Fermi
Gamma-ray
Space Telescope

The Fermi LAT Catalogs

Seth Digel
KIPAC/SLAC
on behalf of the LAT Collaboration

Fermi Summer School 2015
Lewes, Delaware

Outline

- Why make catalogs? Why make LAT catalogs?
- LAT gamma-ray source catalogs in context
- General procedure
  - Source detection and characterization
  - Identifications and associations
- Results and limitations (3FGL)
  - Locations, spectra, light curves
  - Associations and source classes
  - Unassociated sources
- Class-specific LAT source catalogs
  - AGN, Pulsars, GRBs, plus FAVA week-scale transients…
- What's next for catalogs analysis

Why Make (LAT) Catalogs?

- Not to collect butterflies, although obviously we all want to know what the LAT has detected
  - For the LAT especially making catalogs was one approach for finding new source classes
  - And of course once you find enough members of some class: Population studies
- Perhaps less obvious is that the systematic analysis of the sky exercised the LAT analysis tools and tested the assumptions of the analysis
  - From the definition of the event classes and IRFs on up to the effects of residual Earth limb emission and the impact of the moving Sun
- Also, because the standard LAT source analysis is model fitting, for any region of the sky a LAT source catalog provides a good initial guess for detailed study of a (generally newer and longer) data set

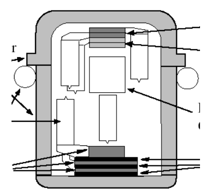
LAT Source Catalogs in Context

- The LAT is by far the most sensitive detector ever in the GeV range
- It has benefitted from a stable response, relatively uniform sky coverage and a long mission
- The opportunities (discovery!) and main challenges for LAT catalog analysis are the same as for earlier missions (bright backgrounds, limited angular resolution and statistics)
  - Although some challenges are LAT analysis-specific, either due to the sensitivity of the LAT or to the observing strategy

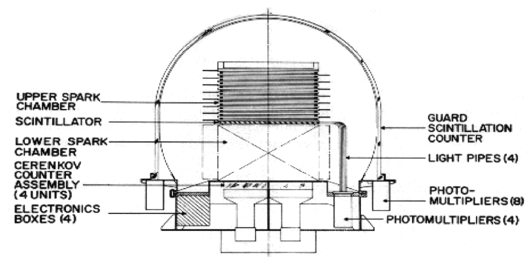
Aside: Brief History of High-Energy Gamma-Ray Detectors Pre-LAT

- 1967-1968, OSO-3 detected Milky Way as an extended γ-ray source, 621 γ-rays
- 1972-1973, SAS-2, ~8,000 celestial γ-rays
- 1975-1982, COS-B, orbit resulted in a large and variable background of charged particles, ~200,000 γ-rays
- 1991-2000, EGRET, large effective area, good PSF, long mission life, excellent background rejection, and >1.4 × 10^6 γ-rays
- 2007-, AGILE, like 1/16-th LAT, with small calorimeter, sensitivity ~EGRET

