LAT Performance

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Outline

- Optimizing the LAT for Science
- Instrument Response Functions (IRFs):
- Validating and Calibrating the IRFs
  - Background Contamination
  - Calibration Samples and Analyses
  - Effective Area
  - Point-spread Function
  - Energy Dispersion
- Summary of Typical Systematic Uncertainties

"LAT Performance" Paper

Ackermann et al.: 2012ApJS..203....4A [arXiv:1206.1896]

arXiv:1206.1896v2 [astro-ph.IM] 24 Aug 2012

The *Fermi* Large Area Telescope On Orbit: Event Classification, Instrument Response Functions, and Calibration

M. Ackermann[1], M. Ajello[2], A. Albert[3], A. Allafort[2], W. B. Atwood[4], M. Axelsson[5,6,7], L. Baldini[8,9], J. Ballet[10], G. Barbiellini[11,12], D. Bastieri[13,14], K. Bechtol[2], R. Bellazzini[15], E. Bissaldi[16], R. D. Blandford[2], E. D. Bloom[2], J. R. Bogart[2], E. Bonamente[17,18], A. W. Borgland[2], E. Bottacini[2], A. Bouvier[4], T. J. Brandt[19,20], J. Bregeon[15], M. Brigida[21,22], P. Bruel[23], R. Buehler[2], T. H. Burnett[24], S. Buson[13,14], G. A. Caliandro[25], R. A. Cameron[2], P. A. Caraveo[26], J. M. Casandjian[10], E. Cavazzuti[27], C. Cecchi[17,18], Ö. Çelik[28,29,30], E. Charles[2,31], R.C.G. Chaves[10], A. Chekhtman[32], C. C. Cheung[33], J. Chiang[2], S. Ciprini[34,18], R. Claus[2], J. Cohen-Tanugi[35], J. Conrad[36,6,37], R. Corbet[28,30], S. Cutini[27], F. D'Ammando[17,38,39], D. S. Davis[28,30], A. de Angelis[40], M. DeKlotz[41], F. de Palma[21,22], C. D. Dermer[42], S. W. Digel[2], E. do Couto e Silva[2], P. S. Drell[2], A. Drlica-Wagner[2], R. Dubois[2], C. Favuzzi[21,22], S. J. Fegan[23], E. C. Ferrara[28], W. B. Focke[2], P. Fortin[23], Y. Fukazawa[43], S. Funk[2], P. Fusco[21,22], F. Gargano[22], D. Gasparrini[27], N. Gehrels[28], B. Giebels[23], N. Giglietto[21,22], F. Giordano[21,22], M. Giroletti[44], T. Glanzman[2], G. Godfrey[2], I. A. Grenier[10], J. E. Grove[42], S. Guiriec[28], D. Hadasch[25], M. Hayashida[2,45], E. Hays[28], D. Horan[23], X. Hou[46], R. E. Hughes[3], M. S. Jackson[7,6], T. Jogler[2], G. Jóhannesson[47], R. P. Johnson[4], T. J. Johnson[33], W. N. Johnson[42], T. Kamae[2], H. Katagiri[48], J. Kataoka[49], M. Kerr[2], J. Knödlseder[19,20], M. Kuss[15], J. Lande[2], S. Larsson[36,6,5], L. Latronico[50], C. Lavalley[35], M. Lemoine-Goumard[51,52], F. Longo[11,12], F. Loparco[21,22], B. Lott[51], M. N. Lovellette[42], P. Lubrano[17,18], M. N. Mazziotta[22], W. McConville[28,53], J. E. McEnery[28,53], J. Mehault[35], P. F. Michelson[2], W. Mitthumsiri[2], T. Mizuno[54], A. A. Moiseev[29,53], C. Monte[21,22], M. E. Monzani[2], A. Morselli[55], I. V. Moskalenko[2], S. Murgia[2], M. Naumann-Godo[10], R. Nemmen[28], S. Nishino[43], J. P. Norris[56], E. Nuss[35], M. Ohno[57], T. Ohsugi[54], A. Okumura[2,58], N. Omodei[2], M. Orienti[44], E. Orlando[2], J. F. Ormes[59], D. Paneque[60,2], J. H. Panetta[2], J. S. Perkins[28,30,29,61], M. Pesce-Rollins[15], M. Pierbattista[10], F. Piron[35], G. Pivato[14], T. A. Porter[2,2], J. L. Racusin[28], S. Rainò[21,22], R. Rando[13,14,62], M. Razzano[15,4], S. Razzaque[32], A. Reimer[16,2], O. Reimer[16,2], T. Reposeur[51], L. C. Reyes[63], S. Ritz[4], L. S. Rochester[2], C. Romoli[14], M. Roth[24], H. F.-W. Sadrozinski[4], D.A. Sanchez[64], P. M. Saz Parkinson[4], C. Sbarra[13], J. D. Scargle[65], C. Sgrò[15], J. Siegal-Gaskins[66], E. J. Siskind[67], G. Spandre[15], P. Spinelli[21,22], T. E. Stephens[28,68], D. J. Suson[69], H. Tajima[2,58], H. Takahashi[43], T. Tanaka[2], J. G. Thayer[2], J. B. Thayer[2], D. J. Thompson[28], L. Tibaldo[13,14], M. Tinivella[15], G. Tosti[17,18], E. Troja[28,70], T. L. Usher[2], J. Vandenbroucke[2], B. Van Klaveren[2], V. Vasileiou[35], G. Vianello[2,71], V. Vitale[55,72], A. P. Waite[2], E. Wallace[24], B. L. Winer[3], D. L. Wood[73], K. S. Wood[42], M. Wood[2], Z. Yang[36,6], S. Zimmer[36,6]

Almost every plot in this talk is taken from this paper.

The paper is long (170 pages in preprint format, w/ 90 figures).

There is a good chance that the answers to your questions about LAT data analysis are in the paper.

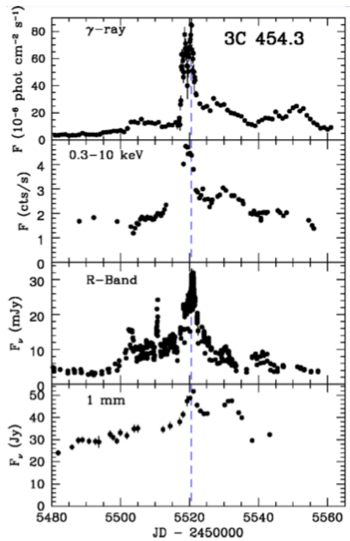
The arXiv version has a table of contents to make it more useful as a reference.

Liz kindly included it in the packet on your memory sticks.

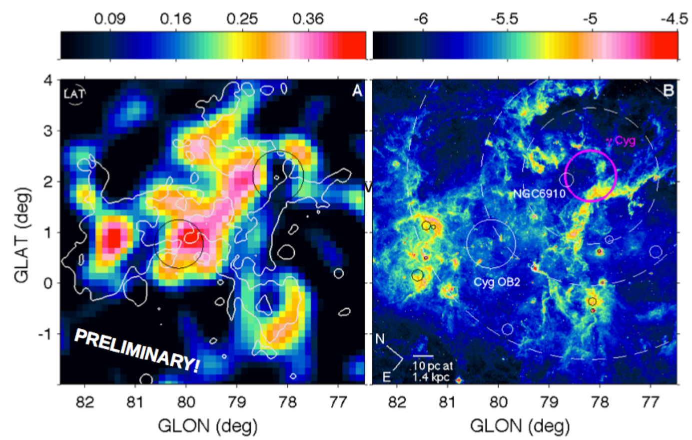
OPTIMIZING THE LAT FOR SCIENCE

Fermi Gamma-ray Space Telescope

Wide Variety of Analysis Subjects



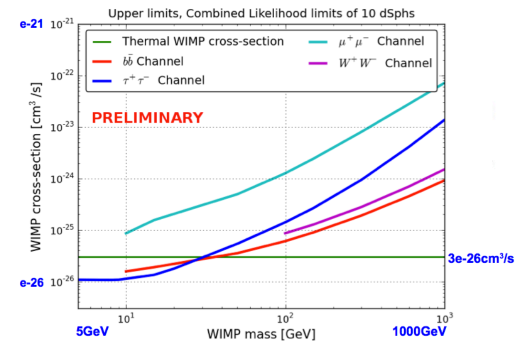
MW Variability



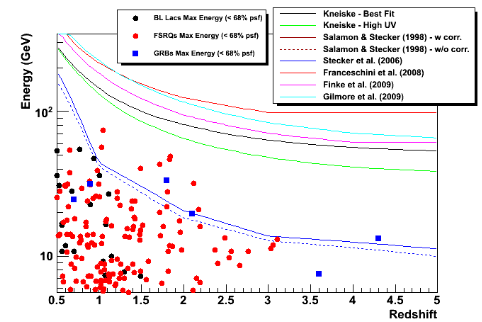
γ-ray residuals >10 GeV (counts/bin)

8 μm – MSX (W m^{-2} sr^{-1})

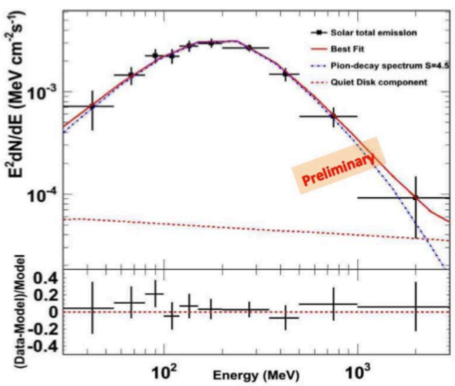
Morphology, Source Extension and Counterpart Identification



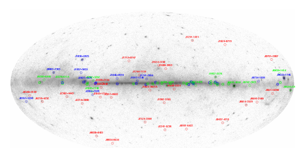
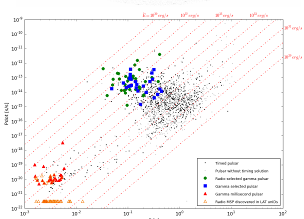
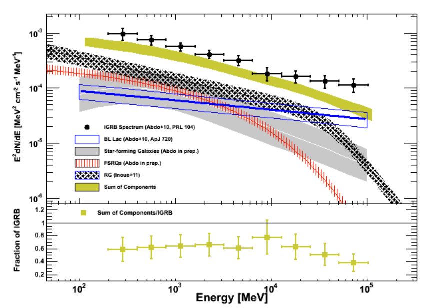
DM Searches



Single Photon Studies



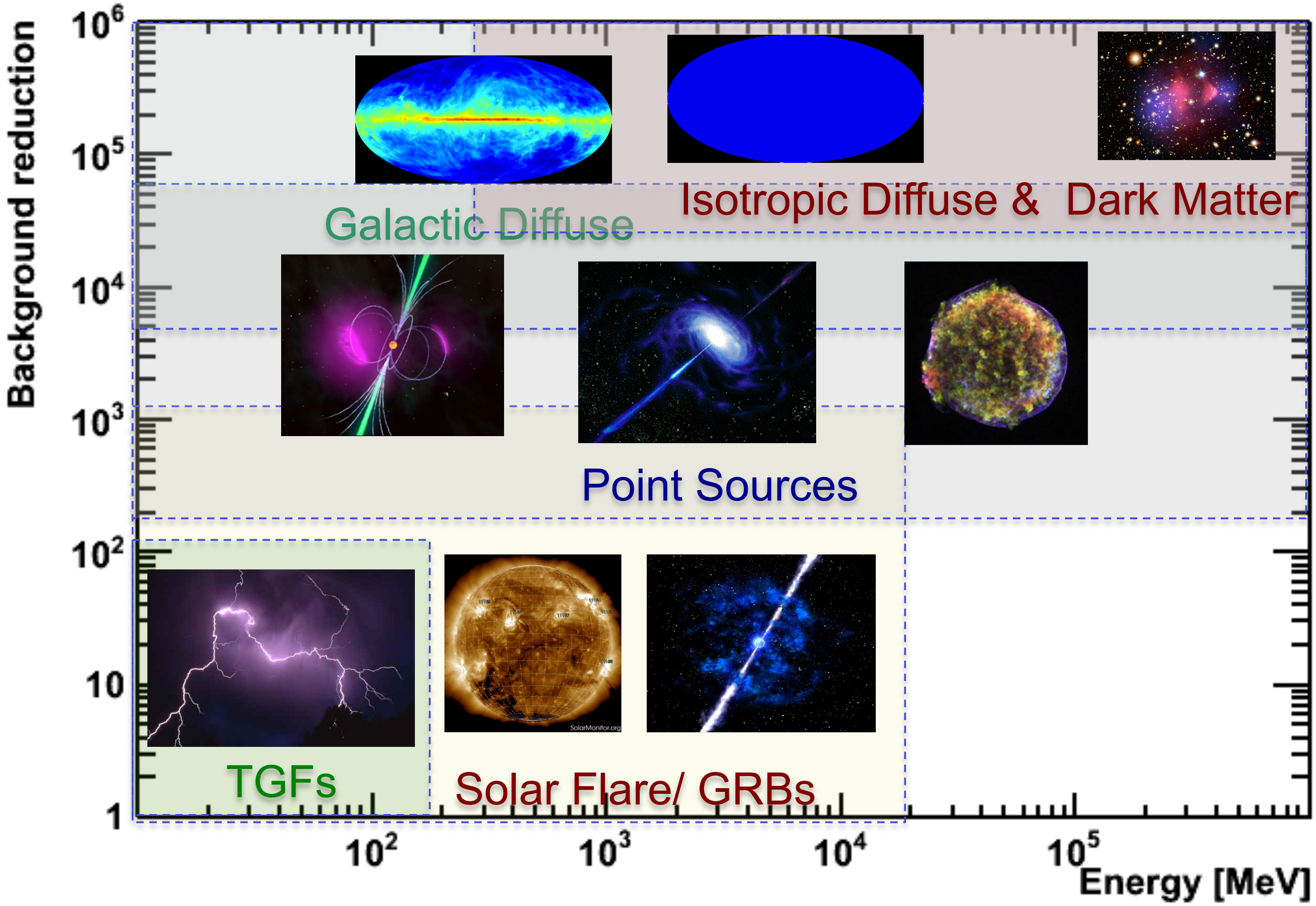
SEDs and Spectral Components

Catalogs, Population Studies and Contribution Estimation

No real "standard" analysis, lots of particular cases.

