
# The Silicon Strip Tracker of the Fermi Large Area Telescope at L + 5

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on behalf of the Fermi LAT collaboration

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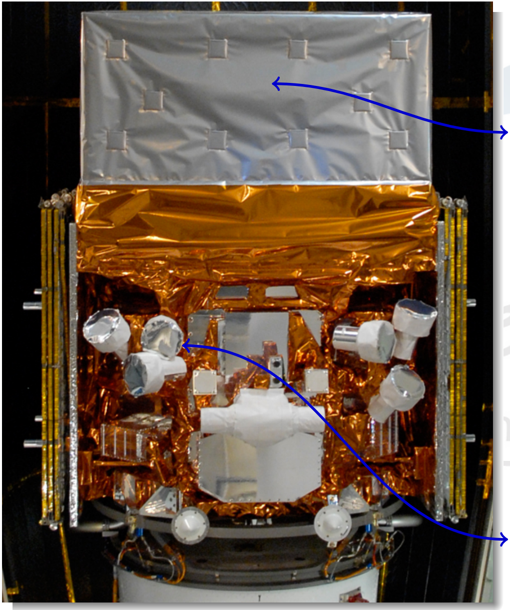
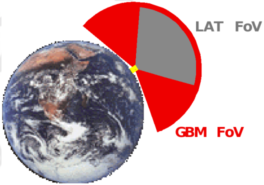
# The Fermi Gamma-ray Space Telescope



## Large Area Telescope (LAT)

- High-energy gamma-ray 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.



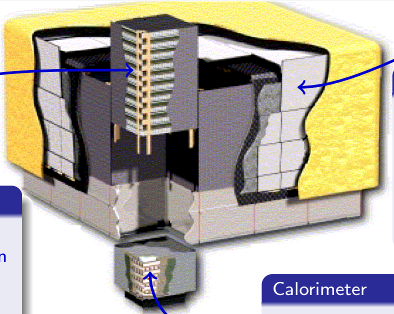

## Gamma-ray Burst Monitor (GBM)

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

# The Large Area Telescope

## Large Area Telescope

- Overall modular design.
- $4 \times 4$ array of identical towers (each one including a tracker and a calorimeter module).
- Tracker surrounded by an Anti-Coincidence Detector (ACD).
- All subsystem contribute to the necessary $\sim 10^6 : 1$ background rejection power.
- $1.8 \times 1.8$ m$^2$ footprint, $\sim 3000$ kg weight, $\sim 650$ W power budget.



## Tracker

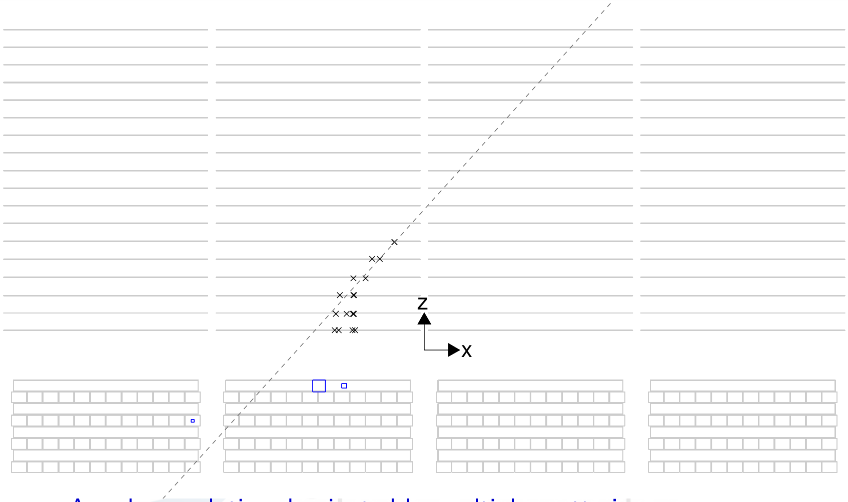
- Silicon strip detectors, W conversion foils; 1.5 radiation lengths on-axis.
- 10k sensors, 73 m$^2$ of silicon active area, 1M readout channels.
- High-precision tracking, short instrumental dead time.

