

National Aeronautics and Space Administration



Fermi
Gamma-ray Space Telescope

www.nasa.gov/fermi



Development of Source Catalogs for the *Fermi* Large Area Telescope

S. Digel (KIPAC/SLAC)
on behalf of the *Fermi* LAT
Collaboration

September 9, 2013
13th International Conference
on Topics in Astroparticle and
Underground Physics
Asilomar

Outline

- **General catalog analysis procedure**
- **LAT Source Catalogs**
 - **0FGL, 1FGL,...**
- **Some particulars about 1FHL**
- **Advances being implemented for 3FGL**
 - **Improved instrument response functions (IRFs)**
 - **Improved model for Galactic diffuse emission**
 - **Some details on evaluating systematic uncertainties from the model**
- **Summary**



General Procedure for LAT Catalog Analysis

1. Define 'seed' source candidates
 - Merged results from multiple algorithms
 2. Optimize their positions and search for additional sources
 - Via *pointlike* analysis system
 3. Evaluate spectral parameters and source significances
 - This is an all-sky analysis but in 'regions of interest' (ROIs) with the LAT likelihood analysis Science Tool*
 - Iteration among the ROIs is required to allow for influences of sources on adjacent ROIs
 - The iteration also includes evaluation of spectral models
- The analysis has many other details, including explicit modeling of known extended LAT sources, evaluation of analysis flags for systematic uncertainties, reanalysis on ~monthly time scales to define light curves and variability

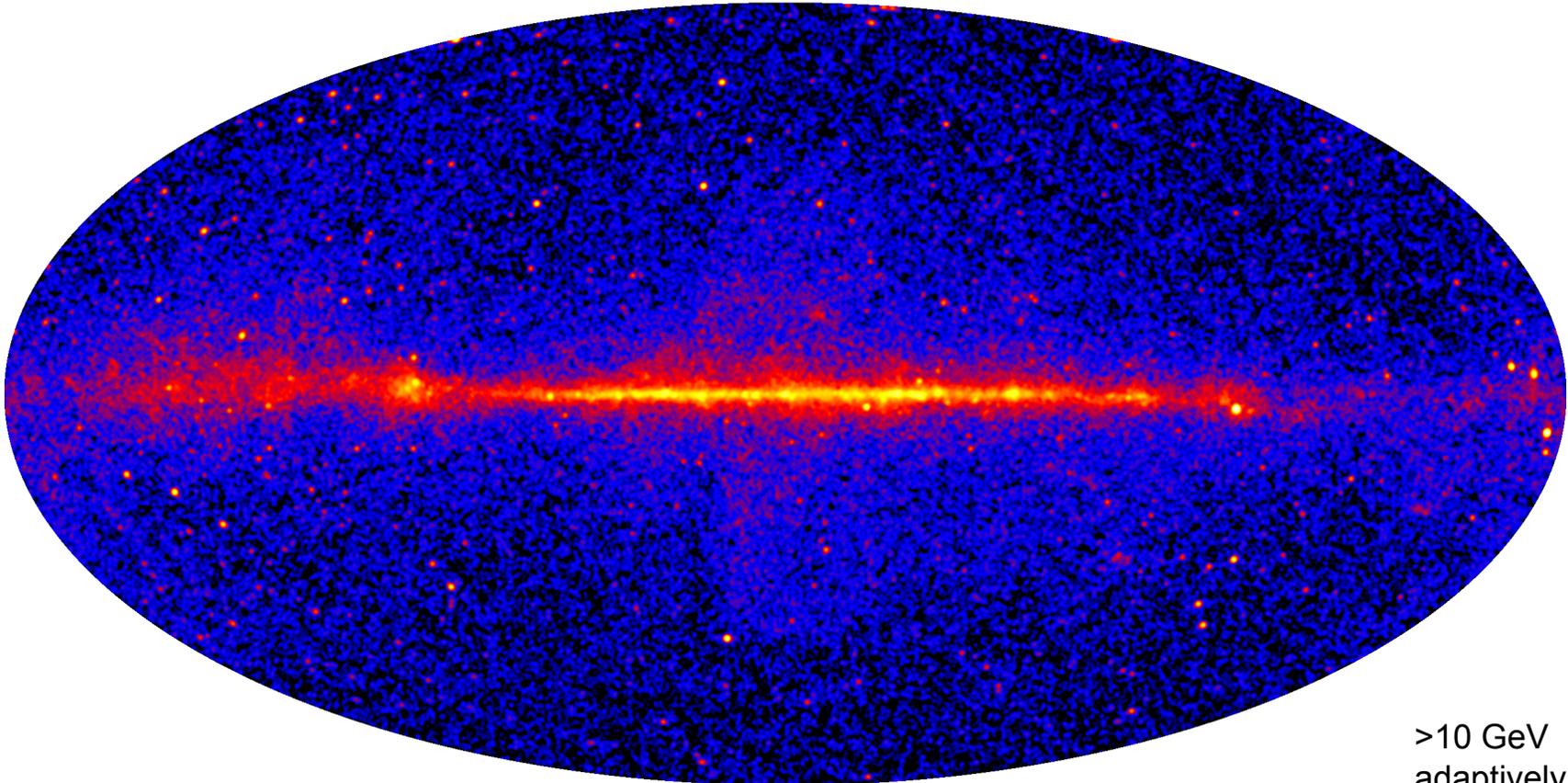
* Available from the *Fermi*
Science Support Center (FSSC)

