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

PhD course 2021 – Padova

Outline

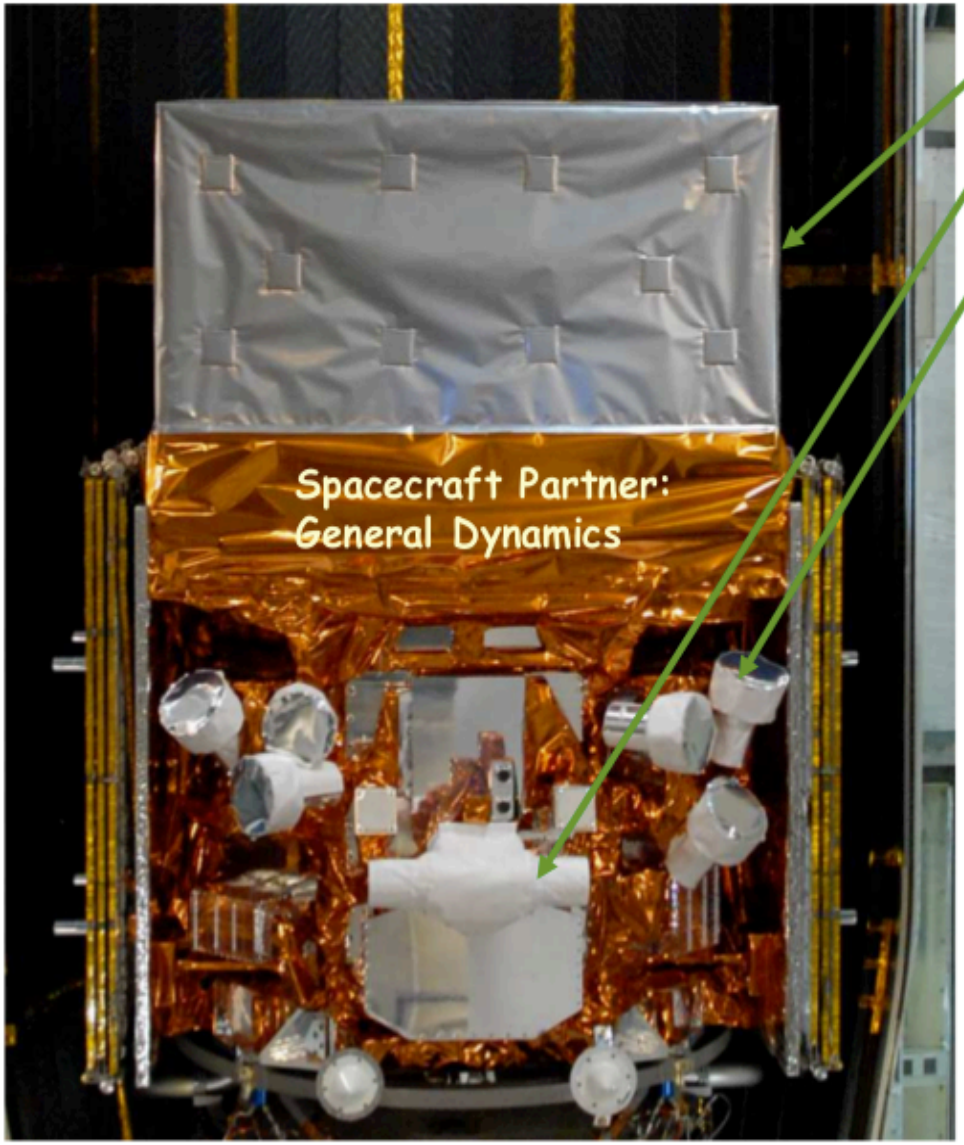
- **Overview of the Fermi Large Area Telescope**
  - How it works
  - LAT data
  - LAT performance
- **Fermi Science Tools**
  - General Introduction
- **Maximum Likelihood Overview**
  - Source modeling
- **One study case:**
  - 3c454.3: Fermipy analysis tutorial
- **gtburst Analysis of GRBs**

Organization

- **Today**
  - Introduction to the LAT data analysis
  - LAT data introduction
  - LAT data exploration & preparation
  - Likelihood analysis of LAT data
  - Description of Sky models
  - Introduction to Fermipy
  - Trouble shooting on SW installation

- **Tomorrow**
  - gtburst fast analysis of GRB
  - fermipy Hands-on on an Extragalactic source
    - SED & Light Curves

The observatory



Large AreaTelescope (LAT)
20 MeV - >300 GeV

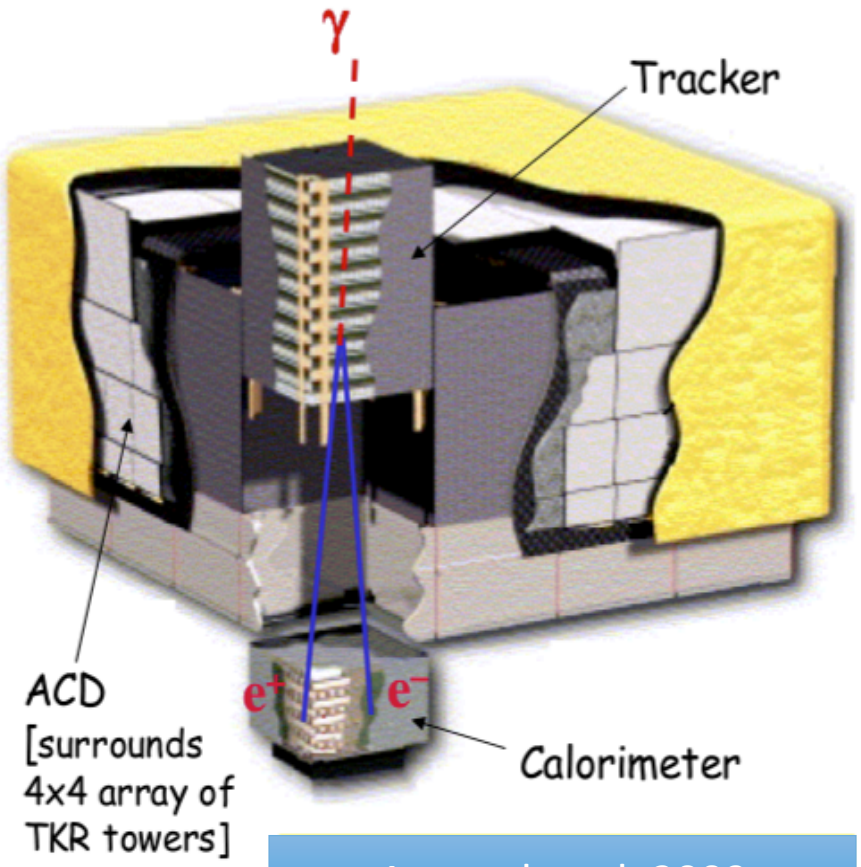
Gamma-ray Burst Monitor (GBM)
NaI and BGO Detectors
8 keV - 30 MeV

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.

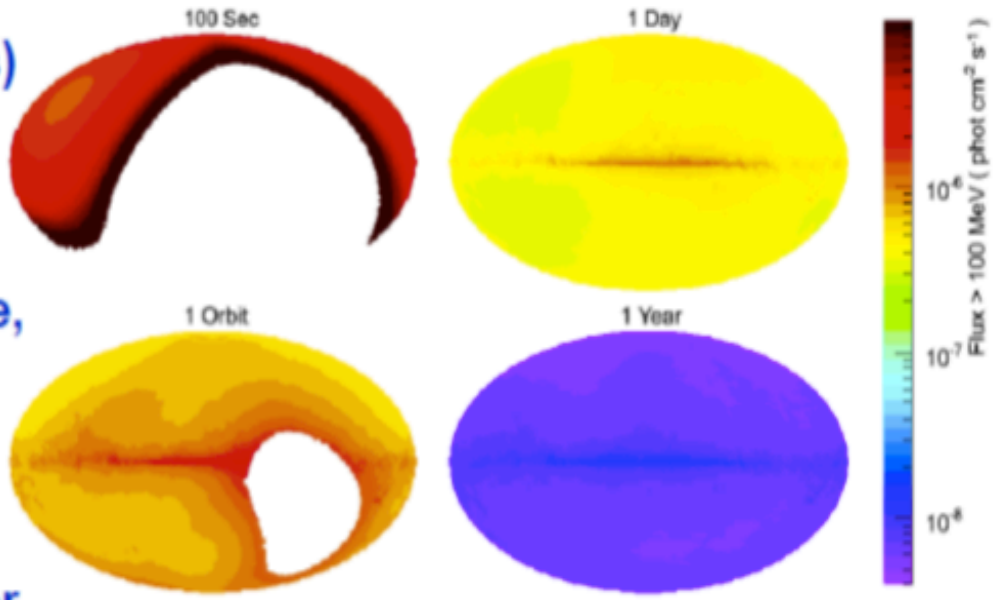


Atwood et al. 2009

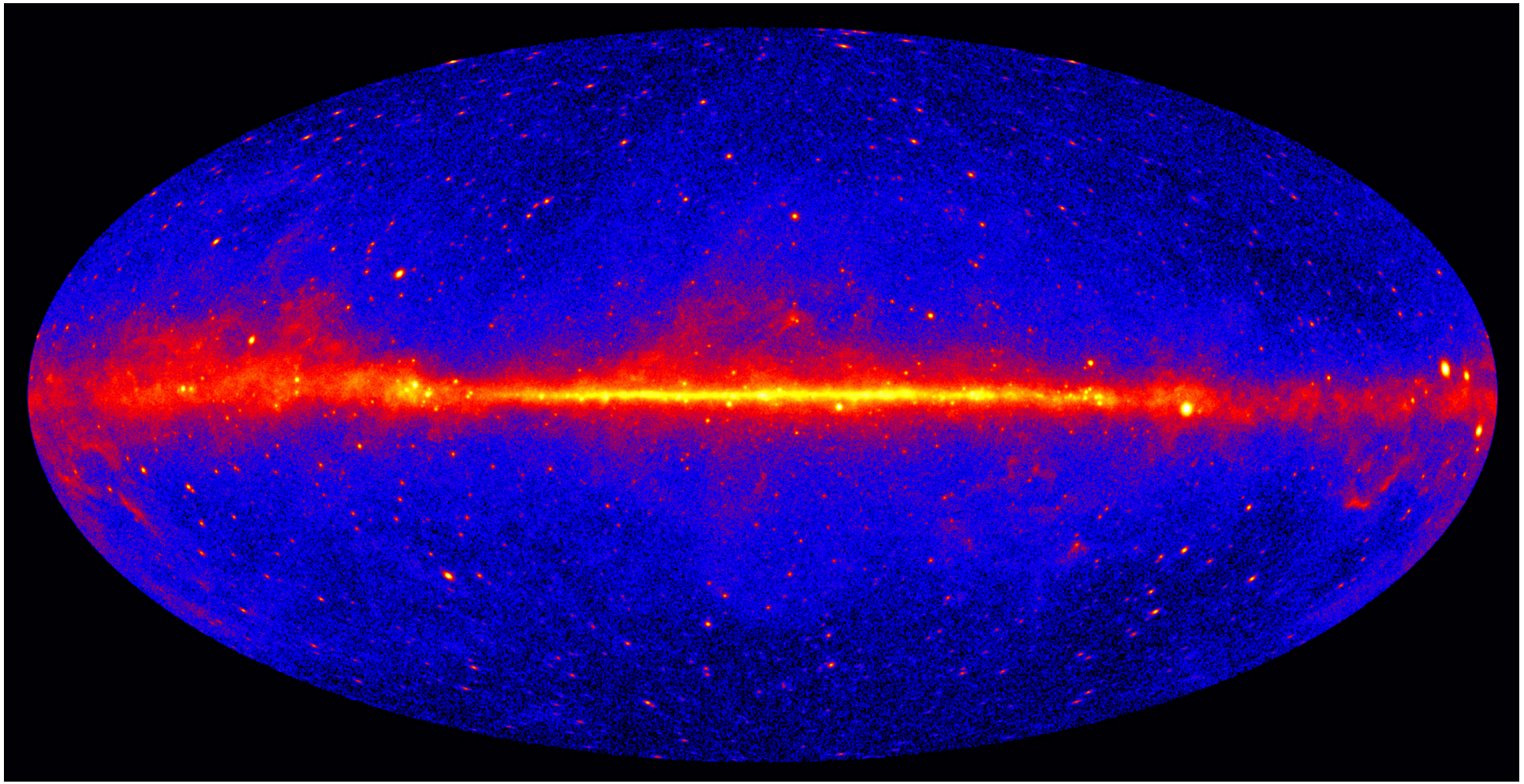
Systems work together to identify and measure the flux of cosmic gamma rays with energy 20 MeV - >300 GeV.

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

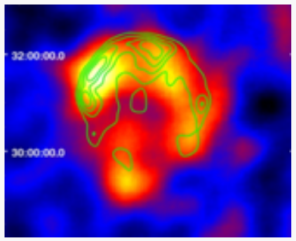


The Fermi Sky



10 years of Fermi !

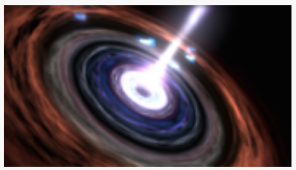
Exploring the Extreme Universe



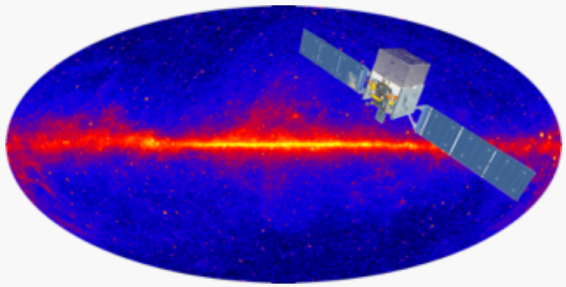
Supernova Remnants

Gamma-ray Bursts

Pulsar Wind Nebulae

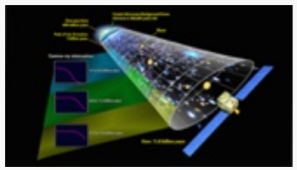


Active Galactic Nuclei

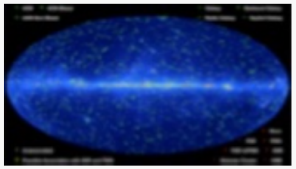


About Fermi

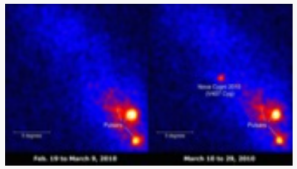
Click on the images or topic name for information about these science topics.



