15th IACHEC meeting

Possible ways to improve the energy calibration process for future X-ray missions

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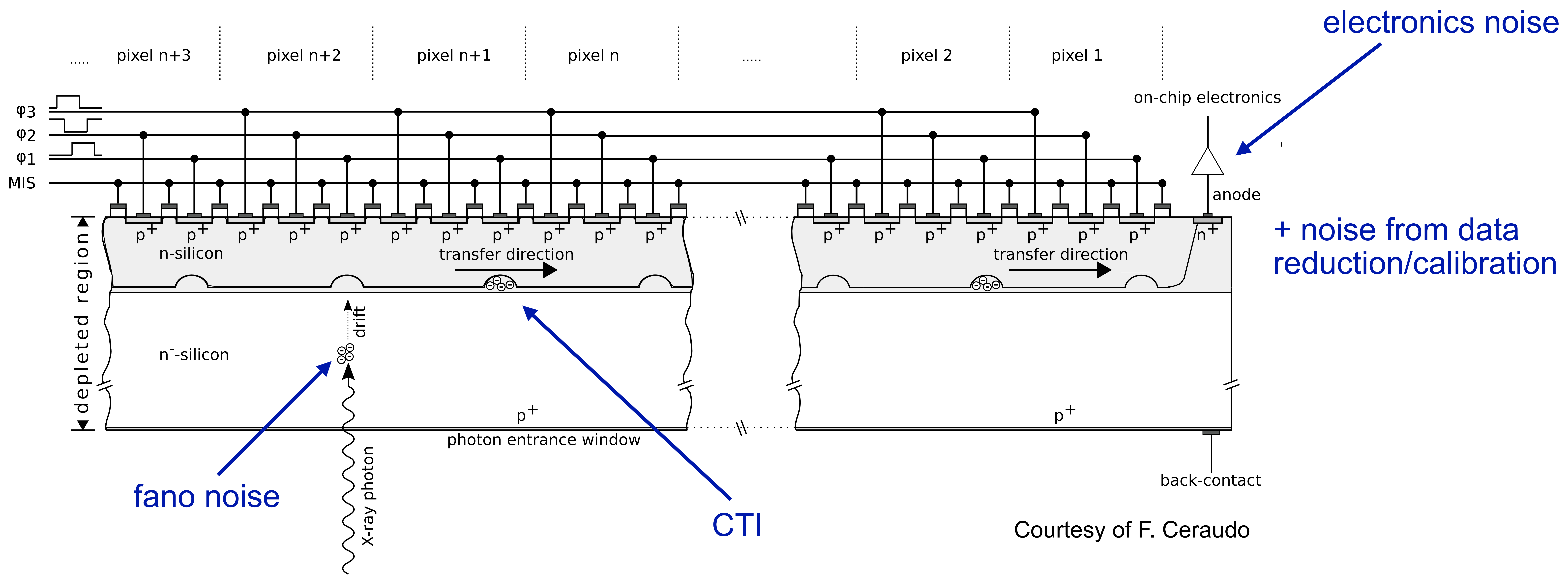
Outline

1. General context

2. Energy calibration via correlation

3. Mitigate the charge sharing noise

X-ray CCD detector noise



Courtesy of F. Ceraudo

- Possible effects affecting the spectral performance of CCD detectors

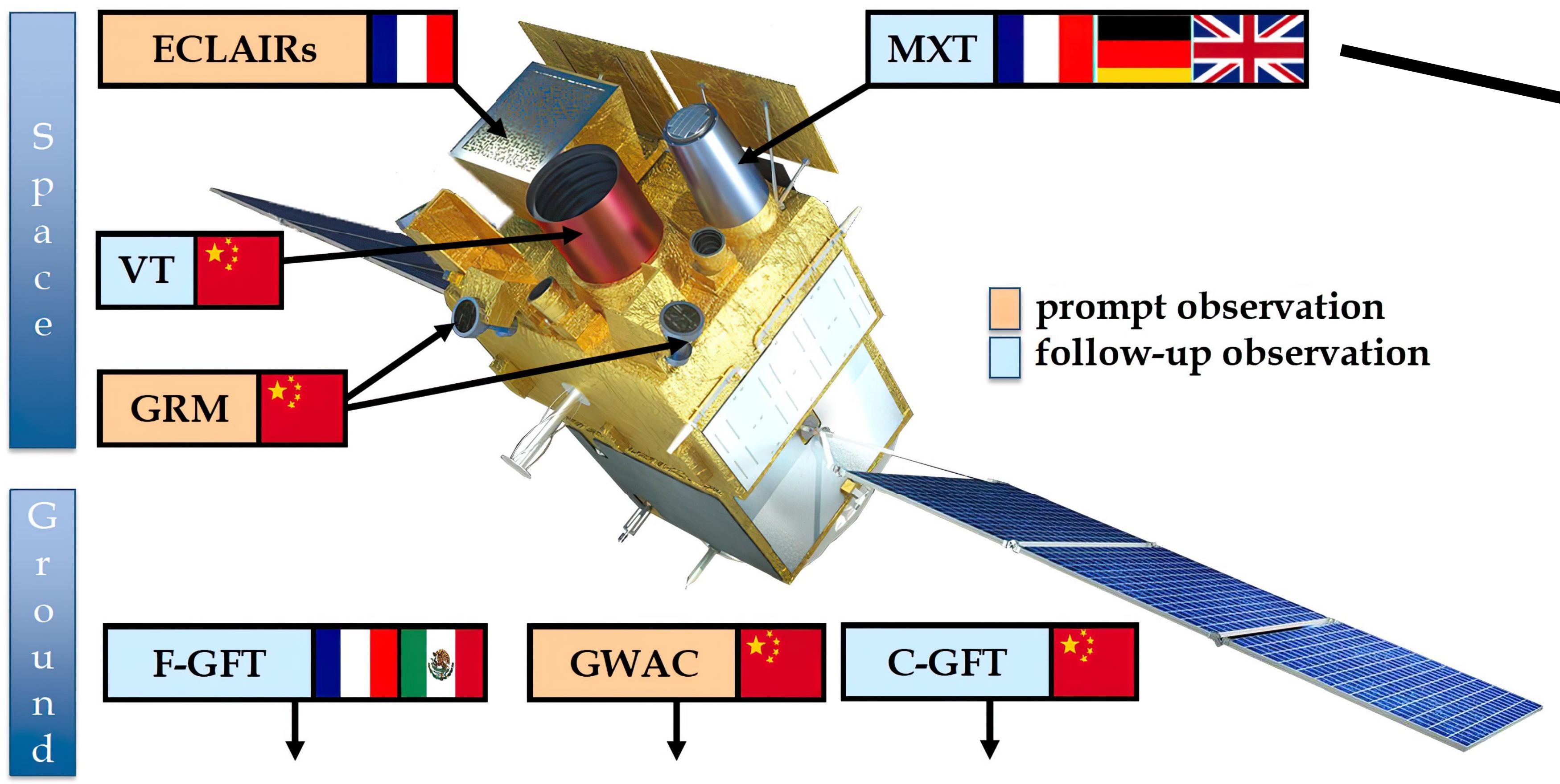
From raw to calibrated events

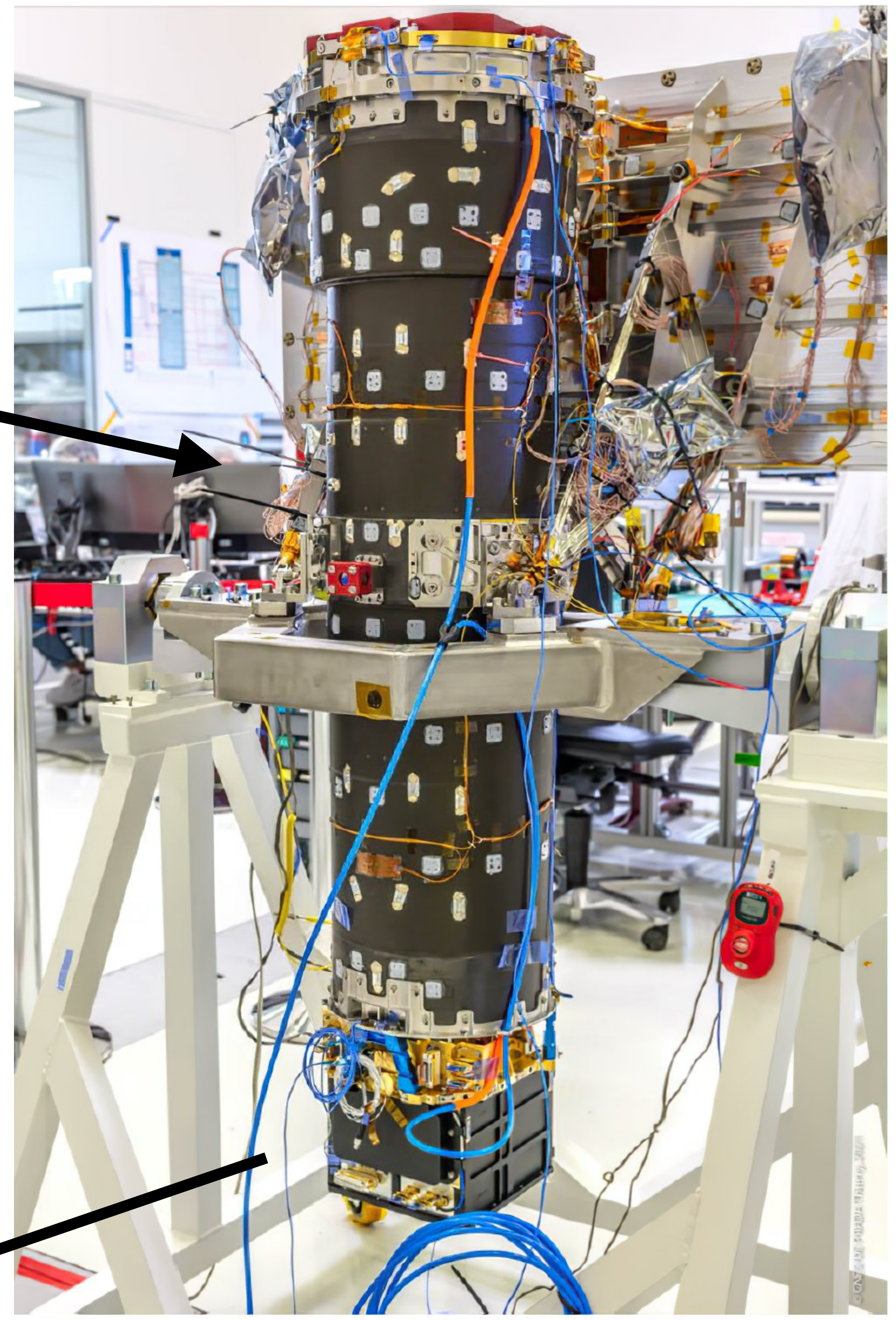
- Accurate and optimized science products → critical for accurate astrophysics interpretations
- Future missions with larger focal plane → think about efficient/optimized methods to reduce/calibrate X-ray data

Space Variable Objects Monitor (SVOM)

- Detect and observe GRBs
- Planned for end of 2023

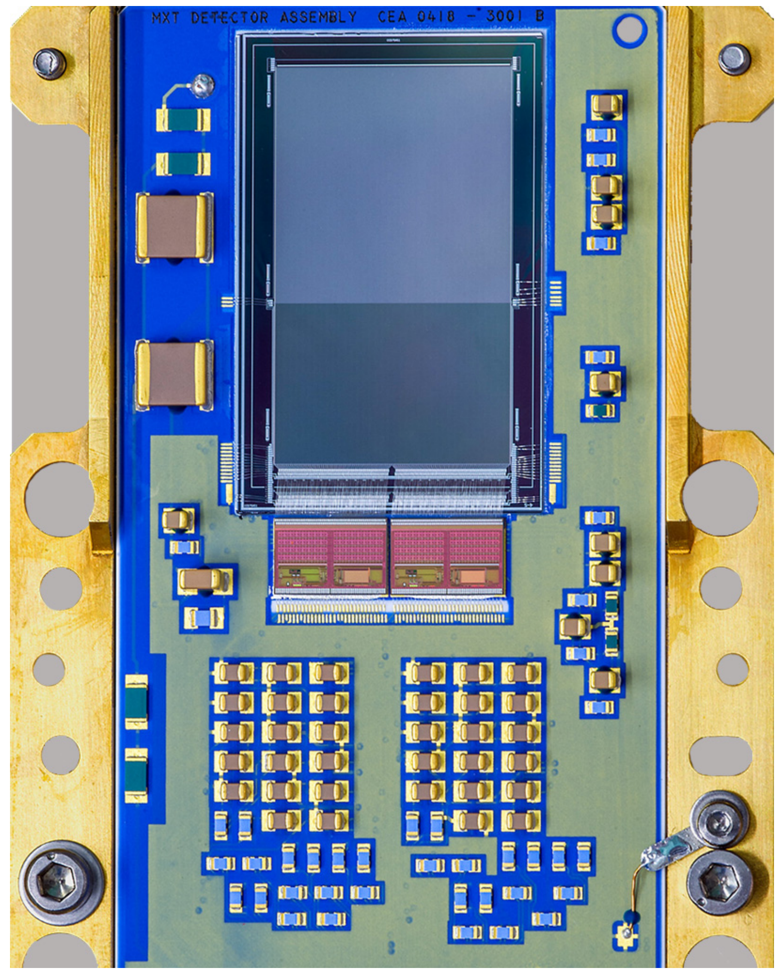
- Onboard instruments:
  - ECLAIRs
  - GRM
  - MXT
  - VT





