The Fermi Large Area Telescope

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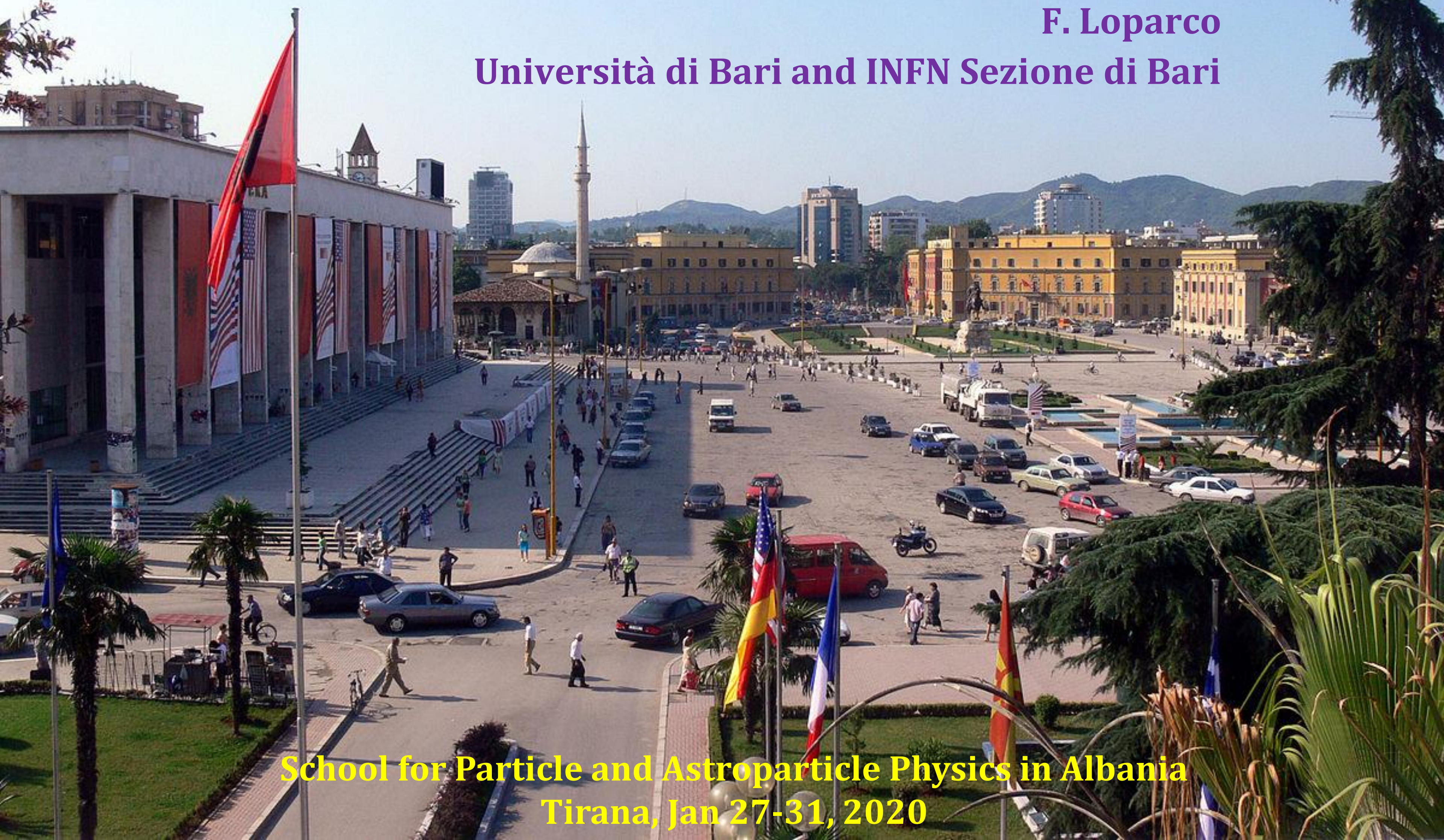

School for Particle and Astroparticle Physics in Albania
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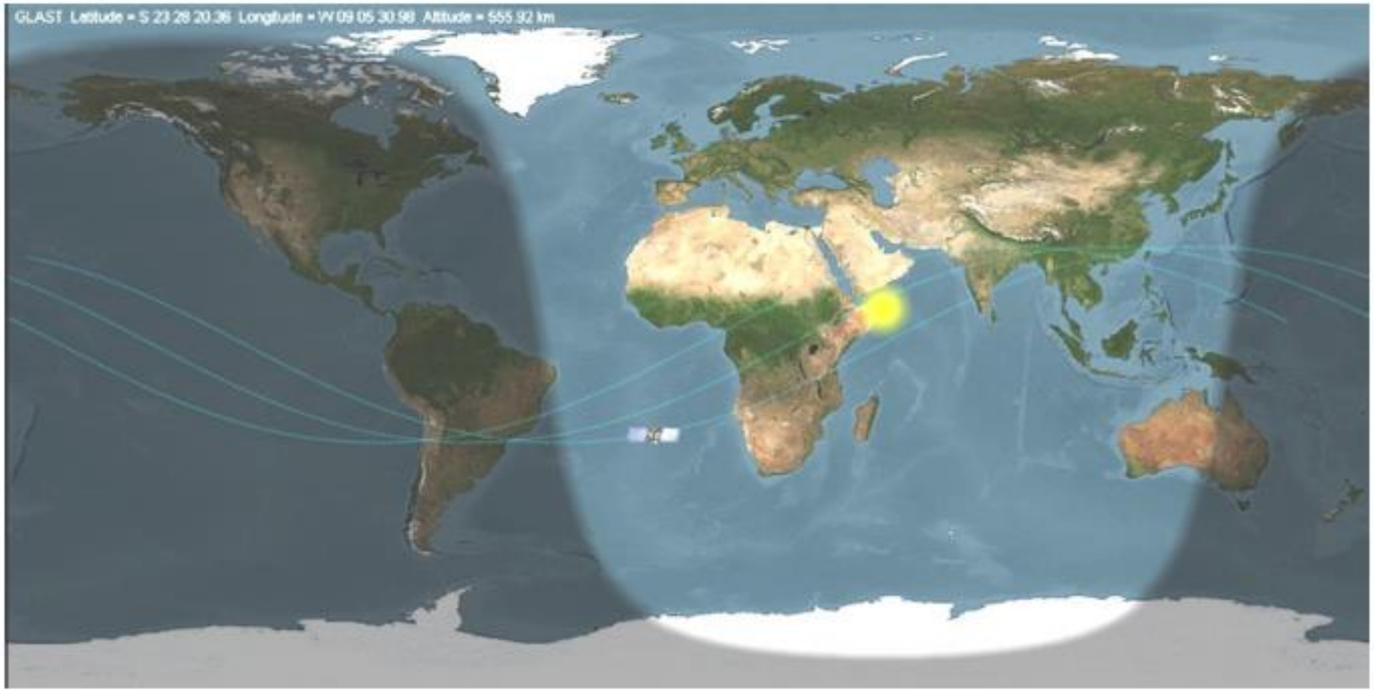
The Fermi satellite

- The Fermi Gamma-Ray Space Telescope (FGST) is an international space mission to study astrophysical gamma rays
- The satellite is equipped with two main instruments:
  - GLAST Burst Monitor (GBM)
    - Energy range from 8keV to 40MeV
  - Large Area Telescope (LAT)
    - Energy range from 20MeV to >300GeV
- The Fermi data are public and can be downloaded from the FSSC website:
  - https://fermi.gsfc.nasa.gov/ssc/data/
- Today we will analyze a set of data collected by the Fermi LAT

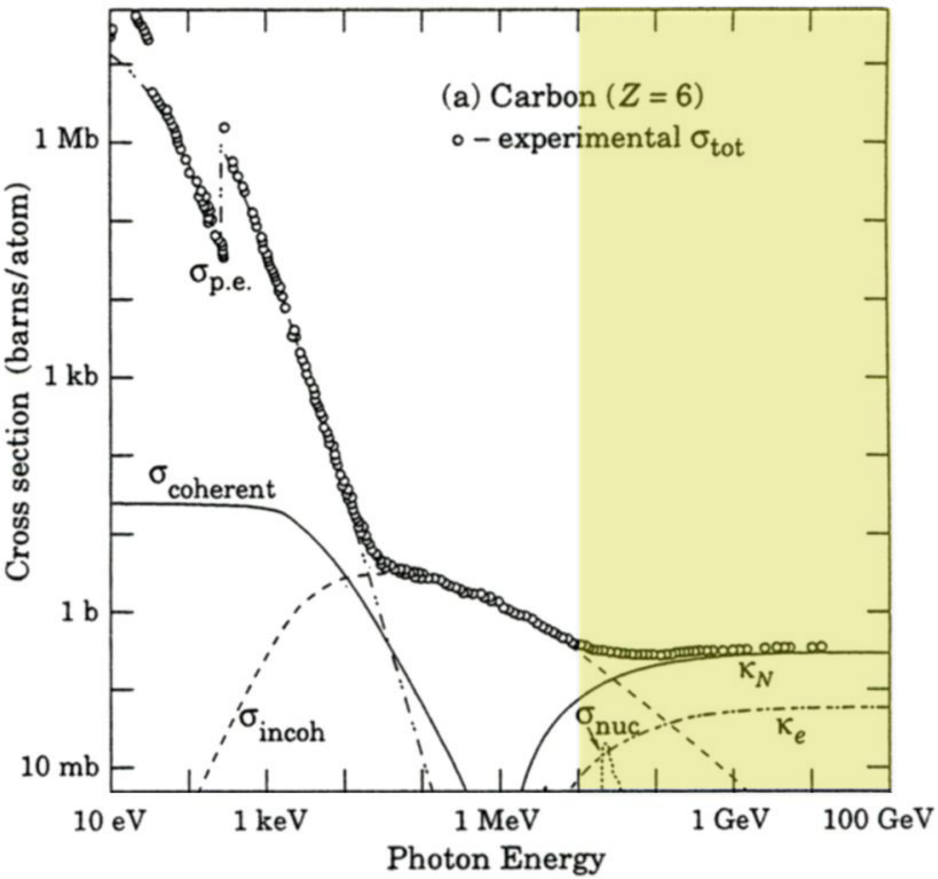
The Fermi mission

- Fermi was launched on June, 11th 2008 from the Cape Canaveral Air Force Station (Florida)
- Fermi is on a nearly circular orbit
  - Altitude = 565 km
  - Inclination = 25.6°
  - Period = 96 minutes
- To see where is Fermi now:
  - http://www.n2yo.com/?s=33053



