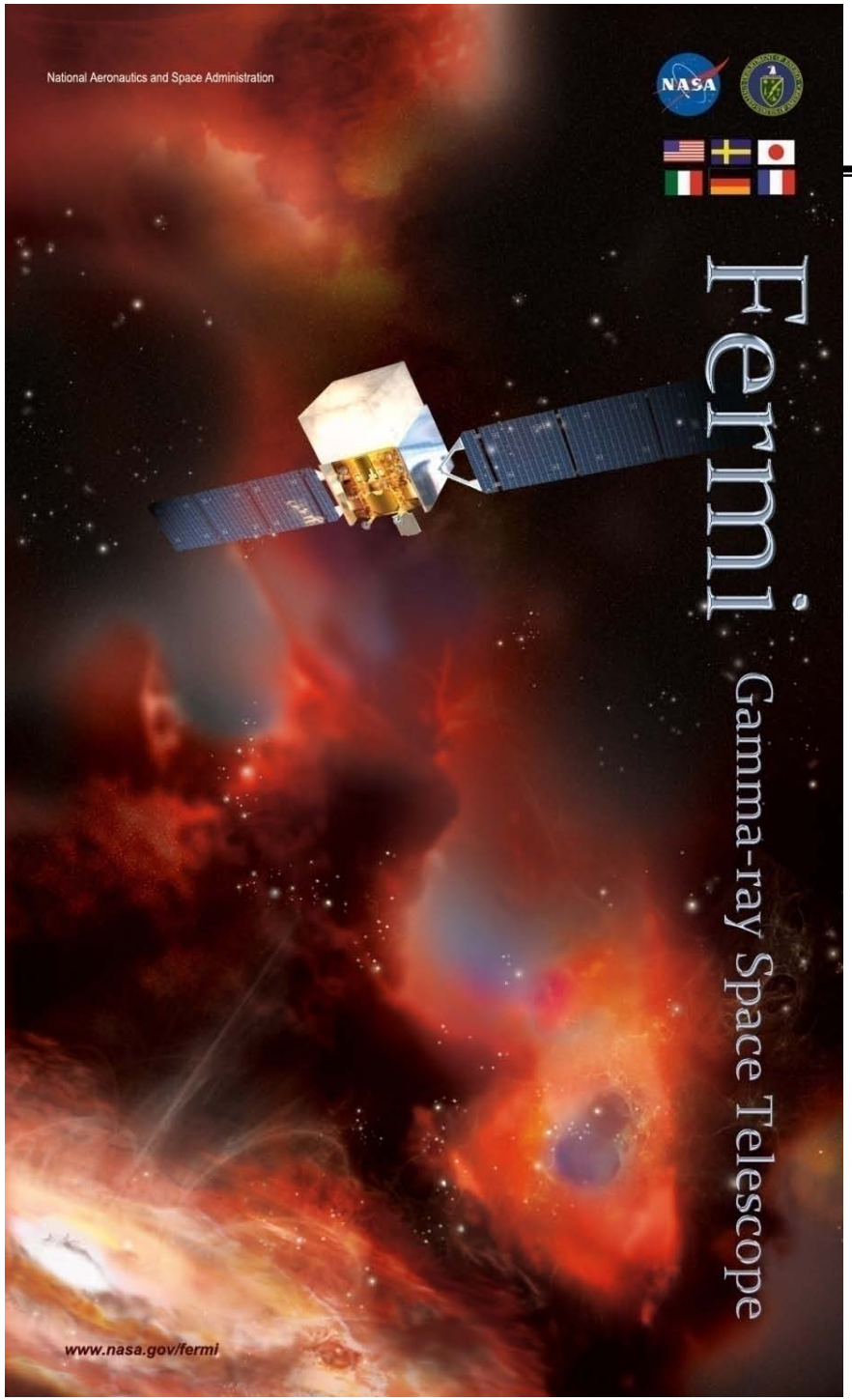


2FGL: The Second Fermi LAT Catalog

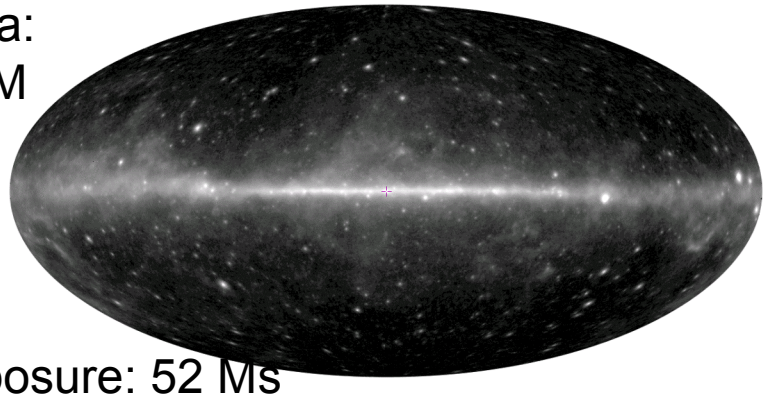
Construction and Content

Toby Burnett
University of Washington
For the *Fermi*-LAT collaboration

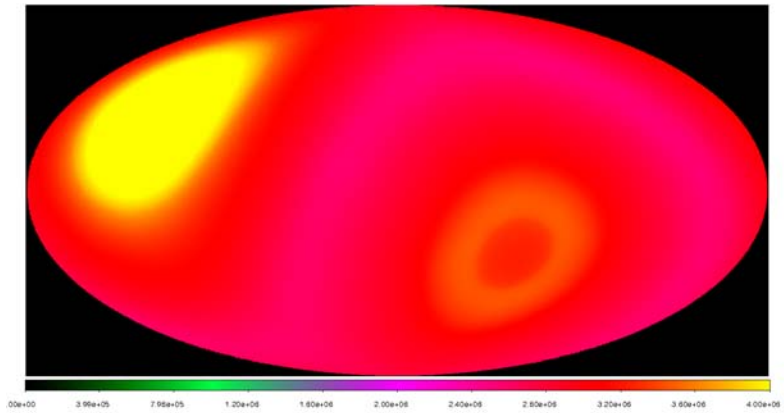
2011 Fermi Symposium
Rome, Italy
May 9, 2011

