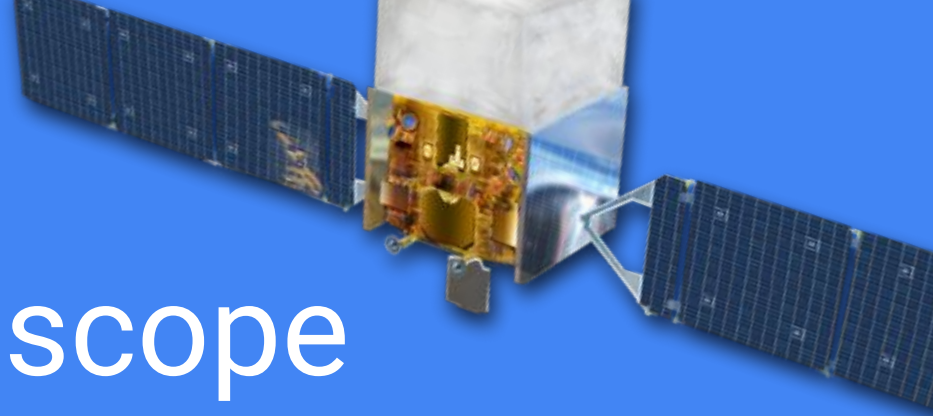
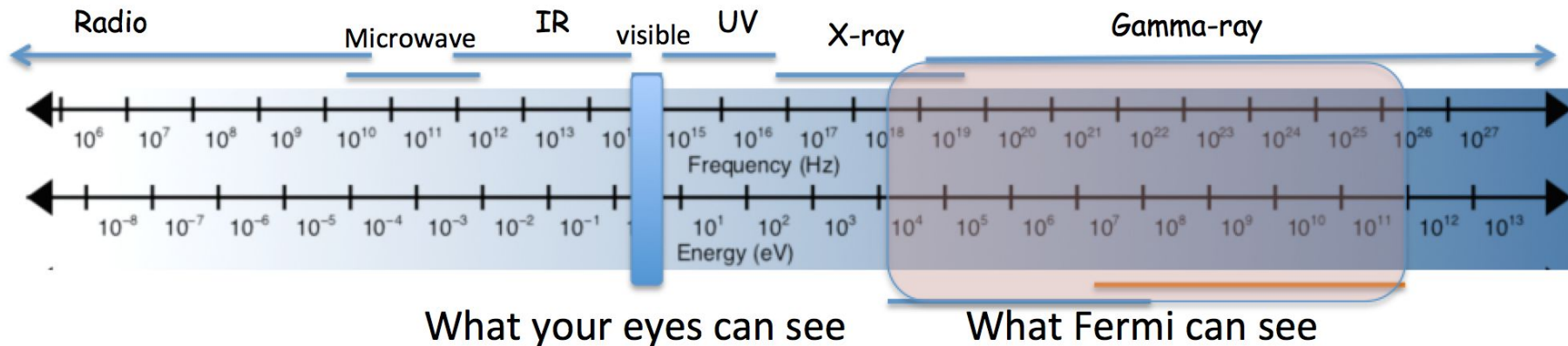


Large Area Telescope Overview

Jeremy S. Perkins (NASA/GSFC)
Slides based on many other people's work



Why High Energy Gamma-rays?

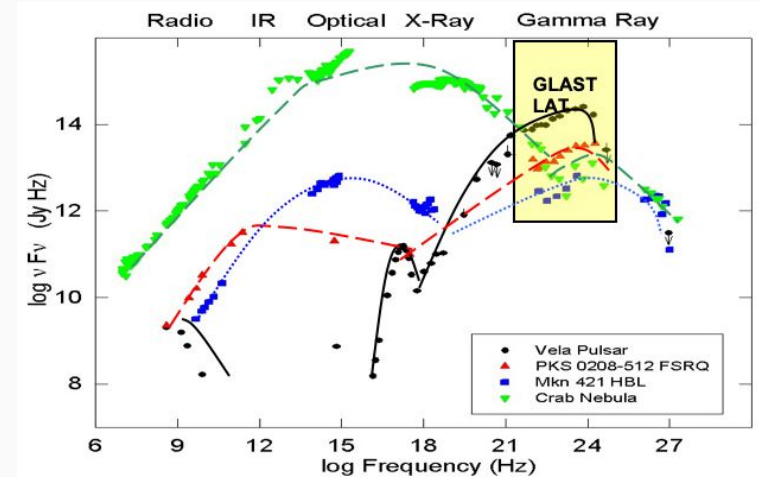
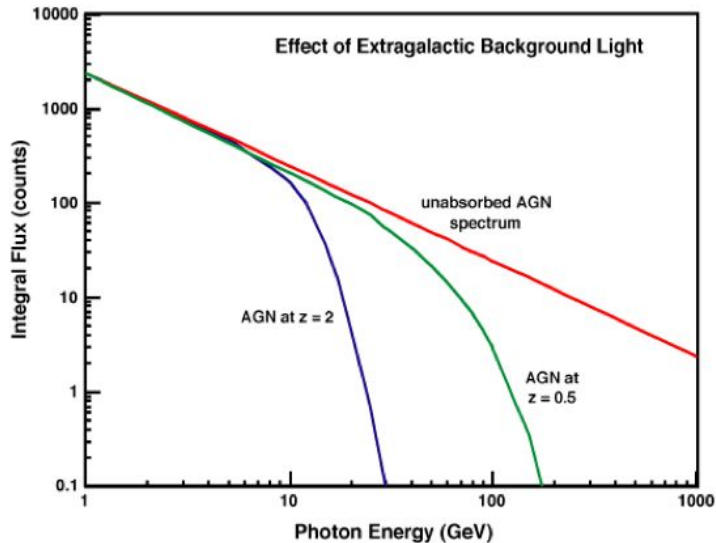


- Gamma-rays cover a **huge swath** of the electromagnetic spectrum
- High Energy gamma-rays produced in **non-thermal processes** (i.e. by energetic charged particles)
 - Explore extreme environments hosting **powerful particle accelerators**
 - Natural connections to **neutrino** and **cosmic-ray** astrophysics.

Why High Energy Gamma-rays?

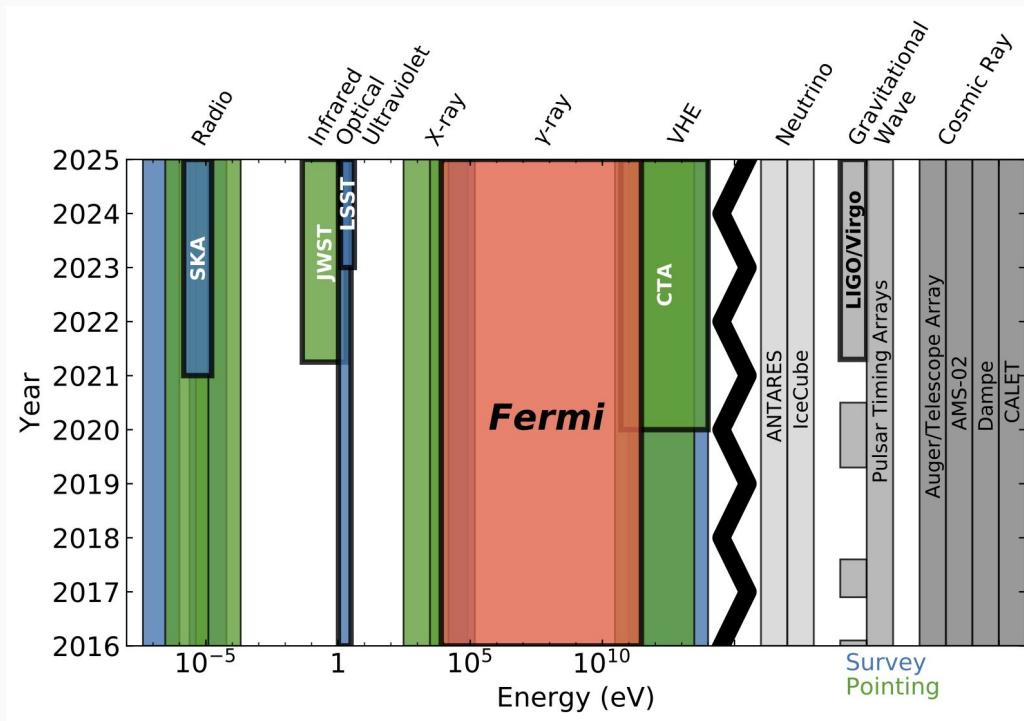
High energy gamma-rays explore nature's accelerators - **"Look where the energetic things are."** Natural connections to UHE cosmic-ray and neutrino astrophysics.

High energy photons often produced in a different process to the lower energy emission providing an **independent handle on the physical conditions.**



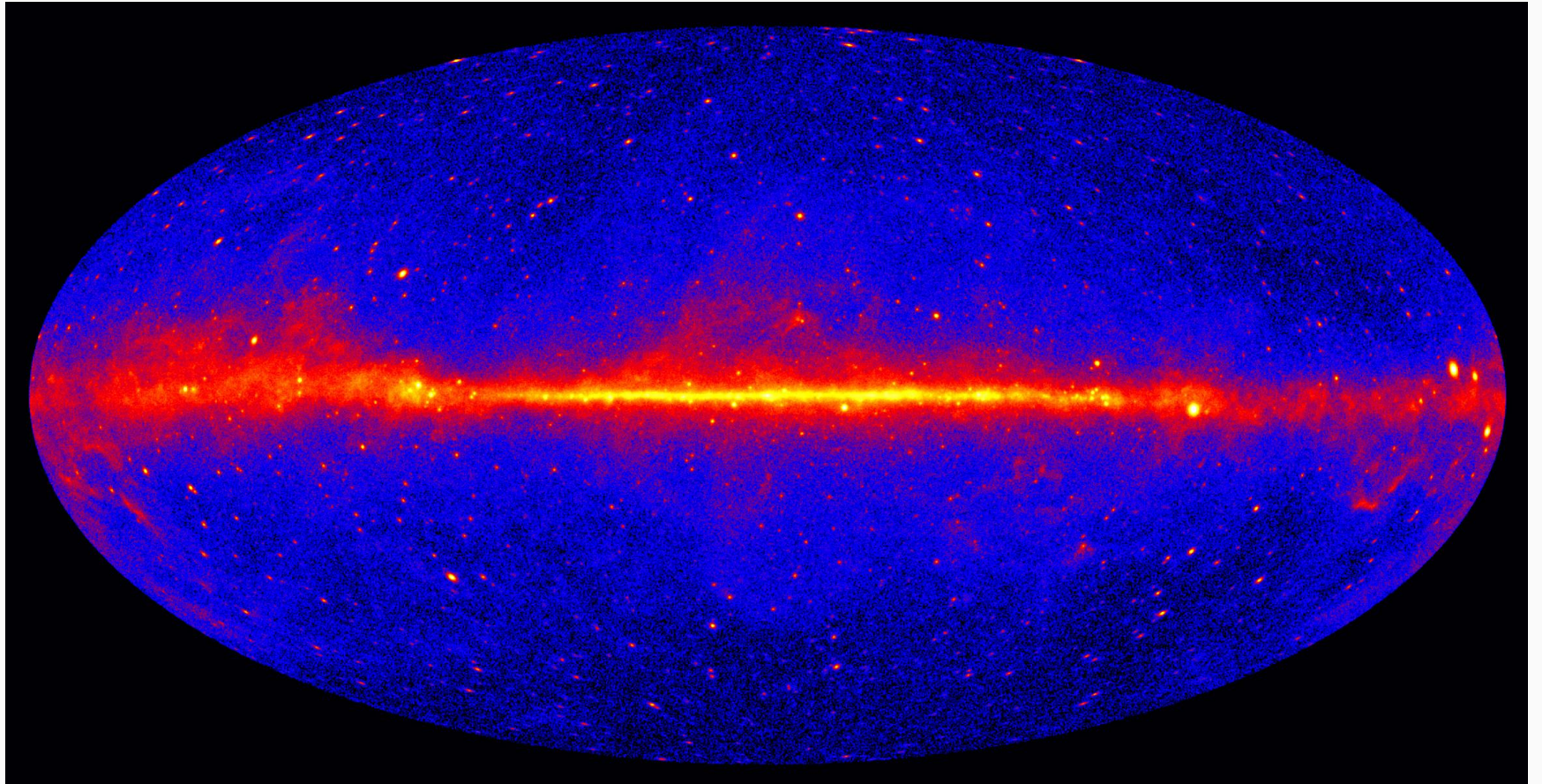
High energy gamma-rays can be attenuated by pair-production with lower energy photons. Probe conditions in emission regions (gammas need to get out). Explore the optical/UV diffuse background.

Fermi in Context

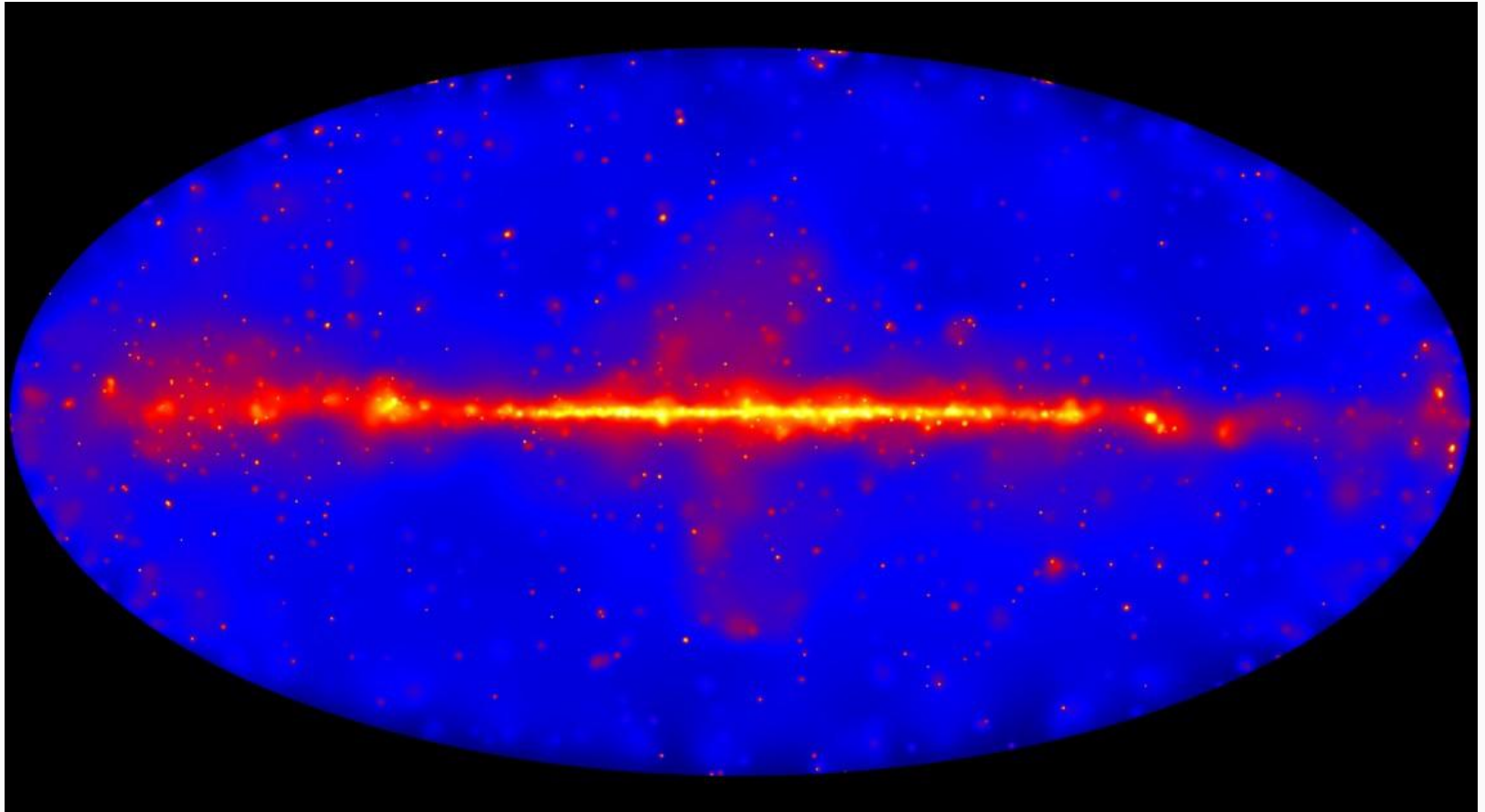


Fermi is the only mission in its waveband for the foreseeable future!
New multiwavelength-multimessenger opportunities have opened up.