## Anti-Coincidence Detector

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

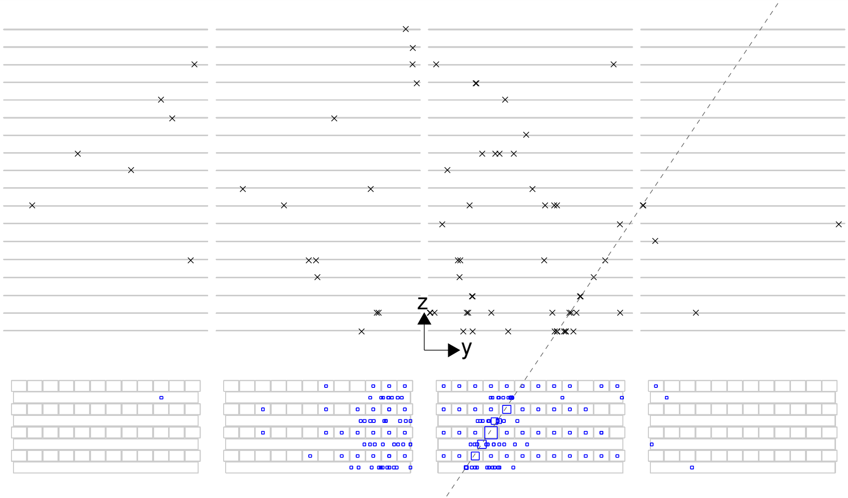
## Calorimeter

- 1536 CsI(Tl) crystals; 8.6 $X_0$ on-axis.
- Hodoscopic, 3D shower profile reconstruction for leakage correction and background rejection.



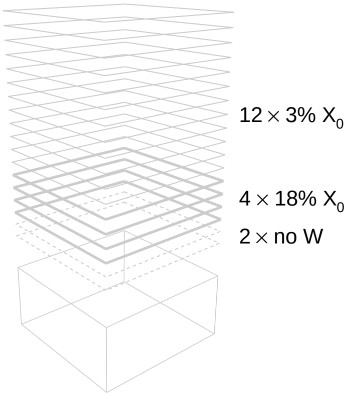

- Angular resolution dominated by multiple scattering:
  - Call for *thin* converters;
  - But need material to convert the gamma-rays!

# Tracker design drivers: high energy
## Simulated 150 GeV gamma-ray



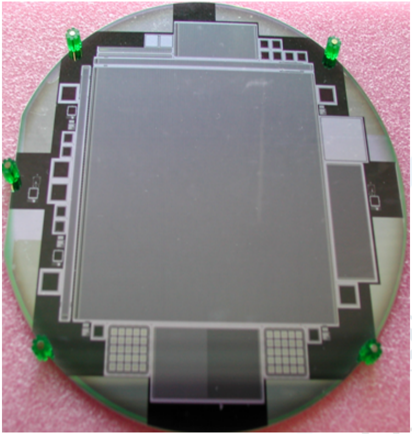

- Angular resolution determined by hit resolution and lever arm:
  - Call for fine SSD pitch, but power budget is a strong constraint;
- Backsplash from the calorimeter also a potential issue.

# Basic tracker design



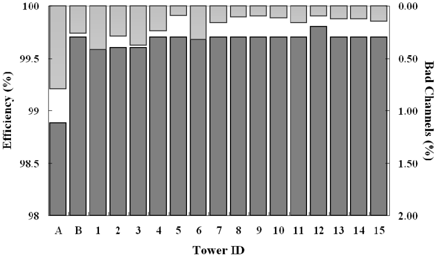

- 19 tray structures supporting 36 (18 $x$-$y$) silicon detection planes.
  - Total depth of 1.5 $X_0$ on axis.
- Two distinct sections with very different performance:
  - Front (thin converters): best angular resolution;
  - Back (thick converters): increased acceptance.

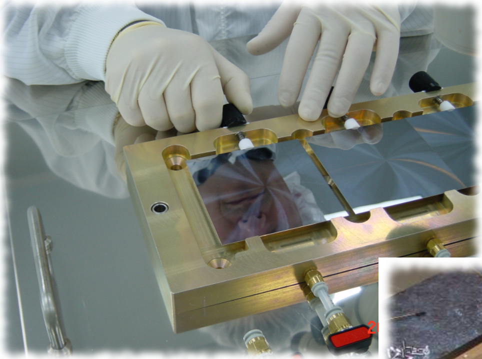
# The Silicon Strip Detectors

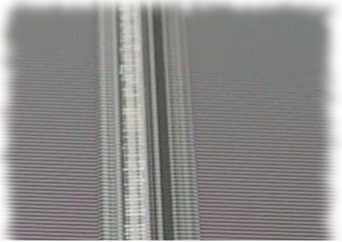


| | |
|---|---|
| Coupling | AC |
| Outer size | $8.95 \times 8.95$ cm$^2$ |
| Strip pitch | 228 $\mu$m |
| Thickness | 400 $\mu$m |
| Depletion voltage | $<$ 120 V |
| Leakage current | a $\sim$ 1 nA/cm$^2$ 150 V |
| Breakdown voltage | $>$ 175 V |
| Bad channels | $\sim 10^{-4}$ (of 900k) |
| # SSD 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.



