ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Fermi Gamma-ray Space Telescope

Development of the analysis for the first catalog of gamma-ray source between 30 and 100 MeV

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Fermi Gamma-ray Space Telescope

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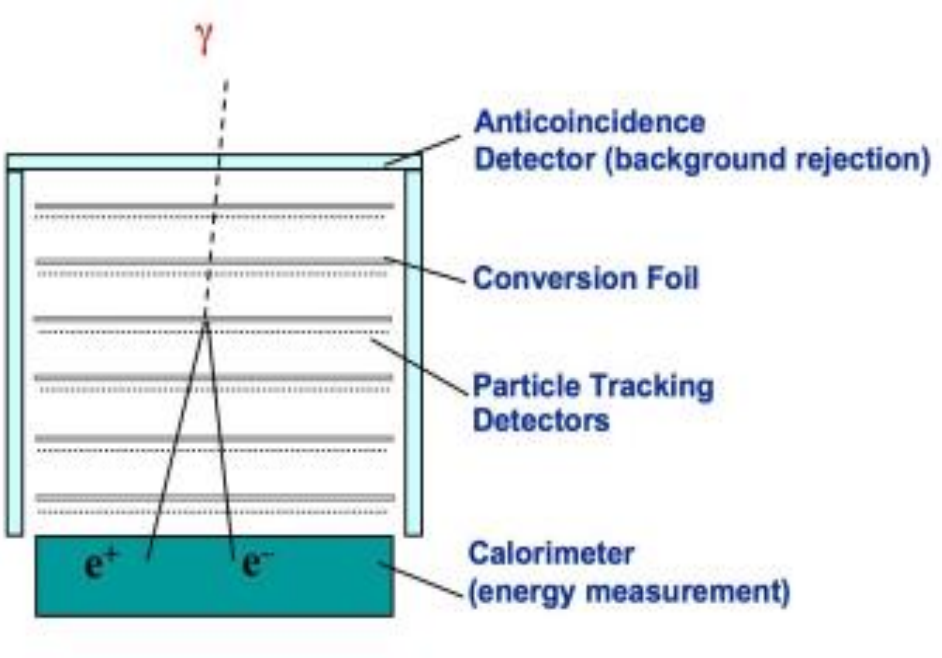
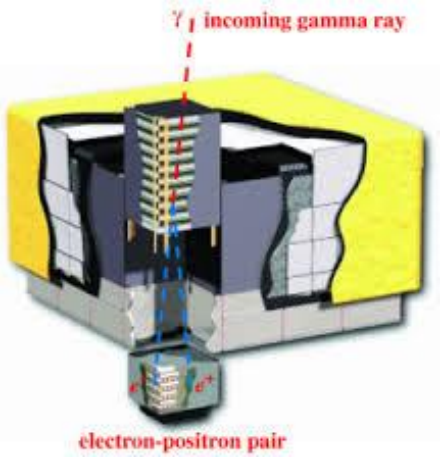
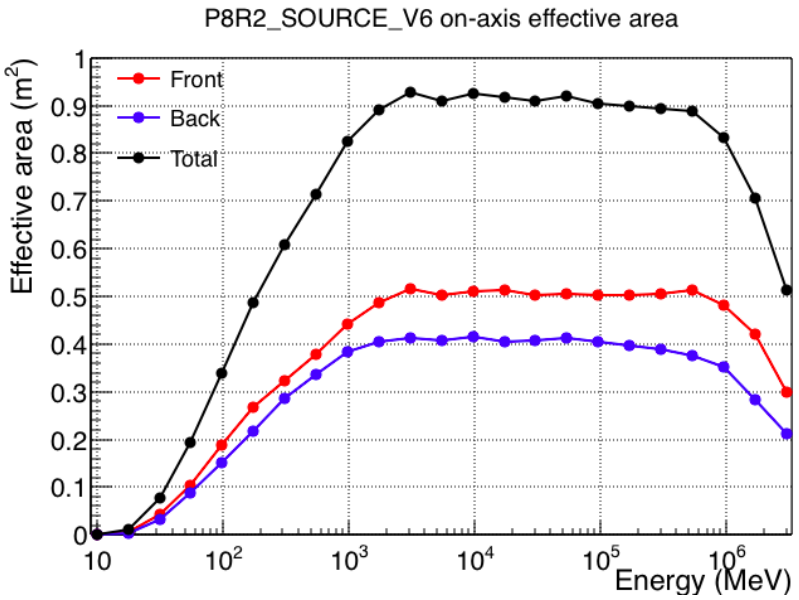
Fermi-LAT Instrument



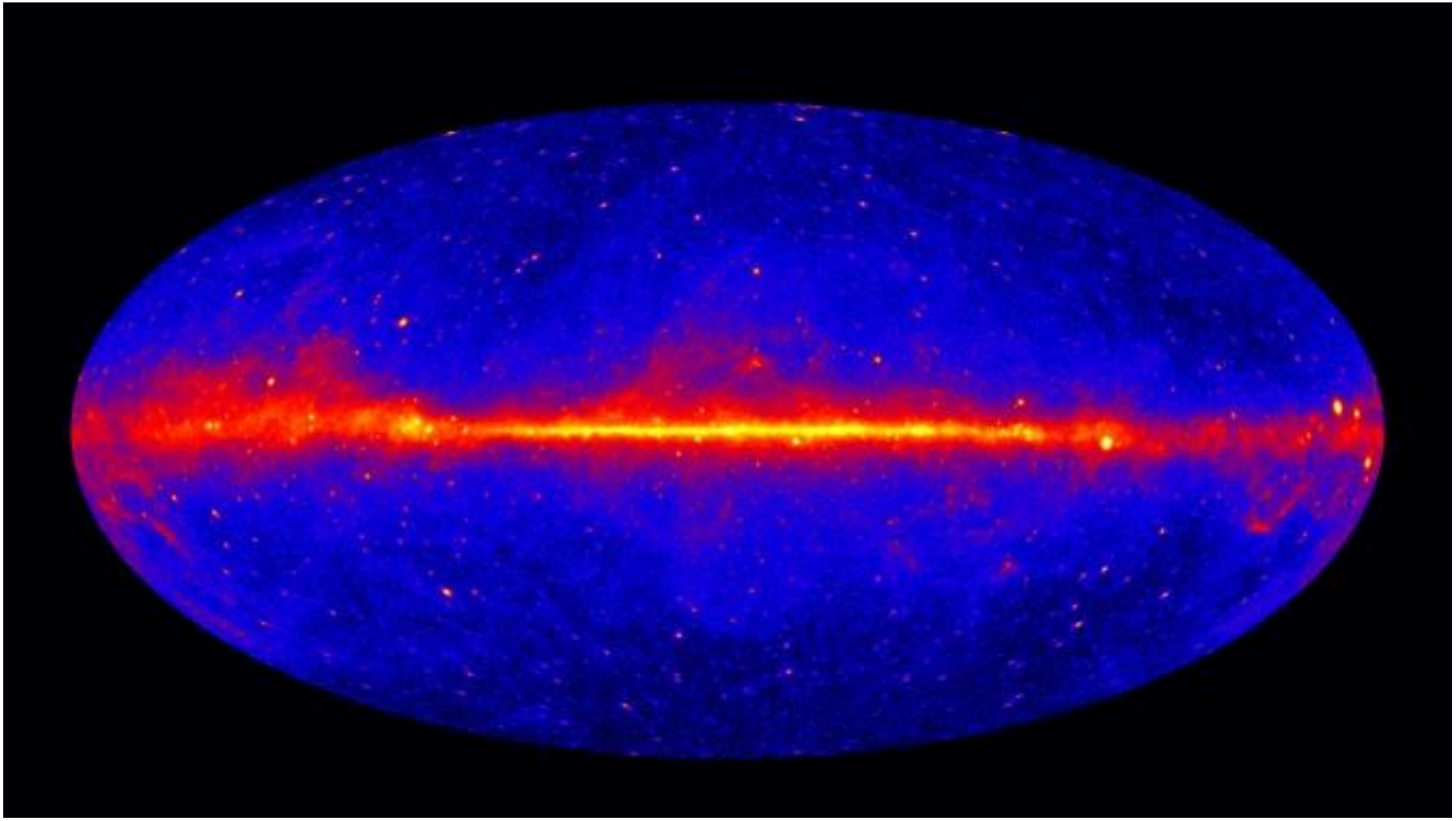




Fermi-LAT energy range: 20 MeV – 2 TeV

W. B. Atwood et al., Astrophys. Journ. 697 (2009), p. 1071.

Fermi-LAT Sky



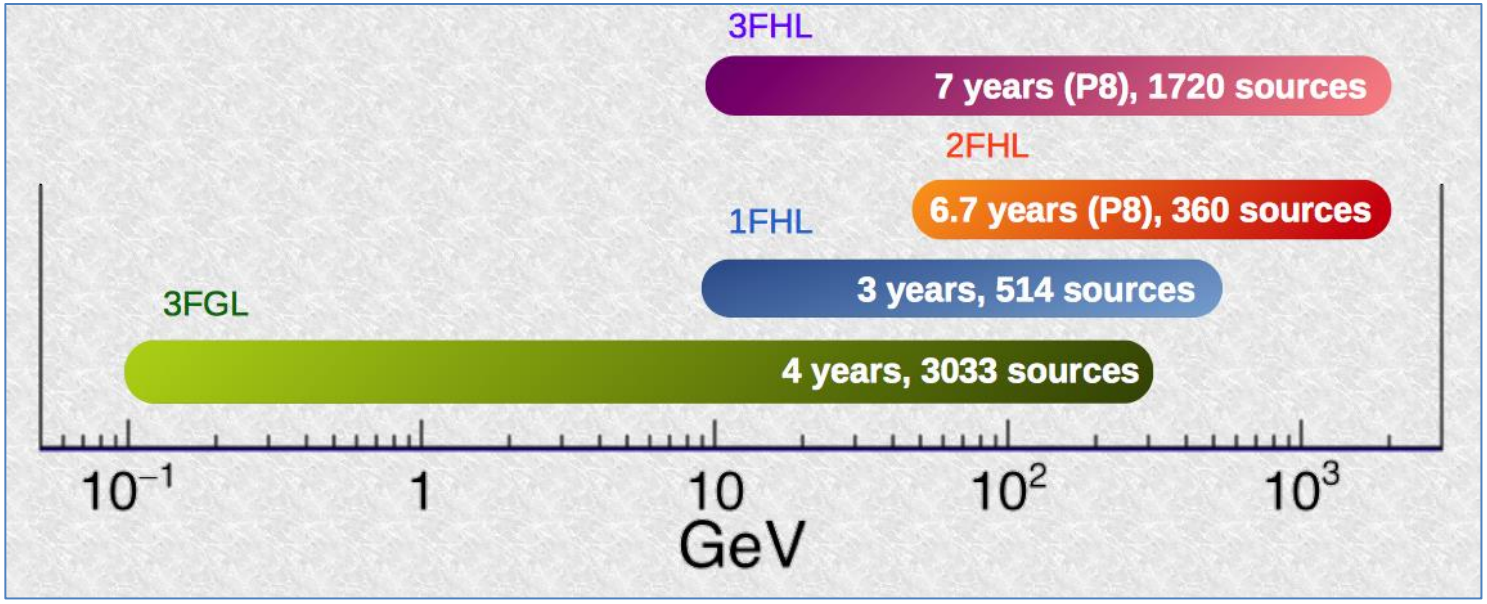
Fermi LAT Sky at energies greater than 1 GeV (5 years)

Fermi-LAT Catalogs

Fermi Catalogs:

- *n*FGL Catalogs detect and characterize sources in the ~0.1-300 GeV energy range
  - 1FGL: 0.1 – 100 GeV (1451 sources / 1 year)
  - 2FGL: 0.1 – 100 GeV (1873 sources / 2 years)
  - 3FGL: 0.1 – 300 GeV (3033 sources / 4 years)
- *n*FHL Catalogs explore the higher-energy sky

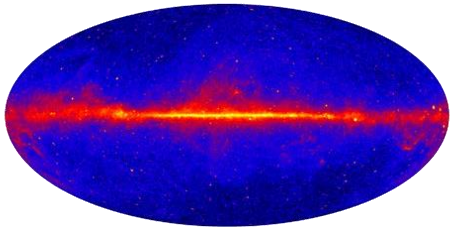
No catalogs below 100 MeV



Diffuse Emission

Galactic diffuse emission

Data



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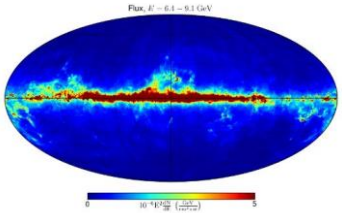
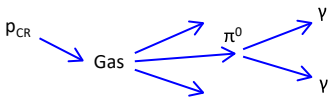
π^0 and bremsstrahlung





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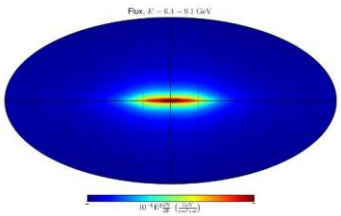
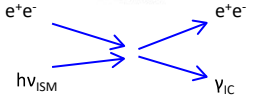
Inverse Compton





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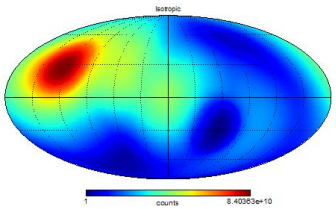
Isotropic



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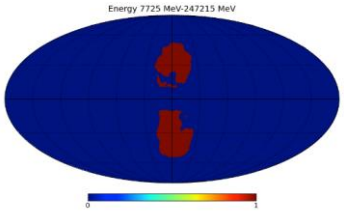
Bubbles



Ackerman et al (Fermi LAT)
ApJ 793 (2014)

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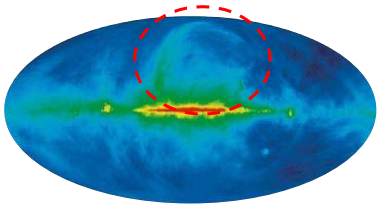
Loop I



Gold et al (WMAP)
ApJS 192 (2011)

