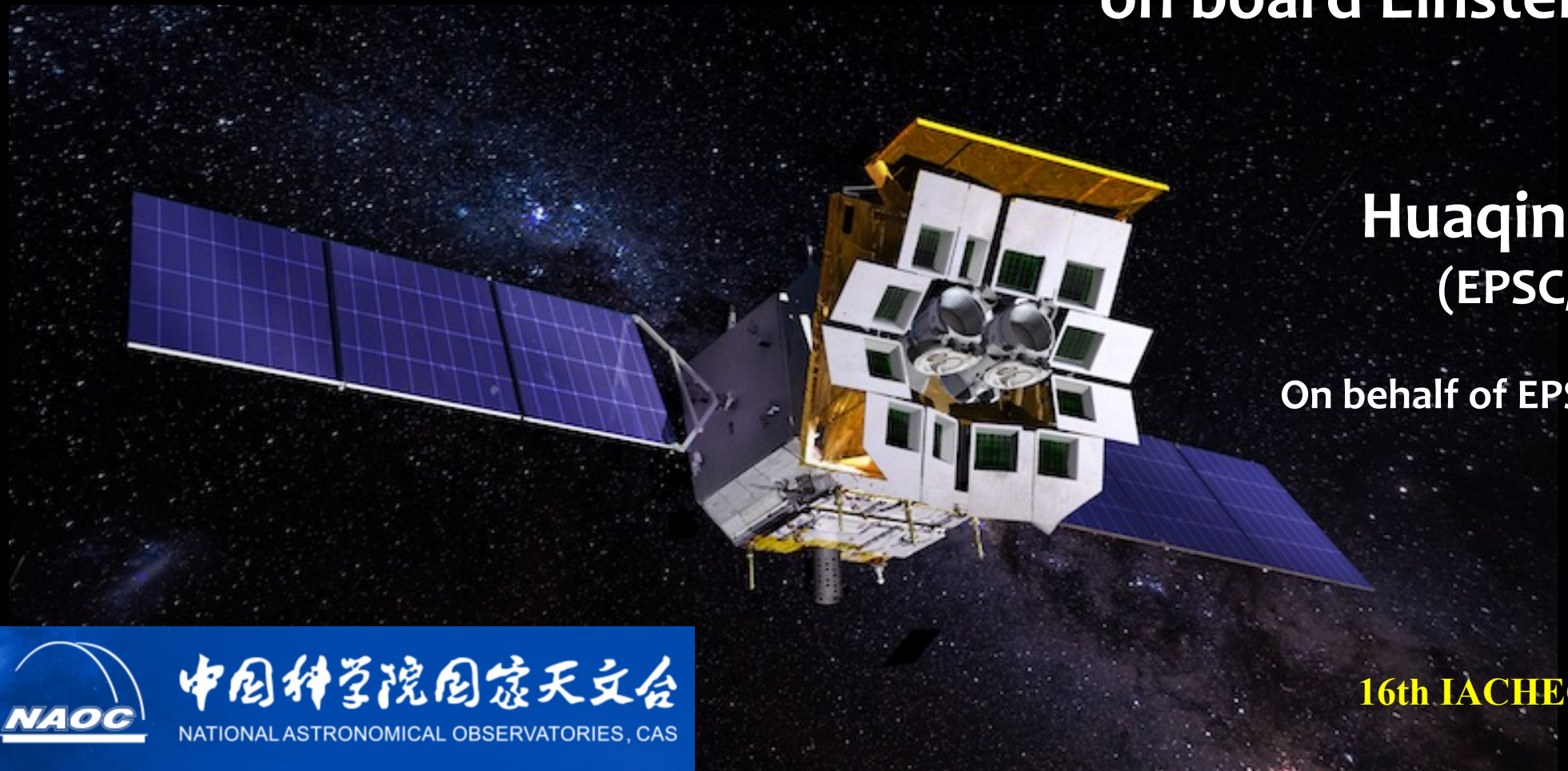
# On-ground calibration of the Wide-field X-ray Telescope (WXT) on board Einstein Probe (EP)




**Huaqing Cheng**
(EPSC/NAOC)

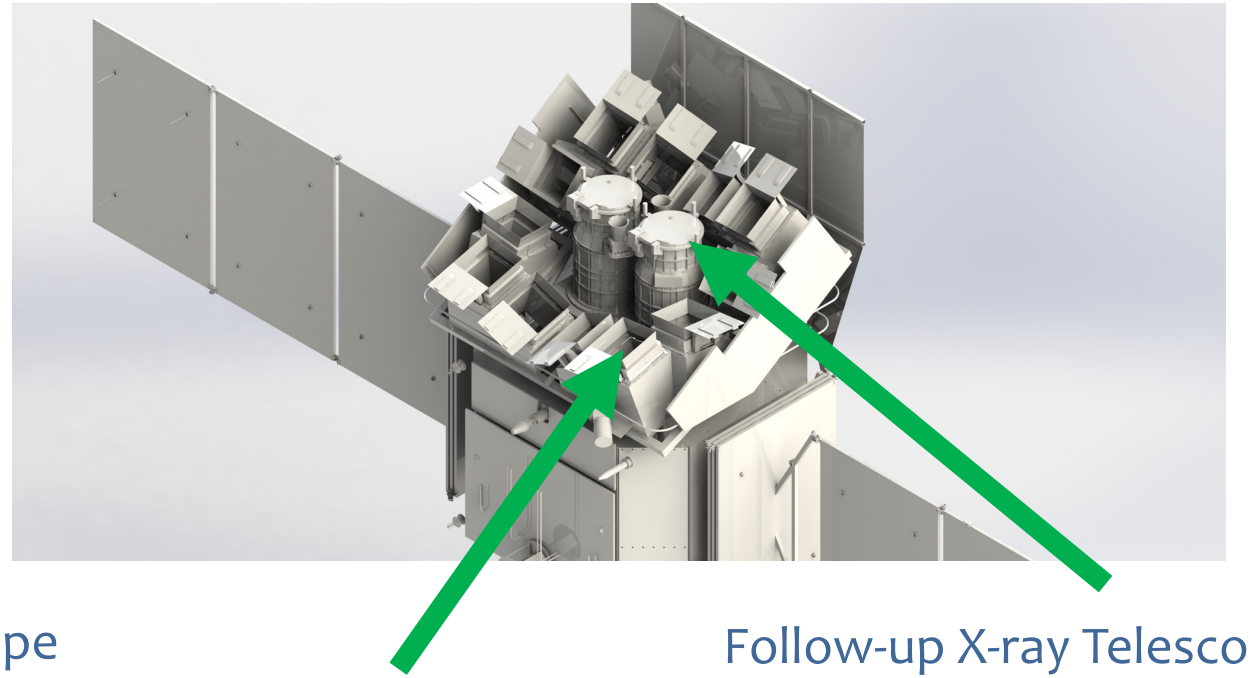
On behalf of EPSC and WXT team


**2024 May 13th**
**16th IACHEC meeting@ Segvia, Spain**

# Outline

- Introduction
- A brief review on the ground calibration of WXT
- Ground calibration
  - MPO and CMOS calibration at NAOC
  - FM5 Calibration at MPE/Panter
  - Module calibration at IHEP/100XF
- Future work
- Summary

# Instruments and Spacecraft



Orbit: 600 km
Inclination: < 30°
Life : 3 + 2 years
Weight: 1.3 ton

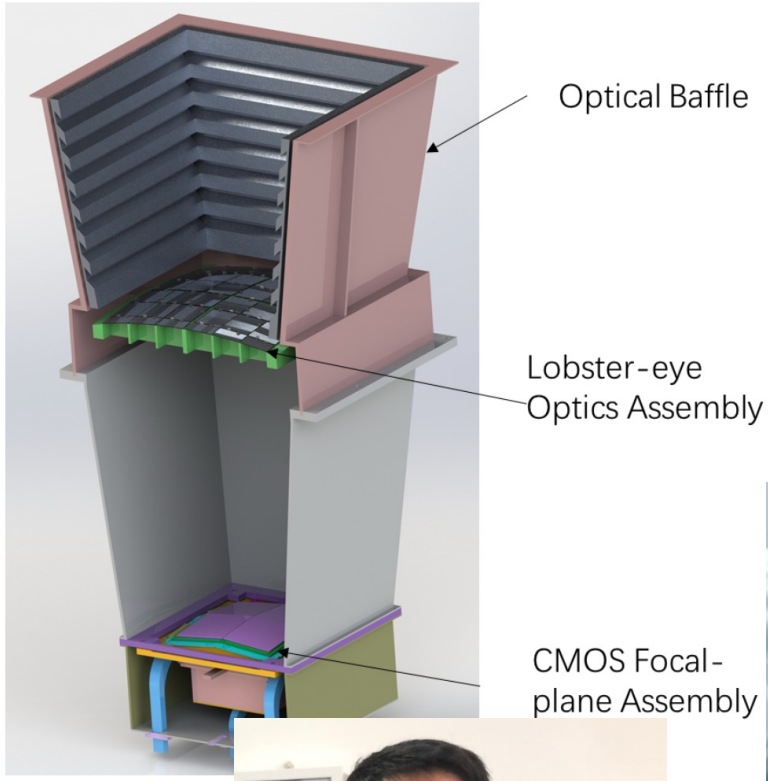
## Wide-field X-ray Telescope
WXT (12 modules)

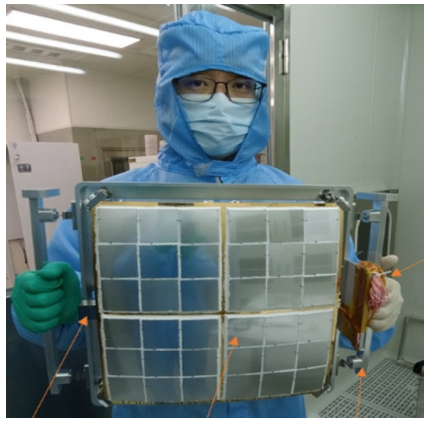
Optics: lobster-eye MPO
Detectors: CMOS
FoV: 3,600 sq deg (1.1 sr)
Band: 0.5 – 4 keV
Spatial resolution: ~ 5' (FWHM)
Effective area : 2 - 3 $cm^2$ @1keV