Gamma-ray interactions with matter

- **Possible interactions:**
  - Raileigh scattering ($\sigma_{coherent}$)
  - Photoelectric effect ($\sigma_{p.e.}$)
  - Compton effect (σ_{incoh})
  - Pair production in the nuclear or electronic field (k_N, k_e)
  - Photonuclear interactions with destruction of the target nucleus (σ_{nuc})
- **The relative probability of each process is proportional to its cross section**
  - The cross sections depend on the projectile energy



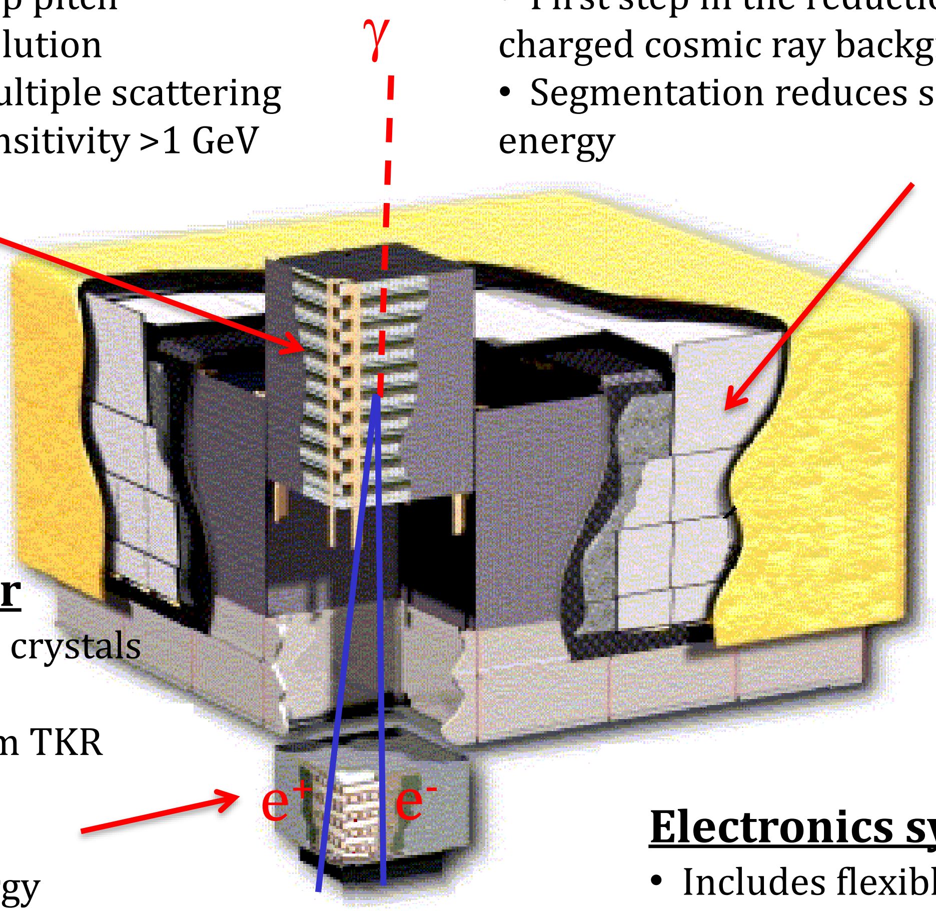
The Fermi LAT

Precision Si-strip Tracker (TKR)

- Measures incident γ-ray direction
- 18 XY tracking planes: 228 μm strip pitch
- High efficiency. Good position resolution
- 12x 0.03 X_0 front end → reduce multiple scattering
- 4x 0.18X_0 back-end → increase sensitivity >1 GeV

Anticoincidence Detector (ACD)

- 89 scintillator tiles
- First step in the reduction of large charged cosmic ray background
- Segmentation reduces self-veto at high energy



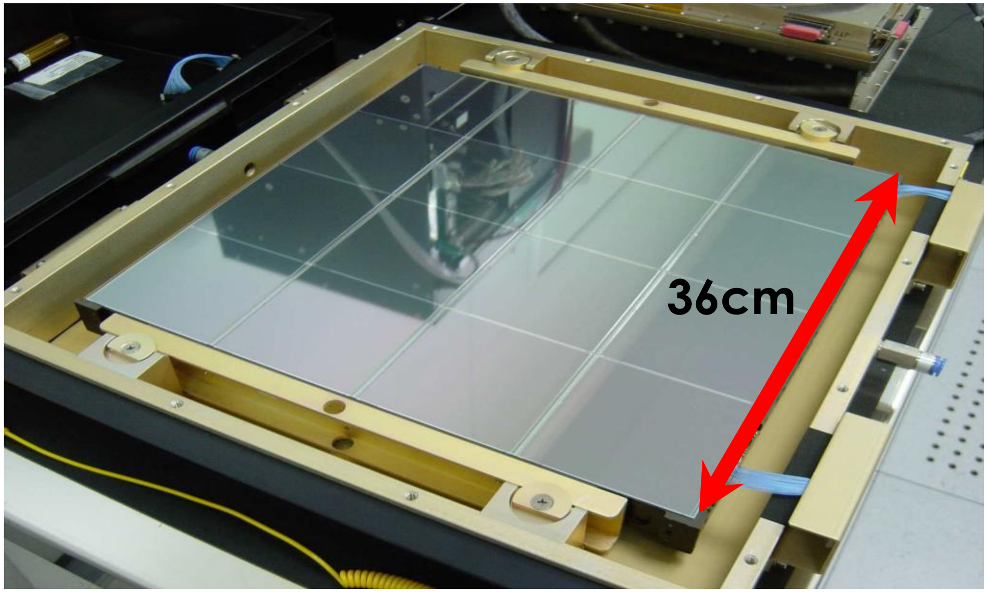
Hodoscopic CsI Calorimeter

- Segmented array of 1536 CsI(Tl) crystals
- 8.6 X_0: shower max contained
  - ~ 200 GeV normal (1.5X_0 from TKR included)
  - ~ 1TeV @ 40° (CAL-only)
- Measures the incident γ-ray energy
- Rejects cosmic-ray background

Electronics system

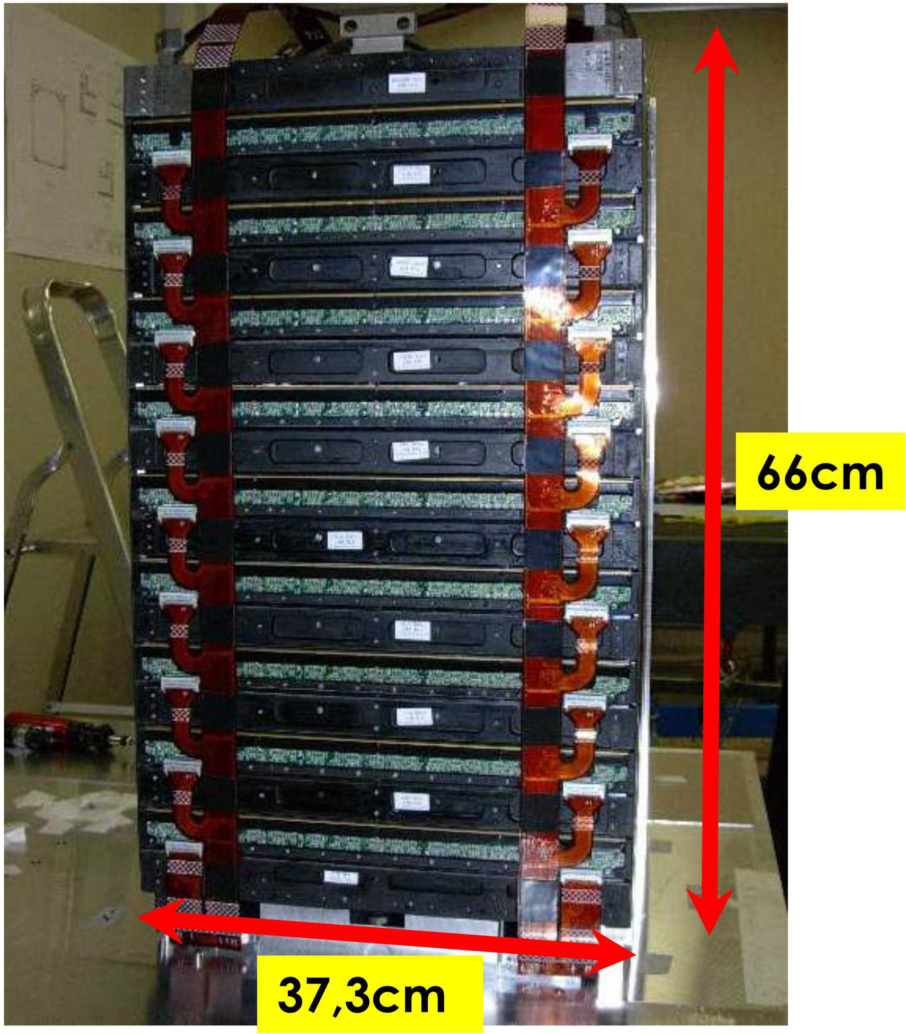
- Includes flexible, highly efficient, multi-level trigger

