The Silicon Strip Tracker of the Fermi Large Area Telescope

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on behalf of the Fermi LAT collaboration

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The Fermi-LAT Collaboration

United States

- Stanford University (SLAC and HEPL/Physics)
- Goddard Space Flight Center
- Naval Research Laboratory
- Ohio State University
- California State University at Sonoma
- University of California at Santa Cruz
- University of Washington

PI: Peter Michelson (Stanford & SLAC)

- $\sim$ 390 Members (including $\sim$ 95 Affiliated Scientists, plus 68 Postdocs, and 105 Graduate Students)
- Cooperation between NASA and DOE, with key international contributions from France, Italy, Japan and Sweden
- Managed at Stanford Linear Accelerator Center (SLAC)

Sweden

- Royal Institute of Technology
- Stockholm University

France

- IN2P3
- CEA/Saclay

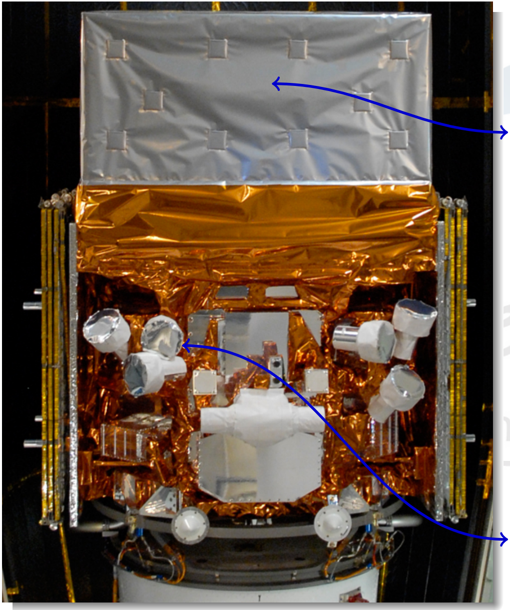
Japan

- Hiroshima University
- ISAS/JAXA, RIKEN
- Tokyo Tech.

Italy

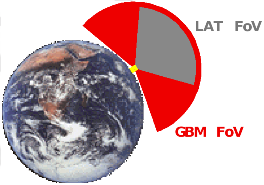
- INFN
- INAF
- ASI

The Fermi observatory



Large Area Telescope (LAT)

- Pair conversion telescope.
- Energy range: 20 MeV–> 300 GeV
- Large field of view ($\approx$ 2.4 sr): 20% of the sky at any time, all parts of the sky for 30 minutes every 3 hours.
- Long observation time: 5 years minimum lifetime, 10 years planned, 85% duty cycle.



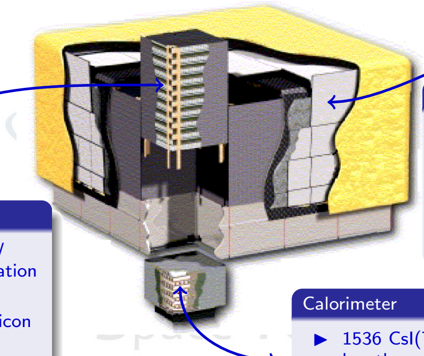
Gamma-ray Burst Monitor (GBM)

- 12 NaI and 2 BGO detectors.
- Energy range: 8 keV–40 MeV.

The Large Area Telescope

Large Area telescope

- Overall modular design.
- 4×4 array of identical towers (each one including a tracker and a calorimeter module).
- Tracker surrounded by an Anti-Coincidence Detector (ACD)



Tracker

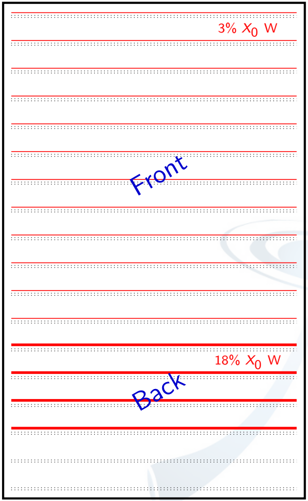
- Silicon strip detectors, W conversion foils; 1.5 radiation lengths on-axis.
- 10k sensors, 73 m^2 of silicon active area, 1M readout channels.
- High-precision tracking, short instrumental dead time.

