Fermi Gamma-ray Space Telescope

Tutorial on Fermi-LAT data analysis the case of 3c454.3

Francesco Longo
(University of Trieste and INFN Trieste)

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

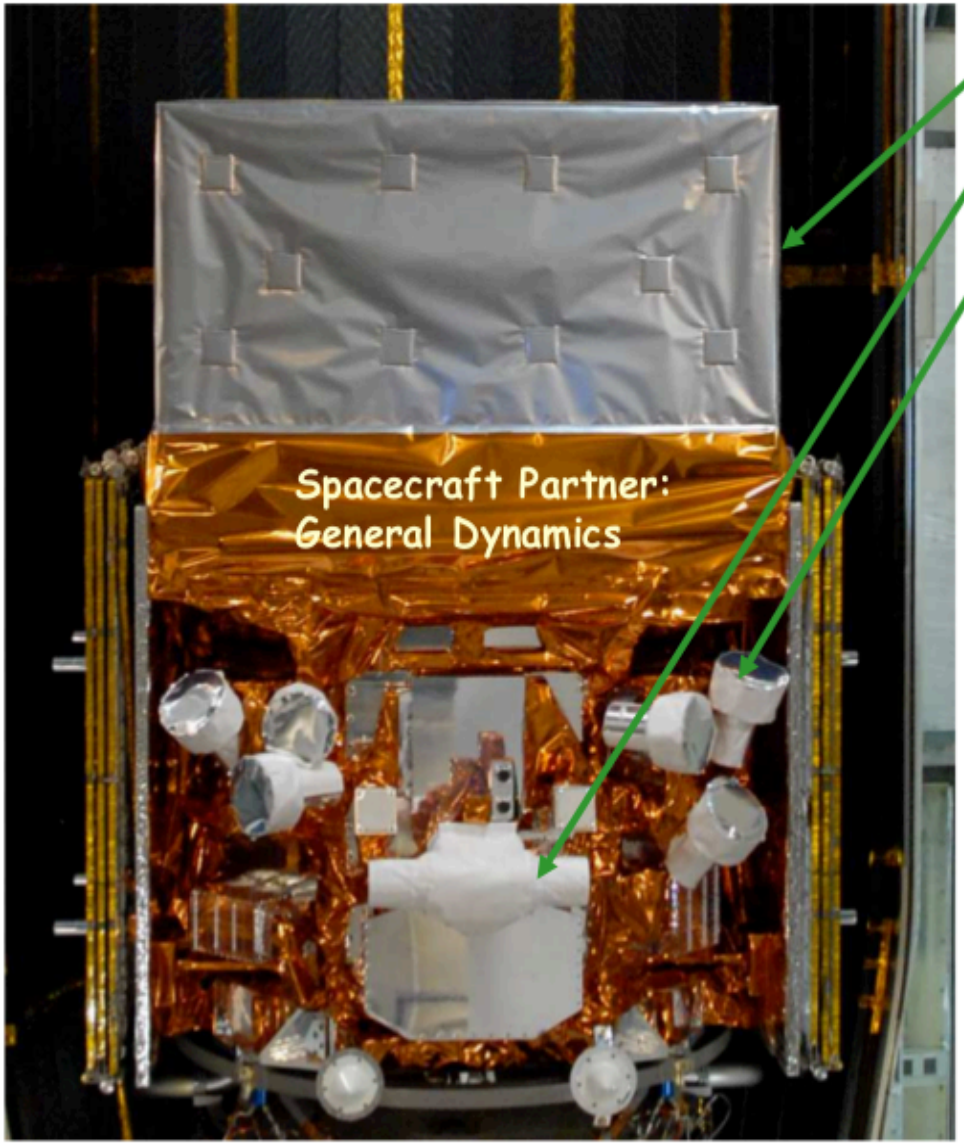
Outline

- **Overview of the Fermi Large AreaTelescope**
  - **How it works**
  - **LAT data**
  - **LAT performance**
- **Fermi Science Tools**
  - **General Introduction**
- **Maximum Likelihood Overview**
  - **Source modeling**
- **Case study:**
  - **3c454.3**
    - **Likelihood analysis tutorial**

Organization

- **Laboratory on Gamma Ray Astrophysics**
  - Introduction to the LAT data analysis
  - LAT data introduction
  - LAT data exploration
  - LAT data preparation
  - Preparation of Sky models
  - Likelihood analysis of LAT data
  - Hands-on an Extragalactic source
    - Likelihood Analysis

The observatory



Large AreaTelescope (LAT)
20 MeV - >300 GeV

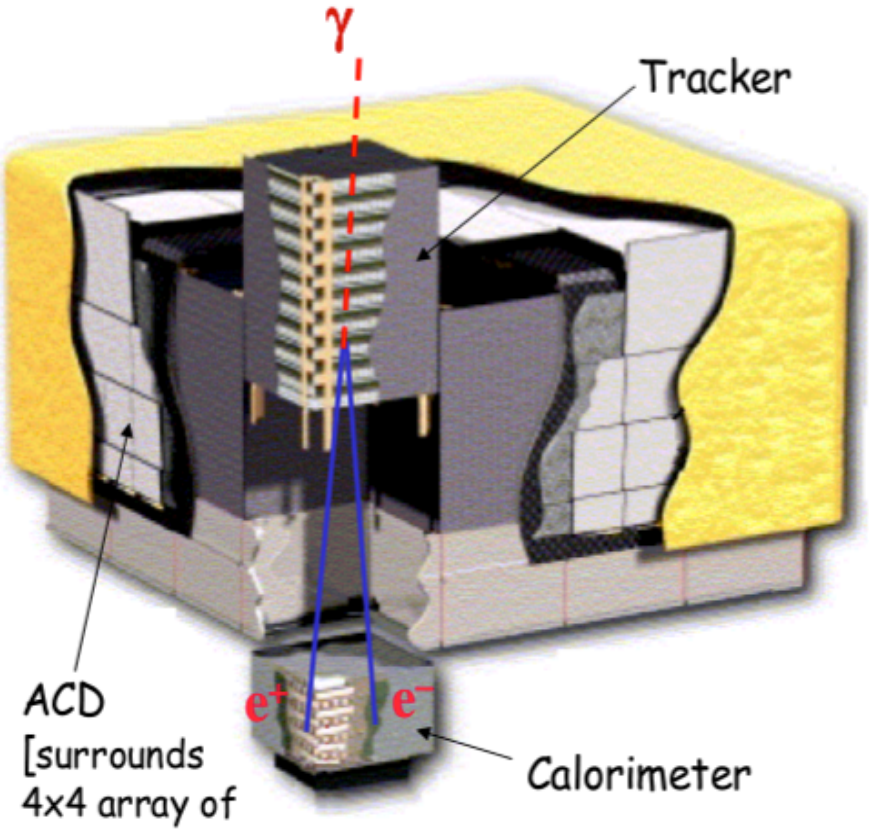
Gamma-ray Burst Monitor (GBM)
NaI and BGO Detectors
8 keV - 30 MeV

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

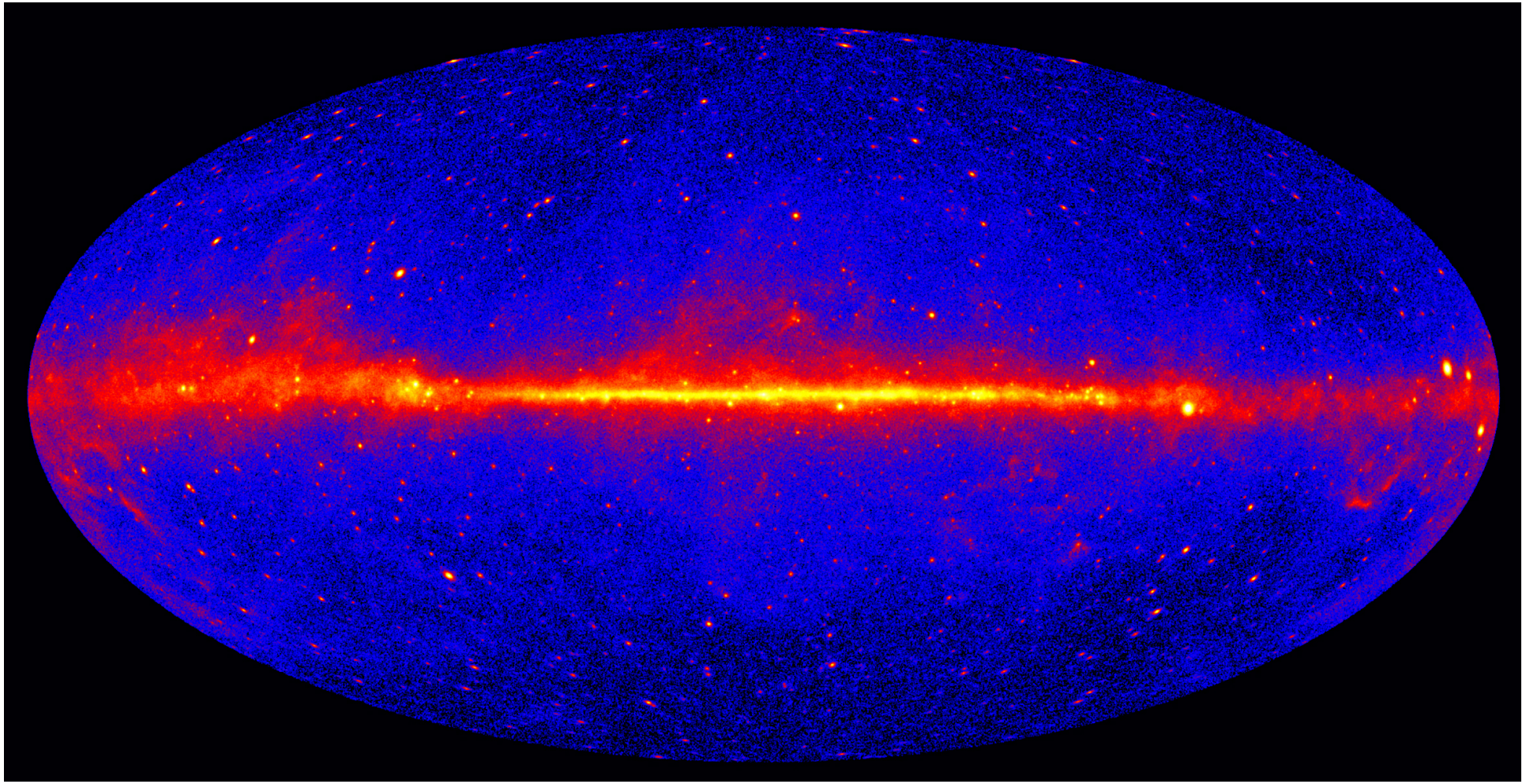
- **Precision Si-strip Tracker (TKR)** Measure the photon direction; gamma ID.
- **Hodoscopic CsI Calorimeter (CAL)** Measure the photon energy; image the shower.
- **Segmented Anticoincidence Detector (ACD)** Reject background of charged cosmic rays; segmentation removes self-veto effects at high energy.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



Atwood et al. 2009

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

The Fermi Sky



What do you need for the analysis

- **Data ...of course!** **LAT DATA ARE PUBLIC!!**
  - 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!

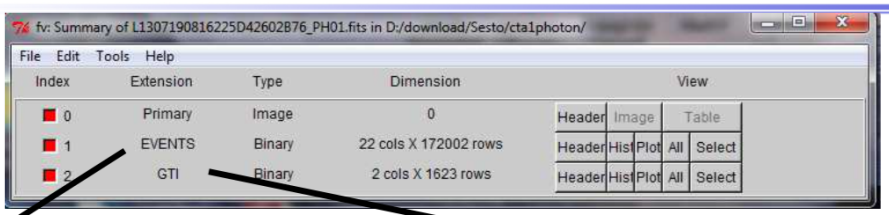
LAT Data

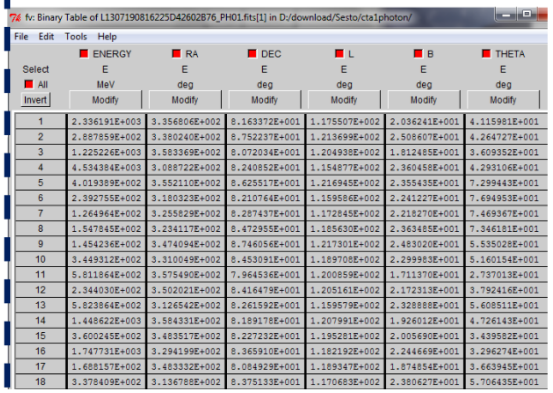
- **LAT data products can be downloaded by the FSSC website**
  - **LAT Data server** http://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi
  - **Archive of weekly files**
  - ftp://legacy.gsfc.nasa.gov/fermi/data/

- **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..)

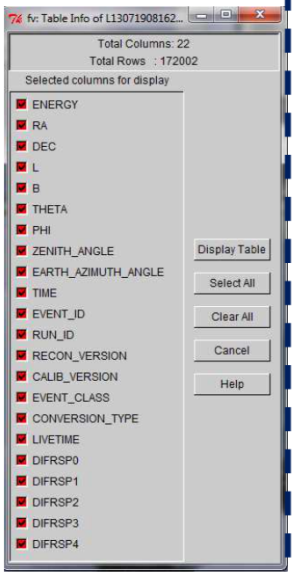
  - **Spacecraft files (FT2)**
  - **i. e. "where the LAT is"**
    - (position, angles..)