The Basic task: find sources in the photon data

Data:
28 M



Exposure: 52 Ms



Two years (excluding 3 GRBs)
"Pass7 processing"

NEW

NEW

[1FGL: 11 months]

2FGL Table

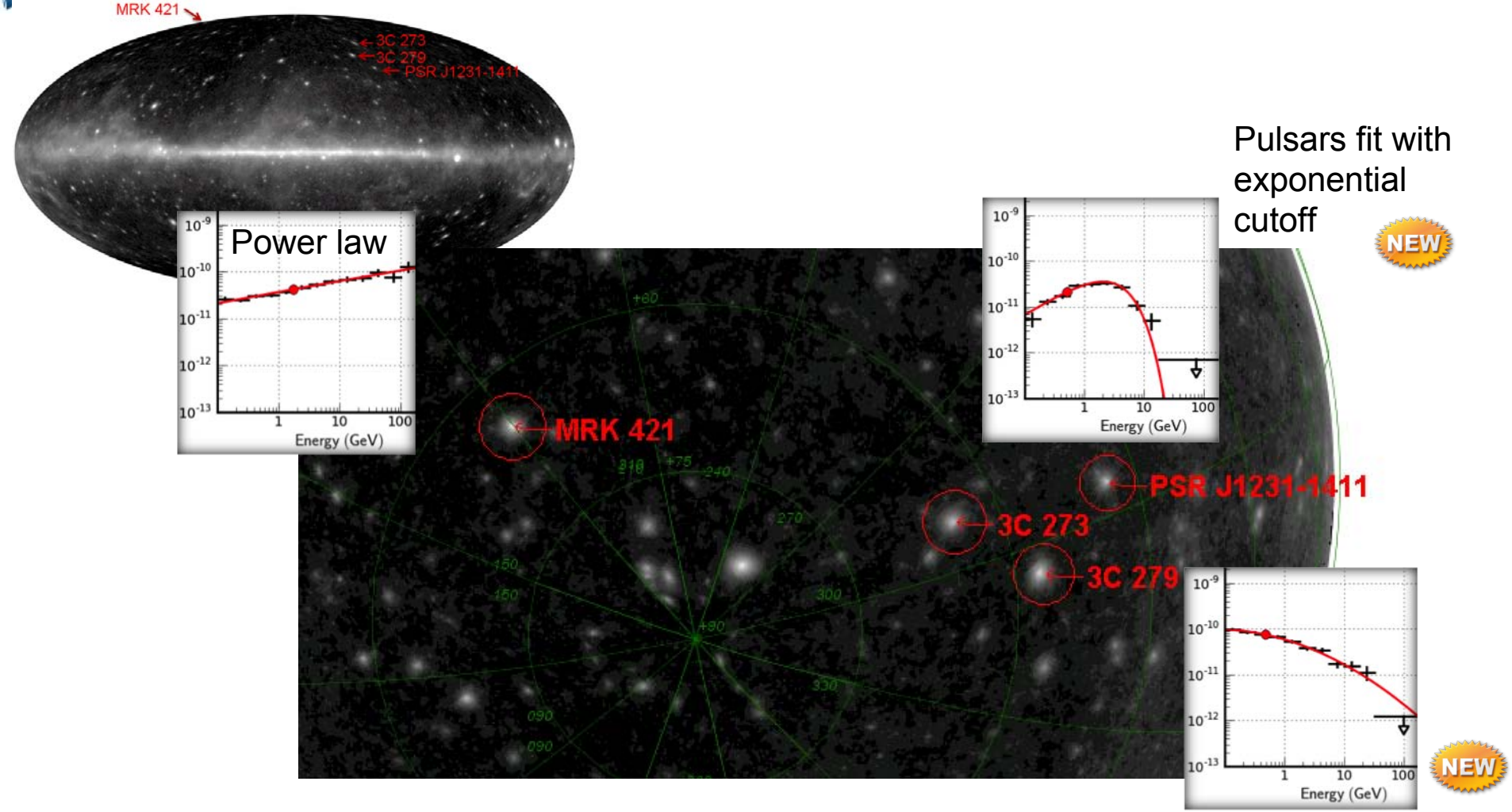
1888 entries
[1FGL: 1451]