## Follow-up X-ray Telescope
FXT (2 units)

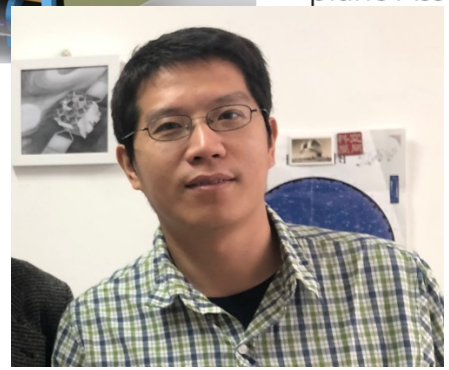
Optics: Wolter-1
Detectors: pn-CCD
FoV: ~1 deg
Band: 0.3 -10keV
spatial resolution: <30" (HPD, on-axis)
Effective area: 300 $cm^2$ @1keV (x 2 units)

# Wide-field X-ray Telescope and designed goals

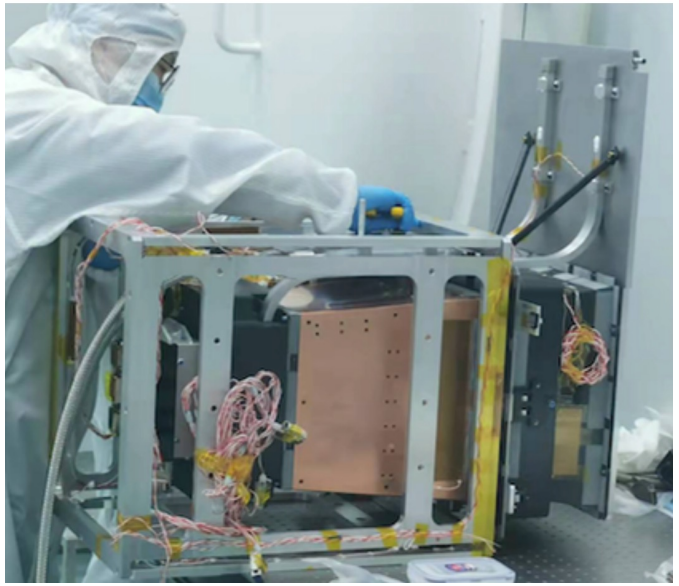


Dr. Chen Zhang



Dr. Zhixing Ling



WXT module in Phase C

| Parameter | Specification |
|---|---|
| Focal Length | 375mm±2% |
| FOV | ≥ 3600 square degrees |
| Modules | 12 |
| Effective Area | ≥2.7cm$^2$@1keV |
| Angular Resolution | ≤5′ @1keV |
| Energy Resolution | ≤170 eV@ 1.25 keV |
| Energy Range | 0.5~4.0 keV |
| Location Accuracy | <2′ (J2000) |
| Time Resolution | ≤0.05 s |

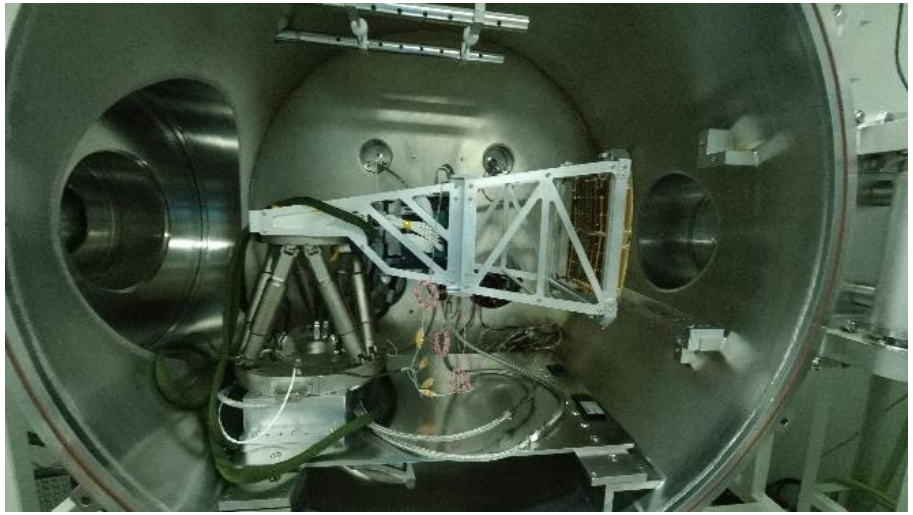
# Calibration schedule of the WXT Flight Model (FM)

| Level of calibration | Object | Calibration Facility | Calibration Time |
|---|---|---|---|
| Device | MPO chips | NNVT | 2022-2023 |
| | CMOS chip | NAOC | 2022-2023 |
| Assembly | Mirror Assembly 1-12 | NAOC/XIB | 2022.4-2023.4 |
| | Mirror Assembly 5 | MPE/Panter | 2022.9-2022.11 |
| | CMOS assembly | SITP | 2022.5-2023.3 |
| Complete Module | FM1 | IHEP/100XF | 2022.8 |
| | FM5 & FM11 | IHEP/100XF | 2023.5 |

The calibration of WXT instrument is a time-consuming and arduous campaign.

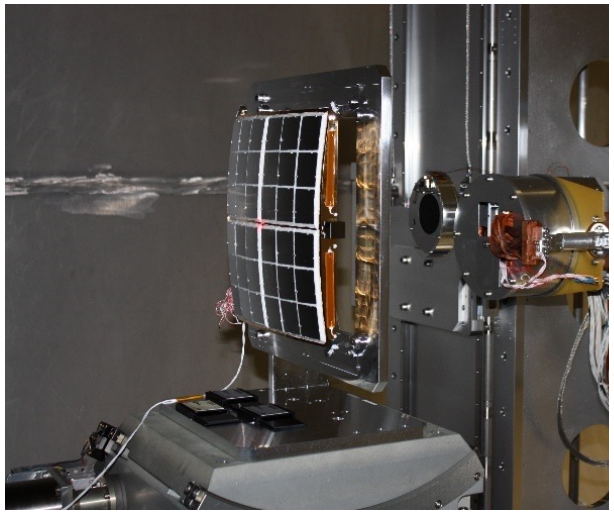
# The ground calibration of WXT instrument

Effective Area, PSF
Source Positioning Accuracy



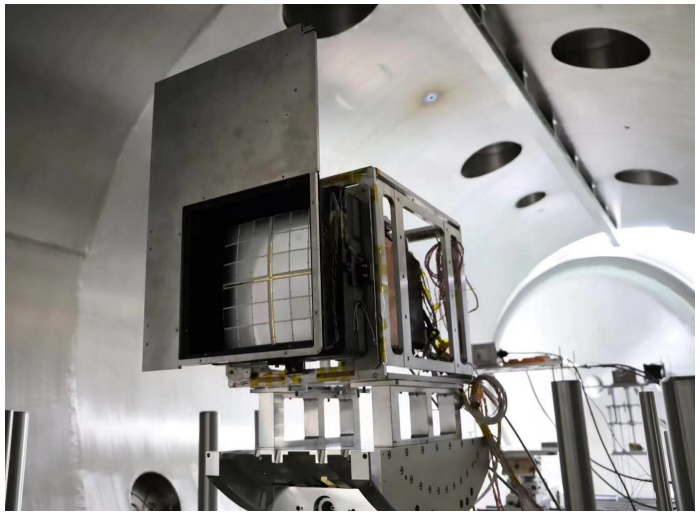
12 assemblies calibration
@NAOC-XIB, 2022-04 to 2023-04

Effective Area, Focus Search
Focal Plane Mapping



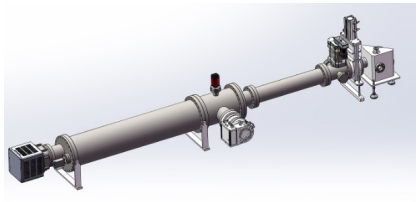
1 assembly calibration
@MPE-Panter, 2022.10

Effective Area, PSF
Source Positioning Accuracy



3 modules calibration
@IHEP, 2022.8 & 2023.5

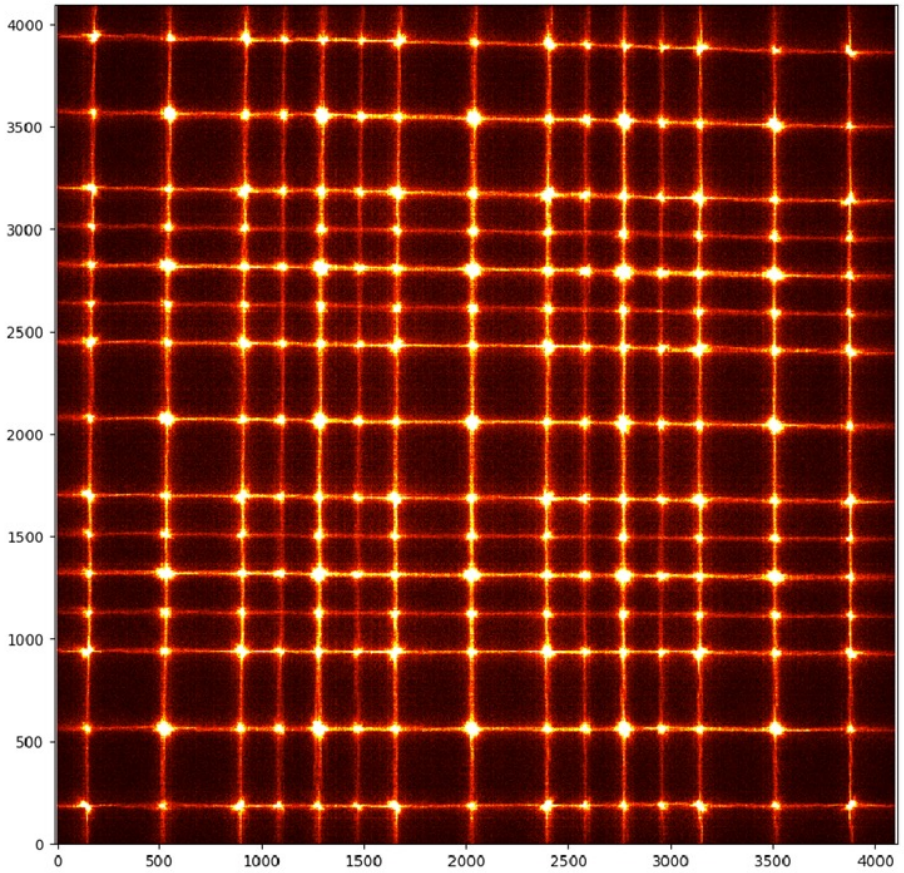
***Credit: Yanfeng Dai***



NAOC/XBC

Meanwhile, 54 CMOS chips (including 6 backups) were calibrated at NAOC.