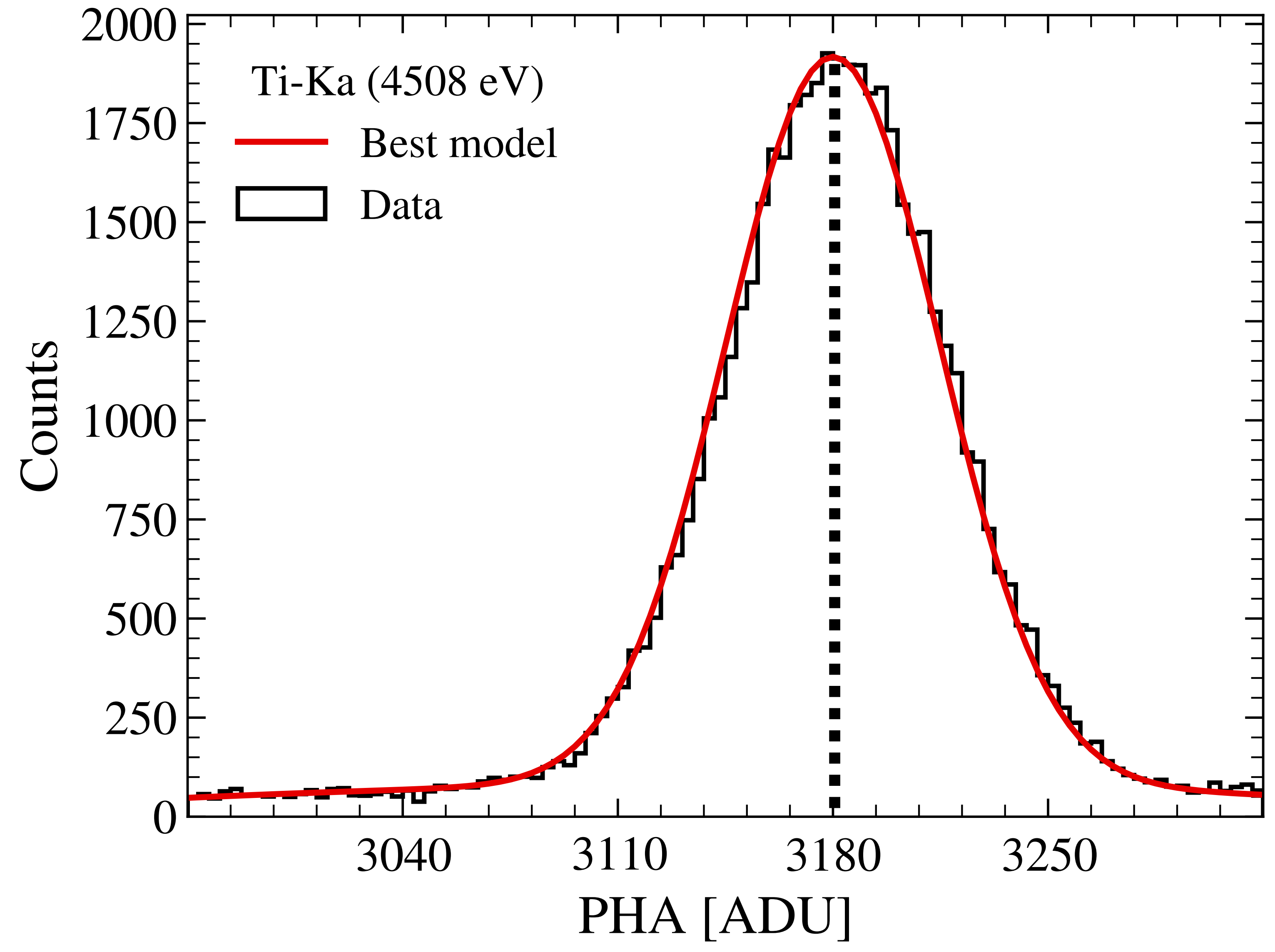
Microchannel X-ray Telescope

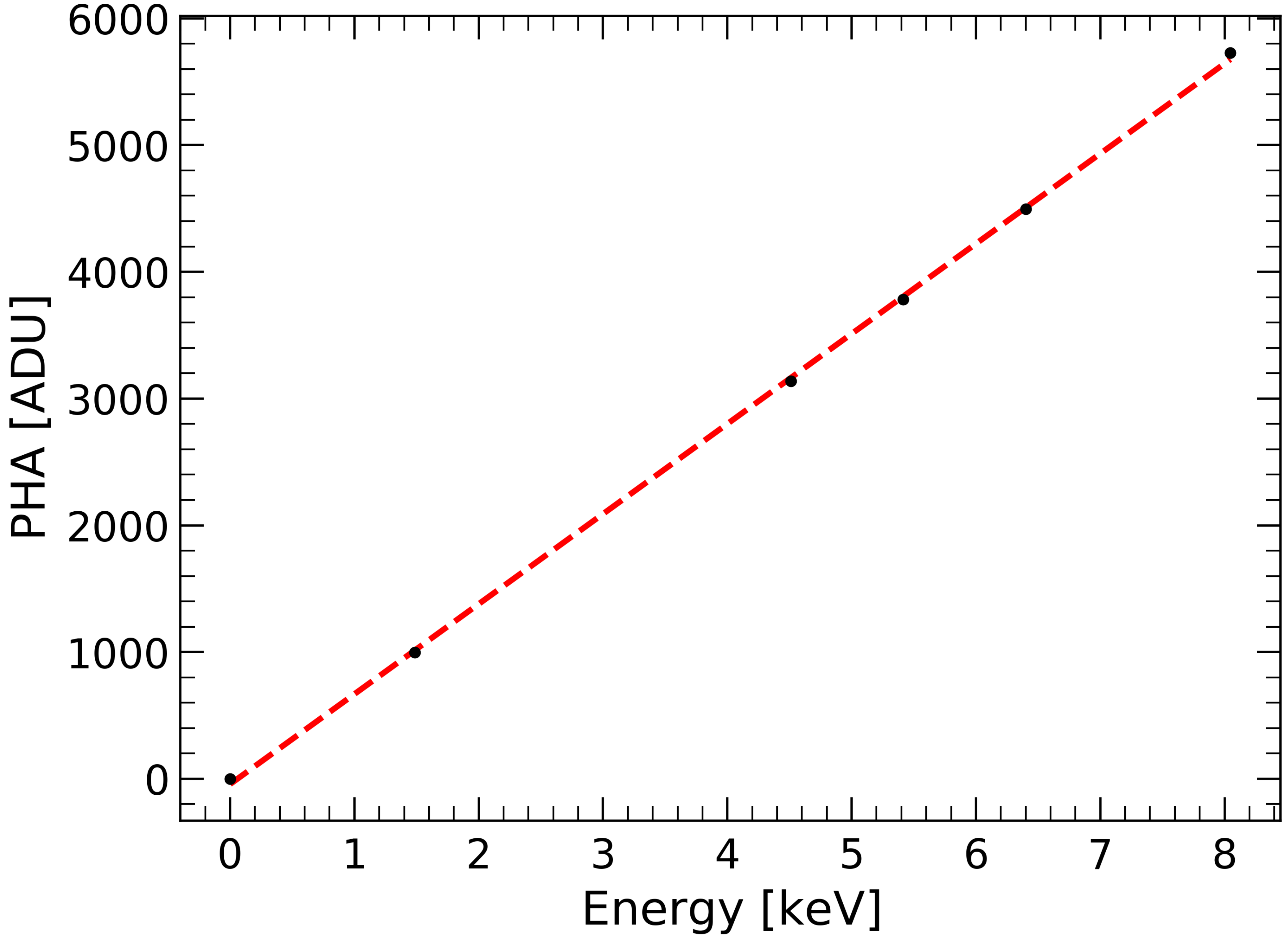
- MXT = compact (1.2 m), light (42 kg) and innovative X-ray telescope based on micropore optics (lobster-eye)
  - energy range: 0.2 - 10 keV
  - back illuminated pnCCD fully depleted (450 µm)
  - 256 × 256 pixels of 75 µm × 75 µm
  - readout by 2 CAMEXs of 128 column each



Energy calibration

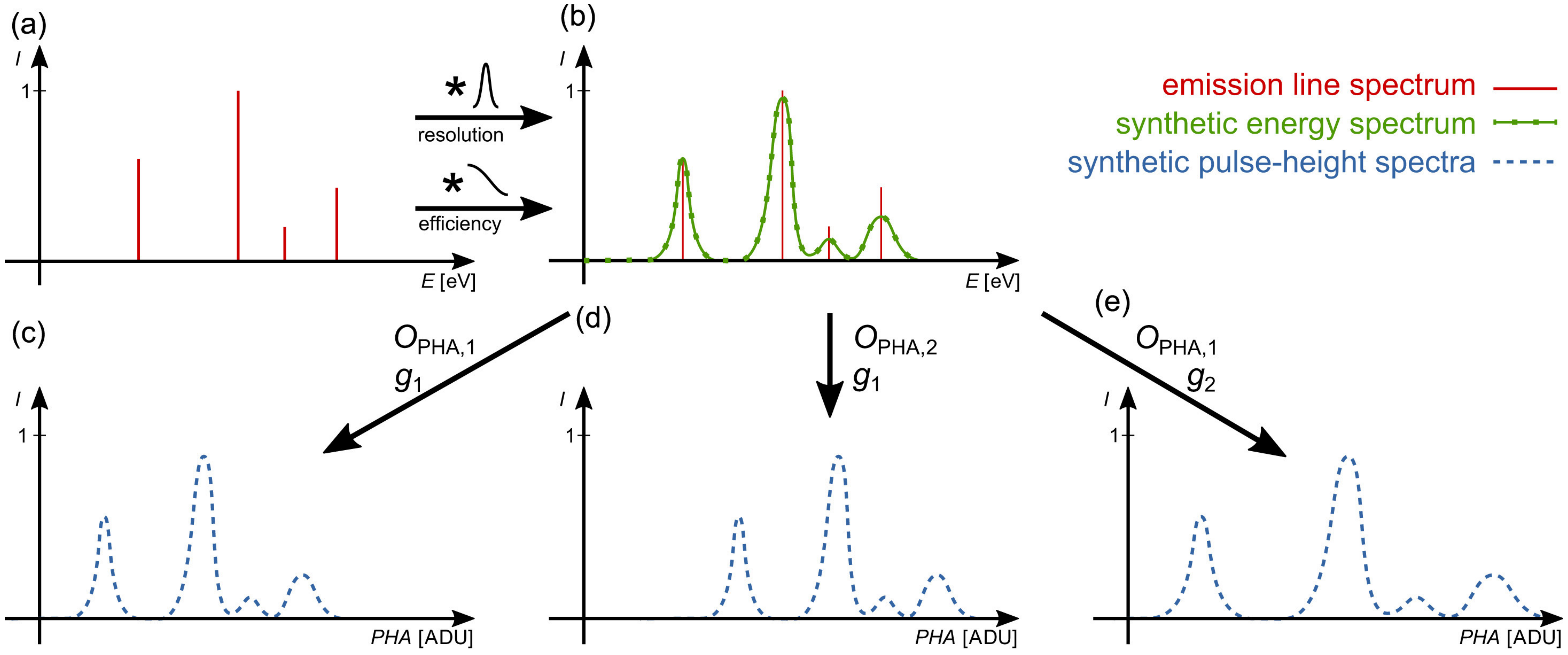
- Energy calibration process = find the relation ADU ↔ keV
- Require priors: known source (e.g., radioactive source)
- Standard method = peak fitting using multiple emission lines
  - relatively slow, not always easy to apply
  - require enough counts in each line





Energy calibration by correlation (ECC)

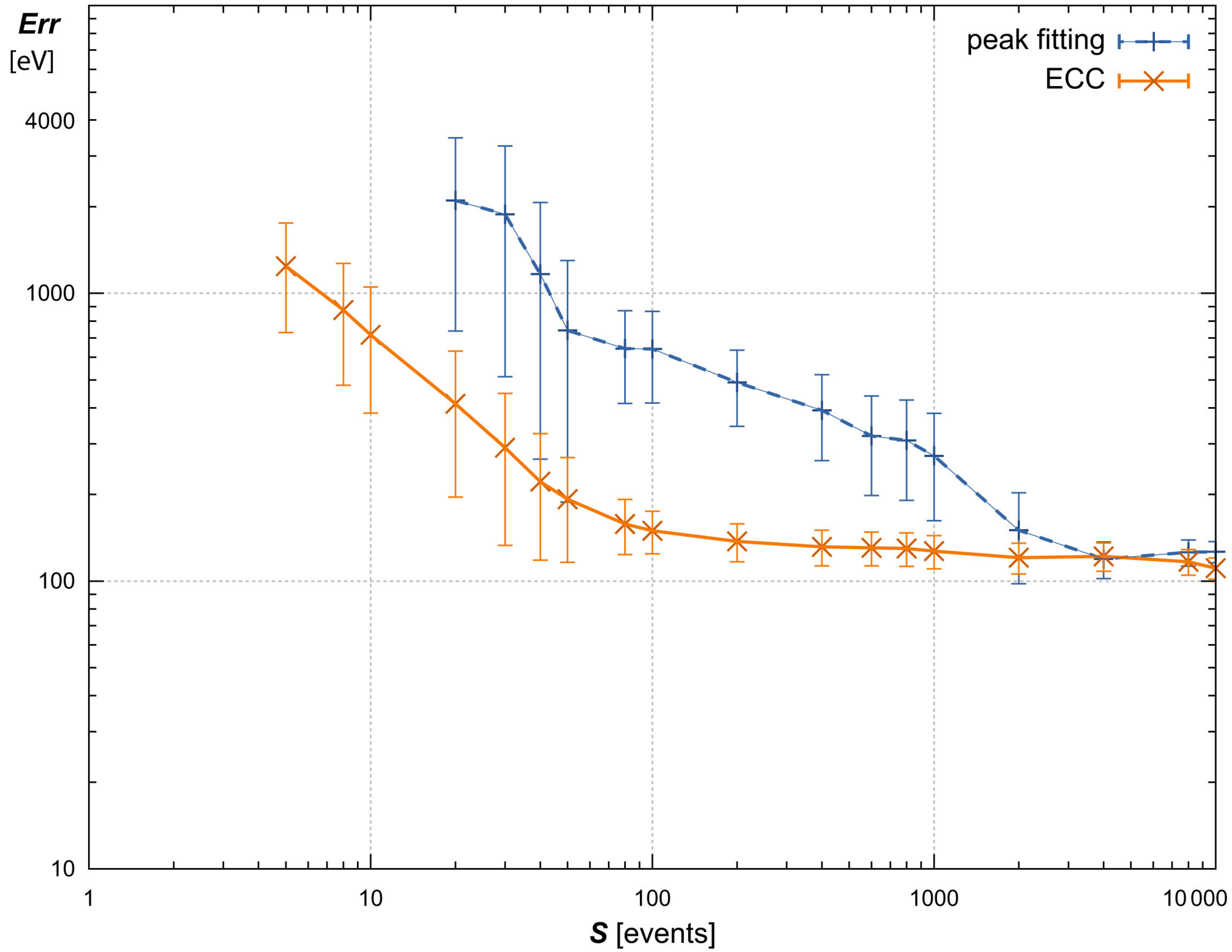
- Firstly developed for CdTe hard X-ray detectors (Maier&Limousin+16)
- Gains and offsets = maximum of correlation between a **synthetic spectrum** and the **raw ADU spectrum**