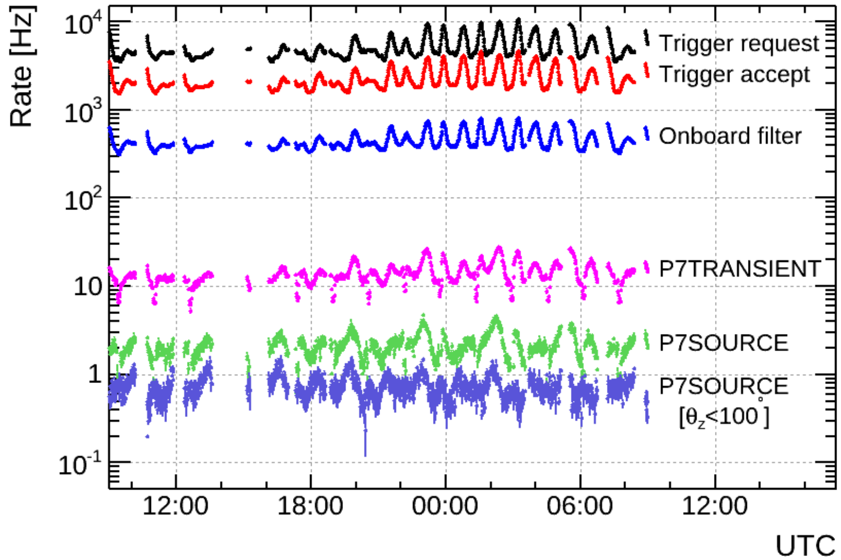
Fermi-LAT Science Covers Huge Phase-Space



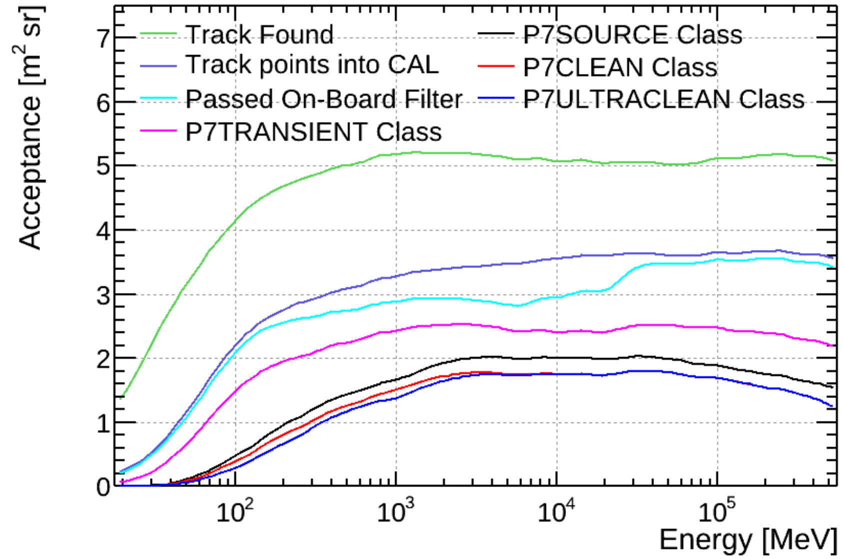
Different data selections for different science cases.

Particle Rate Reduction and Event Selections

Event Rates over 1 Day



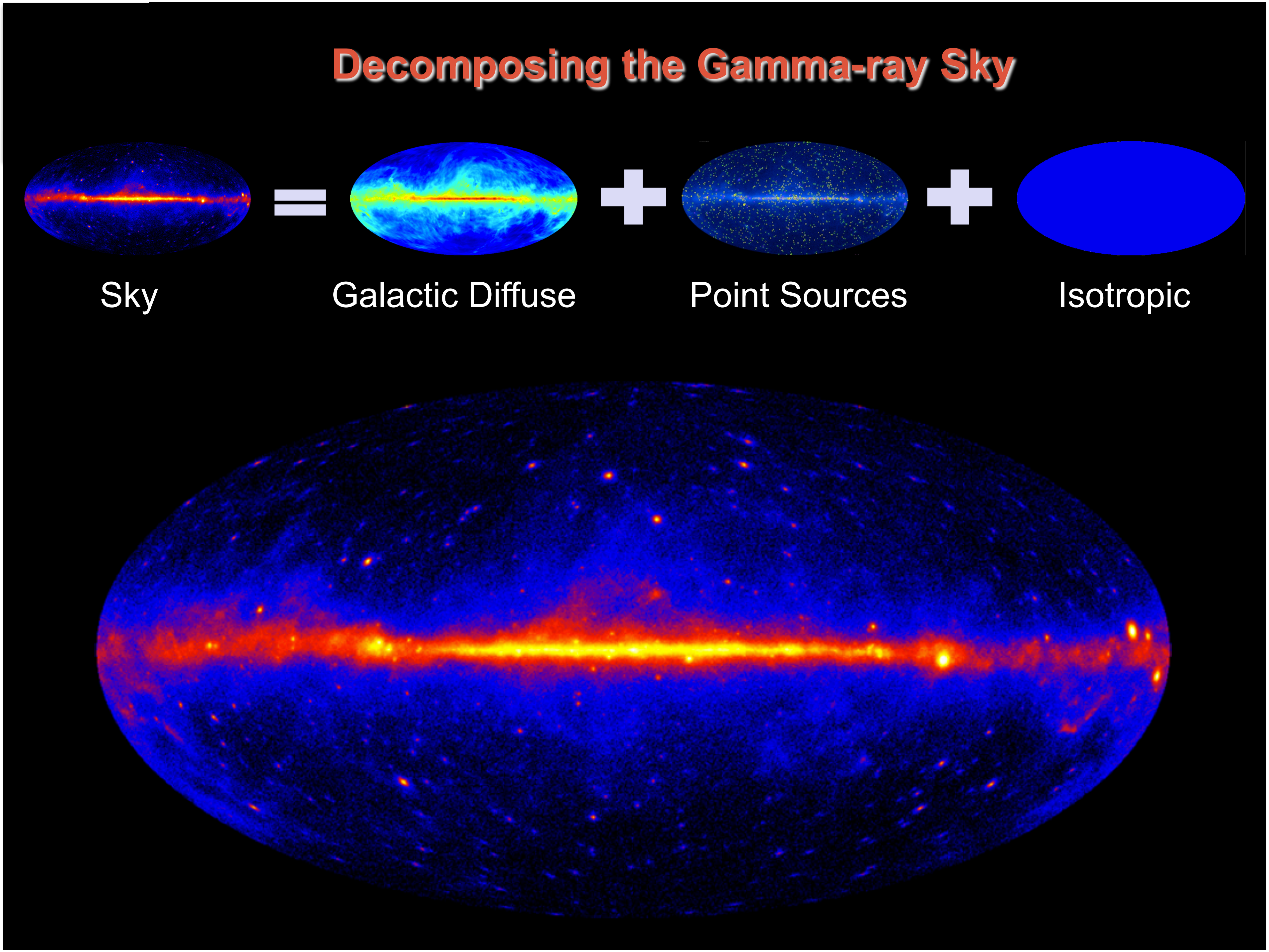
Acceptance for Selections



Factor of > 10^5 in bkg. reduction is achieved in several stages.

About 50% γ-ray efficiency inside fiducial volume from 1-100 GeV.

Instrument Response Functions


Decomposing the Gamma-ray Sky
Sky
Galactic Diffuse
Point Sources
Isotropic

Instrument Response Functions

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

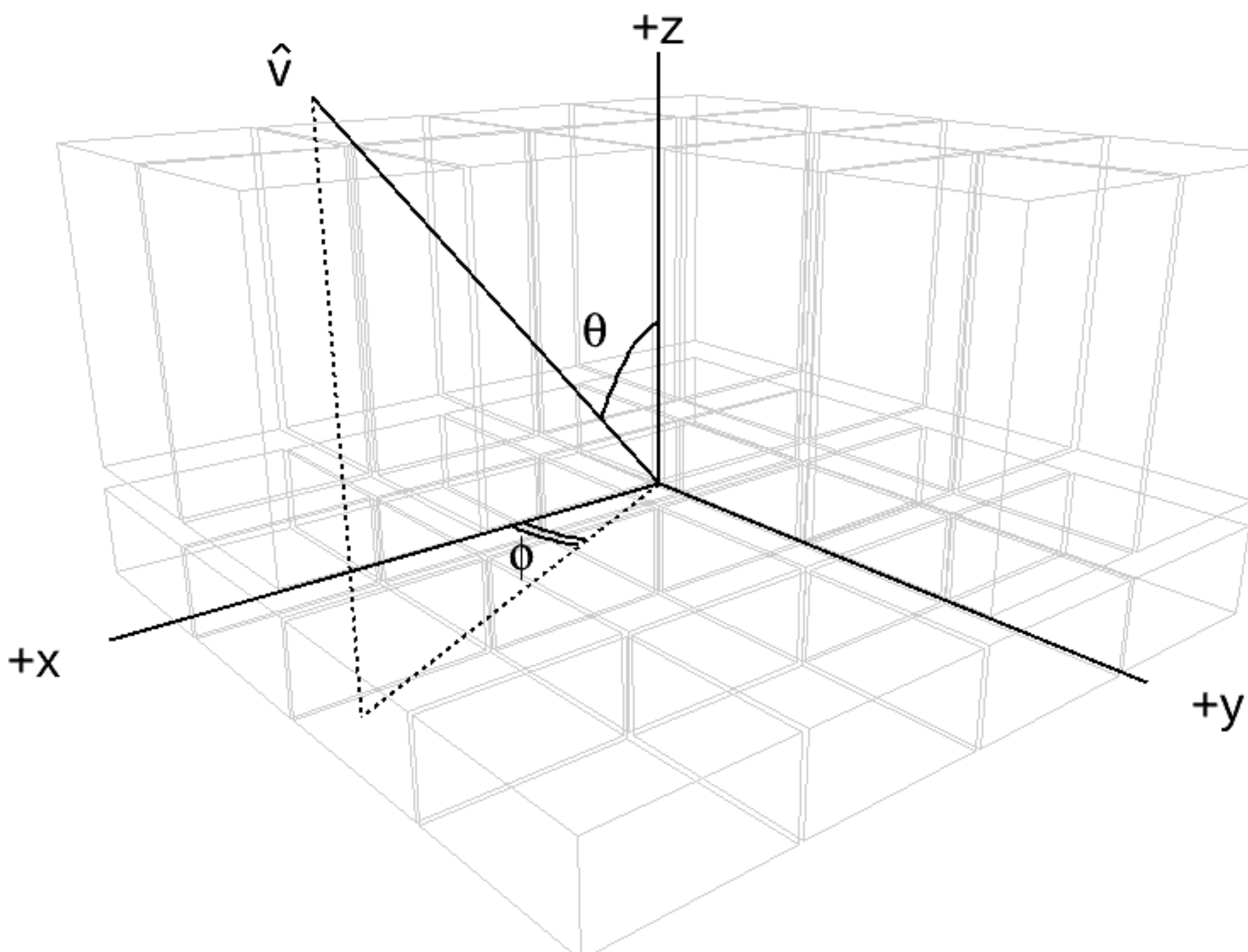
Source Flux

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

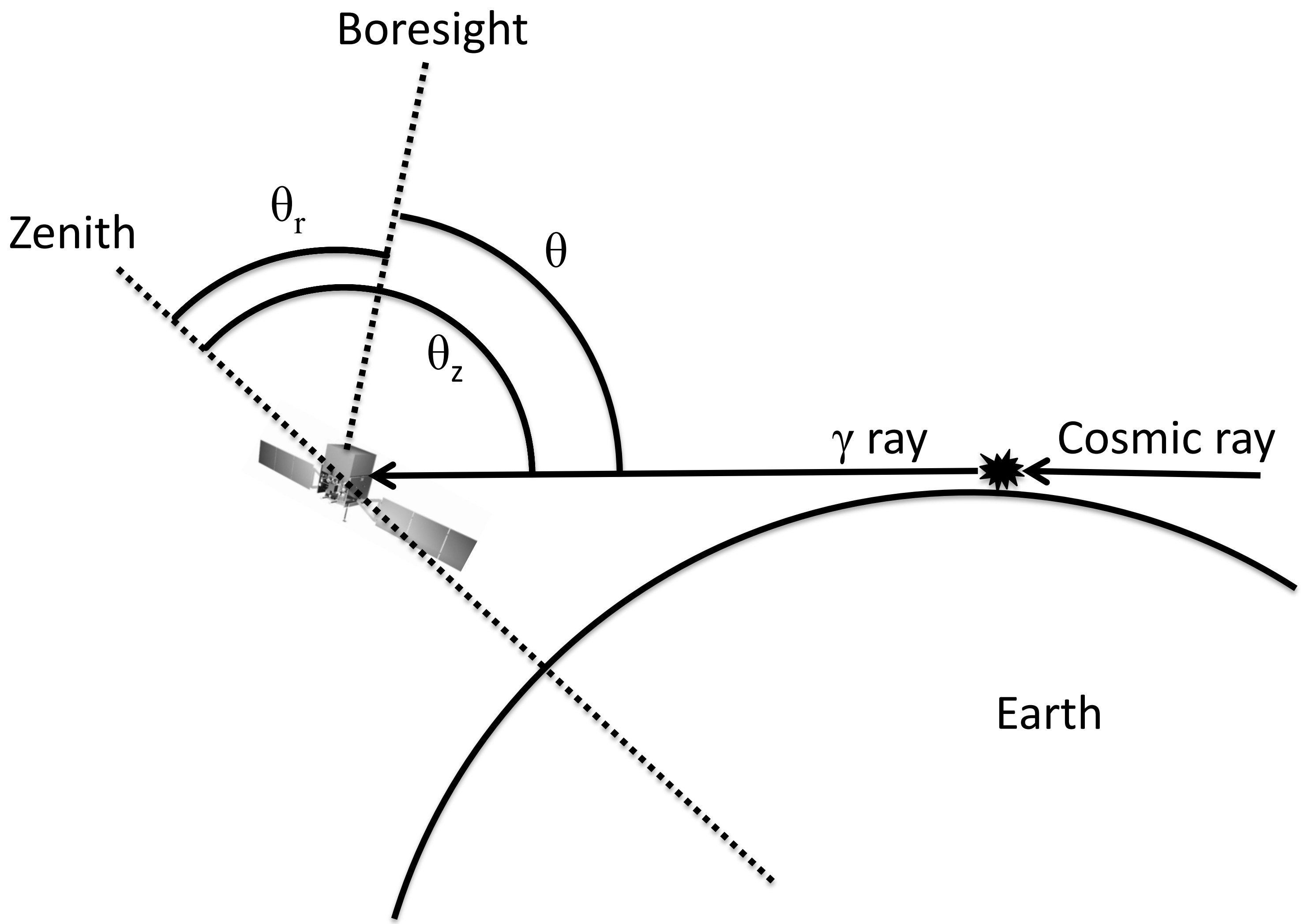
Instrument Response

Likelihood fitting uses lots of information optimally.
This is a double-edged sword. Issues with any of our IRFs can affect fit and can be difficult to disentangle.

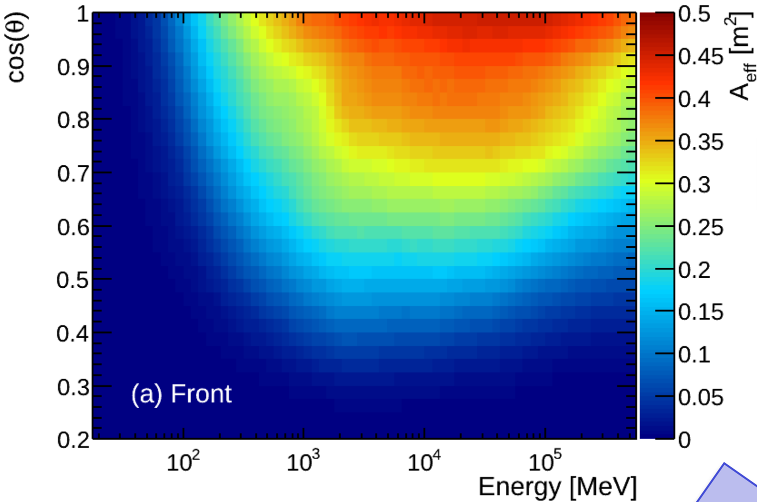
LAT Coordinate system



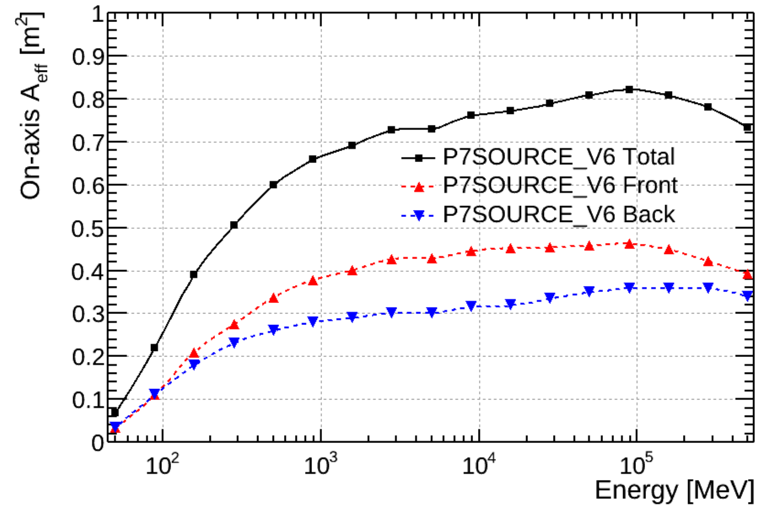
Some other useful angles.



