Fermi-LAT Performance

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Fermi Summer School
Lewes, DE

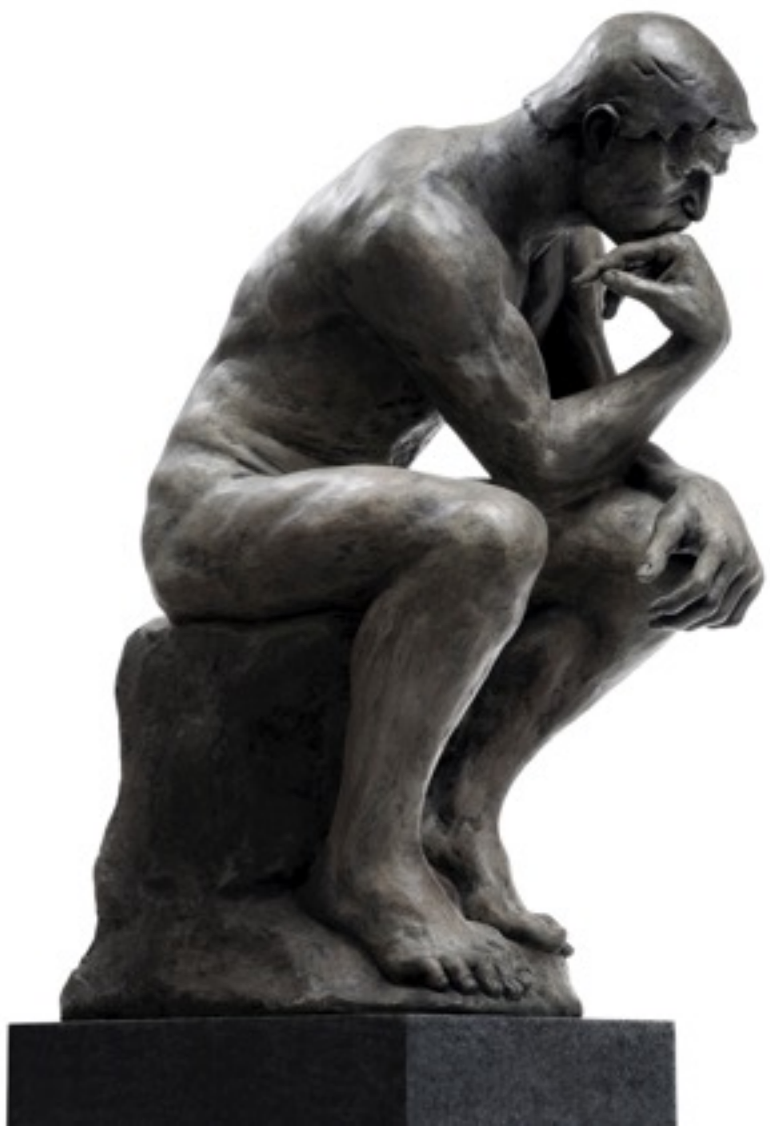
June 8, 2016

Outline

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

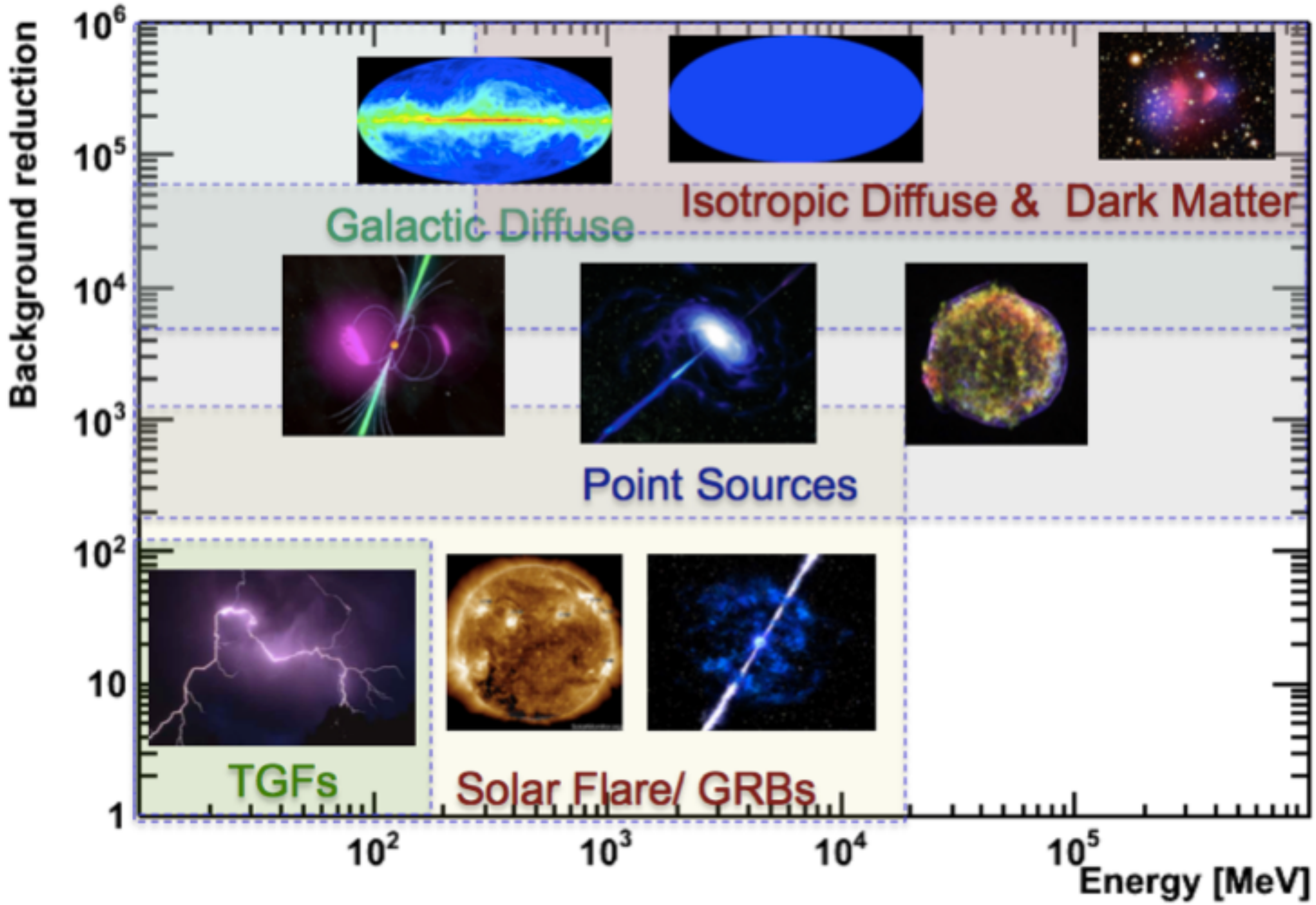
Please refer to:
The Fermi Large Area Telescope On Orbit:
Event Classification,Instrument Response Functions, and Calibration (or How I Learned to Stop Worrying and Love the Instrument)
Fermi-LAT Collaboration, 2012 ApJS, 203, 4
arXiv:1206.1896
And Luca B, Eric C, and Matt W's slides from previous summer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

What is the LAT? and
How do we optimize it for science?



Thankfully Julie already covered (1)

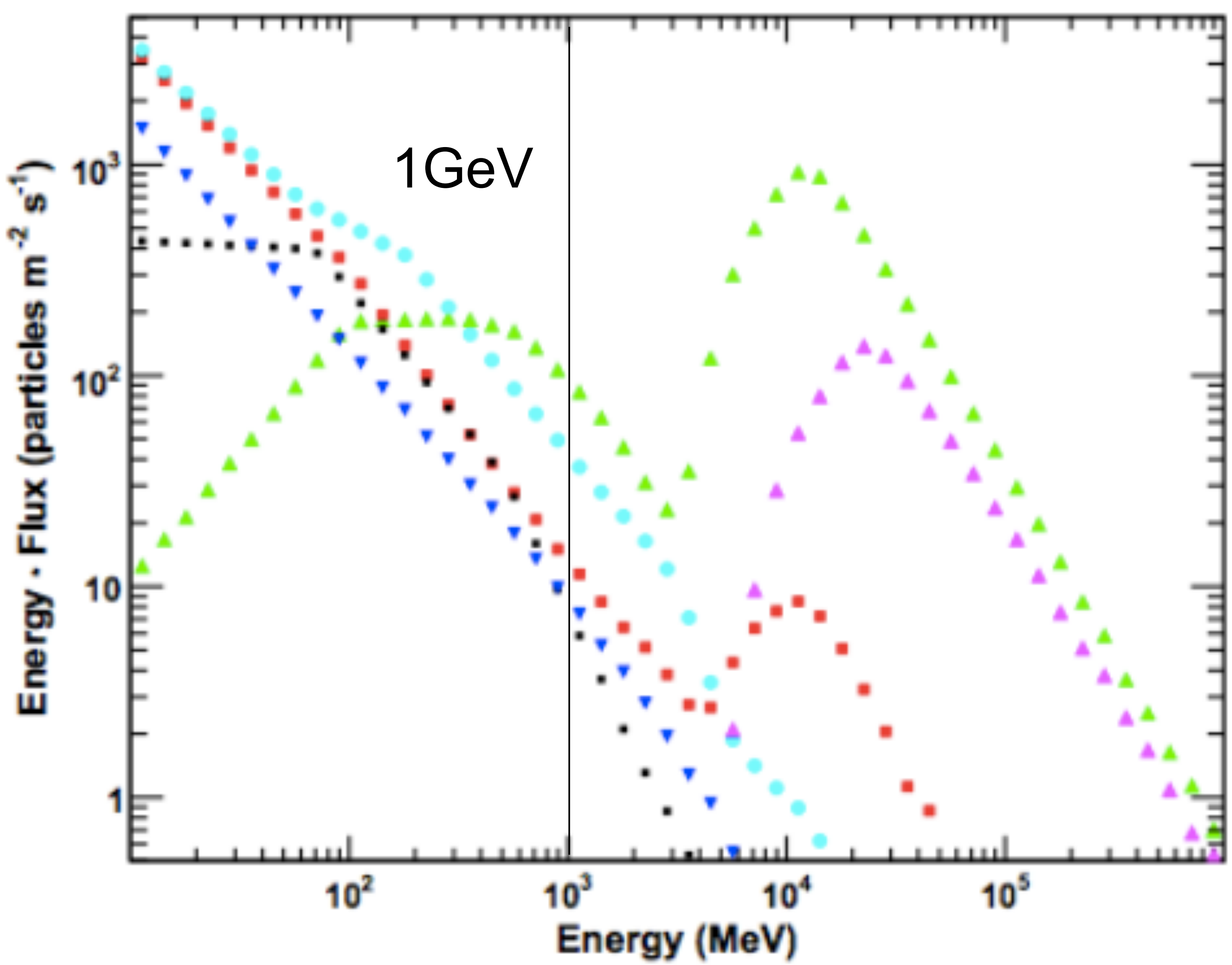
A Broad Range of Fermi-LAT Science



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

Getting to know you… what do you study?