The silicon tracker (TKR)



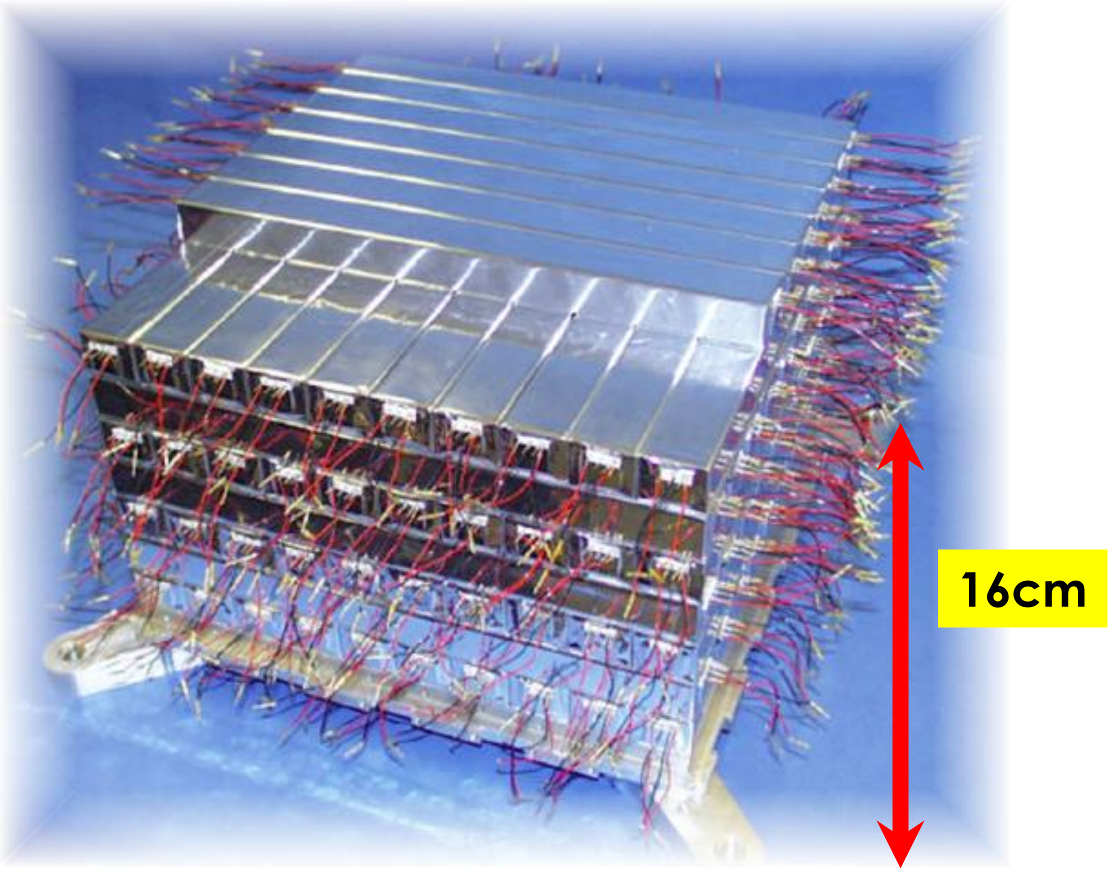
- Each TKR plane consists of 16 wafers
  - Cross section = $9 \times 9 cm^2$
  - Strip pitch = 228 μm
  - 384 strips in each wafer ➔ 1536 strips in each plane
  - Strips of adjacent wafers are bonded
- SSD planes are arranged in «trays»
  - Each tray hosts a SSD plane with strips along the X-axis and a SSD planes with strips along the Y-axis
  - A tungsten converter layer is eventually placed between the two SSD planes

The silicon tracker towers



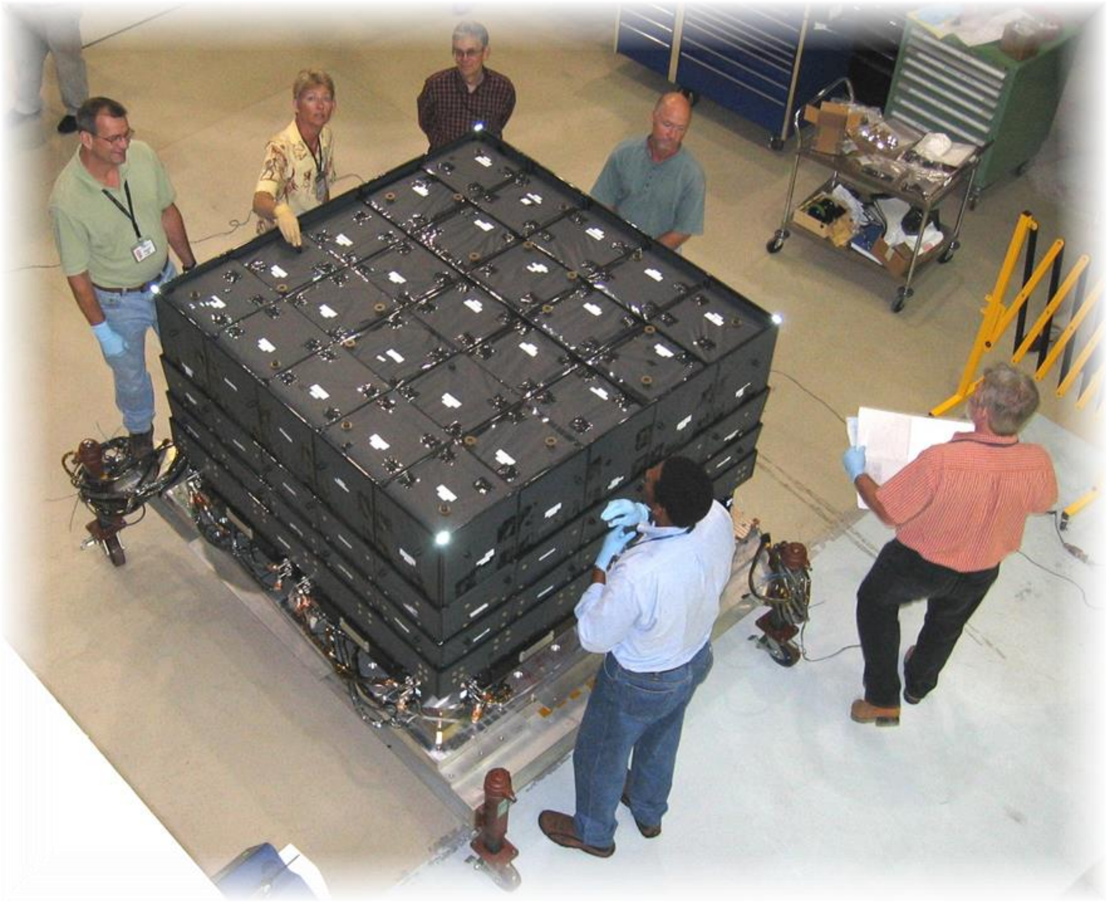
- Each TKR tower hosts 19 trays and 36 SSD planes
  - The top and bottom trays are equipped with only one SSD plane
- 18 SSD planes with strips along the X-axis and 18 planes with strips along the Y-axis
  - 55296 strips per tower
  - About 880k strips in the TKR

The calorimeter (CAL)



