IXPE
Imaging
X-Ray
Polarimetry
Explorer

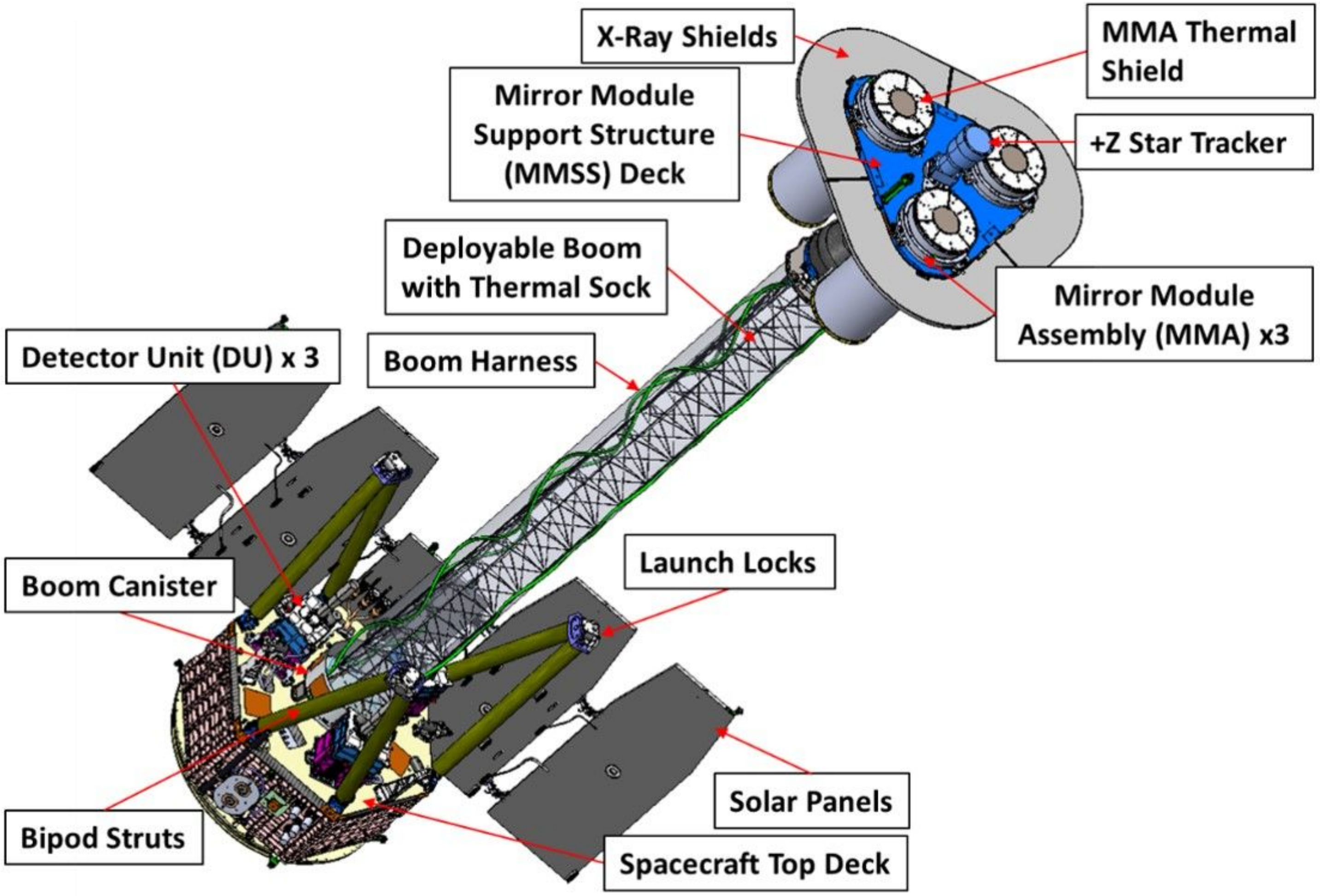
Accounting for systematic uncertainties in the IXPE detector response

Stefano Silvestri (INFN Pisa)

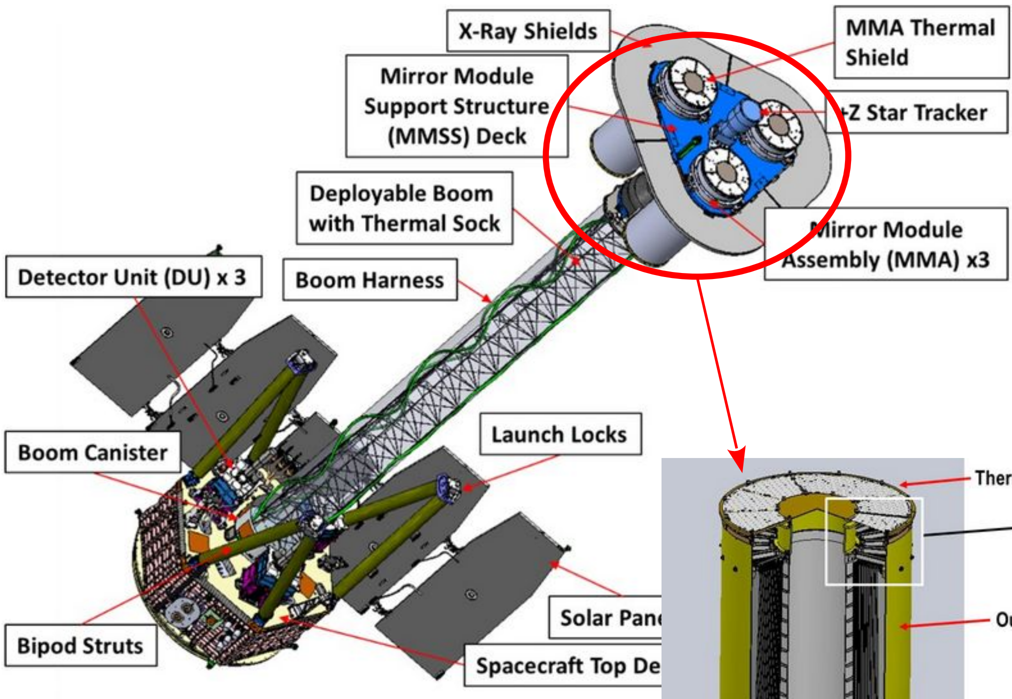
stefano.silvestri@pi.infn.it

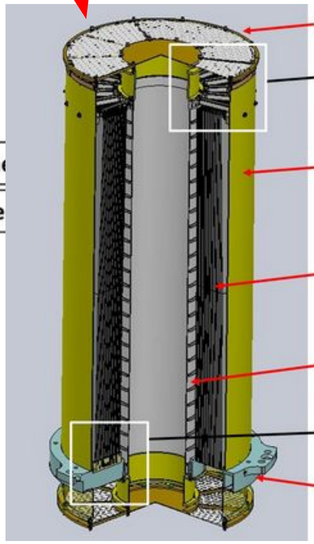
15th IACHEC meeting – April 23–27, 2023 Pelham, Germany