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

Diverse Science: Event Classes/Event Types

P8R2 IRF name	Event Class (evclass)	Class Hierarchy	Photon File	Extended File
P8R2_ULTRACLEANVETO_V6	1024	Standard	X	X
P8R2_ULTRACLEAN_V6	512	Standard	X	X
P8R2_CLEAN_V6	256	Standard	X	X
P8R2_SOURCE_V6	128	Standard	X	X
P8R2_TRANSIENT010_V6	64	Standard		X
P8R2_TRANSIENT020_V6	16	Standard		[illegible]
P8R2_TRANSIENT010E_V6	64	Extended	[illegible]	[illegible]
P8R2_TRANSIENT020E_V6	8	Extend[illegible]	[illegible]	[illegible]
P8R2_TRANSIENT015S_V6	65536	No-ACD	[illegible]	[illegible]

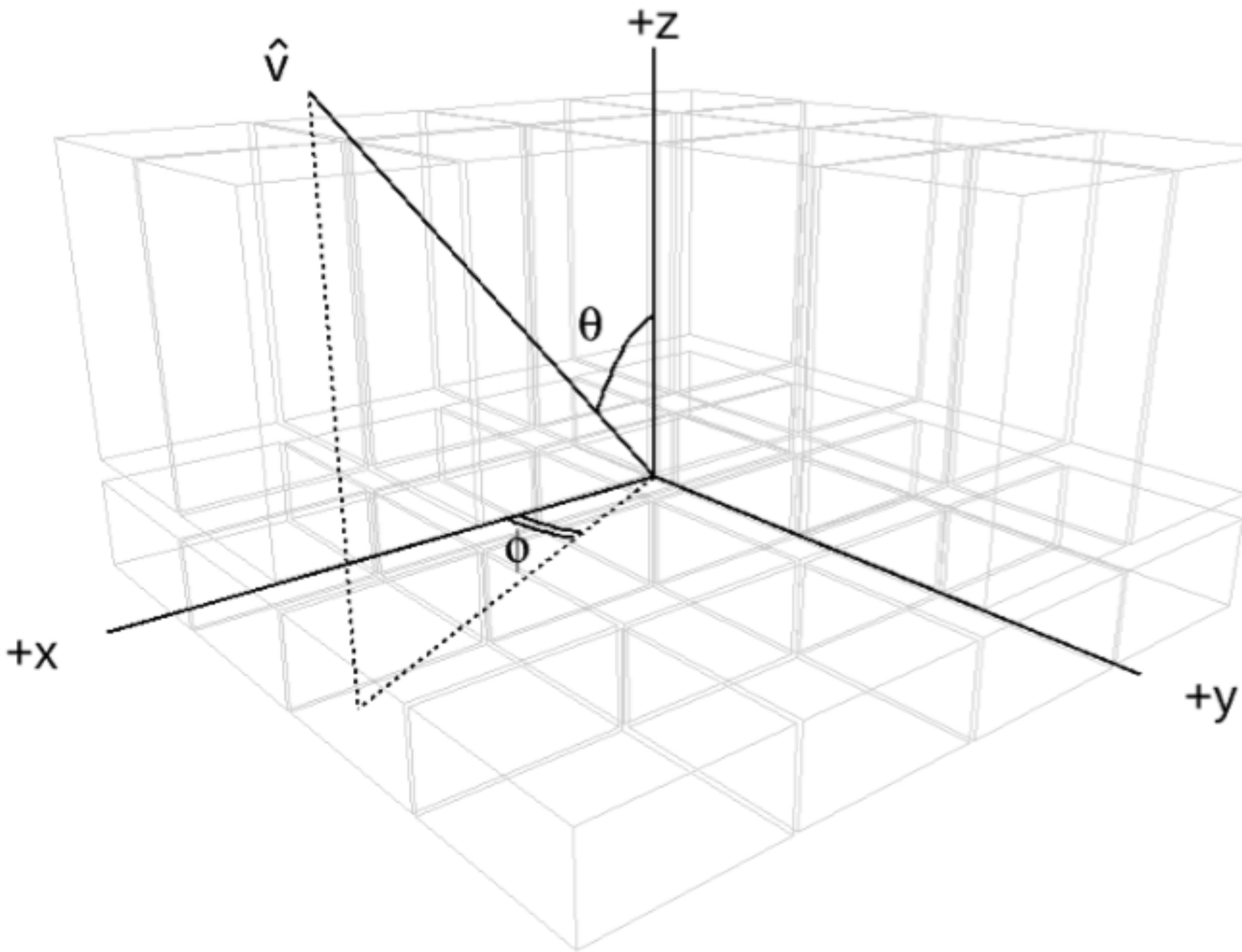
P8R2 Event Type Name	Event Type Partition	Event Type Value (evtype)
FRONT	Conversion Type	1
BACK	Conversion Type	2
PSF0	PSF	4
PSF1	PSF	8
PSF2	PSF	16
PSF3	PSF	32
EDISP0	EDISP	64
EDISP1	EDISP	128
EDISP2	EDISP	256
EDISP3	EDISP	512

Check out the FSSC for more details…

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

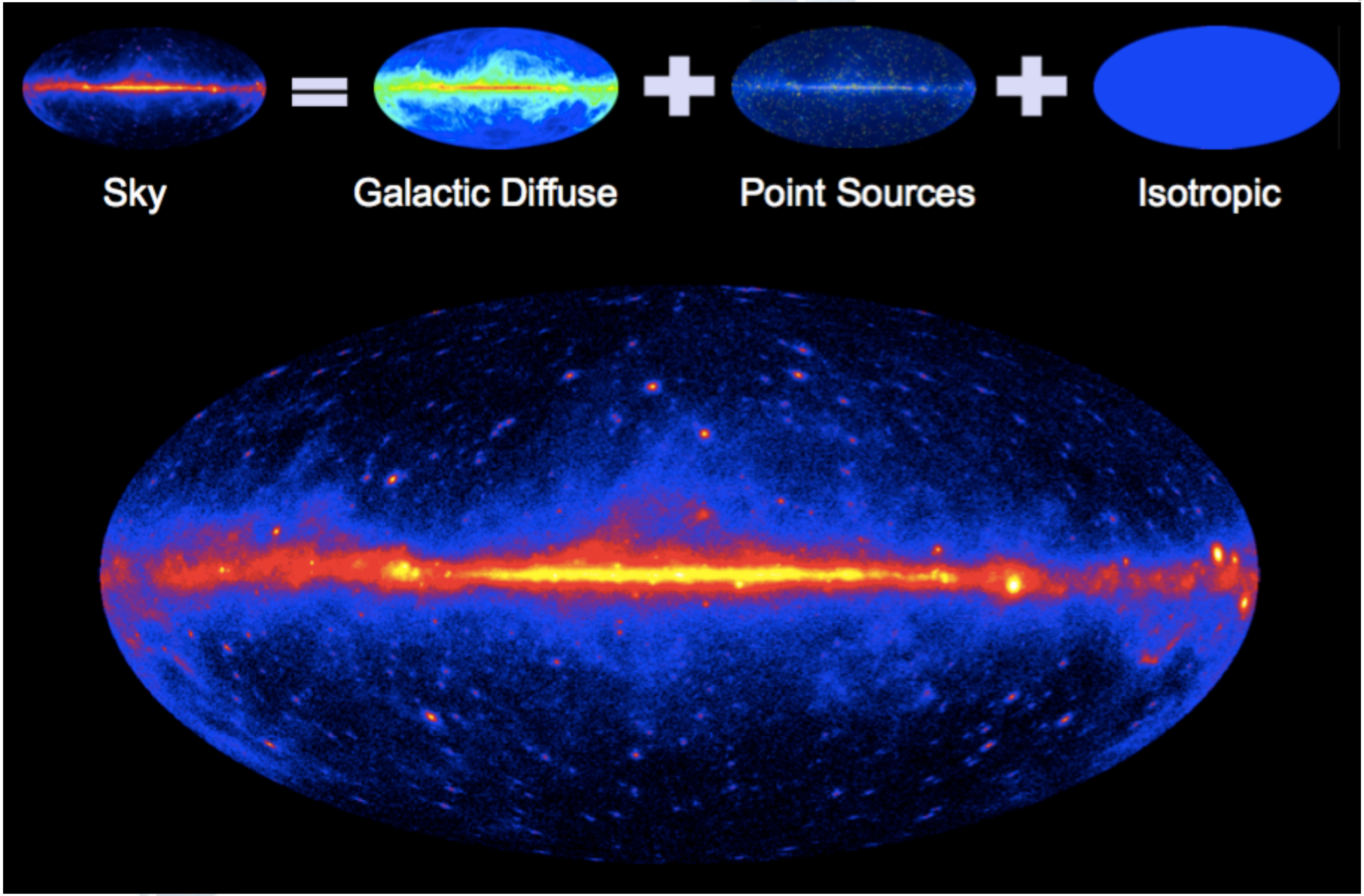
Instrument Response Functions (IRFs)