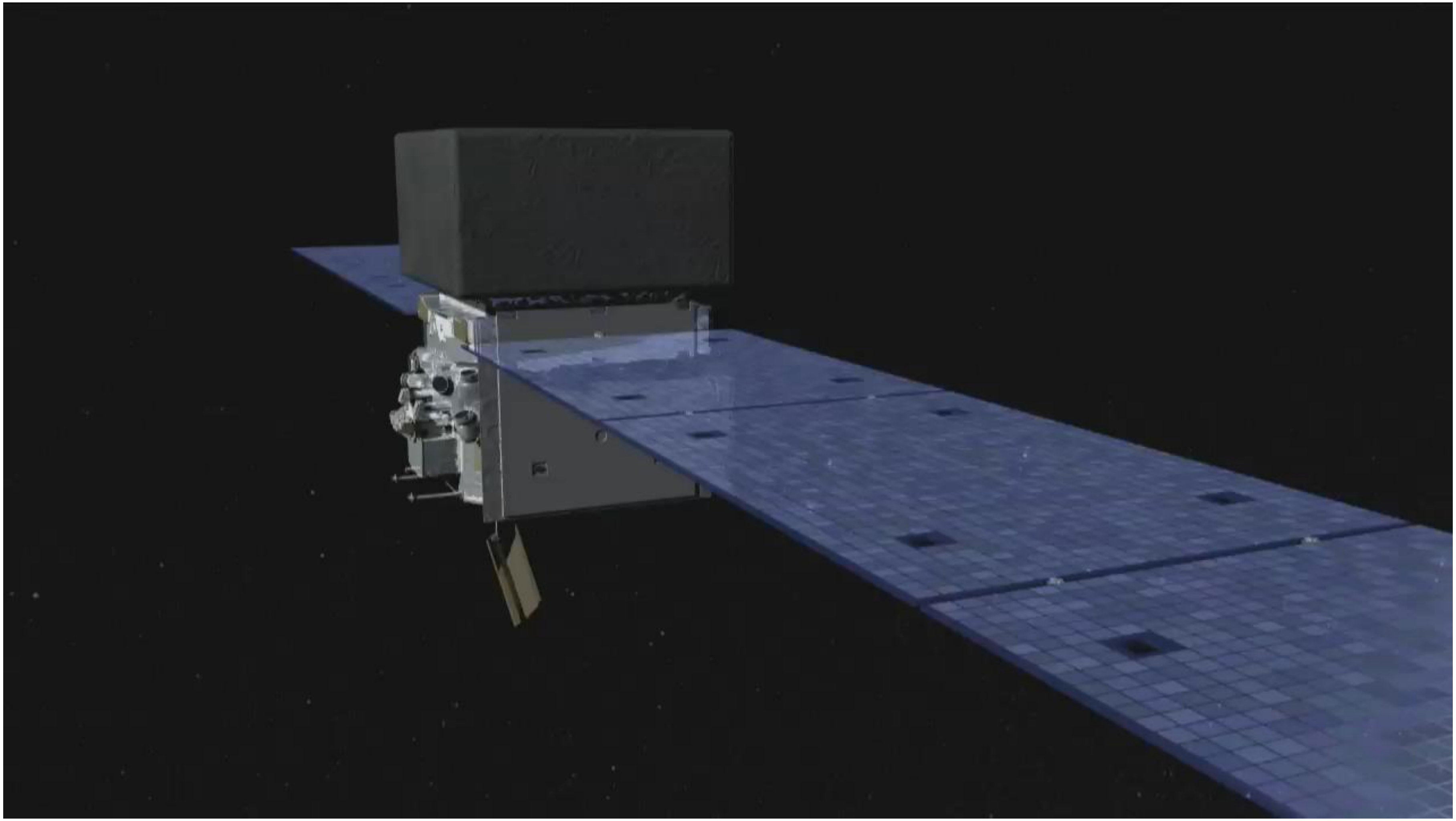
- 1536 CsI(Tl) crystals arranged in 16 towers
  - Crystal size = $2.7 \times 2 \times 32.6 \text{cm}^3$
  - The crystals in each tower are hodoscopically arranged in 8 planes
- Total vertical thickness = 8.6 X_0

The anticoincidence detector (ACD)



- **89 plastic scintillator tiles readout by PMTs**
  - **Empty spaces between tiles filled with plastic scintillator ribbons**