preliminary

	Source_Name	NickName	RAJ2000	DEJ2000	
1	2FGL J0000.9-0748	P72Y0002	0.233711	-7.8155	8
2	2FGL J0001.7-4159	P72Y0005	0.438	-41.9965	334
3	2FGL J0002.7+6220	P72Y0008	0.	3396	117
4	2FGL J0004.2+2208	P72Y0013		365	108
5	2FGL J0004.7-4736	P72Y0015			323
6	2FGL J0006.1+3821	P72Y0016	1.		113
7	2FGL J0007.0+7303	PSRJ0007+7303	1.7735		
8	2FGL J0007.7+6825	P72Y0024	1.92505		
9	2FGL J0007.8+4713	P72Y0025	1.97432	4	
10	2FGL J0008.7-2344	P72Y0027	2.19605	-23.7	
11	2FGL J0009.0+0632	P72Y0028	2.26231	6.54235	
12	2FGL J0009.1+5030	P72Y0030	2.2914	50.5062	
13	2FGL J0009.9-3206	P72Y0031	2.48449	-32.1118	
14	2FGL J0010.5+6556	P72Y0034	2.64068	65.9339	118
15	2FGL J0011.3+0054	P72Y0036	2.82765	0.903578	102
16	2FGL J0012.9-3954	P72Y0040	3.24638	-39.9005	332
17	2FGL J0013.8+1907	P72Y0043	3.46375	19.126	110
18	2FGL J0014.3-0509	P72Y0045	3.58116	-5.15295	95
19	2FGL J0017.4-0018	P72Y0054	4.364	-0.302	104
20	2FGL J0017.6-0510	P72Y0055	4.40364	-5.18249	101
21	2FGL J0018.5+2945	P72Y0057	4.63305	29.7602	114
22	2FGL J0018.8-8154	P72Y0058	4.71587	-81.9027	304
23	2FGL J0019.4-5645	P72Y0059	4.85732	-56.7558	311
24	2FGL J0021.6-2551	P72Y0063	5.41178	-25.852	42
25	2FGL J0022.2-1853	P72Y0064	5.55909	-18.8884	82
26	2FGL J0022.3-5141	P72Y0065	5.59589	-51.6913	313
27	2FGL J0022.5+0607	P72Y0066	5.64299	6.12368	110
28	2FGL J0023.2+4454	P72Y0068	5.81783	44.9046	117
29	2FGL J0023.5+0924	P72Y0069	5.89215	9.40666	111
30	2FGL J0023.9-7204	P72Y0070	5.98558	-72.0825	305
31	2FGL J0024.5+0346	P72Y0073	6.14599	3.78296	110
32	2FGL J0029.2-7043	P72Y0082	7.30062	-70.7255	305
33	2FGL J0030.2-4223	P72Y0085	7.57263	-42.3863	317
34	2FGL J0030.4+0450	PSRJ0030+0451	7.60105	4.83868	113
35	2FGL J0031.0+0724	P72Y0090	7.775	7.414	114
36	2FGL J0032.7-5521	P72Y0094	8.17868	-55.3563	308
37	2FGL J0033.5-1921	P72Y0096	8.39111	-19.357	94
38	2FGL J0034.4-0534	PSRJ0034-0534	8.61312	-5.58218	111
39	2FGL J0035.2+1515	P72Y0098	8.80866	15.2583	117
40	2FGL J0035.8+5951	P72Y0099	8.96431	59.8537	120
41	2FGL J0037.8+1238	P72Y0101	9.47307	12.6449	117
42	2FGL J0038.1+0015	P72Y0102	9.54151	0.264987	115
43	2FGL J0038.3-2457	P72Y0103	9.5827	-24.9632	68
44	2FGL J0038.7-2215	P72Y0104	9.6918	-22.2522	91
45	2FGL J0038.8+6259	P72Y0106	9.72048	62.9967	121
46	2FGL J0039.1+4331	P72Y0108	9.78034	43.5271	120
47	2FGL J0042.5+4114	P72Y0112	10.633	41.245	121
48	2FGL J0043.7+3426	P72Y0116	10.9409	34.4394	121
49	2FGL J0044.7-3702	P72Y0118	11.1951	-37.0404	310
50	2FGL J0045.3+2127	P72Y0120	11.3351	21.4524	121
51	2FGL J0045.5+1218	P72Y0121	11.3964	12.3121	120
52	2FGL J0046.7-8416	P72Y0123	11.6926	-84.27	303

+ Light curves, SED plots, associations

Strong source high latitude example: SED plots



Pulsars fit with exponential cutoff

NEW

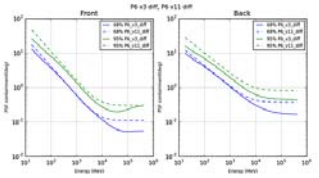
NEW

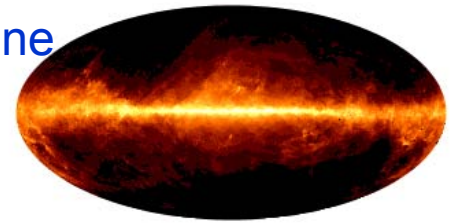
Circles are 3°, 100 MeV PSF ('front' section)
(varies by a factor of 30 with energy!)

Use log parabola if better fit

Measuring point source properties: maximize likelihood

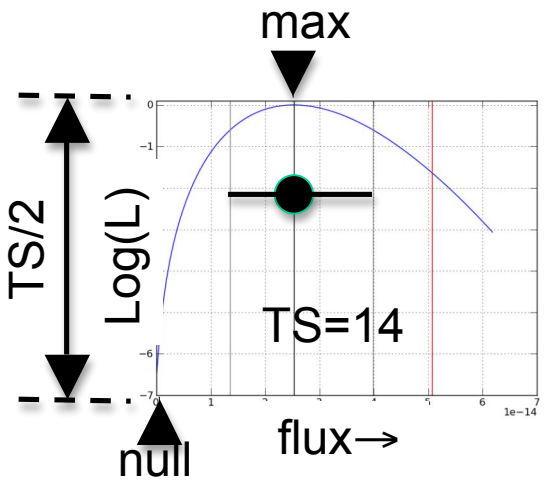
- Model of the sky must account for *all* photons NEW
  - PSF (poster by Roth, Rando, Wood)
  - Aeff (poster by Ackermann, Atwood, Rando)
  - Galactic, isotropic diffuse including CR (talk by J-M Casandjian) 1/8 degree grid, pixels centered on plane
  - Earth limb

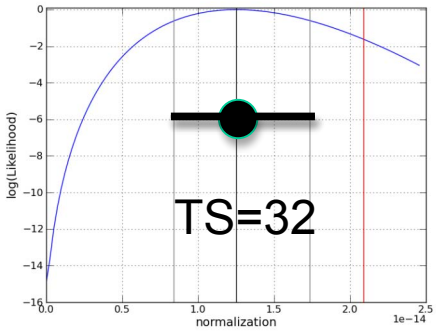


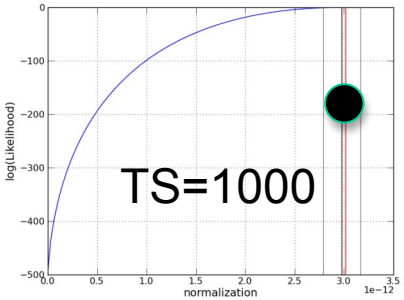


- An important issue: how to measure significance?

  Test Statistic: $TS=-2\log(L_{fit}/L_{null})$







- We conservatively choose only sources with TS>25.