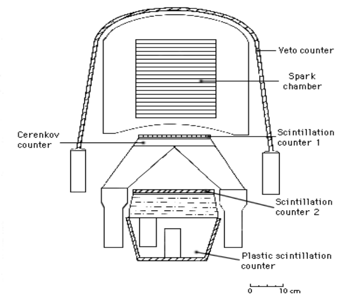
OSO-3



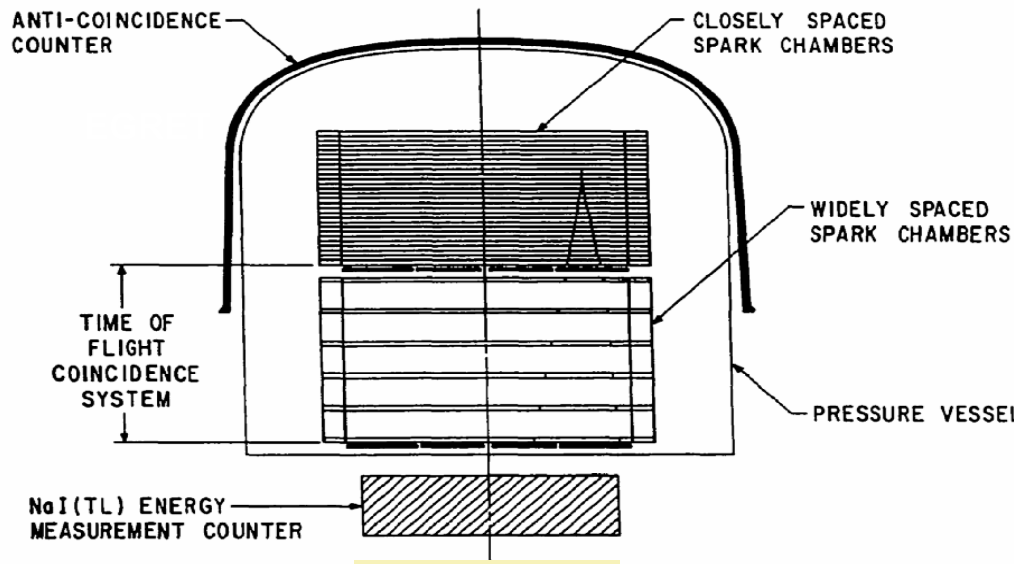
SAS-2



COS-B

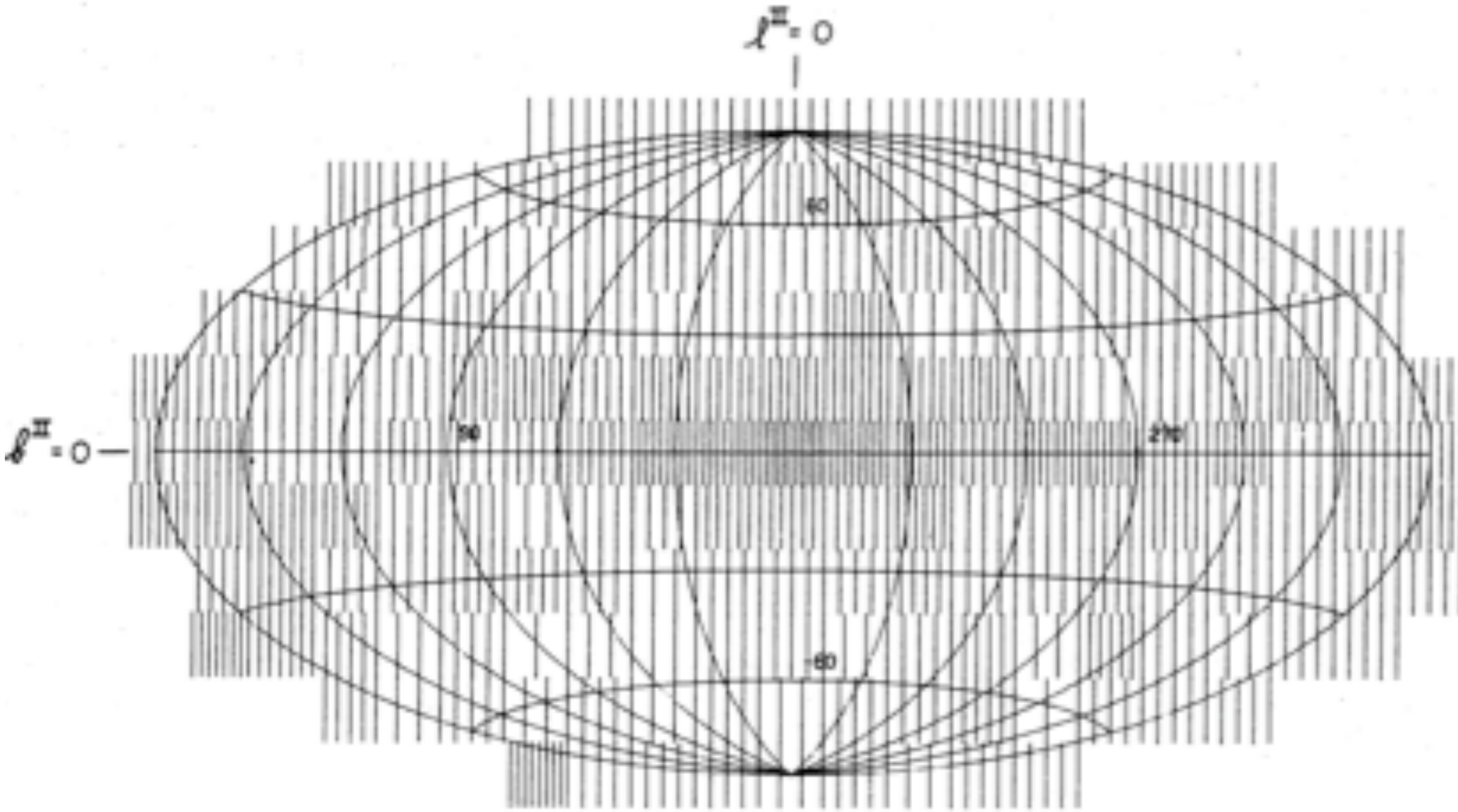


EGRET