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

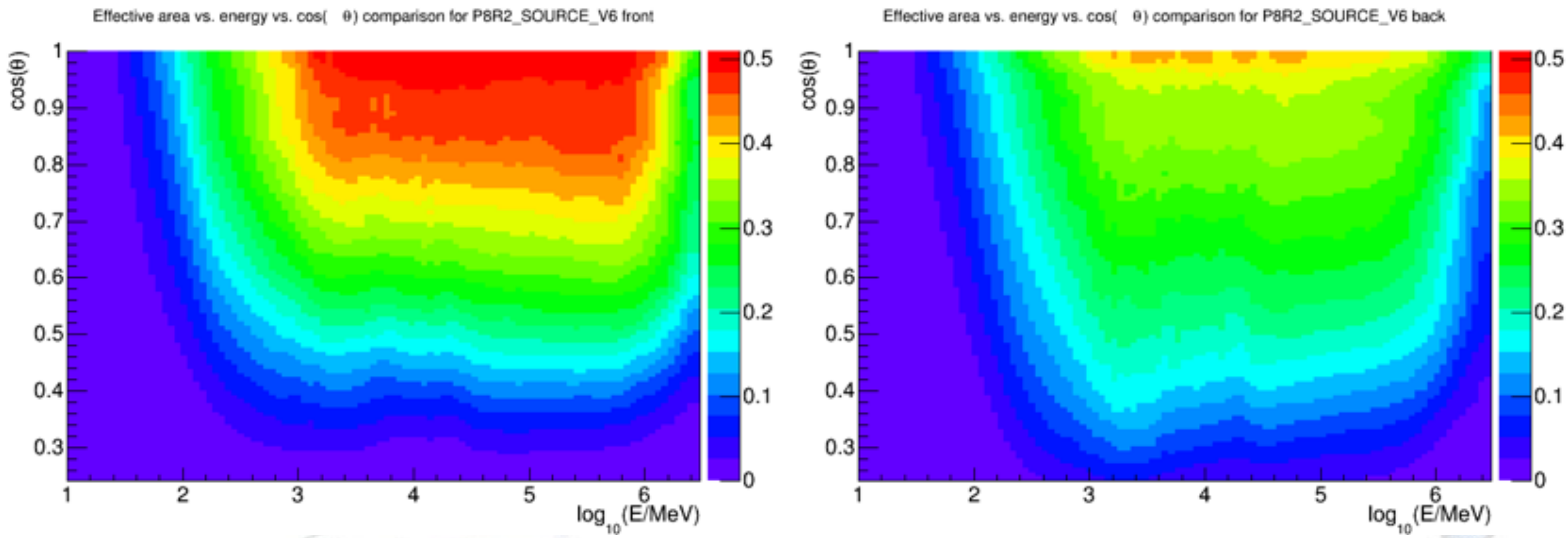
Expected Count Rate

Source Flux

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

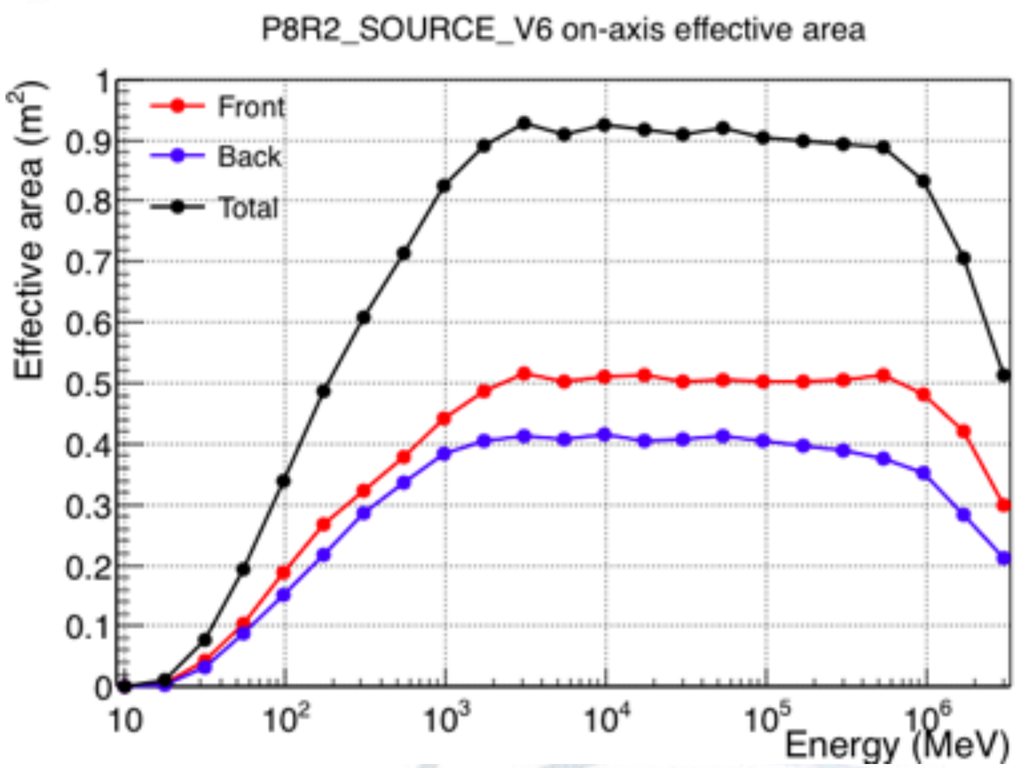
Instrument Response

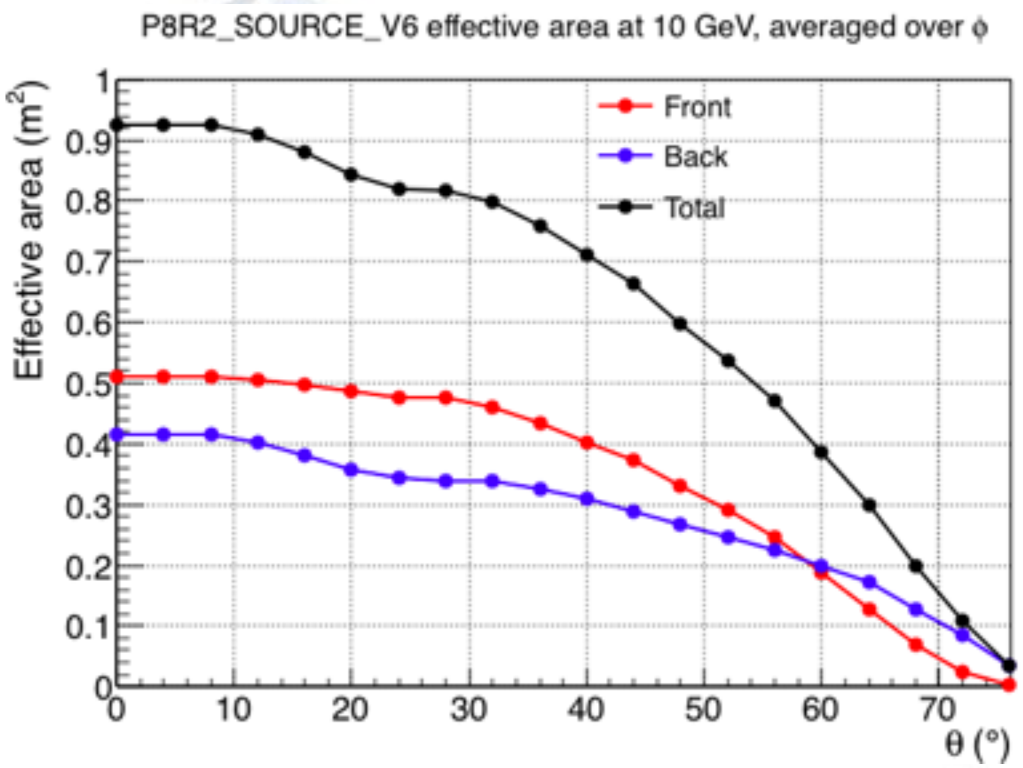
Effective Area



- **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 flus, count events that pass event selection, normalize to input flux**
- **Events binned in log(E) and cos θ**
  - **ScienceTools takes care of interpolations**
  - **ϕ dependence small, treated as correction**

Effective Area



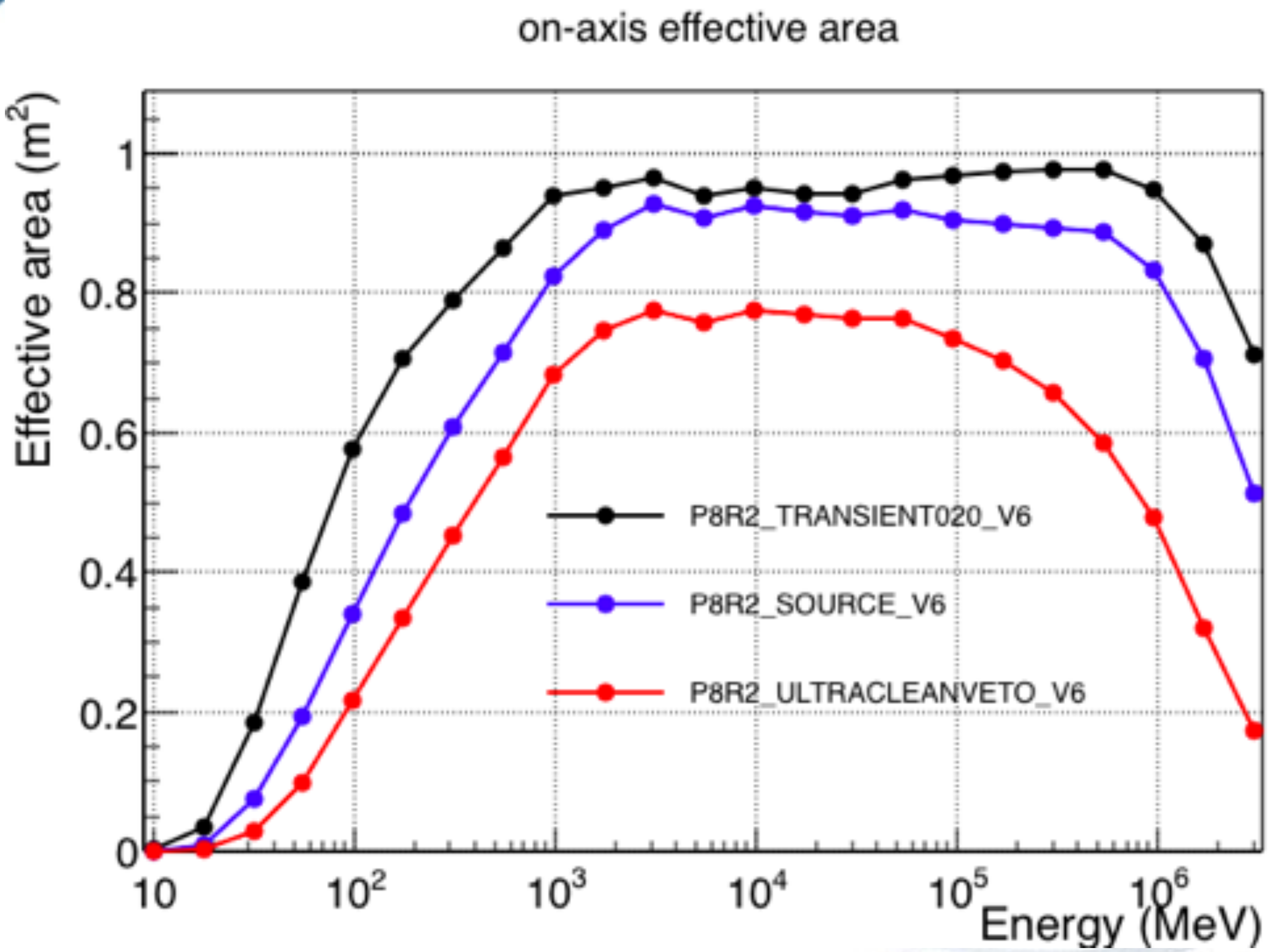


- A_{eff} vs E (at fixed θ)
  - Increases up to 1 TeV
  - >1 TeV events are harder to reconstruct and event rates drop
- A_{eff} vs θ (at fixed E)
  - Less cross section as you go off-axis
  - Off-axis events easier for back-converting events to intercept the calorimeter

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

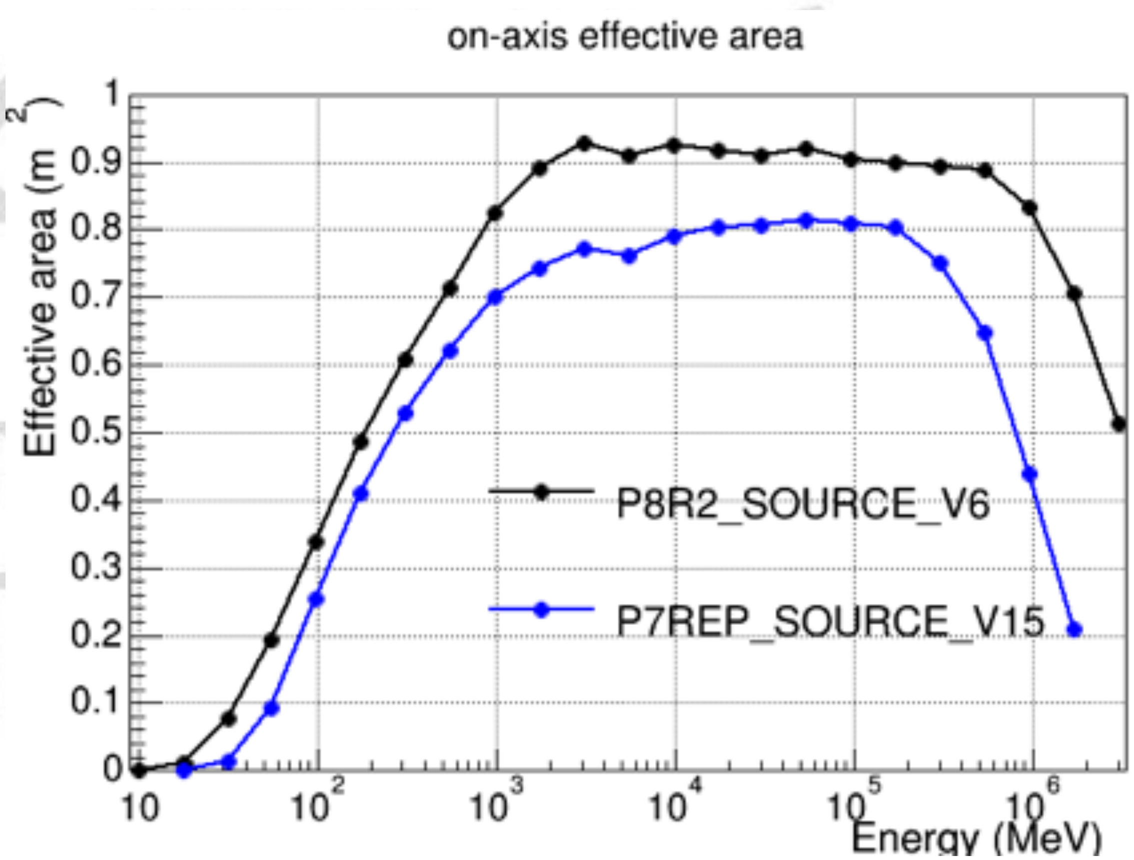
What happens at low energies?