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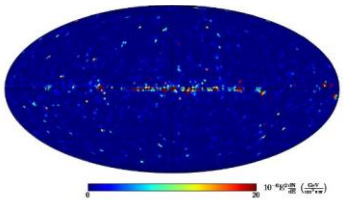
Point sources



Extragalactic + residual CR background

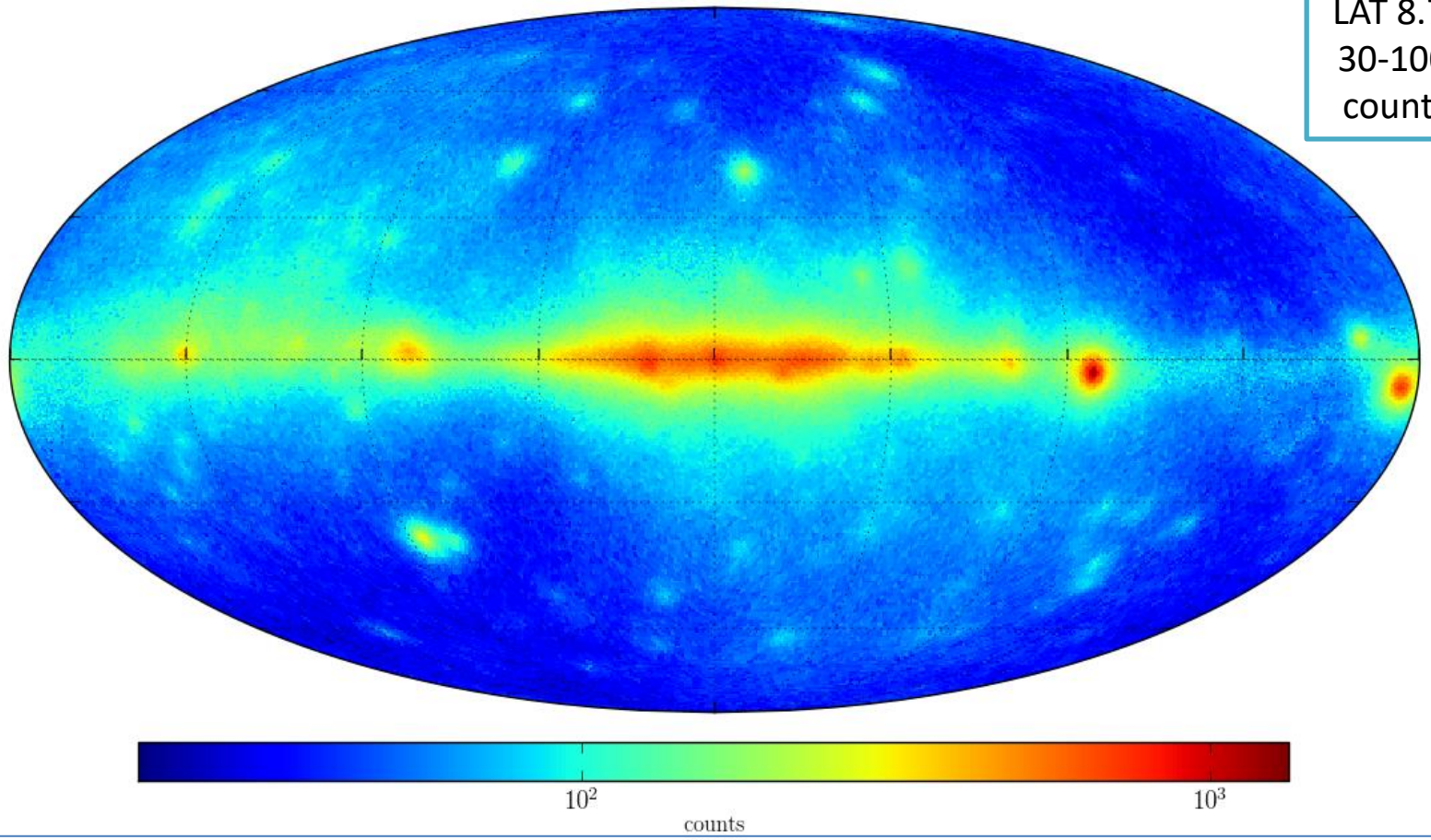
Fermi catalogs

The diffuse model is limited by modelling uncertainties below 10 GeV.

Fermi Low Energy Catalog

We are interested in studying the Fermi-LAT data between **30-100 MeV** since they were not covered in the previous Fermi-LAT Catalogs. To detect the sources and estimate their flux we want to use PGWave, a **background-independent method** already used in the Fermi-LAT catalog pipeline to find candidate sources.

LAT 8.7 years
30-100 MeV
counts map



PGWave: a Wavelet Transform Method

PGWave is a method, based on **Wavelet Transforms** (WTs) [1], to detect sources in astronomical images obtained with photon-counting detectors, such as X-ray or gamma-ray images.

1. The WT of a 2-dim image *f(x,y)* is defined as:

$$w(x,\, y,\, a) = \iint g\left(\frac{x - x'}{a}, \frac{y - y'}{a}\right) f(x',\, y')dx'\, dy'$$

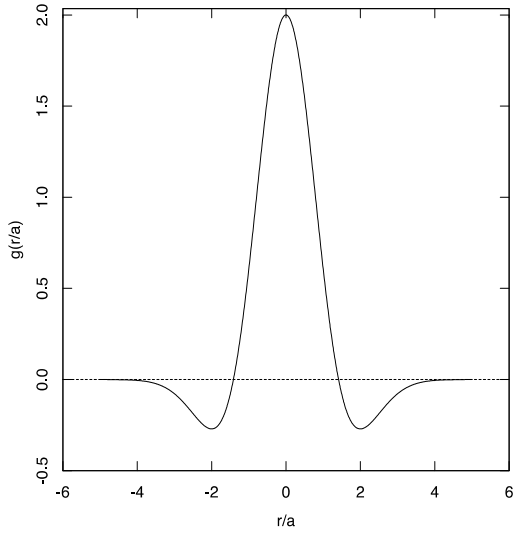
where *g(x/a,y/a)* is the generating wavelet, *x* and *y* are the pixel coordinates, and *a* is the scale parameter.

2. PGWave uses the 2-dim **"Mexican Hat"** wavelet:

$$g\left(\frac{x}{a}, \frac{y}{a}\right) \equiv g\left(\frac{r}{a}\right) = \left(2 - \frac{r^2}{a^2}\right) e^{-r^2/2a^2} \; (r^2 = x^2 + y^2)$$

3. The peak of the WT for a source with Gaussian shape (N_{src} total counts and width σ_{src}) is:

$$w_{\text{peak}}(a) = \frac{2N_{\text{src}}}{(1 + \sigma_{\text{src}}^2/a^2)^2}$$



[1] Damiani F. et. al., A Method Based on Wavelet Transforms for Source Detection in Photon-Counting Detector Images, ApJ 483, 350, (1997)

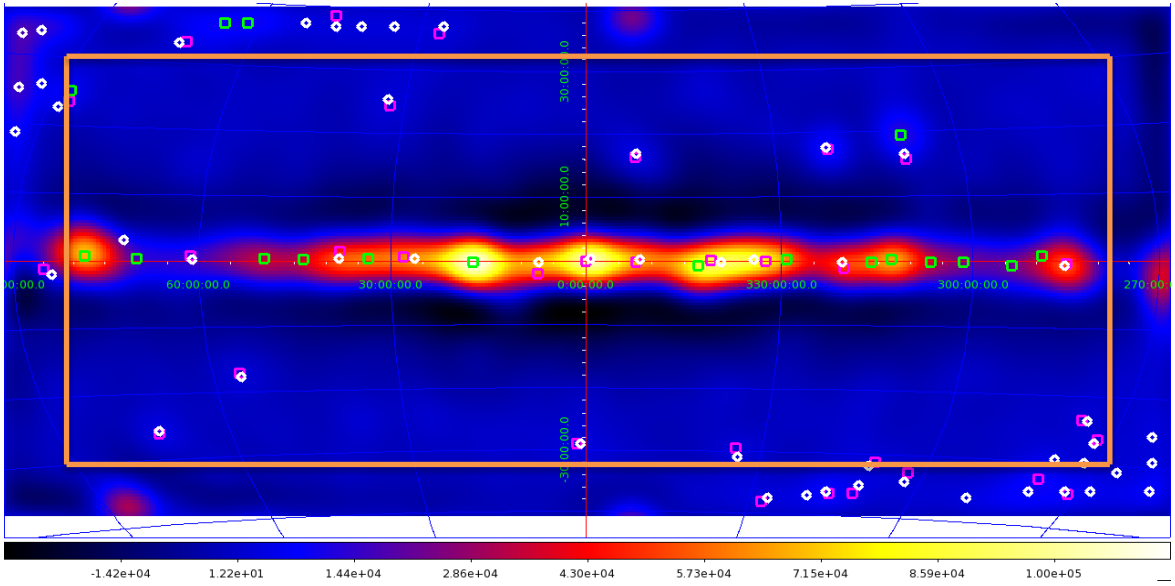
Analysis Procedure

Analysis procedure:

1. Gtbin: we use 12 ROIs of the dimensions of 180° x 90° (LON, LAT)
2. PGWave: we perform PGWave and create a dictionary
3. Restrict area: we eliminate the seeds that are close to the boarder
4. Merge seeds: we merge the seeds in the overlapped regions

(we perform the previous steps 1-4 are performed also for the diffuse maps)

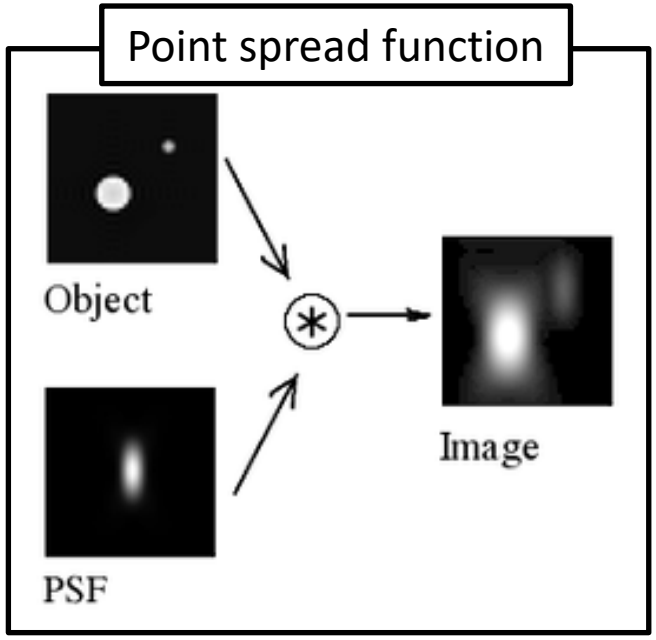
5. Eliminate diffuse: we eliminate the seeds that match with those from the diffuse
6. Comparison: we compare the resulting sources with the 3FGL
7. Flux determination: we determine the flux using the WT peak of PGWave

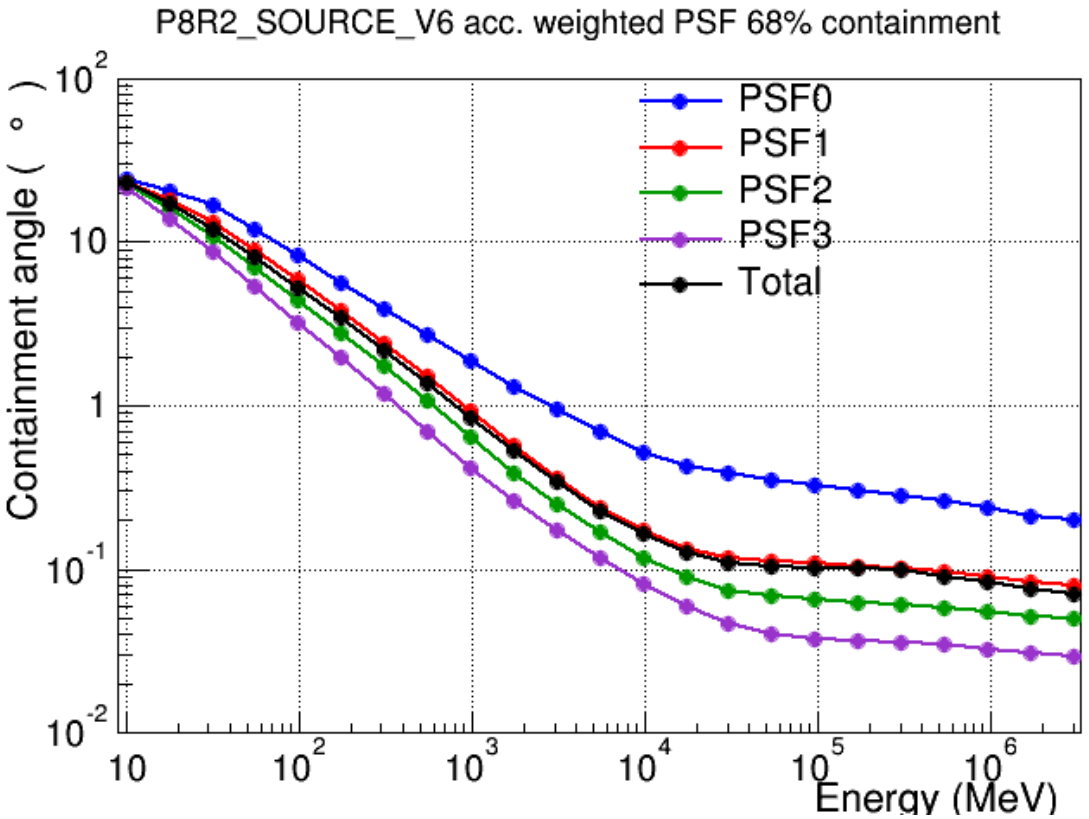


Data Selection
PSF Class Selection

PSF selection (using optimized parameter):