# Calibration of MPO assembly at NAOC




FM MA Focal plane mapping
(209 test points for each FoV quandrant)

| | FWHM R90 arcmin | | | |
|---|---|---|---|---|
| ASSM ID | Sec1 | Sec2 | Sec3 | Sec4 |
| FM1 | 4.3078 | 4.8344 | 4.5685 | 4.7376 |
| FM2 | 4.337443 | 4.641851 | 4.758596 | 4.737322 |
| FM3 | 4.548191 | 5.004448 | 4.970792 | 4.919192 |
| FM4 | 4.139329 | 4.278519 | 4.086142 | 3.984573 |
| FM5 | 4.360381 | 4.76959 | 4.331304 | 4.450248 |
| FM6 | 3.987483 | 3.847239 | 3.904342 | 3.886328 |
| FM7 | 3.787614 | 4.372452 | 4.183869 | 4.049289 |
| FM8 | 4.128201 | 4.329604 | 4.383369 | 4.013506 |
| FM9 | 3.87564 | 3.87423 | 3.967965 | 3.962235 |
| FM10 | 4.277768 | 3.685402 | 4.158209 | 4.327053 |
| FM11 | 4.661242 | 4.406602 | 4.448557 | 4.449075 |
| FM12 | 4.224141 | 4.484852 | 4.297872 | 4.390398 |

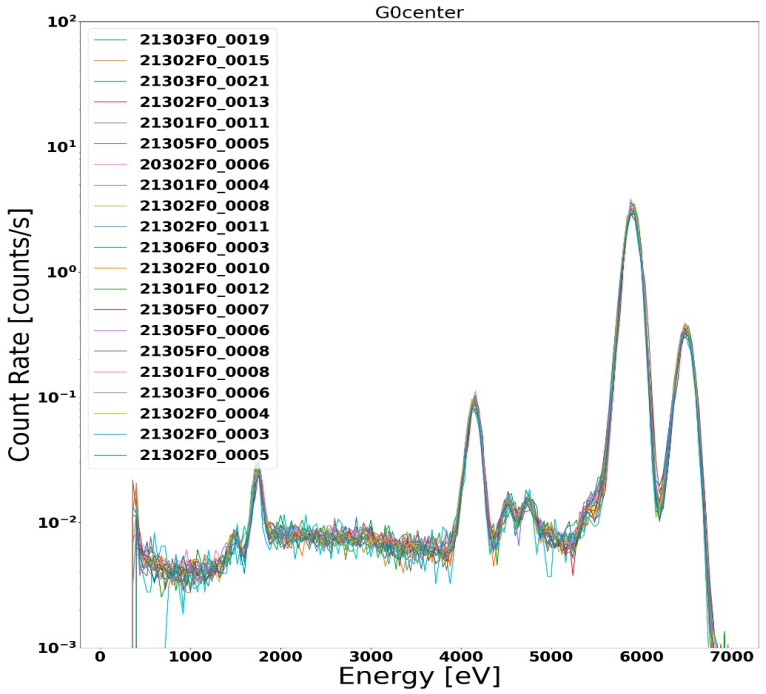
Optics Assemblies FMs Calibration @NAOC

No PSF misalignment

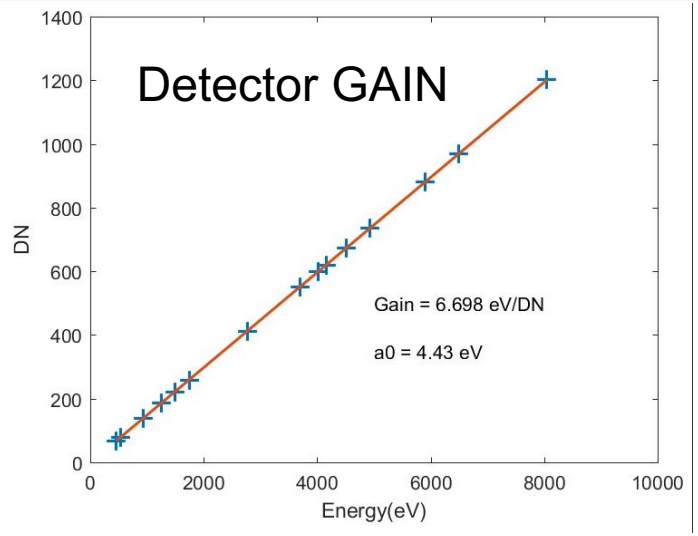
***Credit: Chen Zhang***

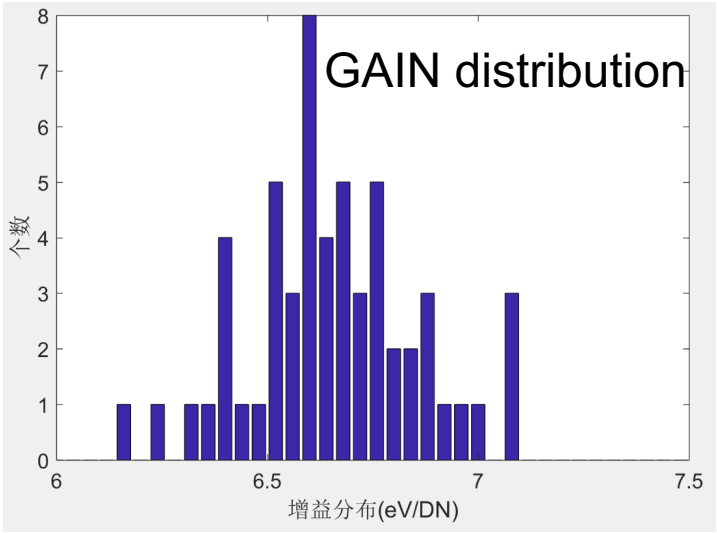
The angular resolution ~3-5 arcmin for Optics Assemblies FMs, better than QMs.

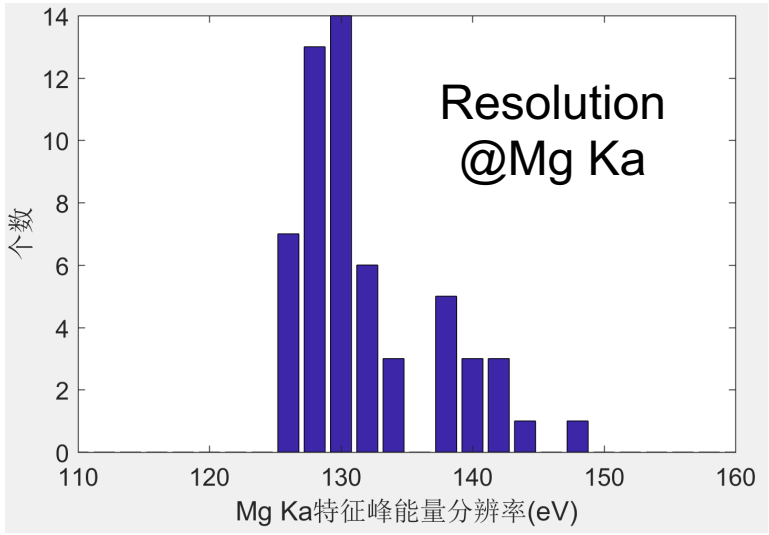
# Calibration of CMOS sensors at NAOC

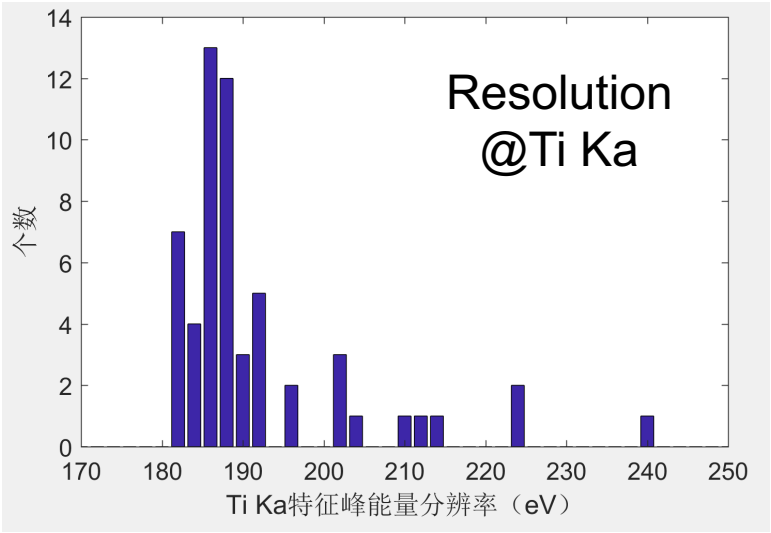



Fe55-illuminated spectra for CMOS FM chips



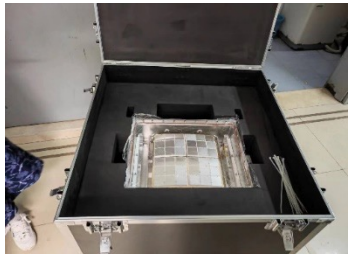



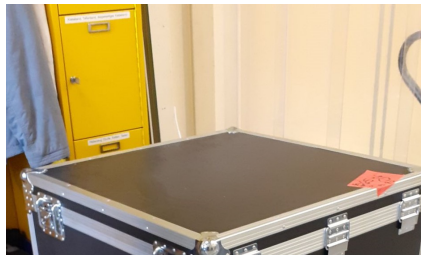

GAIN and energy resolution

*Credit: Zhixing Ling*

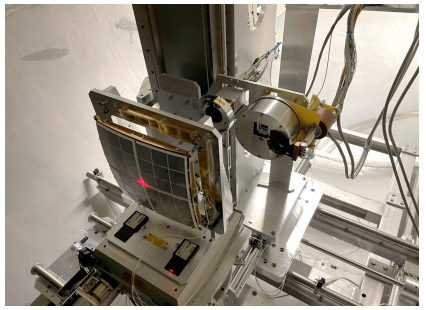
# Calibration of FM5 MA at MPE/Panter facility



