The Fermi Gamma-ray Space Telescope: Spacecraft and Instruments (mostly LAT)

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NASA/GSFC

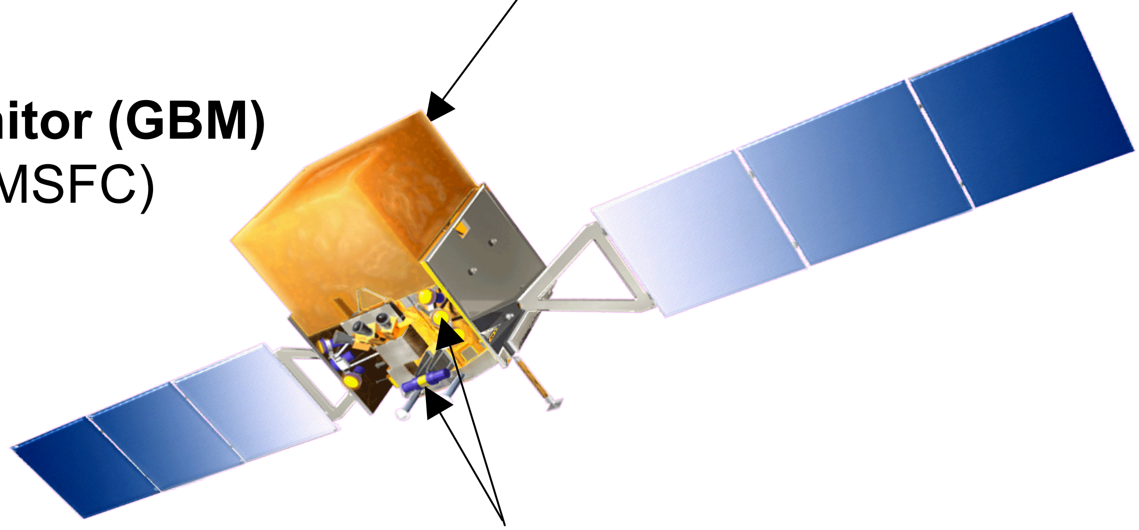
What is Fermi?

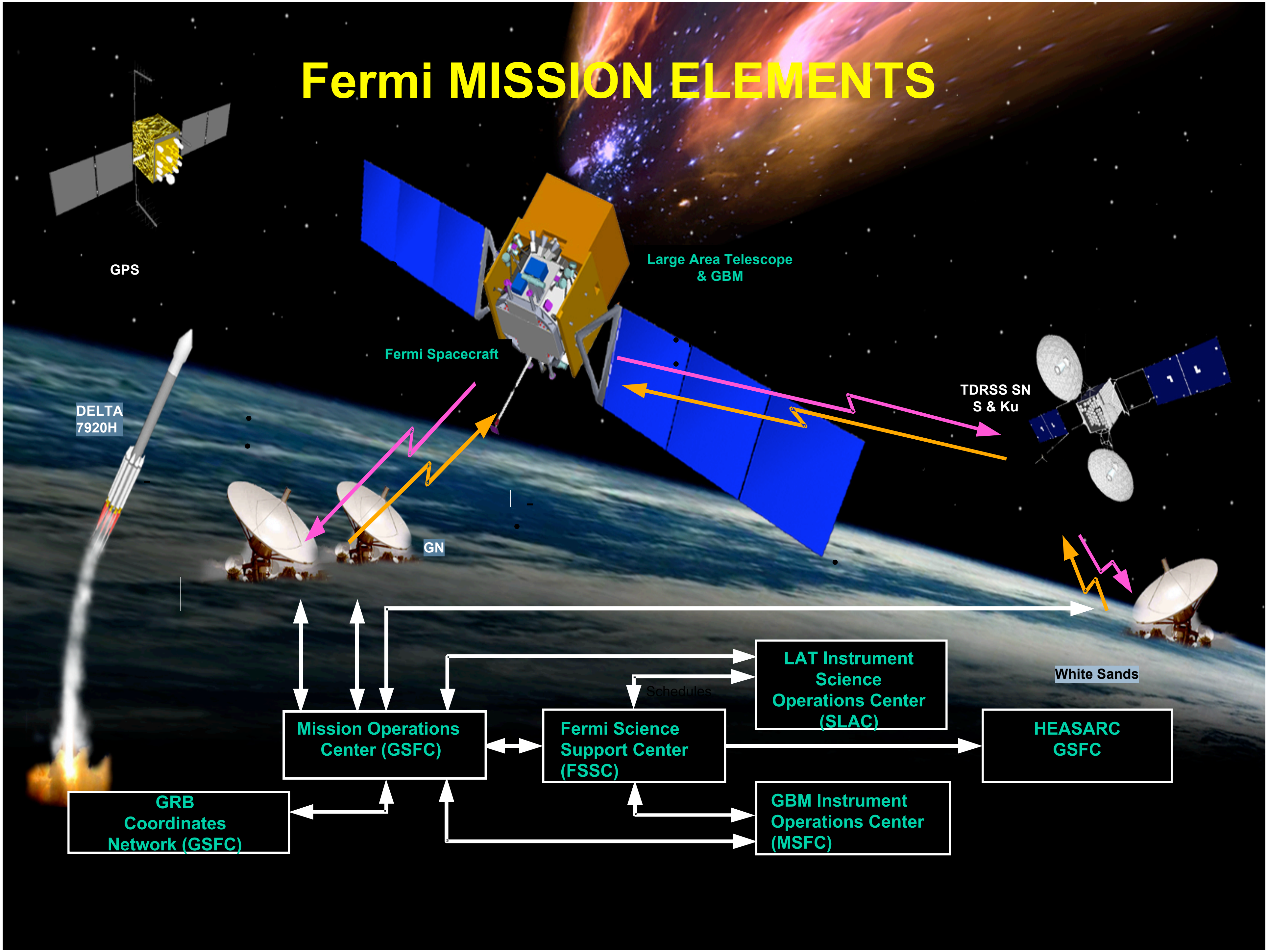
Two Instruments:

Large Area Telescope (LAT)
PI: P. Michelson (Stanford University)
20 MeV - 300 GeV
>2.5 sr FoV

Gamma-Ray Burst Monitor (GBM)
PI: W. Paciesas (NASA/MSFC)
Co-PI: J. Greiner (MPE)
8 keV – 40 MeV
9 sr FoV

Launch: June 11 2008
Lifetime: 5 years (req)
10 years (goal)




Fermi MISSION ELEMENTS
GPS
Large Area Telescope & GBM
Fermi Spacecraft
TDRSS SN S & Ku
DELTA 7920H
GN
White Sands
LAT Instrument Science Operations Center (SLAC)
Schedules
Mission Operations Center (GSFC)
Fermi Science Support Center (FSSC)
HEASARC GSFC
GRB Coordinates Network (GSFC)
GBM Instrument Operations Center (MSFC)

Launch!

- **Launch from Cape Canaveral Air Station 11 June 2008 at 12:05PM EDT**
- **Circular orbit, 565 km altitude (96 min period), 25.6 deg inclination.**
- **Communications:**
  - **Science data link via TDRSS Ku-band, average data rate 1.2 Mbps.**
  - **S-band via TDRSS and ground stations**

Spacecraft performance

- Pointing knowledge
  - <10 arcseconds, using 2 star trackers (a third is available as a spare)
- Absolute Timing
  - Better than 300 ns, using GPS and oscillators
- Orbit location (knowing where we are)
  - ~<10m using GPS
- Observing modes
  - Survey
    - view entire sky every 2 orbits, efficient as the Earth does not enter the LAT FoV.
  - Inertially pointed
    - Scheduled - planned observation at an interesting location
    - Autonomous - to automatically put or keep a GRB location within the FoV of the LAT
  - Slew requirement of 75 deg in 10 mins, but can reach max slew rates of 0.3 deg/s

Spacecraft Performance

- **Data transmission**
  - **Science data: Ku band downlink (TDRSS) ~10 times/day to instrument operations centers**
  - **GBM data and high level LAT data delivered daily, and LAT science data delivered within ~12 hours (often more quickly) to Fermi Science Support Center**
  - **Alerts (from onboard LAT or GBM detection): near real time, via TDRSS S-band demand access service.**
    - **Alert latency to GCN <15 s**

Exploring the gamma-ray sky

- **In the detector:**
  - **Is the event a gamma-ray or charged cosmic-ray?**
  - **What is the energy of the event?**
  - **Where in the sky did the event come from?**
  - **How well can we estimate our knowledge of the above quantities?**
- **With a gamma-ray source:**
  - **Are we sure that it is a source?**
  - **Is there a feature or a cutoff in the energy spectrum?**
  - **Is it a point source or does it have a spatial extent?**
  - **Is it variable?**
  - **Does it show periodic emission?**
- **External information:**
  - **Is it associated with a known object at other wavelengths?**
  - **How does the gamma-ray emission compare with the lower energy emission? Temporally? Spatially?**
  - **How far away is it?**

Gamma-ray Energy Loss Mechanisms

- **For photons in matter above ~10 MeV, pair conversion is the dominant energy loss mechanism.**
  - **Pair conversion telescope**

