Fermi Gamma-ray Space Telescope

Tutorial on Fermi-LAT data analysis

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Material from P.Bruel, M.Razzano, S.Buson and R.Desiante

Sexten 2017

Outline

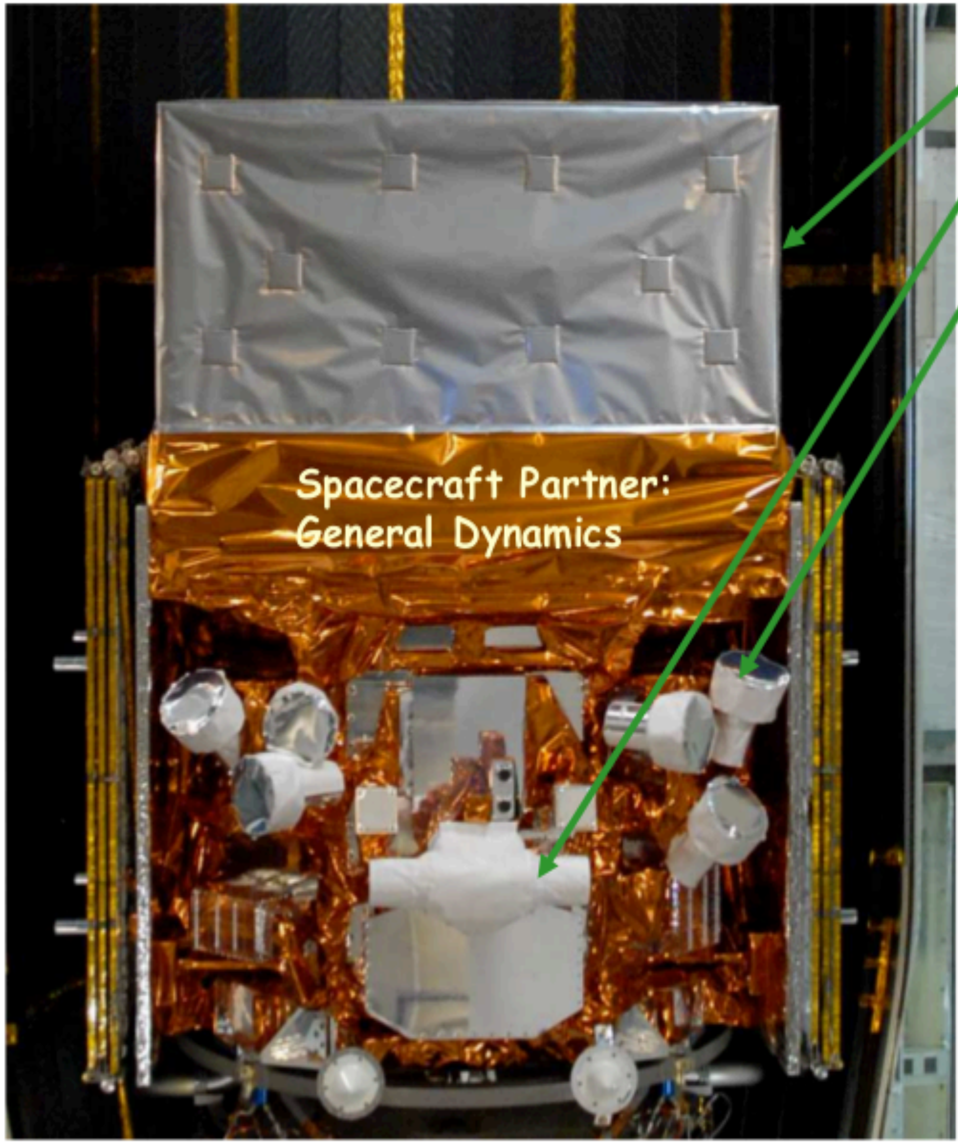
- **Overview of the Fermi Large AreaTelescope**
  - **How it works**
  - **LAT data**
  - **LAT performance**

- **Fermi Science Tools**
  - **General Introduction**

- **Maximum Likelihood Overview**
  - **Source modeling**

- **One study case:**
  - **Crab Nebula: PSR and Nebula analysis**

The observatory



Large AreaTelescope (LAT)
20 MeV - >300 GeV

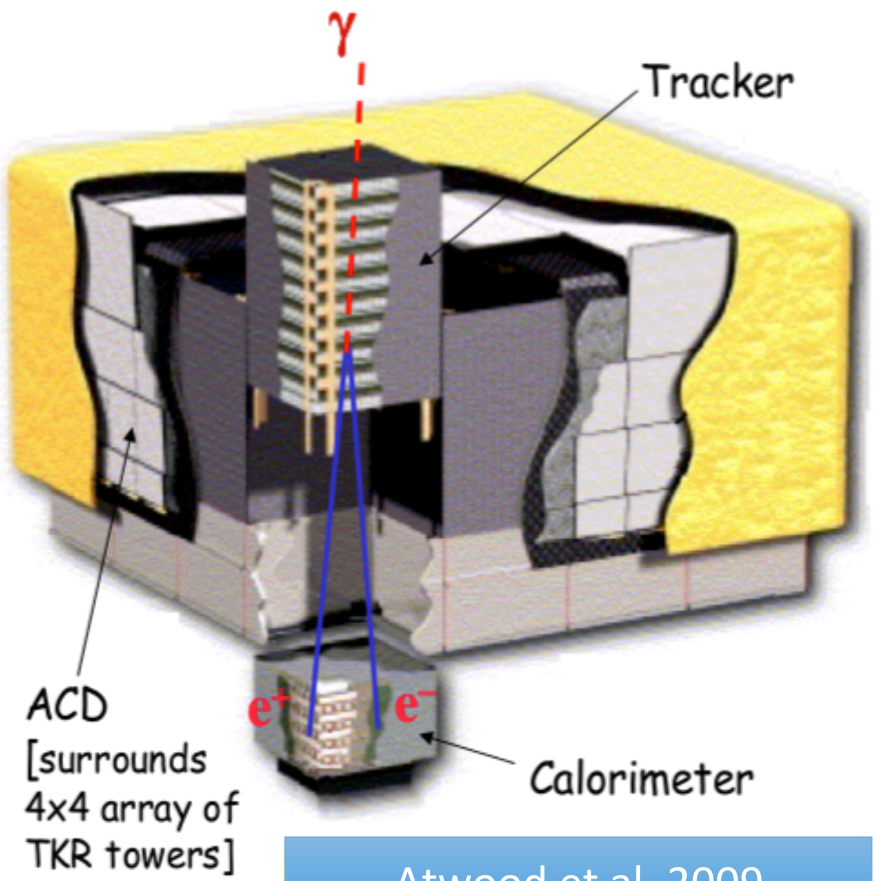
Gamma-ray Burst Monitor (GBM)
NaI and BGO Detectors
8 keV - 30 MeV

KEY FEATURES

- Huge field of view
  - –LAT: 20% of the sky at any instant; in sky survey mode, expose all parts of sky for ~30 minutes every 3 hours. GBM: whole unocculted sky at any time.
- Huge energy range, including largely unexplored band 10 GeV - 100 GeV. Total of >7 energy decades!
- Large leap in all key capabilities. Great discovery potential.

How the LAT works

- <u>Precision Si-strip Tracker (TKR)</u> Measure the photon direction; gamma ID.
- <u>Hodoscopic CsI Calorimeter (CAL)</u> Measure the photon energy; image the shower.
- <u>Segmented Anticoincidence Detector (ACD)</u> Reject background of charged cosmic rays; segmentation removes self-veto effects at high energy.
- <u>Electronics System</u> Includes flexible, robust hardware trigger and software filters.

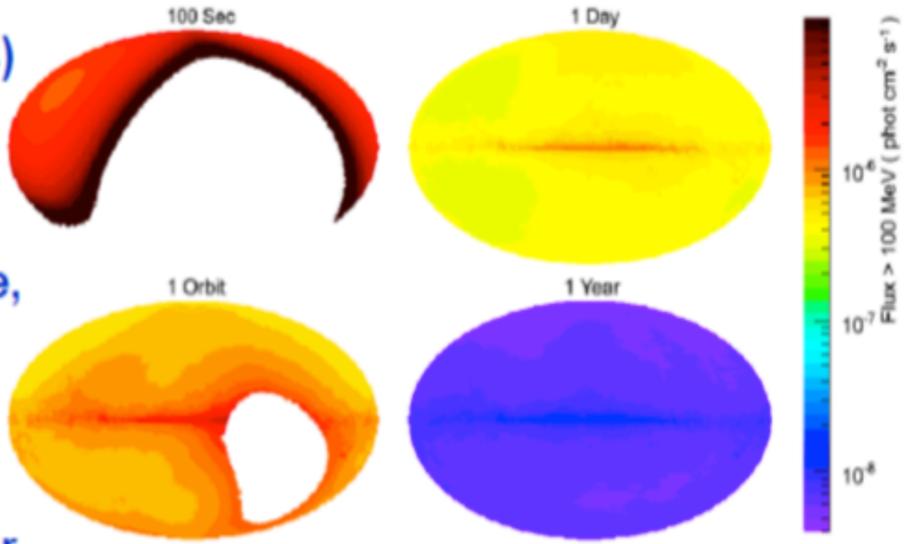


Atwood et al. 2009

<u>Systems work together to identify and measure the flux of cosmic gamma rays with energy 20 MeV - >300 GeV.</u>

Operating Mode

- Primary observing mode is Sky Survey
  - Full sky every 2 orbits (3 hours)
  - Uniform exposure, with each region viewed for ~30 minutes every 2 orbits
  - Best serves majority of science, facilitates multiwavelength observation planning
  - Exposure intervals commensurate with typical instrument integration times for sources
  - EGRET sensitivity reached in days



- Pointed observations when appropriate (selected by peer review in later years) with automatic earth avoidance selectable. Target of Opportunity pointing.
- Autonomous repoints for onboard GRB detections in any mode.

