Position-Sensitive Detectors Applications in Astro-particle Physics

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Introduction

Applications of Position-Sensitive-Detectors in Astro-particle-physics is a very broad field, which I could not possibly survey completely!

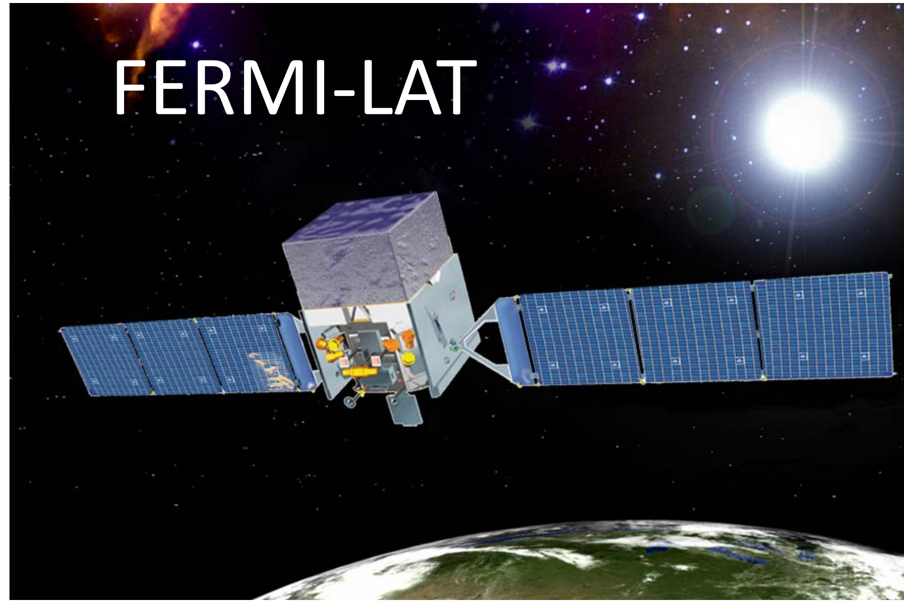
Most astrophysics detectors are position-sensitive to some degree, from precision cosmic-ray tracking detectors, to position-sensitive calorimeters, to pixelated detectors on photon imaging planes.

I will concentrate on areas and examples most familiar to me:

- Orbiting gamma-ray telescopes
- Orbiting or suborbital cosmic-ray telescopes

And I will touch on some technology transfer to medical physics that has arisen from work in these areas.

Gamma-Ray Pair-Conversion Telescopes



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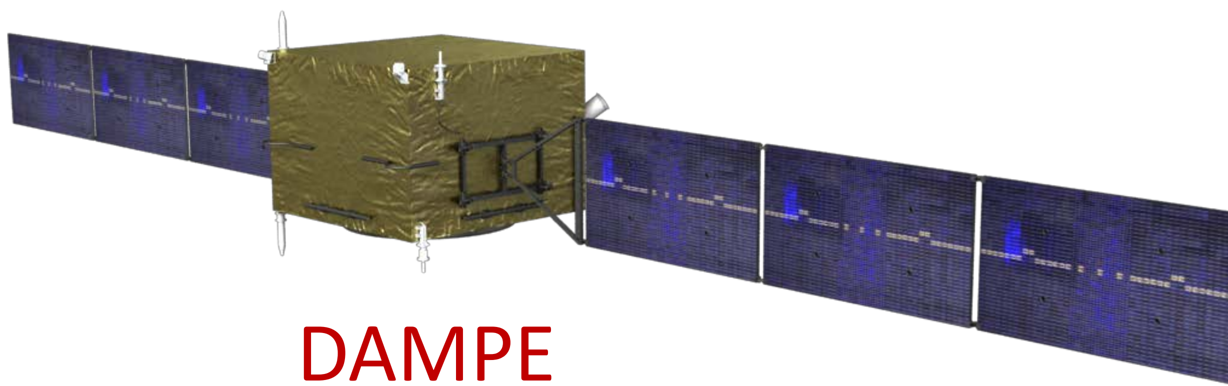
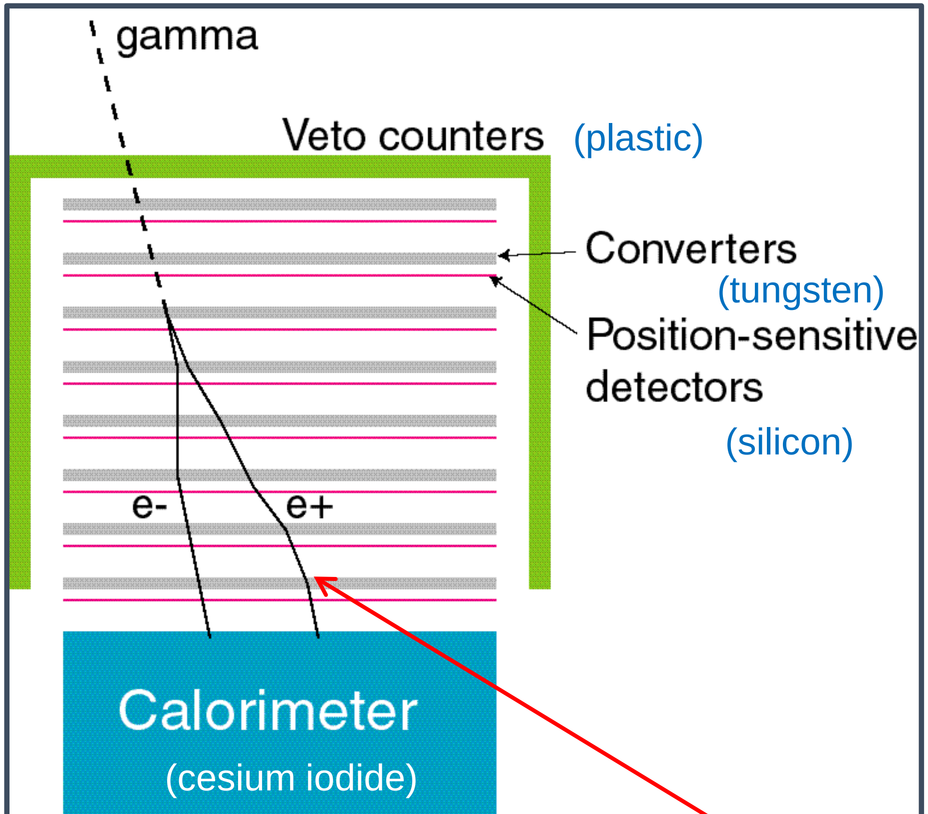


DAMPE

Pair-Conversion Telescope Concept



- Tracker:
  - Silicon sensors detect the e^+e^- to reveal the γ direction.
- Calorimeter:
  - Dense CsI scintillating crystals measure the energy.
- Veto counters:
  - Plastic scintillators detect cosmic-ray background.

Unavoidable random scattering in the material limits the angular resolution of the telescope.

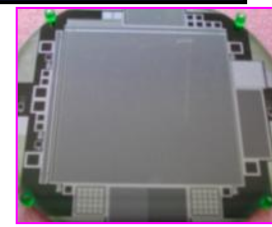
Fermi-LAT Si Tracker Module (1 of 16)

73.8 m^2 of Si sensors! 9216 wafers, 884,763 channels, 14,976 ASICs

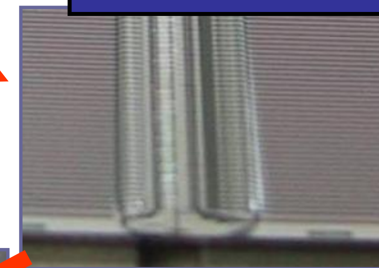
Module Structure Components:
Composite Sidewalls: Italy (Plyform)
Other parts: SLAC

SSD Procurement, Testing
Japan, Italy (HPK)

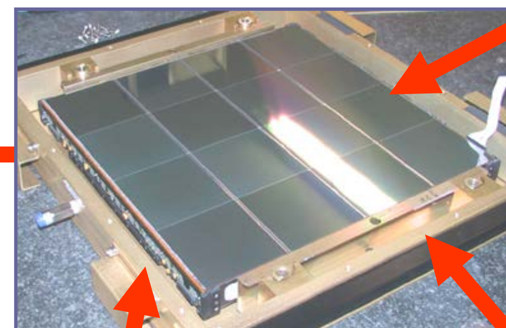
Single-sided,
AC coupled,
0.4 mm thick
228 μm pitch



SSD Ladder
Assembly, Italy
(G&A, Mipot)



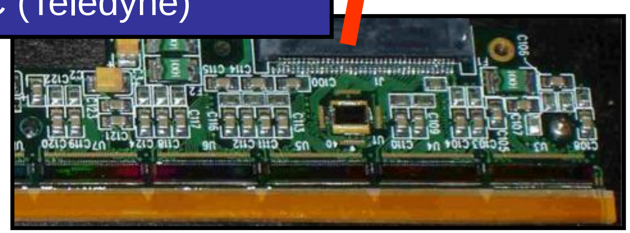
Tracker Module
Assembly, INFN

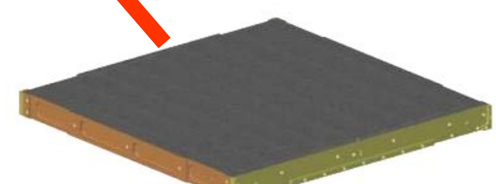


Tray Assembly and
Test, Italy (G&A).
Si on *both* sides.