Maier&Limousin+16, Maier+20

Advantages of ECC

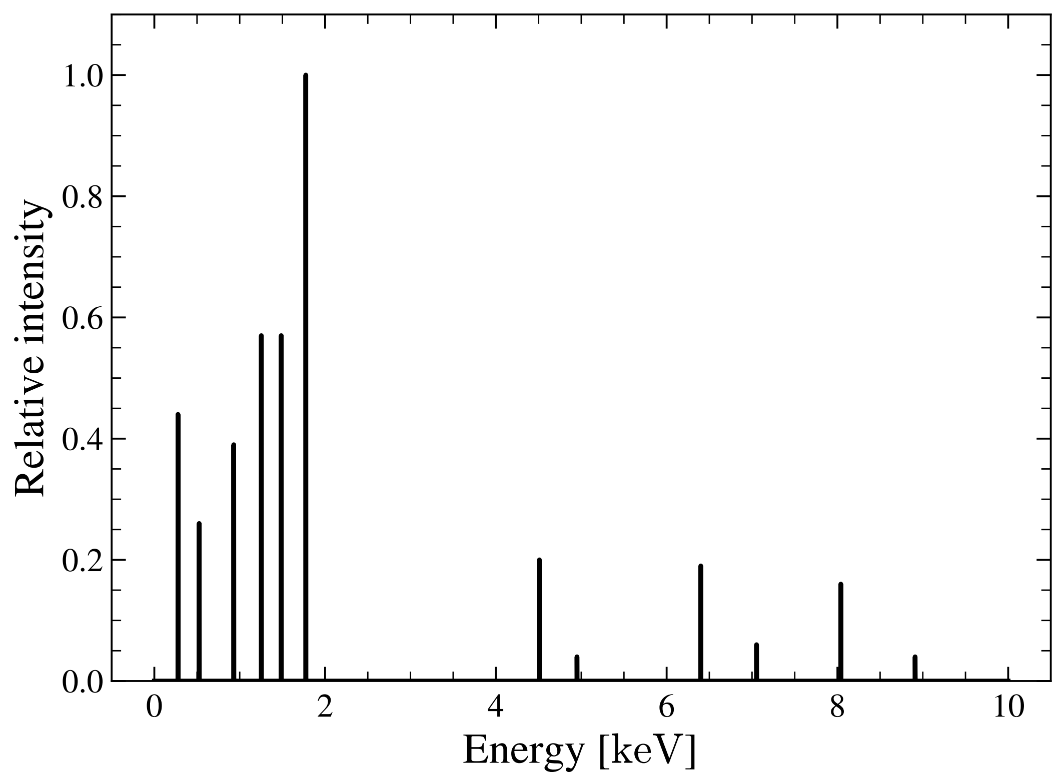
- Very fast (ECC_{AMR}, Maier+20)
  - a few seconds for the 256 columns of MXT
- Better performance with **low count** spectrum
  - reduce data statistics required for calibration
- Able to consider **lines** and/or **background**
  - more robust and accurate calibration
- Also **flexible** method
  - possible to change intensity of lines to favor a part of the energy range
  - past calibrated spectrum as synthetic spectrum to monitor the gain evolution over time



Maier&Limousin+16

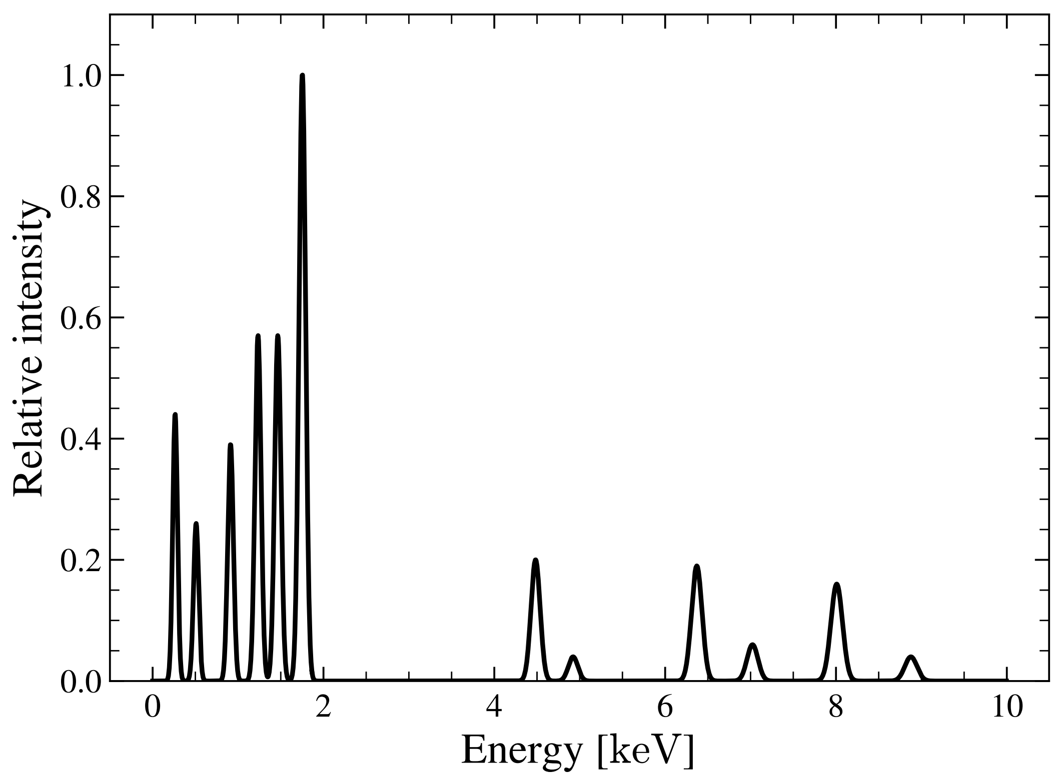
ECC for MXT calibration

Fluorescence lines



* resolution

Synthetic spectrum



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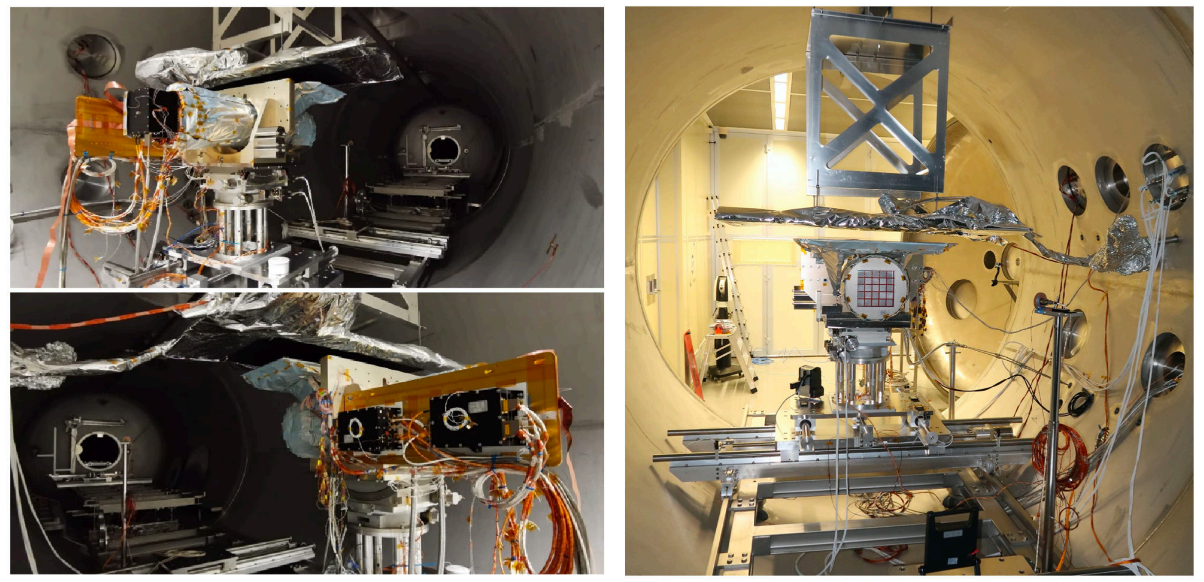
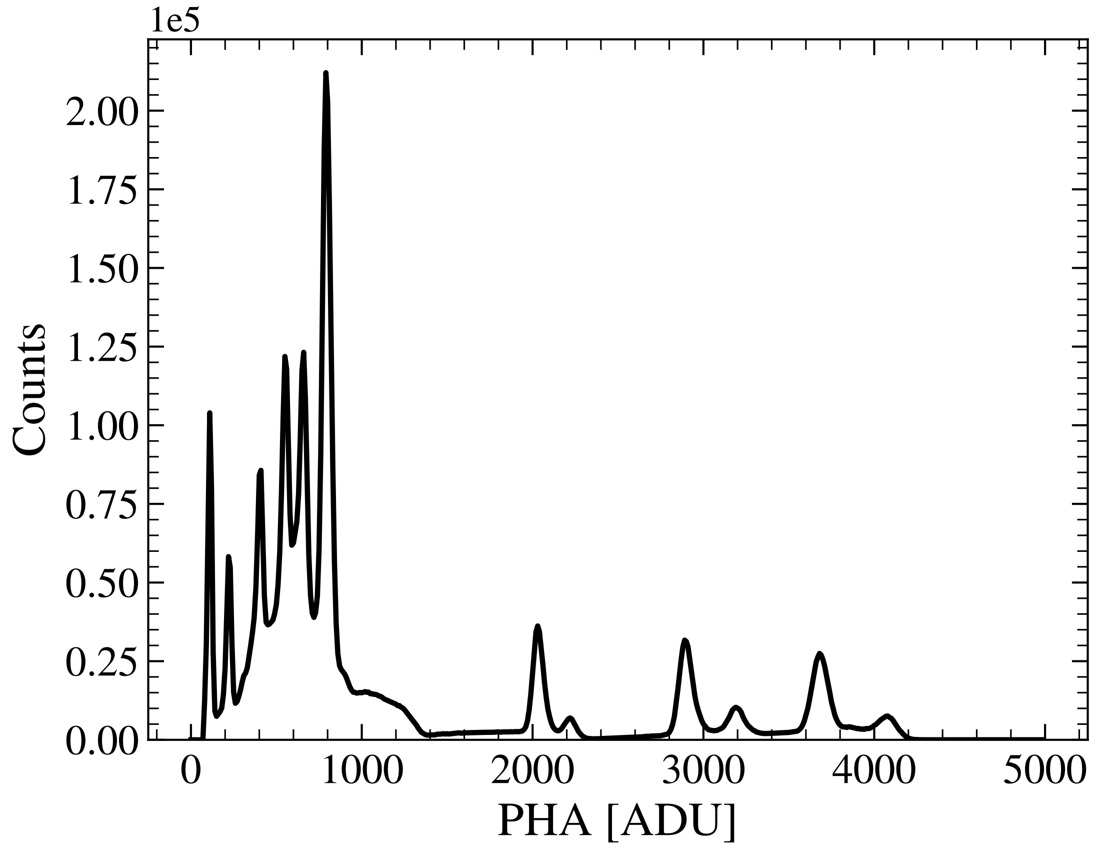
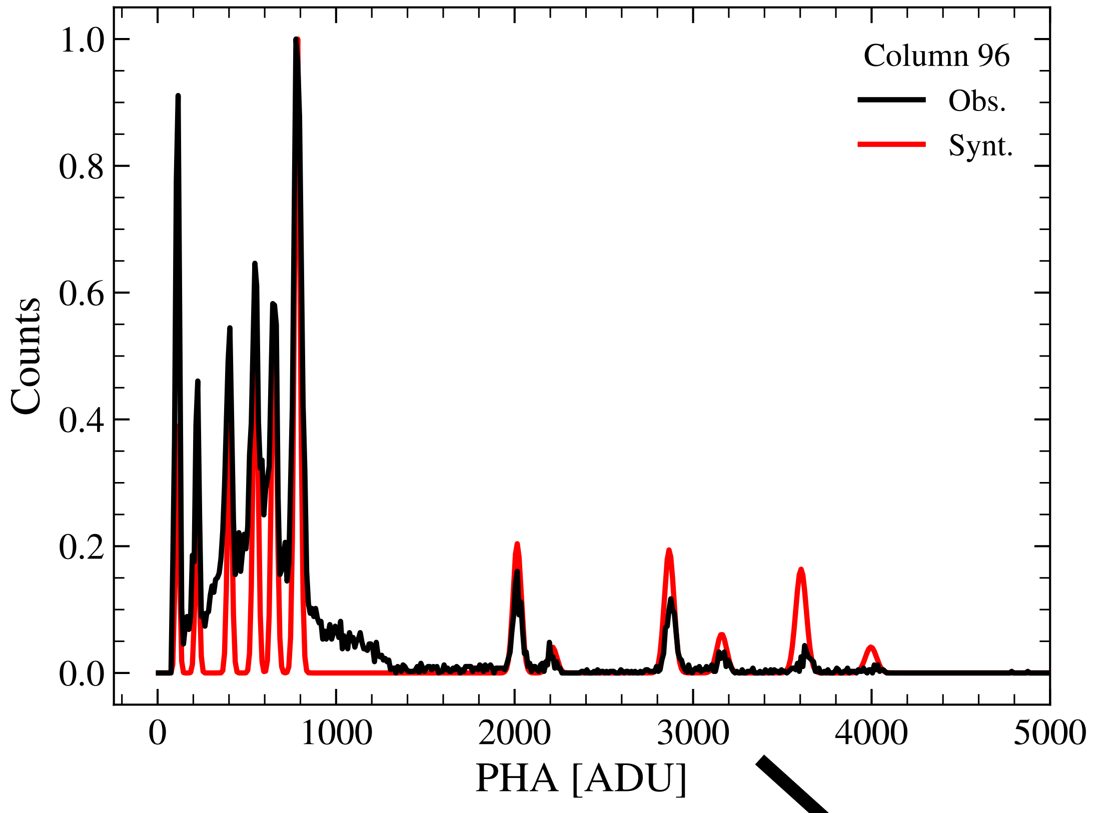