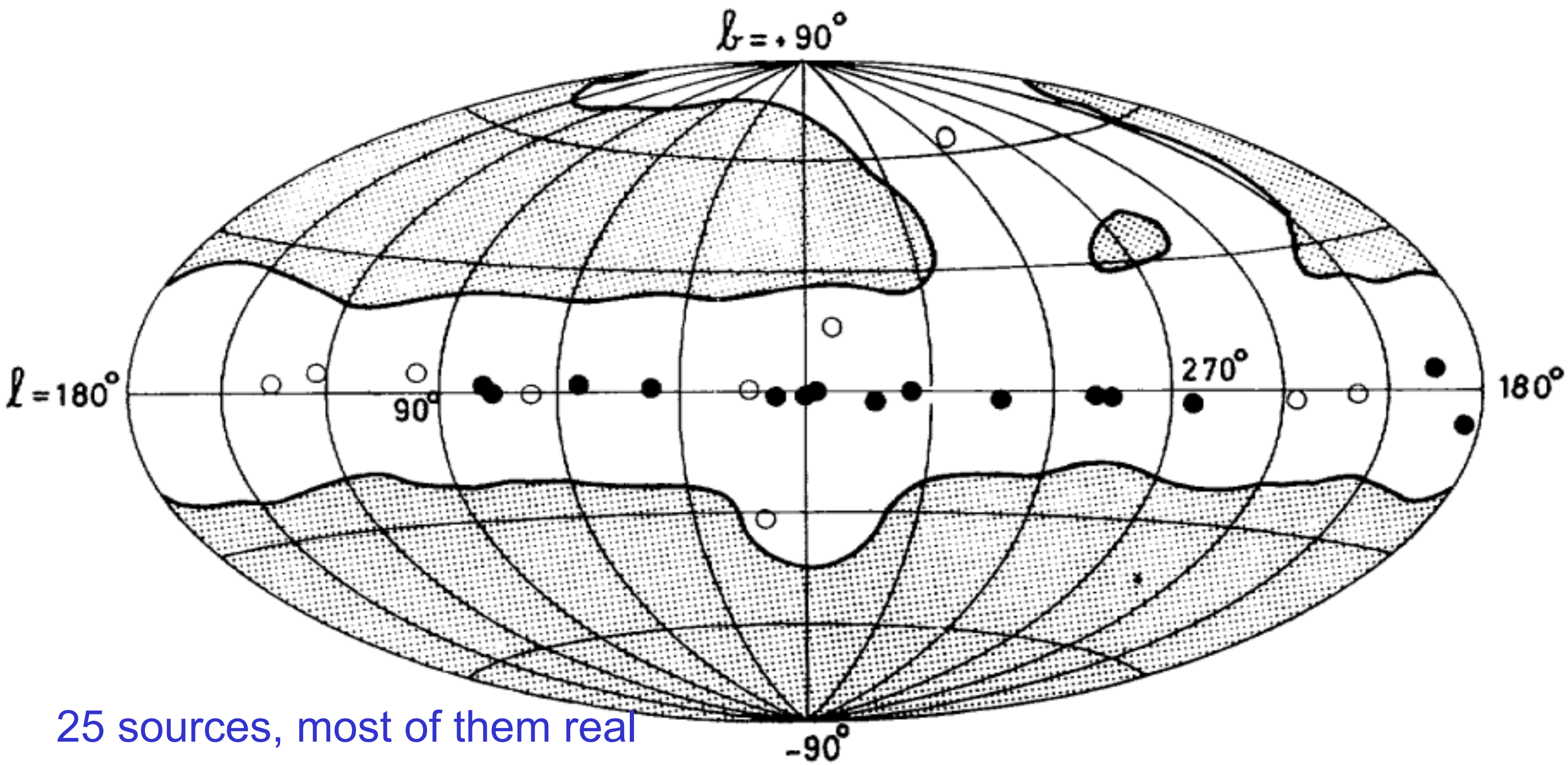
AGILE

OSO-3



OSO-3 (Kraushaar et al. 1972) 1 source

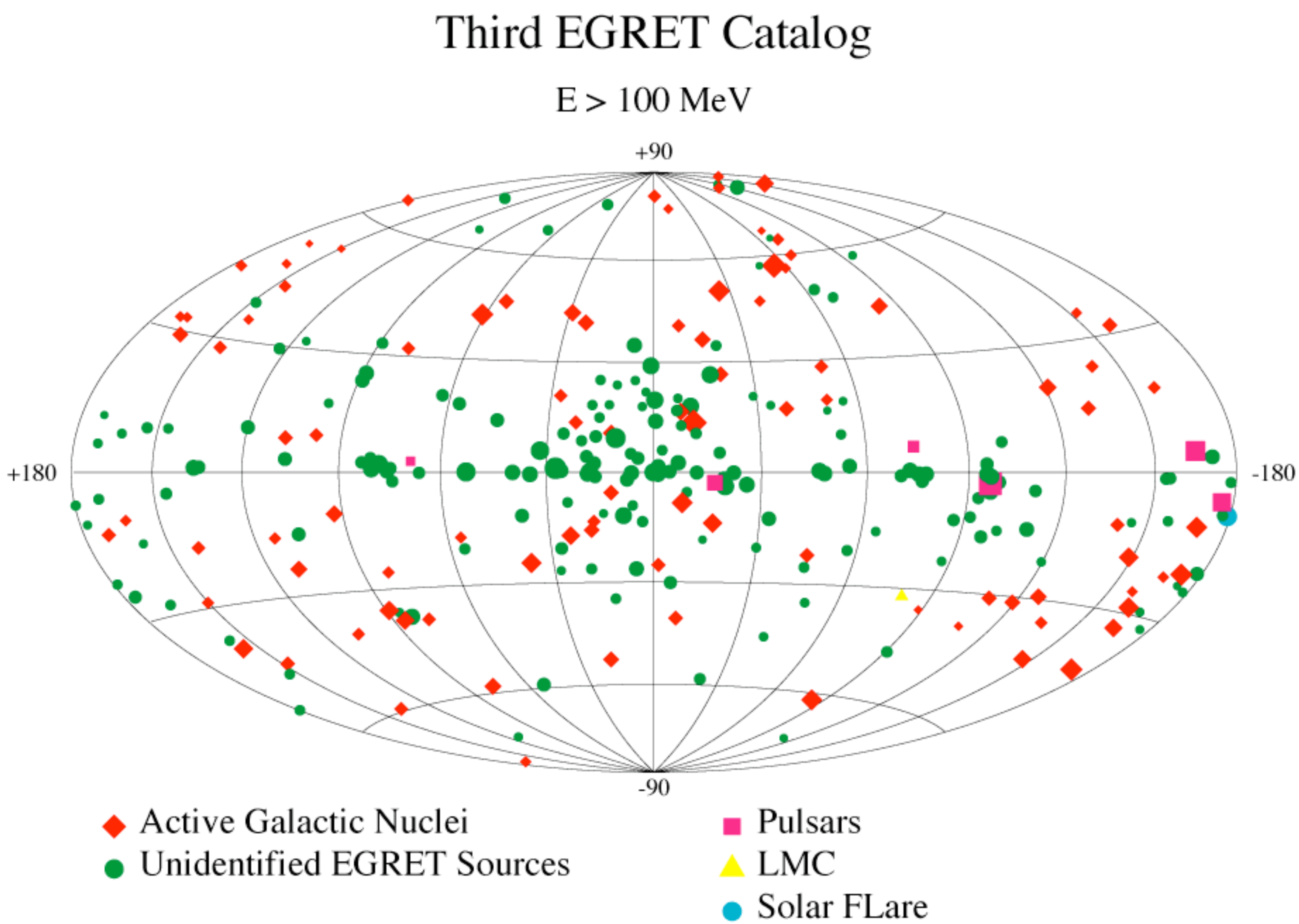
COS-B



25 sources, most of them real

