

National Aeronautics and Space Administration



Fermi  
Gamma-ray Space Telescope

[www.nasa.gov/fermi](http://www.nasa.gov/fermi)



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

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

- **Overview of the Fermi Large Area Telescope**
  - 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

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- **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 Area Telescope (LAT)  
20 MeV - >300 GeV

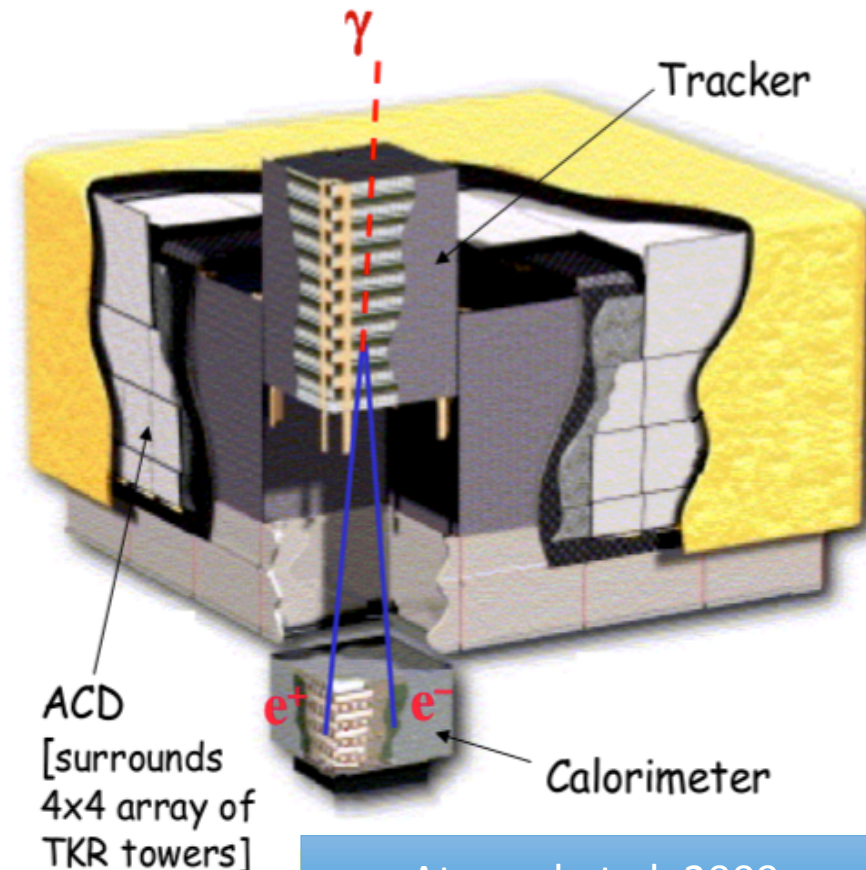
Gamma-ray Burst Monitor (GBM)  
NaI and BGO Detectors  
8 keV - 30 MeV

## 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.

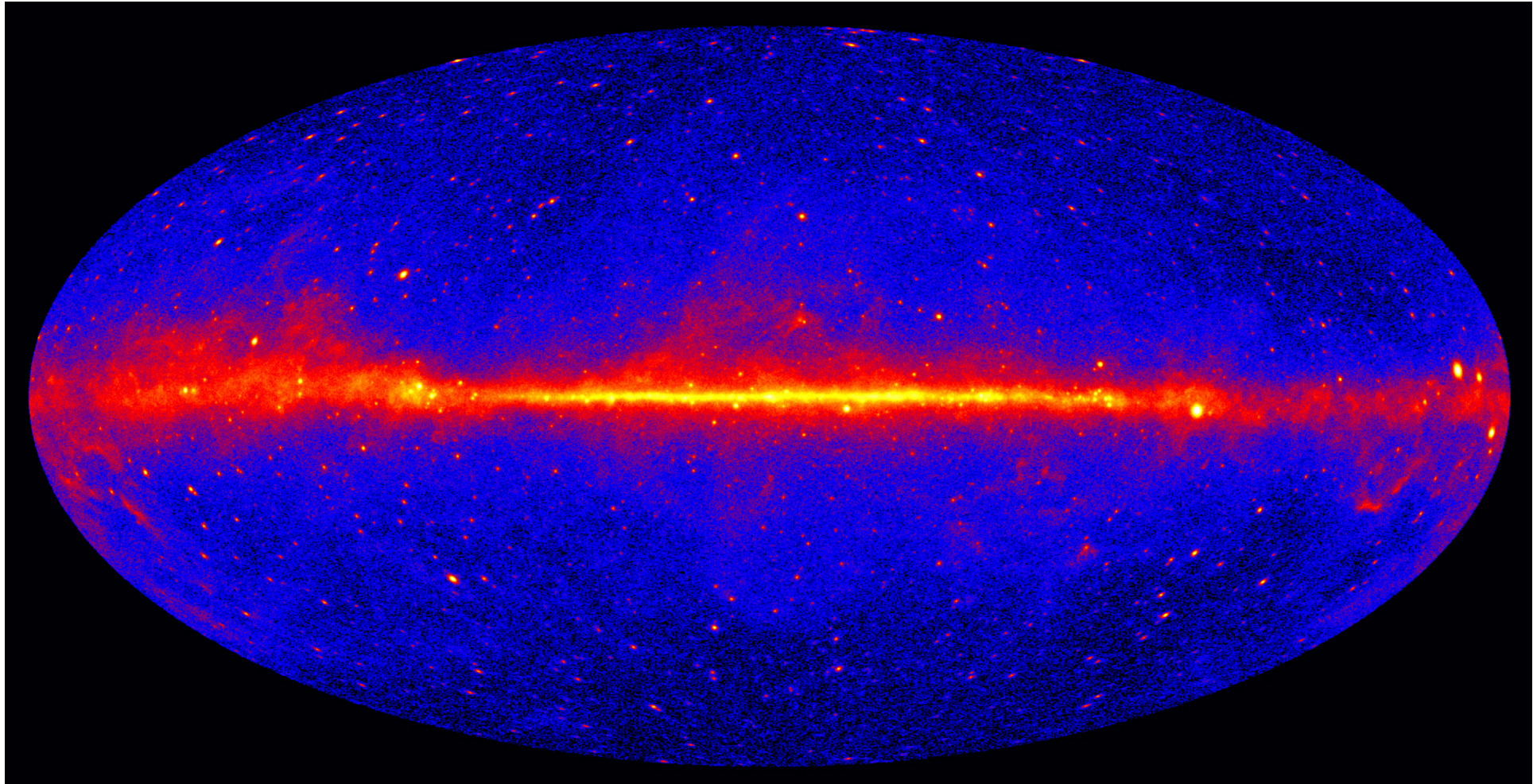


Atwood et al. 2009

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

# The Fermi Sky

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## What do you need for the analysis

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- **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 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...

fv: Summary of L1307190816225D42602B76\_PH01.fits in D:/download/Sesto/cta1photon/

Index	Extension	Type	Dimension	View
0	Primary	Image	0	Header Image Table
1	EVENTS	Binary	22 cols X 172002 rows	Header Hist Plot All Select
2	GTI	Binary	2 cols X 1623 rows	Header Hist Plot All Select

fv: Binary Table of L1307190816225D42602B76\_PH01.fits[1] in D:/download/Sesto/cta1photon/

Select	ENERGY	RA	DEC	L	B	THETA
All	E	E	E	E	E	E
Invert	MeV	deg	deg	deg	deg	deg
1	2.336191E+003	3.356806E+002	8.163372E+001	1.175507E+002	2.036241E+001	4.115981E+001
2	2.887859E+002	3.380240E+002	8.752237E+001	1.213699E+002	2.508607E+001	4.264727E+001
3	1.225226E+003	3.883369E+002	8.072034E+001	1.204938E+002	1.812485E+001	3.609352E+001
4	4.534394E+003	3.088722E+002	8.240852E+001	1.154877E+002	2.360458E+001	4.293106E+001
5	4.019389E+002	3.552110E+002	8.628517E+001	1.216945E+002	2.355435E+001	7.299443E+001
6	2.382755E+002	3.180323E+002	8.210764E+001	1.159565E+002	2.241277E+001	7.494953E+001
7	1.264964E+002	3.255829E+002	8.287437E+001	1.172845E+002	2.218270E+001	7.469367E+001
8	1.547845E+002	3.234117E+002	8.472955E+001	1.185430E+002	2.363485E+001	7.346131E+001
9	1.454238E+002	3.474094E+002	8.746054E+001	1.217301E+002	2.483102E+001	5.835028E+001
10	3.449312E+002	3.310049E+002	8.453091E+001	1.189708E+002	2.299933E+001	5.160154E+001
11	5.811864E+002	3.575490E+002	7.964534E+001	1.200859E+002	1.711370E+001	2.937013E+001
12	2.344030E+002	3.502021E+002	8.416479E+001	1.205161E+002	2.172313E+001	3.792418E+001
13	5.823864E+002	3.126542E+002	8.261592E+001	1.159879E+002	2.328888E+001	5.608511E+001
14	1.448622E+003	3.584331E+002	8.189178E+001	1.207991E+002	1.926012E+001	4.726143E+001
15	3.600245E+002	3.483517E+002	8.227232E+001	1.195281E+002	2.005690E+001	3.439582E+001
16	1.747731E+003	3.294199E+002	8.365910E+001	1.182192E+002	2.244669E+001	3.296274E+001
17	1.68157E+002	3.483332E+002	8.084929E+001	1.189347E+002	1.874454E+001	3.663948E+001
18	3.378409E+002	3.136788E+002	8.375113E+001	1.170663E+002	2.380627E+001	5.706439E+001

fv: Table Info of L13071908162...  
Total Columns: 22  
Total Rows: 172002

Selected columns for display

- ENERGY
- RA
- DEC
- L
- B
- THETA
- PHI
- ZENITH\_ANGLE
- EARTH\_AZIMUTH\_ANGLE
- TIME
- EVENT\_ID
- RUN\_ID
- RECON\_VERSION
- CALIB\_VERSION
- EVENT\_CLASS
- CONVERSION\_TYPE
- LIVETIME
- DIFRSP0
- DIFRSP1
- DIFRSP2
- DIFRSP3
- DIFRSP4

Display Table  
Select All  
Clear All  
Cancel  
Help

Events

fv: Binary Table of L1307190816225D42602B76\_P...