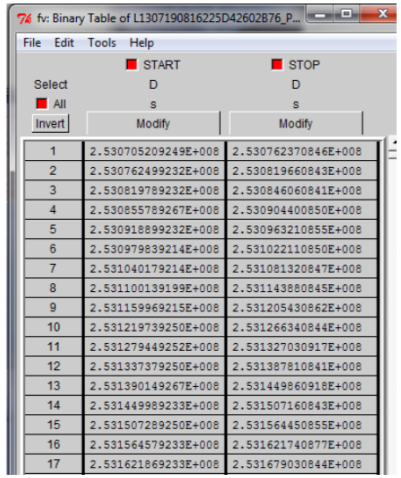
FT1: photons, photons…





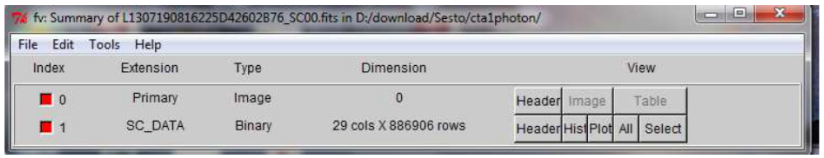
Events





Good Time Intervals (GTIs)

FT2: where is Fermi ?



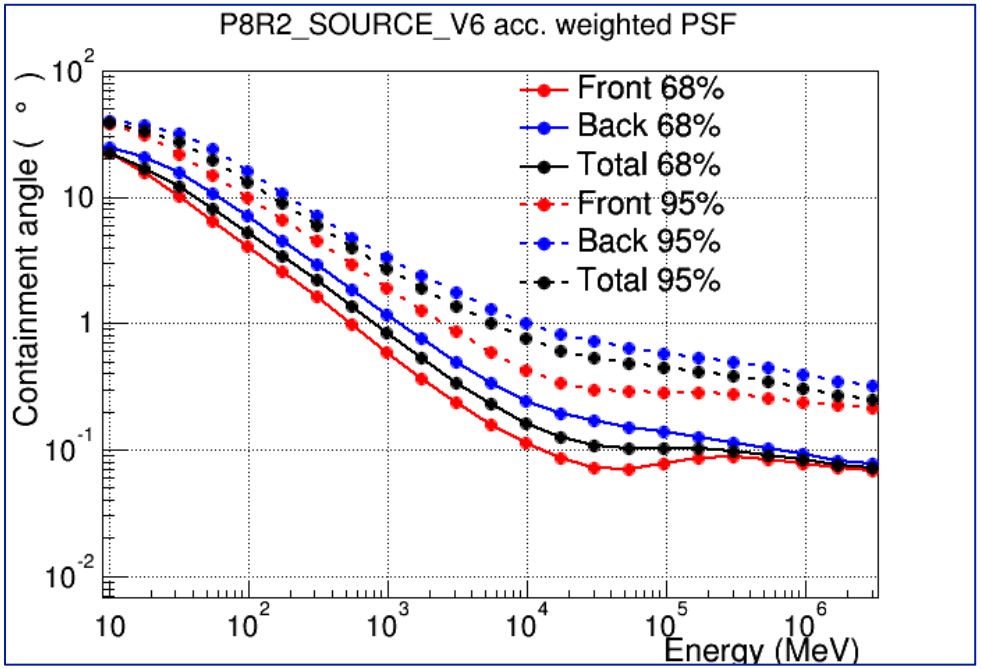
spacecraft Data

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!!**

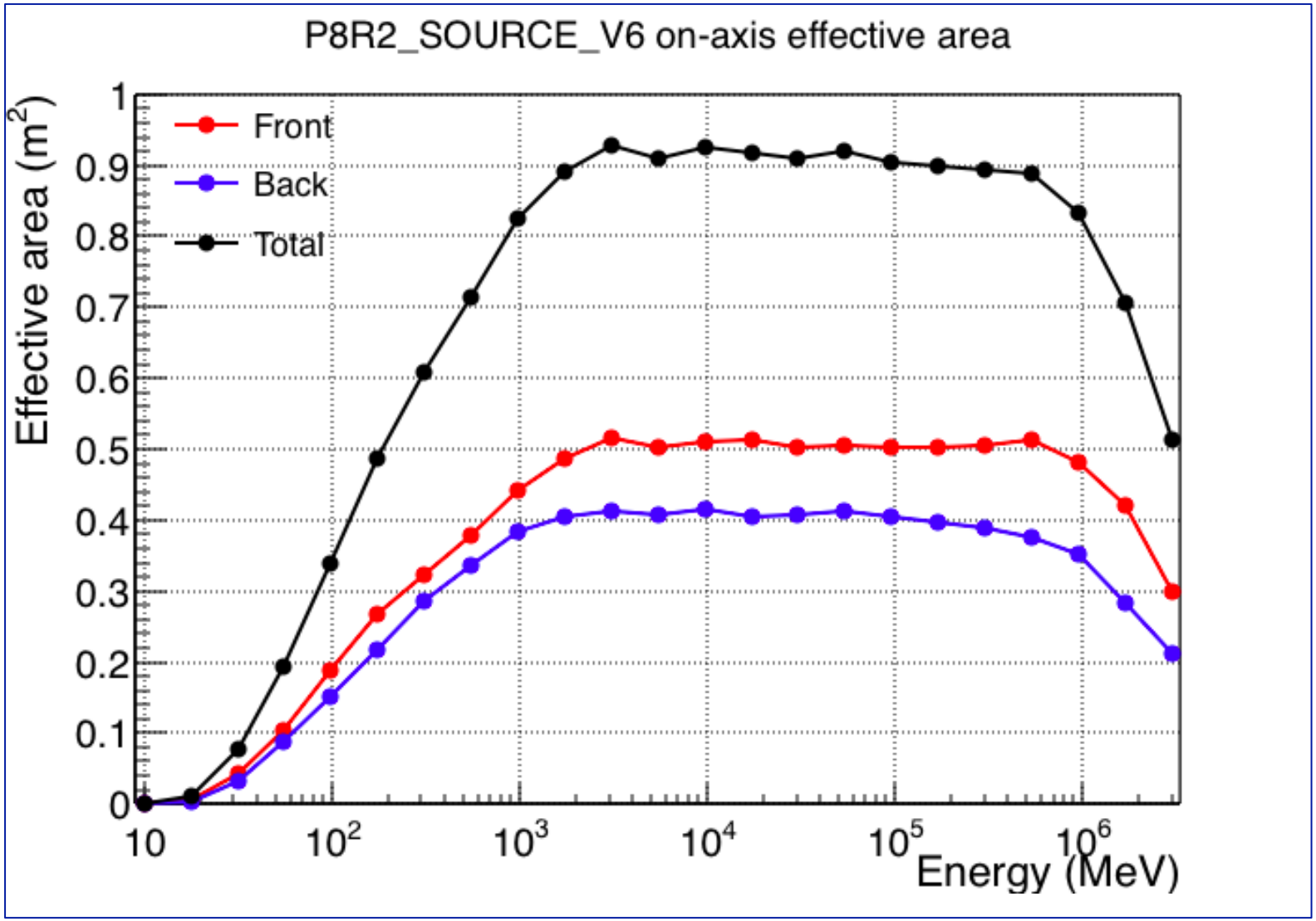


- http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

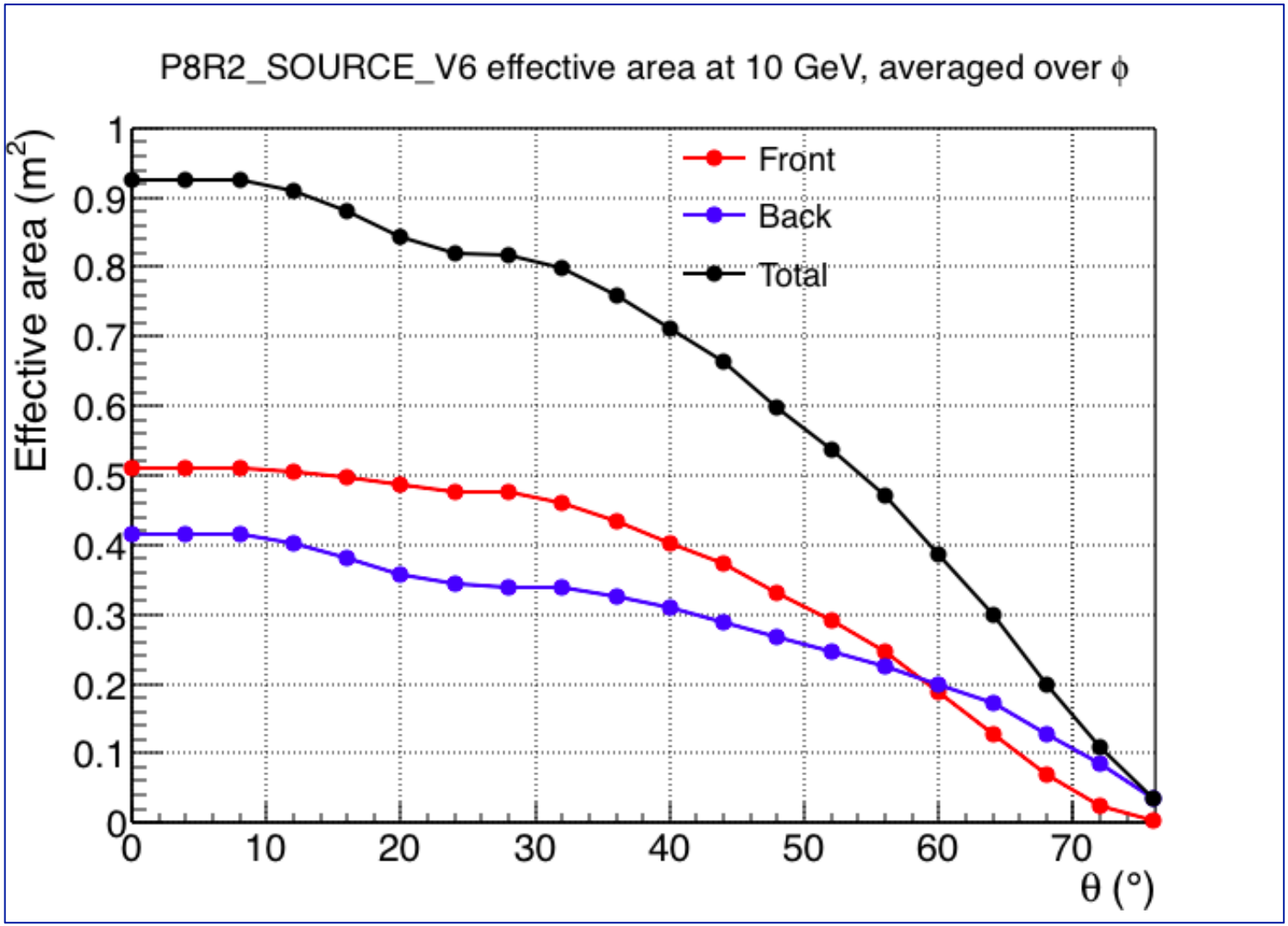