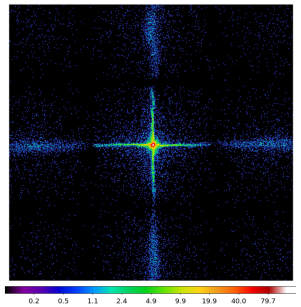
Sep. 5 2022 OFM5@NAOC



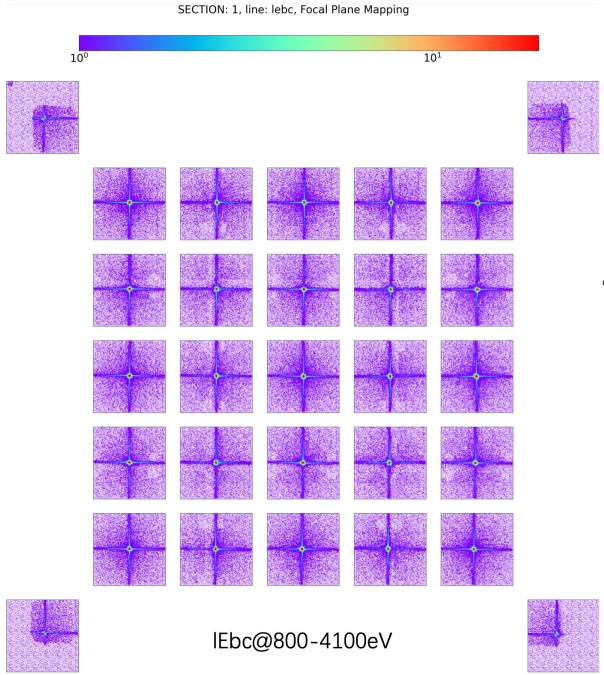
Sep. 20 2022@MPE

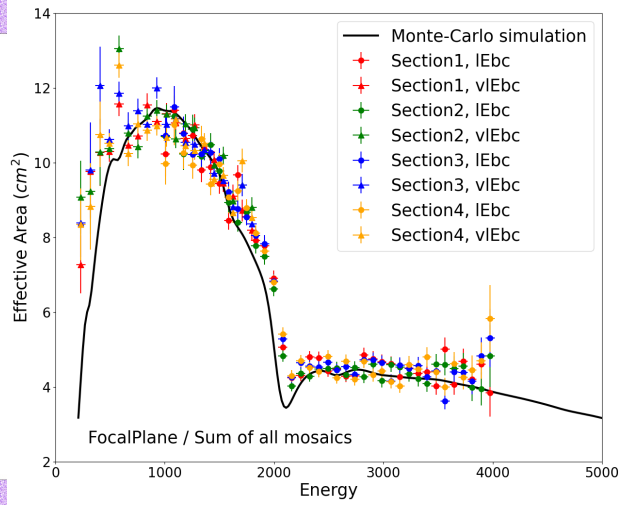


OFM5@PANTER



Dec. 29 2022 Back to NAOC



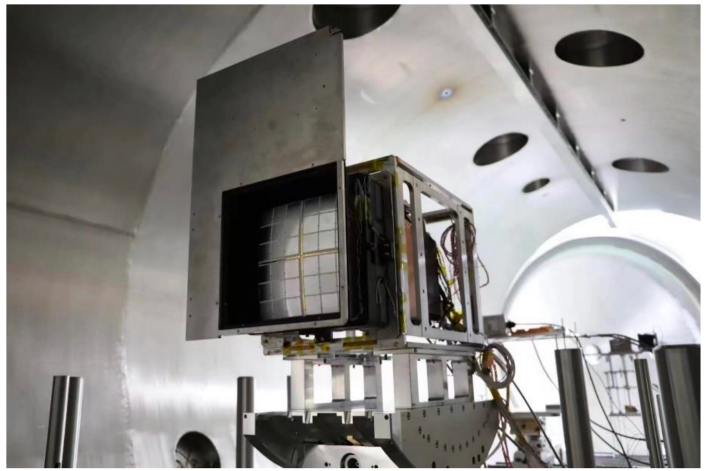

## Optics Assembly Calibration@Panter

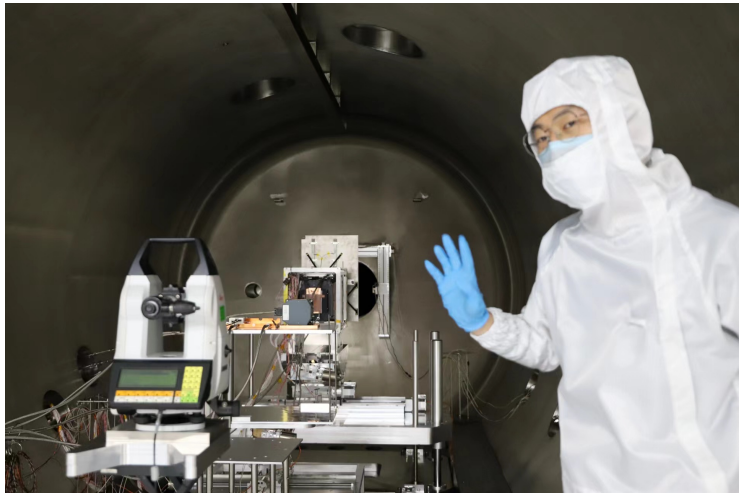
| | LEIA(OQM3) | EP OFM5 |
|---|---|---|
| Focal Length | 375mm | 375mm |
| FOV | >18*18 | >18*18 |
| Angular Resolution | Best 4′<br>Arg<5′ | Best 3′,<br>Arg<4.5′ |
| Effective Area | >95% | >95% |

***Credit: Yanfeng Dai & Vadim Burwitz***

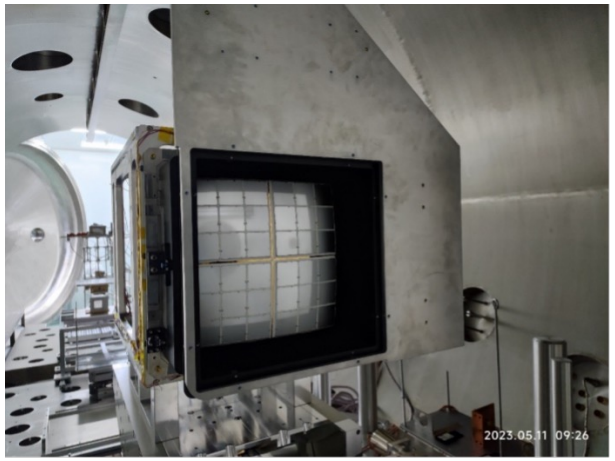
***MPE paper:*** **Rukdee et al. 2023, https://doi.org/10.1117/12.2677479**

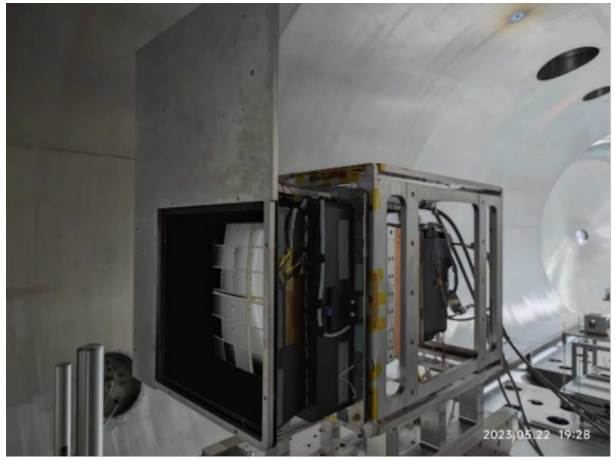
# Calibration of the 3 complete modules at IHEP