Select	START	STOP
All	s	s
Invert	Modify	Modify
1	2.530705209249E+008	2.530762370846E+008
2	2.530762499232E+008	2.530819660843E+008
3	2.530819789232E+008	2.53084660841E+008
4	2.530855789267E+008	2.530904400850E+008
5	2.53091889232E+008	2.530963210855E+008
6	2.530979839214E+008	2.531022110850E+008
7	2.531040179214E+008	2.531081320847E+008
8	2.531100139199E+008	2.531143880845E+008
9	2.531159969215E+008	2.531205430862E+008
10	2.531219739250E+008	2.531266340844E+008
11	2.531279449250E+008	2.531327030917E+008
12	2.531337379250E+008	2.531387810841E+008
13	2.531390149267E+008	2.531449860918E+008
14	2.53144989233E+008	2.531507160843E+008
15	2.531507289250E+008	2.531564450855E+008
16	2.531564579233E+008	2.531621740877E+008
17	2.531621869233E+008	2.531679030844E+008

Good Time Intervals (GTIs)

# FT2: where is Fermi ?

fv: Summary of L1307190816225D42602876\_SC00.fits in D:/download/Sesto/cta1photon/

Index	Extension	Type	Dimension	View
0	Primary	Image	0	Header Image Table
1	SC_DATA	Binary	29 cols X 886906 rows	Header Hist Plot All Select

fv: Table Info of L1307190816225D42602876\_SC00.fits[1] in D:/download/Sesto/cta1photon/

Total Columns: 29  
Total Rows : 886906

Selected columns for display

- START
- STOP
- SC\_POSITION
- LAT\_GEO
- LON\_GEO
- RAD\_GEO
- RA\_ZENITH
- DEC\_ZENITH
- B\_MCILWAIN
- L\_MCILWAIN
- GEOMAG\_LAT
- IN\_SAA
- RA\_SCZ
- DEC\_SCZ
- RA\_SCX
- DEC\_SCX
- RA\_NPOLE
- DEC\_NPOLE
- ROCK\_ANGLE
- LAT\_MODE
- LAT\_CONFIG
- DATA\_QUAL
- LIVETIME

Display Table  
Select All  
Clear All  
Cancel  
Help

fv: Binary Table of L1307190816225D42602876\_SC00.fits[1] in D:/download/Sesto/cta1photon/

Select	START	STOP	SC_POSITION	LAT_GEO	LON_GEO	RAD_GEO
D	D	3E	E	E	D	
s	s	m	deg	deg	m	
Invert	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)**

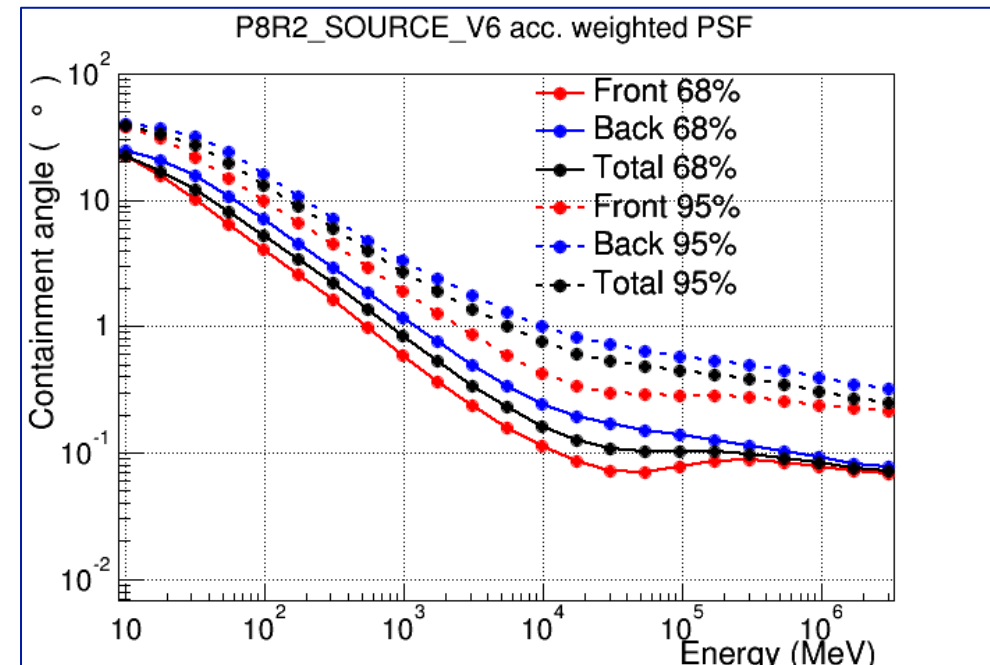
- **Effective Area**

- **Energy Resolution**

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

- **Fundamental for analysis!!**

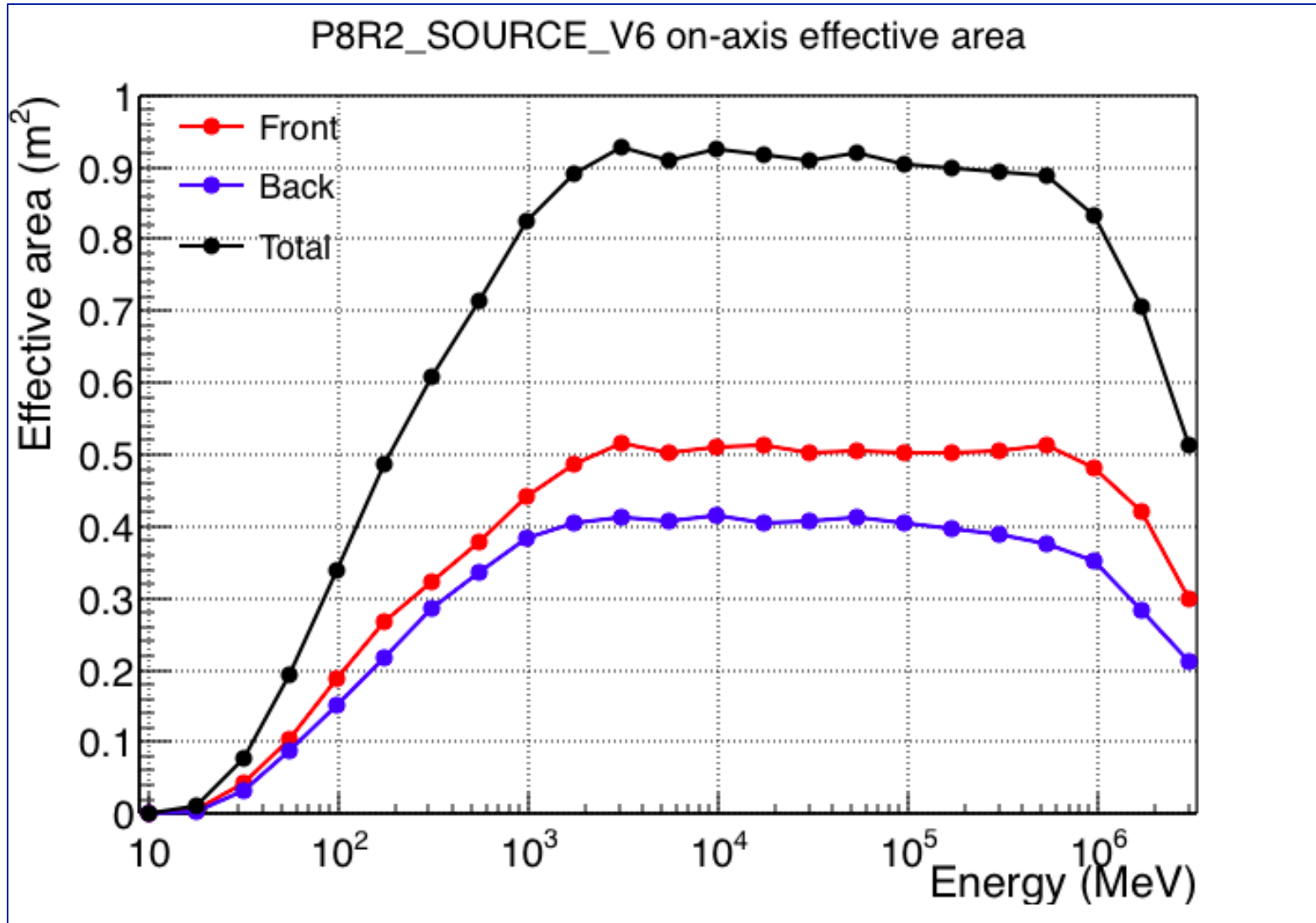
- [http://www.slac.stanford.edu/exp/glast/groups/canda/lat\\_Performance.htm](http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm)



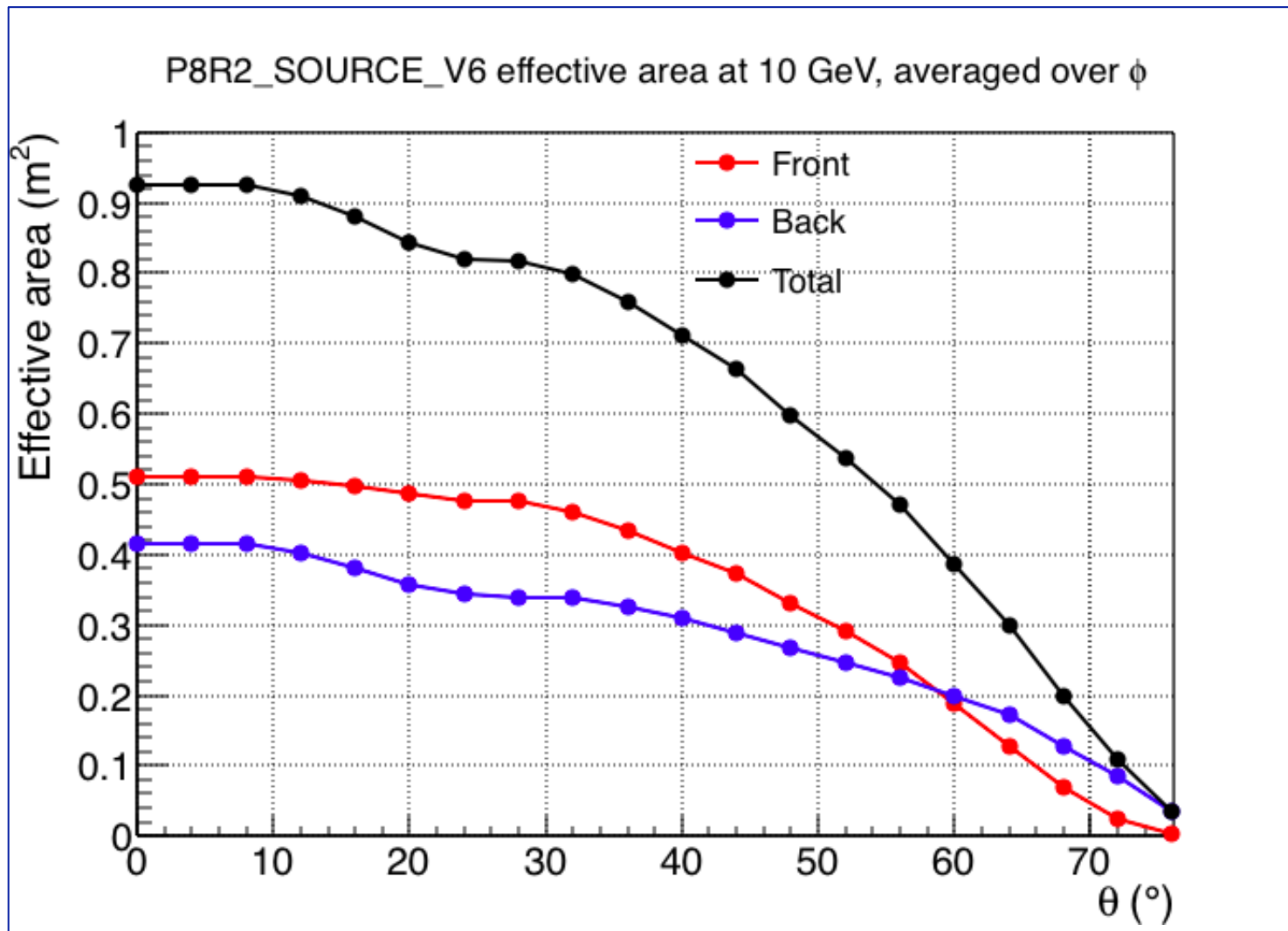
# LAT Pass8 performance

[http://www.slac.stanford.edu/exp/glast/groups/canda/lat\\_Performance.htm](http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm)