LAT Pass8 performance

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

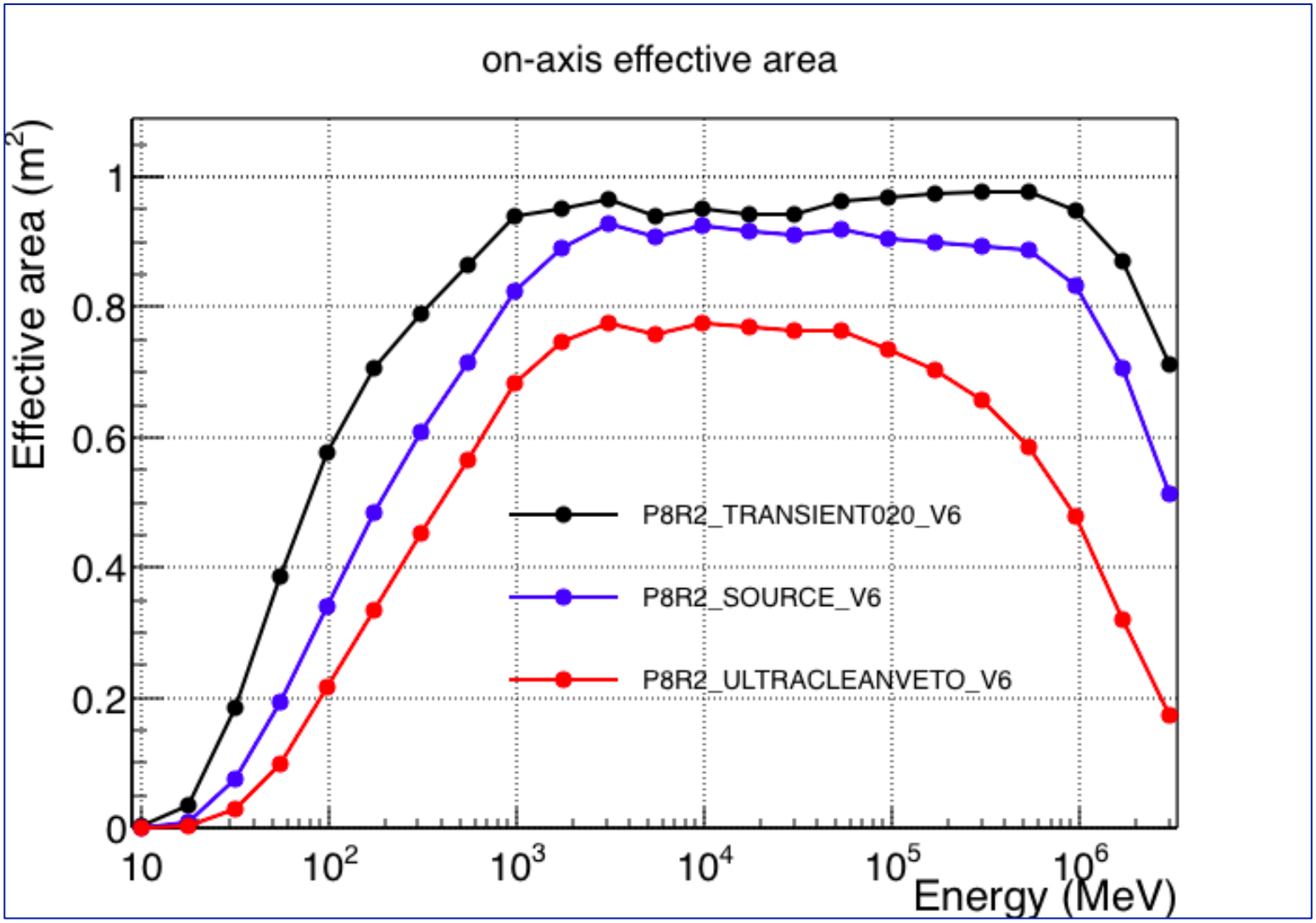
Effective Area



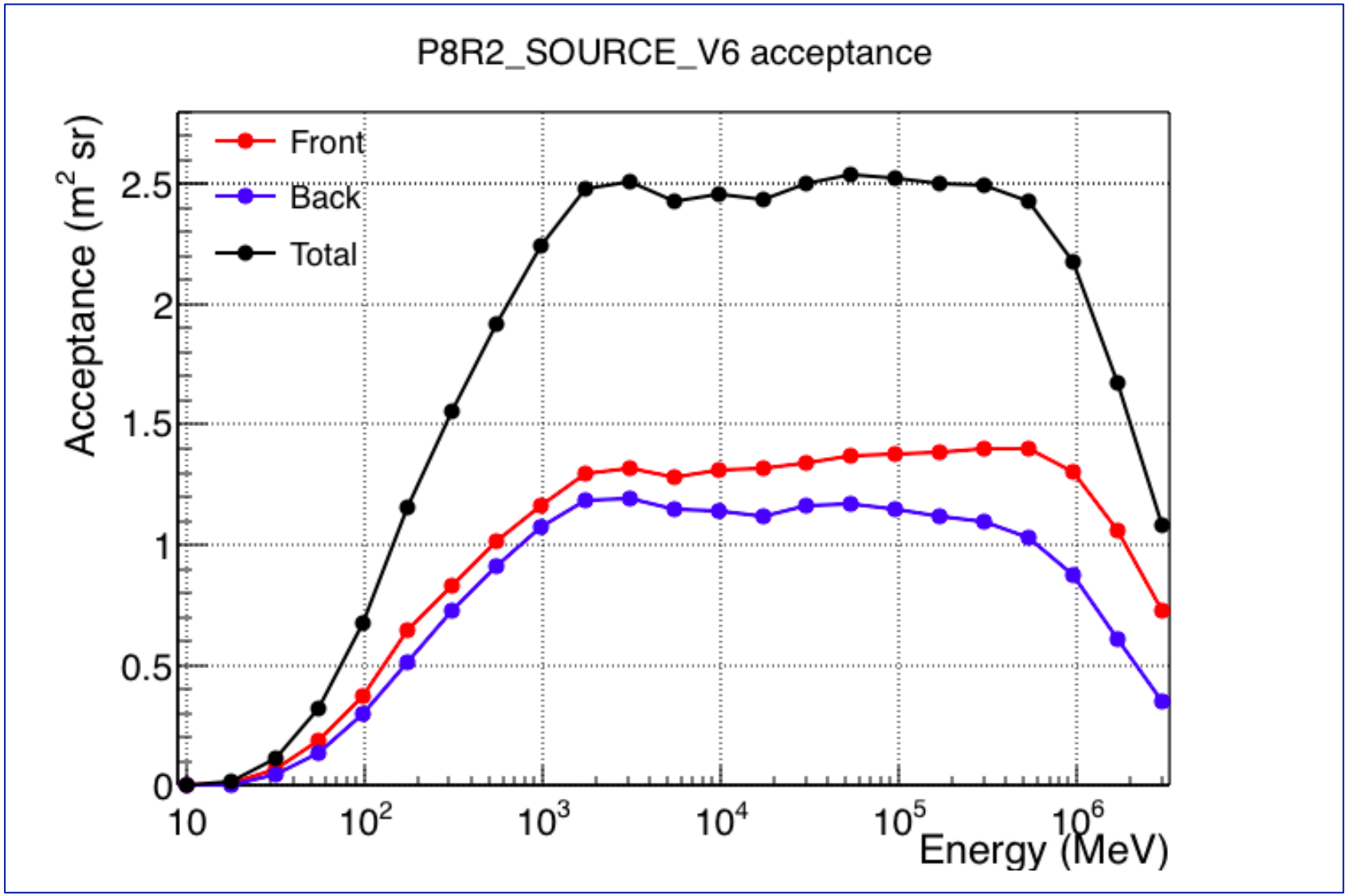
Pass8 Effective Area



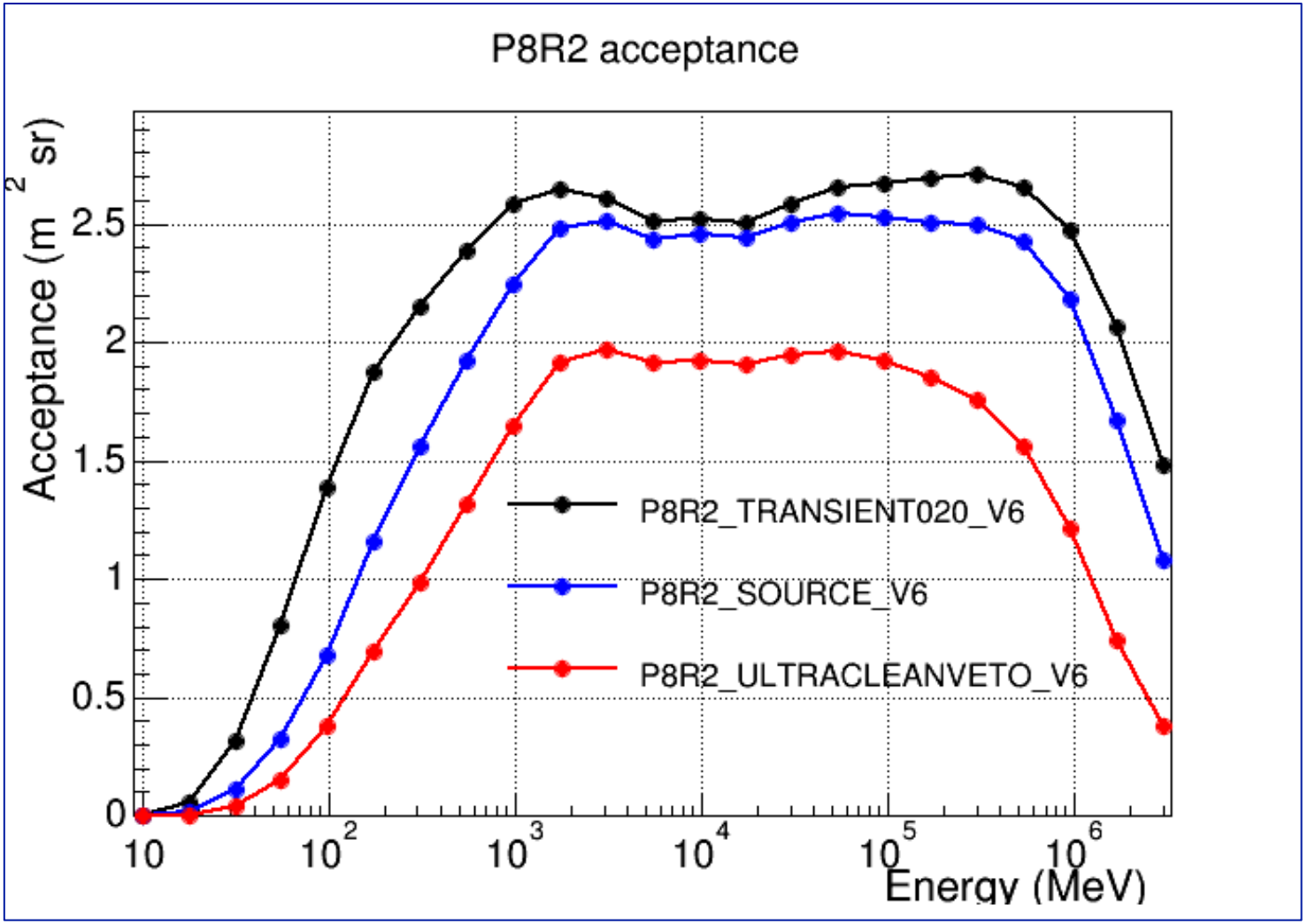
Effective Area



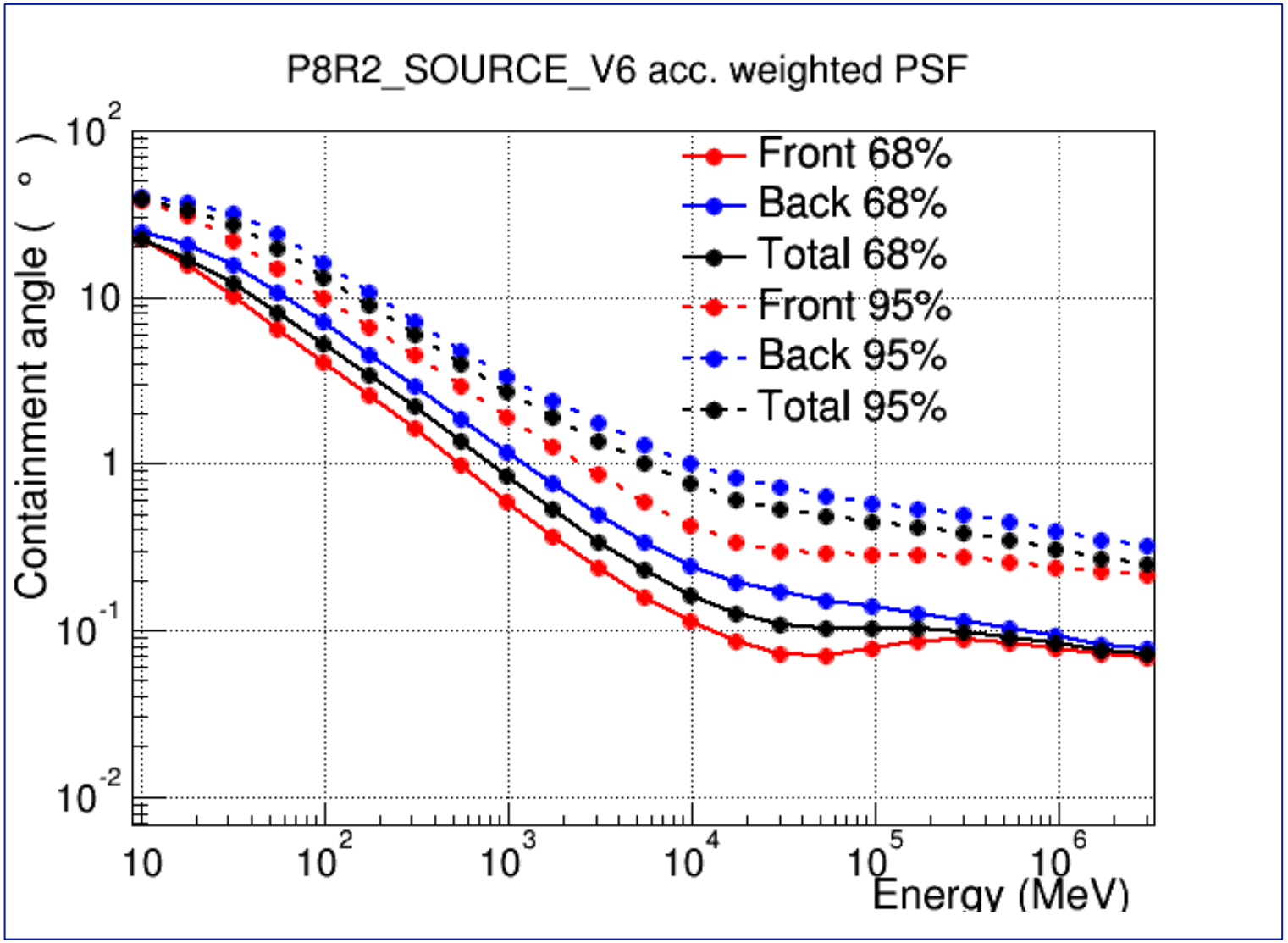
Acceptance


P8R2_SOURCE_V6 acceptance
Front
Back
Total
Acceptance (m^2 sr)
2.5
2
1.5
1
0.5
0
10
10^2
10^3
10^4
10^5
10^6
Energy (MeV)