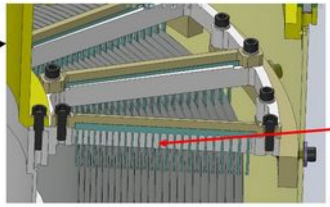
THE TELESCOPE

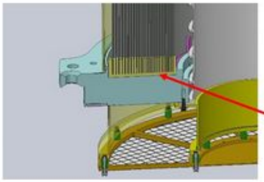


THE MIRRORS





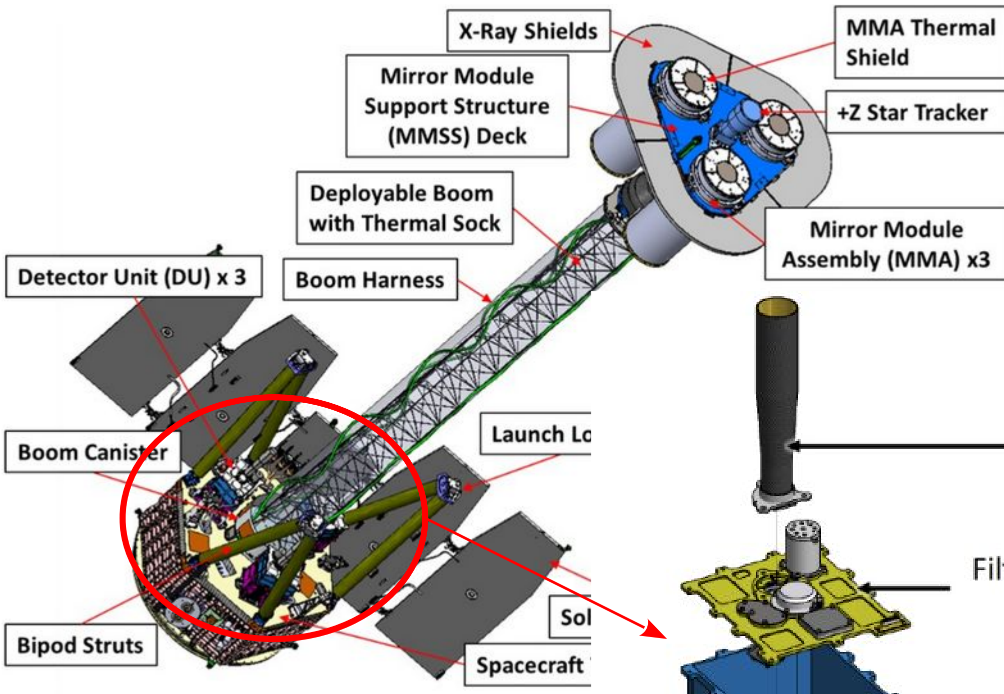


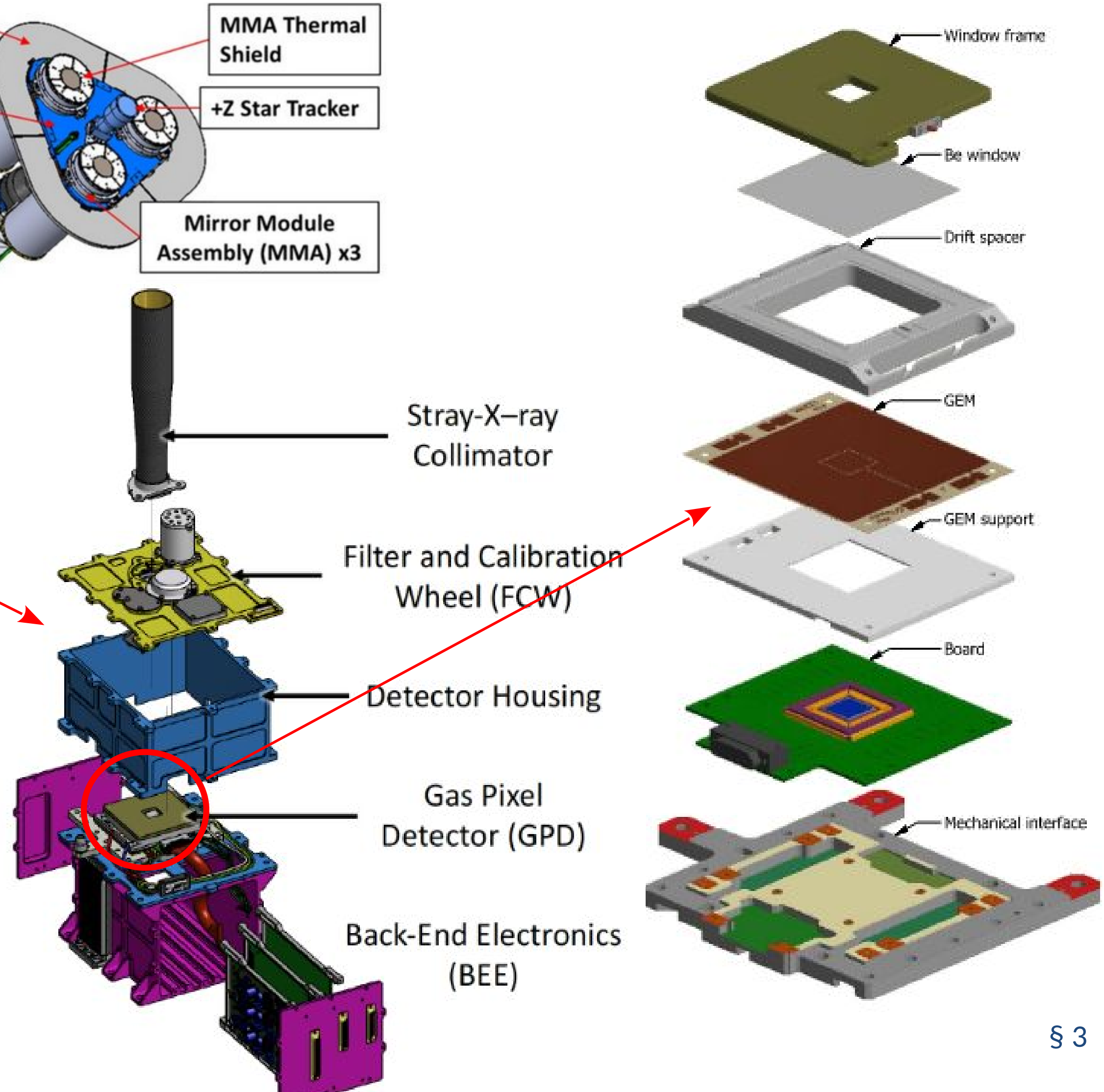


- Reflectivity -> effective area
- Ground calibration performed
- Mileage may vary (cal sources not at infinity, off axis → anglular incidence)