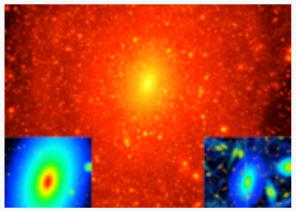
Extragalactic Background



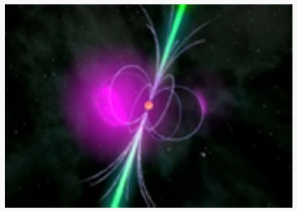
Catalogs



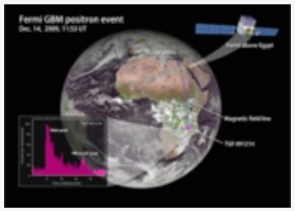
Binary Sources



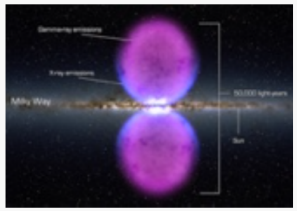
Dark Matter



Pulsars

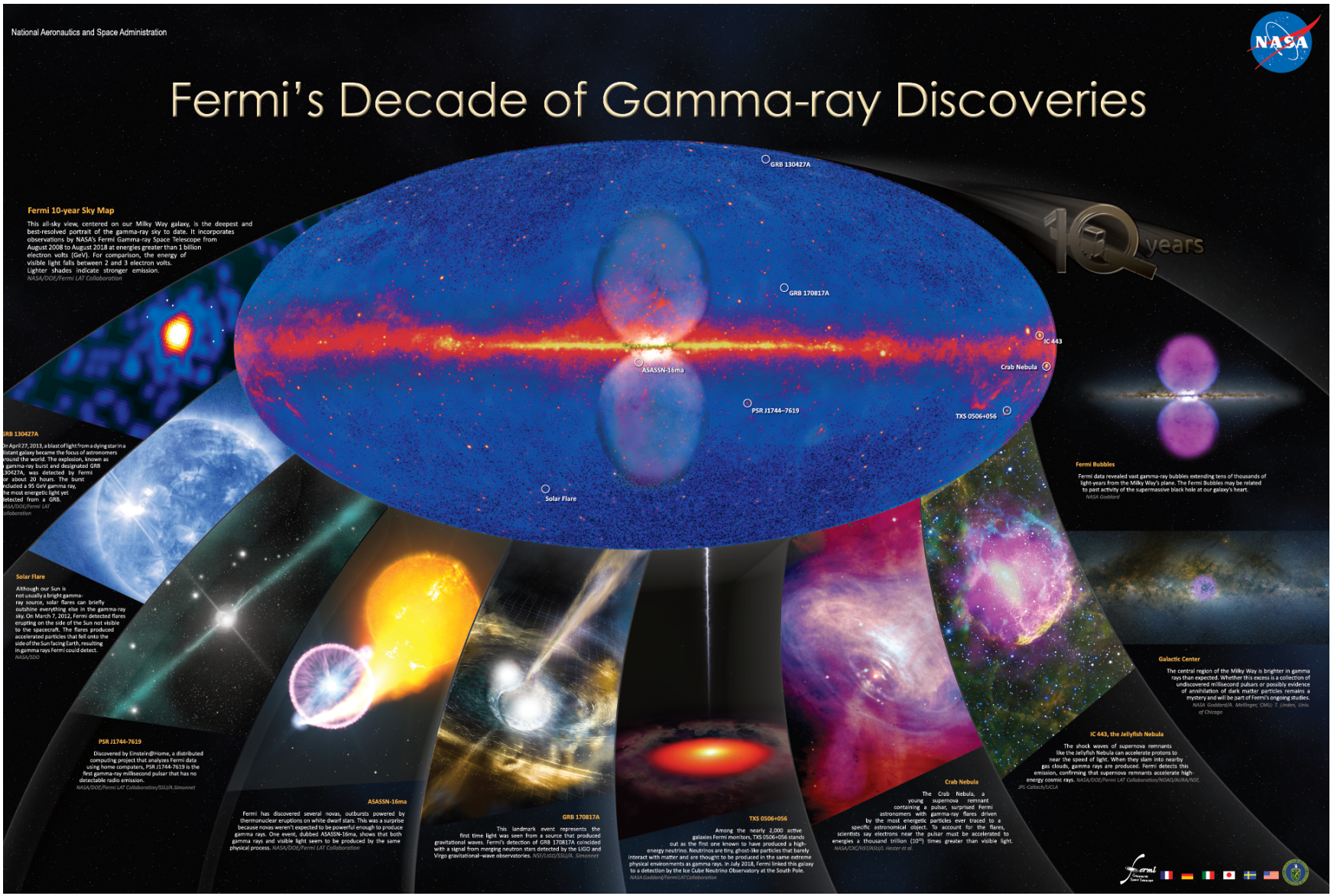


Terrestrial Gamma-ray Flashes

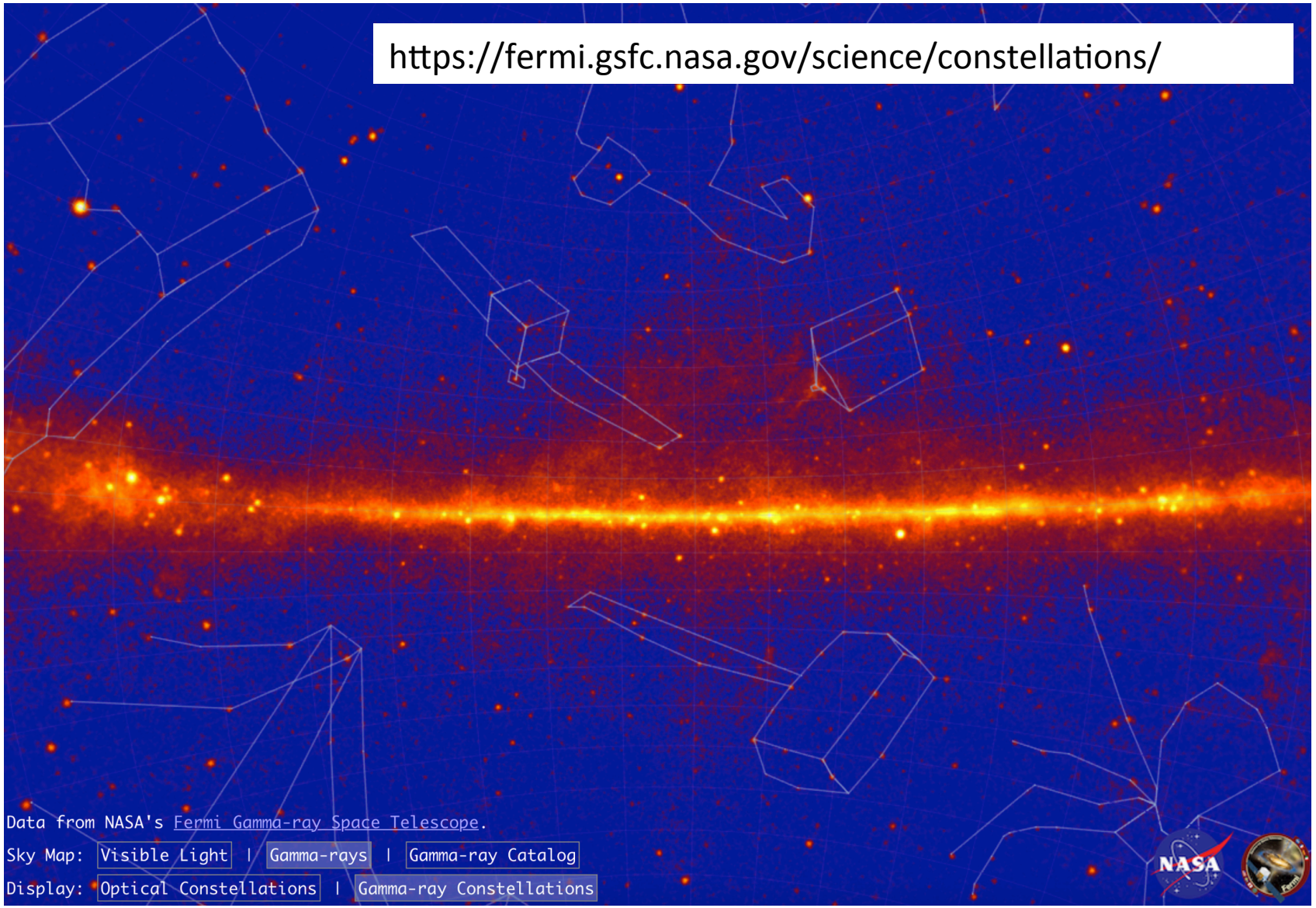


Diffuse Gamma Radiation

10 years of Fermi !



Have Fun !


https://fermi.gsfc.nasa.gov/science/constellations/
Data from NASA's Fermi Gamma-ray Space Telescope.
Sky Map: Visible Light | Gamma-rays | Gamma-ray Catalog
Display: Optical Constellations | Gamma-ray Constellations
NASA

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 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

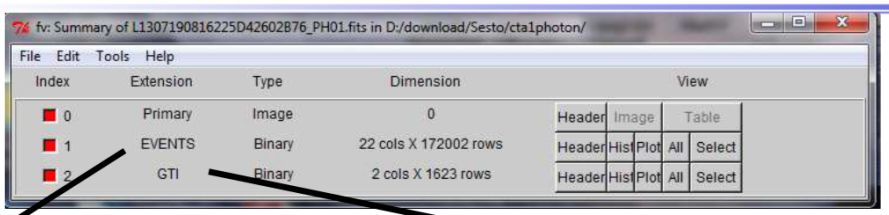
http://fermi.gsfc.nasa.gov/ssc/data/analysis/

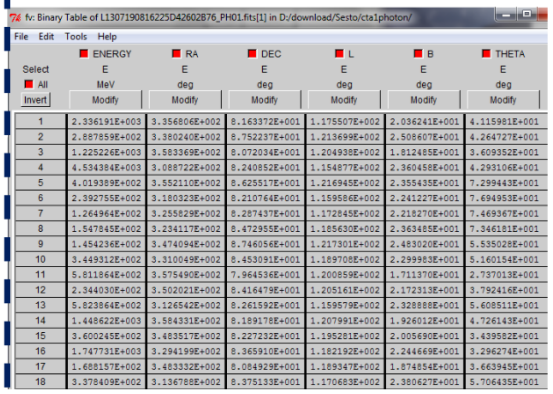
LAT Data

- **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**
  - https://heasarc.gsfc.nasa.gov/FTP/fermi/data/lat/weekly/photon/

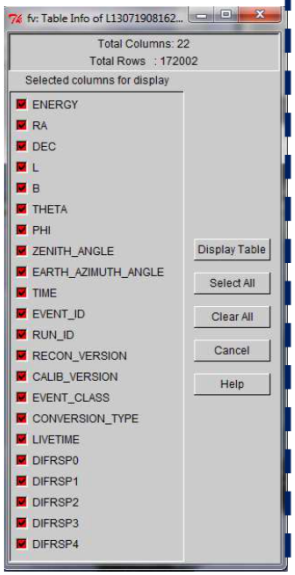
- **Two main data products (stored in FITS format)**
  - **Events file (FT1)**
  - **i. e. "what the LAT sees"**
    - (photons, their energy, coordinates, time, event classes etc..)
  - **Spacecraft files (FT2)**
  - **i. e. "where the LAT is"**
    - (position, angles..)

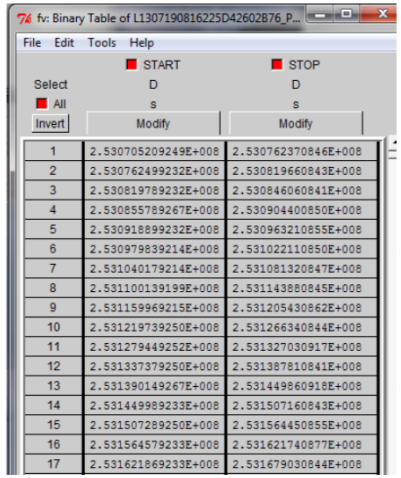
FT1: photons, photons…





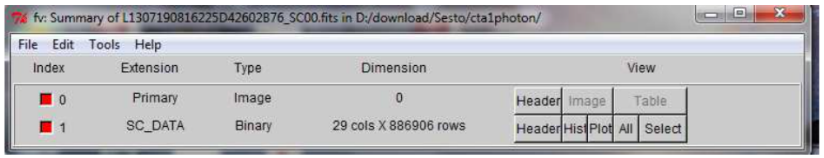
Events





Good Time Intervals (GTIs)

FT2: where is Fermi ?



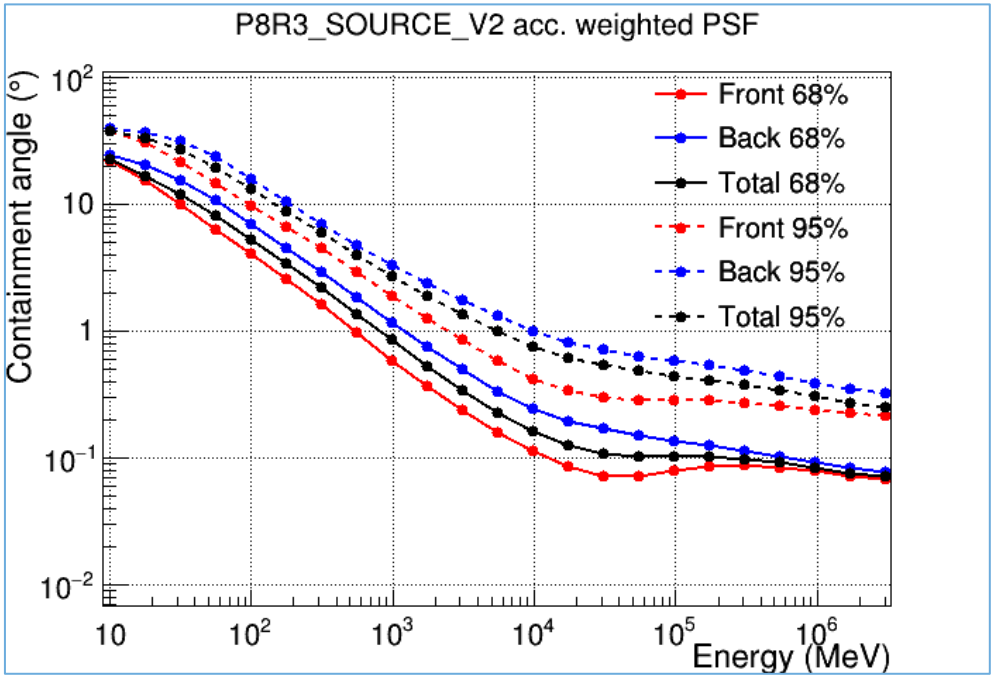
spacecraft Data

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
- https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_LAT_IRFs/IRF_overview.html

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 (4FGL, 3FHL, PSRs, GRB, SNR …)**

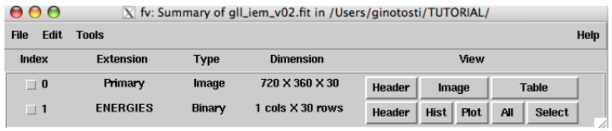
- **Region of Interest model definition (stored in XML files)**
  - More on this later …

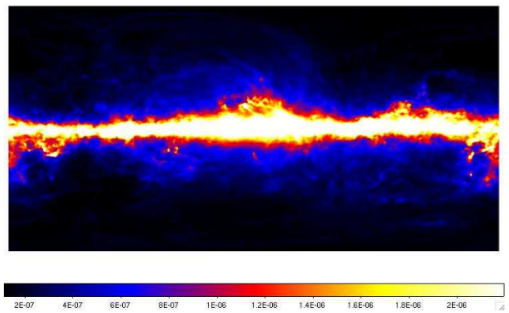
- **Choose the proper combination of**
  - event classes based on the probability of being a photon and background level
    - TRANSIENT (for very short events)
    - SOURCE (suggested for source analysis)
    - CLEAN and ULTRACLEAN (lowest particle contamination – for diffuse sources analysis)
  - Event 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 model (available from this Web page) has been developed, and important caveats on its use, is available **here**. 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_v07.fits (see below for P8R3 usage notes)	Pass 8 Source (front+back, allPSF, allEDISP) P8R3_SOURCE_V3	iso_P8R3_SOURCE_V3_v1.txt
	Pass 8 Source (front only) P8R3_SOURCE_V3::FRONT	iso_P8R3_SOURCE_V3_FRONT_v1.txt
	Pass 8 Source (back only) P8R3_SOURCE_V3::BACK	iso_P8R3_SOURCE_V3_BACK_v1.txt
	Pass 8 Clean (front+back, allPSF, allEDISP) P8R3_CLEAN_V3	iso_P8R3_CLEAN_V3_v1.txt
	Pass 8 Clean (PSF0) P8R3_CLEAN_V3::PSF0	iso_P8R3_CLEAN_V3_PSF0_v1.txt
	Pass 8 Clean (PSF1) P8R3_CLEAN_V3::PSF1	iso_P8R3_CLEAN_V3_PSF1_v1.txt
	Pass 8 Clean (PSF2) P8R3_CLEAN_V3::PSF2	iso_P8R3_CLEAN_V3_PSF2_v1.txt
	Pass 8 Clean (PSF3) P8R3_CLEAN_V3::PSF3	iso_P8R3_CLEAN_V3_PSF3_v1.txt
	Pass 8 Ultraclean (front+back, allPSF, allEDISP) P8R3_ULTRACLEAN_V3	iso_P8R3_ULTRACLEAN_V3_v1.txt

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

LAT catalogs

- LAT catalogs and associated products (high-level products only)
  - LAT Source Catalog
    - LAT 10-year Source Catalog (4FGL-DR2)
    - LAT 8-year Source Catalog (4FGL)
    - Preliminary LAT 8-year Source List (FL8Y)
    - LAT 4-year Source Catalog (3FGL)
    - LAT 2-year Source Catalog (2FGL)
    - LAT 1-year Source Catalog (1FGL)
    - LAT 3-month Bright Source List (0FGL)
  - Aperture Photometry Light Curves
    - Aperture Photometry Light Curves for LAT 10-year Catalog Sources (Updated Weekly)
    - Flaring Sources in the LAT 10-year Aperture Photometry Light Curves (Updated Weekly)
    - Aperture Photometry Light Curves for LAT 4-year Catalog Sources
    - Flaring Sources in the LAT 4-year Aperture Photometry Light Curves
    - Aperture Photometry Light Curves for the LAT 2-year 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)
  - The Fourth Catalog of Active Galactic Nuclei -- Data Release 2 (4LAC-DR2)
  - The Fourth Catalog of Active Galactic Nuclei (4LAC)
  - LAT Monitored Source List Light Curves
  - LAT GRB 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

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

Pass8 data

New Pass8 data

Fermi
Science Support Center

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Data

- Data Policy
- Data Access
- **Data Analysis**
  - + System Overview
  - + Software Download
  - + Documentation
  - + Cicerone
  - + Analysis Threads
  - + User Contributions
- Caveats
- Newsletters
- FAQ

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.