Environmental
Test, Italy
(Alenia-Spazio)

Electronics Fabrication,
burn-in, & Test, UCSC,
SLAC (Teledyne)





Composite panel assembly,
Italy (Plyform)

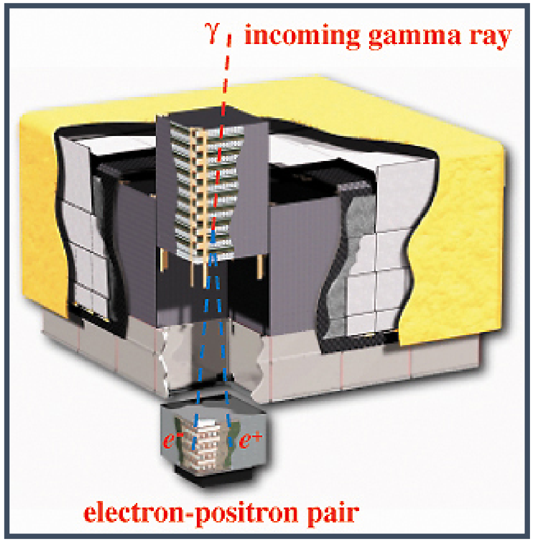
Readout Cables
UCSC, SLAC
(Parlex, Pioneer)

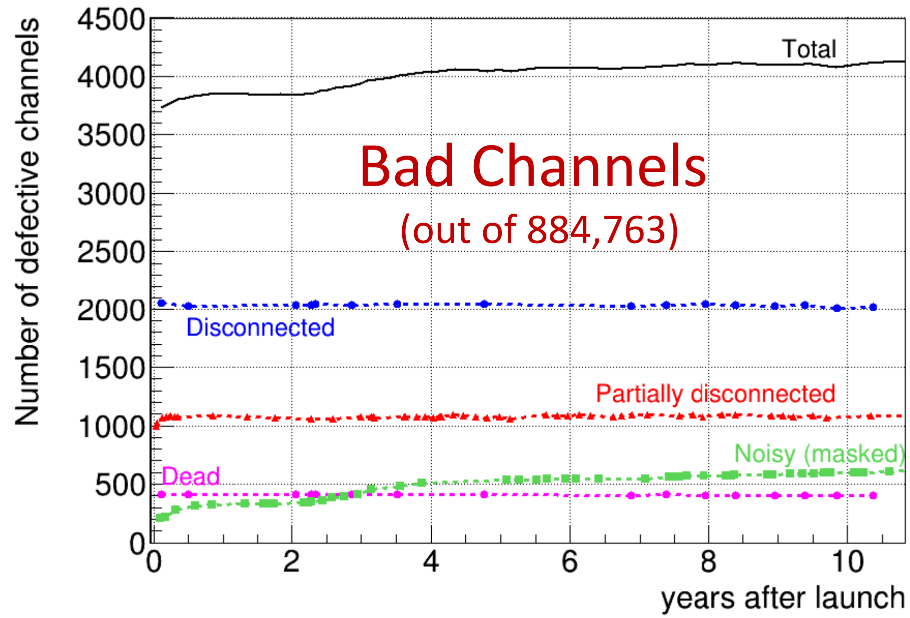
W.B. Atwood et al, Astropart. Phys. 28 (2007) 422.

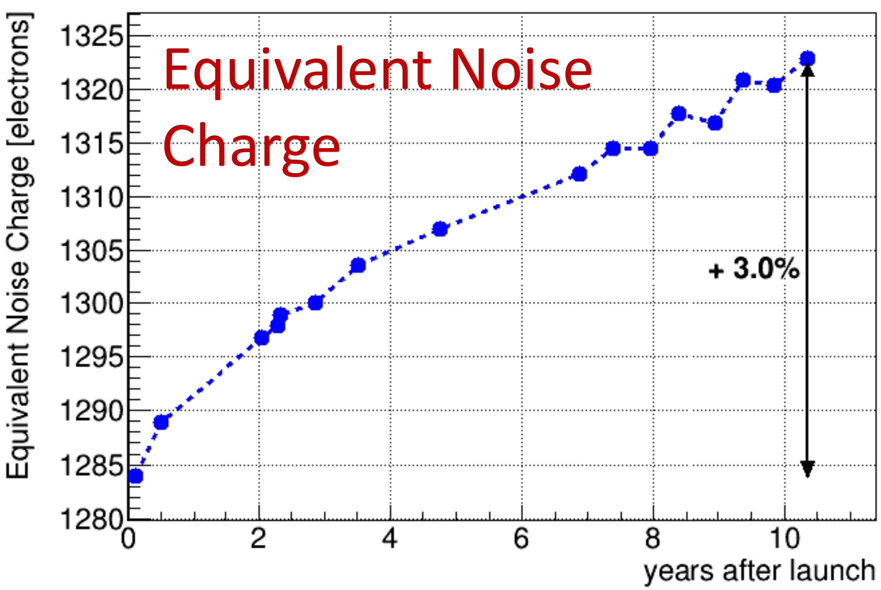
Fermi-LAT Performance after 10 Years on Orbit

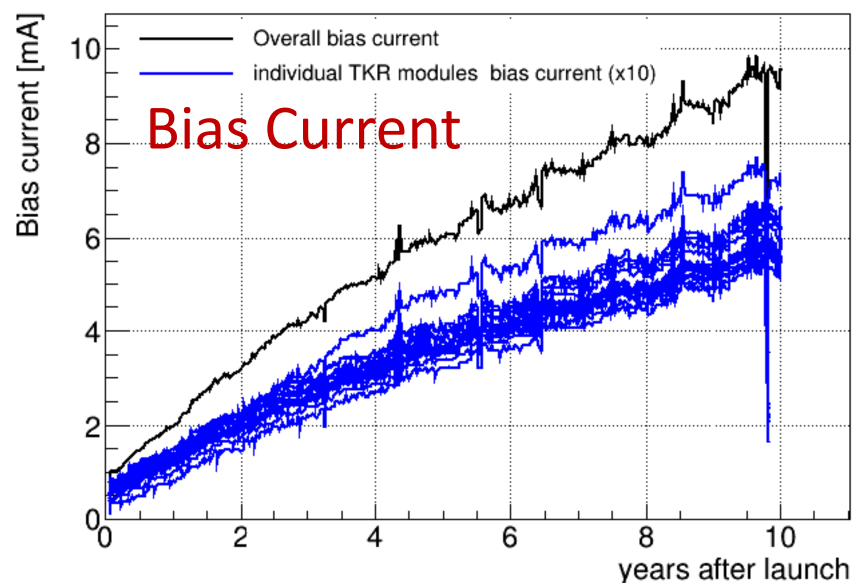
- Fermi began operations on orbit 13 years ago.
- The LAT remains fully operational today, with negligible degradation in detector performance. *Excellent demo of the power of solid-state tech.*
  - See arXiv:2106.12203v2, July 8, 2021
- Of the ≈15,000 ASICs in the tracking system, only one has failed (before launch). Full operation of all channels in that module was maintained because of the left-right readout redundancy.
- The MIP peak (from time-over-threshold) trended upward by ≈11% over 10 years, with most of the change occurring in the first few months.
- Bad channels:
  - 0.31% at launch (concentrated in the first tracker module assembled)
  - 0.46% after 10 years
  - After 10 years, 58% of the 598 masked noisy channels were on 2 of the 2304 silicon-strip ladders
- Radiation damage: visible, but negligible effect on performance. Overall hit efficiency dropped from 99.73% to 99.70% in 10 years.
  - *Very high S/N of Si sensors ensures ≈100% hit efficiency with ≈0 noise!*