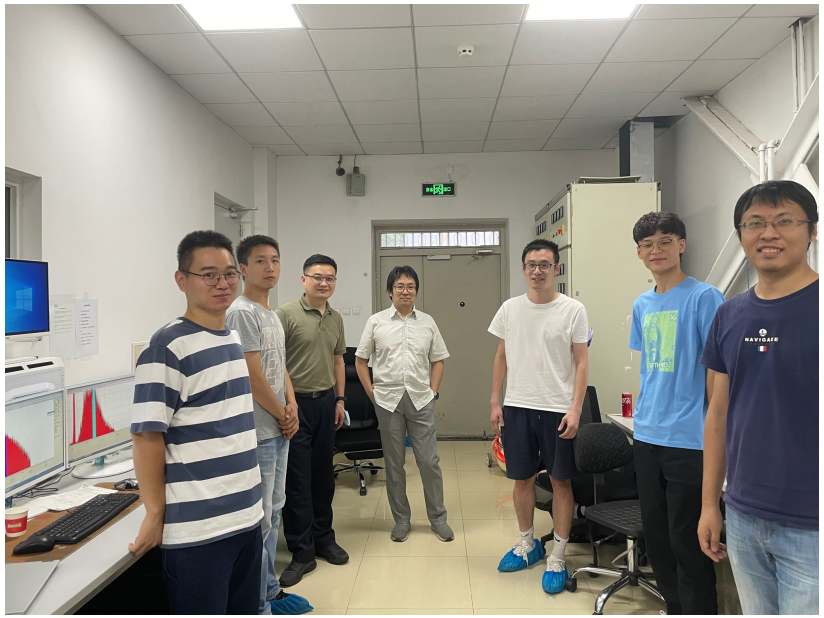


FM1@IHEP 100m facility, 2022.8

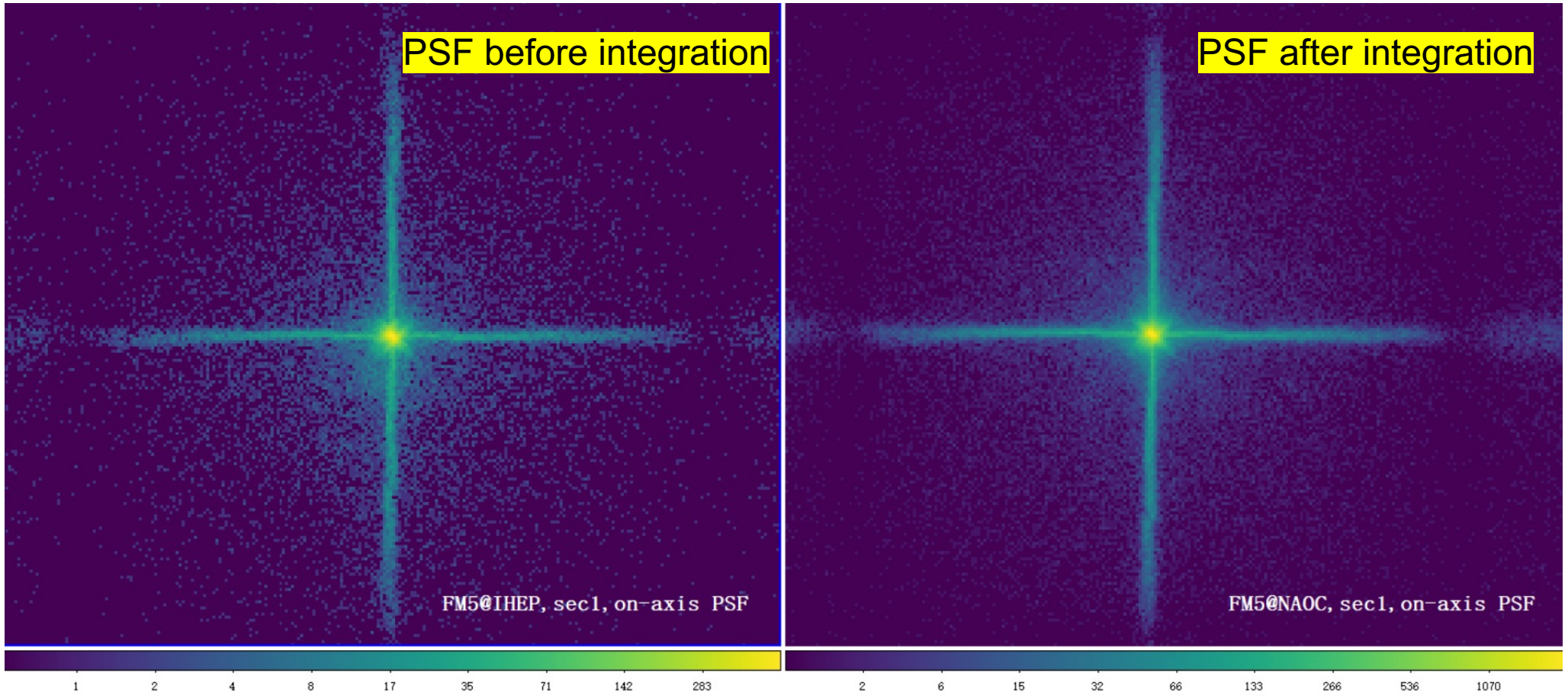



FM5, FM11 @IHEP 100m facility, 2023.5

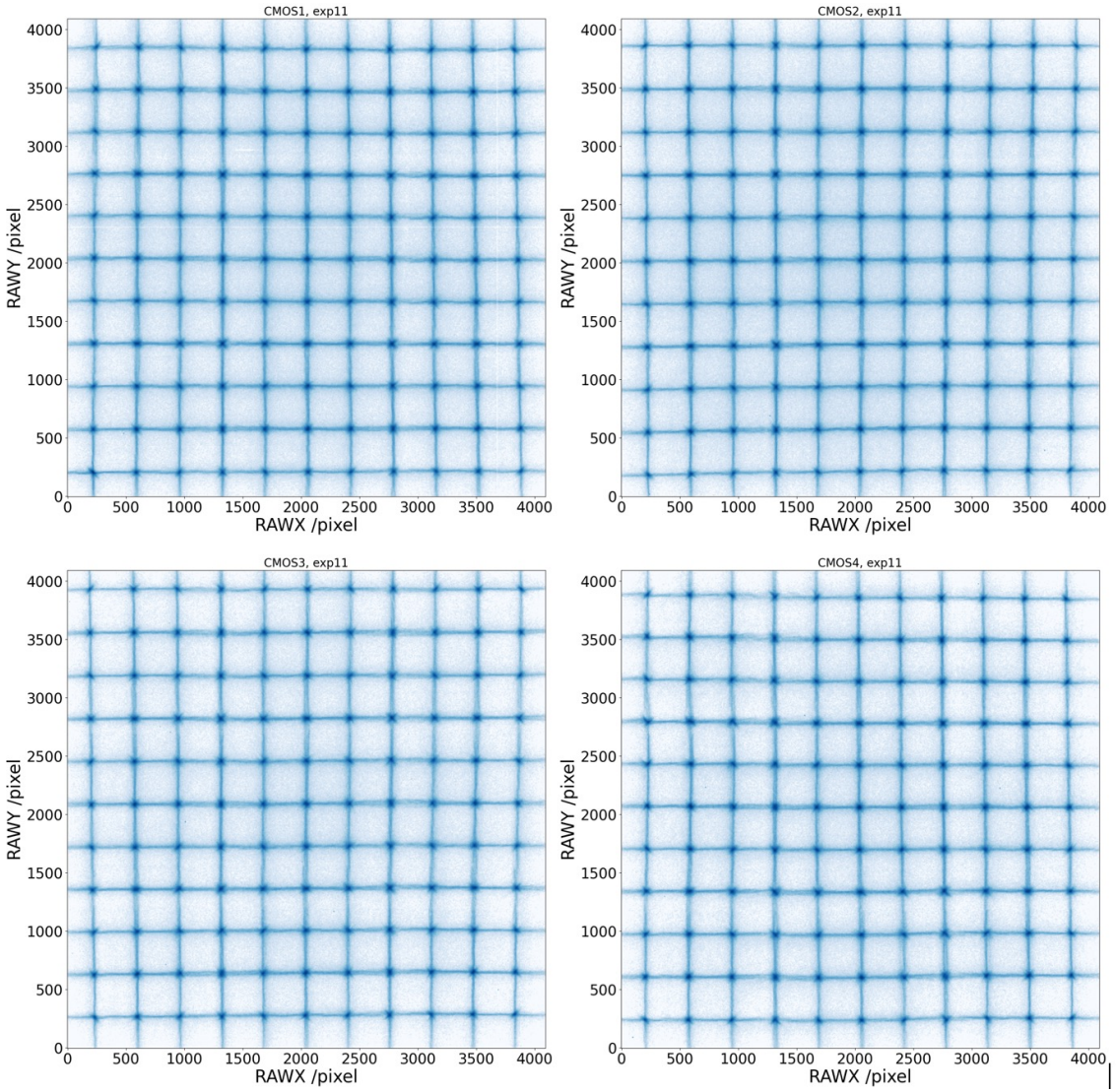


# PSF before and after module module integration

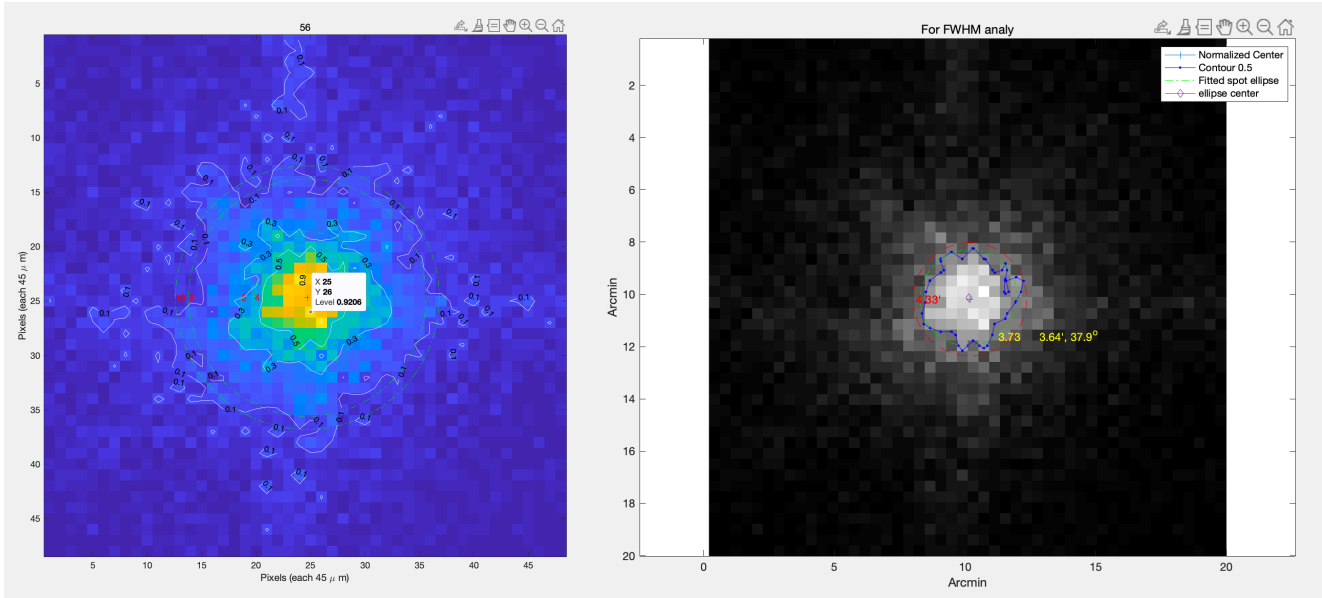



The PSF shape remains stable after integrating to the complete module

# Module calibration: PSF



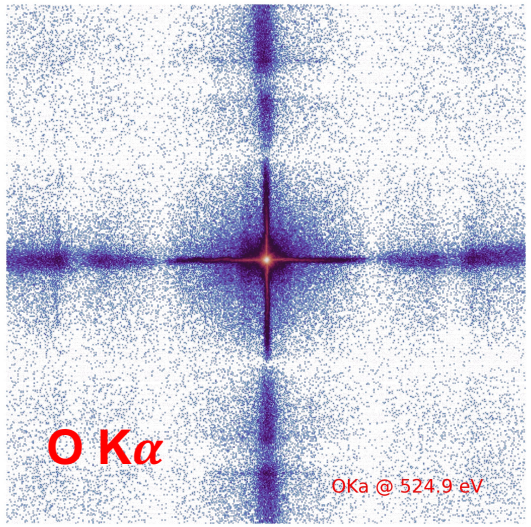