Effective Area from Monte Carlo

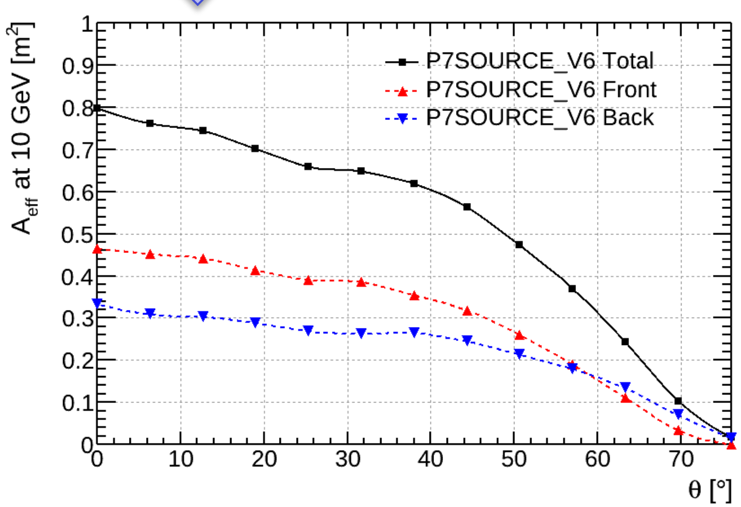


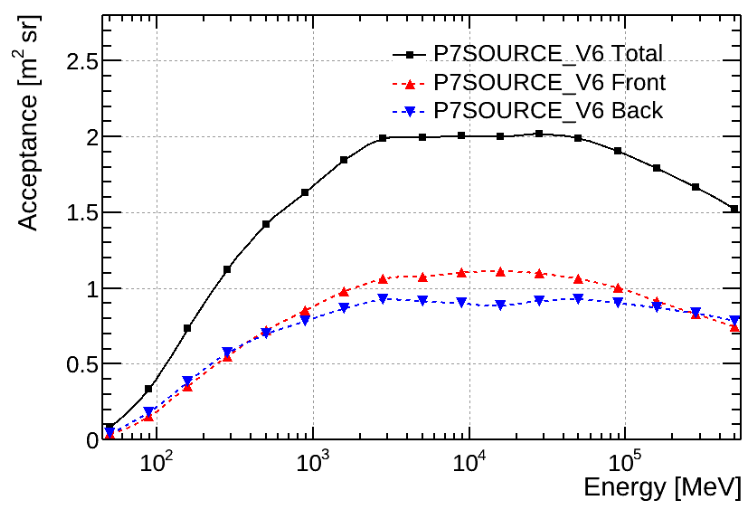
Slice in θ
E dependence
$A_{eff}(E;\theta=0$ on axis)



Slice in Energy
θ dependence
$A_{eff}(\theta;E=1GeV)$

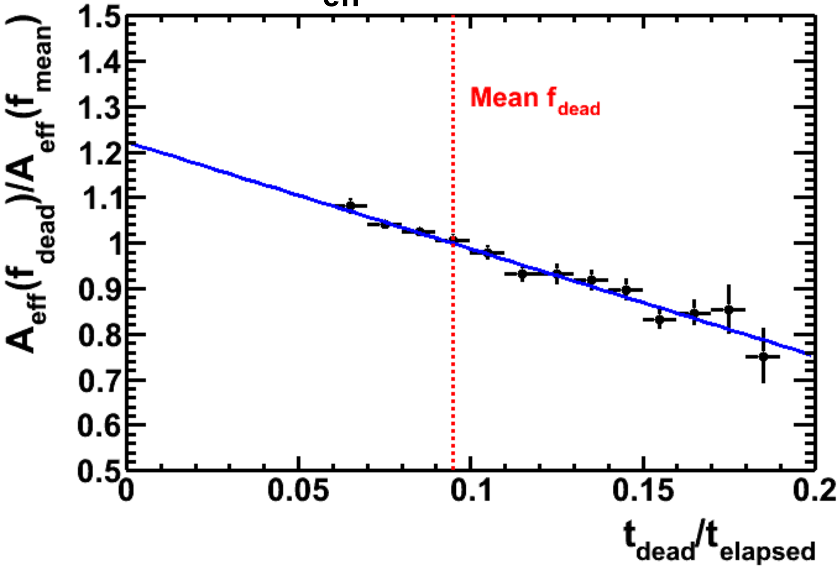
Integrate over θ
Acceptance A(E)



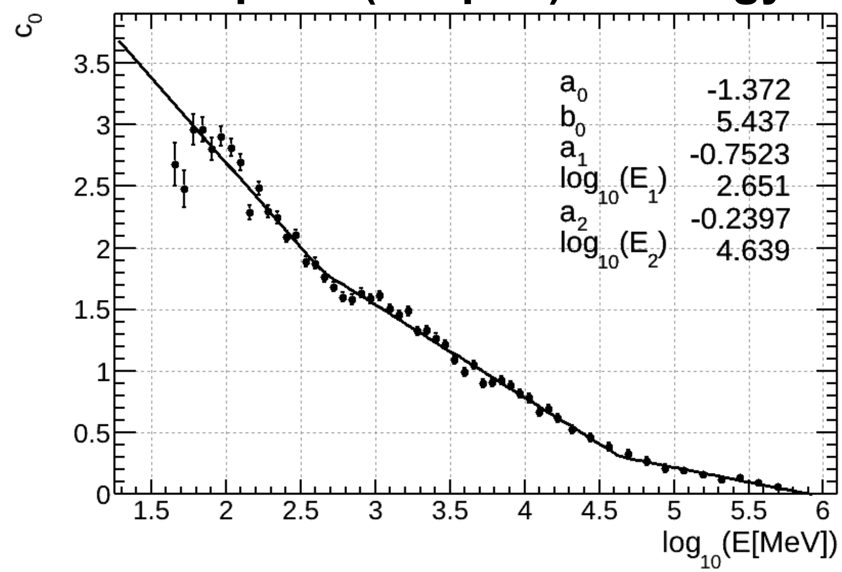


Post Launch MC-Based corrections to A_{eff}

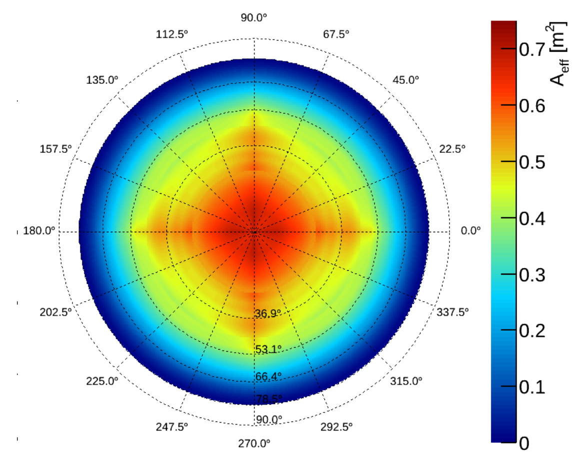
A_{eff} v. Deadtime



Slope of (left plot) v. Energy

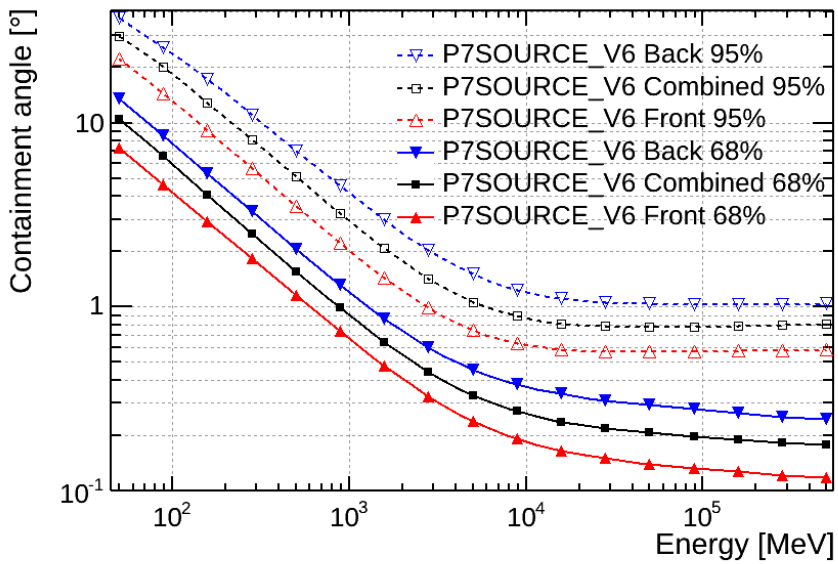


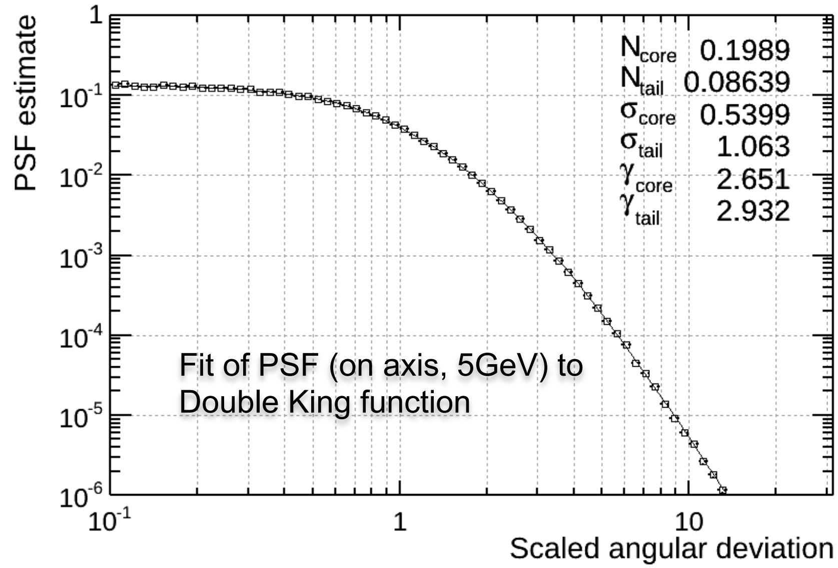
ϕ dependence map @ 10GeV



A_{eff} is affected by ghost signals and correlates with trigger rate and "deadtime fraction".
"Overlay" periodic triggers from flight data on MC events to estimate scale of effect as a function of energy.

Monte Carlo Based PSF

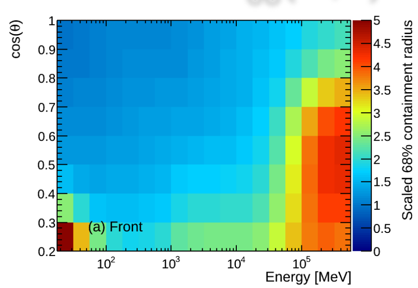




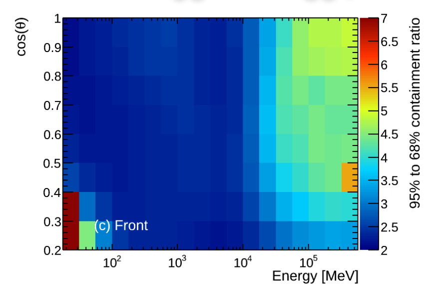
Fit a scaled deviation for the PSF in (E,θ) bins.

Note that the PSF has non-Gaussian tails, which vary with E and θ.

Scaled $R_{68}(E,\theta)$

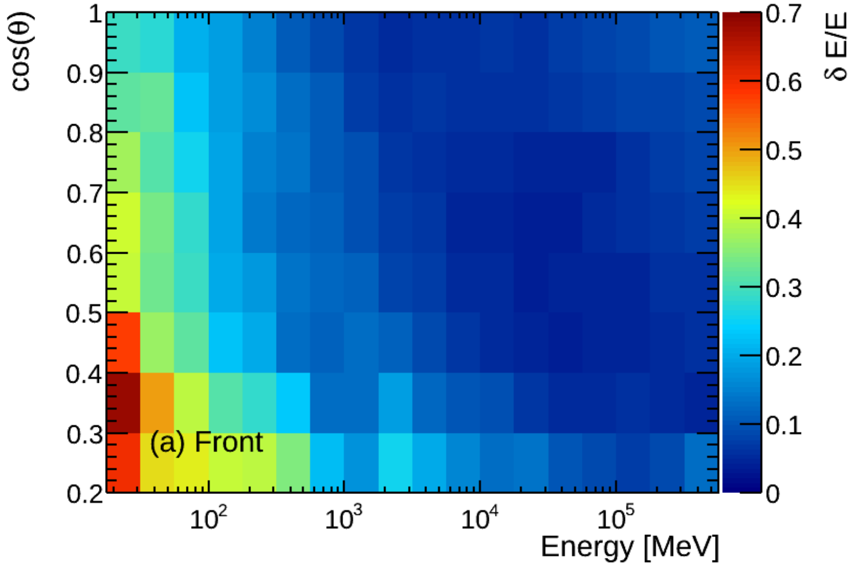


Ratio of R_{95} to $R_{68}(E,\theta)$

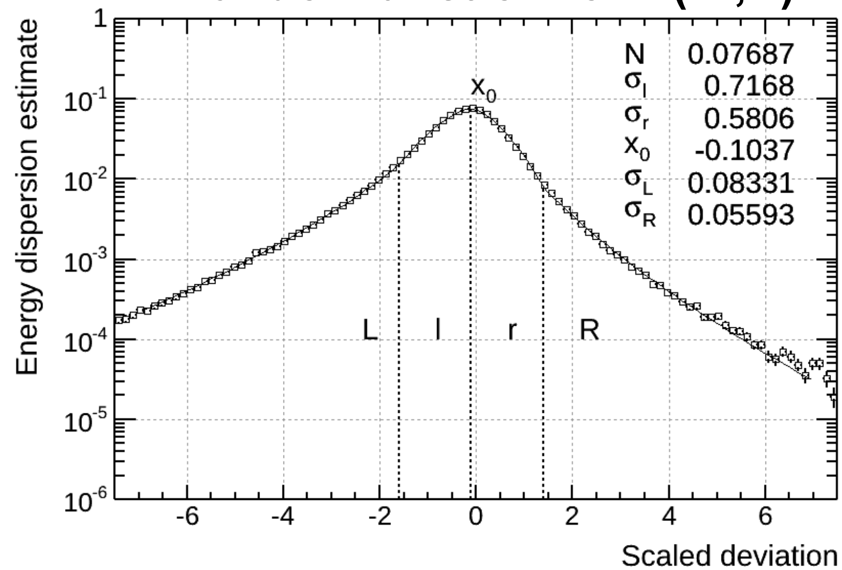


Energy Resolution from MC

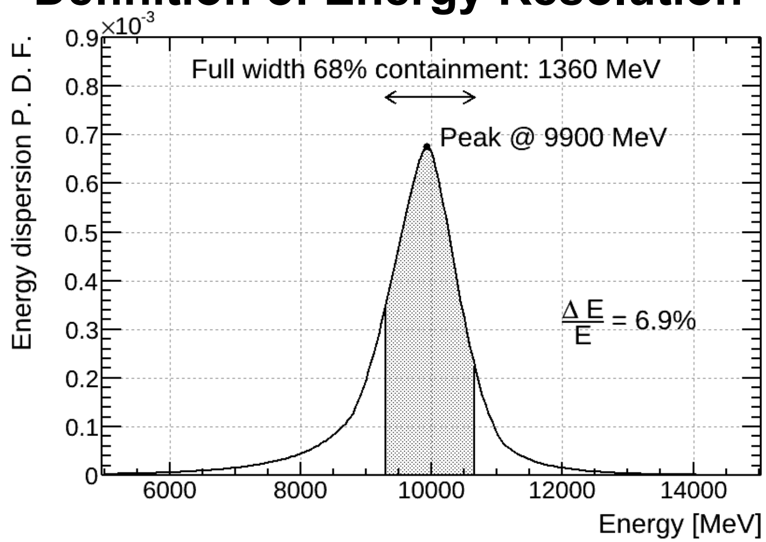
68% δE / E v. E, θ



"Rando" function for D(E';E)