- All PSF classes
- PSF1+PSF2+PSF3 classes
- PSF2+PSF3 classes
- PSF3 class

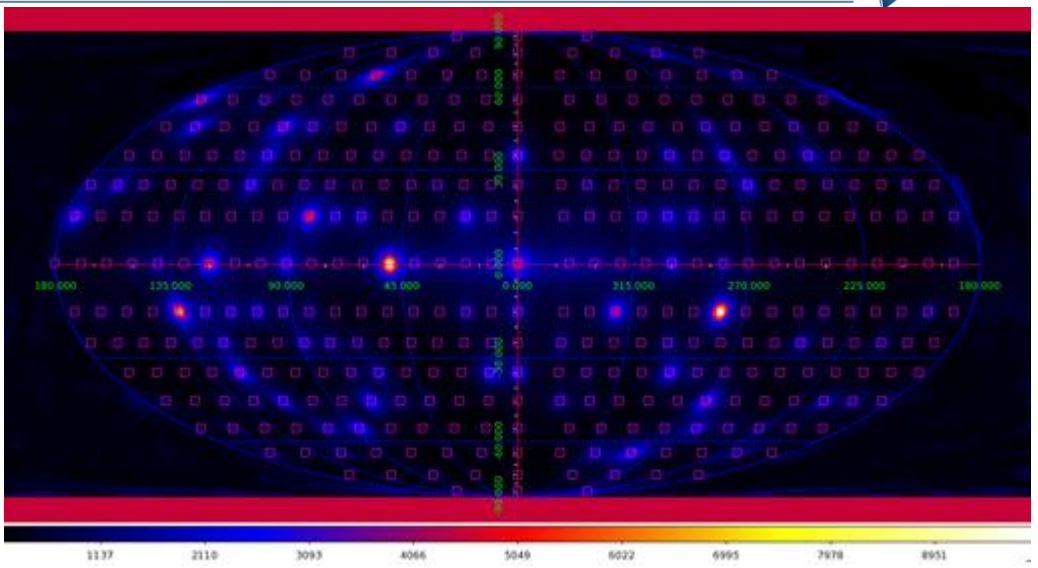




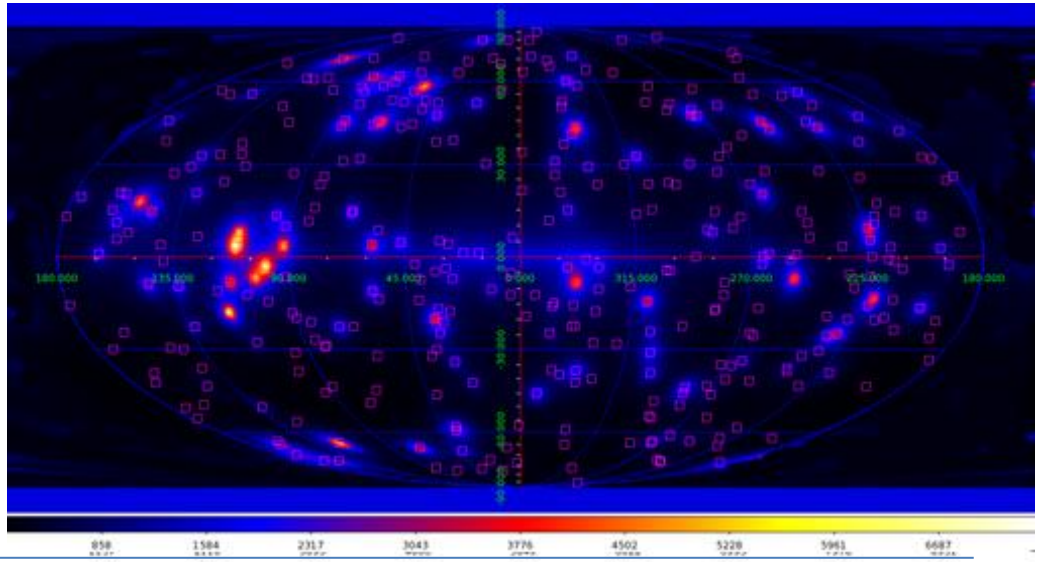
Fermi-LAT performance https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

PSF Class Selection
Setups: Grid PS and Random PS maps

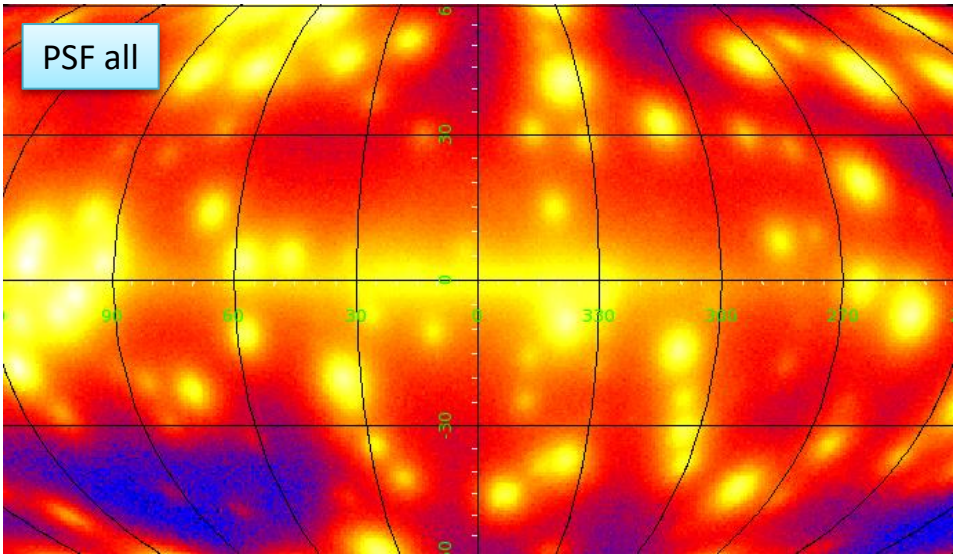
Setup 1 (**Grid PS map**):
- 369 PS (316 PS High Latitude)
- Flux 10^{-8} ph/cm^2/s - $10^{-4.5}$ ph/cm^2/s
- PS positioned in a grid with separation of 10 degrees

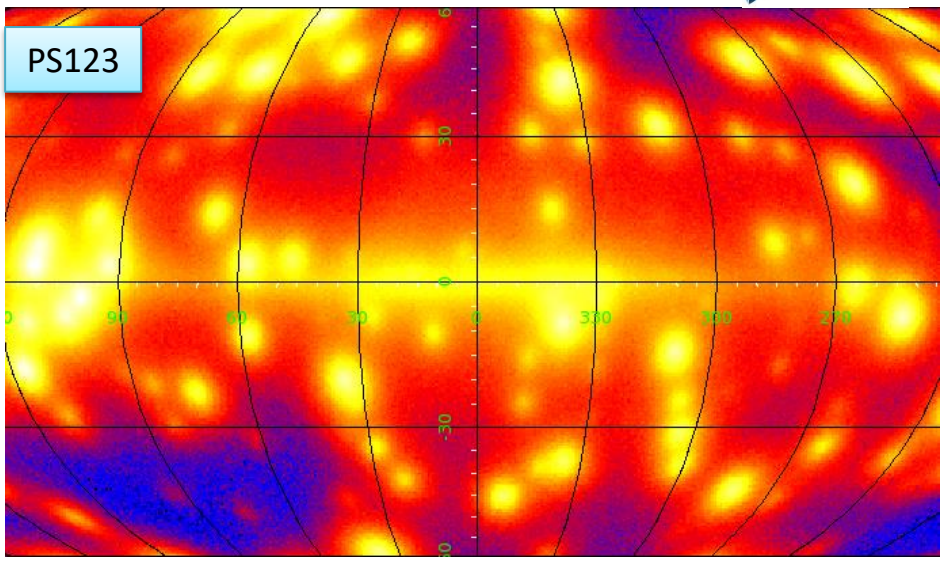


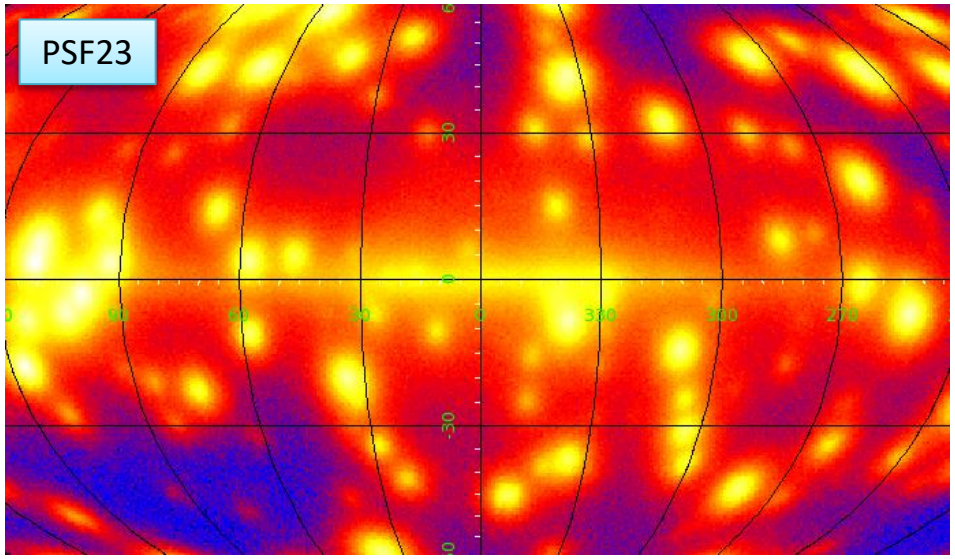
Setup 2 (**Random PS map**):
- 369 PS (306 PS High Latitude)
- Flux: 10^{-8} ph/cm^2/s - $10^{-4.5}$ ph/cm^2/s
- PS randomly positioned in the sky