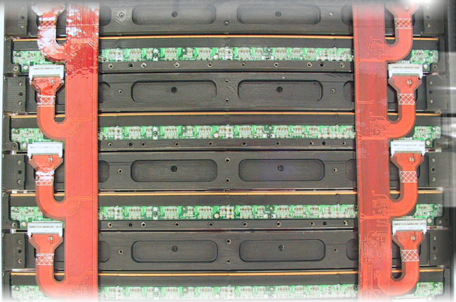


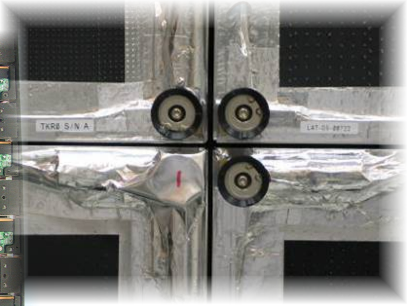


- Wafers glued and wire-bonded in $4 \times 1$ ladders.
- Four ladders integrated into a $36 \times 36$ cm$^2$ detection plane.
- Composite *trays* providing the mechanical structure and housing converters/detectors.

# Mechanical integration (2/2)

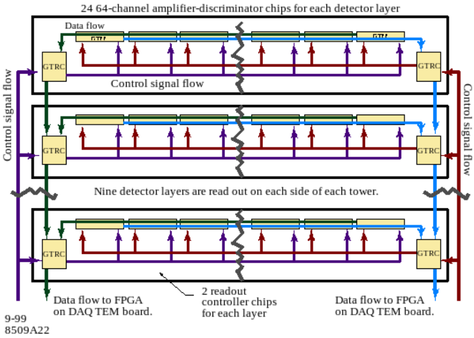
- Less than 2 mm spacing between silicon layers.
- Readout electronics on the tray sides: 90° pitch adapters, read out via flat cables.
- 2 mm inter-tower separation to minimize dead area.





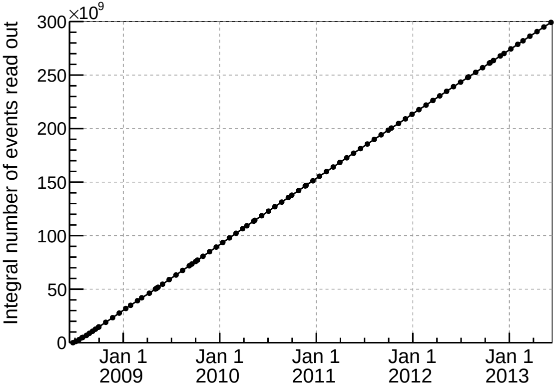
# The Tracker electronics system

- 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 Time Over Threshold in the data stream.
- Two flat cables complete the redundancy.



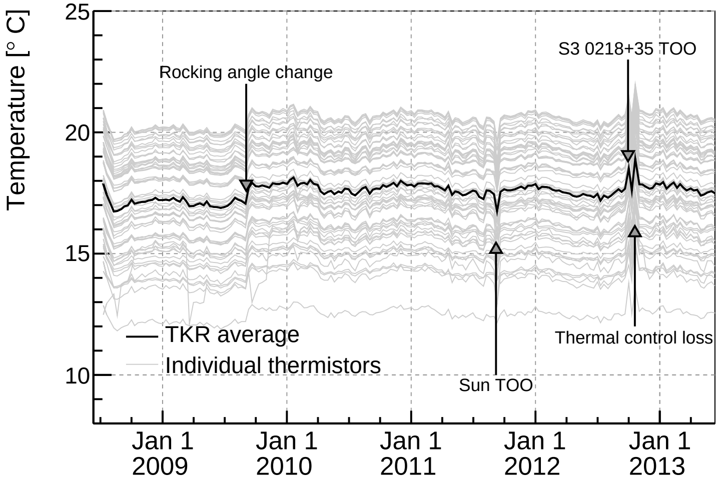

  - Key features:
    - Low power consumption ($\approx 200\ \mu$W/channel).
    - Low noise occupancy ($\approx 1$ noise hit per event in the full LAT).
    - Self-triggering (three $x$–$y$ planes in a row, i.e. sixfold coincidence);
    - Redundancy, Si planes may be read out from the right or from the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