Definition of Energy Resolution

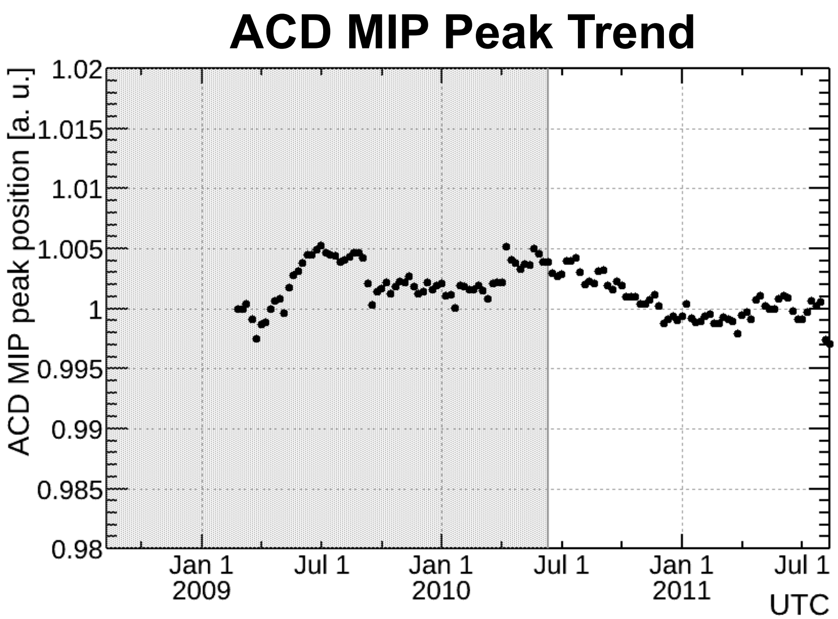


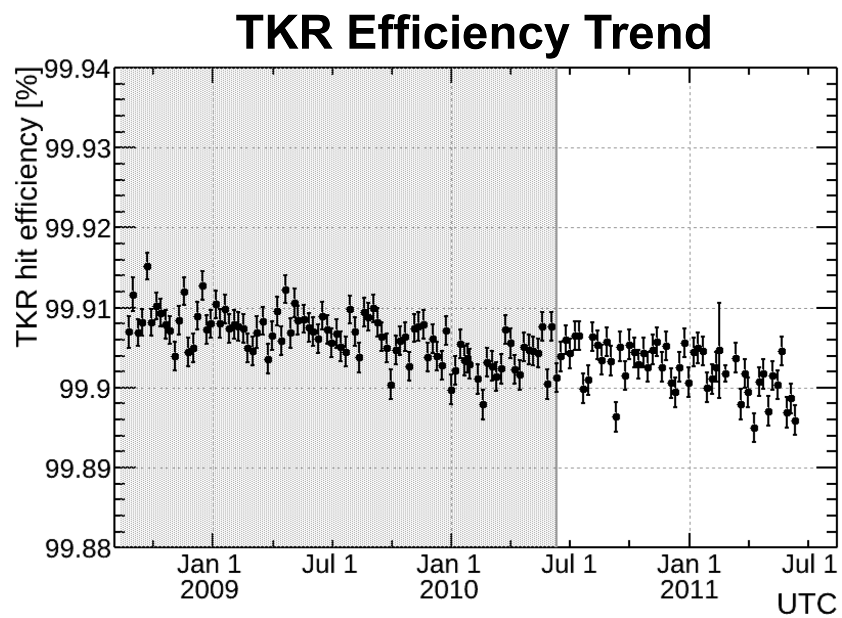
As with PSF, we fit a scaled deviation for the energy dispersion in (E,θ) bins.

Note that the response has non-Gaussian tails, is asymetric, and varies with E and θ.

VALIDATING AND CALIBRATING THE IRFS

Instrument Stability

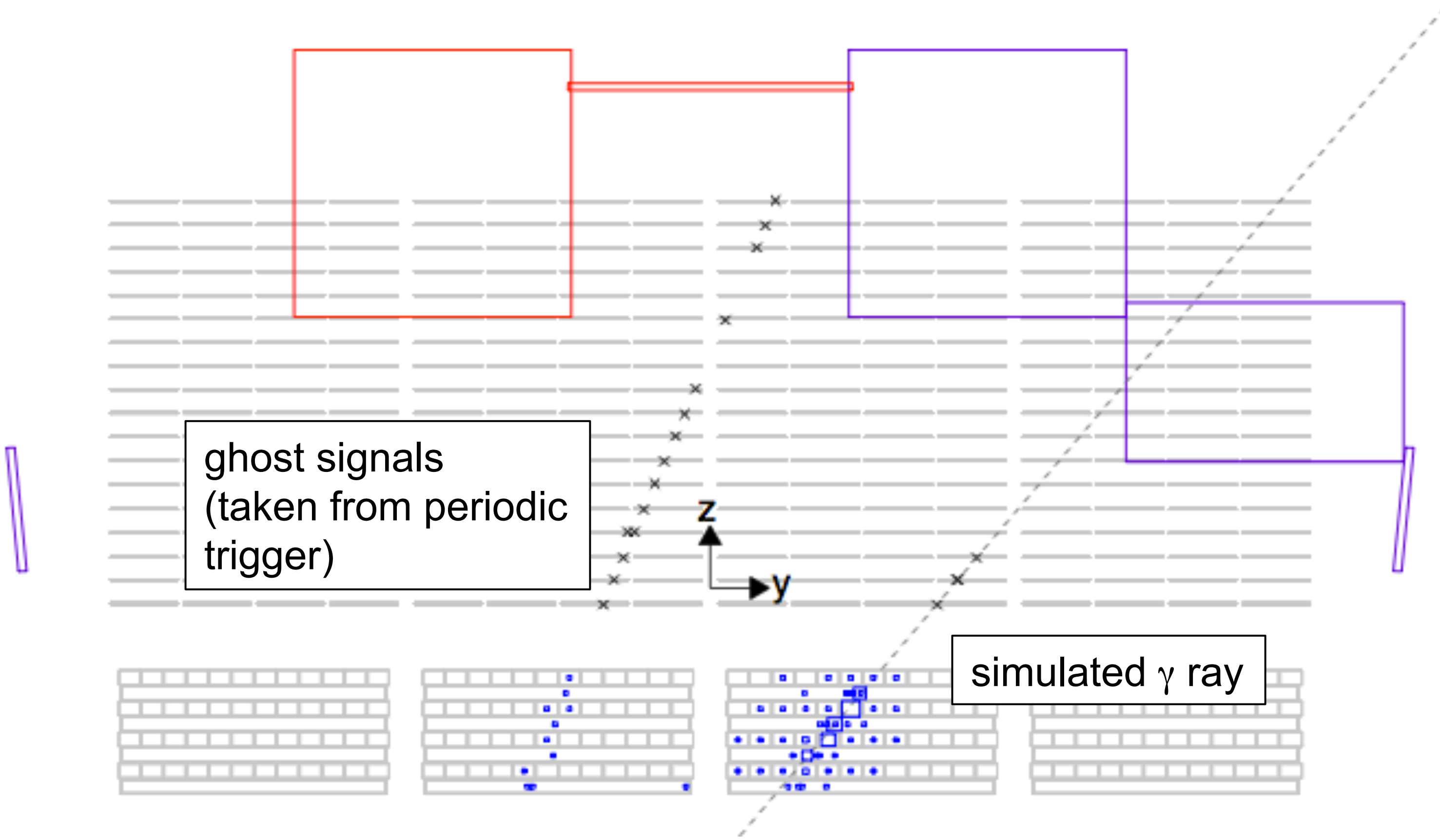




Instrument is very stable: ok to use single IRF set for mission to date.

(Gray region is ~ 2 years data used for these analyses).

Instrument Timing and the Ghost Effect



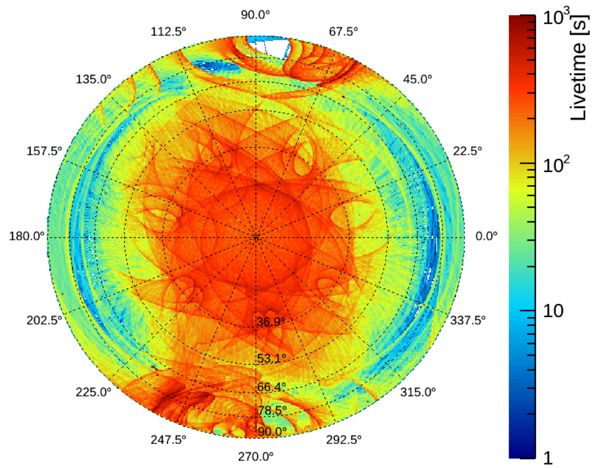
Low power budget -> μs (not ns) electronics.

Sensitive to signals from out-of-time cosmic rays, depends CR rate which varies w/ orbit.

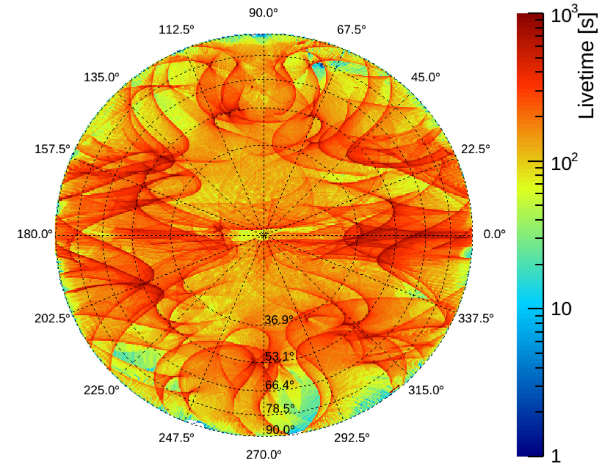
Subsystem	Fast signal (trigger)	Slow signal (event data)
ACD	400 ns	4 μs
CAL	500 ns	3.5 μs
TKR†	1.5 μs	10 μs

Effects of LAT Pointing

Vela: DEC = -45°, β = -60°

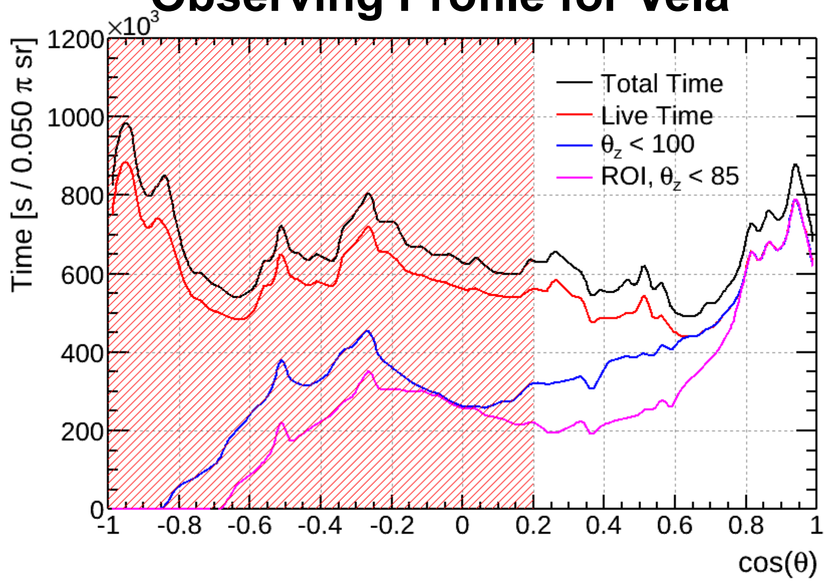


Crab: DEC = +22°, β = -1°



Each point in the sky traces a complicated path in the LAT frame which depends on declination and ecliptic latitude (β)

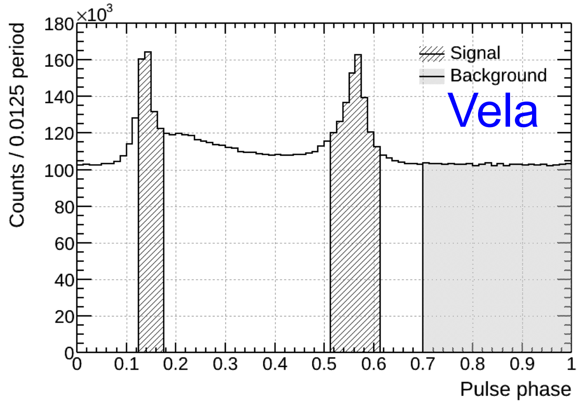
Observing Profile for Vela

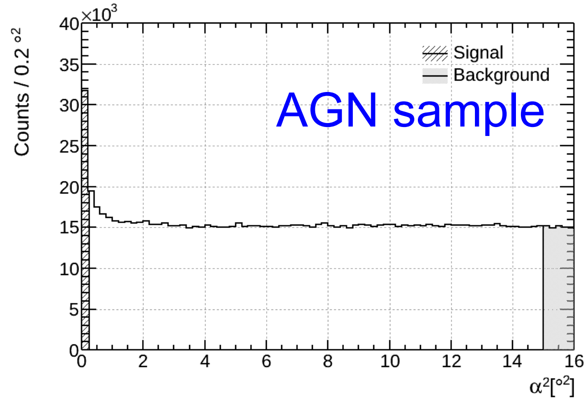


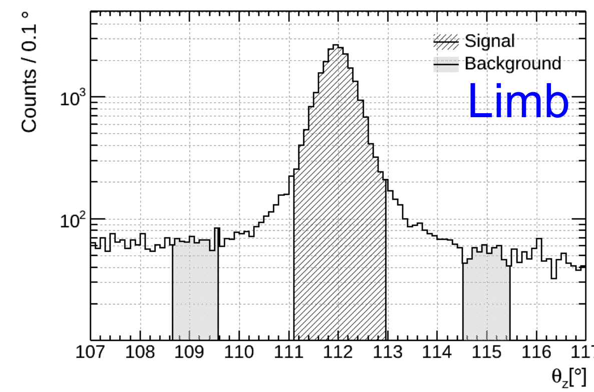
The LAT performance depends primarily on the angle w.r.t. the boresight (θ)