Detecting sources

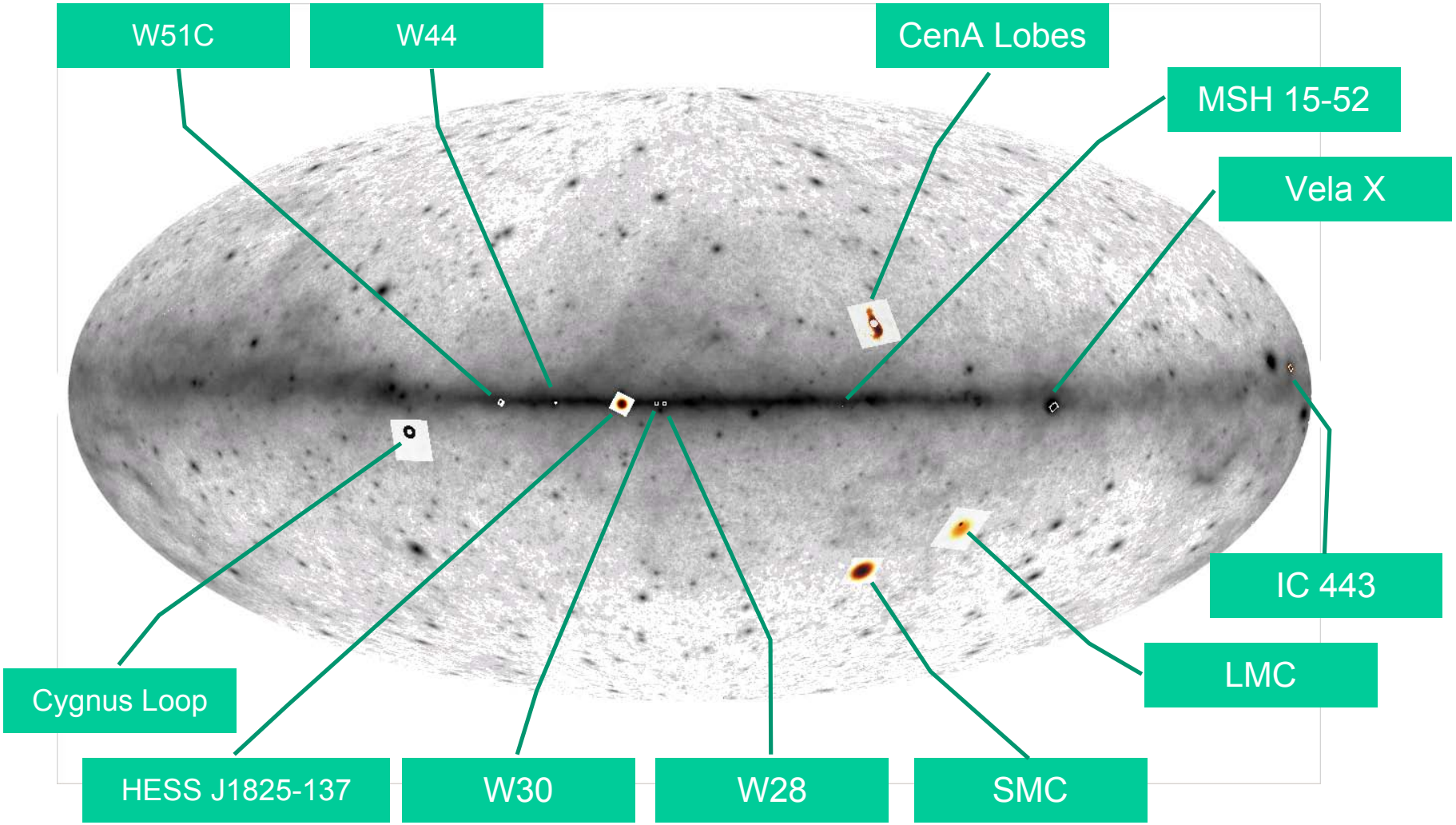
- Initial list: use 1FGL supplemented with:
  - PGWave, MRfilter: image based
  - MST (minimal spanning tree): pattern of high energy photons
- Likelihood, using current model NEW
  - Test each of 3.1 M 0.1° deg pixels with a trial point source, (index 2), record the corresponding TS.
  - Look for clusters with max TS>10, use as seed for new iteration
- Efficiency checks:
  - Test with Monte Carlo – generated sources
  - Recheck by applying PGWave

The 2FGL process: Stage I

Use the *pointlike* tool applied between 100 MeV and 300 GeV.

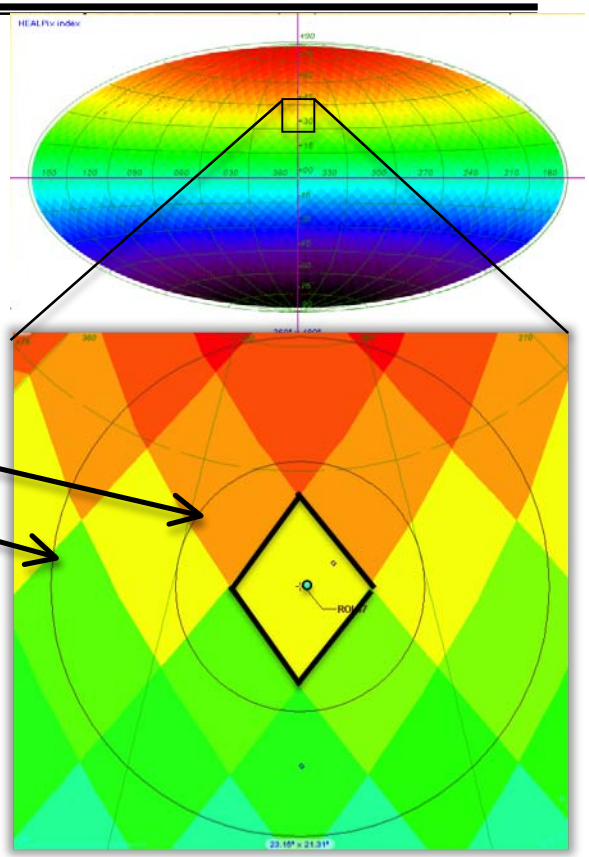
- Initial list: use 1FGL as seeds supplemented with:
  - PGWave, MRfilter: image based
  - MST (minimal spanning tree): pattern of high energy photons
- Create model with point and extended sources, galactic, isotropic and limb diffuse
  - Require exponential cutoff for all LAT pulsars, use log parabola if improves fit
- Fit the entire sky including updating positions (procedure detailed below)
- Create 'residual TS' map:
  - TS for new point source (index 2) at each of 3.1M 0.1° pixels
  - Look for clusters with max TS>10, use as seeds in new model
- Provide all with TS>10 to stage II