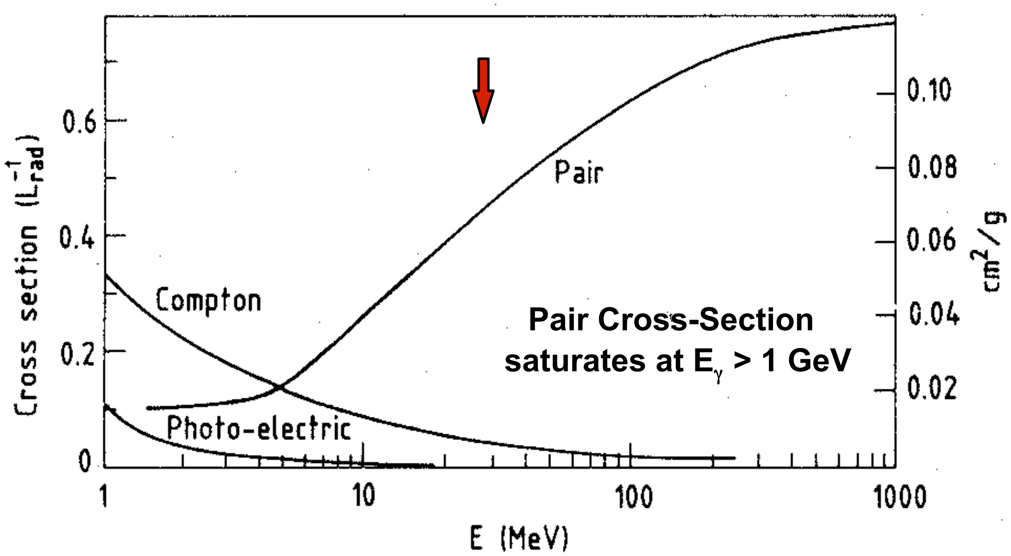
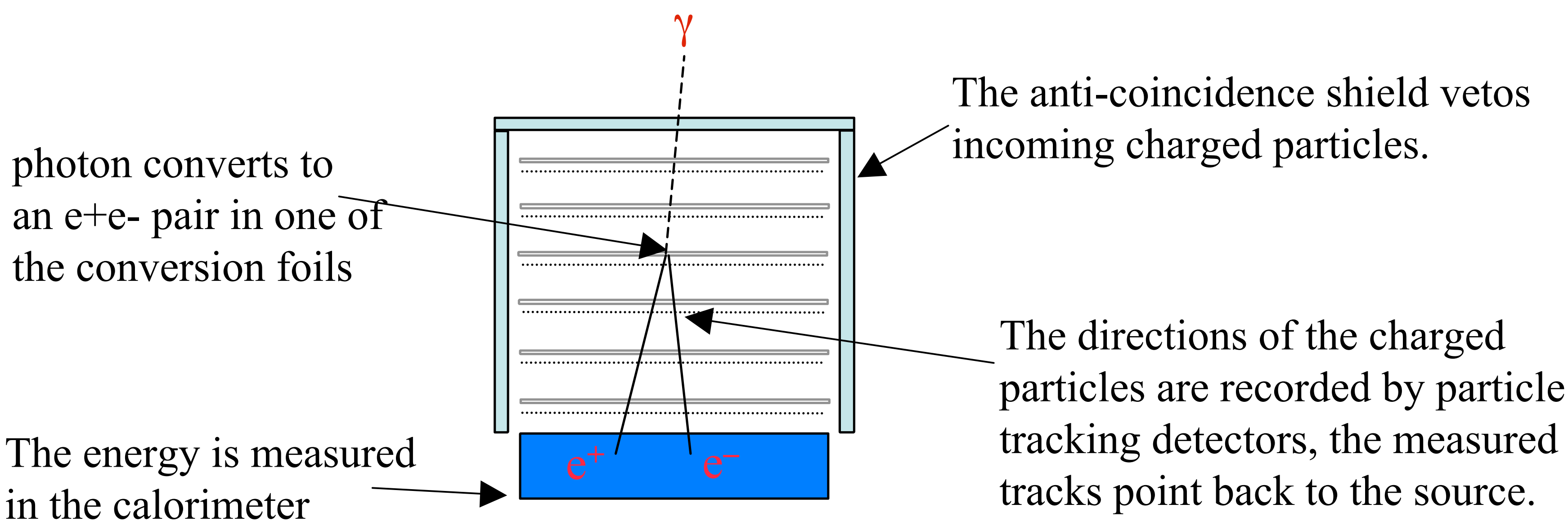


Fig. 2: Photon cross-section σ in lead as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\sigma x)$, where x is the path length in radiation lengths. (Review of Particle Properties, April 1980 edition).

Pair Conversion Technique



Tracker: angular resolution is determined by:
multiple scattering (at low energies) => thin conversion foils
position resolution (at high energies) => fine pitch detectors

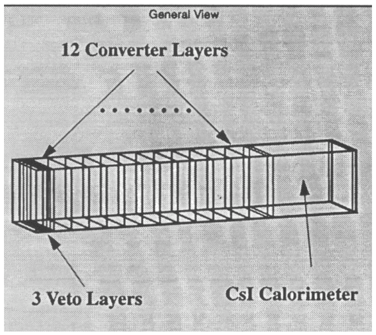
Conversion efficiency -> Thick conversion foils, or many foils

Calorimeter:Enough X_0 to contain shower, shower leakage correction.

Anti-coincidence detector:
Must have high efficiency for rejecting charged particles, but not veto gamma-rays

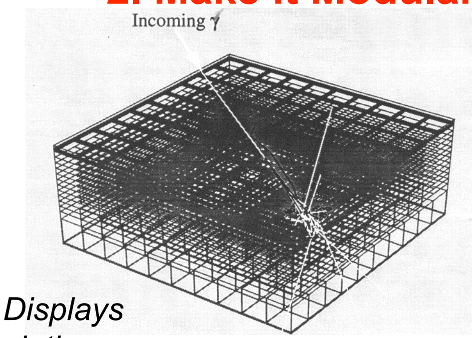
Evolution of Fermi-LAT

1. Select the Technologies



Large area SSD systems and CsI Calorimeters resulted from SSC R&D

2. Make it Modular



Another lesson learned in the 1980's: monolithic detectors are inferior to Segmented detectors

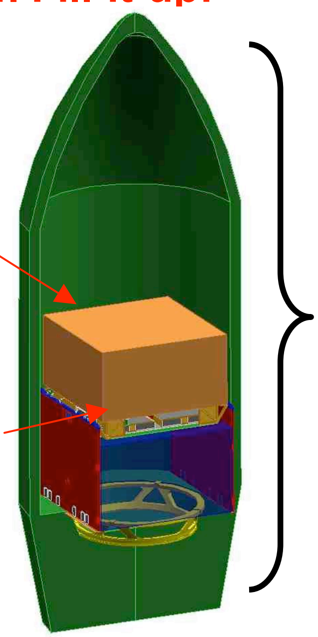
Original GISMO 1 Event Displays from the first GLAST simulations

3. Pick the Rocket

Delta II (launch of GP-B)

Cheap, reliable Communication satellite launch vehicle

4. Fill-it-up!



Diameter sets transverse size

Throw capacity to LEO sets depth of Calorimeter

Rocket Payload Fairing

Power budget of 650 W

The Fermi Large Area Telescope

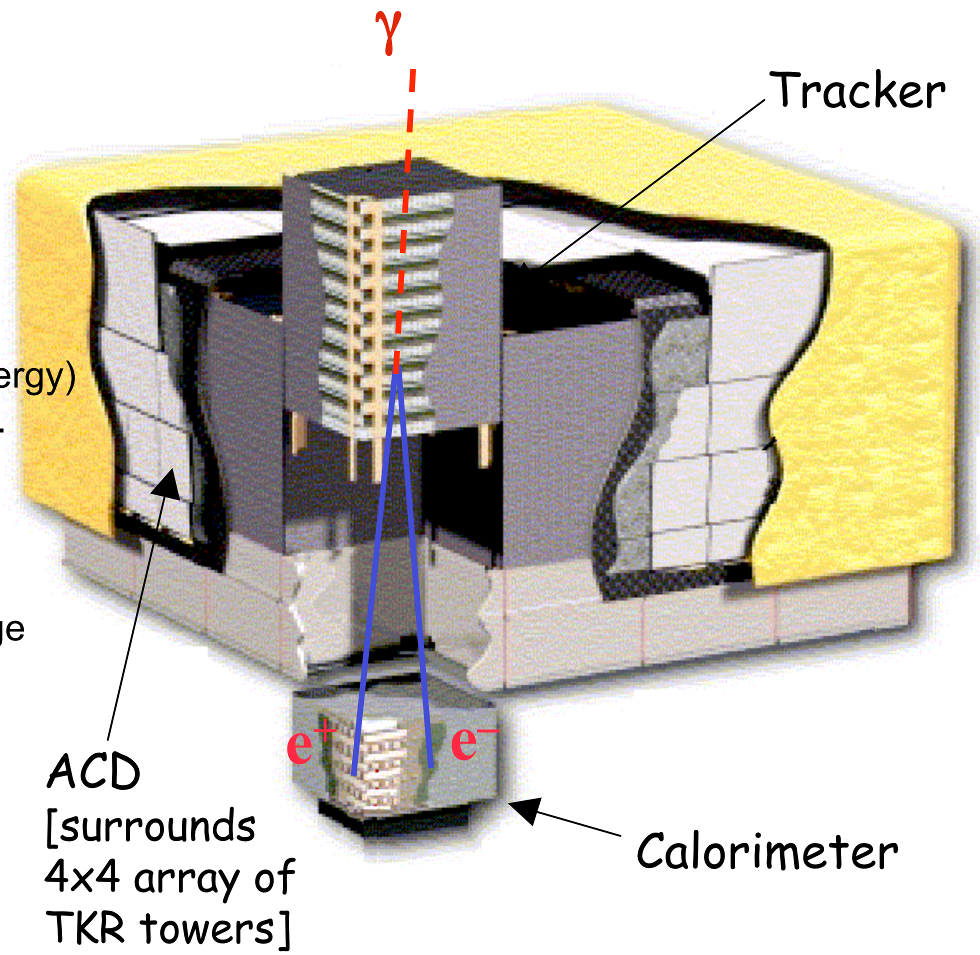
Overall LAT Design:

- 4x4 array of identical towers
- 3000 kg, 650 W (allocation)
- 1.8 m × 1.8 m × 1.0 m

- **Precision Si-strip Tracker (TKR)**
  18 XY tracking planes. 228 μm pitch).
  High efficiency.
  Good position resolution (ang. resolution at high energy)
  12 x 0.03 X_0 front end => reduce multiple scattering.
  4 x 0.18 X_0 back-end => increase sensitivity >1GeV