End-to-end MXT tests at Panter

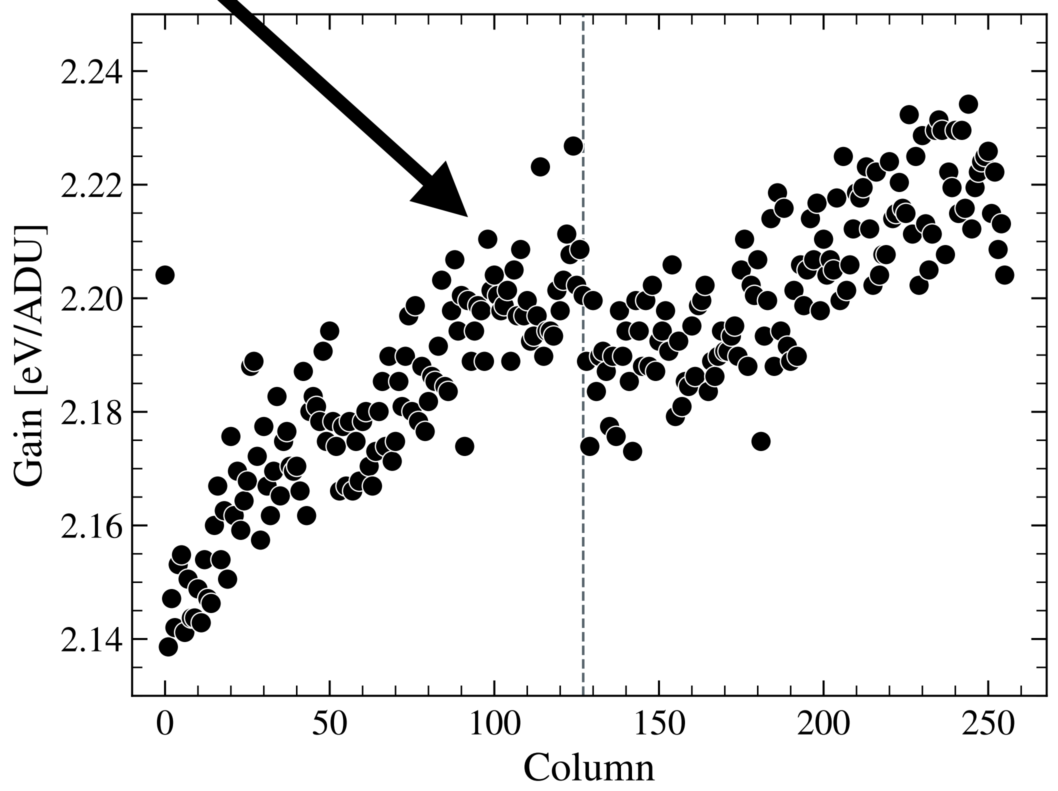


Raw stacked spectrum

Best correlation



Gain measured

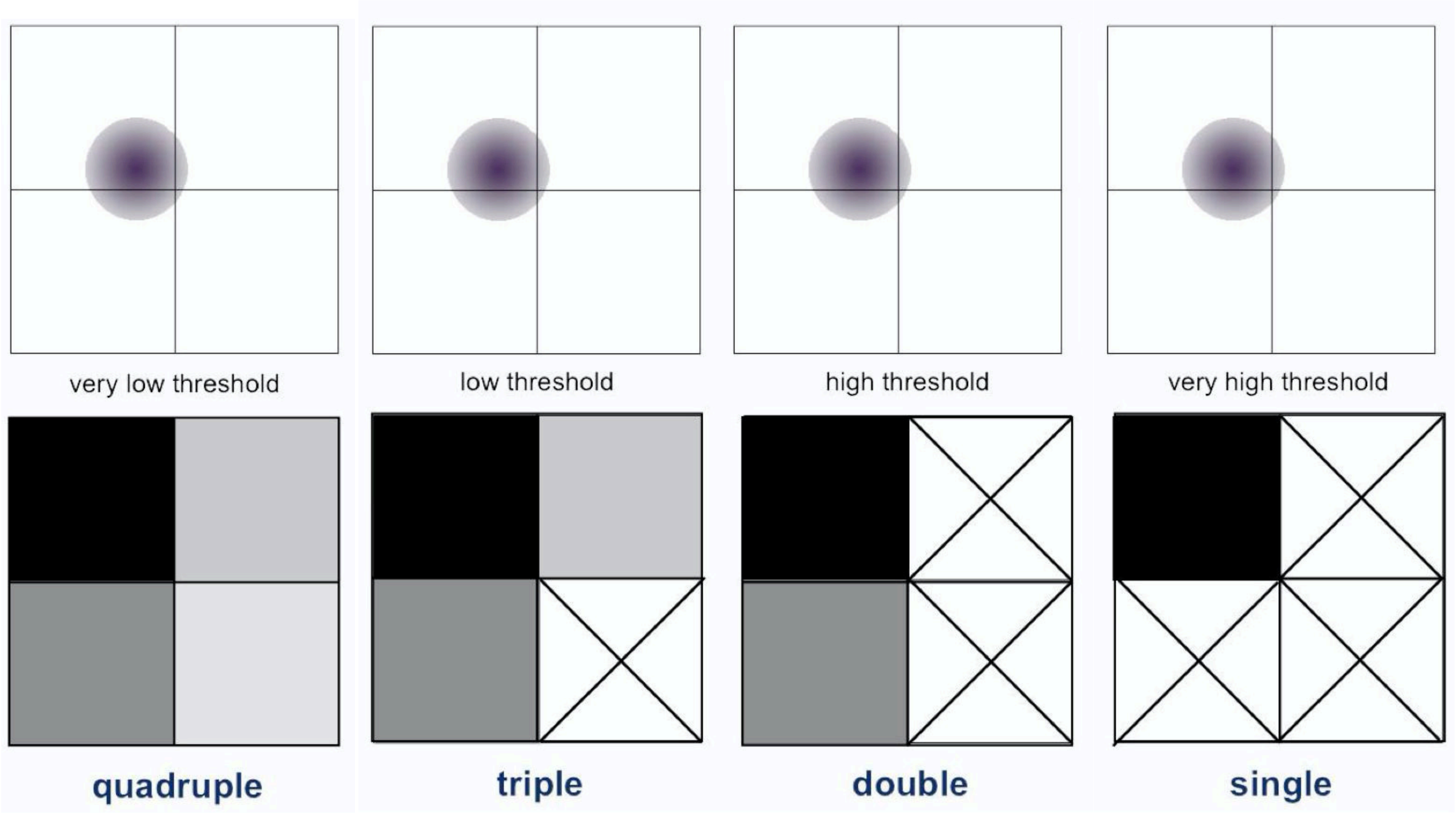


Schneider+22b

Charge sharing (CS) effect

- Charge cloud diffusion → events split over multiple pixels
  - depends on the detector design/operating parameters
- X-ray events extracted from noise using a given threshold
  - usually $4 \times$ noise level
- A fraction of the charge cloud might be lost
  - shift of the energy lines towards lower energy

➡ Charge sharing effect depends on
  - detector design
  - threshold value used to extract events
  - event multiplicity

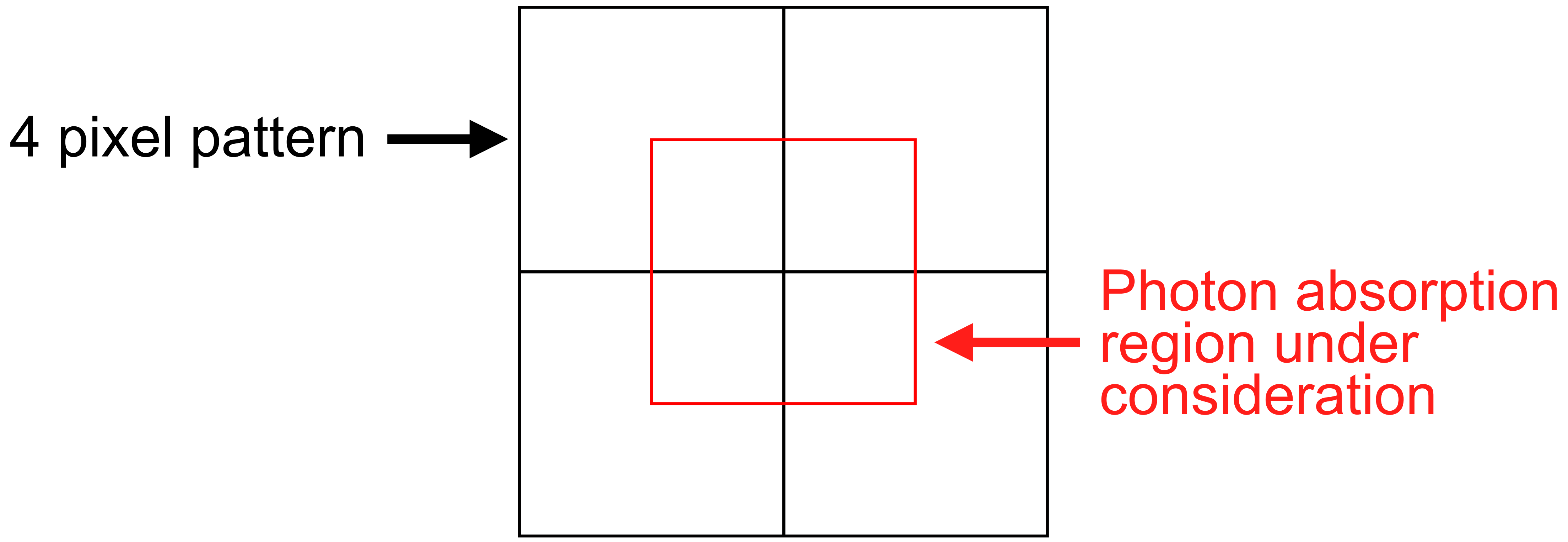


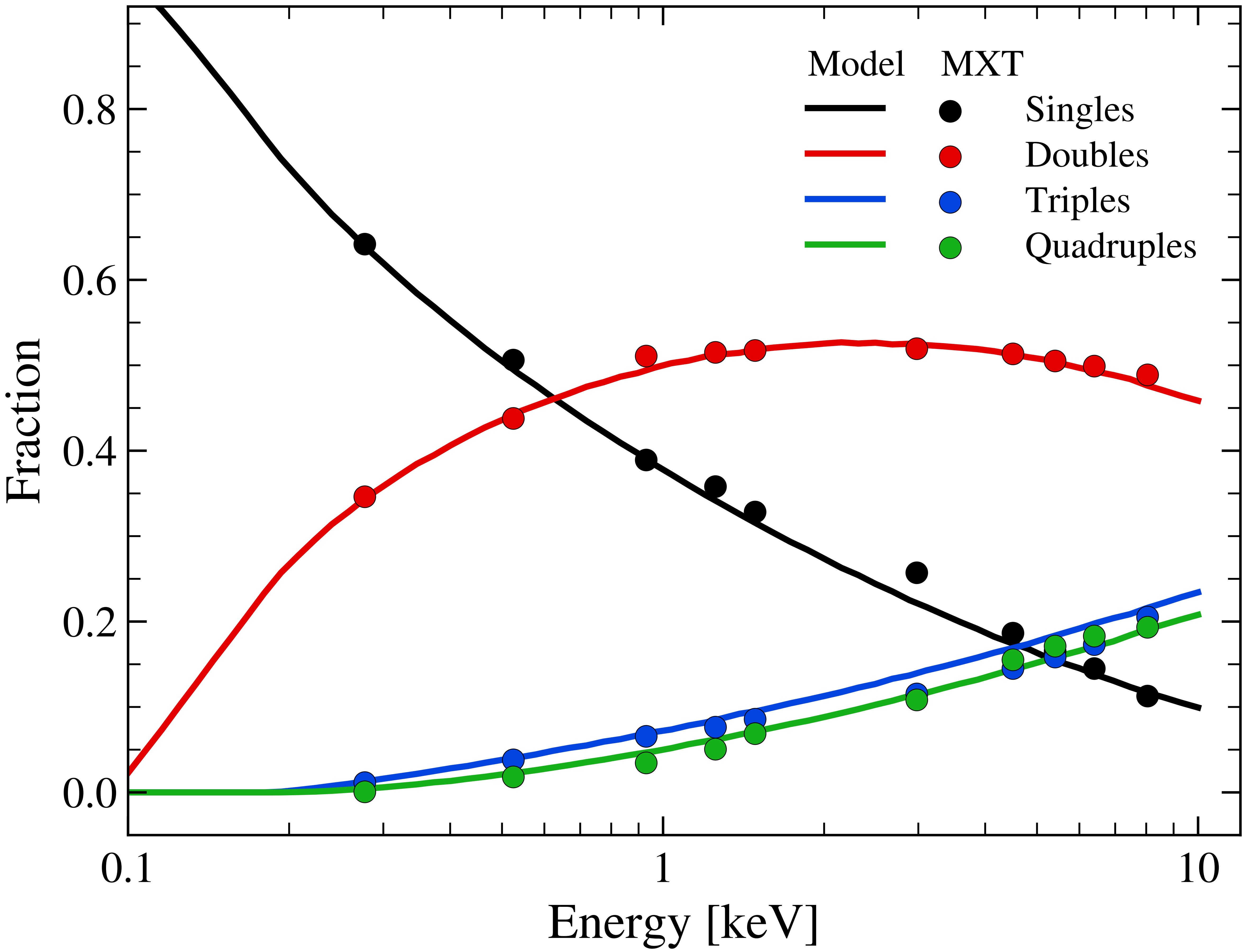
Adapted from Dennerl+12

MonteCarlo simulations of CS

- MXT design ⇒ charge clouds distributed up to 4 pixels

- 100 000 randomly drawn with $0.1 < E_{incident} < 10$ keV





- For each simulated photon:
  - charge distributed assuming a Gaussian-like function
  - split threshold value consistent with lab data