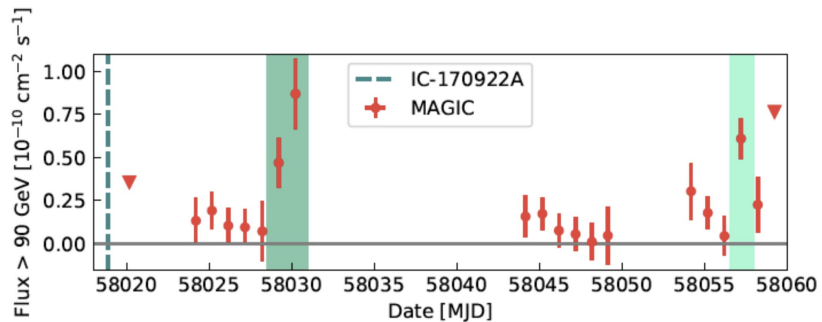
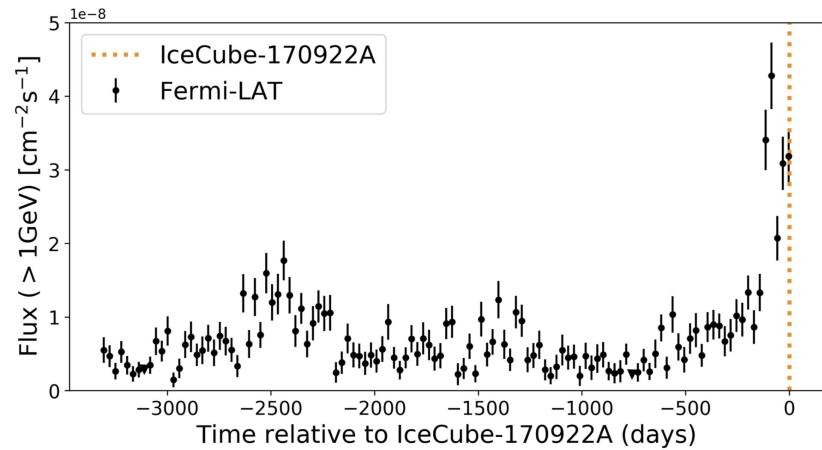
The Sky above 1GeV: >5000 Sources



The Sky above 50 GeV: > 250 Sources



Multimessenger Astrophysics: TXS 0506+056



Chance Coincidence? Pre-trials 4.1σ , post 3.0σ

Fermi-LAT

Modular design with 3 subsystems. Calorimeter and Tracker organized in 4 modules

Public Data Release:

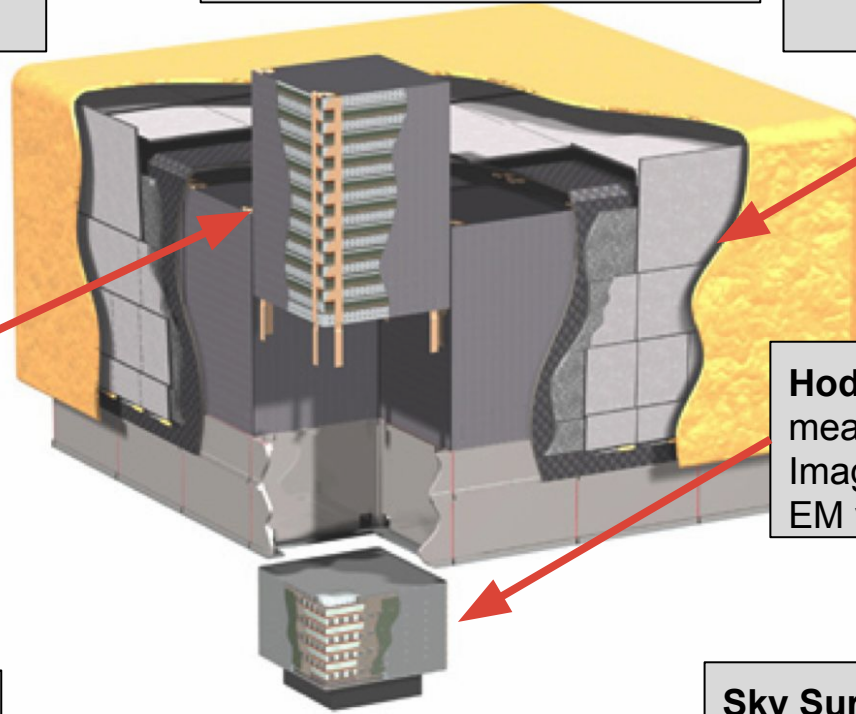
All γ -ray data made public within 24 hours (usually less)

Anti-Coincidence Detector:

Charged particle separation

Si-Strip Tracker:

convert $\gamma \rightarrow e^+e^-$
reconstruct g direction
EM v. hadron separation



Hodoscopic CsI Calorimeter:

measure γ energy
Image EM shower
EM v. hadron separation

Trigger and Filter:

Reduce data rate from
 $\sim 10\text{kHz}$ to 300 - 500 Hz

Sky Survey:

With 2.5 sr Field-of-View LAT
sees the sky every 3 hours

But why is it like this?

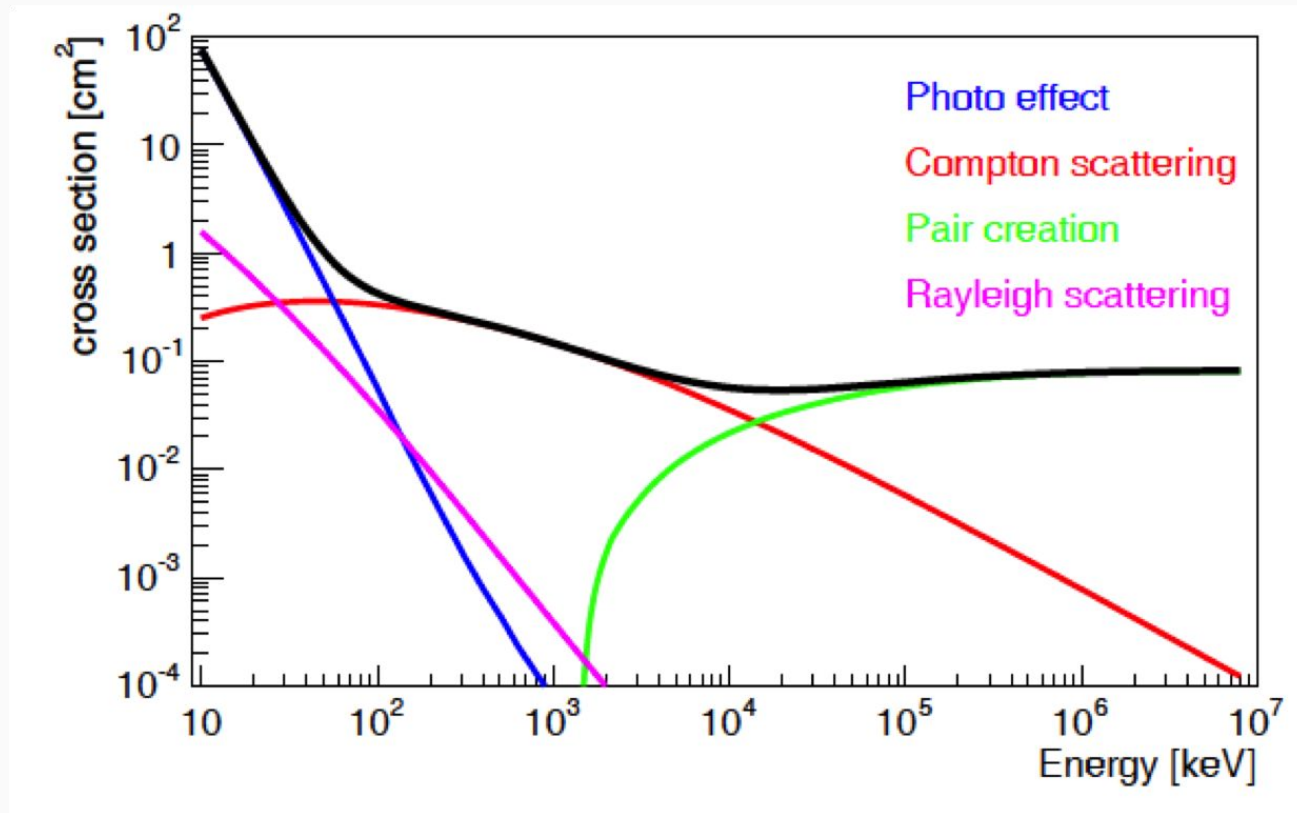
With any instrument you build, you have to make choices about the design. You tune your instrument for things like **energy resolution**, **localization accuracy**, **flux sensitivity**, and so on.

However, when you build an instrument for flight, there are many other technical limitations you have to take into consideration.

- Mass and spatial dimensions of the observatory is constrained to fit within the launch vehicle/rocket
 - Huge leap in cost if you need to jump to a larger rocket
- Power consumption is limited
 - Need low power electronics
- Data rate is limited by downlink bandwidth to the ground
 - Need efficient onboard filtering and data compression



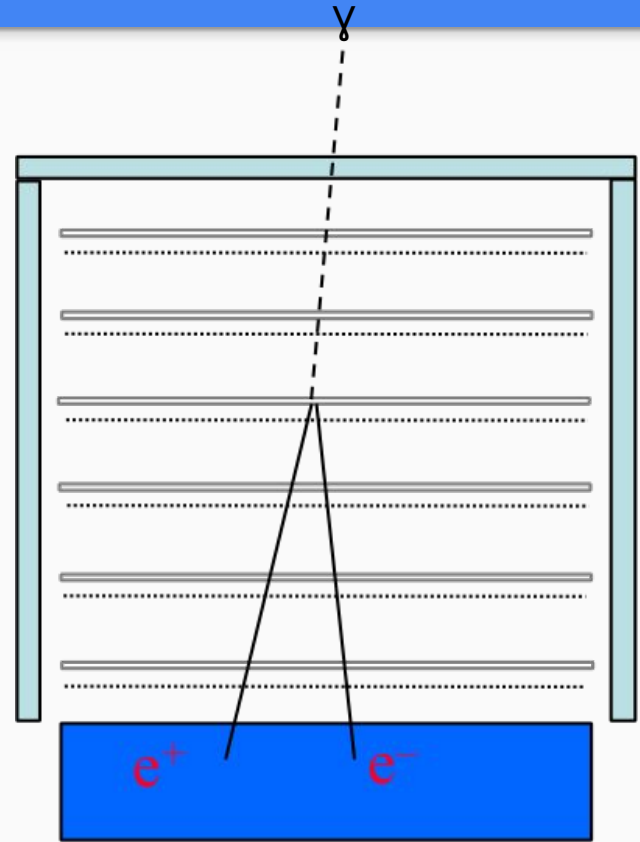
We're interested in high energy gamma-rays



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

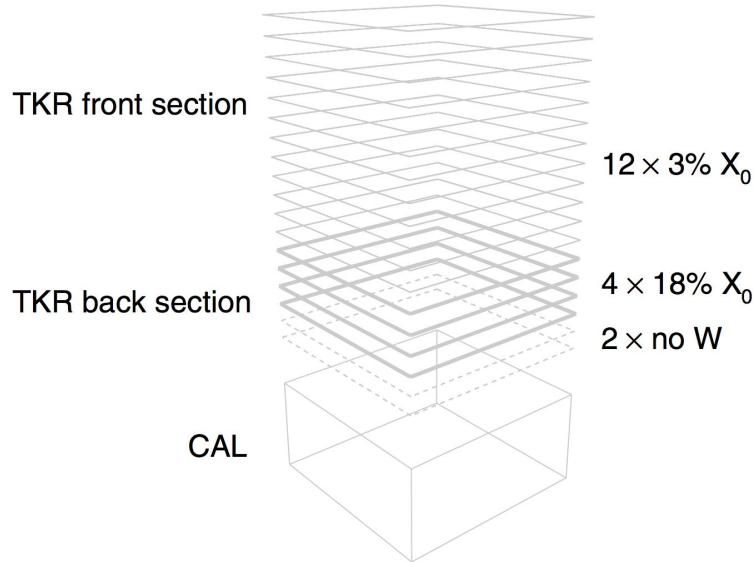
So we build a pair production telescope: Principle of Operation

- Tungsten foils in the tracker induce **conversions** of gamma rays to e^+/e^- pairs
- Interleaved Si Layers record hits left by the e^+/e^- pair as it passes through the tracker and measure the particle **trajectory**
- Calorimeter measures the γ -ray **energy** from the amount of scintillation light produced by the electromagnetic shower
- Anticoincidence detector provides a **veto** against charged particles which enter the LAT



Silicon Tracker (TKR)

