IXPE calibration
from ground to space

High precision X-ray Measurements
Frascati, 2023-06-23

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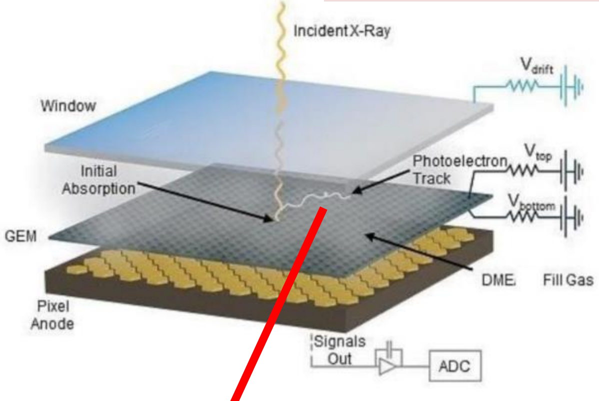
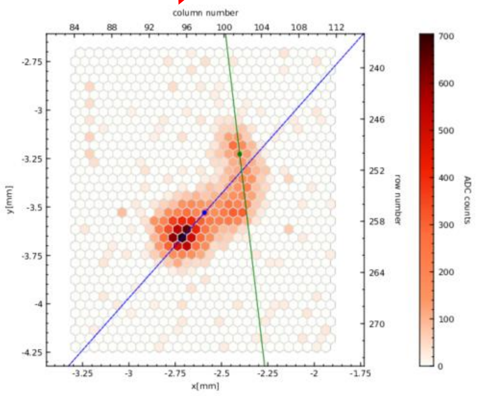
on behalf of the IXPE Science Team (https://ixpe.msfc.nasa.gov/partners_sci_team.html)

IXPE ingredients

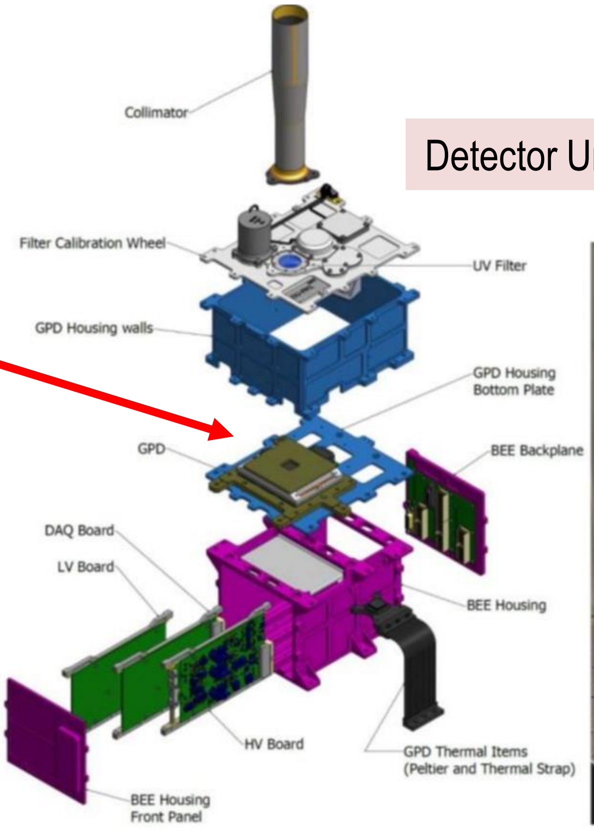
Gas Pixel Detector

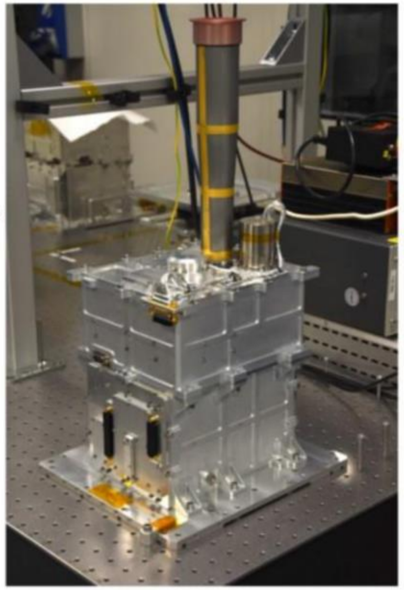




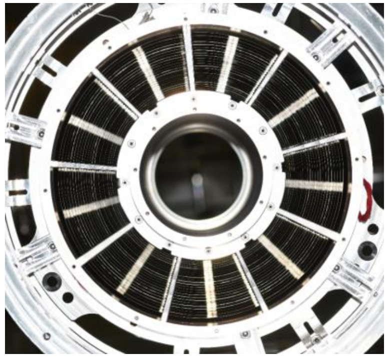
Photoelectron Track

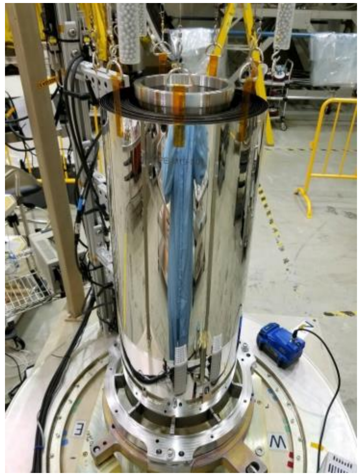
Detector Unit





Mirror Module Assemblies

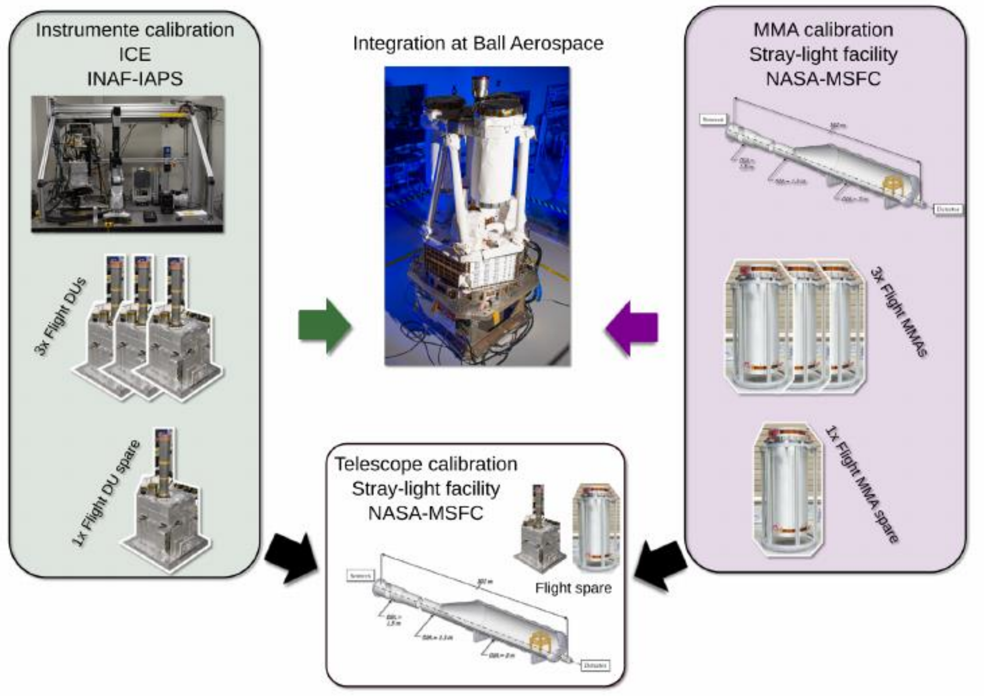




IXPE Imaging X-Ray Polarimetry Explorer

An overview on the IXPE on ground calibration

- **IXPE observatory comprises 3 identical Telescopes**
  - 3 Detector Units (DUs) (Italian contribution including the Detector Service Unit) at the focus of 3 Mirror Module Assemblies (MMAs) (contributed by USA)
  - All DUs and MMAs on board IXPE were calibrated separately in Italy at INAF-IAPS and at the Stray Light Test Facility (SLTF) of MSFC, respectively.
- **The spare DU with the spare MMA were, moreover, calibrated also in the Telescope configuration at the SLTF of the MSFC**

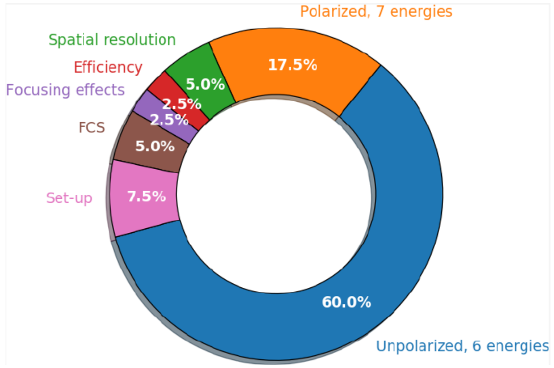


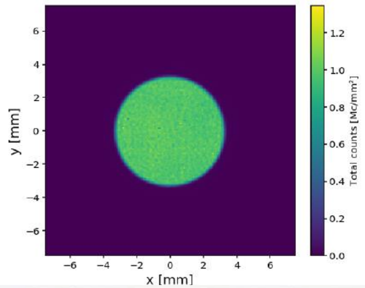
IXPE @ Ball Aerospace, Boulder (Colorado, USA)

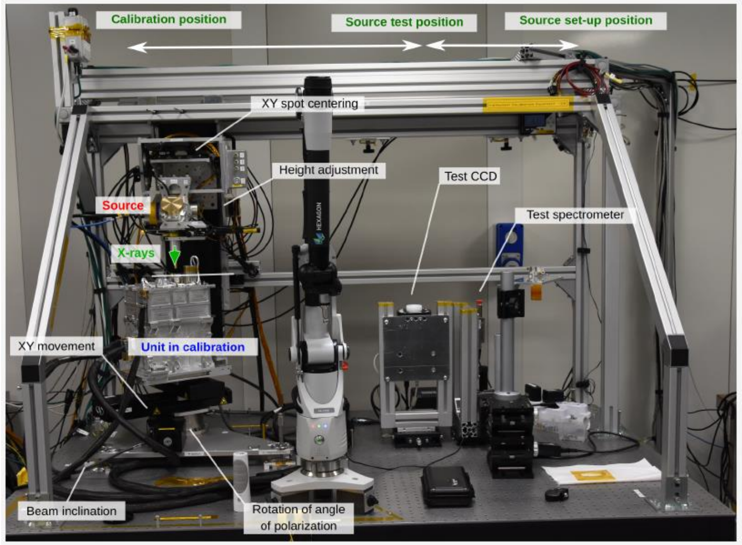
IXPE Imaging X-Ray Polarimetry Explorer

Instrument Calibration @ INAF-IAPS

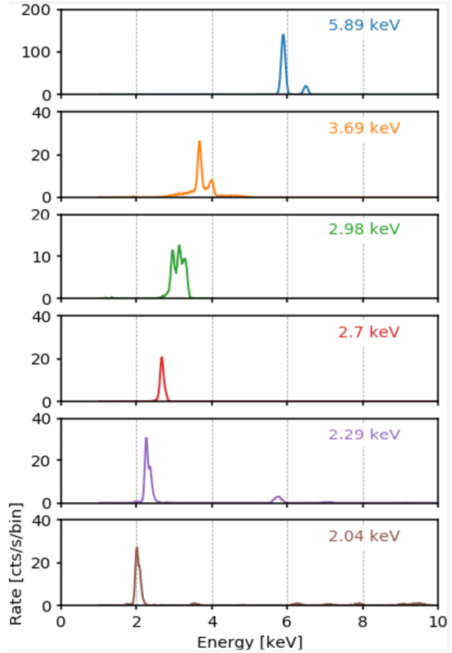
- **Nominally, 40 days of calibration for each one of the 4 DUs:**
  - First measurement 26th July 2019, last measurement 14th Sept. 2020
  - 7 days per week, 24 h a day
  - Set-up and alignments during working hours, then remote monitoring
  - 530 measurements, 4052.2 h of acquisitions and 2.250 bilion counts collected
- **Calibration mainly dedicated to the polarized and unpolarized respense**
  - Requirement on the knowledge of the response <0.1%
- **Deep and extended calibration**
  - Designed and produced custom sources (problem solving during the calibration)
  - Defined new procedures, never experimented before
- **Due to satellite dithering strategy, a dual approach was applied**
  - Deeper calibration at the center of the field of view
  - Illumination with a lower statistics on the full field of view
- **Built ICE versatile facility at INAF-IAPS in a ISO 7 Clean Room (Muleri et al. 2022)**
  - Operating in air with He flowing for reducing absorption at low energy
  - Manual and motorized stages
  - Positioning ~ 10 μm, inclination ~1 arcmin
  - Spot measurements from ~25 μm
  - Commercial SDD (energy spectra) and CDD (images) for source testing before calibration with DUs