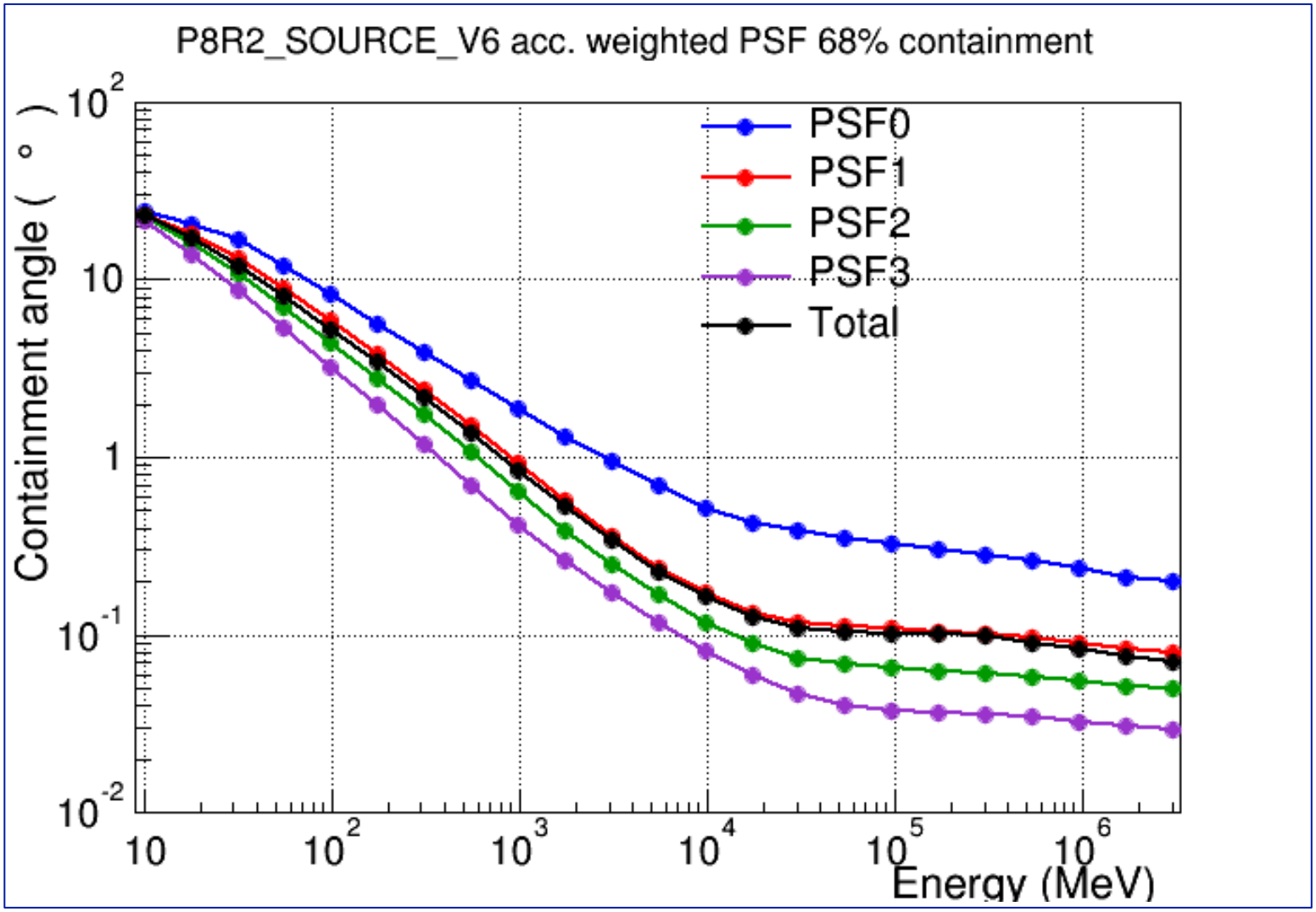
Acceptance


P8R2 acceptance
Acceptance (m^2 sr)
0
0.5
1
1.5
2
2.5
10
10^2
10^3
10^4
10^5
10^6
Energy (MeV)
P8R2_TRANSIENT020_V6
P8R2_SOURCE_V6
P8R2_ULTRACLEANVETO_V6

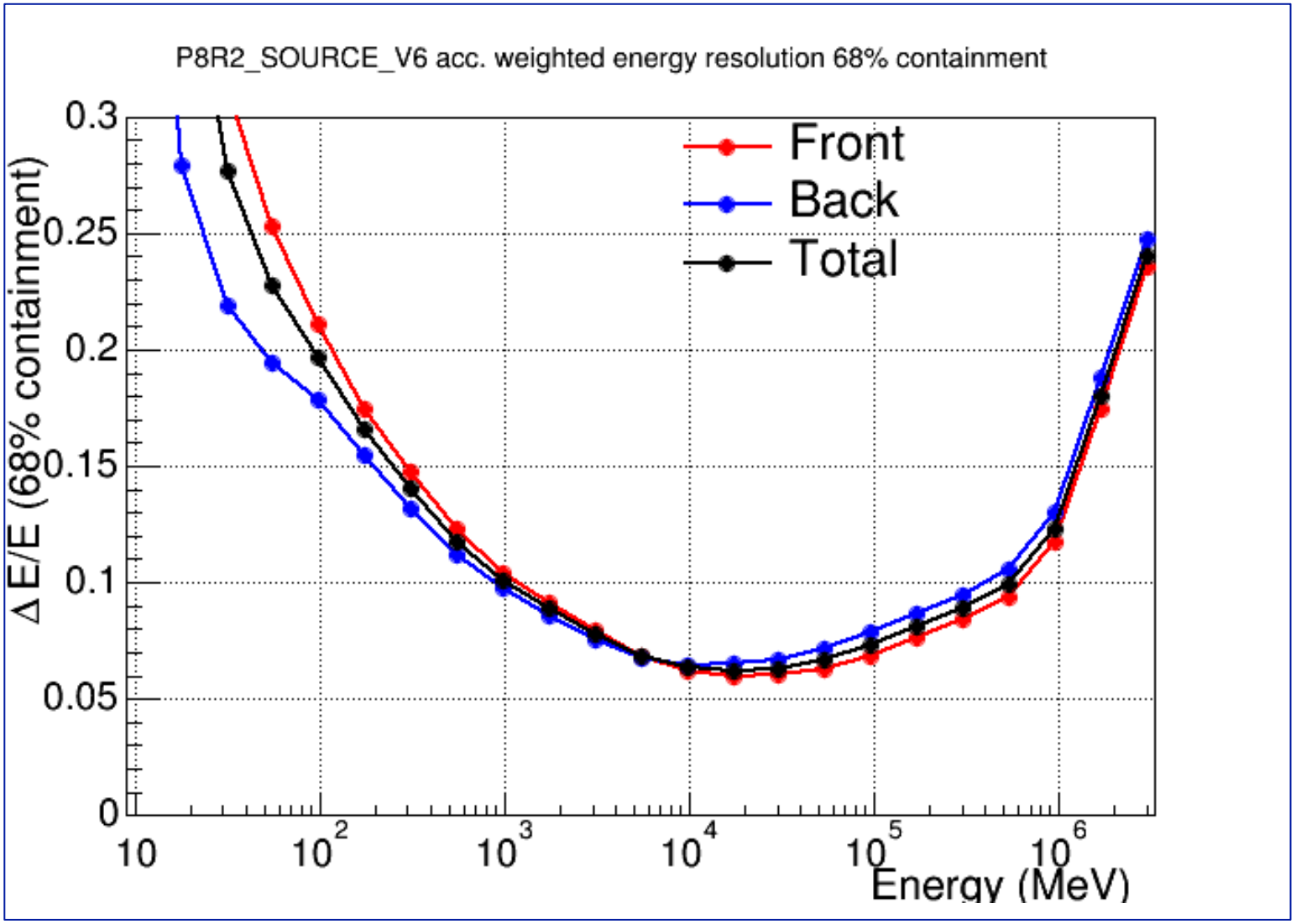
Point Spread Function



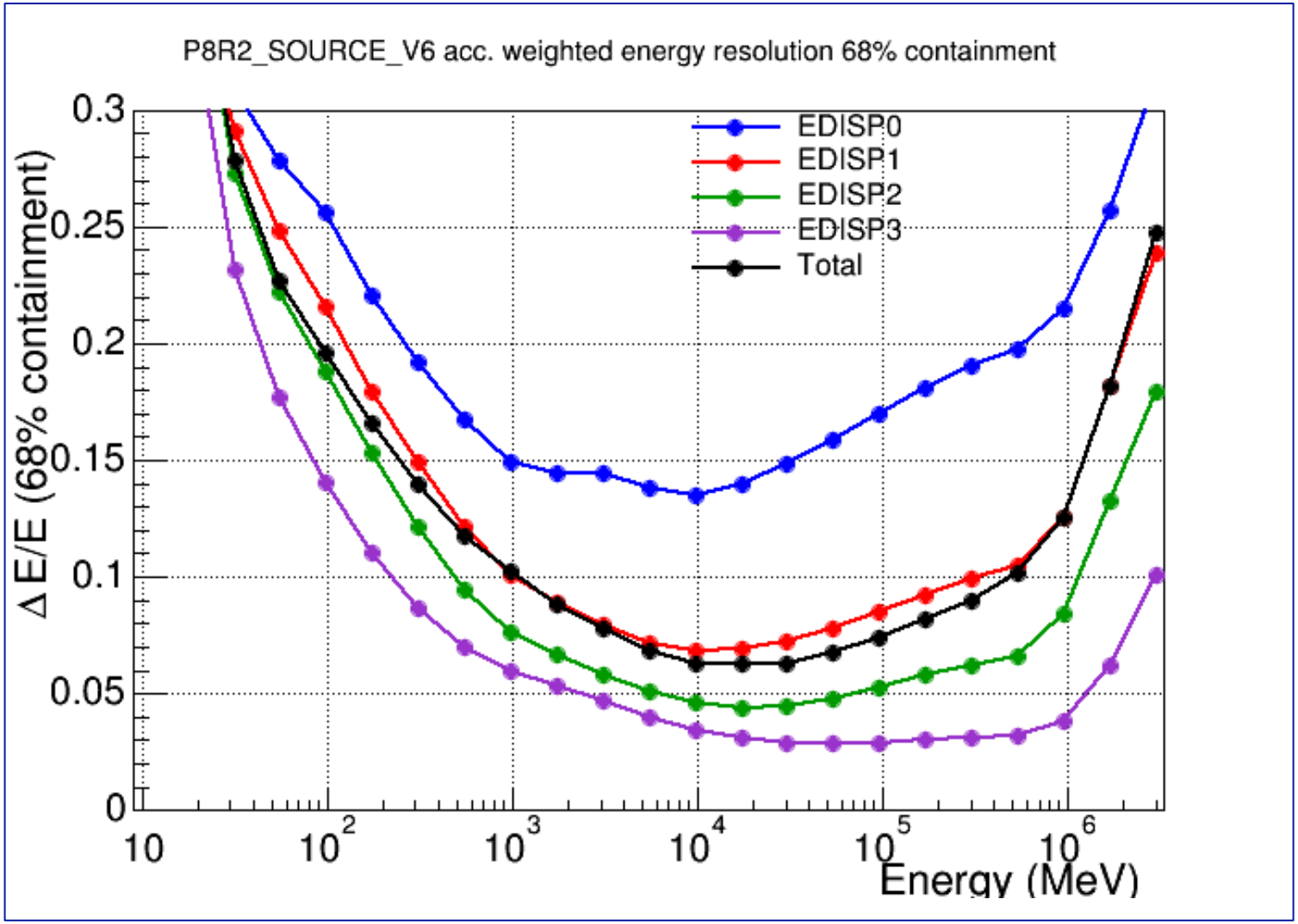
Point Spread Function



Energy resolution



Energy resolution



LAT Pass8 data

Event classes

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.

Event classes

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.

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 direction.
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.

Recommendations

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
Burst and Transient Analysis (<200s)	100 (MeV)	500000 (MeV)	100 (degrees)	16	P8R3_TRANSIENT020_V2
Galactic Diffuse Analysis	100 (MeV)	500000 (MeV)	90 (degrees)	128	P8R3_SOURCE_V2
Extra-Galactic Diffuse Analysis	100 (MeV)	500000 (MeV)	90 (degrees)	1024	P8R3_ULTRACLEANVETO_V2 or P8R3_SOURCEVETO_V2 (when interested in E>1 GeV energy range)
Impulsive Solar Flare Analysis	100 (MeV)	500000 (MeV)	100 (degrees)	65536	P8R3_TRANSIENT015S_V2

Recommendations

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)

IMPORTANT: For analyses where an ROI-based zenith cut is NOT performed, an exposure correction must be made using the "zmax" option in the gtltcube tool.

