Fermi Gamma-ray Space Telescope

Intro to the Fermi-LAT

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Fermi Summer School
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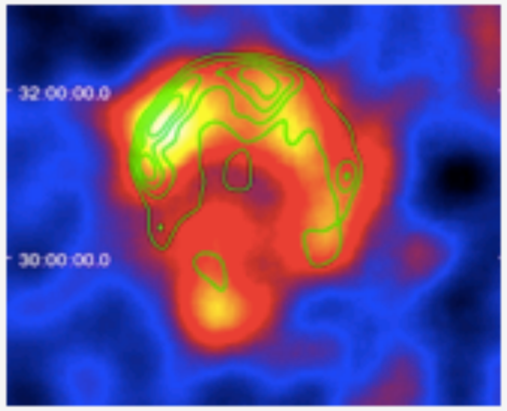
Outline

- Introduction: What is the Large Area Telescope?
  - Optimizing for science
- Instrument Response Functions (IRFs)
  - effective area
  - point spread function
  - energy dispersion
- Validating and Calibrating IRFs
- Assessing Systematics on IRFs
- Source Sensitivity

Please refer to:
The Fermi Large Area Telescope On Orbit: Event Classification,Instrument Response Functions, and Calibration
(or How I Learned to Stop Worrying and Love the Instrument)
Fermi-LAT Collaboration, 2012 ApJS, 203, 4
arXiv:1206.1896
And previous summer schools :)

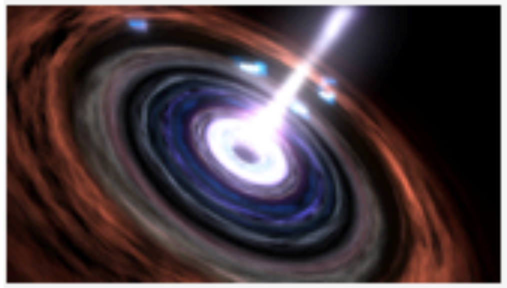
Exploring the Extreme Universe



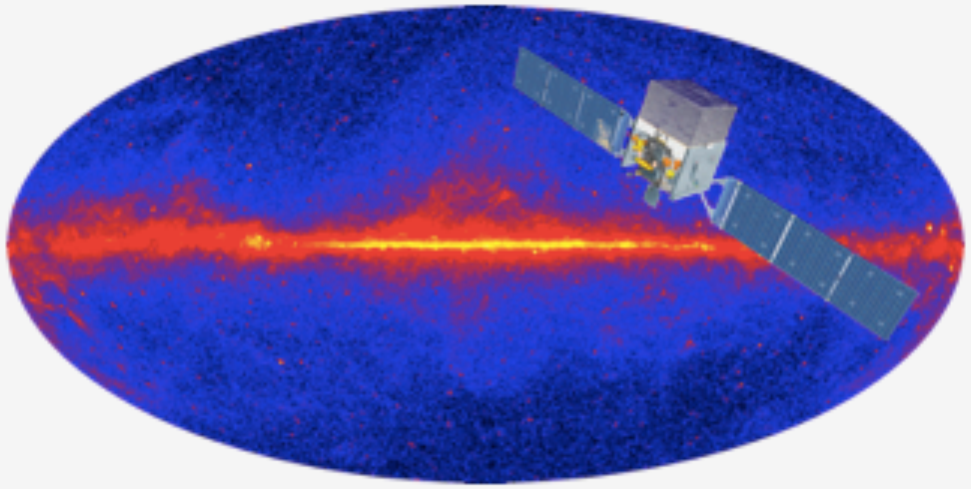
Supernova Remnants

Gamma-ray Bursts

Pulsar Wind Nebulae

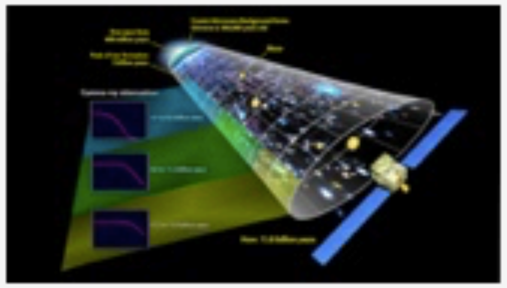


Active Galactic Nuclei

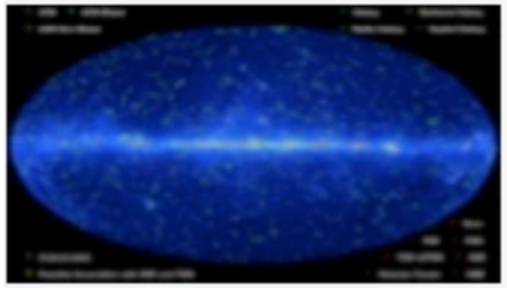


About Fermi

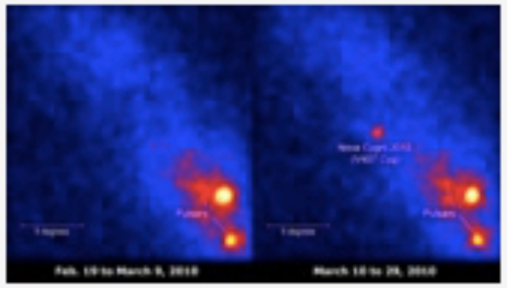
Click on the images or topic name for information about these science topics.