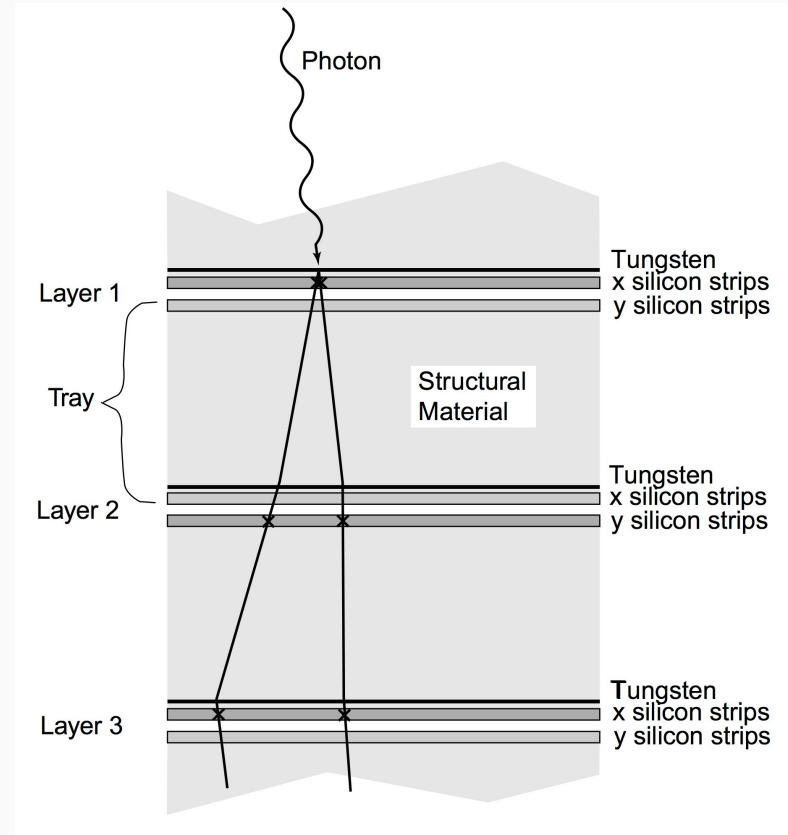
Tracker+CAL Tower

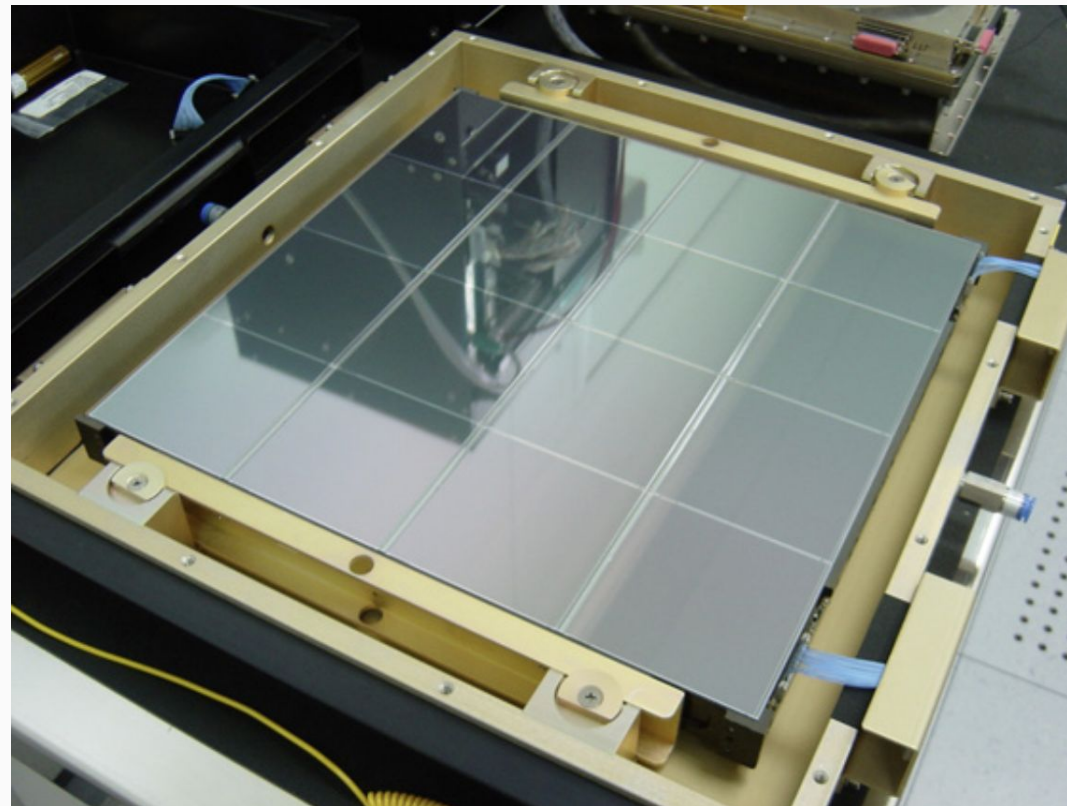


- Silicon tracker is the primary subsystem for **direction** reconstruction
- Tracker is organized in 4 identical towers
- Each tower contains 18 bi-layers, (x,y planes) with silicon strip detectors (SSDs) of thickness $400\ \mu\text{m}$ and pitch $256\ \mu\text{m}$
- Silicon layers are divided into **Front** and **Back** sections by thickness of associated conversion foils
 - Front: 12 Layers thin ($0.03\ X_0$) Tungsten
 - Back: 4 Layers thick ($0.12\ X_0$) Tungsten
 - 2 Layers no Tungsten

Talk about this in a bit

- Probability of gamma-ray conversion within the detector is proportional to material **radiation length (X_0)** – most γ rays convert in tungsten foils (which have high X_0 relative to other components of the LAT)
- The e^+/e^- pair produces hits in X/Y SSDs below each converter which can be used to reconstruct a 3-D coordinate (cluster) for that particle
- Using clusters from adjacent planes we can reconstruct a particle trajectory
- SSDs in the LAT tracker are extremely efficient ($\sim 99.9\%$) and have very low noise ($\sim 10^{-6}$ noise occupancy)





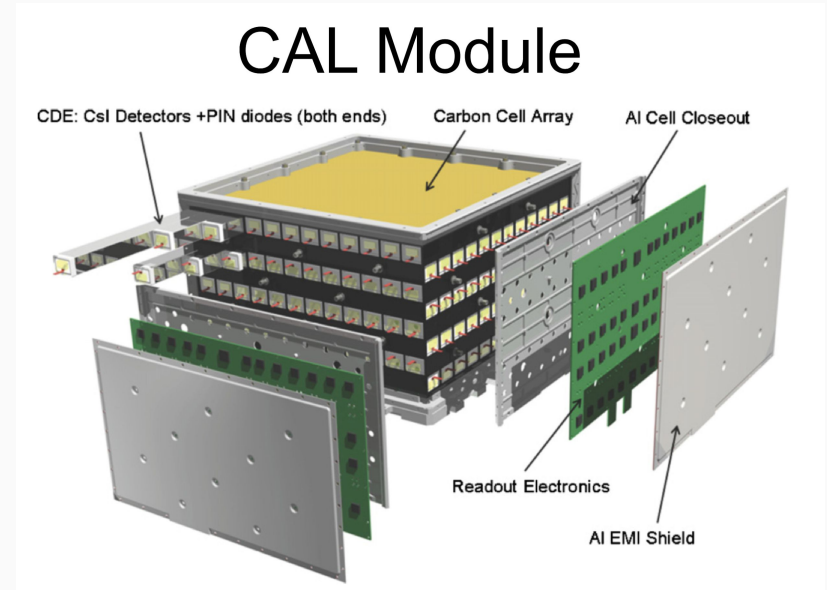
SSD Plane

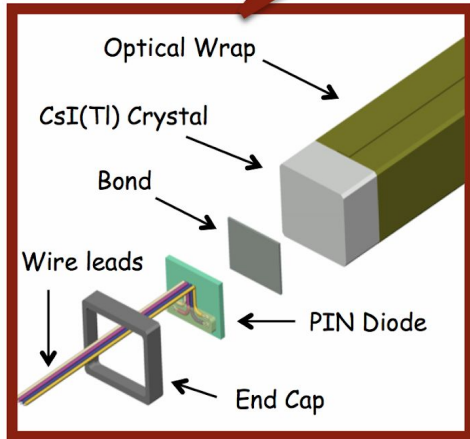
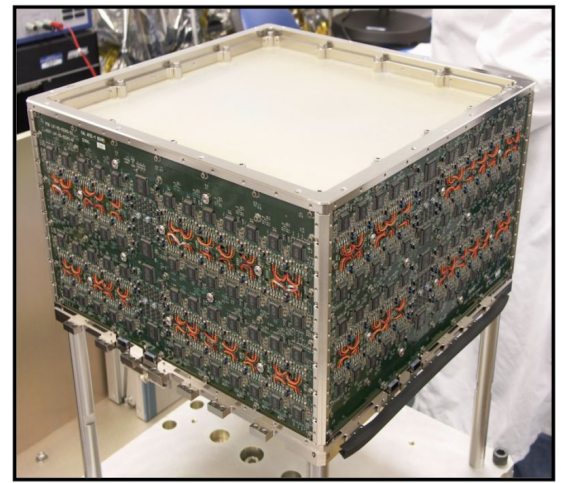
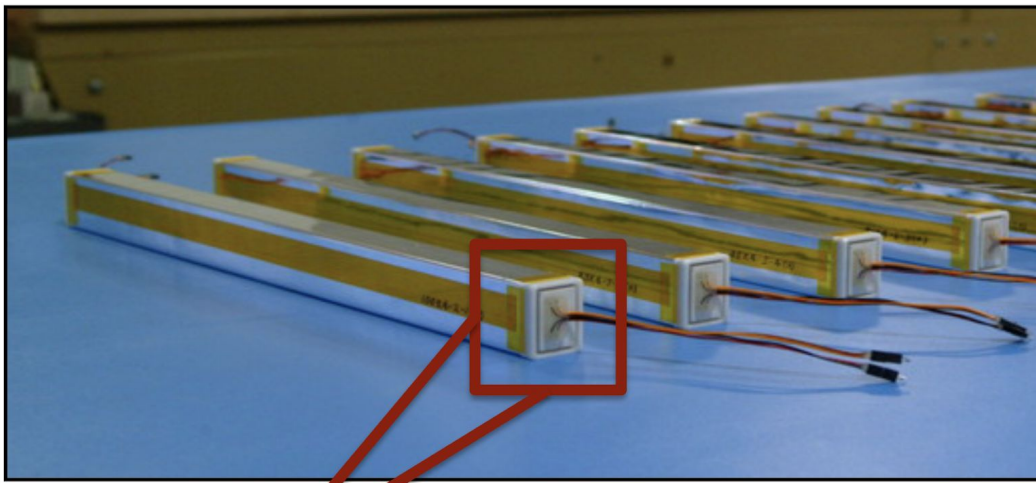
Tracker Tower

Csl Calorimeter (CAL)

Calorimeter

- Calorimeter is the primary subsystem for **energy reconstruction**
- Total radiation length of $8.6 X_0$ on-axis (versus $1.5 X_0$ for tracker)
 - Large radiation length needed to **induce an electromagnetic shower**
 - At high energies many showers are still not fully contained
- Each CAL module is composed of segmented CsI crystals arranged in orthogonal layers
- Relativistic charged particles produce scintillation light in the CAL crystals which is collected by PIN diodes at either end





Basic detector elements are CsI crystals

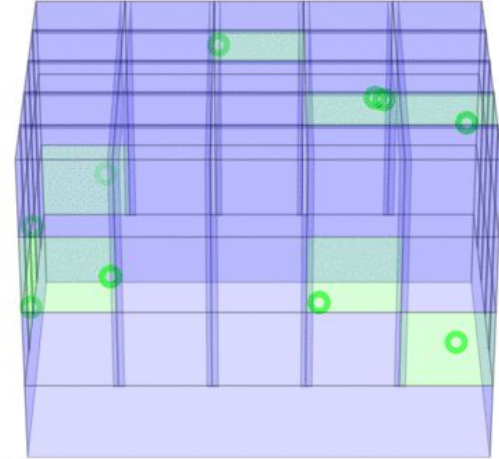
Each CAL module contains 8 layers of 12 crystals arranged in alternating orthogonal layers (hodoscopic)

Light readout at both ends, provides measure of longitudinal position to \sim cm from light ratio

- In addition to measuring shower energy the LAT Calorimeter also has an **imaging capability**
- Asymmetry of light readout at crystal ends can be used to reconstruct a 3-D coordinate for the crystal energy deposition – can be used to build a **3-D image of the EM shower**
- CAL imaging capability is important for many aspects of event reconstruction
 - Major axis of CAL shower provides a seed direction for track reconstruction in the TKR
 - Helps in evaluation of leakage correction for energy reconstruction
 - Consistency between track and CAL directions – very important parameter for background rejection
 - Shower Topology – another useful background rejection parameter; EM showers are generally smoother and more confined along the particle trajectory than hadronic showers

Anti-Coincidence Detector (ACD)

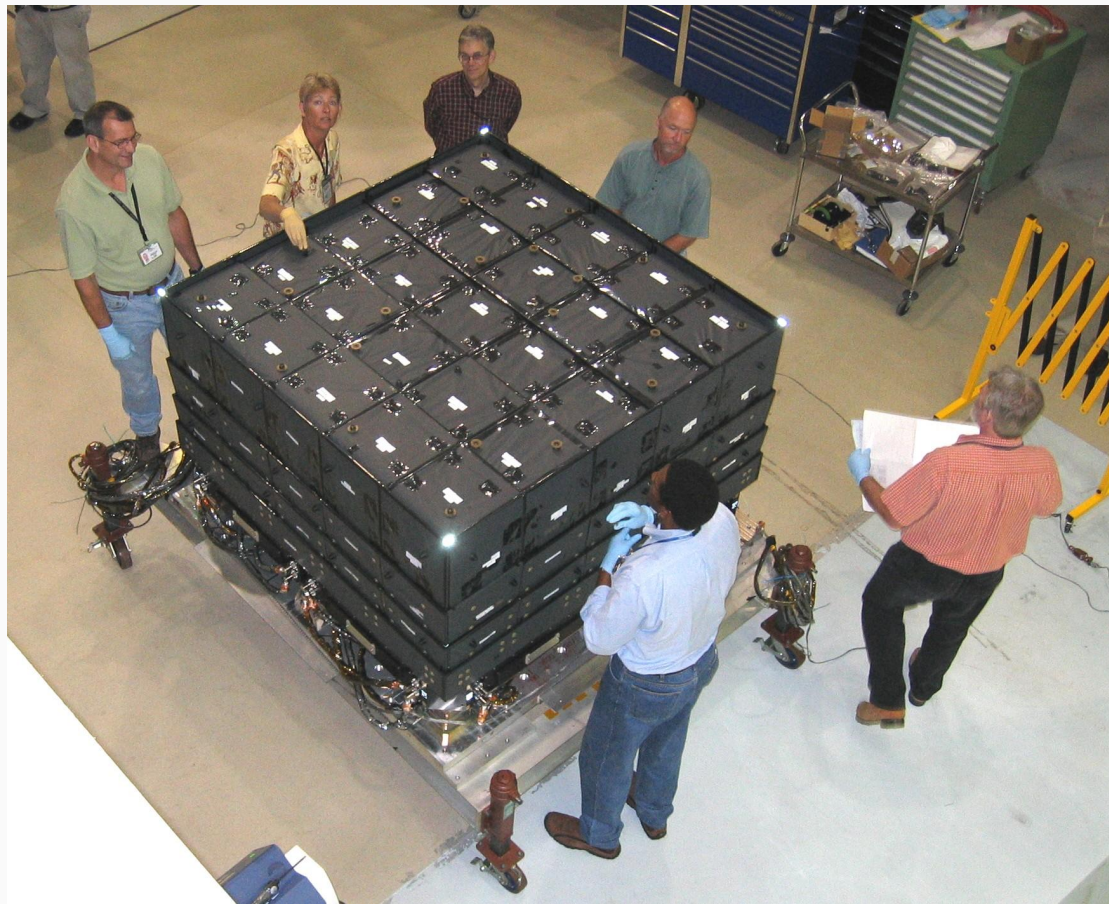
- Primary subsystem for rejection of charged cosmic rays
 - Veto at hardware-level for trigger and onboard filter
 - ACD information also used in offline reconstruction to identify CR events
- Cosmic-ray shield around the four sides and top of the LAT
 - 89 plastic scintillating tiles
 - 8 ribbons to cover remaining gaps
- Segmented design minimizes self-veto effect -- shower backslash from the CAL can be distinguished from genuine cosmic-ray events
- Very high detection efficiency ($\sim 99.97\%$)