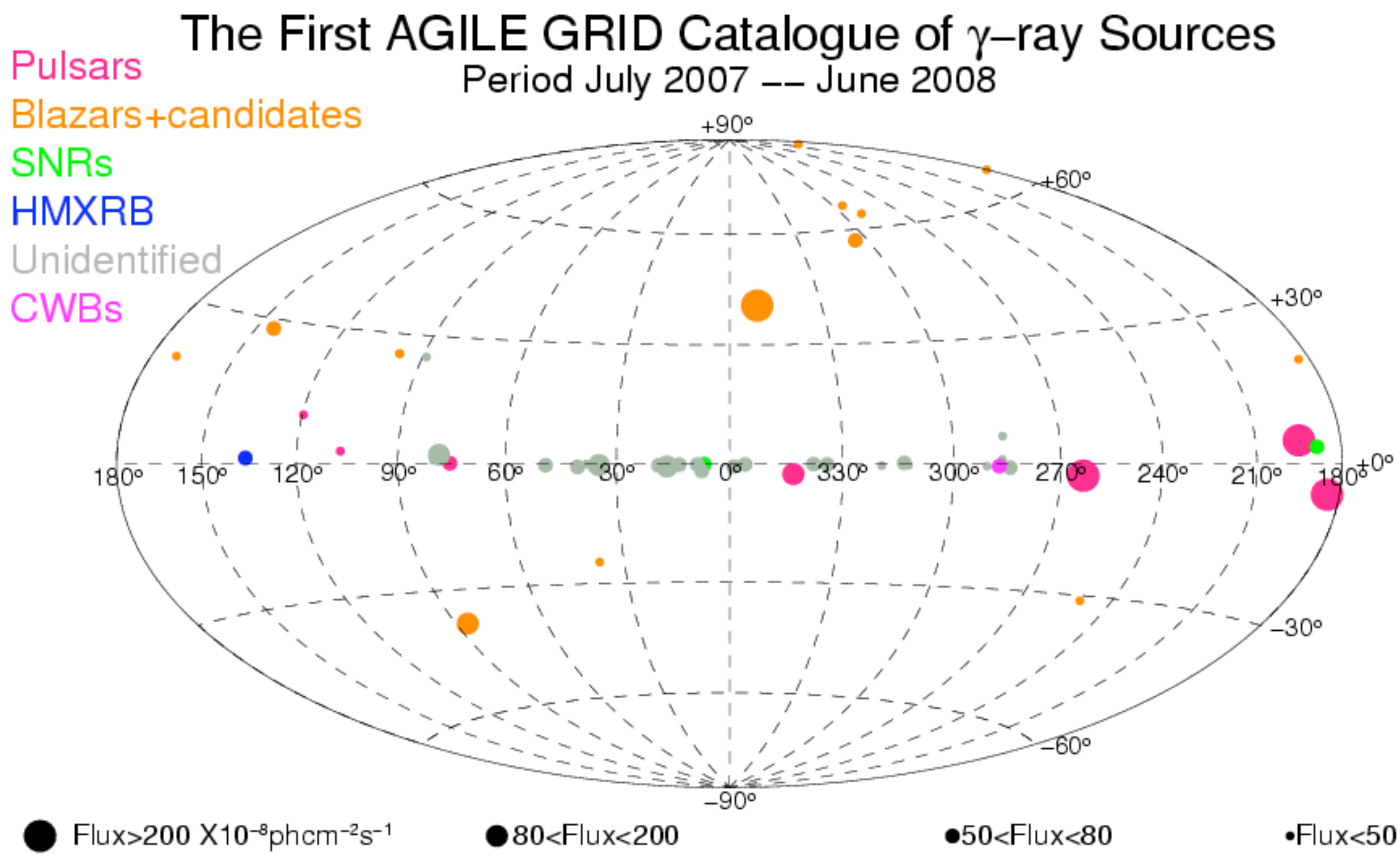
Swanenburg et al. (1981)

EGRET



271 sources (Hartman et al. 1999), ~200 real (EGR catalog, Casandjian & Grenier 2008)