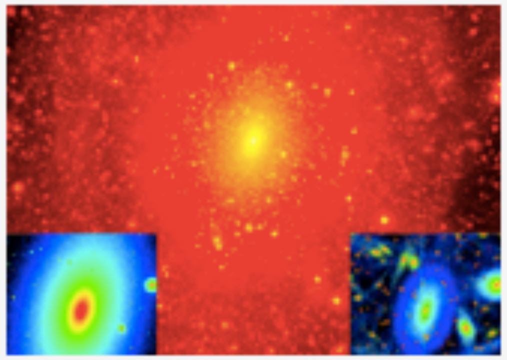
Extragalactic Background



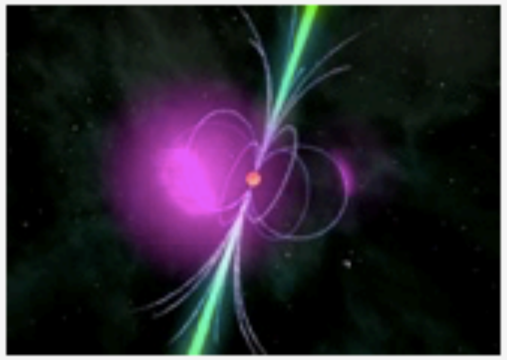
Catalogs



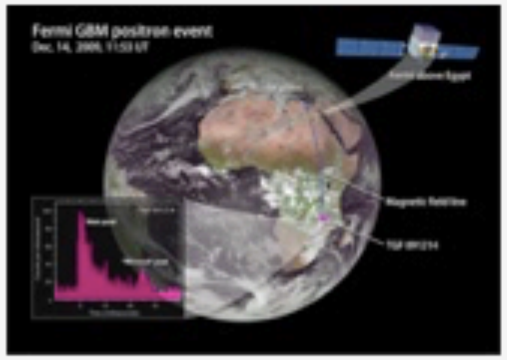
Binary Sources



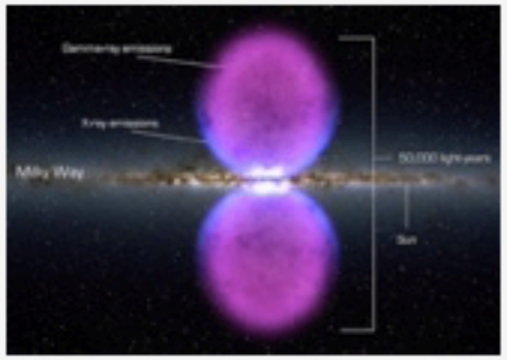
Dark Matter



Pulsars

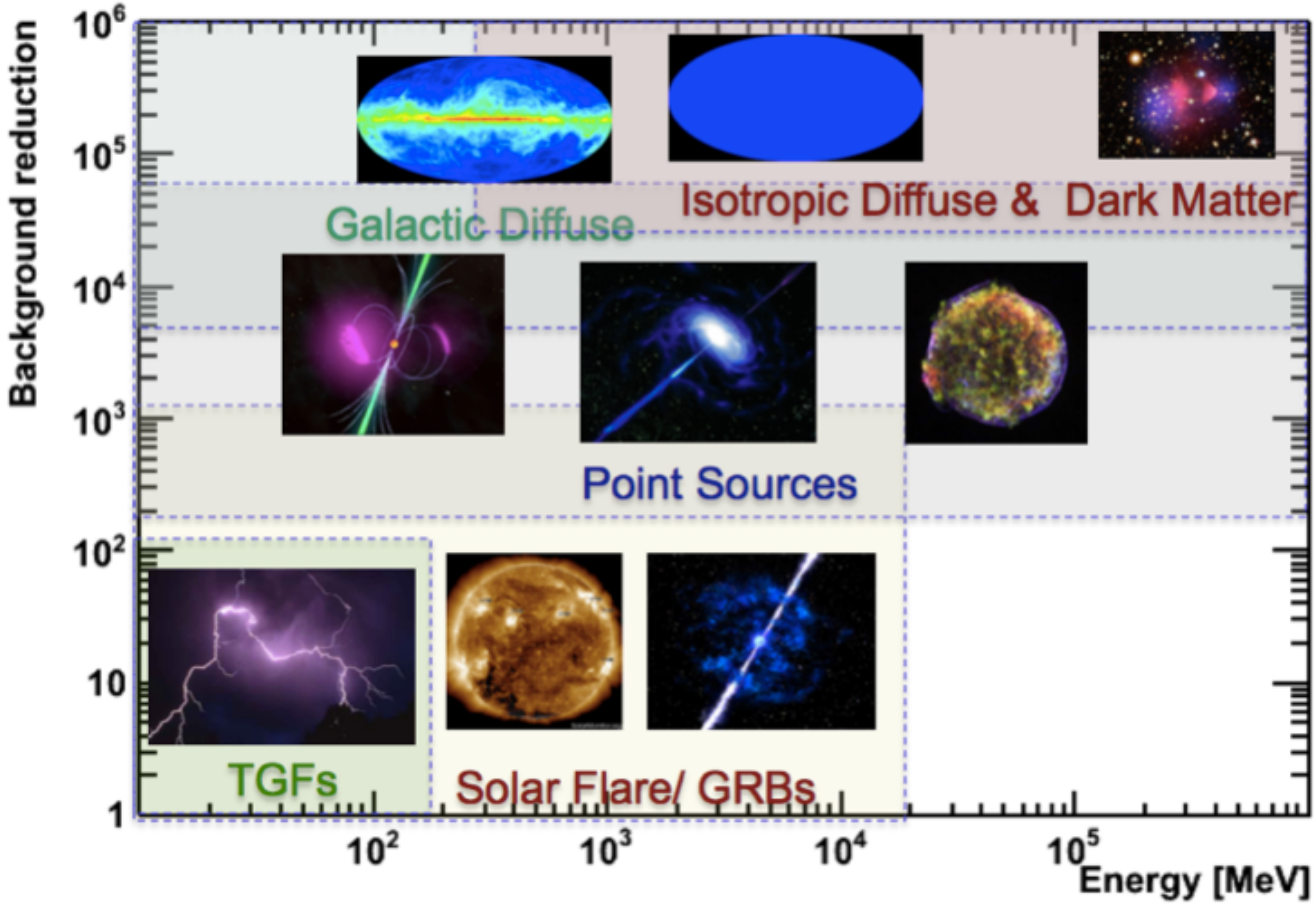


Terrestrial Gamma-ray Flashes



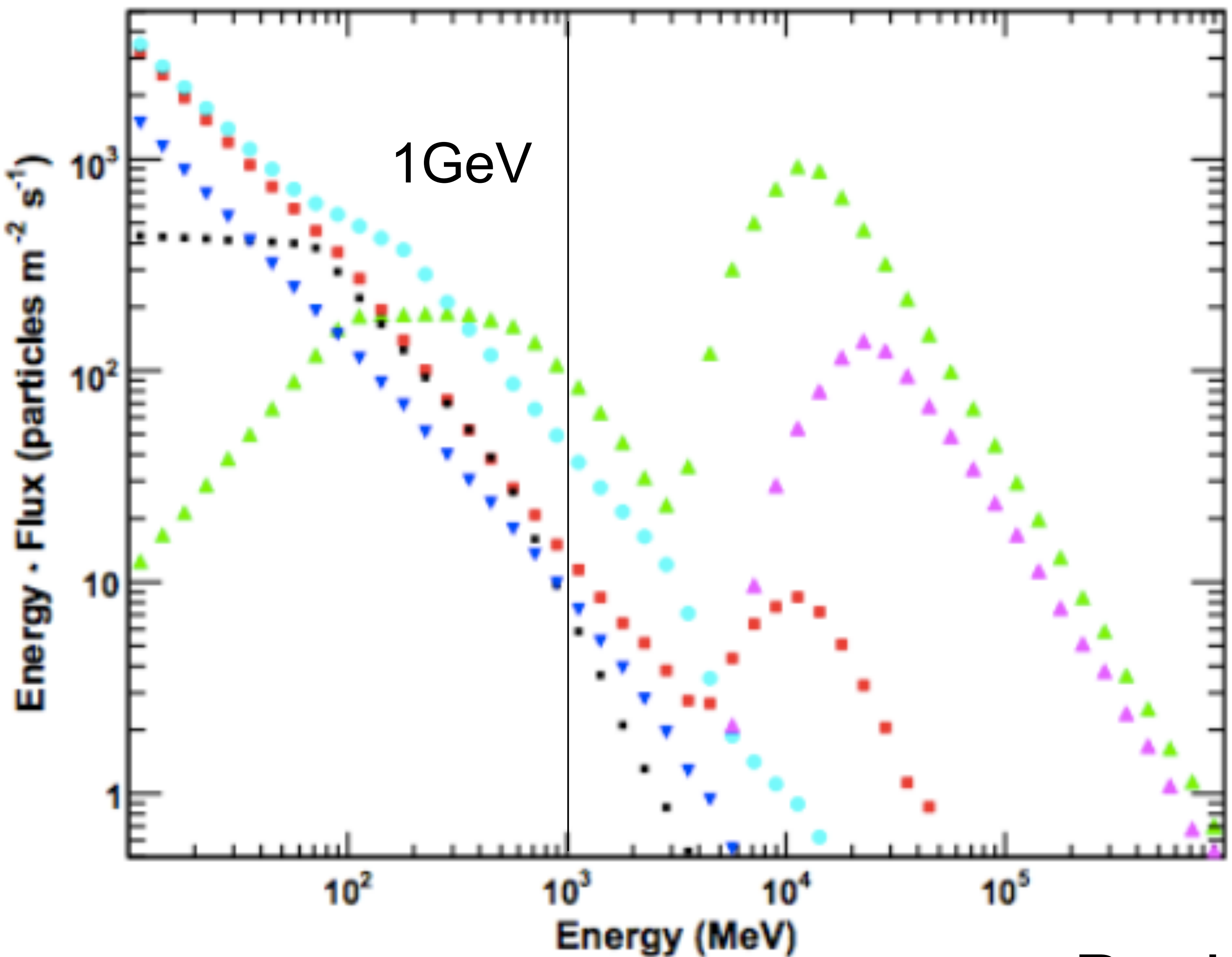
Diffuse Gamma Radiation

A Broad Range of Fermi-LAT Science



Develop event classes and event types specialized for each type of science

Particle Backgrounds

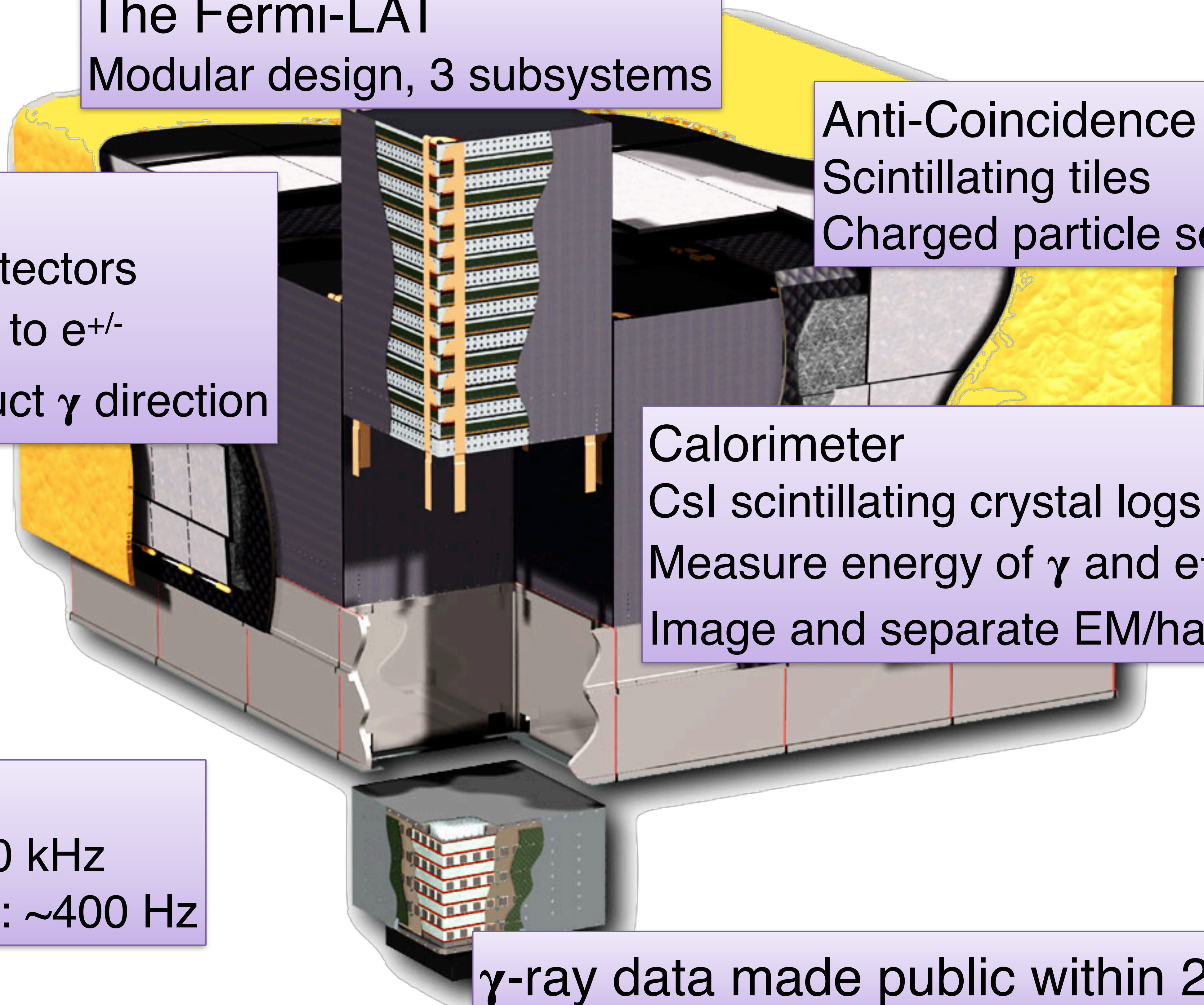


Backgrounds:
protons (green filled triangles up),
He (purple filled triangles up),
electrons (filled red squares),
positrons (light blue squares),
Earth albedo neutrons (black squares),
Earth albedo γ-rays (dark blue triangles dn).

Background to signal: 1000:1

http://arxiv.org/pdf/0902.1089v1.pdf

Fermi Large Area Telescope



The Fermi-LAT
Modular design, 3 subsystems

Tracker
Silicon detectors
Convert γ to $e^{+/-}$
Reconstruct γ direction

Anti-Coincidence Detector
Scintillating tiles
Charged particle separation

Calorimeter
CsI scintillating crystal logs
Measure energy of γ and $e^{+/-}$
Image and separate EM/had. showers

Trigger
rate: ~10 kHz
read out: ~400 Hz

γ-ray data made public within 24 hours

Fermi-LAT Instrument Capabilities

Parameter	Value or Range
Energy Range	~20 MeV to >300 GeV
Energy Resolution	<15% at energies >100 MeV
Effective Area	>8,000 cm^2 maximum effective area at normal incidence
Single Photon Angular Resolution	<0.15°, on-axis, 68% space angle containment radius for E > 10 GeV; < 3.5°, on-axis, 68% space angle containment radius for E = 100 MeV
Field of View	2.4 sr
Source Location Determination	<0.5 arcmin for high-latitude source
Point Source Sensitivity	$<6\times10^{-9}$ ph cm^{-2} s^{-1} for E > 100 MeV, 5σ detection after 1 year sky survey
Time Accuracy	<10 microseconds, relative to spacecraft time
Background Rejection (after analysis)	<10% residual contamination of a high latitude diffuse sample for E = 100 MeV - 300 GeV.
Dead Time	<100 microseconds per event

Diverse Science: Event Class

https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Data/LAT_DP.html

Standard Hierarchy for LAT Event Classes				
Event Class	**evclass**	**Photon File**	**Extended File**	**Description**
P8R3_TRANSIENT020	16		X	Transient event class with background rate equal to two times the A10 IGRB reference spectrum.
P8R3_TRANSIENT010	64		X	Transient event class with background rate equal to one times the A10 IGRB reference spectrum.
P8R3_SOURCE	128	X	X	This event class has a residual background rate that is comparable to P7REP_SOURCE. This is the recommended class for most analyses and provides good sensitivity for analysis of point sources and moderately extended sources.
P8R3_CLEAN	256	X	X	This class is identical to SOURCE below 3 GeV. Above 3 GeV it has a 1.3-2 times lower background rate than SOURCE and is slightly more sensitive to hard spectrum sources at high galactic latitudes.
P8R3_ULTRACLEAN	512	X	X	This class has a background rate very similar to ULTRACLEANVETO.
P8R3_ULTRACLEANVETO	1024	X	X	This is the cleanest Pass 8 event class. Its background rate is 15-20% lower than the background rate of SOURCE class below 10 GeV, and 50% lower at 200 GeV. This class is recommended to check for CR-induced systematics as well as for studies of diffuse emission that require low levels of CR contamination.
P8R3_SOURCEVETO	2048	X	X	This class has the same background rate than the SOURCE class background rate up to 10 GeV but, above 50 GeV, its background rate is the same as the ULTRACLEANVETO one while having 15% more acceptance.

Diverse Science: Event Class

https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Data/LAT_DP.html

Extended Hierarchy				
Event Class	**evclass**	**Photon File**	**Extended File**	**Description**
P8R3_TRANSIENT020E	8		X	Extended version of the P8R3_TRANSIENT020 event class with a less restrictive fiducial cut on projected track length through the Calorimeter.
P8R3_TRANSIENT010E	32		X	Extended version of the P8R3_TRANSIENT010 event class with a less restrictive fiducial cut on projected track length through the Calorimeter.
NON-ACD Hierarchy				
Event Class	**evclass**	**Photon File**	**Extended File**	**Description**
P8R3_TRANSIENT015S	65536		X	Transient event class designed for analysis of prompt solar flares in which pileup activity may be present. This class has a background rate equal to 1.5 times the A10 reference spectrum.

Diverse Science: Event Types

Conversion Type Partition		
Event Type	**evtype**	**Description**
FRONT	1	Events converting in the Front-section of the Tracker. Equivalent to convtype=0.
BACK	2	Events converting in the Back-section of the Tracker. Equivalent to convtype=1.
PSF Type Partition		
Event Type	**evtype**	**Description**
PSF0	4	First (worst) quartile in the quality of the reconstructed direction.
PSF1	8	Second quartile in the quality of the reconstructed direction.
PSF2	16	Third quartile in the quality of the reconstructed direction.
PSF3	32	Fourth (best) quartile in the quality of the reconstructed dire
EDISP Type Partition		
Event Type	**evtype**	**Description**
EDISP0	64	First (worst) quartile in the quality of the reconstructed energy.
EDISP1	128	Second quartile in the quality of the reconstructed energy.
EDISP2	256	Third quartile in the quality of the reconstructed energy.
EDISP3	512	Fourth (best) quartile in the quality of the reconstructed energy.

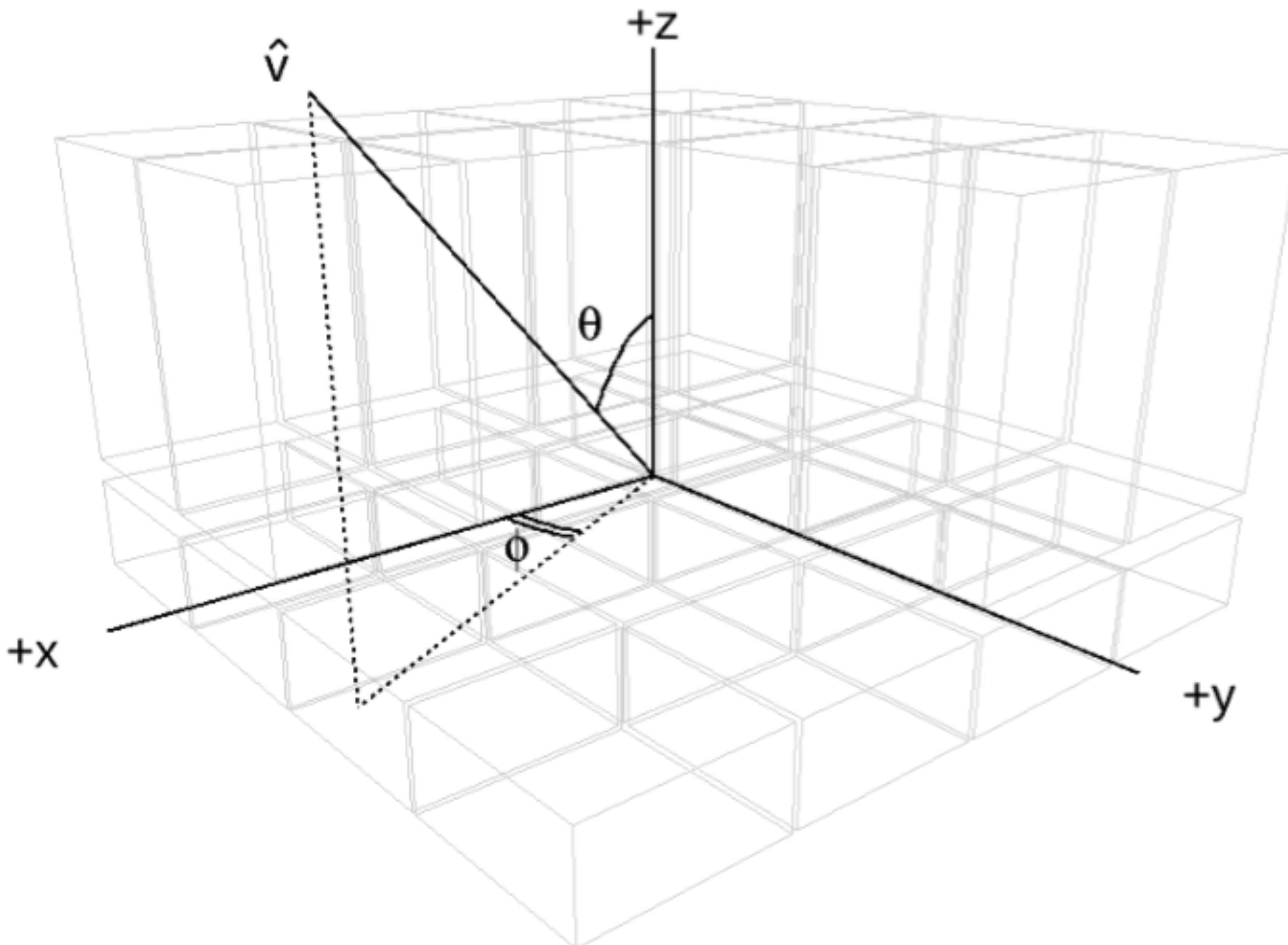
Check out the FSSC for more details…

Which Event Classes/Types have you worked with so far?

Instrument Response Functions (IRFs)

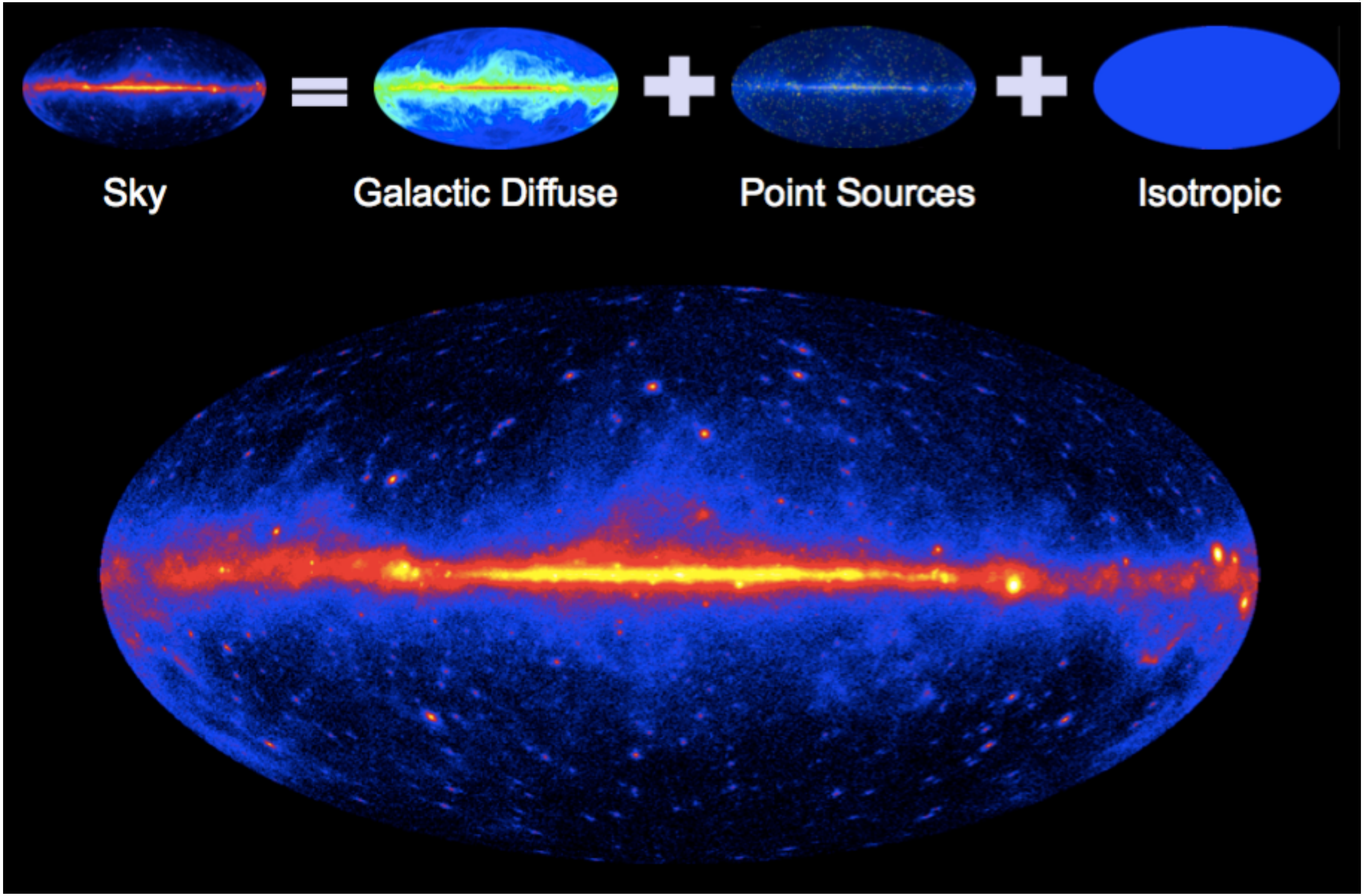
https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_LAT_IRFs/IRF_overview.html

LAT Coordinate System



Instrument Response Functions (IRFs) parameterized as a function of the E and (θ,ϕ) in instrument coordinates

The Gamma-ray Sky



Instrument Response Functions

- **The IRF is factored into three terms:**
  - **efficiency in terms of the detector's effective area,**
  - **angular resolution as given by the point-spread function (PSF),**
  - **energy resolution given by the energy dispersion**