IXPE
Imaging X-Ray Polarimetry Explorer

THE DETECTOR UNITS

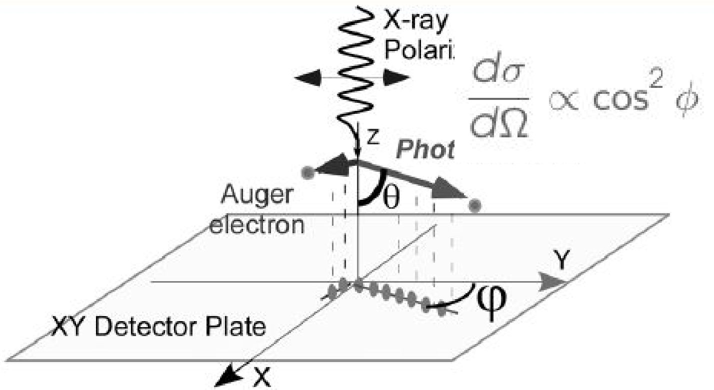


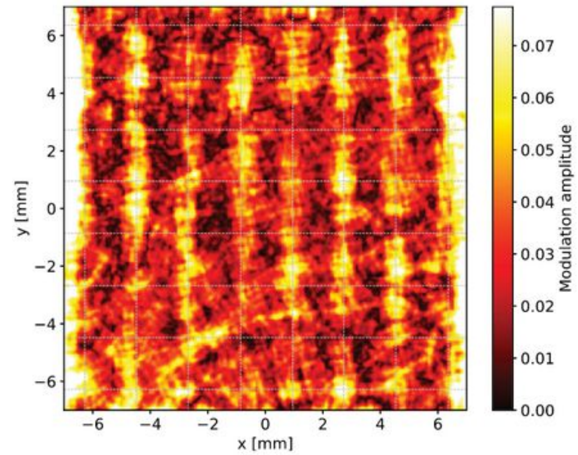


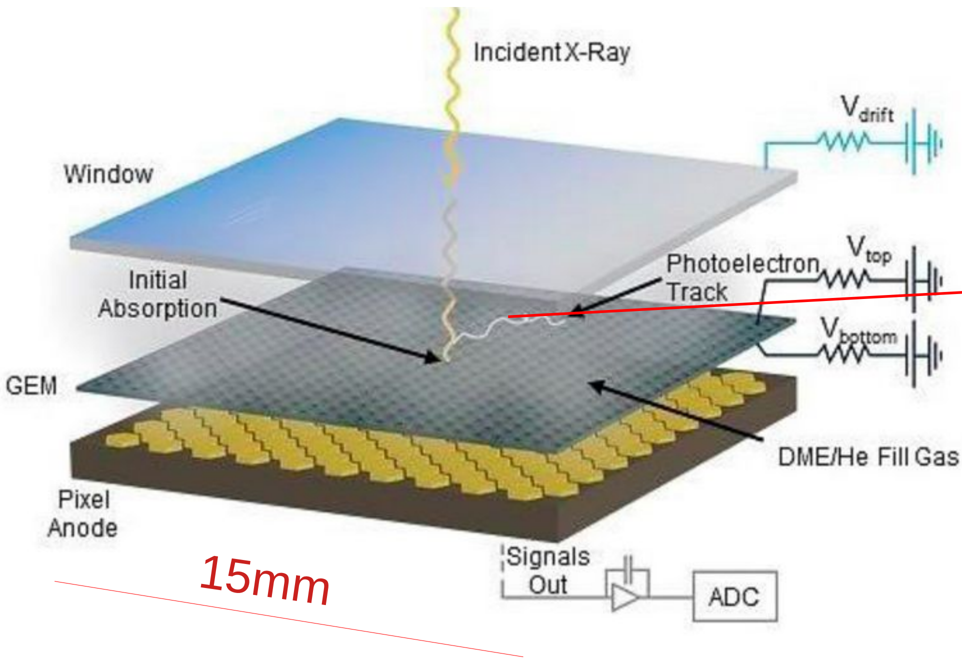
- Quantum efficiency -> effective area
- Modulation function
- Ground calibration
- Mileage may vary (off-axis, spurious modulation map etc.)