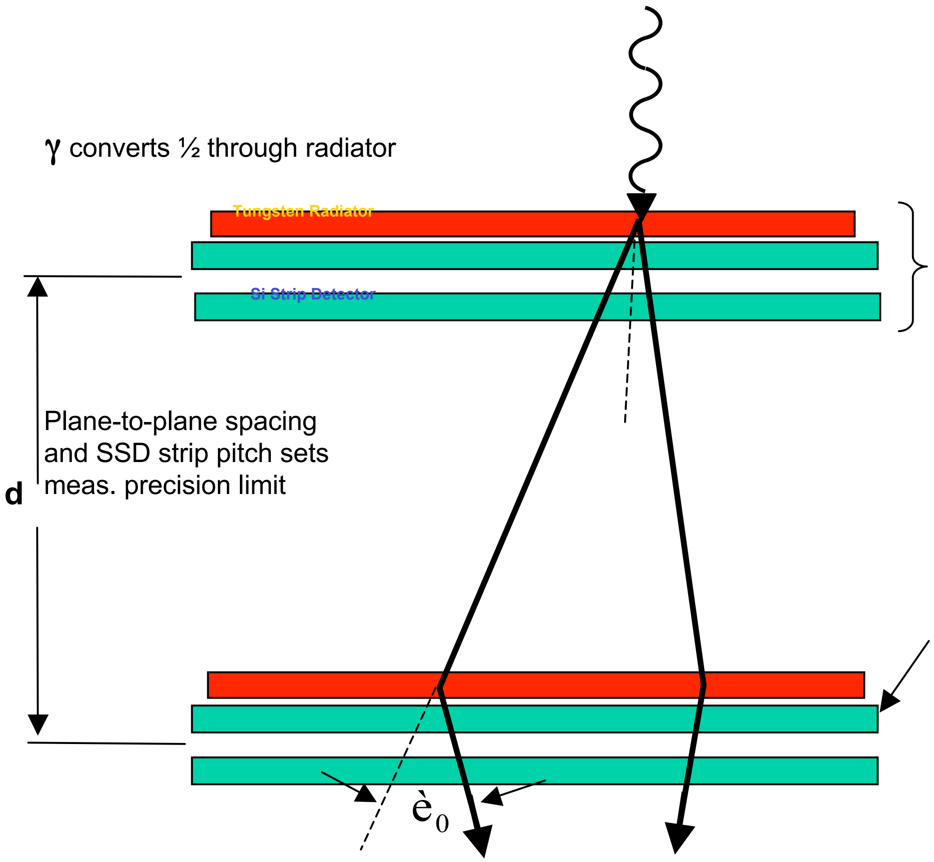
- **CsI Calorimeter(CAL)**
  Array of 1536 CsI(Tl) crystals in 8 layers.
  Hodoscopic => Cosmic ray rejection, shower leakage correction.
  8.5 X_0 => Shower max contained <100 GeV

- **Anticoincidence Detector (ACD)**
  Segmented (89 plastic scintillator tiles)
  => minimize self veto



Systems work together to identify and measure the flux of cosmic gamma rays with energy 20 MeV - >300 GeV.

LAT Tracker - details



Trim Radiator tiles to match active SSD area

Close spacing of Radiators to SSDs minimizes multiple scattering effects

SSD resolution (σ) = strip pitch/sqrt(12)

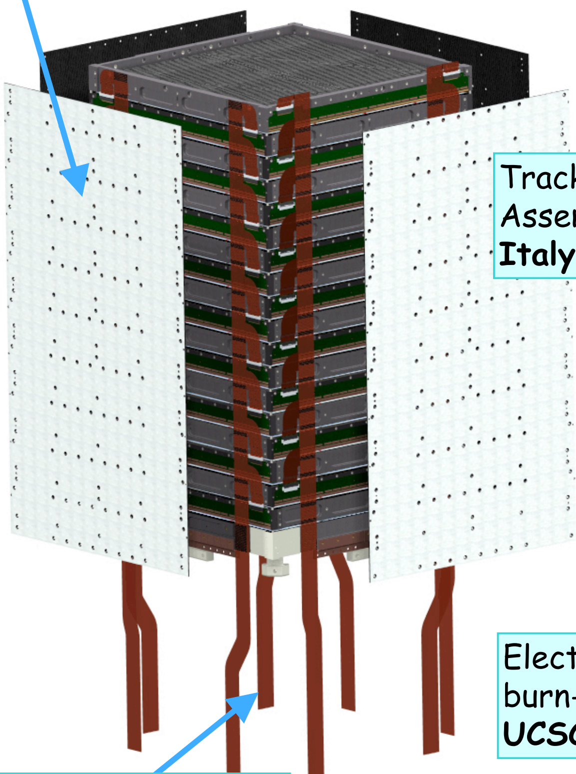
θ_{det}= sqrt(2) * σ_{ssd}/d = 228 μm/(32.9mm.sqrt(6)) = 2.8 mrad = 0.16°

θ_{MS}(100 MeV) ~ 3.1°

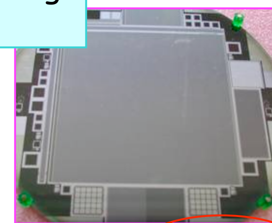
Fermi Gamma-ray Space Telescope

Tracker Production Overview

Module Structure Components
SLAC: Ti parts, thermal straps, fasteners.
Italy (Plyform): Sidewalls



SSD Procurement, Testing
Japan, Italy (HPK)



Parts Count 10,368

SSD Ladder Assembly
Italy (G&A, Mipot)

2592

Tracker Module Assembly and Test
Italy (Alenia Spazio)

18

Tray Assembly and Test
Italy (G&A)

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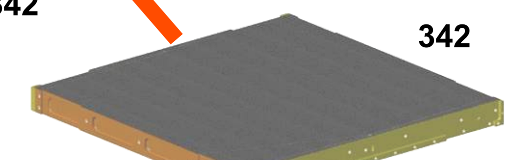

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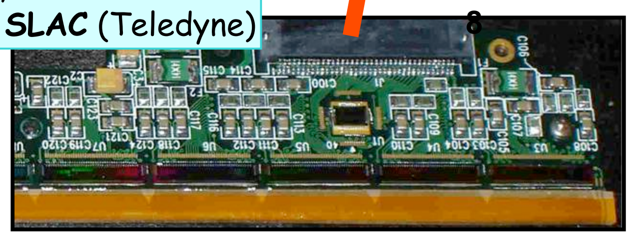
Composite Panel, Converters, and Bias Circuits
Italy (Plyform): fabrication
SLAC: CC, bias circuits, thick W, Al cores

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

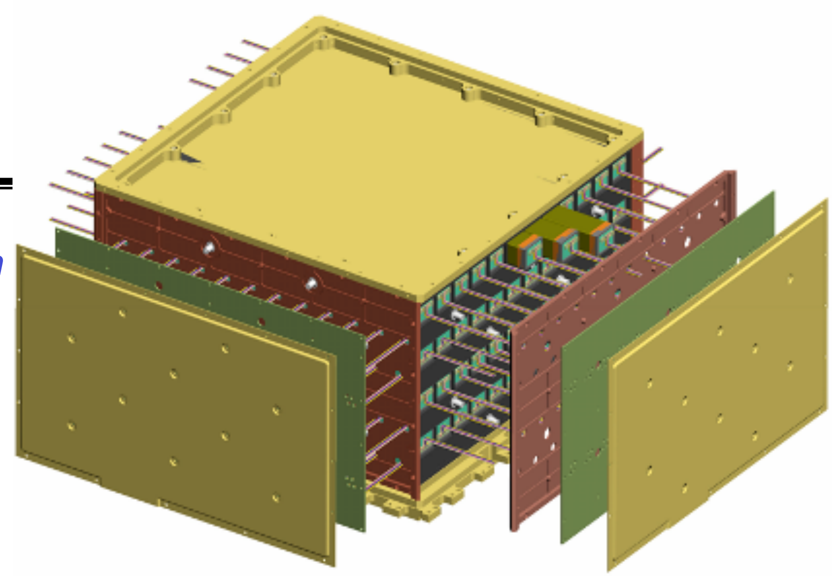
64
8



Readout Cables
UCSC, SLAC
(Parlex)

LAT Calorimeter

Team effort involving physicists and engineers from the United States (NRL), France (IN2P3 & CEA), and Sweden



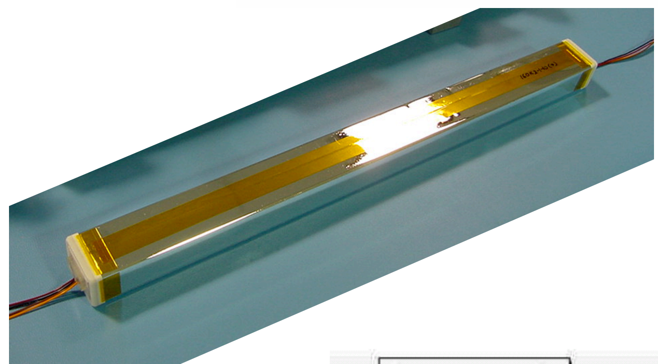
Crossed Hodoscope Log design

(first proposed by Per Carlson, 1989)

Gives 3D image of energy deposition

8 Layers deep (1.08 rad. len./layer)

12 "Logs" per Layer



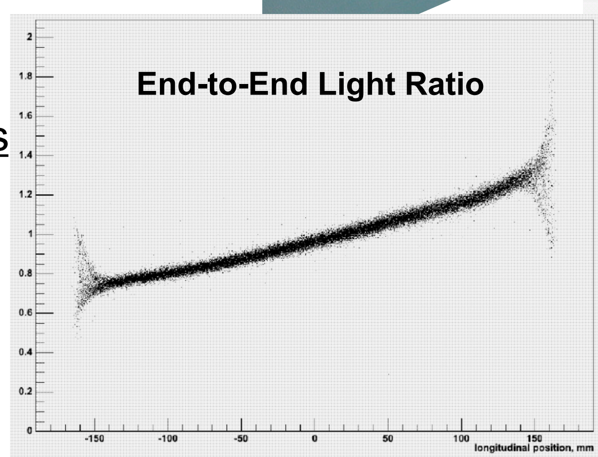
Each Log (or Xtal Element) is readout from both ends by 2 Photodiodes