Effective Area and Event Classes

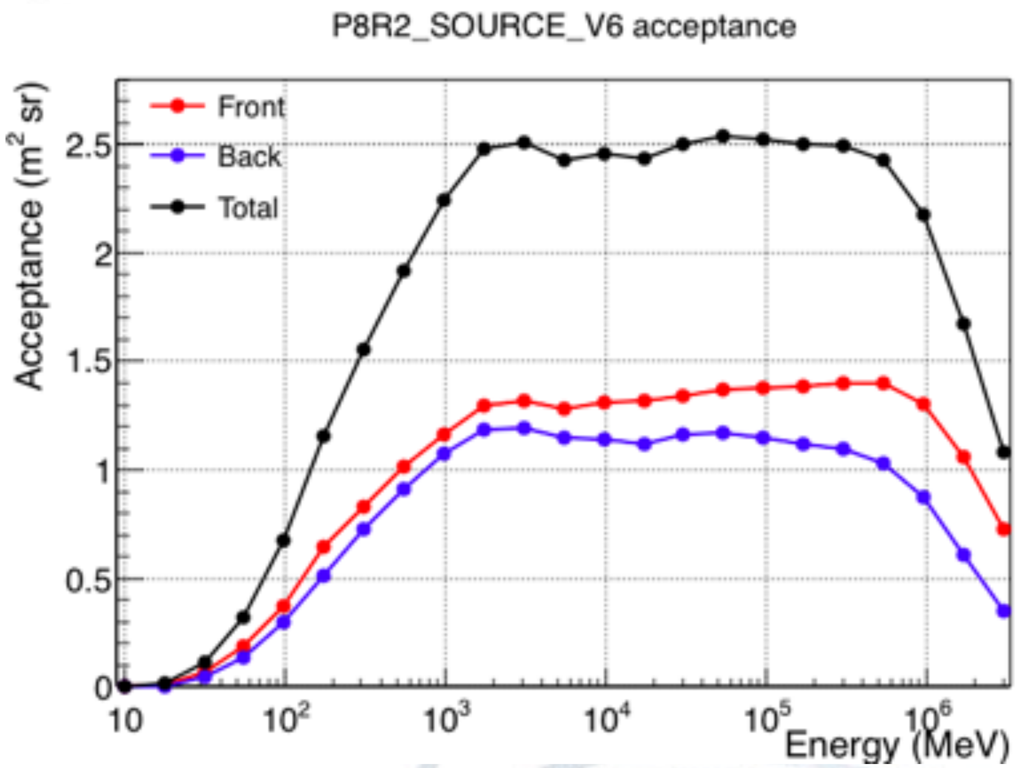


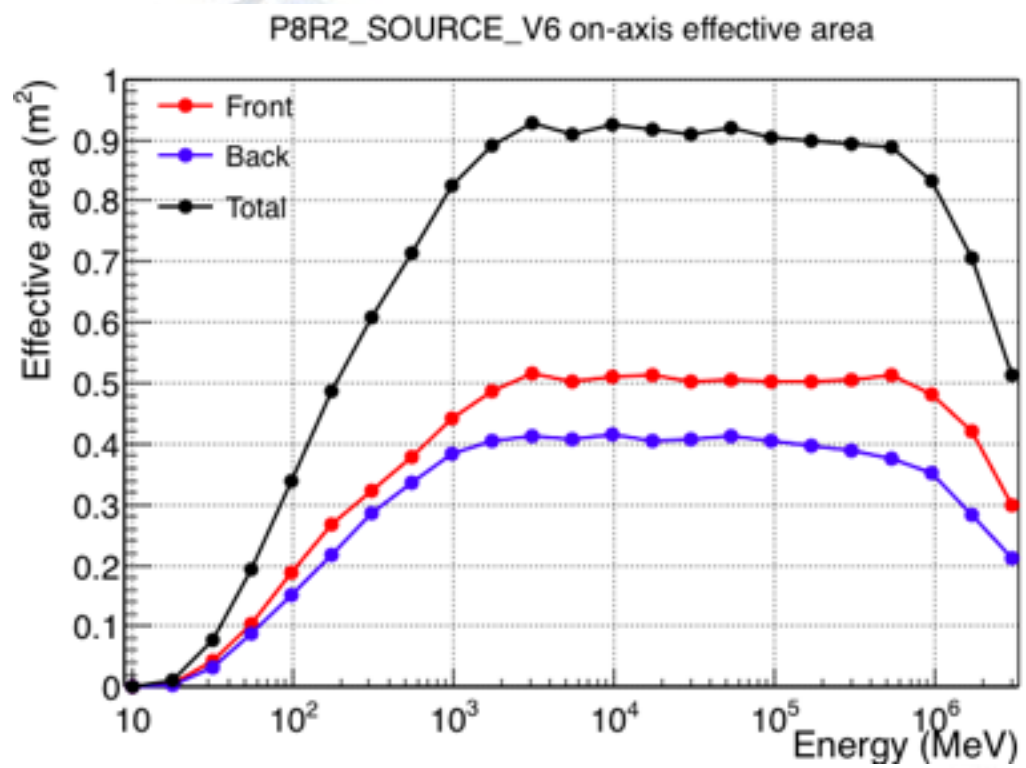
Tip:
Always think about the source signal vs. background

Passes: Event reconstructions
Now vs. Then



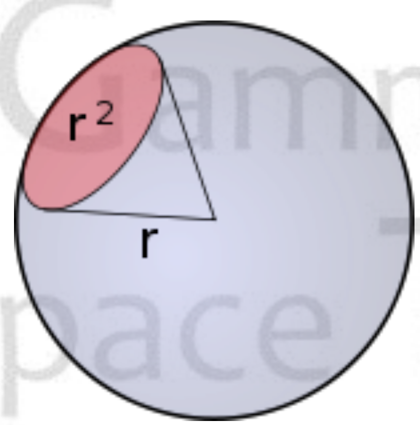
Acceptance and Field of View





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

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



= 1 sr

Point Spread Function

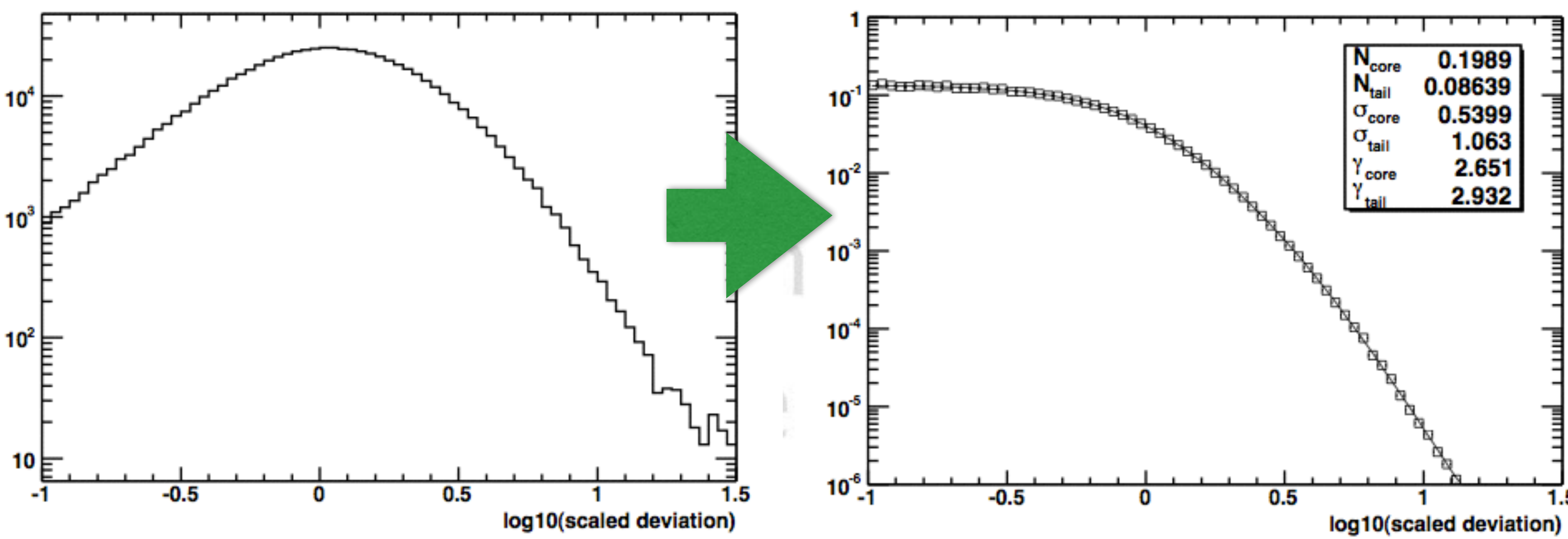
- P(v′;E,v, s): the probability density to reconstruct an incident direction (v′) for a gamma ray with (E, v) in a given event selection, s
- For a given point (E) in the LAT phase space the PSF is a p.d.f.:
  - functional form to parameterize it (for MC PSF): two King Functions

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

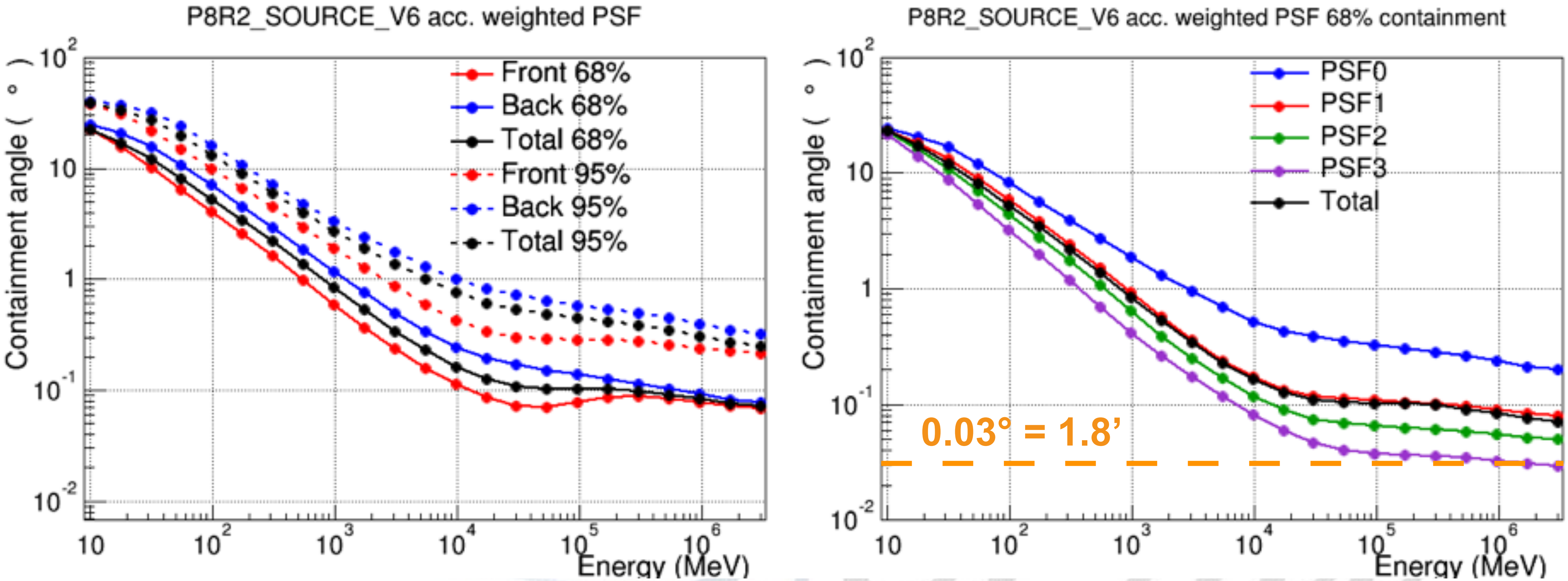
- The PSF varies by orders of magnitude across the LAT energy range
  - low energy dominated by multiple Coulomb scattering in the W conversion foils
  - high energy determined by the tracker strip pitch and lever arm

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.**

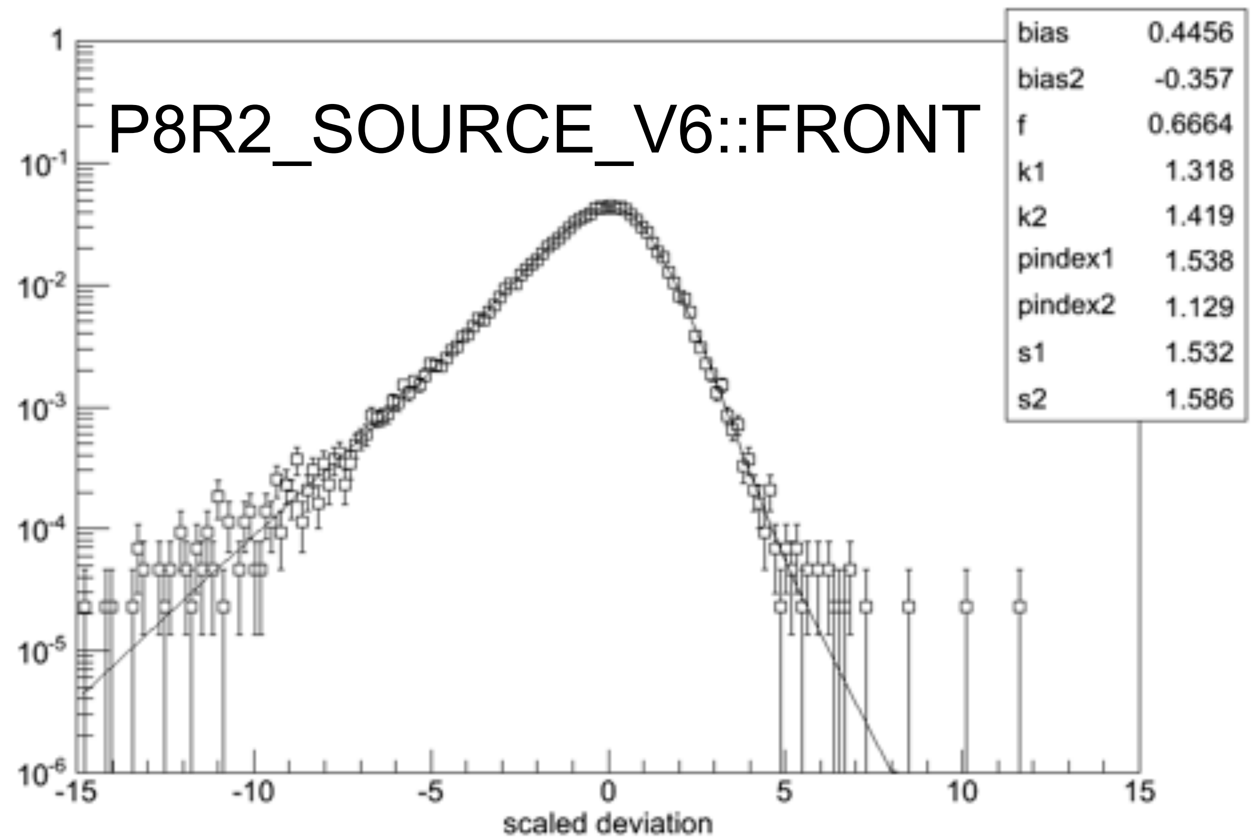
Why do front/back events have a different PSF?