Fermi-LAT Tracker



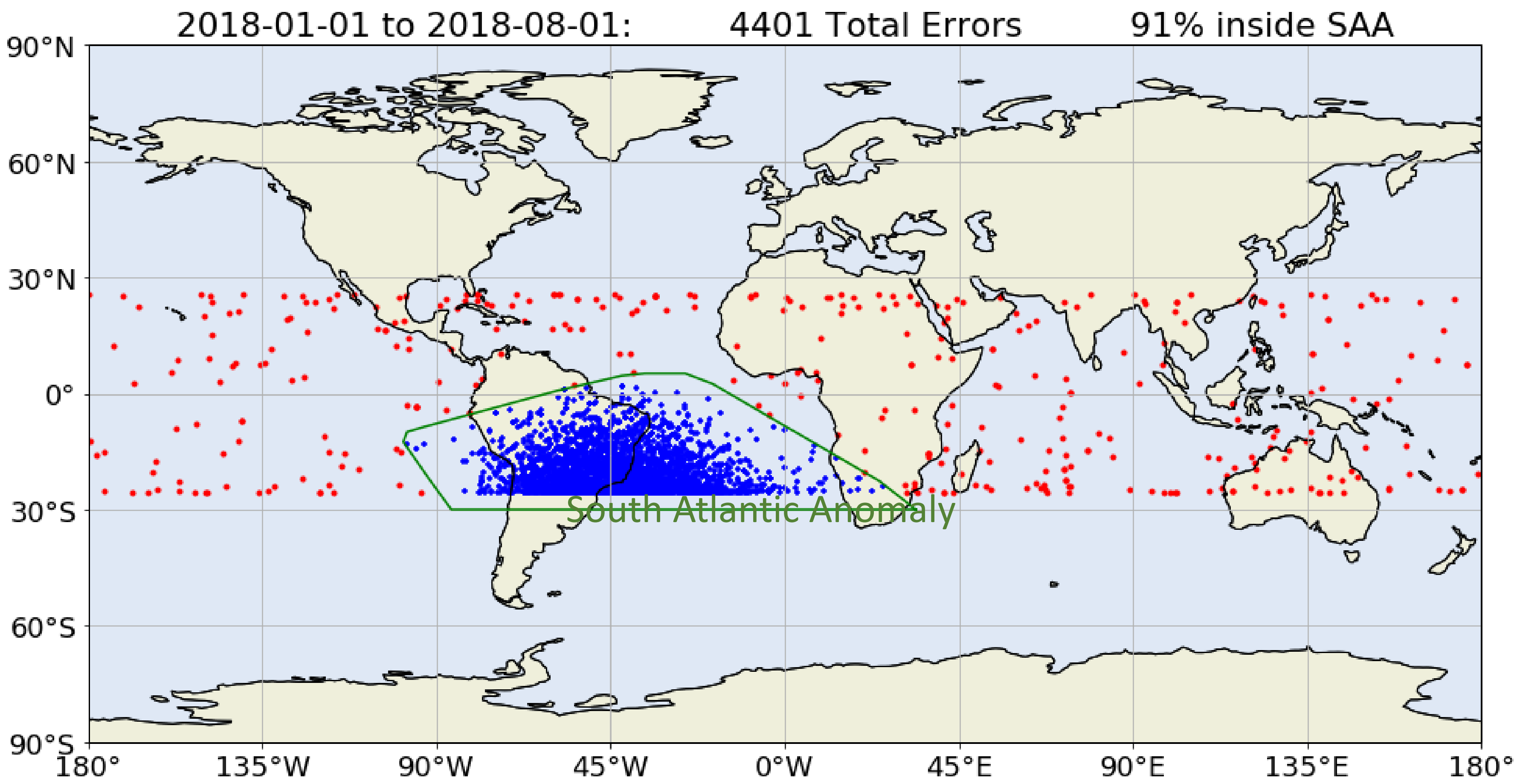




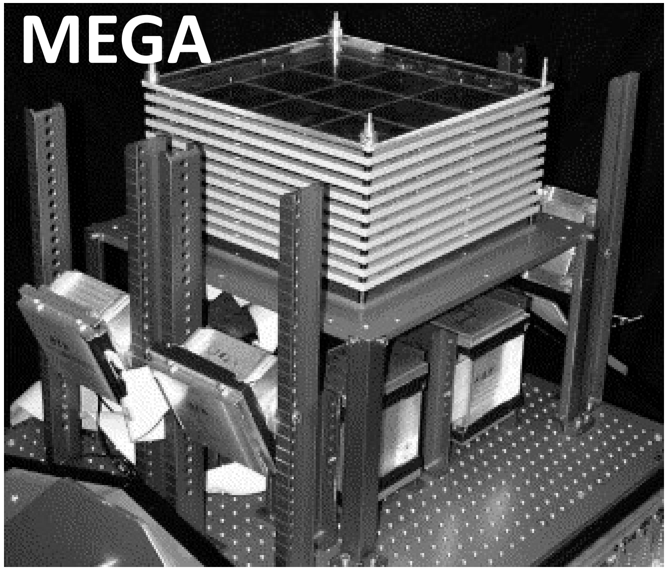


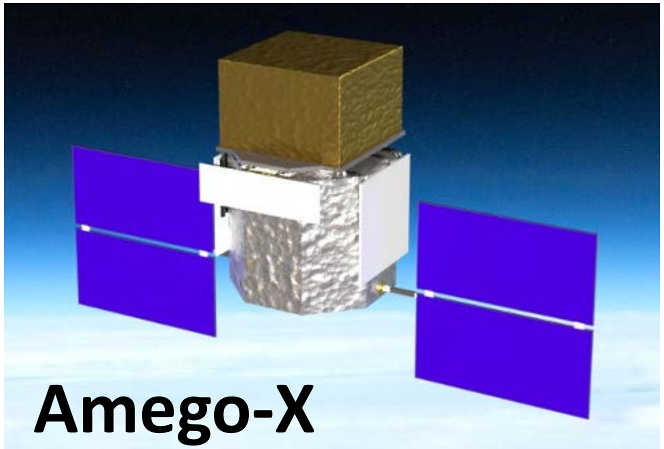
Computer Memory Upsets and the SAA

The radiation environment is relatively benign in low-Earth orbit, but some care has to be taken for single-event upsets (probably from heavy ions).

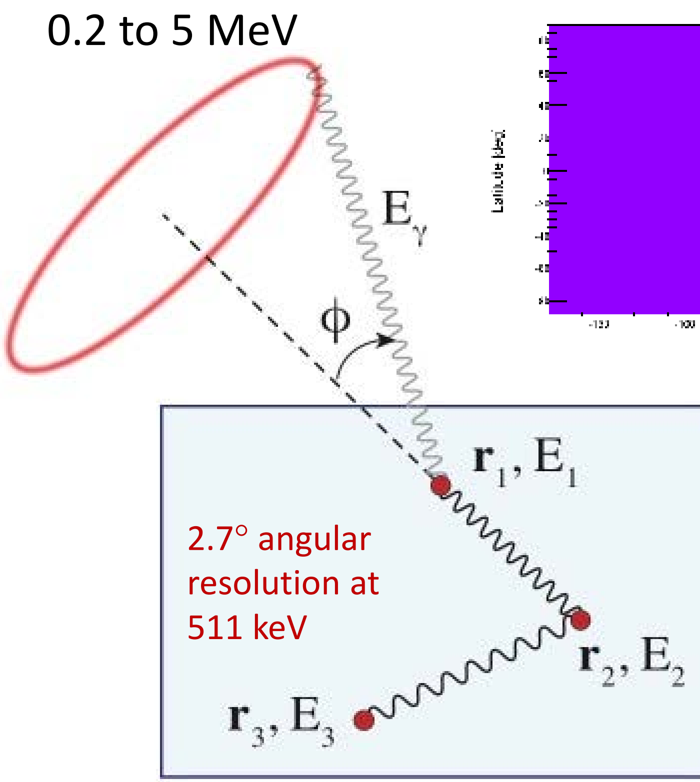


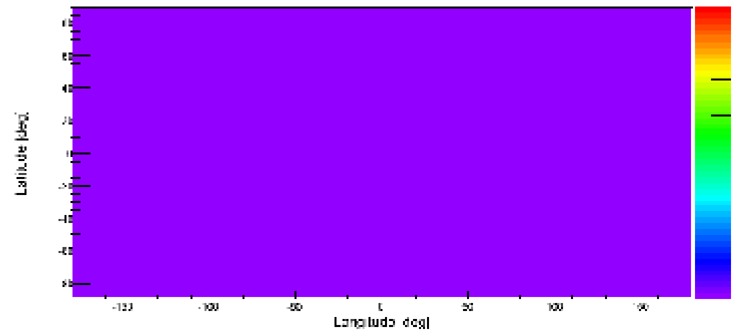
Compton Gamma-ray Telescopes

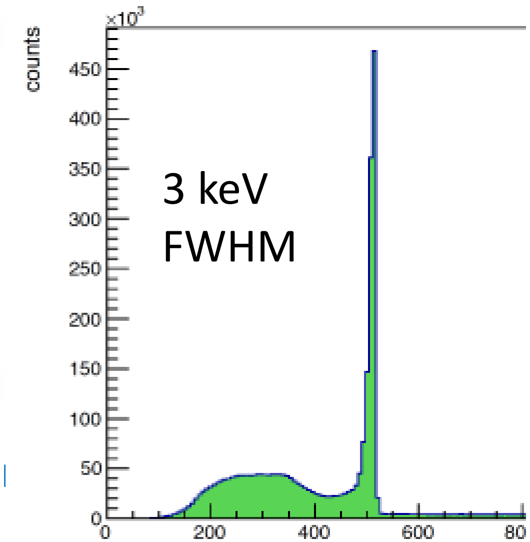




Compton Spectrometer & Imager (COSI)







3D imaging of Compton scatters within cold germanium detectors:

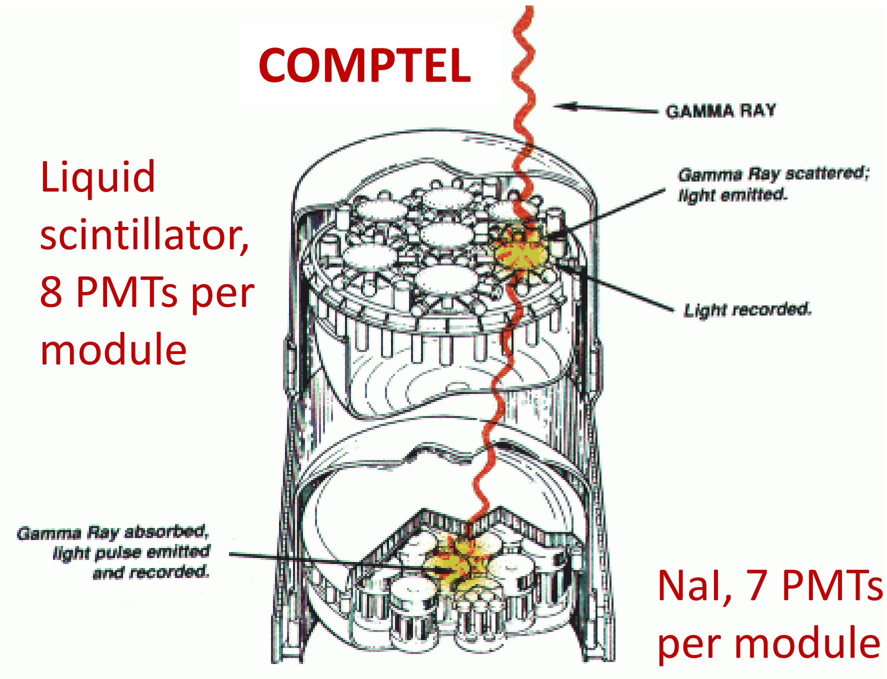
- Double-sided strips at 90-degree stereo
- Time difference of electron and hole collection.