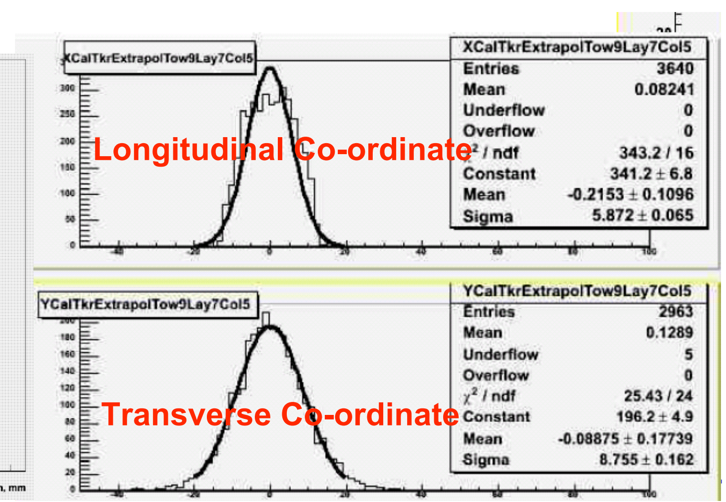
1 - large area, 1 small area

Location of Energy Depositions

2 coordinates by log location

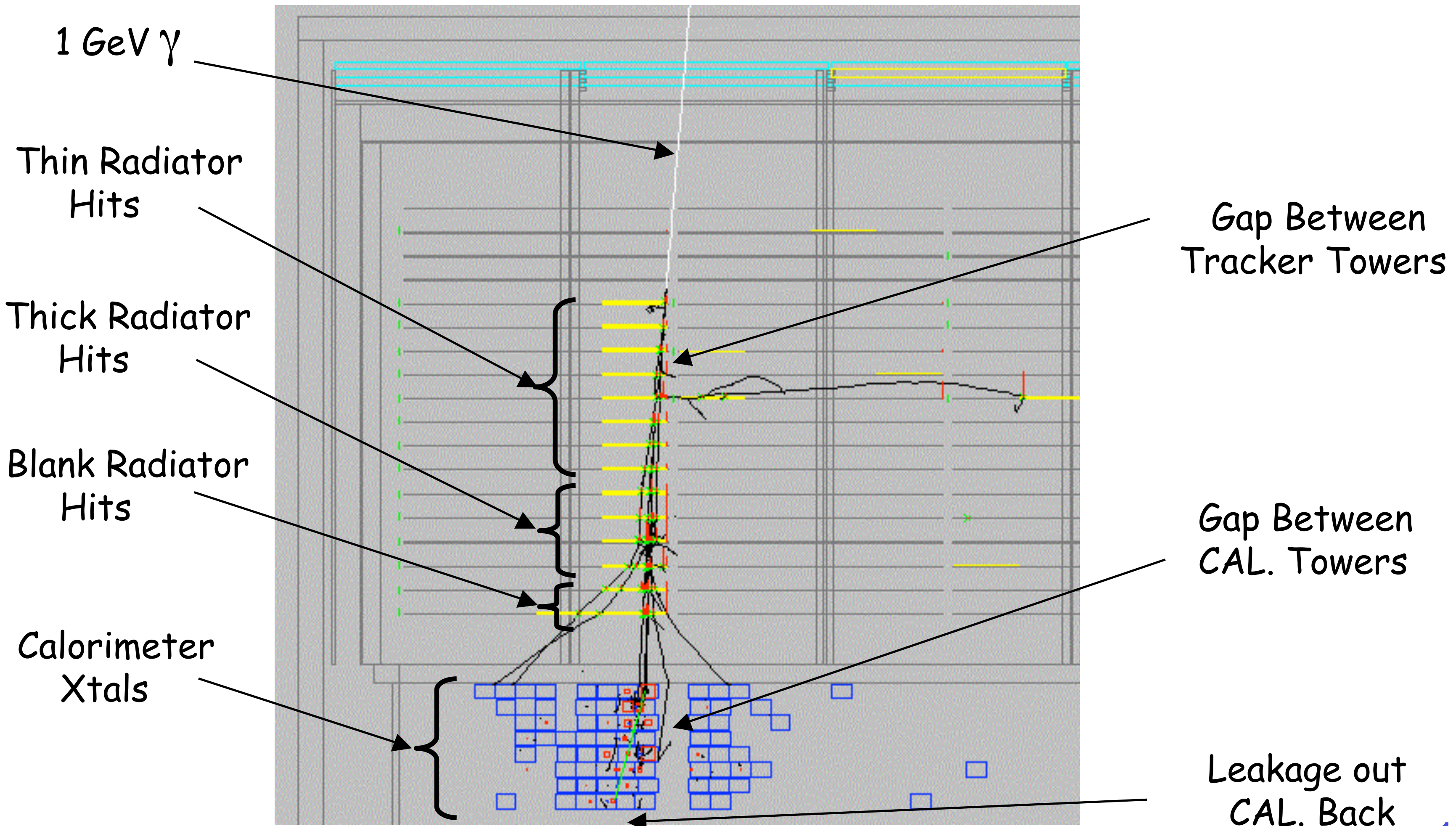
3rd coordinate by end-to-end light asymmetry





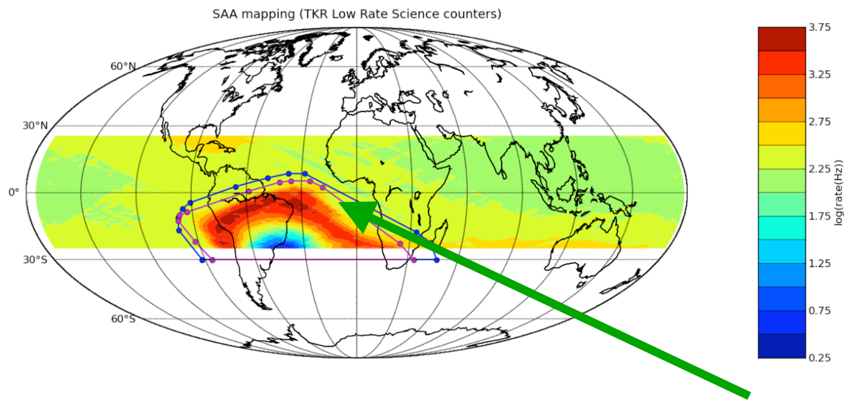
Energy Determination

Issues: Low Energies - Energy loss in Tracker is critical
High Energies - Leakage compensation is critical
Compensation for the numerous gaps

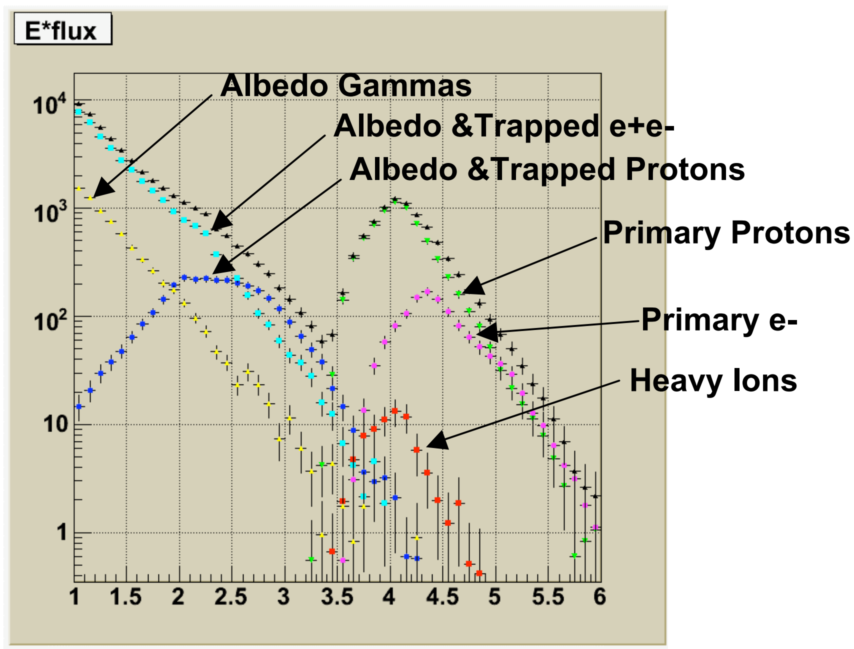


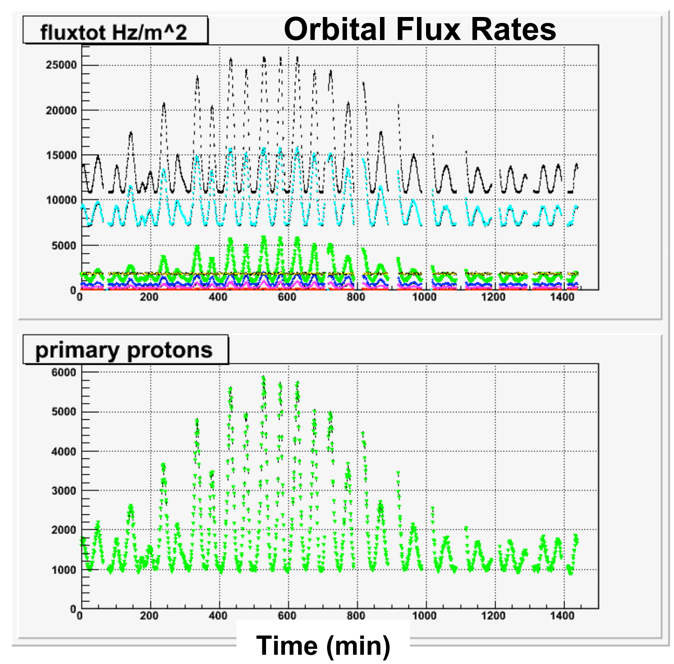
Background Rejection

First: Low Earth Orbit Particle Flux Environment



South Atlantic Anomaly **(Hot Spot)**





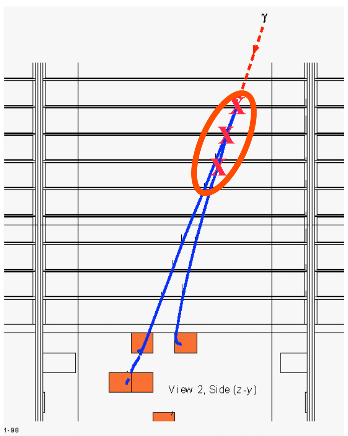
Instrument Triggering and Onboard Data Flow

Hardware Trigger → **On-board Processing**

Hardware trigger based on special signals from each tower; initiates readout

Function: • "did anything happen?"
• keep as simple as possible

Combinations of trigger primitives:



- **TKR 3 $x{\bullet}y$ pair layers in a row**
  workhorse γ trigger
- **CAL:**
  LO – independent check, energy info.
  HI – indicates high energy event:

Upon a trigger, all subsystems are read out in ~27μs

Instrument Total Rate: <3 kHz>*

***using ACD veto in hardware trigger**

Onboard filters: reduce data to fit within downlink, provide samples for systematic studies.