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)

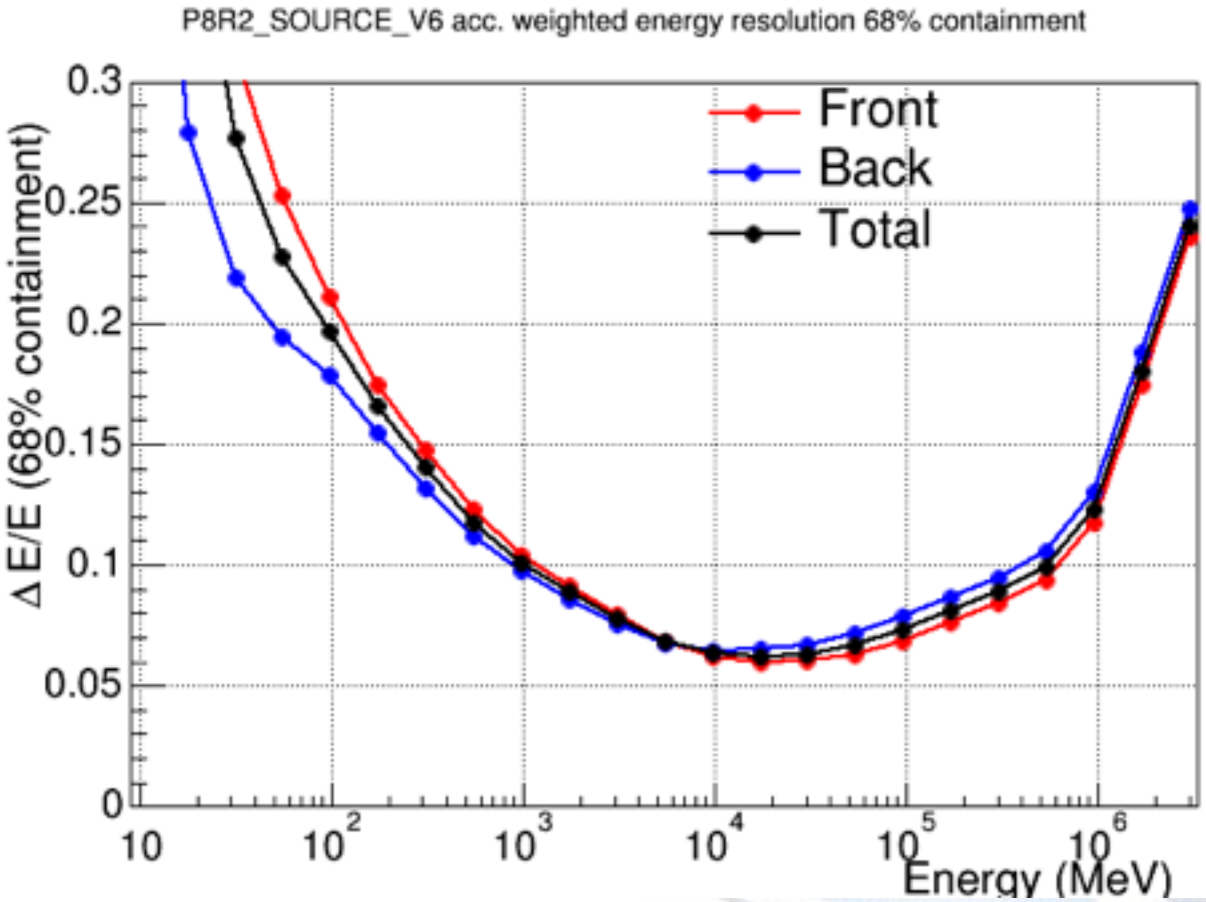
Energy Dispersion

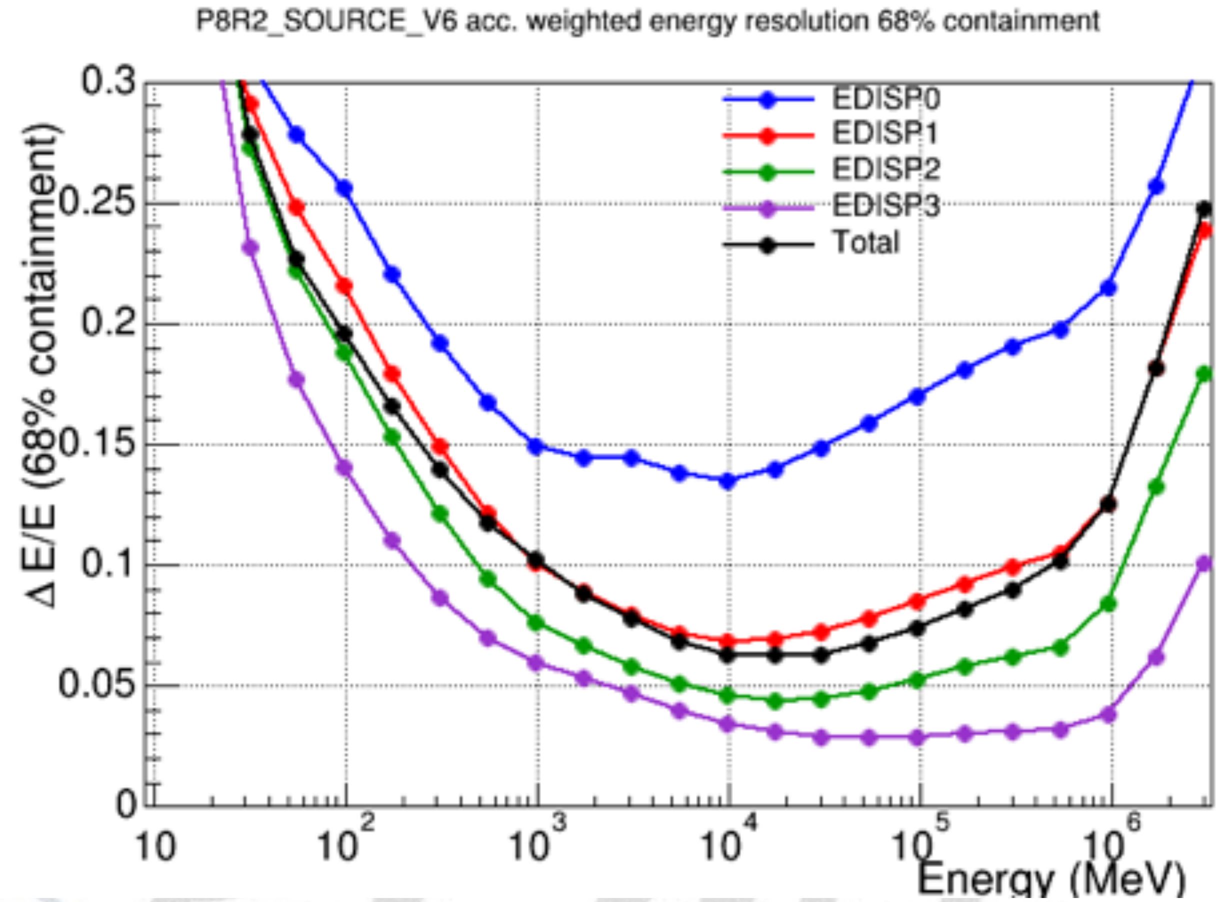
- D(E′; E, v, s): is the probability density to measure an event energy E′ for a gamma ray with (E, v) in the event selection s
- Parameterization strategy similar to the PSF
  - energy dispersion function combines two asymmetric exponential power functions with overall normalization of one
- Unlike 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 ScienceTools



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

Energy Resolution



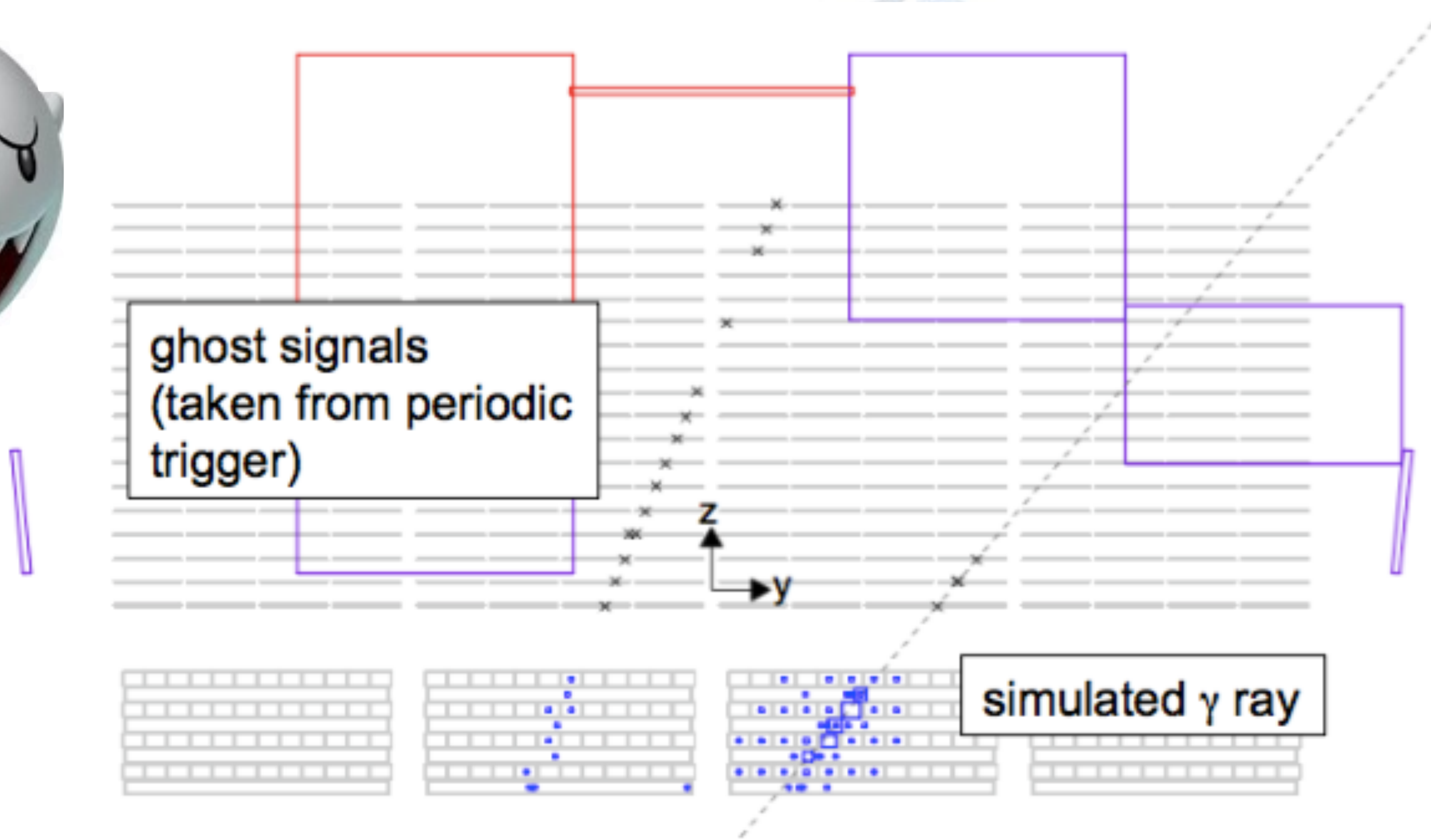


- **Energy resolution vs. E**
  - **left: front/back event types, right: EDISP event types**
- **Low energy limits**
  - **energy deposited in tracker non-negligible**
- **High energy limits**
  - **shower leakage is dominant**

How does E_{res} change as a function of angle?