- Simulations validated by comparing pattern statistic

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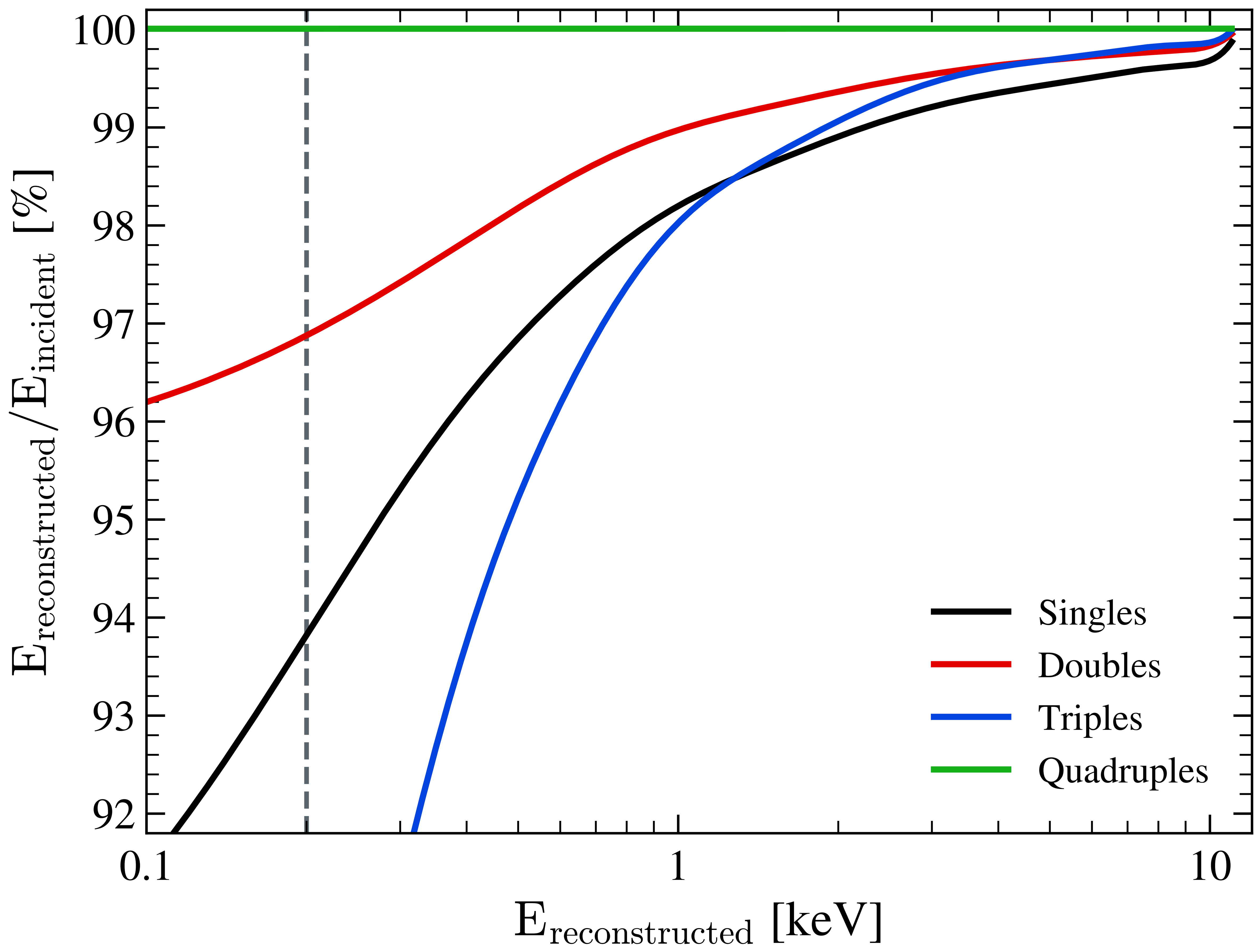
CS correction coefficients

- Gaussian fit to derive the line center of the simulated event distribution
- Average energy loss = difference between **incident** and **reconstructed** energy line center
- MXT design → quadruple events = all pixels passed the threshold and no charge is lost

➡ Coefficients can be updated in-flight by running new simulations



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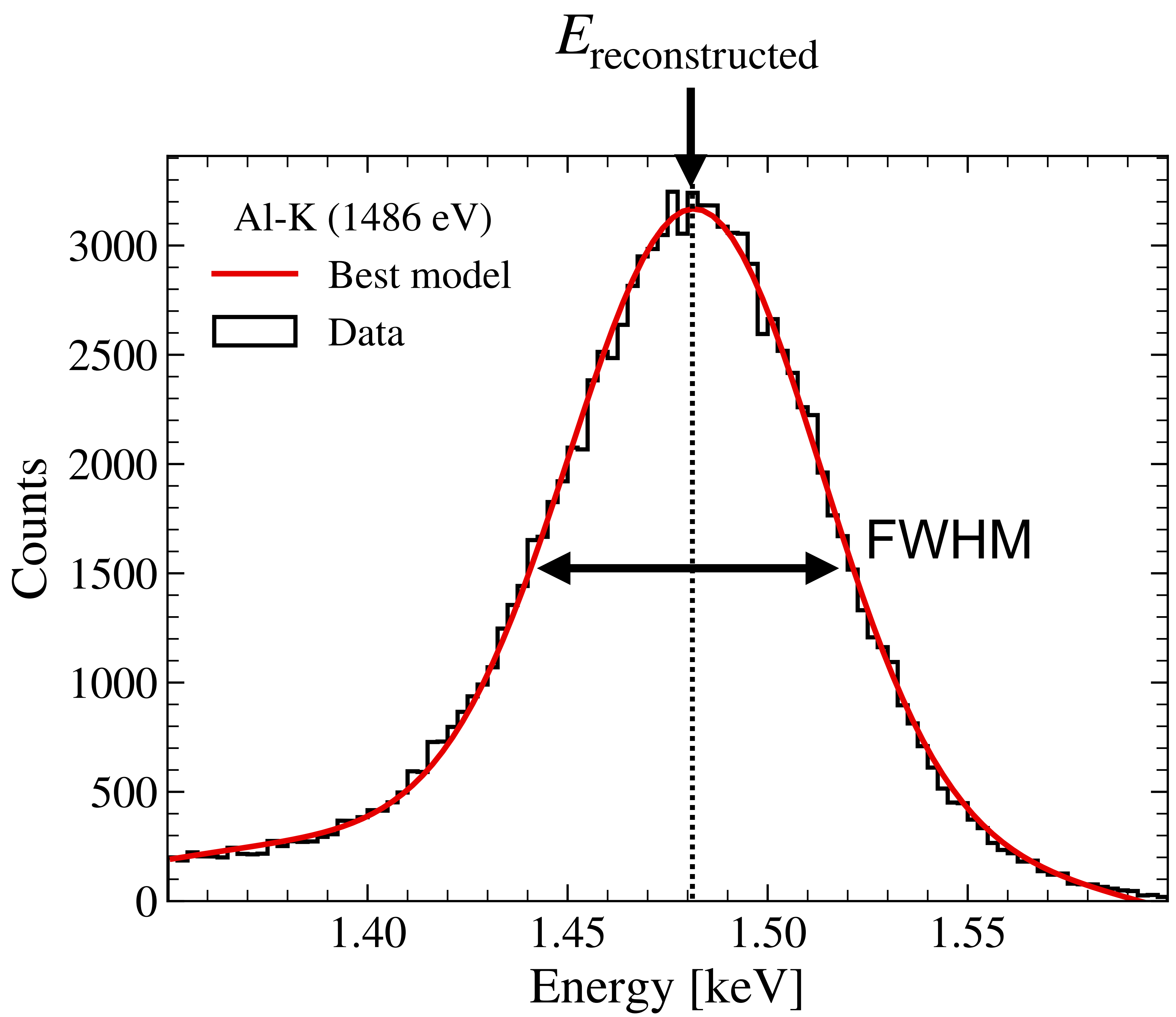
Success criteria to evaluate the spectral performance

- On **single** and **all events**:

  (1) energy scale = $E_{\text{reconstructed}} - E_{\text{incident}}$

  (2) energy resolution = Full width at half maximum (FWHM)