What do you need for the analysis

LAT DATA ARE PUBLIC!!

- **Data ...of course!**
  - LAT detected events
  - Spacecraft related stuff
  - Extras (Backgrounds , catalog sources, timing..)

- **Fermi Science Tools**
  - http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/

- **Other ancillary tools**
  - ftools, HEASOFT, DS9 etc..
  - http://heasarc.gsfc.nasa.gov/docs/software.html

- **Lots and lots of scripts!**
  - Fermi tools are already scriptable
  - You can also use your favourite scripting language... but ..
  - Science Tools can be imported as Python modules!

LAT data analysis references

Fermi Data Analysis: starting points

Fermi Science Support Center: http://fermi.gsfc.nasa.gov/ssc/

Fermi Newsletters: http://fermi.gsfc.nasa.gov/ssc/resources/newsletter/

Fermi Data Access: http://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi

Fermi Science Tools Reference Manual:
http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/references.html

Fermi Analysis Threads:
http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/
http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/

Fermi - LAT Likelihood Algorithm description
http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Likelihood/
Cash W. 1979, ApJ 228, 939
Mattox J. R. et al 1996, ApJ 461, 396
Protassov et al. 2002, ApJ 57, 545

LAT Performance Page: http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm
The Large Area Telescope on the Fermi Gamma-Ray Space Telescope Mission, W.B. Atwood, et. al., ApJ, 2009, 695, 1071.
The On-orbit Calibrations for the Fermi Large Area Telescope, A.A. Abdo, et al. arXiv:0904.2226v1

How to access LAT Data

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

LAT Data

•**LAT data products can be downloaded by the FSSC website**

–**LAT Data server** http://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi

–**Archive of weekly files**

–ftp://legacy.gsfc.nasa.gov/fermi/data/

•**Two main data products (stored in FITS format)**

–**Events file (FT1)**

–**i. e. "what the LAT sees"**

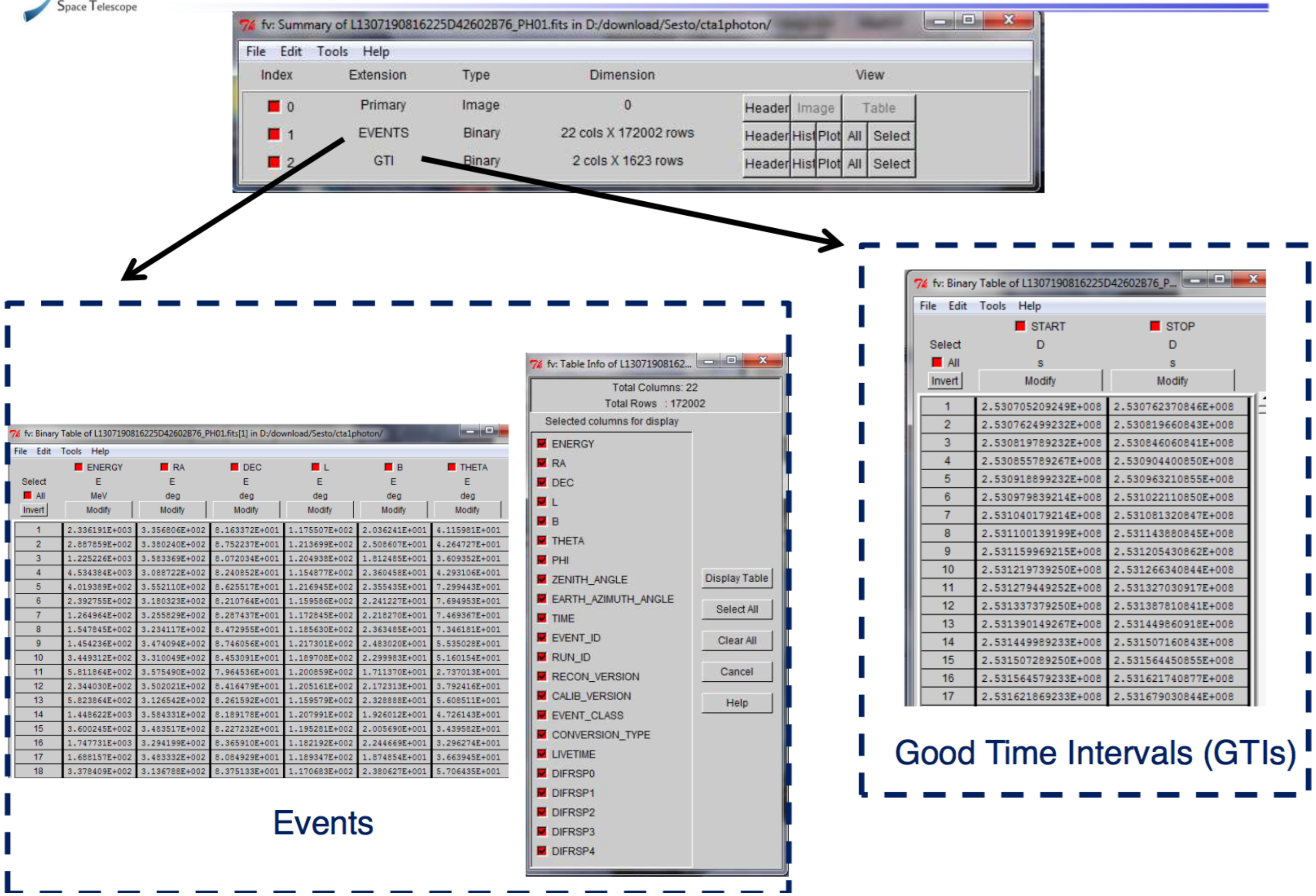
– (photons, their energy, coordinates, time, event classes etc..)

–**Spacecraft files (FT2)**

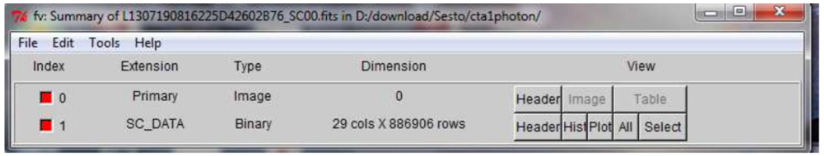
–**i. e. "where the LAT is"**

– (position, angles..)

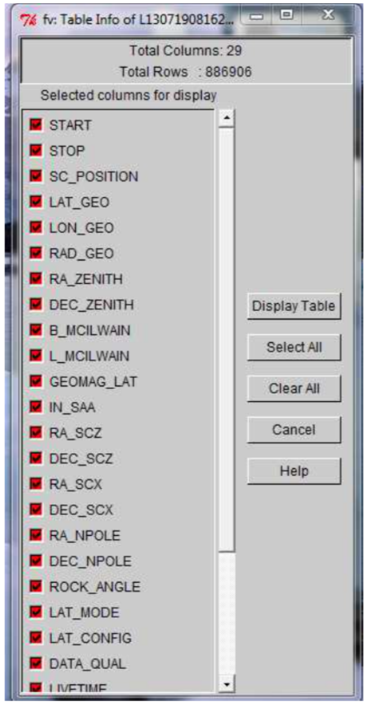
FT1: photons, photons…



FT2: where is Fermi ?