LAT Source Catalogs

Catalog	Energy Range (GeV)	Data Interval (months)	Sources	Event Selection	Release Date
0FGL	0.2-100	3	205	P6V1 DIFFUSE	Feb. 2009
1FGL	0.1-100	11	1451	P6V3 DIFFUSE	Feb. 2010
2FGL	0.1-100	24	1873	P7V6 SOURCE	Aug. 2011
1FHL	10-500	36	511	P7V6 CLEAN	Jun. 2013
3FGL	0.1-300	48	>2500	P7V15 SOURCE	TBD

- **The catalogs are analyses over successively deeper data sets, and also represent successive analysis refinements, from event classification on up**

Highlights of 1FHL

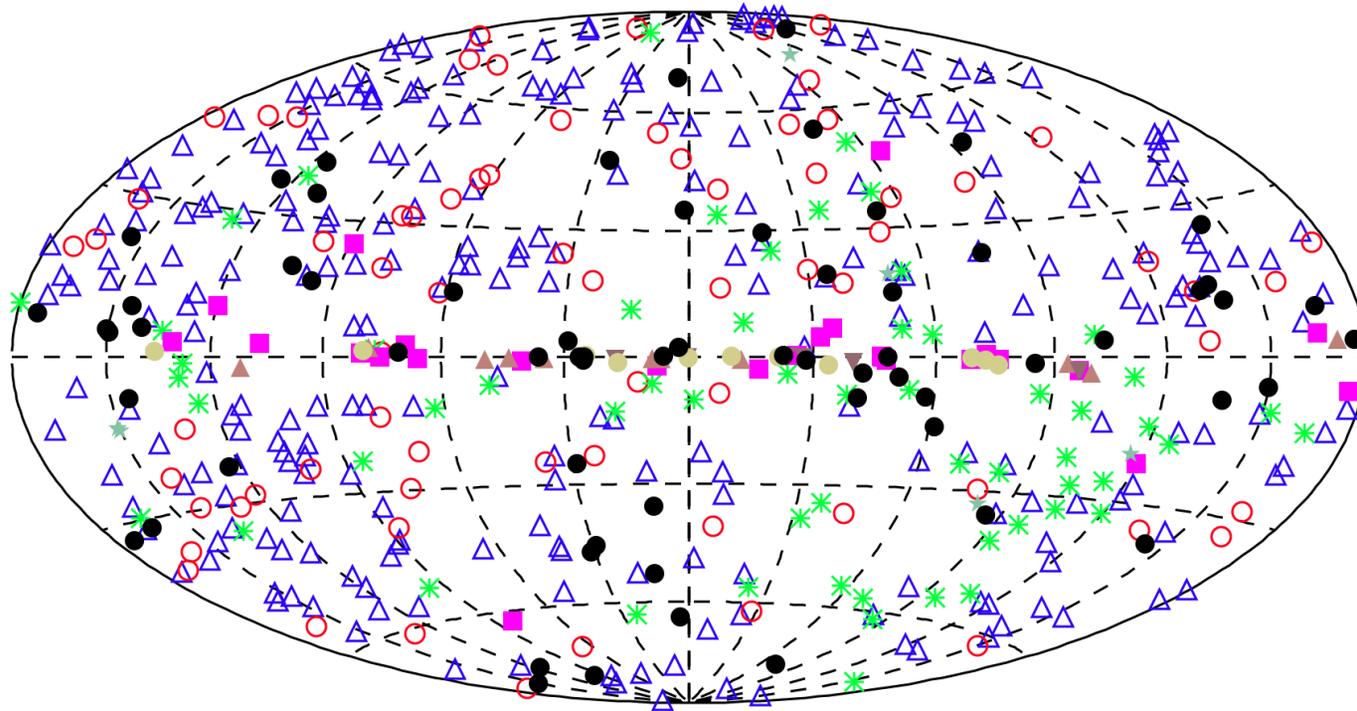


>10 GeV
adaptively
smoothed

- **First 3 years of LAT data (August 2008-August 2011)**
- **Analyzed 10-500 GeV to characterize the high-energy spectra**