Two successive Compton scatter give information needed to reconstruct a circle on the sky. Redundant information from scattering energies allows the interaction order to be inferred.

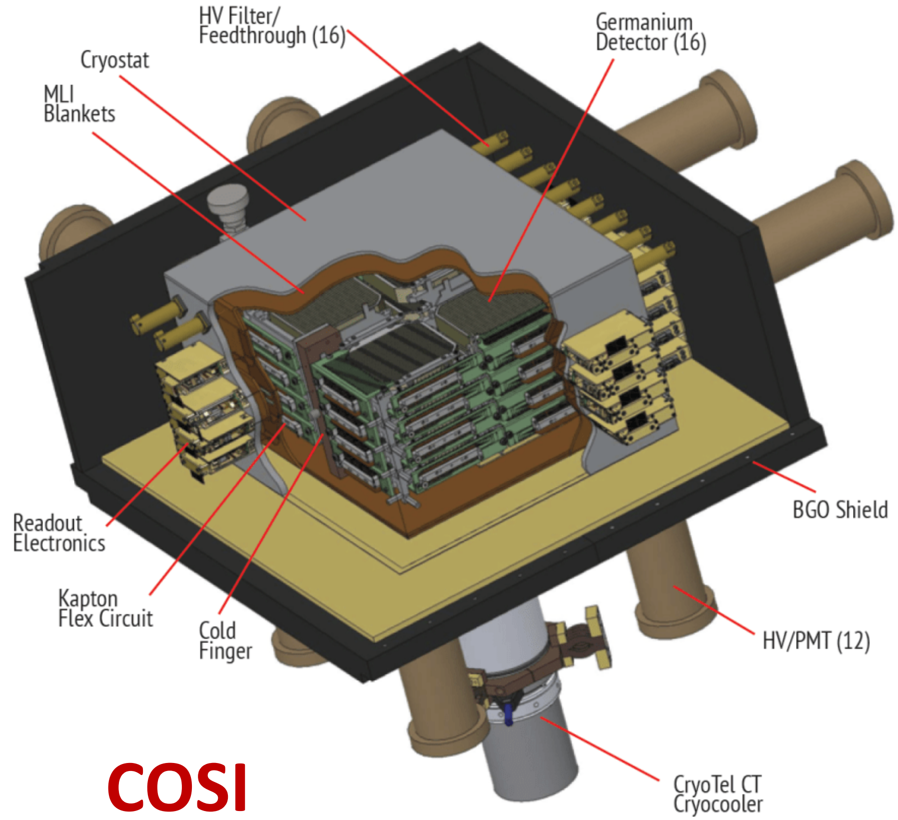
Selected in 2020 for a SMEX Phase-A study.

PI: John Tomsick, UCB Space Sciences Lab

Compact Compton Telescope Concept



- 1.5 m lever arm
- PMT readout with fast timing, to measure TOF.
- Positions within modules derived from relative PMT signals.



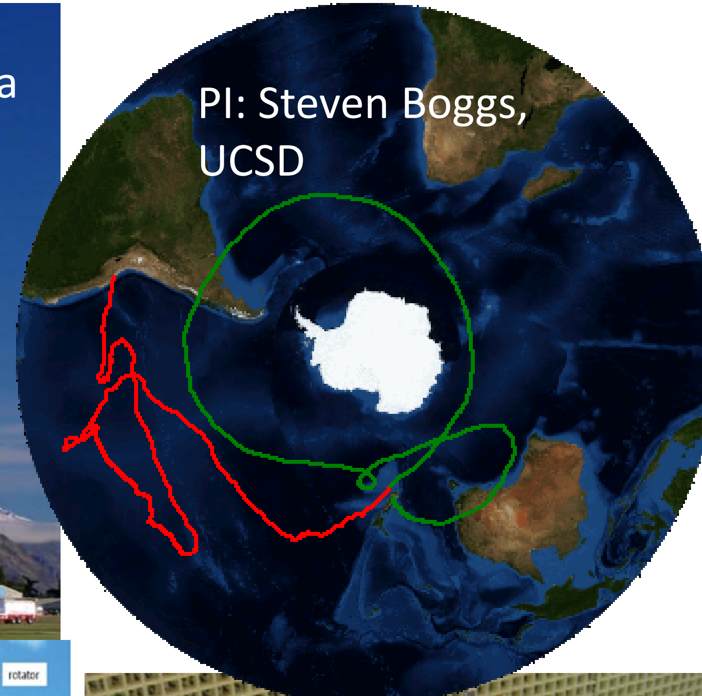
- Compact: photon scatterings and absorption can be confined to a single Ge detector.
- No TOF. Redundant kinematic information is used to determine interaction ordering.

arXiv:1908.04334

COSI-APRA Sub-Orbital Payload (arXiv:1701.05558)

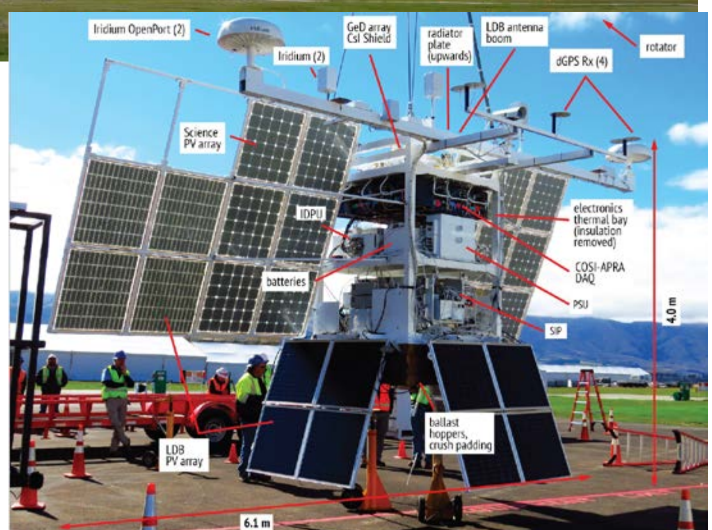
2016 46-day flight on a NASA pressurized balloon (532,000 m^3)

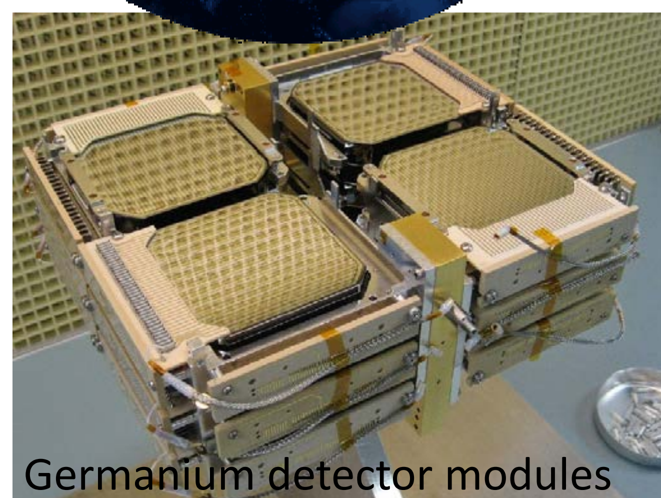
Science Magazine, July 3, 2016



PI: Steven Boggs, UCSD

Two Galactic point sources, an AGN, and one Gamma-Ray-Burst (GRB) were observed.