"Observing profile": observing time as a function of θ

Flight Data Calibration Samples

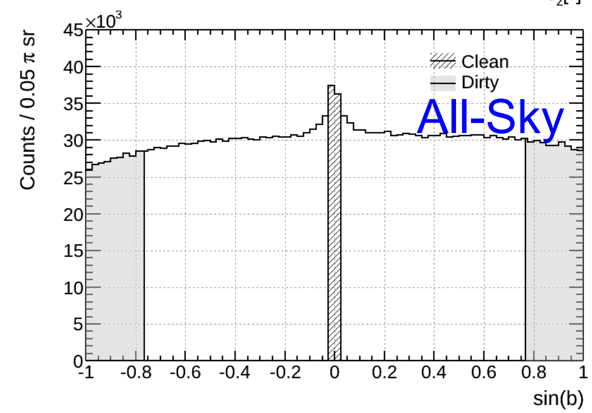


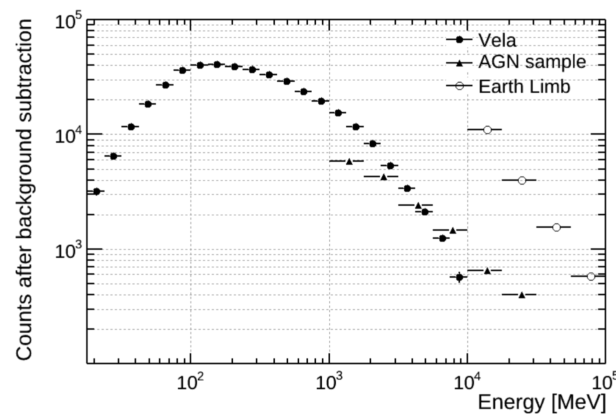




Shown for P7TRANSIENT event class

Calibration Sample	Method
Vela pulsar (2 years) 15° ROI, $q_{z,vela}$ > 85° Very clean bkg. subtraction but cuts off around 3 GeV	Phase-gated
76 Bright, isolated AGN (2 years) 6° ROI, q_z > 100°, E > 1 GeV Need small PSF for bkg. subtraction	Aperture
Earth limb (200 limb-pointed orbits) E > 10 GeV Difficult to model earth limb emission below ~ 10 GeV.	Zenith Angle cut
All Sky E > 10 GeV (also prescaled samples at lower E) Useful for optimizing selections, but not precise	Latitude





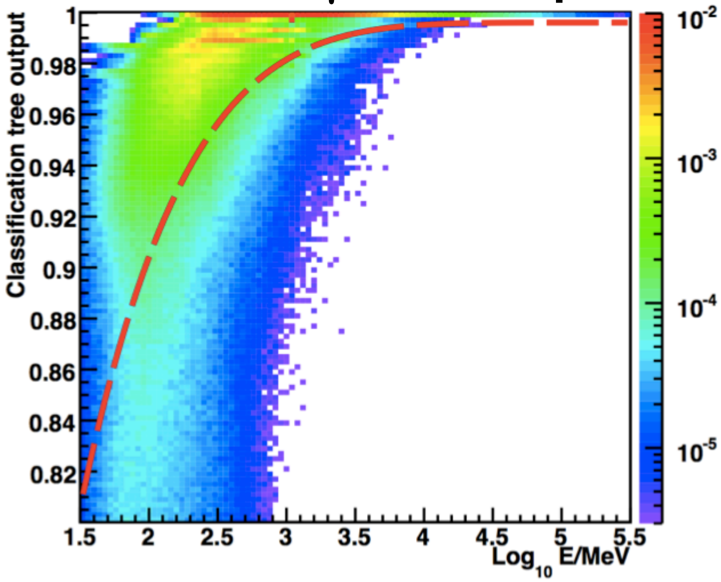
PARTICLE BACKGROUNDS

Any particles misclassified as γ rays will decrease the signal to noise for sources, and may affect spectral measurements if unaccounted for.

Since the θ-distribution and front/back ratio in BKG are different to γ rays they can also confuse the likelihood fit.

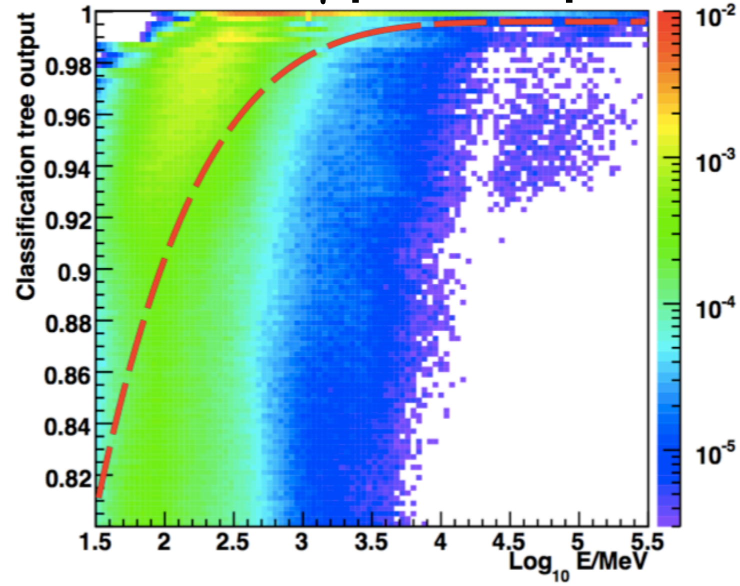
Final Stages of Background Reduction

X v. E for γ-rich sample



Energy dependent cut rejects 5% of event at all energies.

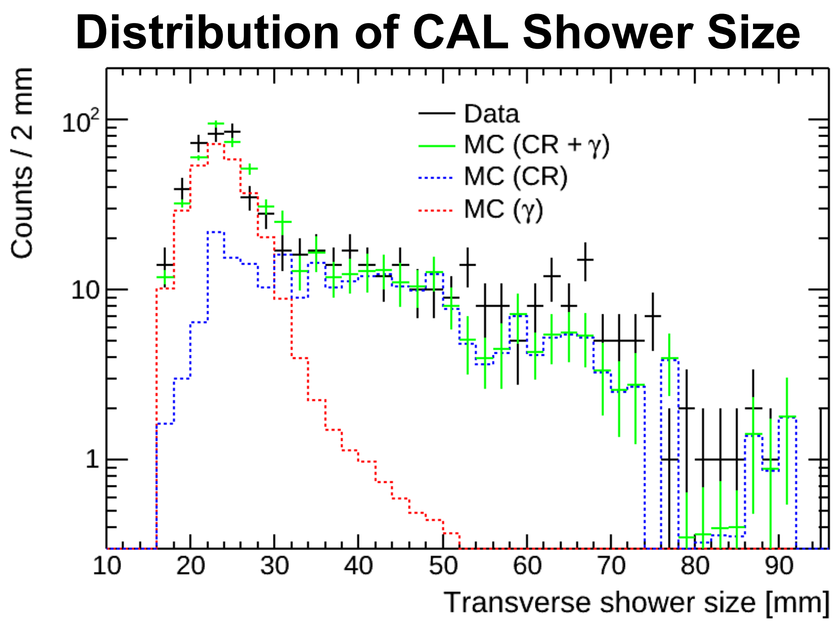
X v. E for γ-poor sample

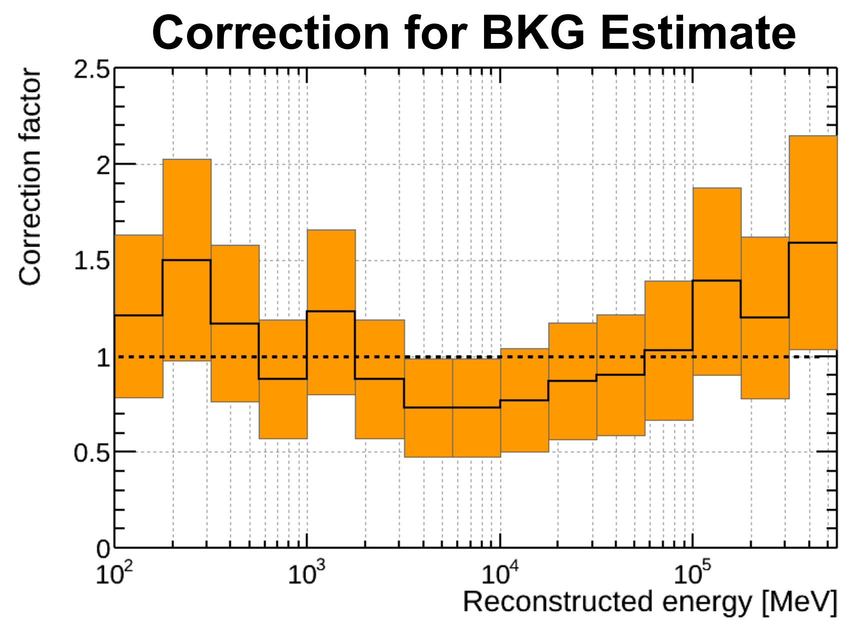


Cut rejects larger fraction of events.

P7SOURCE, P7CLEAN and P7ULTRACLEAN were developed w/ flight data
Too much background to use this method for P7TRANSIENT.

Background Estimation



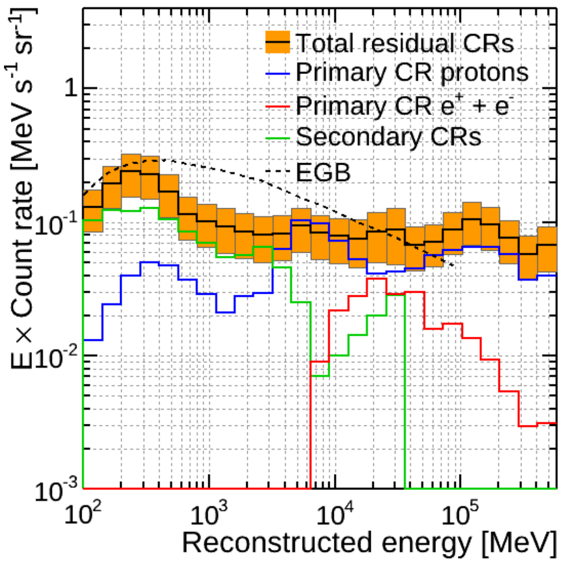


Fit signal + background templates (top) to compare bkg. to MC predictions (bottom).

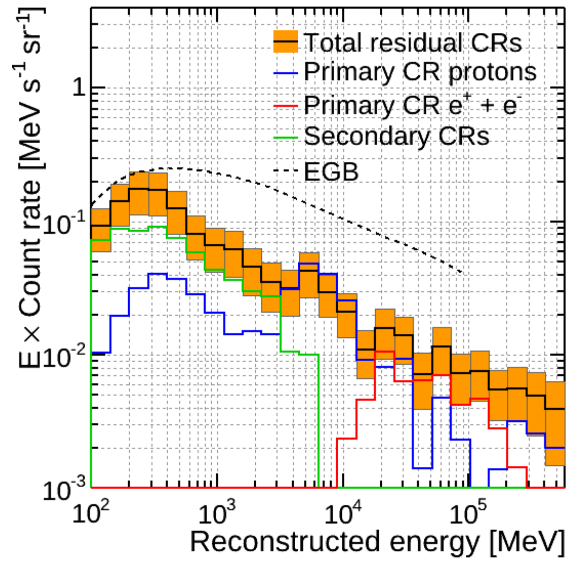
This is needed to disentangle γ rays in fitted isotropic components when measuring the Extra-Galactic background intensity.

Background Contamination spectra

Background Rates for P7SOURCE



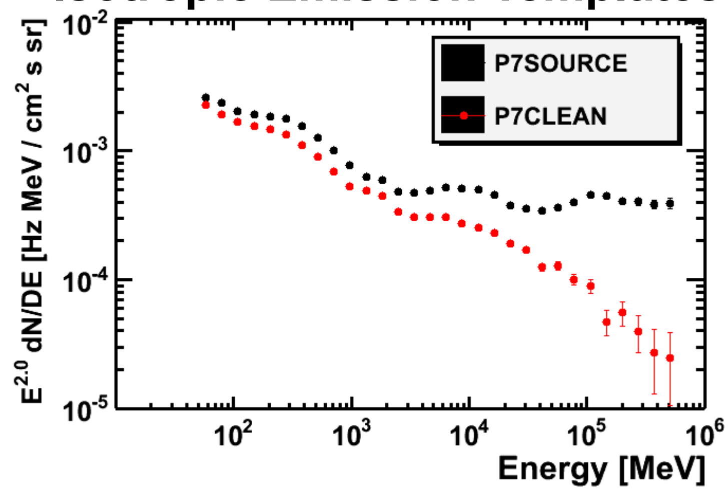
Background Rates for P7CLEAN



Spectra of particle background contamination for various event classes.

These are absorbed into the isotropic component when fitting.

Isotropic Emission Templates

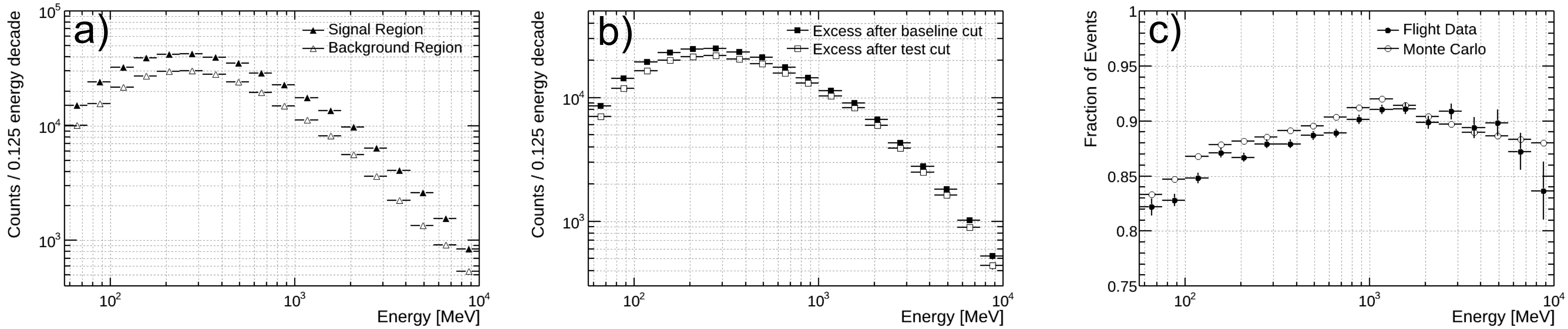


EFFECTIVE AREA

Errors in effective area translate directly to errors in Flux.