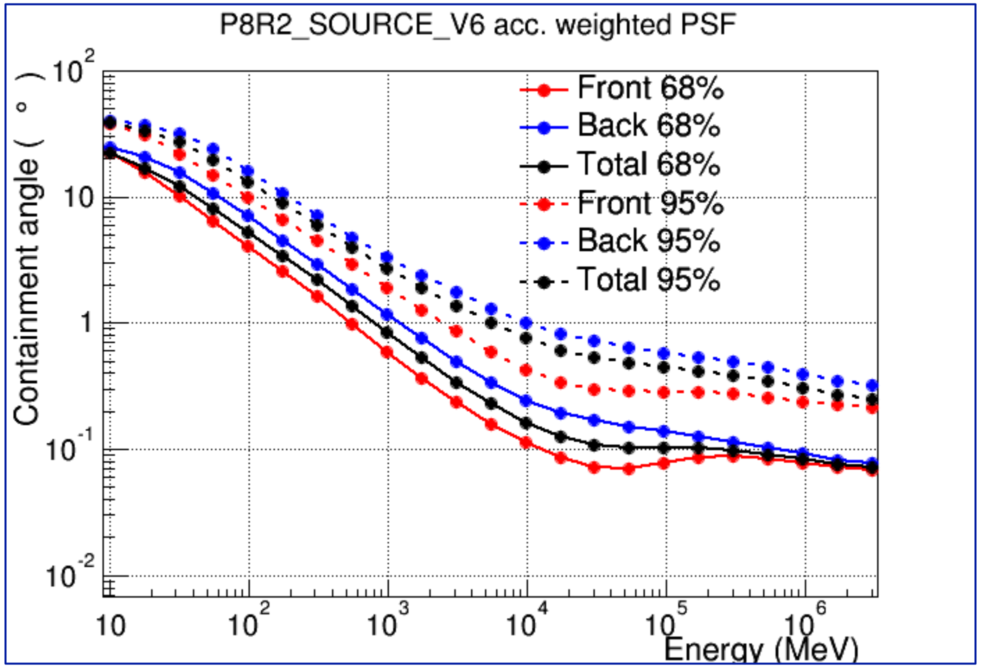
	START	STOP	SC_POSITION	LAT_GEO	LON_GEO	RAD_GEO
	D	D	3E	E	E	D
	s	s	m	deg	deg	m
	Modify	Modify	Modify	Modify	Modify	Modify
1	2.395612776000E+008	2.395613076000E+008	Plot	6.592855E+000	1.288651E+002	5.504893679991E+005
2	2.395613076000E+008	2.395613376000E+008	Plot	7.383996E+000	1.304637E+002	5.501927909688E+005
3	2.395613376000E+008	2.395613676000E+008	Plot	8.168575E+000	1.320687E+002	5.499135114643E+005
4	2.395613676000E+008	2.395613976000E+008	Plot	8.945851E+000	1.336805E+002	5.496488803954E+005
5	2.395613976000E+008	2.395614276000E+008	Plot	9.715078E+000	1.352999E+002	5.494012096987E+005
6	2.395614276000E+008	2.395614576000E+008	Plot	1.047550E+001	1.369274E+002	5.491686522950E+005
7	2.395614576000E+008	2.395614876000E+008	Plot	1.122635E+001	1.385636E+002	5.489517414953E+005
8	2.395614876000E+008	2.395615176000E+008	Plot	1.196685E+001	1.402090E+002	5.487538278698E+005
9	2.395615176000E+008	2.395615476000E+008	Plot	1.269626E+001	1.418642E+002	5.485701226070E+005
10	2.395615476000E+008	2.395615776000E+008	Plot	1.341378E+001	1.435296E+002	5.483998366015E+005
11	2.395615776000E+008	2.395616076000E+008	Plot	1.411865E+001	1.452058E+002	5.482435574869E+005
12	2.395616076000E+008	2.395616376000E+008	Plot	1.481007E+001	1.468931E+002	5.481000357595E+005
13	2.395616376000E+008	2.395616676000E+008	Plot	1.548726E+001	1.485919E+002	5.479706011147E+005



spacecraft Data

Extras - IRFs

- **LAT Instrument Response Functions (IRFs)**
  - **Point Spread Function (PSF)**
  - **Effective Area**
  - **Energy Resolution**



- **Highly dependent on energy**
- **and arrival direction of incident**
- **photon**

- **Fundamental for analysis!!**

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

Pass8 data

Pass8 data

Fermi
Science Support Center

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Using LAT's New Pass 8 Data

The FSSC is now serving Pass 8 LAT data for analysis. The new version of LAT data provides a number of improvements over the reprocessed Pass 7 data, and is considered the best dataset for all types of LAT analysis. As of the release date (June 24, 2015) reprocessed Pass 7 data is no longer being served. However, existing Pass 7 reprocessed data has been archived and is available from the FSSC's FTP server.

Pass 8 provides a full reprocessing of the entire mission dataset, including improved event reconstruction, a wider energy range, better energy measurements, and significantly increased effective area. In addition, the events have been evaluated for their measurement quality in both position and energy. This allows the user to select a subset of the events if appropriate to improve analysis results. To support the use of these data selections, there have been some structural changes to the *Fermi* Science Tools.

Here we discuss the changes to the data and tools, and how they affect your analysis.

Pass 8 Bottom Line

Pass 8 contains a lot of changes, and the rest of this page may seem overwhelming. If you just want to get started doing a standard LAT analysis, here's the bottom line:

- Recommended event class for source analysis is "P8 Source" class (*evclass*=128).
- Add *evtype* parameter to your gtselect call (*convtype* parameter is deprecated). Recommended event type for source analysis is "FRONT+BACK" (*evtype*=3).
- Recommended zenith angle cut to eliminate Earth limb events ("zmax") is 90 degrees for events at 100 MeV and above.
- Recommended source list for analysis is the 3FGL Catalog. A python script is available at the User-Contributed Tools page that creates XML model files using the 3FGL catalog FITS file.

http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Pass8_usage.html

What does Pass mean?

- Each pass corresponds to a version of the Fermi LAT data
- It implies a whole package:
  - Intrument simulation
  - Reconstruction code
  - Event selection
  - Instrument Response Functions (IRFs)
  - Systematic uncertainties
  - Isotropic template (which includes the cosmic-ray residual background)
  - And sometimes more (Galactic diffuse model, Earth limb template, Sun+Moon template)
- It's only when we have validated the whole package that we can release it to the public.

Pass8 introduction

From Pass 6 to Pass 8

- Pass 6 (launch time)
  - Pass 6 reconstruction
  - Pass 6 selection
  - Based on pre-launch instrument simulation
  - First data revealed the issue of out-of-time pile-up (aka ghosts)
  - New: instrument simulation with ghosts -> correct IRFs
- Pass 7
  - Pass 6 reconstruction
  - New: Pass 7 selection optimized with simulations with ghosts
- Pass 8
  - New: improved instrument simulation
  - New: Pass 8 reconstruction, as ghost-proof as possible
  - New: Pass 8 selection

Pass8 Introduction

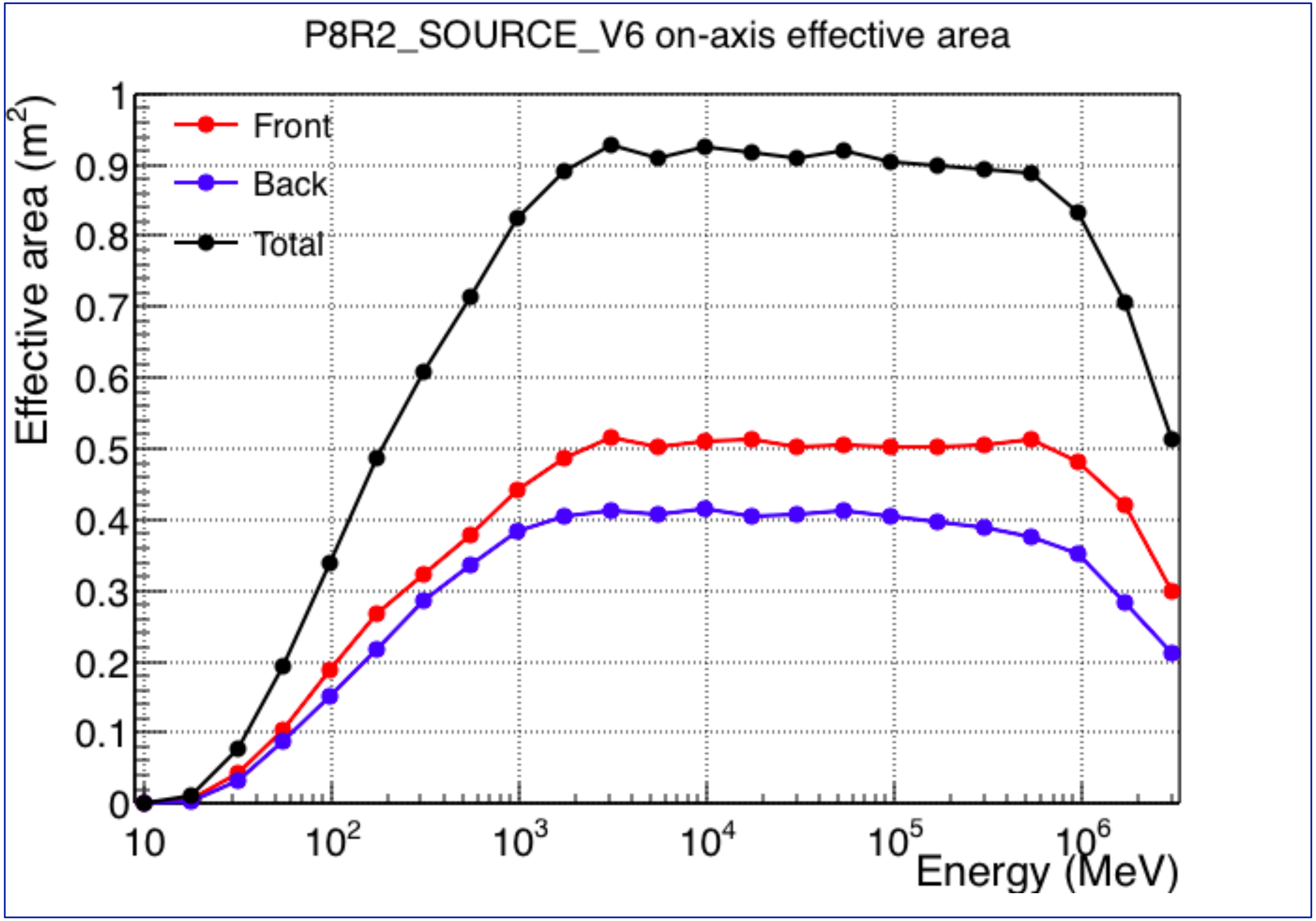
Pass 8 improvements

- Ghost handling
  - Tracker: ignoring ghost hits
  - ACD: partial deghosting
  - Calorimeter: clustering and cluster classification
- Improved direction measurement
  - Tree-based track finder
- Improved energy measurement
  - Extension of the energy range: from ~10 MeV to ~3 TeV
- Improved track/ACD matching information
  - Using the uncertainty of the tracker direction
- Improved event selection
  - Using the ROOT TMVA package (tmva.sourceforge.net)
- Additional sub-classes of events