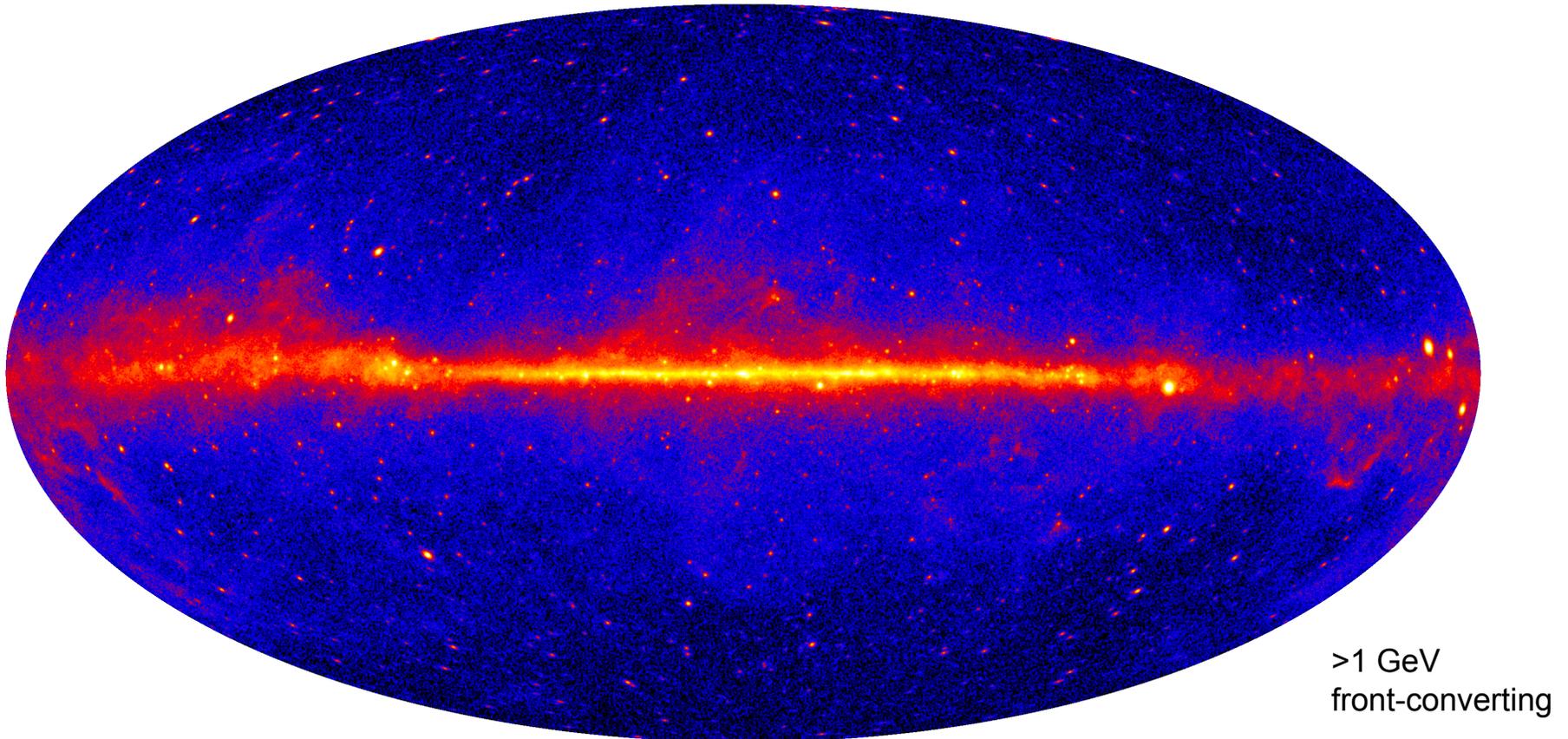
1FHL Catalog Sources

- **Catalog includes source locations, spectra, variability measures, associations**



	BL Lac		FSRQ		AGNs of unknown type
	PSR		SNR		PWN
	Other Galactic objects		Other (non-beamed) Extragalactic objects		No association

Highlights of 3FGL Development

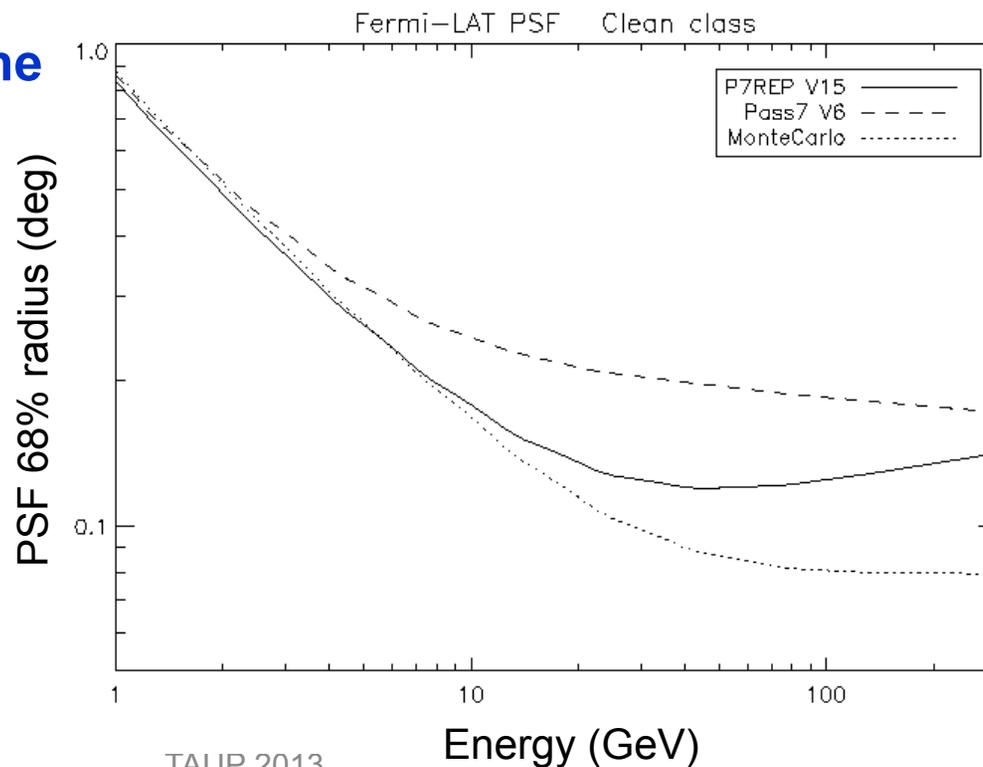


- **First 4 years of LAT data (August 2008-August 2012), 100 MeV-300 GeV**
- **Source detection is based on average flux**