Anti-Coincidence Detector

- Segmented (89 tiles) to minimize self-veto at high energy.
- 0.9997 average efficiency (8 fiber ribbons covering gaps between tiles).

Calorimeter

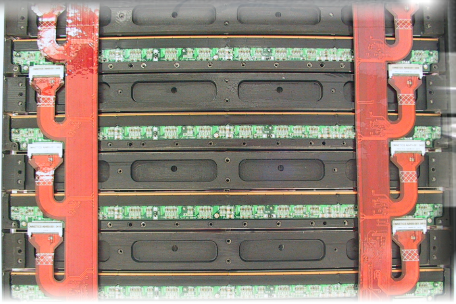
- 1536 CsI(Tl) crystal; 8.6 radiation lengths on-axis.
- Hodoscopic, 3D shower profile reconstruction for leakage correction.

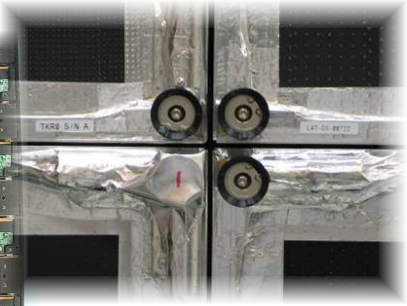


- 19 tray structures
  - Basic mechanical framework
- 18 x-y detection planes
  - Single sided SSDs, below the W foils
- Front: 12 planes with 0.03 X_0 converter
  - Best angular resolution
- Back: 4 planes with 0.18 X_0 converters
  - Increase the conversion efficiency
- Bottom: 2 planes with no converter
  - Tracker trigger needs at least 3 x-y layers
- Total depth: 1.5 X_0 on axis

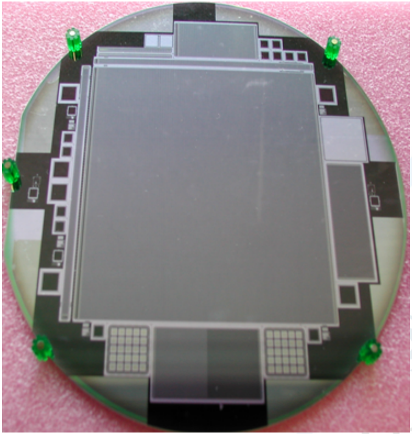
Tracker design: mechanics

- Less than 2 mm spacing between silicon layers
- Readout electronics on the tray sides: 90° pitch adapters, read out via flat cables
- 2 mm inter-tower separation to minimize dead area

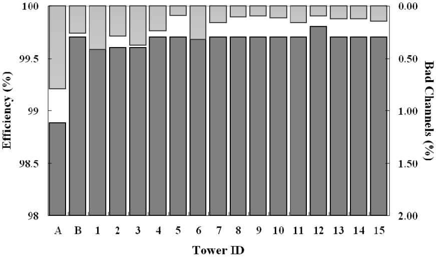




The Silicon Strip Detectors



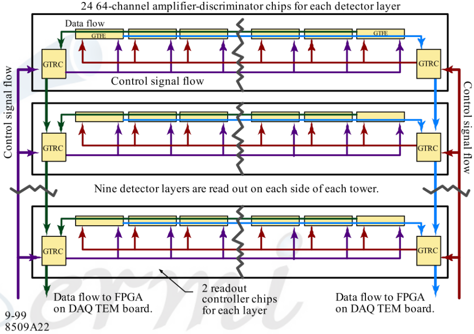
Coupling	AC
Outer size	8.95×8.95 cm^2
Strip pitch	228 μm
Thickness	400 μm
Depletion voltage	$<$ 120 V
Leakage current	1 nA/cm^2 150 V
Breakdown voltage	$>$ 175 V
Bad channels	$\approx 10^{-4}$
# SSD tested	12500
# single strip tests	$\approx$ 30M
Rejected SSDs	0.6%