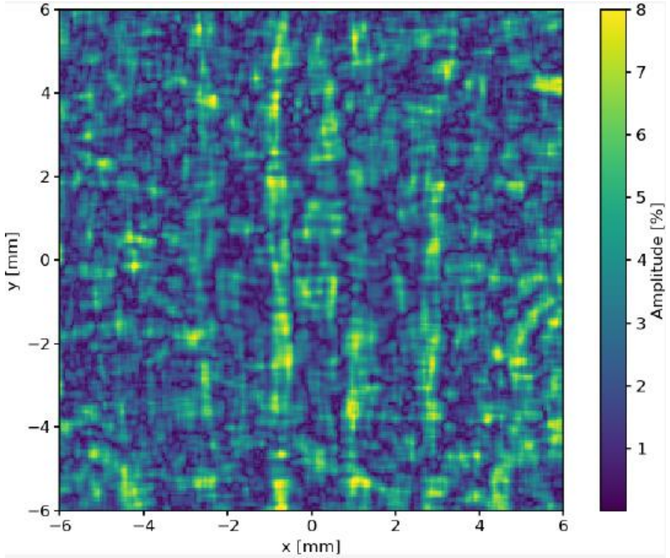


Instrument calibration with unpolarized radiation: spurious modulation

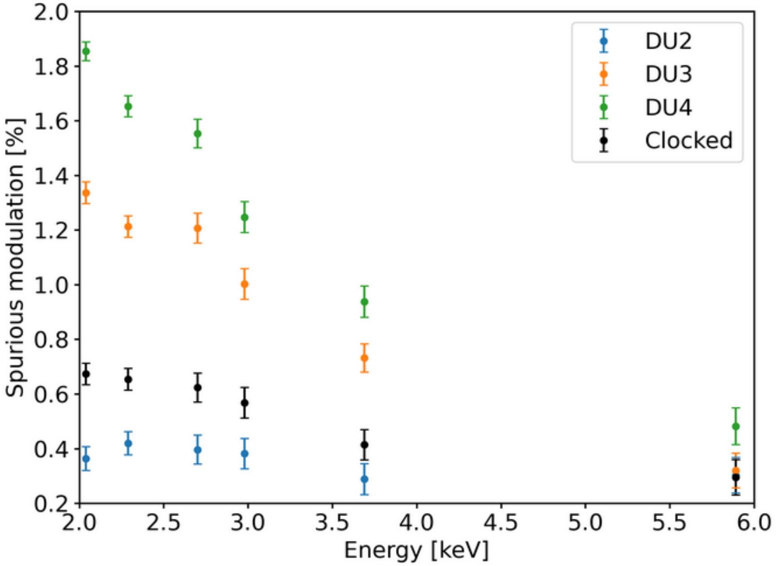


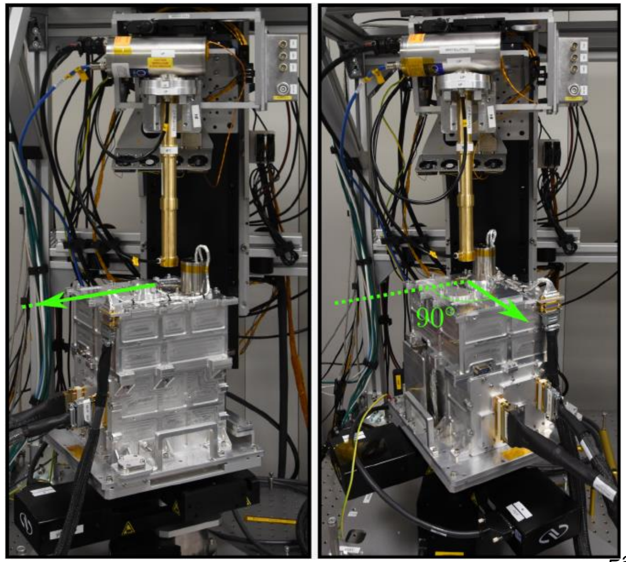
- **Unpolarized measurements at 6 energies:**
  - Commercial X-ray tubes or ^{55}Fe: direct or fluorescence
  - Use of filters to select the desired energy
- **Residual polarization (due to Bremsstrahlung continuum and X-ray tube geometry, diffraction on fluorescence target) removed by summing up two measurements rotated by 90° (residual polarization and Spurious Modulation sum differently for the two measurements)**
- **Spurious modulation removed by SOC pipeline thanks to calibration (Rankin et al. 2022)**

Map of SM @ 2.7 keV for DU-FM2



SM vs energy in a 3 mm diameter spot

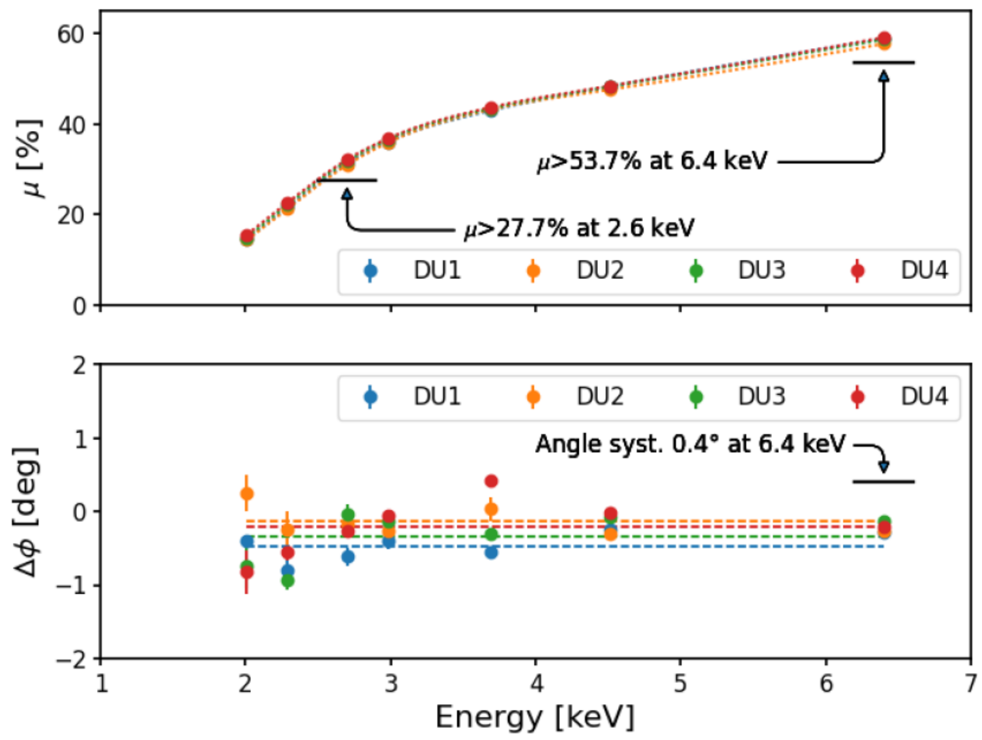




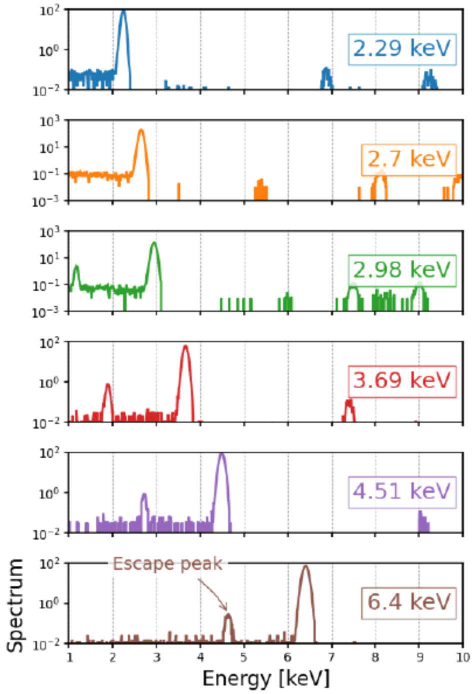
Instrument calibration with polarized radiation: modulation factor

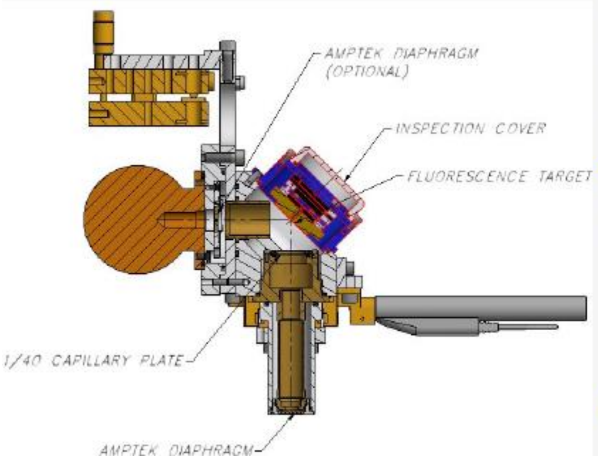
- **Commercial X-ray tubes coupled to custom designed monochromator-polarizers exploiting Bragg diffraction at nearly 45°**
  - Different crystals to diffract photons at different energies
  - Up to five polarization angles for each energy