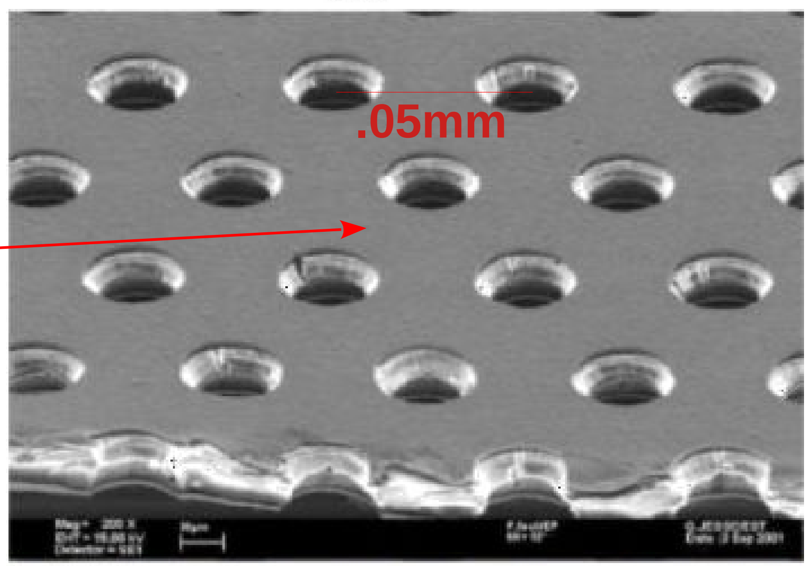
IXPE
Imaging
X-Ray
Polarimetry
Explorer

THE GAS PIXEL DETECTOR





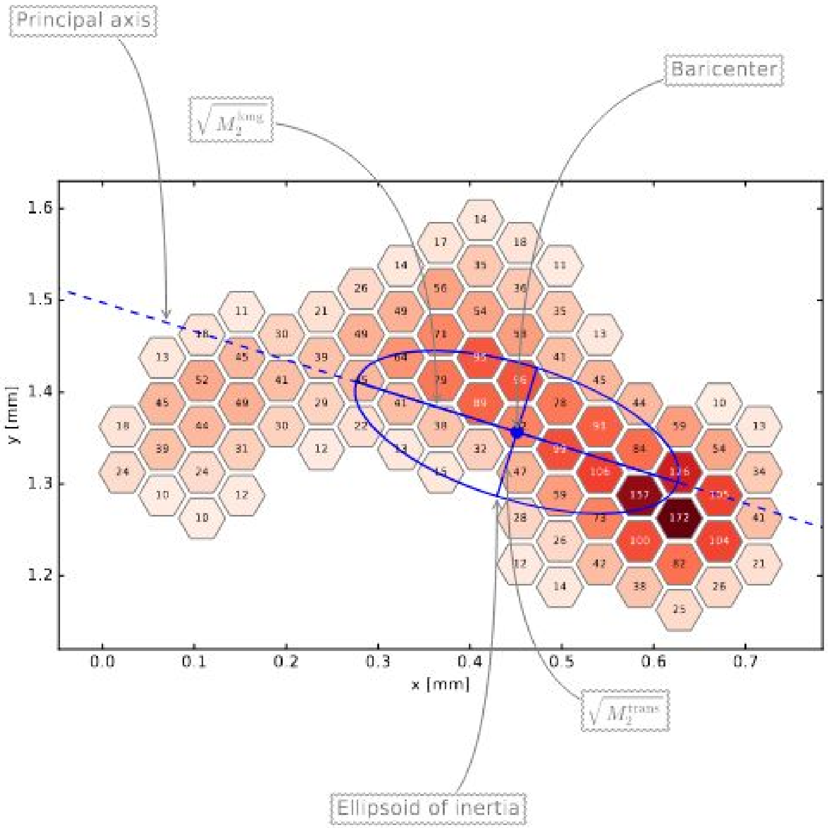


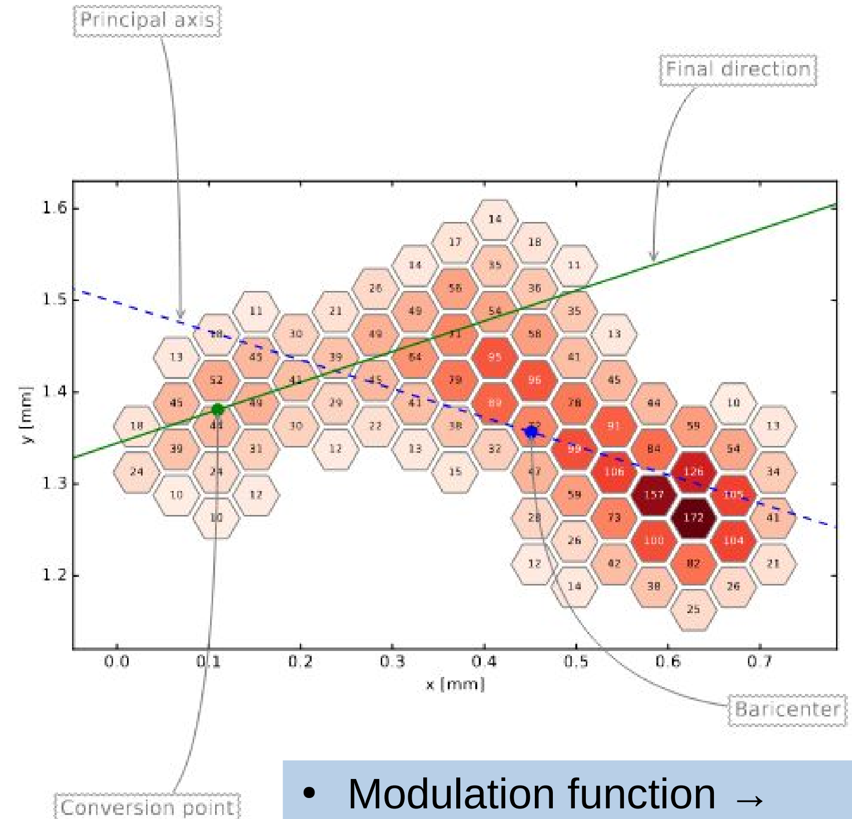


F. Sauli (2016)

IXPE
Imaging X-Ray Polarimetry Explorer

EVENT RECONSTRUCTION





- Modulation function → uncertainty trend with E

1) Calculate the barycenter

2) Get the absorption point and initial direction

WRAP UP: SYSTEMATICS

We have (ground-based) CALDB files for response files

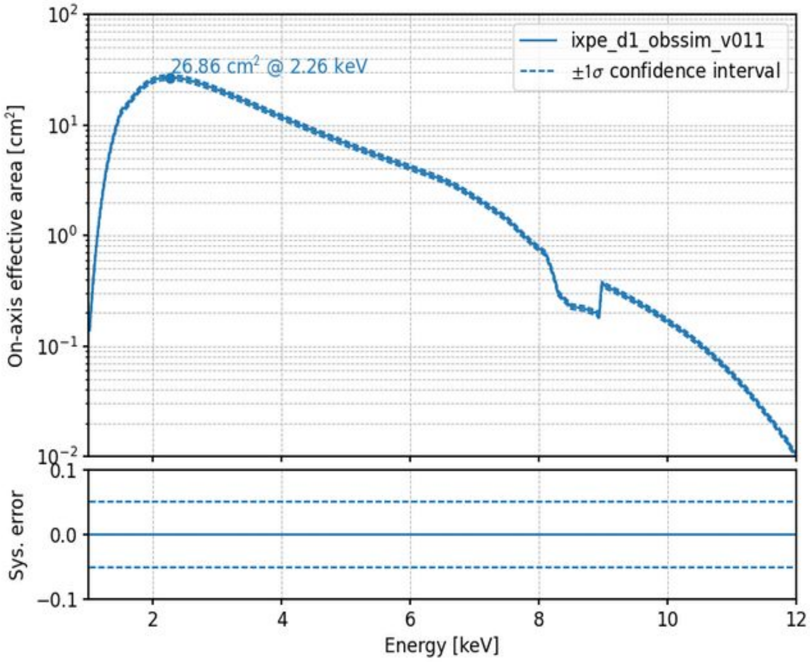
- On-axis effective area
- Modulation function
- Modulation response function (product of the two)

