High-energy 3D calorimeter for use in gamma-ray astronomy based on position-sensitive virtual Frisch-grid CdZnTe detectors

Alexander Moiseev[a]*, Alexey Bolotnikov[b], GianLuigi DeGeronimo[b], Elizabeth Hays[c], Ralph James[d], David Thompson[c], and Emerson Vernon[c]

[a]CRESST/NASA/GSFC and University of Maryland, College Park, Greenbelt, MD 20771, USA E-mail: alexander.a.moiseev@nasa.gov

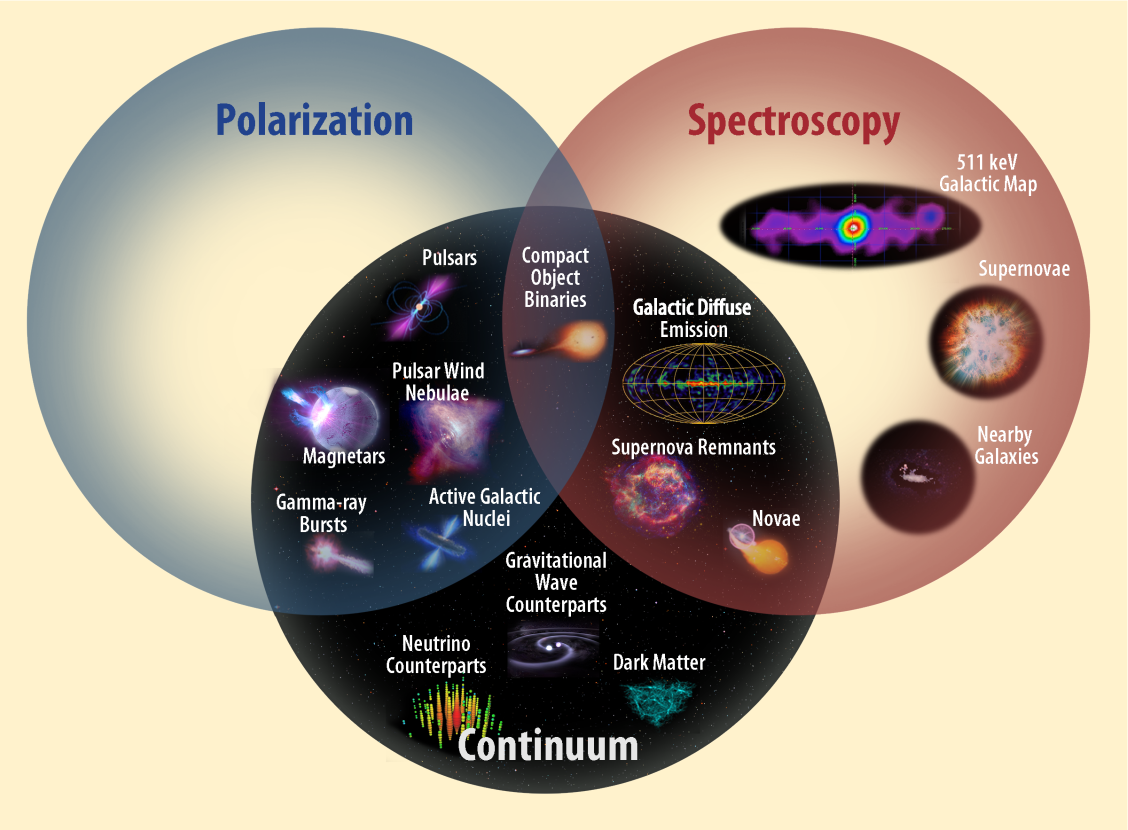
[b] Brookhaven National Laboratory, Upton, NY 11973, USA

[c]NASA/GSFC, Greenbelt, MD 20771, USA

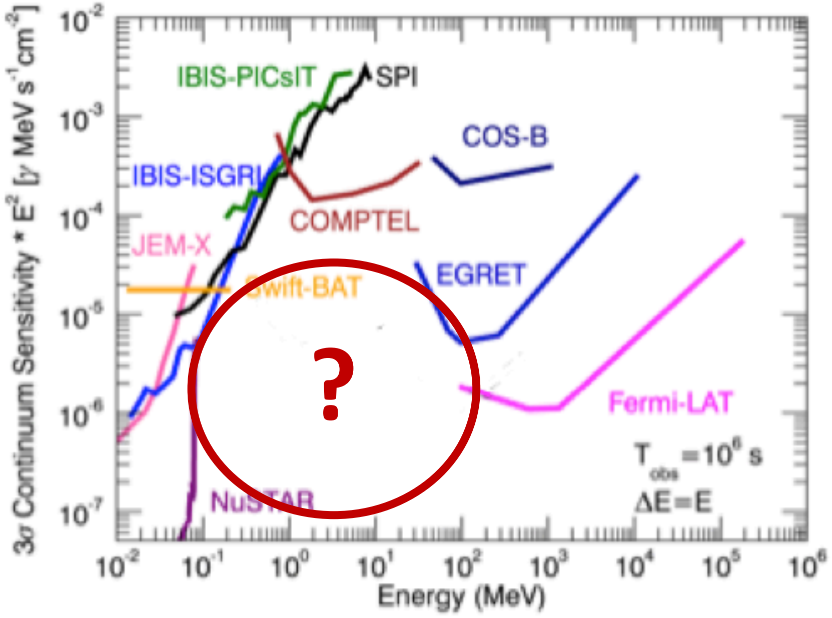
[d]Savannah River National Laboratory, Savannah River, SC, USA