Foal plane mapping within the FoV of FM1 @1.25 keV

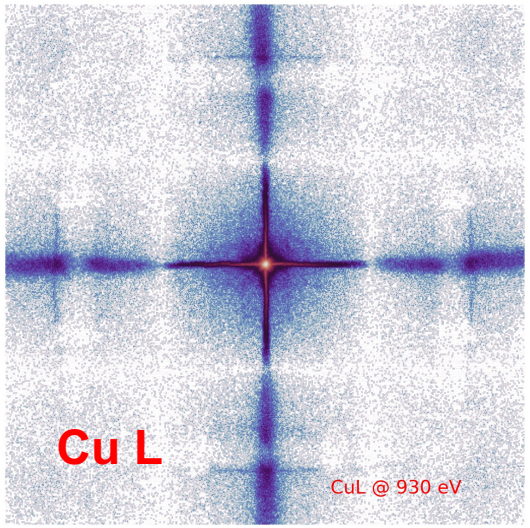


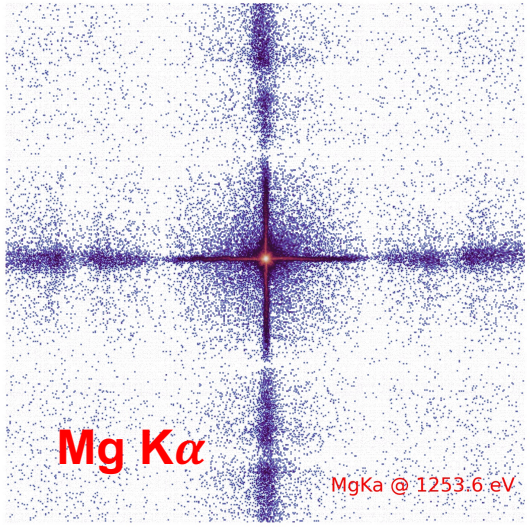

Elliptical fitting of the PSF focal spot

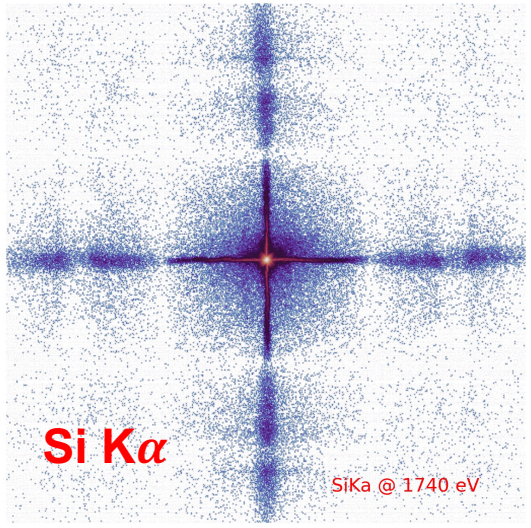
PSF, FWHM~3-5’ @1.25 keV
no significant variations within the FoV

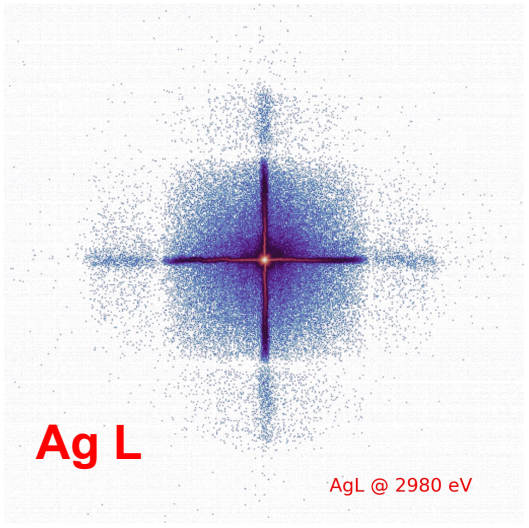
# Module calibration: PSF shape at different energies