Extended source templates



Details about the sky model

- Tessellate sky using HEALPix: 1728 regions
- Each ~5° square pixel defines:
  - Center of circular regions for:
    - data (5 deg)
    - sources (10 deg)
  - sources inside are varied; those outside fixed to results of previous iteration
  - Note ~x3 overlap of data: not independent
- Diffuse component normalizations free
- Iteration procedure:
  - Each region fit (full likelihood maximized) independently
  - Each fit remeasures point source positions: Apply updates between cycles.
  - Check changes in log(L): iterate until none changes by more than 10 (8-10 iterations required)

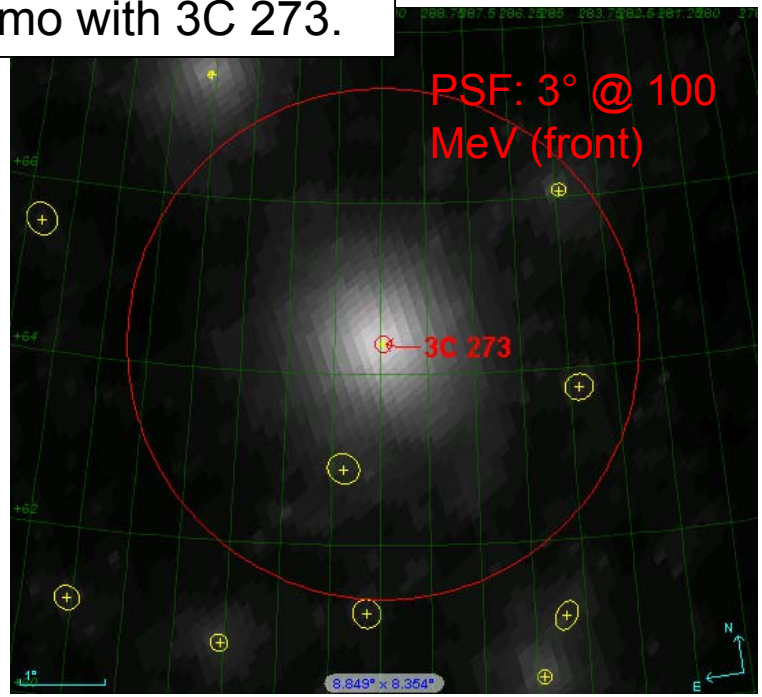


Colors: HEALPix index

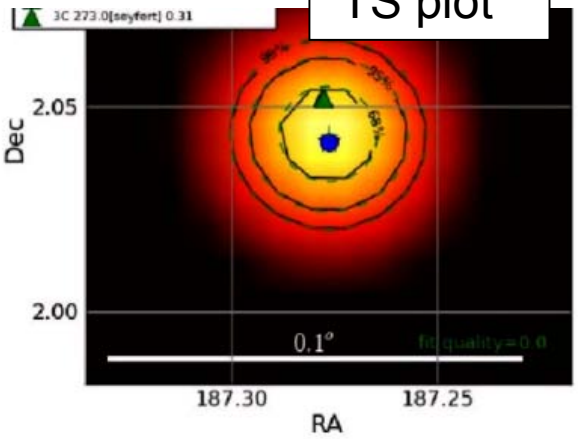
Localization

Basic principle: the likelihood function, as a function of the position of a source, is an estimator of the position, with the curvature defining the resolution.

Demo with 3C 273.

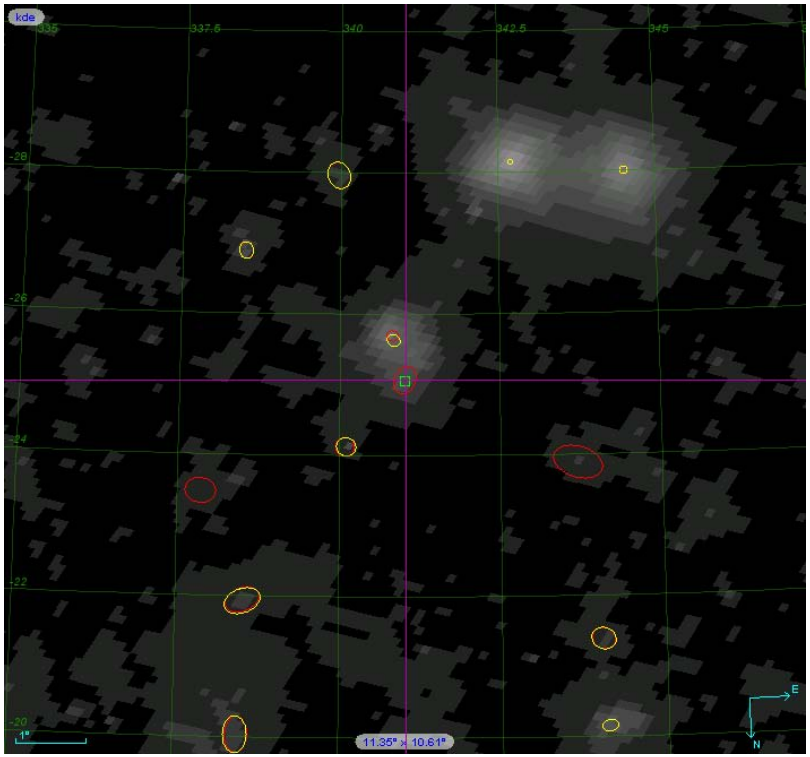


'TS plot'



Error ellipse defined by 95% contour (2.45σ). Plot shows contours, and results of fit to quadratic surface