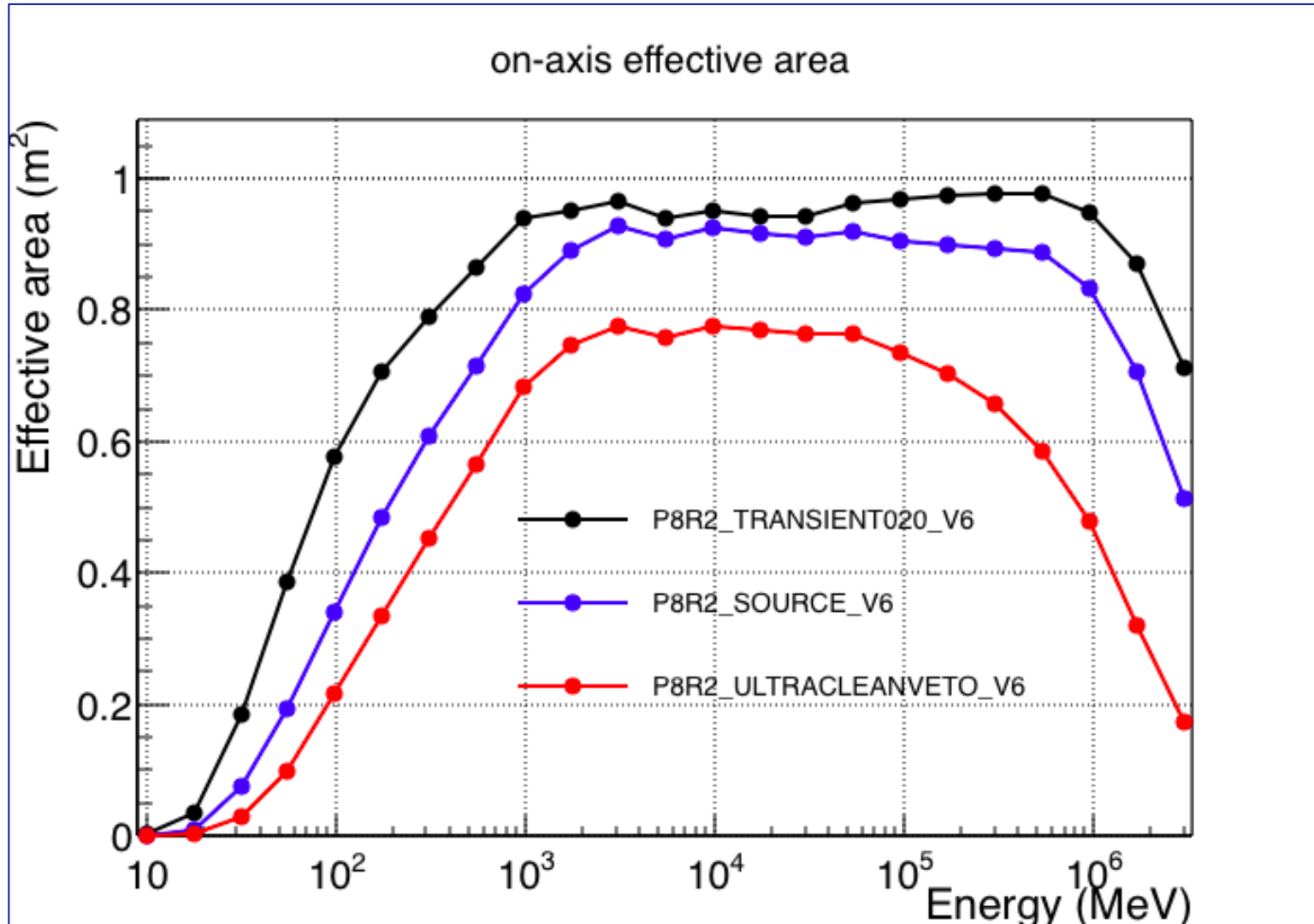
# Effective Area



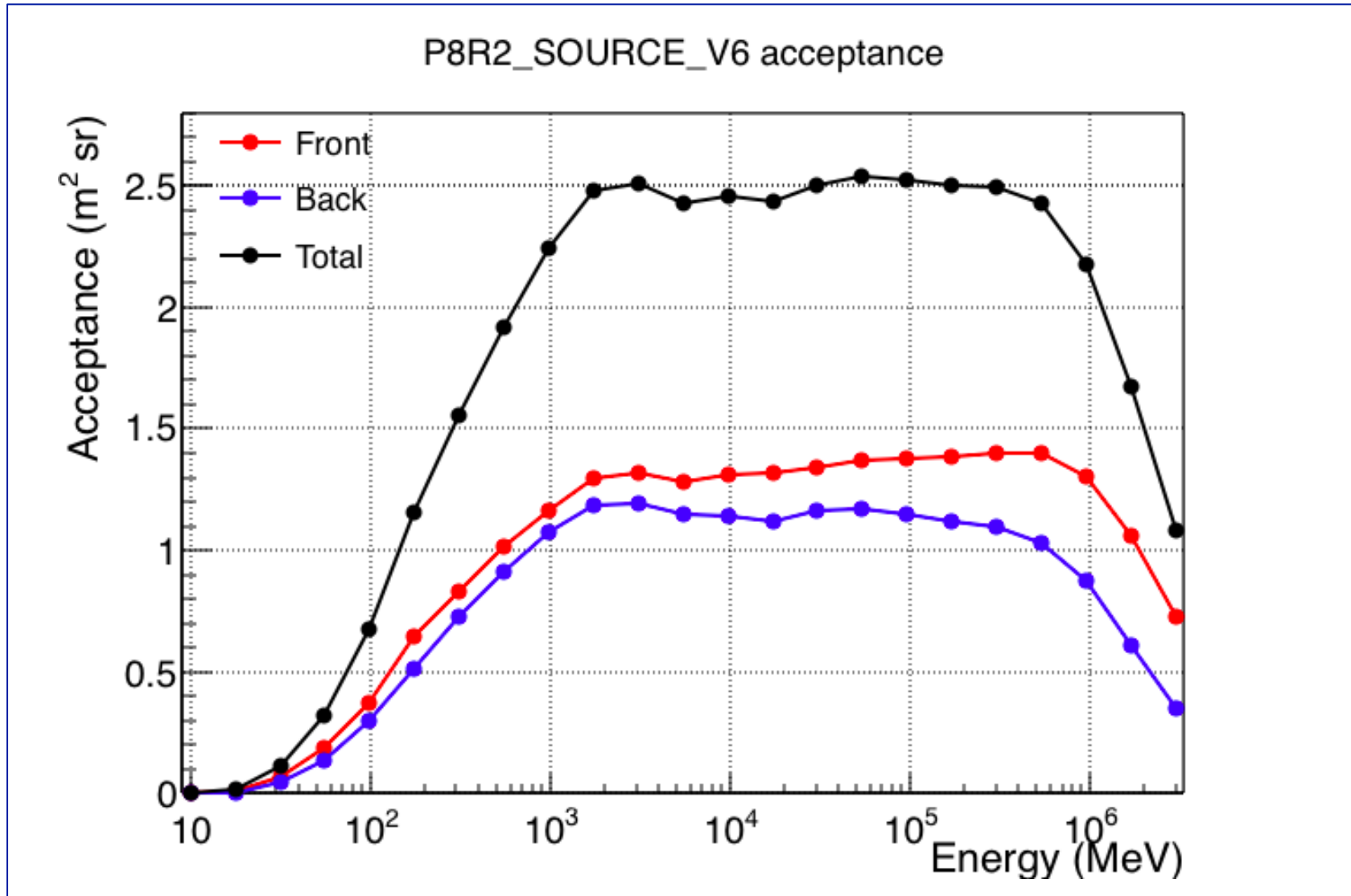
## Pass8 Effective Area



# Effective Area

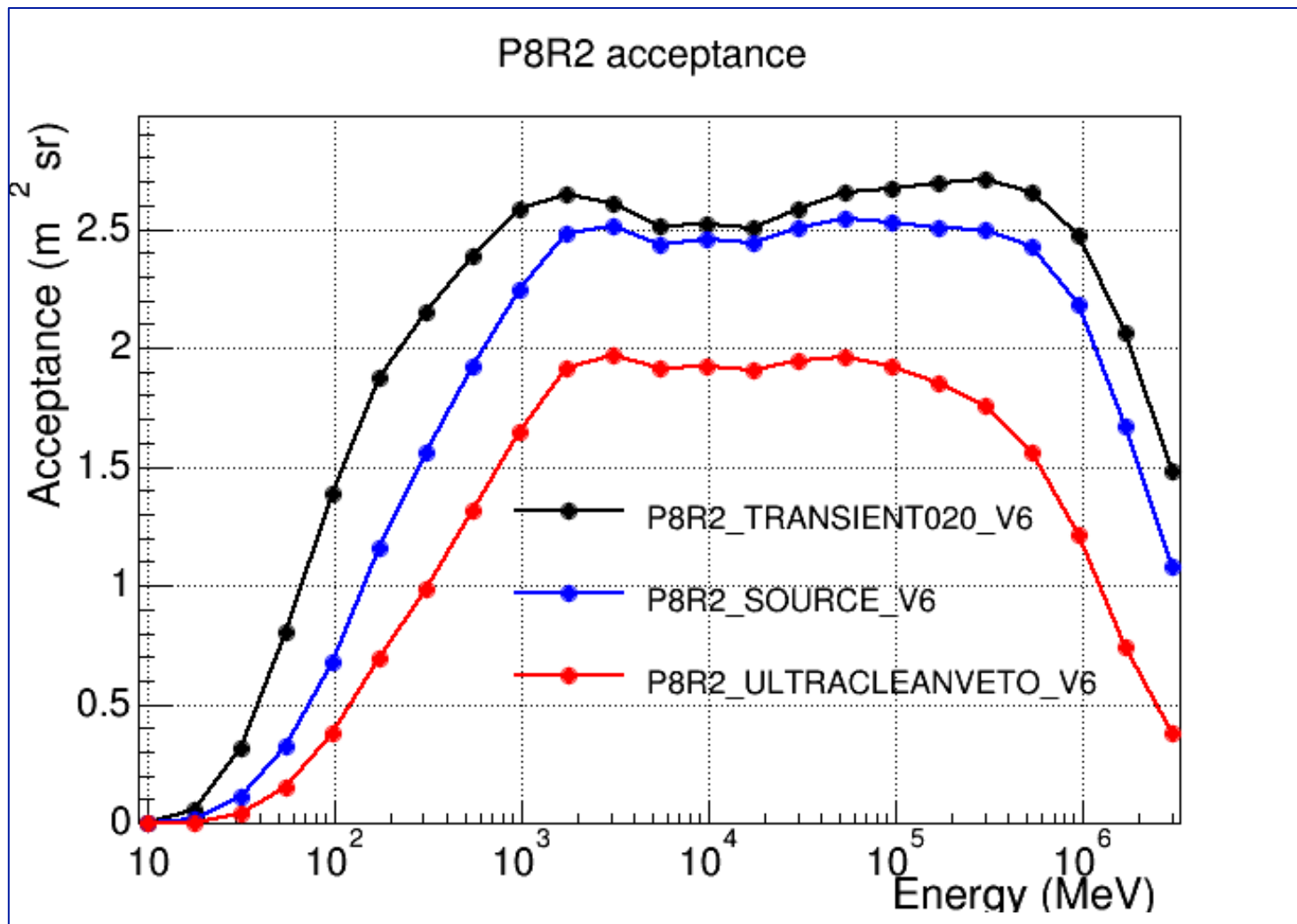


# Acceptance

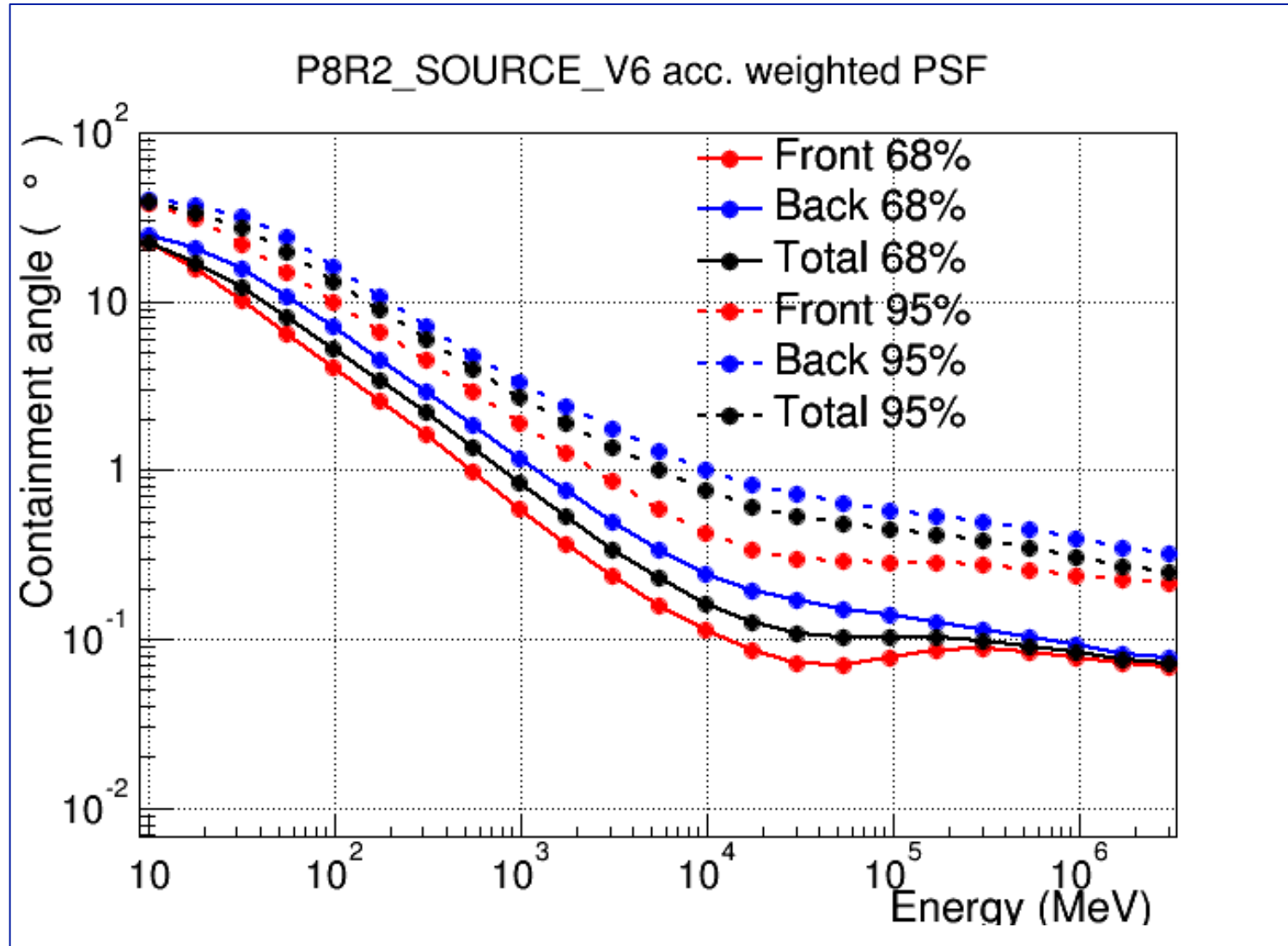




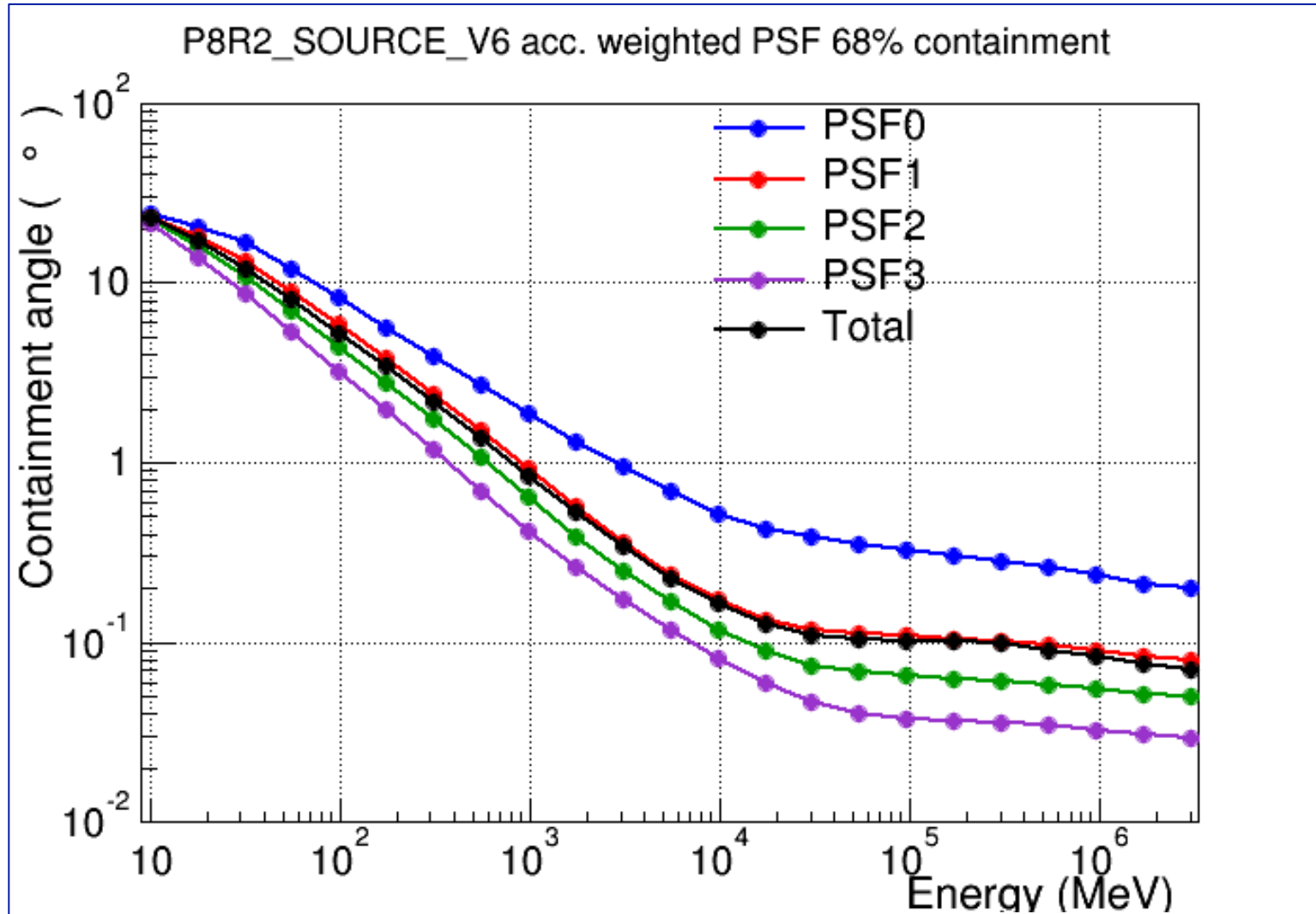
# Acceptance



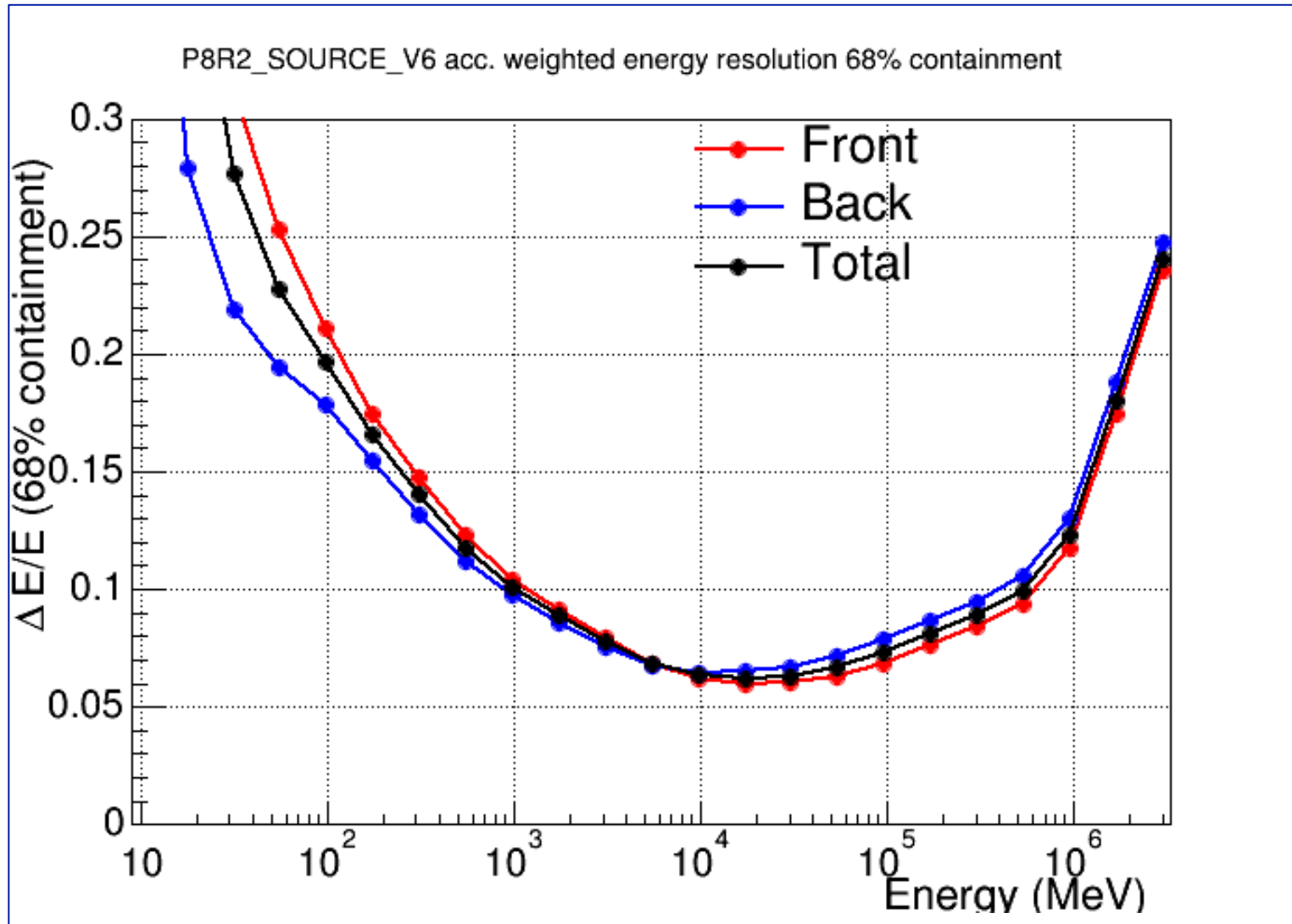
# Point Spread Function



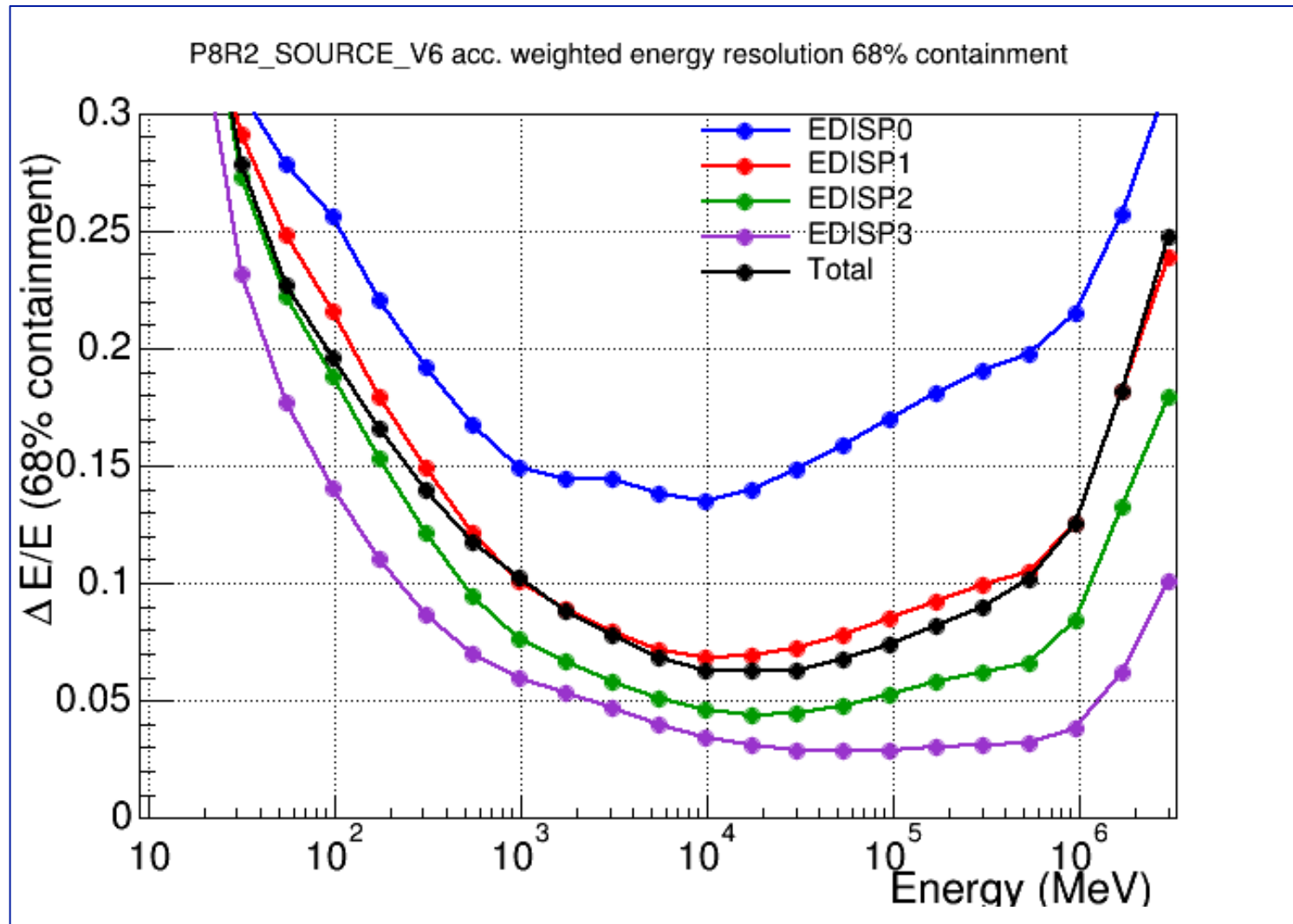
# Point Spread Function



# 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 [gtlucube](#) tool.

# Required info for Analysis

- **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 ...](#)

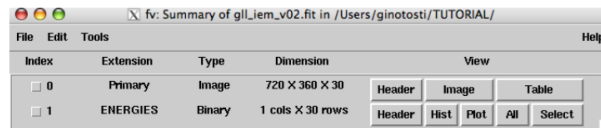
- **Choose the proper combination of**

- 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

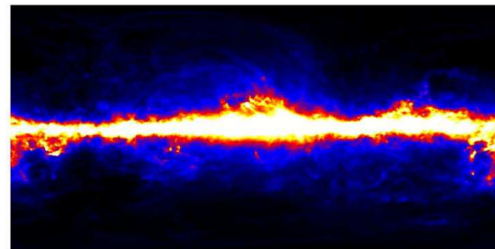
# LAT background models

## Extras 2 : Diffuse Models

Galactic diffuse model	<a href="#">gll_iem_v02.fit</a>
Isotropic spectral template (all)	<a href="#">isotropic_iem_v02.txt</a>
Isotropic spectral template (front)	<a href="#">isotropic_iem_front_v02.txt</a>
Isotropic spectral template (back)	<a href="#">isotropic_iem_back_v02.txt</a>
Detailed description	<a href="#">Model Description</a>