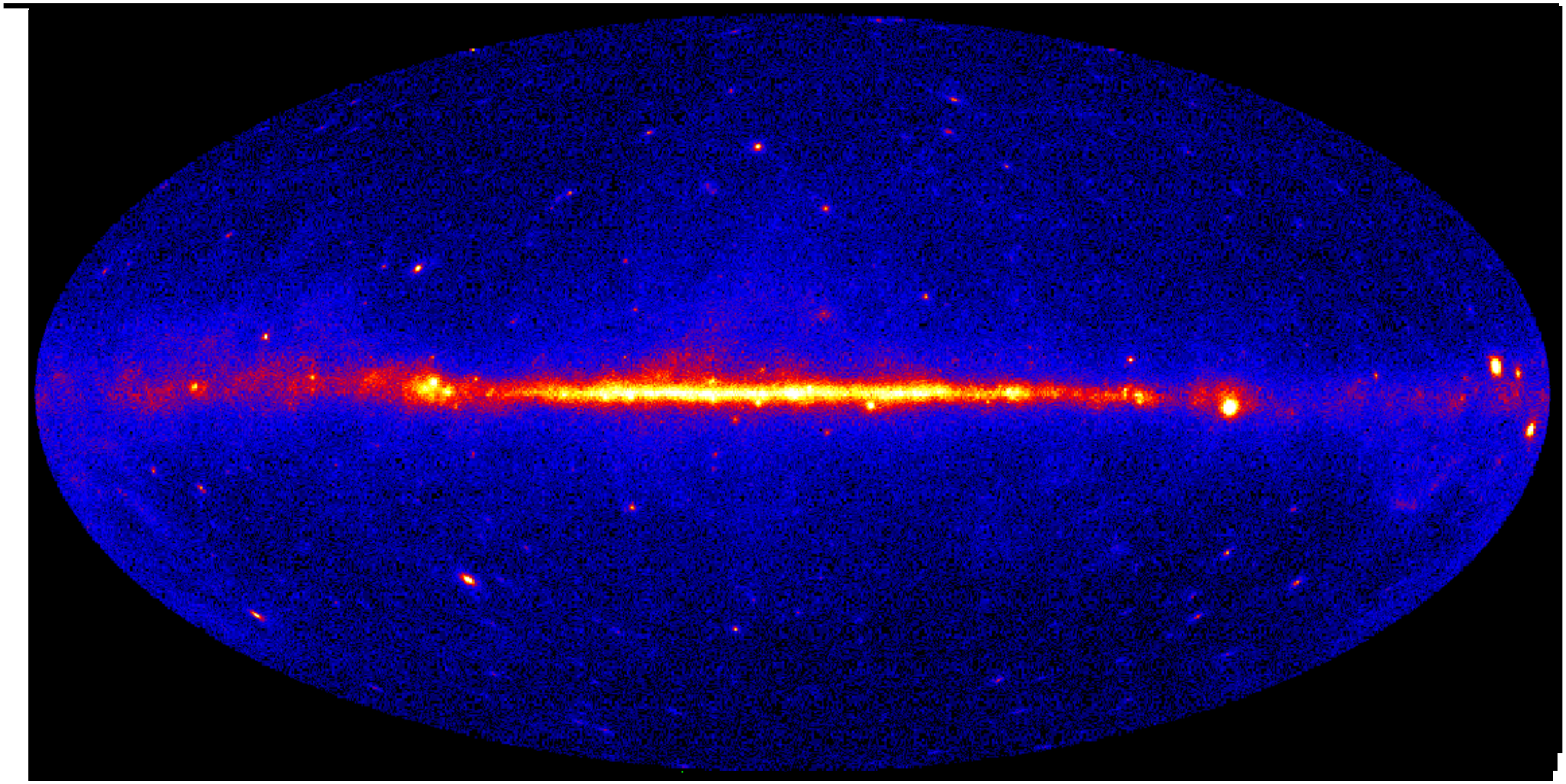
AGILE



47 sources

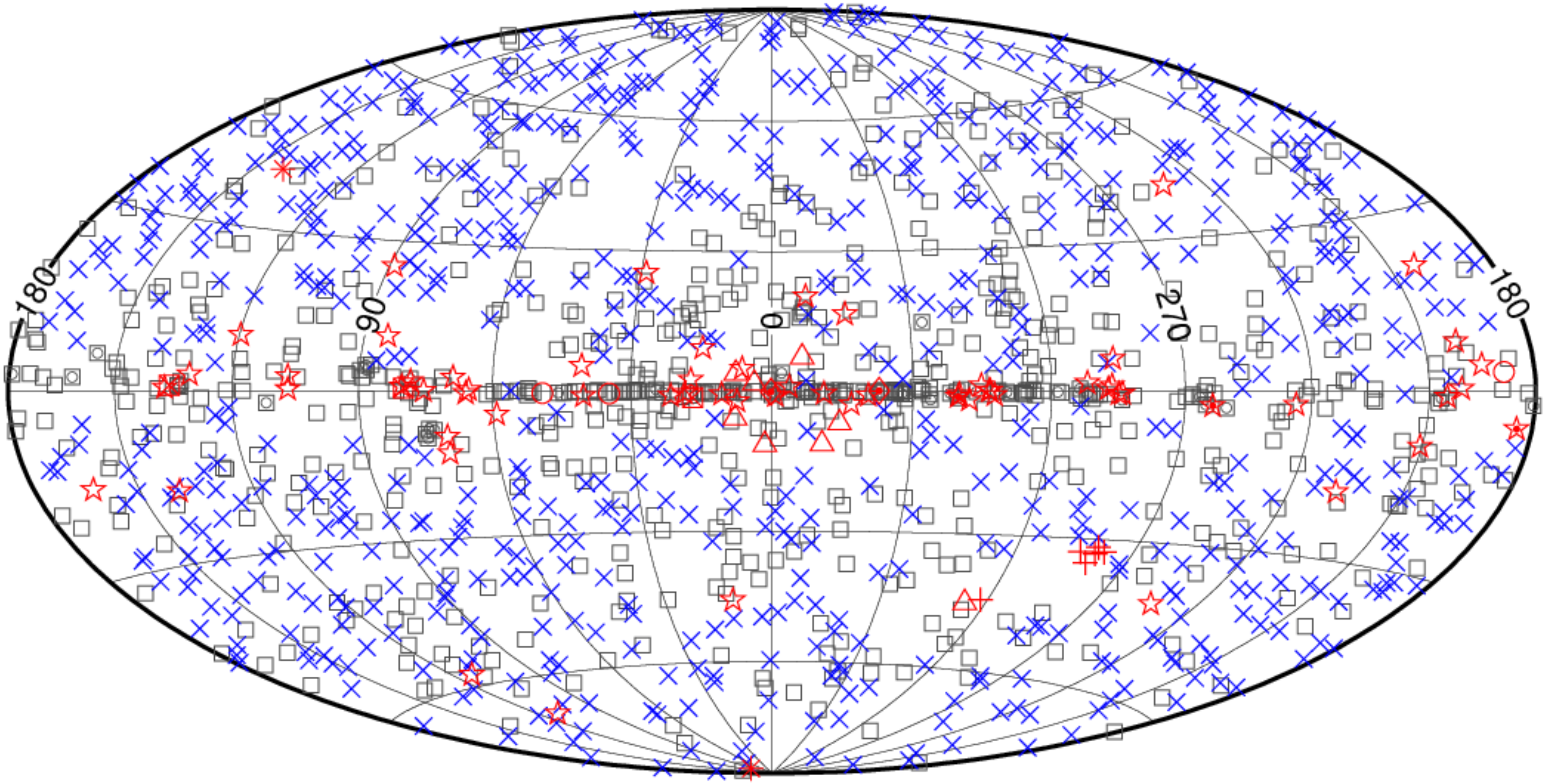
Pittori et al. (2009)