# Mission status at L + 5

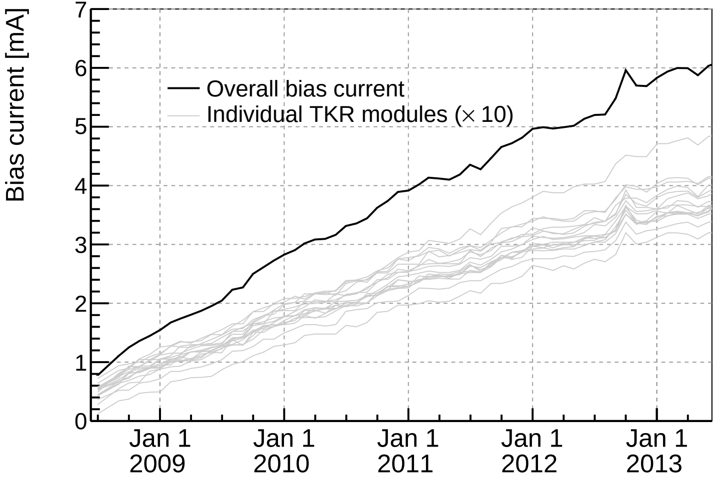


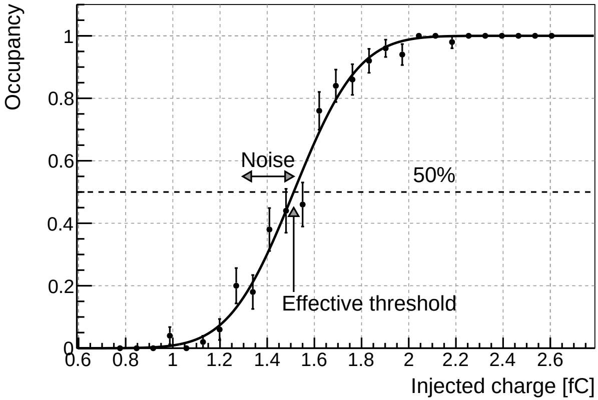

- Event statistics:
  - The LAT hit 300 B triggers in orbit on June 12, 2013 (i.e., exactly after 5 years and 1 day in space);
  - 60,004,450,944 events downlinked (as of June 19, 2013);
  - 770,527,305 gamma-ray candidates distributed to the community.
- More than 99% up-time collecting science data (out of the SAA)
  - Including detector calibrations/hardware issues

# Telemetry data trending: temperature

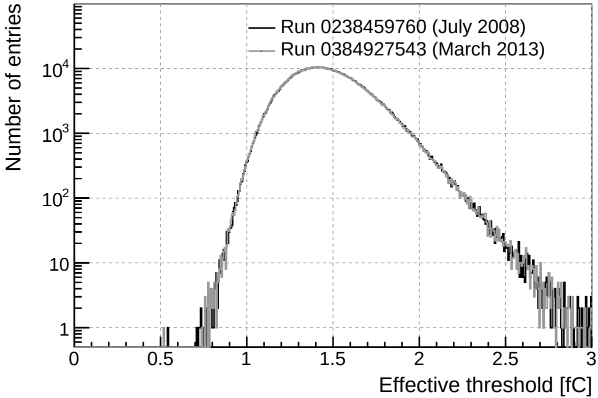


# Telemetry data trending: bias current

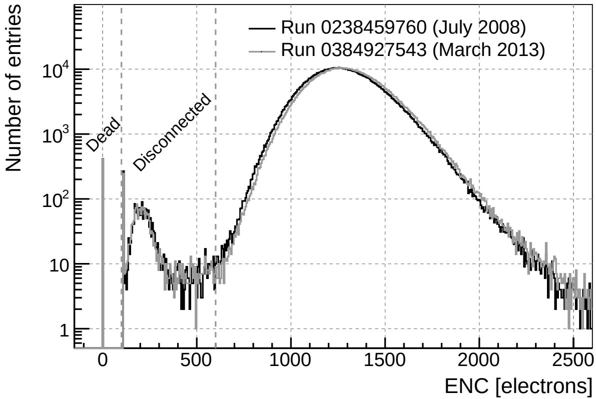





- Set the thresholds to the nominal data taking values.
- Use the internal calibration system to inject a variable amount of charge and record the occupancy.
  - Fit to an erf: $\mu$ gives the effective hit threshold (in fC) and $\sigma$ gives the equivalent noise charge.
  - (We do this on a channel-by-channel basis.)

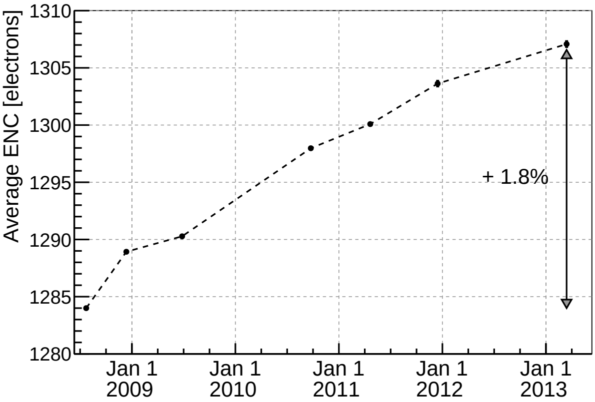



- The two distributions (at the beginning and end of the prime phase of the mission) are indistinguishable.
  - No need to change the discriminator thresholds through the first five years on orbit.



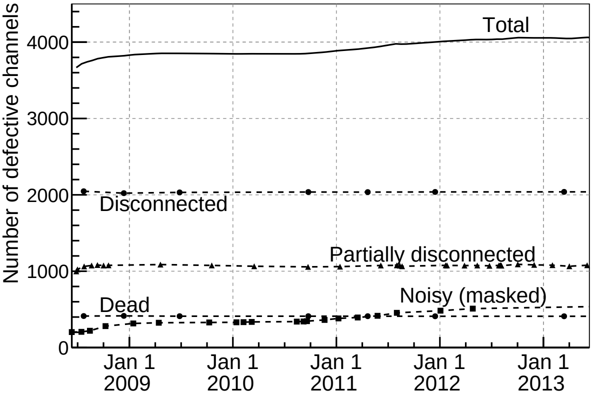

- Some $\sim 2\%$ increase through the first five years in orbit.
  - More on this in the next slide.
- And, in addition to that, this is the starting point for the inventory of the bad channels.
  - Caveat: we're not sensitive to partially disconnected channels (i.e. channels with defective wire bonds in the middle of the ladder).