Index	Extension	Type	Dimension	View
<input type="checkbox"/> 0	Primary	Image	720 X 360 X 30	Header Image Table
<input type="checkbox"/> 1	ENERGIES	Binary	1 cols X 30 rows	Header Hist Plot All Select



```

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 these 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
<a href="#">gll_iem_v06.fits</a> (see below for P8R3 usage notes)	Pass 8 Source (front+back, allPSF, allEDISP) P8R3_SOURCE_V2	<a href="#">iso_P8R3_SOURCE_V2.txt</a>
	Pass 8 Source (front only) P8R3_SOURCE_V2::FRONT	<a href="#">iso_P8R3_SOURCE_FRONT_V2.txt</a>
	Pass 8 Source (back only) P8R3_SOURCE_V2::BACK	<a href="#">iso_P8R3_SOURCE_BACK_V2.txt</a>
	Pass 8 Clean (front+back, allPSF, allEDISP) P8R3_CLEAN_V2	<a href="#">iso_P8R3_CLEAN_V2.txt</a>
	Pass 8 Clean (PSF0) P8R3_CLEAN_V2::PSF0	<a href="#">iso_P8R3_CLEAN_PSF0_V2.txt</a>
	Pass 8 Clean (PSF1) P8R3_CLEAN_V2::PSF1	<a href="#">iso_P8R3_CLEAN_PSF1_V2.txt</a>
	Pass 8 Clean (PSF2) P8R3_CLEAN_V2::PSF2	<a href="#">iso_P8R3_CLEAN_PSF2_V2.txt</a>
	Pass 8 Clean (PSF3) P8R3_CLEAN_V2::PSF3	<a href="#">iso_P8R3_CLEAN_PSF3_V2.txt</a>
	Pass 8 Ultraclean (front+back, allPSF, allEDISP) P8R3_ULTRACLEAN_V2	<a href="#">iso_P8R3_ULTRACLEAN_V2.txt</a>

# LAT catalogs

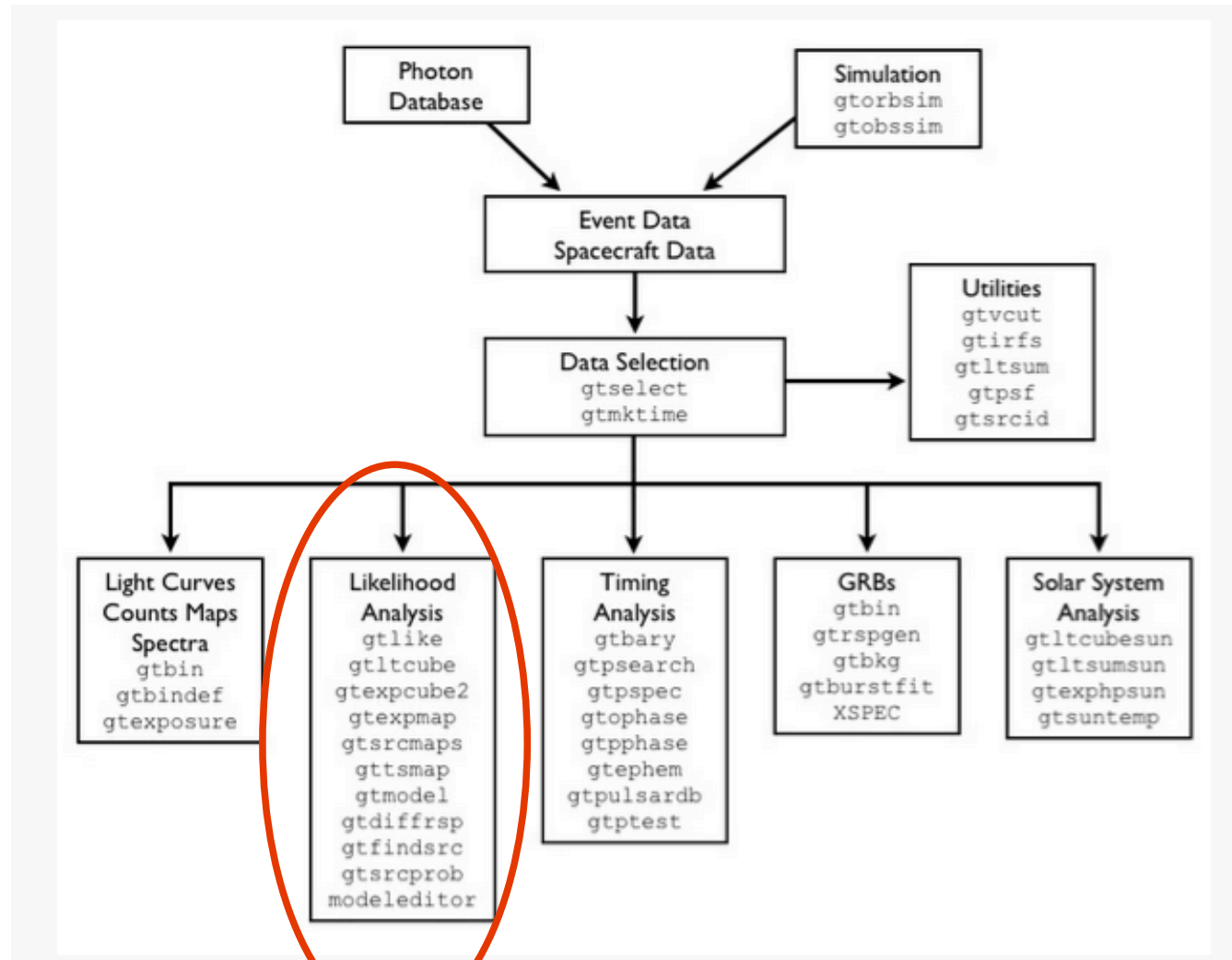
## High-level Data Products

- 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

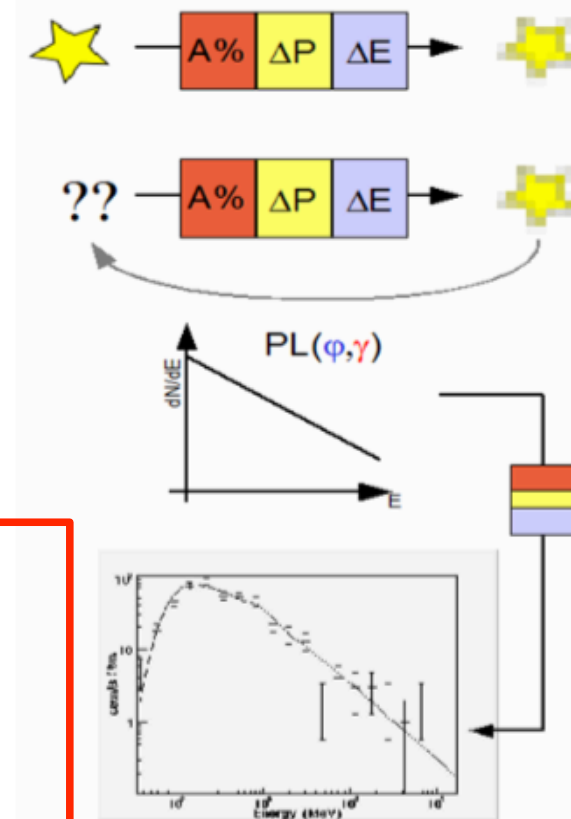
In high energy gamma rays it is never possible to really isolate a source because of limited statistics and strong and structured background.

Therefore statistical techniques have to be applied.

The most used method is the likelihood analysis based on the Poisson statistics.

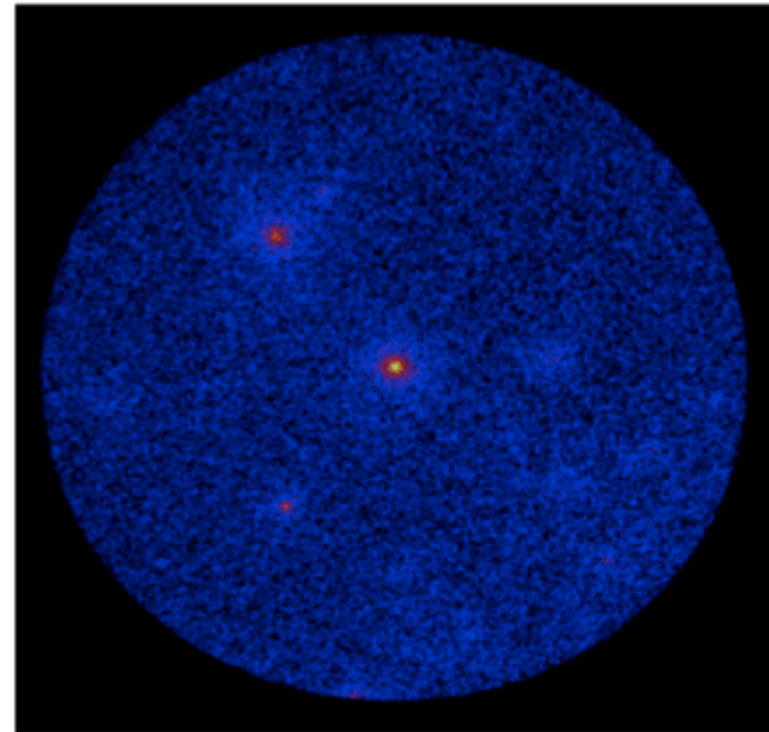
The method requires to assume a model for the signal detected by the telescope.

- Assume a **model**
- Model **convolved** with Instrument response 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.



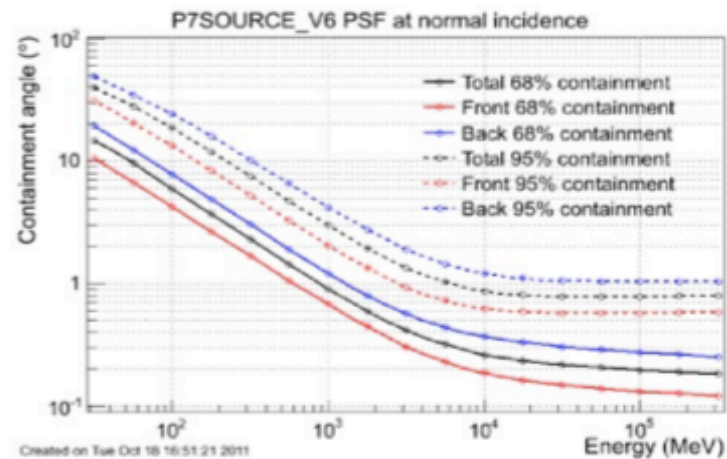
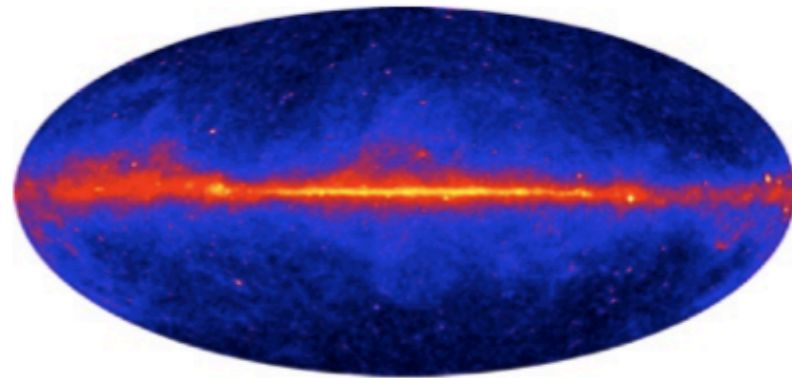
Count Map

# The Procedure

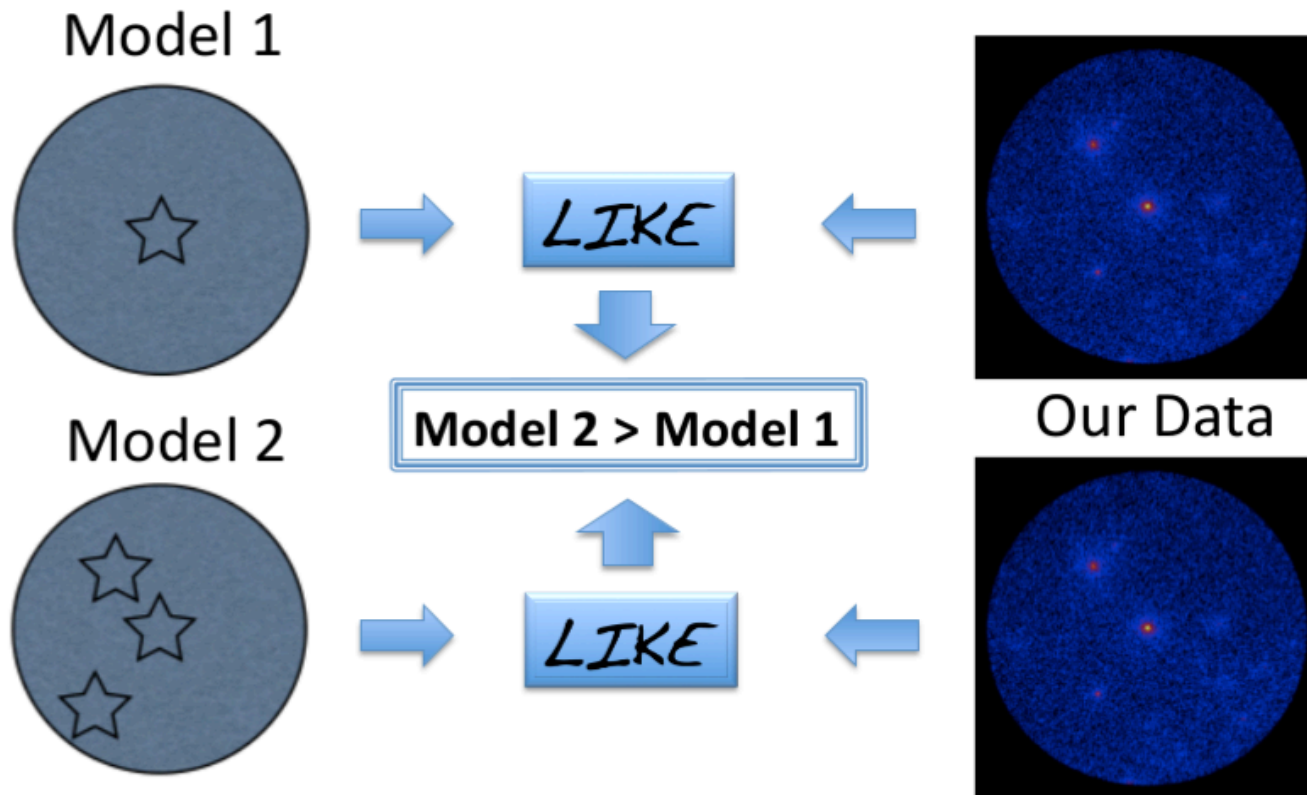
- Basically the initial '**model**' is a guess of the various parameters of the sources in our region:
  - location
  - spectral shape
  - flux
  - etc.
- The guess can be easier if you have a starting point like the 2FGL (3FGL).
- We quantify (using the Likelihood Method) the statistical significance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

# Why Model Fitting?

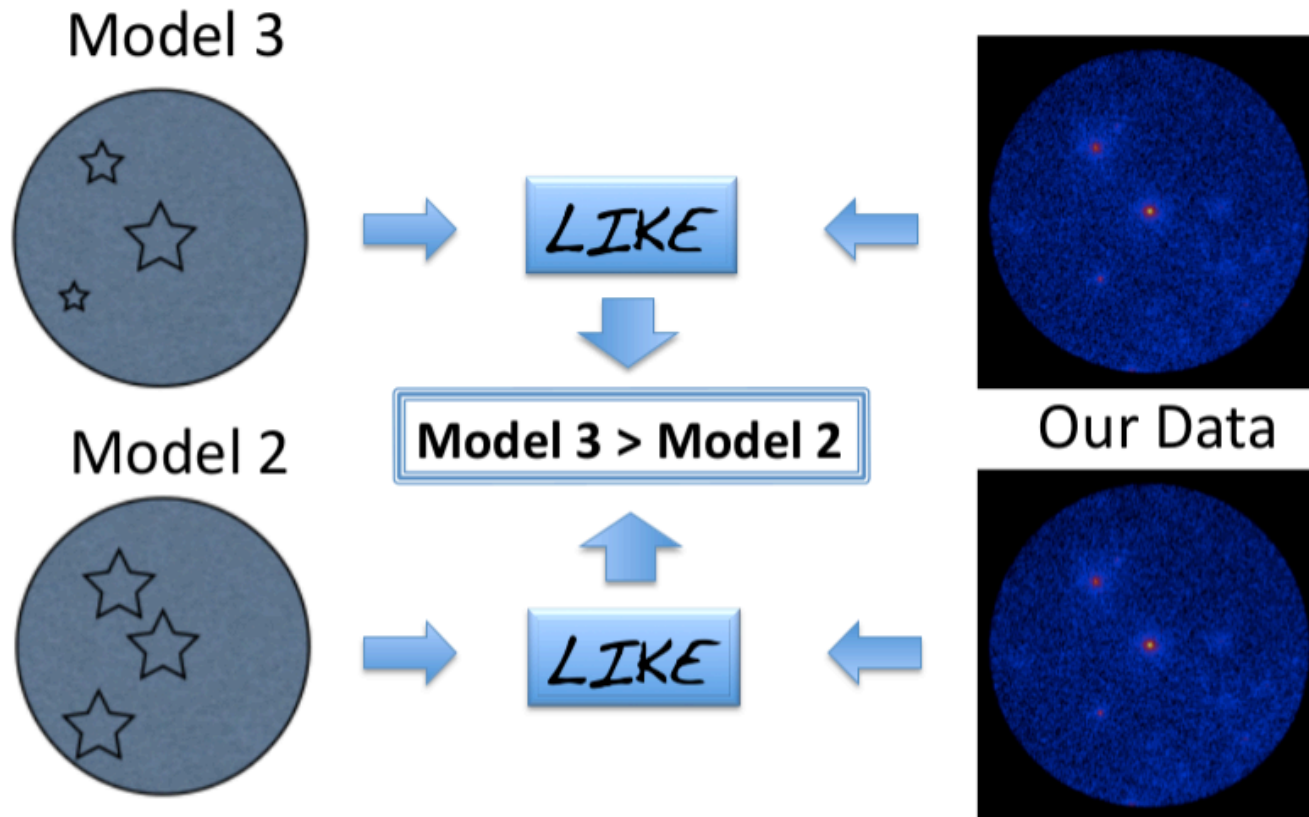