Elapsed Time : 0.00s
No. of Gamma-rays : 0
No. of Cosmic-rays : 2

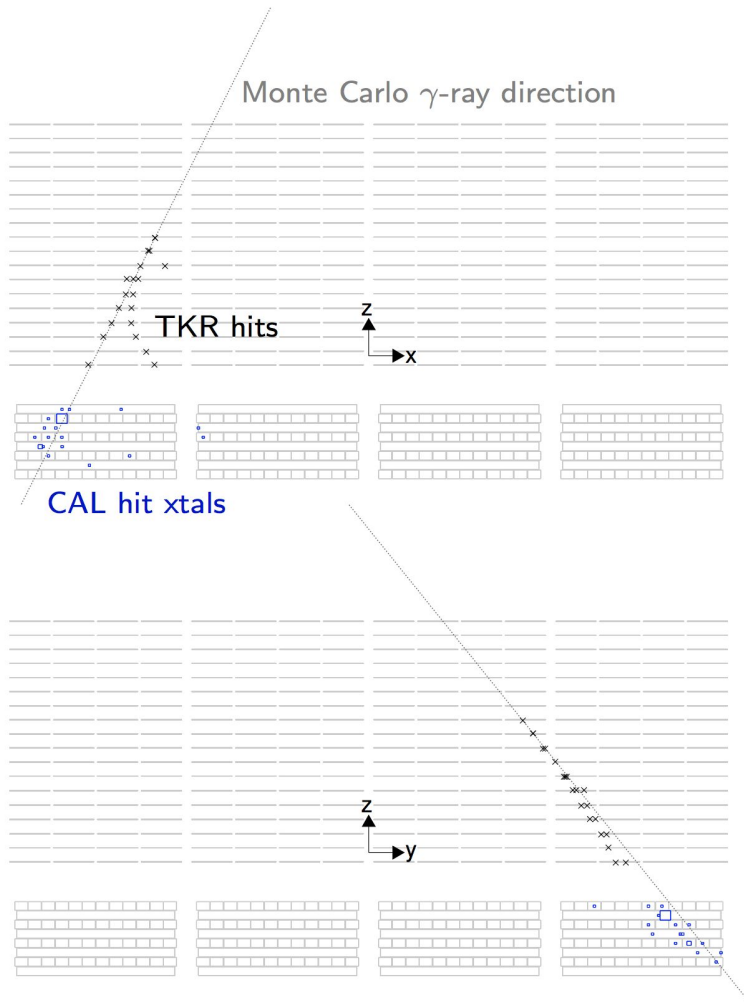


Curved ACD Tile



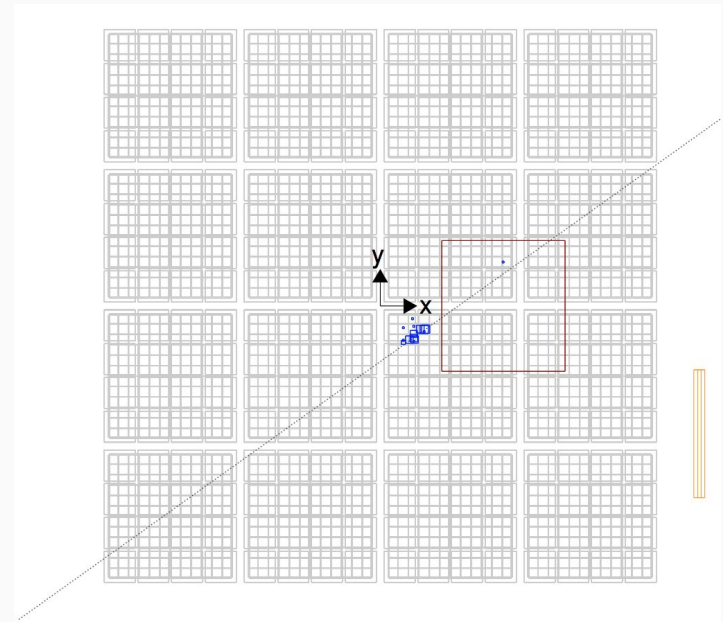
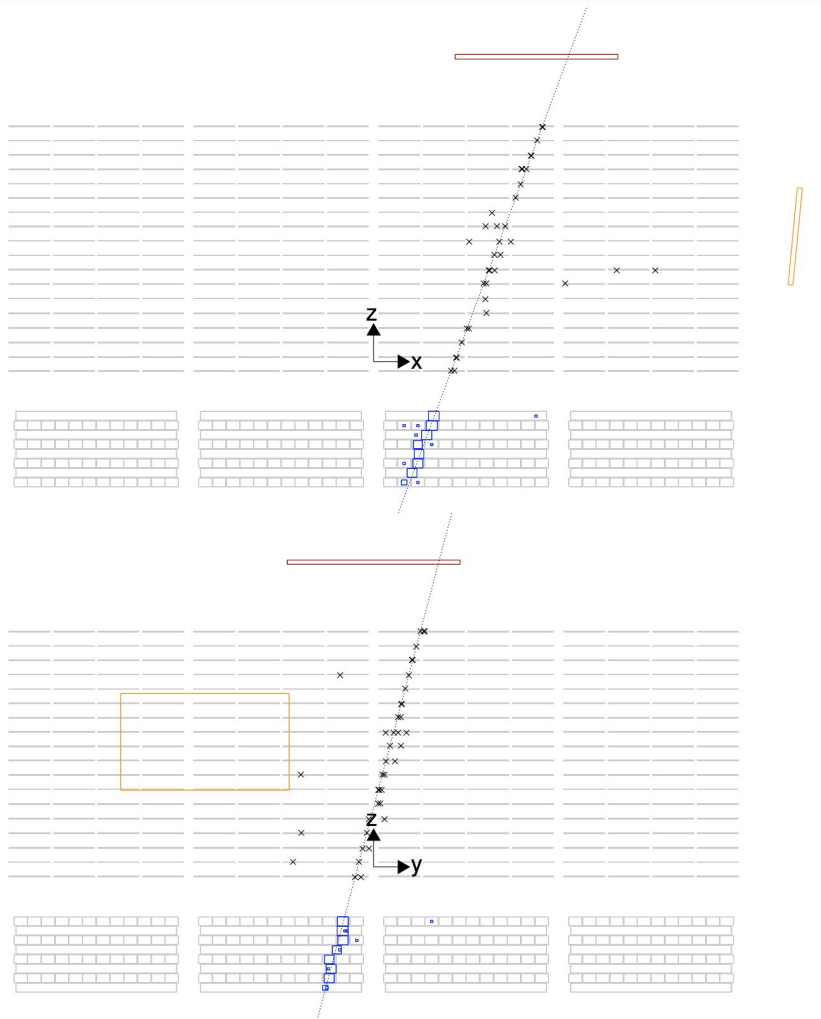
ACD from above

Events and Reconstruction



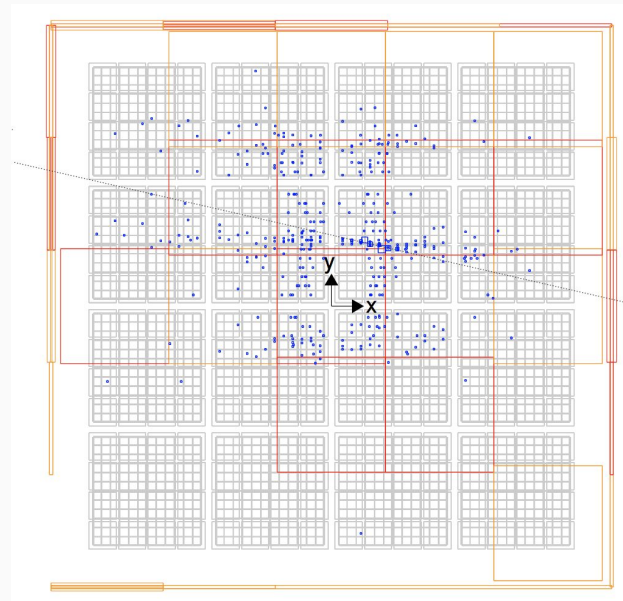
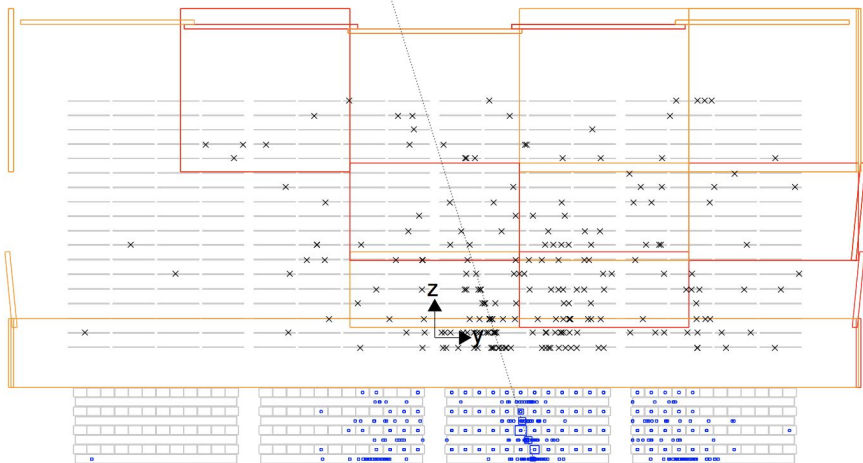
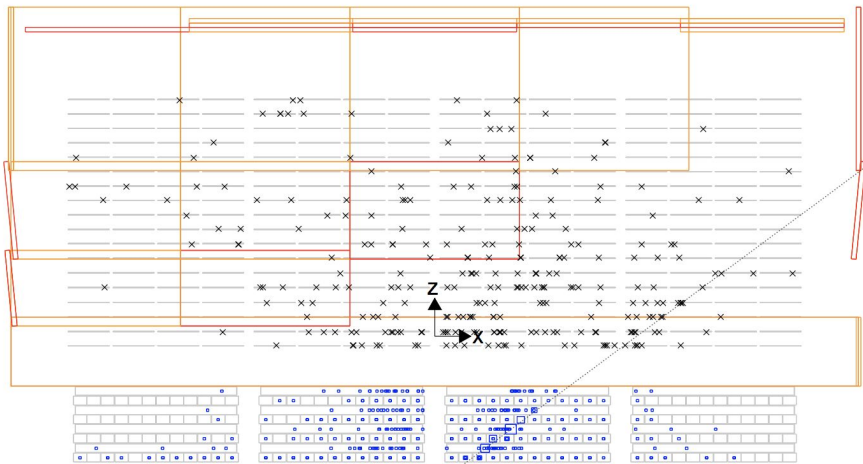
360 MeV γ -ray

- Two clear tracks
- Tracks point to energy deposits in the CAL
- No ACD hit tiles
- Tracks start in the middle of the instrument
- CAL energy deposits well localized



Background Event

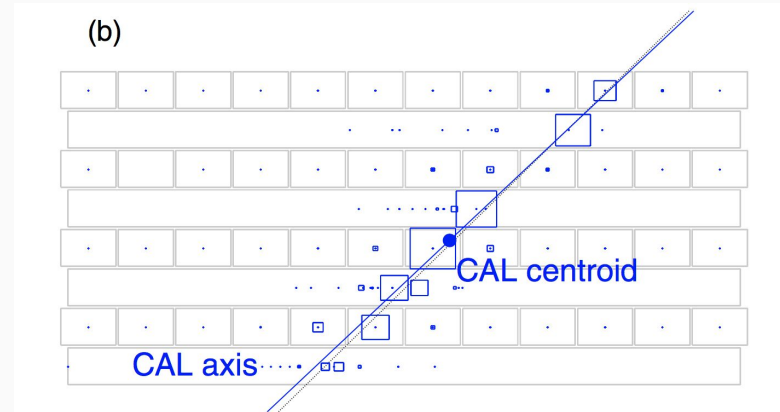
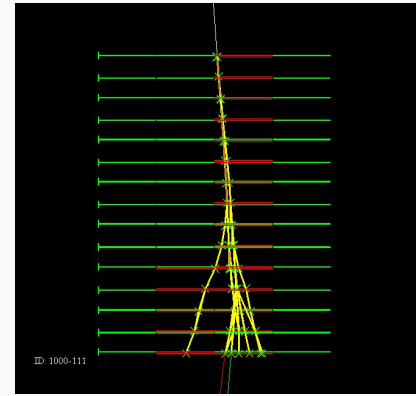
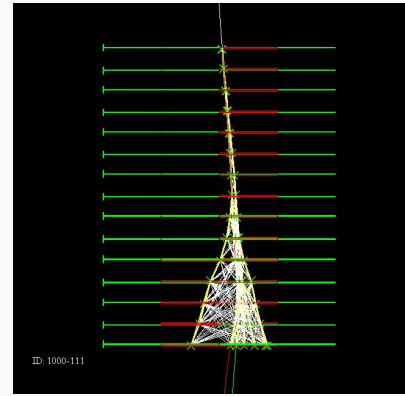
- One Track
- Track points to an ACD hit
- Track starts in edge of TKR
- No shower in CAL



540 GeV γ -ray

- Many many tracks (probably)
- Lots of CAL back-spash
- Tracks point everywhere
- Many hits in the ACD
- We can still get the energy and direction correct

- Tree based pattern recognition in the Tracker (in 3D!)
 - Basically finds x-y points and then connects them with links
 - Biases the direction to be similar to the direction determined from the CAL (reduces the number of options to a manageable number)
 - Builds the 'tree' from the top down
 - Direction is found by looking at the 'straightest branch' in the tree.
- Look for clusters of events in the CAL then performs a moments analysis on each cluster to determine its centroid, direction, and so on
- Look for a reason to veto the event in the ACD
 - Track extrapolation to an ACD hit?
 - Compare ACD energy to CAL energy (catches events where TKR direction is bad)

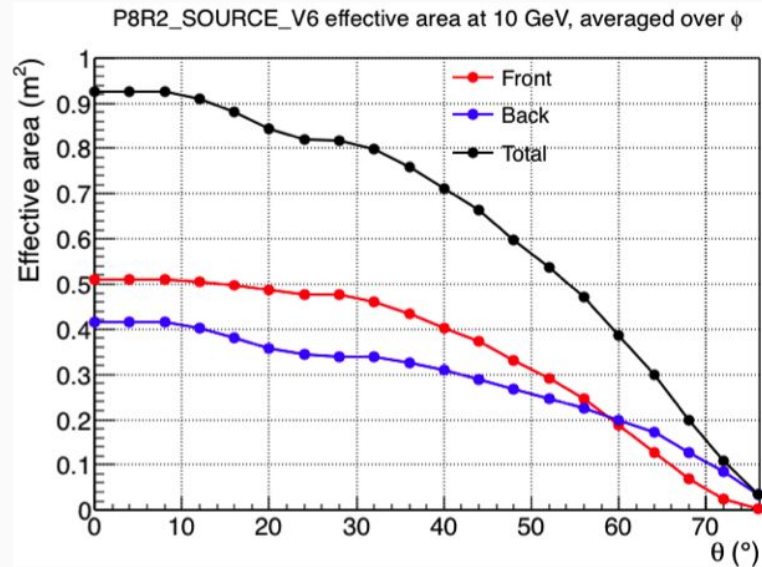
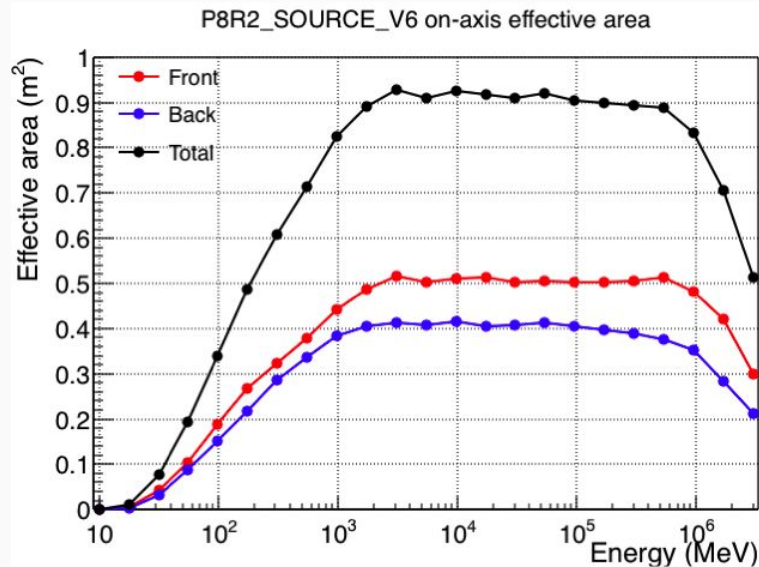