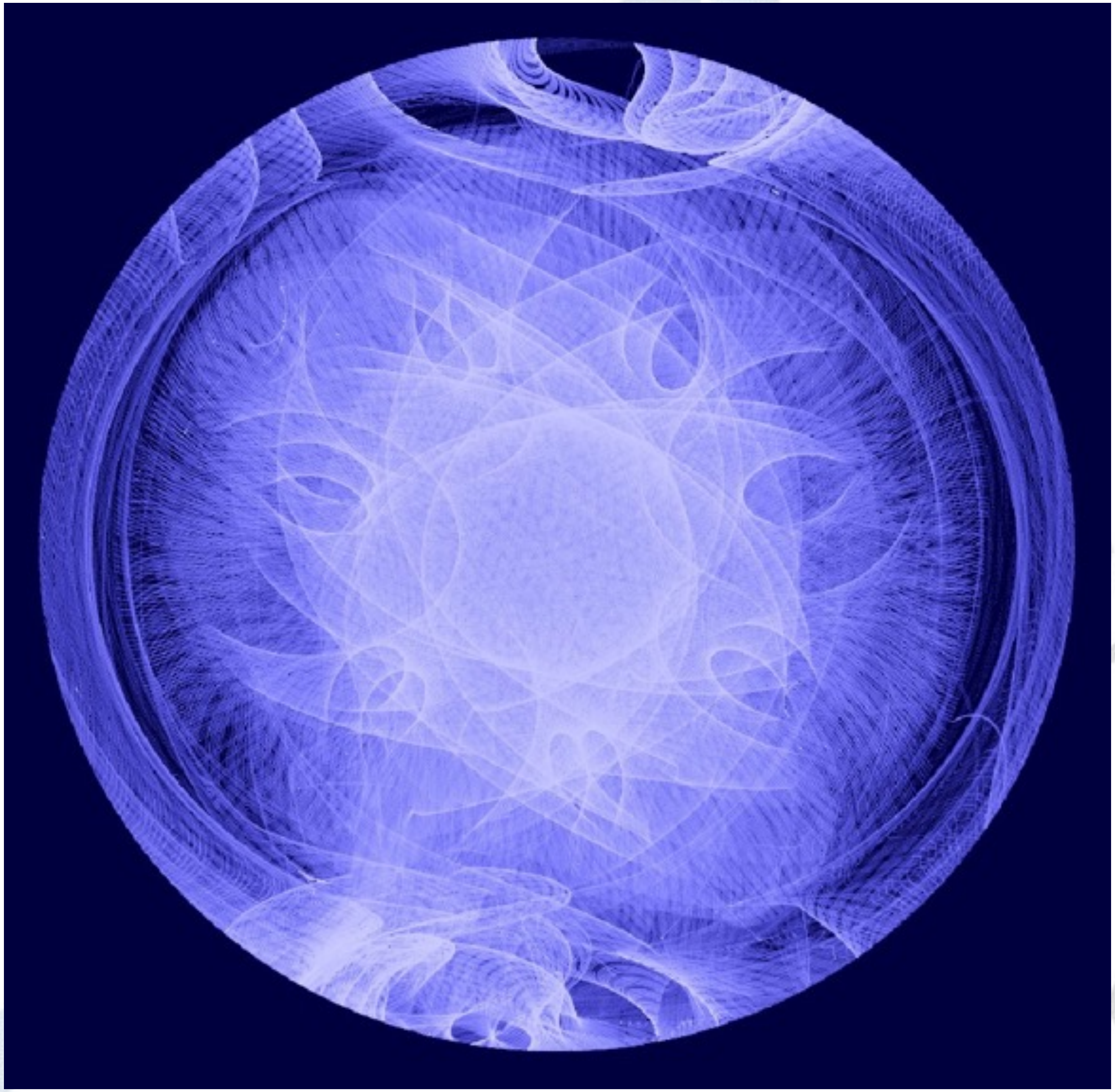
Validating and Calibrating the IRFs

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

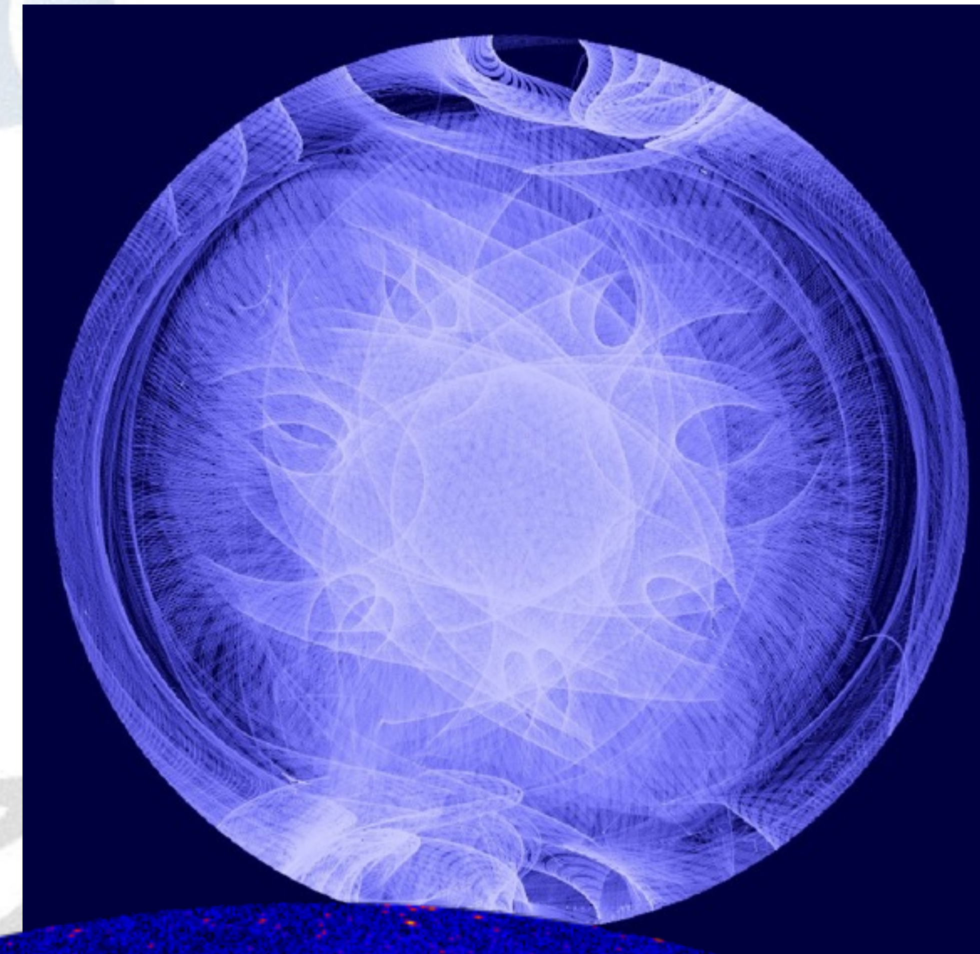
What is this?

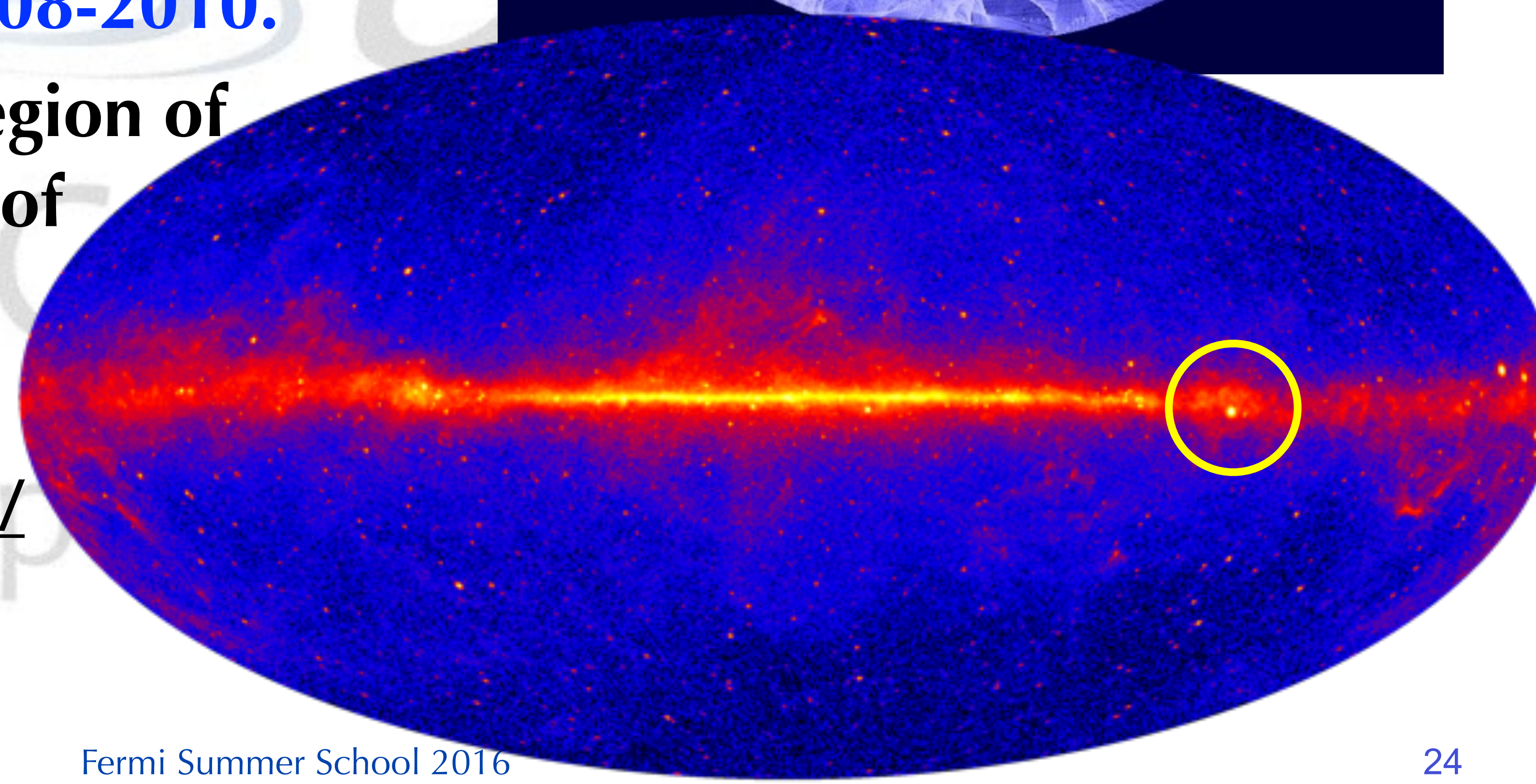


Credit: Eric Charles

What is this: The Vela Pulsar!