Why gamma rays?

- **High-energy photons are produced in different physical processes and carry key information about those processes.**
- **Photons propagate through the Universe without deflection in magnetic fields or continuous energy losses. Their origin direction and spectrum at the source can be directly measured.**



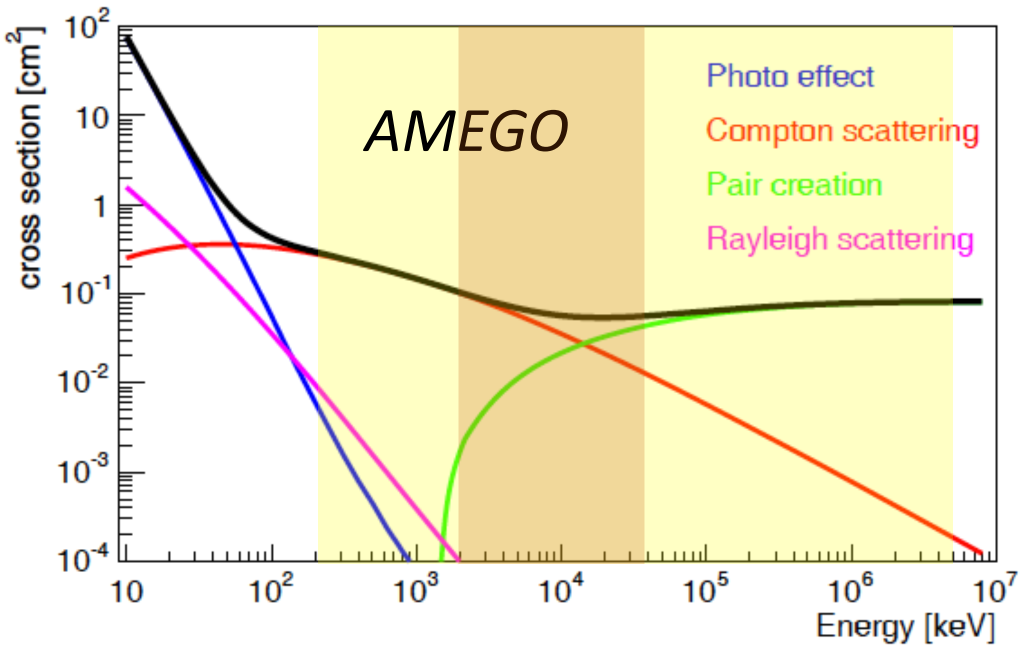
Current measurements in gamma–ray astronomy

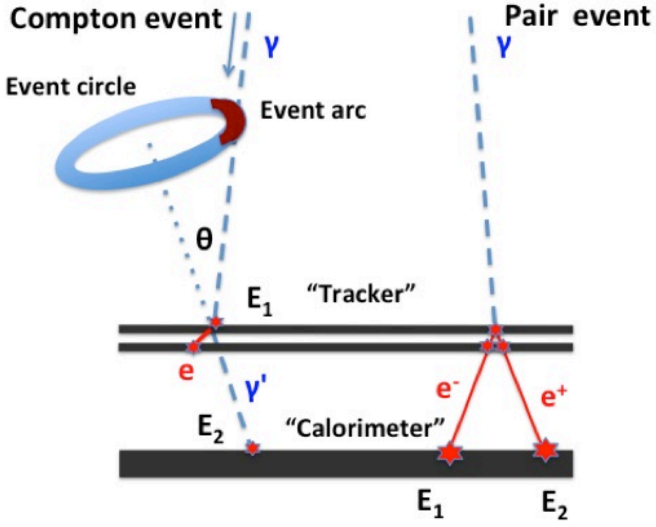


We want to enable three new capabilities in MeV astrophysics:

- sensitive continuum spectral studies,
- polarization,
- nuclear line spectroscopy.