- 18 flight towers integrated and tested in 9 months
  - Flight Module A suffering from some processing issues during the set up of the assembly chain

The Tracker electronics system

- Basic design
  - 24 front-end chips and 2 controllers handle one Si layer
  - Data can shift left/right to either of the controllers (can bypass a dead chip)
  - Zero suppression takes place in the controllers (hit strips + layer OR TOT in the data stream)
  - Two flat cables complete the redundancy



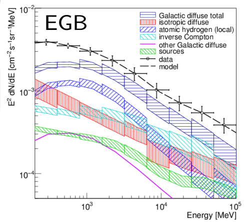
- Key features
  - Low power consumption ($\approx$ 200 μW/channel)
  - Low noise occupancy ($\approx$ 1 noise hit per event in the full LAT)
  - Self-triggering (three x–y planes in a row, i.e. sixfold coincidence)
  - Redundancy, Si planes may be read out from the right or from the left controller chip
  - On board zero suppression

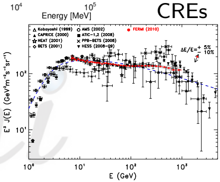
Launch

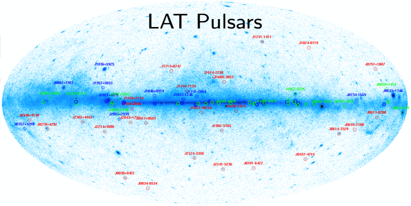
- Launched on June 11, 2008 from the Kennedy Space Center.
- Launch vehicle: Delta 7290H-10.
- Circular orbit, 565 km altitude, 25.6° inclination.
- Some of the milestones: $\approx$ 190 billion triggers $\approx$ 35 billion events downlinked to ground, $\approx$ 610 million photon candidates released to the community, $>$ 99% uptime.

(Some) Fermi Science Highlights !

- Diffuse γ-ray emission
  - no features in the ExtraGalactic Background spectrum
- Dark Matter WIMP annihilation
  - constraints are close to thermal cross–section below $\sim$ 10 GeV
- Cosmic-ray Electrons and positrons
  - spectrum measured from 7 GeV up to 1 TeV
  - rising positron fraction up to 100 GeV
- Gamma-ray Bursts
  - high energy emission
  - testing Lorentz Invariance Violation
- Pulsars
  - 88 pulsars now known: radio loud, gamma-ray selected, millisecond pulsars
- Active Galactic Nuclei, pulsar wind nebulae, novae, solar flare, moon emission. . .



