.0	28.0	20.8

MMA off-axis Angular Resolution

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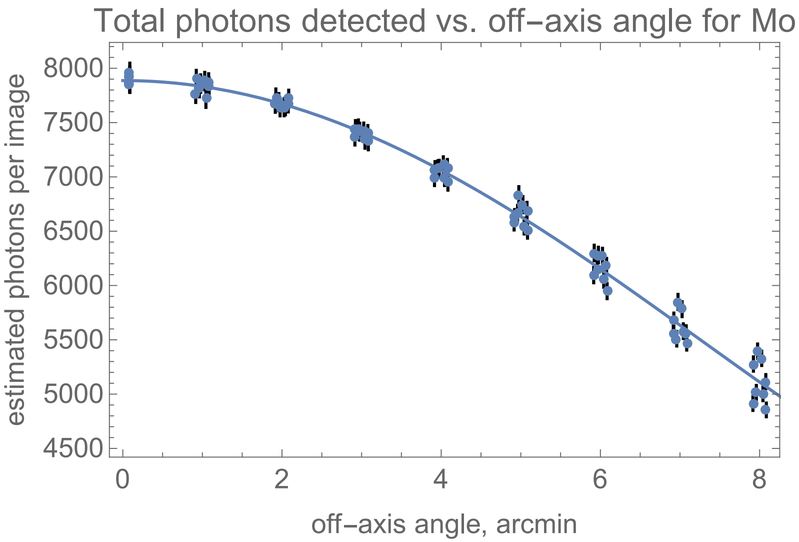
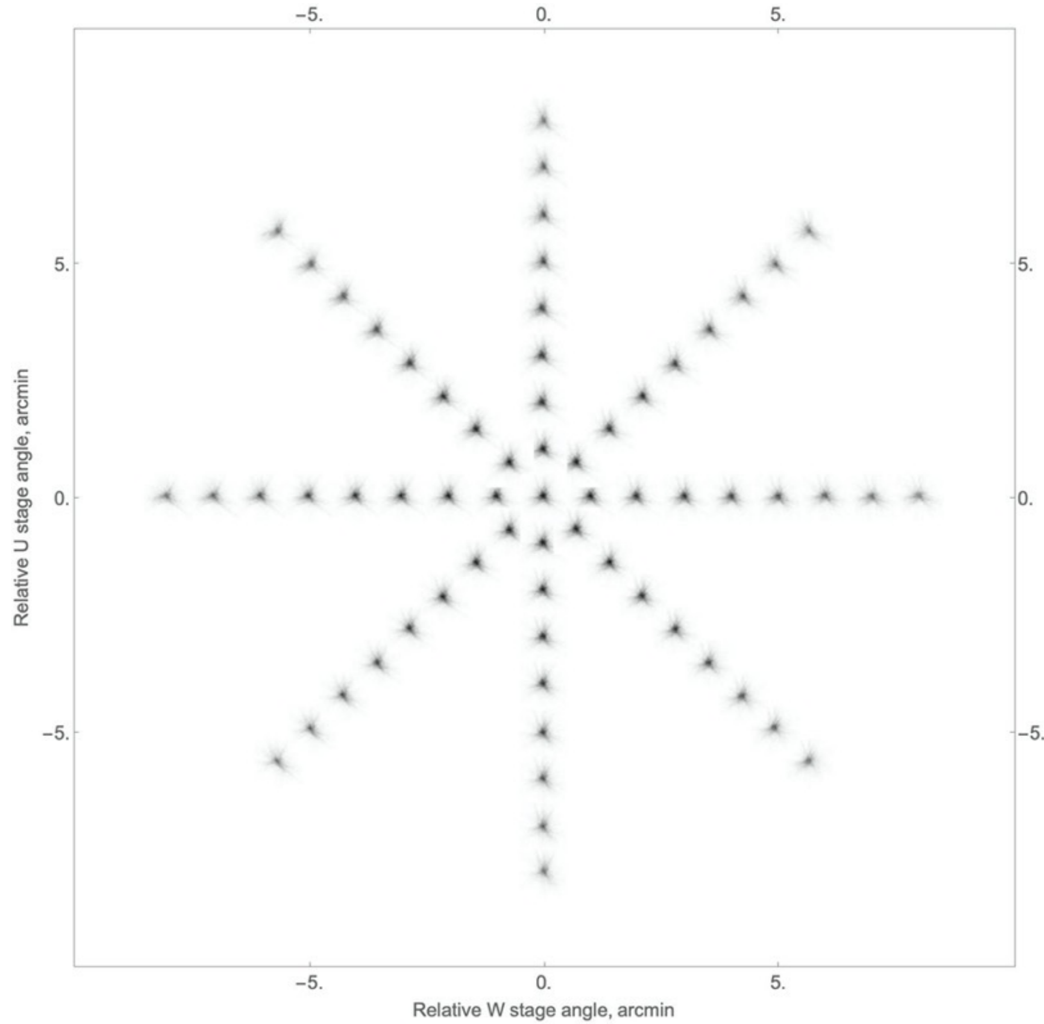


MMA3 vignetting function



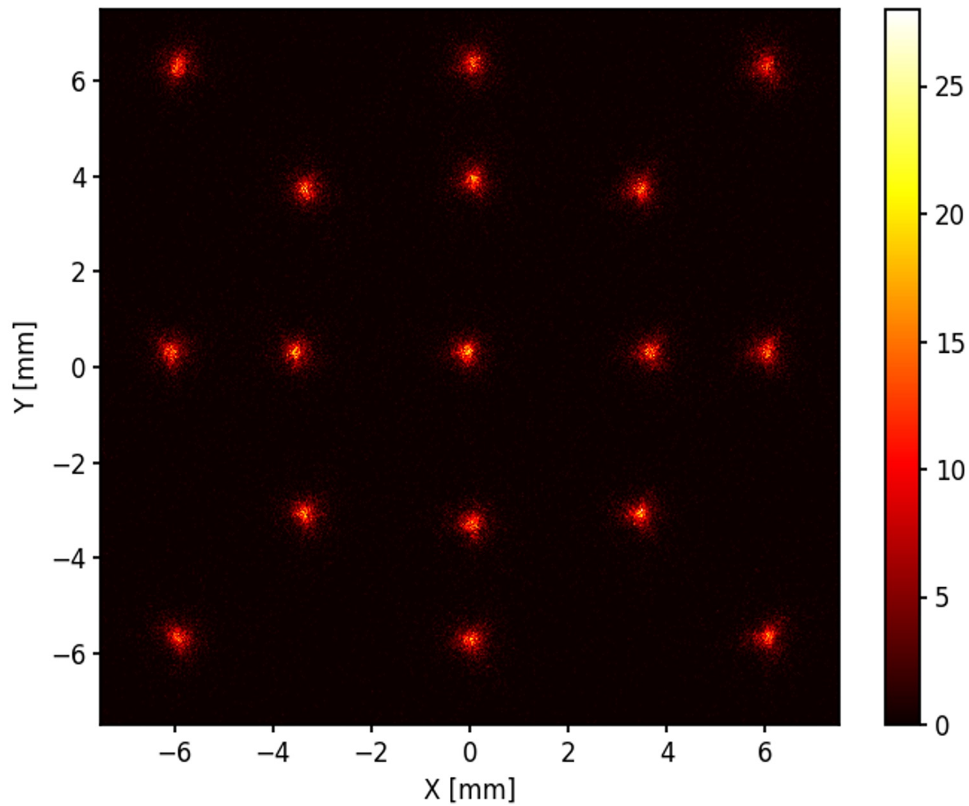
Composite image of MMA1 PSF at several off-axis angles

Telescope Angular Resolution

- **PSF of flight spare MMA4 (HPD =20”) measured with facility CCD camera and flight spare DU-FM1**

- **On-axis PSF:**
  - Essentially convolves MMA PSF with DU spatial resolution

Energy [keV]	PSF on DU [HPD, um]	MMA4 + DU-FM1 HPD [arcsec]
2.3	474.6	22.1
4.5	513.2	23.8
6.4	528.0	24.1

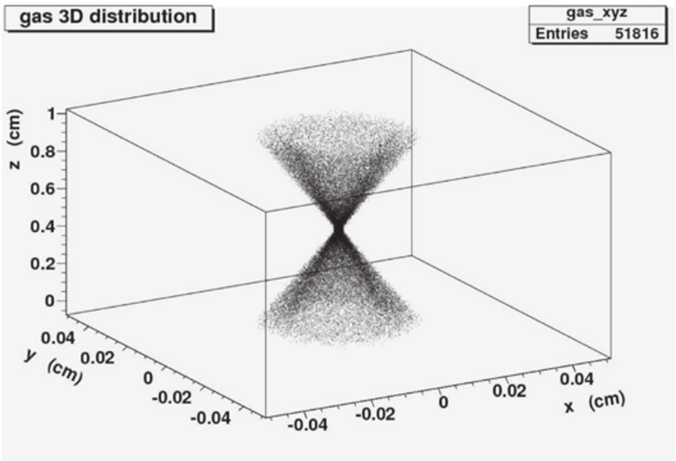


Composite image of on- and off-axis telescope PSF measurements across detector plane

Telescope Angular Resolution
Half Power Diameter

GPD angular resolution

- intrinsic spatial resolution (pixels, blurring due to diffusion, algorithm)
- inclined penetration
- MMA PSF (only MMA)



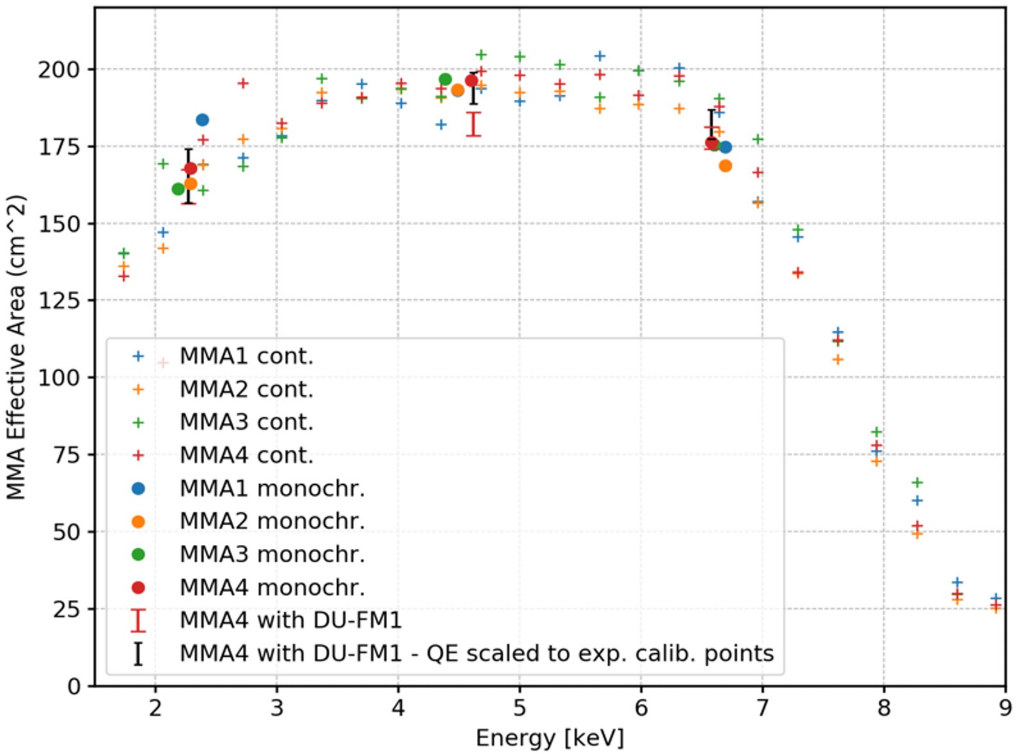
HPD On Axis

- **Refined analysis within 8mm of diameter and PSF fit**

X-ray Tube (Line)	MMA HPD (arcsec)	Detector Spatial Resolution (arcsec)	Detector Defocusing Effects (arcsec)	Derived Telescope HPD (arcsec)	Measured Telescope HPD (arcsec)
2.3 keV	20.0	5.6	6.0	21.6	22.2
4.5 keV	20.8	6.3	7.0	22.8	23.8
5.9 keV	20.1	7.4	7.2	22.6	24.1