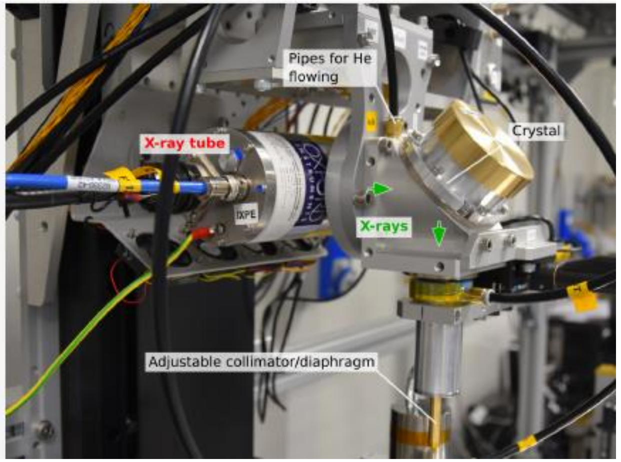
Modulation Factor vs Energy



Di Marco et al., 2022, AJ



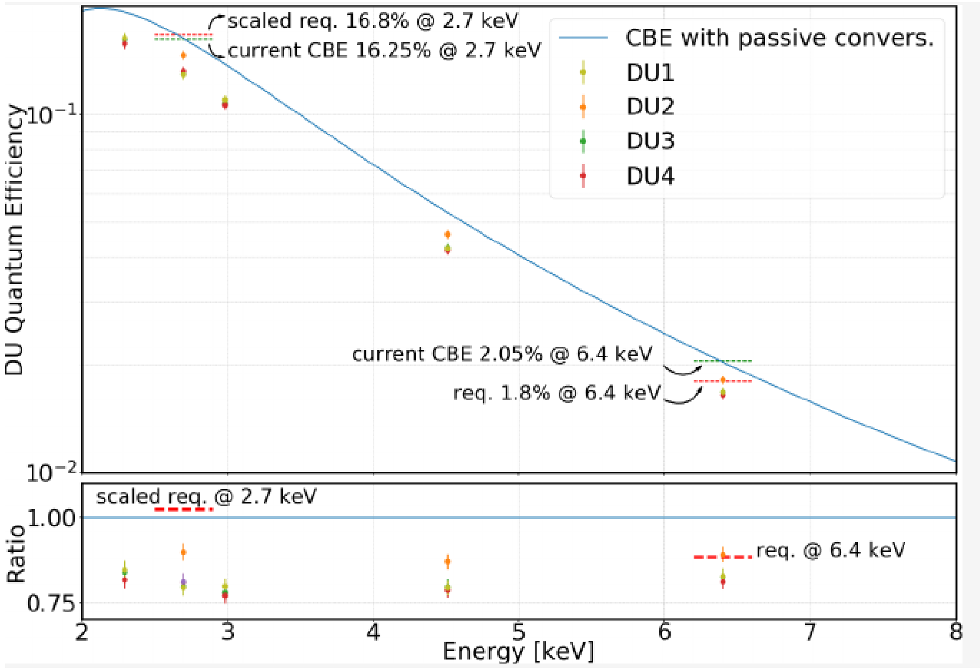




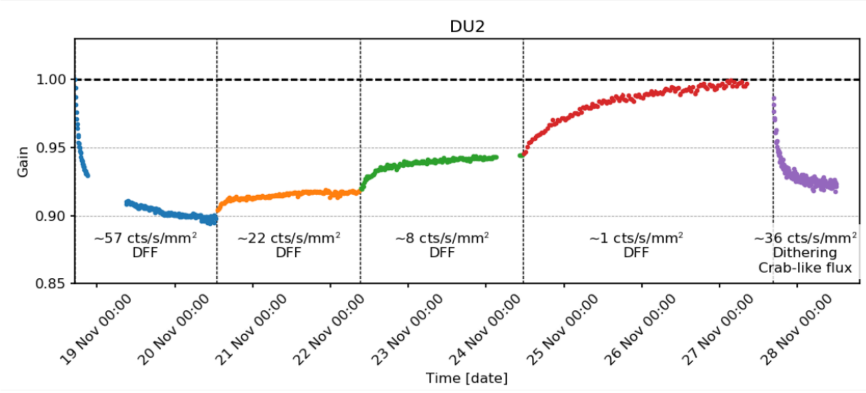
Instrument Calibration: other measurements and results

Other measurements:

- **Absolute Quantum Efficiency: count rate comparison with a reference SDD detector**
  - A QE lower than expected due to gas cell absorption (the effect is nearly saturated). Limited impact on the sensitivity, because modulation factor slightly increases due to pressure reduction (more elongated tracks).
- **Relative QE measured with a 55Fe reference source**



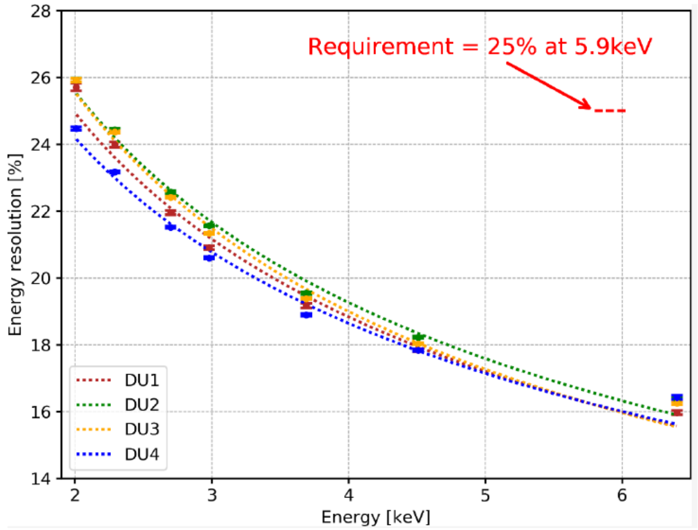
- **Pixel-to-pixel equalization**
  - By-product of polarimetric response calibration
  - Gain of each of the 300×352 pixels equalized with respect to others
- **Gain calibration**
  - Gain changes with illumination (charging effect)
  - Attempt to remove it by modelling it on ground, needed in flight calibration sources



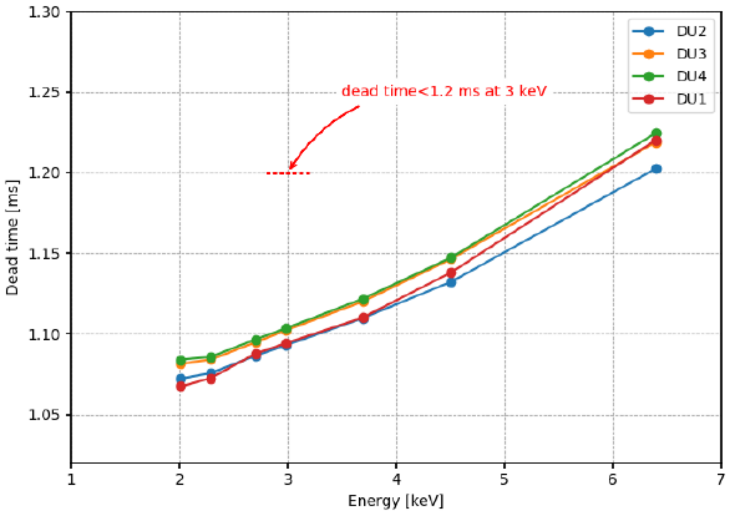
IXPE Imaging X-Ray Polarimetry Explorer

Instrument Calibration: other measurements and results

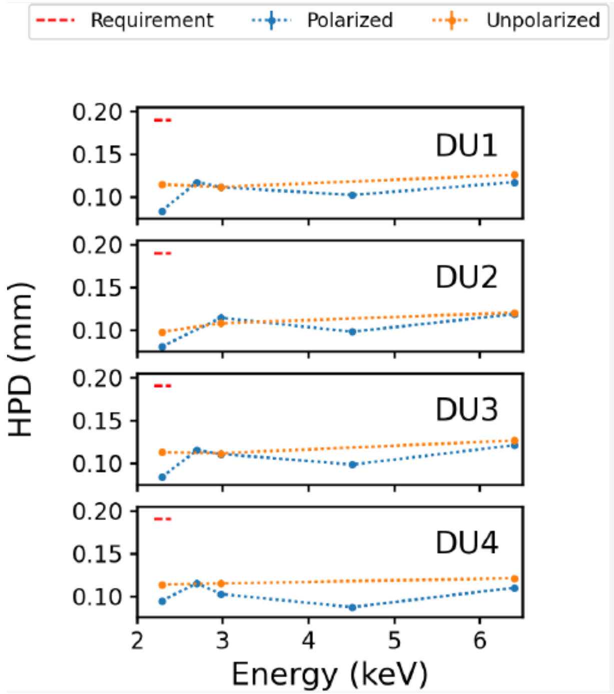
Energy resolution



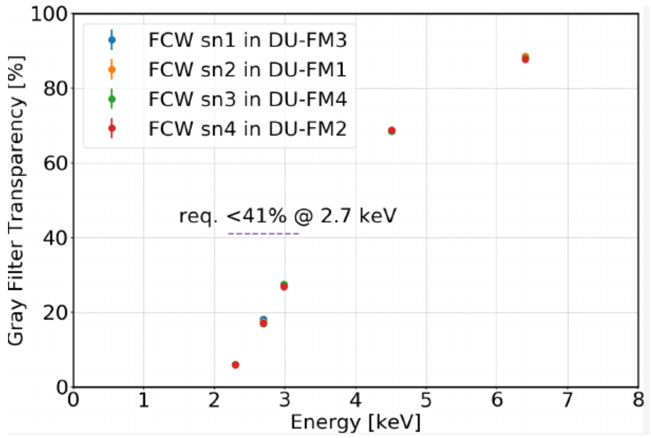
Dead time



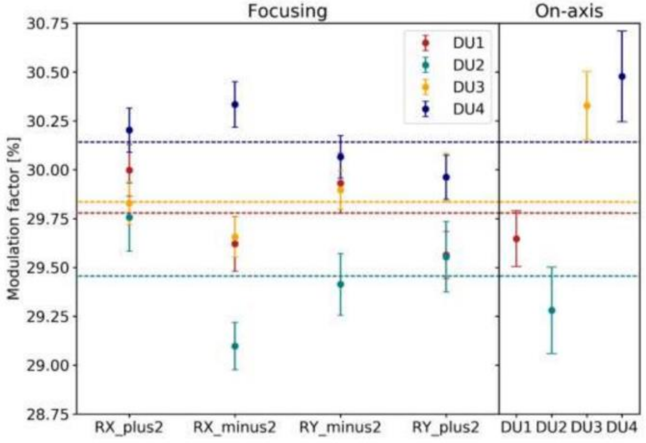
Spatial resolution



Gray filter transparency



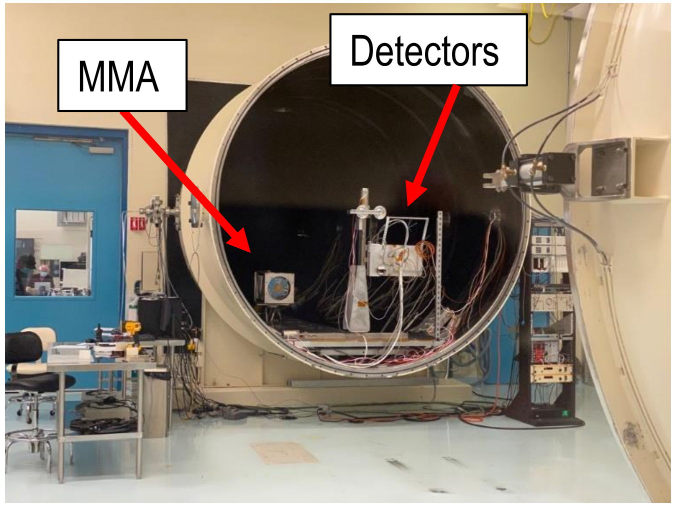
Response to inclined beam (to anticipate the effect of the optics)

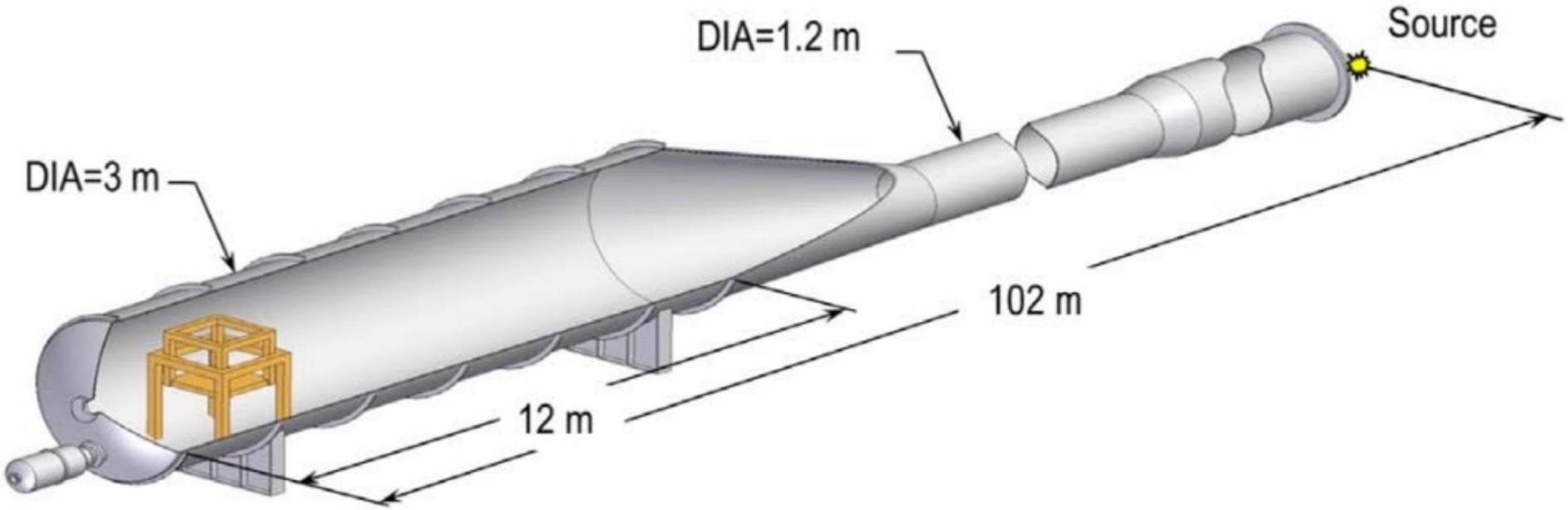


- Modulation factor at 2.7 keV for a beam which is inclined by 2 degrees. The measurement is repeated at four azimuthal angles, to simulate the focusing from an IXPE mirror.
- No deviations from on-axis modulation factor