Required info for Analysis

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 …)**

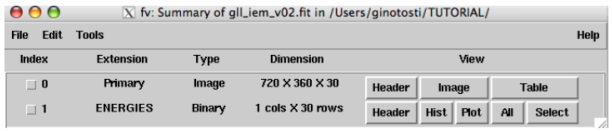
- **Region of Interest model definition (stored in XML files)**
  - More on this later …

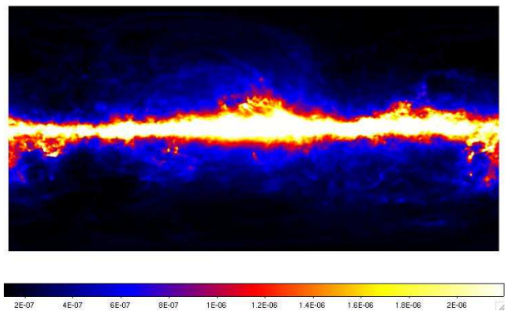
- **Choose the proper combination of**
  - event classes based on the probability of being a photon and background level
    - TRANSIENT (for very short events)
    - SOURCE (suggested for source analysis)
    - CLEAN and ULTRACLEAN (lowest particle contamination – for diffuse sources analysis)
  - Event 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

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 Fermitools 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 P8R3 usage notes)	Pass 8 Source (front+back, allPSF, allEDISP) P8R3_SOURCE_V2	iso_P8R3_SOURCE_V2.txt
	Pass 8 Source (front only) P8R3_SOURCE_V2::FRONT	iso_P8R3_SOURCE_FRONT_V2.txt
	Pass 8 Source (back only) P8R3_SOURCE_V2::BACK	iso_P8R3_SOURCE_BACK_V2.txt
	Pass 8 Clean (front+back, allPSF, allEDISP) P8R3_CLEAN_V2	iso_P8R3_CLEAN_V2.txt
	Pass 8 Clean (PSF0) P8R3_CLEAN_V2::PSF0	iso_P8R3_CLEAN_PSF0_V2.txt
	Pass 8 Clean (PSF1) P8R3_CLEAN_V2::PSF1	iso_P8R3_CLEAN_PSF1_V2.txt
	Pass 8 Clean (PSF2) P8R3_CLEAN_V2::PSF2	iso_P8R3_CLEAN_PSF2_V2.txt
	Pass 8 Clean (PSF3) P8R3_CLEAN_V2::PSF3	iso_P8R3_CLEAN_PSF3_V2.txt
	Pass 8 Ultraclean (front+back, allPSF, allEDISP) P8R3_ULTRACLEAN_V2	iso_P8R3_ULTRACLEAN_V2.txt

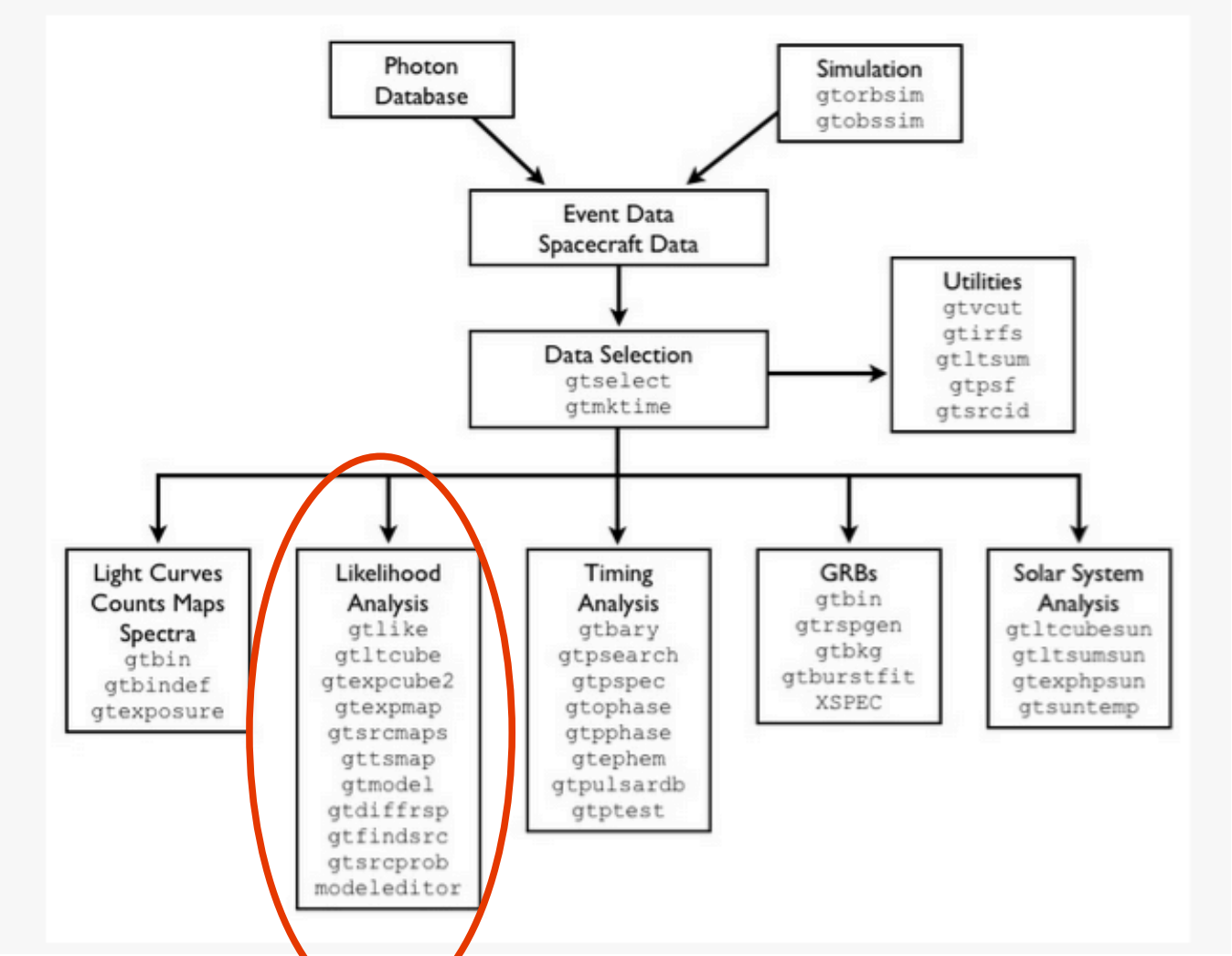
LAT catalogs

High-level Data Products

- Catalogs and associated products
  - LAT Point Source Catalog
    - LAT 8-year Point Source Catalog (4FGL)
    - Preliminary LAT 8-year Source List (FL8Y)
    - LAT 4-year Point Source Catalog (3FGL)
    - LAT 2-year Point Source Catalog (2FGL)
    - LAT 1-year Point Source Catalog (1FGL)
    - LAT 3-month Bright Source List (0FGL)
  - Aperture Photometry Light Curves
    - 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)
    - Aperture Photometry Light Curves for the LAT 2-year Point Source Catalog
    - Flaring Sources in the LAT 2-year Aperture Photometry Lightcurves
  - LAT High Energy Source Catalog
    - LAT Third High Energy Source Catalog (3FHL)
    - LAT Second High-Energy Source Catalog (2FHL)
    - LAT First High-Energy Source Catalog (1FHL)
  - LAT Monitored Source List Light Curves
  - LAT Burst Catalog
  - Extended Sources in the Galactic Plane (FGES)
  - Second Fermi All-sky Variability Analysis Catalog (2FAV)
  - 1st Fermi-LAT SNR Catalog
  - LAT 3-year Catalog of Gamma-ray Pulsars
- Other useful data products
  - List of LAT GRBs announced via GCN notices (external)
  - List of LAT Sources announced via ATels
  - LAT List of Detected Gamma-Ray Pulsars (updated frequently)
  - LAT Pulsar Ephemerides from Publications
  - LAT Background Models
  - List of time gaps in LAT data

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

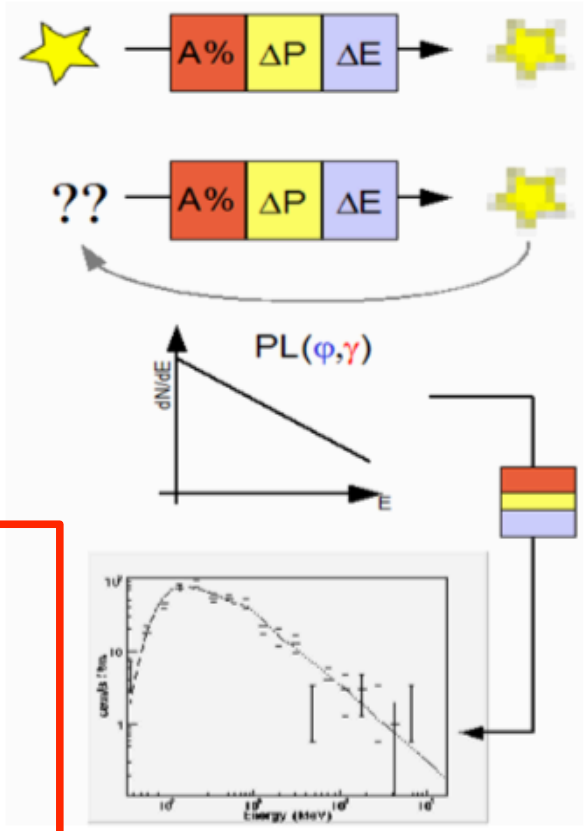
Overview of Fermi Science Tools



Maximum Likelihood Overview

Perform the fit: the likelihood approach

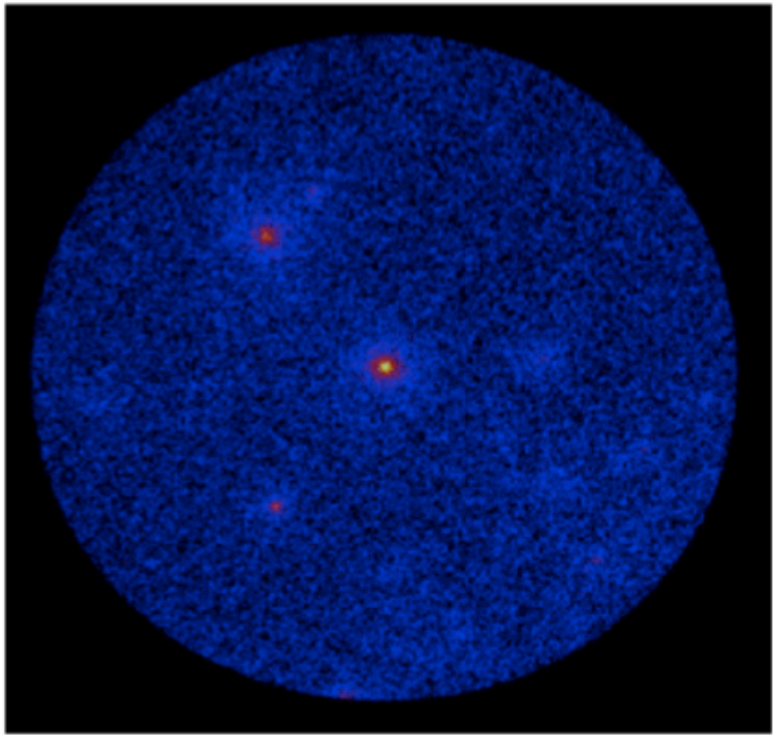
In high energy gamma rays it is never possible to really isolate a source because of limited statistics and strong and structured background.
Therefore statistical techniques have to be applied.
The most used method is the likelihood analysis based on the Poisson statistics.
The method requires to assume a model for the signal detected by the telescope.



- Assume a **model**
- Model **convolved** with Instrument responce Function (IRF)
- Maximizing likelihood find the best set of parameters that reproduce the observed spectrum

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.



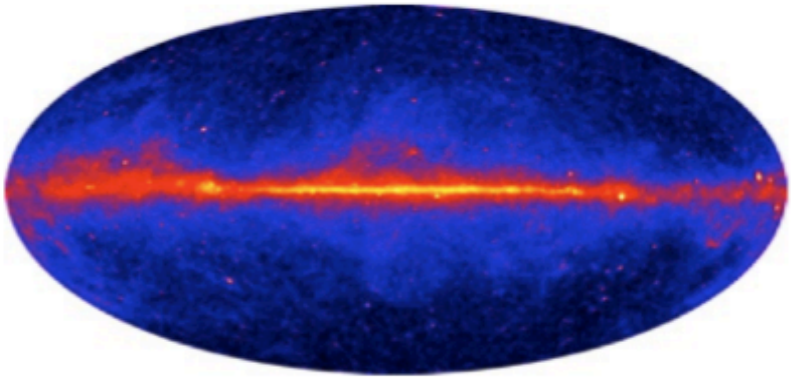
Count Map

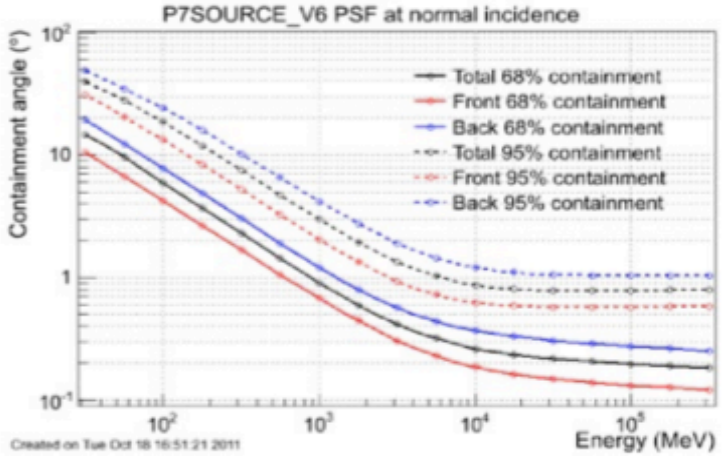
The Procedure

- 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.