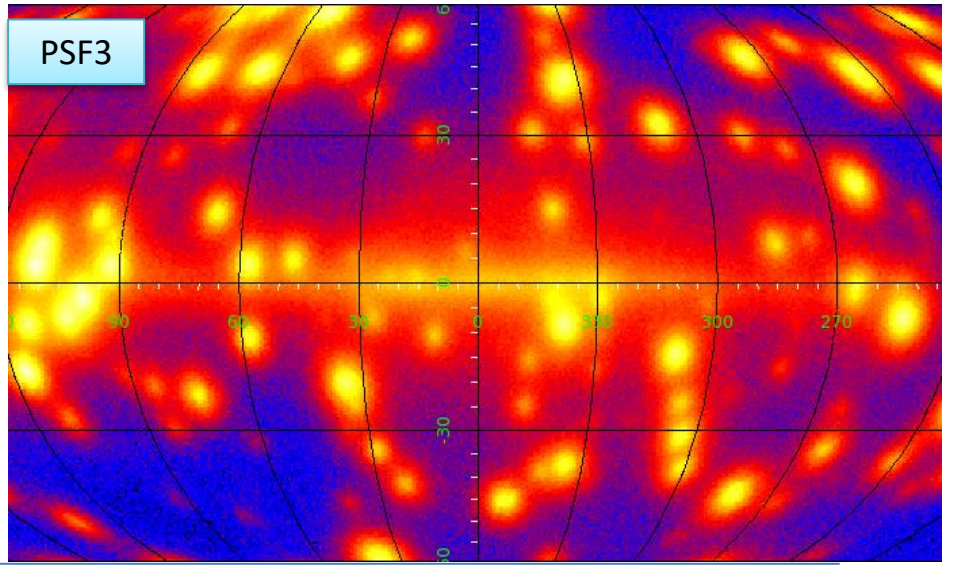


PSF Class Selection
Random PS maps



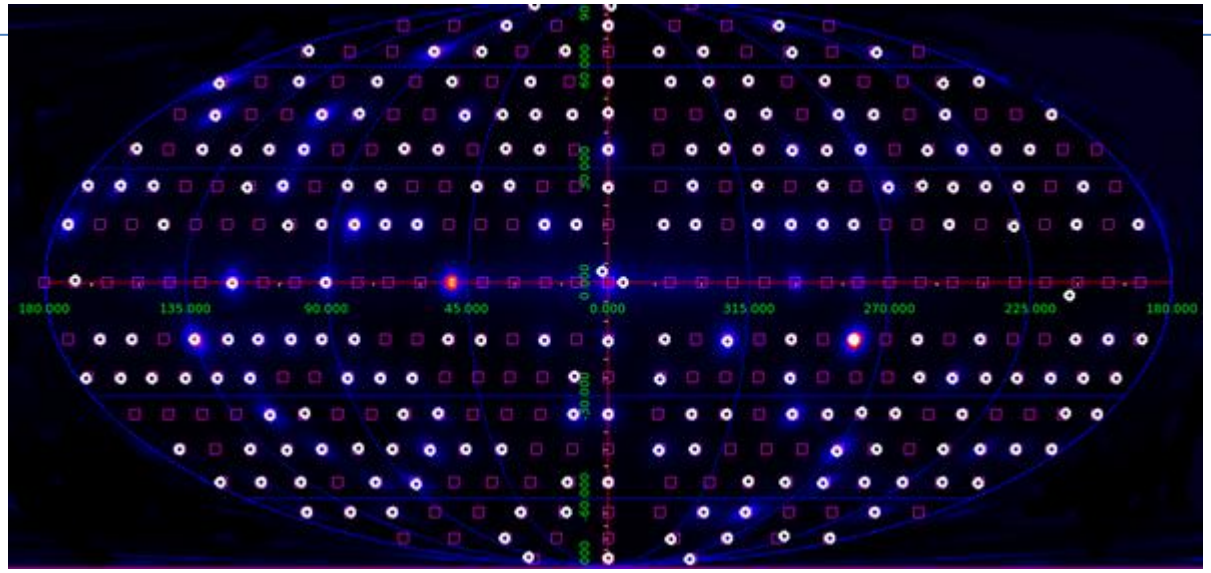


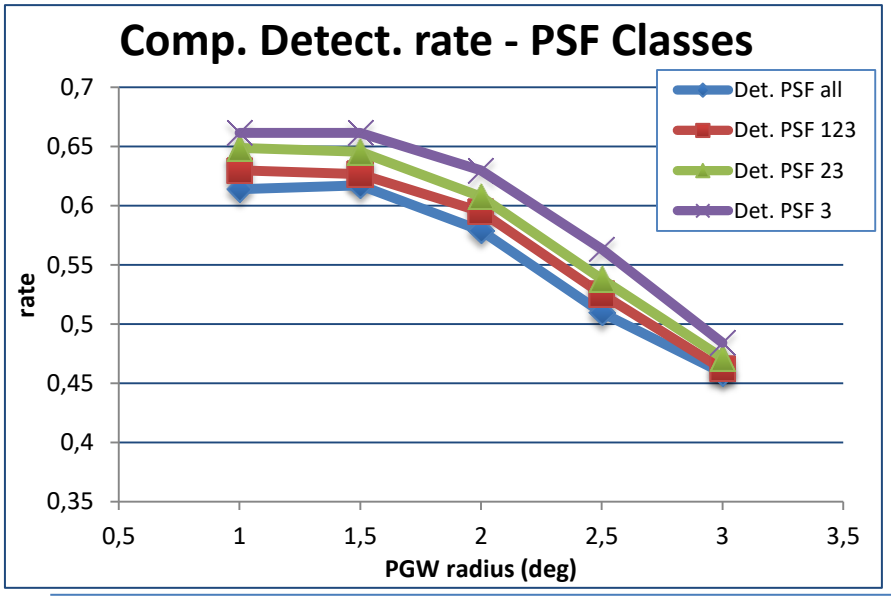


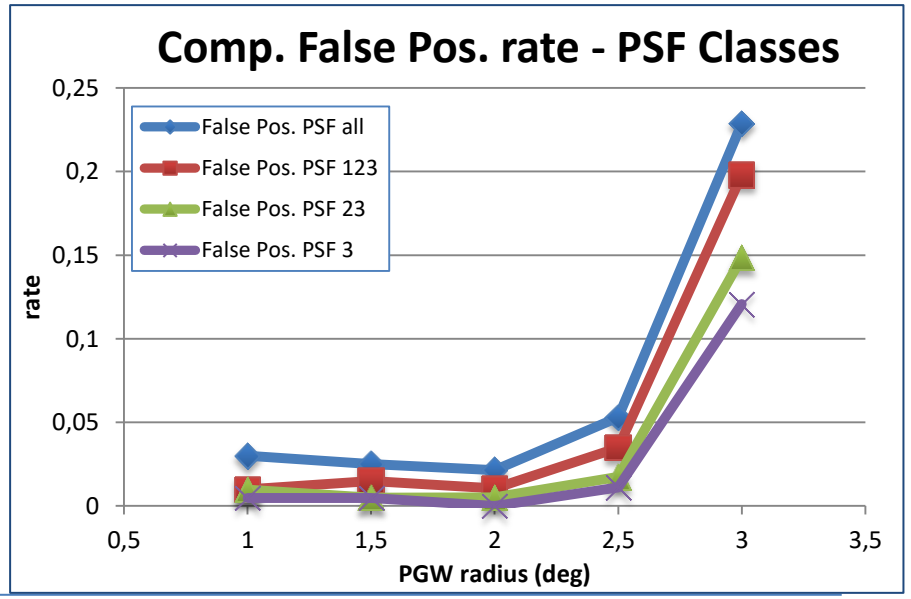


PSF Class Selection

Grid PS map

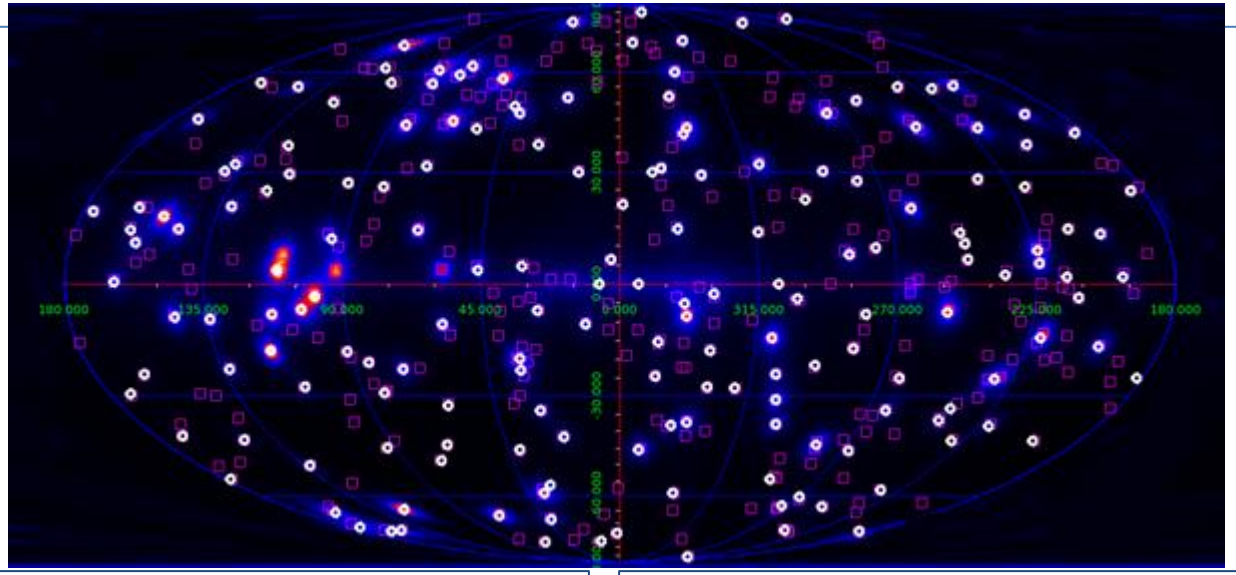


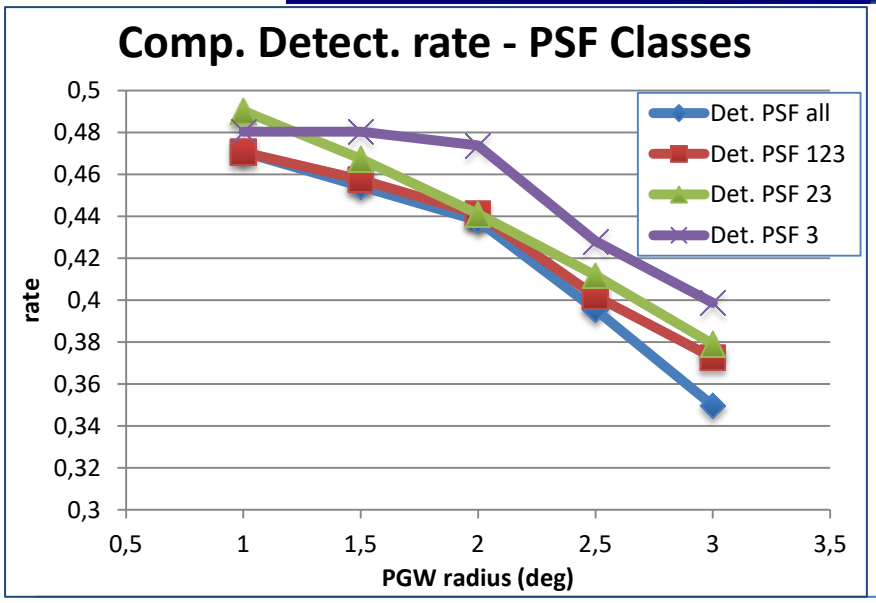


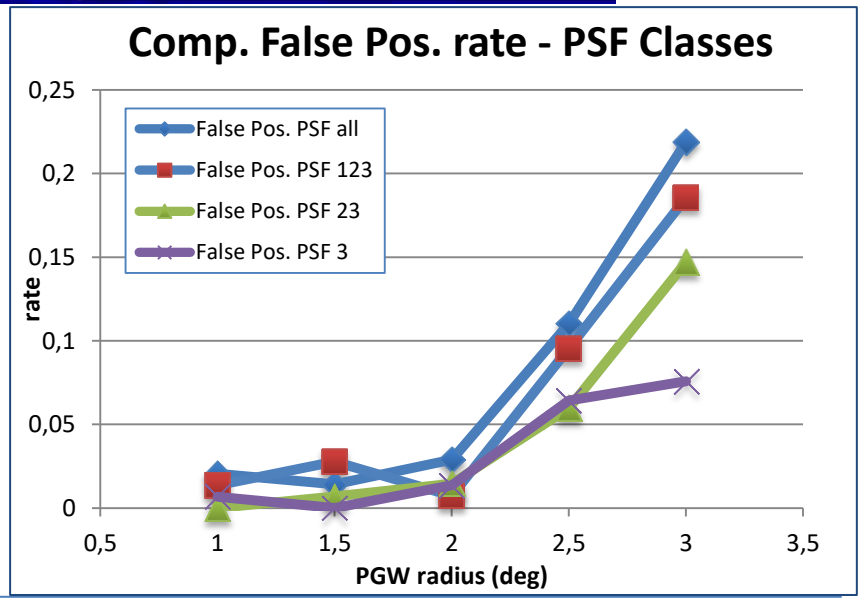


PSF Class Selection

Random PS map







Data Selection

Data Selection	Values
IRFs	P8R2_SOURCE_v6
PSF Classes	PSF3
Time Interval	8.7 years
Energy Range	[30-100 MeV] [100-300 MeV]
Zenith angle	90°

Parameter Optimization – Final Parameters

We optimized the PGWave parameters separately for the two energy bins, using the:

Setup 2 (**Random PS map**):

- 369 PS (306 PS High Latitude)
- Flux: 10^{-8} ph/cm^2/s - $10^{-4.5}$ ph/cm^2/s
- PS randomly positioned in the sky

PGWave parameters	30 – 100 MeV	100 – 300 MeV
Pixel dim.	0.5°	0.5°
N° of sigma for the statistical confidence	3	3
MH Wavelet Transform scale	2.0°	2.0°
Minimum number of connected pixels	6	6
Minimum distance between different sources	3.0°	3.0°

False Positive rate:

- < 3% in the energy bin 30-100 MeV
- < 6% in the energy bin 100-300 MeV

Syst. and Stat. Uncertainty Localization

We used 10 realization of the MC maps with random positioned PS for studying the systematical and statistical error in the localization ([30-100 MeV], {100-300 MeV].

Statistical:
for each reconstructed PS (*K*) we compute the mean and the standard deviation (sigma) of the position of the seeds from the different realization, with the mean position Xmean

$$\sigma = \sqrt{\frac{\sum (X_{PGW_i} - X_{PGW_{mean}})^2}{n}} \qquad \sigma_k = \frac{\sigma}{\sqrt{n-1}}$$

where n is the number of PGWave seeds associated at this reconstructed PS (input PS).
Our statistical Unc. is the mean of all the single sigma_k of each reconstructed PS

$$\sigma_{stat} = \sqrt{\frac{\sum_k \sigma_k^2}{k}}$$

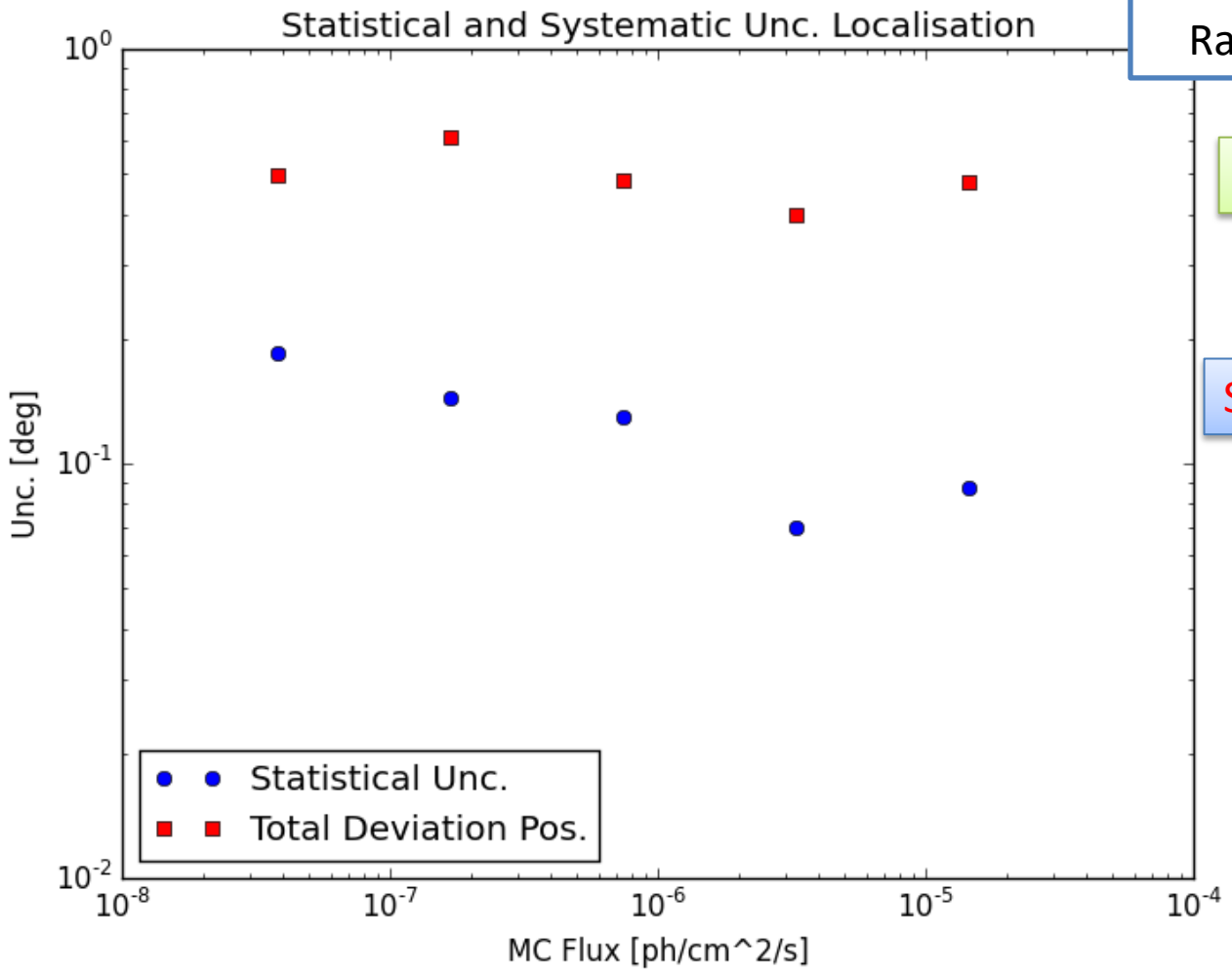
Total Deviation in the Position (Systematic)
We compute the difference between the mean position for the seeds of the same reconstructed PS and the position of the input PS:

$$\Delta_k = X_{PGW_{mean}} - X_{IN}$$

Then for all the reconstructed PS

$$\sigma_{DEV} = \sqrt{\frac{\sum \Delta_k^2}{k}}$$

Syst. and Stat. Uncertainty Localization

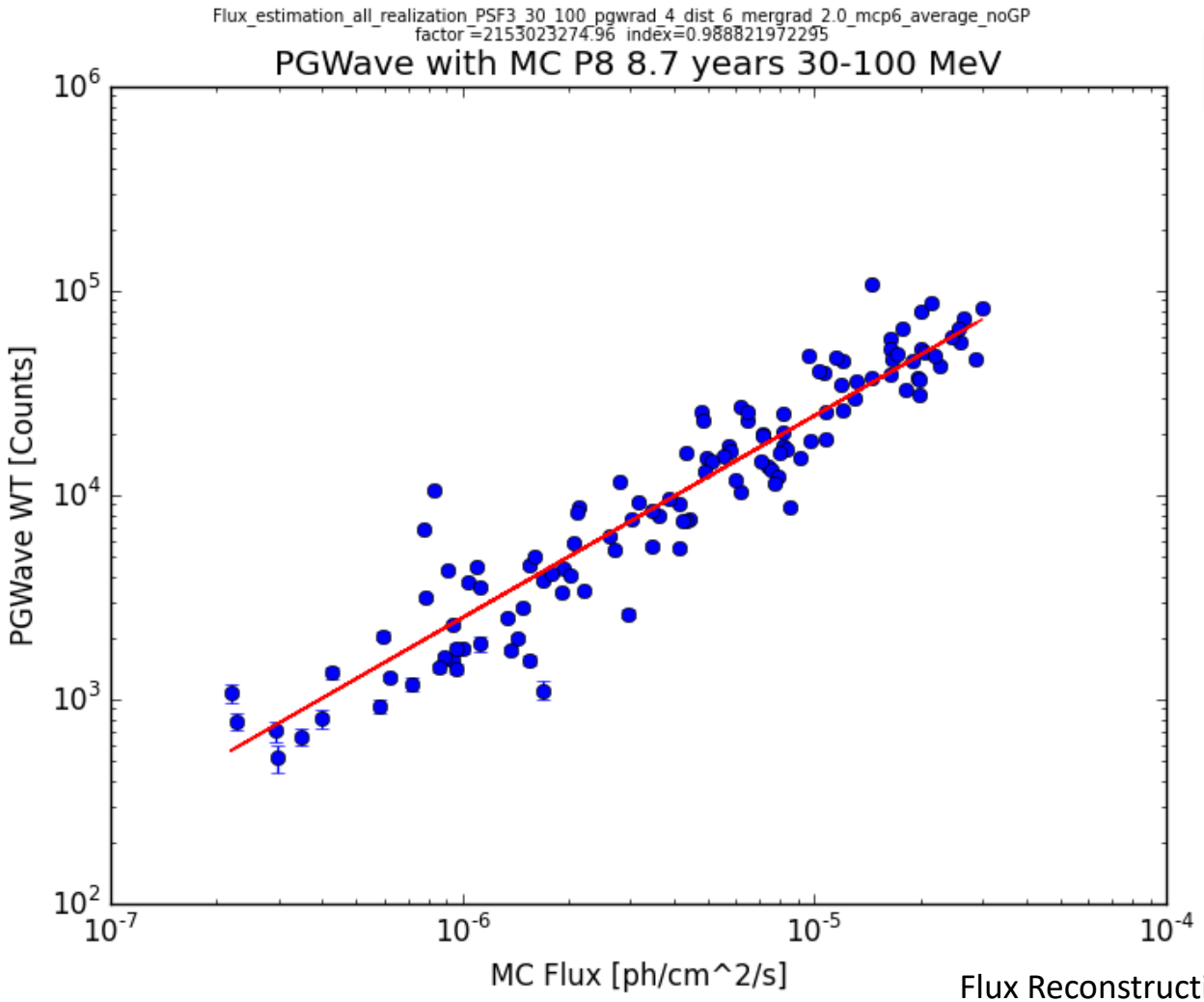


Using 10 realizations
Random PS maps

30 -100 MeV

Syst. Unc 0.5°

Flux Determination



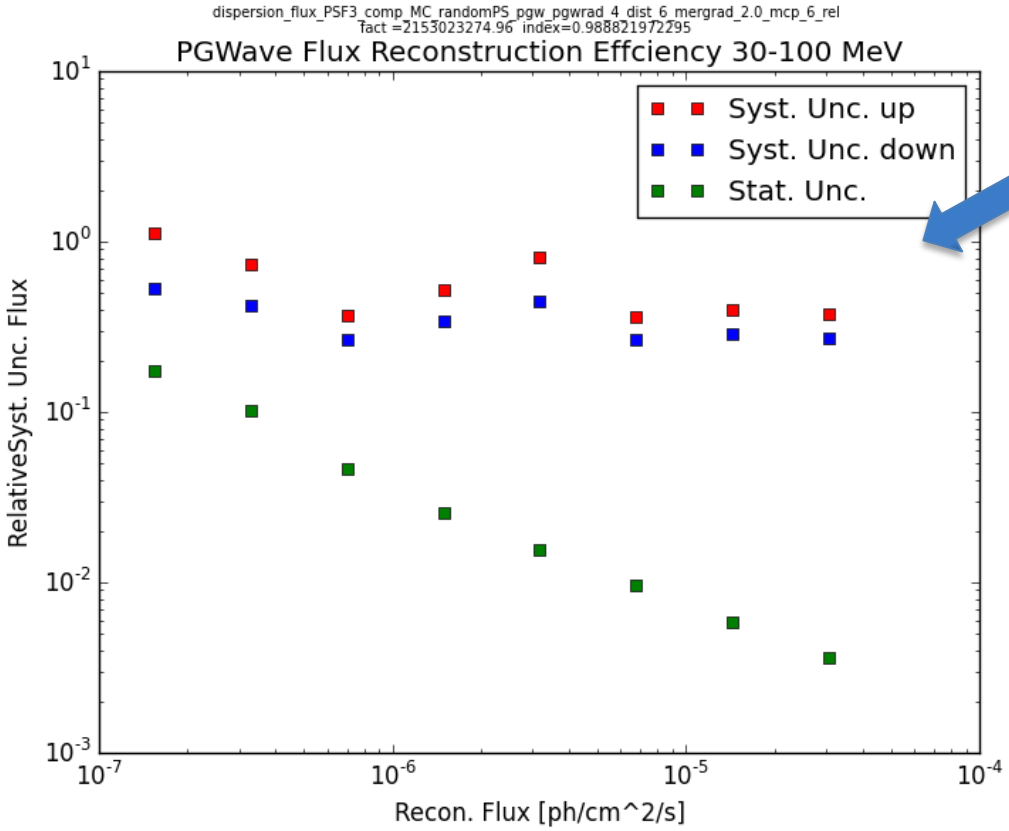
30 – 100 MeV

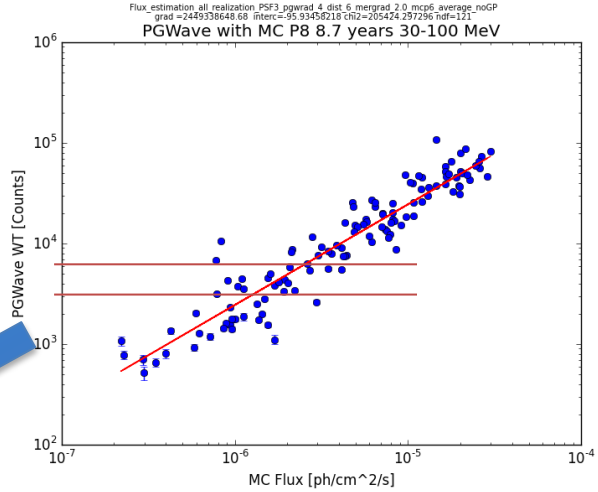
Flux Reconstruction with PGWave

arXiv:1610.01351v2

Stat. and Syst. Unc. Flux Reconstruction

To derive the Syst. Unc. of the Flux Reconstruction, we divide the sources in bins of WT peak, then we estimate the mean distance, inside each bin, between the Input MC Flux and the PGWave best fit. (Stat. Unc. given by PGWave)

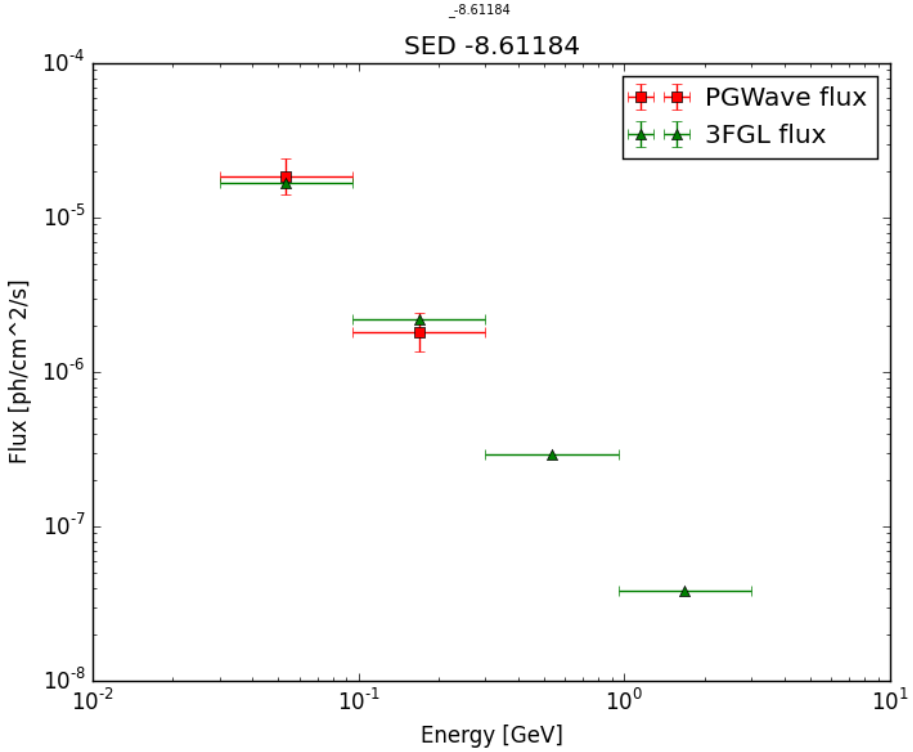


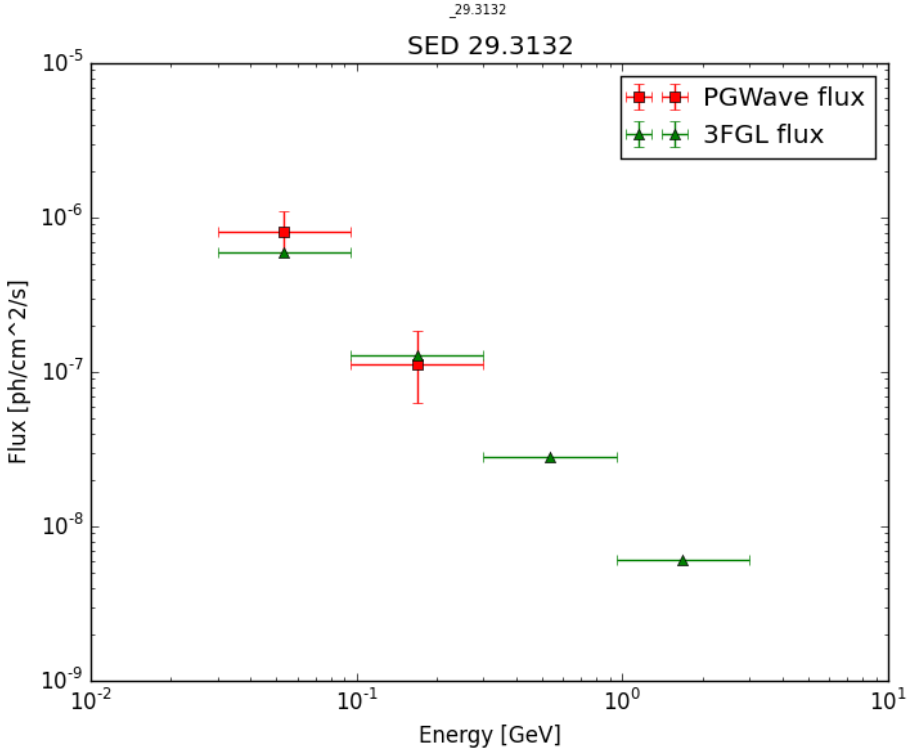


Relative Stat. and Syst. Unc of Flux estimation 30 – 100 MeV

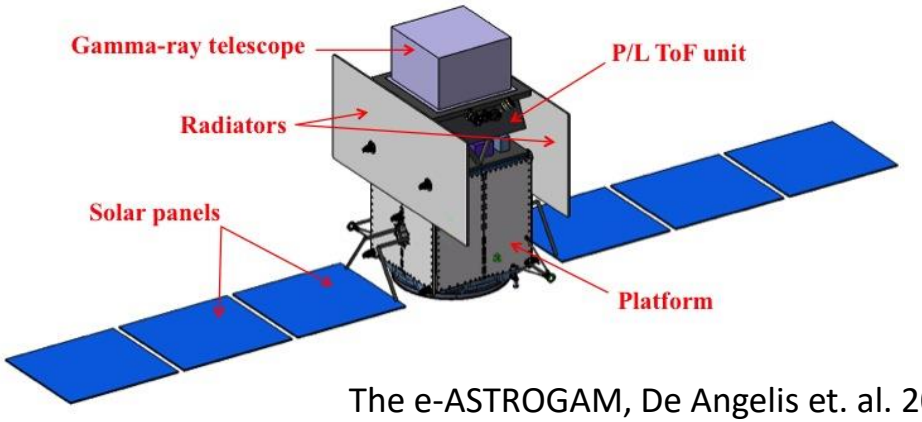
Plot Spectra: test Flux Reconstruction

Two examples of SED to check the flux reconstruction.