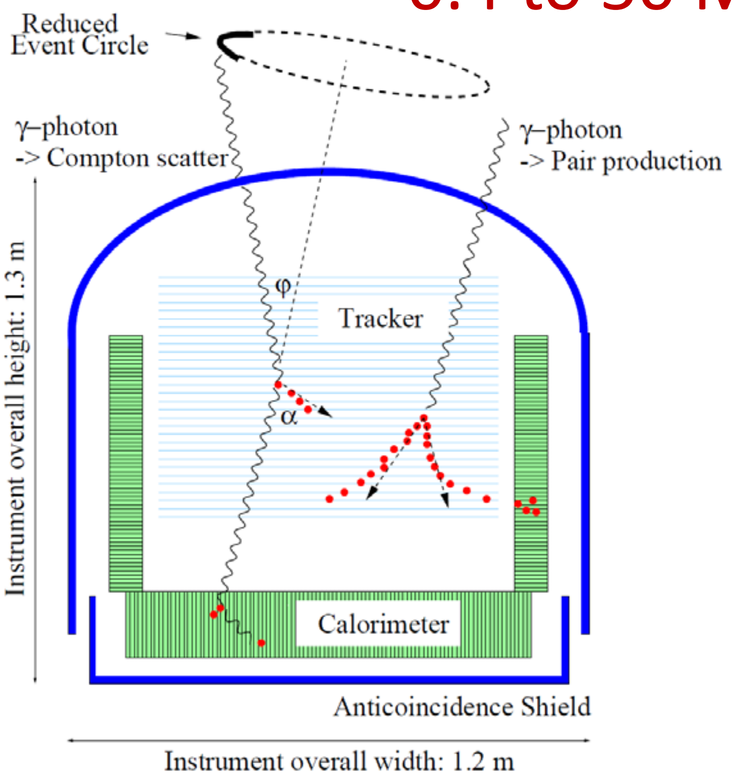


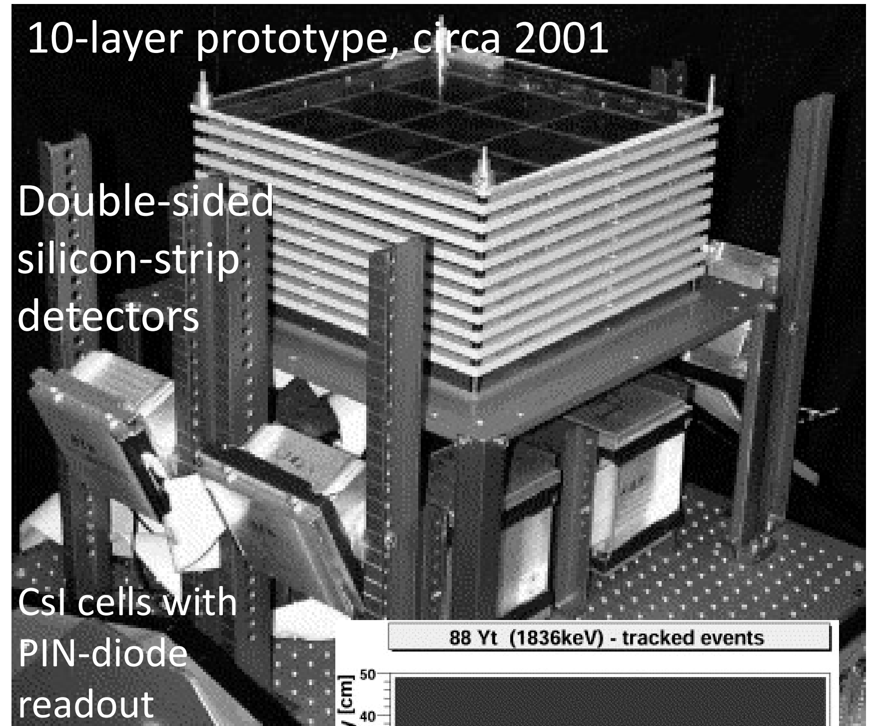
Germanium detector modules

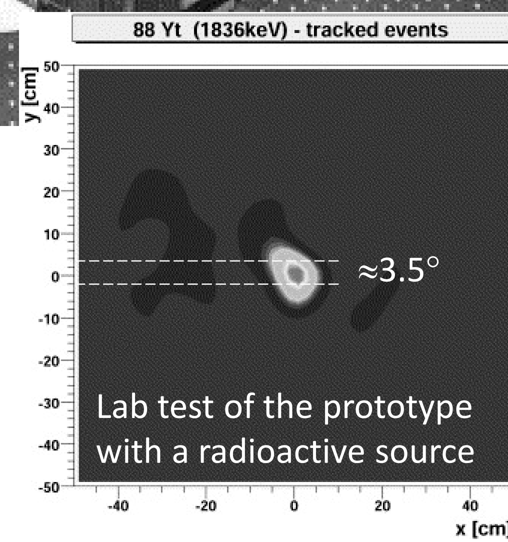
Medium Energy Gamma-ray Astronomy (MEGA)

0.4 to 50 MeV

arXiv:astro-ph/0110129







- Above ≈1.5 MeV the scattered electron can be tracked.
- Above ≈8 MeV pair conversion starts to dominate.
  - *With no heavy metal converter in the tracker, the low-energy conversions are more useful than in Fermi-LAT*
- A large observatory using this technology, eAstrogam, was proposed (arXiv:1711.01265), for 0.15 to 3000 MeV.

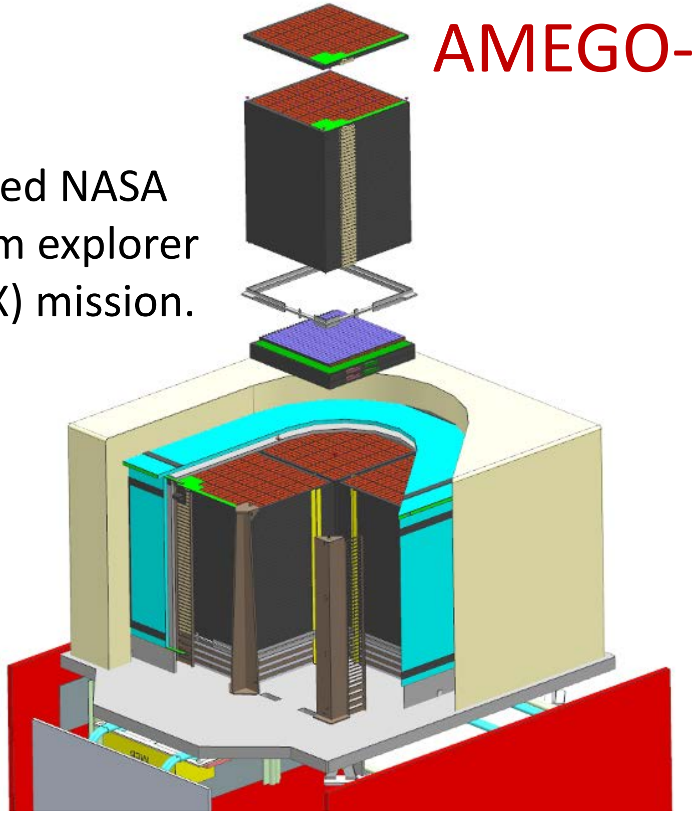
All-Sky Medium Energy Gamma-ray Observatory

- The CsI calorimeter and plastic-scintillator anti-coincidence shield are similar to MEGA & eAstrogam.
  - Horizontal CsI "logs" (*a la* Fermi-LAT) instead of vertical pixels
- The tracking detector is called "AstroPix", based on the ATLASPix monolithic silicon detector technology (HV CMOS)
  - Square pixels 1 to 2 mm in size
  - 0.5 mm thick
- Low pixel capacitance, compared to long double-sided Si strips, could allow much lower thresholds for detection of Compton scattering, and improved energy resolution.
  - 25 keV trigger threshold
  - 5% resolution at 100 keV

PoS (ICRC2021) 649

AMEGO-X

Proposed NASA medium explorer (MIDEX) mission.

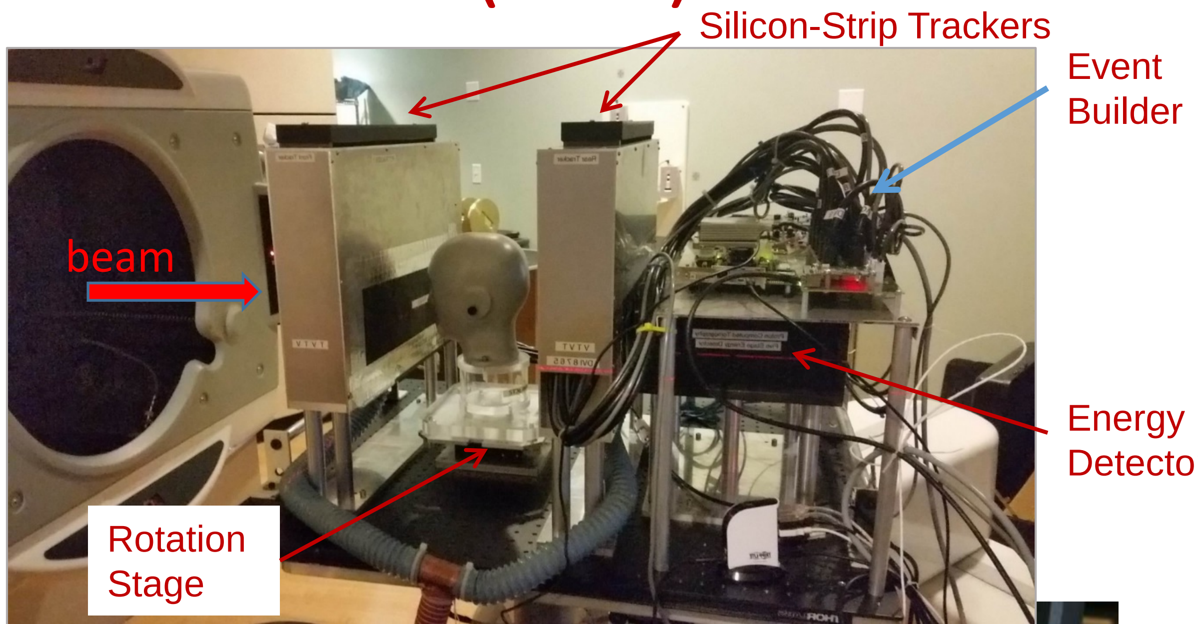


Compton angular resolution is about 5° at 1 MeV.
Pair-conversion resolution is about 5° at 40 MeV.