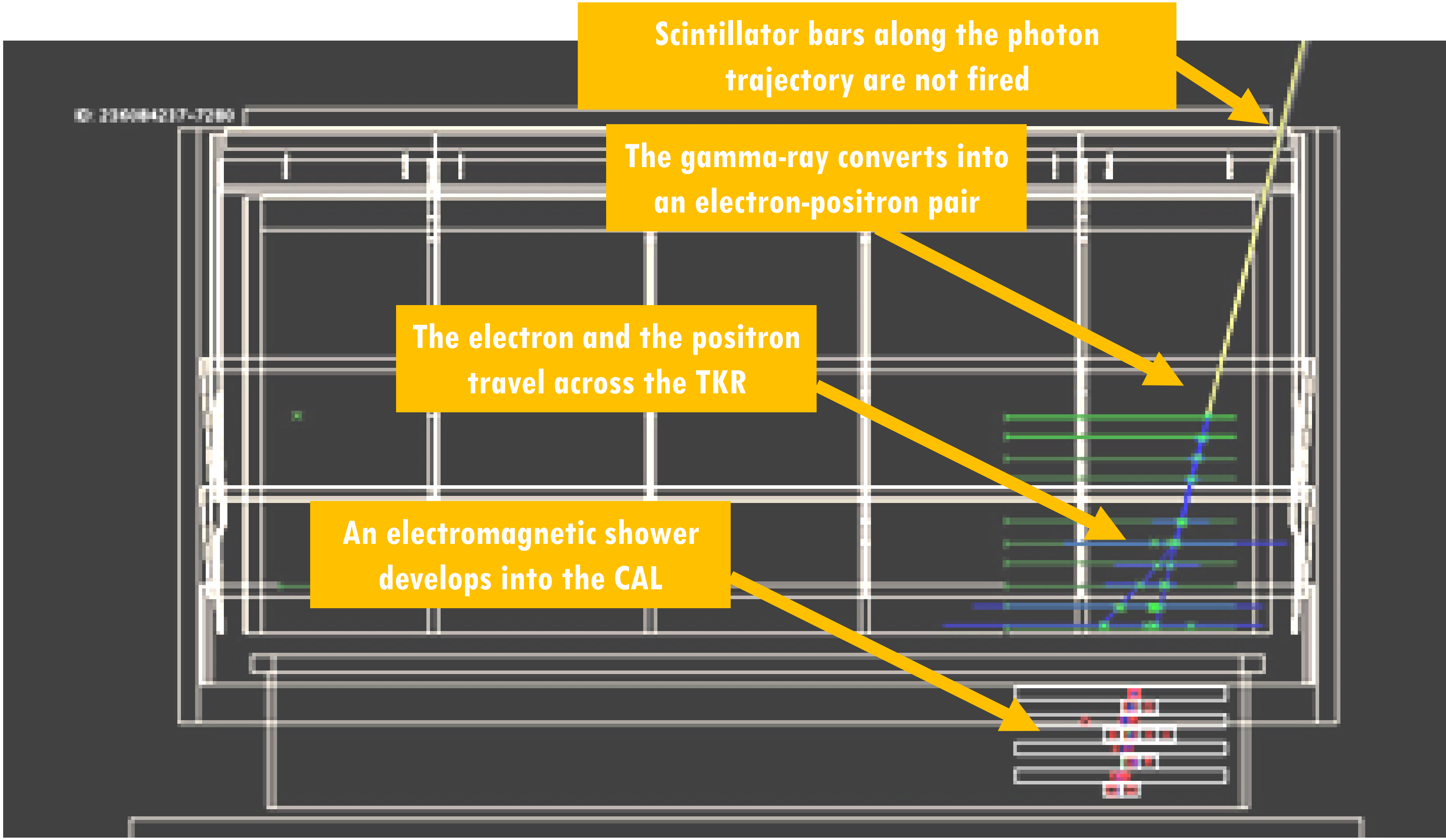
How the LAT detects gamma rays



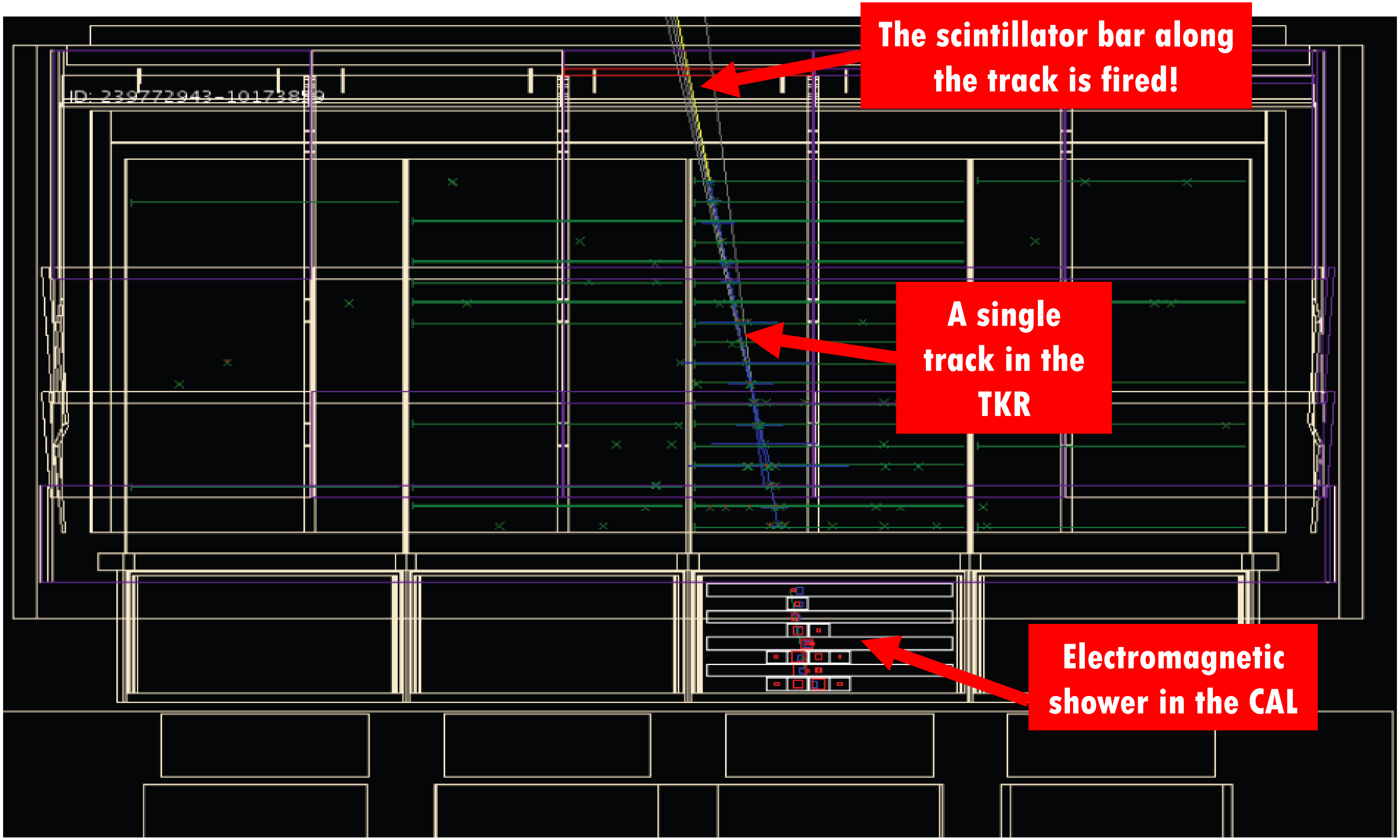
Onboard triggering and filtering

- Five hardware trigger primitives:
  - TKR: 3 x + 3 y tracker planes hit in a row
  - CAL LO: single log with more than 100 MeV
  - CAL HI: single log with more than 1 GeV
  - ROI: MIP signal in a ACD tiles close to a triggering tower
  - CNO: heavy ion signal in the ACD
- Upon L1 trigger the entire detector is read out
- Need onboard filtering to fit the data volume within the allocated bandwidth
  - GAMMA: the purpose is to select γ-ray candidates and events that deposit at least 20 GeV in the CAL
    - High energy events, including electrons, are available for analysis on the ground
  - Heavy Ions: the purpose is to select heavy ions with large energy deposits in the ACD
  - MIP: the purpose is to select not showering charged particles (protons)
    - Disabled in standard science operations
  - Diagnostic: the purpose is to select an unbiased event sample for filter and background performance studies
    - The selected sample is pre-scaled of a factor 250

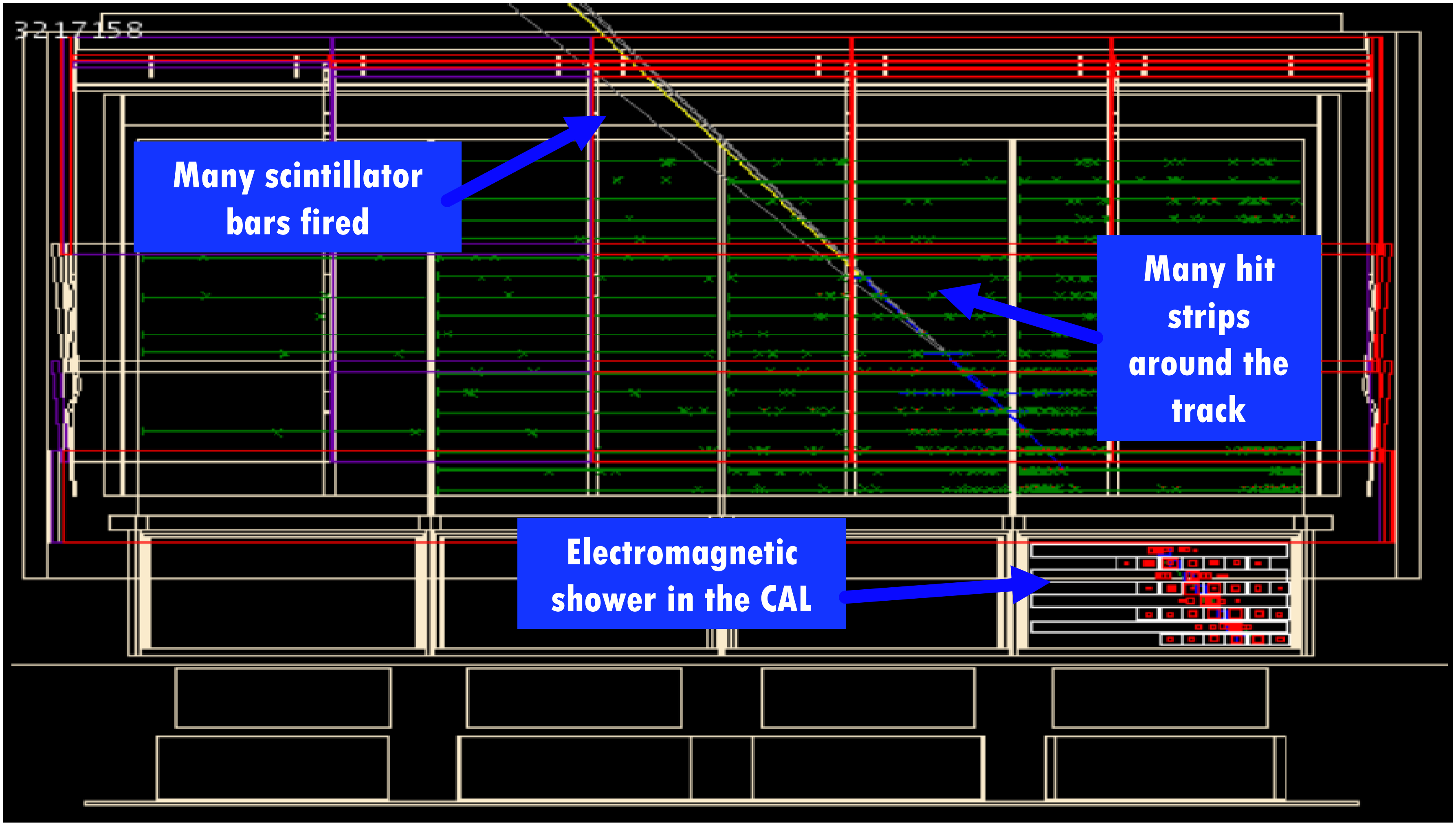
An example of gamma-ray event



An electron (or positron?) event



An example of proton event



The LAT gamma-ray data

- The LAT observes about 20% of the sky at any instant
  - The whole sky is observed every 3 hours
- Uptime fraction ~ 99%
- About 550 billion triggers from launch (@August 2017)
  - ~110 billion events downlinked
    - ~2800 million events available at the FSSC
- Different gamma-ray event classes:
  - Triggered events are dominated by CR background events
    - Need to define additional cuts to get γ-ray rich dataset
  - Several event reconstruction and classification algorithms have been developed during the mission
    - Starting from July 2015, the LAT data are processed with the newest "Pass 8" classification algorithms
  - Nested "event classes" for various types of γ ray sources:
    - Transient: loosest, for flaring sources
    - Source: moderate, for bright sources
    - Clean: tight, for γ-ray diffuse
    - Ultraclean: tightest, for extragalactic γ rays
- The LAT data are public and can be downloaded from the FSSC website (see http://fermi.gsfc.nasa.gov/ssc/)
  - Data are made public after 24 hours (or less)
  - The science tools for data analysis are also provided

Instrument response functions (IRFs)

- The expected count rate from a given source can be expressed as:

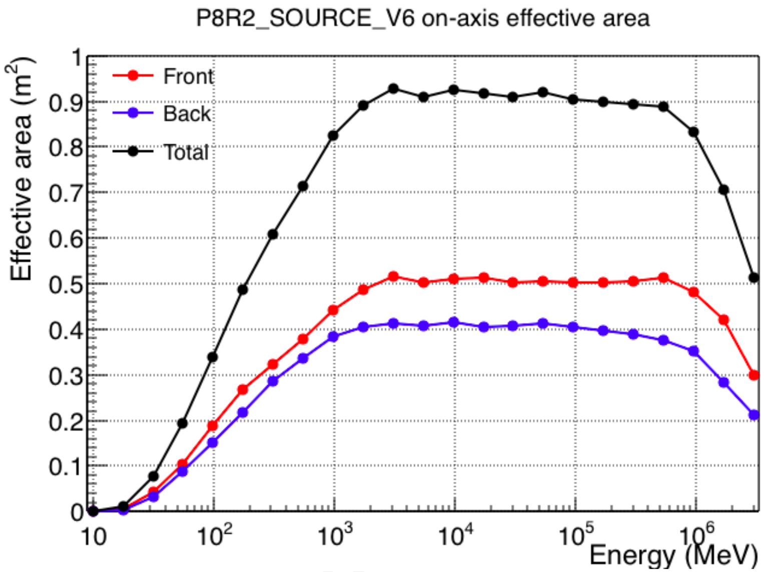
$$r(E',\hat{v}') = \iint dE d\hat{v}\, R(E',\hat{v}',E,\hat{v})\, \Phi(E,\hat{v})$$