Detector

Properties: IRFs

Detector Properties

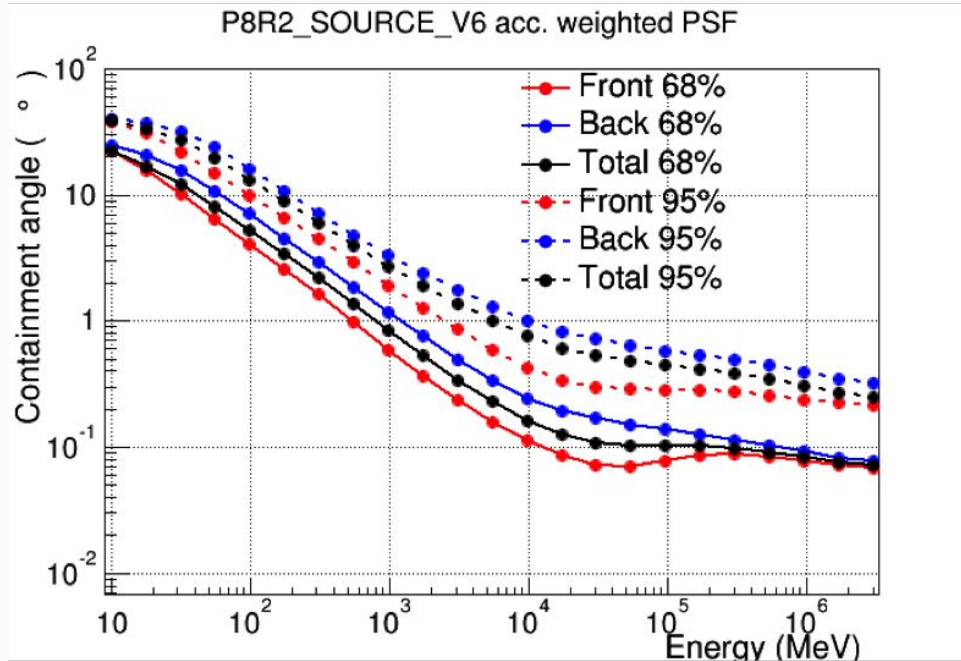
- Every Detector has specific measurable characteristics that include:
 - Angular Resolution: how well can we reconstruct a photon's direction.
 - Time Resolution: how well can we measure the photon's arrival time.
 - Energy Resolution: how well can we measure the energy of the photon.
 - Field of View: how much of the sky can we see at any one time.
 - Effective Area: how big and efficient is the detector.
 - Energy Range: what energies can we detect.



$A_{\text{eff}} = A_{\text{physical}} * \text{Efficiency}$

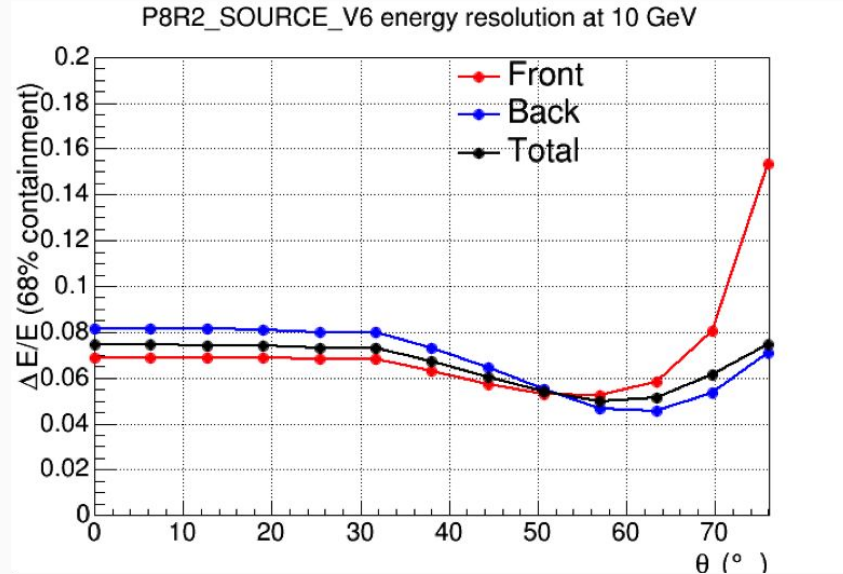
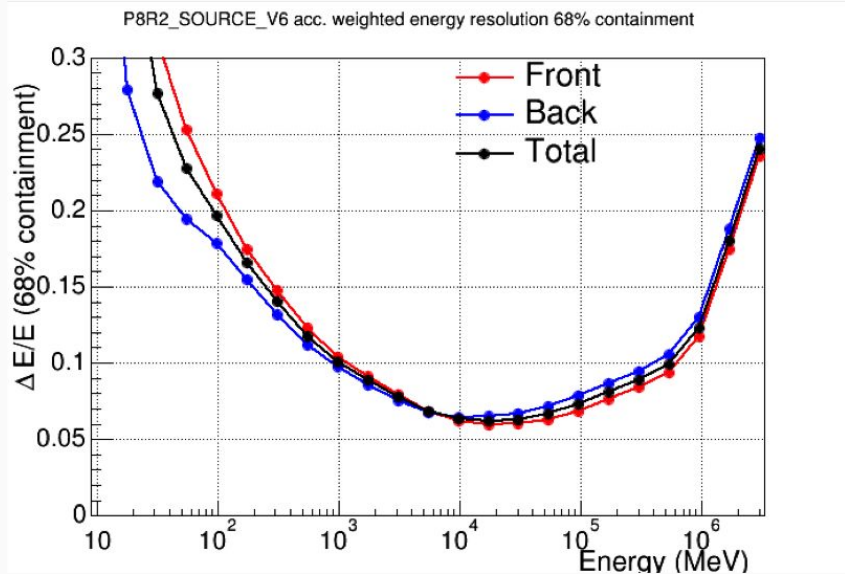
$\text{Flux} * A_{\text{eff}} = \text{number of detected gammas}$

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



Characterized by angular radius that contains the 68% and 95% of the gamma-rays

- Angular resolution rapidly improves with increasing energy.

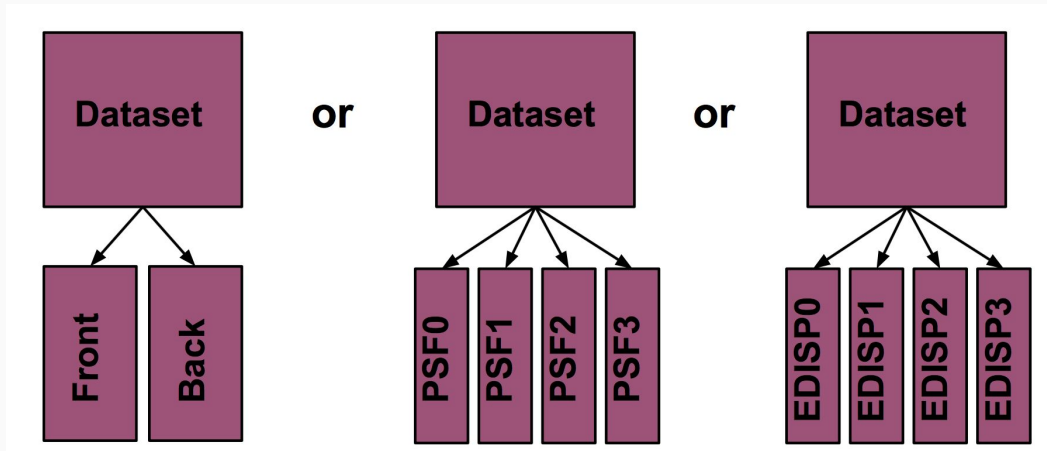


- Energy resolution improves for large theta at high energies

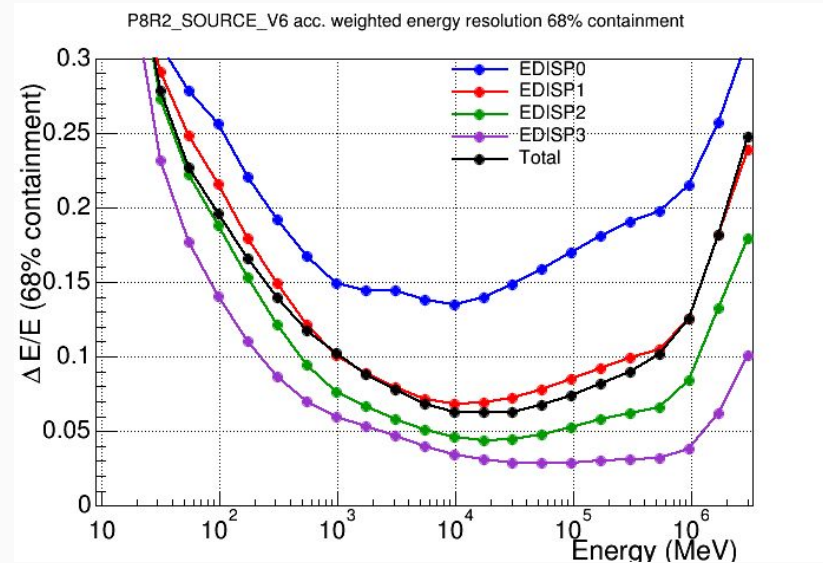
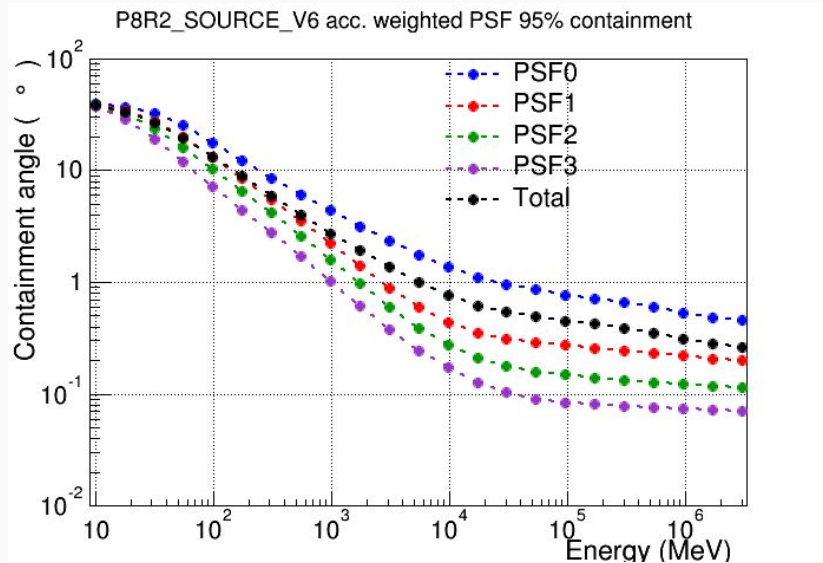
Event Types

Pass 8 introduces a generalization of the conversion type classification in the form of *event types*. In addition to the conversion type partition, Pass 8 defines two additional partitions:

- PSF event type: using an event-level quantity indicating the quality of the reconstructed direction, the data is divided into quartiles, from the lowest quality quartile (PSF0) to the best quality quartile (PSF3)
- EDISP event type: same as PSF except that the event-level quantity used to partition the data indicates the quality of the energy reconstruction.



The likelihood function can be generalized to take advantage of these types and pretty much **everyone** should be doing an event type analysis now (we'll show you how).



LAT Likelihood Analysis: Overview, Livetime, Exposure, and likelihood

See Fermi School for notebook

https://github.com/FermiSummerSchool/fermi-summer-school/tree/master/Likelihood_Analysis

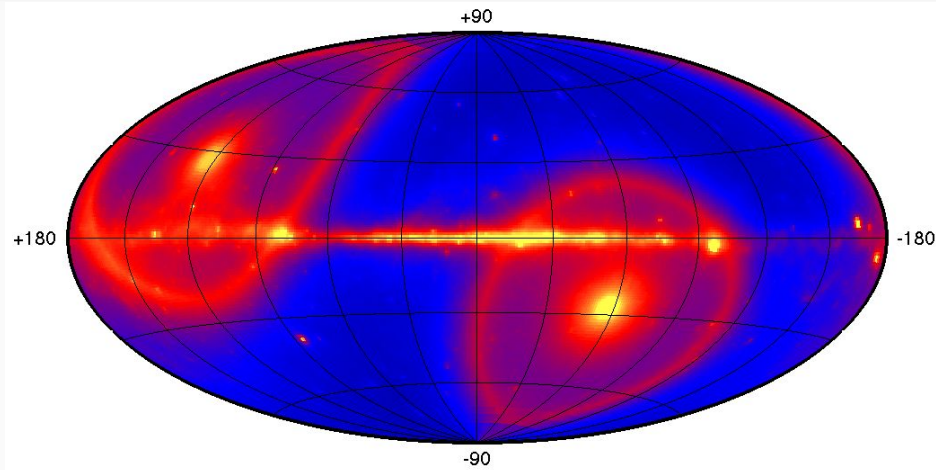
Analysis Goals and Methods

- Test for presence of a source, measure its position in the sky
- Extract fluxes of sources of interest. Measure flux vs. time (“lightcurve”) to test for variability.
- Measure spectra of sources
 - Parameters of fitted spectral type, e.g. index of power-law, energy of exponential cut-off, or “super”-exponential cutoff (pulsars)
 - Flux as function of energy (“flux in bands”)
- Maximum likelihood is framework/cookbook for estimation and hypothesis testing
 - To use, must produce accurate model of data (the rest is derived by following the cookbook)
 - Some portions of model are of interest to us
 - Others are not
 - Background sources
 - Observational response
 - Must be mindful of systematic errors

Maximum Likelihood in the LAT

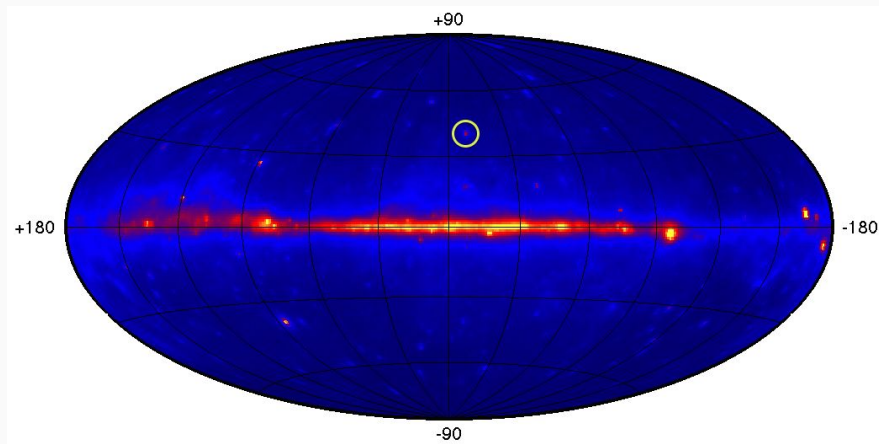
- MLE and hypothesis testing is implemented for Fermi LAT data using FermiTools.
- Data selection and binning into channels.
- Assists in producing of high-level sky model consisting of gamma-ray sources.
- Transforms sky model into low-level Poisson model for each channel (observational response).
- Estimation of parameters through optimization (“minimization”) using log-likelihood.