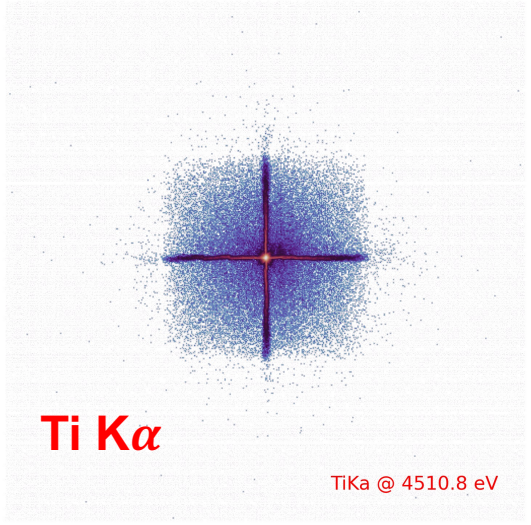


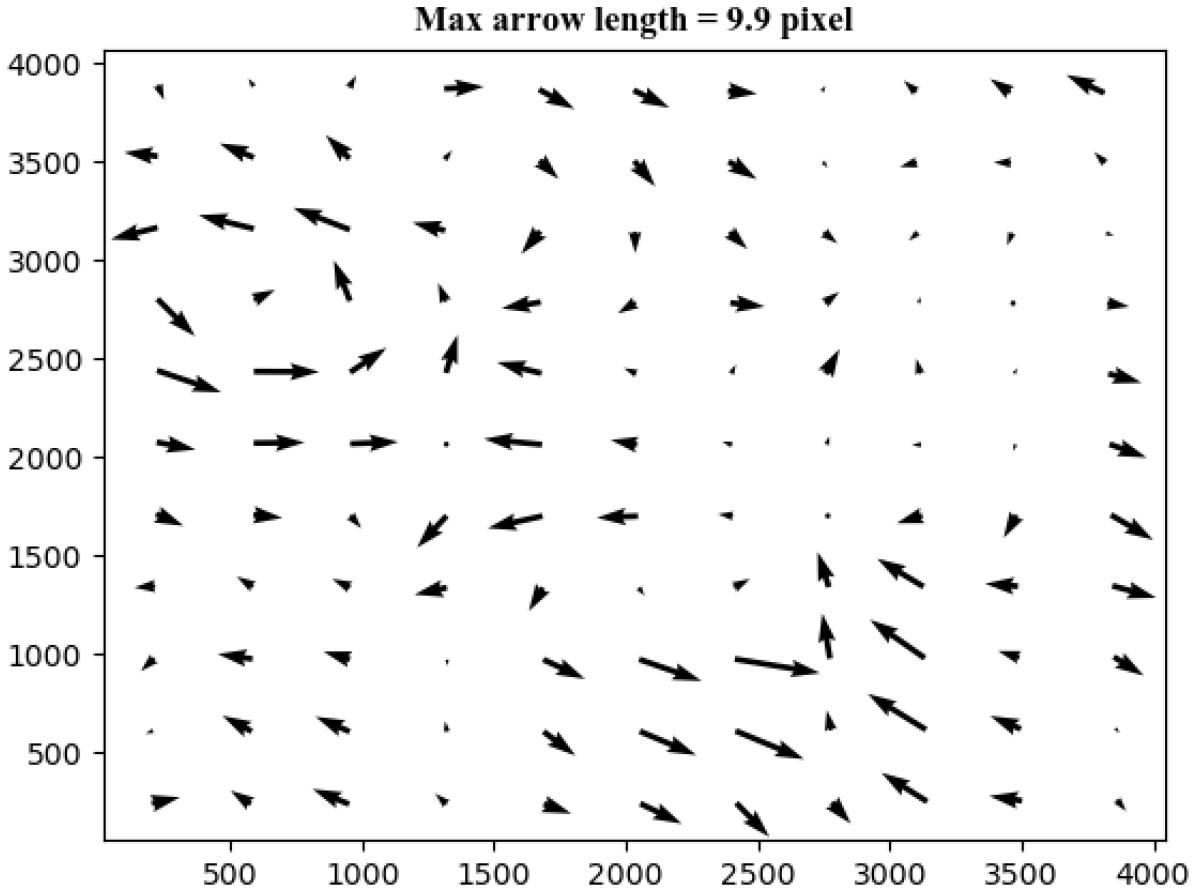



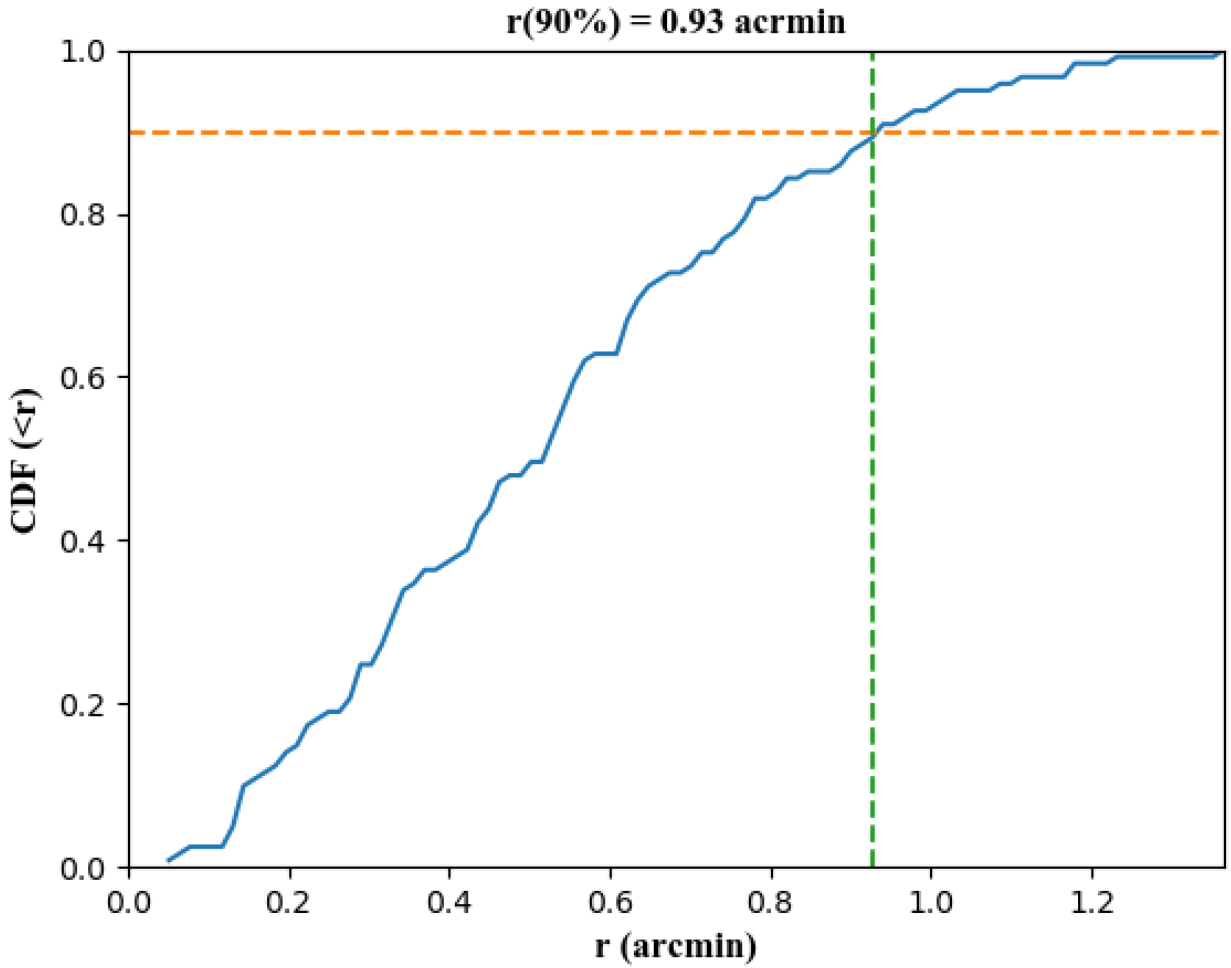




The PSF spread is larger at lower energies due to larger critical angle of grazing incidence.

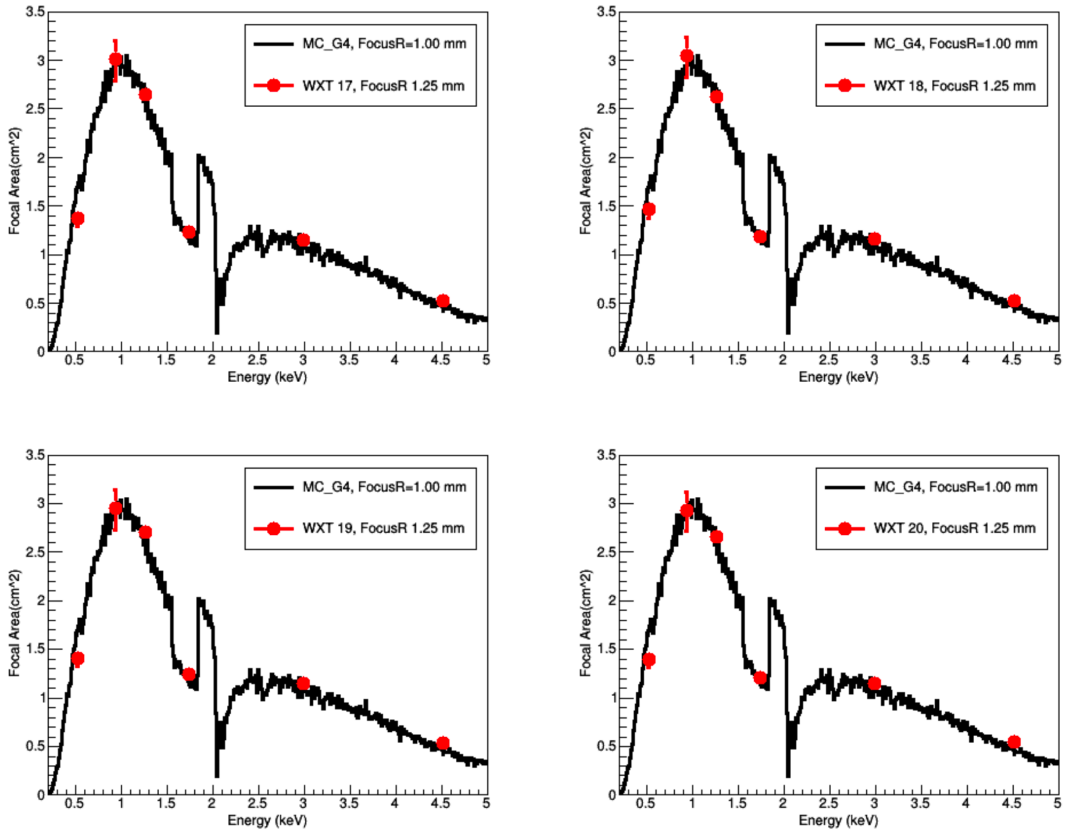
# Module calibration: Localization



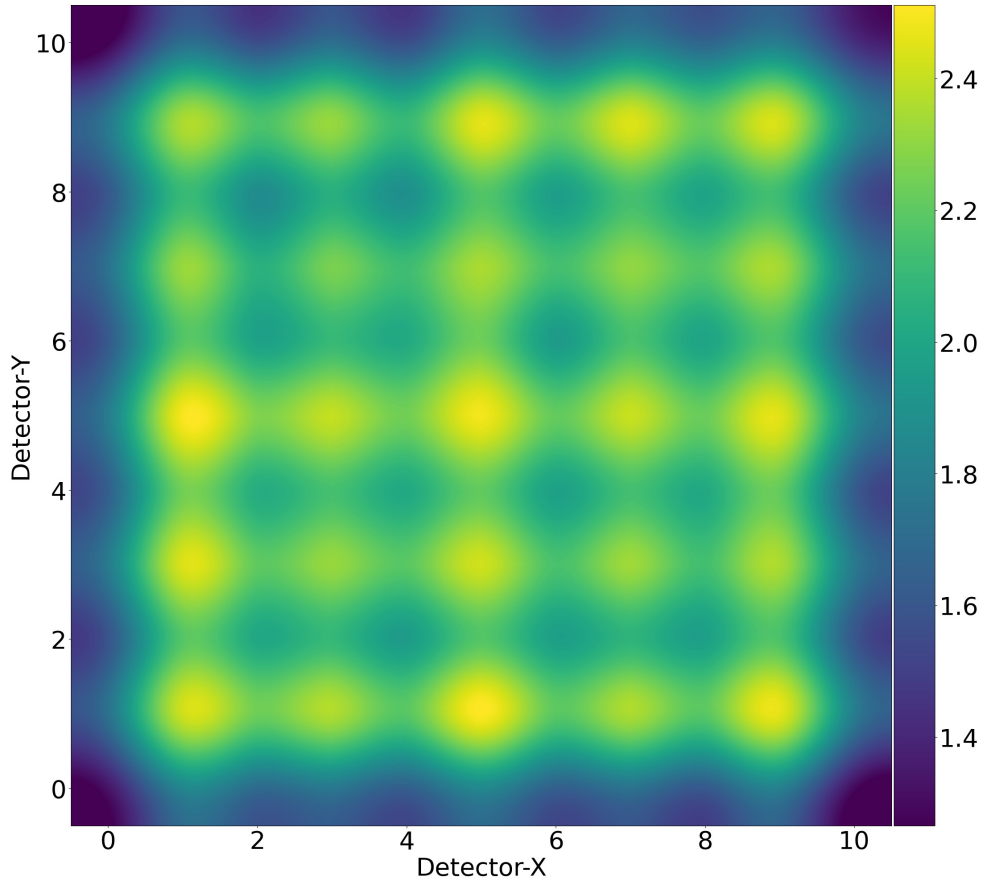




The positional offset of the PSF can be used to calibrate the transform matrix and non-linear corrections.
The estimated positioning accuracy ~ 1-2 arcmin