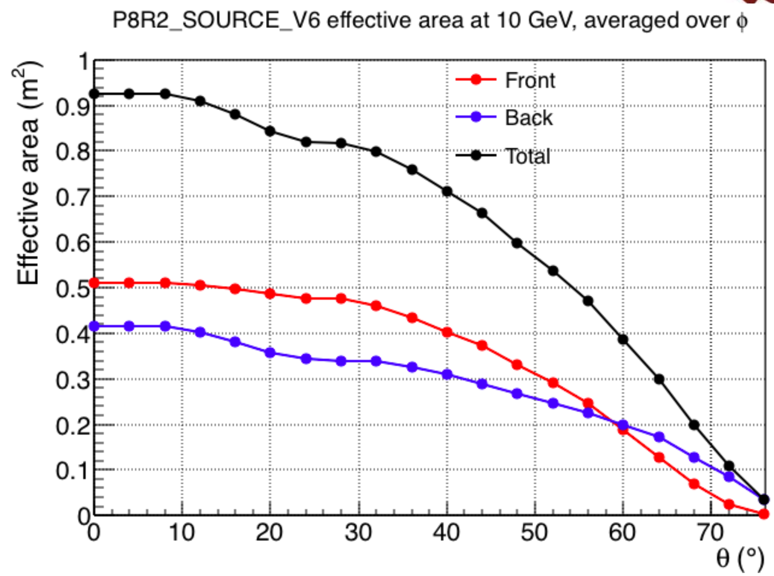
  - E' , $\hat{v}'$ = measured photon energy and arrival direction
  - $E, \hat{v}$ = true photon energy and arrival direction
  - $\Phi(E,\hat{v})$= photon flux from the source
  - $R(E',\hat{v}',E,\hat{v})$ = instrument response function (IRF)
- The IRF can be factorized as:

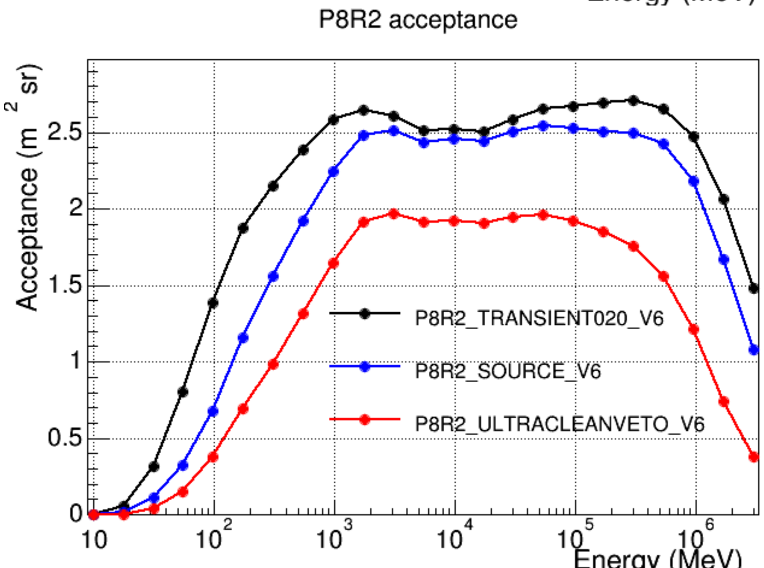
$$R(E',\hat{v}',E,\hat{v}) = A_{eff}(E,\hat{v})\, \mathrm{P}(\hat{v}',E,\hat{v})\, D(E',E,\hat{v})$$

  - $A_{eff}(E,\hat{v})$ = effective area
    - A_{eff} is the cross section of the LAT for detecting a photon with true energy E coming from the direction $\hat{v}$
  - $\mathrm{P}(\hat{v}',E,\hat{v})$ is the point spread function (PSF)
    - The PSF is the probability that a photon with true energy E coming from the direction $\hat{v}$ is observed as coming from $\hat{v}'$
  - $D(E',E,\hat{v})$ is the energy dispersion
    - The energy dispersion is the probability that a photon with true energy E coming from the direction $\hat{v}$ is observed with energy E'

Effective area and acceptance

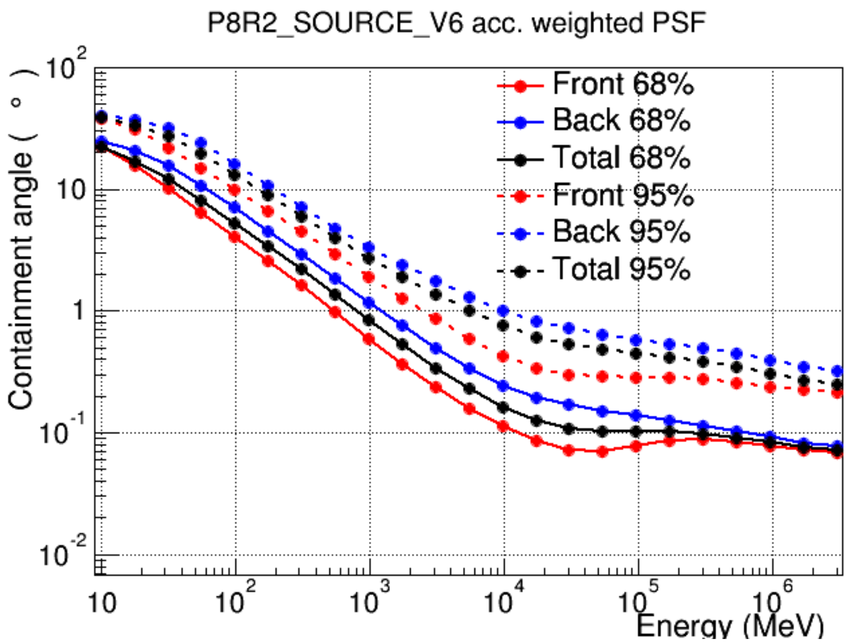






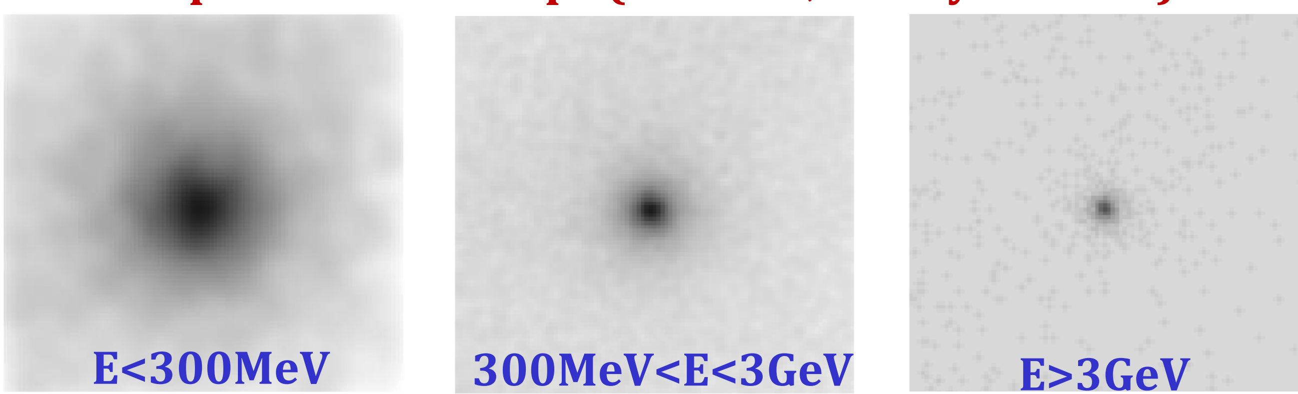
- **Drop at E<100 MeV due to the pair production cross section and to the trigger condition, which requires 3 tracker planes in a row**
- **Drop at E>100 GeV due to backsplash in the ACD**

Point Spread Function (PSF)