3FGL Relative to 2FGL: Improved Data

- **Now using reprocessed Pass 7 data***
 - **Updating the calorimeter crystal calibrations improved energy measurement and the PSF at energies >1 GeV (the range most important for source localization)**
 - **Also improved the sensitivity**

* Anticipated to be released in September, through the FSSC





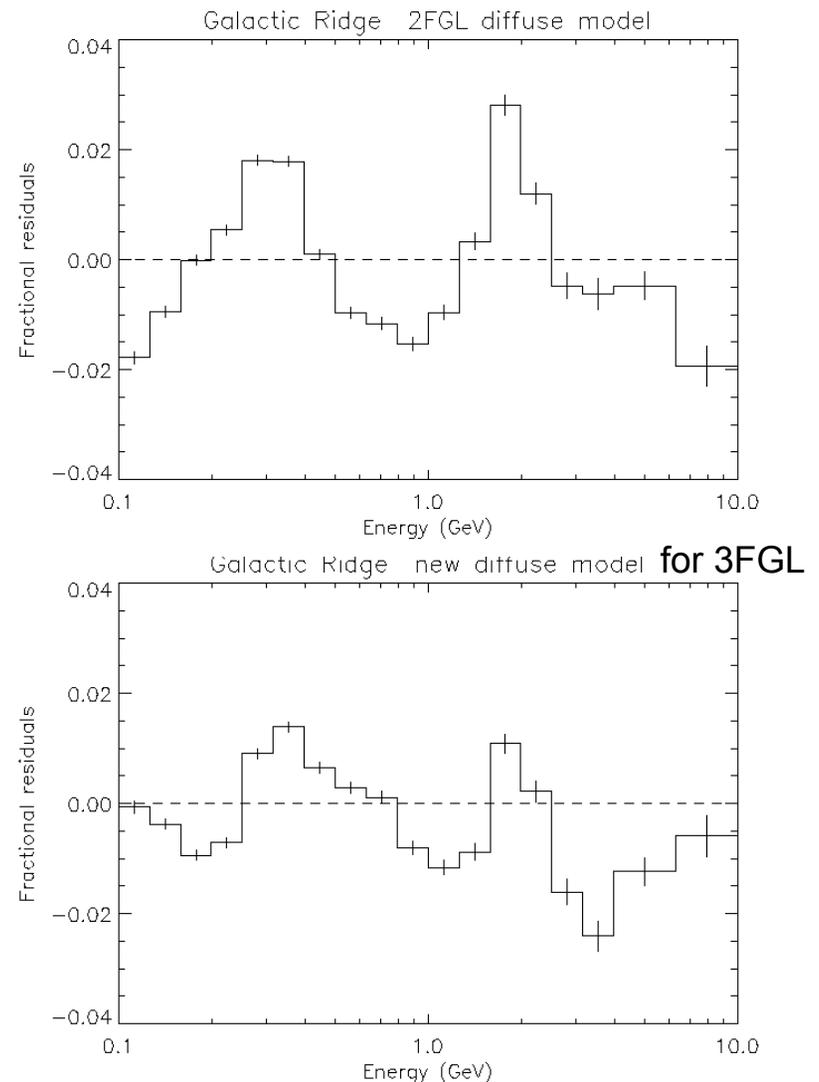
3FGL Relative to 2FGL: Interstellar Emission Model