# Noise trending

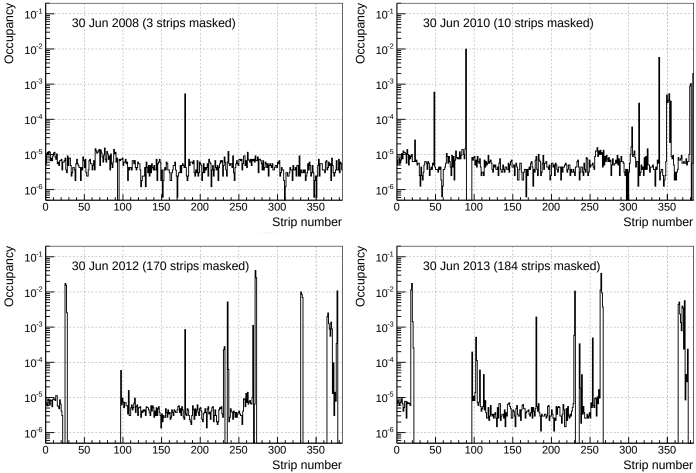



- This is roughly in agreement with what expected from the increase in the bias current from radiation damage.
  - Projects to a negligible noise increase after 10 years.

# Bad channels

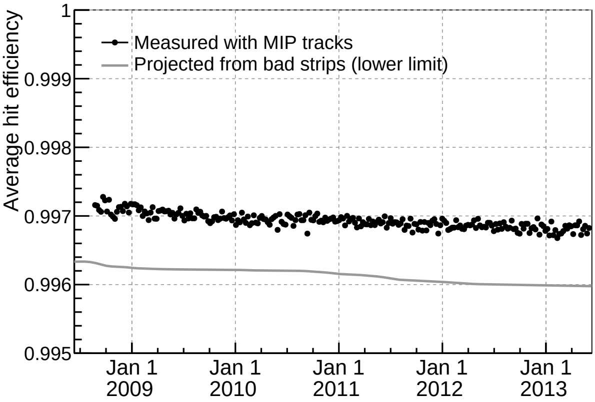



- List of partially disconnected channels compiled from the hitmap distributions.
- 384 new bad channels (i.e., 1 ladder equivalent) from the start of the mission.
  - (Mostly within one defective ladder—see next slide).

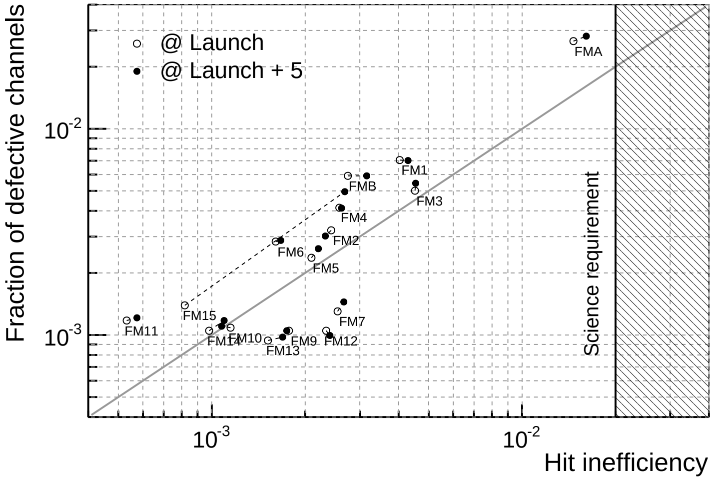



- Noise in one silicon ladder increasing since January 2010
  - Test at reduced HV gave no evidence of reduced noise.
  - Keep masking strips, max loss would be 1 of 2304 silicon ladders...
  - ...But we might have evidence that the phenomenon is saturating.