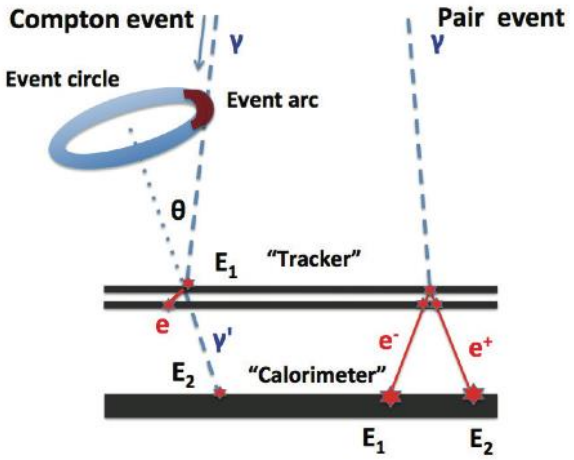


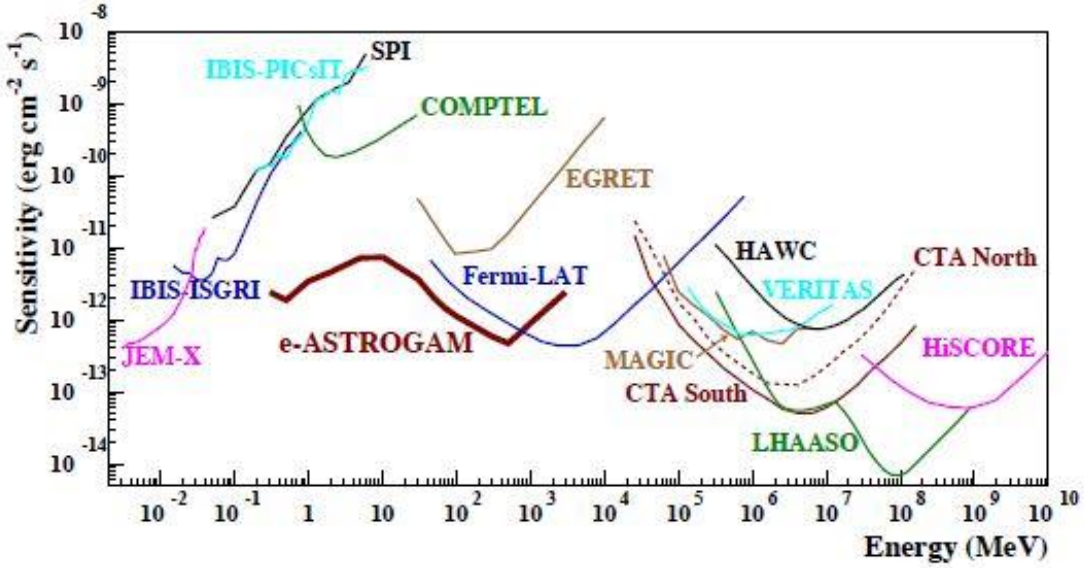


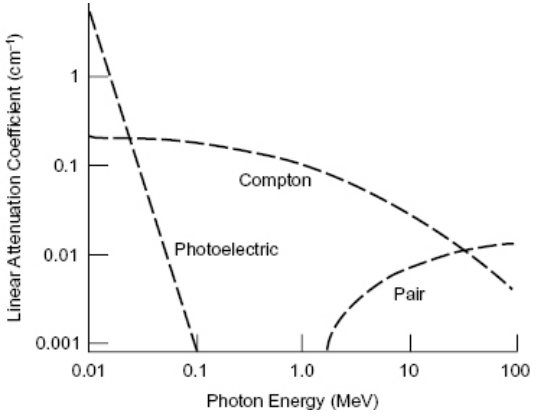
Outlook: e-ASTROGAM



The e-ASTROGAM, De Angelis et. al. 2017







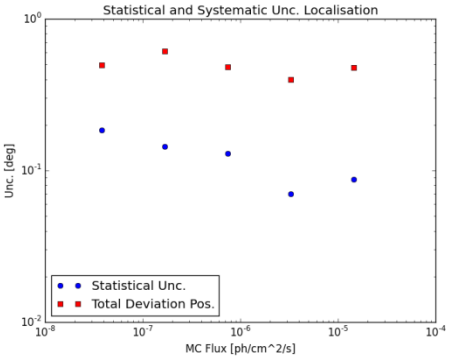
Summary

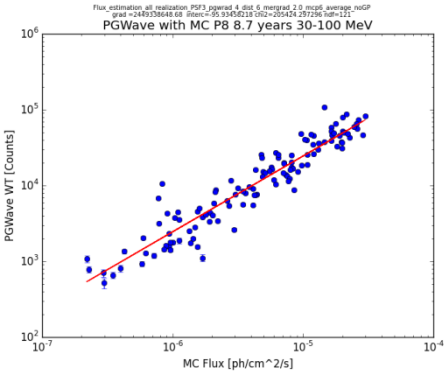
1. Data Selection: We compared different data selection(PSF classes) and we chose to use: P8R6_Source_v2 **PSF3**

2. Optimization Parameter: We optimized the PGWave parameters setup to maximize detection rate and minimize the false positive.

3. Using the 10 realization maps, we estimate the Stat. and Syst. Unc. Source Localization

4. Flux Reconstruction:
   - We reconstruct the flux using the WT peak
   - We estimate the Stat. and Syst. Unc. for flux reconstruction
   - We check the SED of the simulated PS





Results of the Fermi Low Energy Catalog will be presented at the 7th Fermi Symposium, 15-20 October 2017, Garmisch (Germany).

Thanks for your attention

Backup Slides

What does Fermi see?

Diffuse emission

- CR interaction with gas and IRF

Galactic sources

- SNRs
- Pulsars
- PWNe

Extragalactic sources

- Mostly AGN
- Many unidentified

Dark matter search

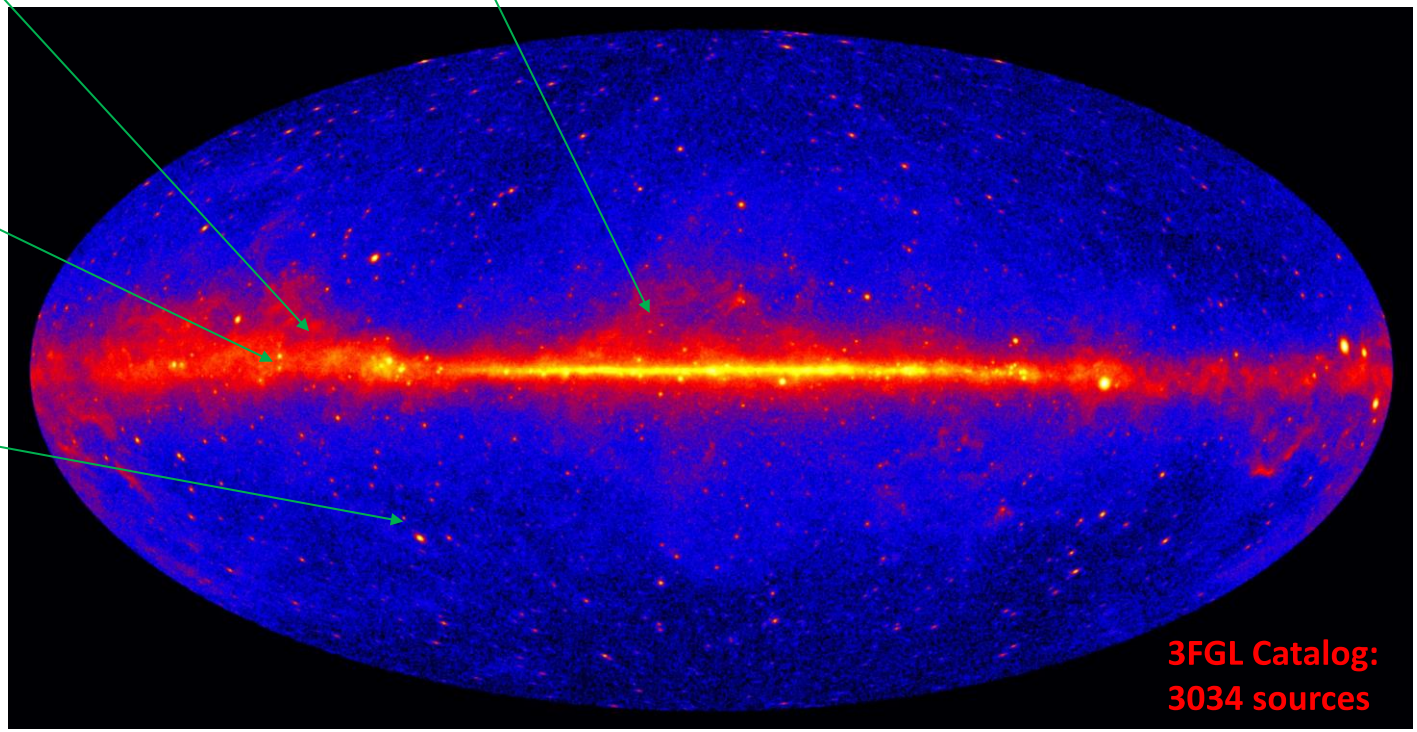
- Dwarf Spheroidal Galaxies
- Galactic center

Solar system

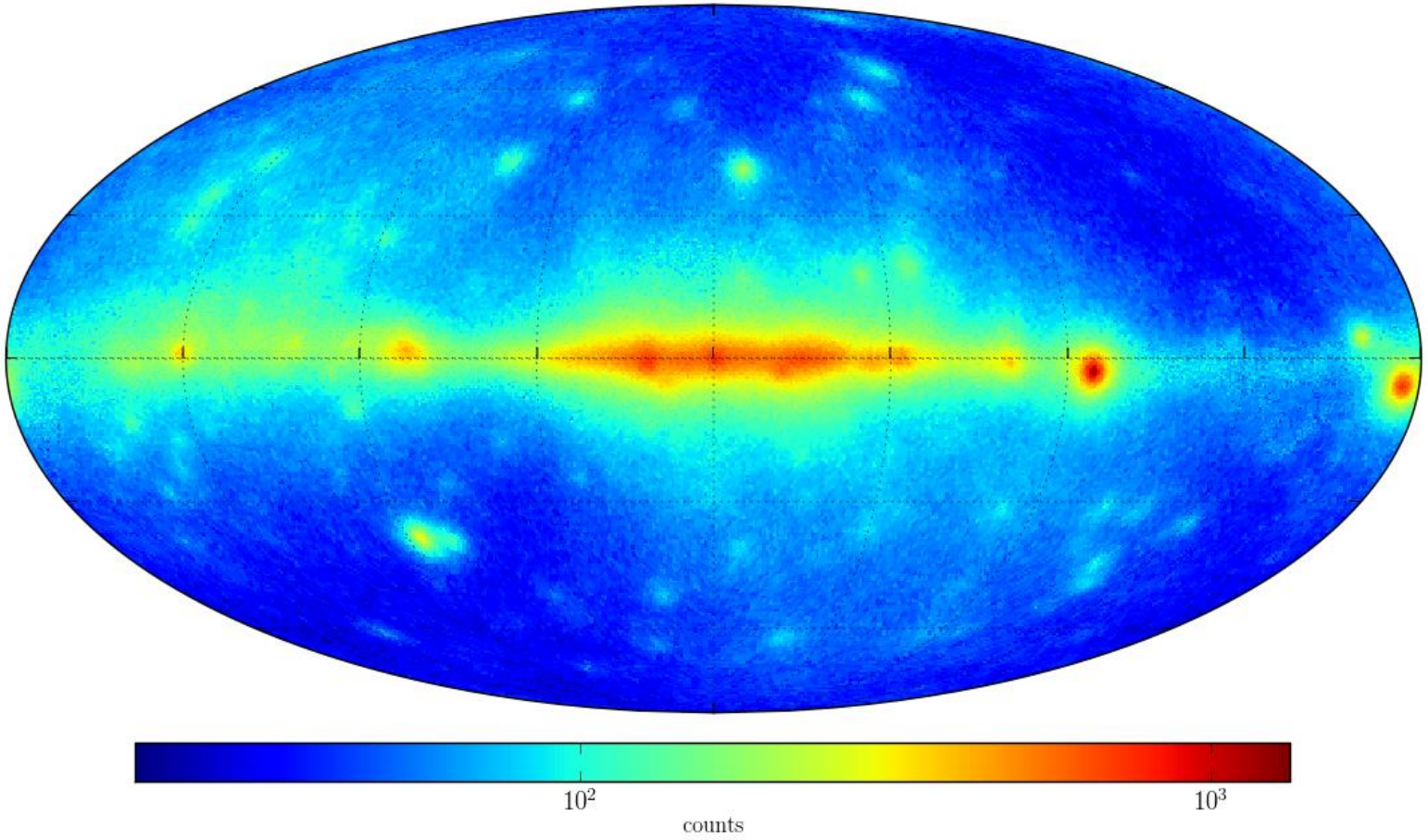
- Sun
- Moon

Transients

- GRBs
- Solar flares
- GW?