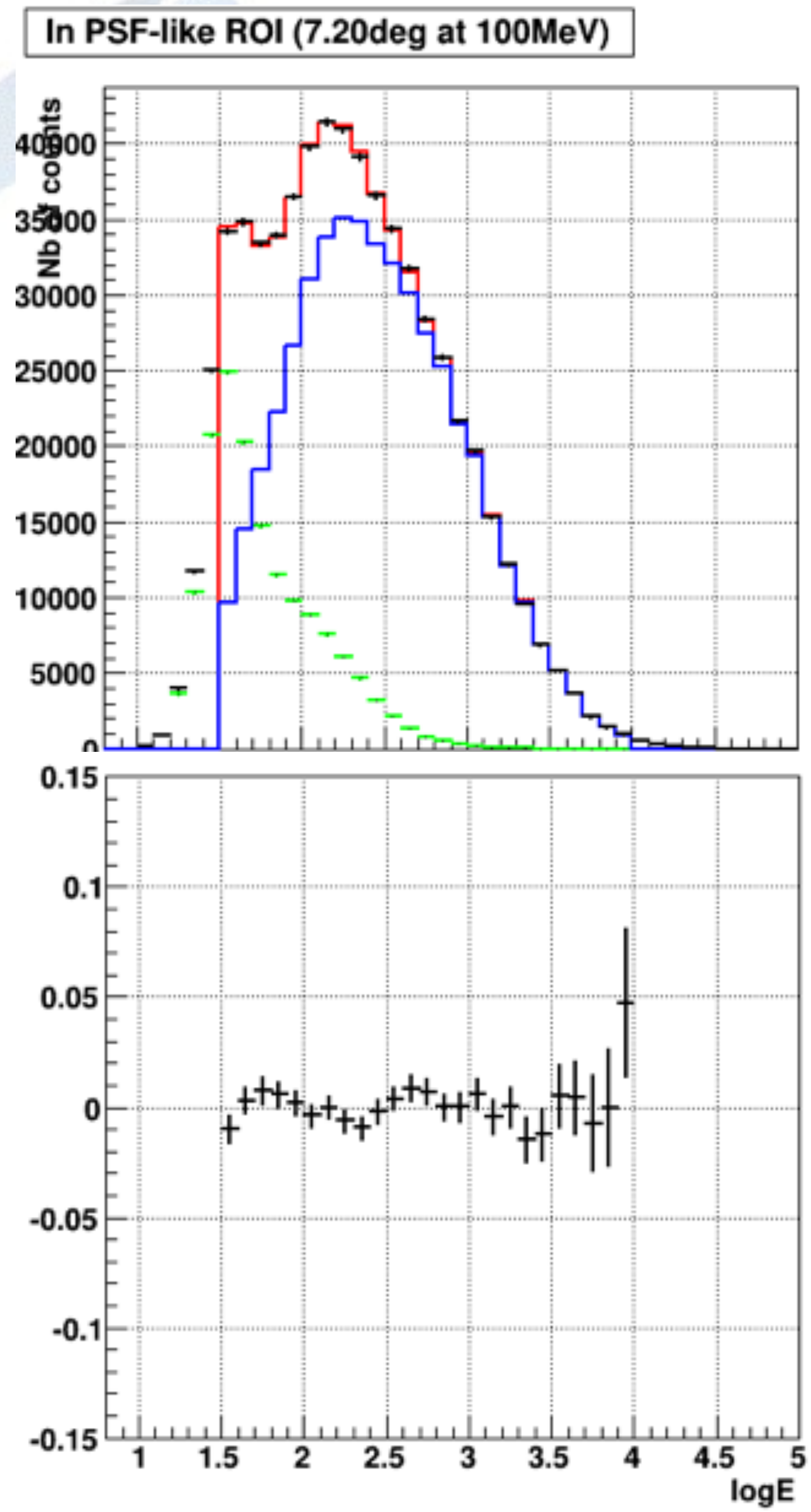
- The effects of pointing!
  - LAT orbits every 95 minutes
  - Rocks N/S on alternate orbits
  - solar panels pointed at the Sun
  - complete rotation every 54 days
- Plot of the path of the Vela Pulsar centered on the instrument FoV
  - 180 degrees and follows Vela's position from August 2008-2010.
- Vela was in the sensitive region of the LAT field during much of that period
- 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

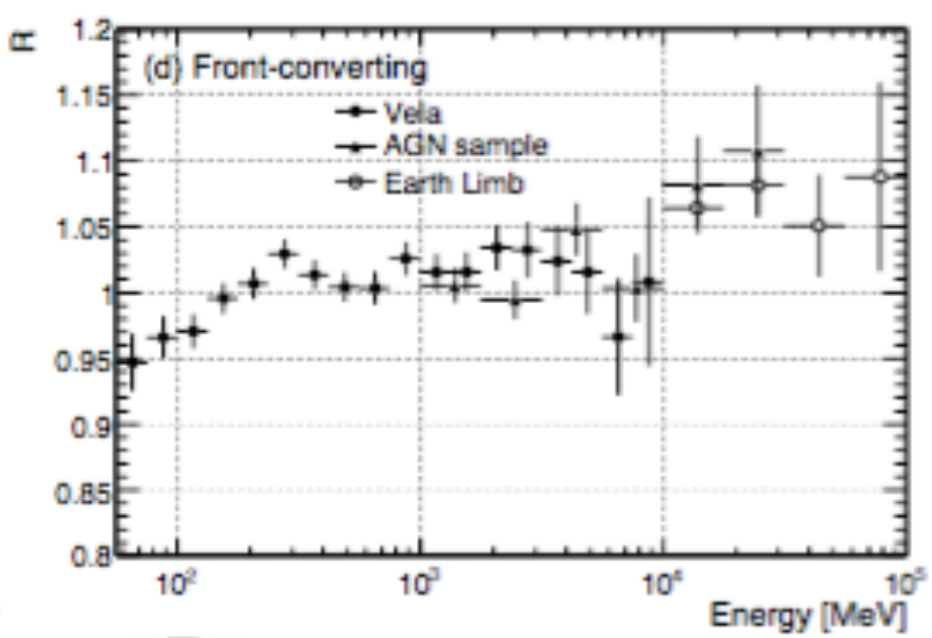


Validation of Effective Area

- 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

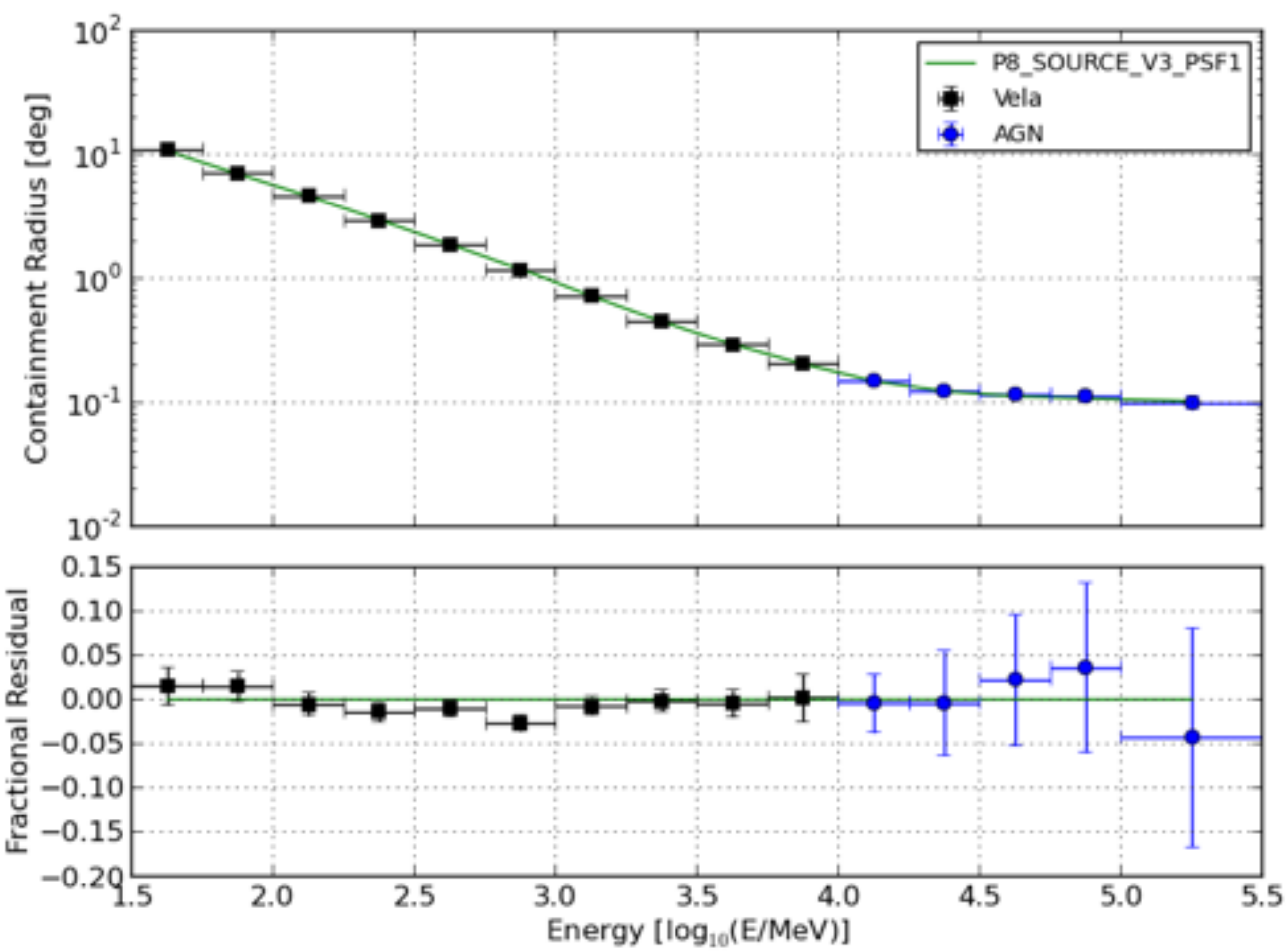
- Consistency checks
  - are event rates for front vs. back events as predicted by simulations?



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

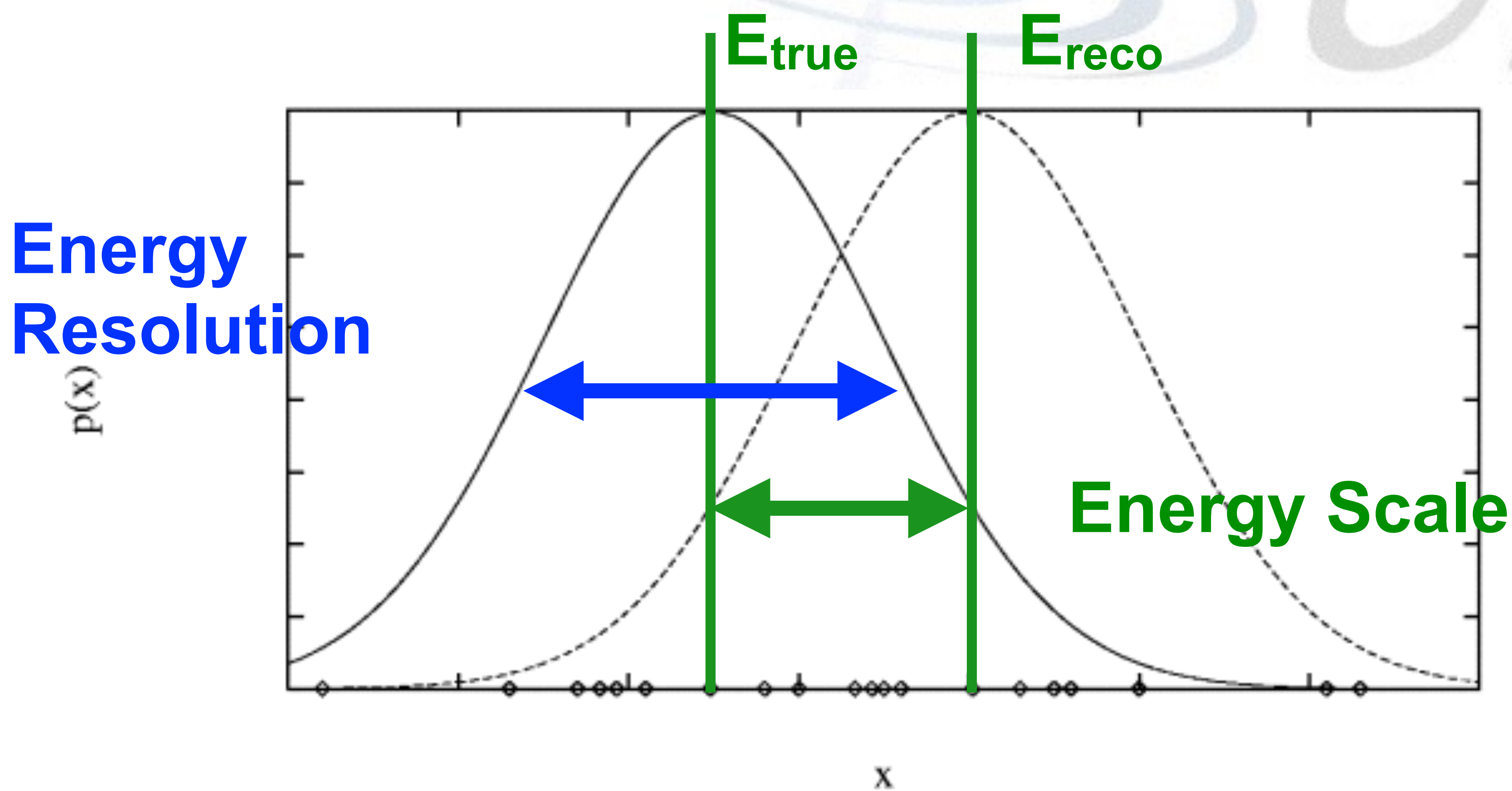
Validation of Point Spread Function

- Somewhat easier than effective area; we have 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