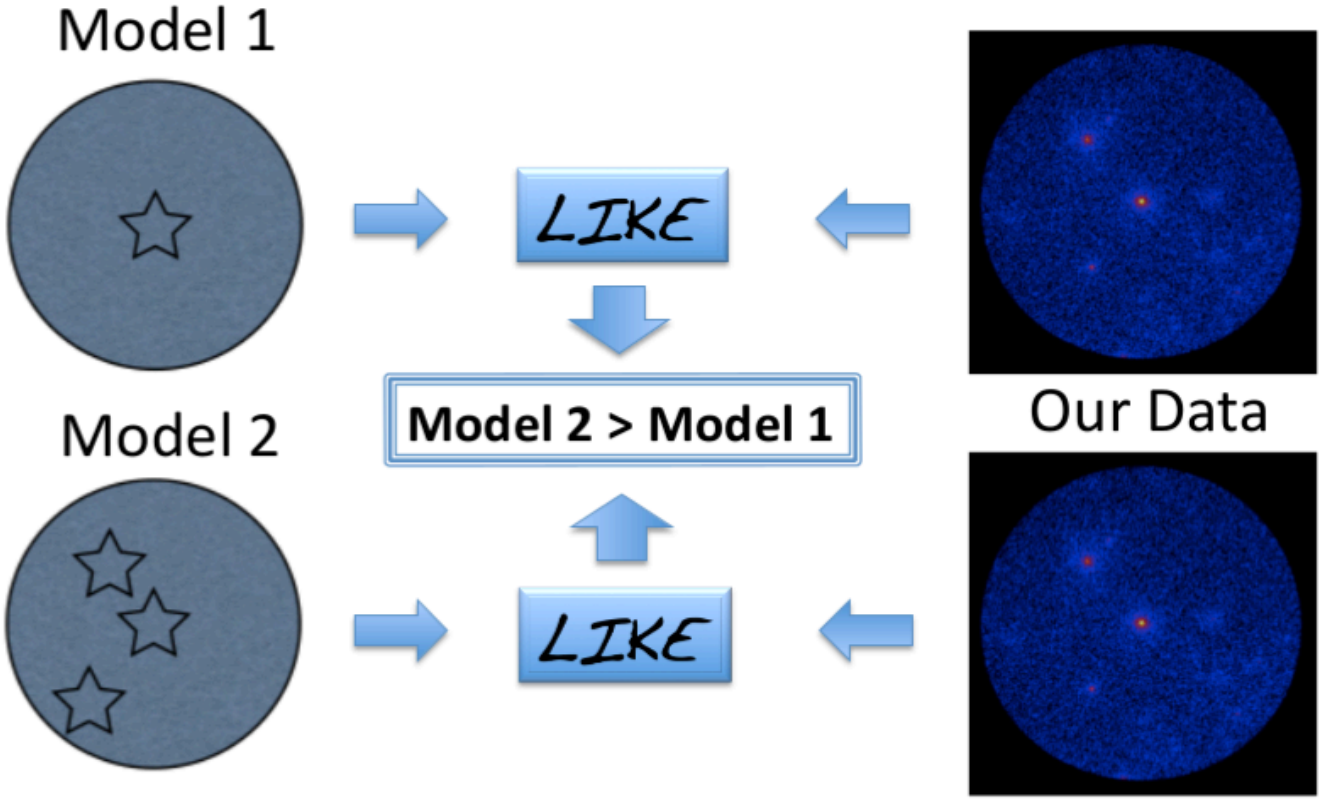
Why Model Fitting?

- 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:
  - It will not answer a question you are not asking (ie. unknown parameters).
- The Likelihood will not tell you if a fit is 'good'. If the model does not represent your data well, the results will also not represent reality well.

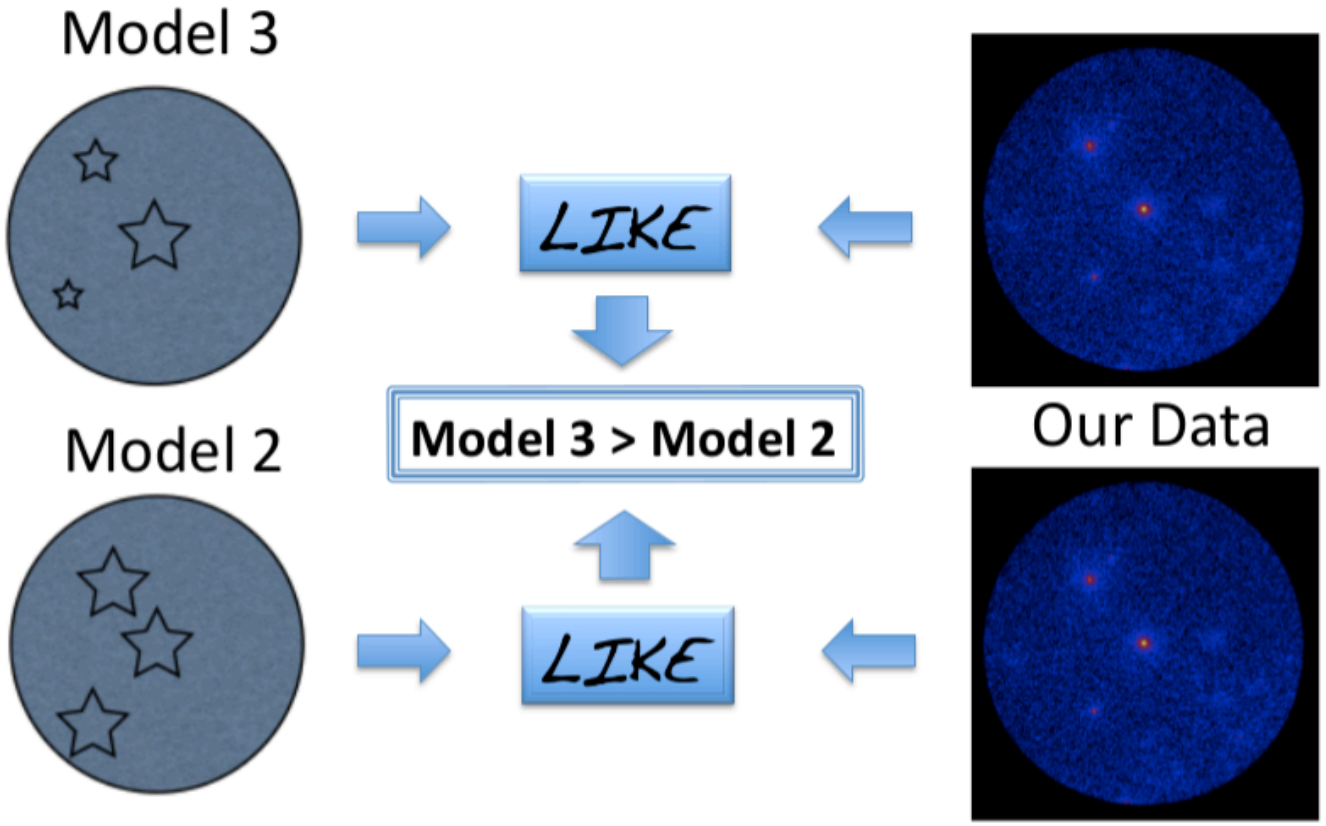




A Graphical Example



A Graphical Example



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.

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.

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

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

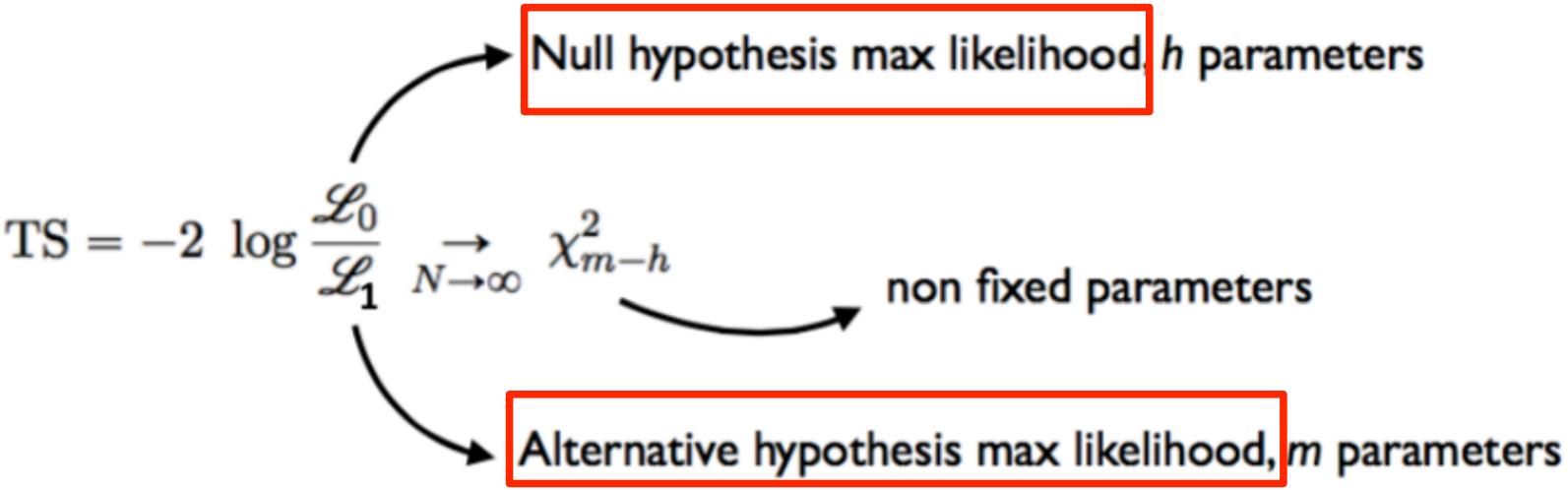
The function to maximize is:

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

where the sum is performed over photons in the ROI. The predicted number of counts is

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

Test Statistic



- 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^2_n 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.

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:

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

- 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:

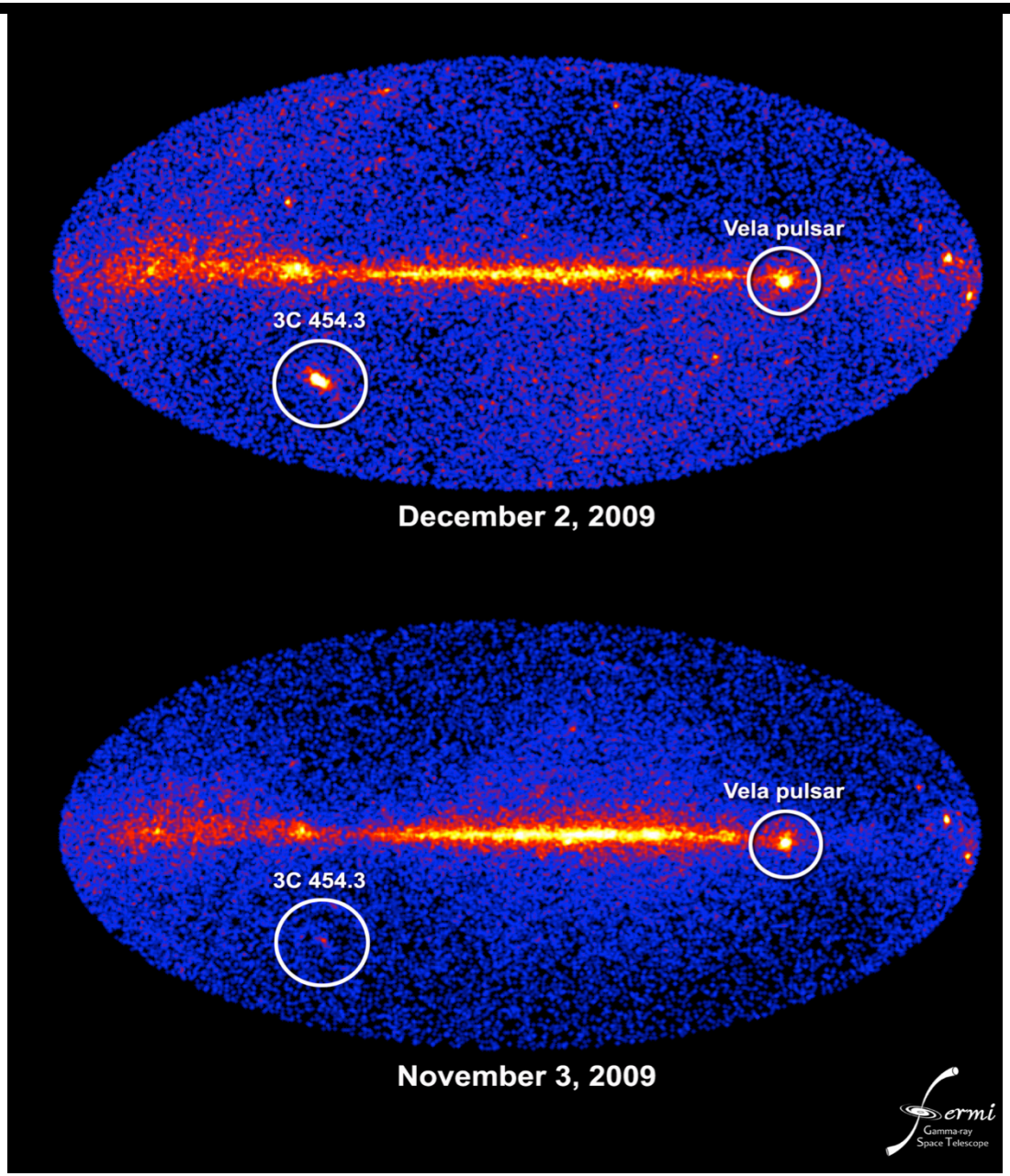
$$\log \mathcal{L} = \sum_j \log M(E'_j, \hat{p}'_j, t_j) - N_{\mathrm{pred}}$$

- Calculate the TS:

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

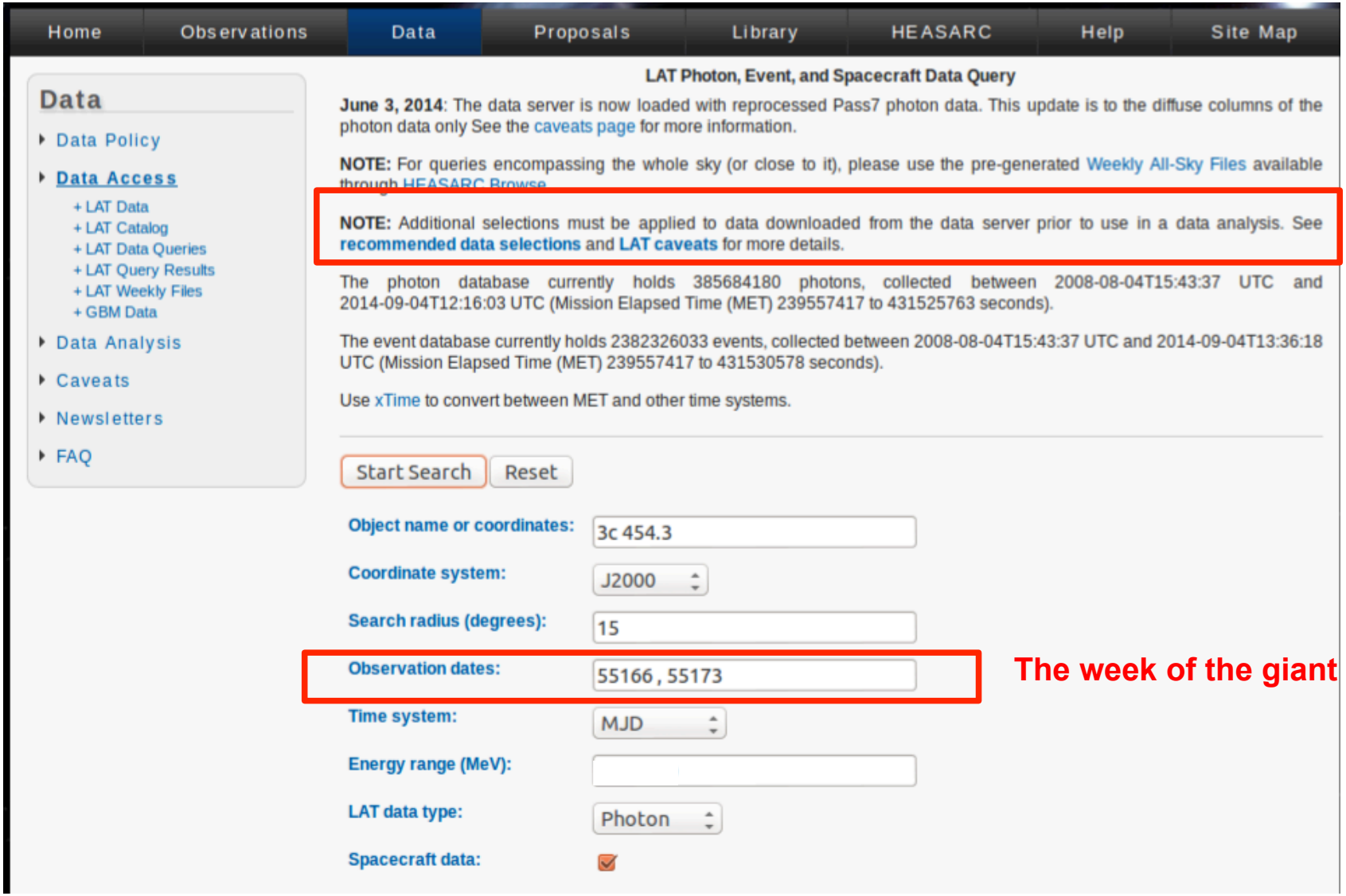
Likelihood Analysis Tutorial

Blazar one of … 3c454.3's record flares!



How to download data

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



The week of the giant outburst!!

→ Download both spacecraft and photon data ←

Take note of the start and stop MET

follow the link

- Data Policy
- **Data Access**
  - + LAT Data
  - + LAT Catalog
  - + LAT Data Queries
  - + LAT Query Results
  - + LAT Weekly Files
  - + GBM Data
- Data Analysis
- Caveats
- Newsletters
- FAQ

Your search criteria were:

Equatorial coordinates (degrees)	(343.491,16.1482)
Time range (MET)	(281318400,281923200)
Time range (Gregorian)	(2009-12-01 00:00:00,2009-12-08 00:00:00)
Energy range (MeV)	(100,300)
Search radius (degrees)	15

The state of your query is 2 (Query complete)

Server	Position in Queue	Estimated Time Remaining (sec)
Photon Server	Query complete	N/A
Spacecraft Server	Query complete	N/A

The filenames of the result files consist of the query ID string with an identifier appended to indicate which database the file came from. The identifiers are of the form: _DDNN where DD indicates the database and NN is the file number. The file number will generally be '00' unless the query resulted in a large data volume. In that case the data is broken up into multiple files. The values of the database field are:

- PH - Photon Database
- SC - Spacecraft Pointing, Livetime, and History Database
- EV - Extended Database

In the event that you do not see any files with the data type you requested listed below, you should try resubmitting your query as there may have been a problem.

Filename	Number of Entries	Size (MB)	Status
L14090420274034A4AC2B81_PH00.fits	3372	0.33	Available
L14090420274034A4AC2B81_SC00.fits	17120	2.52	Available

If you would like to download the files via wget, simply copy the following commands and paste them into a terminal window. The files will be downloaded to the current directory in the terminal window.

```
wget http://fermi.gsfc.nasa.gov/FTP/fermi/data/lat/queries/L14090420274034A4AC2B81_PH00.fits
wget http://fermi.gsfc.nasa.gov/FTP/fermi/data/lat/queries/L14090420274034A4AC2B81_SC00.fits
```

gtselect (select data)

[/home/]$ gtselect evclass=128 evtype=3
Input FT1 file[ph.fits]
Output FT1 file[filtered.fits]
RA for new search center (degrees) (0:360) [343.494812]
Dec for new search center (degrees) (-90:90) [16.1495]
radius of new search region (degrees) (0:180) [15]
start time (MET in s) (0:) [281318400]
end time (MET in s) (0:) [281923200]
lower energy limit (MeV) (0:) [100]
upper energy limit (MeV) (0:) [500000]
maximum zenith angle value (degrees) (0:180) [90]

Events with a high prob. to be gammas

Setting the max ZA, filter gammas from albedo events (gamma from the Earth that can be a significant source of background)

gtmktime (cut the bad time intervals)

Filter out events collected while passing in SAA and other low-quality events

[/home/]$ gtmktime
Spacecraft data file[sc.fits]
Filter expression[(DATA_QUAL>0)&&(LAT_CONFIG==1)]
Apply ROI-based zenith angle cut[no]
Event data file[filtered.fits]
Output event file name[filtered_gti.fits]

Use ZA to filter only proper GTIs

gtbin (Counts Map)

[/home]$ gtbin

Type of output file (CCUBE|CMAP|LC|PHA1|PHA2|HEALPIX) [CMAP]

Event data file name[filtered_gti.fits]

Output file name[CMAP.fits]

Spacecraft data file name[sc.fits]

Size of the X axis in pixels[120]

Size of the Y axis in pixels[120]

Image scale (in degrees/pixel)[0.25]

Coordinate system (CEL - celestial, GAL -galactic) (CEL|GAL) [CEL]

First coordinate of image center in degrees (RA or galactic l) [343.494812]

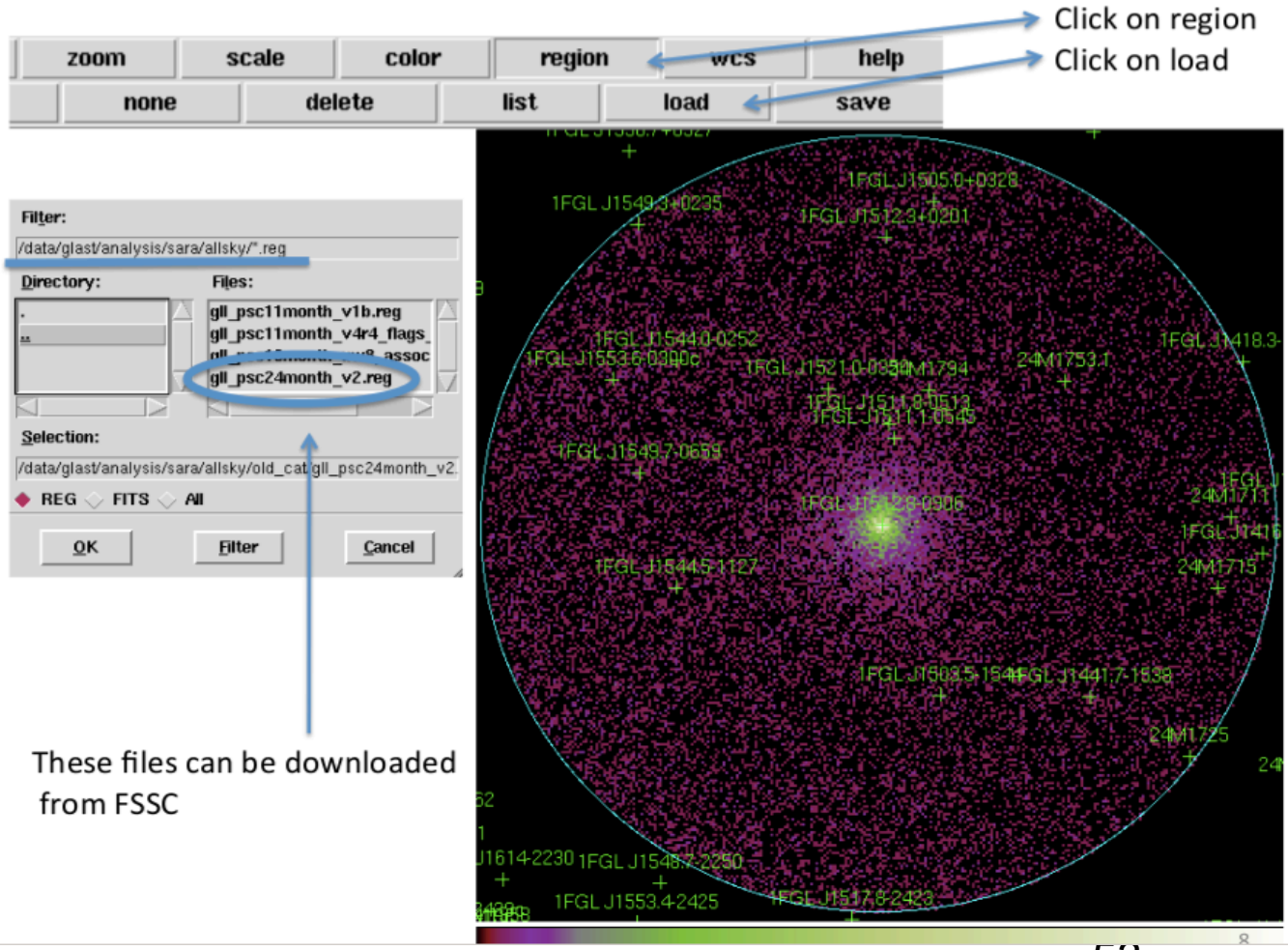
Second coordinate of image center in degrees (DEC or galactic b) [16.1495]

Rotation angle of image axis, in degrees[0]

Projection method e.g. AIT|ARC|CAR|GLS|MER|NCP|SIN|STG|TAN: [AIT]

Look at the counts map

Use DS9 to look at the counts map of your ROI and check for close-by sources
> ds9 CMAP.fits &



Likelihood 1st step: gtltcube

[/home]$ gtltcube zmax=90
Event data file[filtered_gti.fits]
Spacecraft data file[sc.fits]
Output file[ltCube.fits]
Step size in cos(theta) (0.:1.) [0.025]
Pixel size (degrees)[1]
……..