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

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

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.

Caveats

Caveats About Analyzing LAT Pass 8 (P8R3) Data

These caveats are relevant for the P8R3 version of the Pass 8 photon dataset. They supersede the set of caveats for analysis of the previous version of Pass 8 (P8R2), 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 P8R3_V2 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

Energy Range

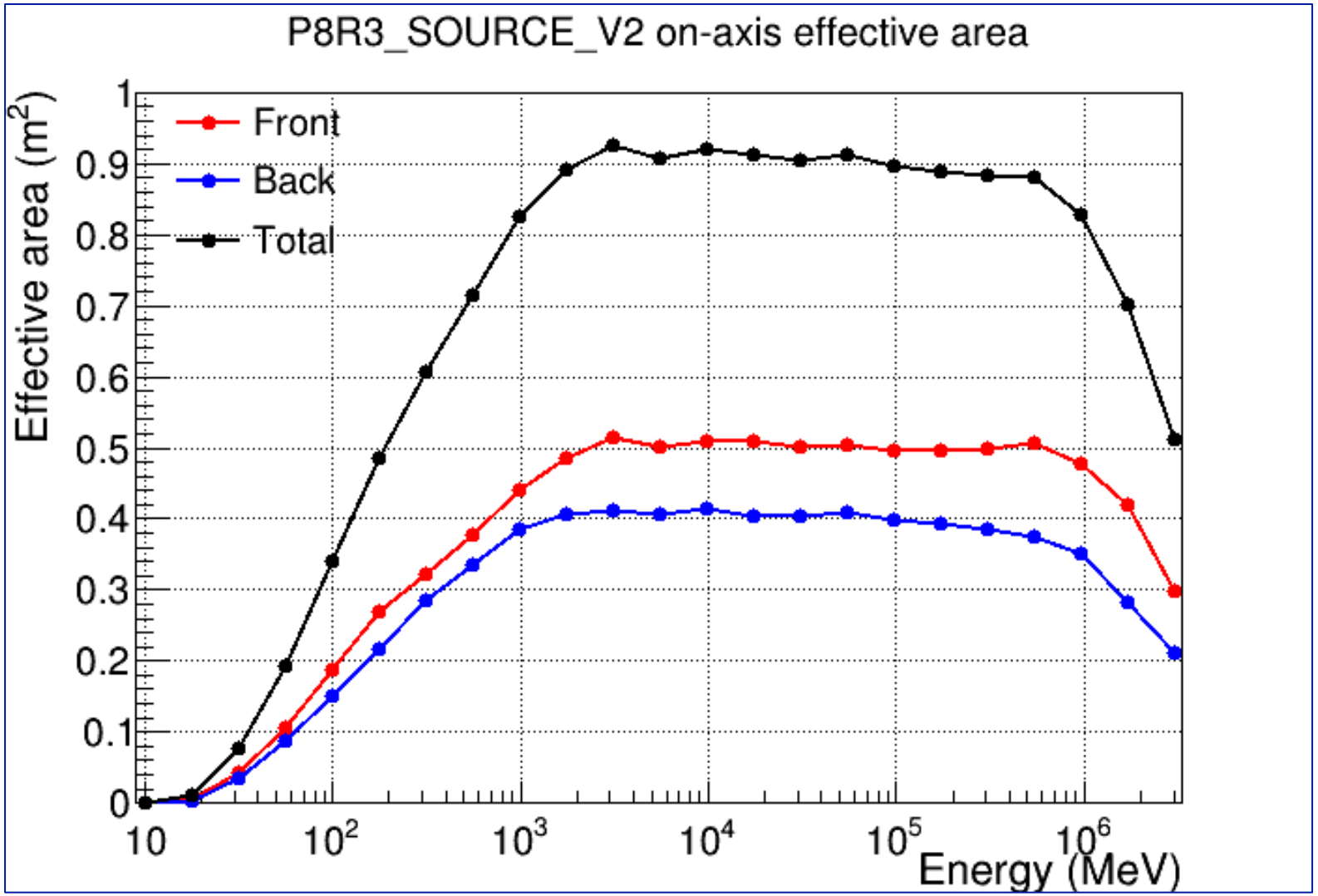
Either because the disagreement between data and the IRFs prediction is too large or because the validation process was hampered by lack of statistics, using data below 30 MeV or above 1 TeV is strongly discouraged. The effect of energy dispersion is particularly large below 100 MeV where there is a non-negligible positive bias in the LAT energy reconstruction. Therefore it is highly recommended to take into account energy dispersion (see the Pass 8 analysis and energy dispersion page) when analyzing data below 300 MeV, and required below 100 MeV.