- We use the Likelihood method because the LAT data are limited by statistics, a bright diffuse background and a broad PSF.
- The model construction defines the questions we want to ask which means:
  - It will not answer a question you are not asking (ie. unknown parameters).
- The Likelihood will not 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.

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

## Write $\mathcal{L}$ 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 functions: Effective Area (proj area of the detector \* efficiency), Energy Dispersion, Point Spread Function

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

- 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

$$TS = -2 \log \frac{\mathcal{L}_0}{\mathcal{L}_1} \xrightarrow{N \rightarrow \infty} \chi_{m-h}^2$$

Null hypothesis max likelihood,  $h$  parameters

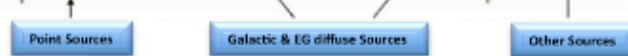
non fixed parameters

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  $\chi_n^2$  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.

## Summarizing

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

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


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

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

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

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

- Adjust the model until this is maximized:

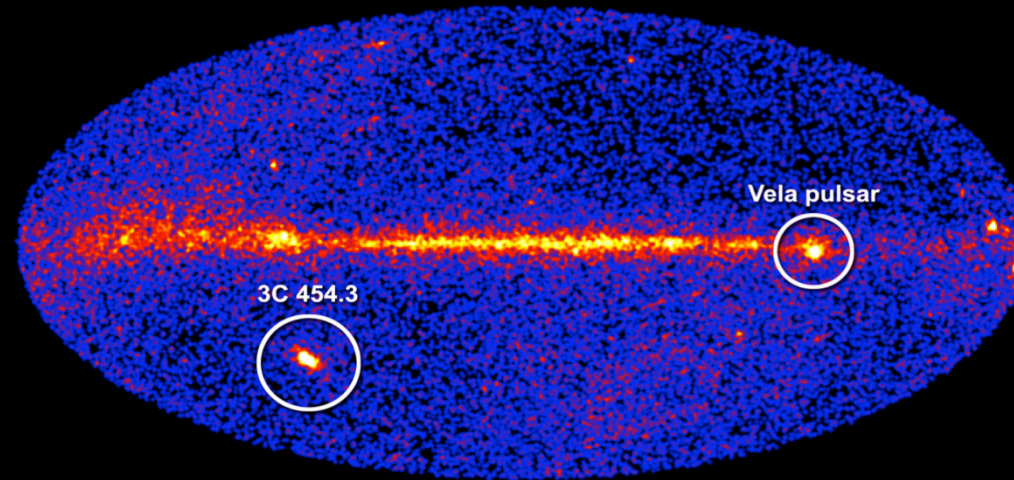
$$\log \mathcal{L} = \sum_j \log M(E'_j, \hat{p}'_j, t_j) - N_{\text{pred}}$$

- Calculate the TS:

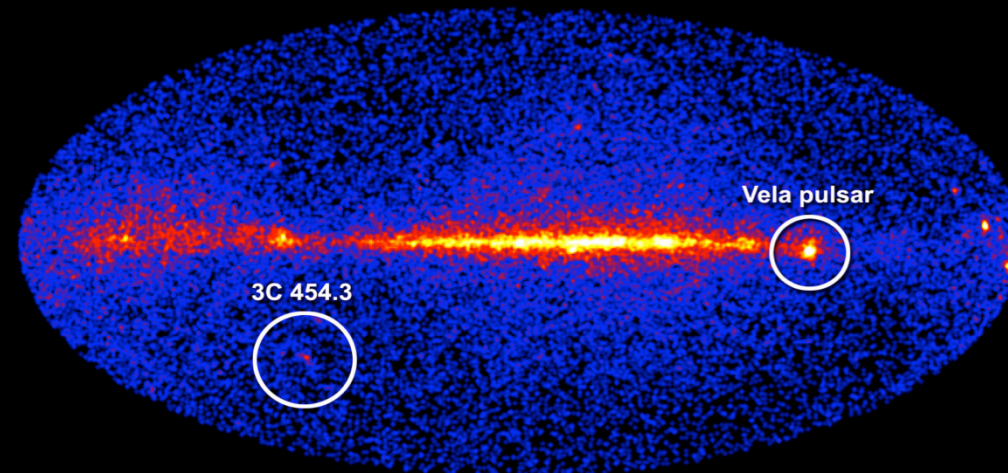
$$\text{TS} = -2 \log \frac{\mathcal{L}_0}{\mathcal{L}_1} \xrightarrow{N \rightarrow \infty} \chi_{m-h}^2$$

# Likelihood Analysis Tutorial

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



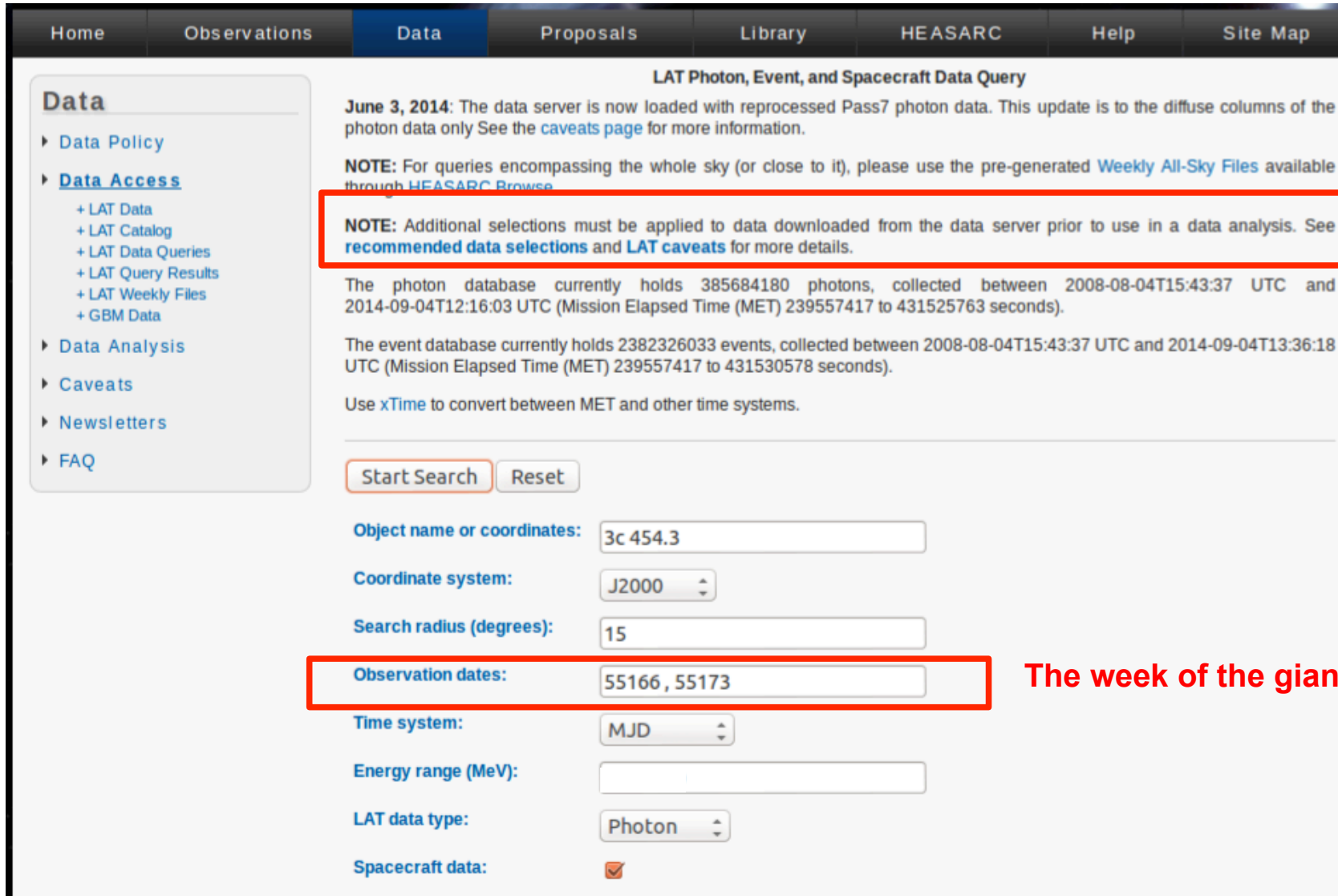
December 2, 2009



November 3, 2009

# How to download data

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



The screenshot shows the 'LAT Photon, Event, and Spacecraft Data Query' web interface. The navigation bar includes 'Home', 'Observations', 'Data' (selected), 'Proposals', 'Library', 'HEASARC', 'Help', and 'Site Map'. A left sidebar contains a 'Data' menu with links for 'Data Policy', 'Data Access' (with sub-links for LAT Data, Catalog, Queries, Results, Weekly Files, and GBM Data), 'Data Analysis', 'Caveats', 'Newsletters', and 'FAQ'. The main content area features a 'NOTE' box