# Hit efficiency 1/2

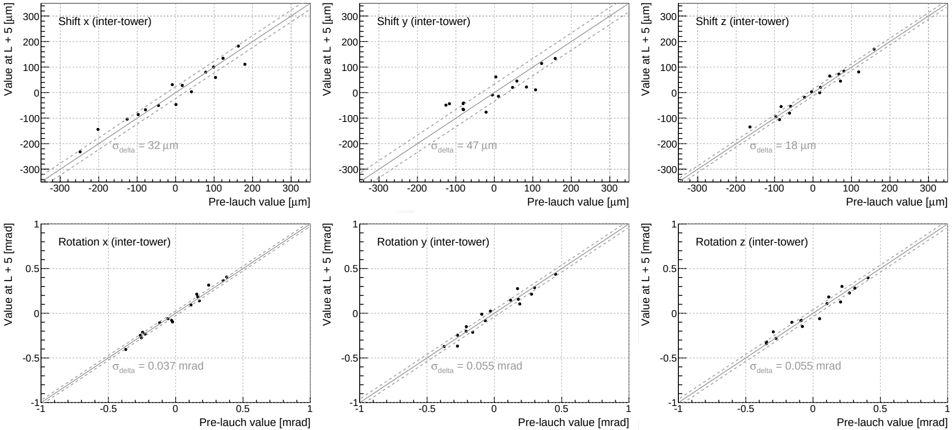



- Minor negative trend, compatible with the new bad chans.
  - Particularly those masked off in Module A and in the noisy ladder.
- (The SRD calls for 98%.)
- Measured noise hit occupancy at the working threshold: $10^{-7}$–$10^{-6}$.



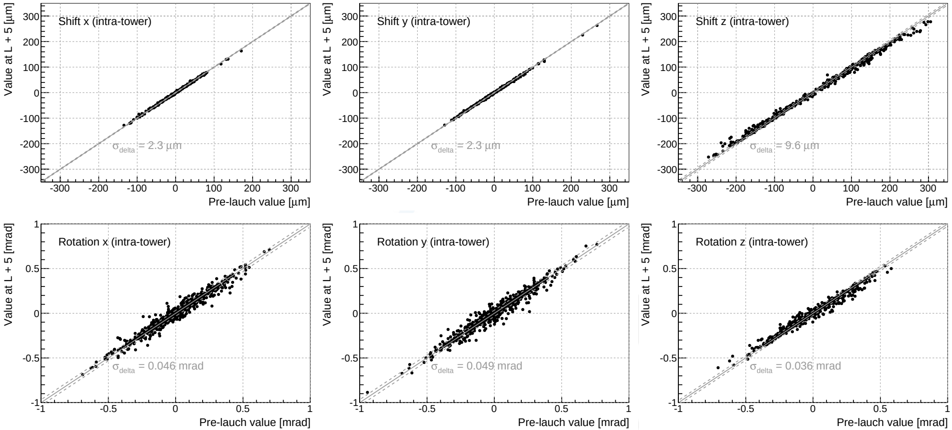

- Again: the bulk of the measured inefficiency is attributable to the bad channels.

# Inter-tower alignment




- Measure 6 parameters (3 shifts and 3 rotations) for each of the 16 tower modules with straight muon/proton tracks.
- No evidence of change through the first five years;
  - Scatter reflecting the statistical error of the measurement.

# Intra-tower alignment

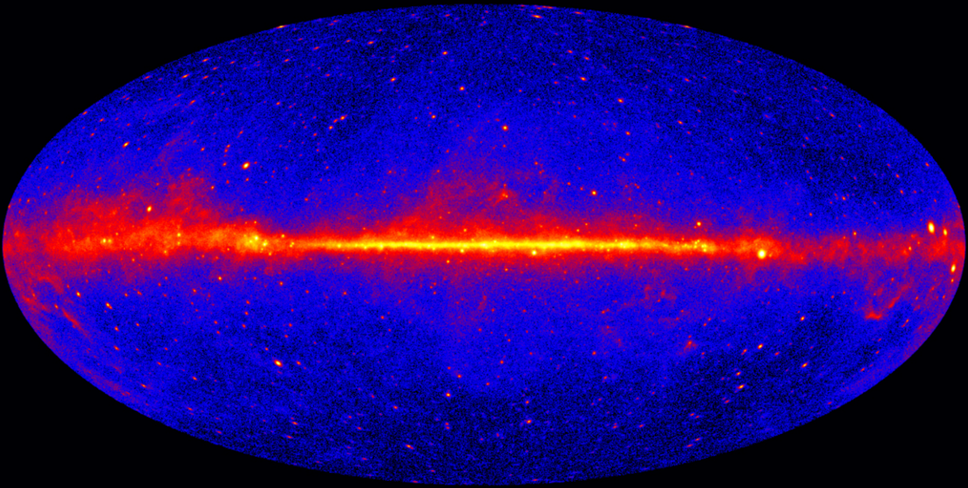



- Measure 6 parameters (3 shifts and 3 rotations) for each of the 576 silicon planes with straight muon/proton tracks.
- No evidence of change through the first five years;
  - Scatter reflecting the statistical error of the measurement.