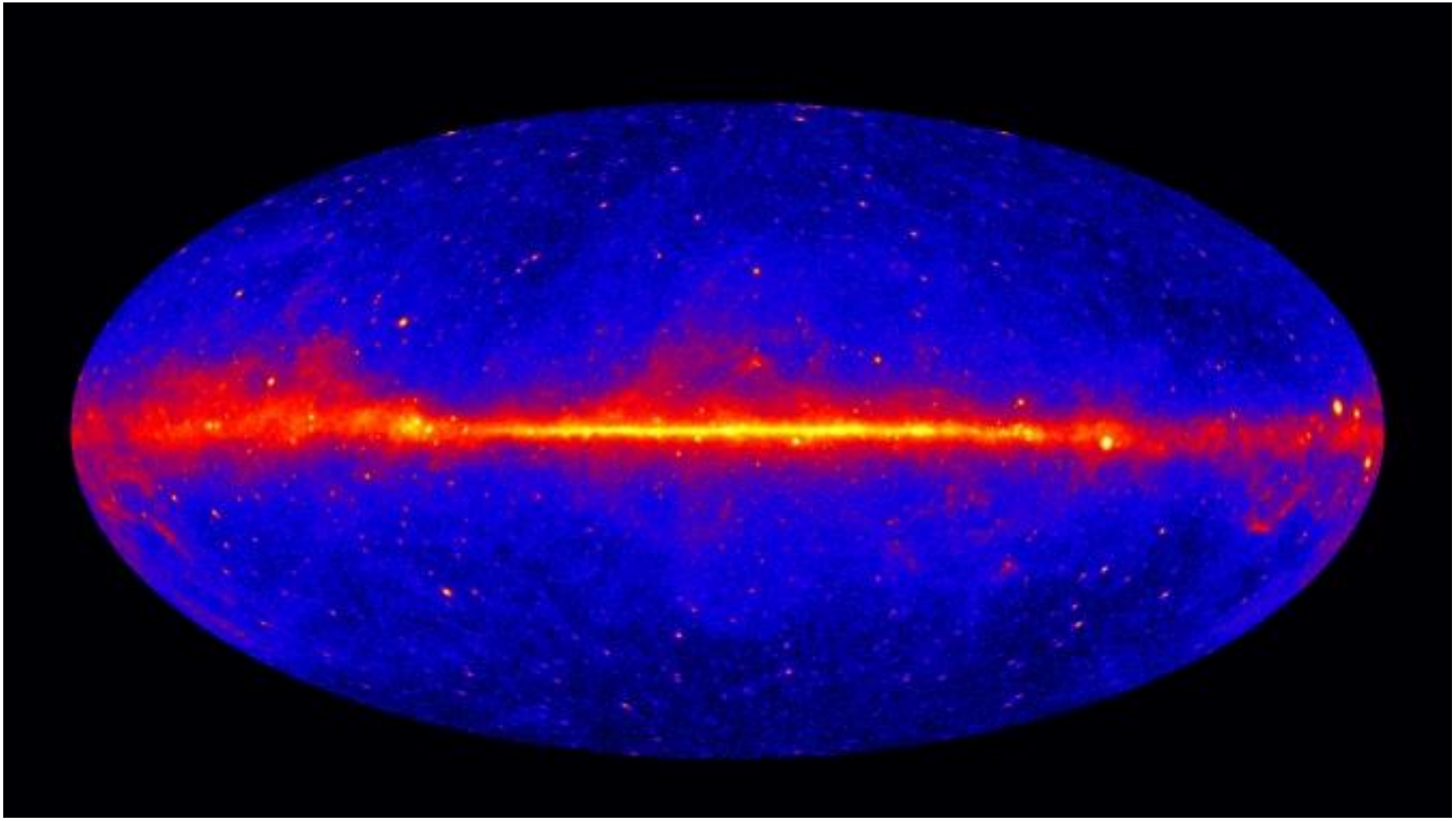


Fermi Low Energy Catalog



Fermi Sky, counts map 30-100 MeV

Fermi-LAT Sky



Fermi LAT Sky at energies greater than 1 GeV (5 years)

Parameter Optimization

PGWave parameters	Values	Step
Pixel dim.	0.5°	-
N° of sigma for the statistical confidence	3	-
MH Wavelet Transform scale	1.0° - 3.0°	0.5°
Minimum number of connected pixels	3 - 7	1 Pixel
Minimum distance between different sources	2.0° - 3.0°	0.5°
Total Combinations	150*	

*We varied also the "merging radius": tolerance radius for merging the seeds from different ROIs.

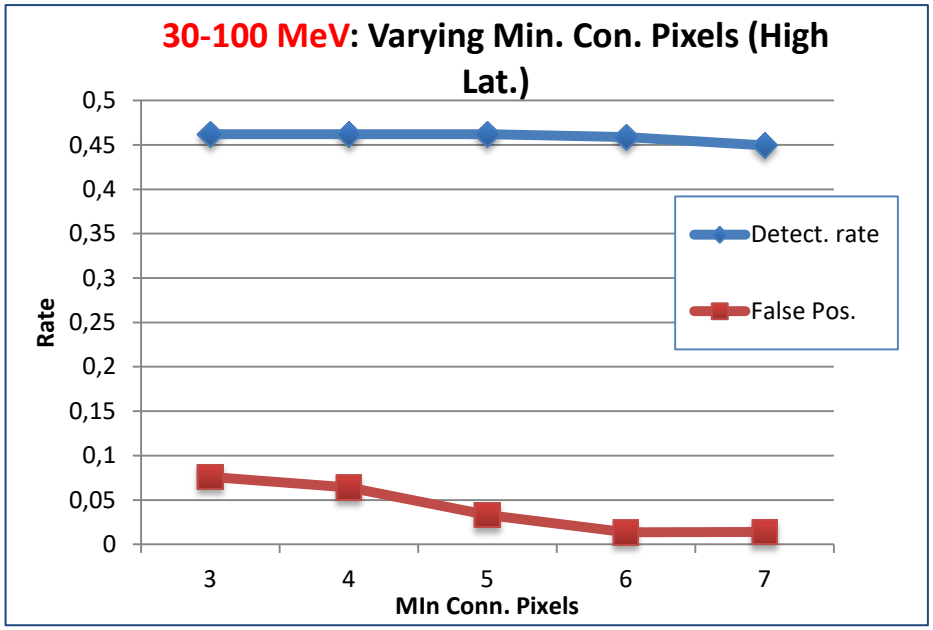
We optimized the PGWave parameters separately for the two energy bin, using the:

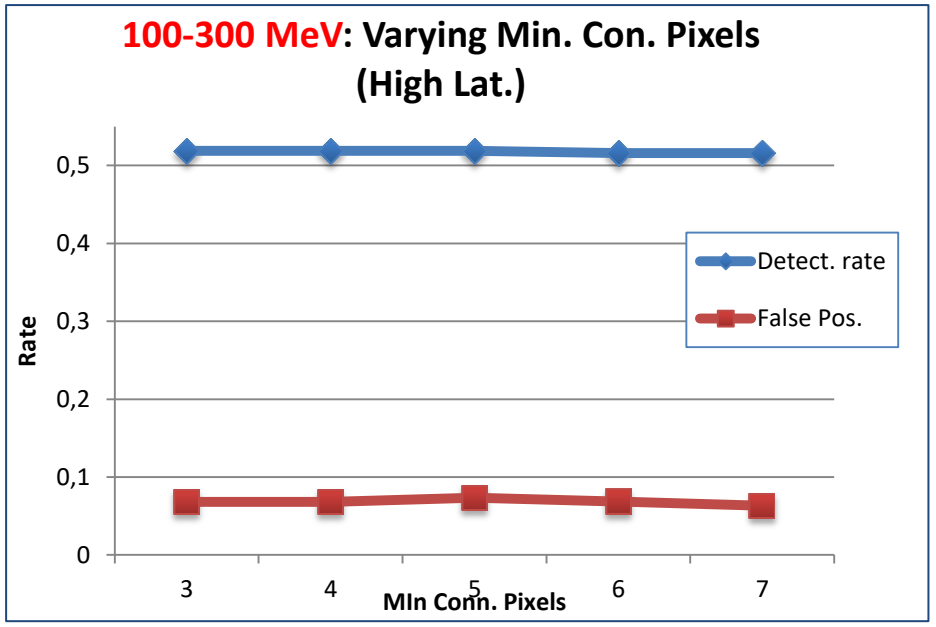
Setup 2 (**Random PS map**):

- 369 PS (306 PS High Latitude)
- Flux: 10^{-8} ph/cm^2/s - $10^{-4.5}$ ph/cm^2/s
- PS randomly positioned in the sky

PGW Par. Optimization – Min. N. Conn. Pix

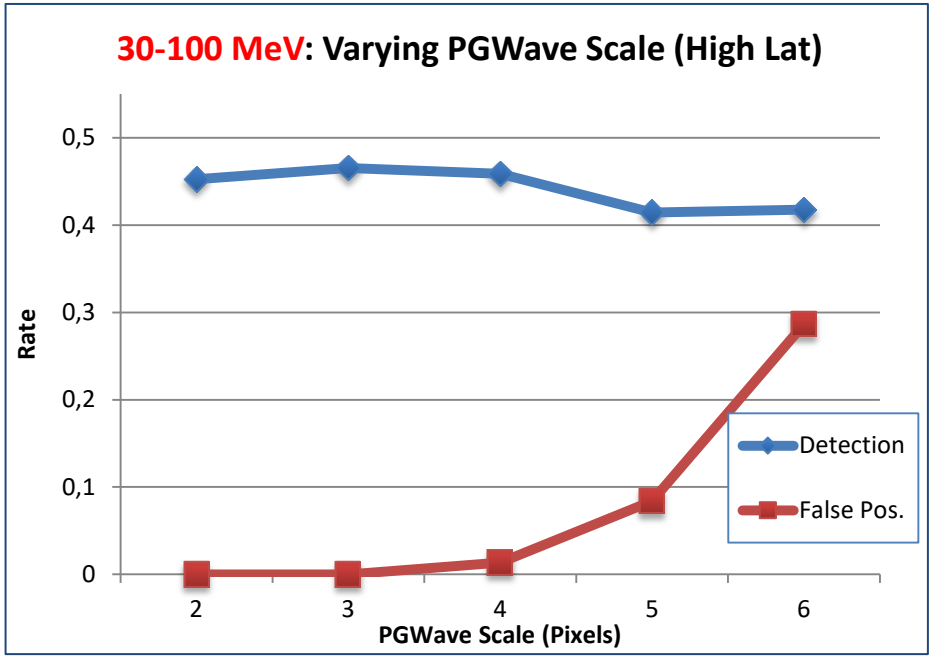
Example of optimizing the minimum number of connected pixels.

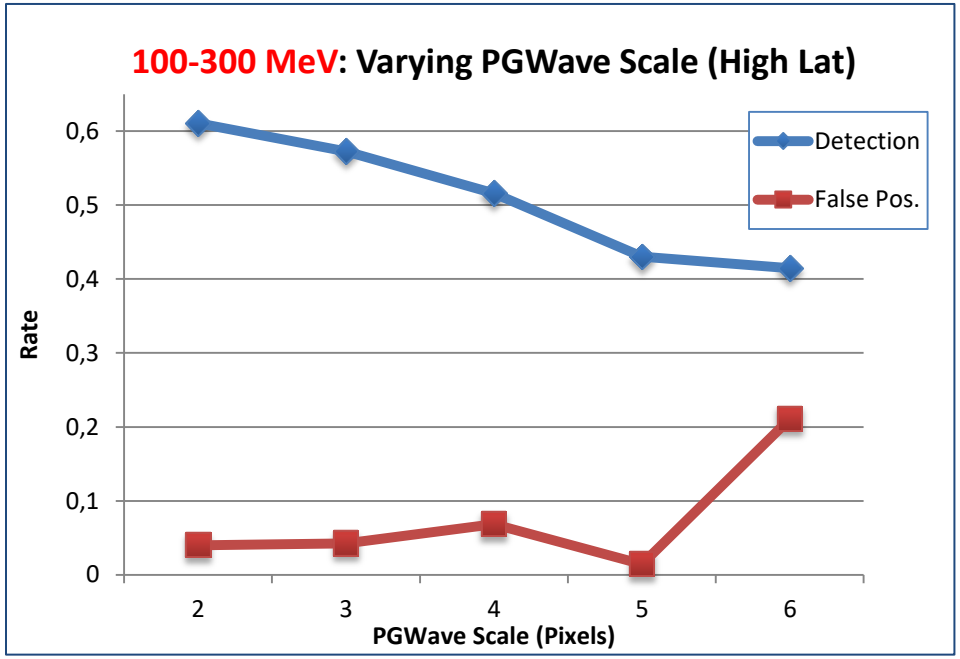




PGW Par. Optimization – WT scale

Example of optimizing the Wavelet Transform scale.