MMAs and Telescope Calibration set-up @ NASA/MSFC

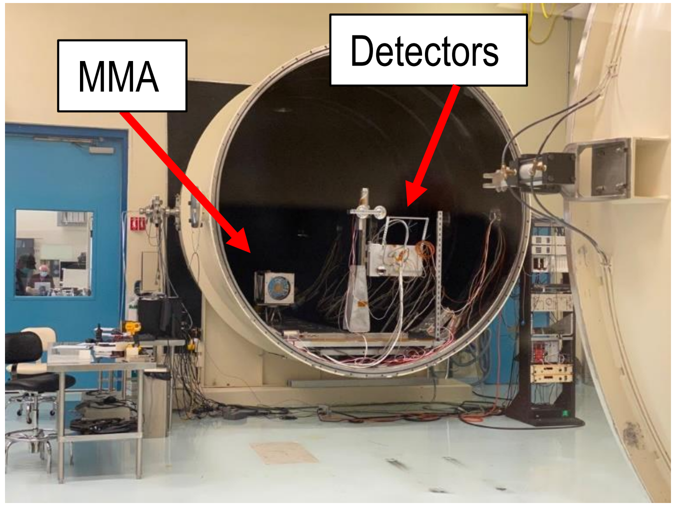
- MMA Optics calibration of MMA 1-3 [16 Jul – 28 Aug 2020], MMA4 [30 Nov - 27 Jan, 2021] in parallel with E2E Telescope calibration
- E2E Telescope calibration during Covid-19 pandemic : training of MSFC colleagues to operate the DU, remote data analysis and feedback, also real time during some measurements (… 8 h time zone difference !). No delays due to pandemic during calibration !
- X-ray calibration of the optics took place at MSFC's 100 m X-ray test facility

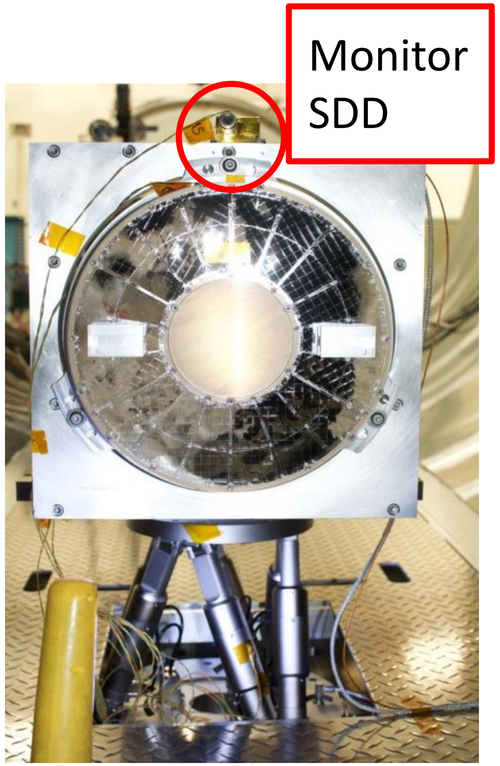


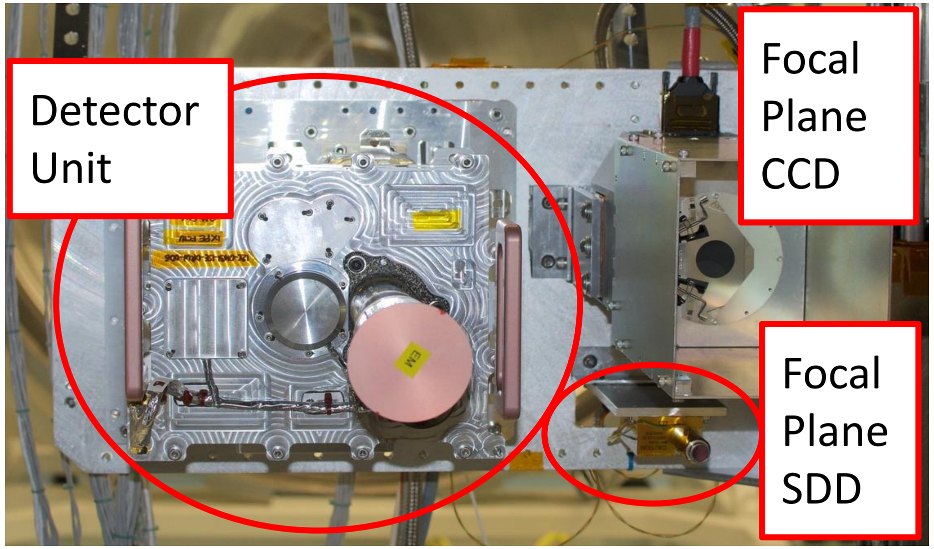


MMAs and Telescope Calibration set-up @ NASA/MSFC

- **The SLTF set-up comprises :**
  - A monitor SDD beside the MMA (reference detector for Effective Area meas.)
  - Focal plane detectors:
    - an SDD (for EA measurement)
    - a CCD (for angular resolution meas. - PSF)
    - the spare DU (during E2E Telescope calibration)





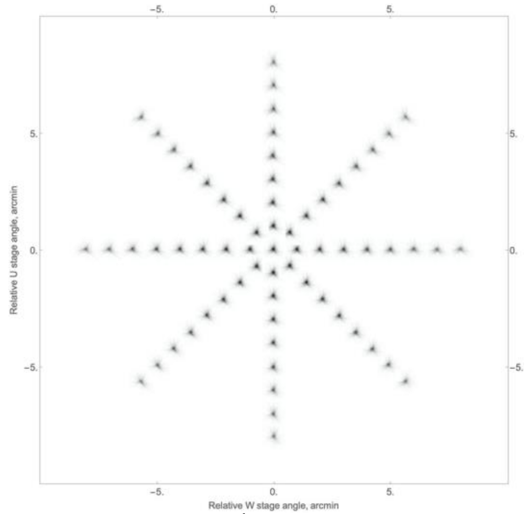


MMAs Calibration @ NASA/MSFC

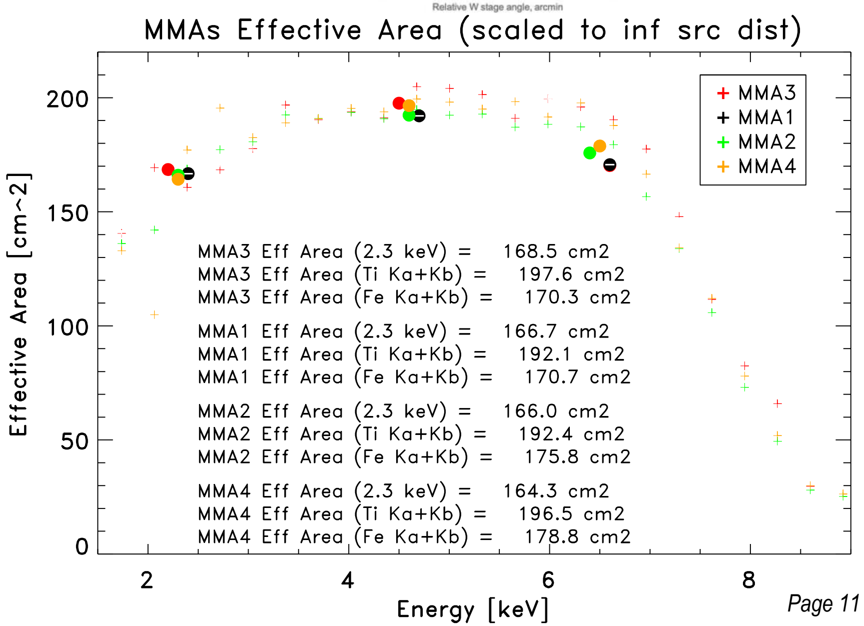
- **Angular resolution on and off axis with a CCD**

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

Composite image of MMA1 PSF at several off-axis angles



- **MMA Effective Area measured with two Silicon Drift Detectors, one beside the MMA (Beam Monitor SDD as reference) and one at the focus (Focal Plane SDD)**
  - Found and corrected a small difference of QE of the two SDDs: both illuminated simultaneously at the same distance
  - FP slightly lower count rate than BM: Correction is ~1.03 * EA (at Mo) , 1.01 * EA (at Ti)
  - Effective area measured at finite source distance (98m) and corrected to infinite source distance using ray trace

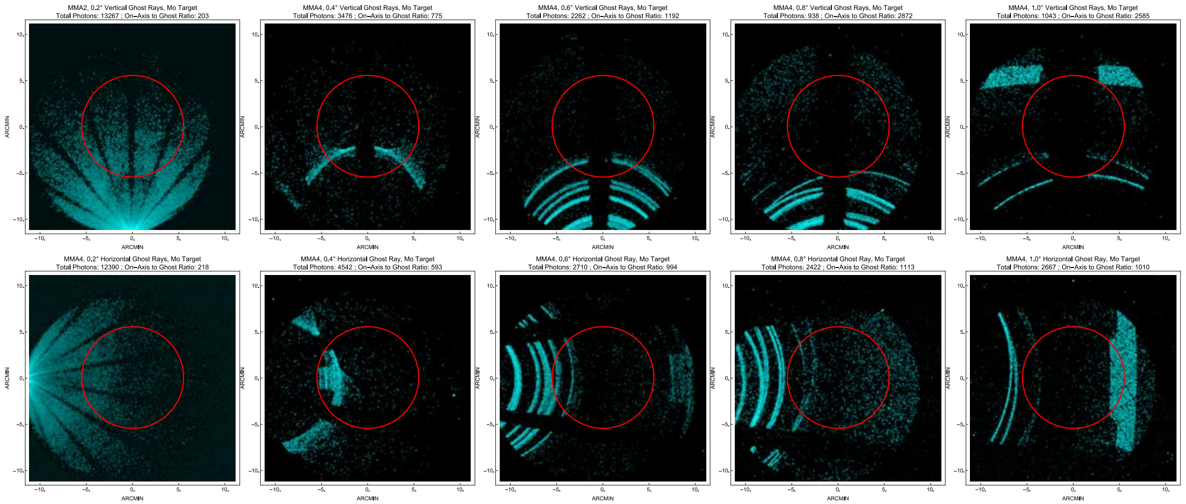


MMAs Calibration @ NASA/MSFC

- **MMA focal lengths measured with Leica laser tracker system**
  - Finite distance focal length measured between MMA and CCD camera, then corrected to infinite source distance focal lengths using the thin lens equation and an X-ray source to optic distance of 98 meters

Inf src dist Focal Length [mm]	
MMA1	3997.2
MMA2	3997.8
MMA3	3997.5

- **Ghost rays measured attenuation factor**
  - Ghost rays are unwanted rays that reach the detector from off-axis angles through unfocused paths (single bounce, or straight through the optic instead of nominal double-bounce path)
  - Ghost-ray intensity measured and compared with on-axis intensity to give attenuation factor.