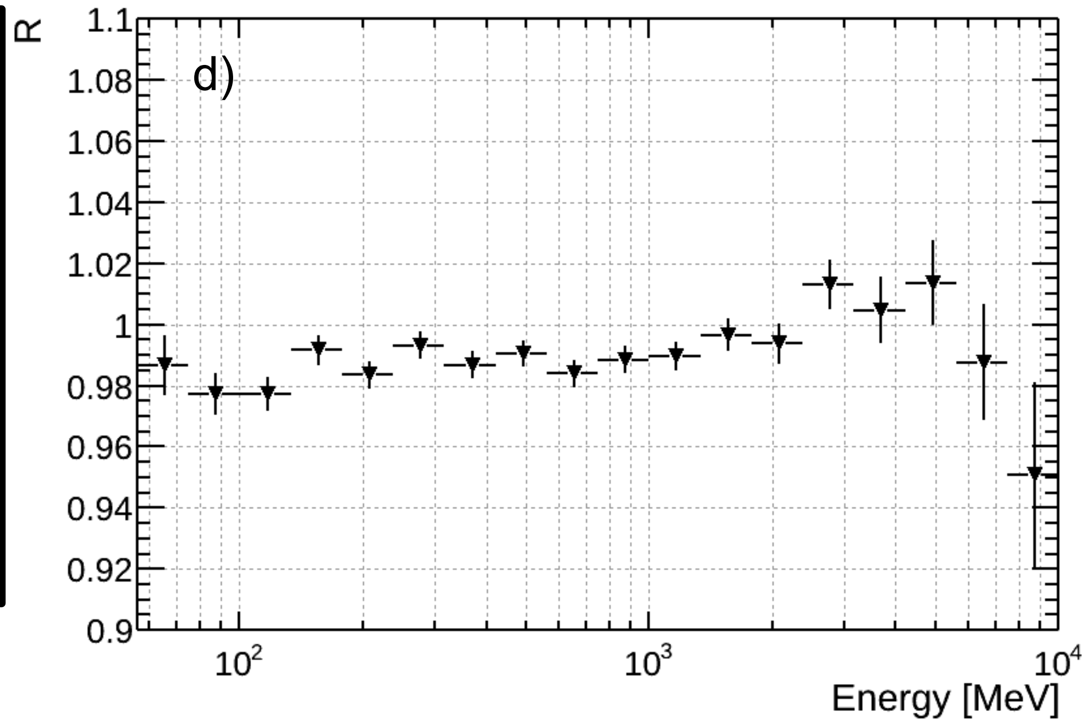
Critical for measuring spectra, extrapolation to other energies, identifying spectral features, source classification…

MC Efficiency Validation Technique



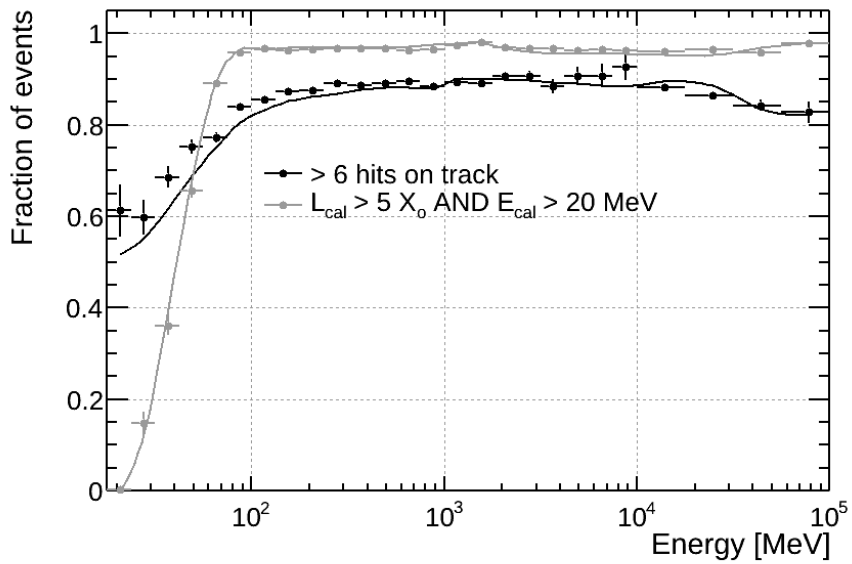
Explain method for data/MC efficiency comparison:

a) Counts spectra in signal and background regions
b) Excess in signal region before and after cut
c) Efficiency of cut on data and MC
d) Ratio of η_{data} / η_{mc}

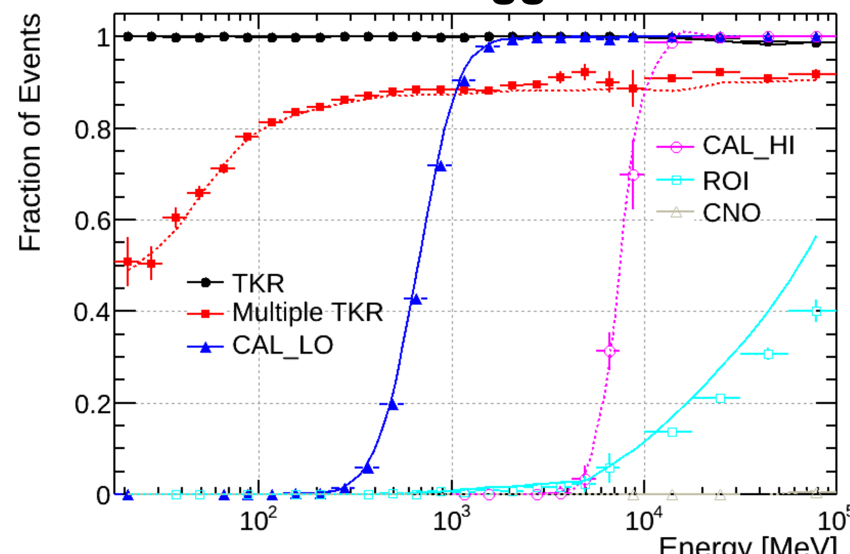


Validation of Fiducial Cuts, Trigger/ OBF

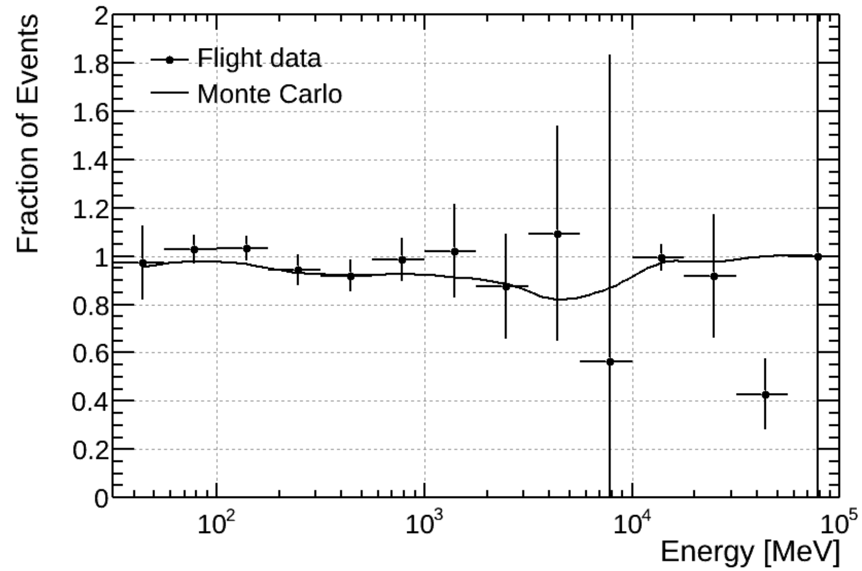
Data v. MC for Fiducial Cuts



Data v. MC for Trigger Primitives



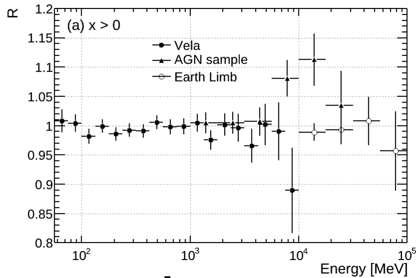
Data v. MC for Onboard Filter



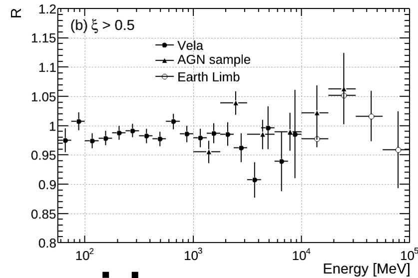
Data/ MC efficiency comparison for

a) Track finding & fiducial cuts
b) Trigger primitives
c) Onboard filter

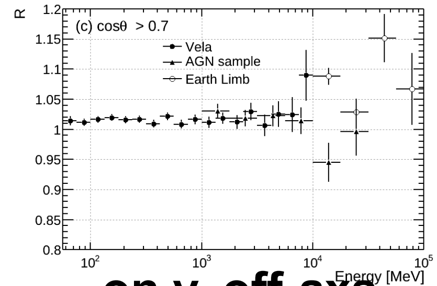
Consistency Checks and A_{eff} Error Bars



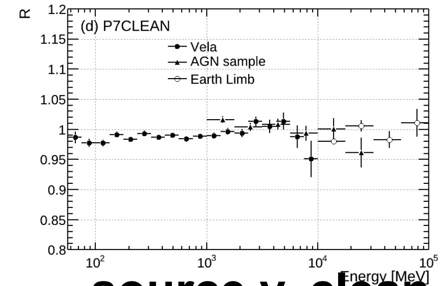
+x v. -x



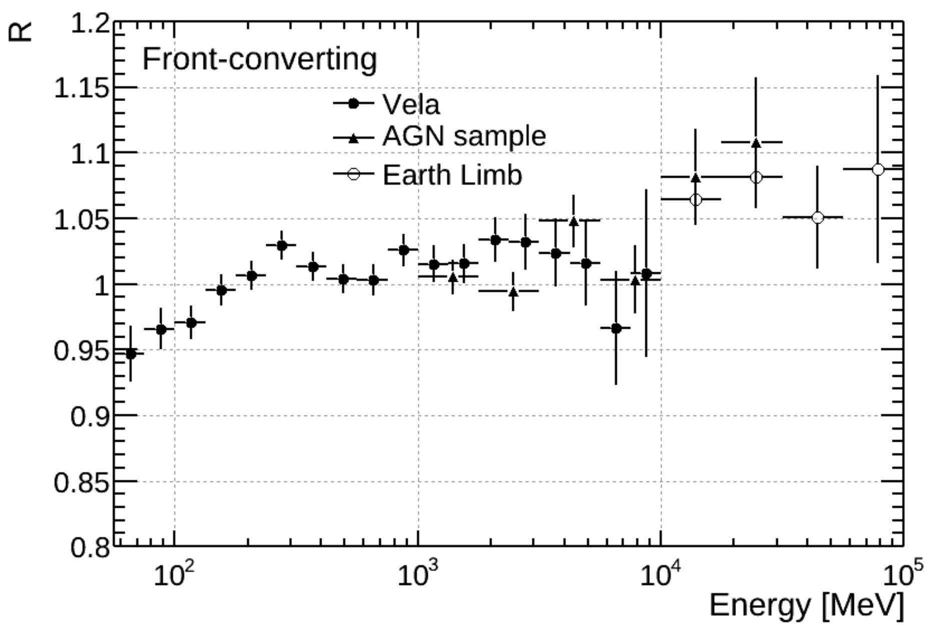
side v. corner

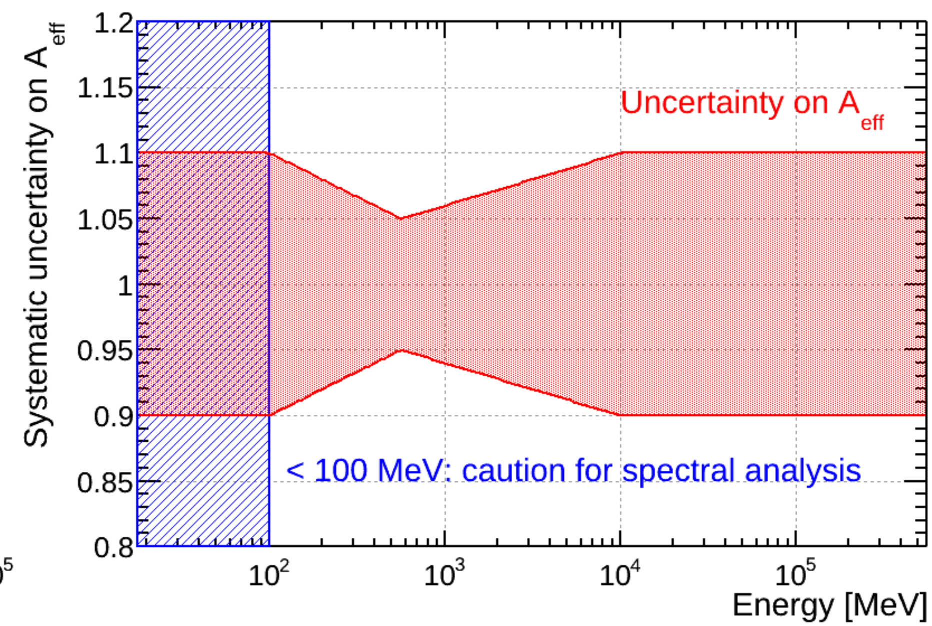


on v. off-axs



source v. clean



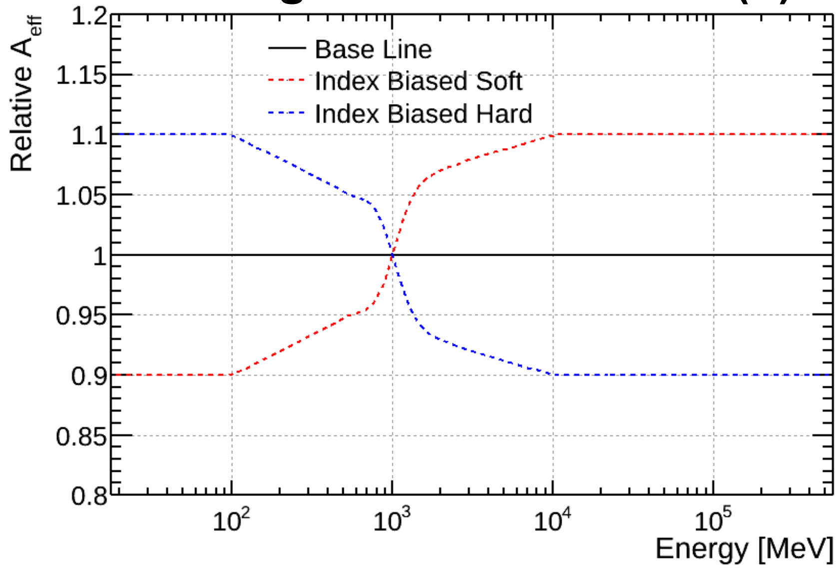


Most consistency checks (top) yield excellent results

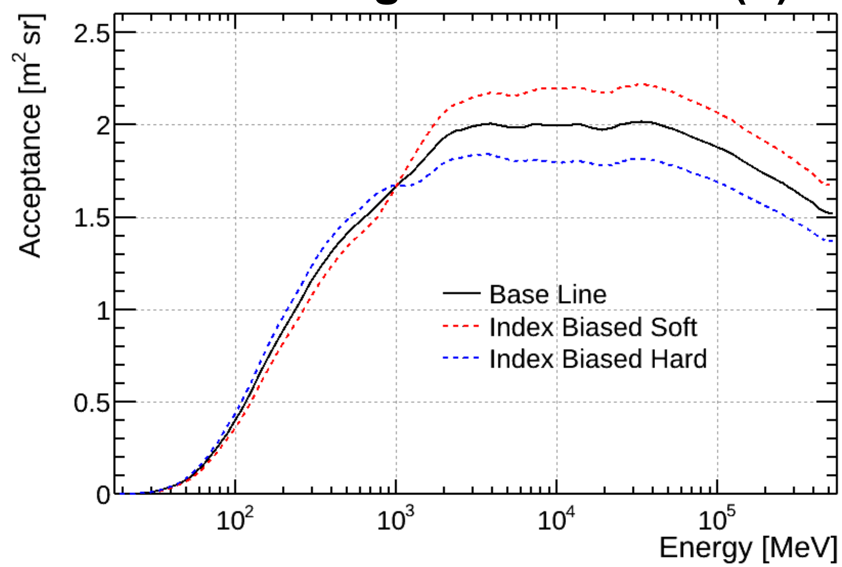
Front/Back fraction (bottom left) sets scale for A_{eff} errors (bottom right)

Propagating A_{eff} errors to Science Results

Bracketing Function for Index(Γ)



Bracketing IRFs for Index(Γ)

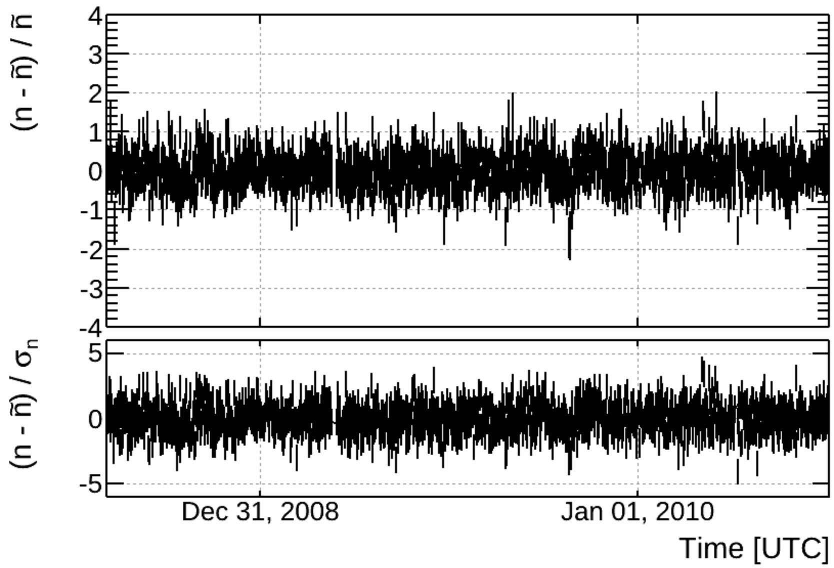


Simple "Bracketing" functions maximize bias within A_{eff} error envelope. Example with two point sources.