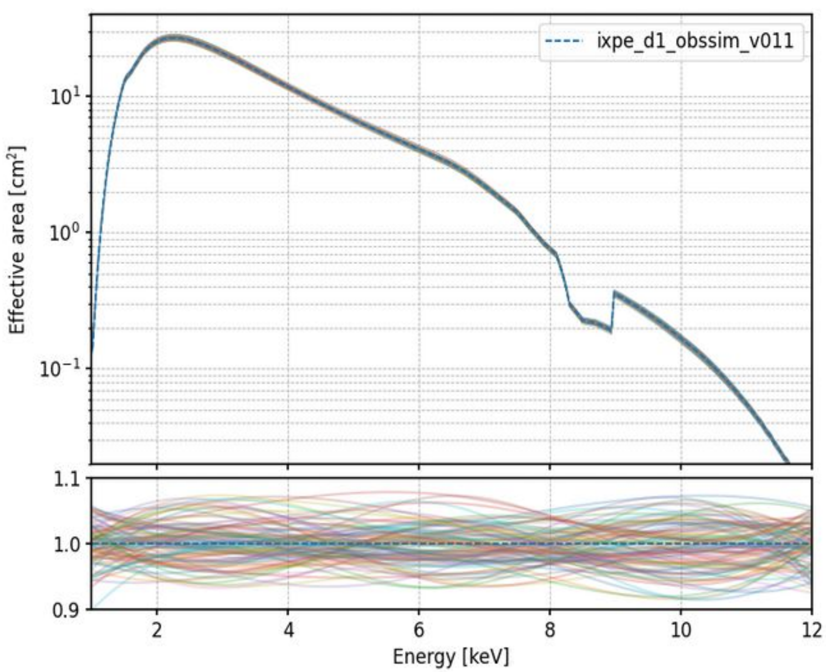
....and uncertainties in the calibration process.

→ We estimate those uncertainties and let them vary on a grid, then we propagate them consistently

SYSTEMATICS I: EFFECTIVE AREA

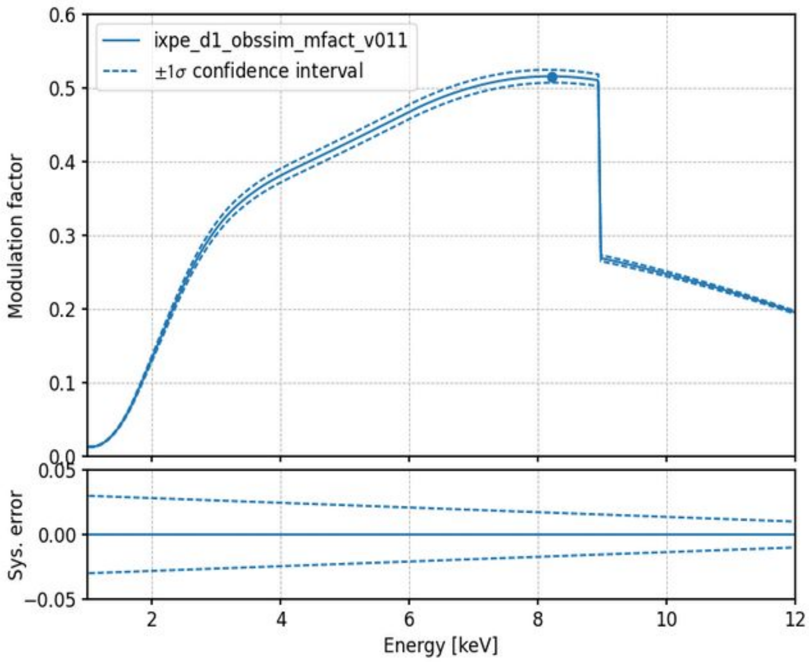
We assign a 5% uncertainty on our knowledge of the effective area. This can be either "flat" or variable in the energy range.

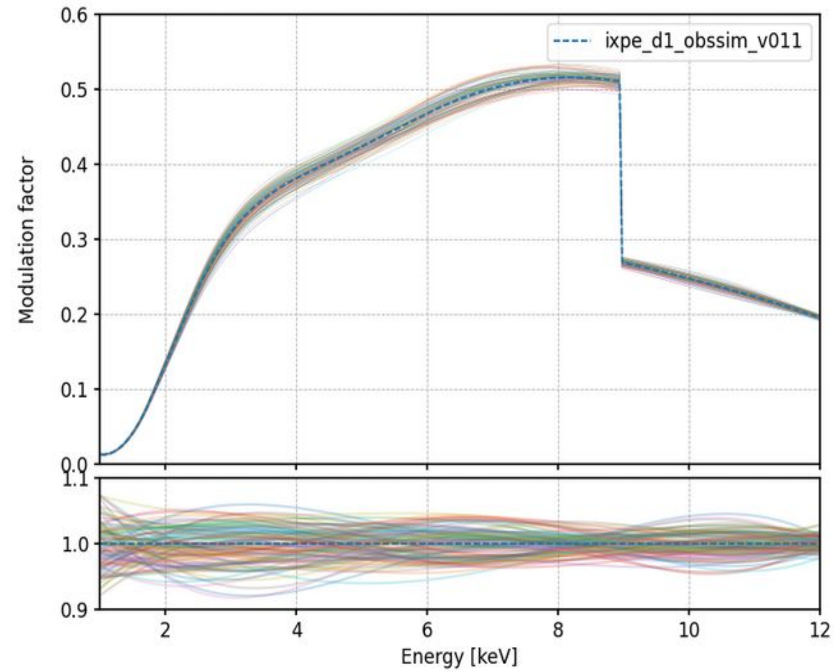




SYSTEMATICS II: MODULATION FACTOR

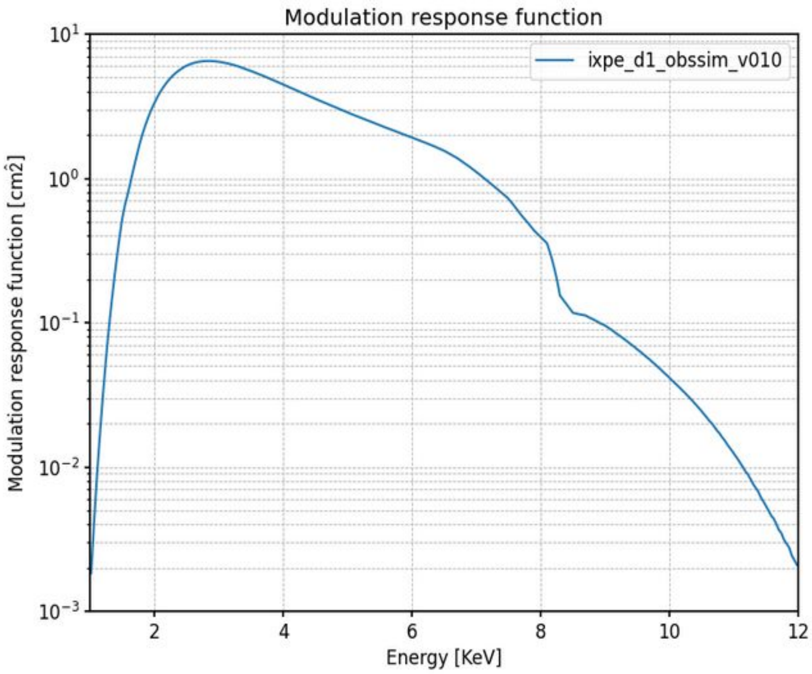
In this case, we do expect a little trend with the energy (it’s easier to calibrate on long tracks)