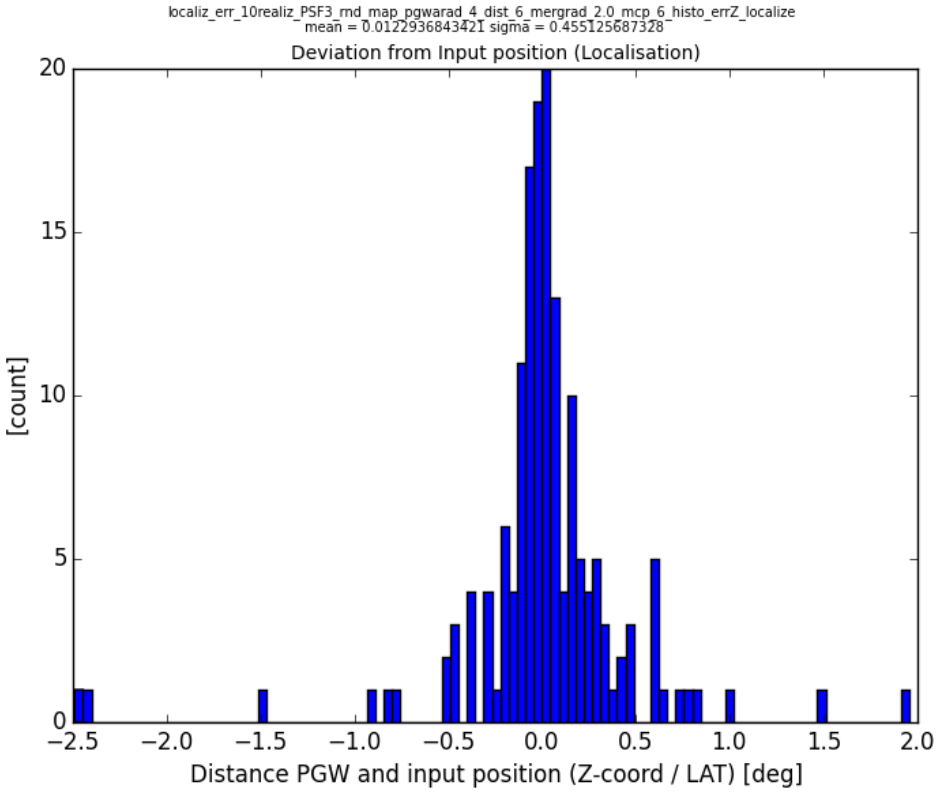


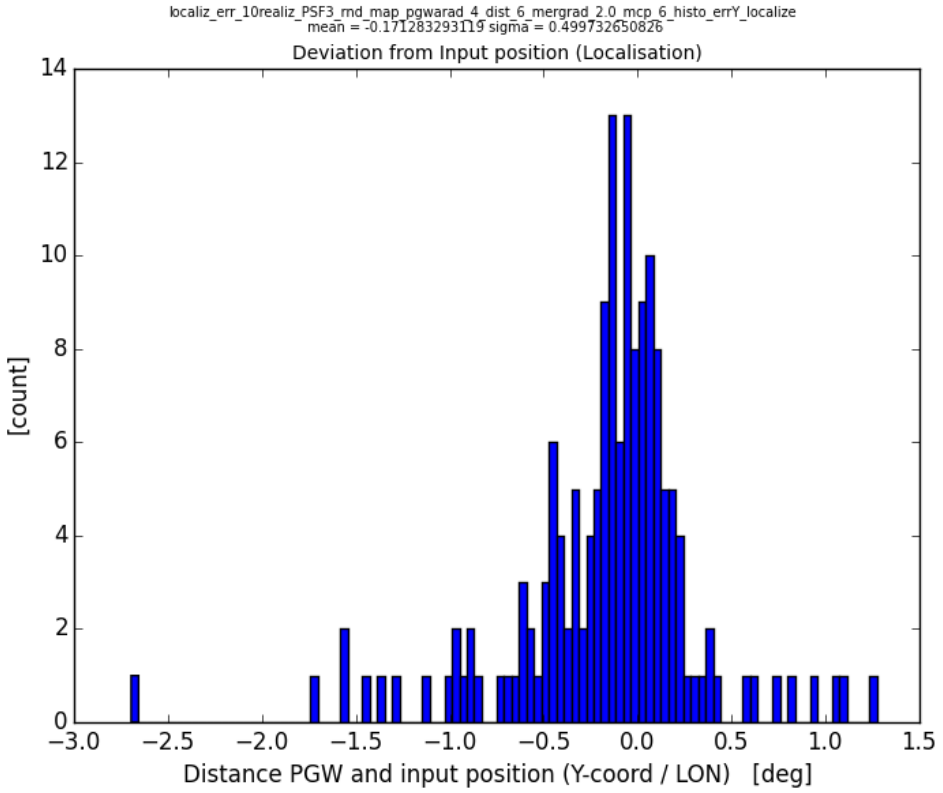


Syst. and Stat. Uncertainty Localization

30 -100 MeV

Random PS maps



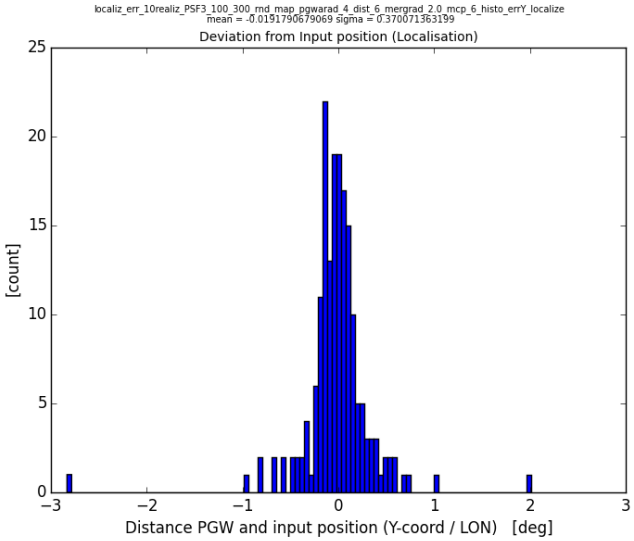


Dispersion in Latitude

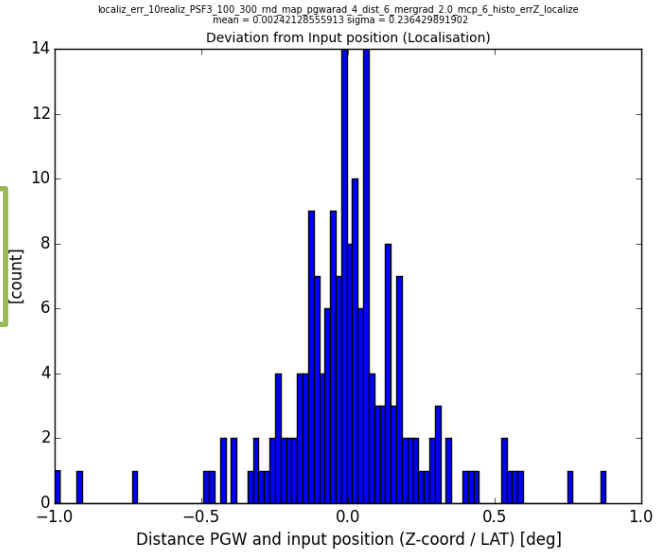
Dispersion in Longitude

Syst. and Stat. Uncertainty Localization

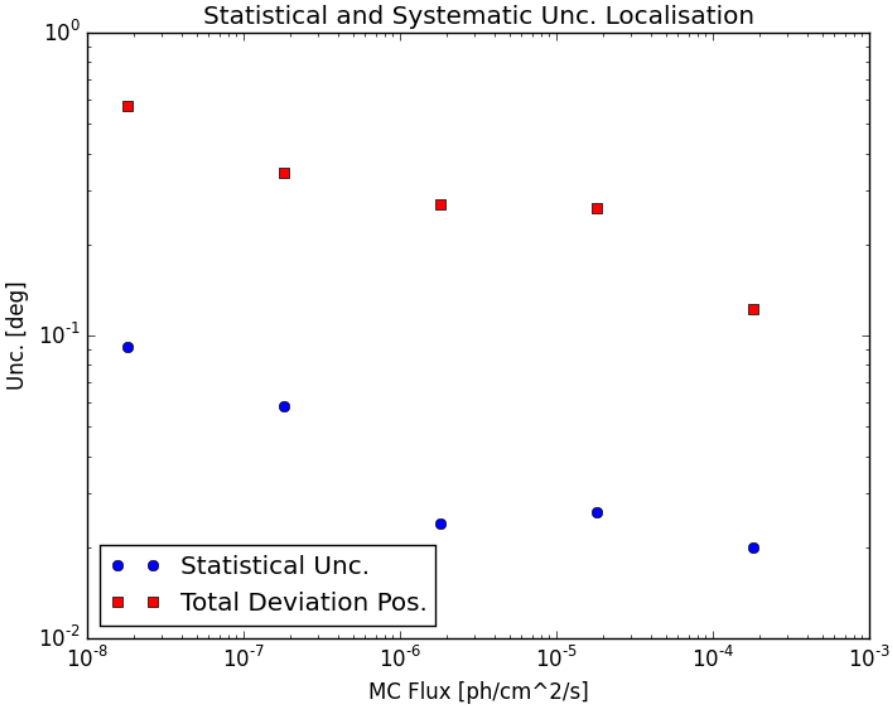
Dispersion in Longitude



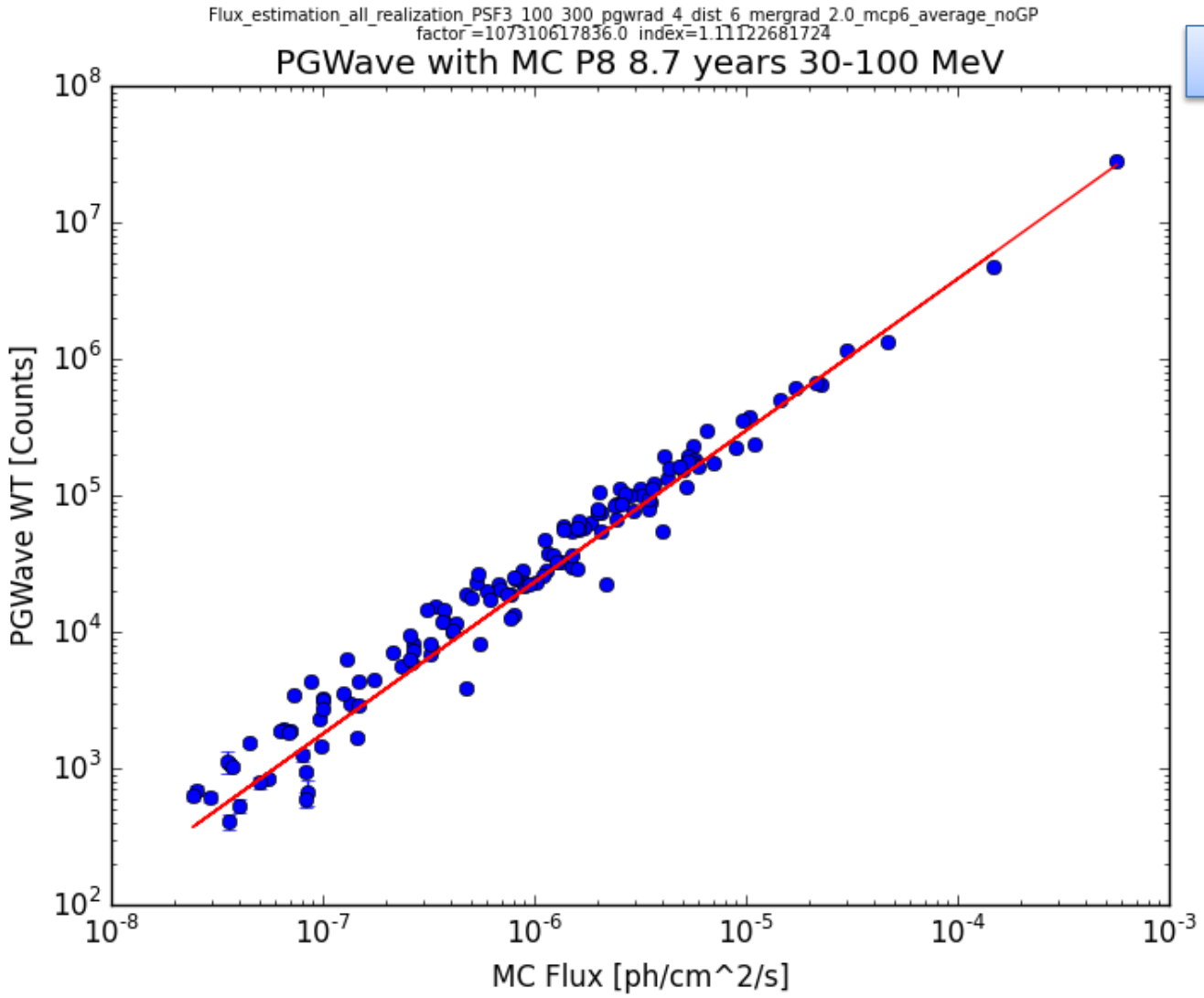
Dispersion in Latitude



Energy bin
100 – 300 MeV

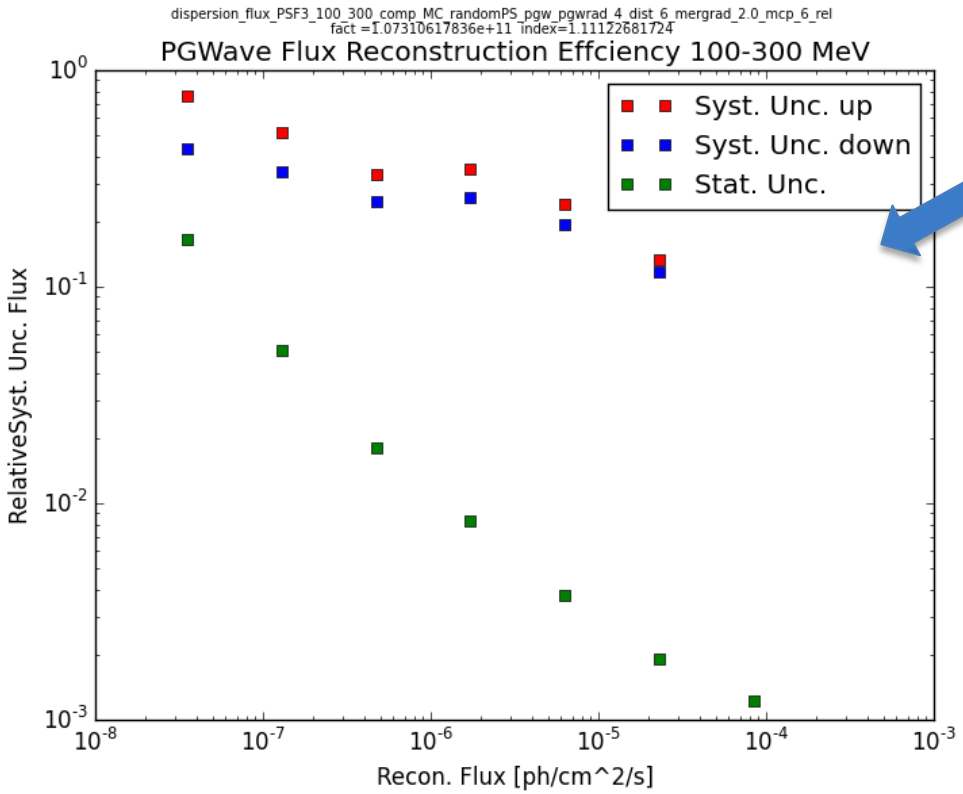


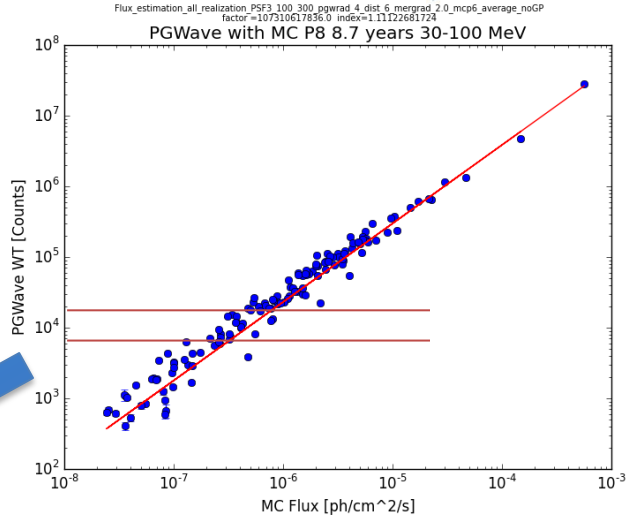
Flux Determination



100 – 300 MeV

Stat. and Syst. Unc. Flux Reconstruction





Relative Stat. and Syst. Unc of Flux estimation 100 – 300 MeV