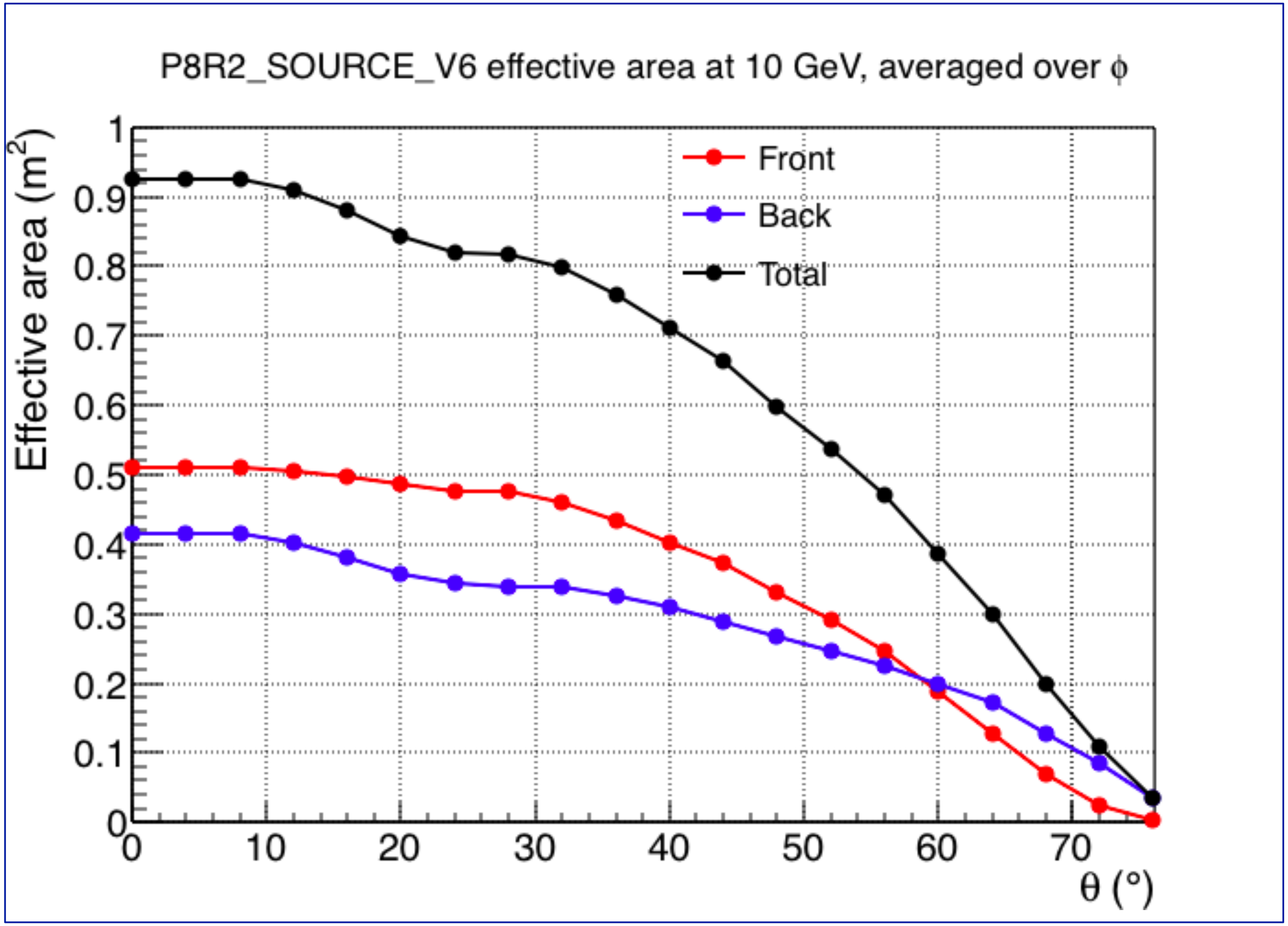
Pass8 performance

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

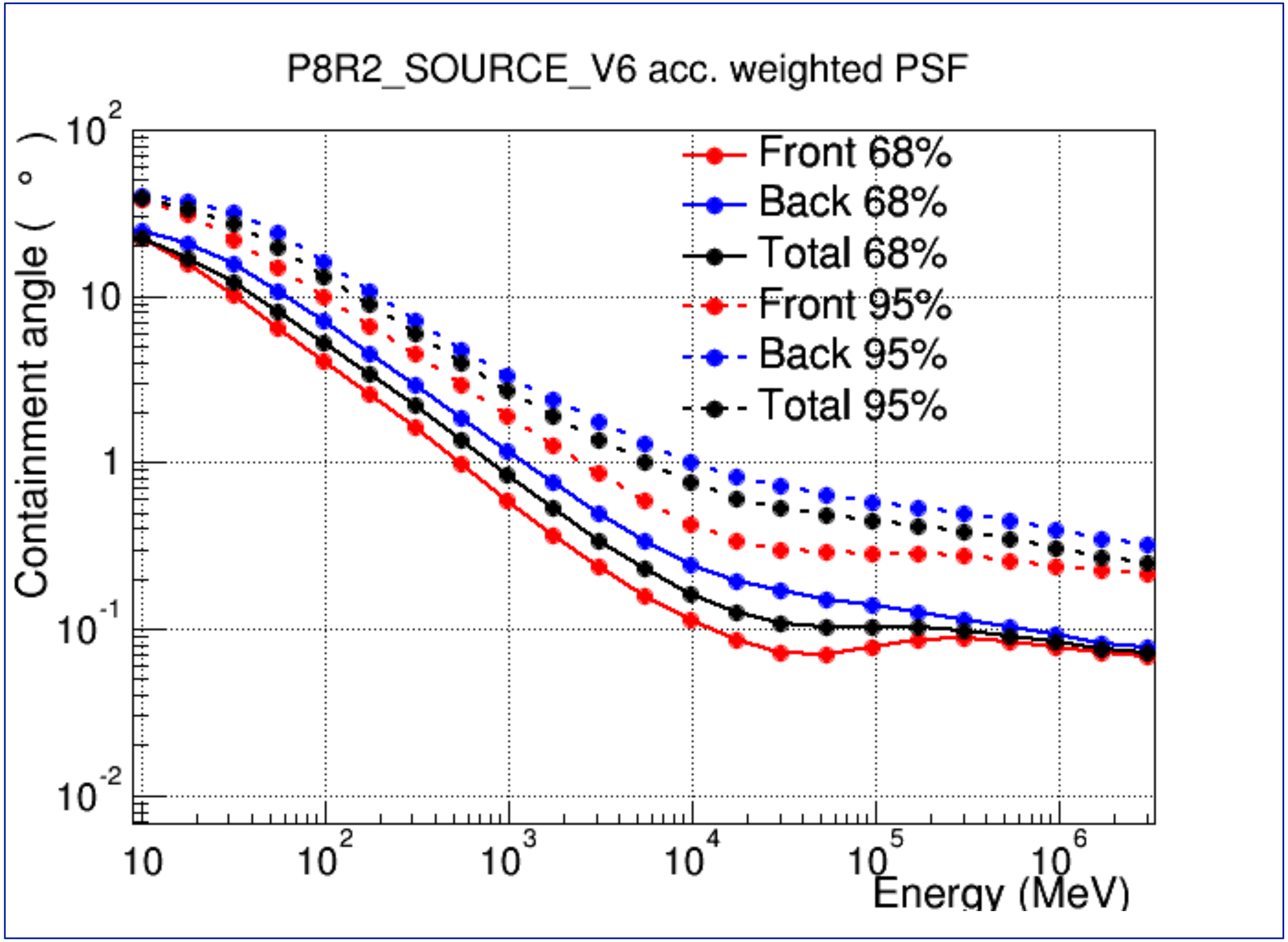
Effective Area



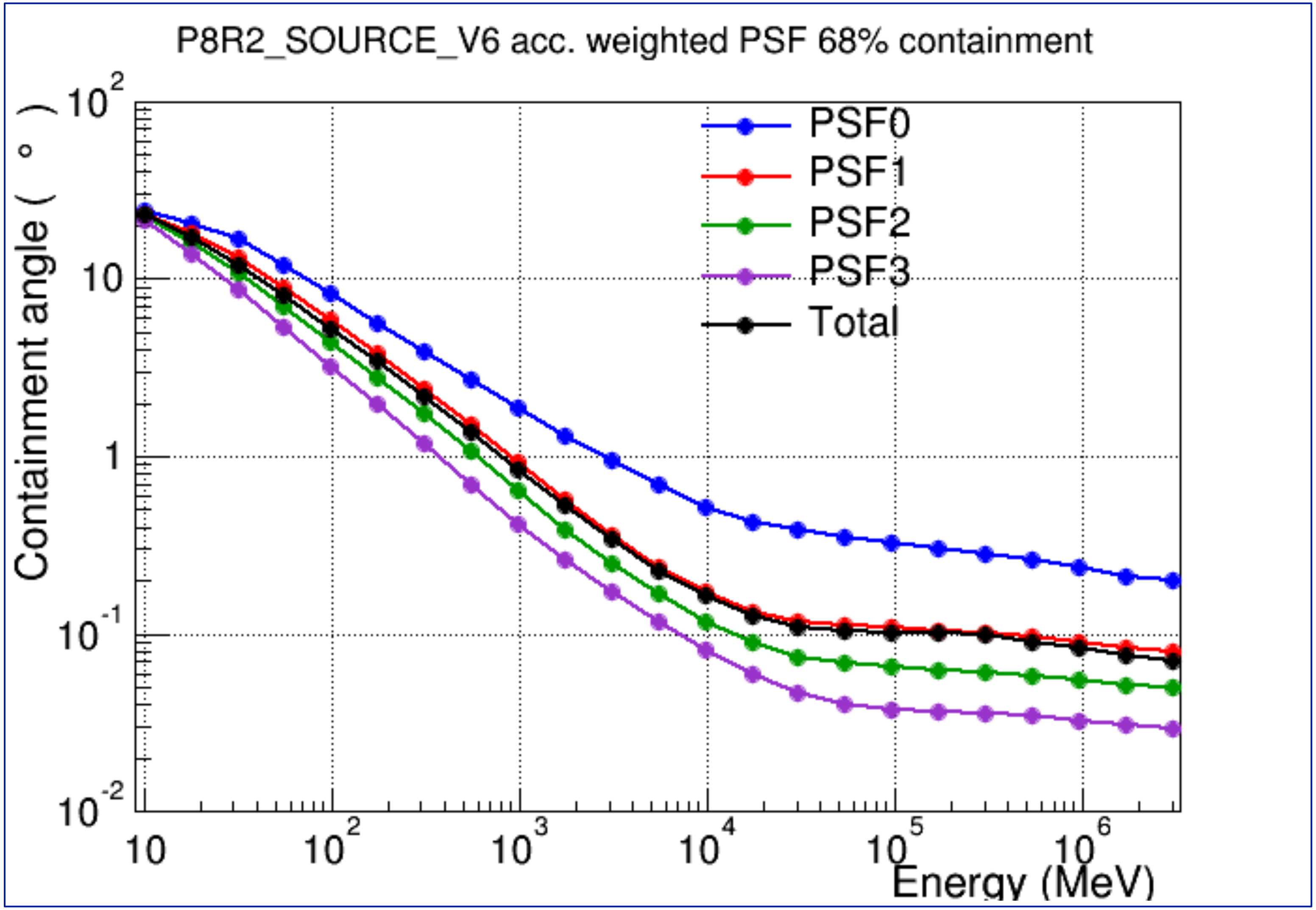
Pass8 Effective Area



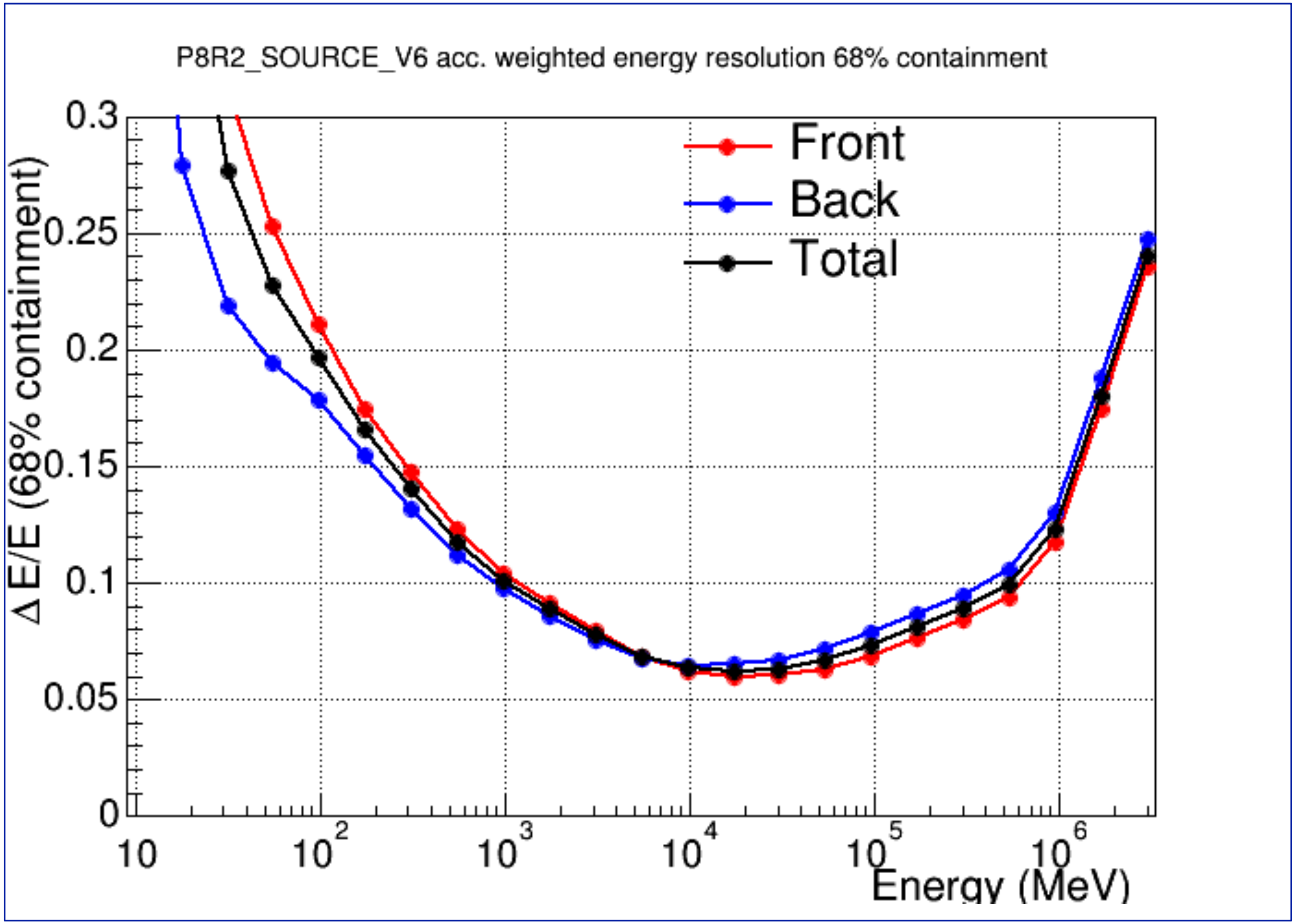
Point Spread Function



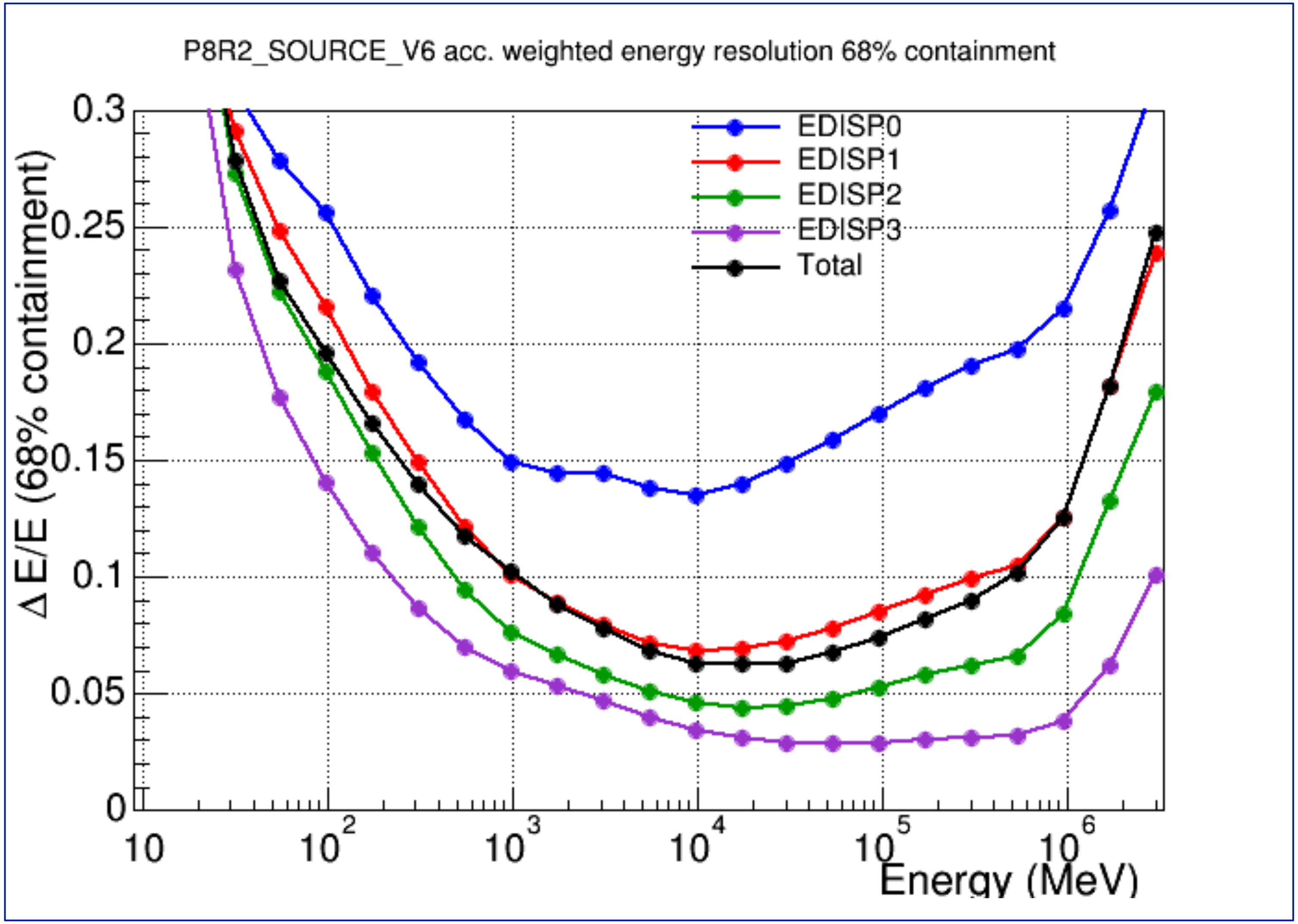
Point Spread Function



Energy resolution



Energy resolution



Extras

•**Diffuse models (.txt & FITS files)**

–**To correctly take into accounts the galactic and extagalactic backgrounds**

–http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html

- **Source Catalogs (3FGL, 3FHL, PSRs, GRB, SNR …)**

- **Region of Interest model definition (stored in XML files)**
  - More on this later …