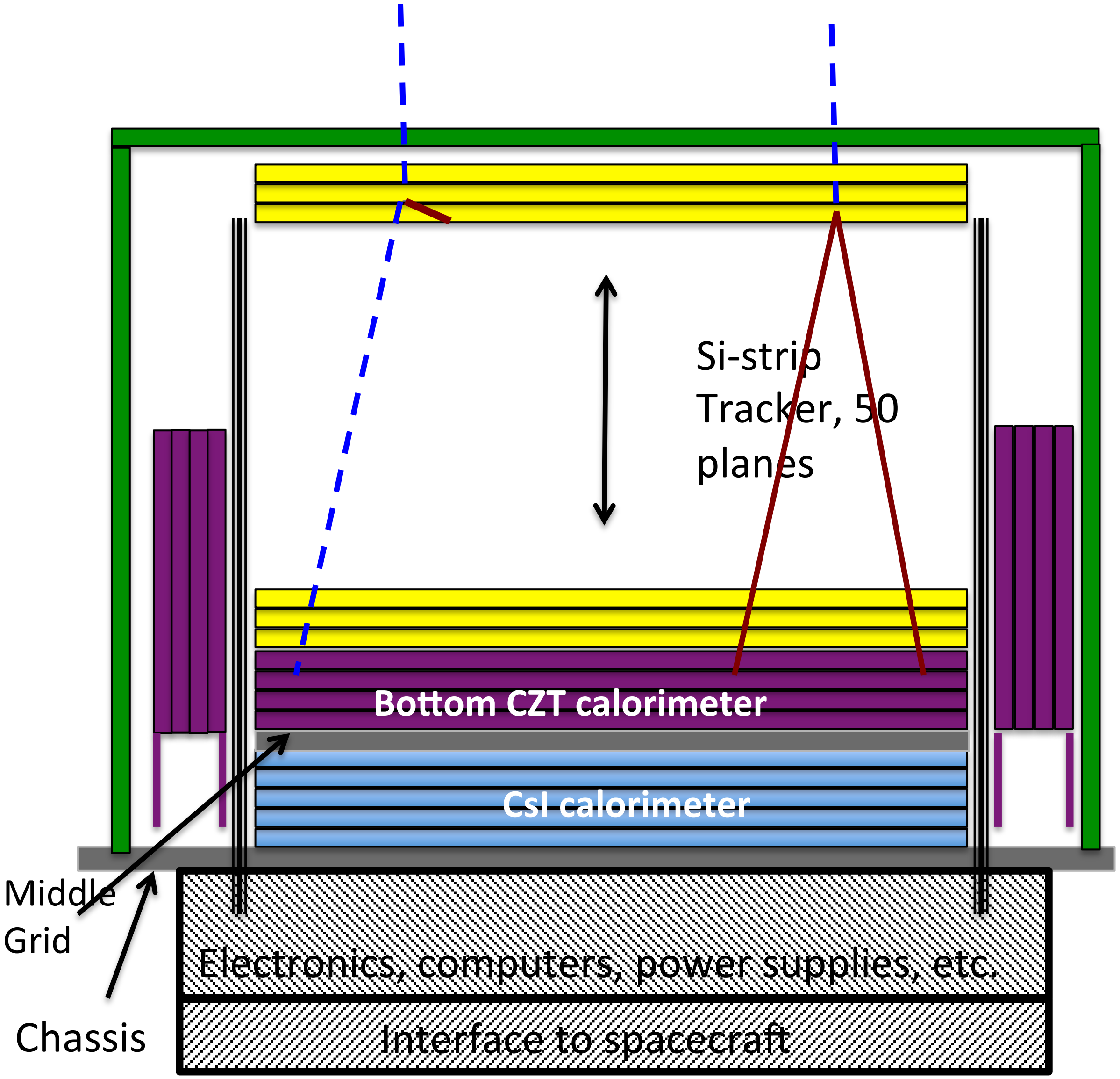
Detecting MeV Gamma rays: Gamma-ray Interactions with Matter
“Impossible energy range”