The “livetime cube” must be re-calculated when a new time-interval or a new ZA is selected

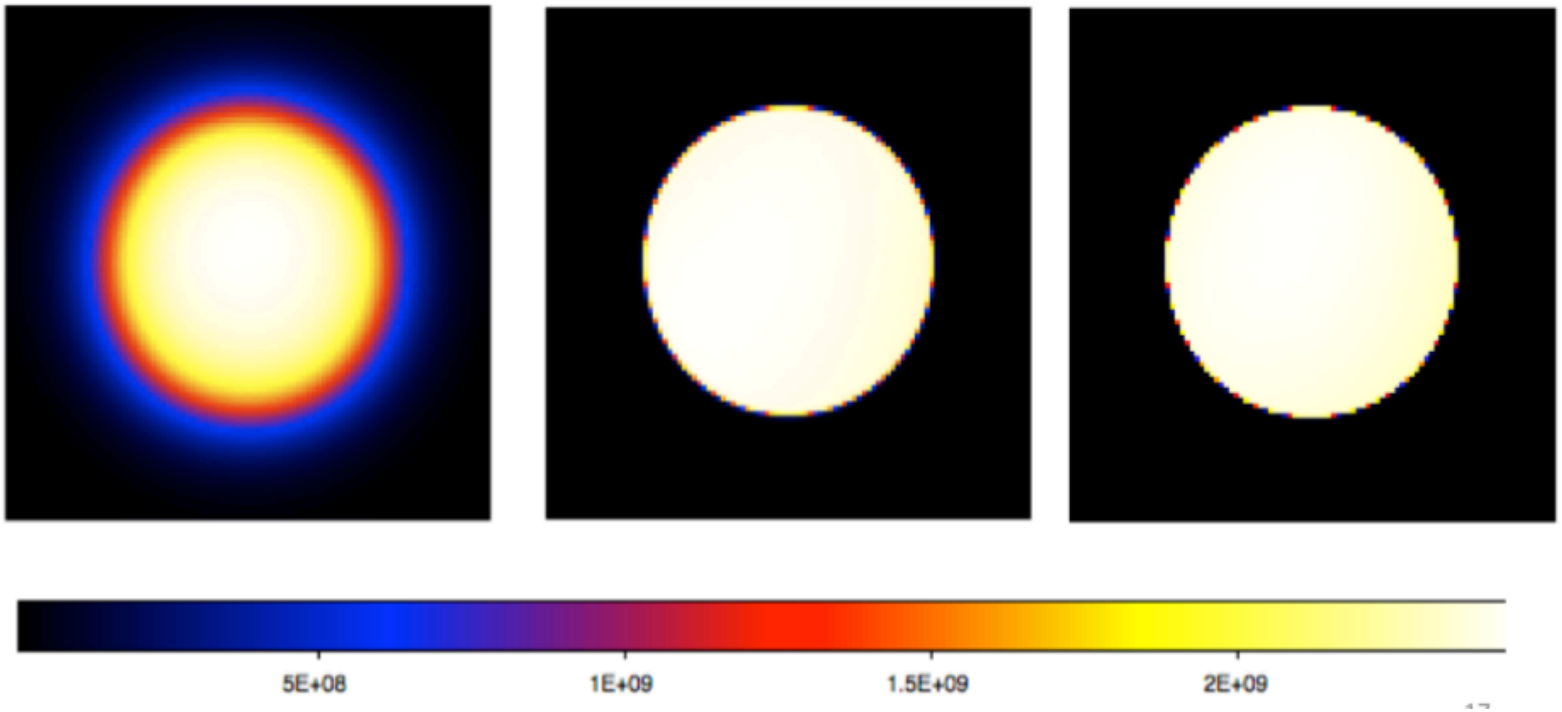
Likelihood 2nd step: gtexpmap

[/home/]$ gtexpmap
Event data file[filtered_gti.fits]
Spacecraft data file[sc.fits]
Exposure hypercube file[ltCube.fits]
output file name[expMap.fits]
Response functions[CALDB] **P8R2_SOURCE_V6**
Radius of the source region (in degrees)[30]
Number of longitude points (2:1000) [120]
Number of latitude points (2:1000) [120]
Number of energies (2:100) [20]
Computing the ExposureMap using ltCube.fits
...

Add 15° to the ROI radius

gtexpmap

Quick check with DS9: fields must be homogenous



Likelihood 3rd step: the XML model

5. Create a source model XML file

The gtlike tool reads the source model from an XML file. The model file contains your best guess at the locations and spectral forms for the sources in your data. A source model can be created using the model editor tool, by using the user contributed tool **make3FGLxml.py** (available at the user-contributed tools page), or by editing the file directly within a text editor.

Here we cannot use the same source model that was used to analyze six months of data in the Unbinned Likelihood tutorial, as the 2-year data set contains many more significant sources and will not converge. Instead, we will use the 3FGL catalog to define our source model by running make3FGLxml.py. To run the script, you will need to download the current LAT catalog file and place it in your working directory:

```
prompt> make3FGLxml.py gll_psc_v16.fit 3C279_binned_gti.fits -o 3C279_input_model.xml
-G $FERMI_DIR/refdata/fermi/galdiffuse/gll_iem_v06.fits -g gll_iem_v06
-I $FERMI_DIR/refdata/fermi/galdiffuse/iso_P8R2_SOURCE_V6_v06.txt
-i iso_P8R2_SOURCE_V6_v06 -s 120 -p TRUE -v TRUE
This is make3FGLxml version 01r0.
The default diffuse model files and names are for pass 8
and assume you have v10r00p05 of the Fermi Science Tools or higher.
Creating file and adding sources from 3FGL
Added 312 point sources, note that any extended sources in ROI were modeled as point sources
because psForce option was set to True
prompt>
```

Note that we are using a high level of significance so that we only fit the brightest sources and we have forced the extended sources to be modeled as point sources. This only affects the lobes of Centarus A which are just outside the FOV.

It is also necessary to specify the entire path to location of the diffuse model on your system. The resulting XML model contains 312 sources. Clearly, the simple 4-source model we used for the 6-month Unbinned Likelihood analysis would have been too simplistic.

This XML file uses the spectral model from the 3FGL catalog analysis for each source. (The catalog file is available at the LAT 4-yr Catalog page.) However, that analysis used a subset of the available spectral models. A dedicated analysis of the region may indicate a different spectral model is preferred. For more details on the options available for your XML models, see:

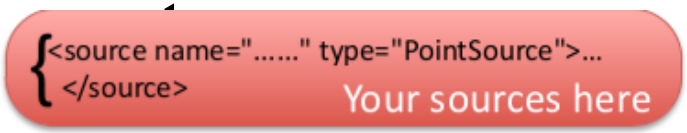
- Descriptions of available Spectral and Spatial Models
- Examples of XML Model Definitions for Likelihood

Likelihood 3rd step

python make3FGLxml.py gll_psc_v16.fit filtered_gti.fits -o 3c454.3.xml –G $FERMI_DIR/refdata/fermi/galdiffuse/gll_iem_v06.fits -g gll_iem_v06 –I $FERMI_DIR/refdata/fermi/galdiffuse/iso_P8R2_SOURCE_V6_v06.txt -i iso_P8R2_SOURCE_V6_v06 -s 120 -p TRUE -v TRUE

XML model

- **Typical source entry for an assumed powerlaw**




```
<source name="3c454.3" type="PointSource">
<spectrum type="PowerLaw2">
<!-- Source is in ROI center -->
<parameter error="0.00" free="1" max="1000" min="1e-06" name="Integral" scale="1e-04"
value="1.000"/>
 <parameter error="0.00" free="1" max="0" min="-5" name="Index" scale="1" value="-2.000"/>
                    <parameter free="0" max="3e6" min="20" name="LowerLimit" scale="1"
value="100."/>
        <parameter free="0" max="3e6" min="20" name="UpperLimit" scale="1" value="300000."/>
        </spectrum>
<spatialModel type="SkyDirFunction">
<parameter free="0" max="360.0" min="-360.0" name="RA" scale="1.0" value="343.494812"/>
<parameter free="0" max="90" min="-90" name="DEC" scale="1.0" value="16.149500"/>
</spatialModel>
</source>
```

XML model

Test different models... power law * HE exponential cut-off

```
<source name="3c454.3" type="PointSource">
<spectrum type="PLSuperExpCutoff">
<parameter free="1" max="1000" min="1e-05" name="Prefactor" scale="1e-07" value="1"/>
<parameter free="1" max="0" min="-5" name="Index1" scale="1" value="-1.7"/>
<parameter free="0" max="1000" min="50" name="Scale" scale="1" value="200"/>
<parameter free="1" max="30000" min="500" name="Cutoff" scale="1" value="3000"/>
<parameter free="0" max="5" min="0" name="Index2" scale="1" value="1"/>
</spectrum>
```

- **Look here for source model definition and XML model definitions:**
  http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/xml_model_defs.html
  http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/source_models.html

- **Useful python script to load 2FGL sources that belongs to your ROI in your XML file model (make3FGLxml.py)**
  http://fermi.gsfc.nasa.gov/ssc/data/analysis/user/

XML model

- Backgrounds

```
<!-- Diffuse Sources -->
<source name="galactic_background"   type="DiffuseSource">
<spectrum type="PowerLaw">
<parameter free="1" max="10" min="0" name="Prefactor" scale="1" value="1"/>
<parameter free="0" max="1" min="-1" name="Index" scale="1.0" value="0"/>
<parameter free="0" max="2e2" min="5e1" name="Scale" scale="1.0" value="1e2"/>
</spectrum>
<spatialModel file="gll_iem_v06.fits" type="MapCubeFunction">
<parameter free="0" max="1e3" min="1e-3" name="Normalization" scale="1.0" value="1.0"/>
</spatialModel>
</source>
<source name="extragalactic_background" type="DiffuseSource">
<spectrum file="iso_P8R2_SOURCE_V6_v06.txt" type="FileFunction">
<parameter free="1" max="10" min="1e-2" name="Normalization" scale="1" value="1"/>
</spectrum>
<spatialModel type="ConstantValue">
<parameter free="0" max="10.0" min="0.0" name="Value" scale="1.0" value="1.0"/>
</spatialModel>
</source>
```

Diffuse response

[/home/]$gtdiffrsp

Event data file[]filtered_gti.fits

Spacecraft data file[] sc.fits

Source model file[] 3c454.3.xml

Response functions to use[] **P8R2_SOURCE_V6**

Finally... gtlike performing the actual fit

[/home/]$ gtlike plot=yes
Statistic to use (BINNED|UNBINNED) [UNBINNED]
Spacecraft file[sc.fits]
Event file[filtered_gti.fits]
Unbinned exposure map[expMap.fits]
Exposure hypercube file[ltCube.fits]
Source model file[../xml_models/_3c454.3_model_ROI15.xml]
Response functions to use[CALDB]
Optimizer (DRMNFB|NEWMINUIT|MINUIT|DRMNGB|LBFGS) [DRMNFB]

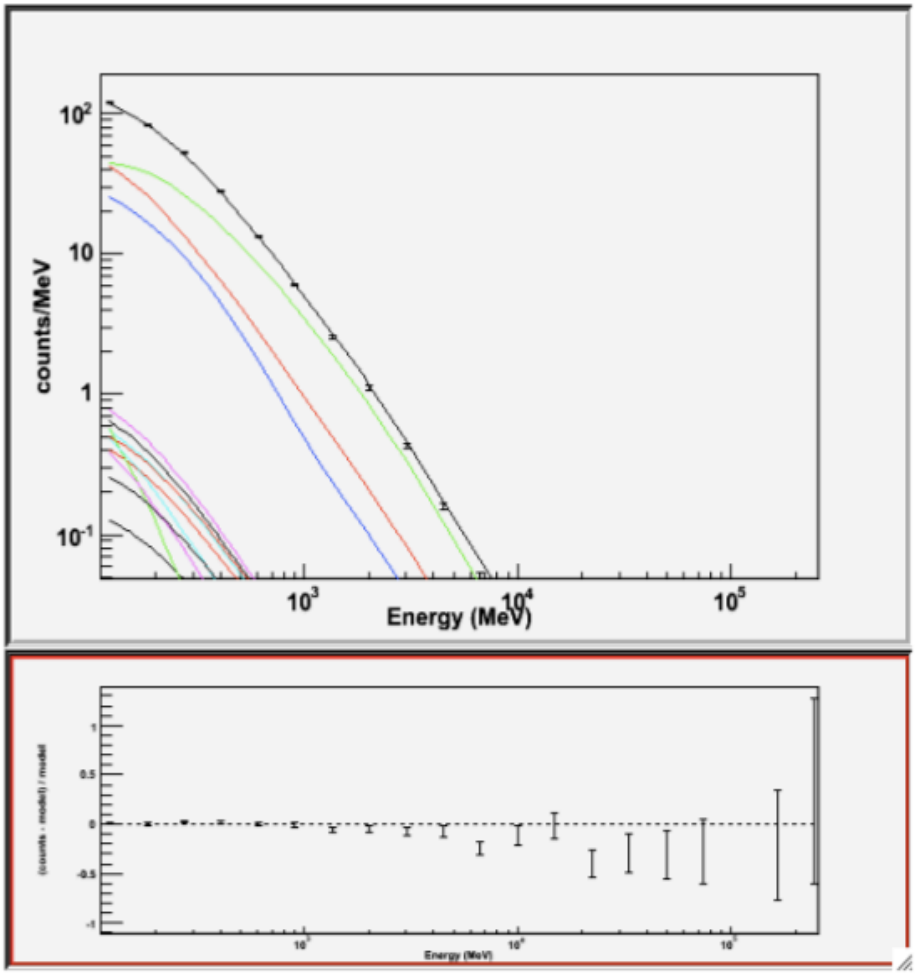
Typically use DRMNGB/DRMNFB to find a rough estimate of the likelihood maxima and refine later on with **MINUIT (or NEWMINUIT)**

Likelihood output

{'3c454.3': {'Integral': '0.146106 +/- 0.00271733',
'Index': '-2.29973 +/- 0.017189',
'LowerLimit': '100',
'UpperLimit': '300000',
'Npred': '4171.85',
'ROI distance': '0',
'TS value': '17548.4',
'Flux': '1.46192e-05 +/- 2.7178e-07',
…
extragalactic_background': {'Normalization': '1.20197 +/- 0.23541',
'Npred': '643.953',
'Flux': '0.000170707 +/- 3.34331e-05',
},
'galactic_background': {'Prefactor': '0.739969 +/- 0.251827',
'Index': '0',
'Scale': '100',
'Npred': '357.929',
'Flux': '0.000215978 +/- 7.35023e-05',

gtlike creates two output files:
1) results.dat: fit results
2) counts_spectra.fits: the counts in a proper energy binning

Plot



Solid lines follows the order as they are listed in the file results.dat:

black) ROI fit

red) 1st source (pks1510)

green) 2nd source (galactic)

blue) 3rd source (istropic)

Magenta) 4th source

Cyan) 5th source

...