MMA4 Effective Area derived from Telescope Measurement

Derivation of MMA Effective Area in Telescope configuration (using Detector QE) matches direct measurement of MMA with facility detectors



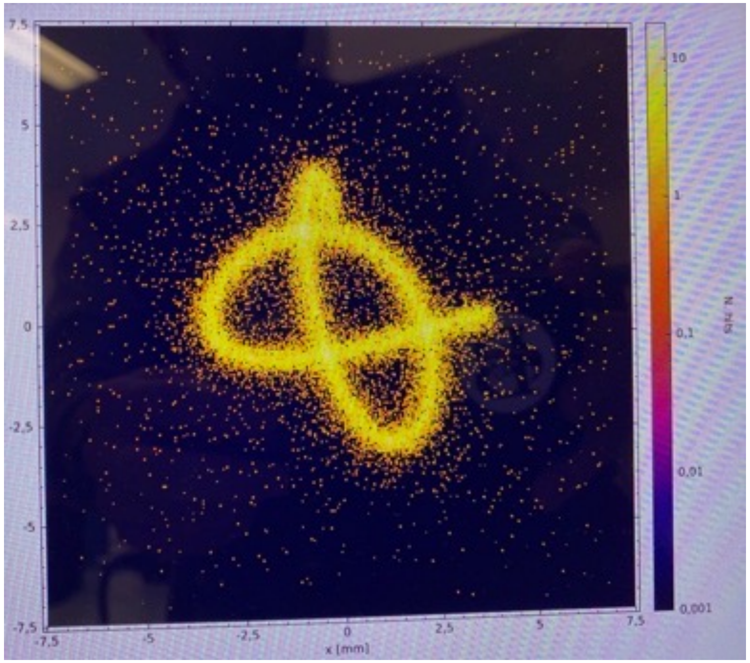
Source	Mean Energy $K_\alpha + K_\beta$ (keV) [or L-lines for Mo]	Measured MMA Effective Area (cm²)	DU quantum efficiency	Derived Telescope Effective Area (cm²)	Measured Telescope Effective Area (cm²)
Mo	2.30	167.7	0.155	26.02	25.38
Ti	4.63	196.3	0.038	7.56	7.37
Fe	6.58	176.3	0.015	2.68	2.67

DITHERING

- **Dithering adopted for flight to average over low level detector systematic effects**

- **And used to reduce calibration time**
  - Fewer measurements needed
  - Two dither radii measured to match anticipated flight pattern and
  - Deep field (and wider) detector calibration taken in Italy

- **Measured in 100m beamline with polarized source**



Dither pattern in progress on DU

Summary of Telescope Modulation Factors

	DU-FM1 alone modulation factor	Telescope (MMA4 + DU-FM1) Modulation Factor (r = 1.86mm)	Telescope (MMA4 + DU-FM1) Modulation Factor (r = 3.72mm)
2.7 keV	(29.87 +/- 0.12) %	(29.69+/- 0.20) %	(29.77 +/- 0.13) %
4.5 keV	(46.04 +/- 0.14) %	(45.43 +/- 0.33) %	(46.18 +/- 0.21) %
6.4 keV	(56.59 +/- 0.09) %	(57.08 +/- 0.42) %	(56.26 +/- 0.23) %

- **Modulation factors with and w/o optics agree**

- **Presence of MMA optics does not affect Polarization performance of detector**

General Observer (GO) Program

- **Proposal submitted recently to NASA**
- **Evaluated over the next several months**
- **If accepted, AO will be out late summer – autumn 2023**
- **Observations to start Jan 2024 (after completion of nominal 2-year baseline mission)**

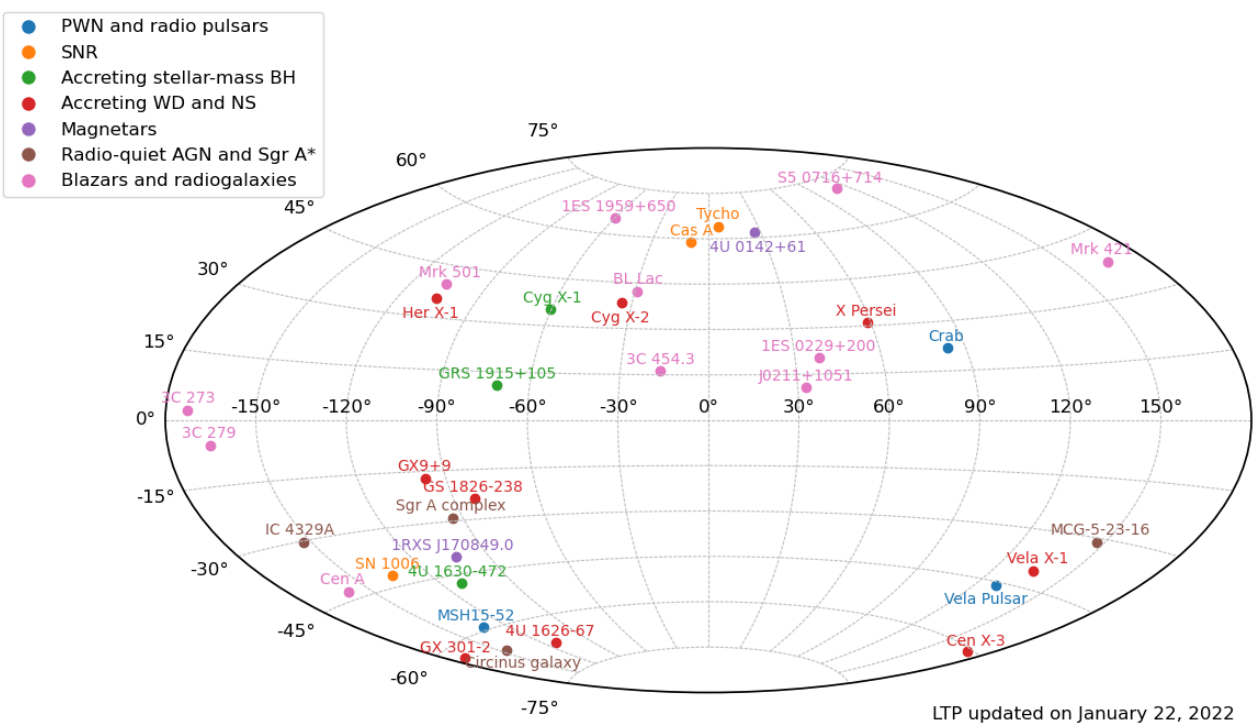
IXPE
Imaging X-Ray Polarimetry Explorer

IXPE SCIENCE TARGETS

So far:

- 74 observations of 46 distinct sources
- > 27 detections of polarization

4	PWN
3	SNR
4	Accreting BH
15	Acc NS
3	Magnetars
5	RQ AGN
1	SGR A Complex
11	Blazars & RG
1	GRB



Imaging X-ray Polarimetry Explorer — IXPE

Mission Status — Detectors

John Rankin

Italian National Institute for Astrophysics — INAF/IAPS

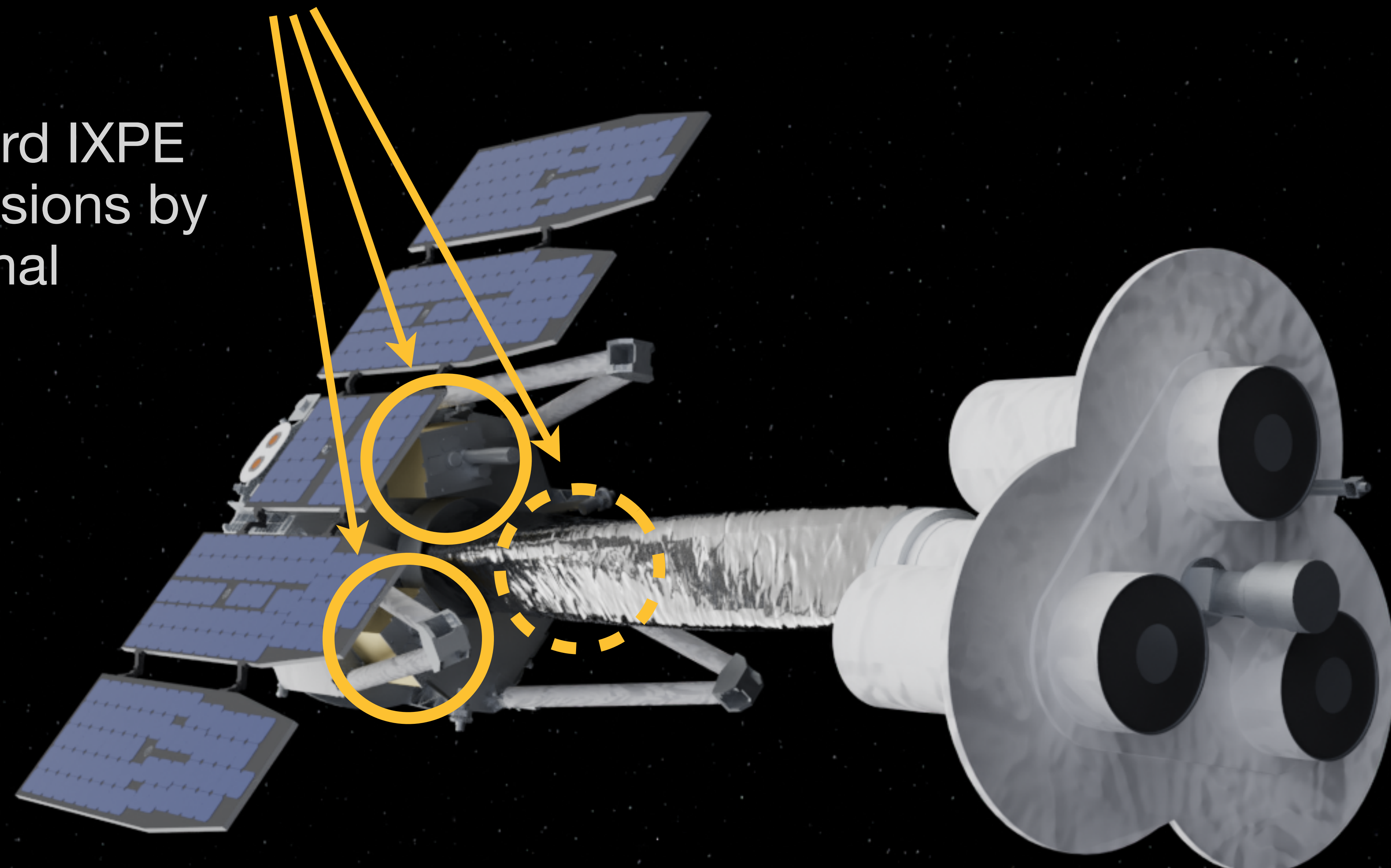
on behalf of the IXPE team

15th IACHEC meeting, 23-27 April 2023 — Seeblick Pelham

The Detectors On-Board IXPE

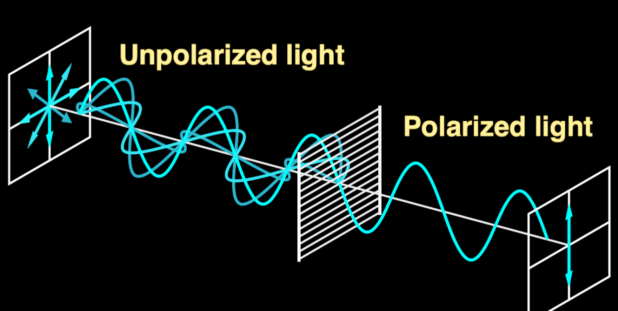
The detectors on-board IXPE expands on other missions by detecting two additional observables:

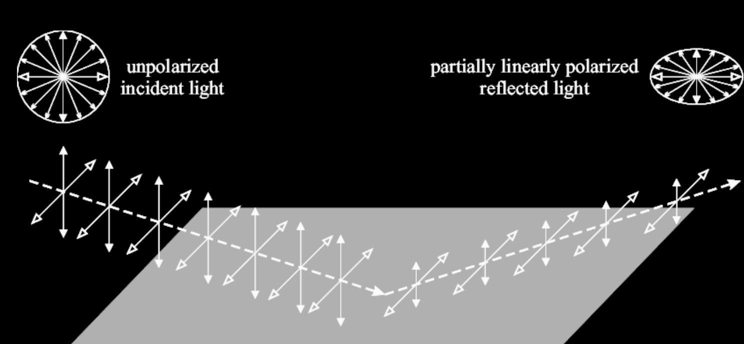
- Polarization degree
- Polarization angle

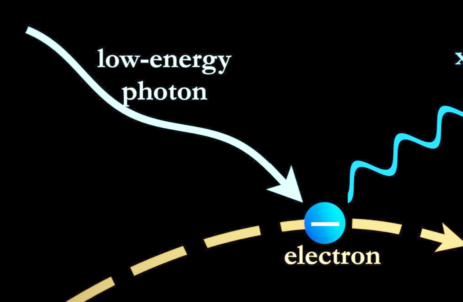


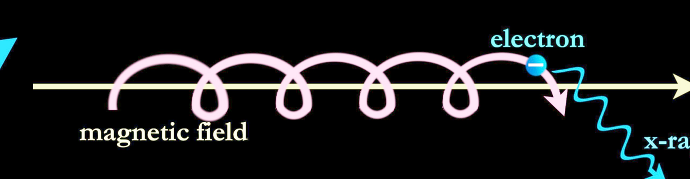
Polarimetry gives info on

- **Geometry** (even of sources too small to be resolved with current X-ray telescopes)
- **Emission mechanisms**







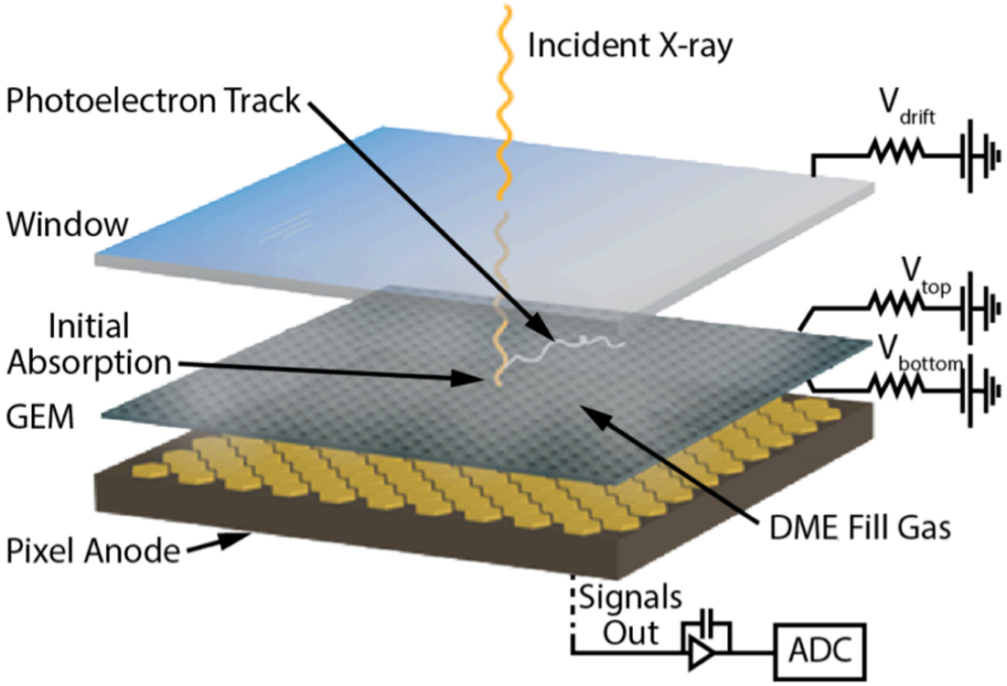


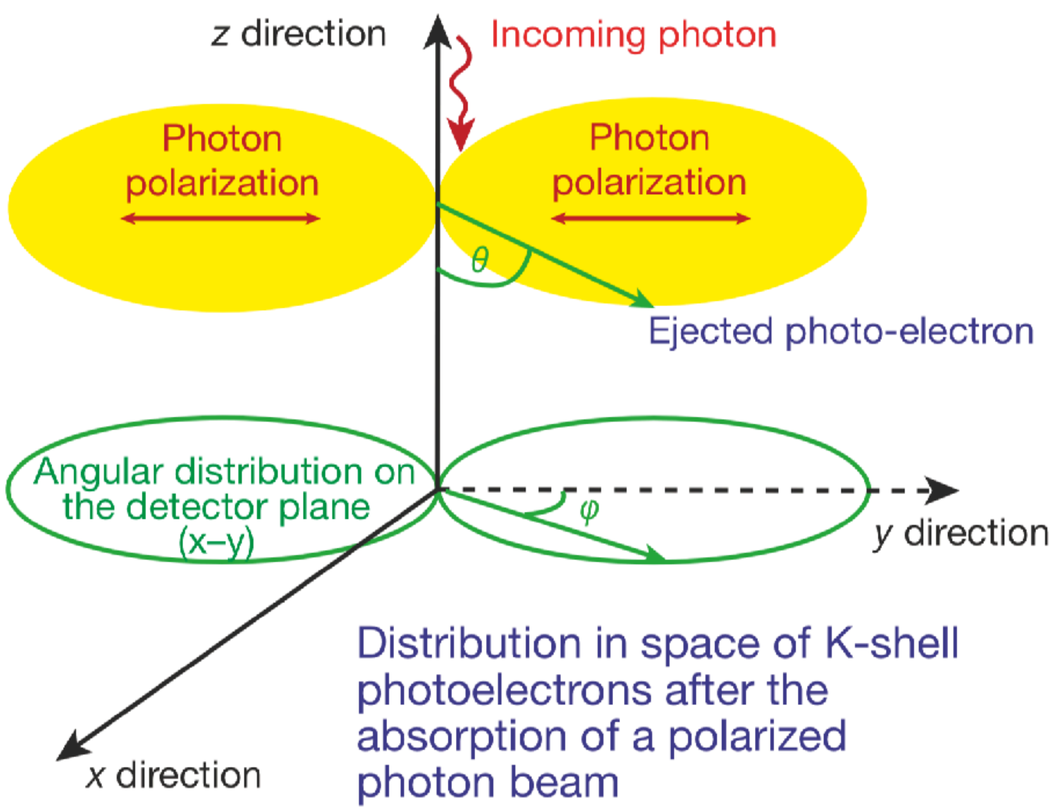
Images credit: NASA, Wikimedia Commons, Horvát+ 2019

How IXPE Measures Polarization

Using the Gas Pixel Detectors, based on the photoelectric effect

- The distribution in angle of ejected photoelectrons is peaked around the polarization's direction