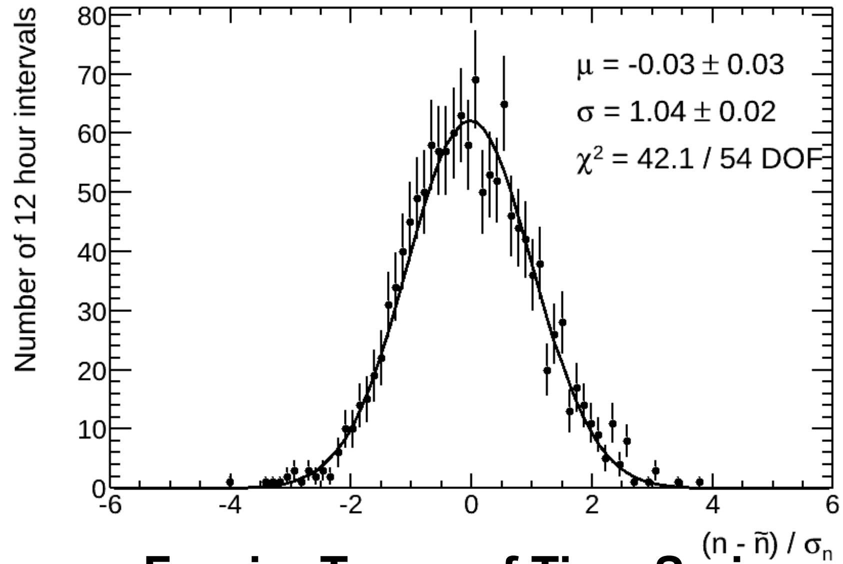
Parameter	B2 1520+31 (soft)		PG 1553+113 (hard)	
$\delta N_0/N_0$	+7.2%	−6.3%	+8.0%	−6.9%
$\delta\Gamma$ ($\delta\alpha$)	+0.09	−0.09	+0.05	−0.05
$\delta\beta$	+0.02	−0.02	-	
$\delta F_{25}/F_{25}$	+8.5%	−7.2%	+7.7%	−6.6%
$\delta S_{25}/S_{25}$	+8.1%	−6.9%	+10.0%	−8.3%

A_{eff} induced variability

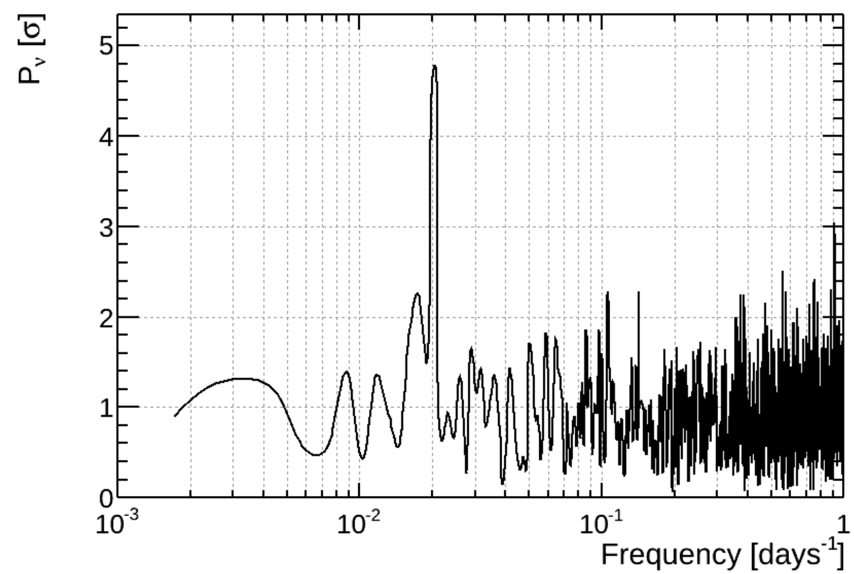
Time series of residuals



Distributions of residuals



Fourier Trans. of Time Series



Use total counts & exposure to predict counts in each 12-hour period

Vela (on-off) excess is very stable
Scaled residuals are ~ unit Gaussian

FFT shows white noise + 53.4 day orbital precession

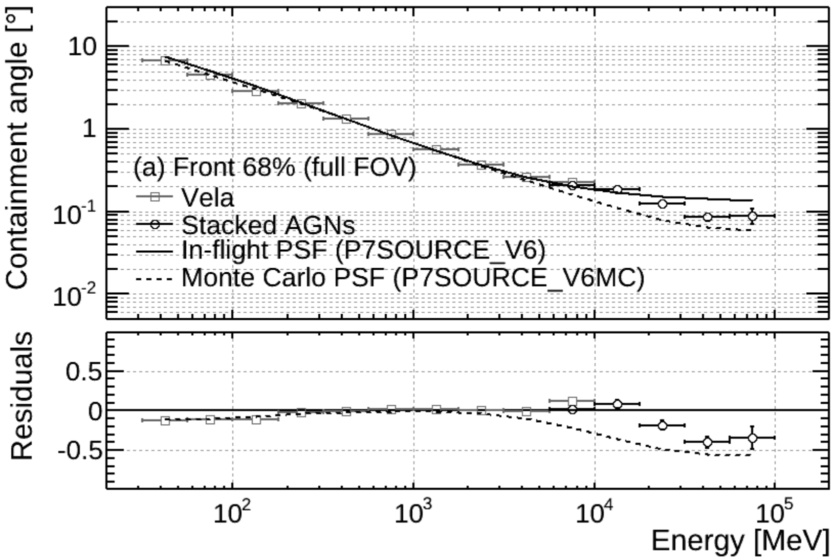
POINT-SPREAD FUNCTION

Errors in the PSF affect localization, studies of morphology, and to a lesser extent fluxes and spectra

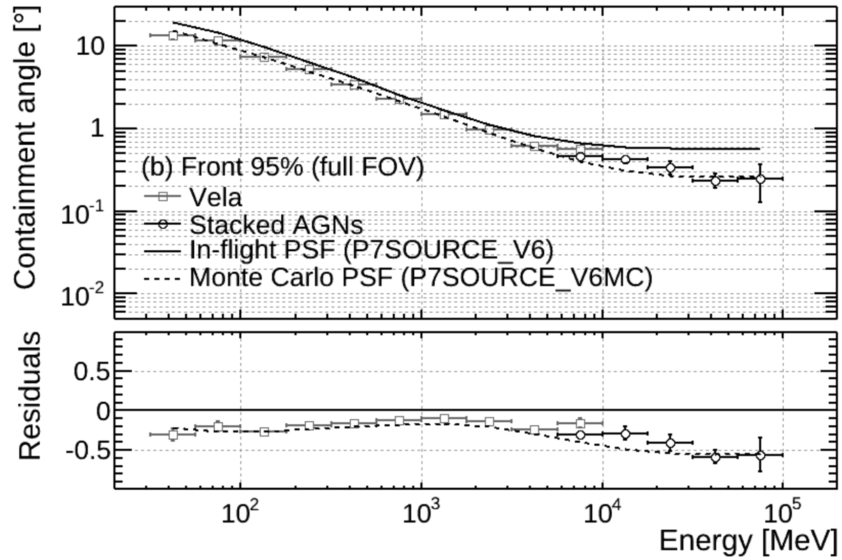
Critical for establishing source extension and morphology

Validation and Calibration of PSF

Event Rates over 1 Day



Event Rates over 1 Day



Monte Carlo underestimates PSF above ~1 GeV, particularly for back-converting events

In-flight PSF based on study of bright AGN with ~11 months of data

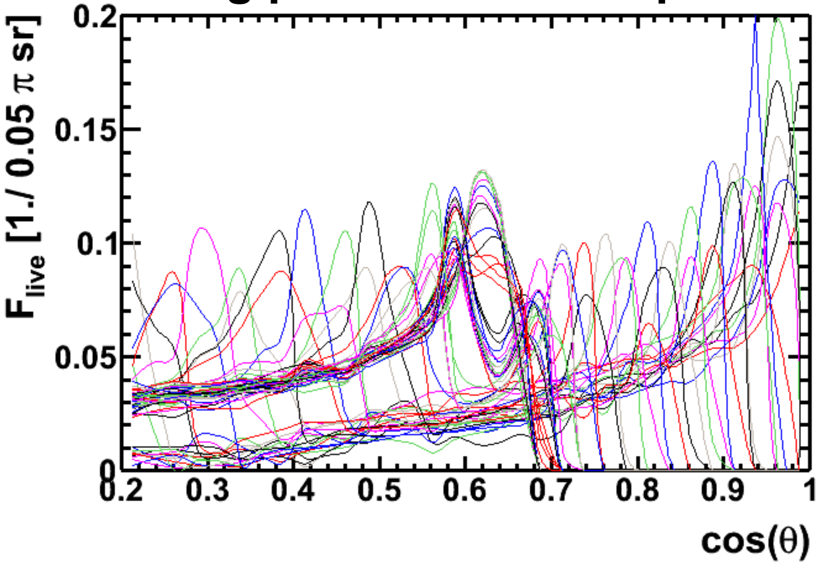
Not enough statistics to study θ-dependence: Averaged it out

Use phase-subtracted pulsar and AGN samples to compare containment of MC PSF to in-flight PSF

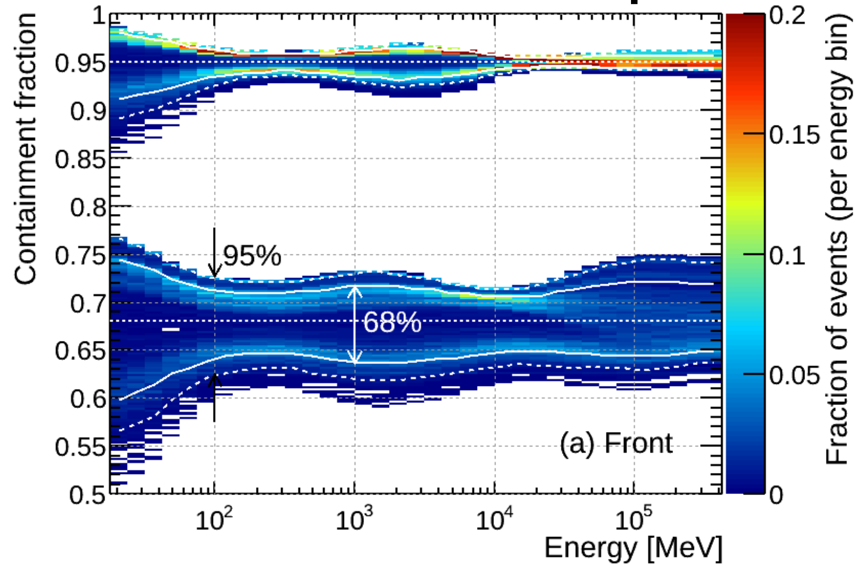
In-flight PSF fits the core of distribution better, but overestimates tails

Propagating PSF errors to Science Results

Observing profiles for 12hr periods



PSF Containment for 12hr periods



Error band on aperture coming when ignoring θ-dependence of PSF for a series of 12 hour observation

Comes from variations in observing profile (inset)

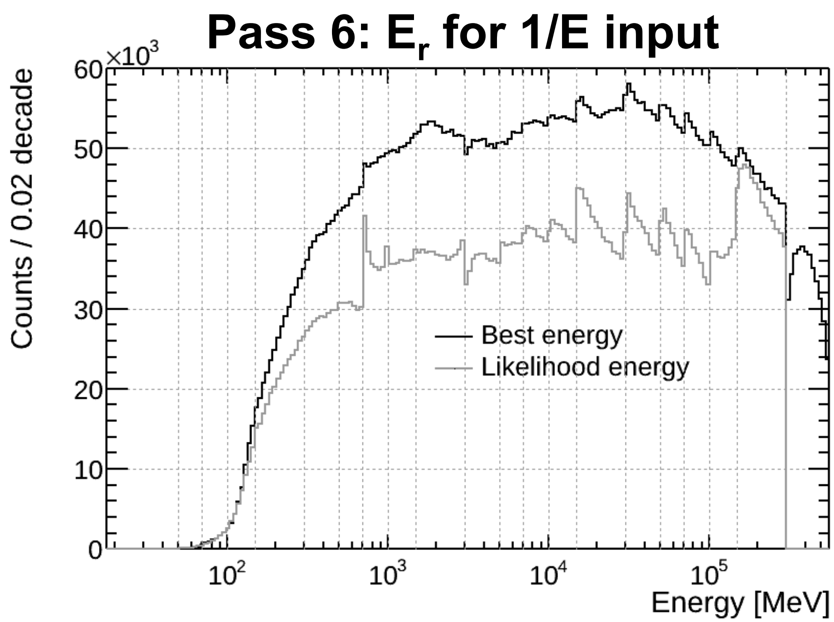
In General: quantify bias on fit as a function parameters using bracketing IRF technique.