- **Same method as 2FGL model:**
 - Rings of HI/CO/dark gas with spectrum fit to the data
 - Inverse Compton from a GALPROP model (rescaled)
 - Isotropic emission, spectrum fit to the data
 - Additional diffuse components for residual Earth limb emission and for emission of the (moving) Sun and Moon
- **Improvements with respect to the 2FGL model:**
 - More LAT data for the fitting (iterated with source detection)
 - Dark gas component improved (more later)
 - Remaining (non-template) structures (Loop I, *Fermi* bubbles, ...) modeled from large scale positive residuals

3FGL Relative to 2FGL: Interstellar Em. Model (2)

- **Illustration of the improvement in the Galactic ridge**
 - Point sources are taken into account in these residual plots
 - Source characteristics do remain much more uncertain in the Galactic plane
- **Quantifying the systematic uncertainties due to modeling the diffuse emission is challenging**
 - For **2FGL** the approach was to re-evaluate source properties when they were **re-fit using the 1FGL-era model** for Galactic diffuse emission*
 - **Similar approach for 3FGL**

* 44 of the 2FGL sources had fluxes change by $>3\sigma$ by this method



2FGL Era

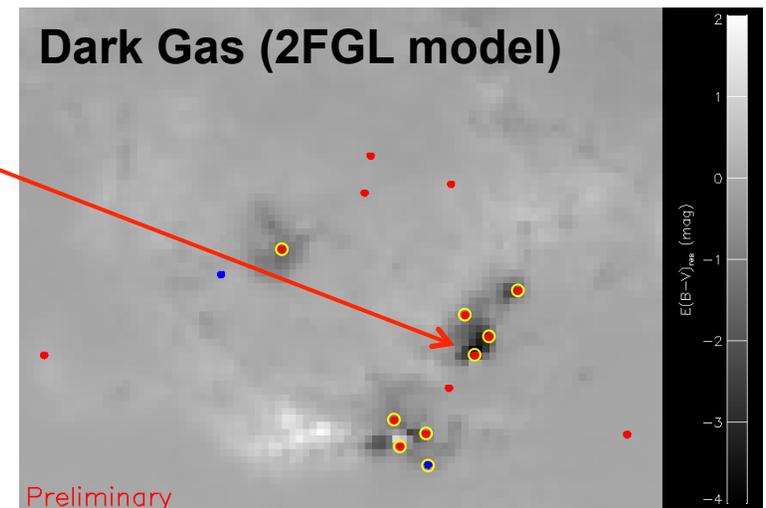
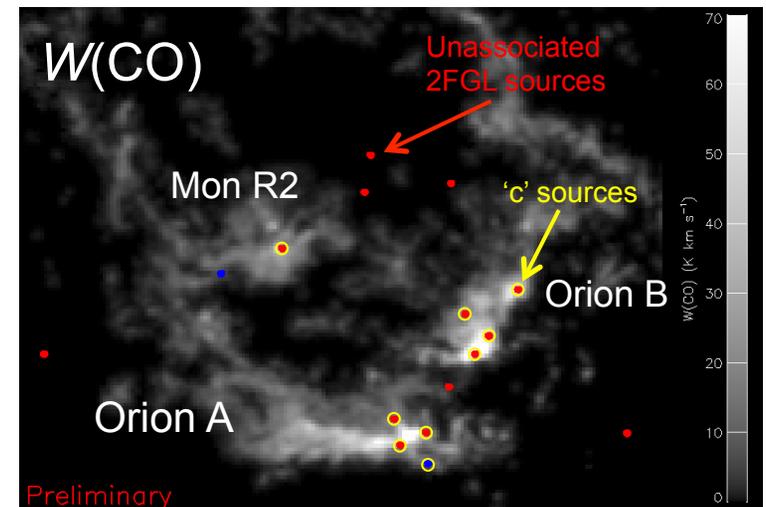
- **Diffuse model-related flags**
 - **Large impacts on significance (1), location (2), or flux (3)**
- **Also, location of sources with respect to likely defects in the model for Galactic diffuse emission (6)**