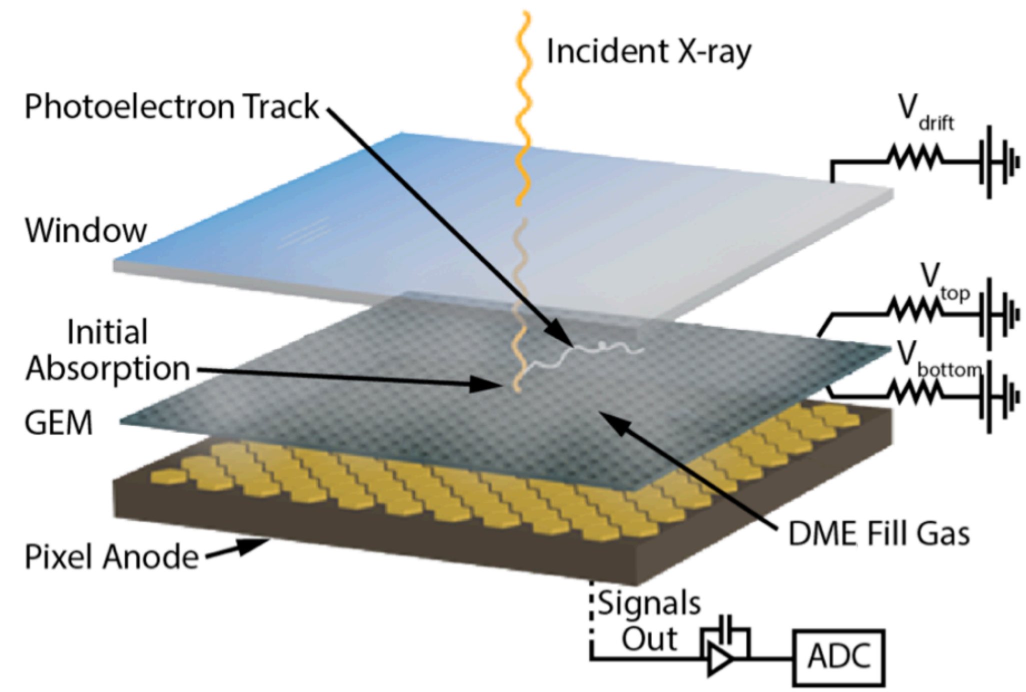




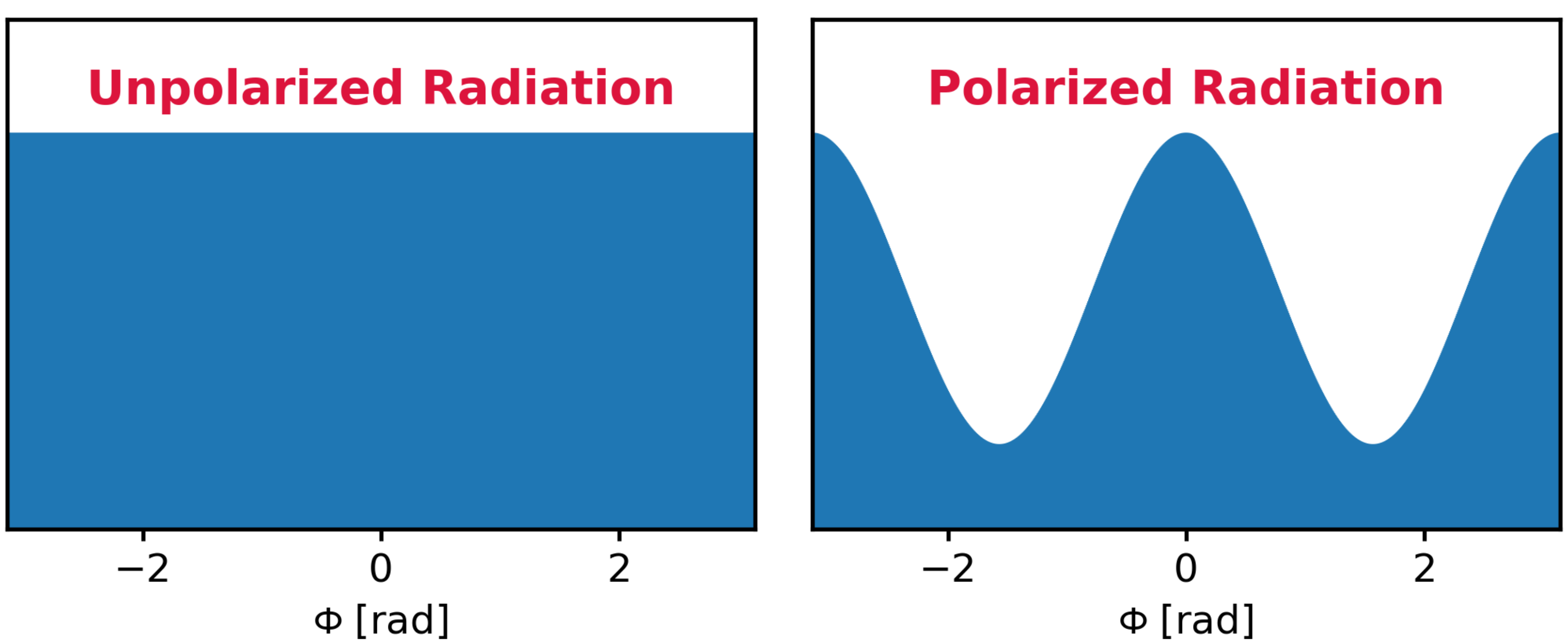
Costa+ 2001

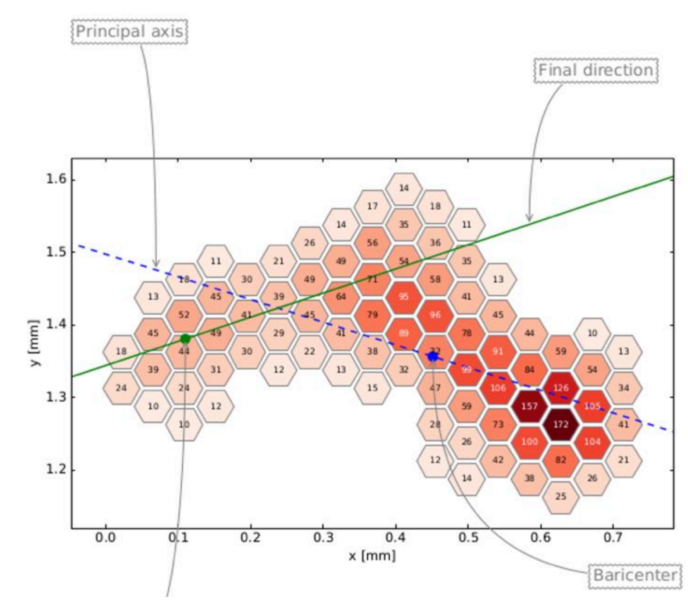
How IXPE Measures Polarization

Using the Gas Pixel Detectors, based on the photoelectric effect



- The incident X-ray extracts a photoelectron that produces a ionization track in the gas
- The track is amplified and read
- A histogram of the directions of all tracks is produced

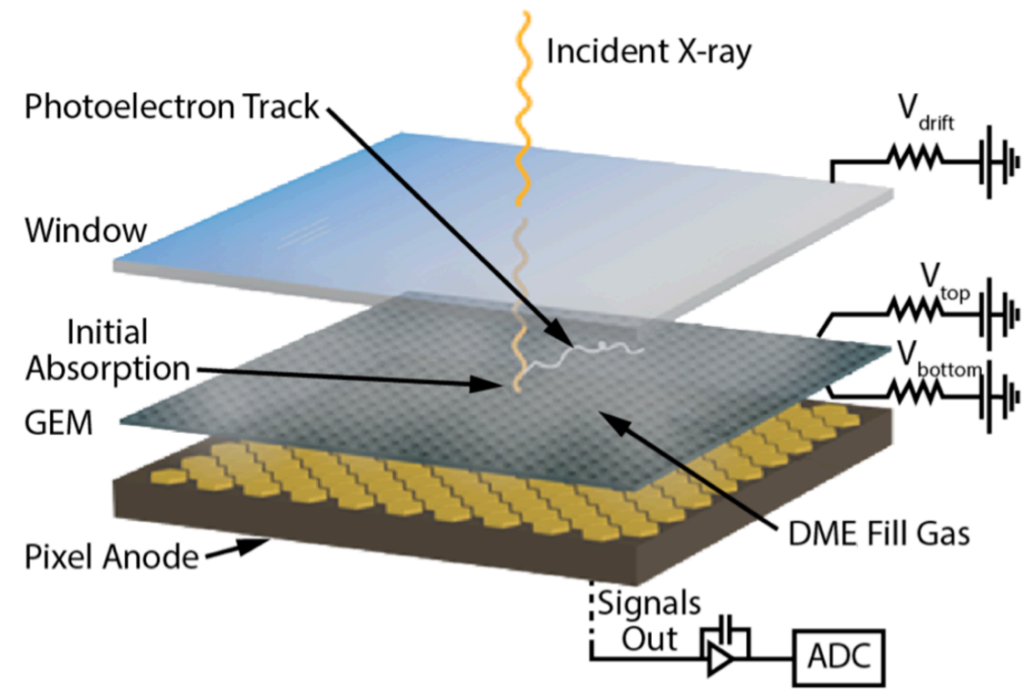


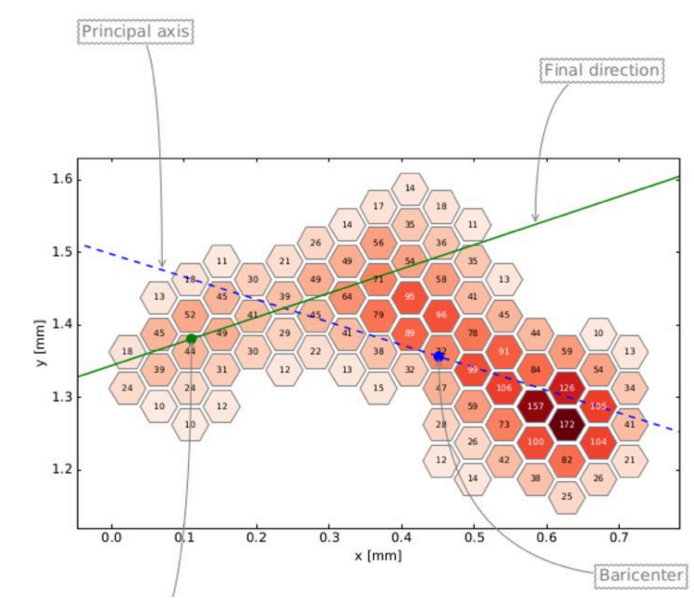


How IXPE Measures Polarization

Using the Gas Pixel Detectors, based on the photoelectric effect

- For each X-ray it detects
    - Photoelectric track direction
    - Energy
    - Position
    - Time of arrival





Calibrations of IXPE

Calibration Sources

- Crab Nebula: only source with previous X-ray polarization measurements

  Variable over time: cannot be used

↓

- Calibration using ground calibration sources

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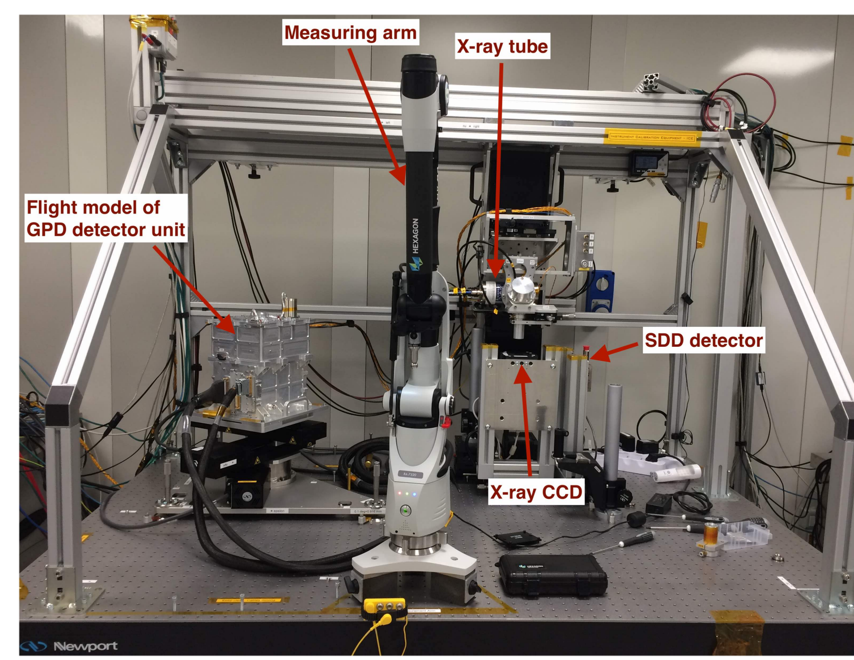
- In-flight monitoring using on-board calibration sources