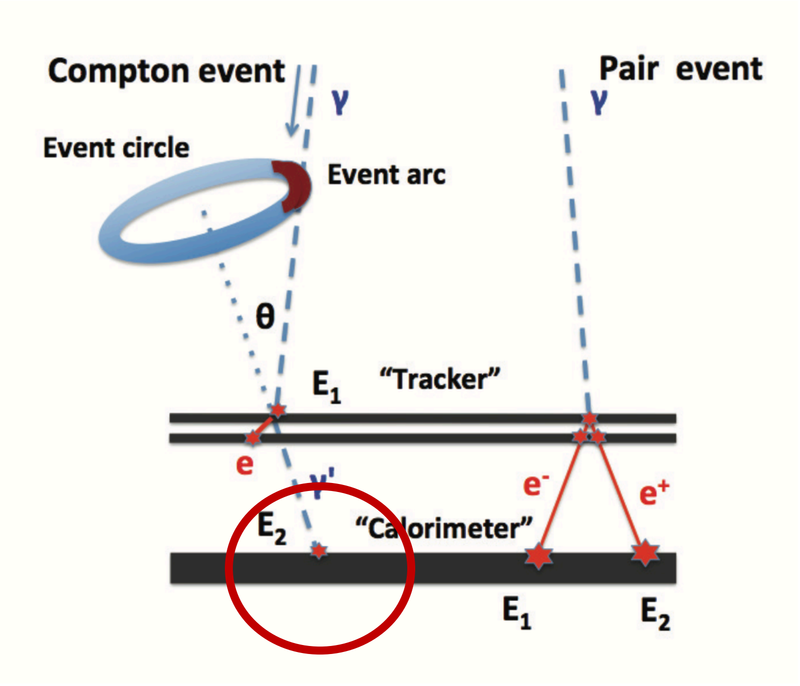




- From 1 to ~100 MeV, two photon – matter interaction processes compete: Compton scattering and pair-production
- To fill the “MeV Gap” we need to consider both Compton Scattering and Pair Production
- At low energies, pair-production components (e^+ and e^-) suffer large multiple scattering, causing large uncertainty in the incident photon direction reconstruction

Viable Instrument Concept for MeV gamma-ray astronomy





A critical detector is a *position-sensitive Calorimeter with good energy resolution*

- *Detect position of scattered photon interaction(s) with accuracy consistent with energy and position resolution of the First detector – the Tracker: of the order of a fraction of mm*
- *Measure the energy deposition with accuracy of a fraction of %*
- *Be sufficiently deep to provide adequate detection efficiency and event containment – order of 15-20 g/cm²*
- ***It appeared that BNL-developed virtual Frisch-grid CdZnTe(CZT) detectors ideally suit our goal***

Why CZT?

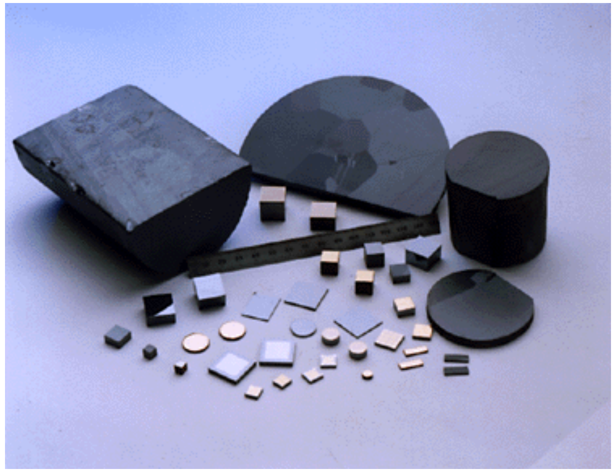
- CZT has several advantages: high atomic number, high density, (important for detecting gamma rays) and can operate at room temperature

- CZT detectors are very similar to classic gas ionization chambers; most CZT detectors employ designs originally proposed for ionization chambers

- The feasibility of CZT detectors has been demonstrated by many researchers using different detector designs

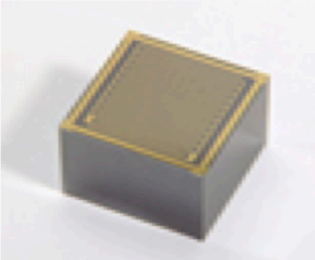
- The main challenge today is not how to make these detectors but how to make them less expensive and more widely available for practical applications

- The main obstacle: response non-uniformities caused by crystal defects that are present even in the best quality commercial material



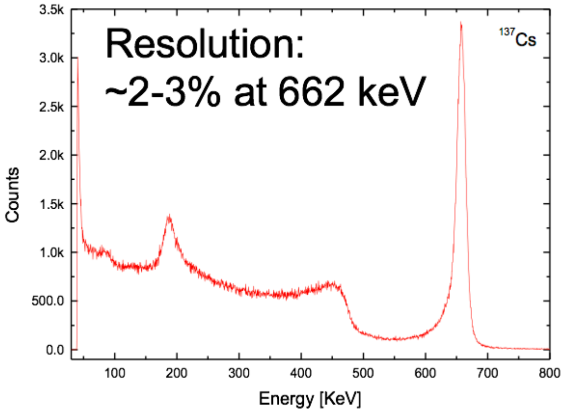
Most commonly used CZT gamma-ray detectors (with limited ability to correct response non-uniformities)

CPG detector
20x20x15 mm^3

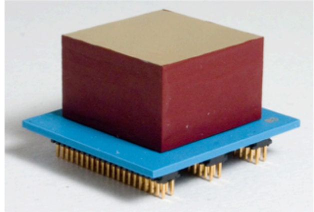


First demonstrated P. Luke

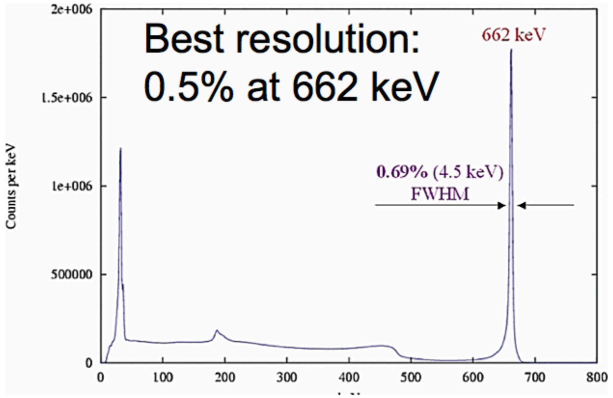
Drift-time correction only



20x20x15 mm^3 3D position-sensitive detector with~2-mm pixel sizes



Developed by Z. He et al.