Measured Energy & Direction

Effective Area

Energy Dispersion

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

Point-spread Function

True Energy & Direction

Expected Count Rate

Source Flux

$$\frac{dM(E',\hat{v}')}{dt} = \int\int R(E',\hat{v}';E,\hat{v})F(E,\hat{v})d\hat{v}dE$$

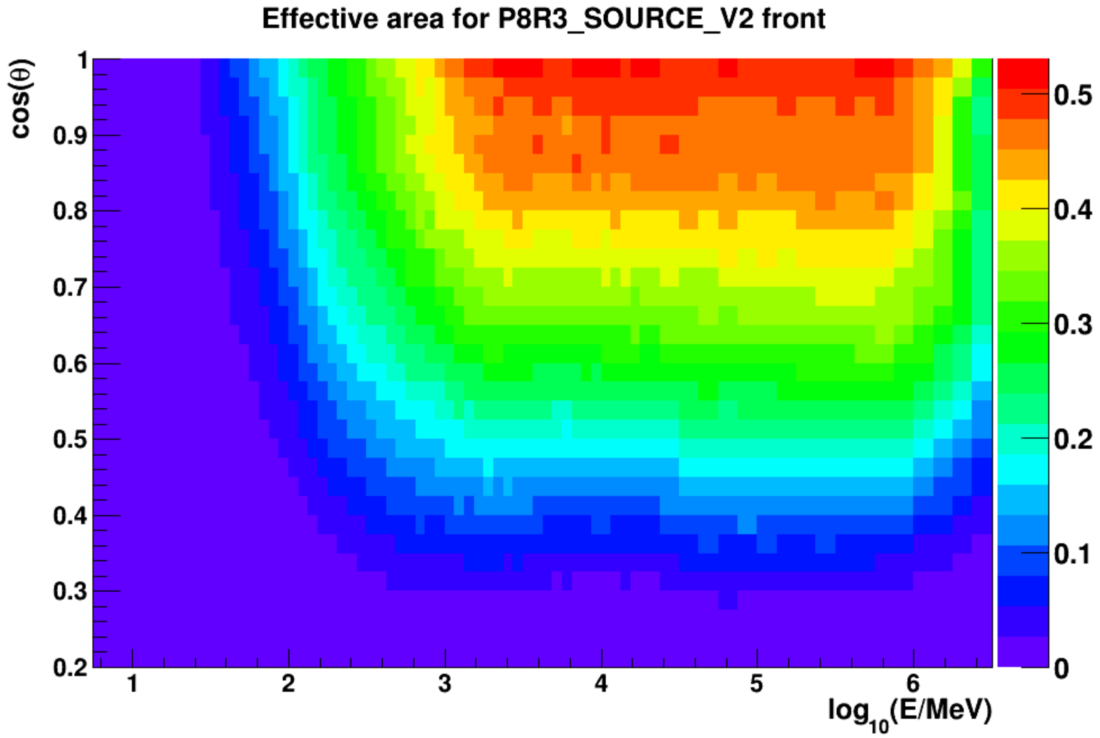
Instrument Response

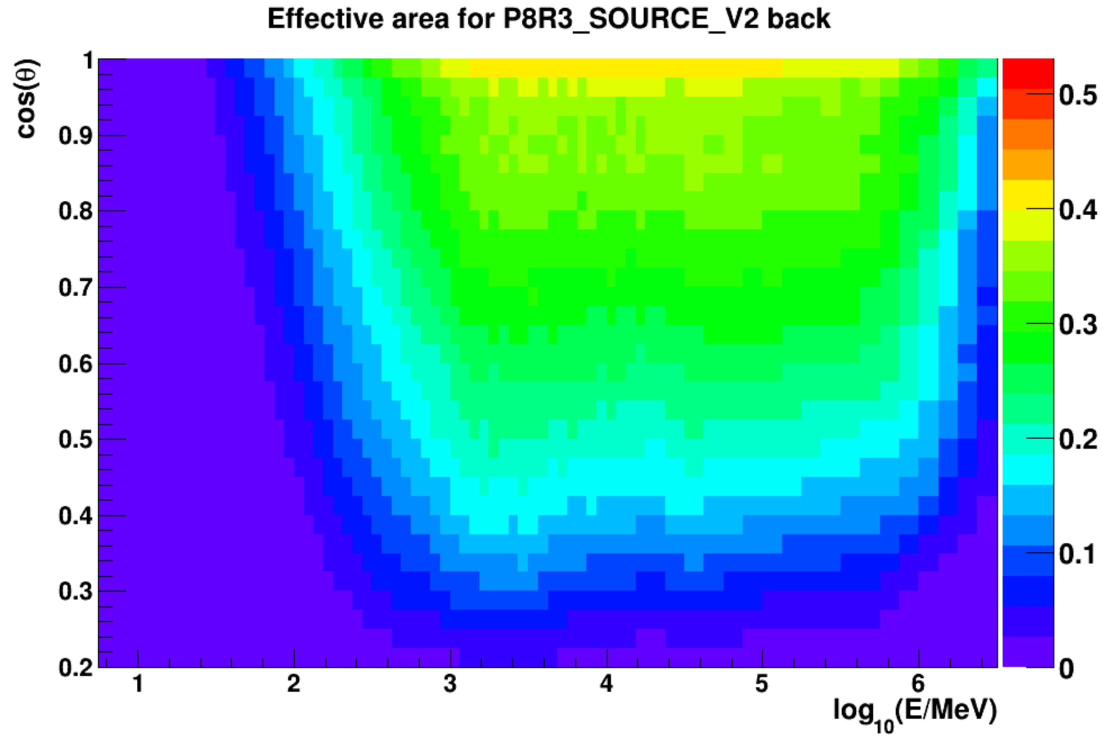
Instrument Response Functions

P8R3 IRF name	Event Class (evclass)	Class Hierarchy	Photon File	Extended File
P8R3_SOURCEVETO_V2	2048	Standard	X	X
P8R3_ULTRACLEANVETO_V2	1024	Standard	X	X
P8R3_ULTRACLEAN_V2	512	Standard	X	X
P8R3_CLEAN_V2	256	Standard	X	X
P8R3_SOURCE_V2	128	Standard	X	X
P8R3_TRANSIENT010_V2	64	Standard		X
P8R3_TRANSIENT020_V2	16	Standard		X
P8R3_TRANSIENT010E_V2	32	Extended		X
P8R3_TRANSIENT020E_V2	8	Extended		X
P8R3_TRANSIENT015S_V2	65536	No-ACD		X

Look Familiar?…

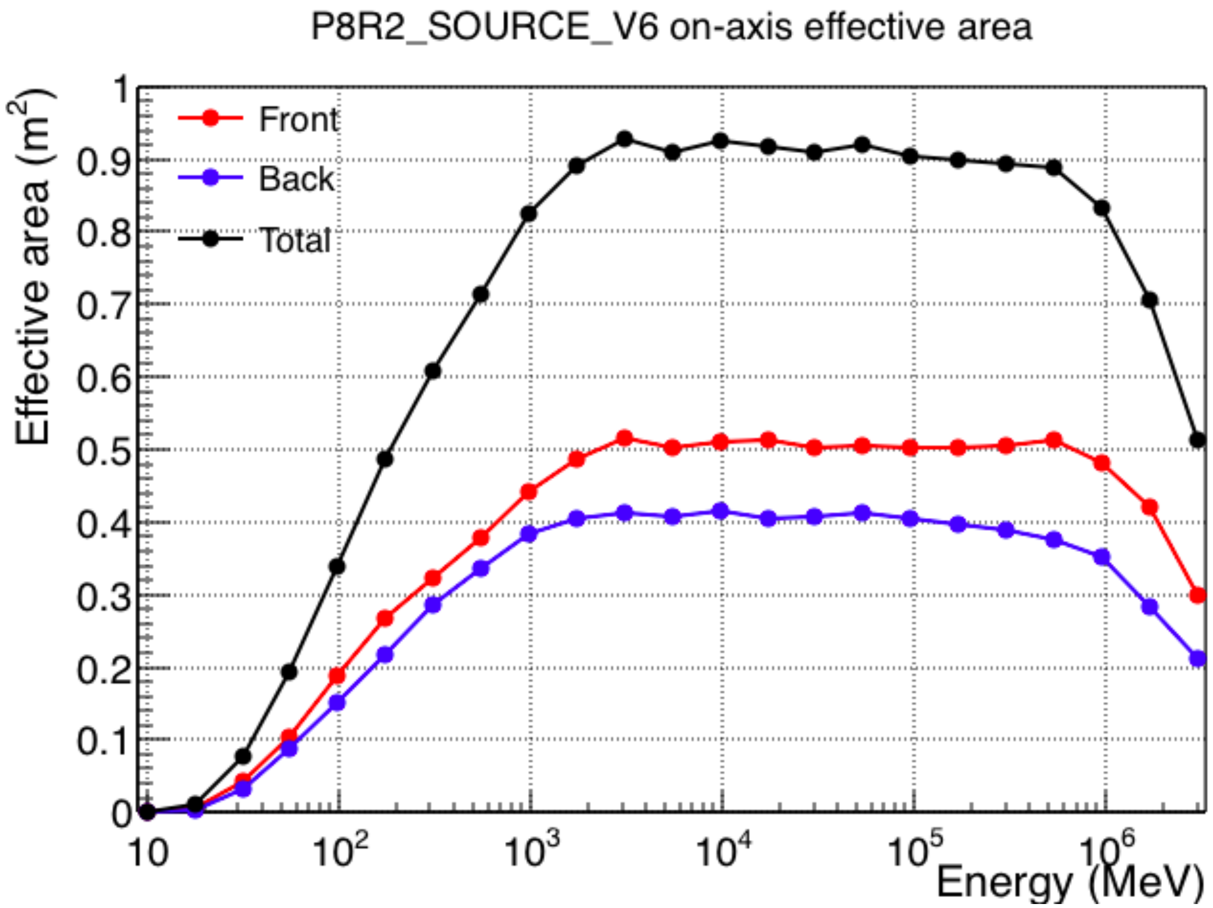
Effective Area

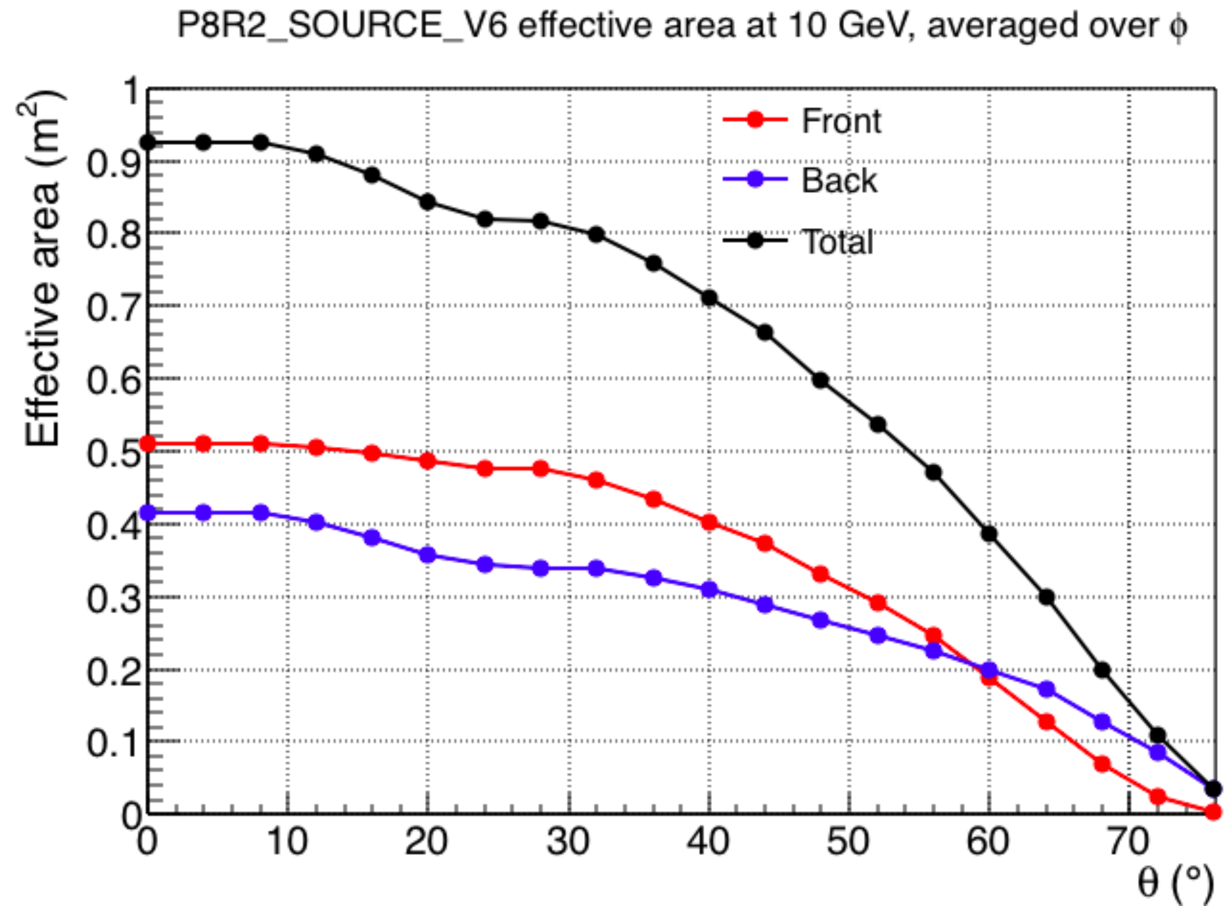




- A_{eff}(E,v, s): product of the geometrical collection area, gamma-ray conversion probability and selection efficiency for a gamma-ray with energy E and direction v in the LAT frame
- Generating A_{eff} tables
  - generate isotropic incoming flux, count events that pass event selection, normalize to input flux
- Events binned in log(E) and cos θ
  - Fermitools takes care of interpolations
  - ϕ dependence small, treated as correction

Effective Area



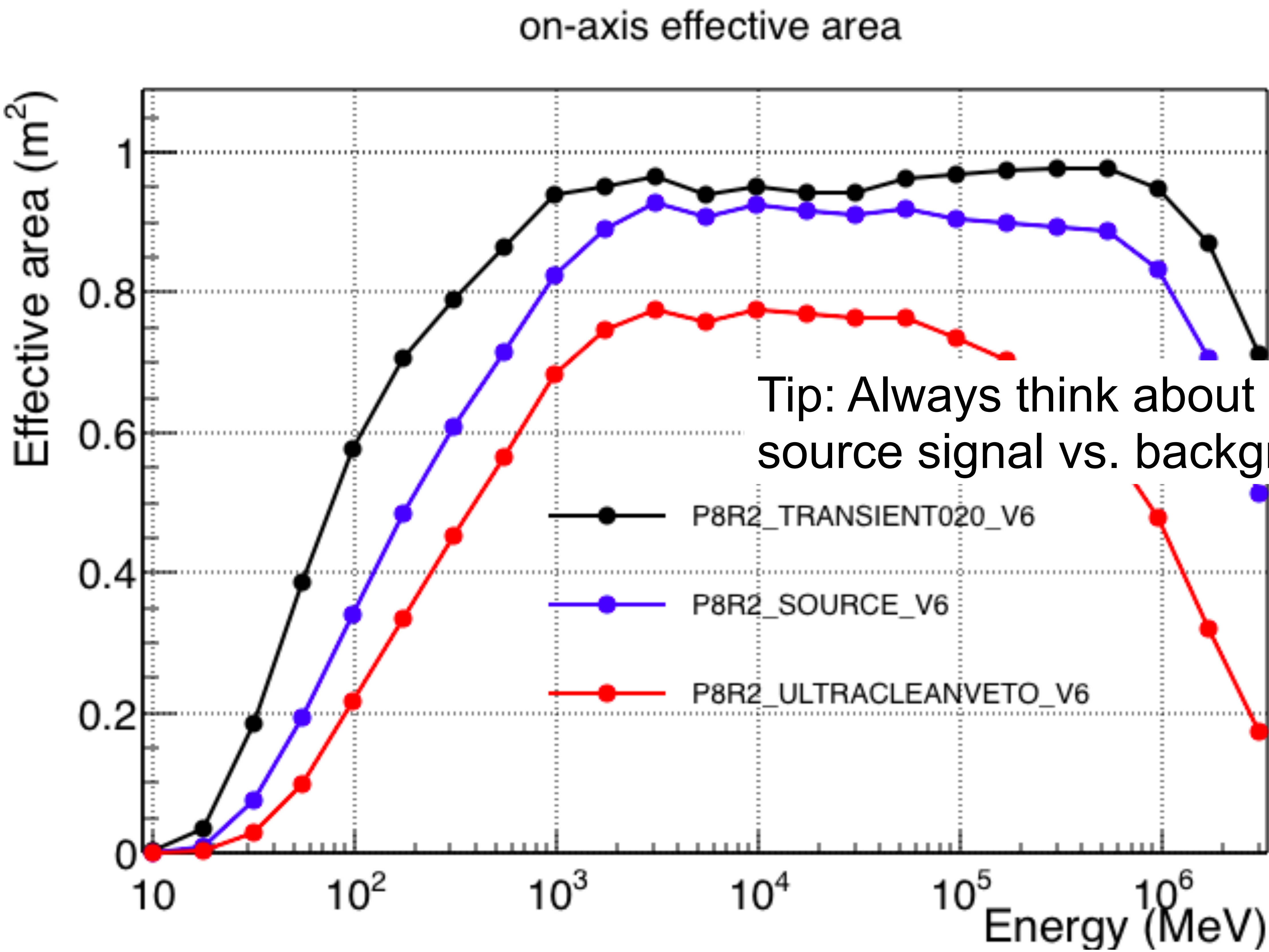


- A_{eff} vs E (at fixed θ)
  - Increases up to 1 TeV
  - >1 TeV events are harder to reconstruct and event rates drop
- A_{eff} vs θ (at fixed E)
  - Less cross section as you go off-axis
  - Off-axis events easier for back-converting events to intercept the calorimeter