Data and Selection



Data Before Cuts (4.8 years)

- Data set that we would like to analyze (using ML).
- Or in fact, it is a simplification.. the energy and time dependence are not shown!



Apply Selection

- Zenith cut to remove photons from the Earth ($\angle Z_n < 90\text{deg}$)
- Photon class to select best reconstructed and lowest background (P8R2_Clean_V6)

Data Selection, Time Filtering, and Binning

gtselect

Data are already filtered when you get them from the FSSC

gtselect is used to do more filtering

inputs include a list of event files

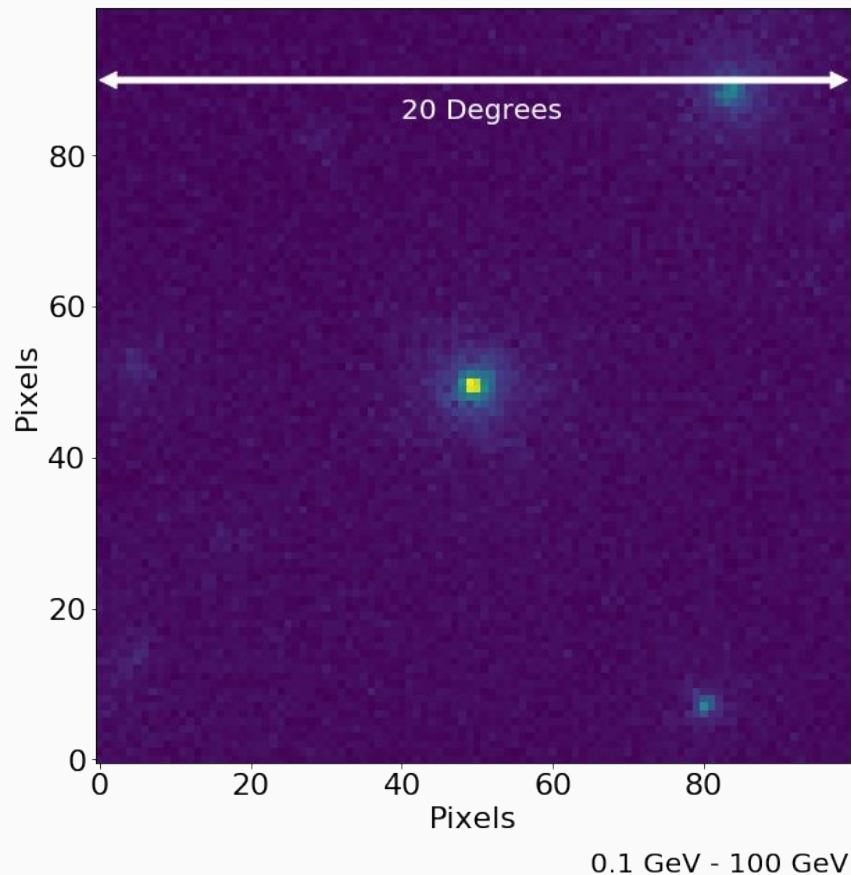
gtmaketime

This program marks times of bad data

Can also do complex filtering

gtbin

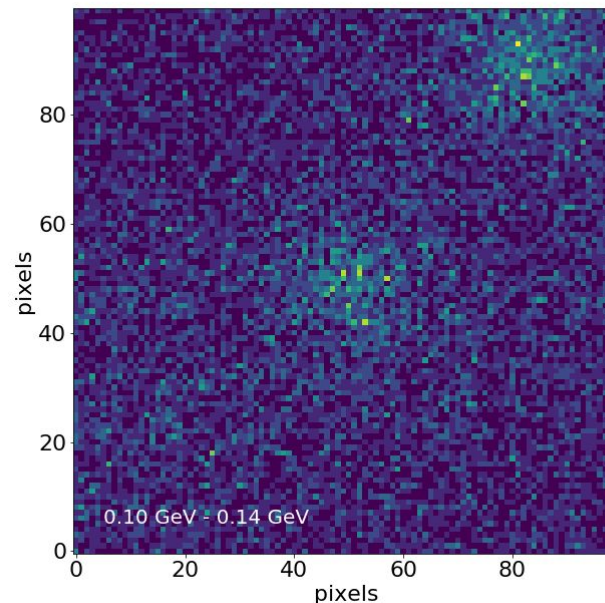
Used to make counts maps (pictures) or bin the data in time and/or energy.



Channels of Position and Energy

Binned Data

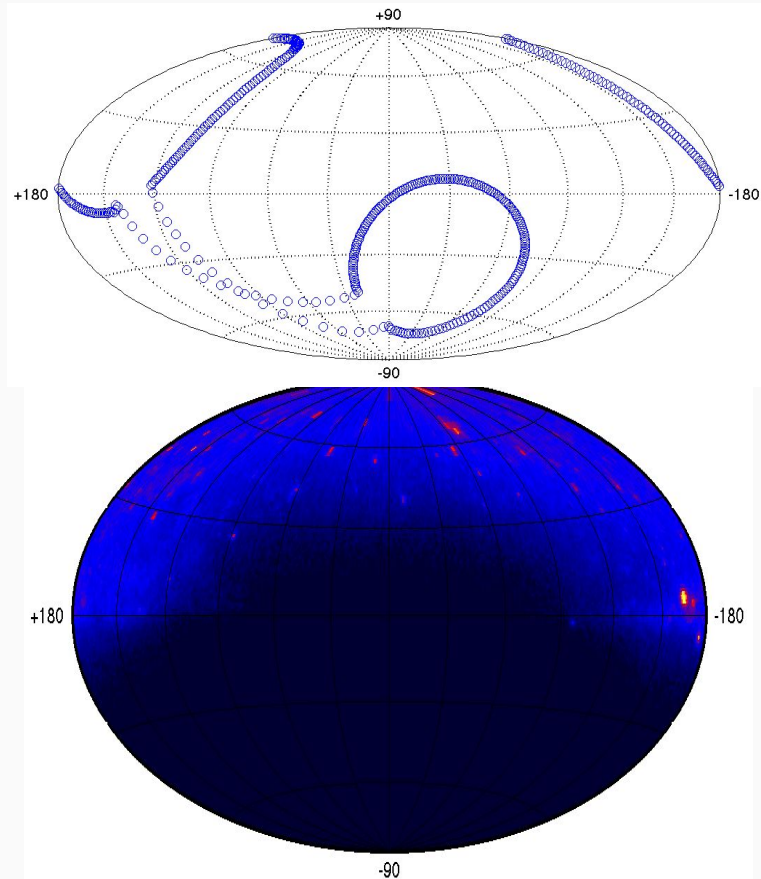
- Build a counts cube (counts map binned in energy)
- This is useful to see how our ROI changes with energy
- Analyze events in channels of position and energy...
 - ... as we are interested in spatial and energy dependence of sources
 - ... best sensitivity achieved by using all information possible (as long as it can be modeled accurately!)



At higher energies there are fewer photons,
At lower energies there are lots of photons,
Sources are most clearly detectable somewhere in the middle.

Calculating Livetime and Exposure: A Two Step Process

- **Livetime:** formally the time when the detector is available to collect data
 - For analysis, we additionally require good data quality and select to remove high background
 - The LAT has a large FoV with varying response: need to know when and where
- **Exposure:** for practical purposes, the number that converts counts to photon flux
 - Apply expected photon detection efficiency and angular resolution
 - Depends on the event selection
 - Depends on the direction of the photon relative to the instrument boresight and energy
- Modeling must also account for the “observing profile”.
- Rate of γ rays from source depends on its (constantly changing) position in the field of view of the LAT.

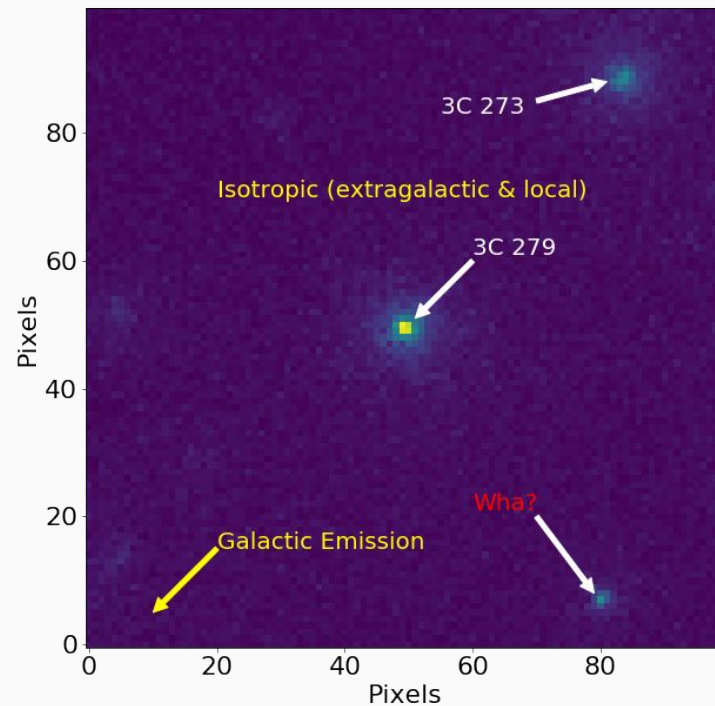


We Have:

- Observational response (“exposure”)
 - Observational profile
 - Instrument response functions (IRFs)

We Need

- Sky model
 - Spatial distribution of sources in ROI (point-like and extended sources)
 - Spectral model for each source



Likelihood

- We observed a photon from a location with a specific energy
- We assume a model:

$$S(E, \hat{p}) = \sum_i s_i(E) \delta(\hat{p} - \hat{p}_i) + S_G(E, \hat{p}) + S_{eg}(E, \hat{p}) + \sum_l S_l(E, \hat{p})$$

- The model is defined as
 - a summation over point sources,
 - the galactic and isotropic diffuse
 - and a summation over anything else.
- We bin these photons into channels of energy and position: (E_i, \hat{p}_i) of size: $\Delta E_i \Delta \hat{p}_i : n_i$
- We calculate the probability of that photon being detected assuming our model (Poissonian mean):

$$\begin{aligned} \lambda_i(S) &= \Delta E_i \Delta \hat{p}_i \int dE \int_{ROI+} d\hat{p} S(E, \hat{p}) R(E_i, \hat{p}_i, E, \hat{p}) \\ &= \Delta E_i \Delta \hat{p}_i \int_{ROI+} d\hat{p} S(E_i, \hat{p}) R(E_i, \hat{p}_i, \hat{p}) \end{aligned}$$

Likelihood

- Then we calculate the total number of predicted counts assuming our model:

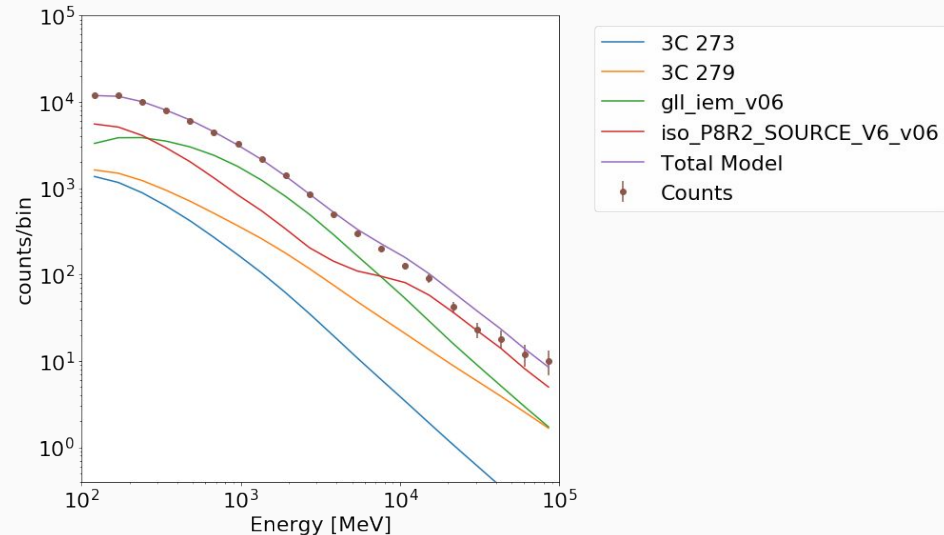
$$N_{pred} = \sum_i \lambda_i(S)$$

- We can precompute some of the values in the integral. Namely $S(E_i, \hat{p})R(E_i, \hat{p}_i, \hat{p})$ in such a way that we can still adjust it as needed (so compute generic source templates convolved with the response - the Source Map).
- The Log likelihood is

$$\ln \mathcal{L}(S) = \sum_{i \in \text{Bins}} n_i \ln \lambda_i(S) - N_{pred}(S)$$

- We adjust the model (S) until this is maximized (or minimized)
- And we calculate the TS

$$TS = -2 \log \frac{L_{max,0}}{L_{max,1}}$$



Summary: (Fermi Summer School 2019)



Deadline was March 15,
but you can still apply.

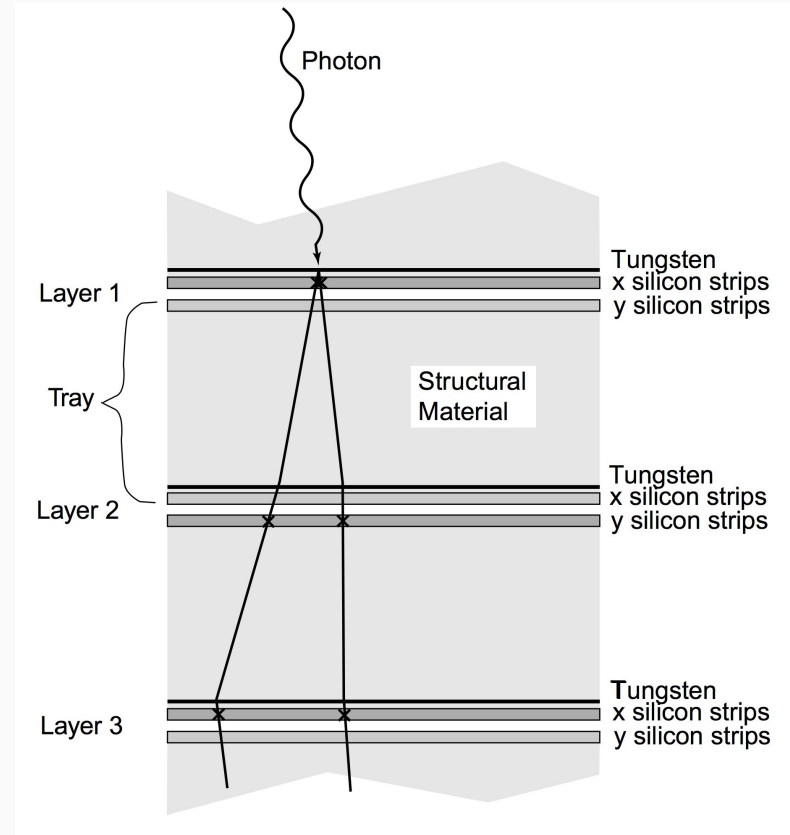
Two weeks on the beach learning
Gamma-ray Astrophysics.

What's not to love about that?