3D correction but with a coarse spatial resolution

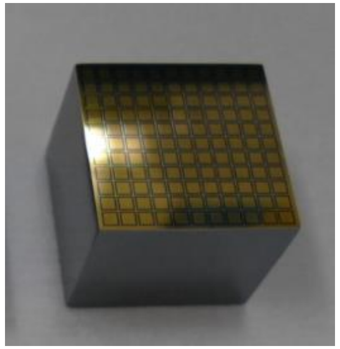
These detectors relay on the highest quality crystals to achieve the high performance → Such crystals have low production yields and very expensive!

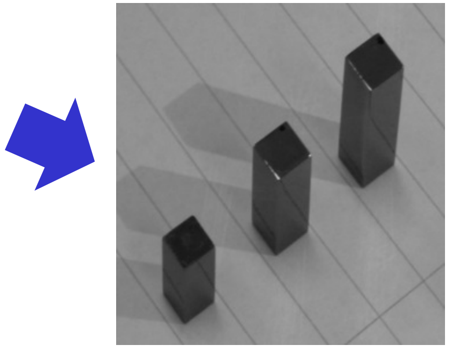
15 mm is the maximum thickness of today's CZT detectors

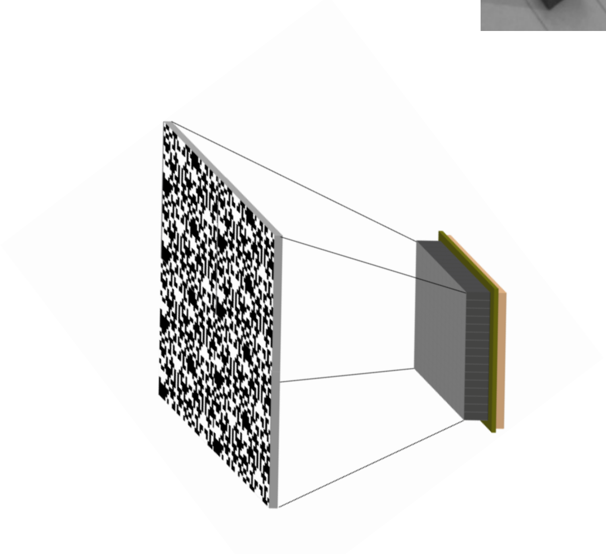
Arrays of virtual Frisch-grid detectors

- To overcome the high cost and low availability of big CZT crystals (which are required for detection of gamma rays up to several MeV) we propose arrays of small cross-section, <7x7 mm^2, but long, up to 5 cm, detectors (bars)
- Such crystals have much higher production yield and lower cost than crystals used for big pixelated detectors
- They can provide good energy resolution, <1% at 662 keV, and position resolution, < 1 mm, and can be used in coded aperture and Compton telescopes
- Bonus: CZT bars can be configured as the high-granularity position-sensitive detectors with ability to correct the response non-uniformities → <u>we can utilize off-the-shelf unselected crystals available at low cost</u>

20x20x15 mm^3







Large-area detecting plane coupled with a coded aperture mask

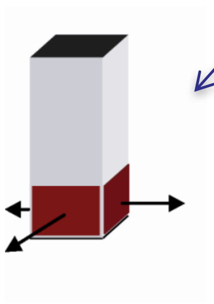
Arrays of virtual Frisch-grid detectors

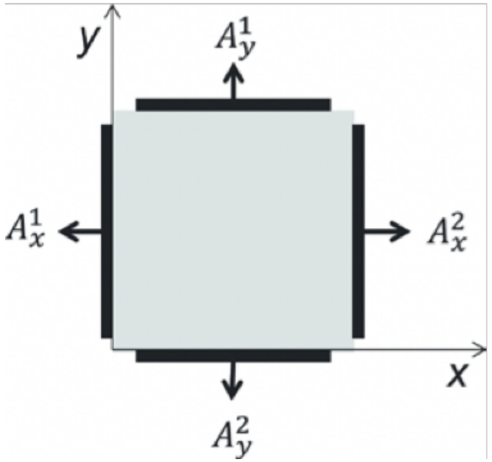
- Use large aspect ratio crystals, ~20 mm long, and with small cross-sections, ~6x6 mm^2
- 5-mm wide shielding (grounded) electrodes are placed near the anode
- Use cathode signals to measure electron drift times and interaction depths