MMA1

Angle	0.2°	0.4°	0.6°	0.8°	1.0°
Azimuth = 0°	280	735	872	1381	1780
Azimuth = 90°	241	595	858	897	650

MMA2

Angle	0.2°	0.4°	0.6°	0.8°	1.0°
Azimuth = 0°	229	712	890	1160	1517
Azimuth = 90°	237	508	818	834	529

MMA3

Angle	0.2°	0.4°	0.6°	0.8°	1.0°
Azimuth = 0°	262	776	770	1533	1543
Azimuth = 90°	221	510	981	796	681

MMA4

Angle	0.2°	0.4°	0.6°	0.8°	1.0°
0°	203	775	1192	2872	2585
90°	218	593	994	1113	1010

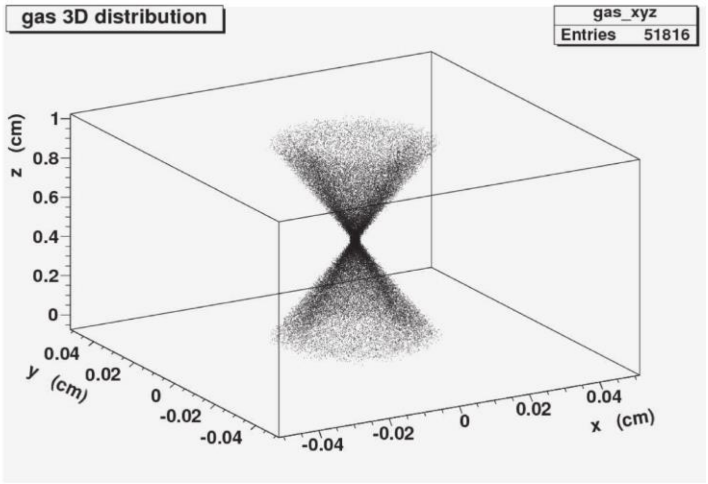
E2E Telescope Calibration @ NASA/MSFC with our collaboration

- **Telescope Angular Resolution (Half Power Diameter)**
  - GPD angular resolution
    - intrinsic spatial resolution (pixels, blurring due to diffusion, algorithm)
    - inclined penetration
    - MMA PSF (only MMA)

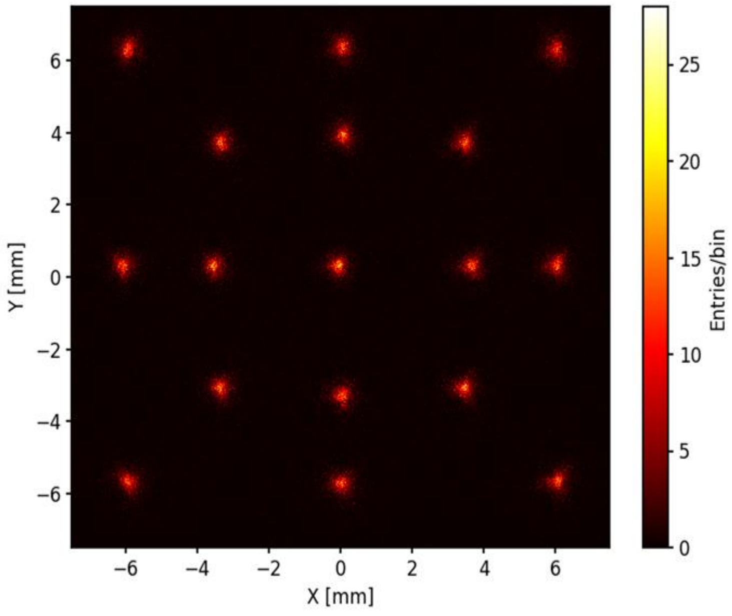
  - Three energies: Mo, Ti, Fe; on and off-axis

Source on axis	Mo+filter – 2.28 keV	Ti +filter– 4.63 keV	F+filter - 6.62 keV
Only MMA4 (arcsec)	20.0	20.8	20.1
MMA4 + DU-FM1 (arcsec) misalignment effect subtracted in quadrature	22.0	23.8	24.0

Simulation of Inclined penetration due to focusing



Off axis



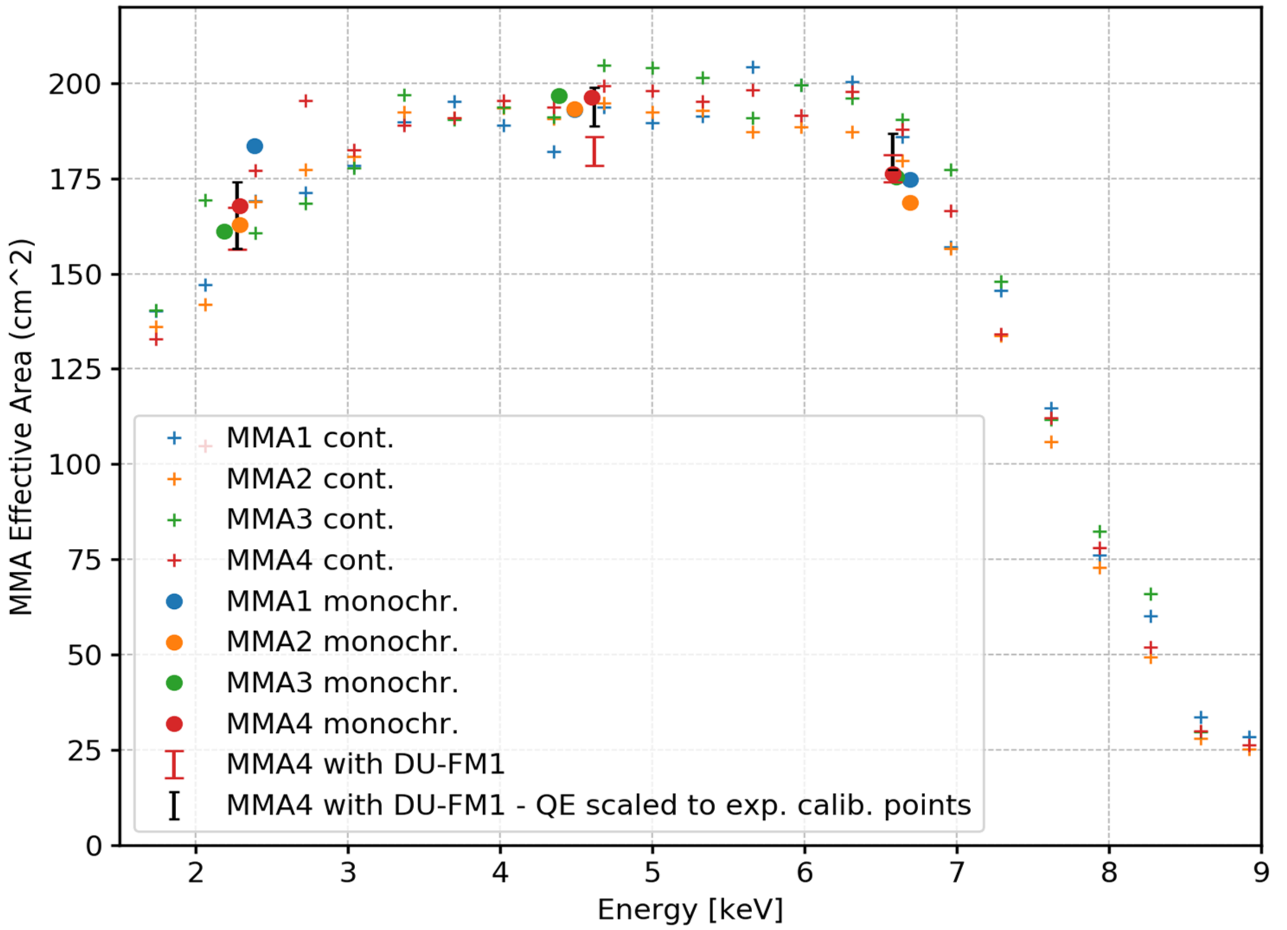
Composite image of on- and off-axis telescope PSF measurements across detector plane

E2E Telescope Calibration @ NASA/MSFC with our collaboration

- **Telescope Effective Area**
  - Simultaneous with Angular Resolution
  - Telescope MMA measured directly with DU+MMA
  - Possible to check the MMA EA measured independently by MSFC with CCD + MMA

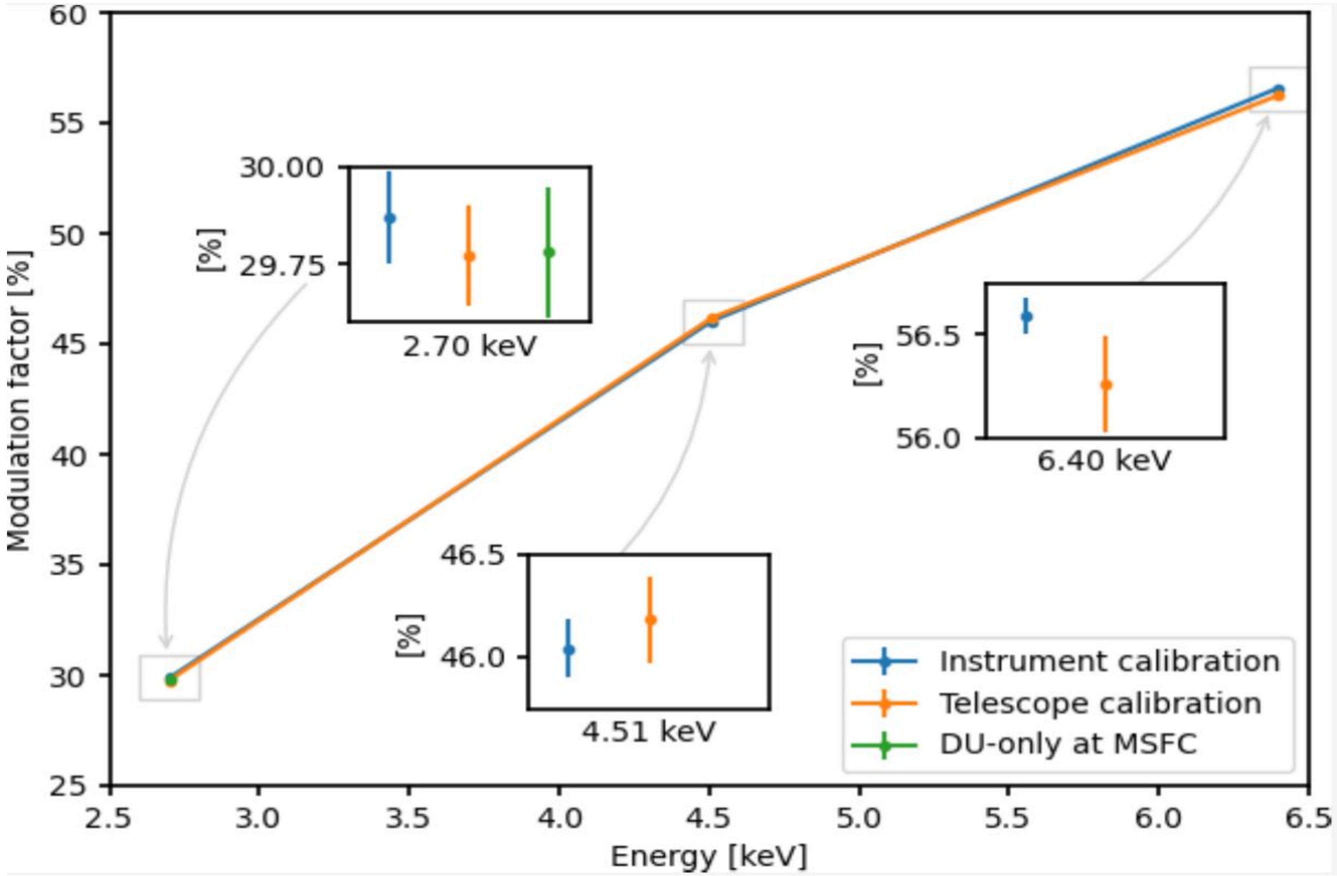
MMA EA = Telescope EA / DU QE(t)

  - By anchoring the model of pressure drop QE(t) to experimental points measured during DU calibration at INAF-IAPS, the MMA Effective Area in Telescope configuration matches direct measurements of MMA with SLTF detectors (small deviation recovered)