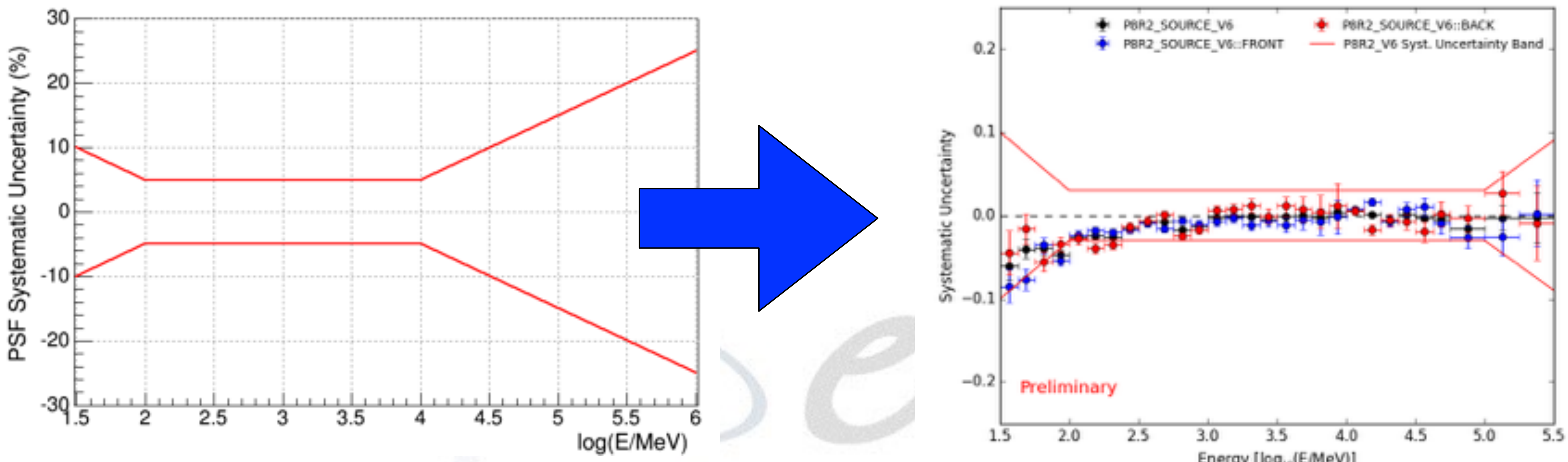


Would you prefer a low energy or a high energy tail?

Systematic Uncertainties

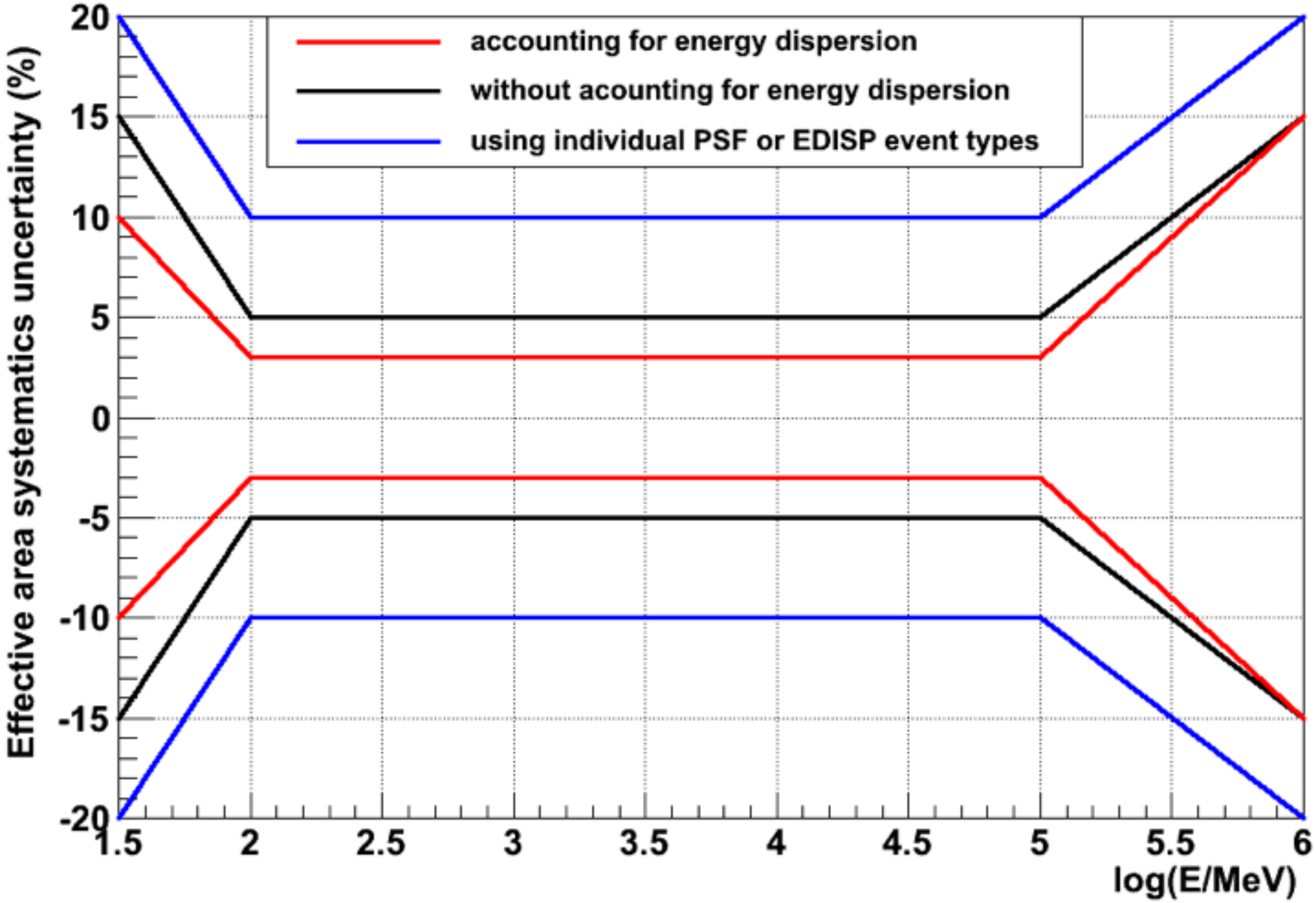
Bracketing Functions

- 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)

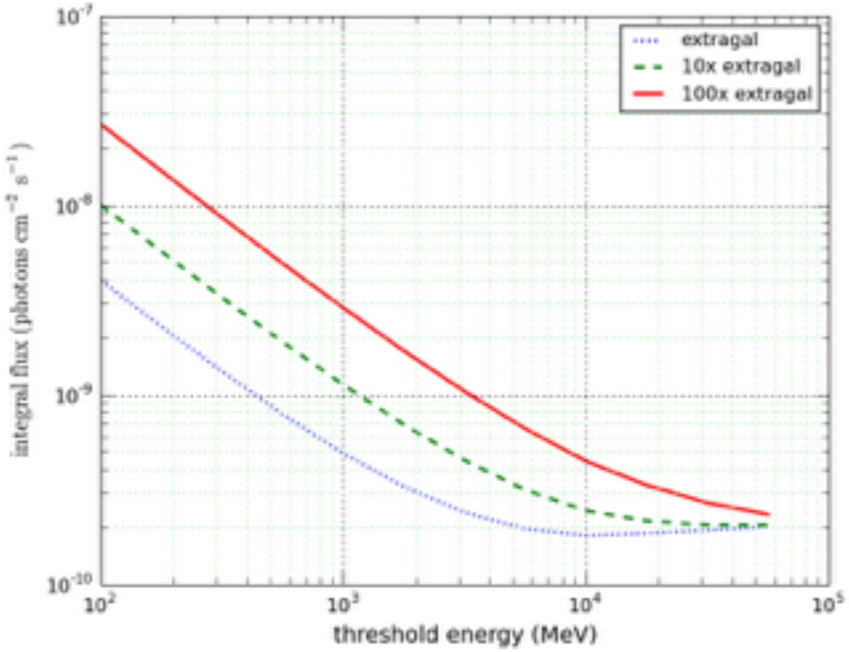
Assessing the Systematic Uncertainty

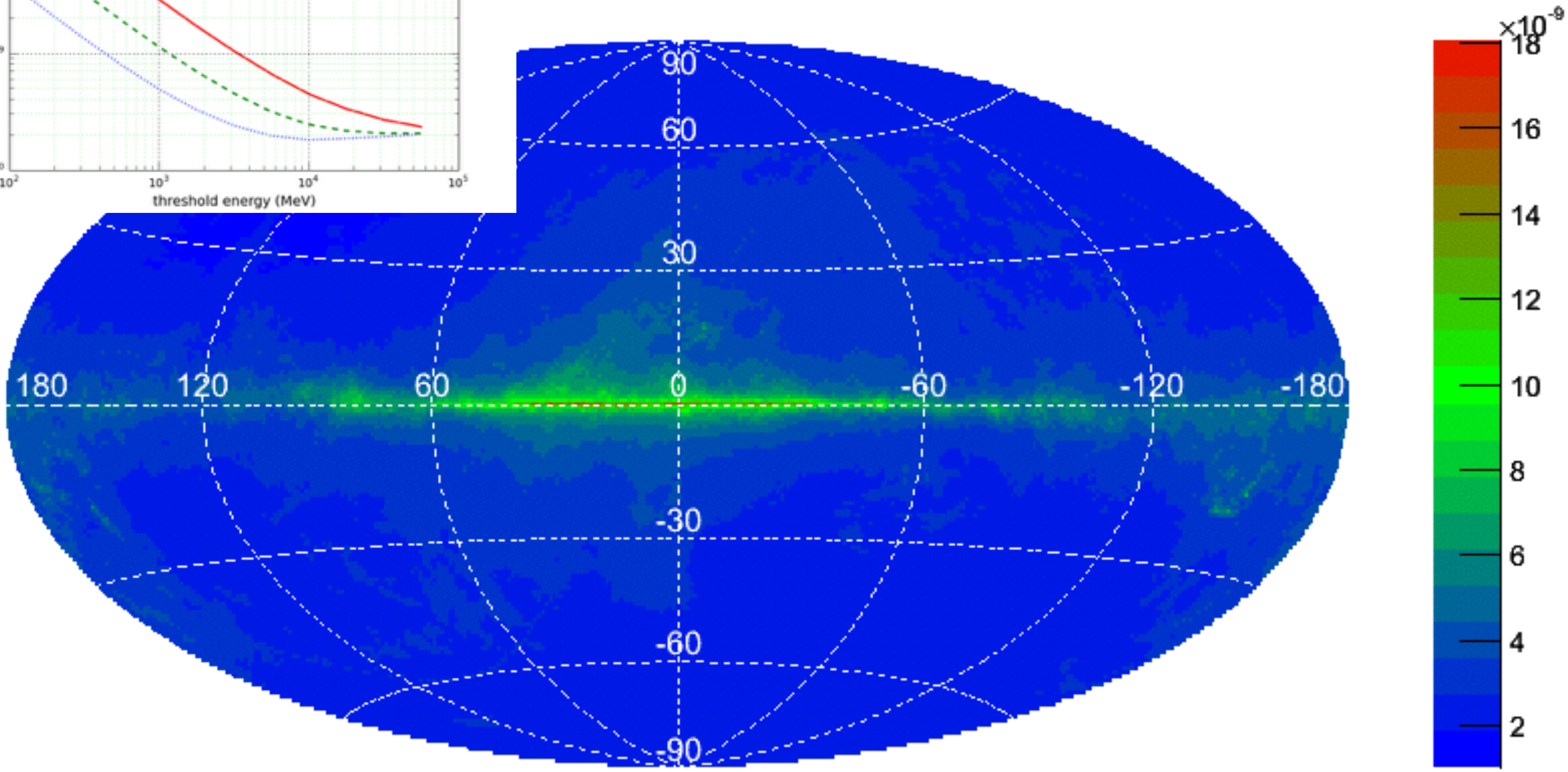


http://fermi.gsfc.nasa.gov/ssc/data/analysis/LAT_caveats.html

Source Sensitivity

Source Sensitivity





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 (awesome) 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…

Backups

Trigger Rates