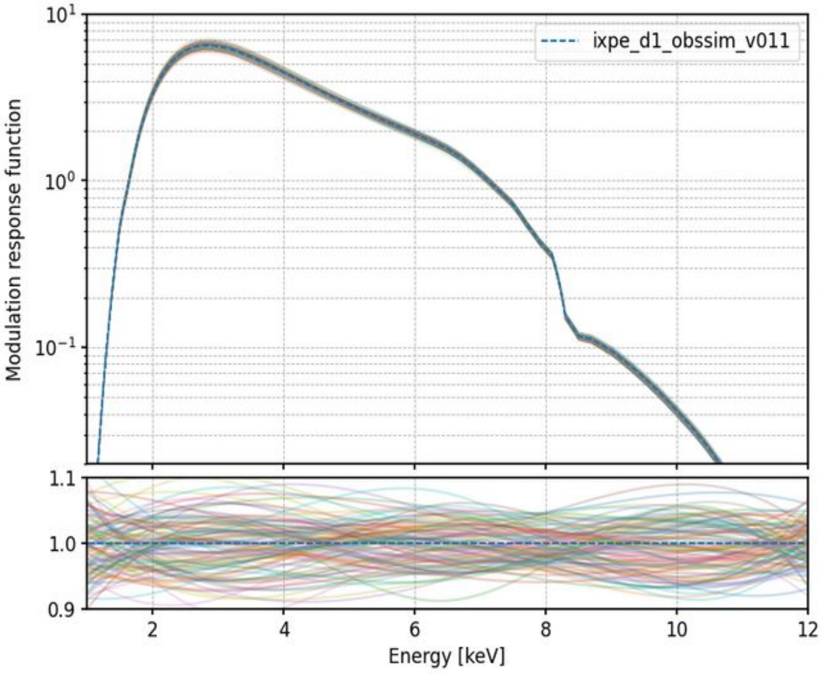




SYSTEMATICS III: MODULATION RESPONSE FUNCTION

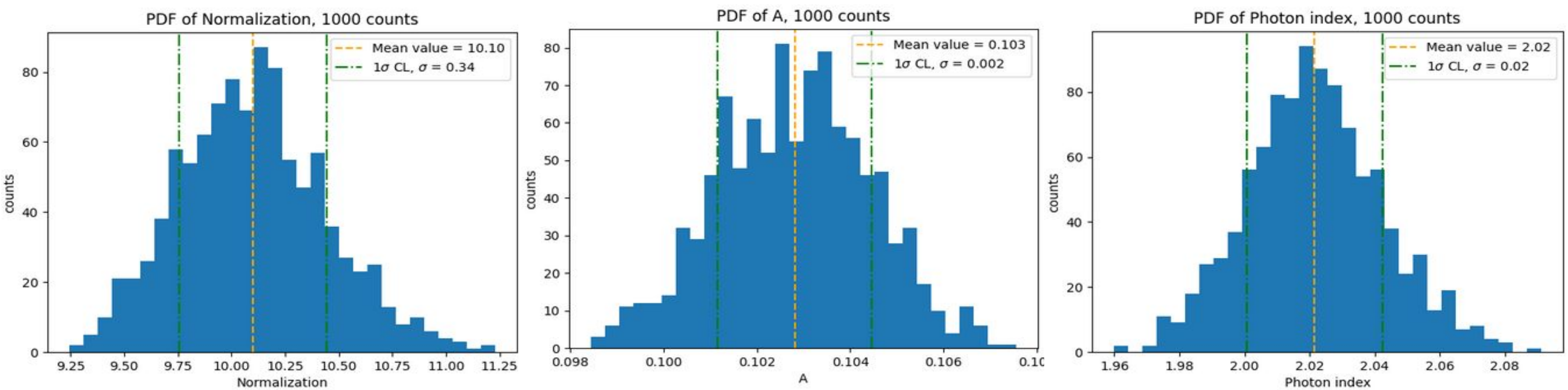
What happens when you put them together?





EFFECTS ON THE OBSERVABLES

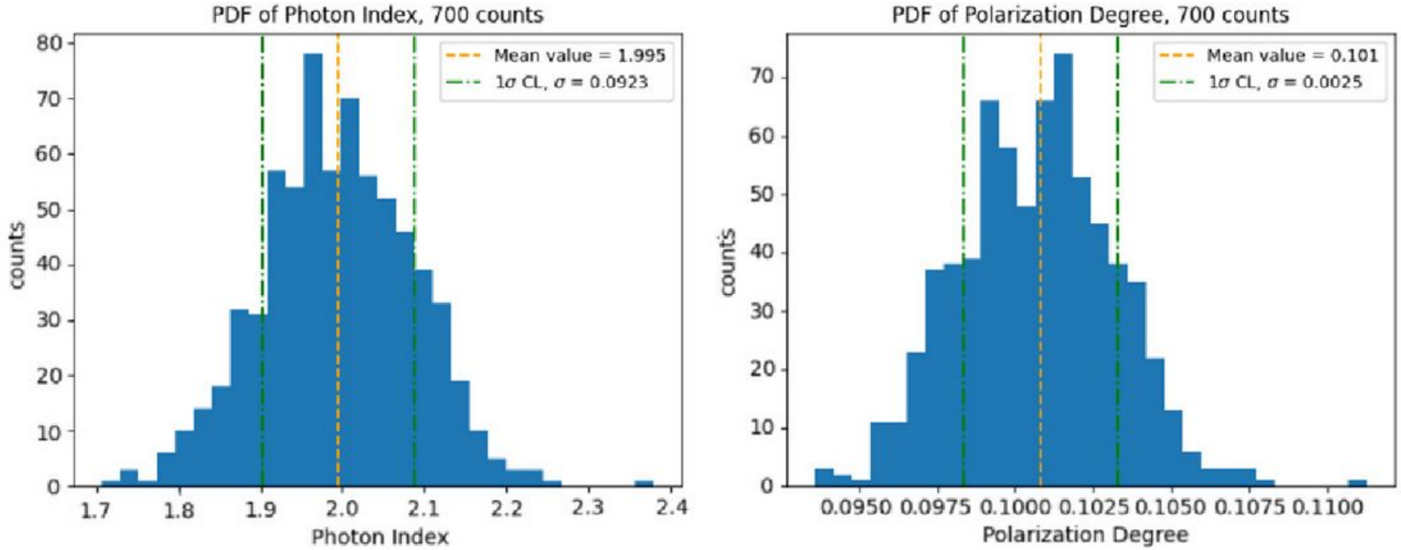
We interpret the same simulated observation with all those different response functions and see the error induced in the parameters



Parameter	Target	Result	Systematic IRF
Ph. index	2	2.000 ± 0.001	2.02 ± 0.02
Normalization	10	10.00 ± 0.01	10.10 ± 0.35
Pol. degree	0.1	0.098 ± 0.0015	0.103 ± 0.002

SYSTEMATICS IV: ENERGY SCALE

GEMs are subject to charging, which alter the gain and the energy scale. We perturbed the energy scale by 2% to see the effect on the parameters.