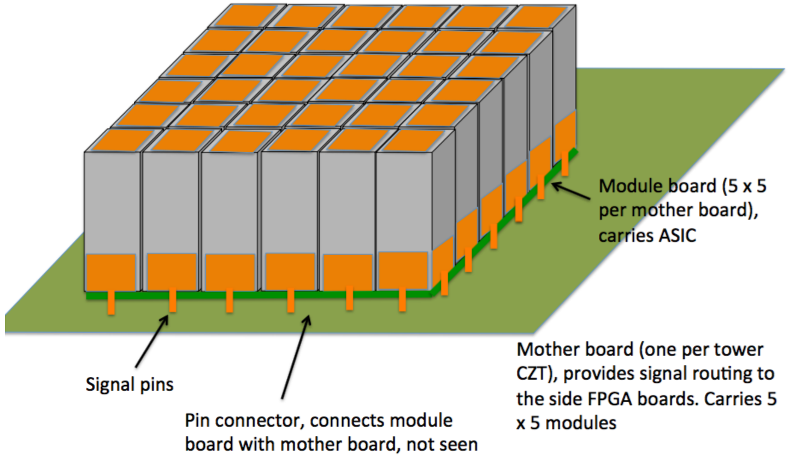
4 sensing pads (position-sensitive)

The 4 signals from the sensing pads are converted into X-Y coordinates, while the drift times (or C/A ratio) gives Z coordinate, like in TPC

Schematic of the array



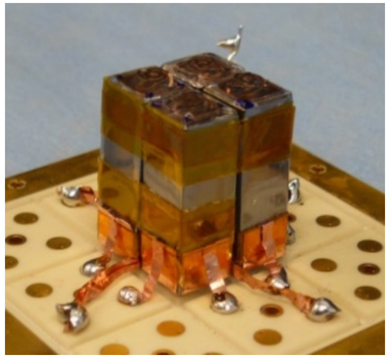




Electrodes are separated from the crystal surface by a thin, ~100 μm, insulating layer

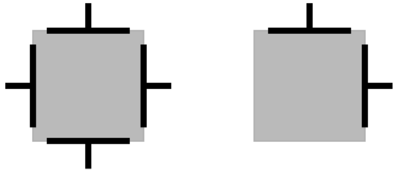
End of Basics

We want to minimize the number of readout channels (space instrumentation!)



- Adjacent bars share the sensing pad (unavoidable due to principle of operation based on induced charge collection)
- But to more minimize the number of readout channels we connected the side pads from the adjacent detectors
- Ambiguity caused by multiple-interaction events ?

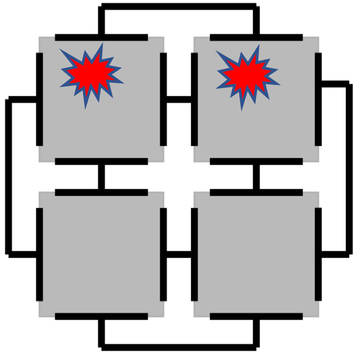
Single detector layout



1 anode
1 cathode
4 channels for 4 sensing pads (or
2 channels for 2 pads)