- **flexible, loose cuts**
- **The FSW filter code is wrapped and embedded in the full detector simulation**
- **leak a fraction of otherwise-rejected events to the ground for diagnostics, along with events ID for calibration**
- **signal/background can be tuned**

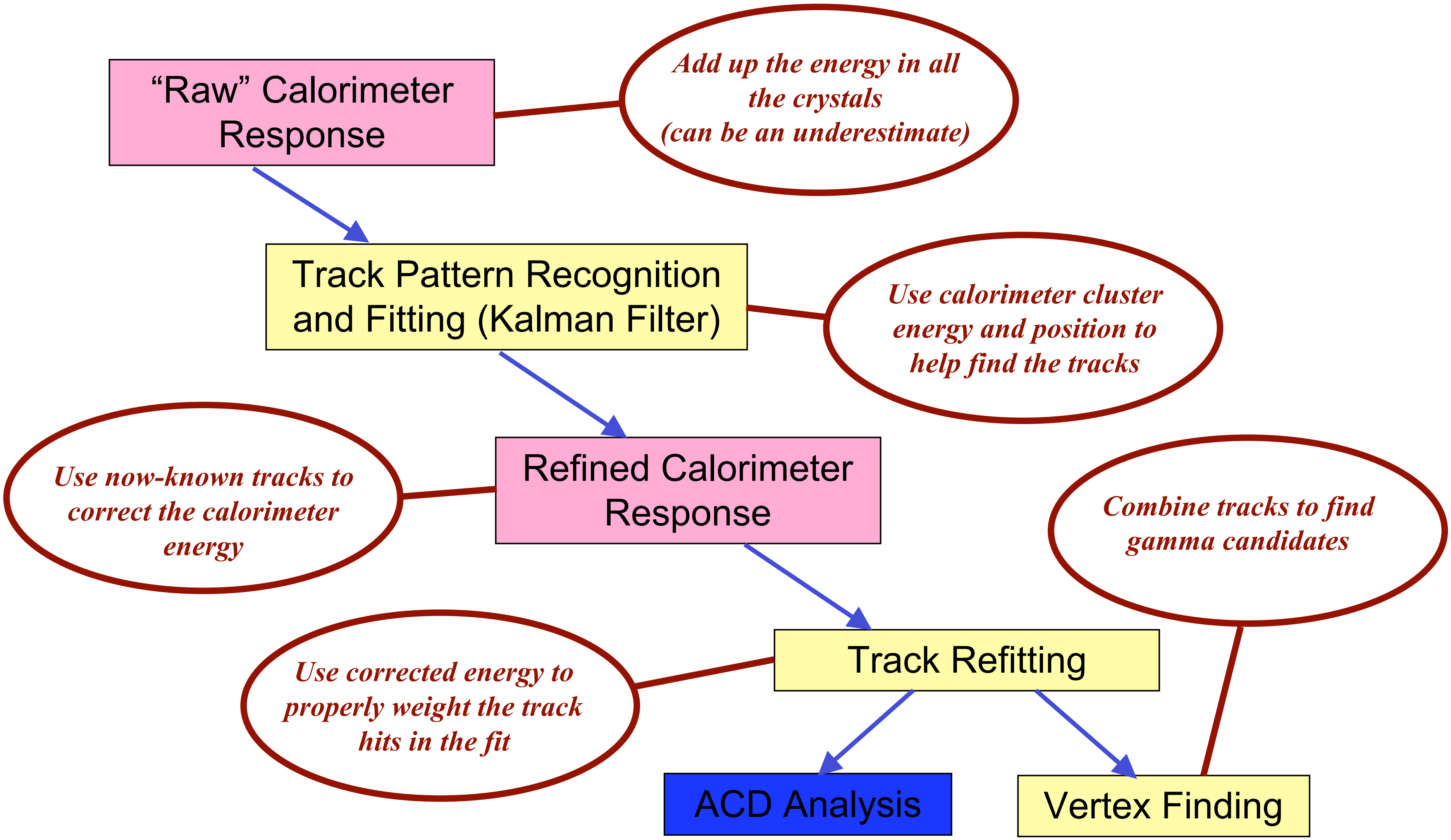
γ rate: a few Hz

Total Downlink Rate: <~400 Hz>

On-board science analysis:
transient detection (bursts)

Spacecraft

Event Reconstruction



Event Classification and Background Rej

- **Several Classification trees:**
  - Energy resolution
    - Choose between 3 energy recon methods
    - Calculate probability that energy is well measured (use this as an analysis knob to tune final energy resolution performance)
  - PSF analysis

    Divide events into thick and thin (depending on the thickness of the radiator where they converted)

    Evaluate vertex and single track solutions separately

    Divide events into energy bins (characteristics change dramatically)

    - Decide whether or not to use vertex solution
    - Calculate probability that track was well measured (use to tune final angular resolution performance)
  - Background rejection

    Divide events into vertex/single track and several energy bins

    - Each path has a set of hard cuts followed by a classification tree that yields a probability that the event was a gamma-ray (use this to tune final background rejection).

Event Selections

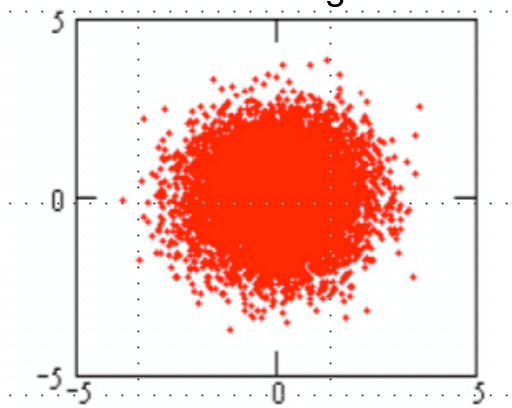
- We have optimized cuts on the CT probability variables for different analysis to provide predefined event selections.
  - Transient class: Relatively loose cuts on background rejection and angular resolution, suitable for short duration (<200 s) analysis (3-5 hz event rate)
  - Diffuse class: Tighter cuts, suitable for analysis of point and extended sources, and analysis of galactic diffuse emission.
  - Ultradiffuse: Currently under validation, very tight cuts to produce clean gamma-ray sample suitable for studies of the extragalactic diffuse emission.

- Montecarlo data is used to parameterise the instrument response for each of these event selections. These parameterizations are known as Instrument Response Function (IRFs)
  - Current IRFs are P6_V3_DIFFUSE and P6_V3_TRANSIENT

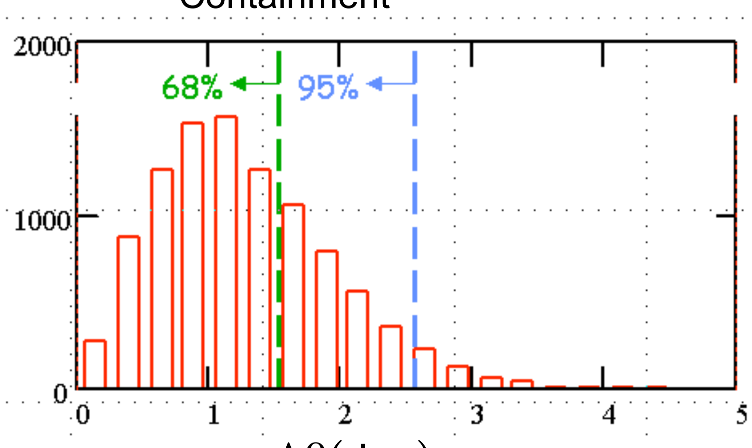
Jargon: PSF, Effective Area

Point-Spread-Function

2D Point Source Image at 275 MeV



PSF Characterized by 68% & 95% Containment



Effective Area- A_{eff}

Not all entering γs pair-convert

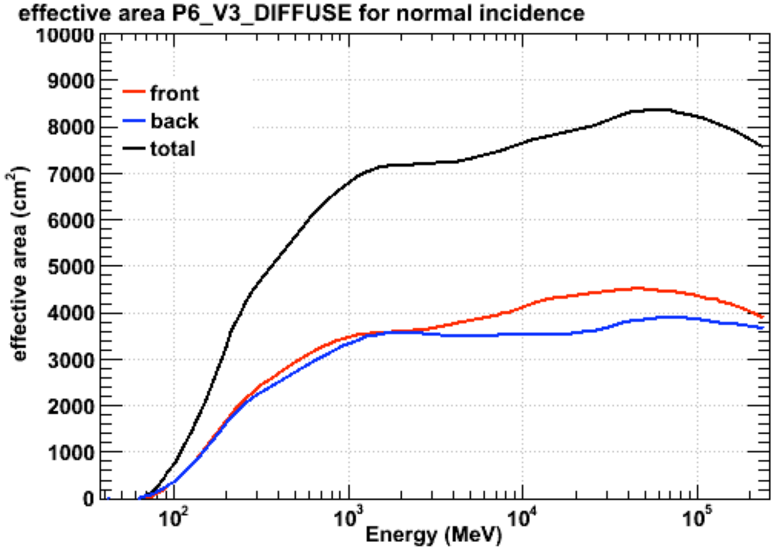
$$P_{conv}(x) = 1 - \exp\left(-\frac{7}{9}\frac{x}{\div_{Mat}}\right)$$