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

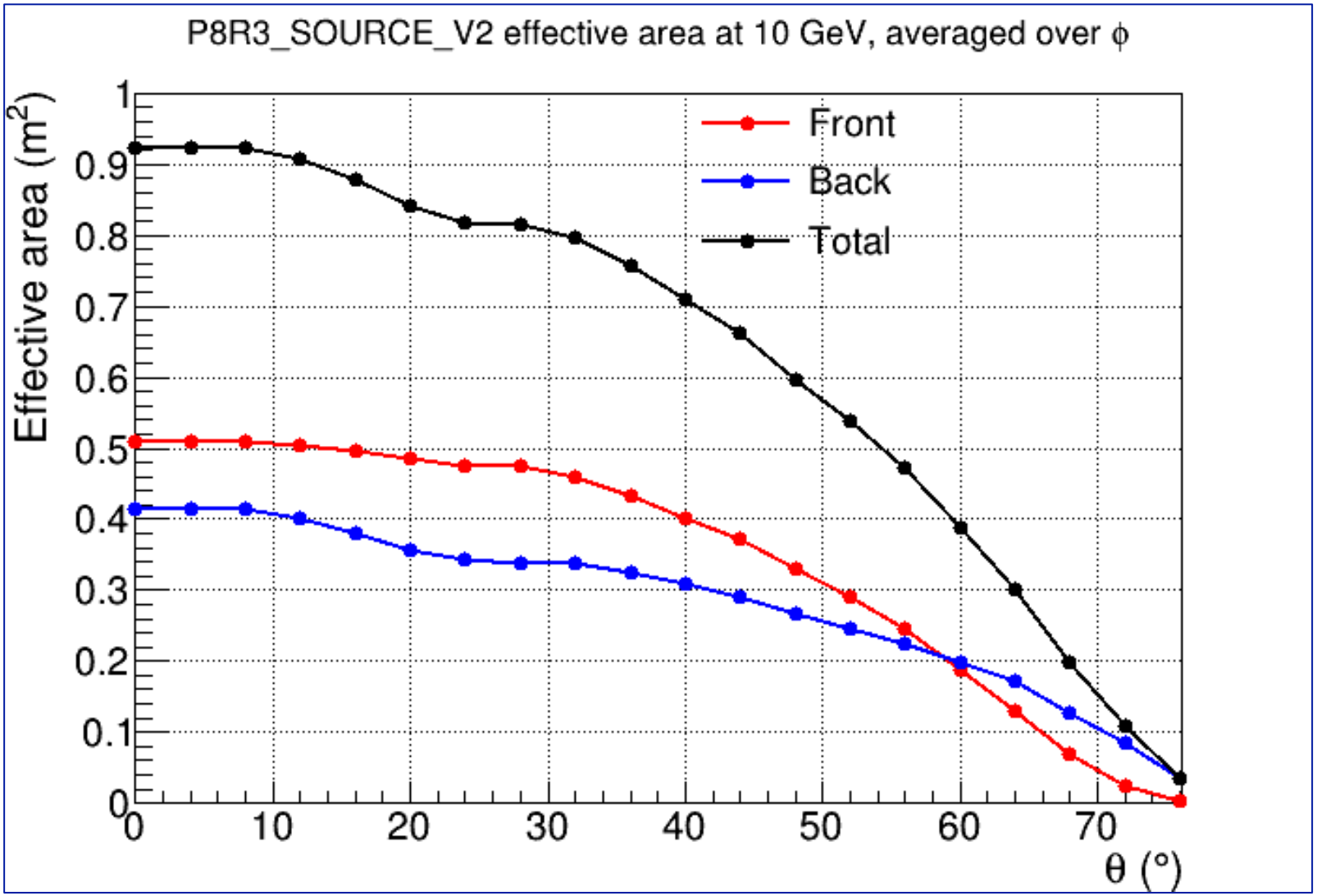
Pass8 performance

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

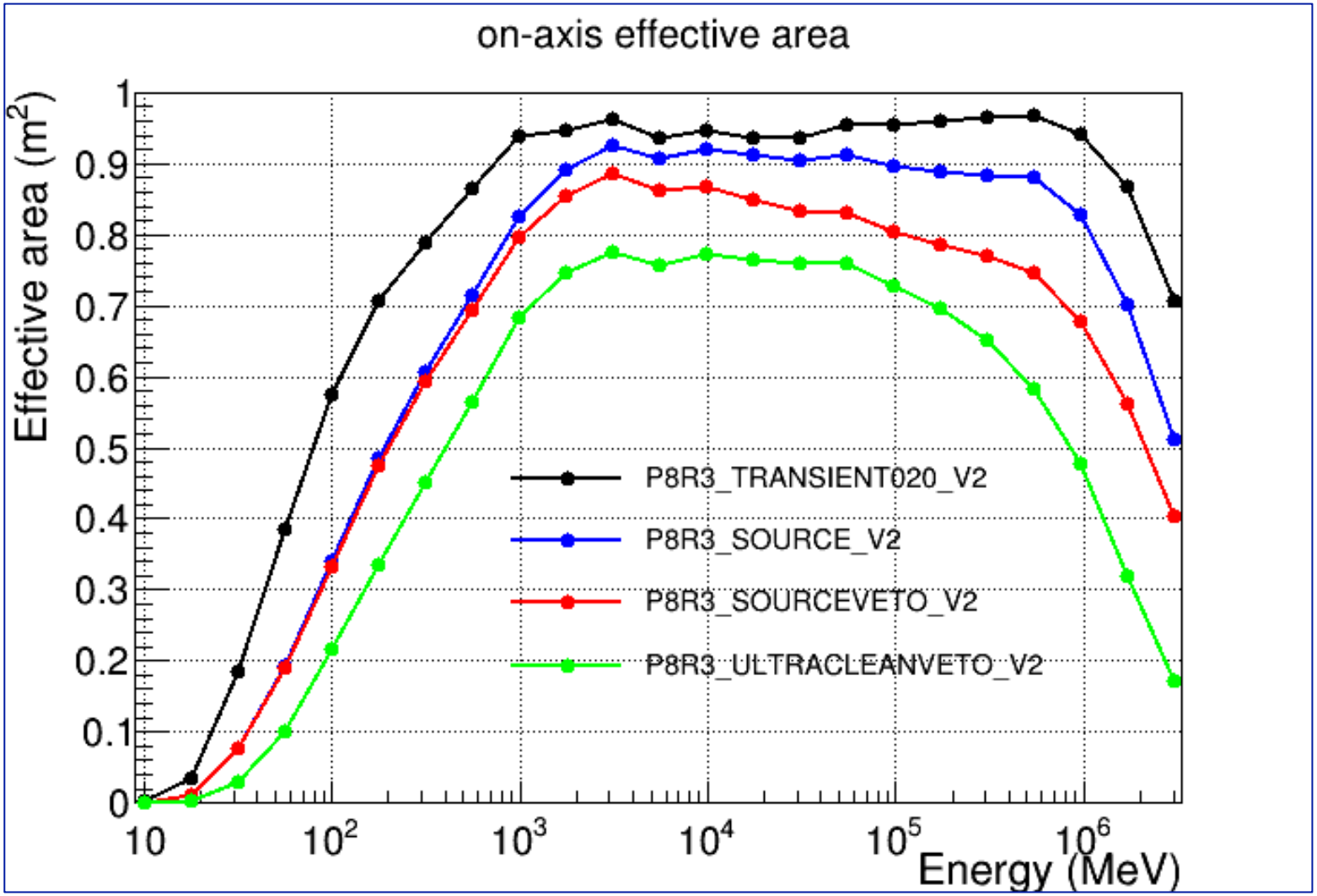
Effective Area



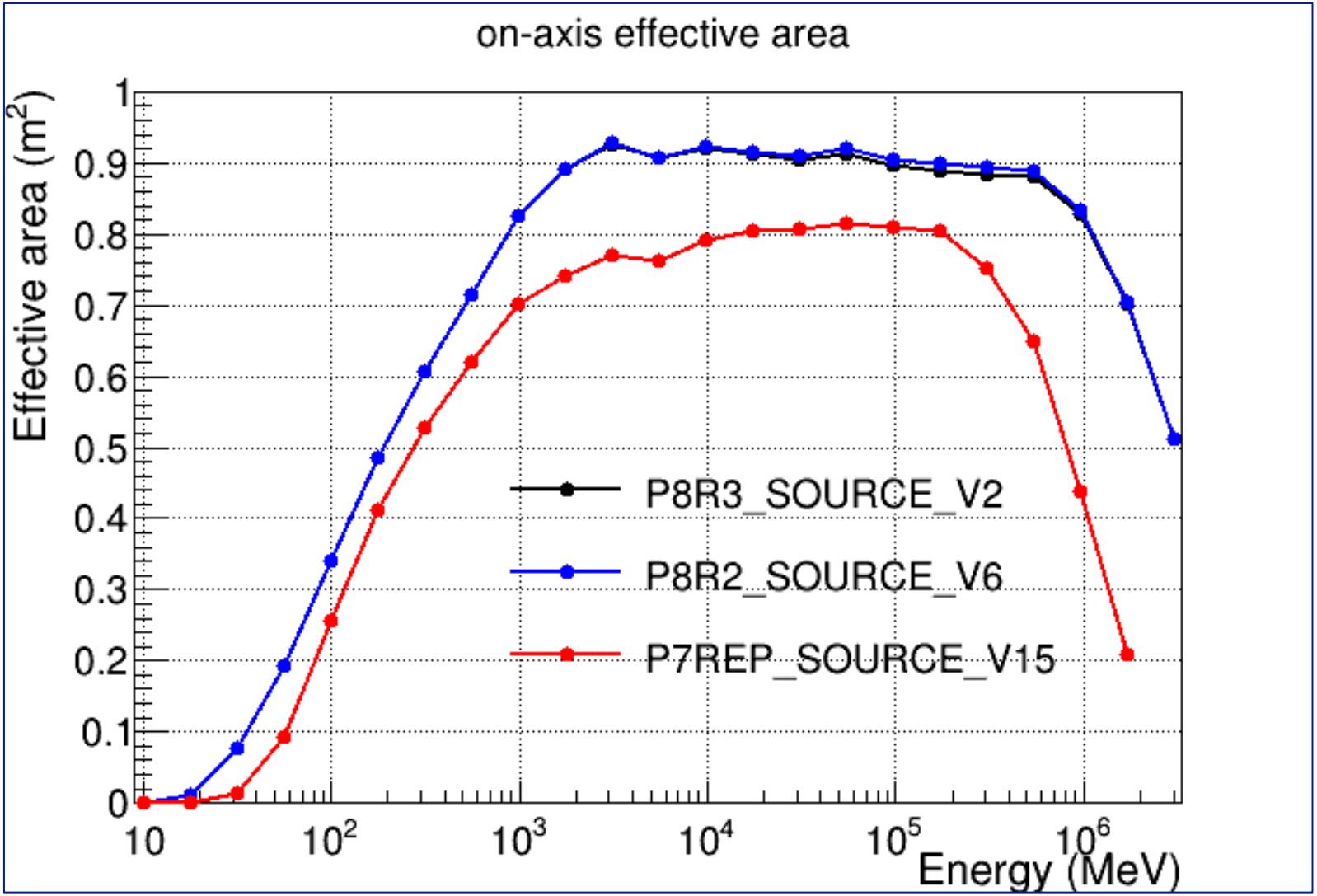
Pass8 Effective Area



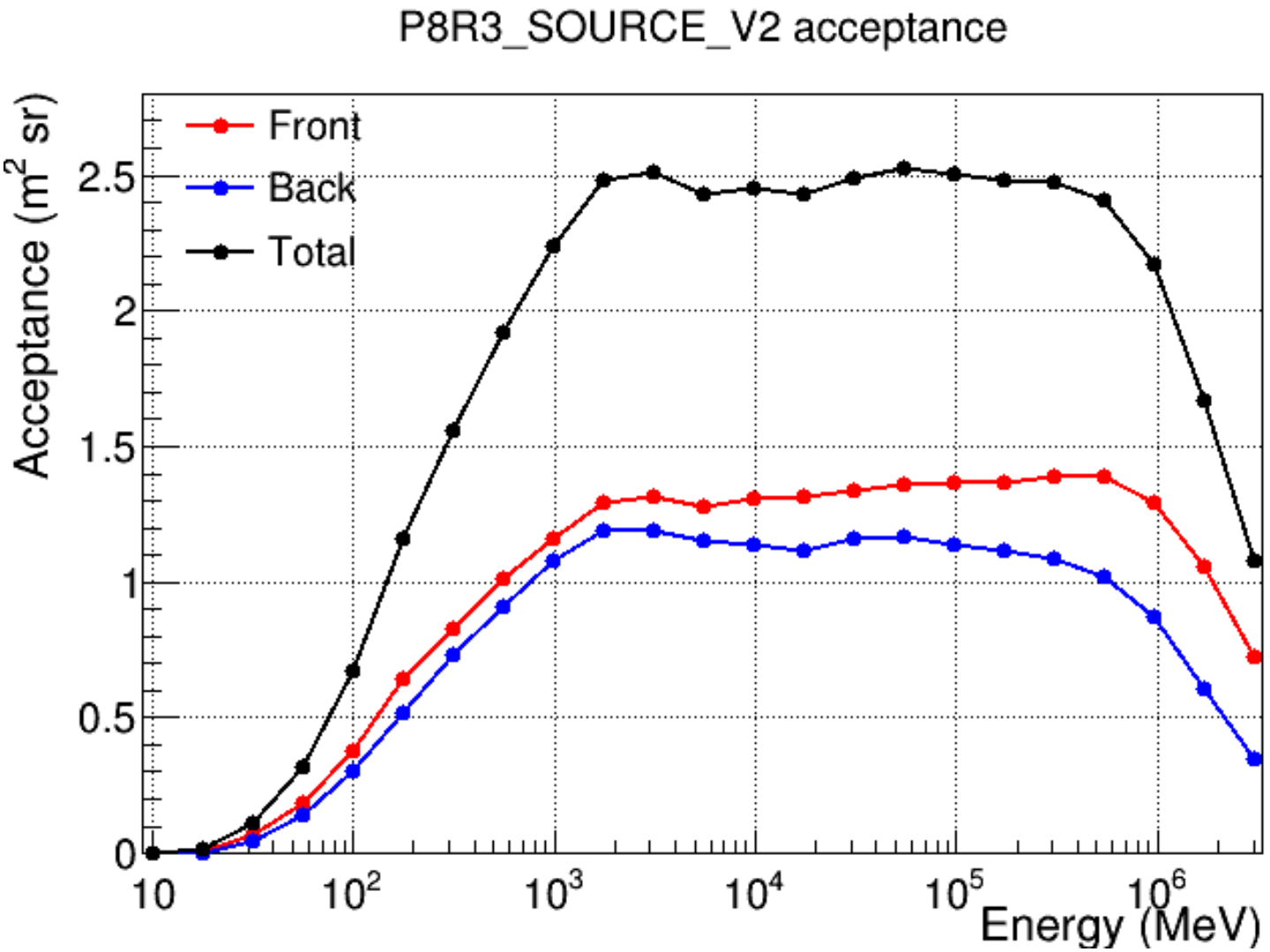
Effective Area



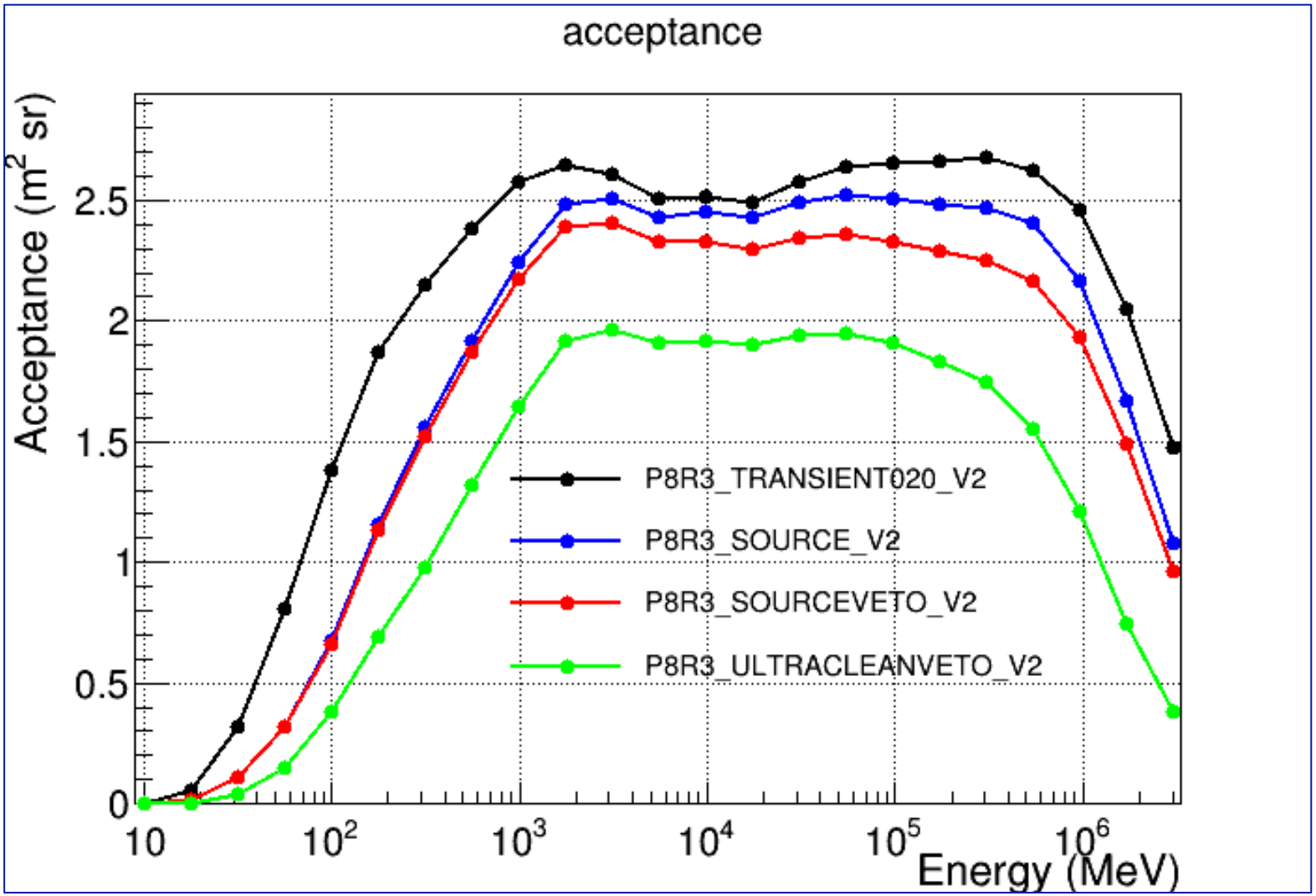
Effective Area



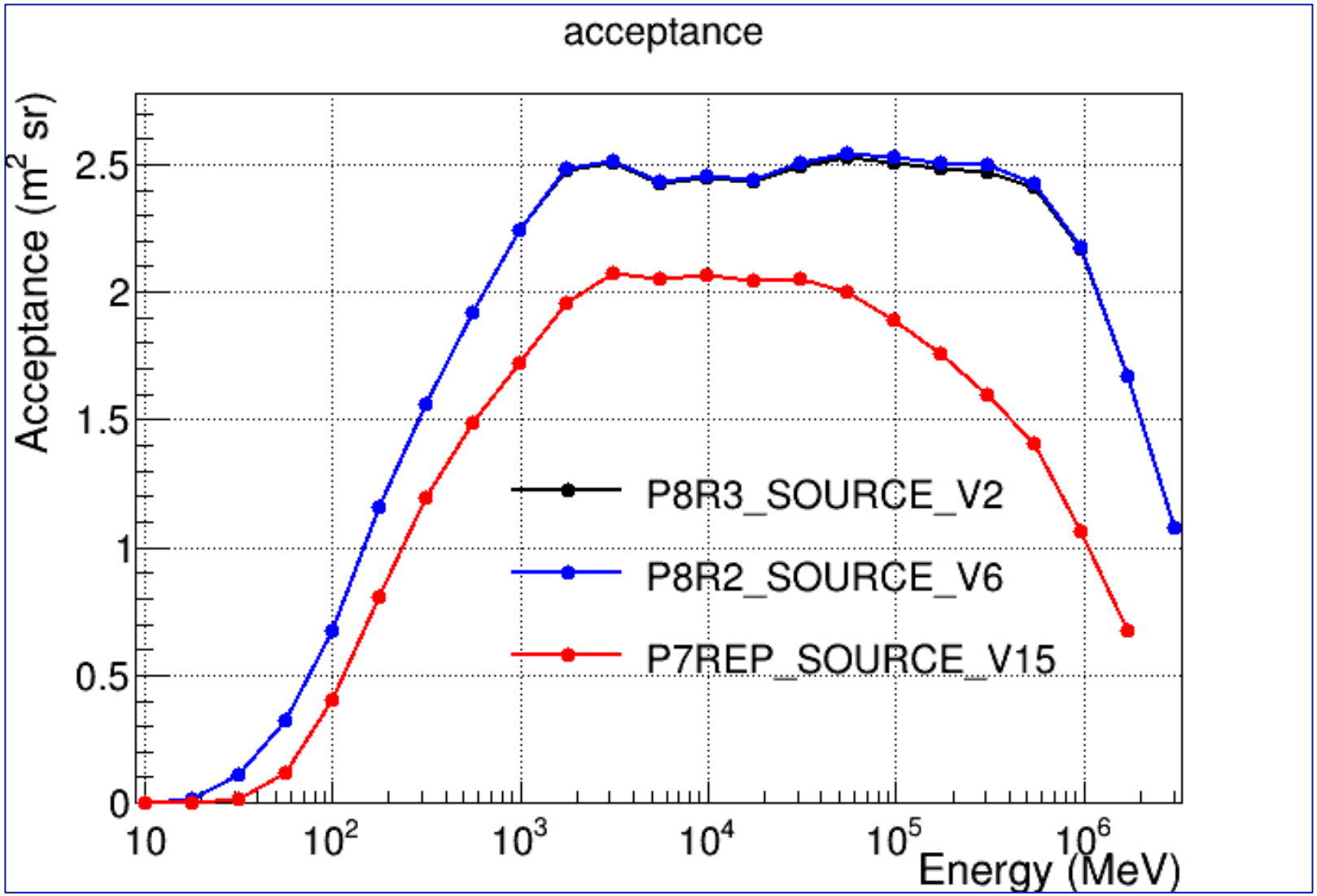
Acceptance


P8R3_SOURCE_V2 acceptance
Front
Back
Total
Acceptance (m² sr)
2.5
2
1.5
1
0.5
0
10
10²
10³
10⁴
10⁵
10⁶
Energy (MeV)

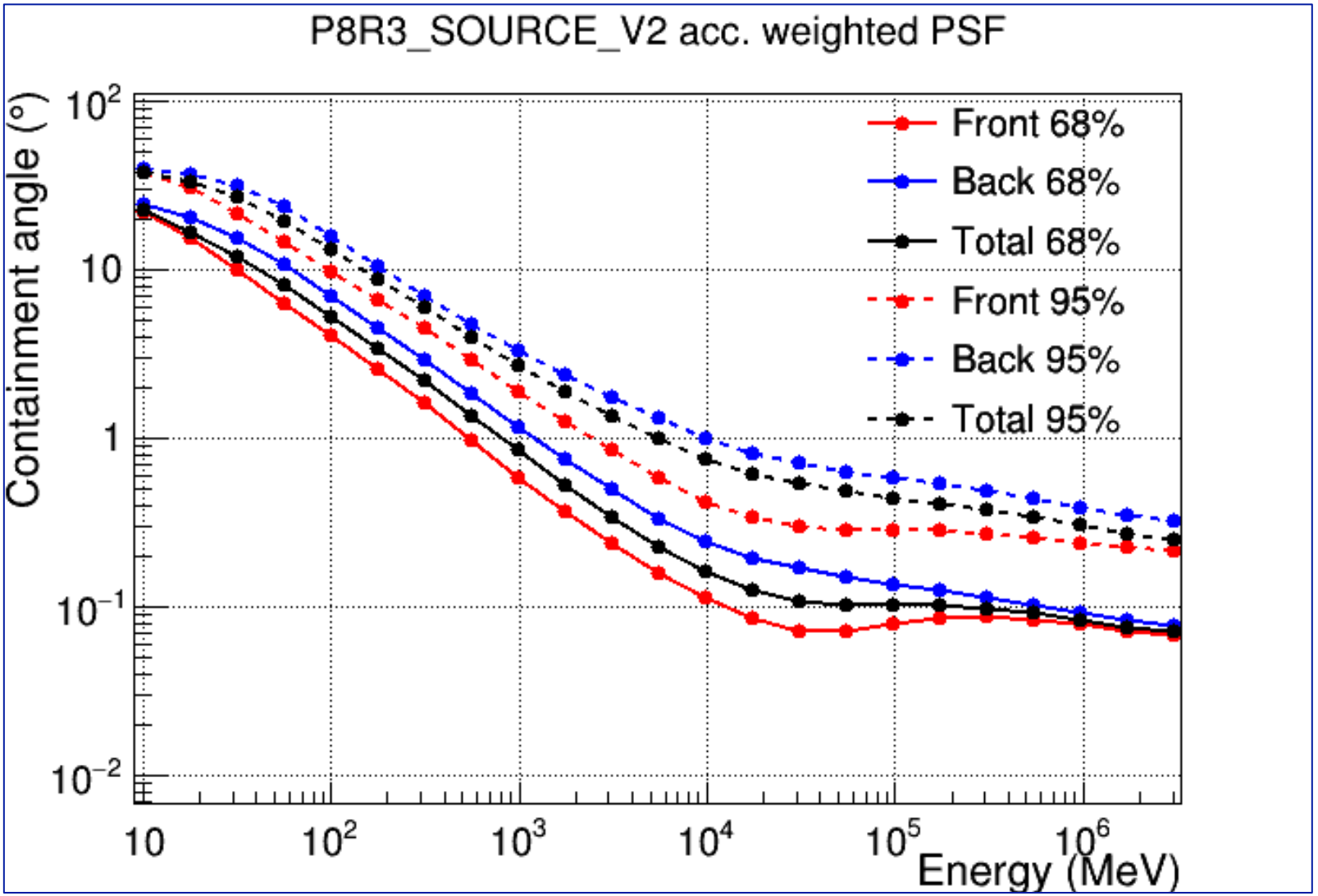
Acceptance


acceptance
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)
P8R3_TRANSIENT020_V2
P8R3_SOURCE_V2
P8R3_SOURCEVETO_V2
P8R3_ULTRACLEANVETO_V2