LAT Bright Source List (3 mo)



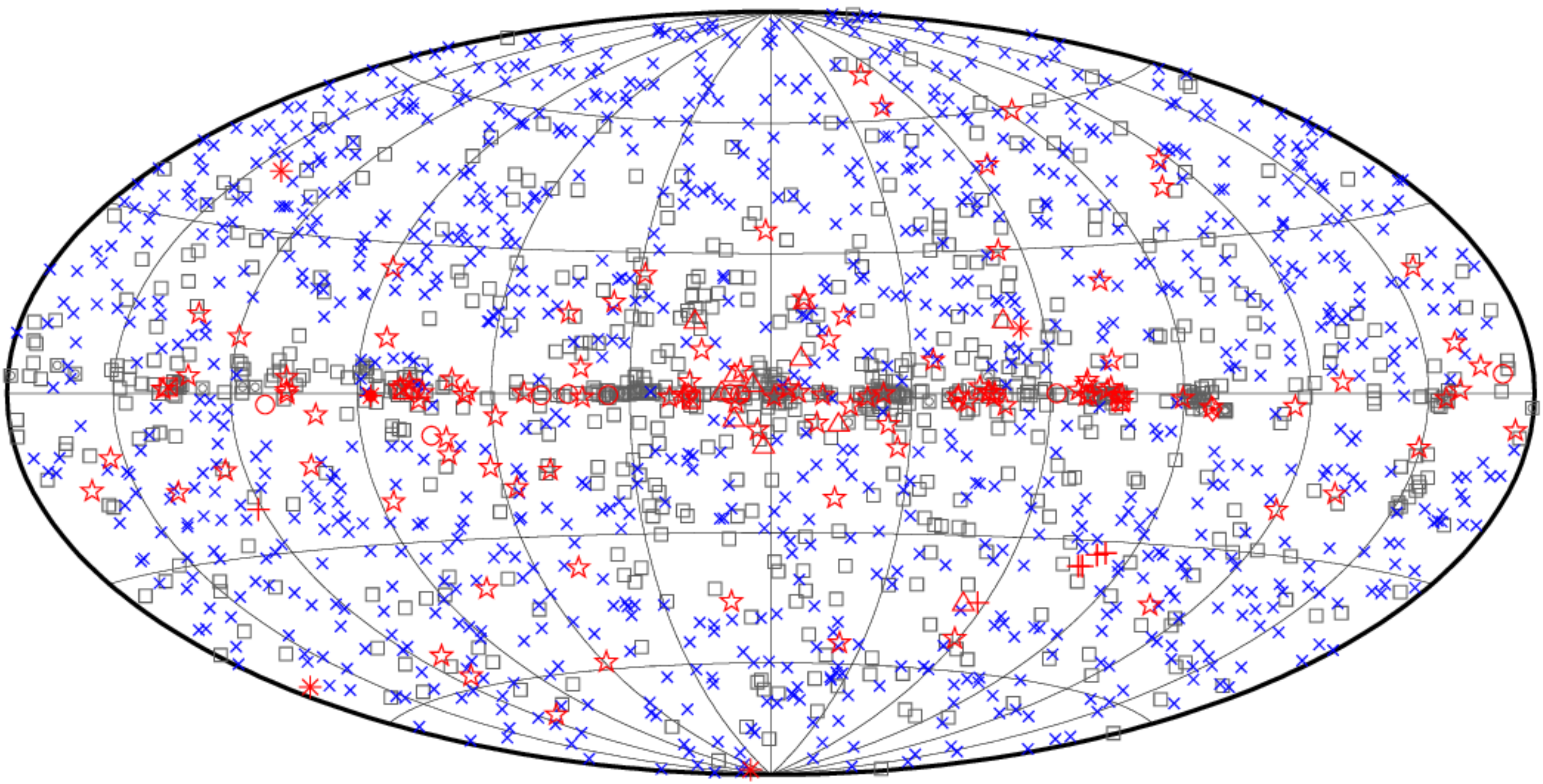
205 sources >10 σ Abdo et al. (2009)