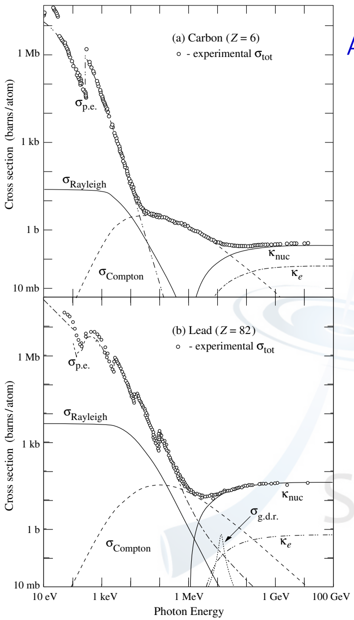
# Conclusions

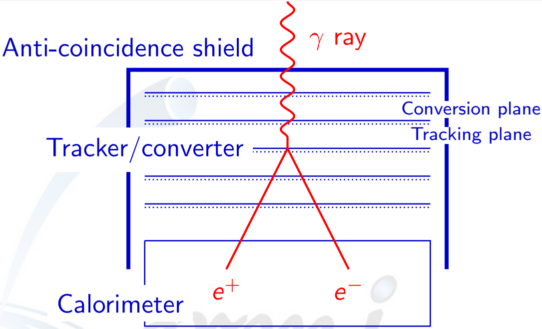
- The LAT tracker is the largest solid-state tracker ever built for a space application:
  - 73 $m^2$ of single-sided silicon strip detectors;
  - Almost 900,000 independent electronics channels.
- All design goals met with large margins:
  - Single-plane hit efficiency in excess of 99%;
  - Noise occupancy at the level of $< 1$ channel per million;
  - 160 W of power consumption.
- It has served beautifully the science of the prime phase of the mission:
  - No noticeable degradation of performance observed.
- Fermi is negotiating mission extensions every two years:
  - Current baseline is to operate at least through 2016 (8 years);
  - 10-year mission goal.
  - No consumables. No hardware reason that the mission has to end after 10 years. We can hope for more.

# Grand summary
## A 5-year sky map above 1 GeV



# Spare slides

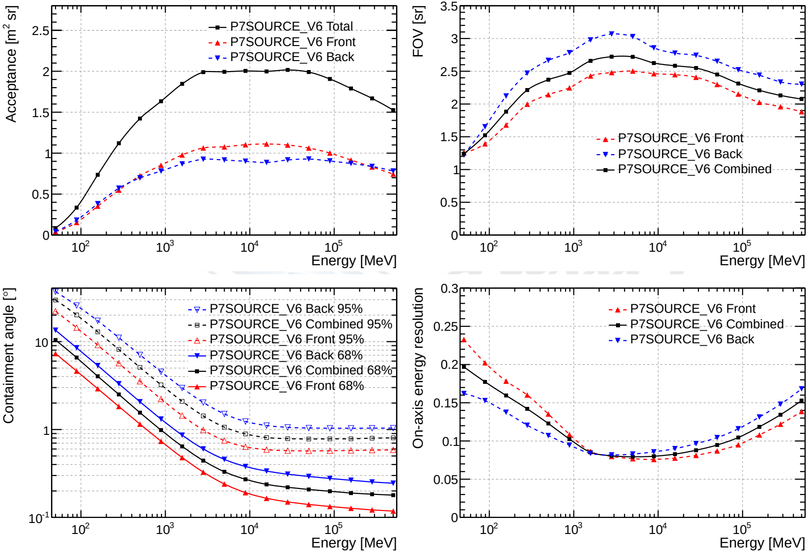


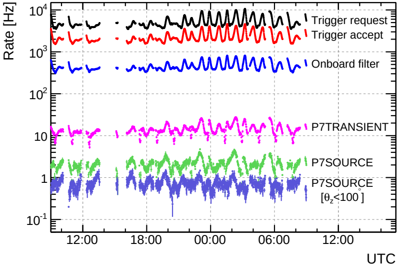

- Pair production is the dominant interaction process for photons in the LAT energy range;
- $e^+e^-$ pair provides the information about the $\gamma$-ray direction/energy;
- $e^+e^-$ pair provides a clear signature for background rejection (really?).

# Instrument Response Functions

http://arxiv.org/abs/1206.1896

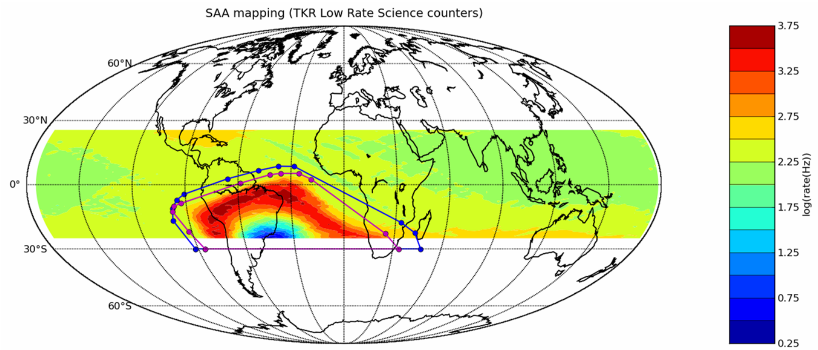


# Trigger and On-Board Filter




- All subsystems contribute to the L1 hardware trigger ($\sim$ 2.2 kHz):
  - `TKR`: three consecutive TKR *x*-*y* planes hit in a row;
  - `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 the ACD tiles close to the triggering TKR tower;
  - `CNO`: signal in one of the ACD tiles compatible with a heavy.
- Adjustable hardware prescales to limit the deadtime fraction:
- Programmable on-board filter to fit the data volume into the allocated bandwidth ($\sim$ 1.5 Mb/s average).
  - Most of the $\sim$ 400 Hz of events passing the gamma filter and downlinked to ground are actually charged-particle background.