Parameter	Target	Result	Systematic PI
Ph. index	2	2.000 ± 0.001	1.995 ± 0.09
Normalization	10	10.00 ± 0.01	9.95 ± 0.6
Pol. degree	0.1	0.098 ± 0.0015	0.101 ± 0.0025

IS THIS A LOT? IS THIS A LITTLE?

- Polarization is the urgent business here
- Systematic IRF actually includes also statistical error
- For 5e6 photons you get around 1.5% statistical error, for comparison our first 100kS on the crab had 6.6e6 photons per DU (including all regions and bkg)
- You should start worrying only with very bright sources or long observations

Parameter	Target	Result	Systematic IRF
Ph. index	2	2.000 ± 0.001	2.02 ± 0.02
Normalization	10	10.00 ± 0.01	10.10 ± 0.35
Pol. degree	0.1	0.098 ± 0.0015	0.103 ± 0.002

IS THIS A LOT? IS THIS A LITTLE?

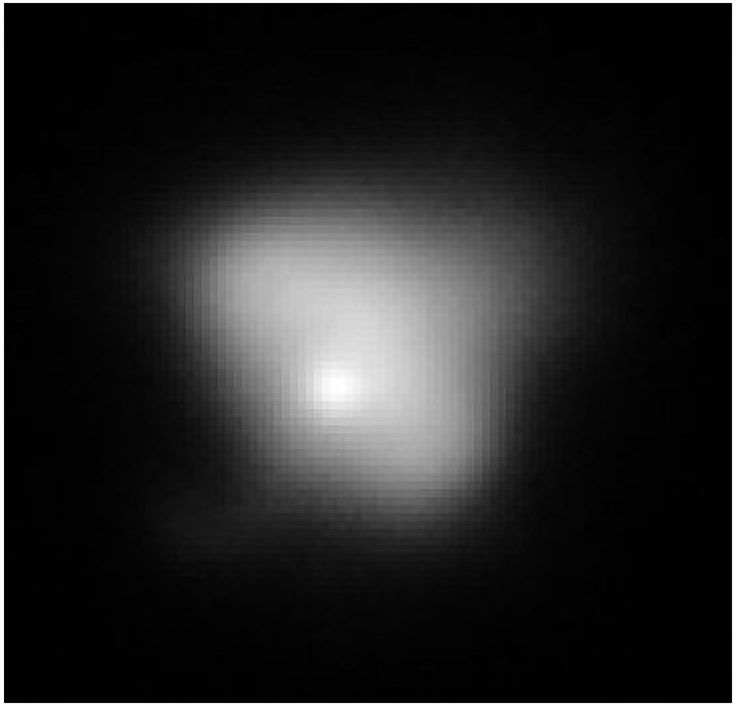
The energy scale *looks* worrysome but it's not

- It is unlikely that we keep a constant high rate on a single pixel (dithering)
- Extended sources are going to illuminate the same pixel for a longer time despite of dithering but they are fainter
- The effect on PD starts to become relevant just now

Parameter	Target	Result	Systematic PI
Ph. index	2	2.000 ± 0.001	1.995 ± 0.09
Normalization	10	10.00 ± 0.01	9.95 ± 0.6
Pol. degree	0.1	0.098 ± 0.0015	0.101 ± 0.0025

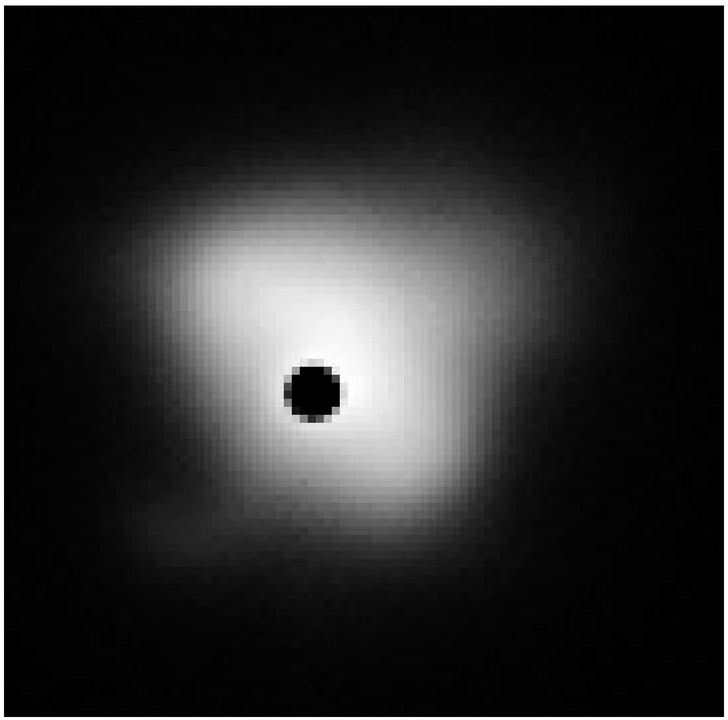
CONCLUSIONS: KNOW YOUR ASTROPHYSICISTS

- Crab observation: 6e6 photons

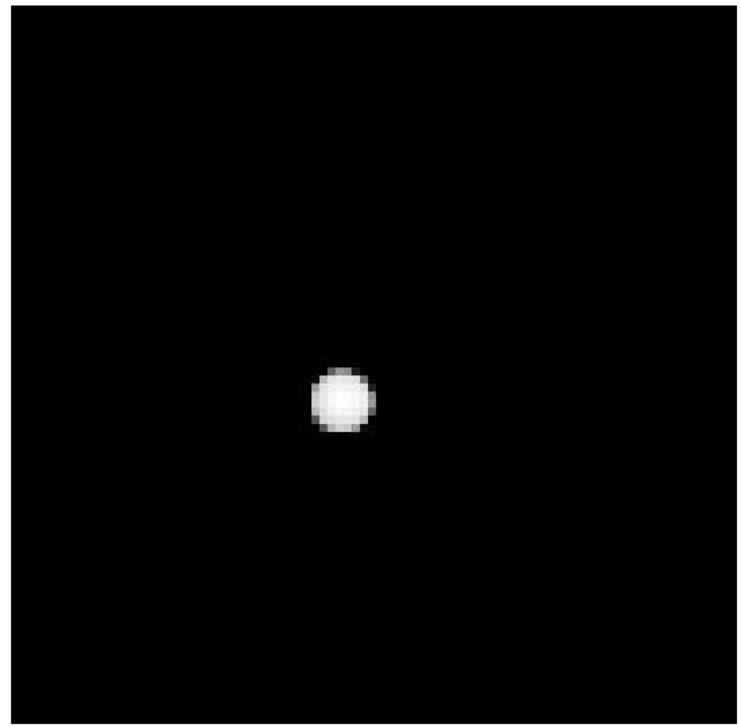


CONCLUSIONS: KNOW YOUR ASTROPHYSICISTS

Nebula: 6.21e6 photons



Pulsar: 428k photons



CONCLUSIONS: KNOW YOUR ASTROPHYSICISTS

Nebula: 6.21e6 photons

- Smoothed map
- Kernel size 0.5’
- 6Hz

Pulsar: 428k photons

- 4Hz, 0.16’
- 7 phase bins
- Dithering!