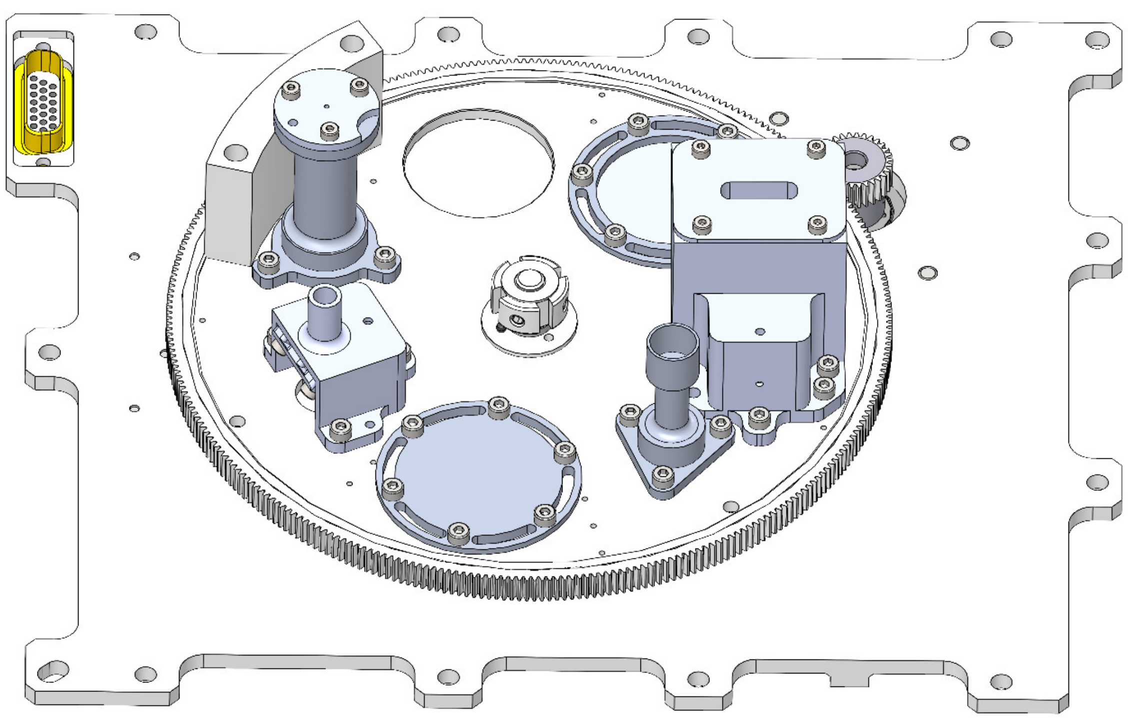
Image credit: NASA

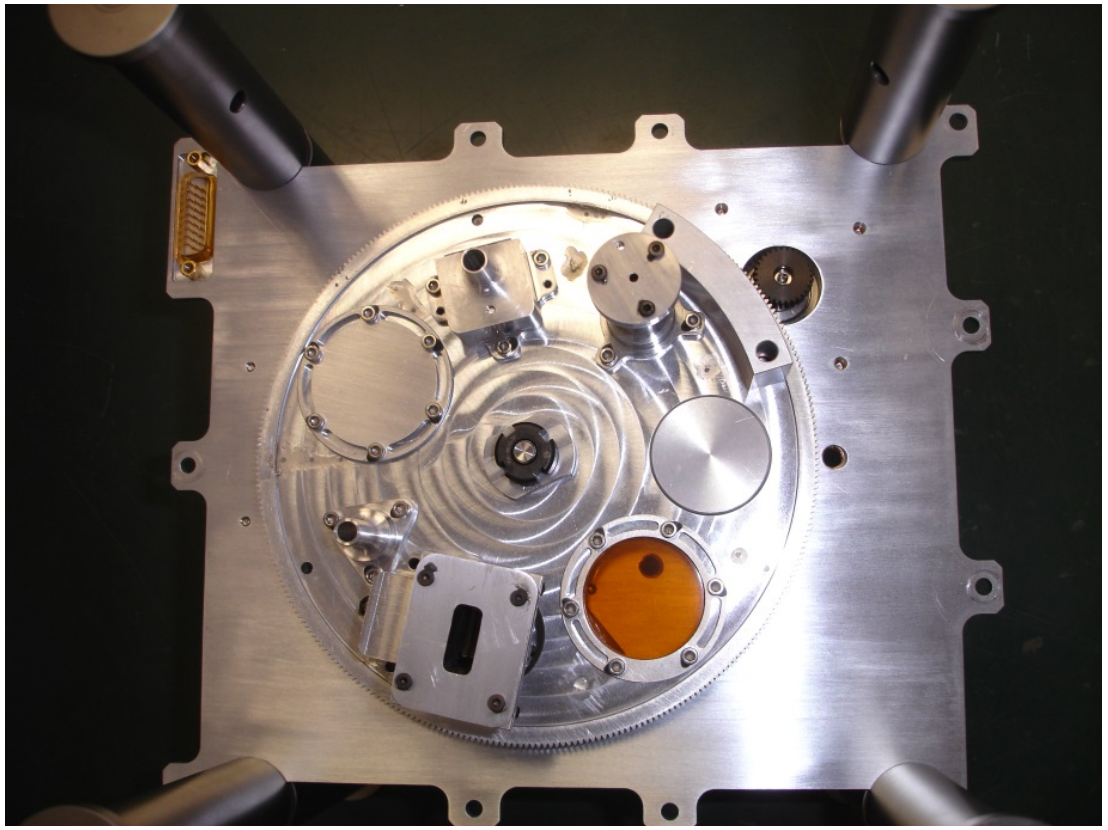


On-Board Calibration Sources

4 Calibration sources

- 3 unpolarized and 1 polarized
- Based on ^{55}Fe radioactive nuclides





Filter and calibration wheel housing the sources

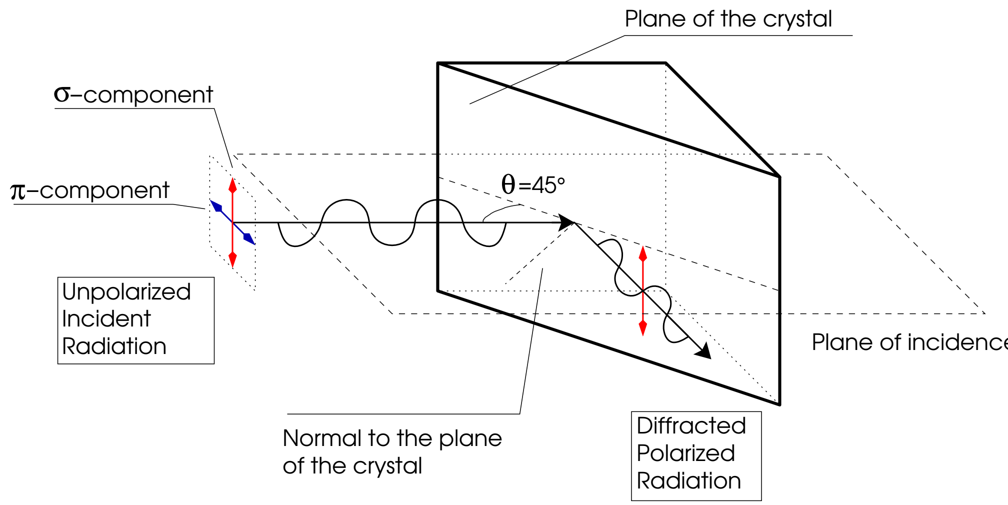
Ferrazzoli+ 2020

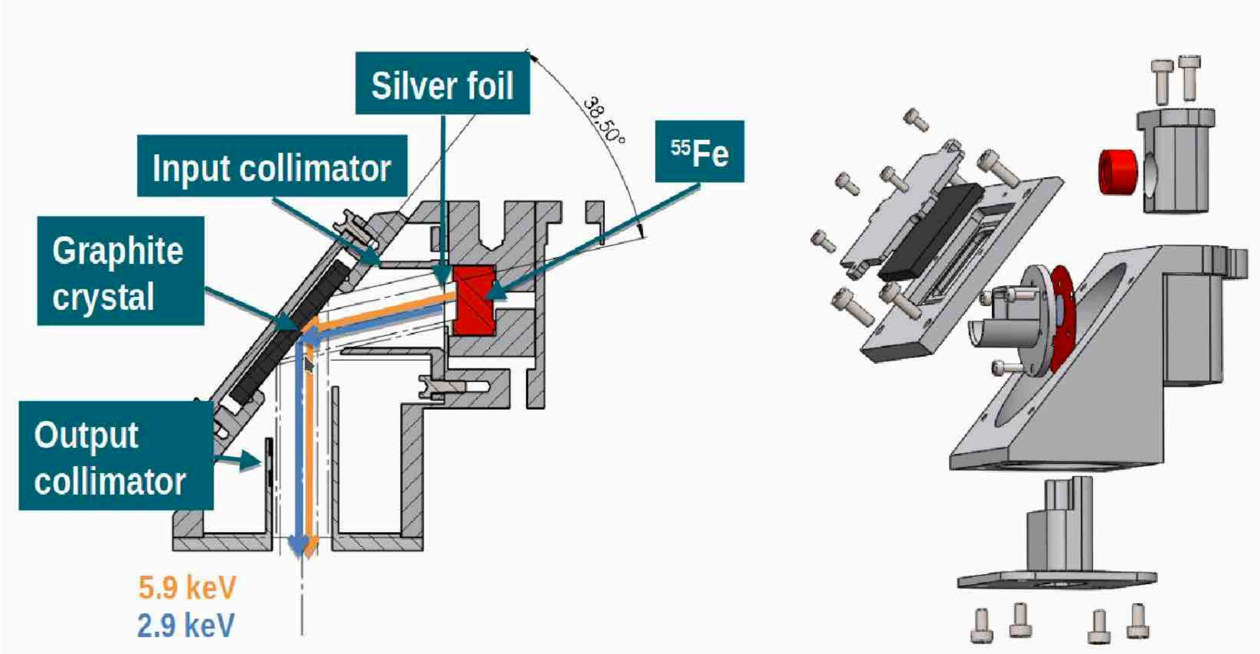
Producing Polarized Radiation

Bragg diffraction close to 45° on a graphite crystal

Two lines are scattered:

- ^{55}Fe radioactive source at 5.89 keV
- Photons from the ^{55}Fe source absorbed by silver foil and reemitted at 2.9 keV





CalA source

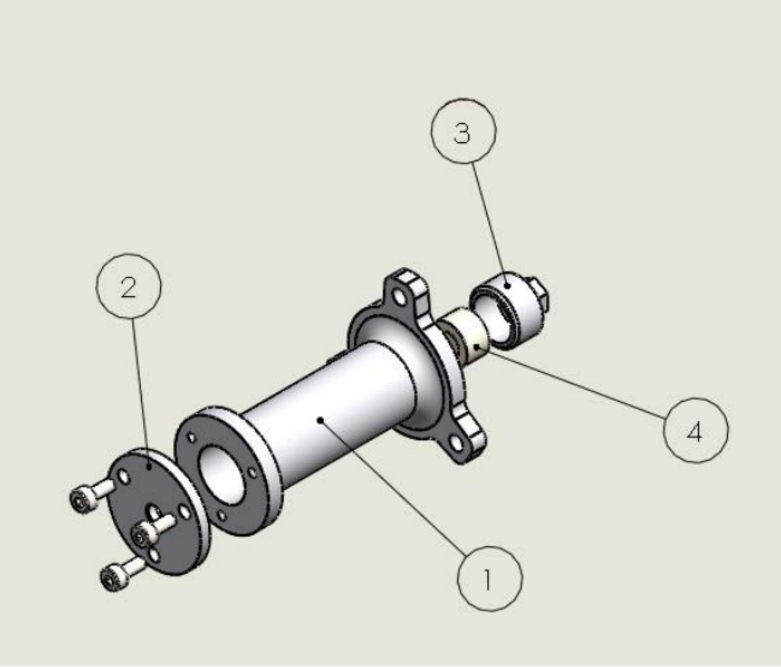
Ferrazzoli+ 2020

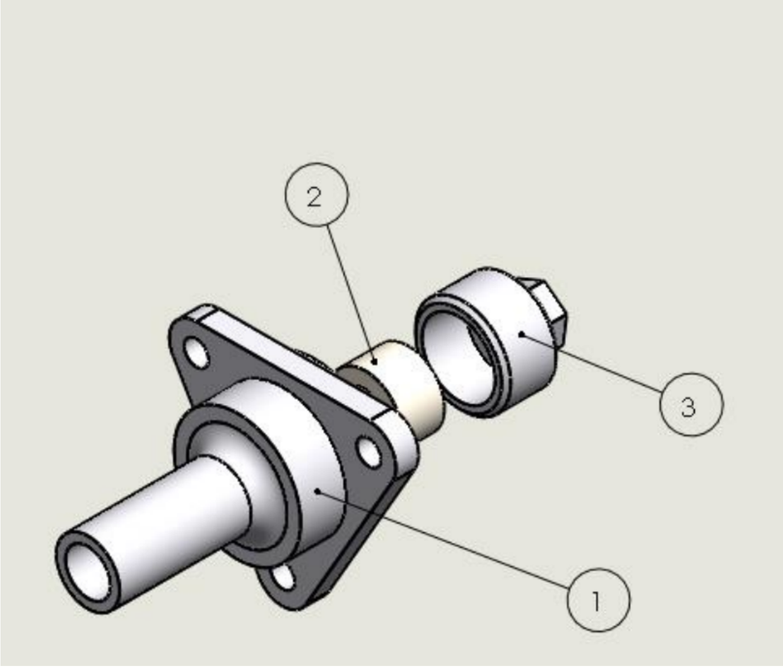
Producing Unpolarized Radiation

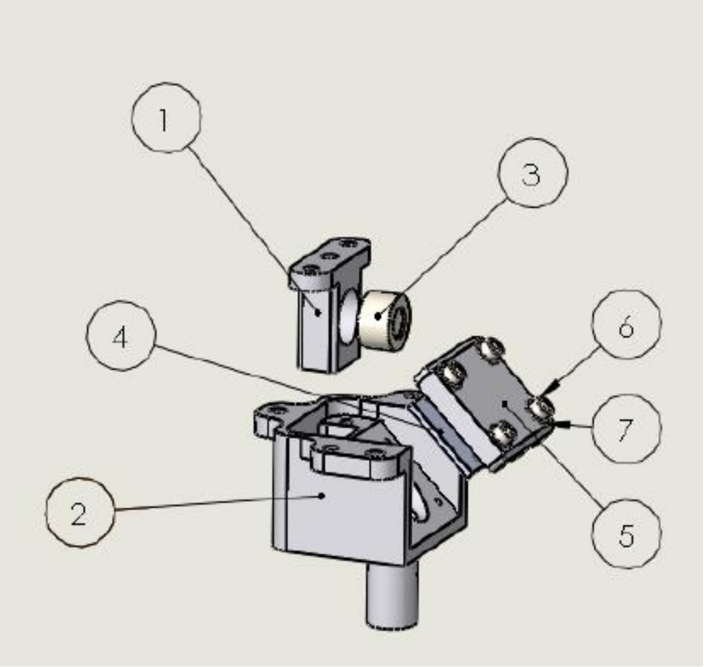
CalB source
5.89 keV in a spot

CalC source
5.89 keV over entire surface

CalD source
1.7 keV over entire surface







^{55}Fe radioactive source at 5.89 keV

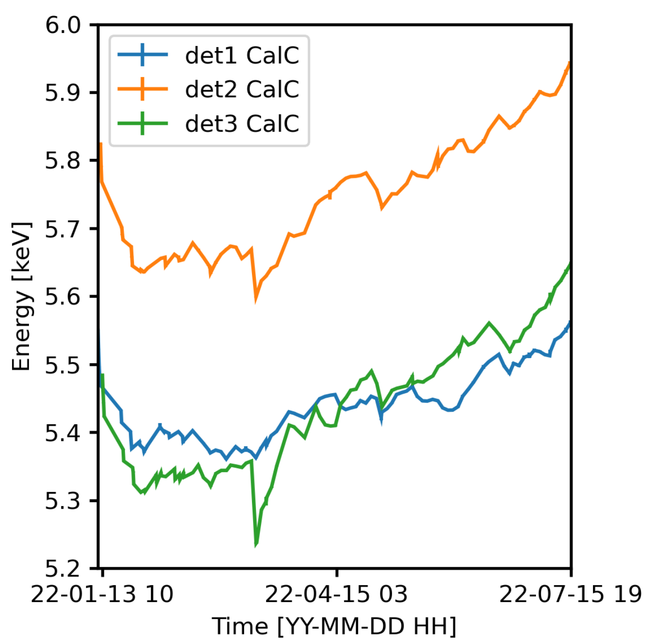
Radiation from ^{55}Fe source reemitted by a silicon crystal as a 1.7 keV fluorescence line