See: http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

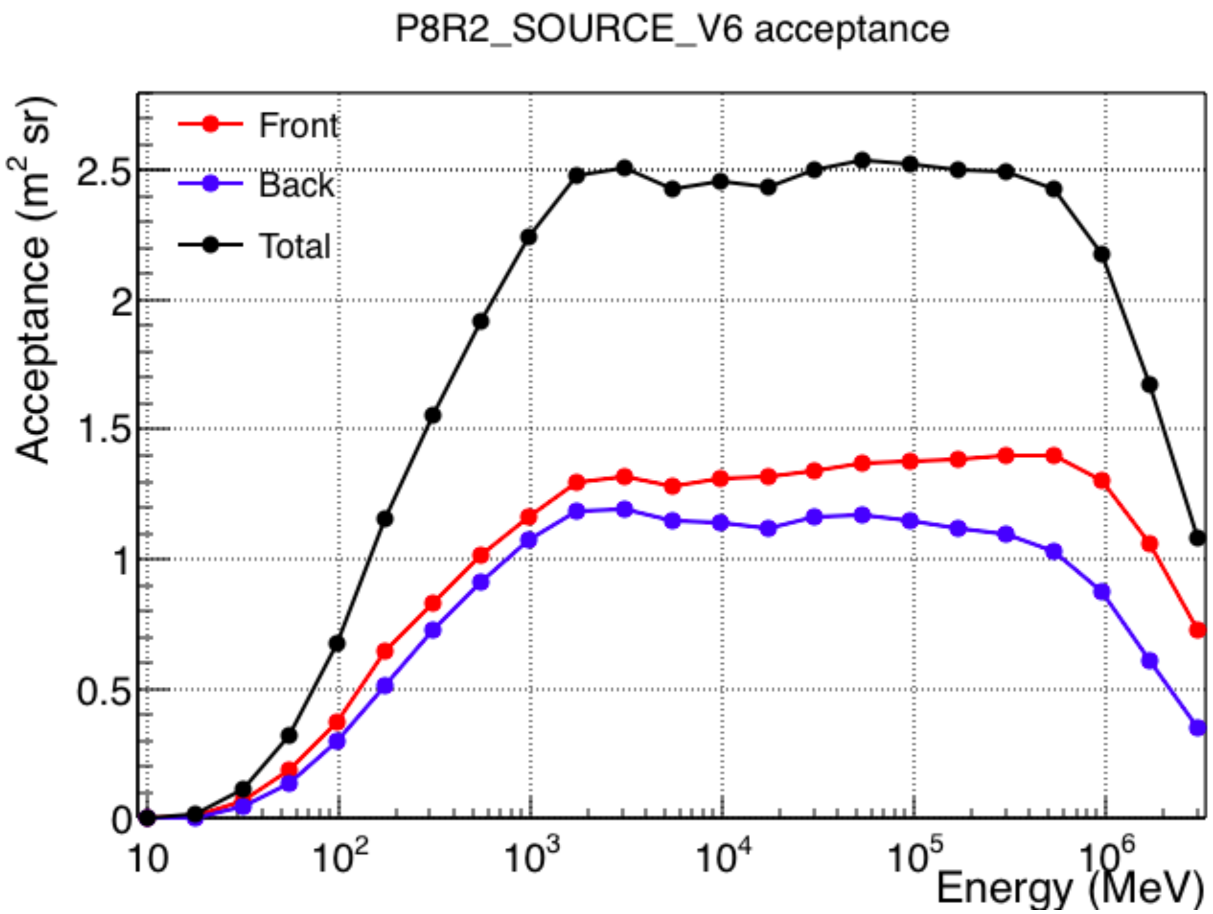
What happens at low energies?

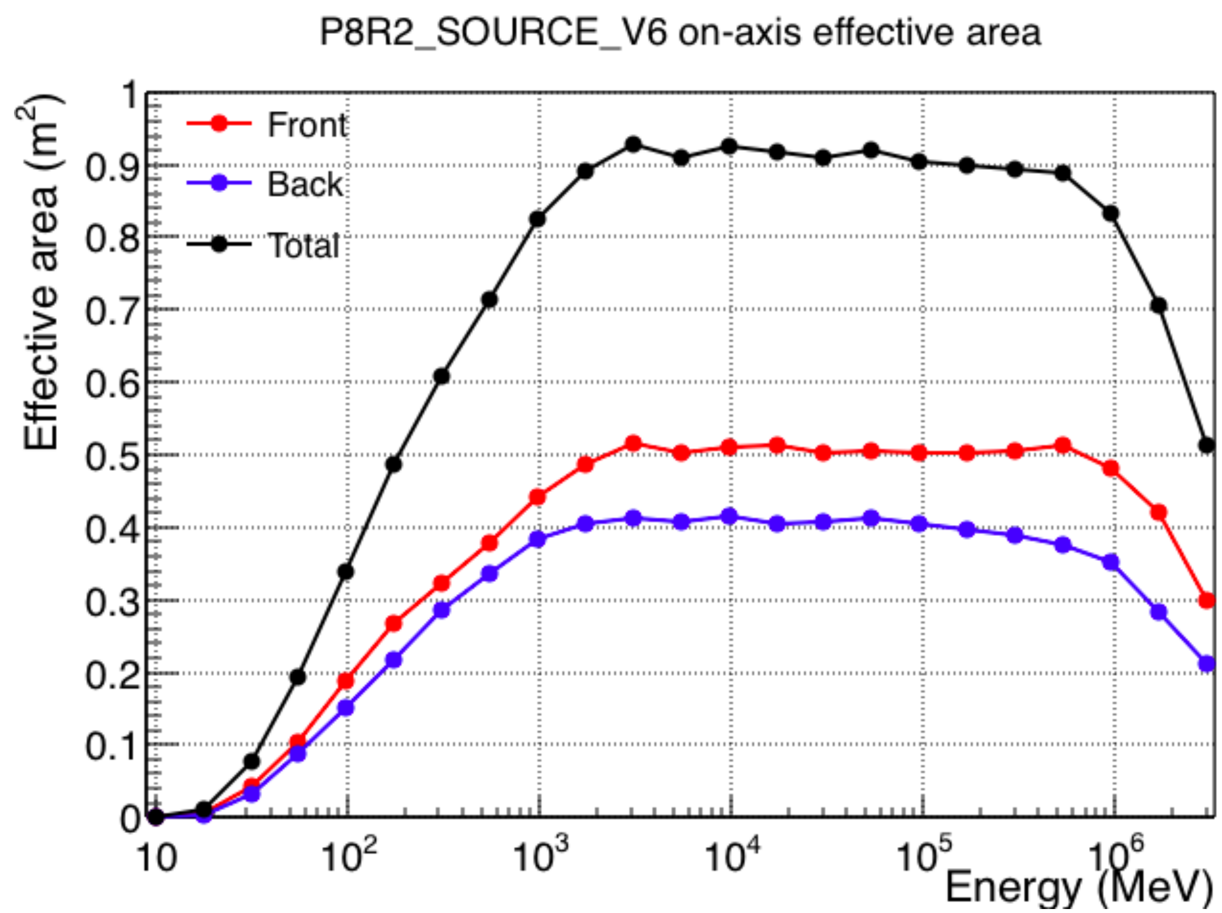
Effective Area and Event Classes



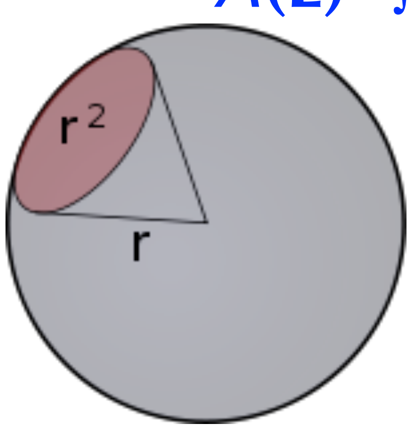
Tip: Always think about the source signal vs. background

Acceptance and Field of View





- **Acceptance $A(E)$**
  - $A(E) = \int A_{eff}(E,\theta,\phi)\, d\Omega$



= 1 sr

- **Field-of-view**
  - **$FoV(E) = A(E)/A_{eff}(\theta=0)$**
  - **Fermi-LAT: 2.4 sr (>1 GeV)**

Point Spread Function

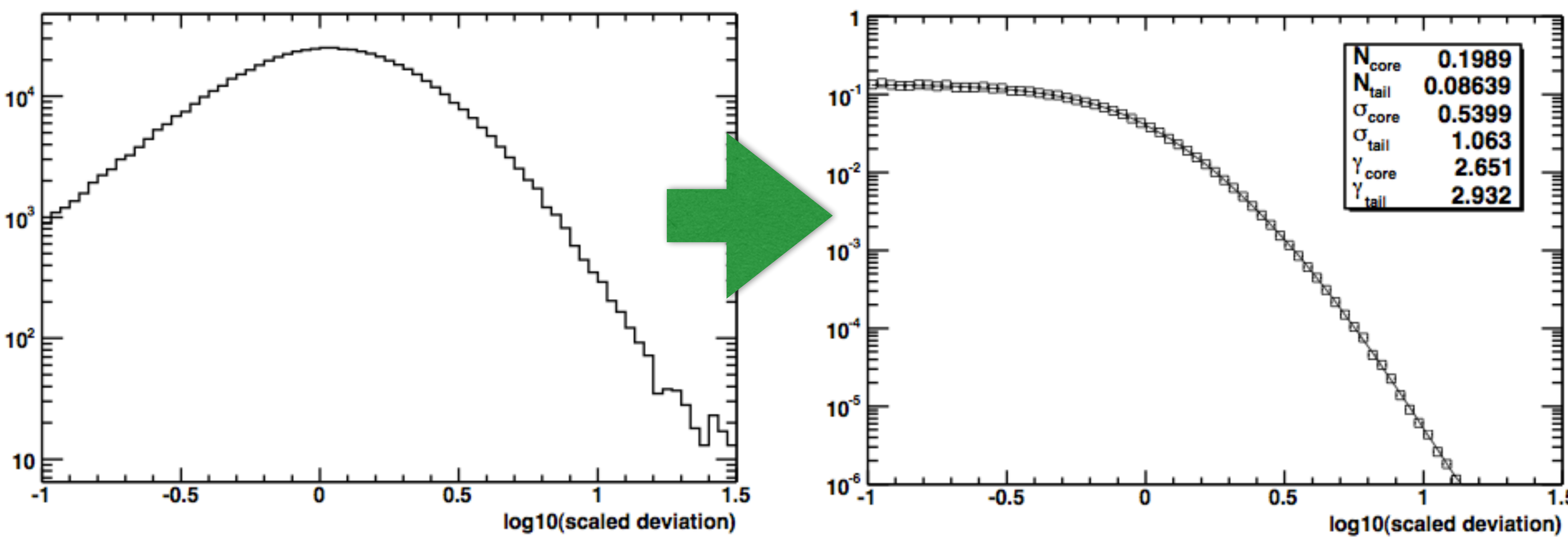
- P(v′;E,v, s): the probability density to reconstruct an incident direction (v′) for a gamma ray with (E, v) in a given event selection, s
- For a given point (E) in the LAT phase space the PSF is a p.d.f.:
  - functional form to parameterize it (for MC PSF): two Moffat Functions

$$K(x,\sigma,\gamma) = \frac{1}{2\pi\sigma^2}\left(1-\frac{1}{\gamma}\right)\cdot\left[1+\frac{1}{2\gamma}\cdot\frac{x^2}{\sigma^2}\right]^{-\gamma}$$

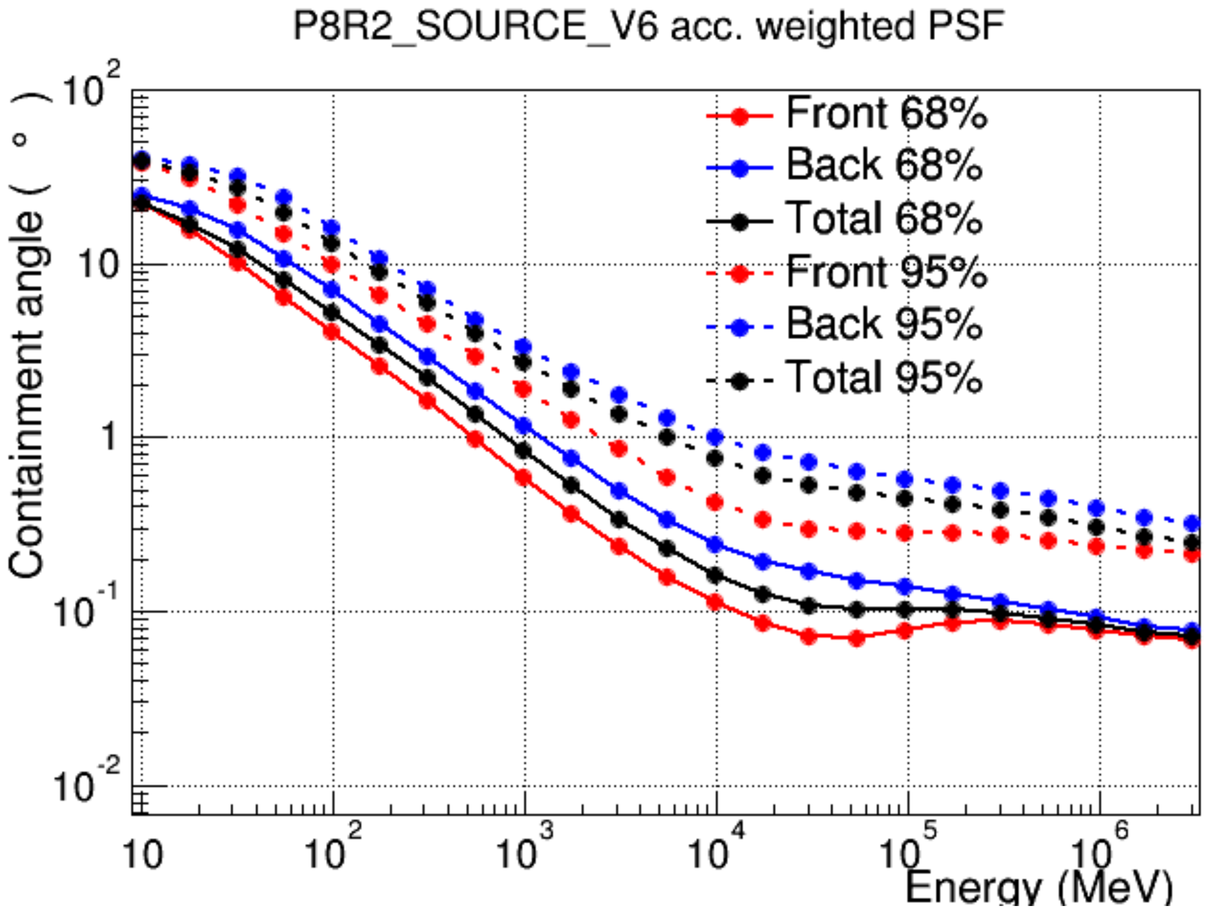
- The PSF varies by orders of magnitude across the LAT energy range
  - low energy dominated by multiple Coulomb scattering in the W conversion foils
  - high energy determined by the tracker strip pitch and lever arm