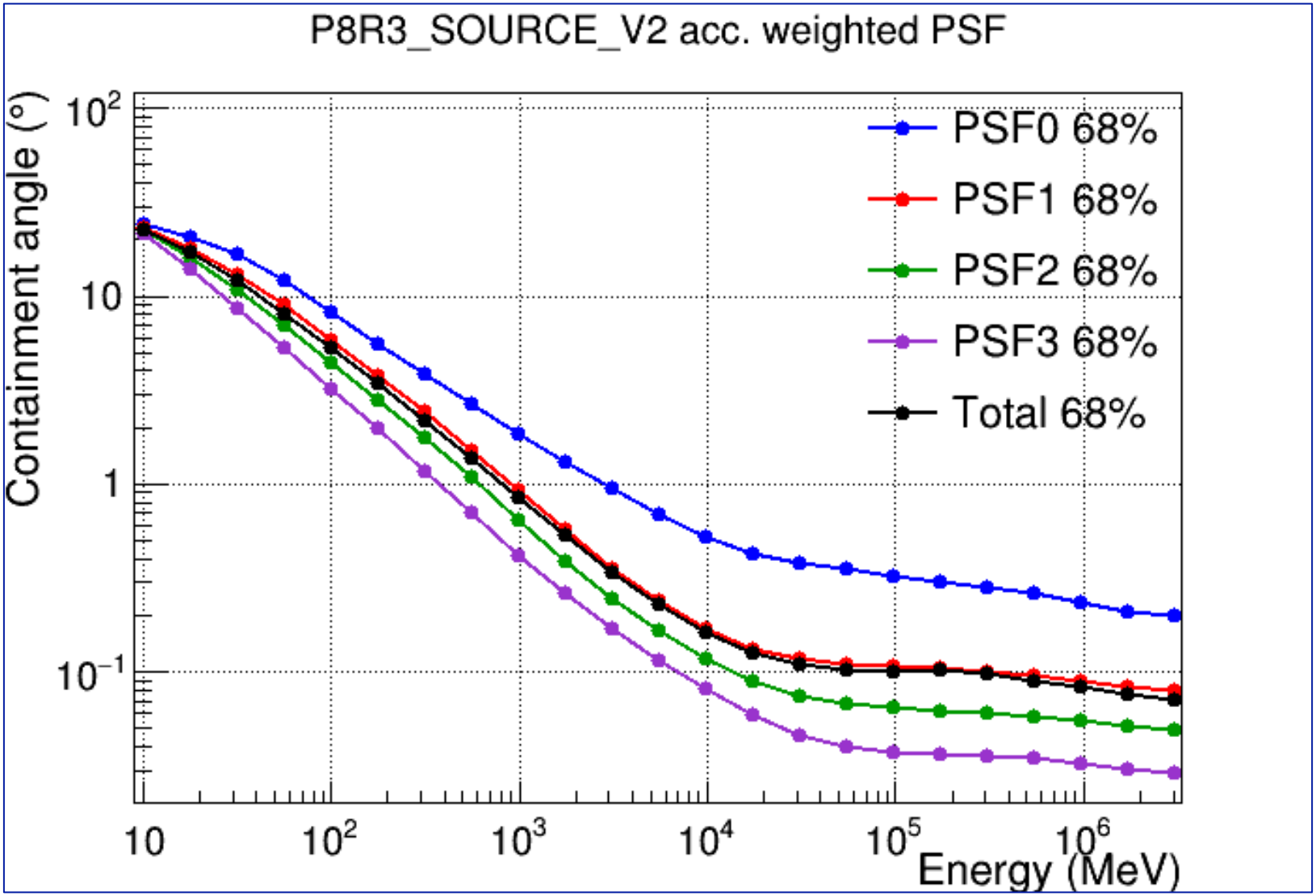
Acceptance


acceptance
Acceptance (m² sr)
2.5
2
1.5
1
0.5
0
10
10²
10³
10⁴
10⁵
10⁶
Energy (MeV)
P8R3_SOURCE_V2
P8R2_SOURCE_V6
P7REP_SOURCE_V15