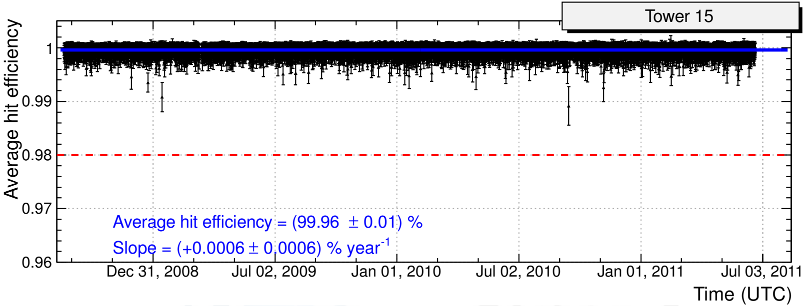


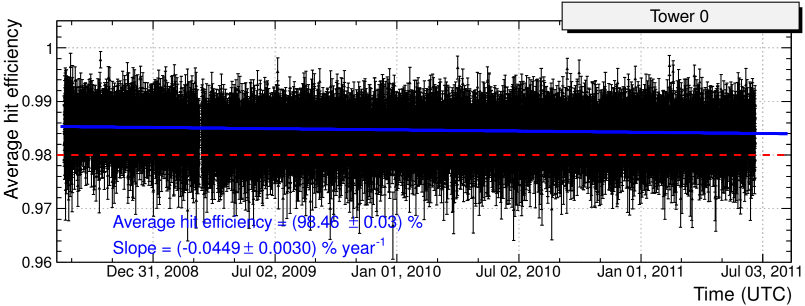


LAT TKR monitoring

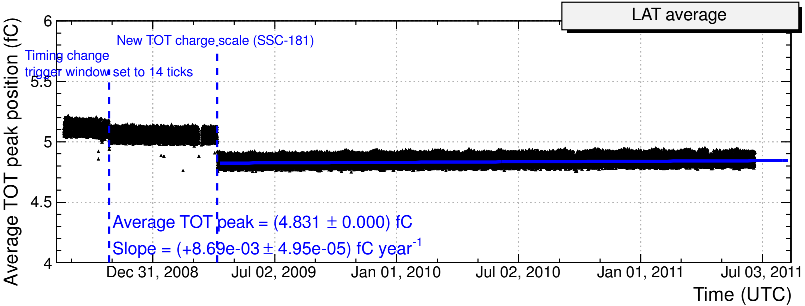
- All the relevant tracker quantities are monitored on a run by run basis:
  - noise occupancy;
  - hit and trigger efficiency;
  - Time over Threshold distributions;
  - alignment.
- Run selection for this summary:
  - roughly all the runs taken in the nominal data taking configuration;
  - more than 1500 s long, most of them are $\sim$ 5000 s long and contain $\sim$2M events;
  - not including the early phase of the *L&EO*.

$\Rightarrow$ numerology: $\approx$ 17000 runs, from September 2008 to June 2011.

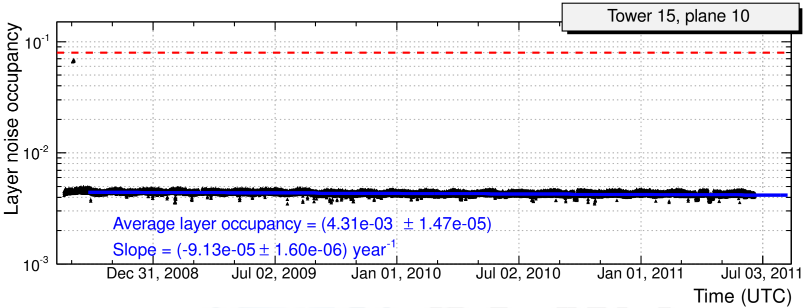

Tower 15
Average hit efficiency
1
0.99
0.98
0.97
0.96
Average hit efficiency = (99.96 ± 0.01) %
Slope = (+0.0006 ± 0.0006) % year-1
Dec 31, 2008
Jul 02, 2009
Jan 01, 2010
Jul 02, 2010
Jan 01, 2011
Jul 03, 2011
Time (UTC)


Tower 0
Average hit efficiency
1
0.99
0.98
0.97
0.96
Average hit efficiency = (98.46 ± 0.03) %
Slope = (-0.0449 ± 0.0030) % year-1
Dec 31, 2008
Jul 02, 2009
Jan 01, 2010
Jul 02, 2010
Jan 01, 2011
Jul 03, 2011
Time (UTC)

Time over threshold

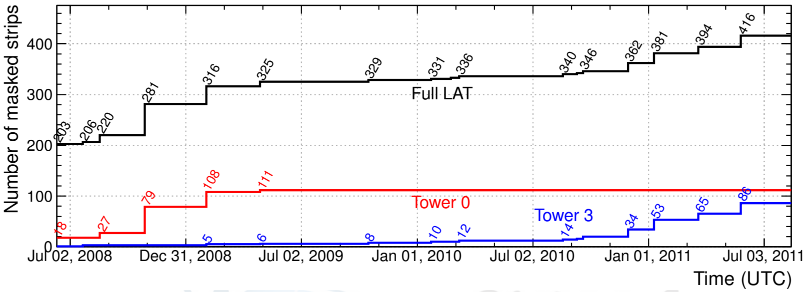


- Long term trending of the position of the MIP peak in the Tracker Time Over Threshold (averaged over the LAT)
- The two noticeable discontinuities are due to hardware/software changes
  - Analog signal remarkably stable (within much less than 1%) since the last of the two changes.