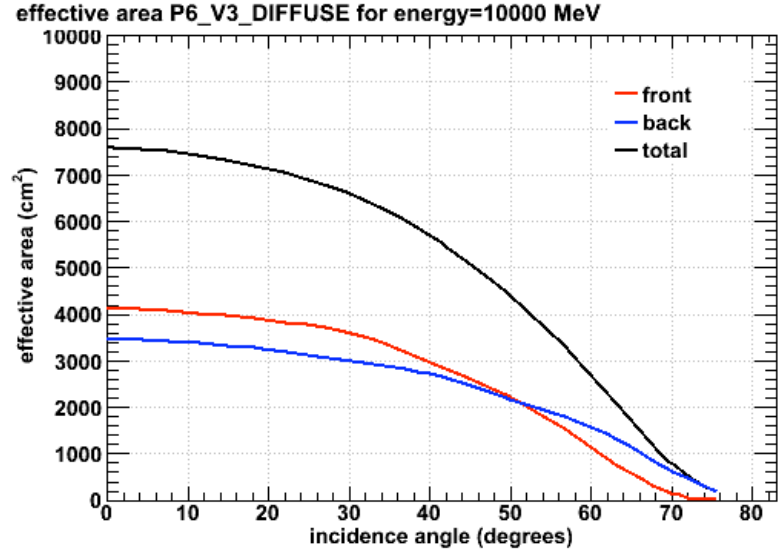
$$A_{eff} \cong A_{Geom} \cdot P_{conv}(depth) \cdot Eff_{Analysis}$$

Typically $Aeff \leq \frac{1}{2} A_{Geom}$

LAT Performance Aeff

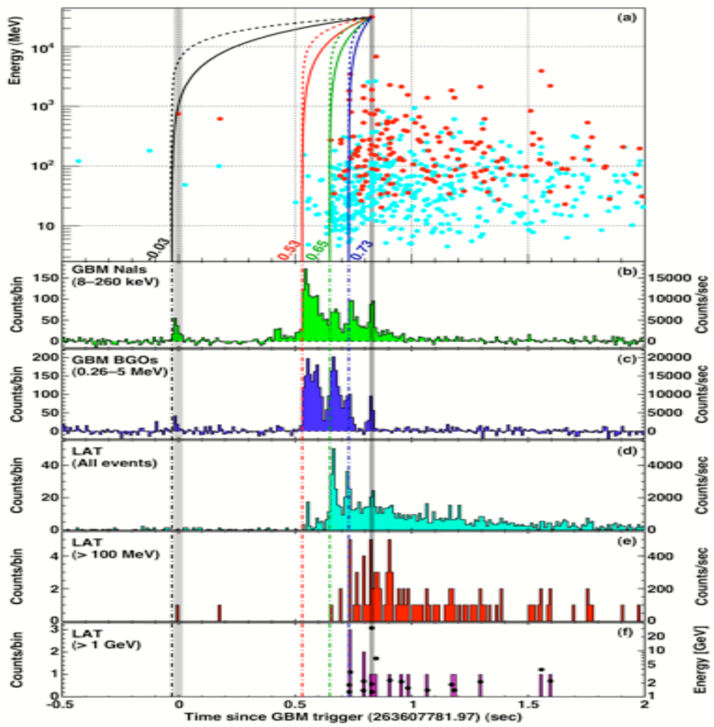
c.f. EGRET
~1500 cm2

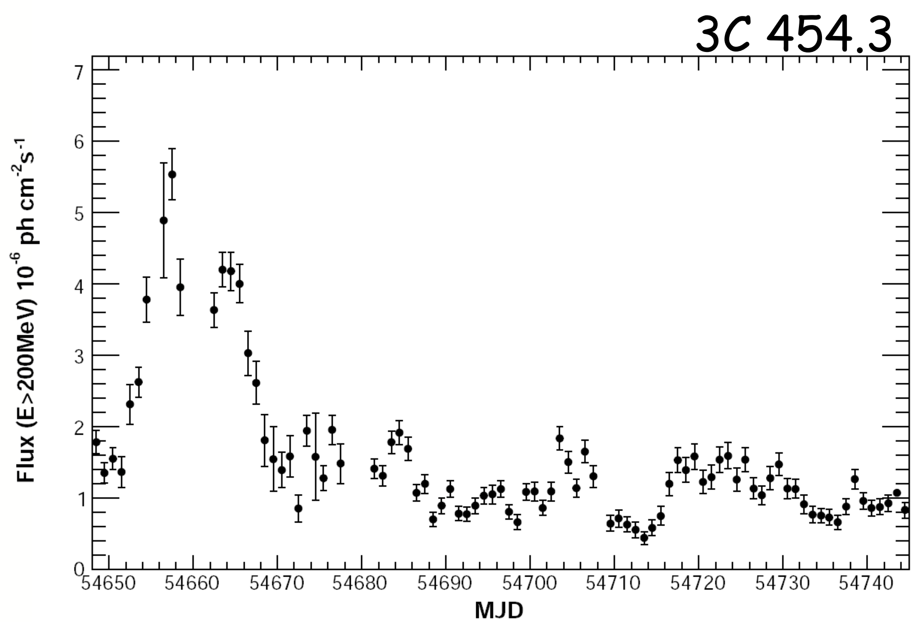




- **Effective area rises rapidly up to 1 GeV.**
- **Useful data collected out to 65-70 deg from the LAT boresight.**

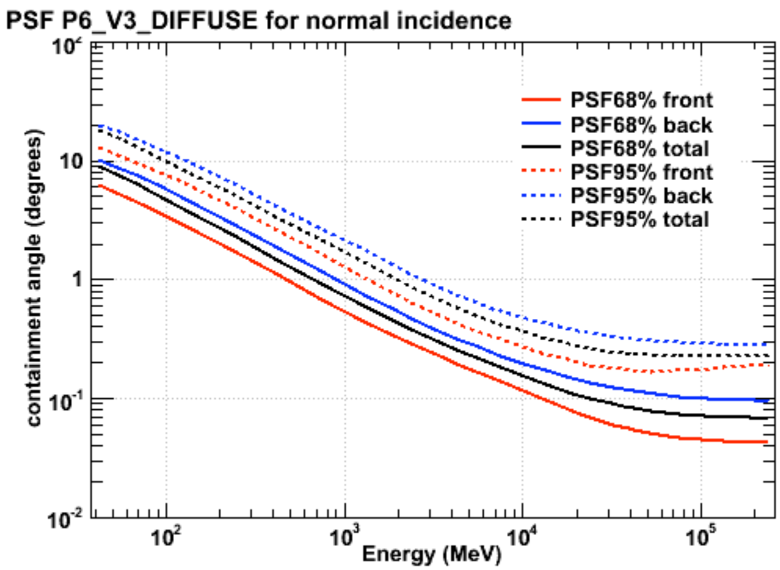
Effective area

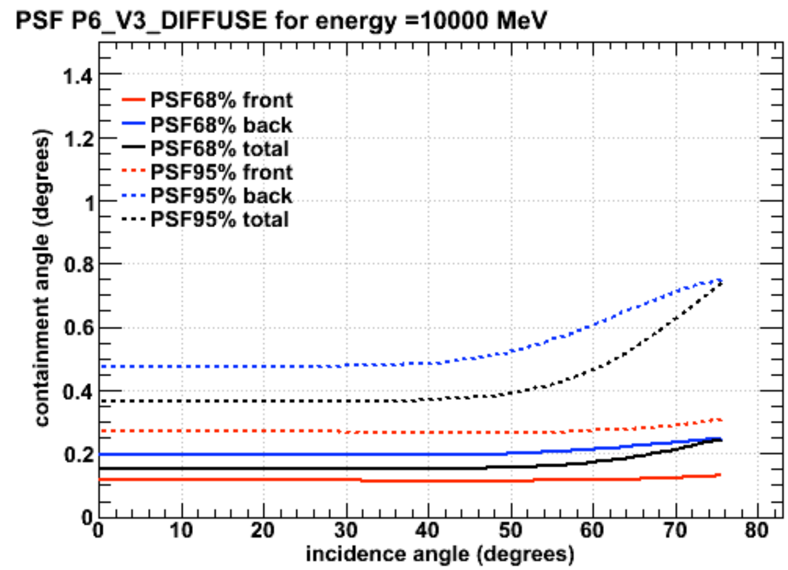




- **Large effective area means that more gamma-rays are detected by LAT for a given source brightness.**
- **Improves sensitivity; observations of rapid variability/transients (typical minimum integration for bright sources is 1 day, but can go smaller for brightest sources)**

LAT Performance: Angular Resolution

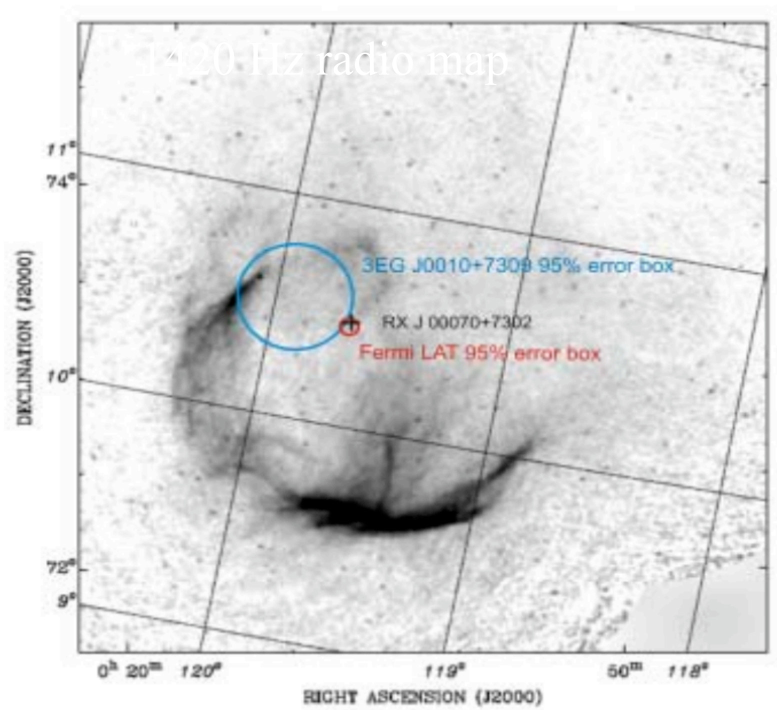




- **Angular resolution rapidly improves with increasing energy.**
- **Improved sensitivity (less background); greatly improved source locations, reduced source confusion - particularly for hard spectrum sources.**
- **Source localizations 5-10's arcmin typically - can follow up with MW observations.**
  - **Everything is better when we know where to look!**