CONCLUSIONS: KNOW YOUR ASTROPHYSICISTS

Nebula: 6.21e6 photons

- Smoothed map
- Kernel size 0.5’
- 6Hz

Pulsar: 428k photons

- 4Hz, 0.16’
- 7 phase bins
- Dithering!

If you have too many photons
you are not binning hard enough
(and that’s your own fault)

BIBLIOGRAPHY

S. Silvestri, “Accounting for systematic uncertainties in the Imaging X-ray Polarimetry Explorer (IXPE) detector response”, *Nuclear Instruments and Methods in Physics Research A*, 10.1016/j.nima.2022.167938 (2023) – The proceeding containing the results of this work

L. Baldini et al. “Design, construction, and test of the Gas Pixel Detectors for the IXPE mission”, *Astroparticle Physics*, 10.1016/j.astropartphys.2021.102628 (2021) – Description of our GPD and its issues (including the charging)

F. Muleri et al. “Calibrating the IXPE observatory from ground to space”, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 10.1117/12.2275133 (2017) – Design of the ground calibration campaign

F. Muleri et al.: “The IXPE instrument calibration equipment”, *Astroparticle Physics*, 10.1016/j.astropartphys.2021.102658 (2022) – Calibration process, especially aimed at the polarization sensitivity

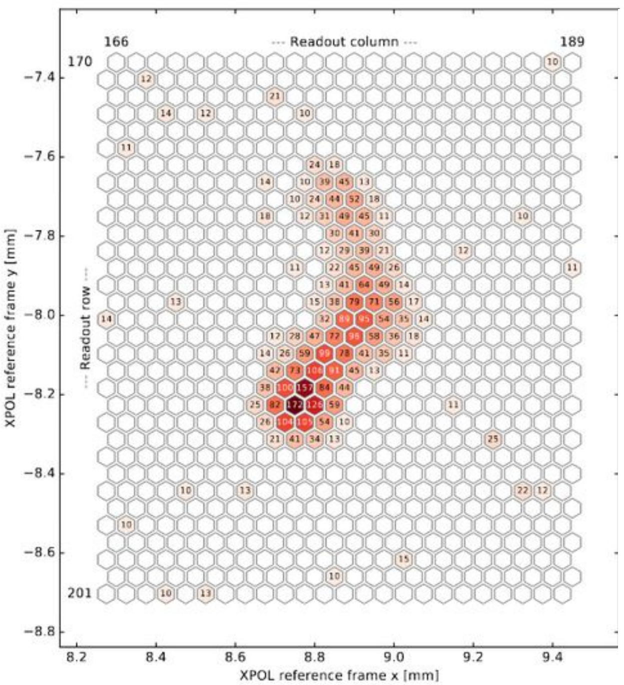
J. Rankin et a.: “An Algorithm to Calibrate and Correct the Response to Unpolarized Radiation of the X-Ray Polarimeter Onboard IXPE”, *Astrophysical Journal*, 10.3847/1538-3881/ac397f (2022) - Algorithm for correcing the spurious modulation

BACKUP

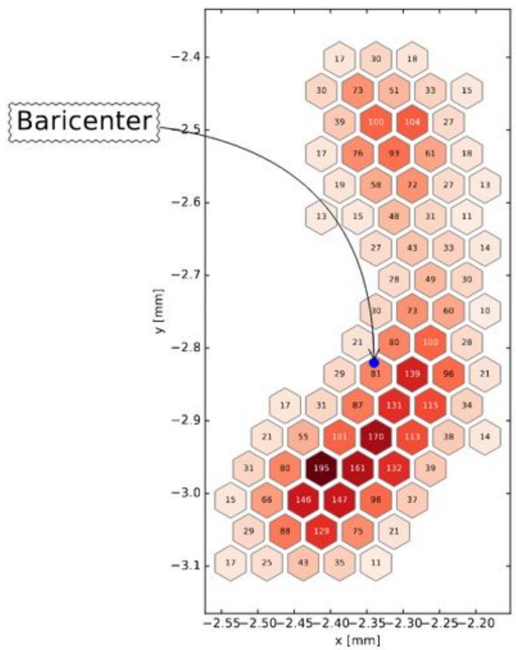
IXPE Imaging X-Ray Polarimetry Explorer

RECONSTRUCTION ALGORITHM

Thresholding (sigma clipping)

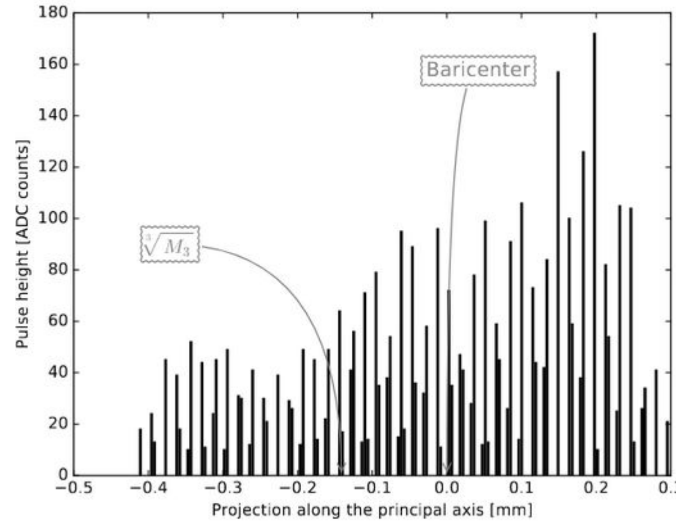


Baricentering
(count sum on cluster)



Distribution along the
Principal axis and skewness

$$\gamma_1 = \frac{M_3^{\mathrm{long}}}{(M_2^{\mathrm{long}})^{\frac{3}{2}}}$$



From the moment analysis get the impact point
From the impact point get the EVPA by weighting nearby pixels