Flag ^a	Meaning
1	Source with $TS > 35$ which went to $TS < 25$ when changing the diffuse model (§ 3.7). Note that sources with $TS < 35$ are not flagged with this bit because normal statistical fluctuations can push them to $TS < 25$.
2	Moved beyond its 95% error ellipse when changing the diffuse model.
3	Flux (> 1 GeV) or energy flux (> 100 MeV) changed by more than 3σ when changing the diffuse model. Requires also that the flux change by more than 35% (to not flag strong sources).
4	Source-to-background ratio less than 20% in highest band in which $TS > 25$. Background is integrated over πr_{68}^2 or 1 square degree, whichever is smaller.
5	Closer than θ_{ref} from a brighter neighbor. θ_{ref} is defined in highest band in which source $TS > 25$, or the band with highest TS if all are < 25 . θ_{ref} is set to $2'.17$ (FWHM) below 300 MeV, $1'.38$ between 300 MeV and 1 GeV, $0'.87$ between 1 GeV and 3 GeV, $0'.67$ between 3 and 10 GeV and $0'.45$ above 10 GeV ($2r_{68}$).
6	On top of an interstellar gas clump or small-scale defect in the model of diffuse emission; equivalent to the 'c' designator in the source name (§ 3.9).
7	Not used.
8	Inconsistent position determination (§ 3.1.4); best position from optimization outside the 1σ (39% in 2D) contour from the TS map.
9	Elliptical quality > 4 in <i>pointlike</i> (i.e., TS contour does not look elliptical).
10	Spectral Fit Quality > 16.3 (Eq.3).
11	Possibly due to the Sun (§ 3.6).
12	Highly curved spectrum; LogParabola β fixed to 1 or PLExpCutoff Spectral_Index fixed to 0 (see § 3.3).

On 2FGL Analysis Flag 6

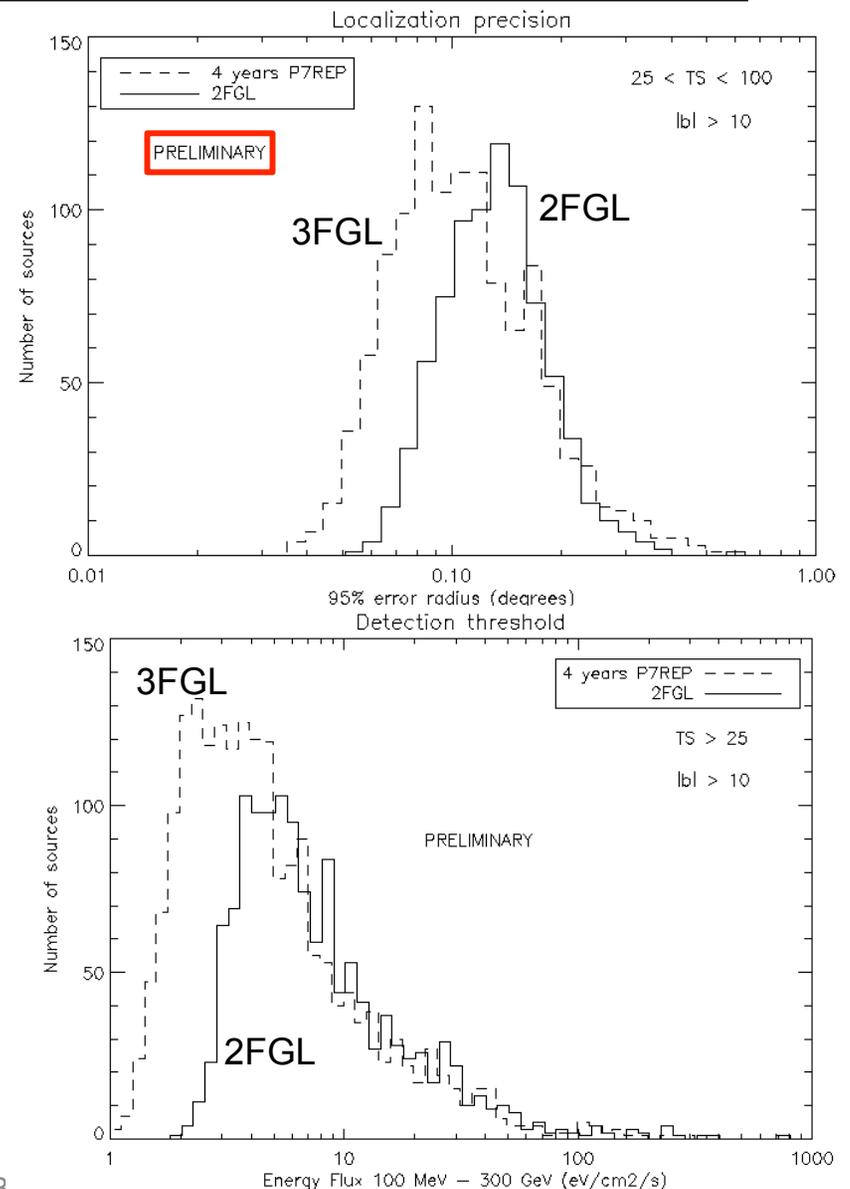
- The dark gas component of the interstellar medium is derived using dust column density (inferred from IR observations) as a tracer of total column density
- In the 2FGL model, the Dark Gas component around bright IR sources like the Orion Nebula had negative deficits
 - Unassociated LAT point sources tended to congregate there
- These are many of the 'c' sources
- Filtering of these small-scale defects is greatly improved for the diffuse emission modeling for 3FGL