New Pulsar in CTA 1

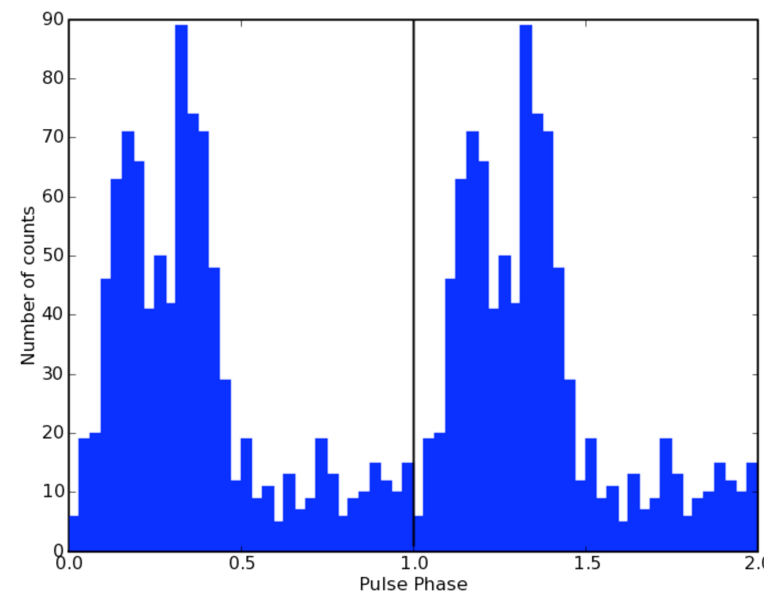
Science Express October 16
Abdo et al., 2008, Science



LAT 95% error radius = 0.038 deg
EGRET 95% error radius = 0.24 deg

P ~ 316 ms
Pdot ~ 3.6×10^{-13}
Flux (>100MeV) = $3.8 \pm 0.2 \times 10^{-7}$ ph cm-2 s-1

Pulse undetected in radio/X-ray

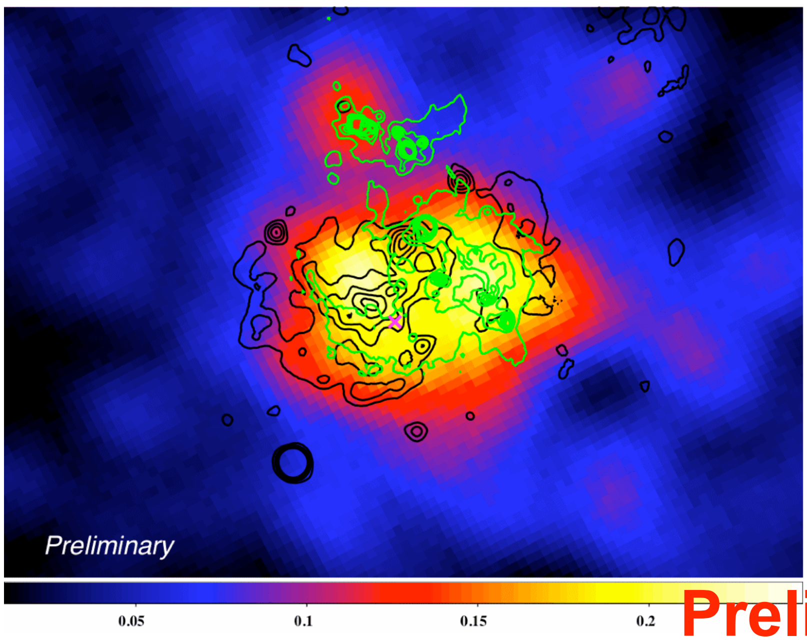


Unidentified EGRET sources - many are pulsars!

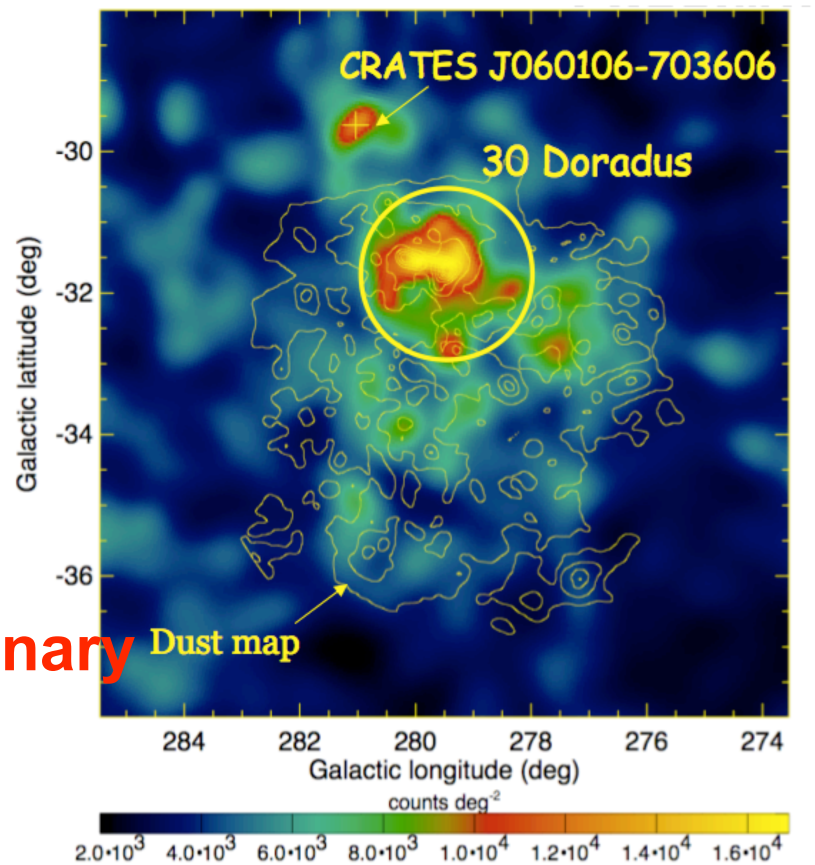
Extended Sources

- LAT is resolving the MeV-GeV gamma-ray emission from extended sources.