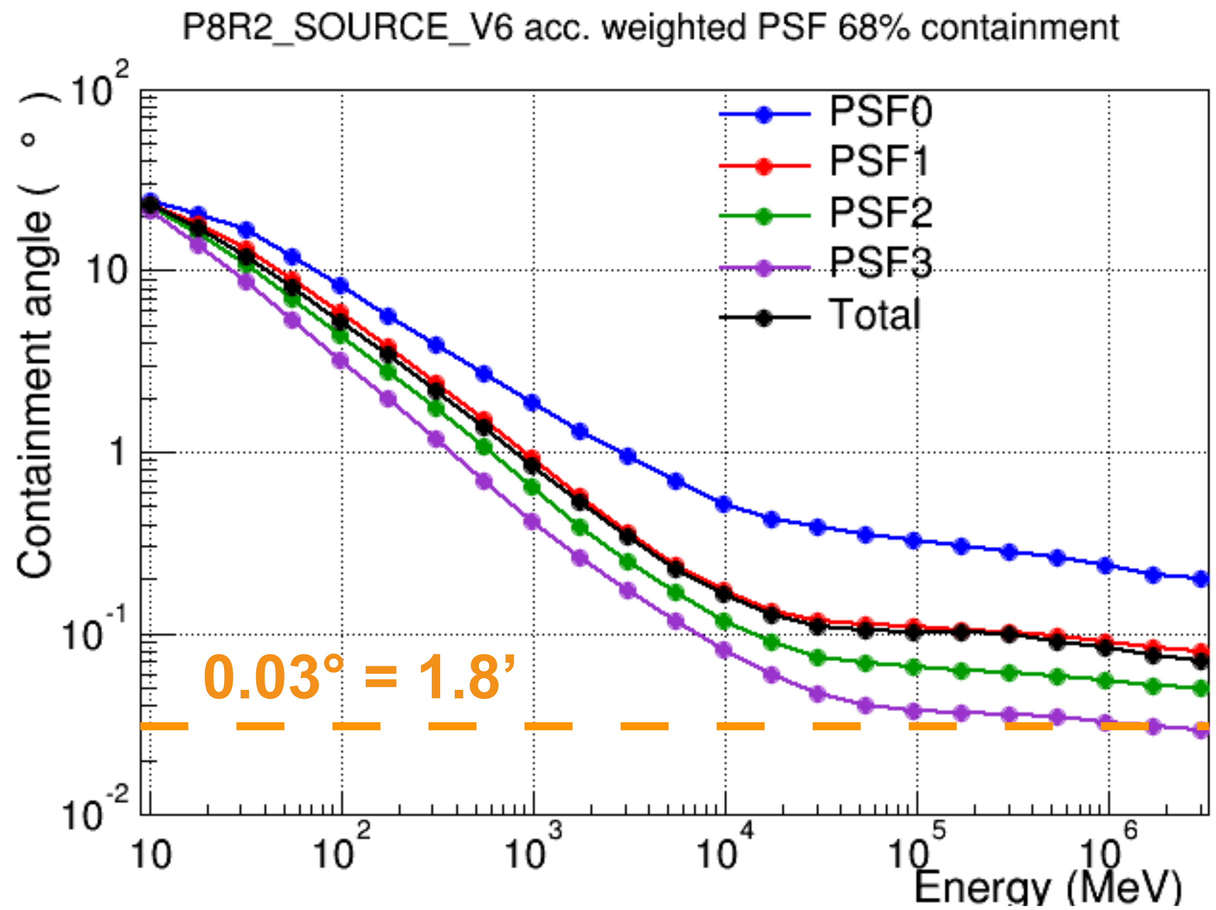
Derivation of the PSF

- Scaled angular deviation for each bin in log E_{MC} and $\cos(\theta_{MC})$.
  - histogram for the bin centered at 7.5 GeV, and 30° for Front events
- Divide the contents of each bin by the bin width.
- The resulting density histogram is then fit to extract the PSF parameters for that bin



Point Spread Function





- **For previous data releases, simulations underestimated the PSF at energies above few GeV**
- **Improvements to the MC description in Pass 8 have resolved this discrepancy.**
- **In the P8R2_V6 IRFs the PSF model is derived entirely from MC simulations and contains no in-flight correction.**

Why do front/back events have a different PSF?

Fisheye Effect

- Bias in the reconstructed gamma-ray direction toward the LAT boresight
- WHY DOES THIS HAPPEN??!?
  - Particles scattering toward the LAT foresight are more likely to trigger the instrument and be reconstructed
  - Especially true at low energies and large angles
- Is this important?
  - Usually not, long integration times mean that a source is typically seen at all angles
  - However… it is potentially important for short observations

- How do you measure it?
  - Users must implement: FISHEYE_CORRECTION
  - Extension of the PSF IRF contains tables binned in E_{true} and θ. The correction is defined as a rotation with respect to the azimuthal axis away from the LAT boresight (for more details see FSSC)

Energy Dispersion

- D(E′; E, v, s): is the probability density to measure an event energy E′ for a gamma ray with (E, v) in the event selections

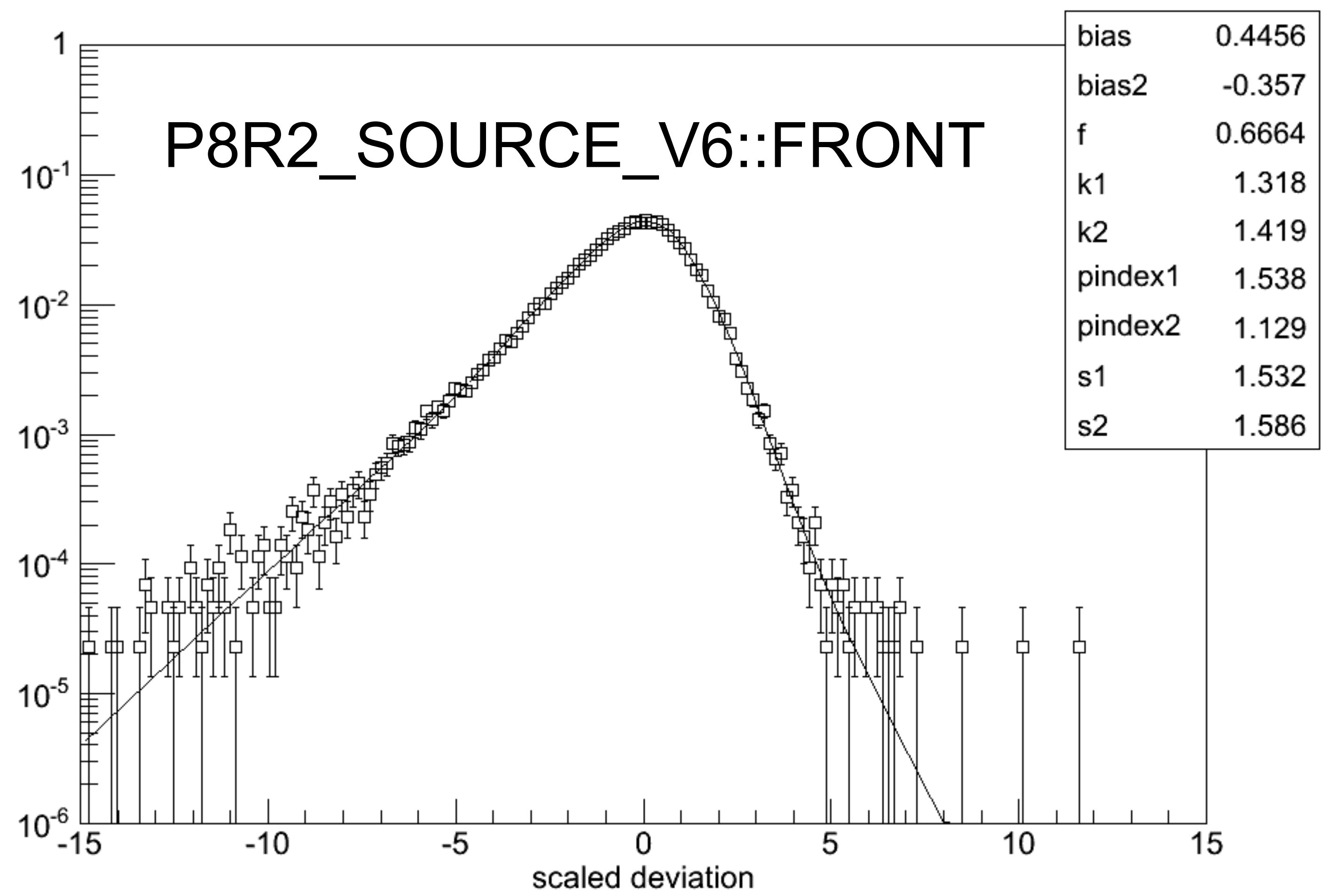
- Parameterization strategy similar to the PSF
  - energy dispersion function combines two asymmetric exponential power functions with overall normalization of one
  -

$$g(x;\sigma,k,b,p) = \frac{p}{\sigma\Gamma(1/p)}\frac{k}{1+k^2}\begin{cases}\exp\left(-\frac{k^p}{\sigma^p}|x-b|^p\right) & \text{if} \quad x-b \geq 0 \\ \exp\left(-\frac{1}{k^p\sigma^p}|x-b|^p\right) & \text{if} \quad x-b < 0\end{cases}$$

  - http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Pass8_edisp_usage.html

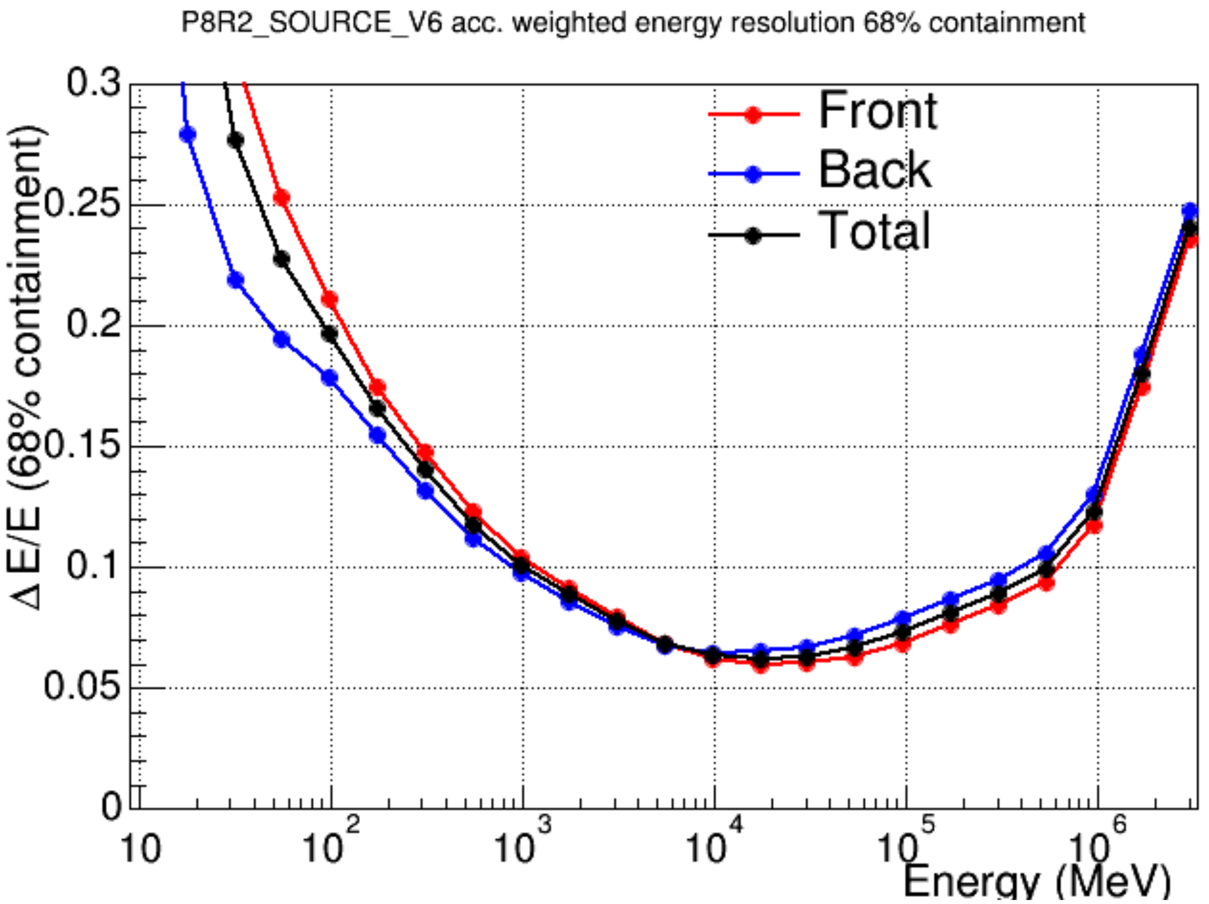
Energy Dispersion

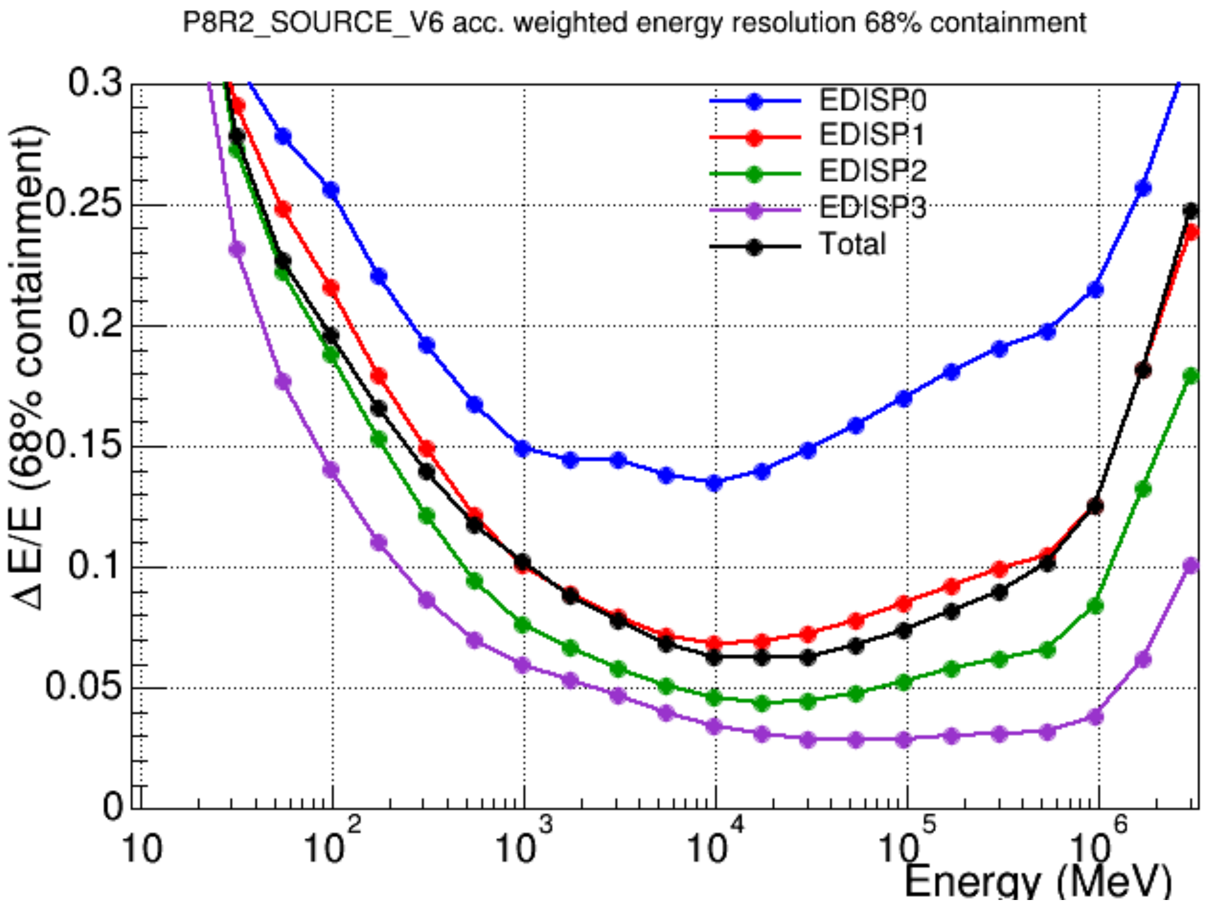
- **Unlike the PSF, energy dispersion is ignored by default in the standard likelihood fitting**
  - **negligible in many situations (above 100 MeV)**
  - **can be taken into account in Fermitools**