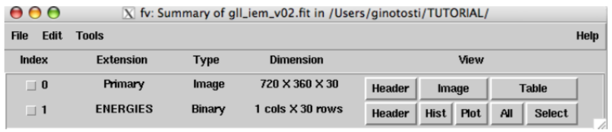
•**Choose the proper combination of**

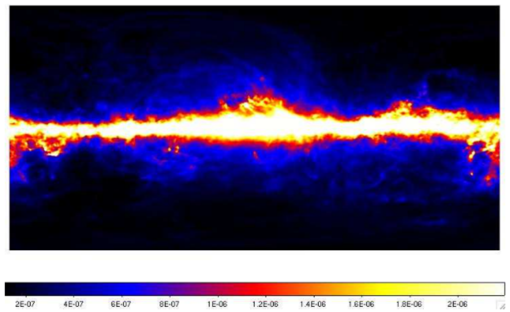
- event classes based on the probability of being a photon and background level
  - TRANSIENT (for very short events)
  - SOURCE (suggested for source analysis)
  - CLEAN and ULTRACLEAN (lowest particle contamination – for diffuse sources analysis)
- Event types based on conversion point or PSF or Energy reconstruction

LAT background models

Extras 2 : Diffuse Models

Galactic diffuse model	gll_iem_v02.fit
Isotropic spectral template (all)	isotropic_iem_v02.txt
Isotropic spectral template (front)	isotropic_iem_front_v02.txt
Isotropic spectral template (back)	isotropic_iem_back_v02.txt
Detailed description	Model Description

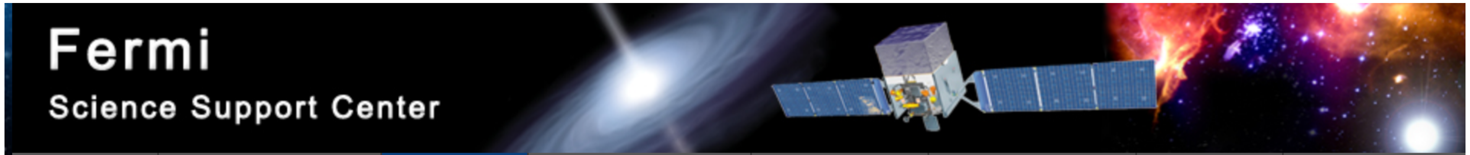




39.3884	6.57144e-07	4.6946e-08
64.0414	4.09665e-07	5.72124e-09
104.125	1.72000e-07	8.35794e-10
169.296	6.60007e-08	2.15325e-10
275.257	2.24126e-08	7.58059e-11
447.539	7.21114e-09	2.95711e-11
727.651	2.20758e-09	1.16796e-11
1183.08	7.20365e-10	4.68072e-12
1923.57	2.35566e-10	1.93256e-12
3127.52	7.36933e-11	8.02165e-13
5085.02	2.75583e-11	3.52098e-13
8267.71	8.41675e-12	1.44008e-13
13442.4	2.61572e-12	6.04568e-14
21856	9.93124e-13	2.77996e-14
35535.5	4.07167e-13	1.32929e-14
57777	1.48419e-13	6.31664e-15
93939.4	6.49806e-14	3.22598e-15
152736	2.13205e-14	1.49108e-15
248332	6.498e-15	4.85176e-16
403761	2.1144e-15	2.60915e-16

http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html

LAT background models



Data

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  - + LAT Catalog
  - + LAT Data Queries
  - + LAT Query Results
  - + LAT Weekly Files
  - + GBM Data
- Data Analysis
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LAT Background Models

Many analyses of LAT data require models of Galactic diffuse and isotropic emission. Detailed discussion of how the latest Galactic diffuse emission models, which are available from this web page, have been developed is available, Acero et. al. (2016). Please refer to the binned or unbinned likelihood analysis tutorials for some examples of how to incorporate theses models into your own Fermi data analysis. Here is a list of IRFs and diffuse models to be used with the various data sets. We have provided the model files for you to download. However, the files for the most recent data release are included in the science tools installation (in the $(FERMI_DIR)/refdata/fermi/galdiffuse/ directory). As a result, it is unlikely that you will need to download each file separately.

For Pass 8, each event class and event type combination has a dedicated IRF and isotropic model. Only a subset are shown here, as examples.

Galactic interstellar emission model	Event Selection/ IRF Name	Isotropic spectral template
gll_iem_v06.fits (see below for usage notes)	Pass 8 Source (front+back, allPSF, allEDISP) P8R2_SOURCE_V6	iso_P8R2_SOURCE_V6_v06.txt
	Pass 8 Source (front only) P8R2_SOURCE_V6::FRONT	iso_P8R2_SOURCE_V6_FRONT_v06.txt
	Pass 8 Source (back only) P8R2_SOURCE_V6::BACK	iso_P8R2_SOURCE_V6_BACK_v06.txt
	Pass 8 Clean (front+back, allPSF, allEDISP) P8R2_CLEAN_V6	iso_P8R2_CLEAN_V6_v06.txt
	Pass 8 Clean (PSF0) P8R2_CLEAN_V6::PSF0	iso_P8R2_CLEAN_V6_PSF0_v06.txt
	Pass 8 Clean (PSF1) P8R2_CLEAN_V6::PSF1	iso_P8R2_CLEAN_V6_PSF1_v06.txt
	Pass 8 Clean (PSF2) P8R2_CLEAN_V6::PSF2	iso_P8R2_CLEAN_V6_PSF2_v06.txt
	Pass 8 Clean (PSF3) P8R2_CLEAN_V6::PSF3	iso_P8R2_CLEAN_V6_PSF3_v06.txt

LAT catalogs

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Currently Available Data Products

The Fermi data released to the scientific community is governed by the data policy. The released instrument data for the GBM, along with LAT source lists, can be accessed through the Browse interface specific to Fermi. LAT photon data can be accessed through the LAT data server.

The FITS files can also be downloaded from the Fermi FTP site. The file version number is the 'xx' in the characters before the extension in each filename; you should keep track of the version numbers of files you analyze since the instrument teams may update them.

- LAT Photon and Extended Data
  - LAT Data Server (Pass 8 data updated 24-Jun-2015)
  - LAT Low-Energy (LLE) Data
  - Pass 8 Weekly Files
  - Filtered Weekly Photon Files with Diffuse Response Columns
  - Pass 7 Reprocessed Weekly Files
  - Pass 7 (V6) Weekly files (Archived)
  - Pass 6 (V11) Weekly files (Archived)
  - Pass 6 (V3) Weekly files (Archived)
  - FTP LAT Data
  - ASDC data server (external)
- LAT Data (high-level products only)
  - Catalogs and associated products
    - Preliminary LAT Third High Energy Source Catalog (3FHL)
    - Extended Sources in the Galactic Plane (FGES)
    - Second Fermi All-sky Variability Analysis Catalog (2FAV)
    - 1st Fermi-LAT SNR Catalog
    - LAT Burst Catalog
    - LAT 4-year Point Source Catalog (3FGL, Interactive Table)
    - Aperture Photometry Light Curves for LAT 4-year Catalog Sources (Updated Weekly)
    - Flaring Sources in the LAT 4-year Aperture Photometry Light Curves (Updated Weekly)
    - LAT Second High-Energy Source Catalog (2FHL)
    - LAT 2-year Point Source Catalog (2FGL)
    - Aperture Photometry Light Curves for the LAT 2-year Point Source Catalog
    - Flaring Sources in the LAT 2-year Aperture Photometry Lightcurves
    - LAT 3-year High-Energy Source Catalog (1FHL)
    - LAT 1-year Point Source Catalog (1FGL)
    - LAT 3-month Bright Source List (0FGL)
    - LAT 3-year Catalog of Gamma-ray Pulsars

https://fermi.gsfc.nasa.gov/ssc/data/access/

Event types

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

Event classes

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		X
P8R2_TRANSIENT010E_V6	64	Extended		X
P8R2_TRANSIENT020E_V6	8	Extended		X
P8R2_TRANSIENT015S_V6	65536	No-ACD		X

Recommendations

Event Selection Recommendations (P8R2)

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	P8R2_SOURCE_V6
Off-plane Point Source Analysis	100 (MeV)	500000 (MeV)	90 (degrees)	128	P8R2_SOURCE_V6
Burst and Transient Analysis (<200s)	100 (MeV)	500000 (MeV)	100 (degrees)	16	P8R2_TRANSIENT020_V6
Galactic Diffuse Analysis	100 (MeV)	500000 (MeV)	90 (degrees)	128	P8R2_SOURCE_V6
Extra-Galactic Diffuse Analysis	100 (MeV)	500000 (MeV)	90 (degrees)	1024	P8R2_ULTRACLEANVETO_V6
Impulsive Solar Flare Analysis	100 (MeV)	500000 (MeV)	100 (degrees)	65536	P8R2_TRANSIENT015S_V6

Caveats

Caveats About Analyzing LAT Pass 8 Data

These caveats are relevant for the P8R2 version of the Pass 8 photon dataset. They are an updated version of previous sets of caveats for analysis of Pass 7 reprocessed (P7REP), Pass7 (P7_V6) and Pass 6 (P6_V3 and P6_V11) event selections and Instrument Response Functions (IRFs).