<https://fermi.gsfc.nasa.gov/science/mtgs/summerschool/2019/>

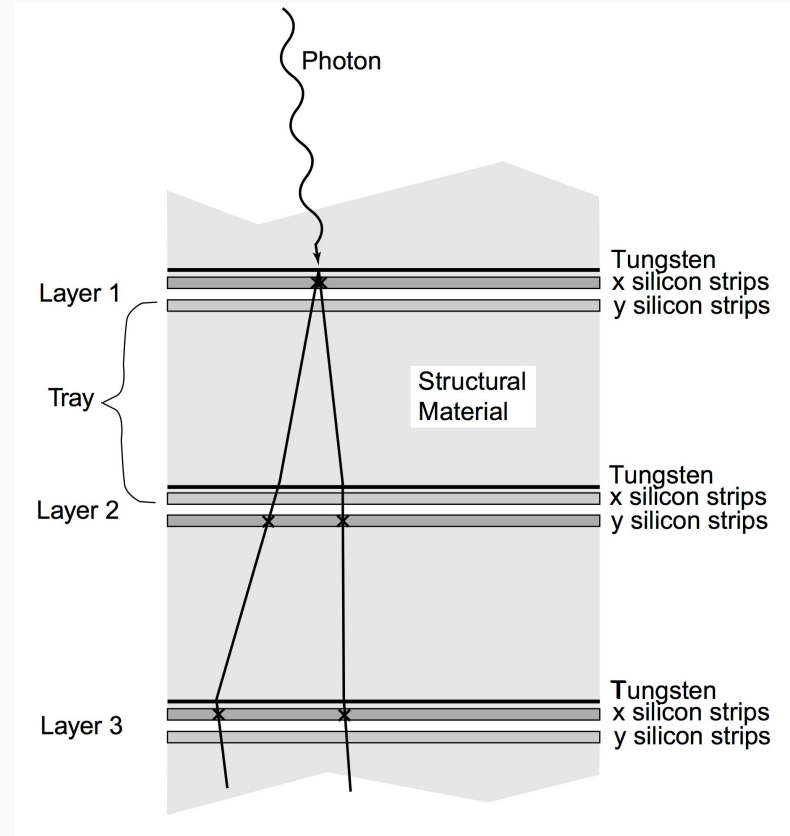
- Tracker angular resolution is limited by **multiple scattering** at low energies and **strip pitch** at high energies
- Tracker design is a tradeoff between FoV, PSF, and effective area
 - Large X_0 provides high conversion efficiency (effective area) but worse PSF
 - Larger spacing between tracker planes improves PSF but decreases FoV
- Front and Back sections provide a balance between conversion efficiency and good PSF
 - Back PSF is $\sim 2x$ worse than Front PSF due to larger radiator thickness but provides the same conversion efficiency in only 4 layers



- Converter Thickness:
 - We need a reasonable chance for conversion
 - $N(x) = N_0 e^{-\mu x}$
 - $\mu \sim 9/(7X_0)$
 - $X_0 = \text{radiation length} \sim 1/Z^2$
 - X/X_0 is the number of radiation lengths

Could just have a really thick converter but need to balance this with multiple scattering in the converter.

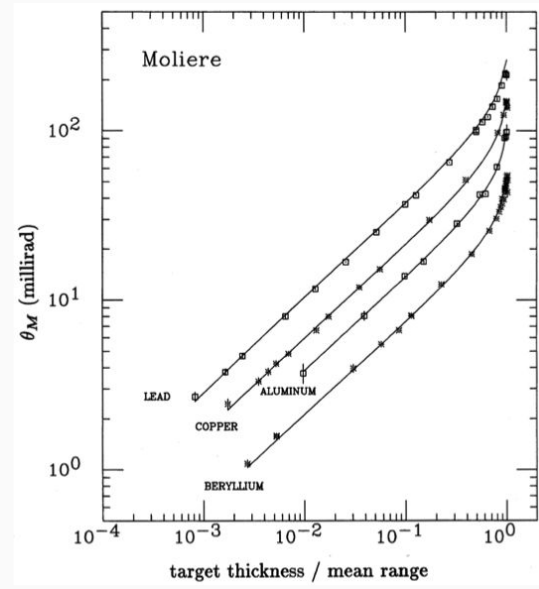
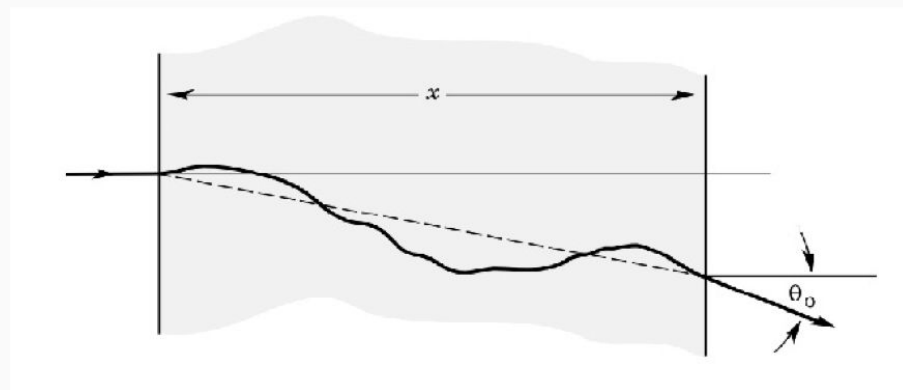
Anything that happens in the converter stays in the converter (i.e. we don't know about it).

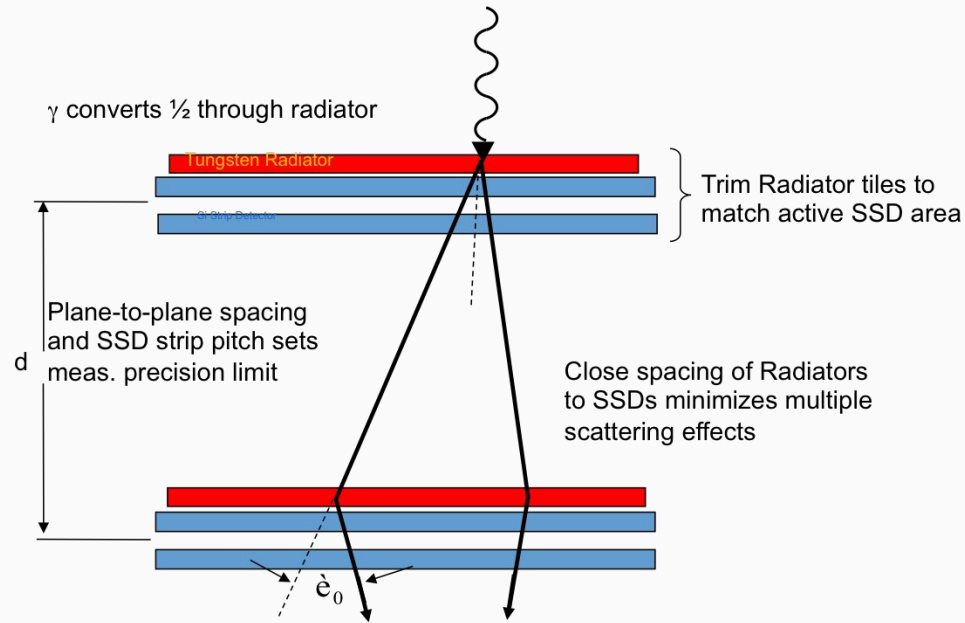


- Multiple Scattering: e^+/e^- undergo repeated elastic Coulomb scattering with nuclei
 - Energy transfer is negligible but each small deviation adds up.
- We can approximate multiple scattering by

$$\theta_{MS} = \frac{13.6}{E_\gamma/2} \sqrt{X} (1 + .038 \ln(X))$$

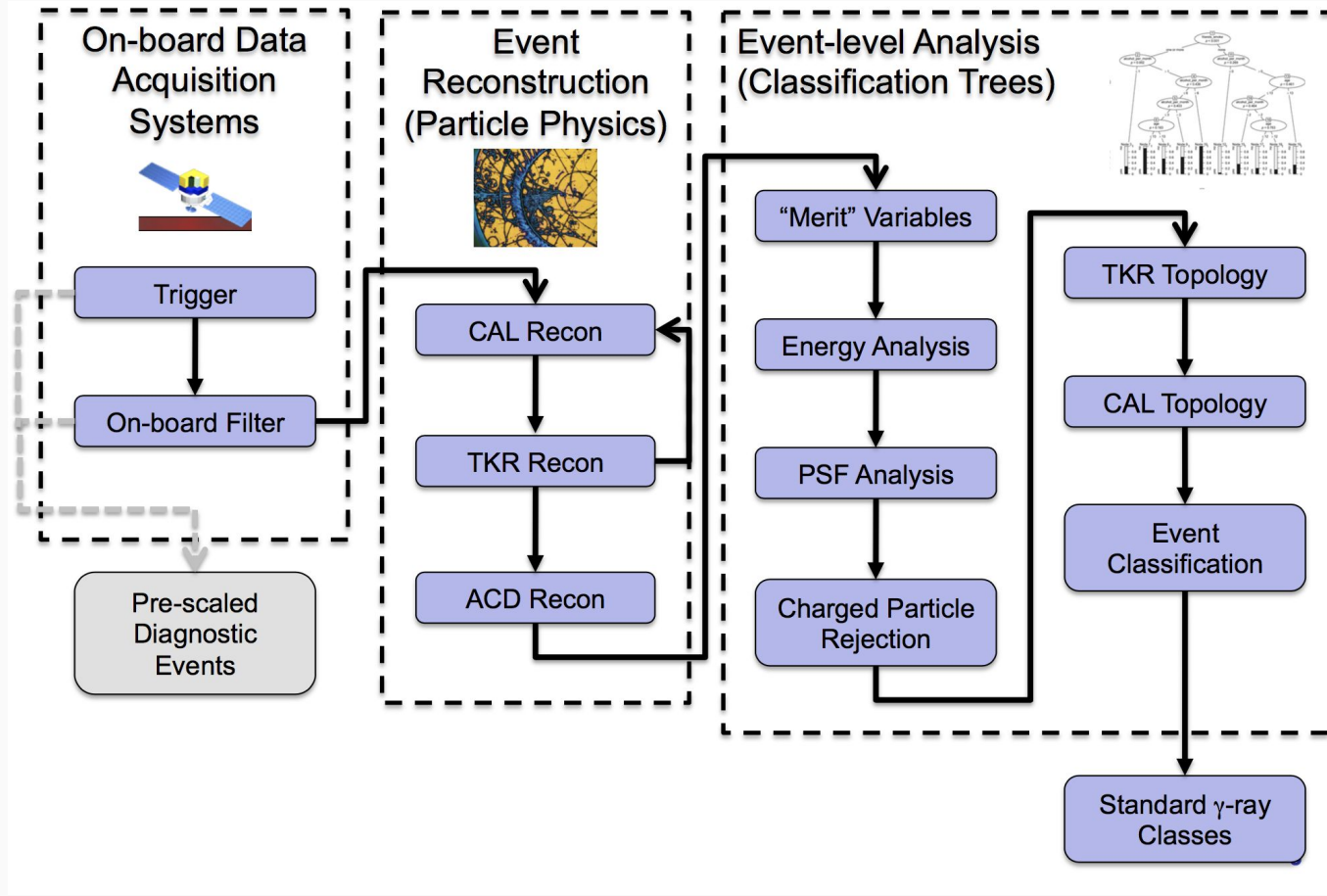
θ_{MS} in mrad, E_γ in GeV, X in rad. Len.





Position Resolution (σ) = strip pitch / $\sqrt{12}$

$$\text{LAT: } \theta_{\text{det}} = \sqrt{2} * \sigma_{\text{ssd}} / d = 228 \mu\text{m} / (32.9\text{mm} * \sqrt{6}) = 2.8 \text{ mrad} = 0.16^\circ$$



CAL Reconstruction:

Sum signals in CAL, analyze topology, correct for energy lost in gaps, out sides and in TKR pre-shower

**TKR Reconstruction:**

Find tracks & vertices. If possible use CAL shower axis as a directional seed

**ACD Reconstruction:**

Project tracks to ACD, look for reasons to reject event.

Reconstruction:

Developed with simulated data.
Simulations validated in beamtests.

Classification Analysis:

Use combined subsystem information to get best estimates of direction, energy.
Reject particle background and select highest quality events

**Photon Samples and IRFs:**

Build descriptions of Instrument Response for each selection of events

Event Classification:

Developed with simulated + flight data
Validated primarily with flight data

You have to simulate *everything*

- Active material (Si, Csl, Plastic)
- Inactive material
 - Tungsten
 - Carbon Fiber
 - Glue
 - Cables
 - Tape
 - Closeouts
 - Brackets
 - Alignment fixtures
 - Nuts, bolts,...



Direction Analysis:

Decides which direction solution (vertex or non-vertex, TKR or TKR + CAL) is best

Gives estimate of quality of direction estimate

P_{CORE} = "prob." that direction is within R68%

Energy Analysis

Decides which energy method (Parametric or Profile) is best

Gives estimate of quality of energy estimate

$P_{\text{BestEnergy}}$ = "prob." event is within P68%

Charged Particle Analysis

Reject charged particles using ACD,TKR,CAL

P_{CPFGAM} = "prob." event is a photon

Topology Analysis

Reject hadrons using TKR, CAL

$P_{\text{TKRGAM}}, P_{\text{CALGAM}}$ = "prob." event is a photon

Photon Analysis

Combine everything

P_{ALL} = "prob." that event is a photon

Photon Samples

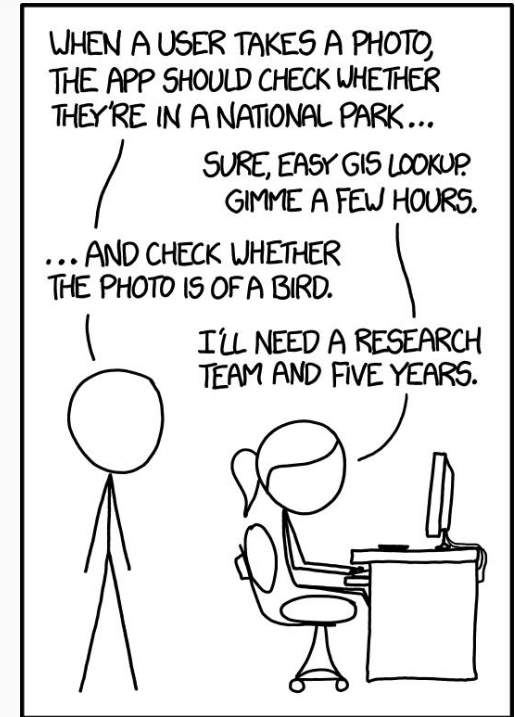
Apply cuts tuned to for particular samples

Might require good direction, energy recon in addition to high photon "prob."

The Perfect Tracker

- Infinitesimally thin converter -> minimize multiple scattering
- Infinitely large number of layers -> to allow 100% conversion efficiency
- Infinitesimally small strip pitch -> minimize intrinsic detector resolution

Unfortunately, this kind of instrument is unbuildable, so we have to make choices...



IN CS, IT CAN BE HARD TO EXPLAIN THE DIFFERENCE BETWEEN THE EASY AND THE VIRTUALLY IMPOSSIBLE.