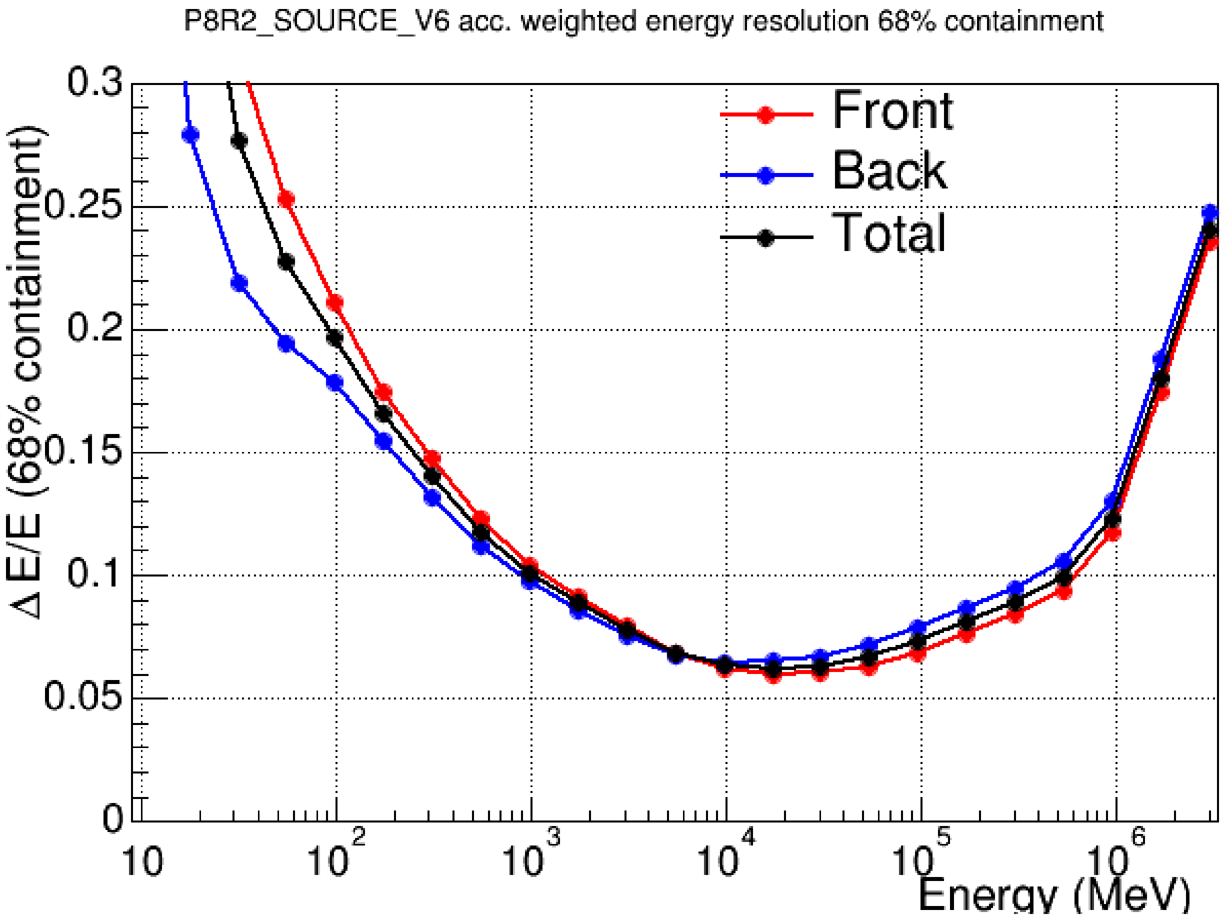
- **At low energies the PSF is poor because of multiple scattering of the e+e- pairs in the tracker planes**
- **At high energies the PSF is limited by the strip pitch (228μm)**

Vela pulsar count maps (10°×10°, 75 days of data)



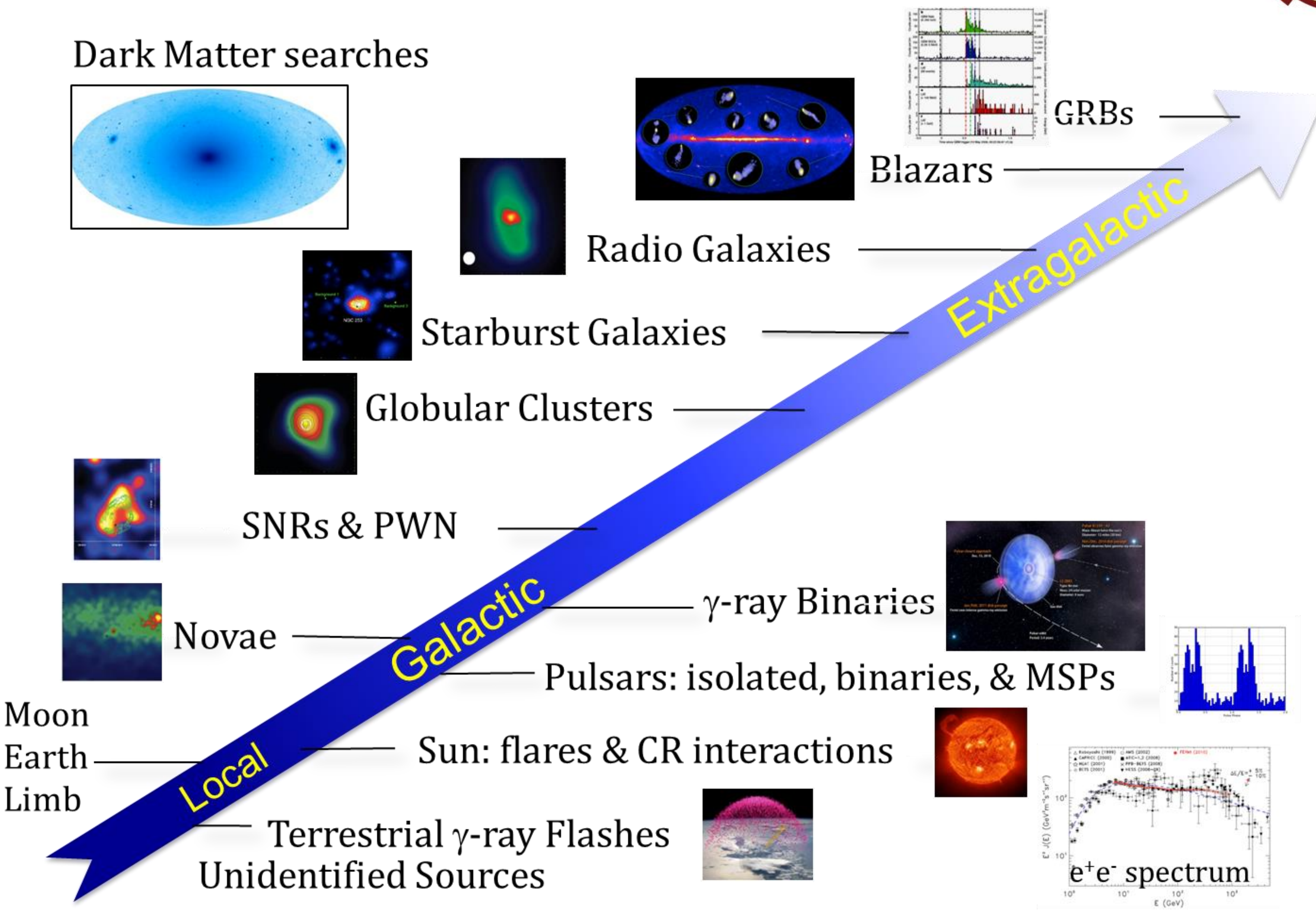
Plots taken from Astrophys. J. 696, 1084A (2009)

Energy dispersion

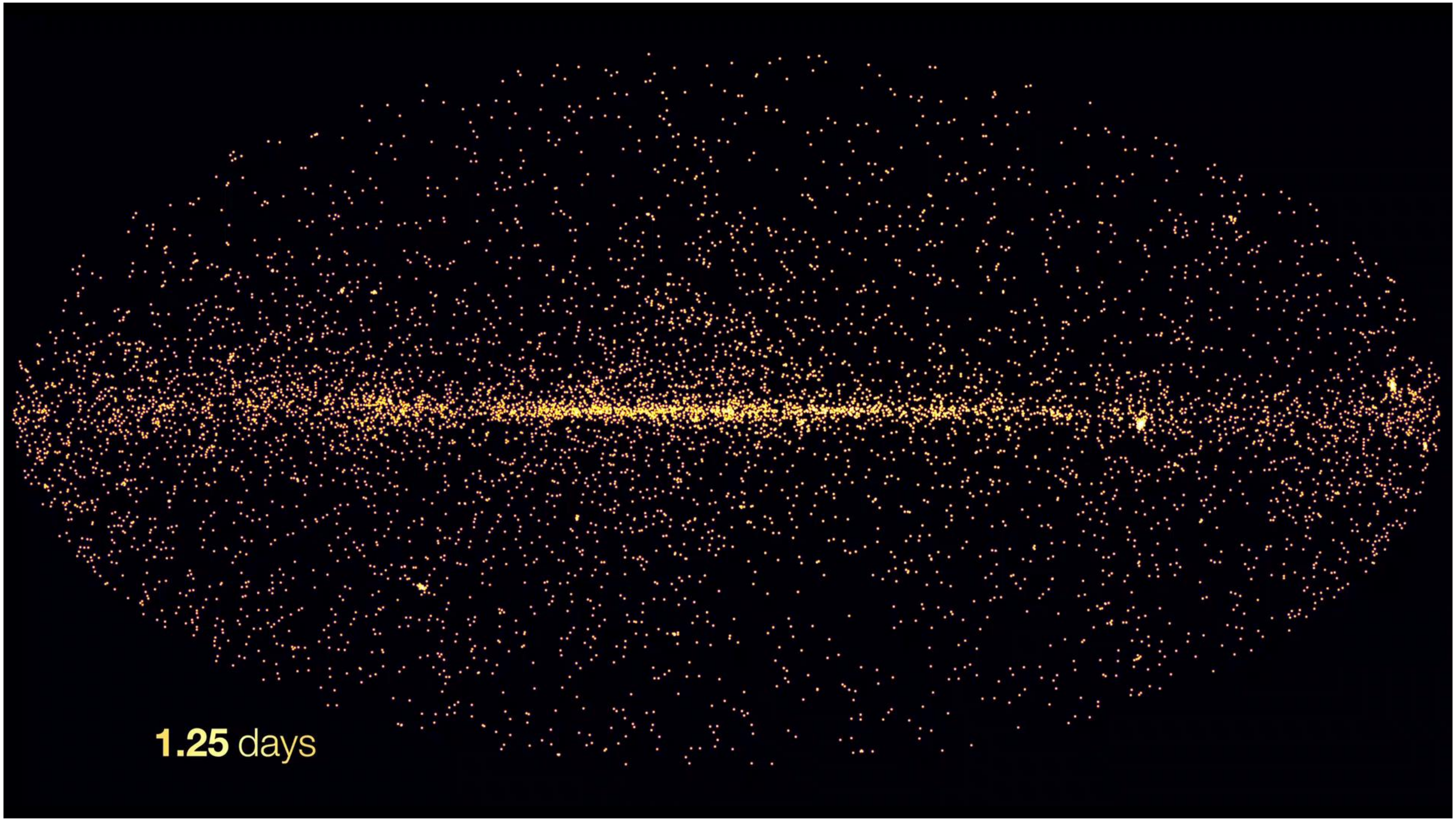


- **Limited at low energies by energy loss in the tracker**
- **Limited at high energies by saturation of the CsI crystals and by partial shower containment in the calorimeter**