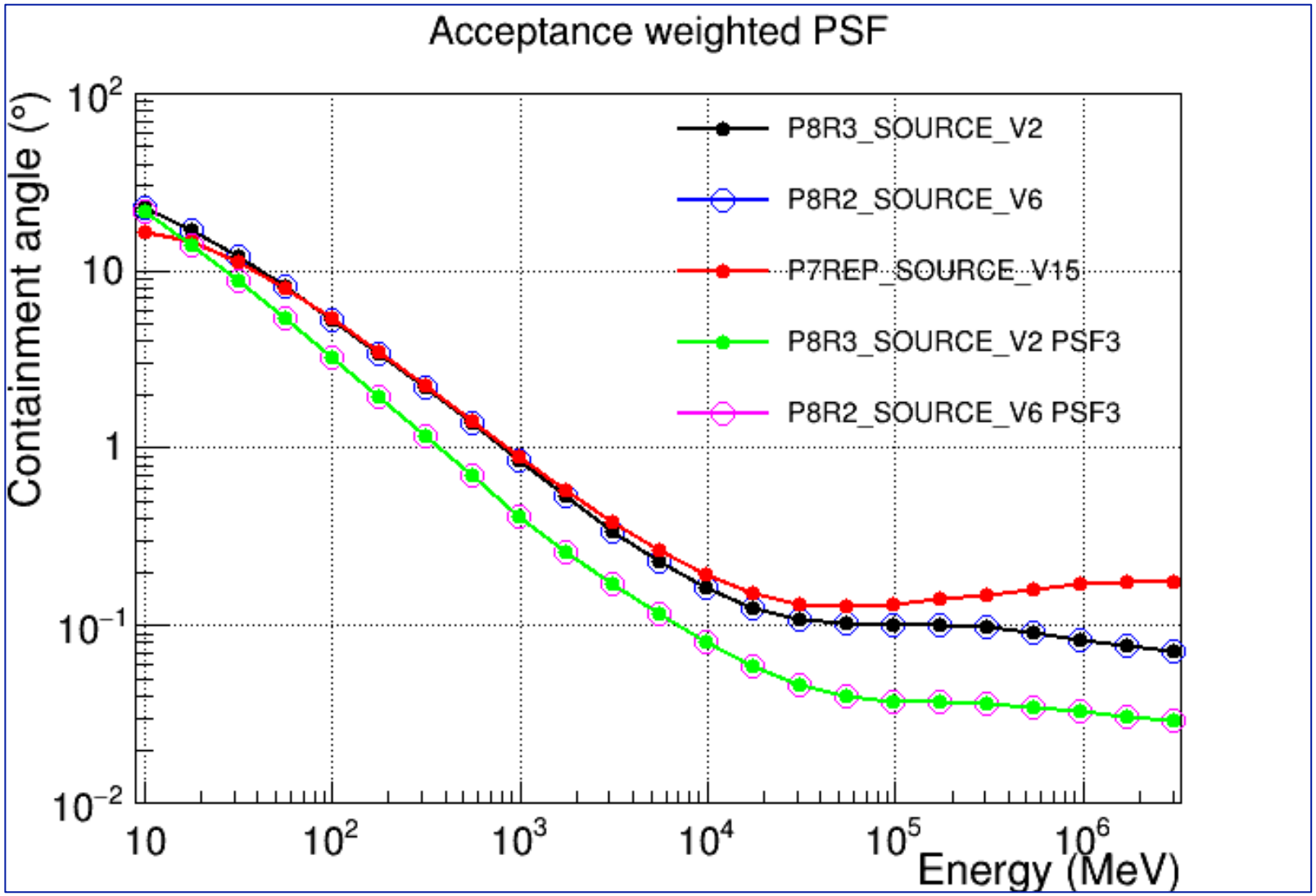
Point Spread Function



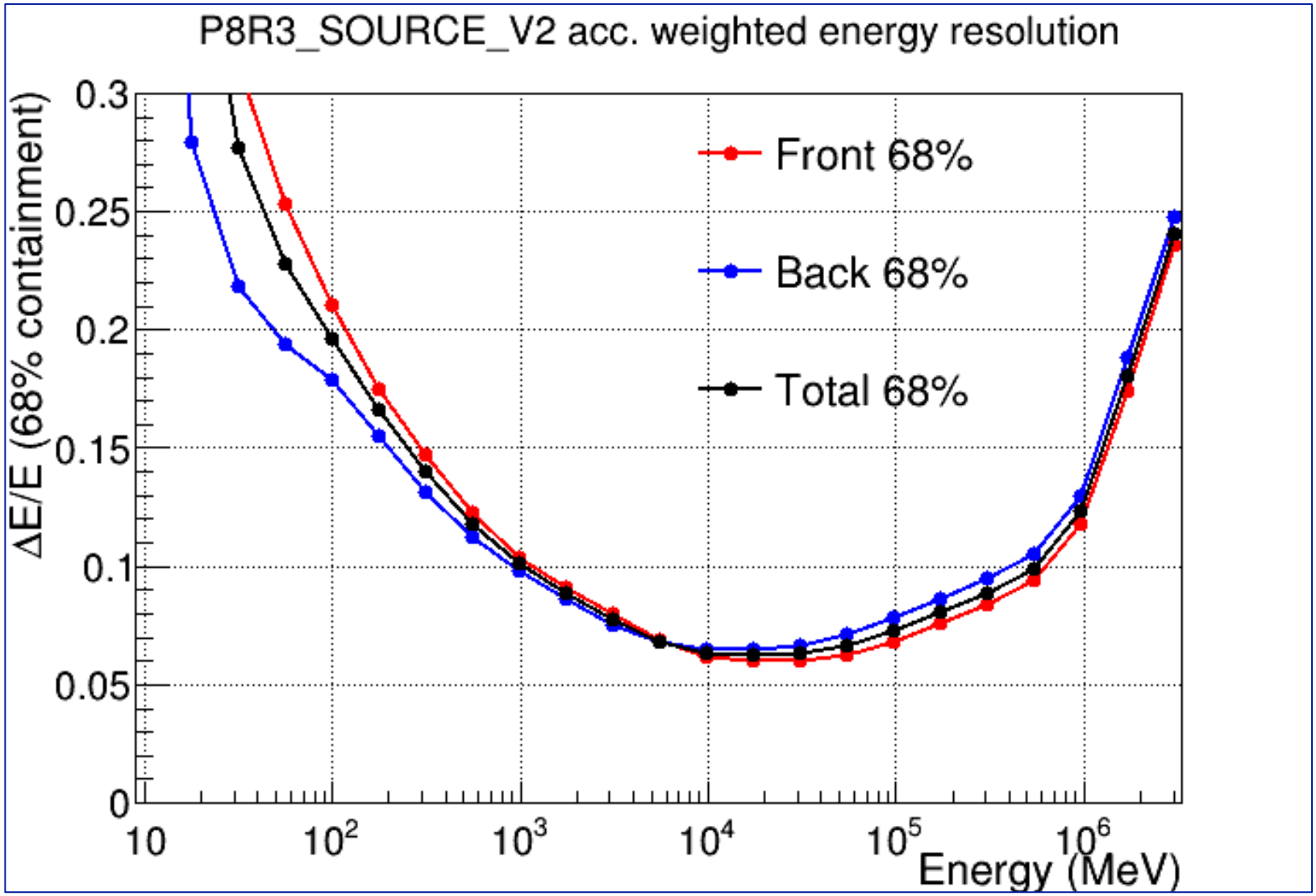
Point Spread Function



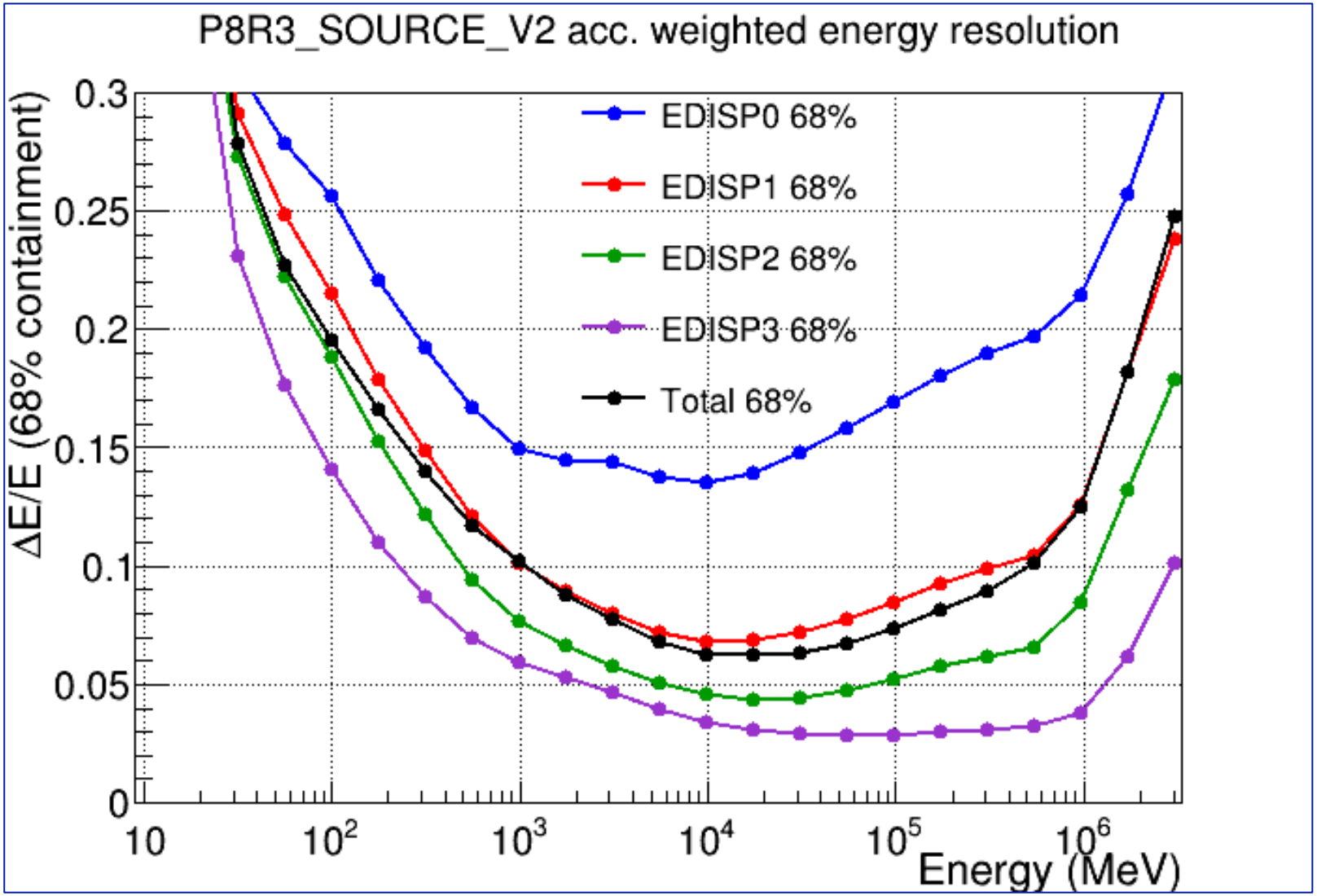
Point Spread Function



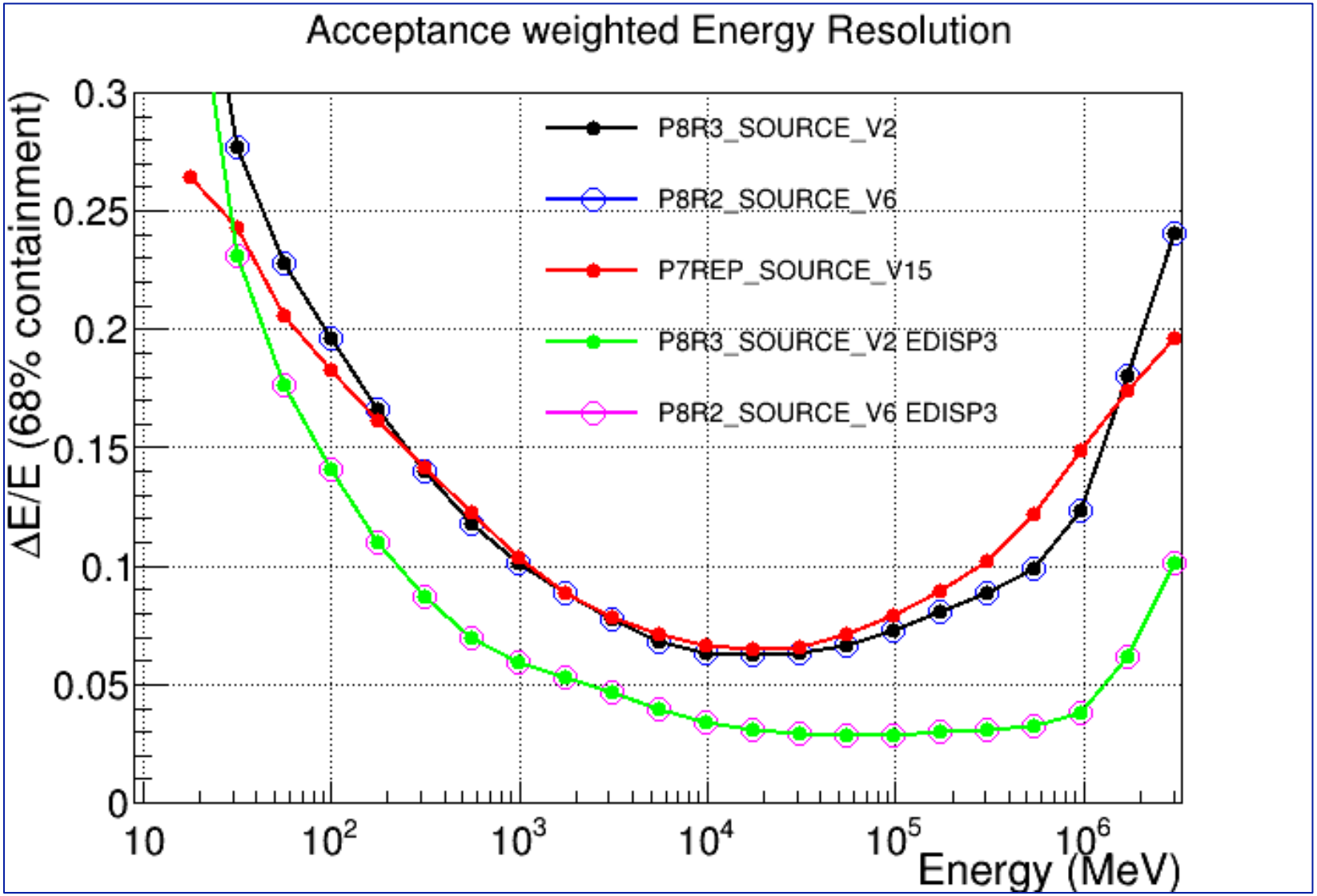
Energy resolution



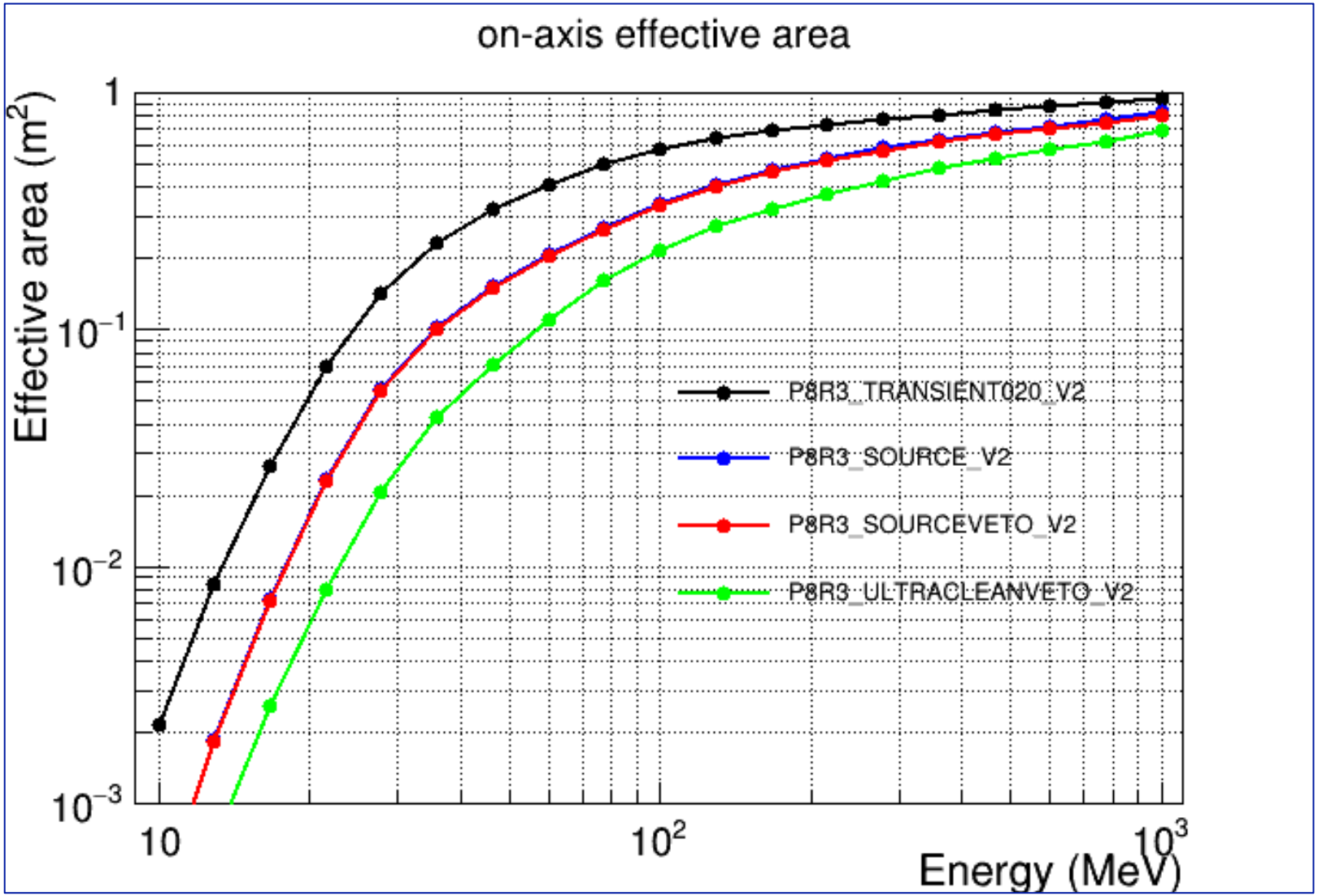
Energy resolution



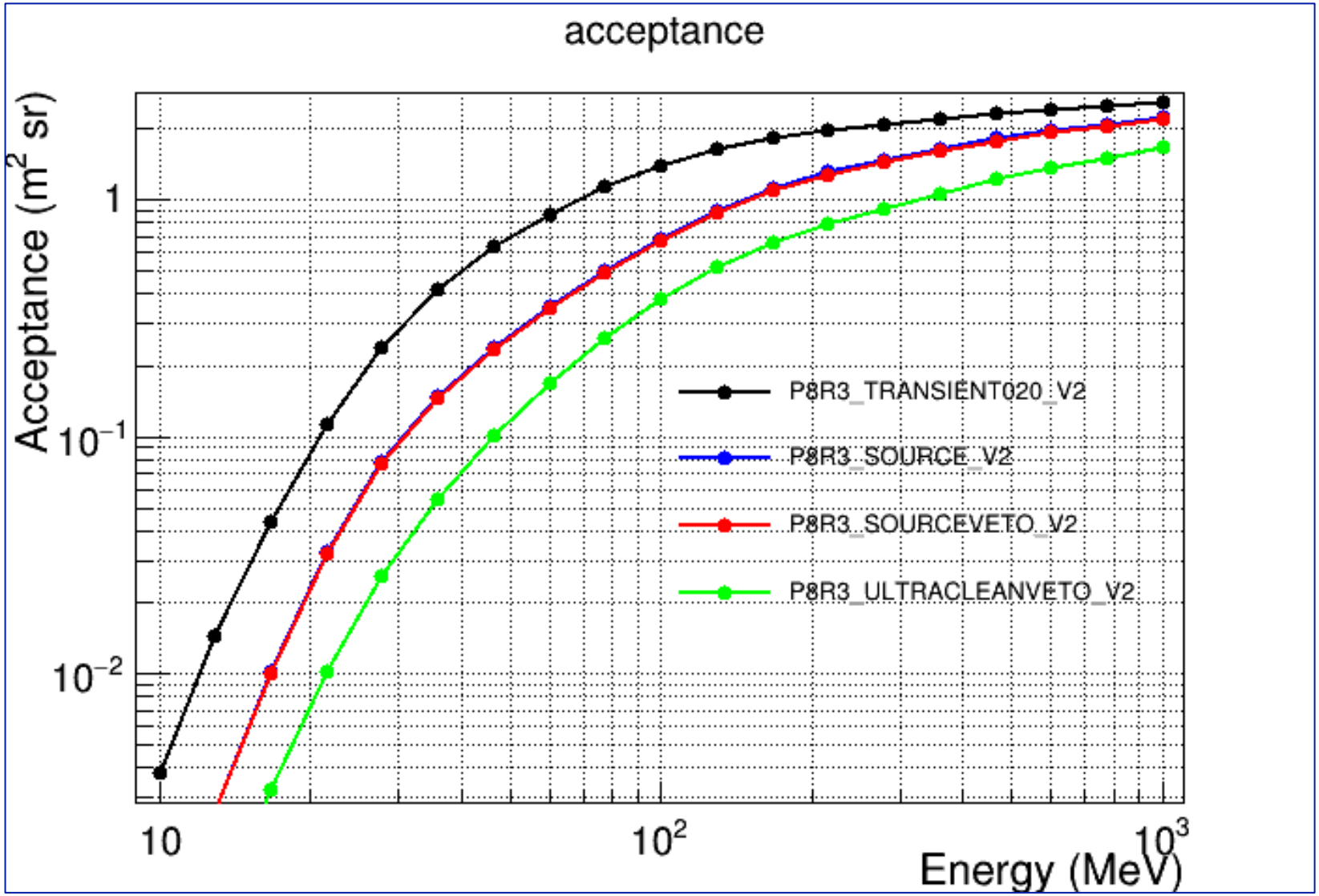
Energy resolution



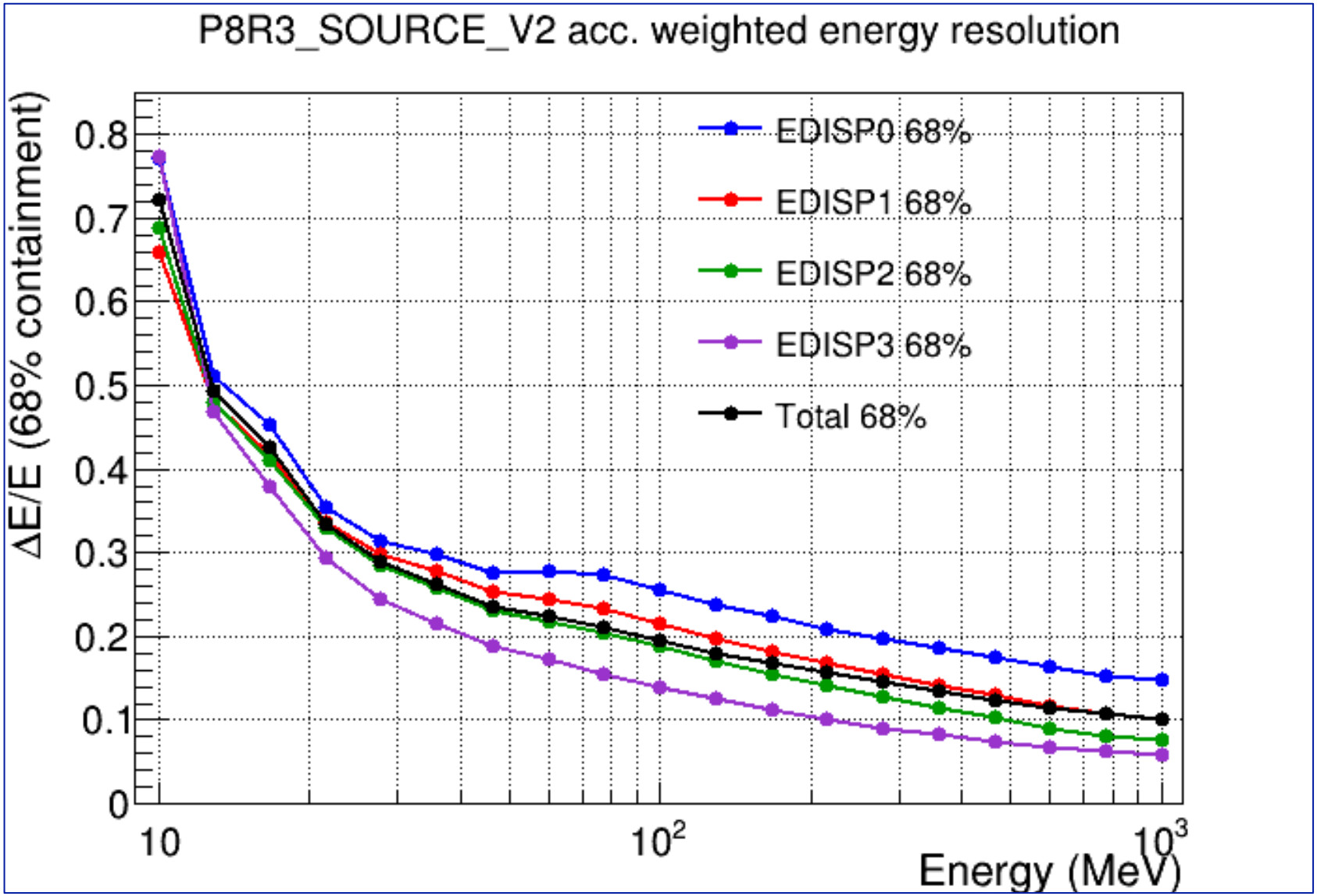
New! IRFs at Low Energy



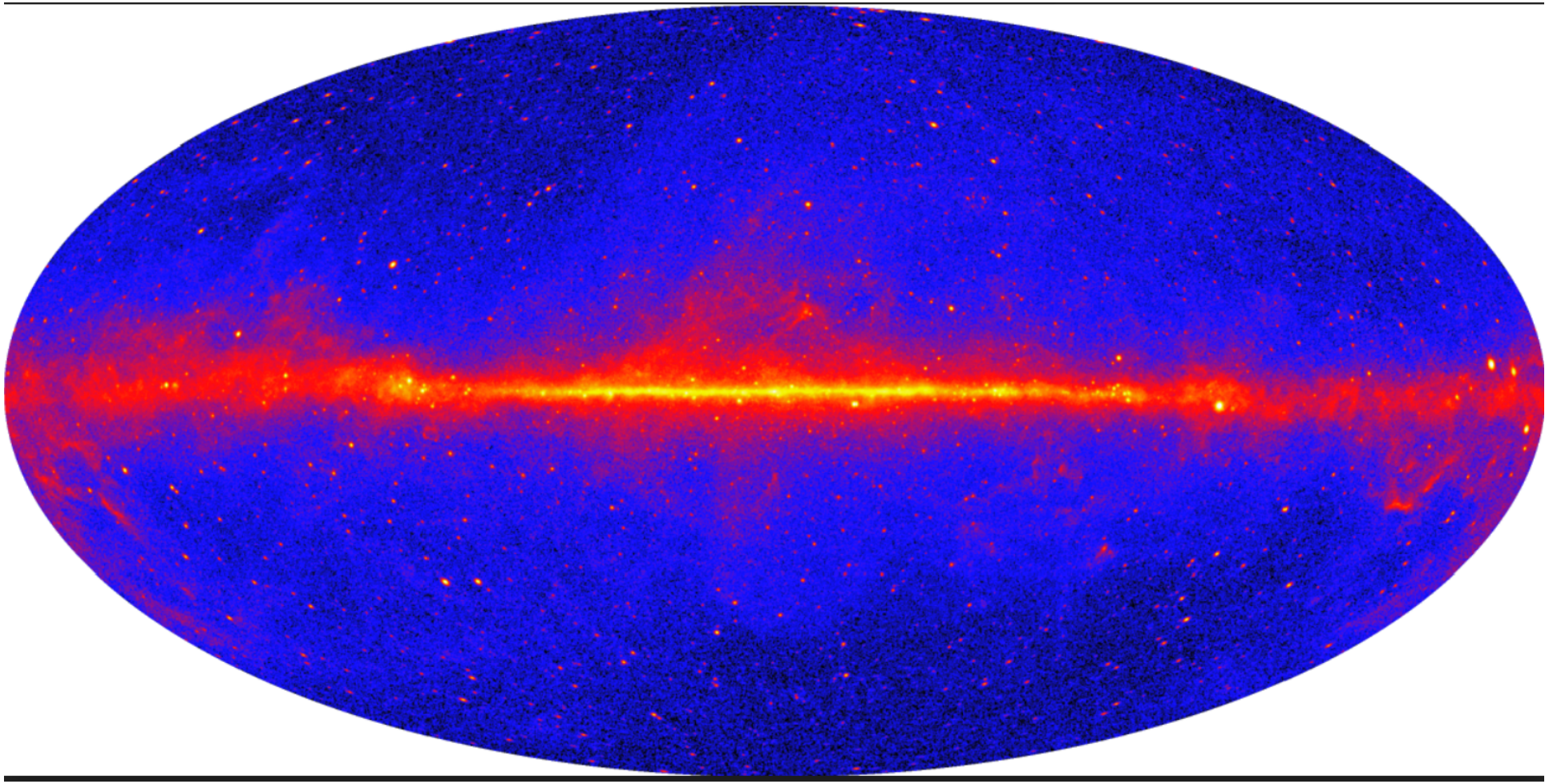
New! IRFs at Low Energy



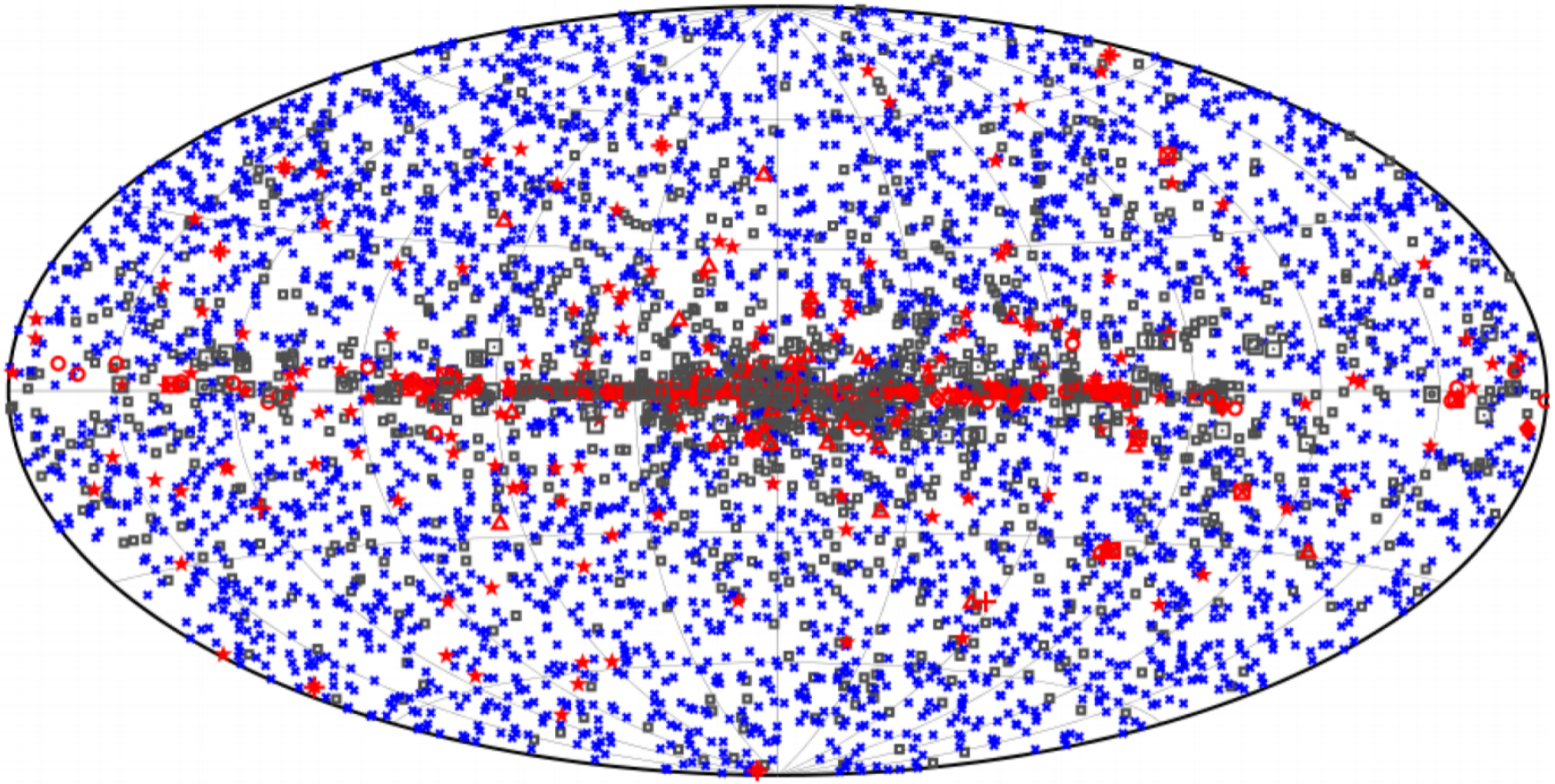
New! IRFs at Low Energy



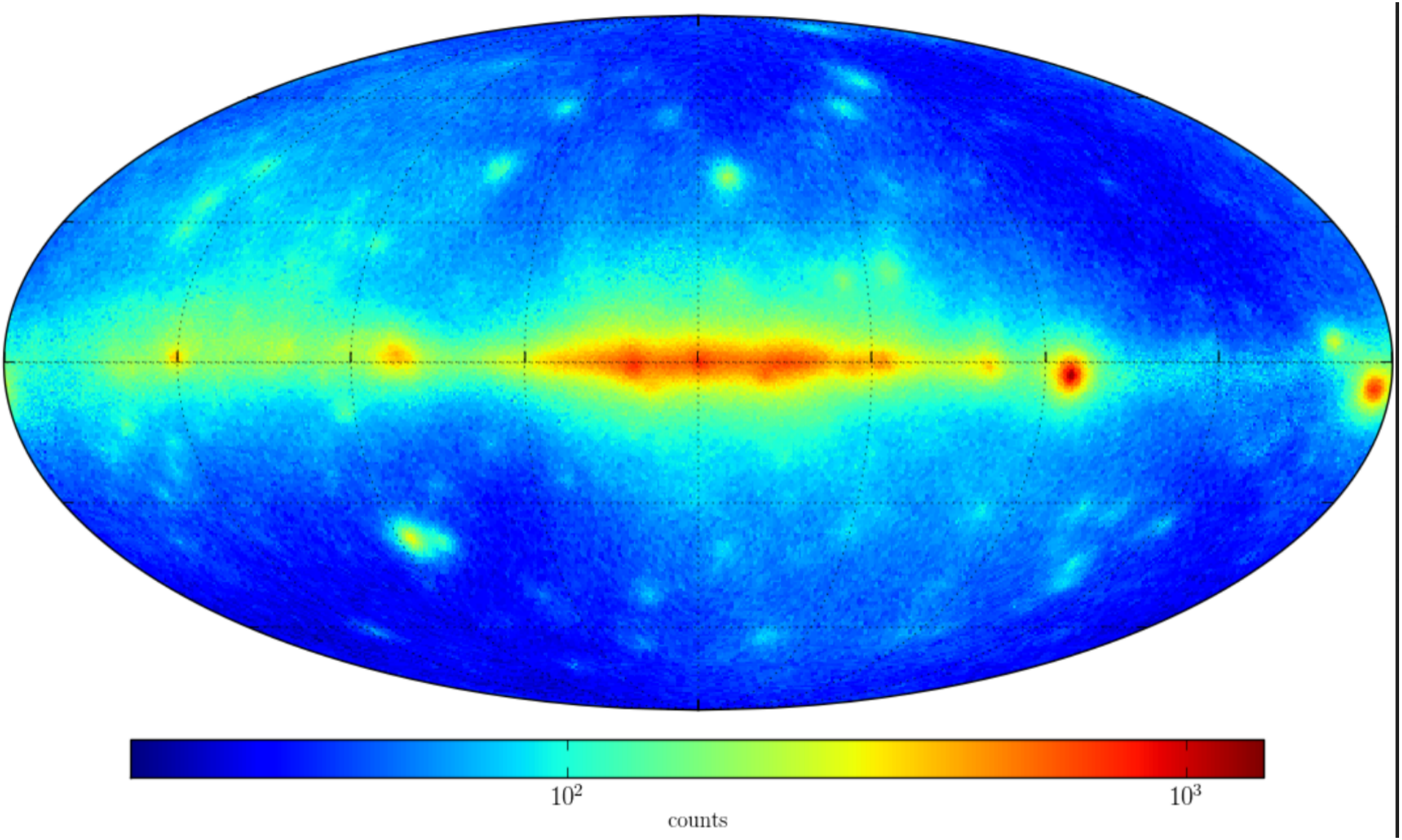
LAT sky