with a red border stating: 'NOTE: Additional selections must be applied to data downloaded from the data server prior to use in a data analysis. See recommended data selections and LAT caveats for more details.' Below this, there are search controls: 'Start Search' and 'Reset' buttons, and input fields for 'Object name or coordinates' (3c 454.3), 'Coordinate system' (J2000), 'Search radius (degrees)' (15), 'Observation dates' (55166, 55173), 'Time system' (MJD), 'Energy range (MeV)', 'LAT data type' (Photon), and 'Spacecraft data' (checked).

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)

---

[/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]

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

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]

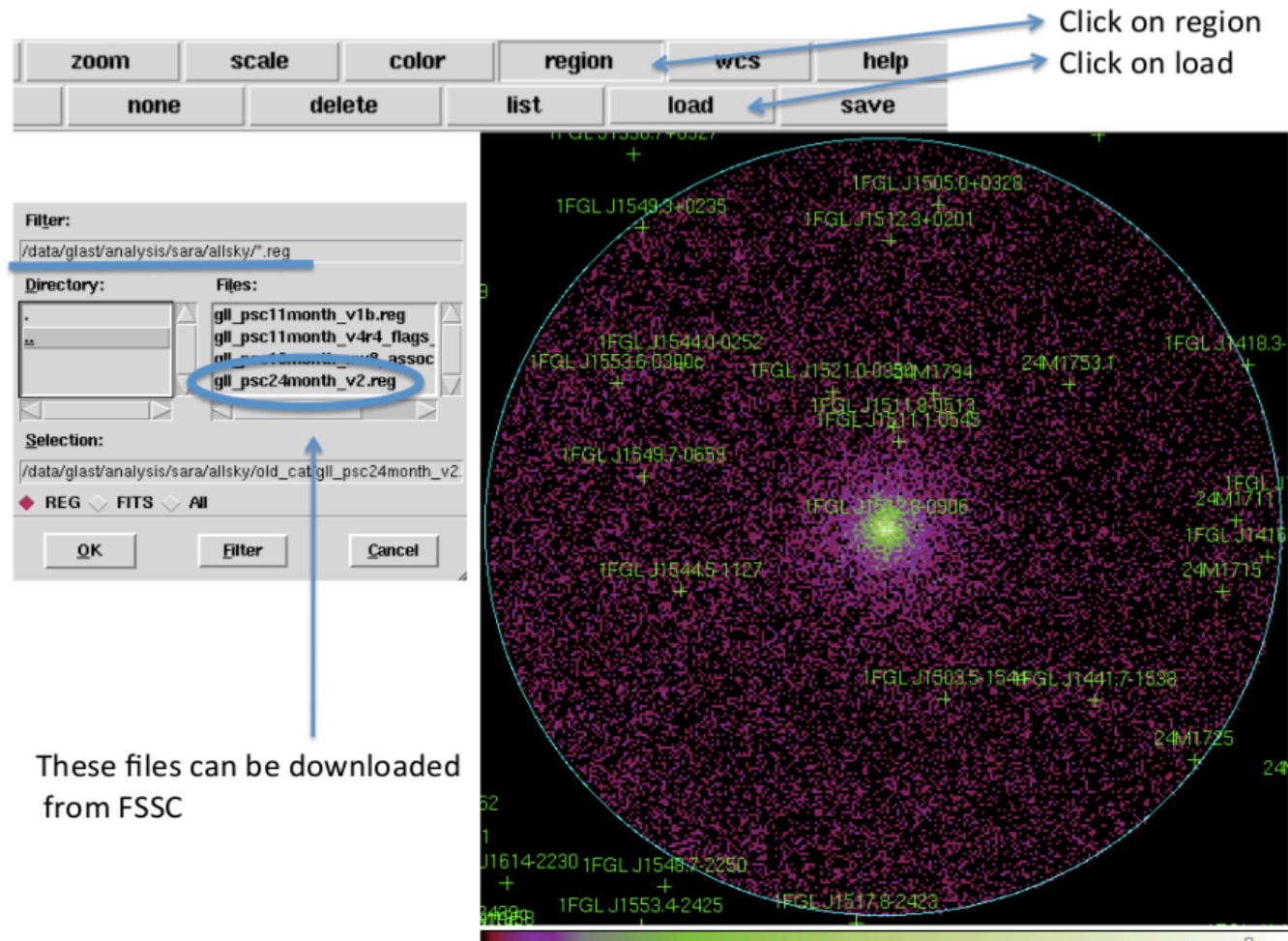
Rotation angle of image axis, in degrees[0]

Projection method e.g. AIT|ARC|CAR|GLS|MERC|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 &



The image shows the DS9 software interface. At the top, there is a menu bar with buttons for zoom, scale, color, region, wcs, and help. Below this is a secondary menu bar with buttons for none, delete, list, load, and save. A file selection dialog is open on the left, showing a directory path and a list of files. The file 'gll\_psc24month\_v2.reg' is selected and circled in blue. A blue arrow points from this file to the 'load' button in the menu bar. Another blue arrow points from the 'region' button to the text 'Click on region'. A third blue arrow points from the 'load' button to the text 'Click on load'. The main window displays a counts map with a circular region of interest (ROI) overlaid. The map shows a dense field of sources, with several labeled with coordinates such as 1FGL J1549.3+0235, 1FGL J1505.0+0328, and 1FGL J1511.6+0513. A color bar at the bottom indicates the intensity scale.

Click on region

Click on load

Filter:  
/data/glast/analysis/sara/allsky/\*.reg

Directory: Files:  
gll\_psc11month\_v1b.reg  
gll\_psc11month\_v4r4\_flags.  
gll\_psc11month\_v8\_assoc.  
gll\_psc24month\_v2.reg

Selection:  
/data/glast/analysis/sara/allsky/old\_cat/gll\_psc24month\_v2.  
REG FITS All

OK Filter Cancel

These files can be downloaded from FSSC

## Likelihood 1st step: gtlcube

---

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

.....

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

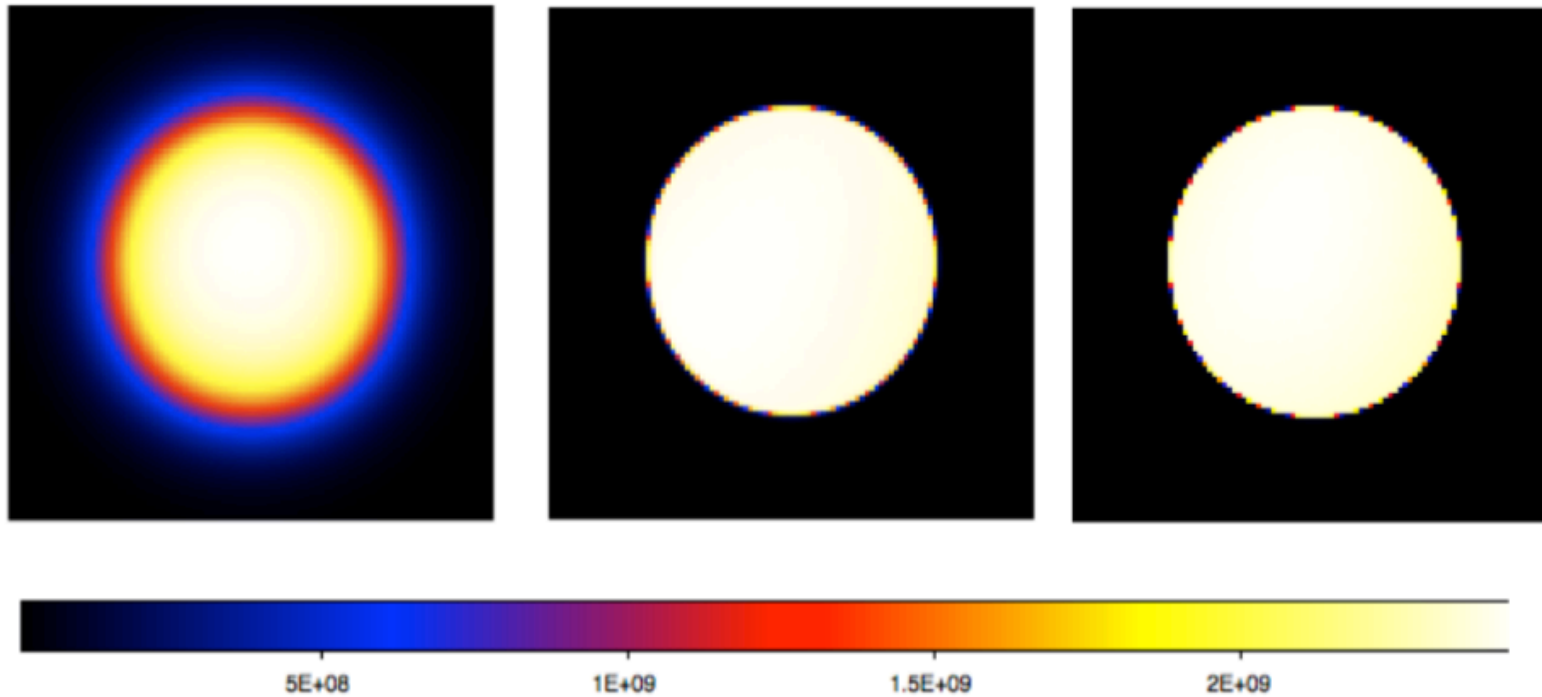
## Likelihood 2nd step: gtexpmap

---