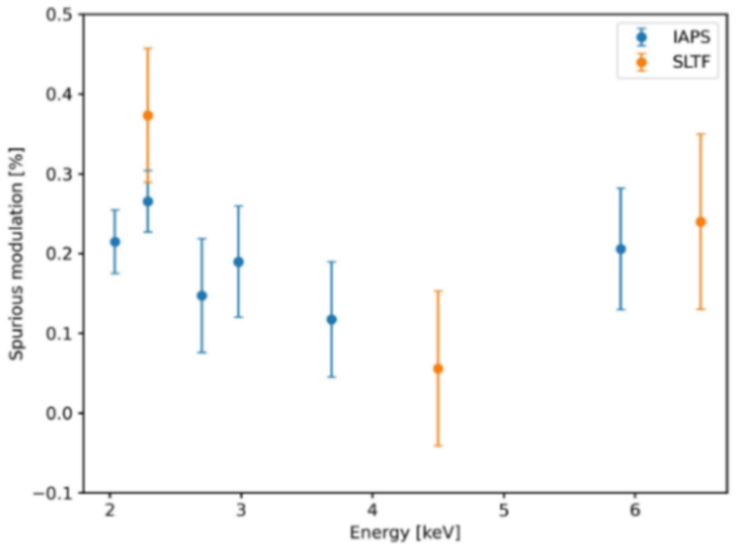
E2E Telescope Calibration @ NASA/MSFC with our collaboration

- **Telescope Modulation Factor**
  - Response to 100% polarized X-rays
  - Three energies (2.7, 4.5, 6.4 keV) with polarized source
  - Modulation factors with and w/o optics agree
  - Presence of MMA optics does not affect polarization performance of detector

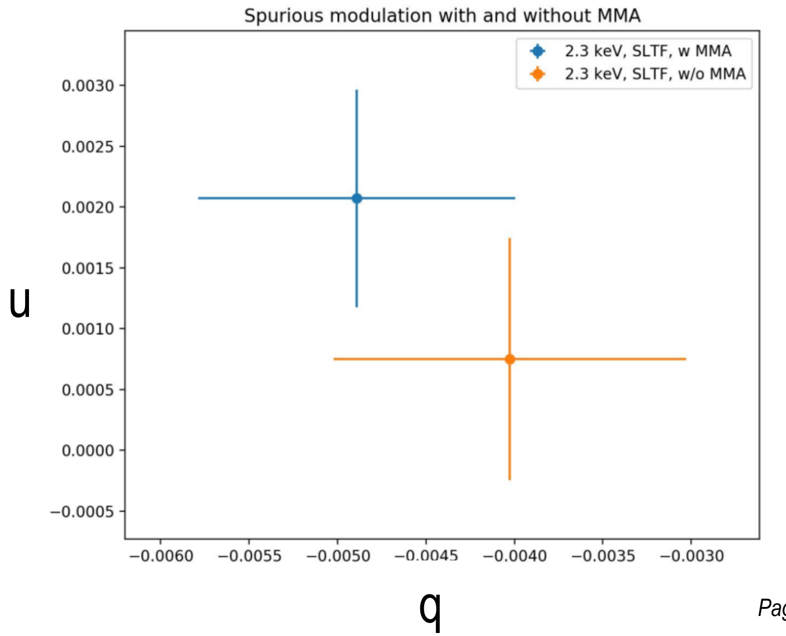


E2E Telescope Calibration @ NASA/MSFC with our collaboration

- **Spurious Modulation @SLTF vs @INAF-IAPS**
  - Two measurements rotated by 90 deg at 3 energies
  - Measurements perfomed at MSFC match the ones performed at INAF-IAPS

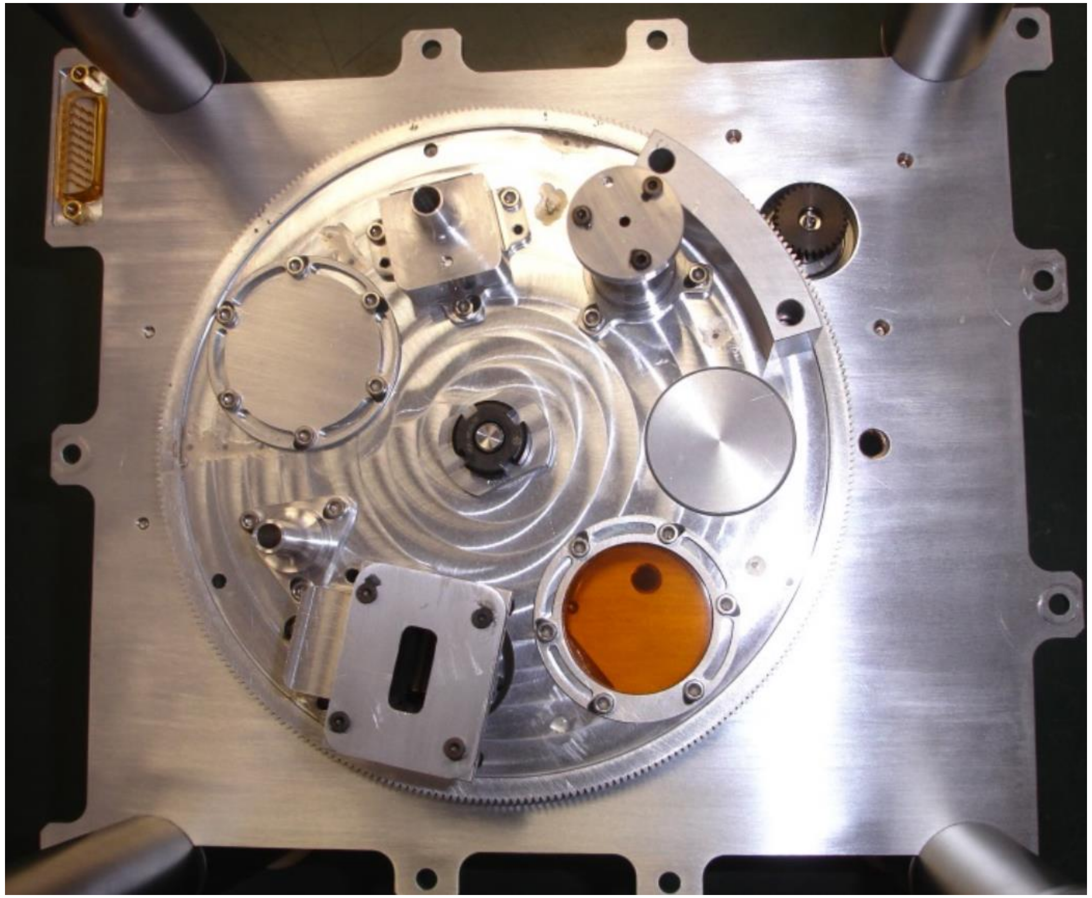


- **Spurious Modulation with and without MMA at 2.3 keV**
  - Two measurements rotated by 90 deg
  - No effect of the MMA
    - As known by Fresnel equations



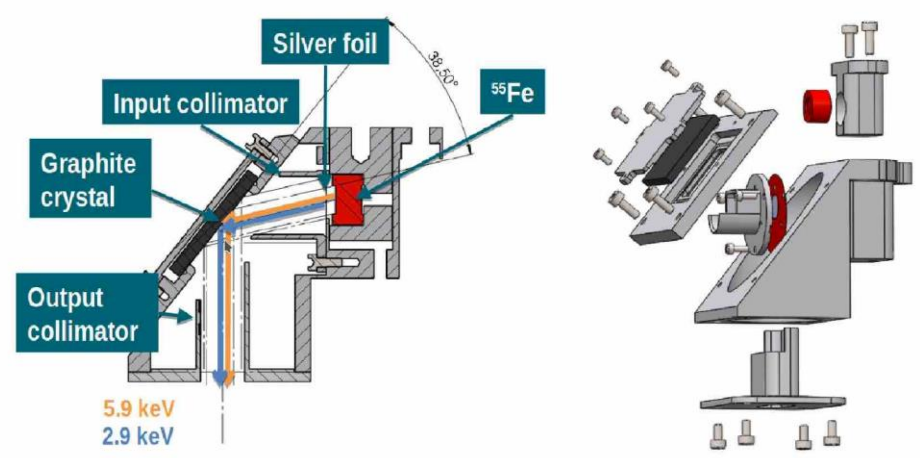
Calibration in flight: the filter and calibration whel

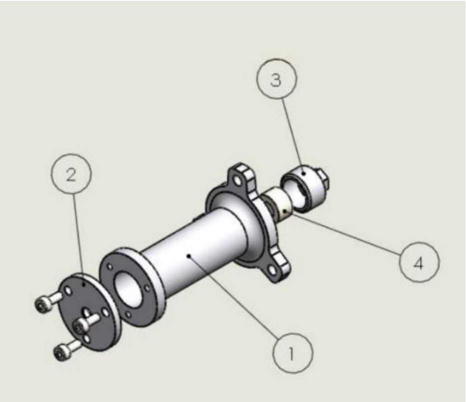
- A set of 4 calibration sources are installed on a wheel
- By rotating this wheel each source illuminates the detector once at time
- Why calibration in flight?
  - Gain calibration:
    - while observing astrophysical sources charges accumulates on the dielectric exposed in the GEM holes and gain reduces (this reversible effect is called “charging”)
    - a pressure reduction (still acting, but nearly stable) causes a small long term gain increase (called “secular”)
  - Monitoring of main parameters:
    - Modulation factor : response to polarized radiation
    - Spurious modulation : systematic effect on the modulation to be subtracted (measured with high accuracy on ground)
    - Energy resolution
  - Support the update of response matrices and applied HV to GEM
- Astrophysical sources not as standard candles, but someone (i.e Crab PWN) useful to check mutual calibration of the DUs

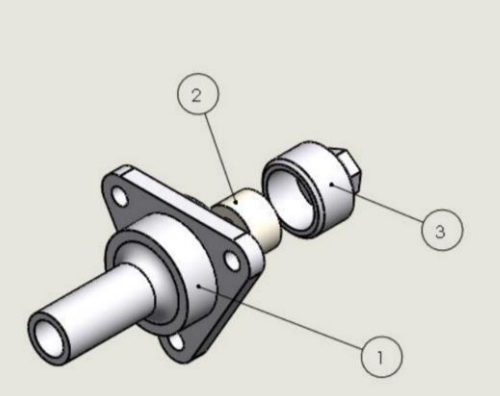


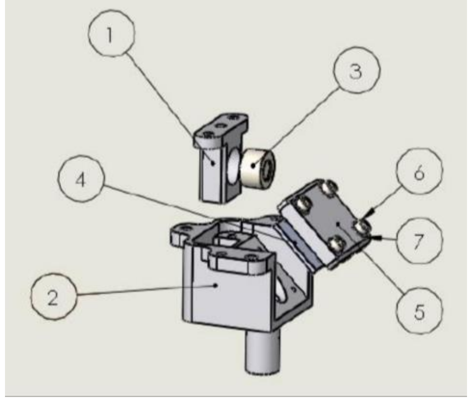
On board calibration sources

- ❑ Cal A
- ❑ Cal B
- ❑ Cal C
- ❑ Cal D









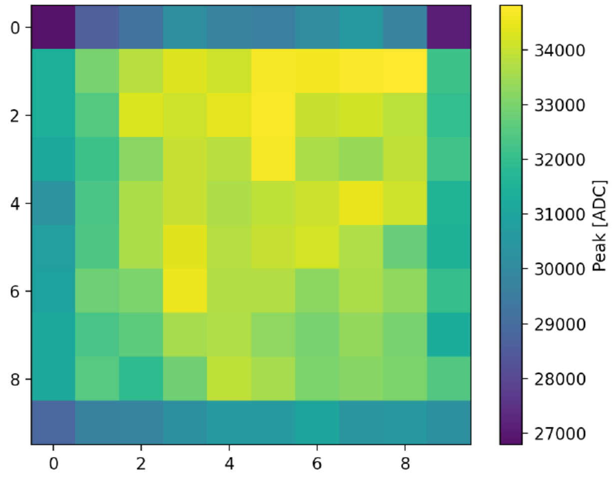
- ❑ ^{55}Fe radioactive source at 5.9 keV
- ❑ Passing through a silver foil induces fluorescence at 3.0 keV
- ❑ Bragg diffraction close 45° produce polarized radiation of both energies