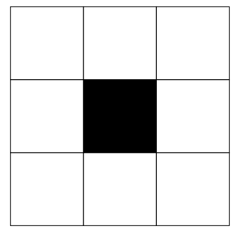


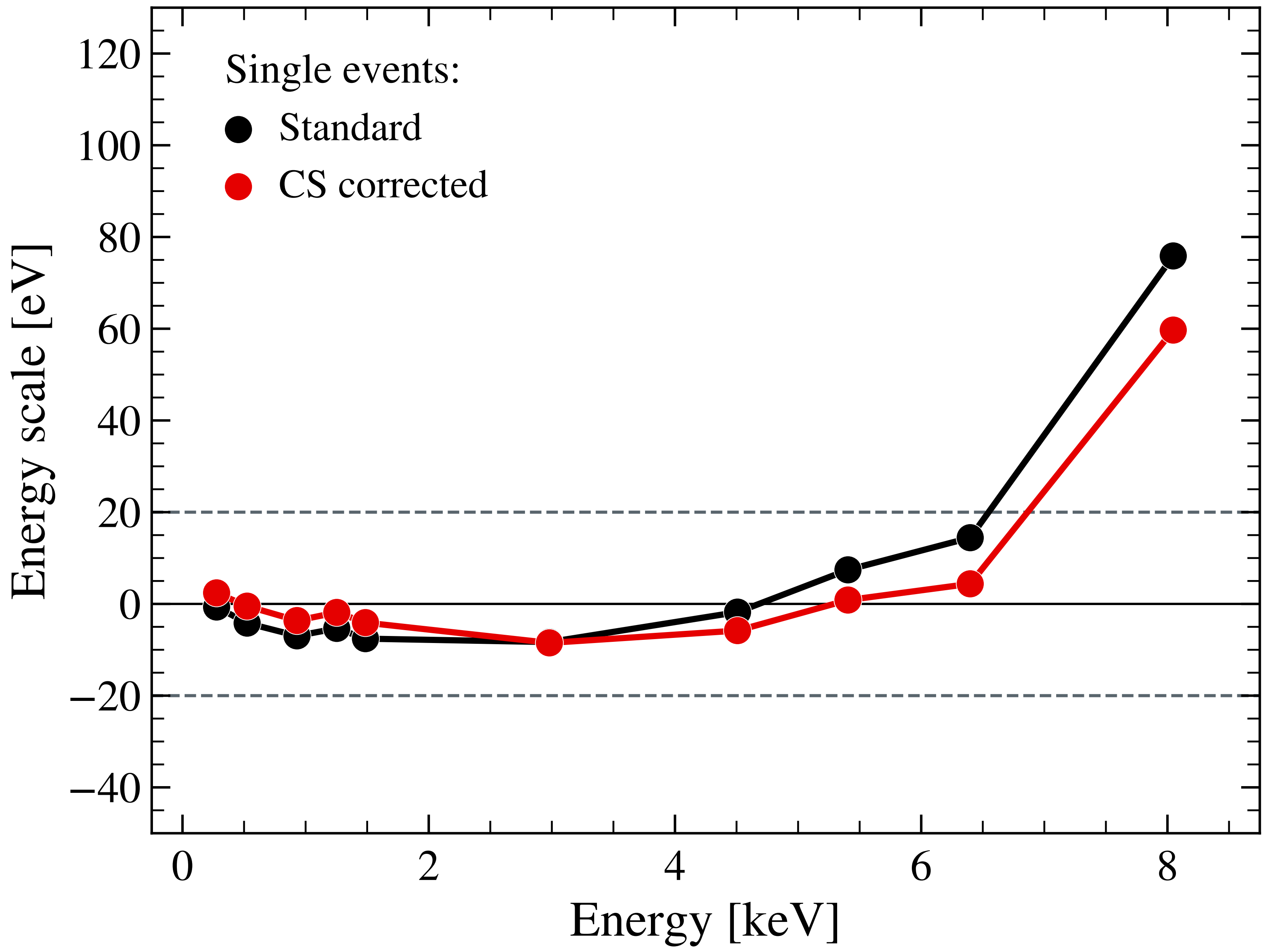
Spectral performance of MXT

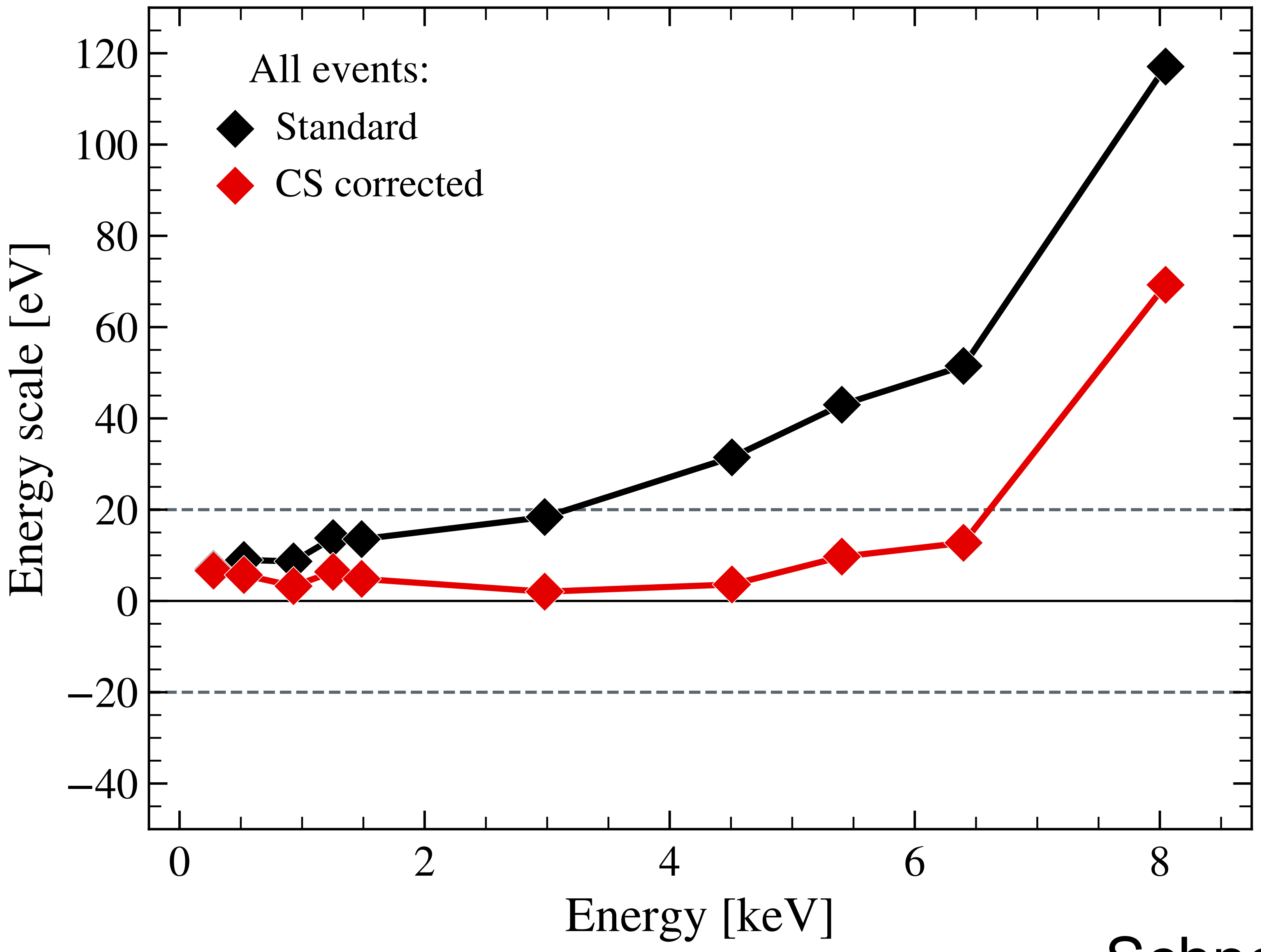
- Interest of an optimized calibration + additional corrections:

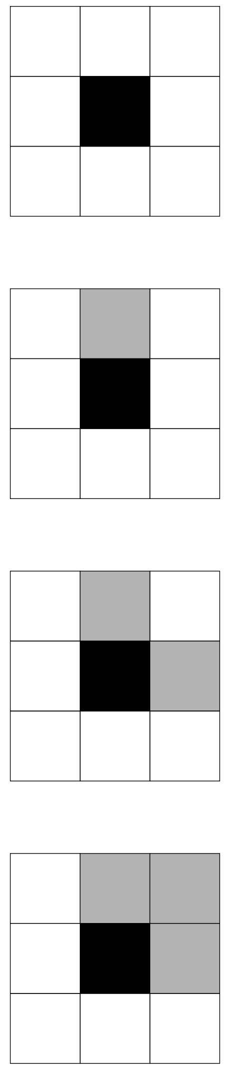
  (1) Energy scale:

  ➡ within ± 20 eV up to 5 keV
  ➡ non-linearity at E > 5 keV?
  } -10 to -30 eV with CS correction









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Spectral performance of MXT

- Interest of an optimized calibration + additional corrections:

(1) Energy scale:

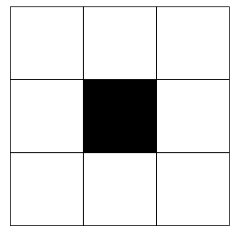
➡ within ± 20 eV up to 5 keV
➡ non-linearity at E > 5 keV?

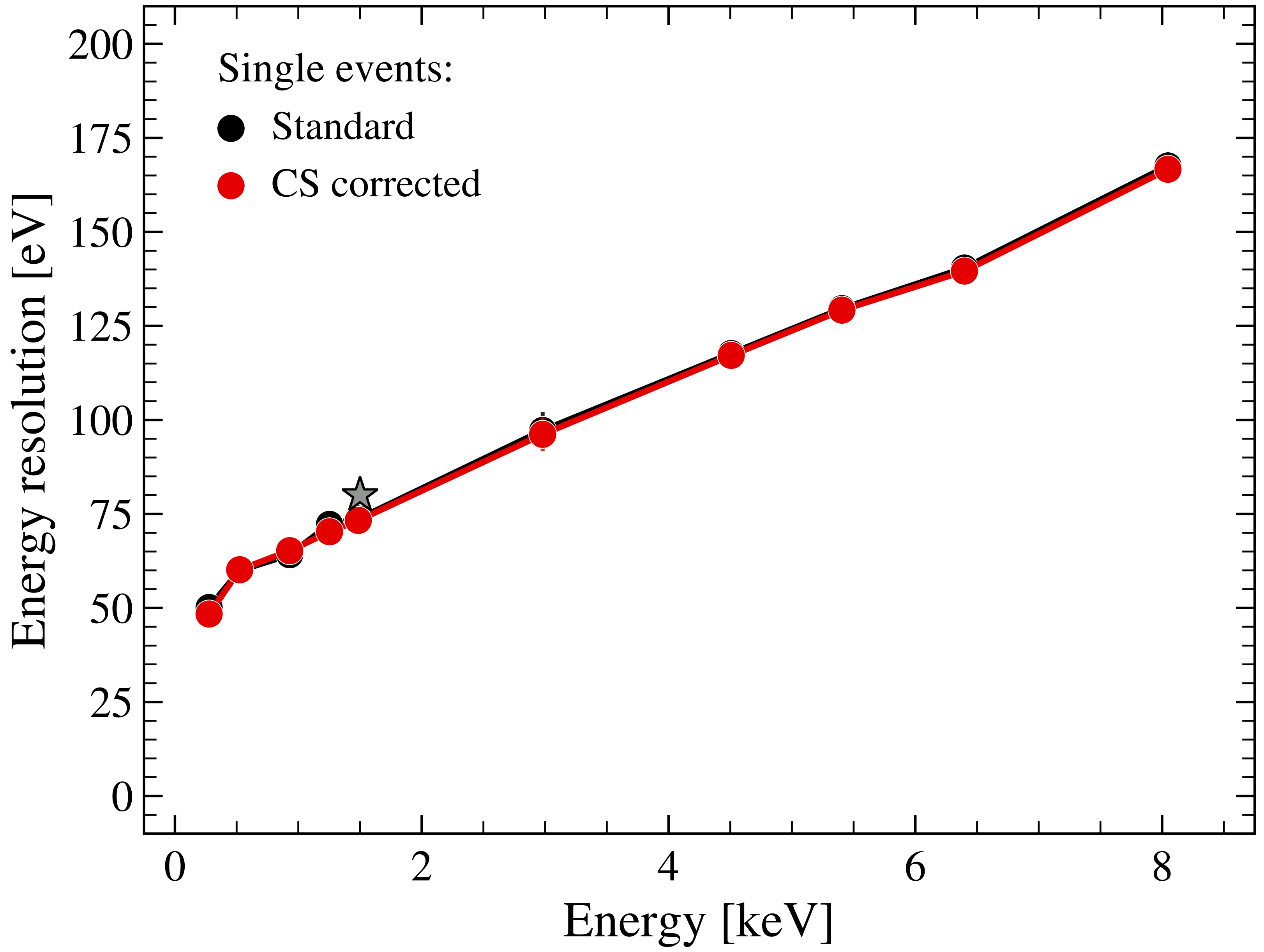
} -10 to 30 eV with CS correction

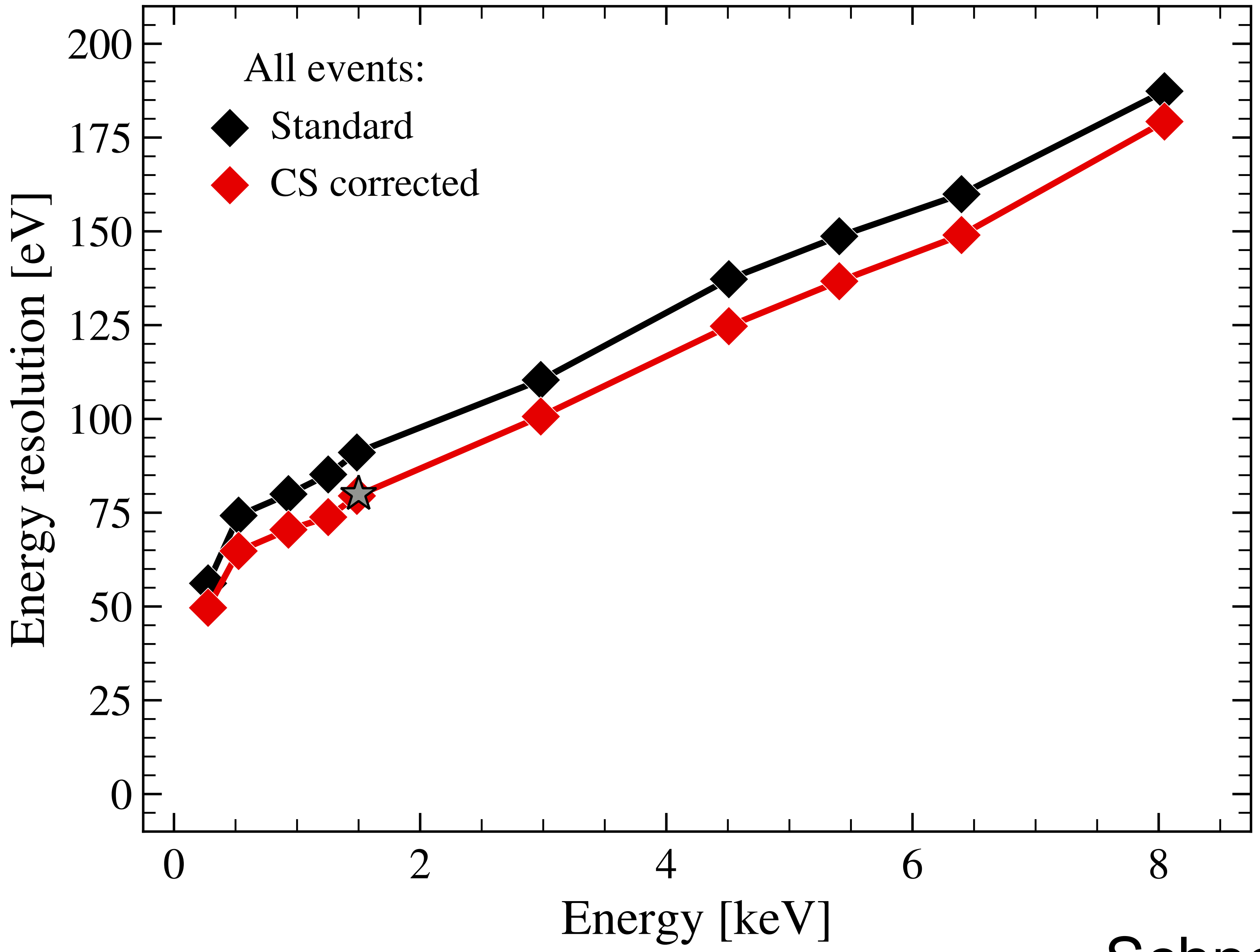
(2) Energy resolution:

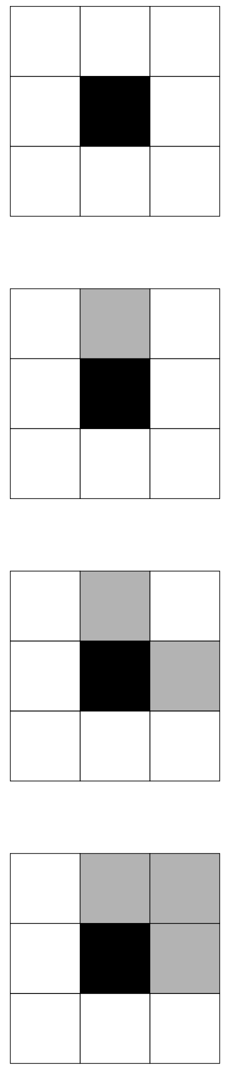
➡ <80 eV at 1.5 keV
➡ performance at the state of the art