```
[/home/]$ gtexpmap  
Event data file[filtered_gti.fits]  
Spacecraft data file[sc.fits]  
Exposure hypercube file[lcCube.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 lcCube.fits  
...
```

Add 15° to the ROI  
radius

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 3<sup>rd</sup> 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
```

### • Typical source entry for an assumed powerlaw

```
{<source name="....." type="PointSource">...
  </source>
  Your sources here
```

```
<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."/>
    </parameter>
  </parameter>
</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/xml_model_defs.html)

[http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/source\\_models.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/>

## •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[lcCube.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)

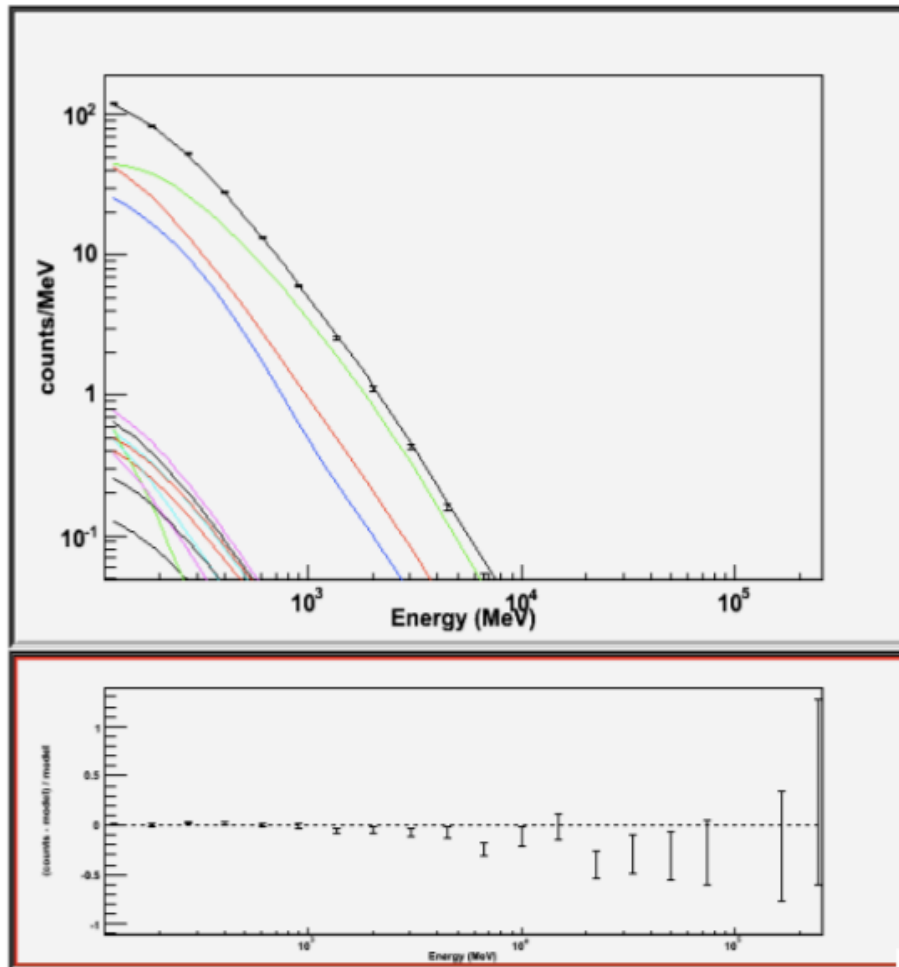
## Likelihood output

```
{'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) 1<sup>st</sup> source (pks1510)

green) 2<sup>nd</sup> source (galactic)

blue) 3<sup>rd</sup> source (istropic)

Magenta) 4<sup>th</sup> source

Cyan) 5<sup>th</sup> source

...