Source confusion



Yellow: intermediate iteration
Red: added in final iteration

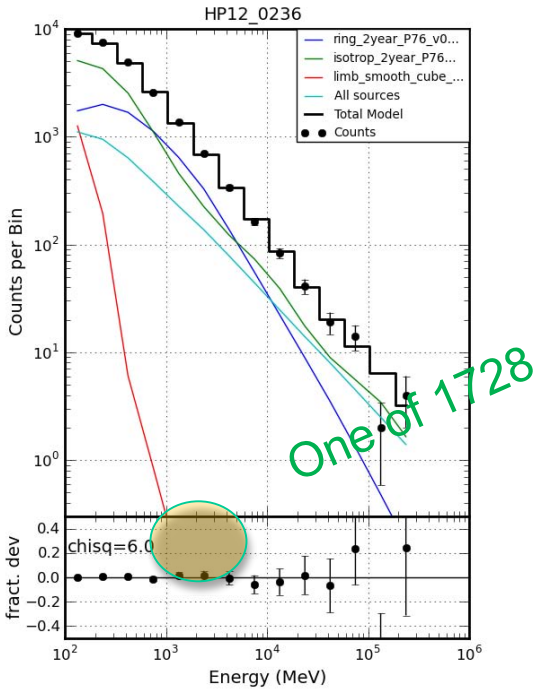
Example of overlapping sources resolved by PGWave: missed source close (0.65°) to a stronger source

Analysis of nearest neighbor distribution (for high latitudes) indicates missing fraction of 5.5%, vs. 7.6% for 1FGL

Localization assessment

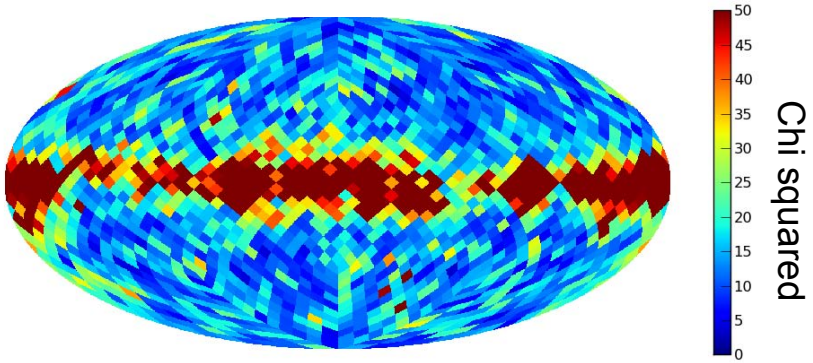
- Since localization errors are determined by the PSF, itself defined by data, a consistency check is to compare the distribution of deviations of associated sources with the expected
  - Preliminary indications are that in fact we need to scale the error ellipse dimensions by a factor of 1.1, as in 1FGL.
- Some apparent associations, or pulsar identifications, are far off due to diffuse confusion; the final catalog positions for 2 such LAT-identified pulsars will be fixed to the radio locations.

Stage I Summary

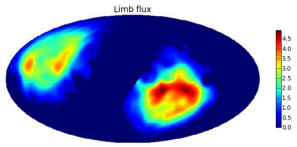


Example consistency check:
all photons in 5° radius circle
(Approx. 12 d.o.f.)

Consistency mostly good

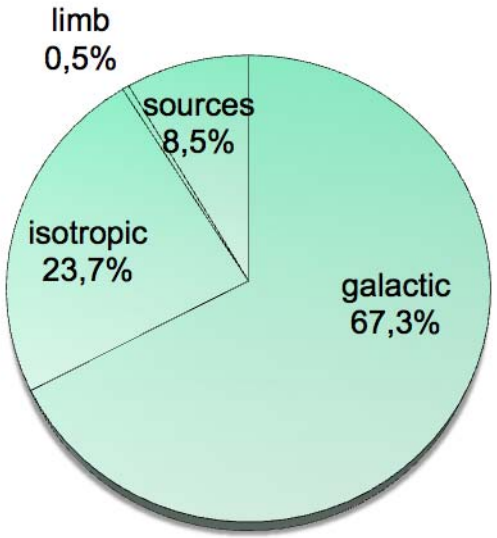


Limb distribution



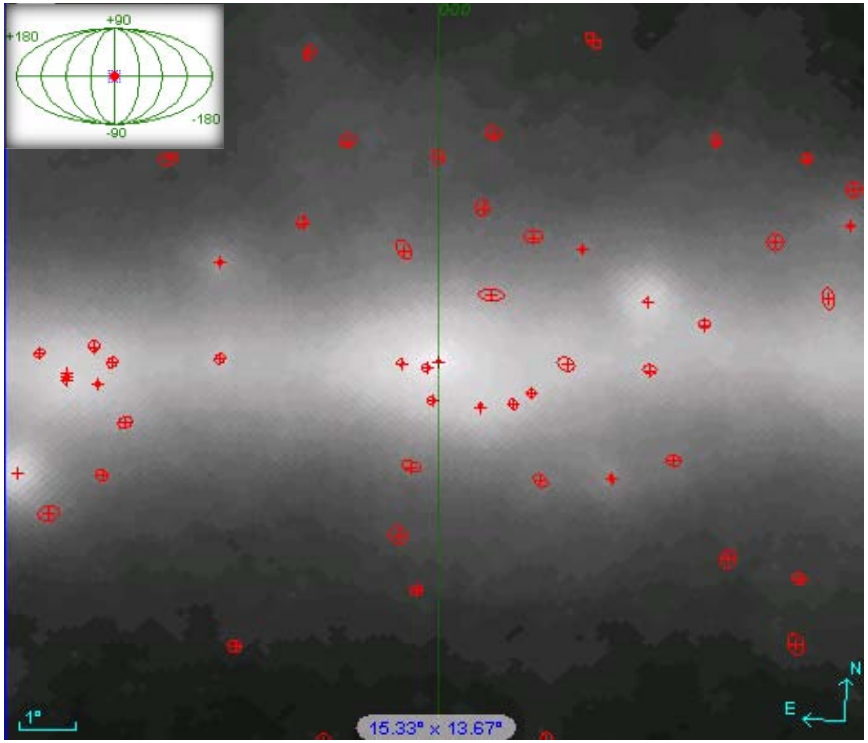
Free parameters	
Type	Number
Spectra	7603
Diffuse normalization	3456
Location (2 per TS>16 source)	5096