} -10 eV with CS correction









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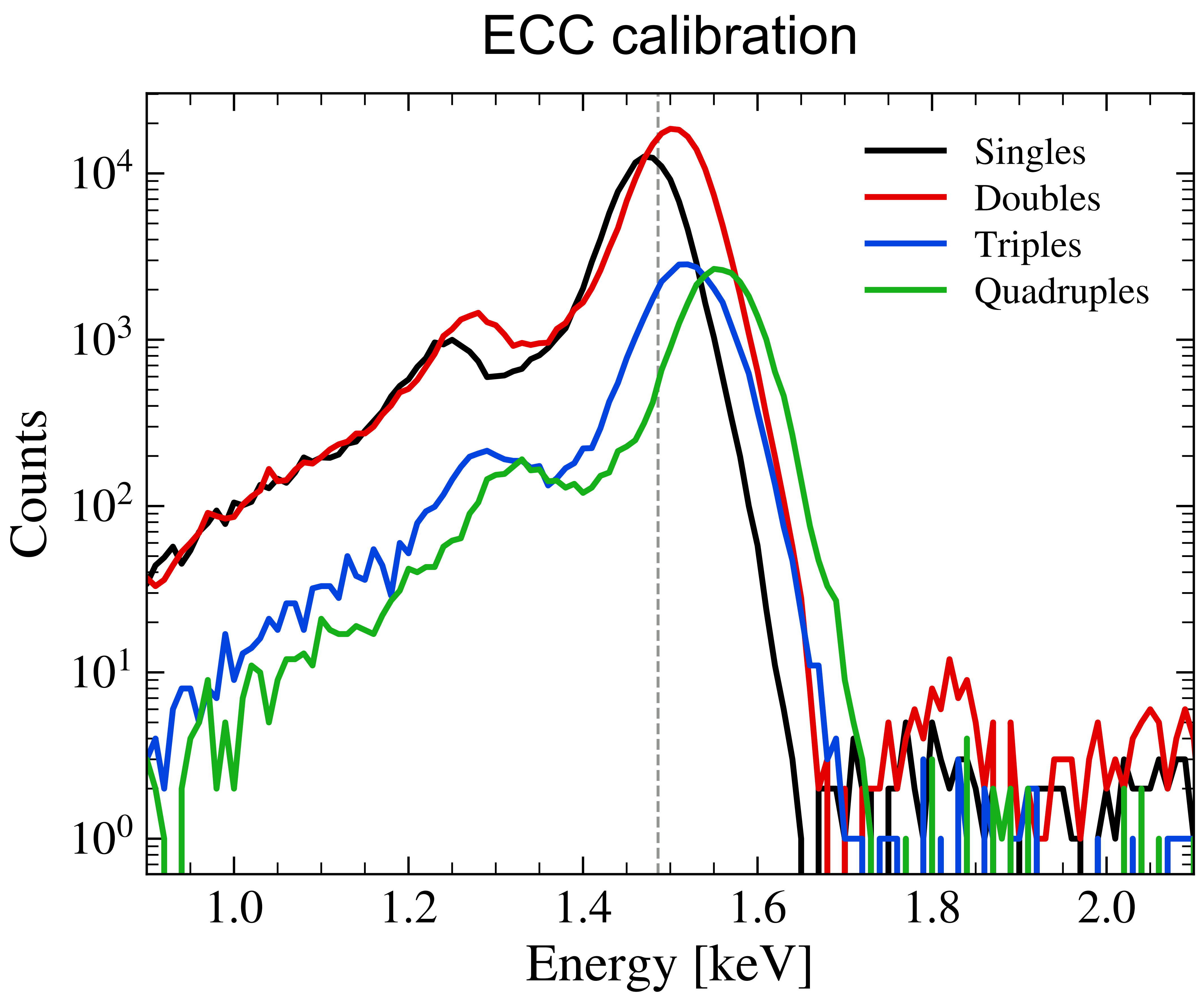
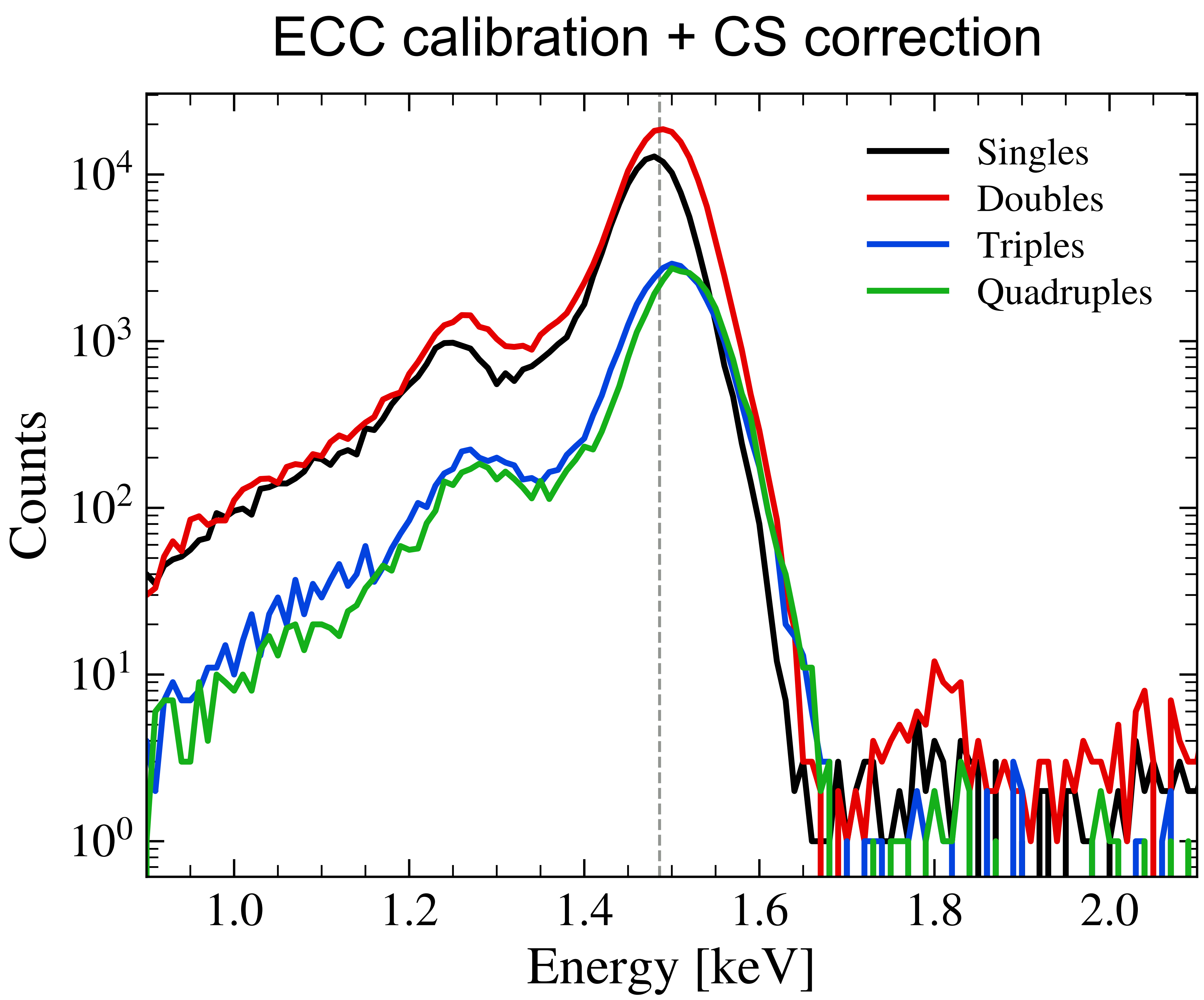
CS correction





Conclusion

- Energy calibration = key aspect to perform accurate astrophysics interpretations
    - larger focal plane of future missions might require more efficient methods
    - ECC is a promising method for on-ground and in-flight calibrations
        - ✓ fast, low count spectrum, consider the spectrum as a whole

- X-ray detectors (CCD, sCMOS) also suffer from multiple bias degrading their spectral performance
    - charge sharing effect might be mitigated and tracked over time using a statistical approach

- ECC and CS correction were successfully used to optimize the on-ground spectral performance of the MXT flight instrument

❖ B. Schneider, et al. — Spectral performance of the Microchannel X-ray Telescope on board the SVOM mission 2022, arXiv, Experimental Astronomy

Backup slides

The Microchannel X-ray Telescope (MXT)

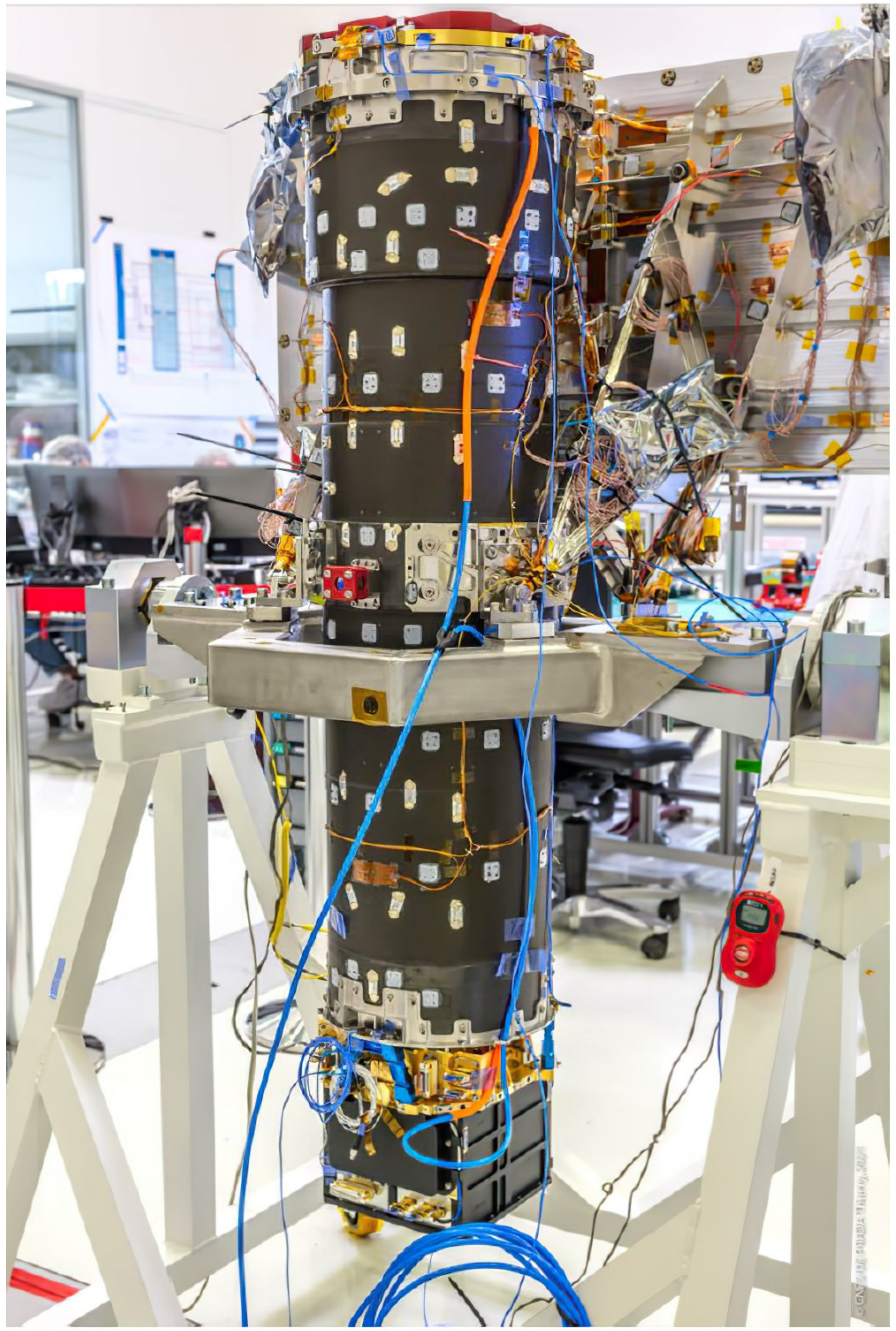
- MXT = compact (1.2 m), light (42 kg) and innovative X-ray telescope based on micropore optics (lobster-eye)

Energy range	0.2 − 10 keV
Field of View	57 × 57 arcmin
Angular resolution	10 arcmin at 1.5 keV
Source location accuracy	<120 arcsec for 80% GRBs
Effective area	~35 cm^2 at 1.5 keV
Sensitivity (5σ)	150 μCrab in 10 ks
Energy resolution	<80 eV at 1.5 keV
Time resolution	100 ms