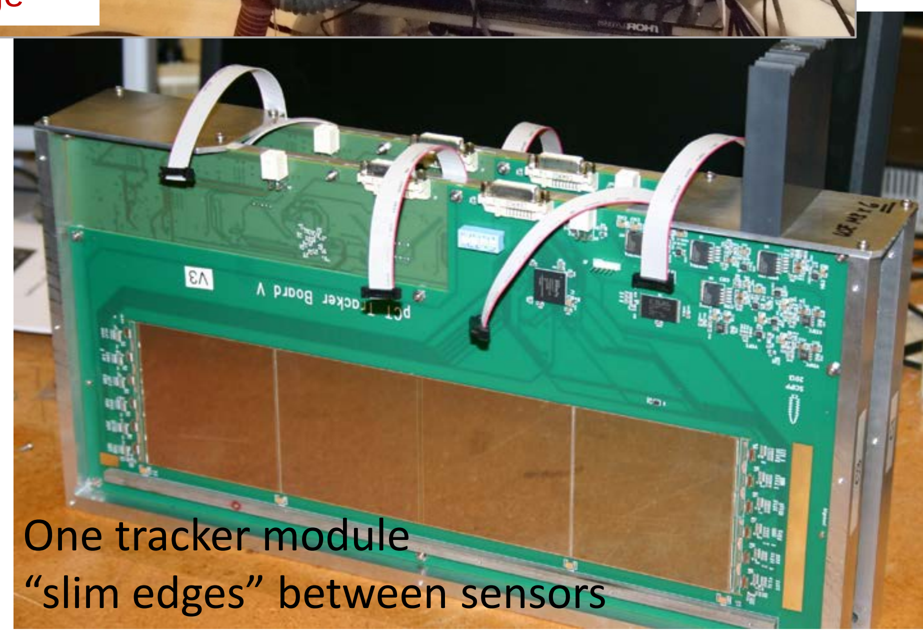
See also "*The CMOS pixel sensors particle tracker for the CSES-02 space experiment*", S. Beole, in this session.

Technology Transfer to Proton (& He) CT

- Make 3D images of proton stopping power for planning proton cancer therapy.
- Measures directly proton energy loss, instead of inferring it from X-ray images.
- But, more difficult and expensive than X-ray CT.



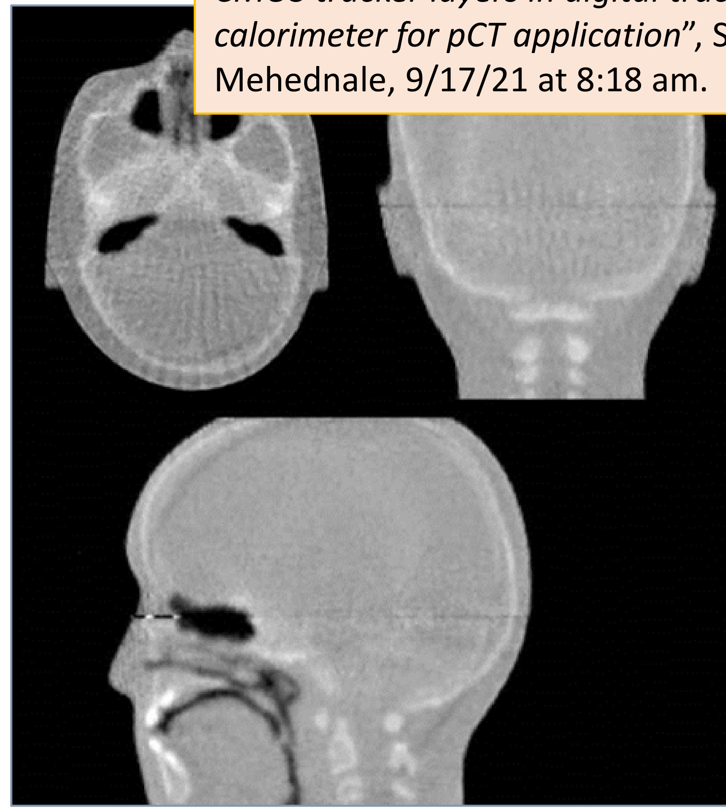
- Track protons entering and exiting the phantom.
  - Each tracker has 4 layers of Fermi-LAT single-sided SSD.
  - Front-end readout by a new, custom VLSI ASIC.
- Measure the residual proton energy by stopping them in plastic scintillators.


One tracker module
"slim edges" between sensors

R. Johnson et al, IEEE Trans Nucl Sci 63, 2016, p 5.

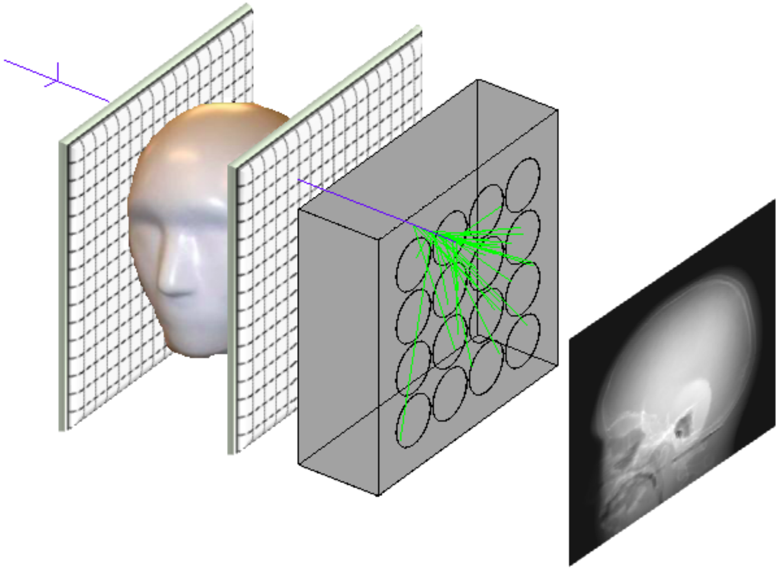
UCSC/Loma-Linda pCT Scanner

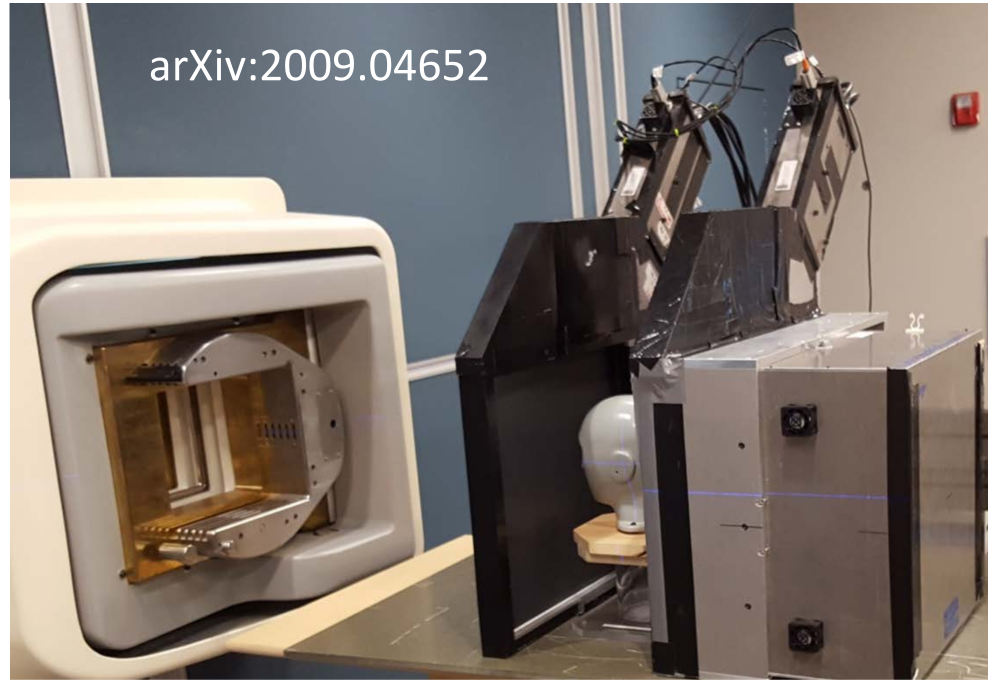
See also the posters “*Bergen proton-CT project*”, V. Eikeland, 9/16/21 at 11:00 am, and “*Design and integration of CMOS tracker layers in digital tracking calorimeter for pCT application*”, S. Mehednale, 9/17/21 at 8:18 am.



- About 360 million proton measurements make one 3D image.
  - 6 minutes of acquisition, at 1 million protons per second.
- This device has been used by several groups in the USA and Germany to study extensively this imaging modality, including imaging with He ions in Heidelberg, Germany.