Contributions for all energies, full sky

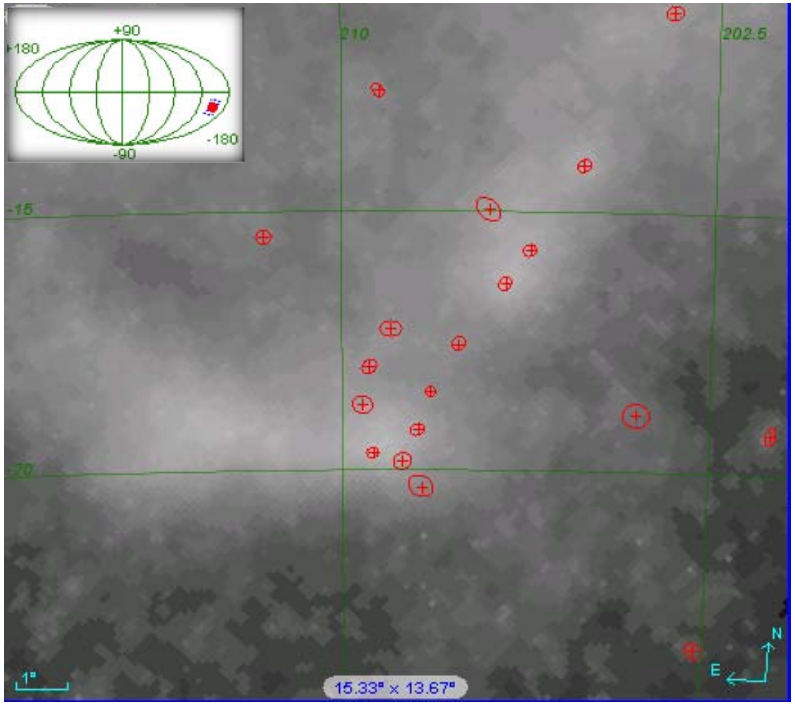


It is not all so rosy…

Most sources apparently associated with diffuse structures probably result from inadequate representation of the diffuse itself



Galactic center is complicated!
See talk by T. Porter



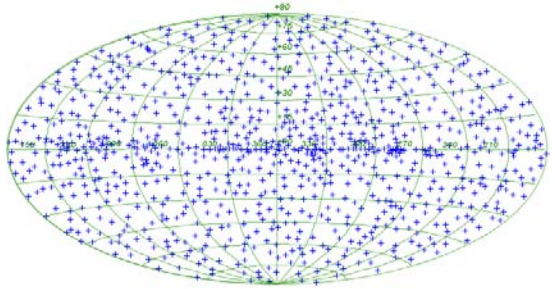
Orion molecular cloud: poster
by S. Digel & F. Giordano

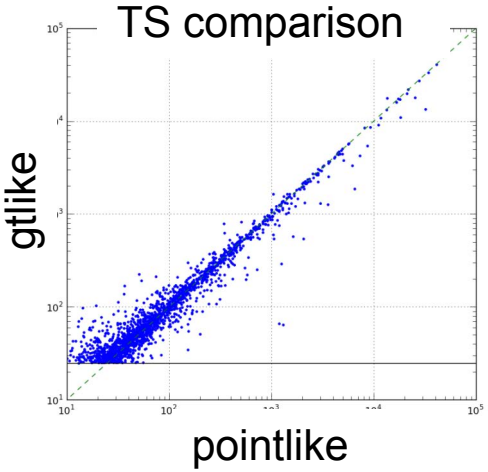
Sources: TS>10 seeds for 2FGL

2FGL process: Stage II

Use the standard tool *gtlike* in binned mode NEW

- ❑Accept all 3499 TS>10 sources from stage I
- ❑Similar iterative scheme, but with 933 overlapping regions chosen to equalize number of sources
- ❑Refit spectra and diffuse normalization
- ❑Fit pulsars with exponential cutoff
  - Everything else with power law: try log parabola
  - Retain all with *gtlike* TS>25 when generating model
    The *pointlike* fit and TS generally agree well, but some scatter for low values.
- ❑Generate:
  - Table
  - spectral plots
  - light curves
  - associations





Discussion

- 277 1FGL sources are not represented. Recall that they were only used as seeds at the start of the new process
  - Some reasons:
    - New requirements for localization
    - Extended sources were represented by more than one point source
    - Improved galactic diffuse model
    - There, but not significant enough (flared during first 11 months)
  - Dominant effect is new fitting procedure: application of current procedure (especially now using binned vs. unbinned *gtlike*) to 1FGL accounts for nearly all.
- The 5 LAT pulsars that are not (DC) detected are put in 'by hand'

Summary

2FGL almost ready to go, with following features

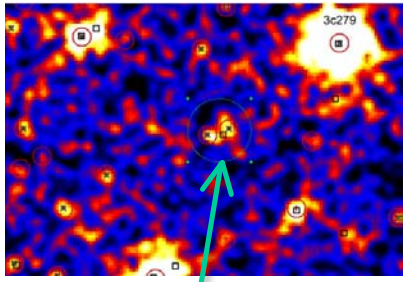
- Much improved diffuse representation, new limb component
- ~1888 sources, vs. 1451 1134 for (revised)1FGL
- 12 extended sources
- Pulsars fit with exponential cutoff, others log parabola if appropriate
  - better characterization of sources, improved fits to nearby weaker sources
- Better source finding efficiency: both detecting faint sources and resolving nearby sources