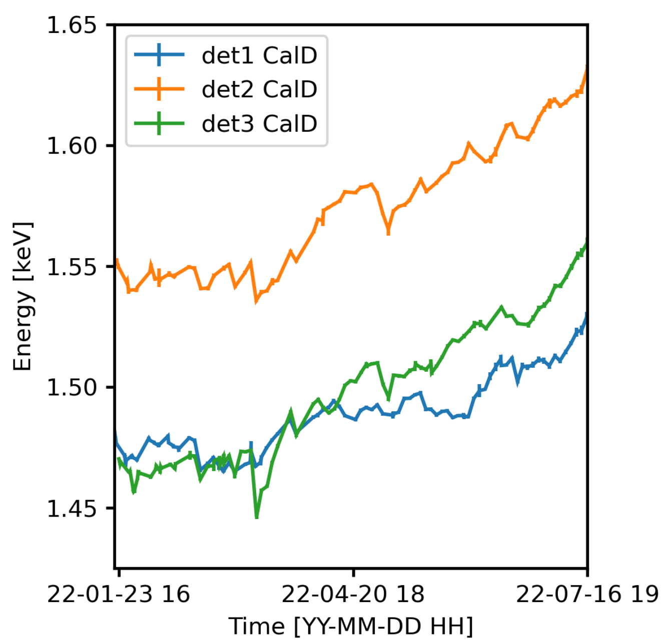
Ferrazzoli+ 2020

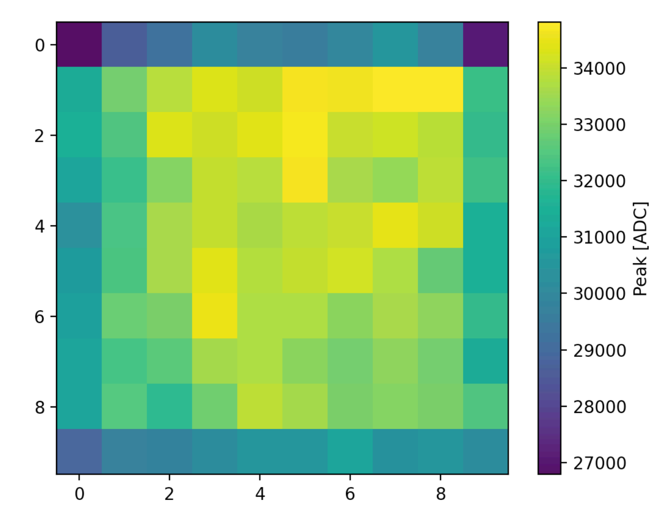
Energy Calibration

In-flight energy calibration

- As is common for gas detectors, energy varies due to temperature, charging effects, ...
- Calibration sources at two energies (CalC and CalD) can be used to perform a linear energy calibration
  - 10x10 calibration maps interpolated over time
  - Calibration sources observed alternatively once per day, during occultations





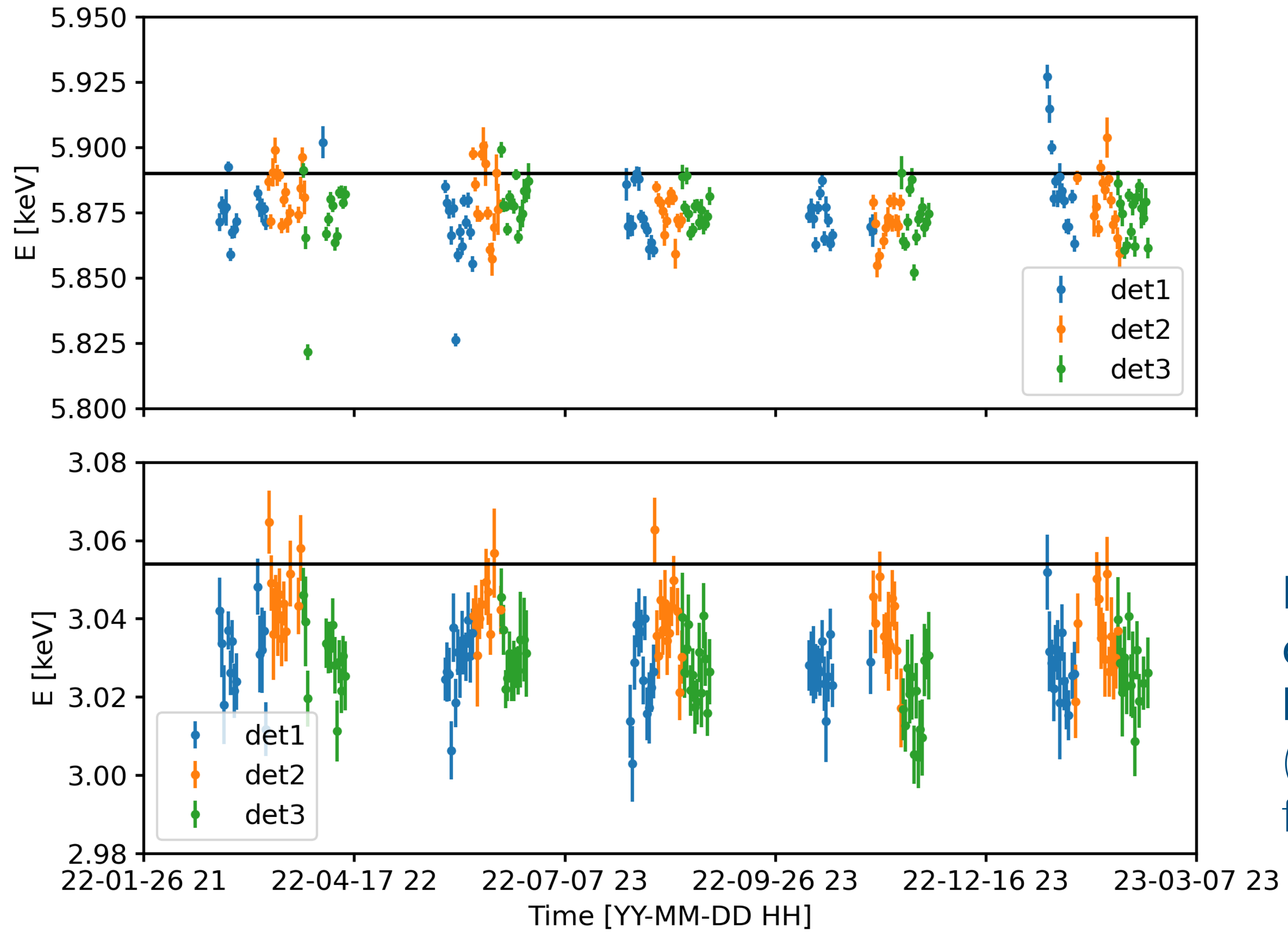


Example CalC calibration map

In-flight energy calibration

After calibration the energy reconstruction is correct to ~1%

- Good value compared to the energy resolution of ~20%
- Working on cross-normalization with other observatories using simultaneous observations

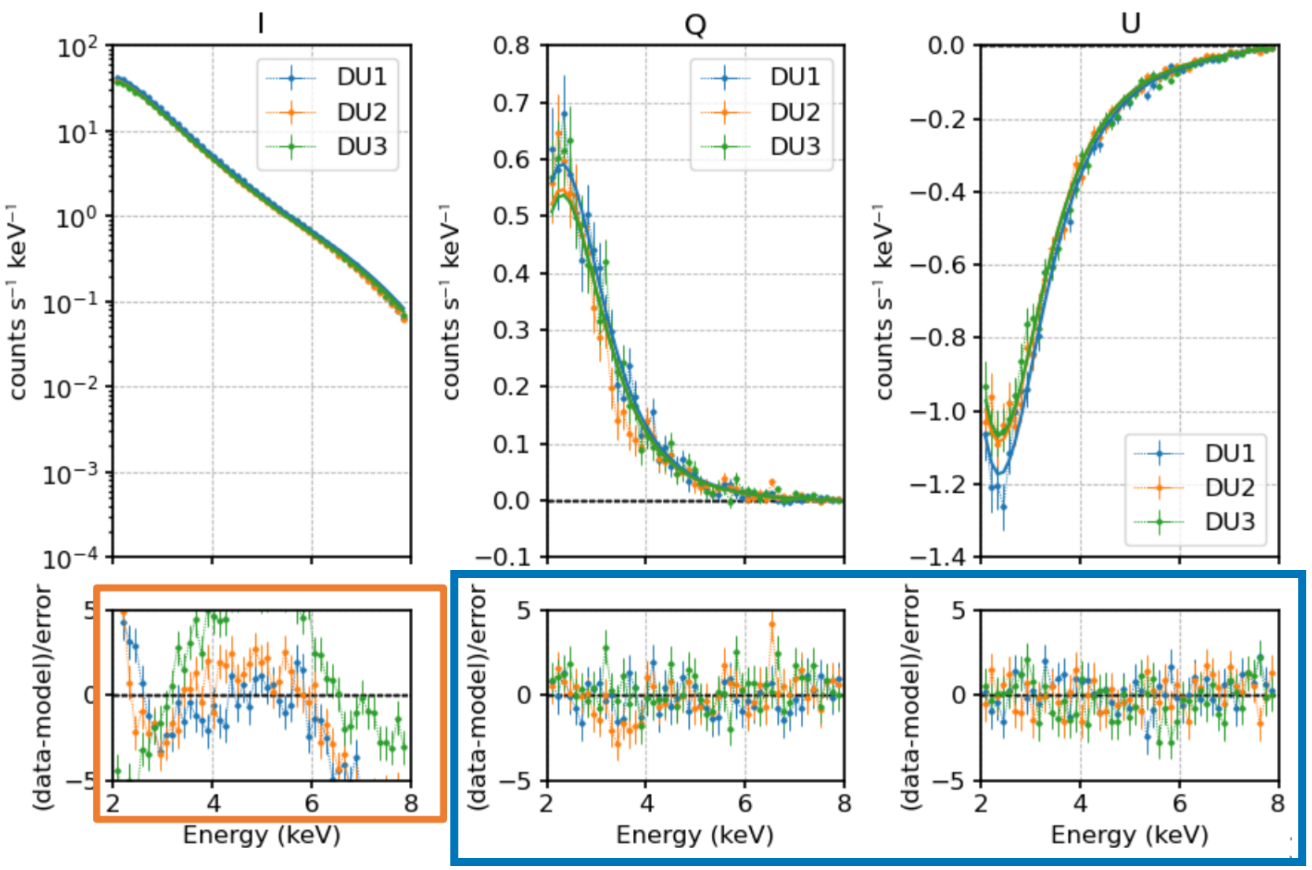


Efficacy of energy calibration over time, with CalA on-board calibration source (one of the sources not used for energy calibration)