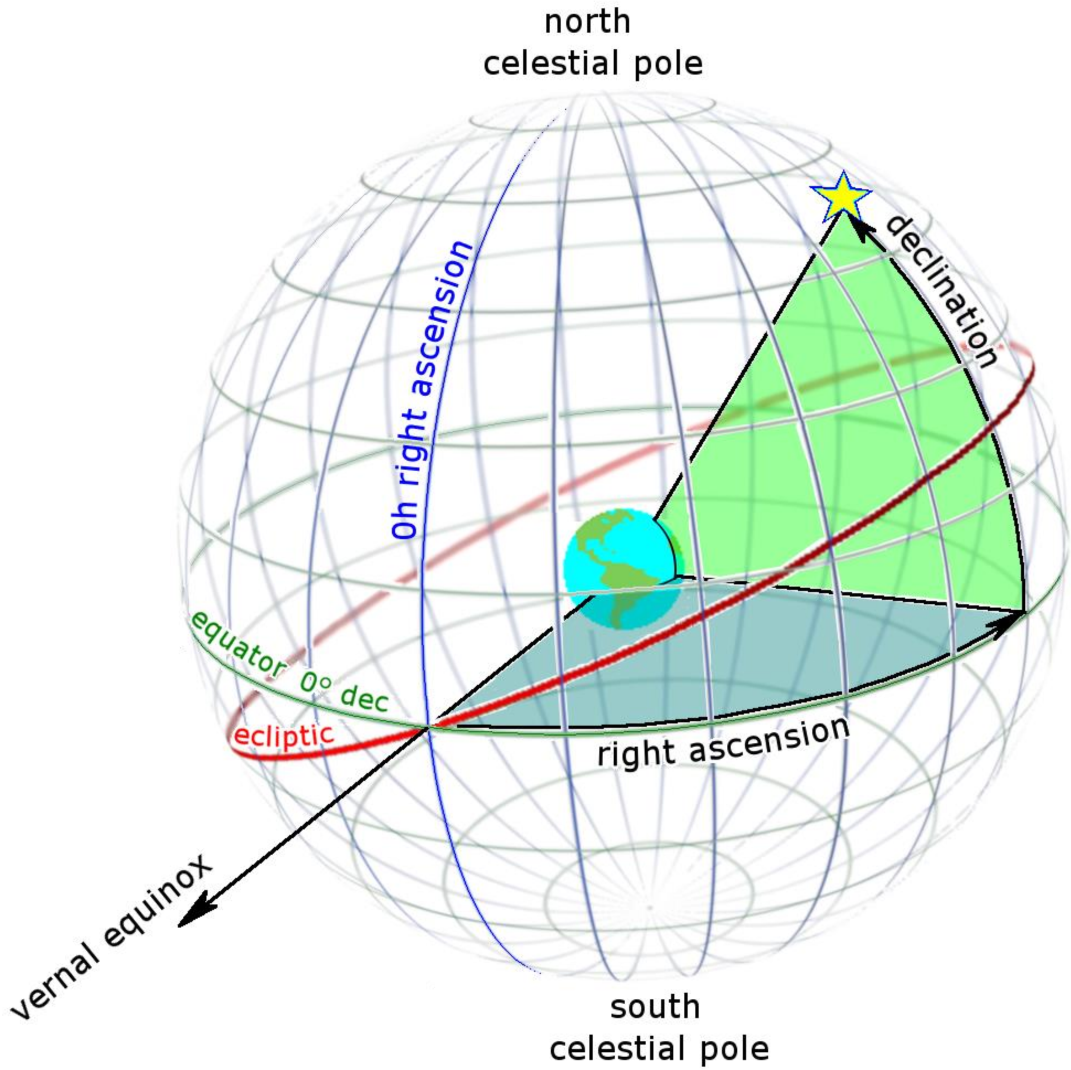
Science with the Fermi LAT



The high-energy gamma-ray sky seen by the Fermi LAT

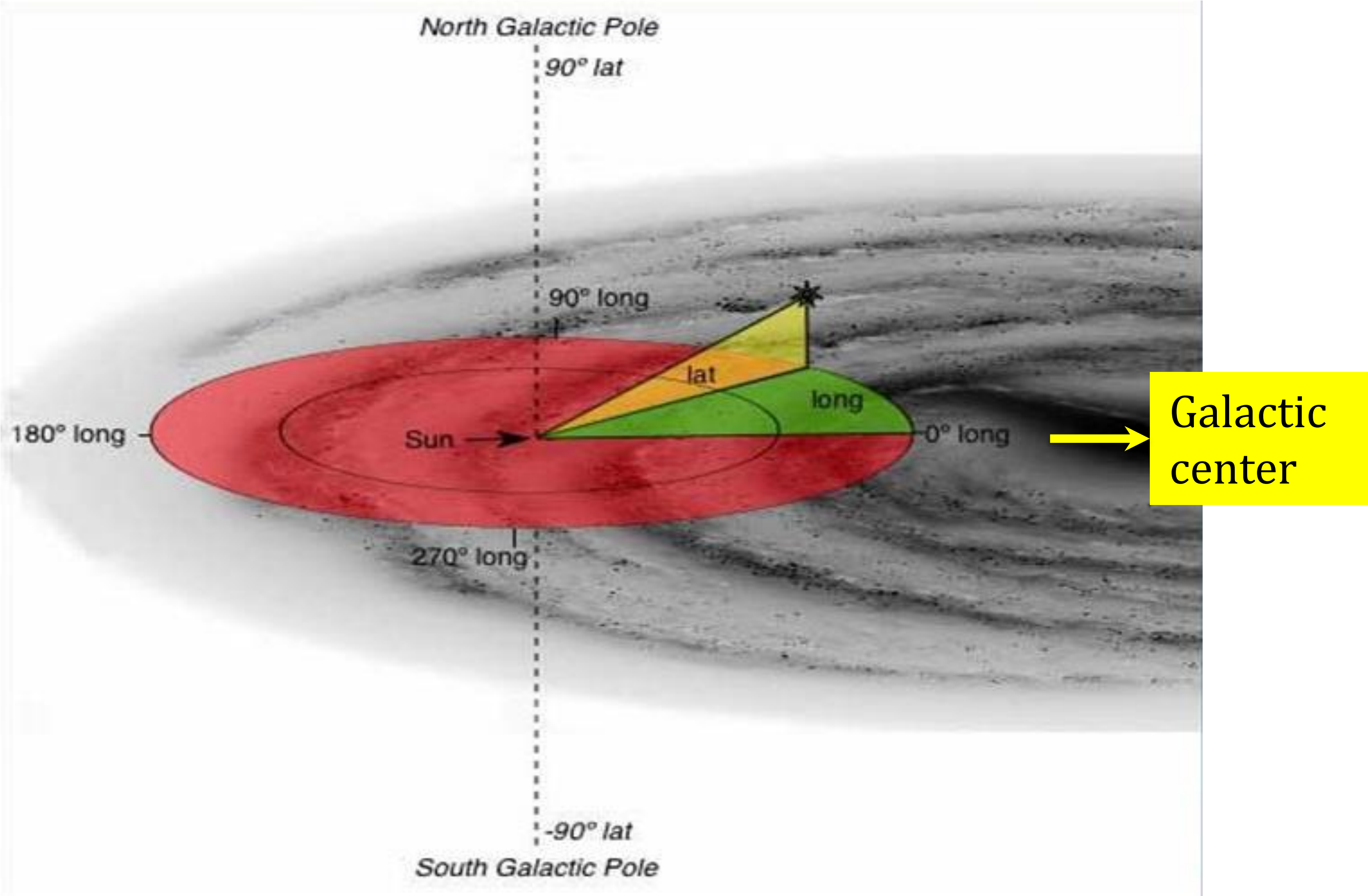


Equatorial coordinates



- The fundamental plane is the projection of the Earth Equator on the Celestial Sphere (Celestial Equator)
- The primary direction is the ascending node of the Ecliptic on the Celestial Equator (Vernal Equinox)
- Right Ascension (RA) is measured eastwards from the Vernal Equinox
- Declination (DEC) is measured northwards from the Celestial Equator

Galactic coordinates



- **Galactic longitude (L)** is measured with primary direction from the Sun to the center of the galaxy in the galactic plane
- **Galactic latitude (B)** measures the angle of the object above the galactic plane

Today's source: the blazar 3C 454.3