- ❑ ^{55}Fe radioactive source at 5.9 keV
- ❑ Spot
- ❑ Full area illumination

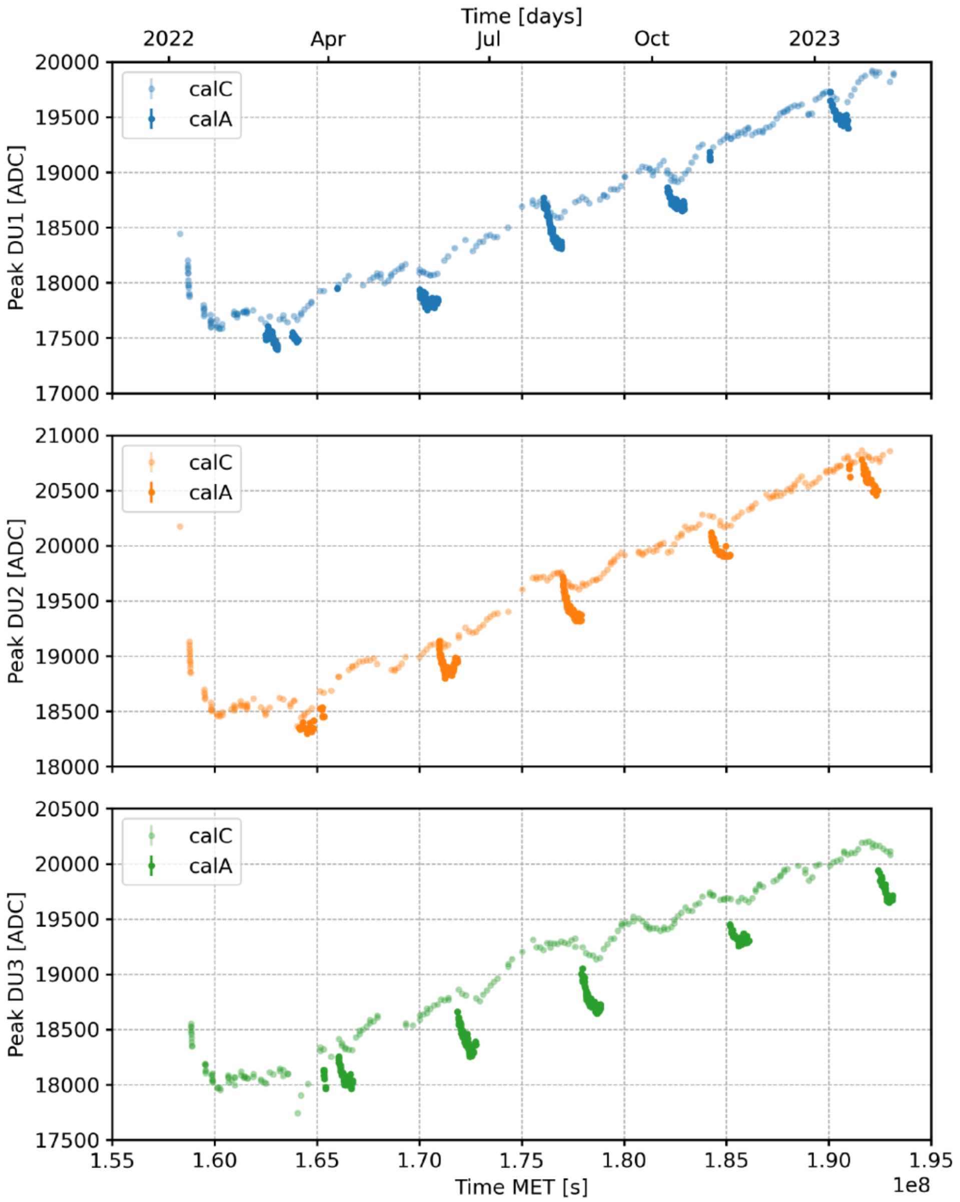
- ❑ Radiation from ^{55}Fe induces fluorescence by a silicon crystal at 1.7 keV

Gain calibration in flight

- **The CalC and CalD calibration sources allow a linear energy calibration**
  - 10x10 calibration maps interpolated over time
  - CalC and CalD observed alternatively, during occultations (when astrophysical source is hidden by the Earth)
  - After calibration the energy reconstruction is correct to ~1%

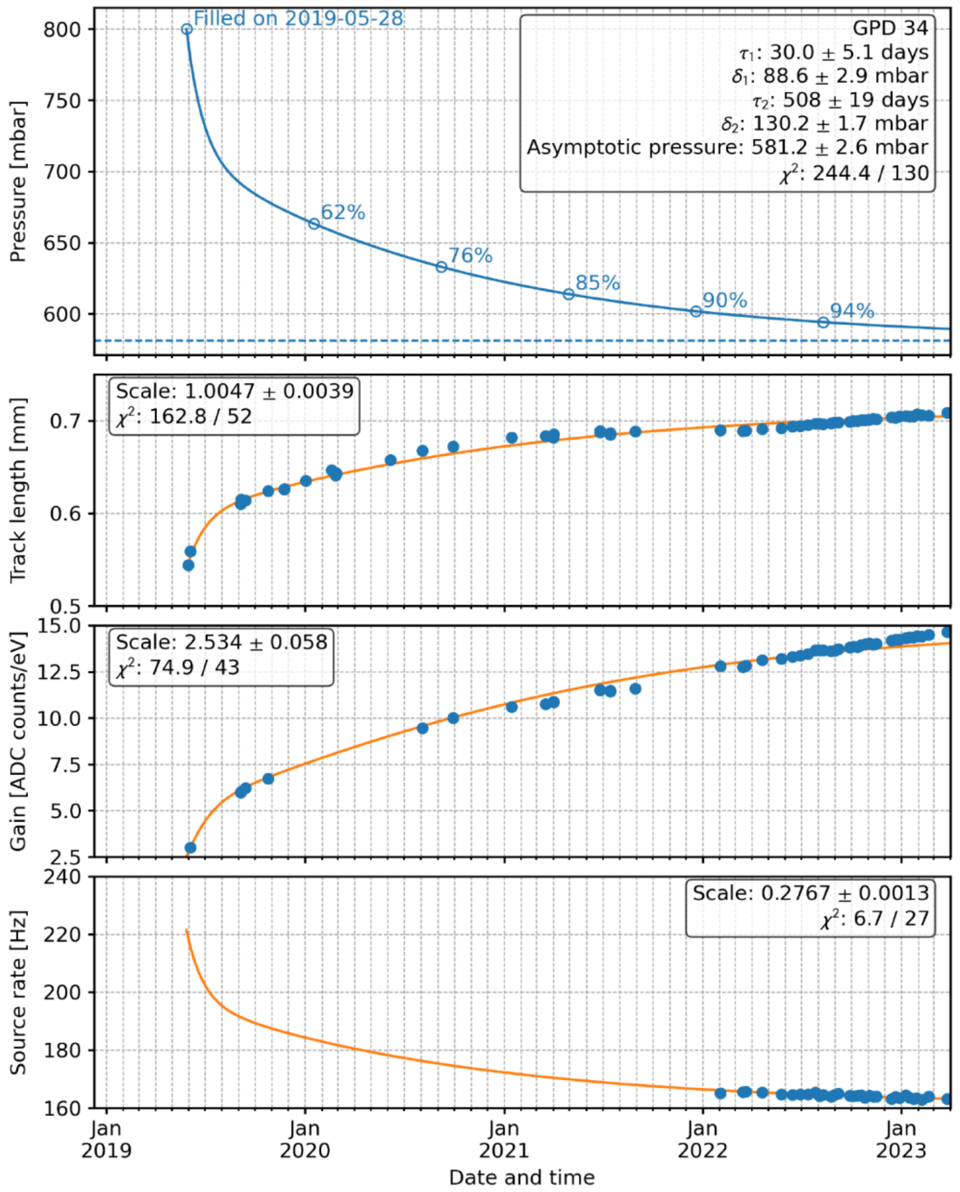


Example CalC calibration map



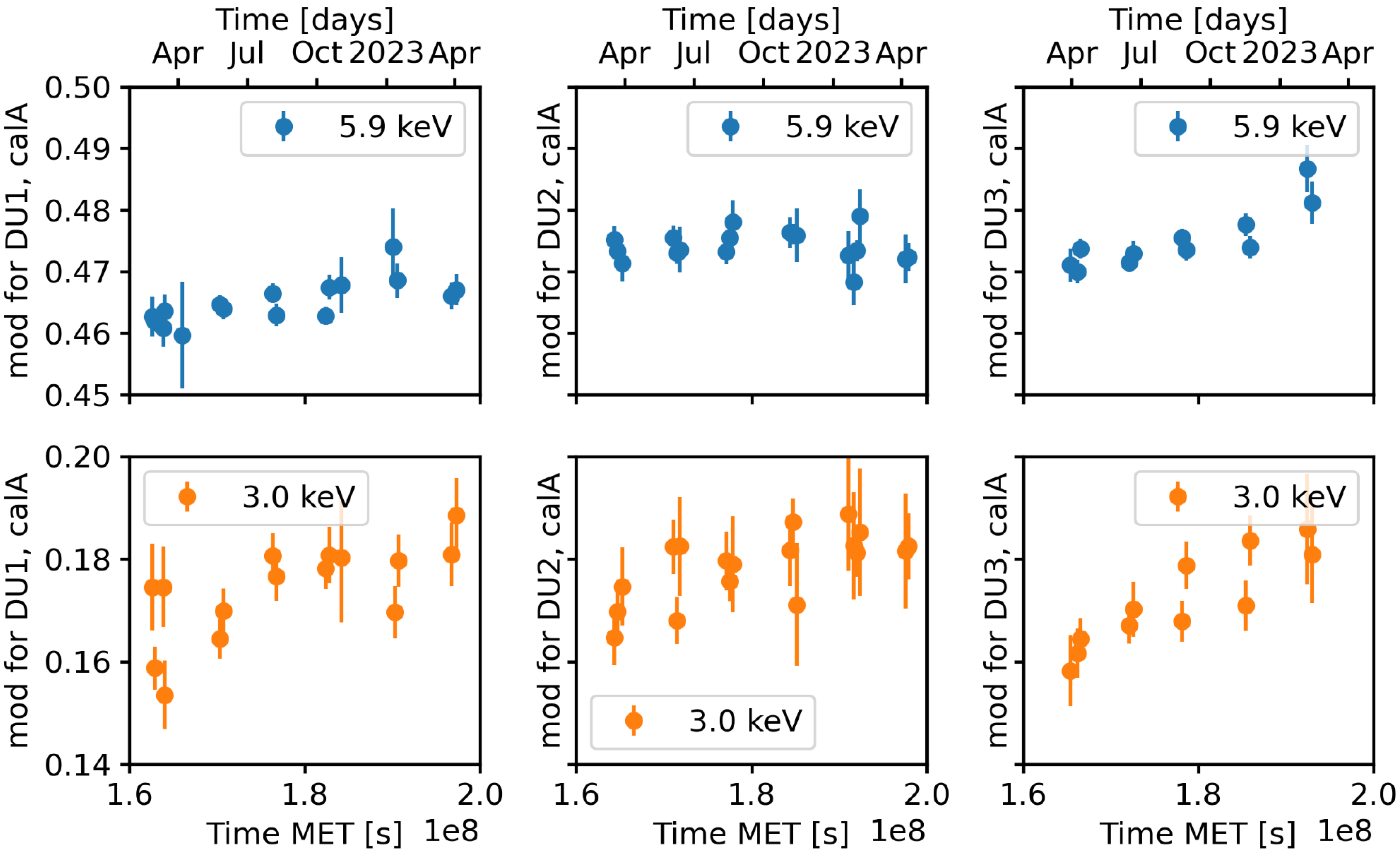
Monitoring of the DUs

- Gain, Count Rate, 5.9 keV photoelectron track length are measured directly and a combined fit is performed
- Fit model by Luca Baldini+ 2021
  - Double exponential fit of track length, gain and rate to estimate gas pressure in the sealed GPD
- GPD34 (DU2) as an example
  - Initial pressure at GPD filing was 800 mbar
  - Reduction of gas pressure is due to absorption by materials (slowing down with time)
  - This pressure reduction referred ad “secular” pressure variation