1FGL Catalog



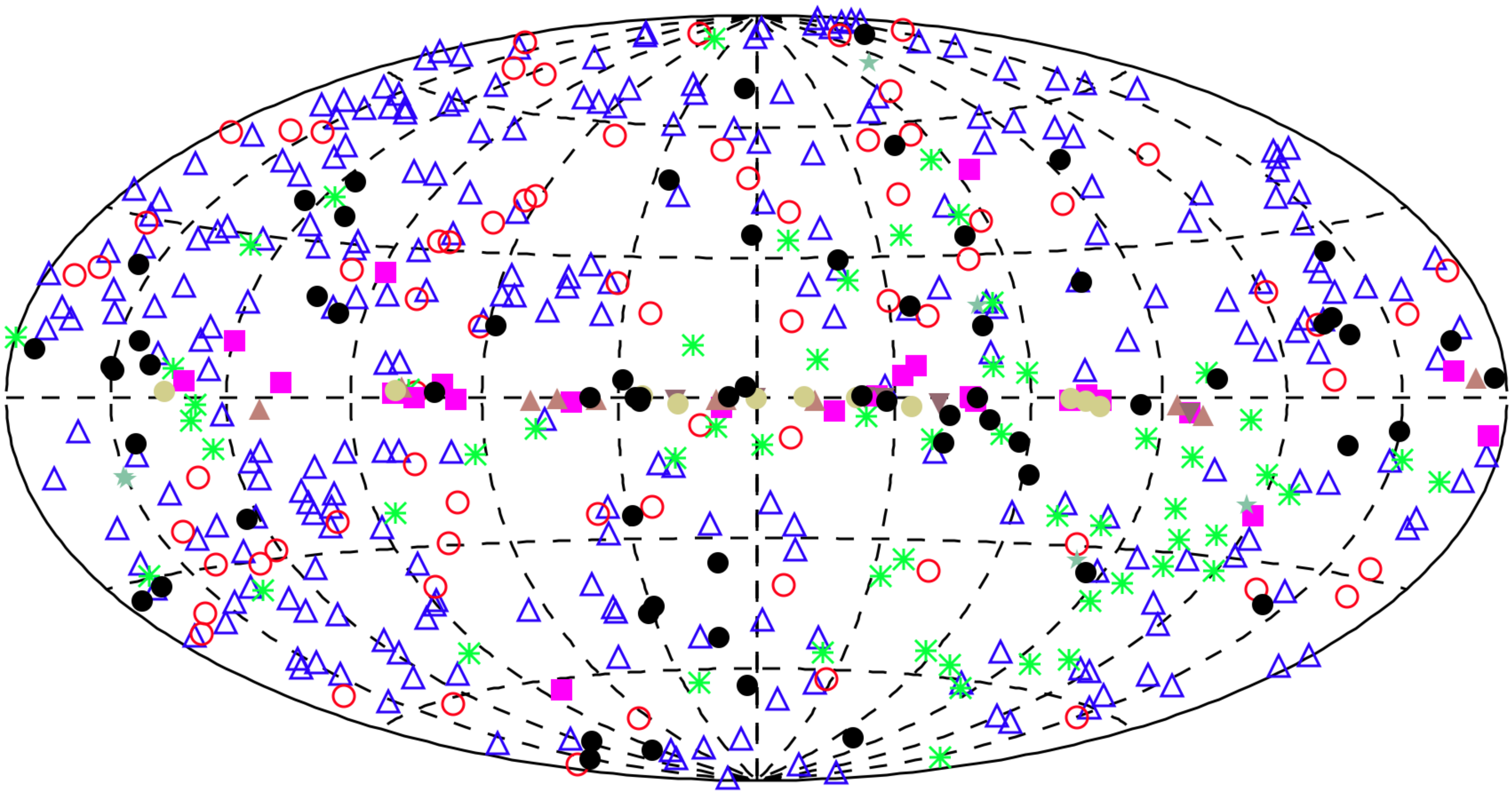
1451 sources >4.1 σ   Abdo et al. (2009)