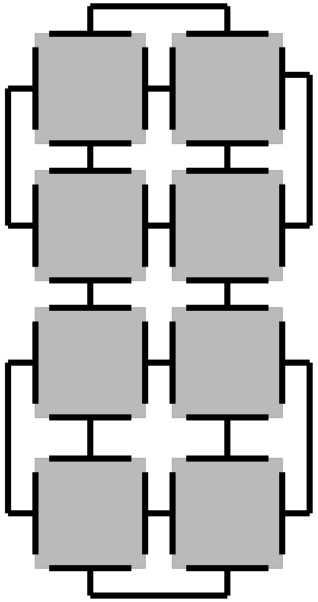
Total: 6 or 4 readout channels

2x2 module layout



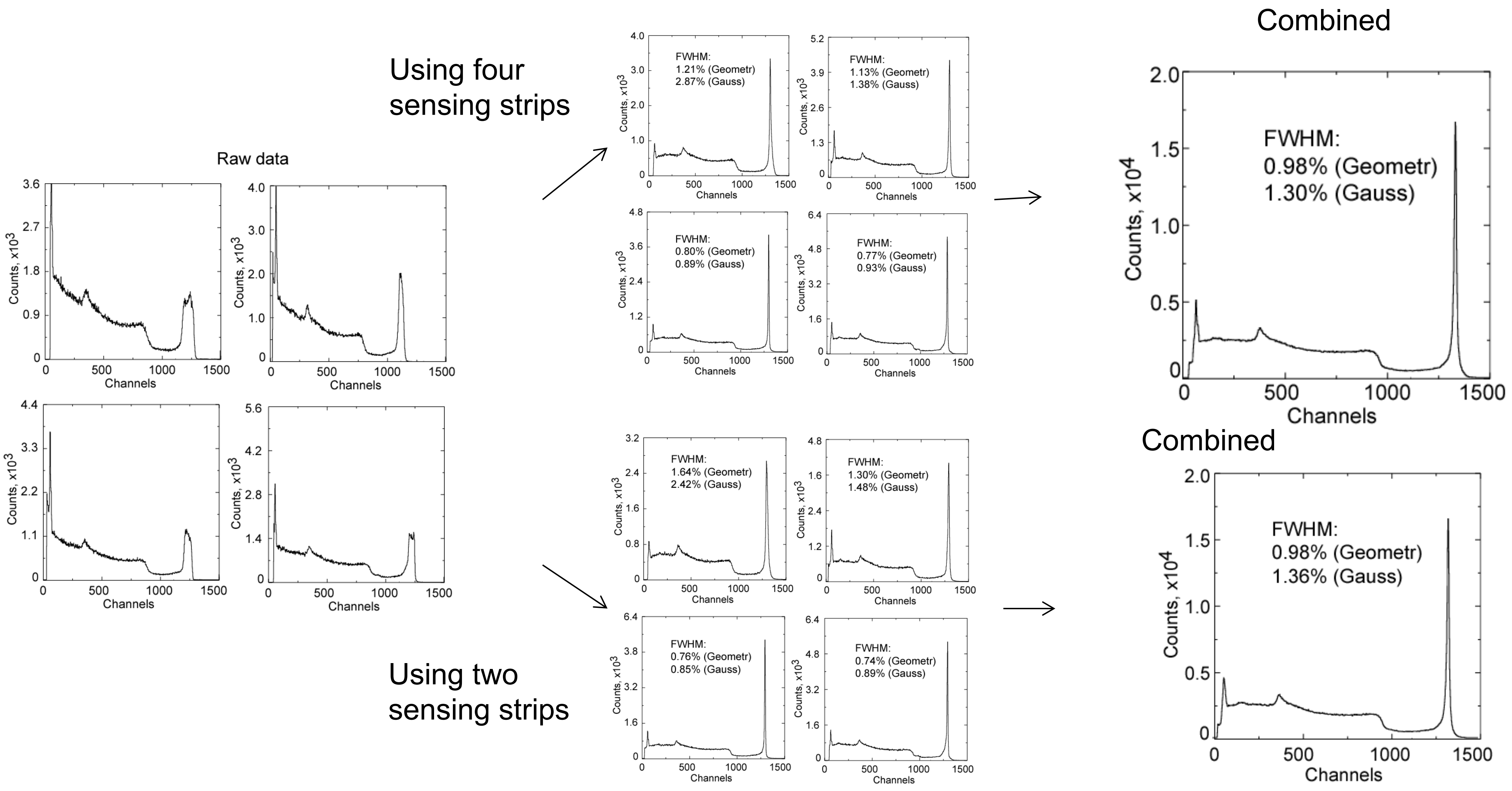
4 anodes
1 common cathode
8 channels for 16 sensing pads
Total: 13 readout channels