- **http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Pass8_edisp_usage.html**

Energy Resolution

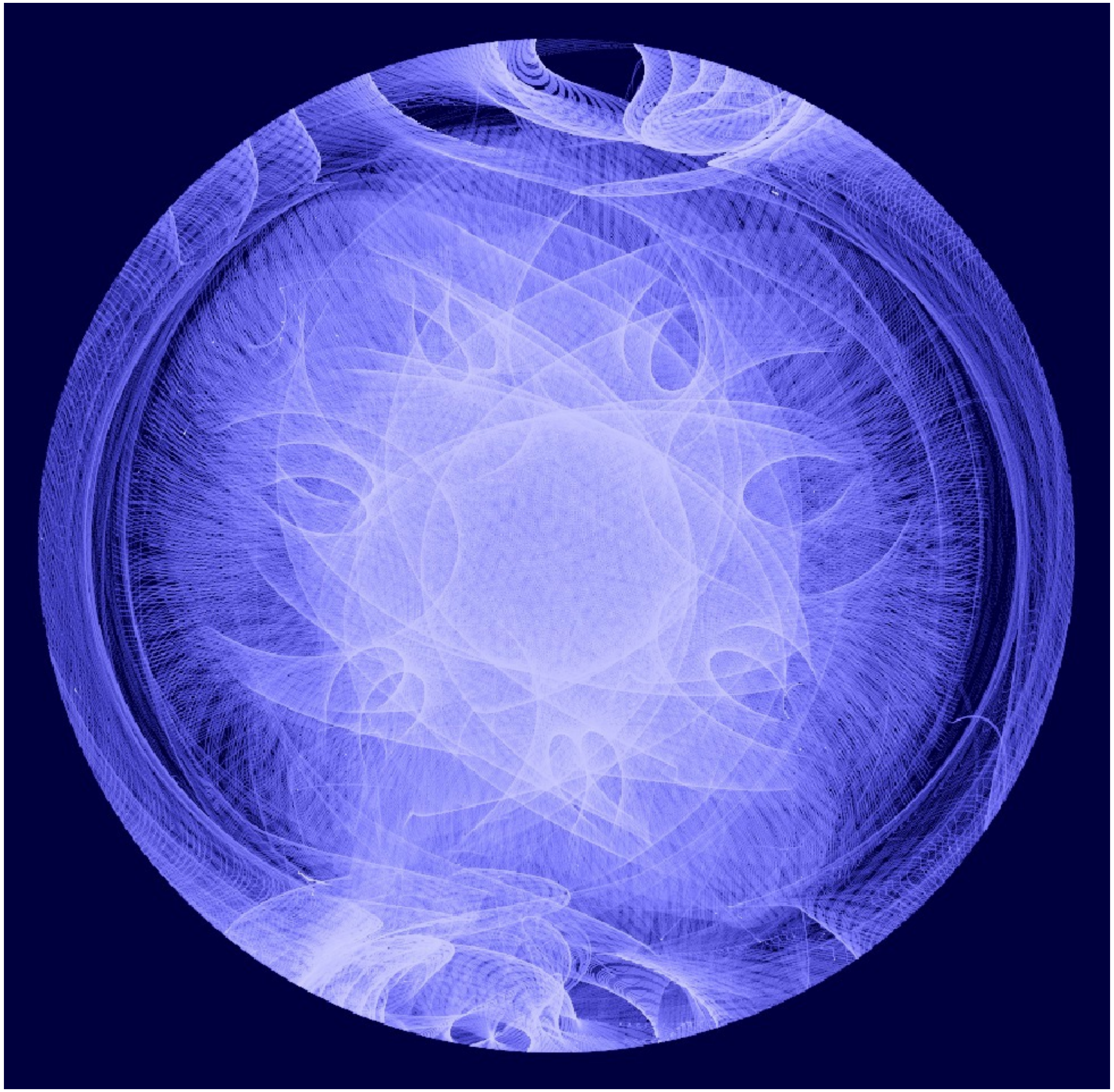




- **Energy resolution vs. E**
  - left: front/back event types, right: EDISP event types
- **Low energy limits**
  - energy deposited in tracker non-negligible
- **High energy limits**
  - shower leakage is dominant

Validating and Calibrating the IRFs

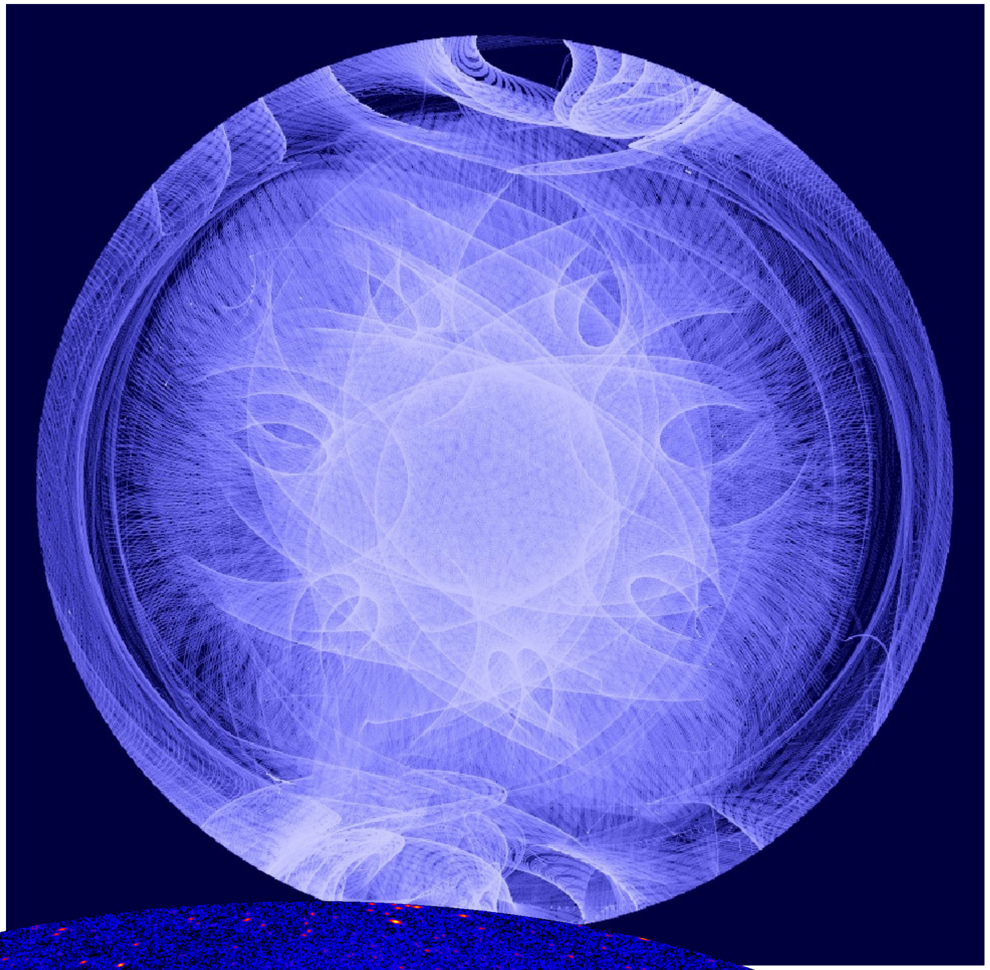
What is this?



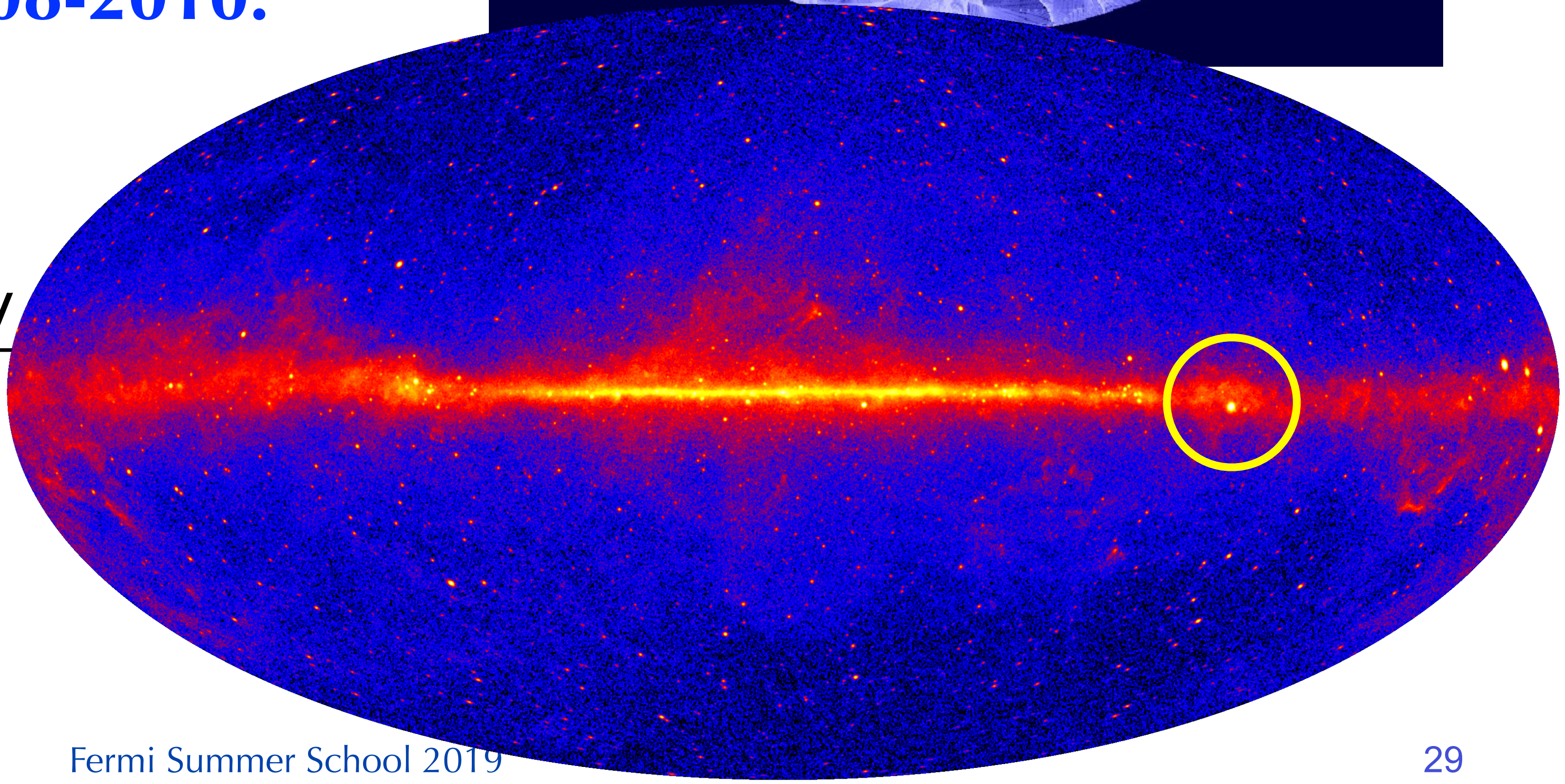
Credit: Eric Charles

What is this: The Vela Pulsar!

- The effects of pointing!
  - LAT orbits every 95 minutes
  - Rocks N/S on alternate orbits
  - solar panels pointed at the Sun



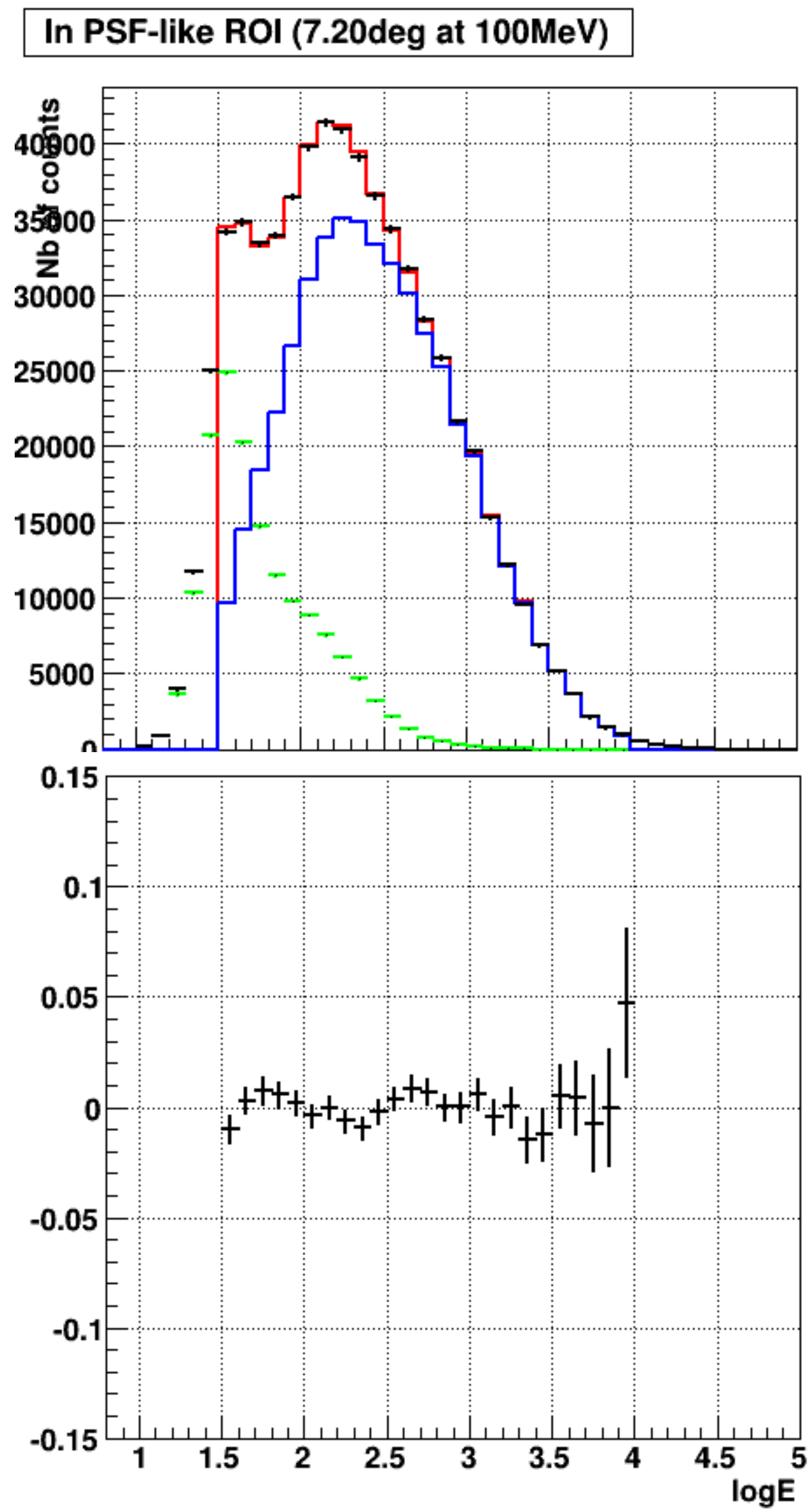
- Plot of the path of the Vela Pulsar centered on the instrument FoV
  - 180 degrees and follows Vela's position from August 2008-2010.