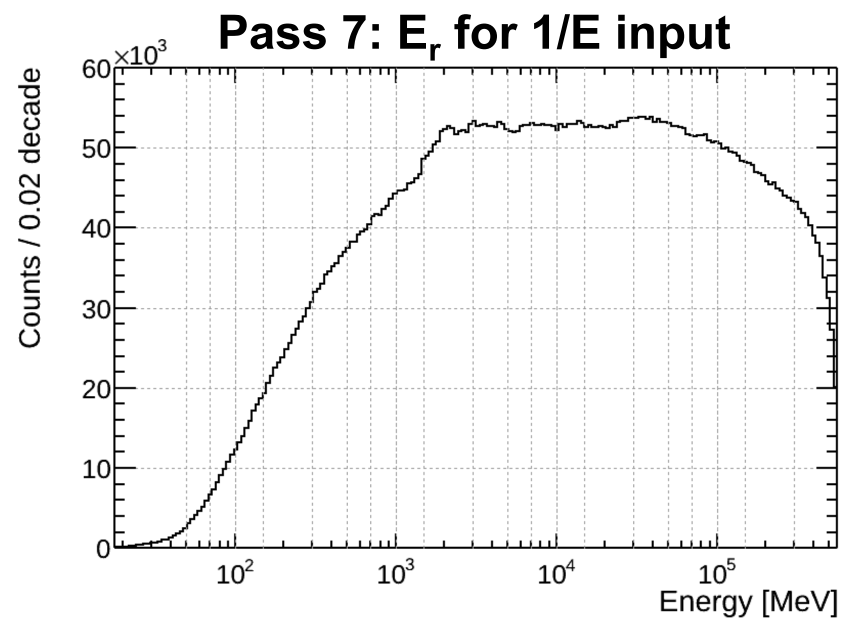
ENERGY RESOLUTION

Errors in the Energy Resolution affect spectral and spectral features

Critical for measuring spectra, extrapolation to other energies, identifying spectral features, source classification…

Spectral Features in Simulations



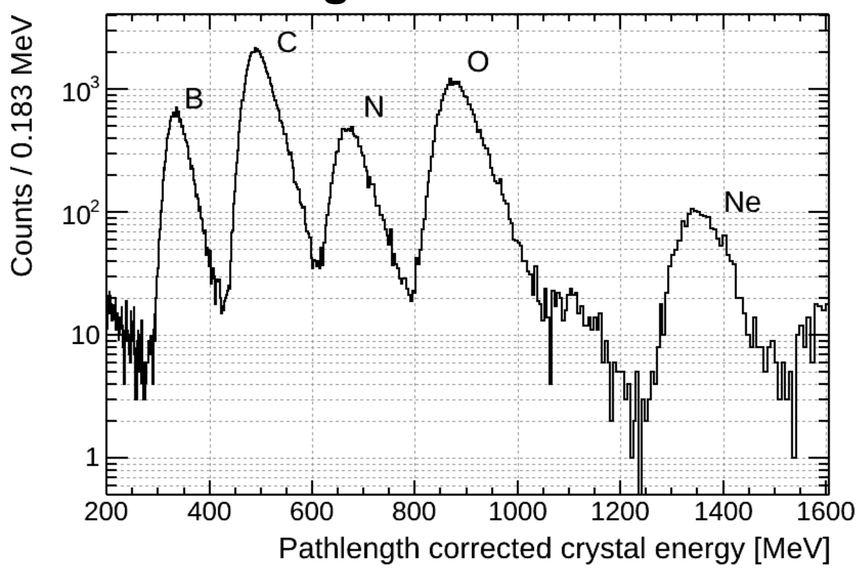


Reconstruction provides 3 energy estimates.

The likelihood based energy estimation method has sharp features at bin edges. We removed it from consideration and achieve much smoother response

Energy Calibration, Trending and Scale

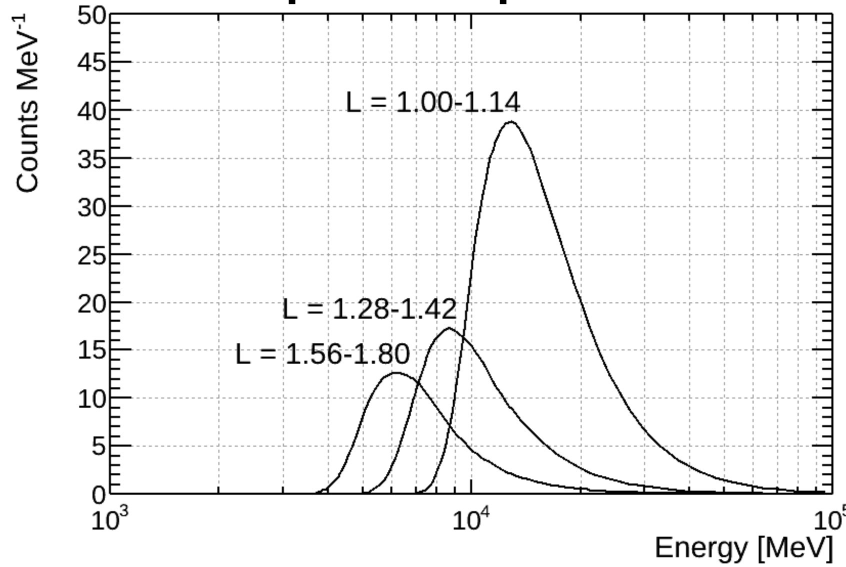
Path-length corrected E / xtal



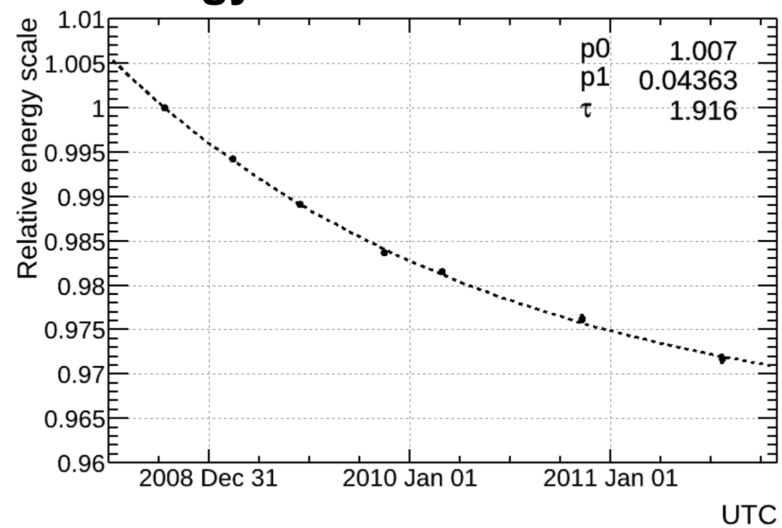
Range	Diode	Gain	Energy range	MeV/ADC
LEX8	Small	High	2–100 MeV	0.033
LEX1	Small	Low	2–1000 MeV	0.30
HEX8	Large	High	0.03–7 GeV	2.3
HEX1	Large	Low	0.03–70 GeV	20

Use heavy ions (C,N,O…) to calibrate crystal response in high ranges
Use Geomagnetic cutoff and e^+e^- to calibrate energy scale near 10GeV
3% degradation over mission to date

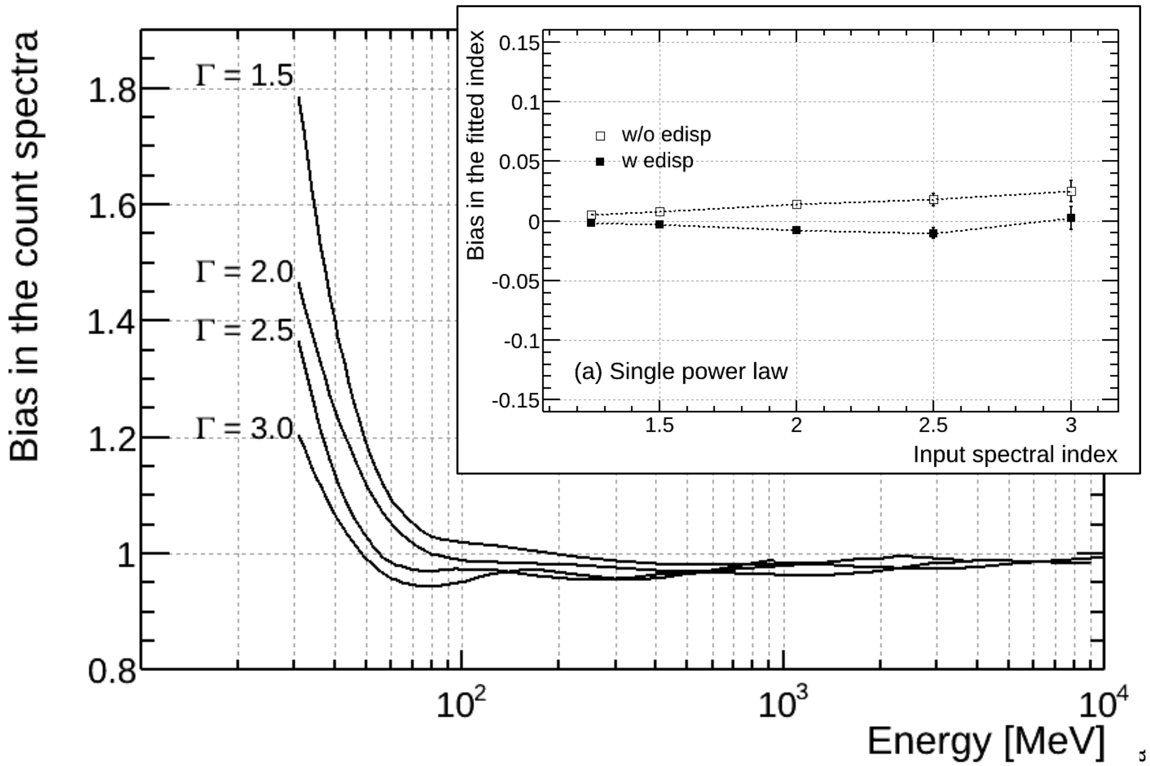
e+e- spectra at parts of orbit



Energy scale variation to date

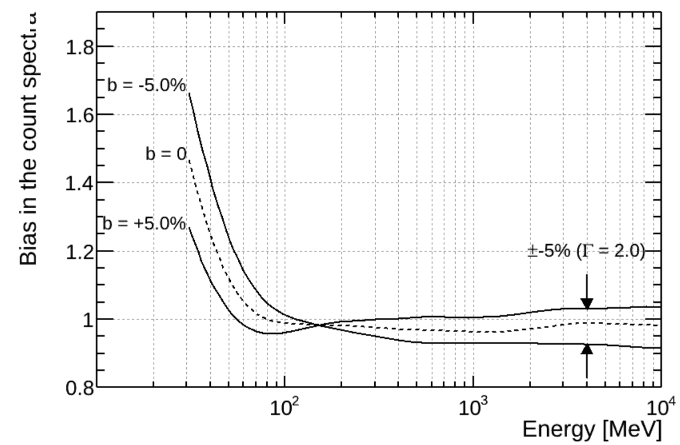


Propagating E_{disp} in Fitting



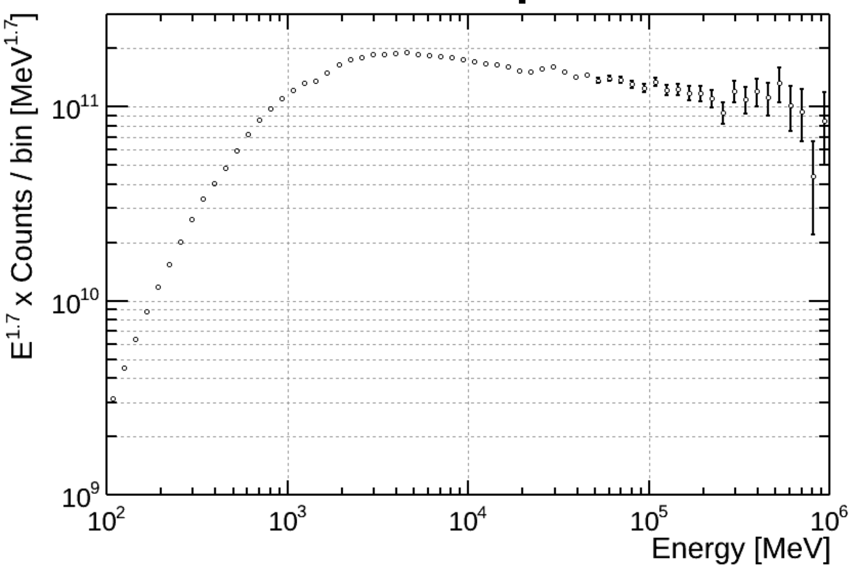
Use simulations to show effect of ignoring energy dispersion in counts spectra and in fitting (inset).

Also study the effect of bias in energy scale on spectra.

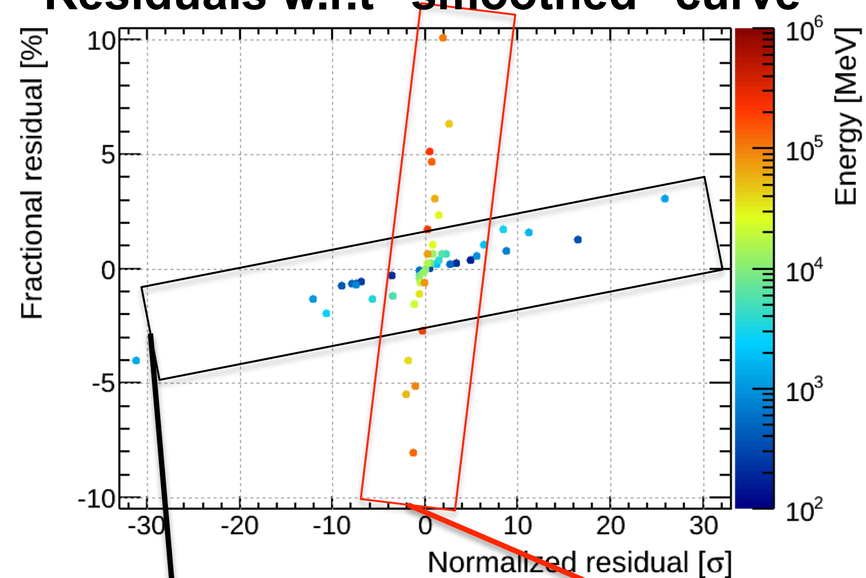


Instrument Induced Spectral Features

Earth Limb Spectrum



Residuals w.r.t "smoothed" curve



Given the extreme smoothness of the Earth albedo spectrum we can quantify the significance of any residual local (< 1 decade width) features

The most significant (25σ) is about 4% relative (near 3 GeV, related to Geomag. cutoff)

Highly significant deviation around ±2% relative near 3GeV

Large fractional deviation at high energy with low stats.

Summary: Table of Systematic Errors

Quantity	A_{eff}	PSF	Energy	
			Dispersion	Scale
F_{25}	$\sim 8\%$ (§ 5.7)	$\sim 8\%$ (§ 6.5)	$\sim 3\%$ (§ 7.4)	$+13\% - 5\%$ (§ 7.4)
S_{25}	$\sim 10\%$ (§ 5.7)	$\sim 6\%$ (§ 6.5)	$\sim 2\%$ (§ 7.4)	$+4\% - 2\%$(§ 7.4)
Γ	~ 0.09 (§ 5.7)	~ 0.07 (§ 6.5)	~ 0.04 (§ 7.4)	-
Variability	$\sim 3\%$ (§ 5.6)	$\sim 3\%$ (§ 6.5)	-	-
Localization	-	$\sim 0.005^{\circ}$ (§ 8.2)[a]	-	-

These are just rough estimates of systematic errors on commonly measured quantities. (Section number refer to "performance paper").

It is not meant to replace actually estimating the systematic errors which are relevant for a particular analysis.

SUMMARY

Summary

- LAT data is used to study a many topics in the γ-ray sky
  - Flexibility is need to account for many types of analysis
  - Huge amount of instrumental phase space to calibrate
- Data reduction to “public” event classes is tremendous effort
  - Lots of places where it can go wrong in subtle ways
- Current analysis and IRFs provide tremendous potential
  - ~10% errors from 100MeV – 300GeV
    - LAT analyses are becoming correspondingly ambitious
  - Ongoing work to expand energy range, reduce systematic errors
    - Needed to support next generation of LAT analyses

For this afternoon

- To follow the derivation of the IRFs please download this file:
  - http://www.slac.stanford.edu/~echarles/FermiSchool/FermiSchoolData.tar.gz
  - (Maybe not all at once though)
- Also available on memory stick
- The tar file includes:
  - The IRF files for the P7SOURCE_V6 IRFs
  - A file of simulated events you can use to derive IRFs.