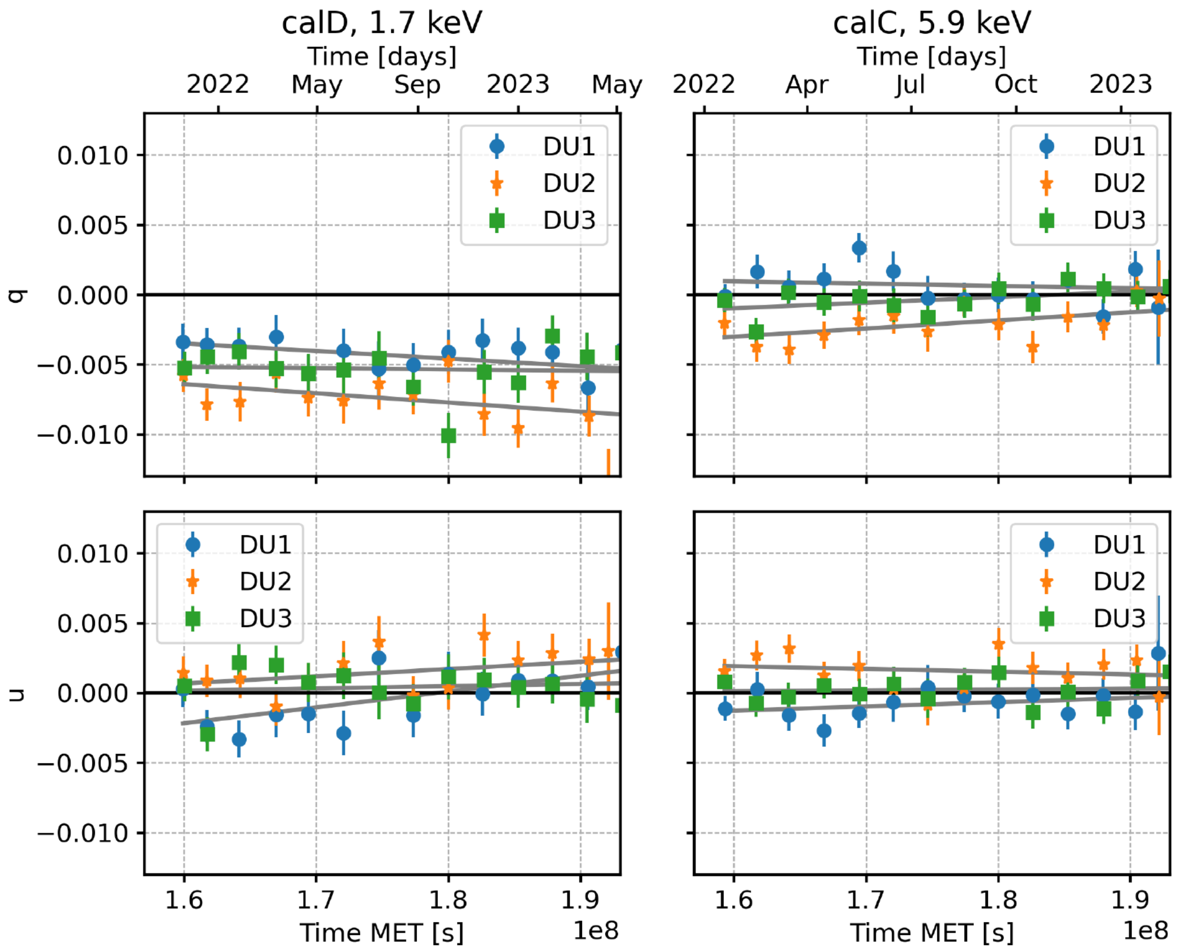
Modulation factor

- Polarization = Modulation / Modulation factor
- Cal A source
- Modulation factor increases slightly due to pressure decrease



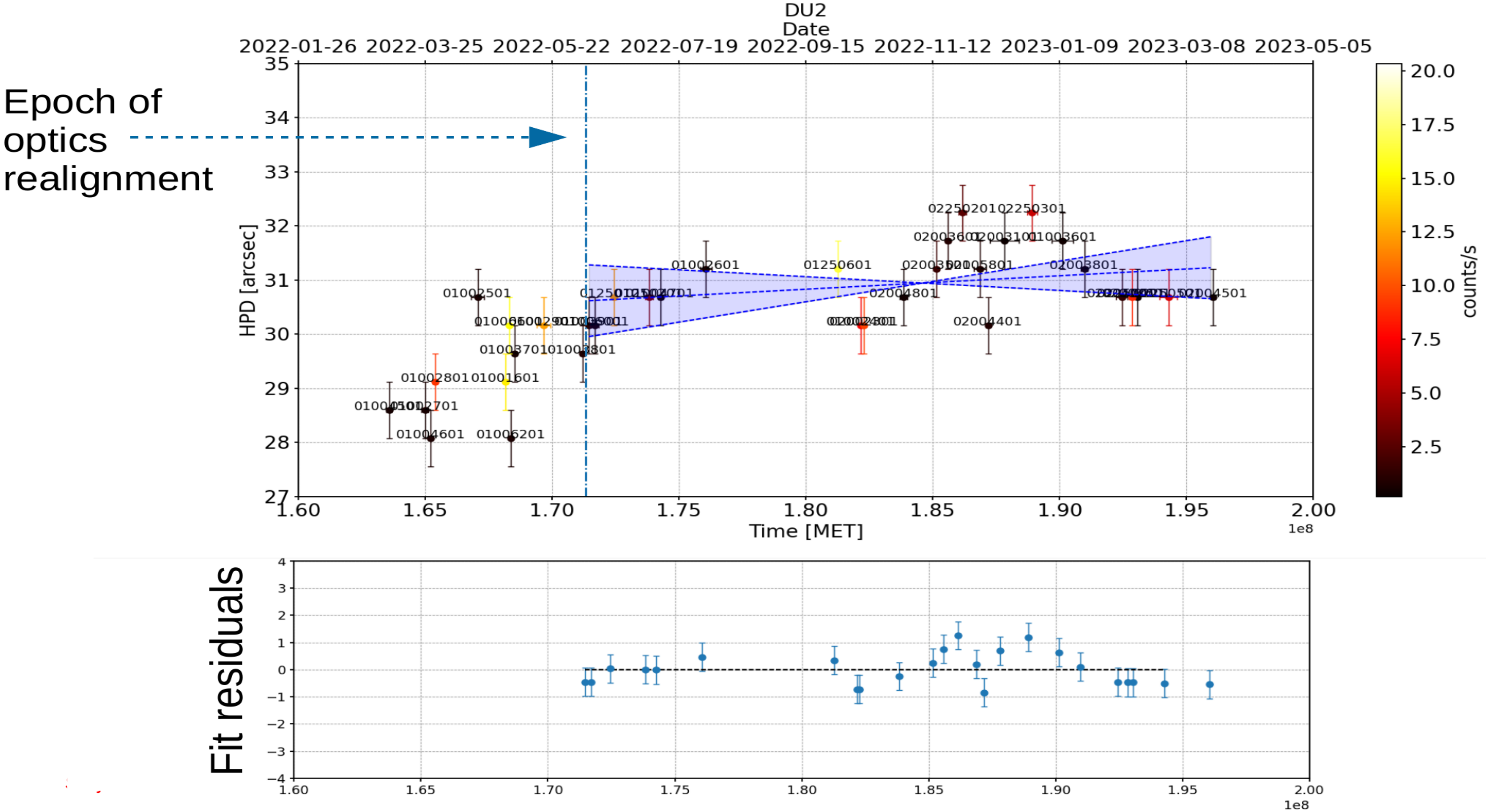
Spurious modulation

- Response to unpolarised radiation
- Plots in terms of normalized Stokes parameters q and u
- Variations, if any, are smaller than 0.3%



Monitoring of Point Spread Function

- Monitoring of Telescope (Mirrors + DUs) Point Spread Function (PSF) with point astrophysical sources
- Monitored the Half Power Diameter (circle diameter containing 50% of photons)
- DU2 as an example
- HPD increase rate: ~2x10^{-3} arcsec/day



Conclusions

- **On ground calibration of IXPE comprises:**
  - Calibration of each DU at INAF-IAPS (3 on board IXPE + the spare one)
  - Calibration of the MMA at SLTF of MSFC (3 on board IXPE + the spare one)
  - E2E Telescope calibration of the spare DU coupled with the spare MMA at SLTF of MSFC
- **In flight calibration:**
  - After calibration energy reconstruction is good at 1% level
  - Polarimetric response monitored at about 1% level, absolute
  - Suppot to calDB update due to pressure reduction vs time
- **Summary**
  - Calibration matched the requirements, excepted the significant deviation for QE reduction due to pressure drop in the gas cell. The effect is nearly saturated.
    - Marginal effect on the sensitivity due to the consequent increased elongation of tracks and thus modulation factor
  - E2E calibration confirmed that :
    - Angular resolution due to the coupling of the MMAs with Gas Pixel Detector only slightly increases with respect to the one of the MMA alone
    - No spurious additional effects on polarization measurements due to optics, as already known by theory

IXPE Imaging X-Ray Polarimetry Explorer

ICE polarized sources

- Fabiani+ 2021, SPIE

Table 1. Set-ups and energies of the polarized sources available on the ICE. In black color the set-ups used for IXPE DU-FMs calibration.

Crystal	X-ray tube	Energy (keV)	2d	Diffraction angle (deg)	Rp/Rs	Polarization (%)
PET(002)	Continuum	2.01	8.742	45.000	0.0000	$\sim$ 100.0
ADP(200)	Mo Lα	2.29	7.500	46.209	0.0027	99.46
InSb(111)	Mo Lα	2.29	7.481	46.361	0.0034	99.32
Graphite(0002)	Continuum	2.61	6.708	45.000	0.0000	$\sim$ 1000.0
Ge(111)	Rh Lα	2.70	6.532	44.877	0.0024	99.53
Si(111)	Ag Lα	2.98	6.271	41.562	0.0252	95.08
Al(111)	Ca Kα	3.69	4.678	45.909	0.0031	99.38
CaF_2(220)	Ti Kα	4.51	3.840	45.716	0.0023	99.54
Si(220)	Ti Kα	4.51	3.840	45.716	0.0023	99.54
LiF(220)	Fe Kα	6.40	2.848	42.859	0.0529	$\sim$ 89.95
Si(400)	Fe Kα	6.40	2.716	45.511		$\sim$ 100.0

ICE unpolarised sources

- **Fabiani+ 2021, SPIE**

Table 2. Residual polarization of the ICE "Unpolarized" X-ray sources.

Nominal Energy (keV)	Source Set-Up	Measured Polarization (%)
2.04	Fluorescence of Zn target illuminated by Rh X-ray tube	1.02 ± 0.19
2.29	Fluorescence of Mo target illuminated by Ag X-ray tube	0.73 ± 0.12
2.70	Direct X-ray tube with Rh anode with a PVC filter	6.29 ± 0.10
2.98	Direct X-ray tube with Ag anode with an Ag filter	13.02 ± 0.09
3.69	Direct X-ray tube with Ca anode	Undetected MDP(99%)=0.23%
5.89	^{55}Fe nuclide, 4mCi	Undetected MDP(99%)=0.22%