# Module calibration: Effective area

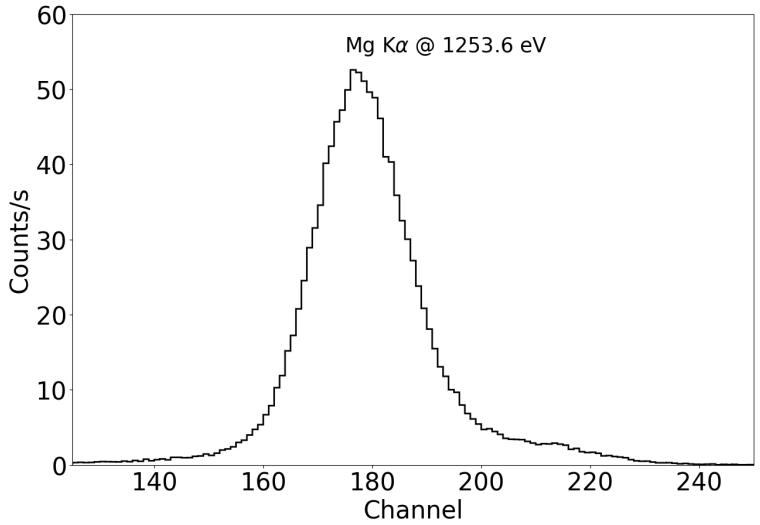


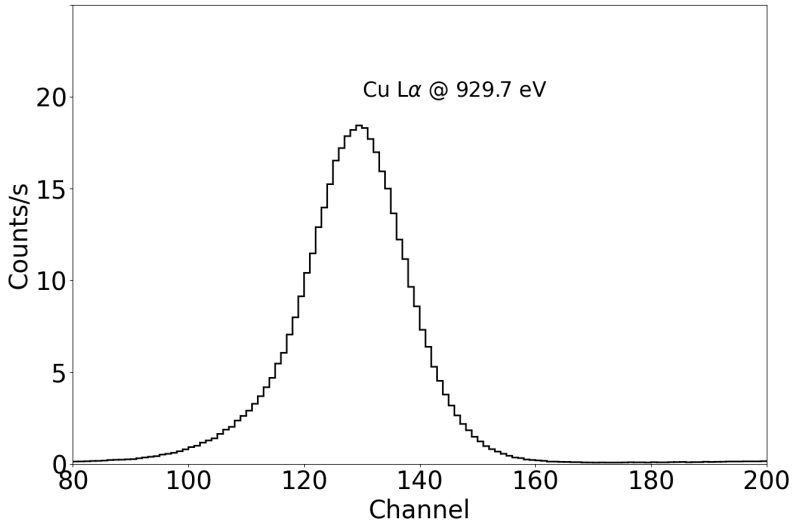

The measured effective areas are generally consistent with simulation curve.

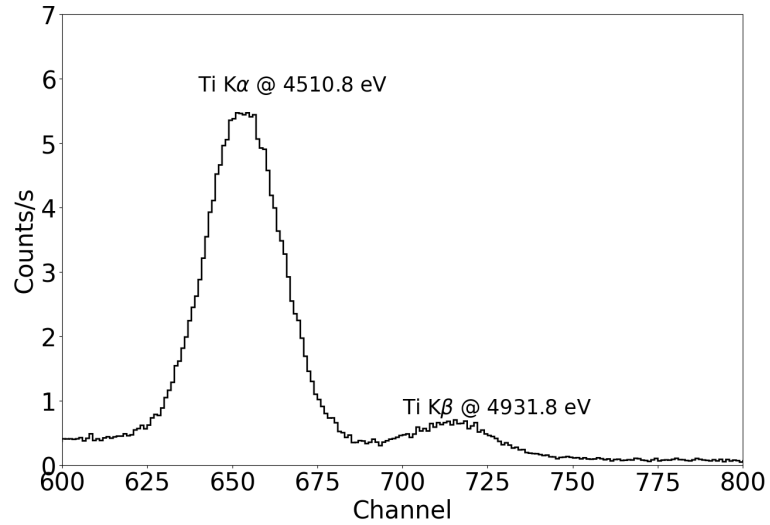


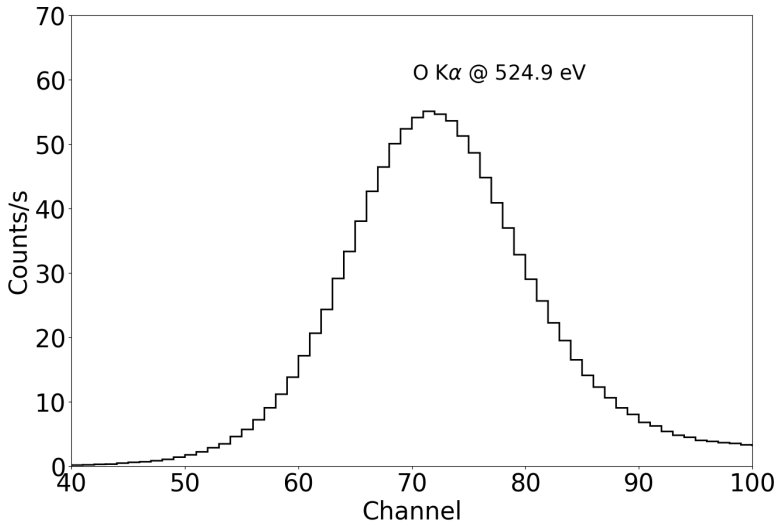

- The effective area is around 2-3 $cm^2$
- Slight non-uniformity within the FoV (vignetting near the edge & blocking of the mounting frame)
- The pattern can be reproduced by Monte Carlo simulations

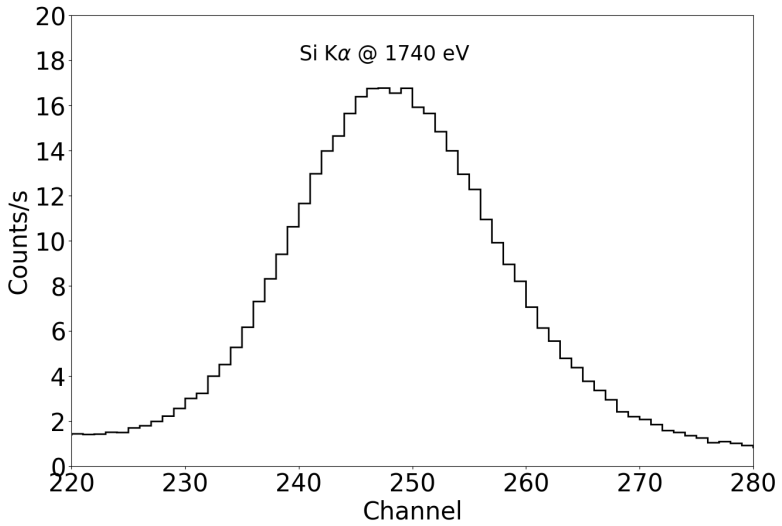
# Module calibration: Energy response of CMOS detectors

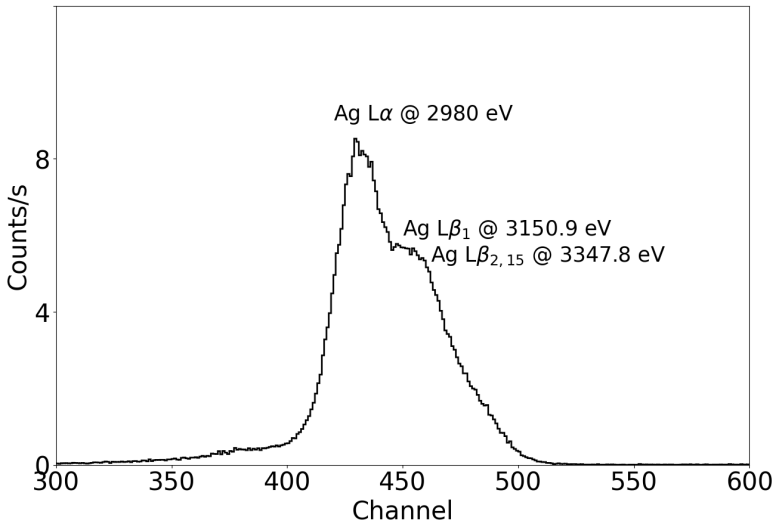



The measured properties of the CMOS detectors (GAIN, energy resolution) remain unchanged after integration.

# Goals and achievements

| Parameter | Specification/Goals | Measurements |
|---|---|---|
| **Focal Length** | 375mm±2% | ~374.9 - 382.5mm |
| **FOV** | ≥ 3600 square degrees | ~3850 square degrees |
| **Modules** | 12 | 12 |
| **Effective Area** | ≥2.7 $cm^2$@1keV | ≥3 $cm^2$@1keV |
| **Angular Resolution** | ≤5′ @1keV | ~3-5′ @1keV |
| **Energy Resolution** | ≤170 eV@ 1.25 keV | ~130 eV@ 1.25 keV |
| **Energy Range** | 0.5-4.0 keV | ~0.35-6 keV |
| **Location Accuracy** | <2′ (J2000) | ~1-2′ (J2000) |
| **Time Resolution** | ≤0.05 s | 0.05 s |

In general, the designed goals are fulfilled based on ground measurements.

# Future work

- The 1st version CALDB has been constructed based on ground calibration results and applied to EP-WXT data analysis
- Update the calibration database with in-flight calibration observations (see Heyang's talk)
- Paper publication

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RESEARCH

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**Ground calibration result of the *Lobster Eye Imager for Astronomy***

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The ground calibration result of LEIA has been published (Cheng et al. 2024)
Doi: 10.1007/s10686-024-09932-0

# Summary

- Extensive tests and calibrations on different levels of devices, assemblies and complete modules were carried out before the launch of EP.
- The FMs show generally **better performance** than QM(LEIA).
- The **angular resolution** of WXT can reach ~**3-5 arcmin**, without significant variations within the FoV.
- The **effective area is ~ 3 $cm^2$ @ 1keV, ~ 1 $cm^2$ @ 4keV**, only showing **mild non-uniformity** within the FoV.
- The CMOS detectors show **similar performance in GAIN and energy resolution.**
- The 1$^{st}$ version of calibration CALDB has been built and applied to EP/WXT data analysis, and will be updated via in-flight calibration recently.

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