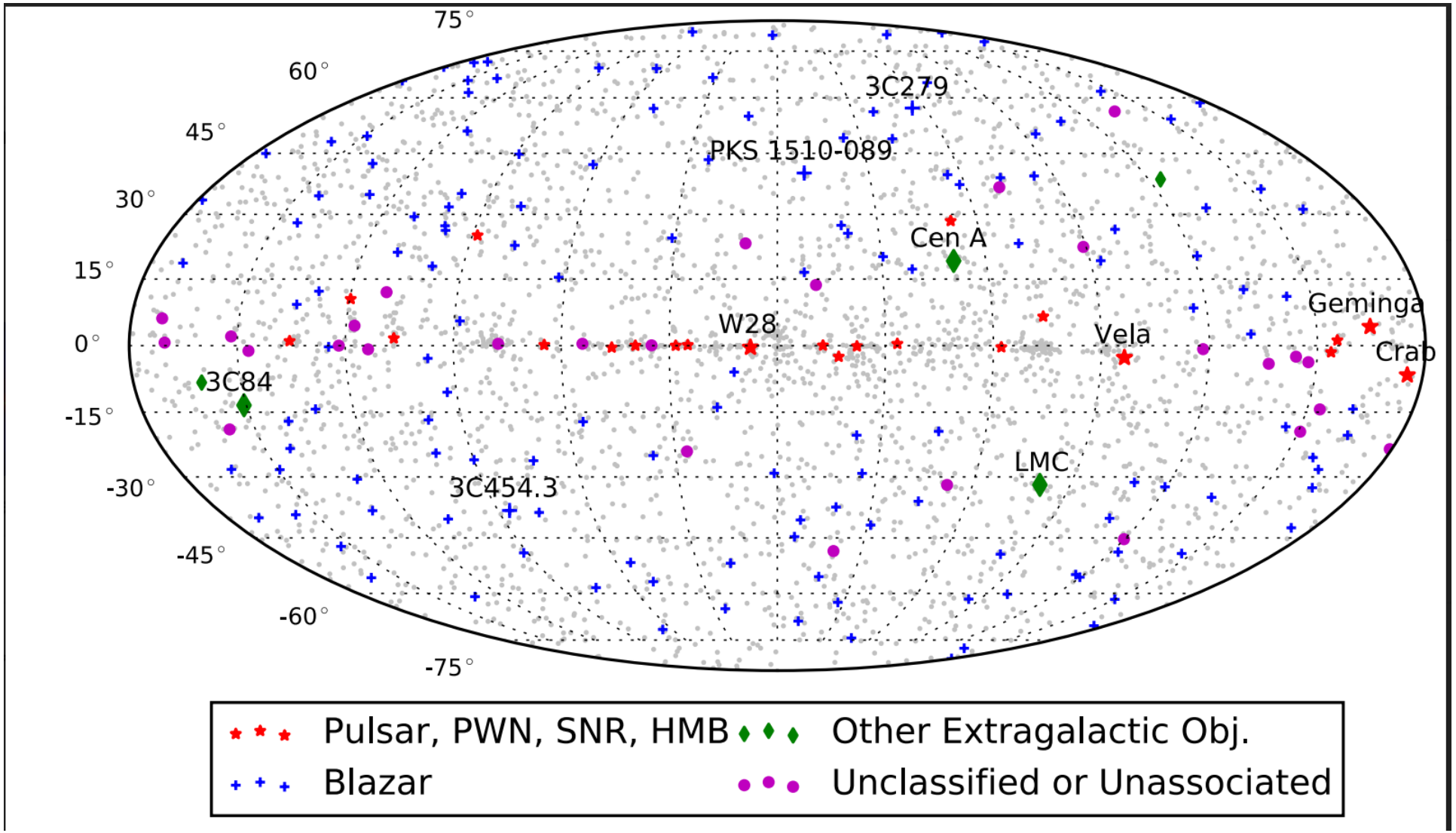
LAT 4FGL catalog



LAT – Low Energy (30 – 100 MeV) sky



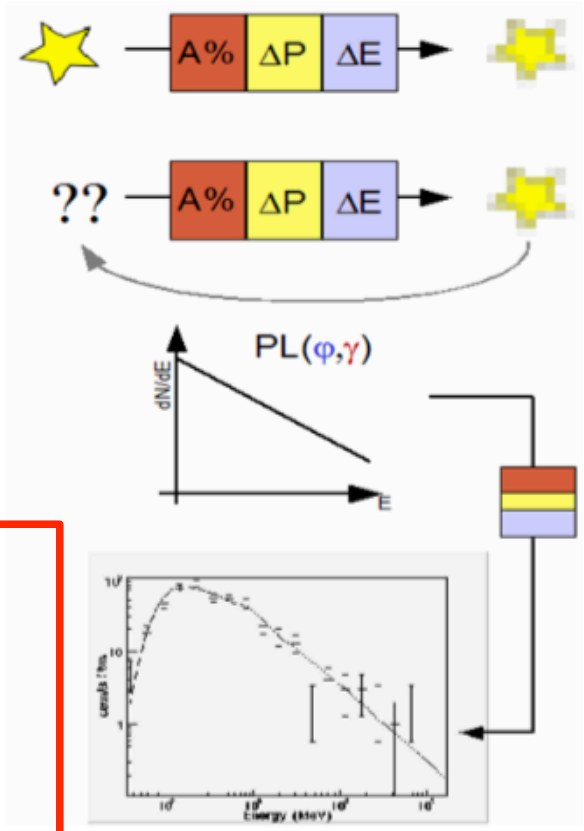
LAT – 1FLE catalog



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

Maximum likelihood technique

Given a set of observed data:

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

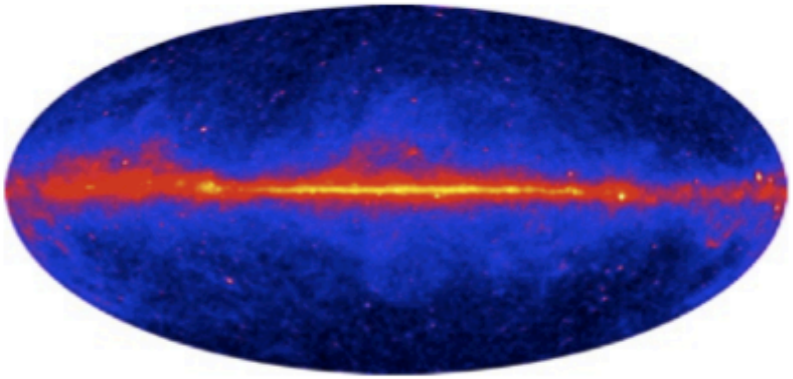
→ derive the probability (density) for the data given the model (PDF)

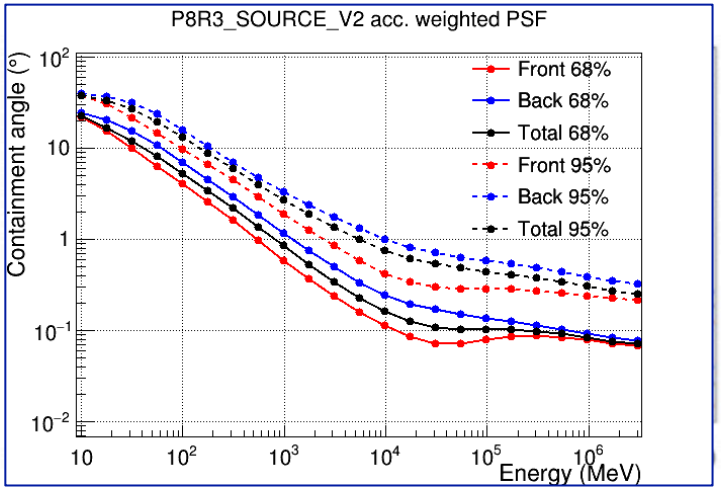
→ treat this as a function of the model parameters (likelihood function)

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

Why Model Fitting?