2x4 module layout

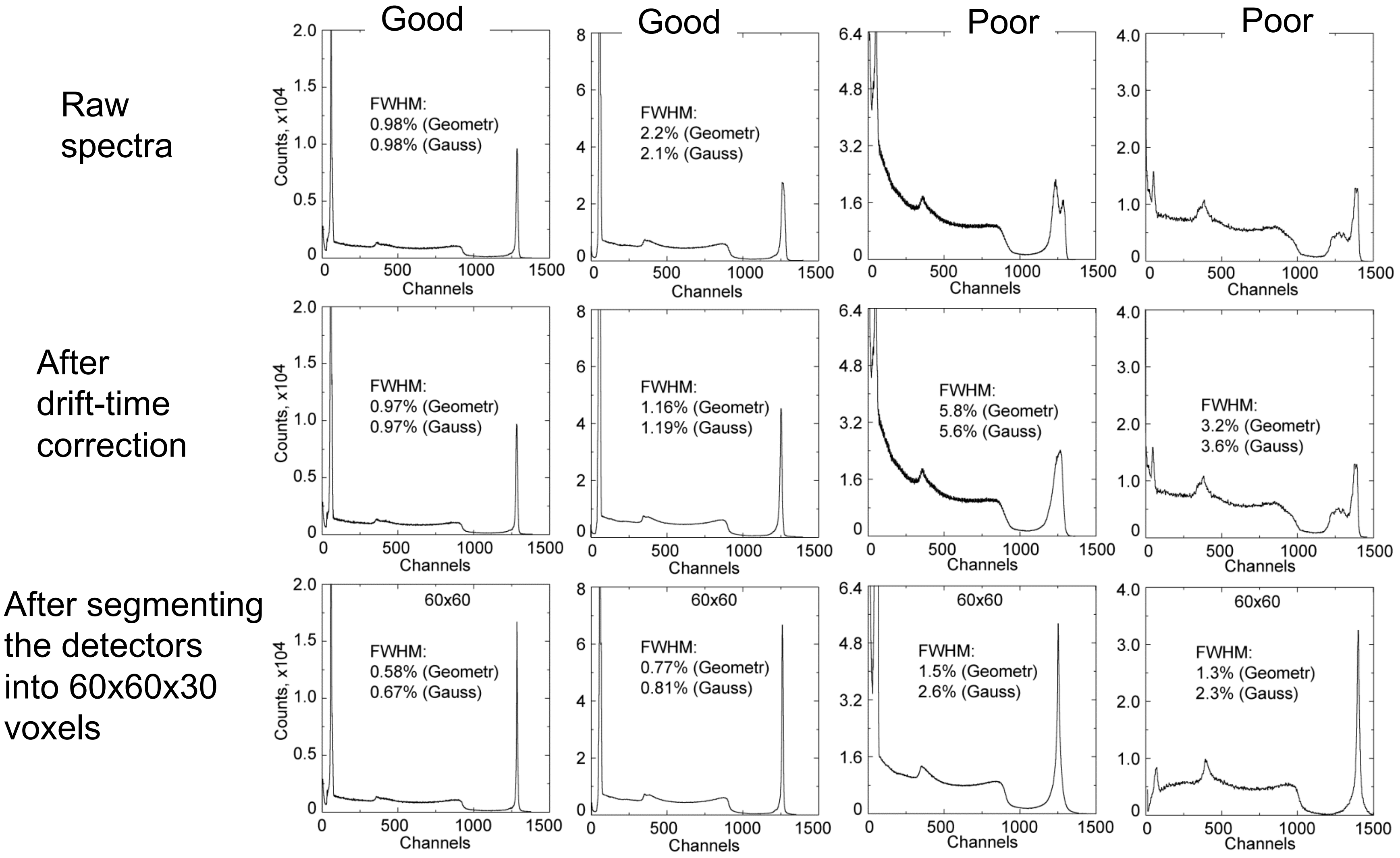


8 anodes
2 common cathodes
16 channels for 32 sensing pads
Total: 26 readout channels

Results from testing a 2x2 array prototype of 20-mm thick detectors:
Reading out two sensing strips per bar is sufficient



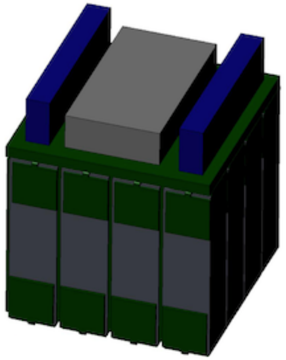
We want to reduce the cost by using regular grade crystals: how we can improve the results using different quality crystals

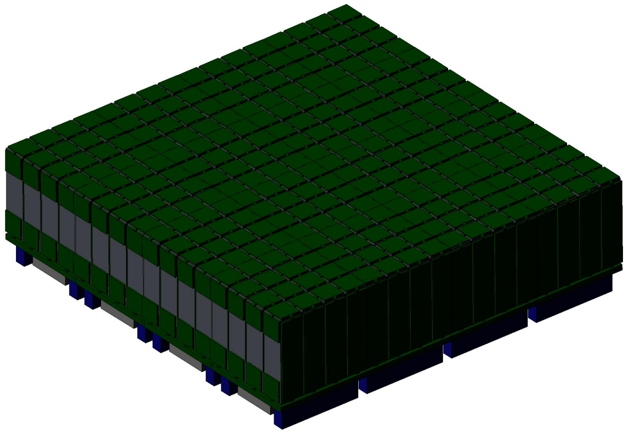


We tested over 50 detectors with different dimensions from different suppliers, and we always achieved much better performance!

Concept for the CZT Calorimeter

- Positioned under the bottom and at all 4 sides of the Tracker
- CZT Drift-bar approach is used
- Segmented calorimeter. 1 segment is made of 4x4 CZT bars, each bar 6x6 mm area (module area 2.5cm x 2.5cm to match Si-strip module) and 2cm long, served by a single ASIC, to create 2cm thick calorimeter (~2 X_0) – to be investigated if it can be increased to 3 and more cm
- 16 x 16 segments are put together to make a 40cm x40cm tower tray
- Expected energy resolution is <1% at 662 keV, 2-3% at 5 MeV
- Expected position resolution <0.5mm at <1 MeV, 2-3mm at 5 MeV





We are currently working on the flight-like prototype of a 4x4 bar module. We are planning extensive beam tests as well as environmental tests.

To improve the performance for multi-hit events we are planning to test waveform sampling ASIC

THANK YOU!