But: is not perfect, D. Thompson will next discuss caveats

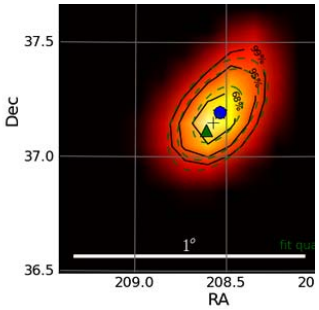
Fermi Gamma-ray Space Telescope

Backup, or discarded for now

Checking for missing sources: PGWave

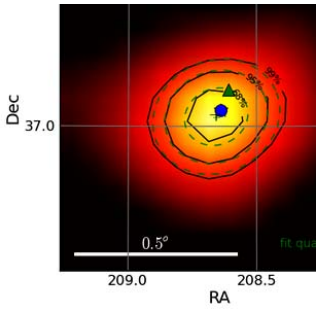


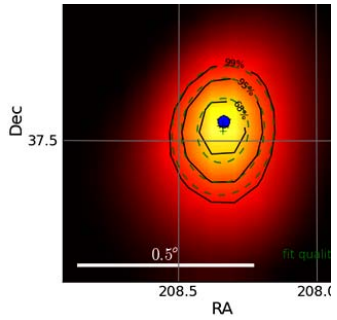
PGWave determines that this is two close sources

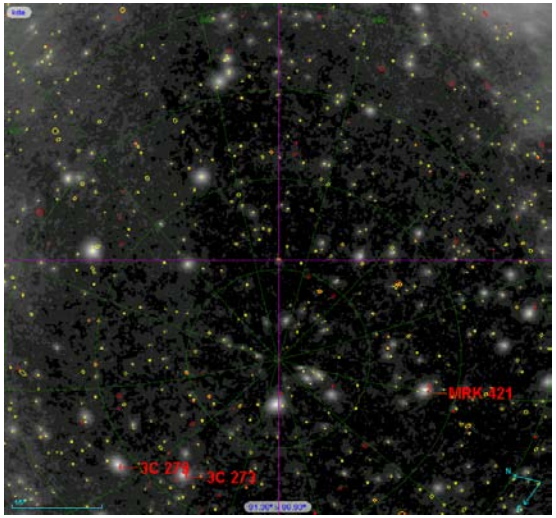


TS map is rather distorted

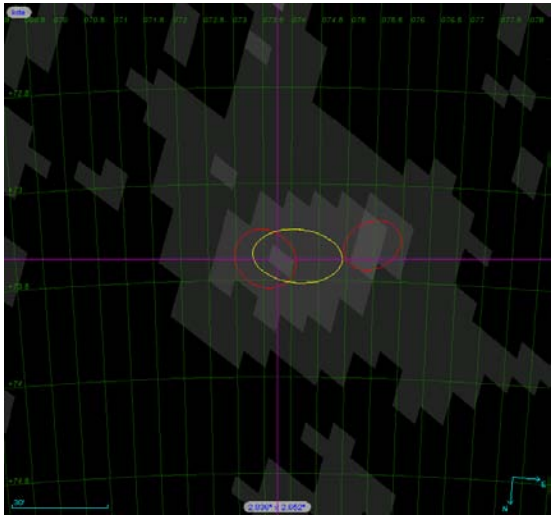
After split







An overview of the territory

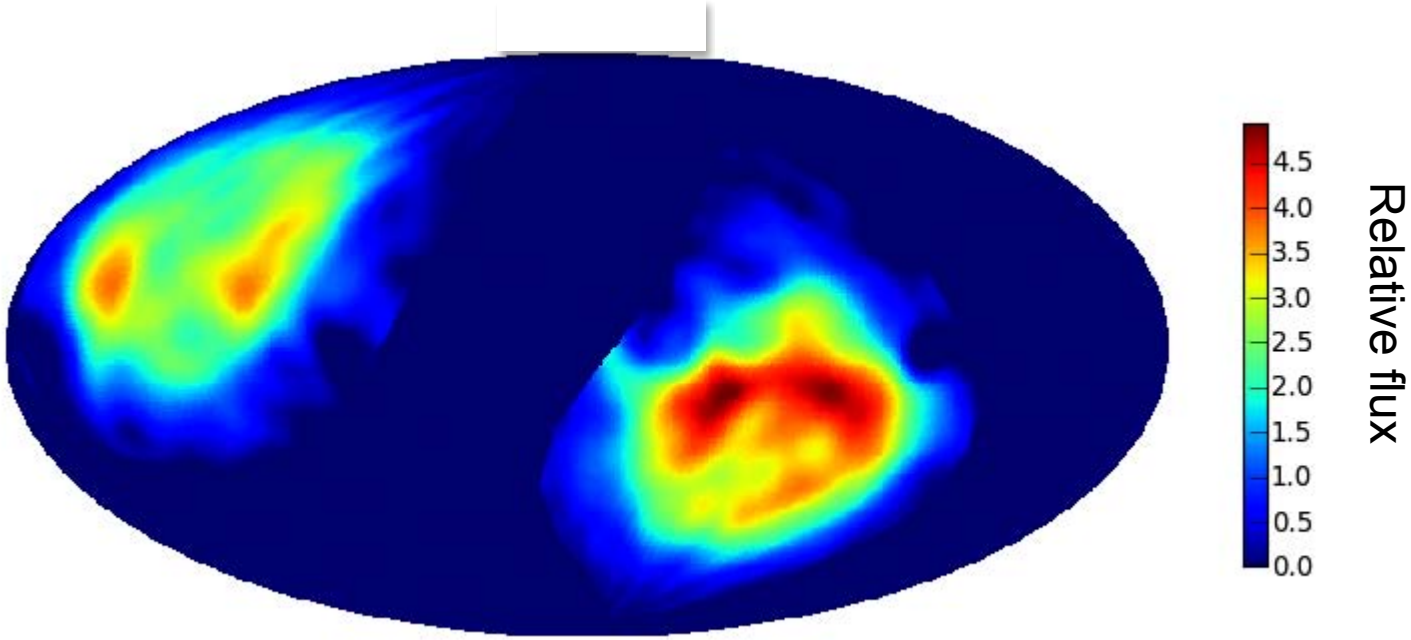


Blowup, showing before (yellow) and after (red).

Contribution from the Earth's limb

NEW

Gamma rays from Earth limb in tails of PSF



Required at celestial poles, low energies only