The LAT team is still working to validate all aspects of Pass 8 data and analysis. As a consequence it is expected that, in the coming year, the range of application of Pass 8 data will be increased, the tools and files will be improved and the systematic uncertainties will be decreased. These caveats will be modified accordingly.

The P8R2_V6 IRFs are defined between 5.62 MeV and 3.16 TeV but that does not mean that they have been fully validated over this whole energy range. Following the Pass 7 validation effort, the LAT team has started performing studies in order to check the consistency and precision of the instrument simulation and the instrument response representation provided by the IRFs. These studies are based on the analysis of Vela (E < 10 GeV), bright AGN (3 GeV < E < 100 GeV) and the Earth limb (E > 10 GeV). They include:

- comparing the distributions of reconstructed quantities between data and the simulation of the instrument for a given selection (e.g. SOURCE class)
- comparing the fraction of events of a loose selection (e.g. TRANSIENT020 class) that are accepted in a more stringent selection (e.g. SOURCE class) in data and as predicted by the instrument simulation or the IRFs
- comparing the fraction of events in each event type for a given selection in data and as predicted by the instrument simulation or the IRFs
- comparing the radial profiles of a point source in data and as predicted by the IRFs

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

Overview of Fermi Science Tools

Maximum Likelihood Overview

Maximum likelihood technique

Given a set of observed data:

→ Produce a model that accurately describes the data, including parameters that we wish to estimate

→ derive the probability (density) for the data given the model (PDF)

→ treat this as a function of the model parameters (likelihood function)

→ maximize the likelihood with respect to the parameters - ML estimation.

Maximum likelihood ingredients

Data: $X = \{x_i\} = \{x_1, x_2, ..., x_N\}$

Model parameters: $\Theta = \{\theta_j\} = \{\theta_1, \theta_2, ..., \theta_M\}$

Likelihood: $\mathcal{L}(\Theta|X) = P(X|\Theta)$

Conditional probability rule
for independent events: $P(A,B) \underset{\text{CPR}}{=} P(A)P(B|A) \underset{\text{Independence}}{=} P(A)P(B)$

For independent data:

$$P(X|\Theta) = P(\{x_i\}|\Theta) = P(x_1|\Theta)P(x_2,..,x_N|\Theta) = \cdots$$
$$= P(x_1|\Theta)P(x_2|\Theta)\cdots P(x_N|\Theta) = \prod_i P(x_i|\Theta)$$

$$\mathcal{L}(\Theta|X) = \prod_i P(x_i|\Theta)$$

$\mathcal{L}$ is the product of the probability of observing the detected counts in each bin.

Maximum likelihood estimation

Parameters can be estimated by maximizing likelihood.

→ Easier to work with log-likelihood:

$$\ln \mathcal{L}(\Theta) = \ln \mathcal{L}(\Theta|X) = \sum_i \ln P(x_i|\Theta)$$

Estimates of $\{\hat{\theta}_k\}$ from solving simultaneous equations:

$$\left.\frac{\partial \ln \mathcal{L}}{\partial \theta_j}\right|_{\{\hat{\theta}_k\}} = 0$$

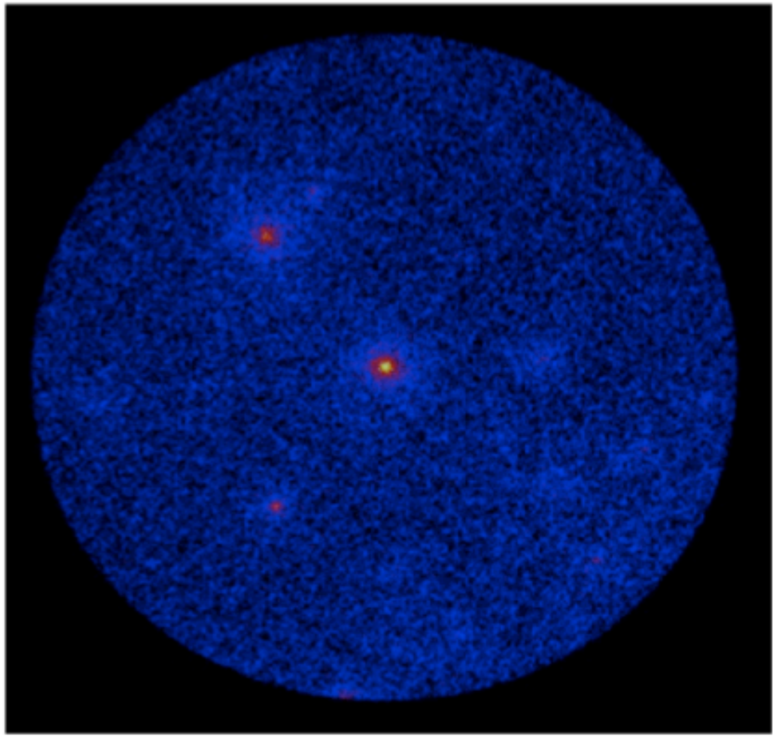
For one parameter, if we have: $\mathcal{L}(\theta) \sim e^{-\frac{(\theta-\hat{\theta})^2}{2\sigma_\theta^2}}$ **Gaussian approximation**

then: $$\left.\frac{\partial^2 \ln \mathcal{L}}{\partial \theta^2}\right|_{\hat{\theta}} = -\frac{1}{\sigma_\theta^2}$$

so 2nd derivative is related to "errors"

The Challenge

- Gamma-ray data is a list of counts (photons) reconstructed in the detector.
- Qualitative exploration of the data suggests the presence of sources (spatial clustering).
- Quantitative analysis requires evaluating the significance of a 'model' of our region.



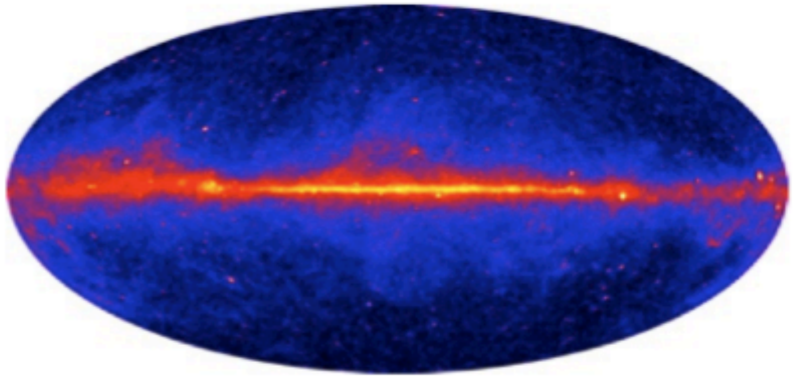
Count Map

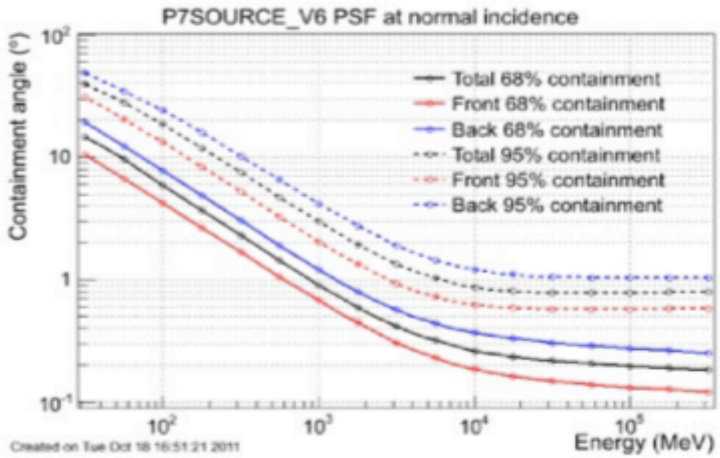
The Procedure

- Basically the initial '**model**' is a guess of the various parameters of the sources in our region:
  - location
  - spectral shape
  - flux
  - etc.
- The guess can be easier if you have a starting point like the 2FGL (3FGL).
- We quantify (using the Likelihood Method) the statistical significance of the model and vary the parameters to determine the most likely parameter values.