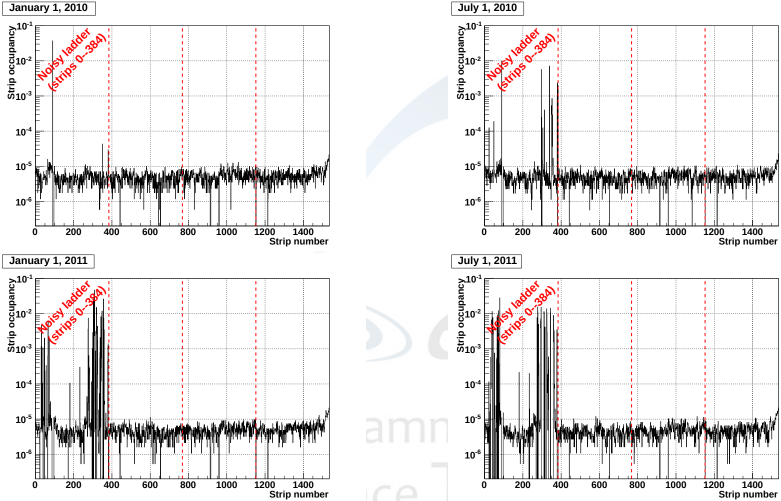
- Long term trending of the noise occupancy for a typical silicon layer
  - Measured accumulating counts on the silicon layers far from triggering towers (and cross-checked with dedicated periodic triggers)
- Noise occupancy at the level of 4×10^{-3} for a layer (1536 strips)
  - Translating into 2–3 $\times 10^{-6}$ at the single strip level (dominated by accidental coincidences)...
  - ...or 2–3 noise hits per event in the full LAT

Strip masks trending

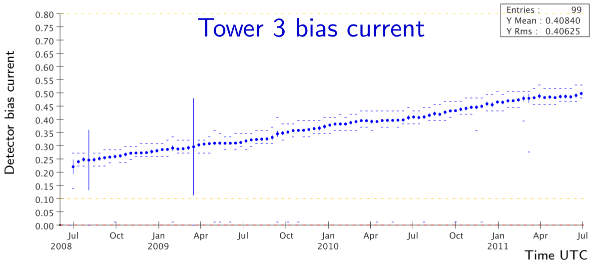


- Some 200 noisy strip masked prior to launch (0.02%)
- 213 additional noisy strips masked over the first three years of mission, for a total of 416 (0.05%)
- Two major contributors
  - Tower 0 (Fligth Module A): the first one being assembled, suffering from some processing issues—showed some evolution throughout the first year
  - Tower 3 (Flight Module 15): noise issue in one ladder—more on that later

A minor hardware issue

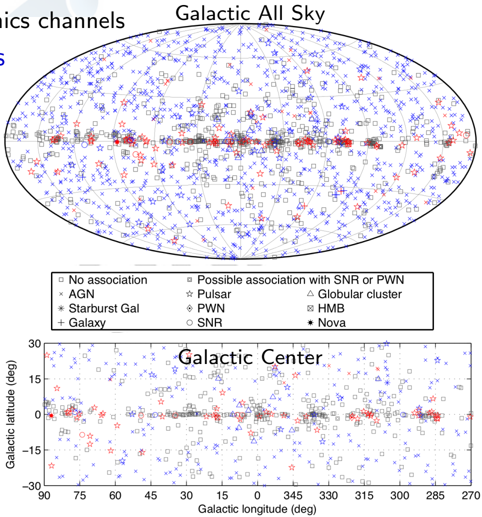


- Noise in one silicon ladder steadily increasing since January 2010
  - Really only one of the 2304 silicon ladders in the LAT