Crab Nebula Observation

Not used as a standard candle but to check mutual calibration of the detectors

A simple model: Tbabs × powerlaw × pollin

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Model Model Component  Parameter  Unit     Value
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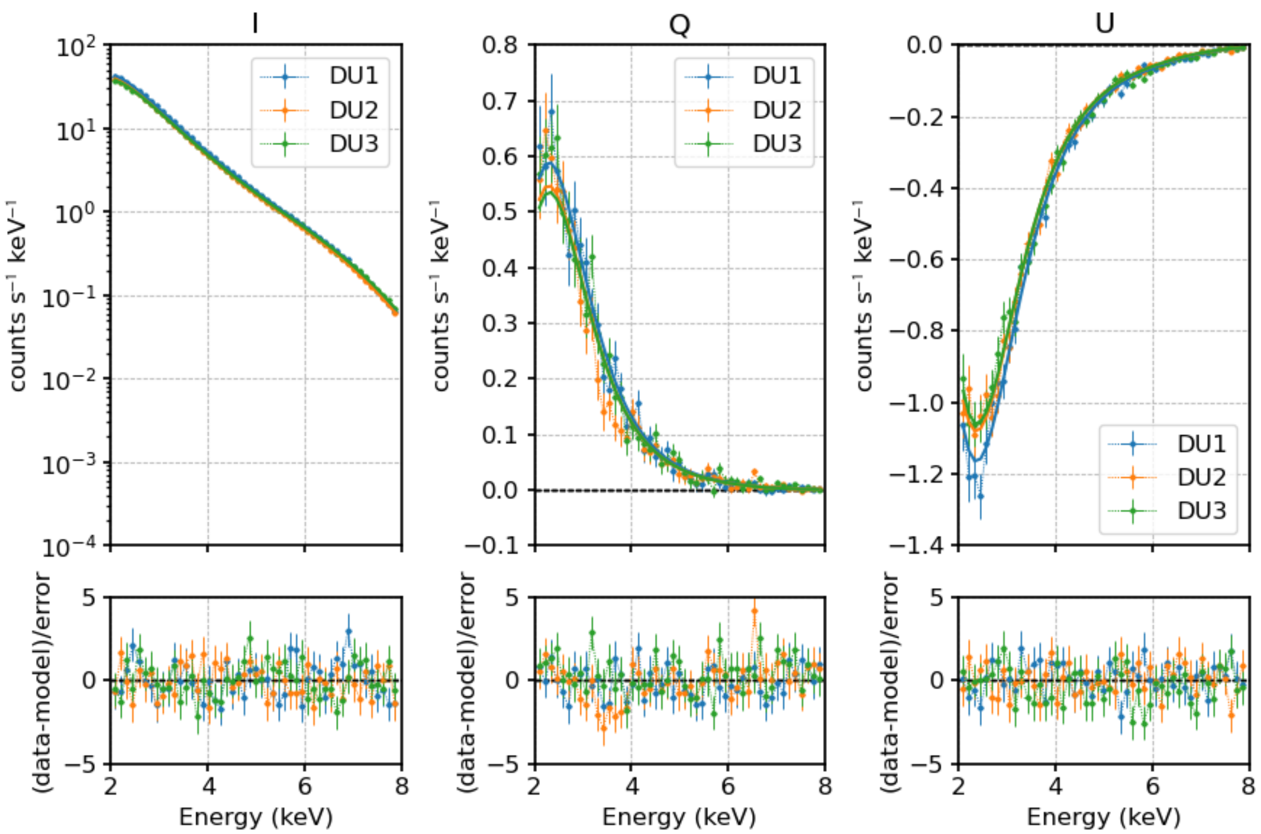
                      Data group: 1
   1    1   constant   factor              1.00000      frozen
   2    2   TBabs      nH         10^22    0.487281     +/-  9.63210E-03
   3    3   powerlaw   PhoIndex            2.25200      +/-  2.83502E-03
   4    3   powerlaw   norm                10.3669      +/-  4.47073E-02
   5    4   pollin     A1                  0.178552     +/-  3.11115E-03
   6    4   pollin     Aslope              6.34104E-03  +/-  1.16486E-03
   7    4   pollin     psi1       deg      -28.6451     +/-  0.454061
   8    4   pollin     psislope            -2.14514     +/-  0.164114
                      Data group: 2
   9    1   constant   factor              0.947187     +/-  5.59843E-04
  10    2   TBabs      nH         10^22    0.487281     = p2
  11    3   powerlaw   PhoIndex            2.25200      = p3
  12    3   powerlaw   norm                10.3669      = p4
  13    4   pollin     A1                  0.178552     = p5
  14    4   pollin     Aslope              6.34104E-03  = p6
  15    4   pollin     psi1       deg      -28.6451     = p7
  16    4   pollin     psislope            -2.14514     = p8
                      Data group: 3
  17    1   constant   factor              0.912789     +/-  5.39999E-04
  18    2   TBabs      nH         10^22    0.487281     = p2
  19    3   powerlaw   PhoIndex            2.25200      = p3
  20    3   powerlaw   norm                10.3669      = p4
  21    4   pollin     A1                  0.178552     = p5
  22    4   pollin     Aslope              6.34104E-03  = p6
  23    4   pollin     psi1       deg      -28.6451     = p7
  24    4   pollin     psislope            -2.14514     = p8
```

- Different residuals for different telescopes
- Polarimetric response good!

Crab Nebula Observation

Acceptable fit if using bknpower instead of powerlaw

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========================================================================
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Model Model Component  Parameter  Unit     Value
 par  comp
                           Data group: 1
   1    1   constant   factor              1.00000      frozen
   2    2   TBabs      nH         10^22    0.302047     +/-  1.82508E-02
   3    3   bknpower   PhoIndx1            2.20502      +/-  5.64022E-03
   4    3   bknpower   BreakE     keV      5.96234      +/-  4.65551E-02
   5    3   bknpower   PhoIndx2            3.17511      +/-  5.55432E-02
   6    3   bknpower   norm                9.62439      +/-  8.10594E-02
   7    4   pollin     A1                  0.174061     +/-  3.20304E-03
   8    4   pollin     Aslope              8.42536E-03  +/-  1.20647E-03
   9    4   pollin     psi1       deg      -28.5726     +/-  0.461672
  10    4   pollin     psislope            -2.17965     +/-  0.167514
                           Data group: 2
  11    1   constant   factor              0.950960     +/-  3.02378E-03
  12    2   TBabs      nH         10^22    0.302047     = p2
  13    3   bknpower   PhoIndx1            2.20502      = p3
  14    3   bknpower   BreakE     keV      5.96234      = p4
  15    3   bknpower   PhoIndx2            3.17511      = p5
  16    3   bknpower   norm                9.62439      = p6
  17    4   pollin     A1                  0.174061     = p7
  18    4   pollin     Aslope              8.42536E-03  = p8
  19    4   pollin     psi1       deg      -28.5726     = p9
  20    4   pollin     psislope            -2.17965     = p10
                           Data group: 3
  21    1   constant   factor              0.913724     +/-  2.64159E-03
  22    2   TBabs      nH         10^22    0.302047     = p2
  23    3   bknpower   PhoIndx1            2.20502      = p3
  24    3   bknpower   BreakE     keV      5.96234      = p4
  25    3   bknpower   PhoIndx2            3.17511      = p5
  26    3   bknpower   norm                9.62439      = p6
  27    4   pollin     A1                  0.174061     = p7
  28    4   pollin     Aslope              8.42536E-03  = p8
  29    4   pollin     psi1       deg      -28.5726     = p9
  30    4   pollin     psislope            -2.17965     = p10
________________________________________________________________________

Response parameters defined:
========================================================================
Source No.: 1
Rpar Spectrum Rmodel   Rpar_name  Unit    Value

   1     2    gain     slope              1.00382      +/-  7.66325E-04
   2     2    gain     offset             -1.16966E-02 +/-  4.18351E-03
   3     3    gain     slope              1.01830      +/-  7.91108E-04
   4     3    gain     offset             -3.71765E-02 +/-  3.97899E-03
________________________________________________________________________

 Test statistic : Chi-Squared                    460.14     using 441 bins.
  Null hypothesis probability of 1.23e-01 with 426 degrees of freedom
```

- Spectral break at 5-6 keV
- Cross-normalization among the three telescopes:
  - det1: 1.0, det2: 0.95, det3: 0.91
- Gain adjustment:
  - det1: 0, det2: 0.5%, det3: <2%