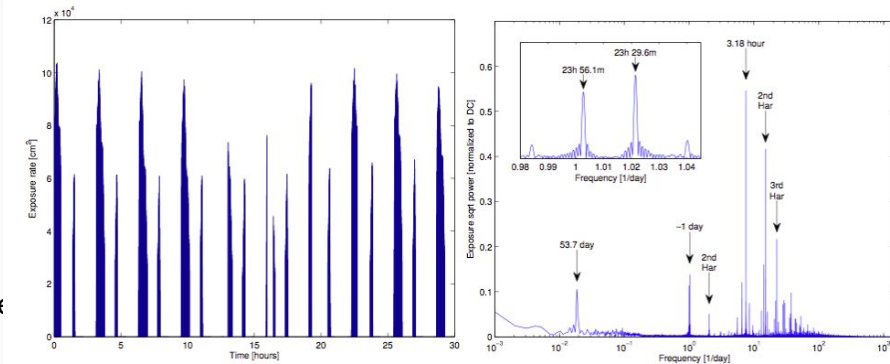
<https://xkcd.com/1425/>

Observational Profile and Livetime

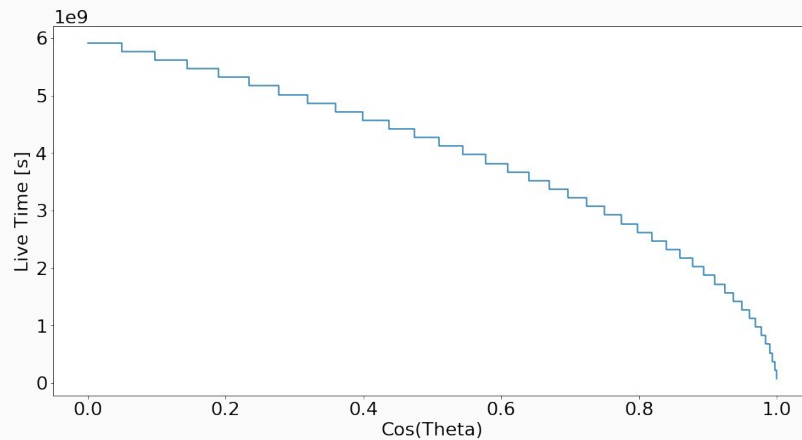
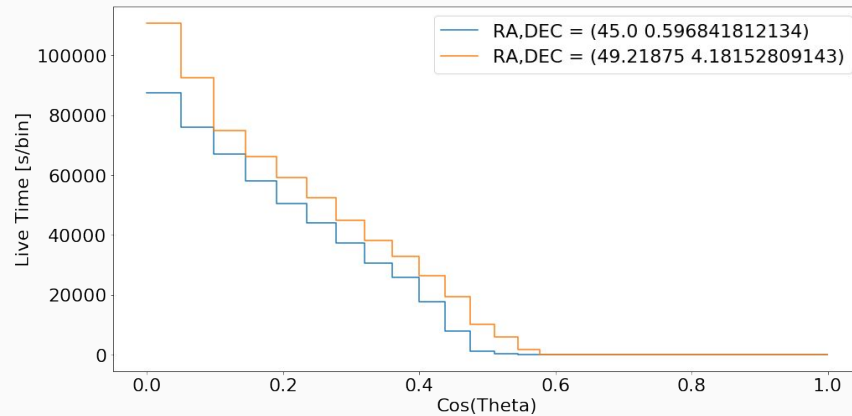
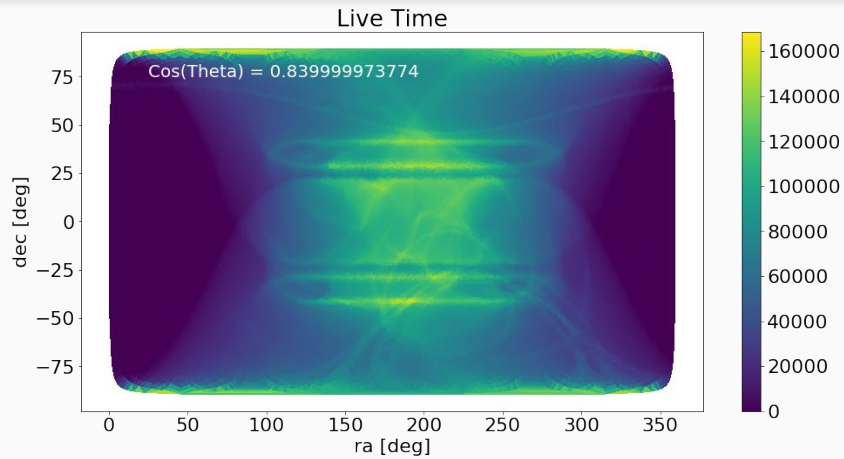
- Pointing records from spacecraft file - every 30 seconds
- RA & Dec of LAT pointing direction, the z-axis
 - (and of x-axis for phi dependence)
- Observation mode - sky survey, pointed
- See the Data Exploration Notebook for a description

Livetime

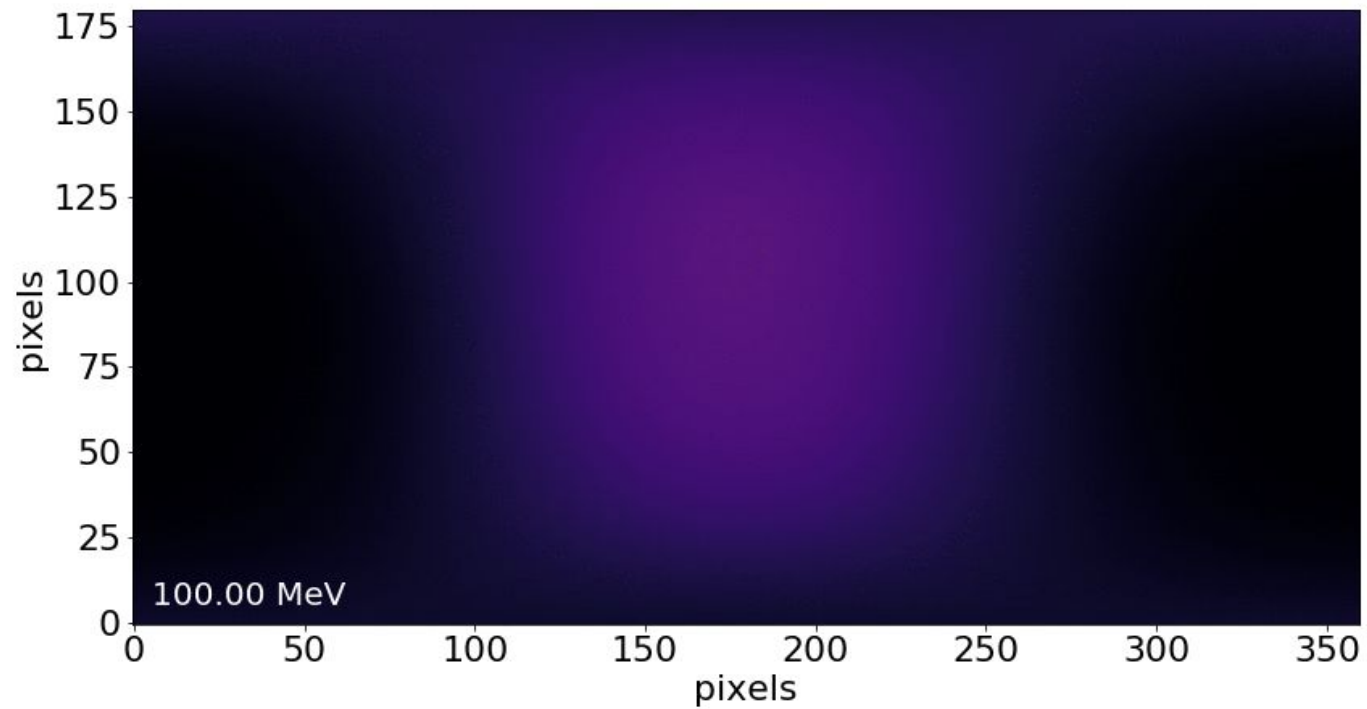
- Sum up time spent in the field of view for each position in the celestial sphere
 - Inputs are the photon and spacecraft files
 - Options are pixel size and step size for the instrument angular coverage
 - Output is a livetime 'cube'
 - Respects time-based selection cuts made with gtmktime (GTIs)
- **Livetime and Maximum Zenith Angle**
 - gtltcube knows about the field of view and the spacecraft pointing (via the spacecraft file) and can make exposure corrections related to this coordinate systems.
 - If you are doing an all-sky analysis or non-standard zenith cut, gtltcube can make a correction for the exposure loss from a zenith angle cut in gtselect.
 - **note:** this assumes perfect reconstruction
 - **If you're doing a basic source analysis and using the standard ROI cut you don't need to do this.**
- Example: if you use $zmax = 100$ in *gtselect* and set *ROIcut = no* in *gtmktime* then you **must** use $zmax=100$ in *gtltcube*.



Livetime

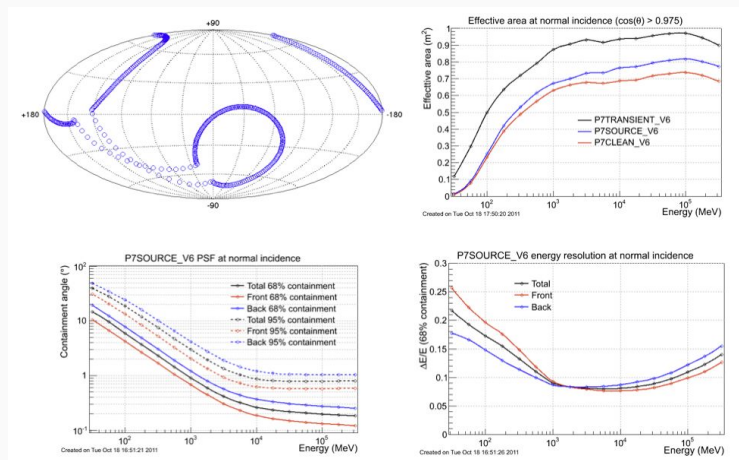


Exposure

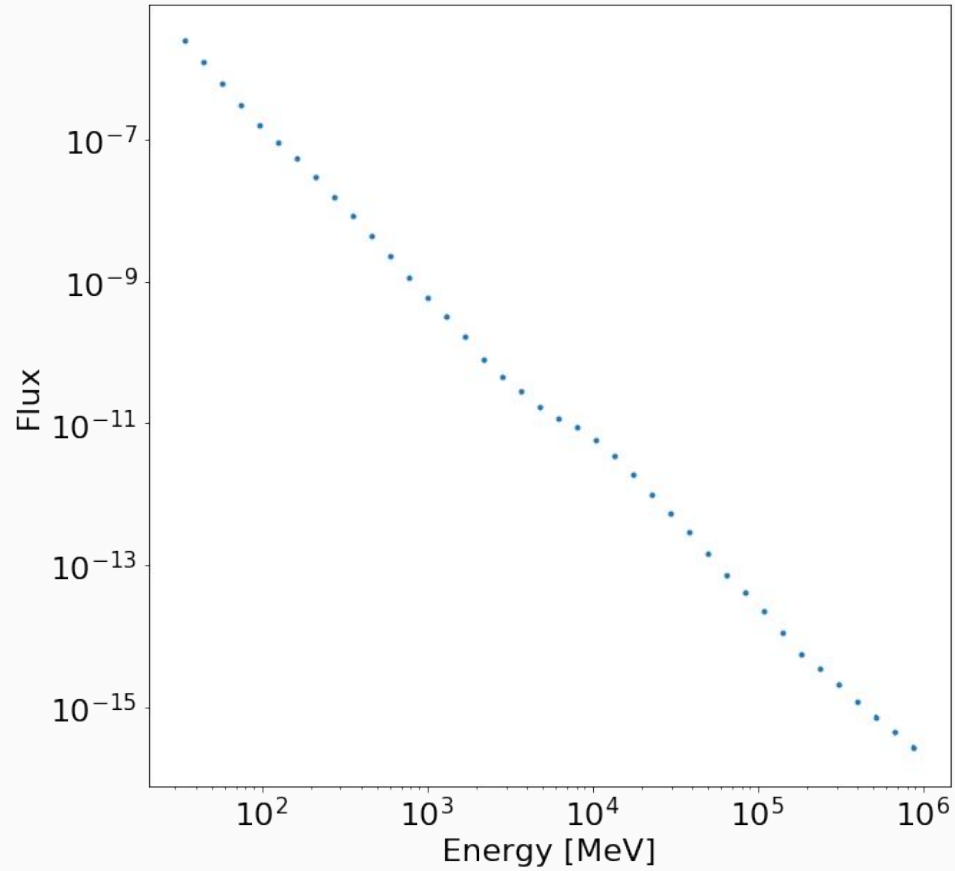


Instrument Response Functions

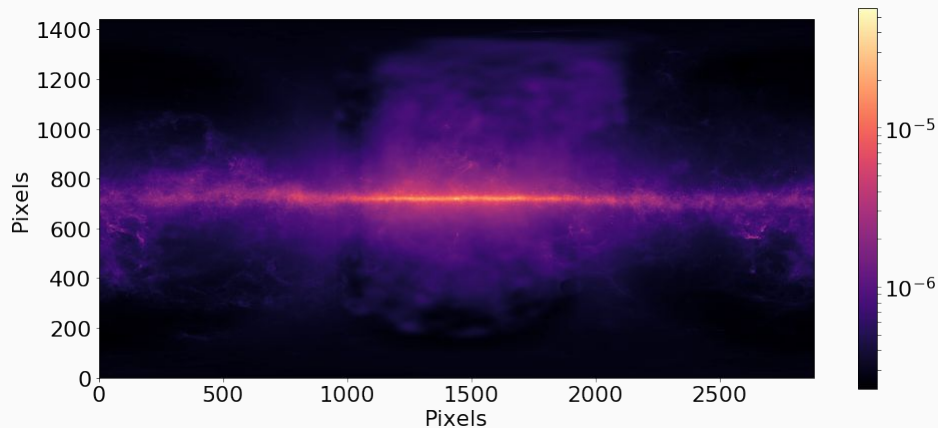
- Effective Area - how the photon collecting area depends on energy and angle
- Point Spread Function (PSF) - how the reconstructed photon angles from a point source are distributed around the true direction in the sky
- Energy Dispersion - how reconstructed photon energy is distributed around the true energy - **often neglected in analysis but important for Pass 8 below ~100 MeV**
- IRF set must match event selection used in analysis, eg. "P8R2_SOURCE_V6"



Isotropic Diffuse



Galactic Diffuse



- **Template based approach:**
 - The gamma-ray emission is optically thin
 - CR flux depends on distance from GC only to first order
 - Pragmatic approach, fitting functions are phenomenological

- **Templates included:**
 - HI, CO, and IC split into "rings" for 9 ranges of Galactocentric distance + CMZ for CO
 - DNM split into positive and negative correction
 - Sun and Moon (same as catalog) (*Not in final model*)
 - Unresolved Galactic sources + isotropic template
 - Point Sources (*Not in final model*)
 - "Patch" component derived from residuals to account for unmodeled emission (Loop I, Bubbles, ...)

Trigger & Filter

Trigger and Filter

- In an ideal instrument we would record every event and perform all analysis offline
- The hardware trigger and filters are needed to reduce the data rate to a manageable level before offline analysis
 - Every readout incurs instrument deadtime (26.5 μs)
 - Need to further reduce data volume to fit within finite downlink bandwidth
- **General Goals of Trigger/Filter Design**
 - Keep a very high efficiency for gamma-ray events
 - Minimize the background rate (without impacting gamma efficiency)
- Trigger is also used to collect extra diagnostic events with a prescale (i.e. accept only 1 out of N events)

Onboard Filter

- Onboard filter provides an additional level of data reduction at hardware level
 - Needed to keep data volume within downlink bandwidth (~ 1 Mb/s)
 - Uses all available event information (ACD+CAL+TKR) to identify whether an event is a candidate gamma-ray
- Multiple filters applied in parallel
 - GAMMA: Select gamma-ray events
 - HIP: Select heavy ion events for CAL calibration
 - DIAGNOSTIC: Select unbiased sample of all trigger types (used to monitor trigger/filter efficiency)

Final downlink rate is 300 - 500 Hz

"p7performance" style. Revision: 1.22