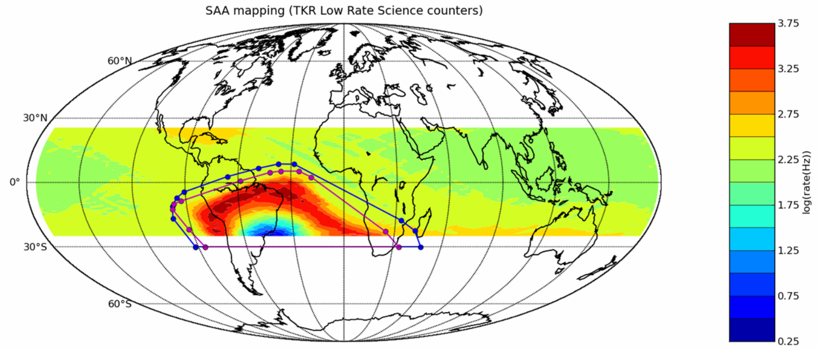
- One power supply per tower
  - We only monitor the currents at the tower level (i.e. each HV line is biasing $36 \times 4 = 144$ silicon ladders)
  - Not trivial to measure a relative increase in the leakage current at the level of a single ladder
- Test runs with reduced bias HV (40, 60, 80 V vs. nominal 105 V)
  - Normal data taking, charge injection calibration
- No obvious root cause identified
  - Even if we lose the entire ladder it's less than 0.05% of the tracker
  - No evidence of similar phenomena in any other part of the LAT

- The LAT tracker is the largest solid-state tracker ever built for a space application
  - 73 m^2 of single-sided silicon strip detectors
  - Almost 900,000 independent electronics channels
- All design goals met with large margins
  - Single-plane hit efficiency $> 99\%$
  - Noise occupancy at the level of 10^{-6}
  - 160 W of power consumption
- Major science results obtained during the first three years
  - $\Rightarrow$ Fermi 2-year point source catalog 1873 sources, including 12 extended!
    http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2yr_catalog
- No noticeable degradation of the performances observed
  - $\Rightarrow$ Fermi is a 5 to 10 years mission!



Spare slides

Mapping of the SAA



- The South Atlantic Anomaly is a region with a high density of trapped particles (mostly low-energy protons)
- We do not take physics data in the SAA (ACD HV is lowered) but we do record the trigger rate from CAL and TKR
- The mapping of the SAA was one of the goals of the commissioning phase, now routinely monitored

Trigger

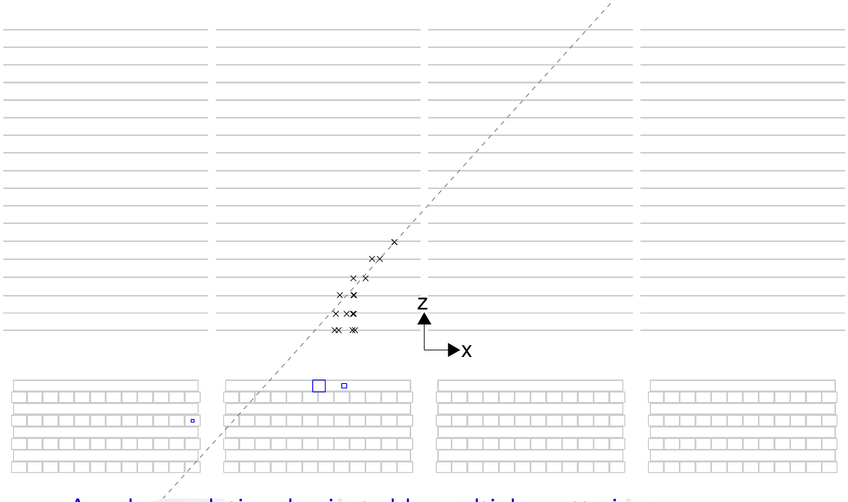
- Hardware trigger at the single tower level
  - All subsystems contribute
  - TKR: three consecutive xy planes in a row hit
  - CAL_LO: single CAL log with more than 100 MeV (adjustable)
  - CAL_HI: single CAL log with more than 1 GeV (adjustable)
  - ROI: MIP signal in one of the ACD tiles close to the triggering TKR tower
  - CNO: heavy ion signal in one of the ACD tiles
- Event readout
  - Each particular combination of trigger primitives is mapped into a so called trigger engine (determines hardware prescale factors, and readout mode)
  - Upon a valid L1 trigger the entire detector is read out