Molecular and Dark Gas in Orion



3FGL Relative to 2FGL: Localization & Threshold

- Illustration of localization improvement, for sources of **similar significance** away from the Galactic plane
- The average localization region radius is 15% smaller
- For **all sources with $TS > 25$** detected away from the Galactic plane, the distribution of energy fluxes extends down to $\sim 2 \text{ eV cm}^{-2} \text{ s}^{-1}$ vs. $\sim 3 \text{ eV cm}^{-2} \text{ s}^{-1}$ for 2FGL



Summary

- **The LAT catalog analysis procedure has been applied, with successive refinements, several times**
 - **The 1FHL catalog (3 years of data, >10 GeV) characterizes the LAT sources in the range of overlap with VHE telescopes**
 - **The 3FGL catalog (4 years of data) is in production and will have >2500 sources**
- **3FGL has several advances over 2FGL**
 - **Refinements include improvements in event classification (IRFs) and definition of the Galactic diffuse emission model**
- **The systematic uncertainties associated with modeling the Galactic diffuse emission remain appreciable**
 - **They are quantified approximately by flagging sources with sensitive dependence on the diffuse emission model**



Backup Slides

Abstract

- **The Large Area Telescope (LAT) on the Fermi Gamma-ray Space Telescope has been surveying the sky since 2008, and a succession of general source catalogs based on deepening exposures and refinements of the analysis at all levels has been developed. The third general catalog of sources detected above 100 MeV, based on four years of LAT observations, is underway. In addition a catalog specifically of sources detected above 10 GeV recently has been released. The catalogs have been the basis of many follow-up studies. I will describe the approach for development of the catalogs, their properties, and refinements developed for the most recent, with particular emphasis on modeling the Galactic diffuse emission.**

On LAT Source Catalogs

- **They are a uniform analysis of the entire sky, and the basis for many follow-up studies, including**
- **Initial definitions of source models for studies of different time intervals or time ranges**
- **Searches for new populations of gamma-ray sources (including identification of unassociated LAT sources)**
- **Characterization of known populations**

Summary of Systematics for Catalog Analyses

- Systematic uncertainties for **source location region sizes** and variability measures were determined empirically
- **Spectral fit parameters and fluxes** were reported only with statistical uncertainties but goodness-of-fit-type measures included systematic uncertainties in the effective area
- Systematics due to the **diffuse emission model** were difficult to define but were investigated for 2FGL using the 1FGL model
- Except for the source location region sizes, systematic uncertainties are indicated primarily in the **Analysis Flags**
 - **The 2FGL Catalog ended up with 11 different flags**