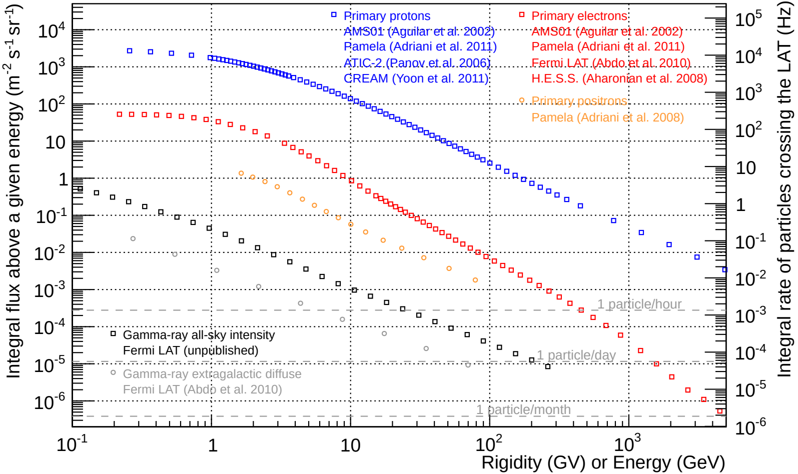
# Mapping of the SAA



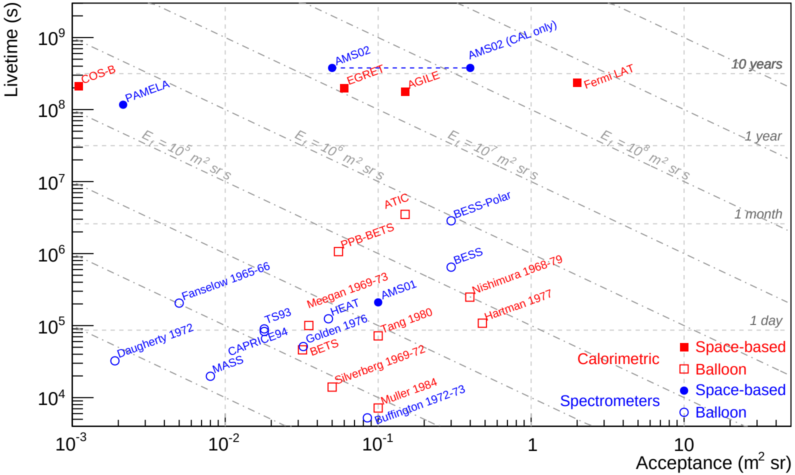

- The South Atlantic Anomaly is a region with a high density of trapped particles (mostly low-energy protons)
- We do not take physics data in the SAA (ACD HV is lowered) but we do record the trigger rate from CAL and TKR
- The mapping of the SAA was one of the goals of the commissioning phase, now routinely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

# CR chemical composition

## A somewhat un-conventional look

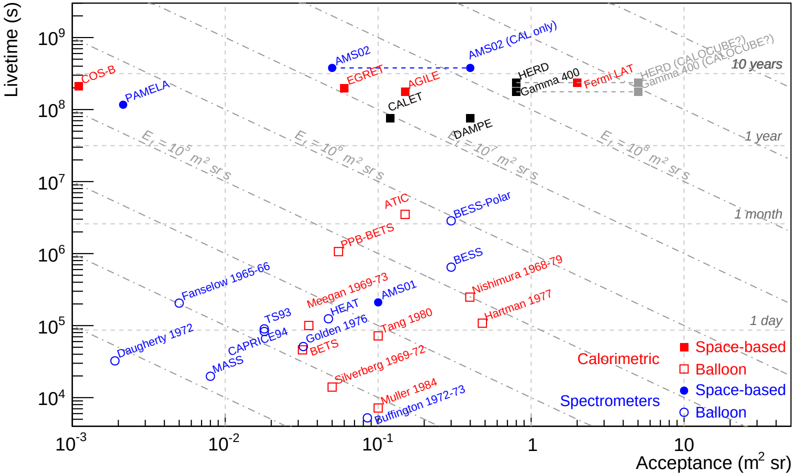



- Celestial $\gamma$-rays constitute a tiny fraction of the cosmic radiation.
  - $\sim 1$ $\gamma$-ray per week above 1 TeV *crossing* the LAT;
  - A handful/year of which from the isotropic background.




- Fermi was deliberately designed maximizing the acceptance:
  - Hard to imagine a bigger $\gamma$-ray detector in the near future.
- Key complementarity in design and science menu with AMS-02.

# Fermi in context




- Most future detectors optimized for energy resolution:
  - And no spectrometer competitive with AMS planned.
- And CTA, not shown, is coming along!