- Filter basics
  - Need software onboard filtering to fit the data volume into the allocated bandwidth
  - Full instrument information available to the onboard processor
  - Flexible, fully configurable (the following reflects the nominal science data taking setting)
- Nominal implementation
  - Each event is presented to up to 4 (adjustable) different filters
  - `GAMMA`: rough photon selection (main source of science data)
  - `HIP`: heavy ions (continuously collected for calibration purposes)
  - `MIP`: used in calibration runs
  - `DGN`: configured to provide a prescaled ($\times$250) unbiased sample of all trigger types
  - Final gamma selection performed on ground (see the following)

- Science design drivers
  - Effective area and angular resolution: design of the tracker converter
  - Energy range and resolution: thickness and design of the calorimeter
  - Charged particle background rejection: mainly driving the ACD design, but also impacts the tracker and calorimeter design, along with the trigger and data flow
- Mission design drivers
  - Launcher vehicle: instrument footprint (1.8×1.8 m^2)
  - Mass budget (3000 kg): maximum depth of the calorimeter
  - Power budget (650 W overall): maximum number of electronics channels in the tracker—i.e. strip pitch and number of layers
  - Launch and operation in space: sustain the vibrational loads during the launch, sustain thermal gradients, operate in vacuum

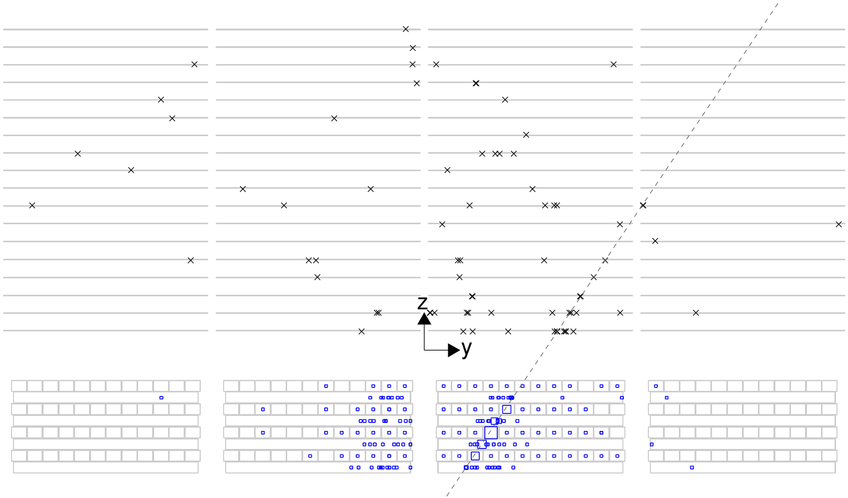
Tracker reconstruction: low energy

Simulated 80 MeV gamma-ray



- Angular resolution dominated by multiple scattering
  - Call for *thin* converters. . .
  - . . . but need material to convert the gamma-rays!

Tracker reconstruction: high energy
Simulated 150 GeV gamma-ray



- Angular resolution determined by hit resolution and lever arm
  - Call for fine SSD pitch, but power consumption is a strong constraint
- Backsplash from the calorimeter also a potential issue