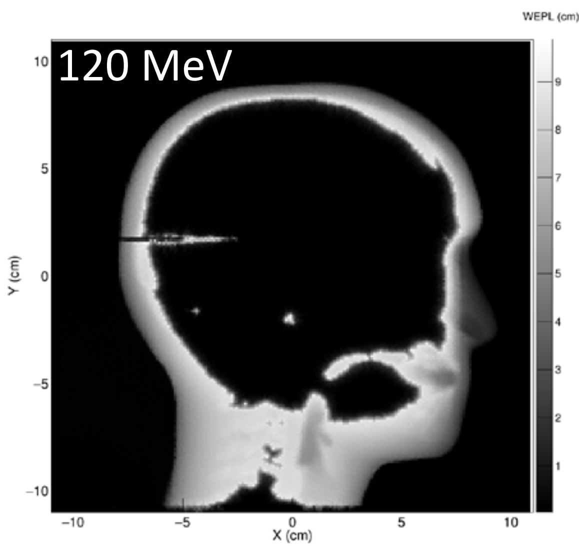
Proton-VDA Scanner

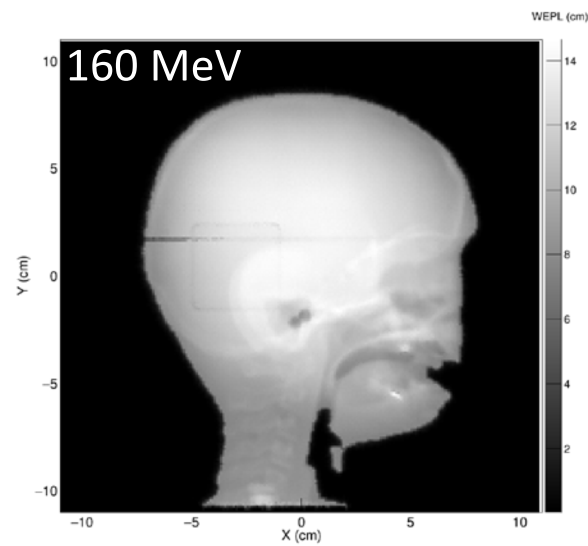




- Start-up company funded by US government SBIR funds.
- Only existing effort that I know of that is currently targeting clinical applications.
  - Scintillating-fiber tracking.
  - Thin monolithic calorimeter read out by 16 PMTs.
  - Adjust beam energy according to the phantom thickness.

https://protonvda.com/

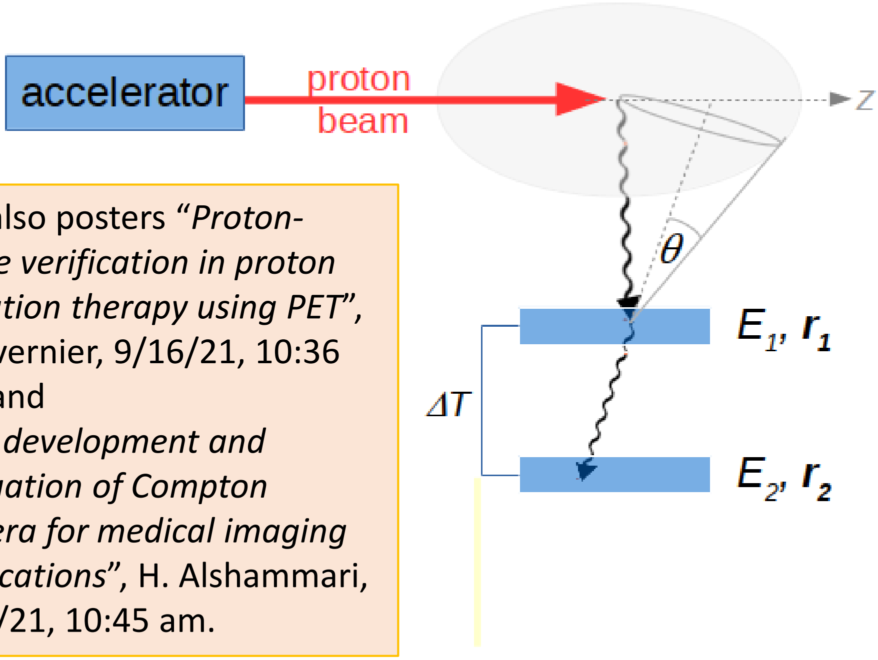




Technology Transfer to Prompt-Gamma Imaging

- *Real-time* monitoring of the Bragg-peak location during proton cancer therapy.
- MeV photons are emitted instantaneously from the Bragg peak and exit the patient with little interaction
- Many groups have worked on imaging the photons using Compton cameras.

See also posters "*Proton-range verification in proton radiation therapy using PET*", S. Tavernier, 9/16/21, 10:36 am, and "*The development and evaluation of Compton camera for medical imaging applications*", H. Alshammari, 9/16/21, 10:45 am.



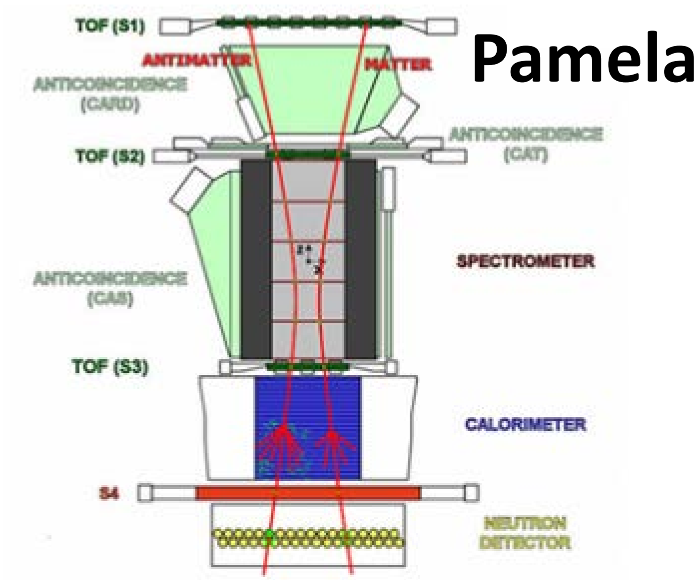
A few different examples:

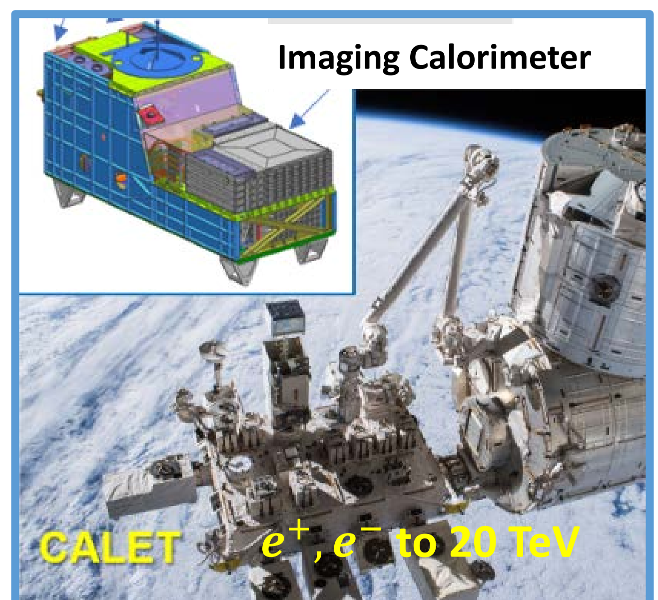
- Double-sided Si with $LaBr_3$ crystals: *S. Aldawood et al, Rad. Phys. & Chem. 140, 2017, p. 190.*
- CZT strip detectors plus LSO crystal: *F Hueso-González et al, JINST 9, 2014, P05002.*
- Multiple layers of commercial CZT detectors: *J. Polf et al, Phys. Med. Biol. 60, 2015, p. 7085.*
- Scintillating fibers of heavy material (e.g. LYSO:Ce) read by SiPM: *A. Wronska et al, Acta Phys. Pol. B 51, 2020, p. 17.*

I have not seen any use of Ge strip detectors such as in COSI.

No efforts have yet reached clinical, or pre-clinical, use. A typical problem is inadequate efficiency. Expense and complexity are other issues.