- **Scientific objectives**

  (1) Improve GRBs localization

  (2) N_{H_X} measurement

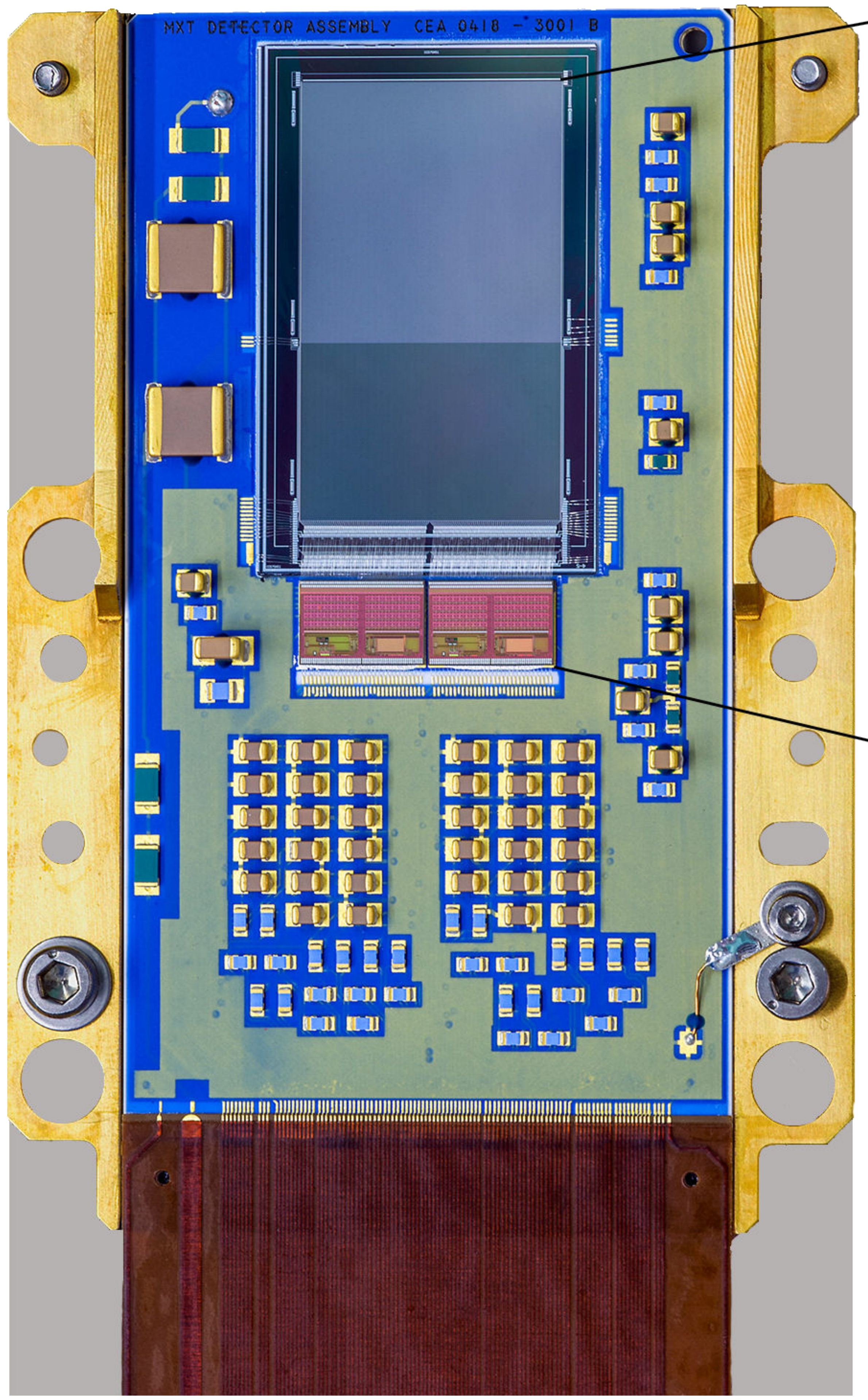


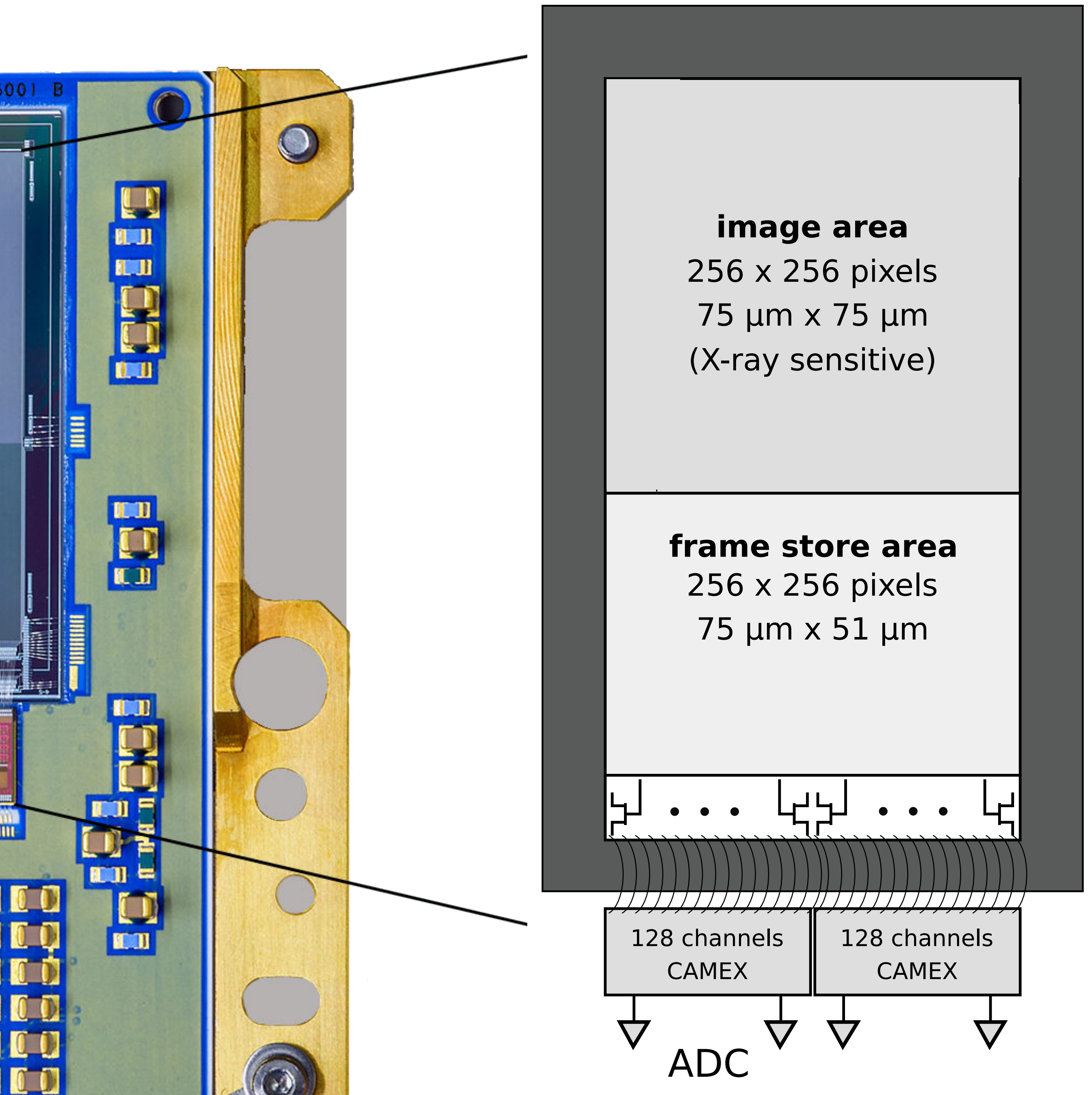
The MXT detector

- Back illuminated **pnCCD** fully depleted (450 µm)
  - Provided by the MPE
  - 2 area of 256×256 pixels each
  - Integration time: 100 ms
  - Transfer time: 230 µs

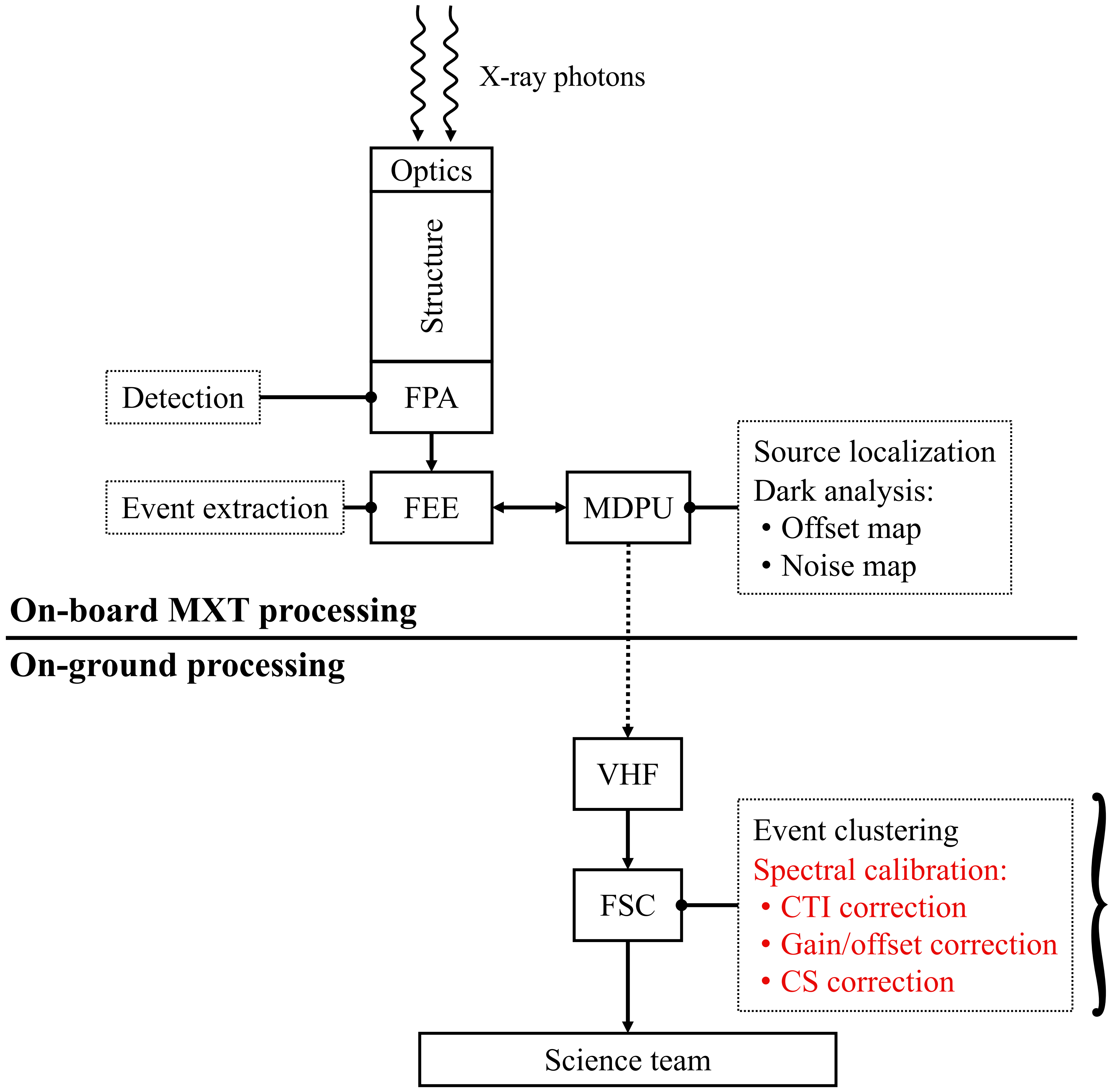
- Readout electronics:
  - 2 CAMEXs of 128 column each
  - Readout time: 8 ms

- Nominal temperature: -65°C

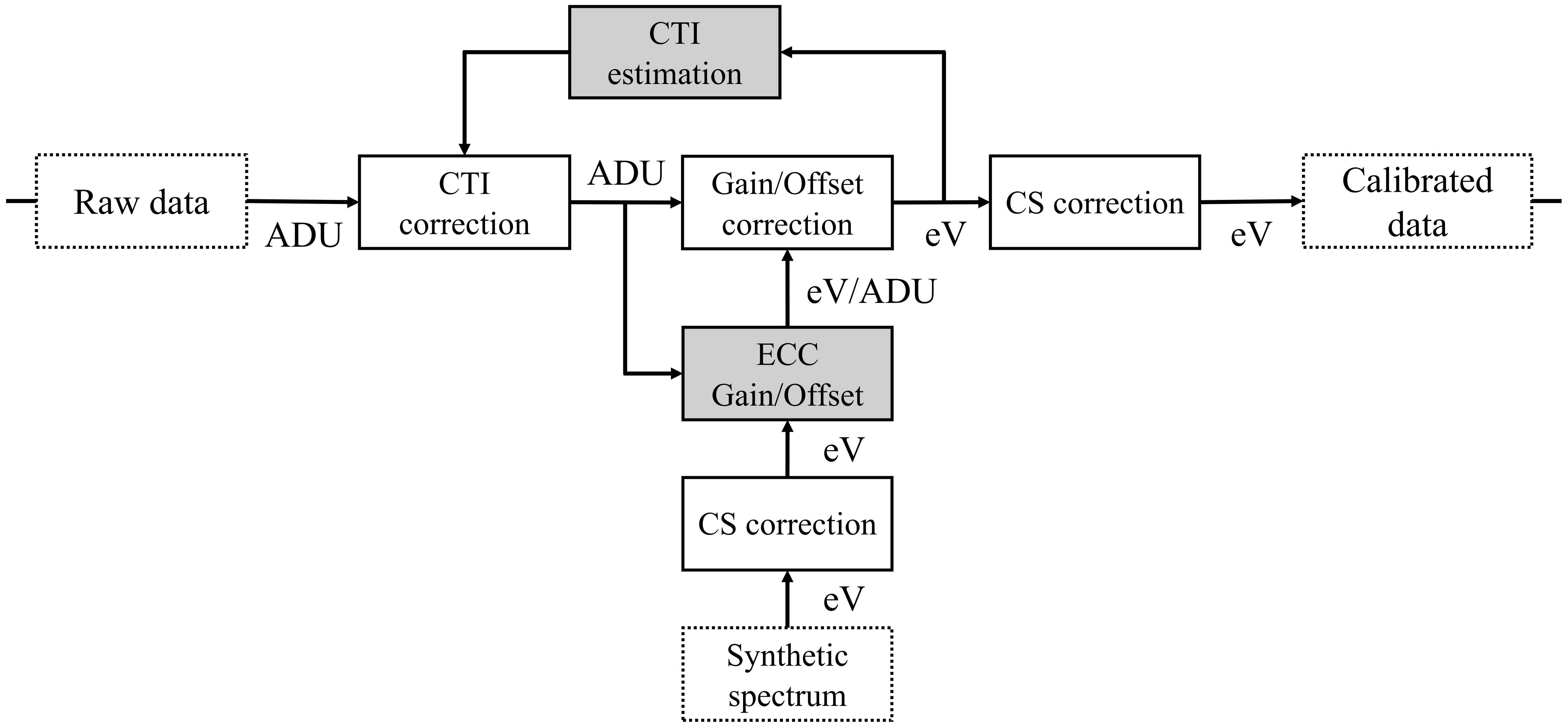




Proposed MXT spectral calibration



Spectral calibration steps (single events)



Gain/offset evolution