- http://apod.nasa.gov/apod/ap120504.html
-

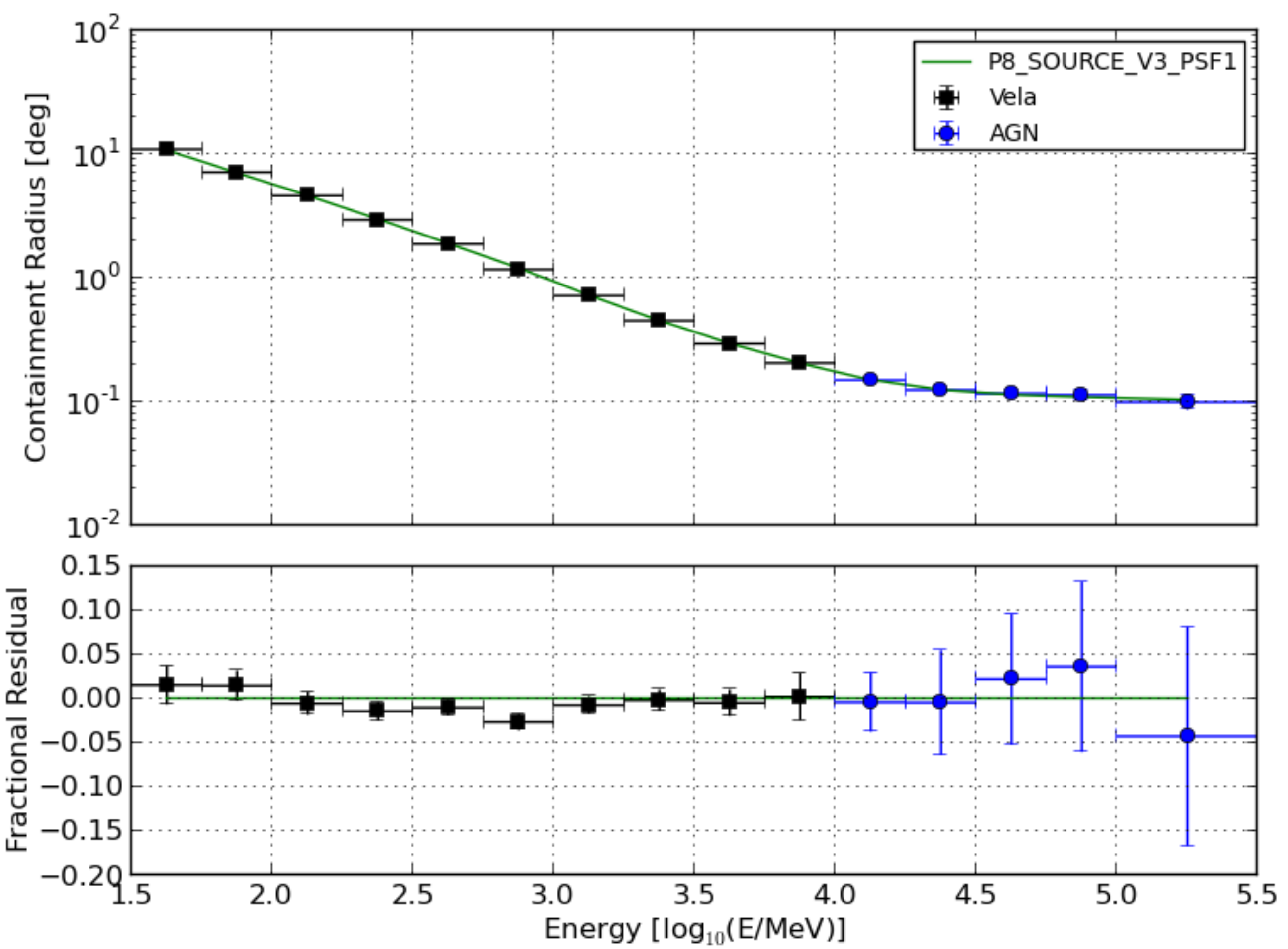
Flight Data Calibration Samples

- Vela pulsar
  - 30° ROI
  - ~4.7 years
  - phase gated
  - $\theta_z < 100°$
- AGN (~20)
  - 4° ROI around AGN (PSF)
  - 4.8 years
  - standard DQ
  - $\theta_z < 100°$
- Limb
  - $\theta_z > 107°$
  - E>10 GeV
- All Sky
  - E>10 GeV



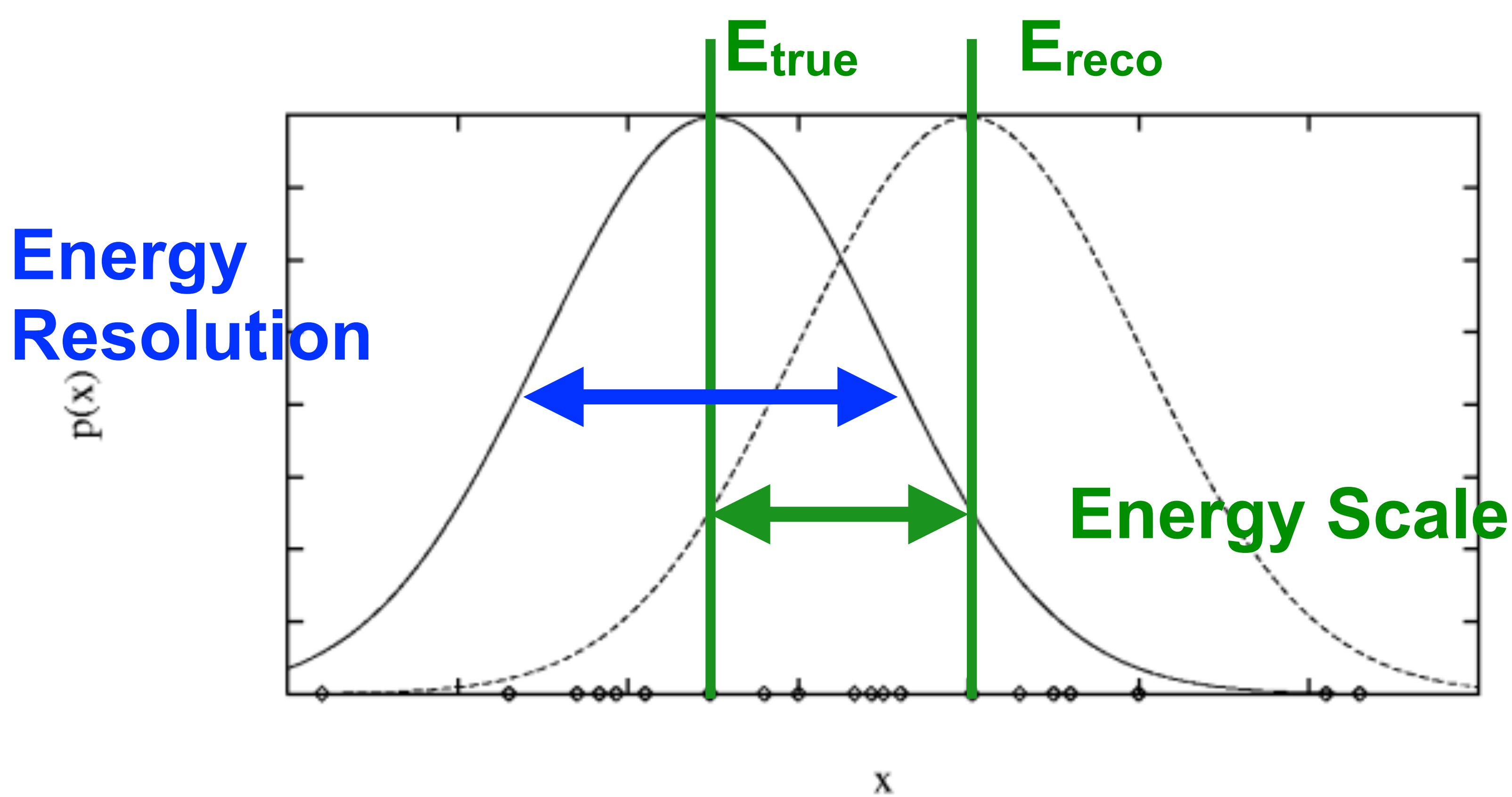
Validation of Point Spread Function

- Point sources at known locations (from other wavelengths)
  - most notably pulsars and AGN
  - Note: deviation from a point source (e.g. a halo) is the physical effect we're searching for
- Compared the measured 68% and 95% PSF containment radii for selected point sources with the PSF parameterization
  - on axis vs. off axis events
- By default you are using a PSF parameterization averaged over the LAT field of view
  - Always be careful when using short time observations



Validation of Energy Scale and Resolution

- Two aspects of the validation of the energy measurement
  - energy scale: the true value vs. the reconstructed value
  - energy resolution: event by event fluctuations around a true value
- Example: studying a gamma-ray line
  - no known astrophysical source with GeV gamma-ray line
- Ground tests, beam tests, measurement of CRE geomagnetic cutoff
  - energy resolution at the ~10% level
  - energy scale at the +/-5 % level

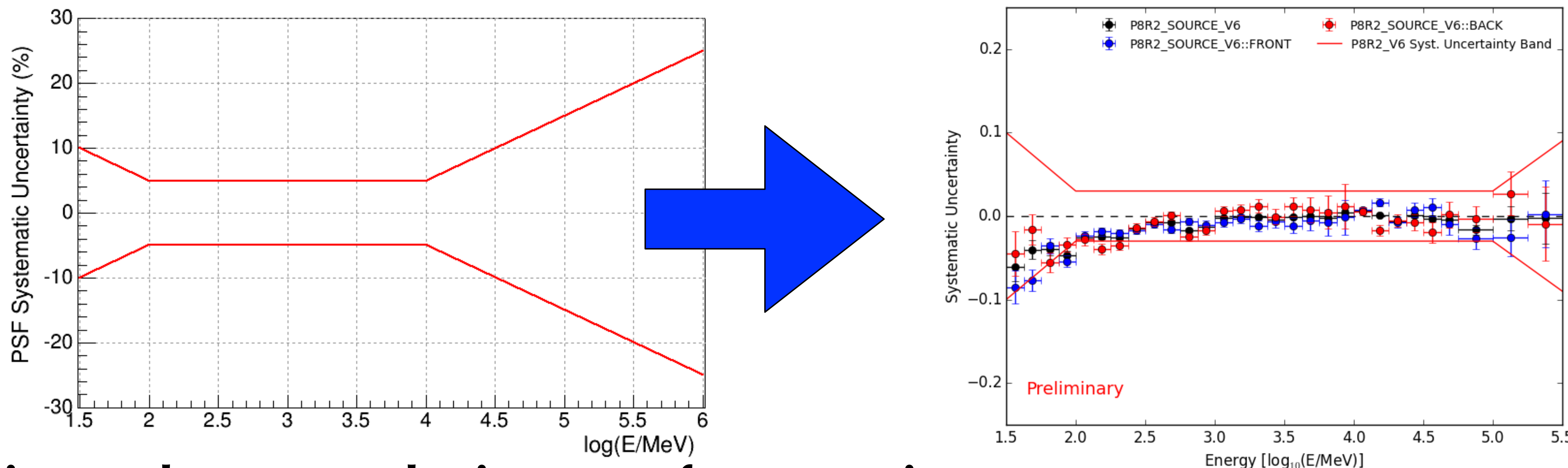


Would you prefer a low energy or a high energy tail?

Systematic Uncertainties

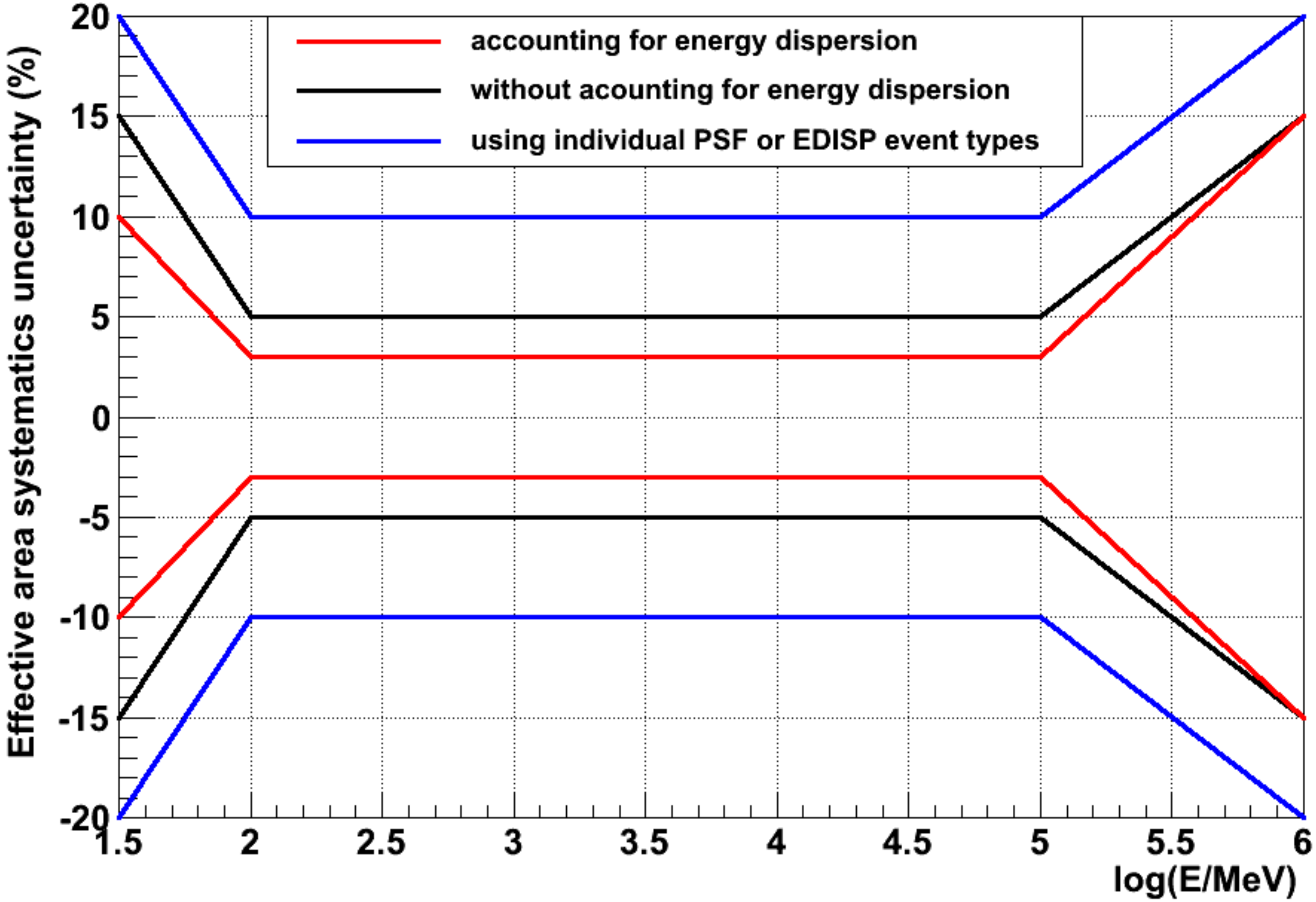
Bracketing Functions

- **Define a conservative systematic uncertainty**
  - **draw envelope that encompasses the largest residual observed in the A_{eff}/PSF/E_{disp} validation at each energy**



- **This envelope tests the impact of systematics on your analysis**
- **Note instrumental systematics are only one component of the total systematic uncertainty**
  - **astrophysical uncertainties in modeling the sky can be as large or larger than the instrumental systematics (unmodeled point sources, errors in the isotropic an galactic diffuse templates)**