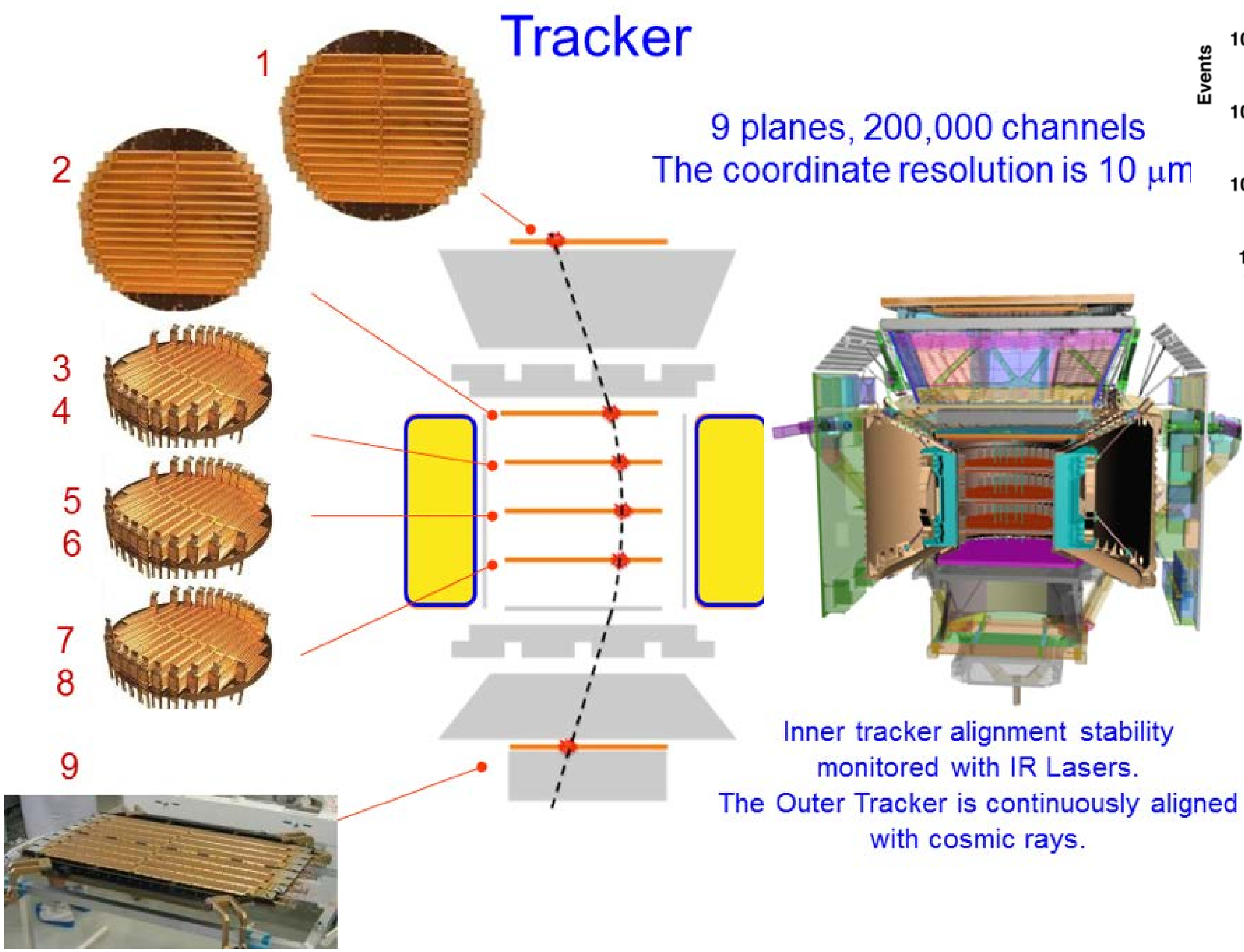
Cosmic-Ray Telescopes

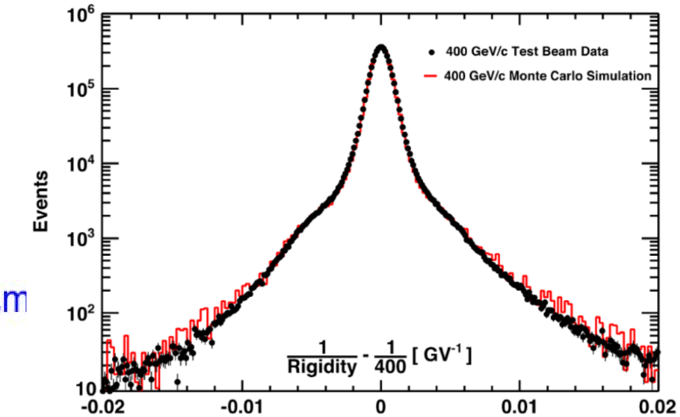




AMS Tracking Detector

- 9 planes of *double-sided* SSD supported by carbon-fiber structures.
- Alignment precision of about 6 microns.
- Can measure the cosmic-ray rigidity up to 2 TeV.





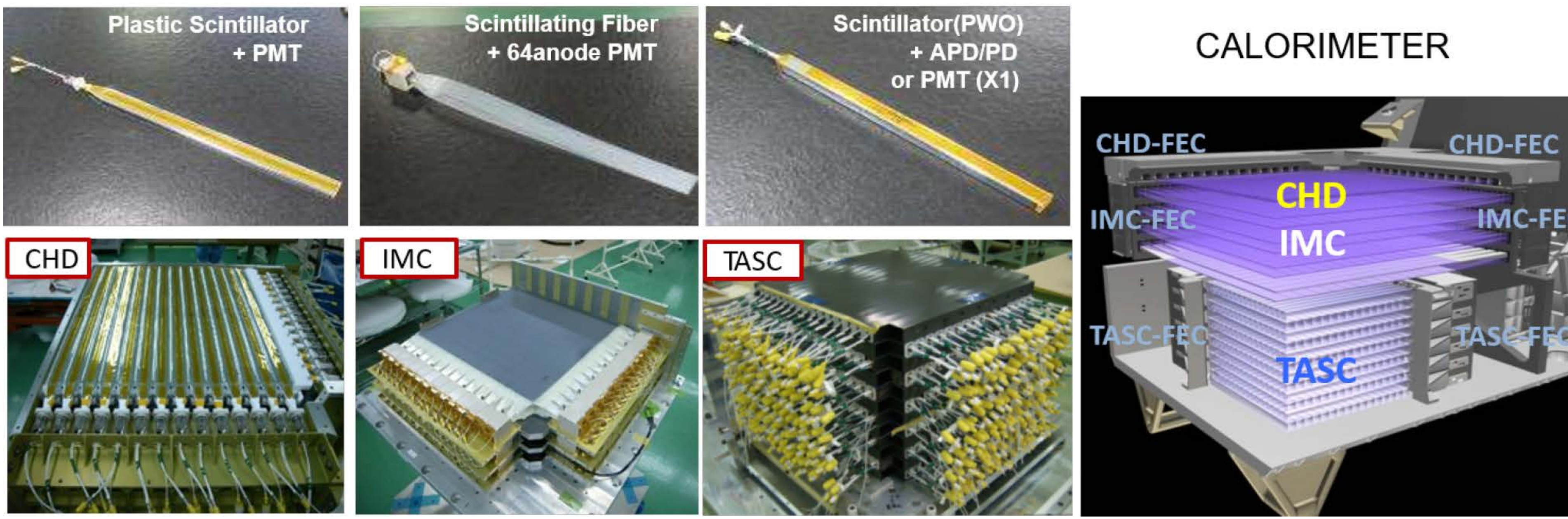
Error in 1/rigidity for 400 GeV test-beam protons.

Nucl. Phys. B Proc. Suppl. 243-244 (2013) p 12

CALorimetric Electron Telescope (CALET)

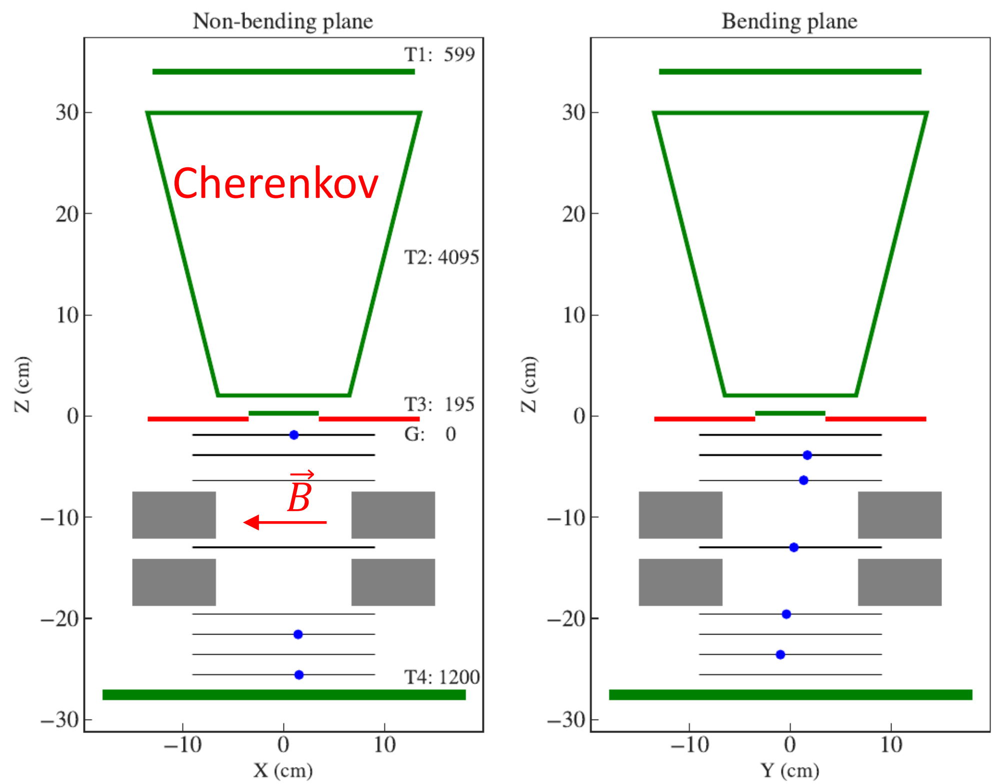
- Similar to the Fermi-LAT but
  - Thicker by about $\times$3, for very high energy electrons and photons
  - Scintillating fibers instead of silicon-strips
  - Much smaller area (about 1/20)
  - Lots of ISS material in parts of the field of view
- Cannot compete very much with the Fermi-LAT on photon science, but electron cosmic-ray measurements extend to higher energy

Astropart. Phys. (2018) 10029



AESOP-Lite High Altitude Balloon Experiment

- Measure the electron and positron CR fluxes at low energy (down to 20 MeV).
- Flew from northern Sweden to Ellesmere Island, Canada in 2018.
- Second flight, with detector upgrade and a larger (higher) balloon in Antarctica, 2022.



- 8 Si tracking planes:
  - Fermi-LAT SSDs.
  - ASICs from pCT project.
- Permanent magnet (≈0.3 T)
- Cherenkov detector
- Scintillators, with TOF

Mechbal et al., Ap.J. 903 (2020) 21

Conclusions

- Position sensitive detectors are widely used in space-based particle detection and tracking.
  - Silicon strips are especially by now an old, standard, well-proven technology.
- One of the biggest contemporary challenges is a sensitive Compton telescope to explore the MeV universe.
  - Many proposals with Ge and Si, plus now pixel detectors.
- The same technologies have found their way into medical physics applications (see Reinhard Schulte's talk).
  - Proton Computed Tomography and Radiology are poised to begin an entry into clinical use.
  - Prompt gamma imaging could have an even greater medical impact, but there the challenges posed by Compton telescopes are again a big factor.