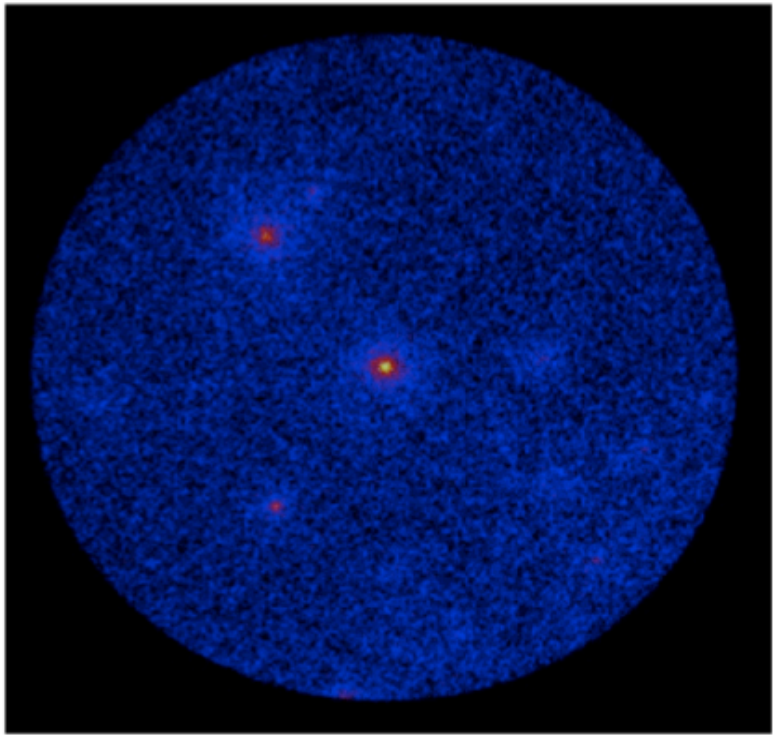
- We use the Likelihood method because the LAT data are limited by statistics, a bright diffuse background and a broad PSF.
- The model construction defines the questions we want to ask which means:
  - It will not answer a question you are not asking (ie. unknown parameters).
- The Likelihood will not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





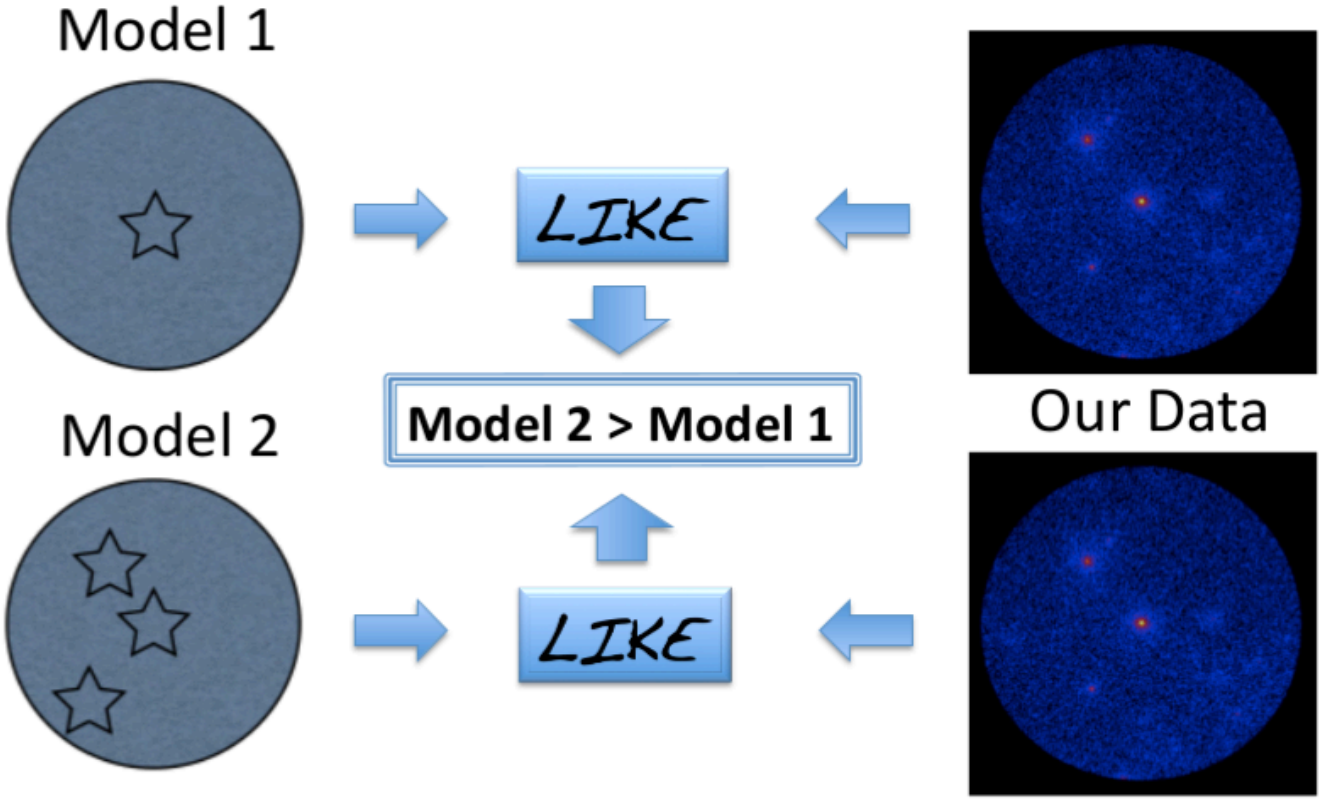
The Challenge

- 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.

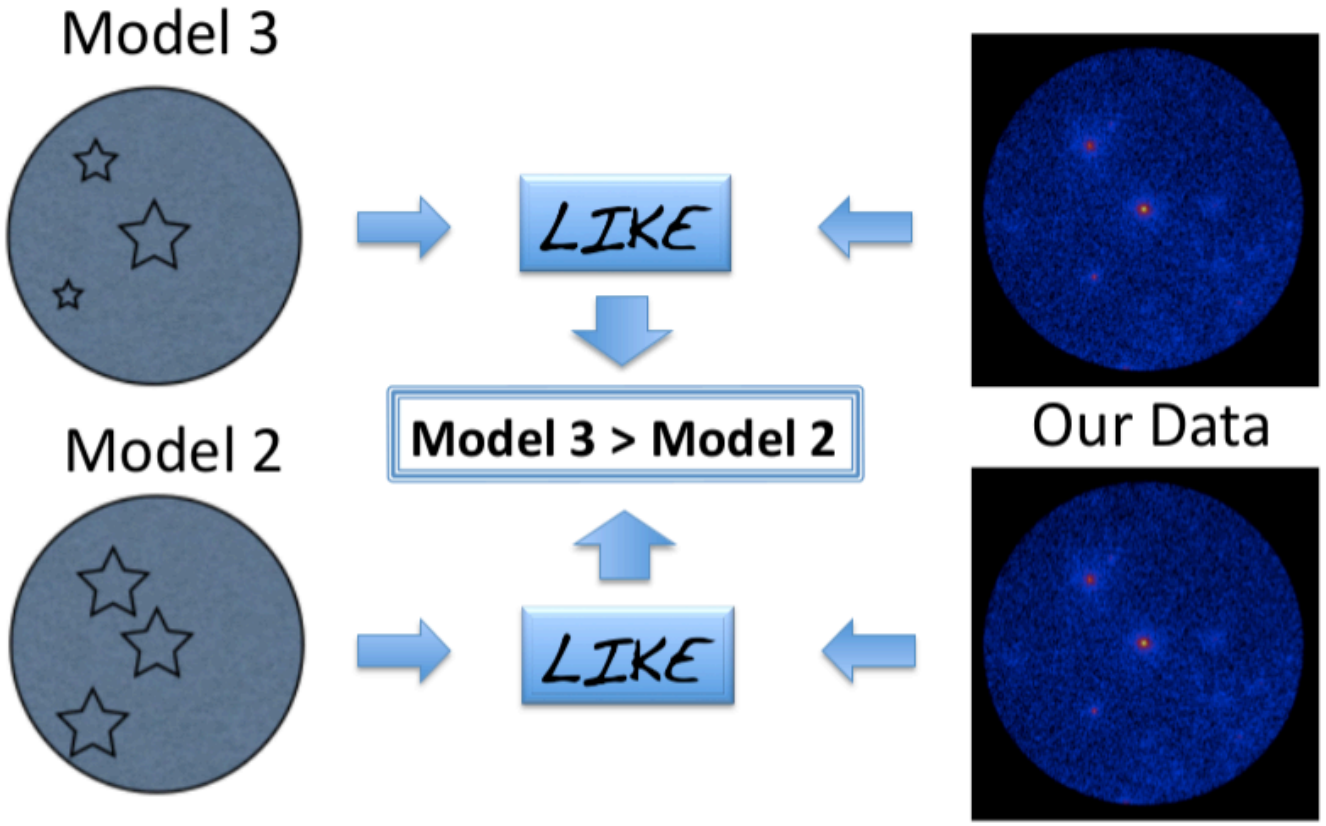


Count Map

A Graphical Example

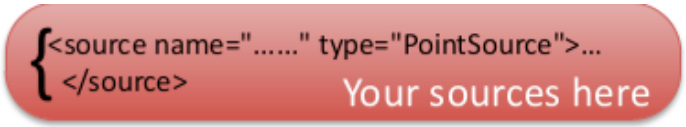


A Graphical Example



Describing the Source Model: the XML model

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




```
<!-- Point Sources -->

<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 4FGL sources that belongs to your ROI in your XML file model (make4FGLxml.py)**

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

Describing the Source Model: the 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_v07.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_P8R3_SOURCE_V3_v1.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>
```

Describing the Source Model: the 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_v07.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_P8R3_SOURCE_V3_v1.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>
```

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

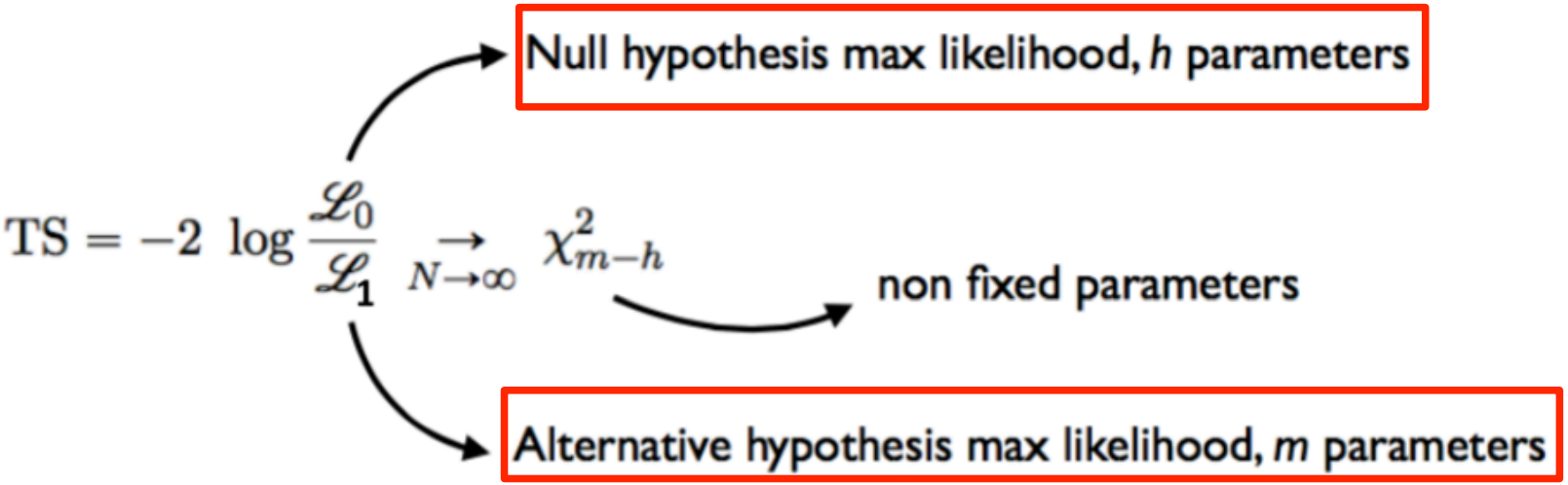
The function to maximize is:

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

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.

Perform the fit: the likelihood approach

- Absolute value of likelihood meaningless!
- Comparison between model w/ and w/o source to reject H_0 = no source
- Many variables may be calculated BEFORE selecting the models
- IRFs depend on inclination angle:
  Livetime Cube: seconds in $\Delta\Omega$ with a given z,
  the time that the LAT observed a given position on the sky at a given inclination angle
  Exposure Map: integration of the effective area over the FoV weighted by the livetime over a position-energy grid, $N_{model} = \int \Phi_{model}(\Omega, E(t)) \times A_{LAT}(\Omega, E)$

The Livetime cube

- **The LAT instrument response functions are a function of the inclination angle, the angle between the direction to a source and the LAT normal.**
- **The number of counts that a source should produce should therefore depend on the amount of time that the source spent at a given inclination angle during an observation.**
- **This livetime quantity, the time that the LAT observed a given position on the sky at a given inclination angle, depends only on the history of the LAT's orientation during the observation and not on the source model.**

https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Likelihood/Exposure.html

The Exposure Map

- **The likelihood consists of two factors: the first is dependent on the detected counts; and the second is equal to the exponential of the negative of the predicted total number of counts for the source model.**
- **The exposure map is the total exposure (effective area multiplied by live time) for a given position on the sky producing counts in the Region of Interest. Since the effective area is a function of the photon energy, the exposure map is also a function of this energy. Thus the counts produced by a source at a given position on the sky is the integral of the source flux and the exposure map (a function of energy) at that position.**
- **The exposure map should be computed over a Source Region that is larger than the Region of Interest by ~50%. This is necessary to ensure that all source photons are included due to the size of the LAT instrument PSF at low energies.**

https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Likelihood/Exposure.html

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.

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

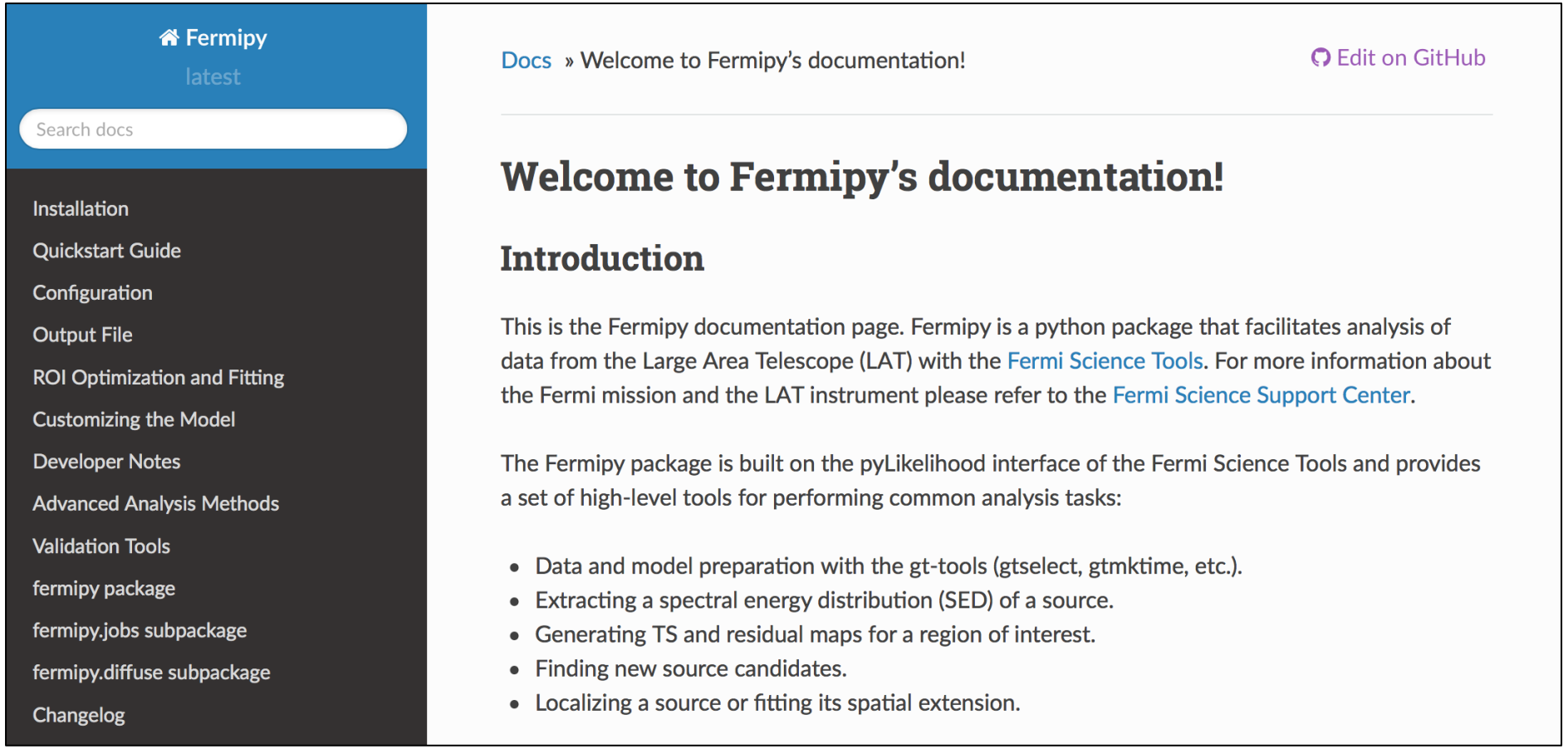
- Adjust the model until this is maximized:

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

- Calculate the TS:

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

Fermipy



https://fermipy.readthedocs.io/en/latest/