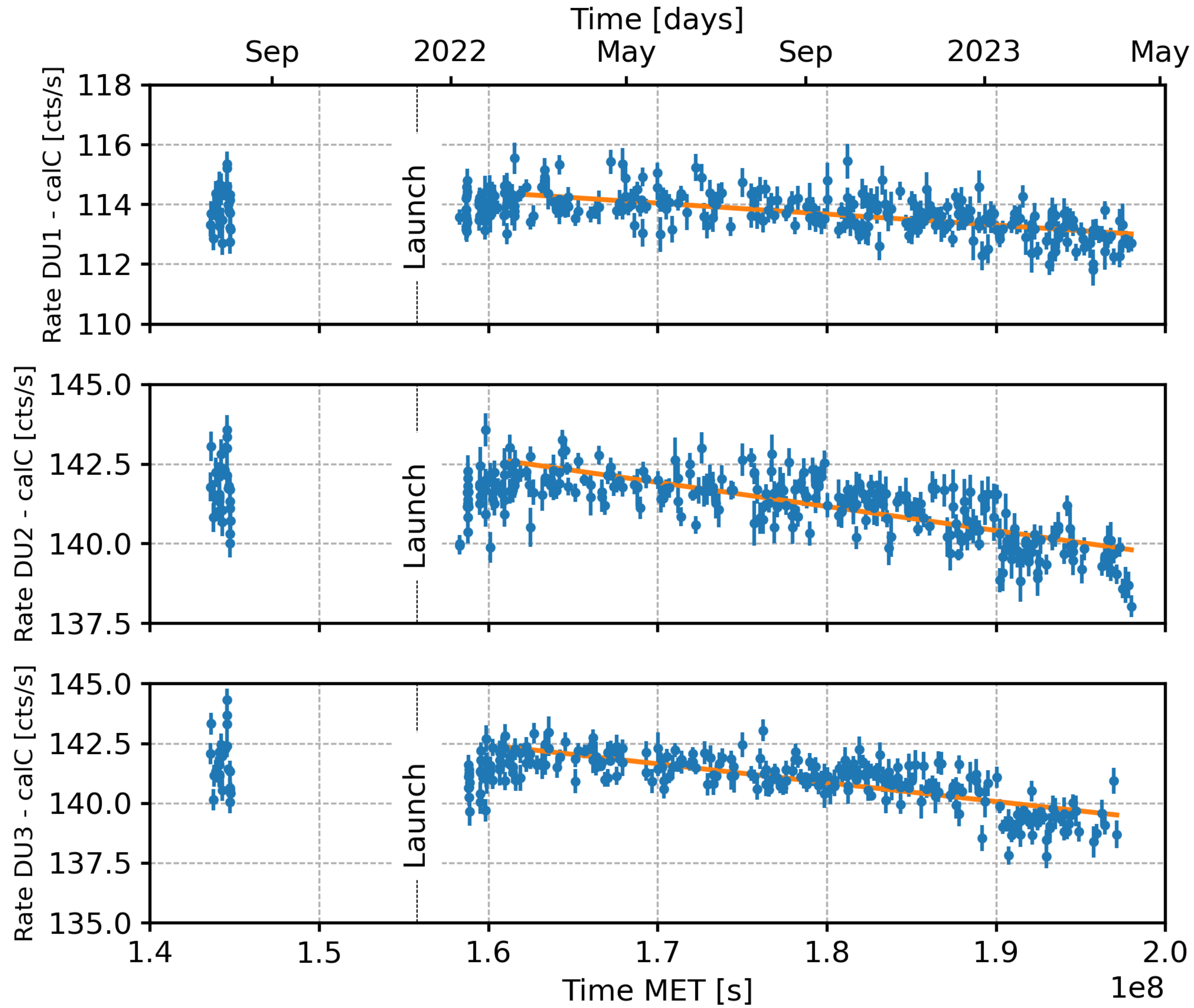
Polarimetric Response

Monitoring of the IXPE instrument

Rate

Corrected for ^{55}Fe calibration source decay

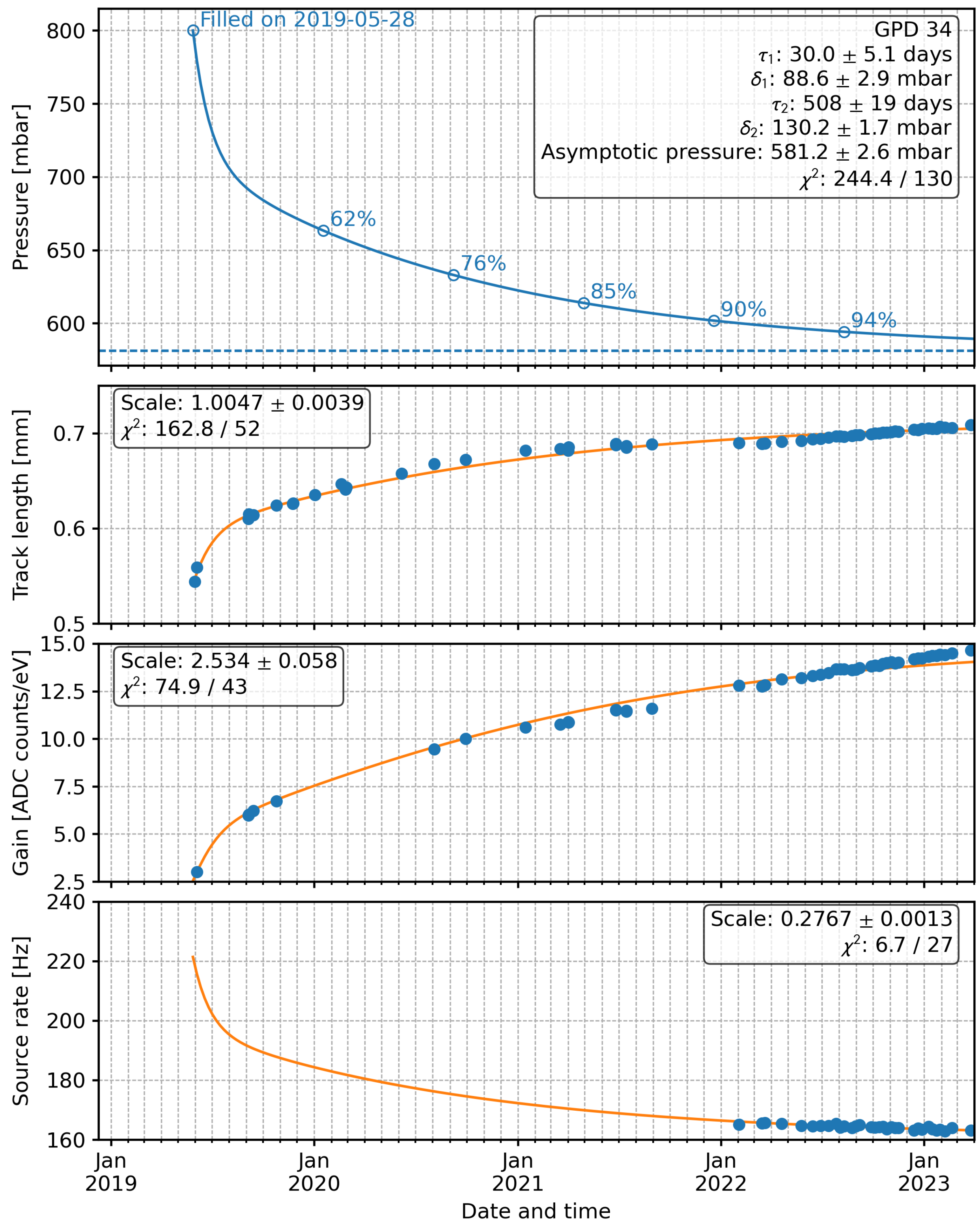
- The detectors on board IXPE present secular pressure variations, so some decrease is expected
    - Observed to be <1.5%
- Small or no effect on sensitivity
- Arf (and mrf) to be updated



Monitoring of the IXPE instrument

The combined variations in the detectors are fit by a model described in Luca Baldini+ 2021

- Double exponential fit of track length, gain and rate is good
- det2 shown on the right as example



Monitoring of the IXPE instrument

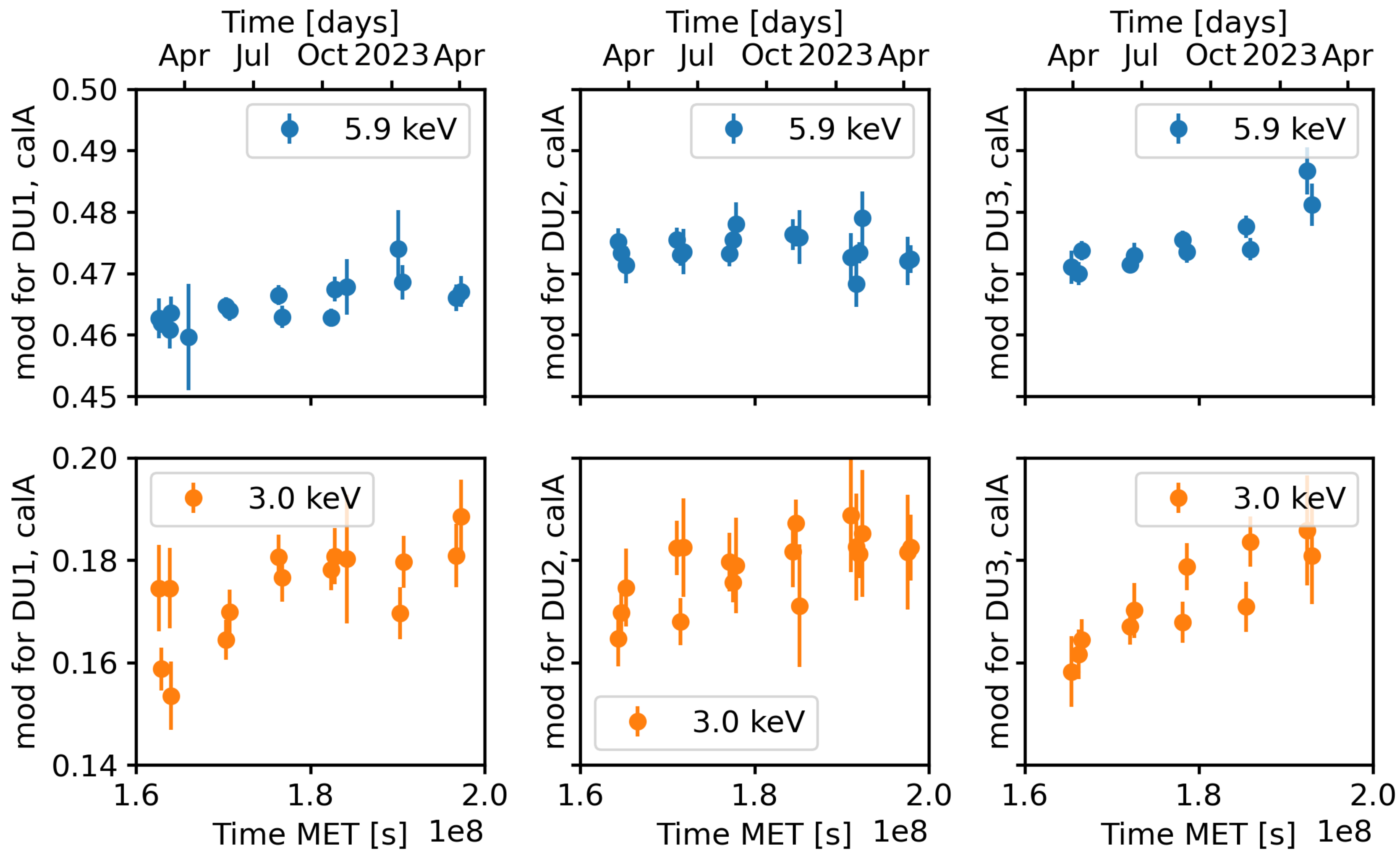
Modulation factor

The modulation factor encapsulates the response of the detector to polarization

$$\text{Polarization} = \frac{\text{Amplitude of modulation}}{\text{Modulation factor}}$$

Monitored using the polarized source (Cal A) at two energies

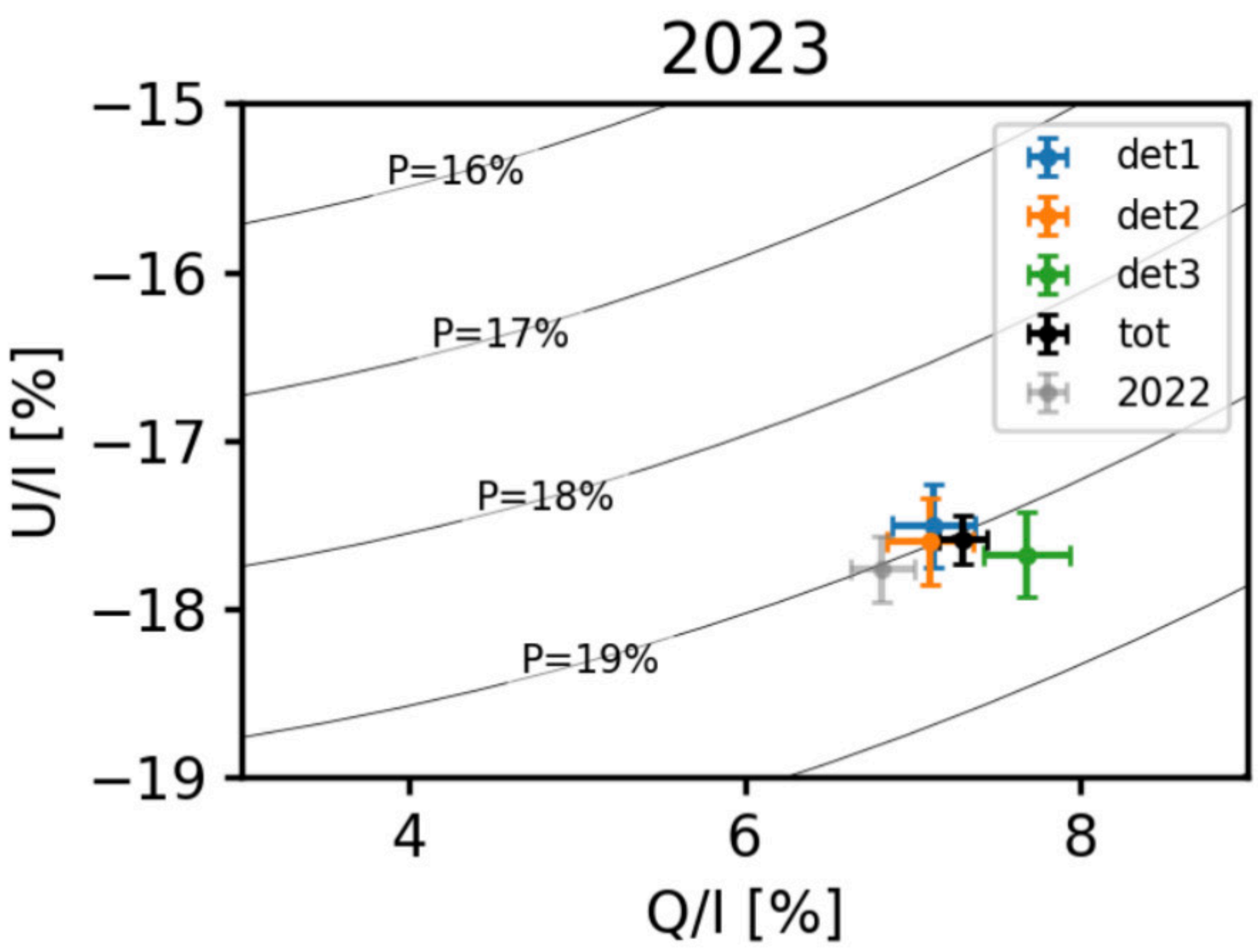
- Small increase, expected from secular pressure variations



Cross-calibration with the Crab Nebula

For the Crab Nebula the statistical uncertainties on measurement and calibration are comparable

- The three detectors are in agreement and so correctly calibrated



Conclusion

- IXPE was launched in December 2021, opening this X-ray polarimetry window
    - Many detections of X-ray polarization
- Some systematic effects in the spectra seen with high statistics
    - Detectors cross normalization
    - Energy calibration good to ~1%
    - No effect on polarization
- Polarimetric response monitored to ~1%
    - Pre-launch response matrices will be updated soon