W51C



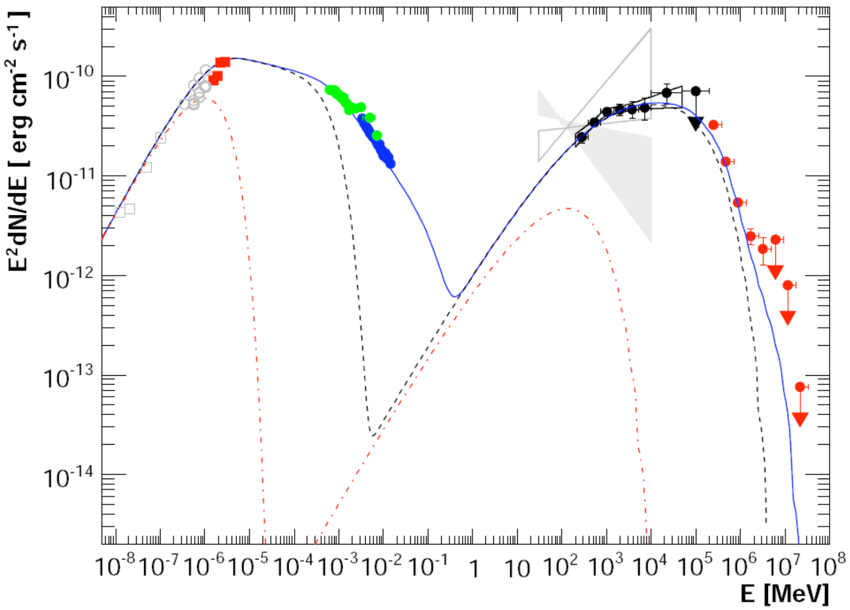
LMC



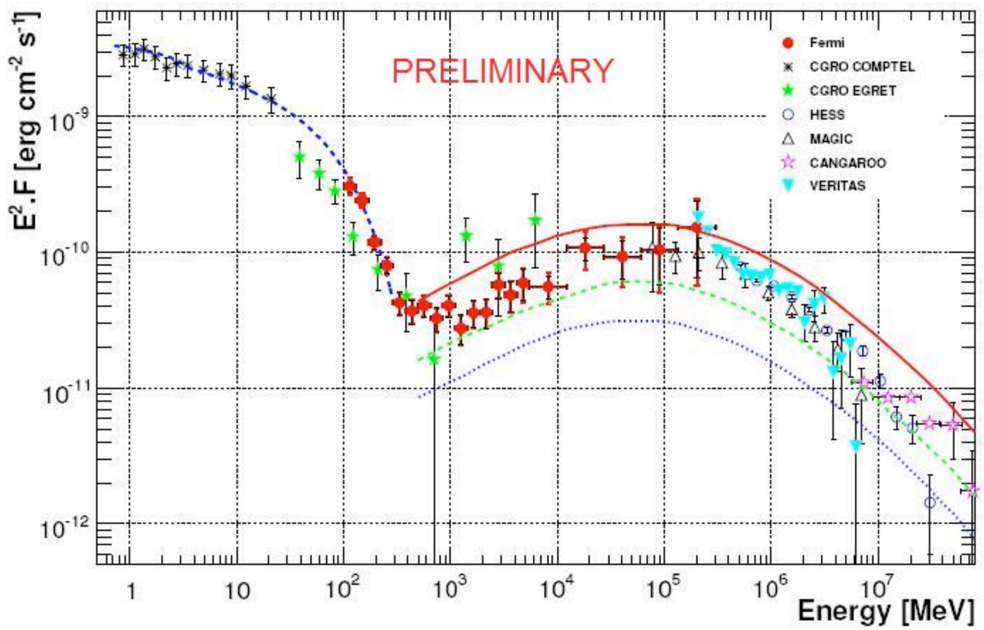
Preliminary

LAT Energy Reach

PKS 2155-304



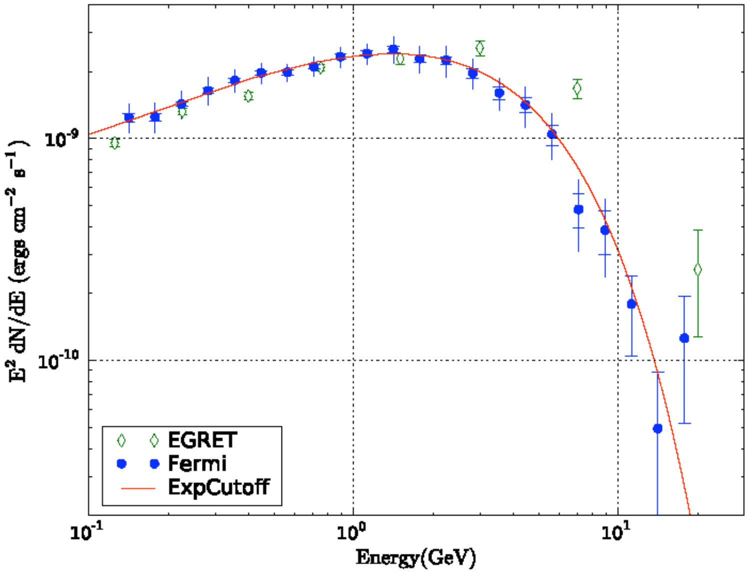
High energy Crab Nebula Spectrum



- **Finally closed the unexplored energy range between 10 and 100 GeV**
- **Joint fits between LAT (MeV-GeV) and IACTs (GeV-TeV)**
- **Peak sensitivity at a few GeV for typical spectra**

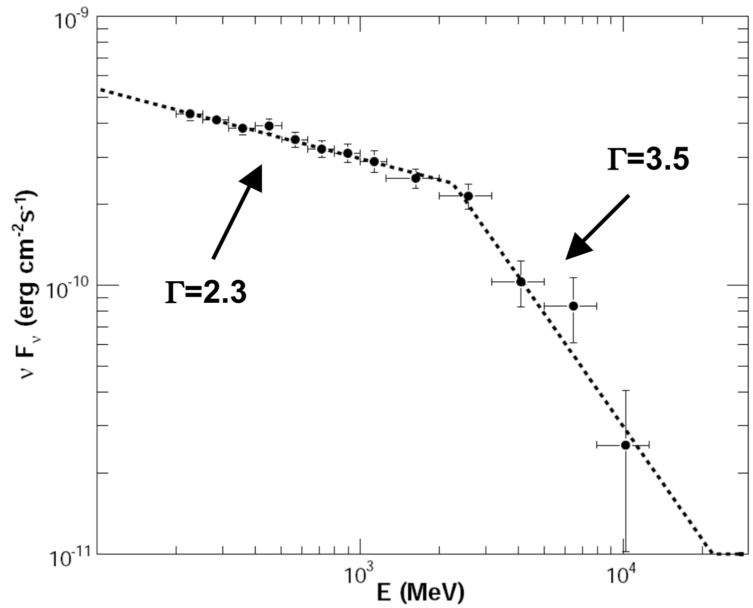
Spectral fits

- **LAT sensitivity and wide bandpass allows the measurement of many non power-law spectra**

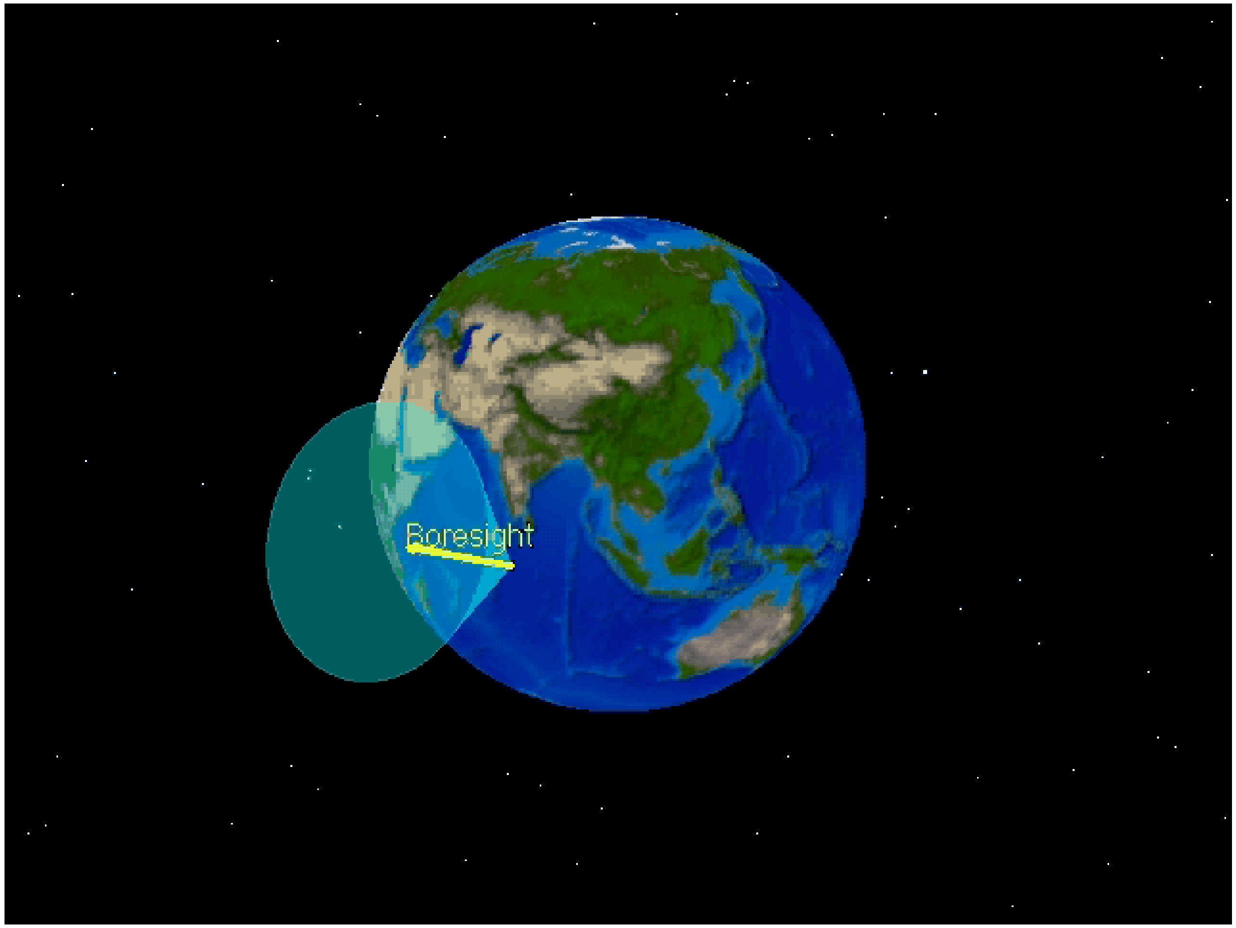


Phase averaged Vela Pulsar spectrum (power-law with exponential cutoff)

3C454.3: Broken power-law

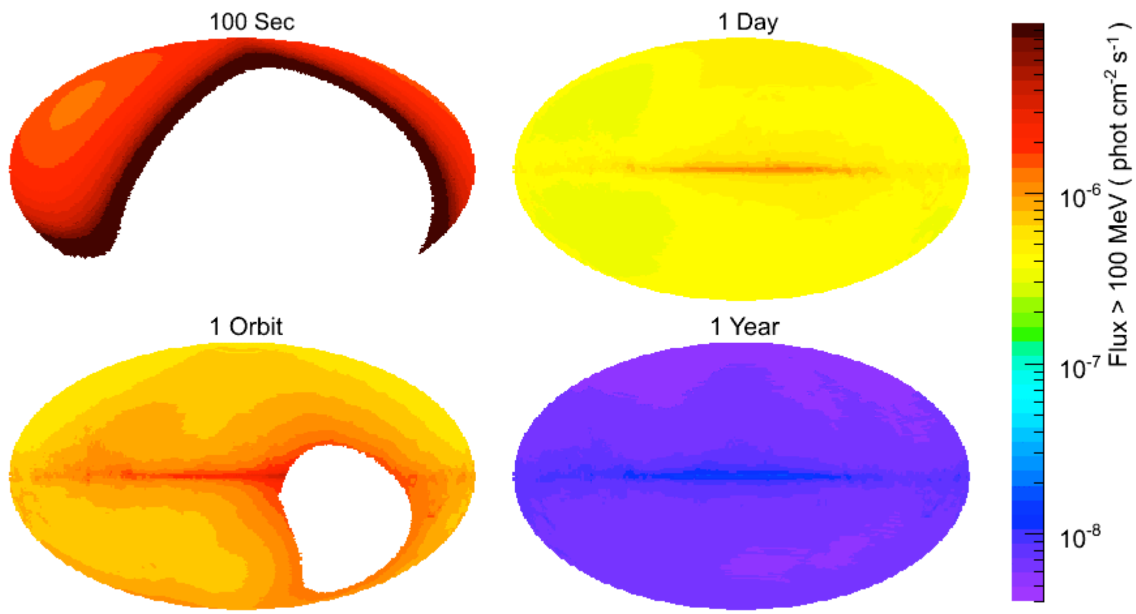


Survey mode



- Rock north for one orbit and south for the next
- Cover entire sky and always keep LAT FoV away from the Earth limb

All Sky Sensitivity on Different timescales



LAT sensitivity on 4 different timescales: 100 s, 1 orbit (96 mins), 1 day and 1 year

- **In survey mode, the LAT observes the entire sky every two orbits (~3 hours), each point on the sky receives ~30 mins exposure during this time.**
- **Multiwavelength observations in coordination with the LAT will be limited only by the ability to coordinate to other observations in other wavebands.**
- **Can also perform pointed observations of particularly interesting regions of the sky.**

All Sky Sensitivity