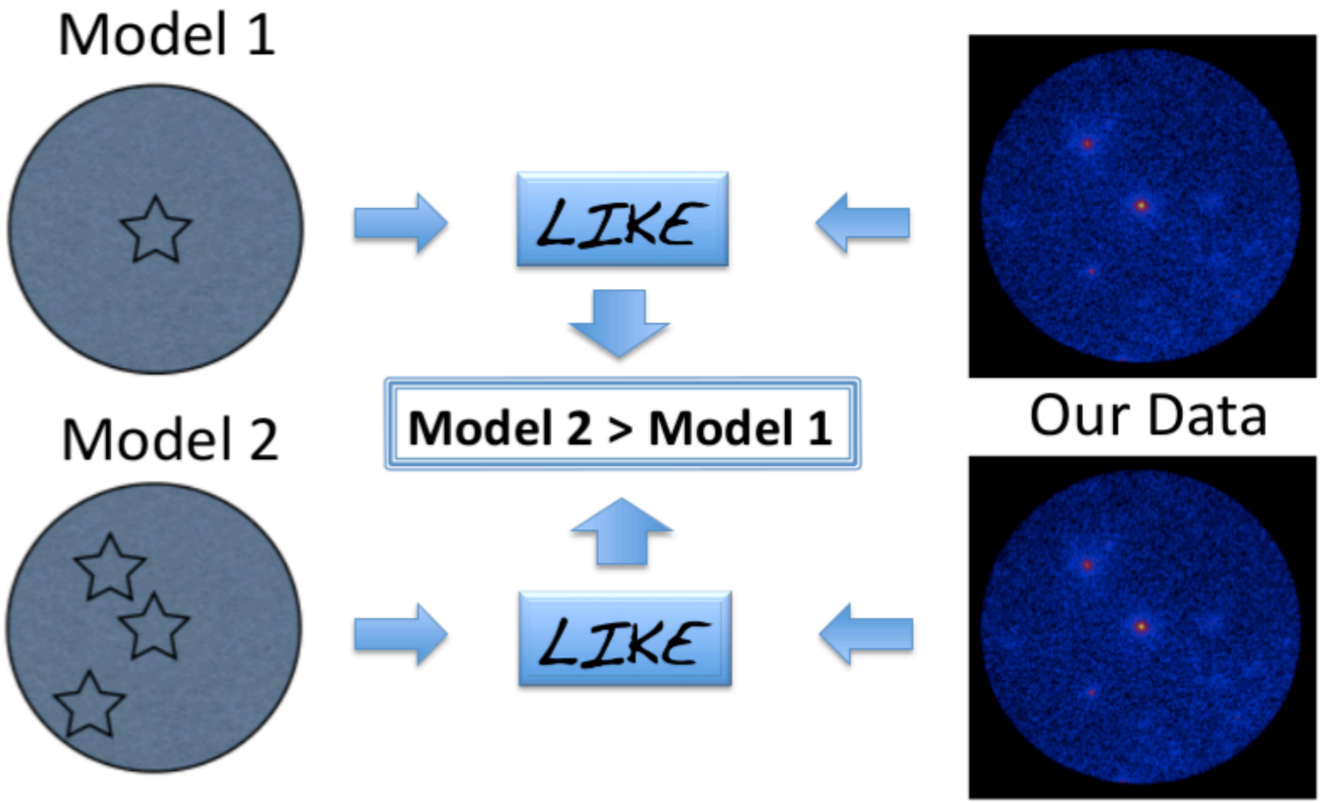
Why Model Fitting?

- We use the Likelihood method because the LAT data are limited by statistics, a bright diffuse background and a broad PSF.
- The model construction defines the questions we want to ask which means:
  - <u>It will not answer a question you are not asking</u> (ie. unknown parameters).
- The Likelihood will <u>not tell you if a fit is 'good'</u>. If the model does not represent your data well, the results will also not represent reality well.

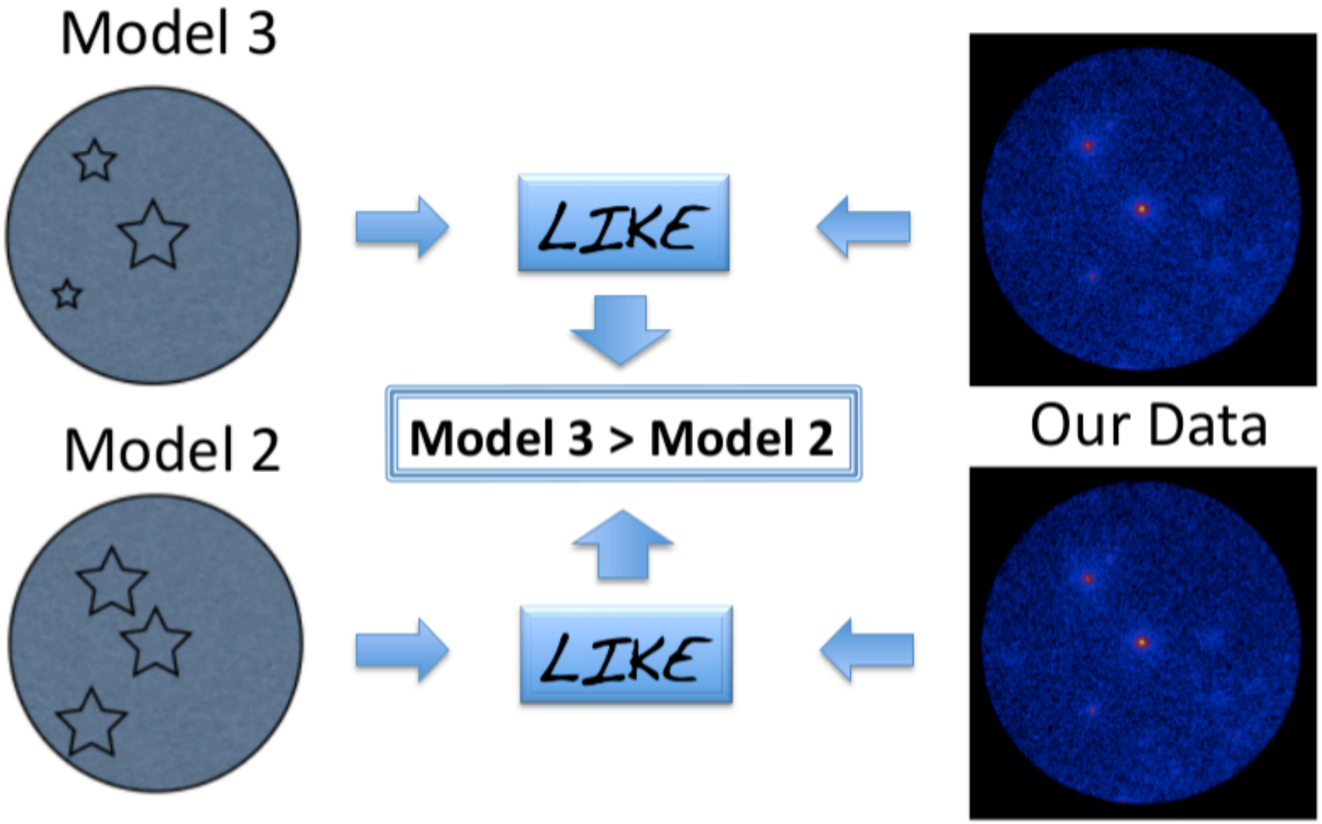




A Graphical Example



A Graphical Example



Likelihood Analysis

- The likelihood $\mathcal{L}$ is the probability of obtaining your data given an input model.
- In our case, the input model is the distribution of gamma-ray sources on the sky and includes their intensity and spectra.
- One will maximize $\mathcal{L}$ to get the best match of the model to the data. Given a set of data, one can bin them in multidimensional (energy, sky pixels, ...) bins.
- $\mathcal{L}$ is the product of the probabilities of observing the detected counts in each bin.

$$\mathcal{L} = \prod p_k$$

Write L as a function of the source model

- The source model is folded with the IRFs in order to obtain the predicted number of counts

- The IRFs can be decomposed into three funtions: Effective Area (proj area of the detector * efficency), Energy Dispesion, Point Spread Function

- Small number of counts in each bin --> Poisson distribuiton

- Bin size infinitesimally small

- Assume only steady source for standard analysis

The function to maximize is:

$$\log \mathcal{L} = \sum_j \log M(E'_j, \hat{p}'_j, t_j) - N_{\text{pred}}$$

where the sum is performed over photons in the ROI. The predicted number of counts is $N_{\text{pred}} = \int_{\text{ROI}} dE' d\hat{p}' \, dt M(E', \hat{p}', t)$

Test Statistic

Null hypothesis max likelihood, h parameters

$$\mathrm{TS} = -2\,\log\frac{\mathcal{L}_0}{\mathcal{L}_1}\ \underset{N\to\infty}{\to}\ \chi^2_{m-h}$$

non fixed parameters

Alternative hypothesis max likelihood, m parameters

- In the limit of a large number of counts, Wilk's Theorem states that the TS for the null hypothesis is asymptotically distributed as χ_n^2 where n is the number of parameters characterizing the additional source.
- As a basic rule of thumb, the square root of the TS is approximately equal to the detection significance for a given source.

Fermi Gamma-ray Space Telescope

Summarizing

- Observed a photon from a location, at a time, with an energy.
- Assume a model:

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

Point Sources — Galactic & EG diffuse Sources — Other Sources

- Calculate the probability of that photon being detected assuming our model:

$$M(E',\hat{p}',t) = \int_{SR} dE\,d\hat{p}\,R(E',\hat{p}',t;E,\hat{p})S(E,\hat{p},t)$$

- Calculate the total number of predicted counts assuming our model.

$$N_{\mathrm{pred}} = \int_{\mathrm{ROI}} dE'\,d\hat{p}'\,dt\,M(E',\hat{p}',t)$$

- Adjust the model until this is maximized:

$$\log \mathcal{L} = \sum_j \log M(E'_j,\hat{p}'_j,t_j) - N_{\mathrm{pred}}$$

- Calculate the TS:

$$\mathrm{TS} = -2\ \log \frac{\mathcal{L}_0}{\mathcal{L}_1} \underset{N\to\infty}{\rightarrow} \chi^2_{m-h}$$

Keep in mind that ..

- Many variables may be calculated BEFORE selecting the models
- Very important to have a reliable model
- Absolute value of likelihood meaningless!
  - Likelihood function has no meaning itself, e.g., it is not a probability. Its usefulness comes from theorems such as the LRT.
- Comparison between model w/ and w/o source to reject null hypothesis = no source (TS large → reject null hypothesis)