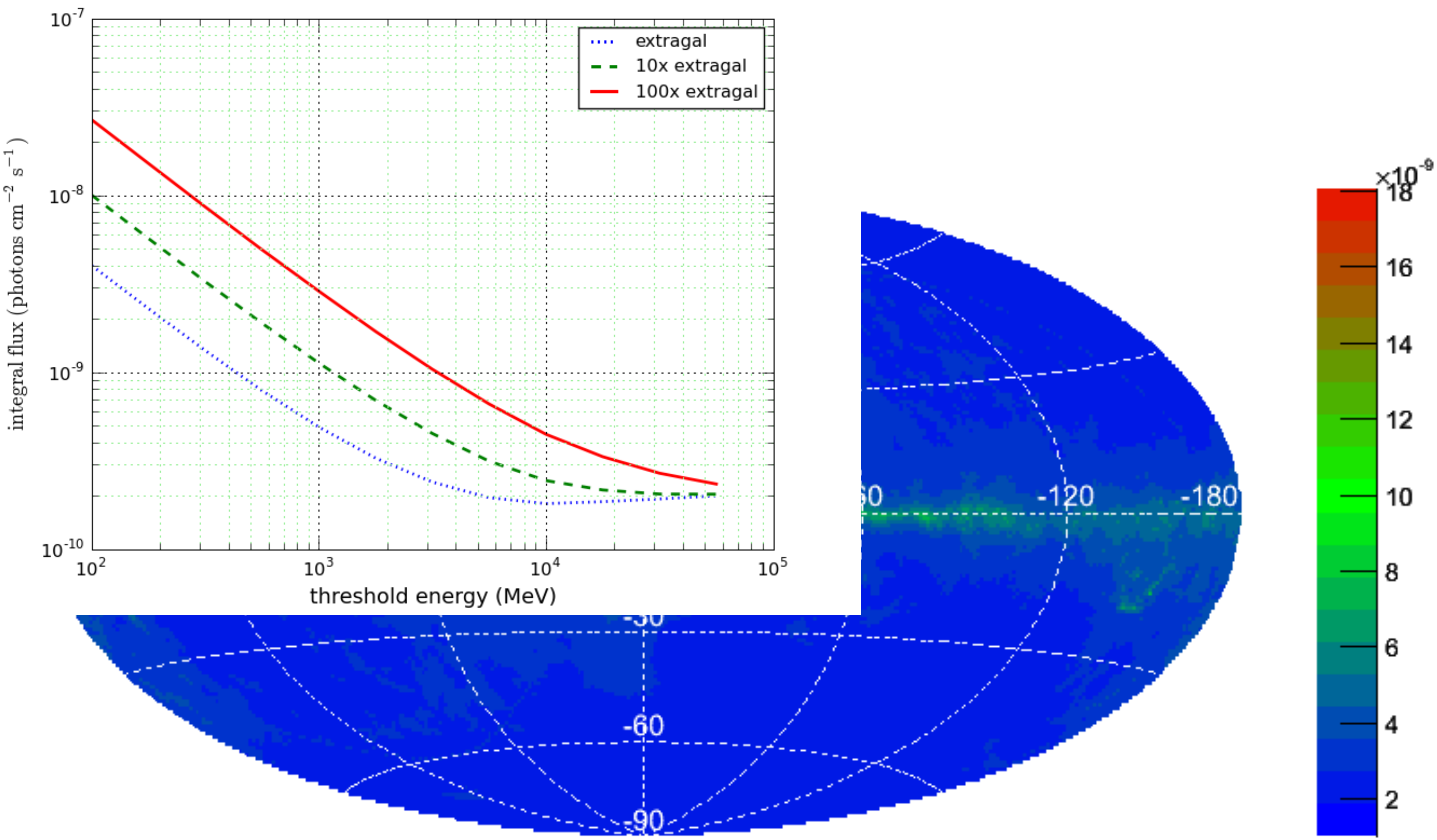
Assessing the Systematic Uncertainty



http://fermi.gsfc.nasa.gov/ssc/data/analysis/LAT_caveats.html

Source Sensitivity

Source Sensitivity



Determining which event class to use

Event Selection Recommendations (P8R3)

Analysis Type	Minimum Energy (emin)	Maximum Energy (emax)	Max Zenith Angle (zmax)	Event Class (evclass)	IRF Name
Galactic Point Source Analysis	100 (MeV)	500000 (MeV)	90 (degrees)	128	P8R3_SOURCE_V2
Off-plane Point Source Analysis	100 (MeV)	500000 (MeV)	90 (degrees)	128	P8R3_SOURCE_V2

Time Selection Recommendations

Analysis Type	ROI-Based Zenith Angle Cut (roicut)	Relational Filter Expression (filter)
Galactic Point Source Analysis	no	(DATA_QUAL>0)&&(LAT_CONFIG==1)
Off-plane Point Source Analysis	no	(DATA_QUAL>0)&&(LAT_CONFIG==1)
Burst and Transient Analysis	yes	(DATA_QUAL>0)&&(LAT_CONFIG==1)
Galactic Diffuse Analysis	no	(DATA_QUAL>0)&&(LAT_CONFIG==1)
Extra-Galactic Diffuse Analysis	no	(DATA_QUAL>0)&&(LAT_CONFIG==1)
Burst and Transient Analysis	yes	(DATA_QUAL>0||DATA_QUAL==-1)&& (LAT_CONFIG==1)

https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Data_Exploration/Data_preparation.html

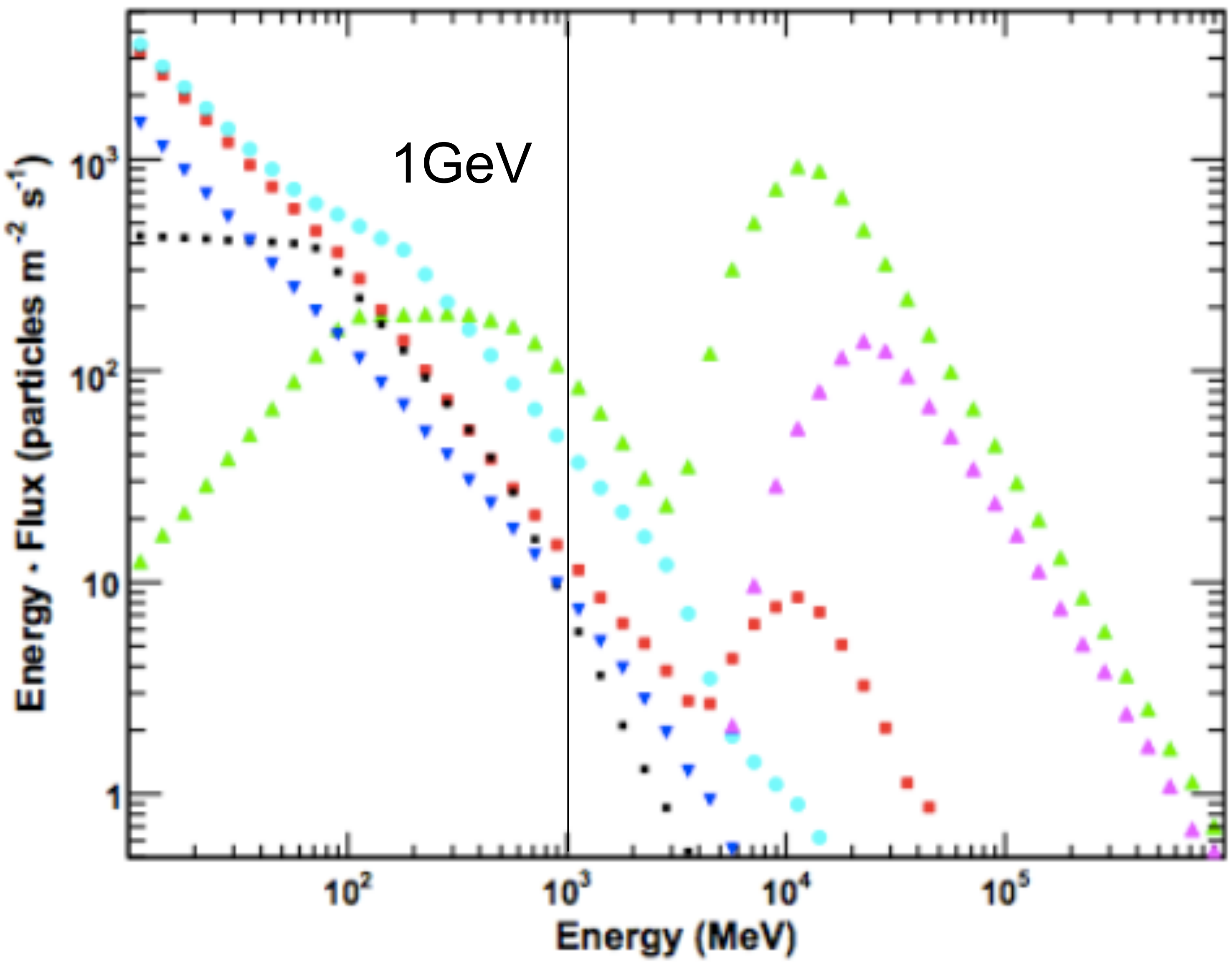
Summary

- The LAT is designed to be used for a diverse range of scientific topics
  - flexibility for these diverse topics adds to the complexity
  - huge amount of instrumental phase space to calibrate
- The LAT team has put a huge effort into understanding the instrument
  - validation studies verify that the IRFs provide a good description of the instrument
  - residuals usually ~2-3% and conservatively assess the systematic uncertainty on the A_{eff} at 3-10% between 100 MeV and 500 GeV
- Propagating systematic uncertainties to high-level analyses can be tricky
  - analysis dependent… Do NOT skip this step…

KAHOOT TIME!

Backups

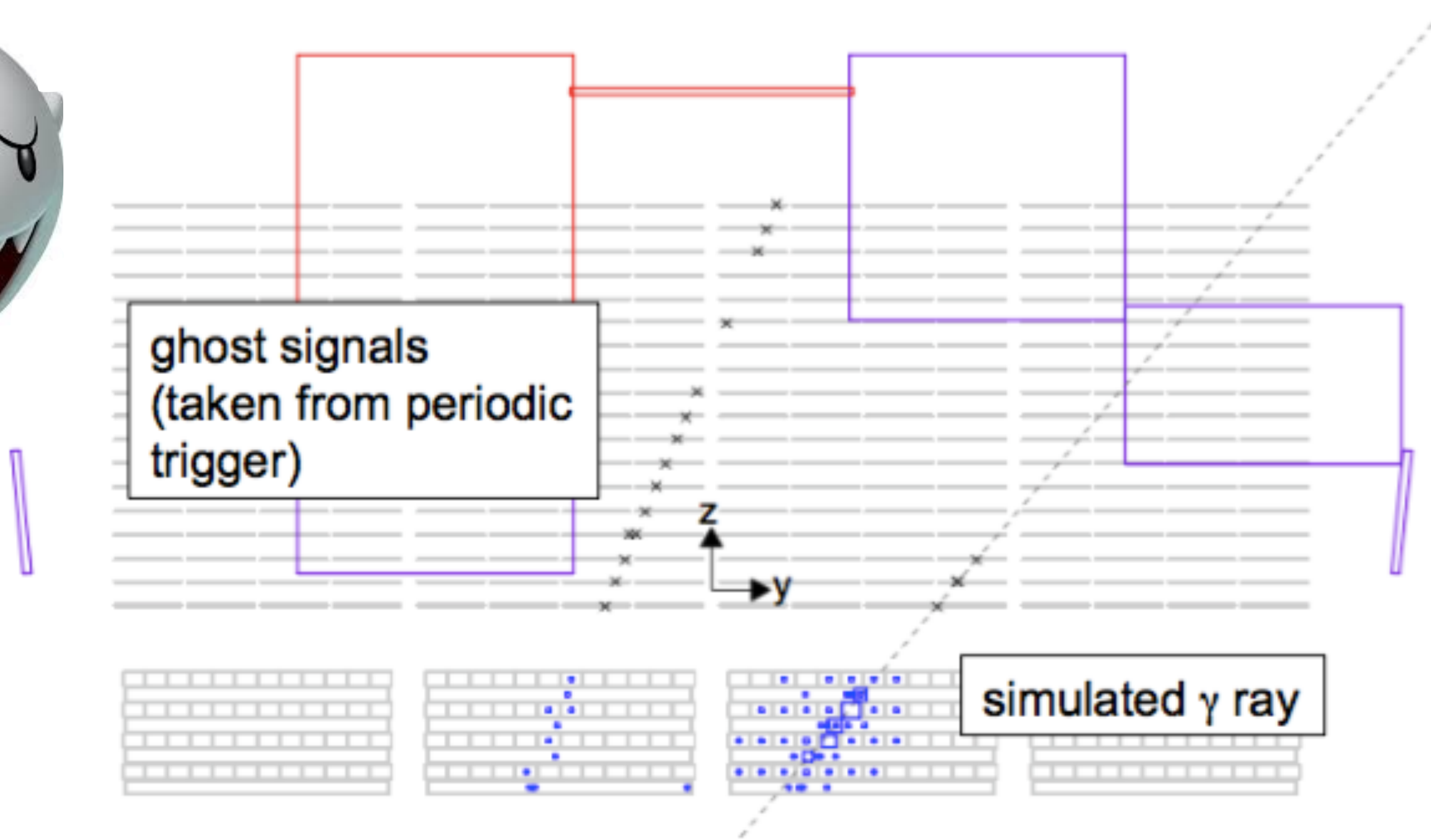
Particle Backgrounds



Backgrounds:
protons (green filled triangles up),
He (purple filled triangles up),
electrons (filled red squares),
positrons (light blue squares),
Earth albedo neutrons (black squares),
Earth albedo γ-rays (dark blue triangles dn).

http://arxiv.org/pdf/0902.1089v1.pdf

Ghost events



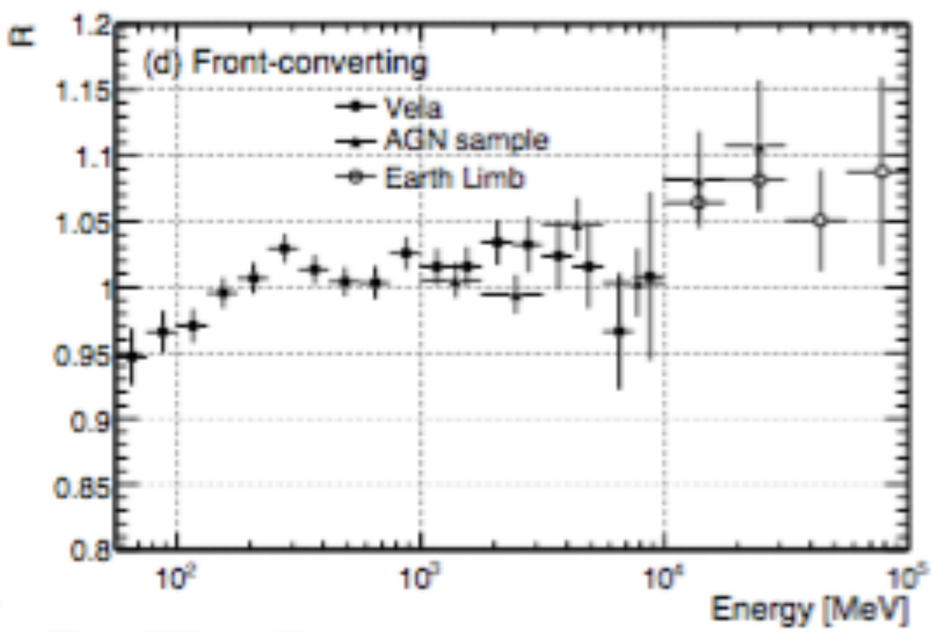
- Response also depends on pile-up - “ghost” signals left by out-of-time events
- Model ghost signals by injecting overlay events into the MC
- Overlay events are from a library of periodic triggers which sample the quiescent state of the detector

Validation of Effective Area

- No astrophysical source with perfectly known flux
- Measure of the selection efficiency
  - efficiency cut by cut (ie transient vs. source vs. clean)
  - includes all selection steps from trigger to filter to event classes

- Compare cut efficiency on MC and flight data sets

- Consistency checks
  - are event rates for front vs. back events as predicted by simulations?



Fraction of events converting in the front section relative to MC prediction
➜ sensitive to inaccuracies in detector description materials and geometry

Trigger Rates