2FGL Catalog



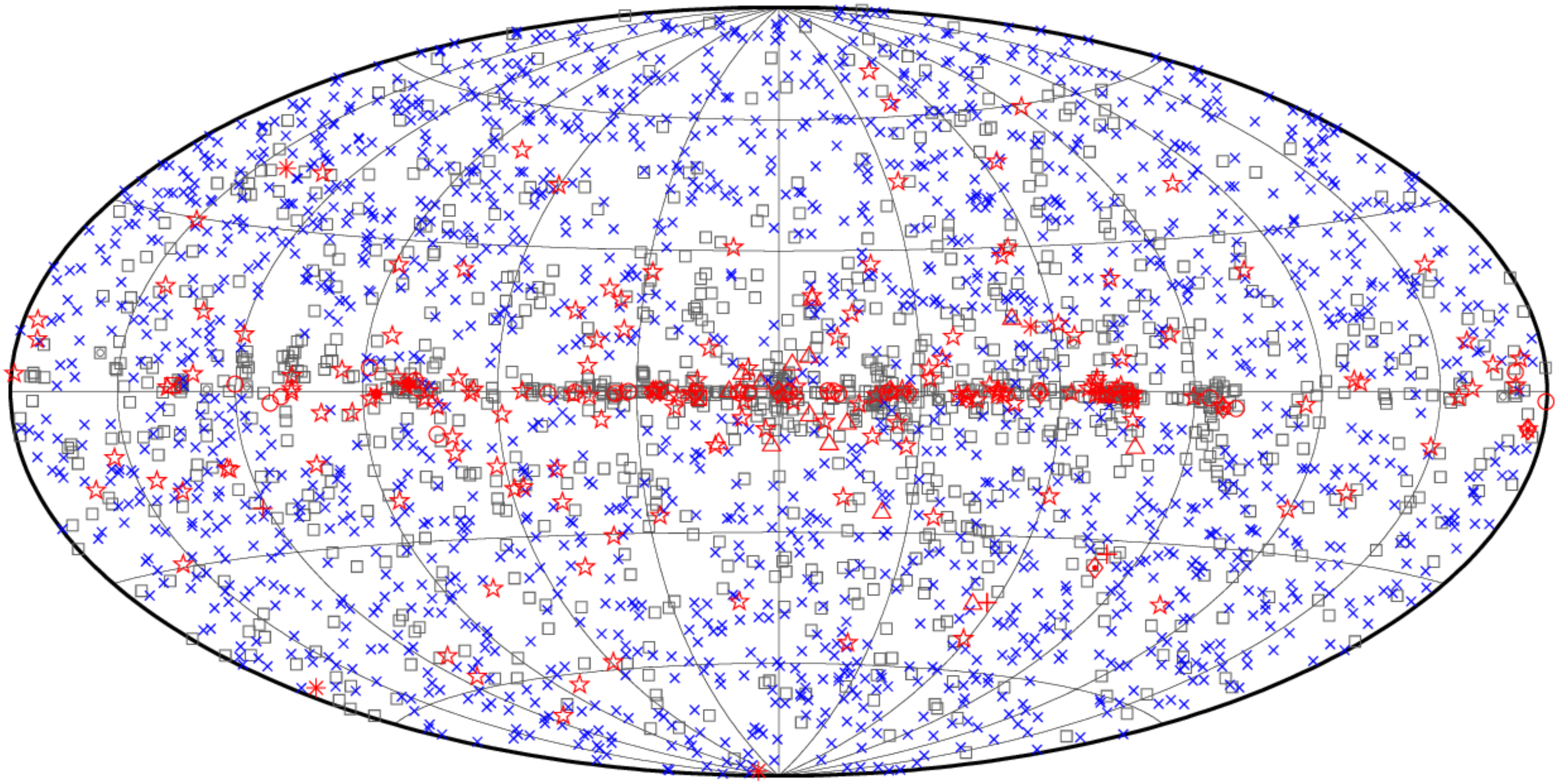
1873 sources >4.1 σ Nolan et al. (2012)

1FHL (>10 GeV) Catalog



514 sources >4.1 σ   Ackermann et al. (2013)

3FGL Catalog



3033 sources >4.1 σ Acero et al. (2015, in press)

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	3033	P7V15 SOURCE	Jan. 2015

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

General Procedure for LAT Catalog Analysis

1. Define 'seed' source candidates
   - Pre-2FGL, merged results from multiple algorithms; now start with previous catalog, iteratively find seeds from TS maps
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 Tools
   - 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 spatially extended LAT sources, evaluation of analysis flags for systematic uncertainties, reanalysis on ~monthly time scales to define light curves and variability

More on Catalog Analysis

- Source spectral models
  - Power law, log parabola, exponential cutoff
  - Crab combination
- Extended sources
  - 3FGL includes 25 extended sources with characteristics defined in other LAT publications
  - For technical reasons it is currently not possible to fit source extent or shape as part of the routine catalog analysis; for the extended sources, the positions are fixed and only the spectra are fit
- Additional diffuse emission components
  - Galactic diffuse, isotropic diffuse, residual Earth limb, Sun/Moon and associated degrees of freedom

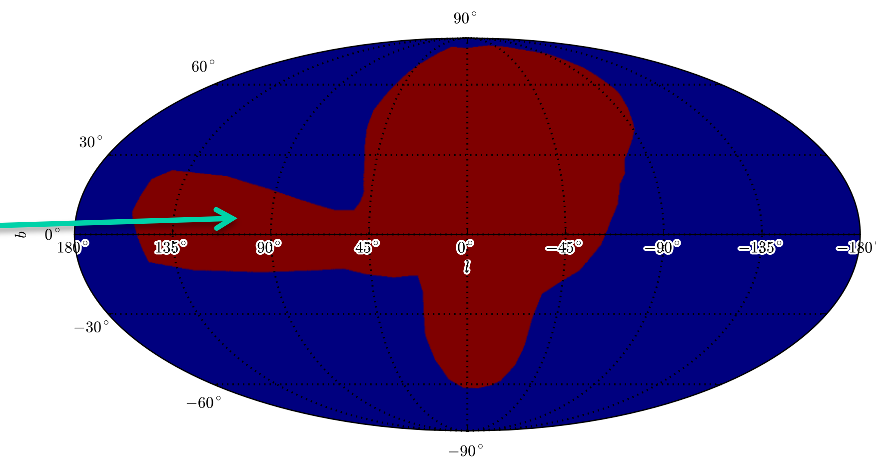
More on the Galactic Diffuse Emission Model

- Specifics of interstellar diffuse emission will be considered in a talk on Monday
- The model used for 3FGL analysis (released with Pass 7 Reprocessed data) was developed for 3FGL based on 4 years of Pass 7 data; Acero et al. (2015, submitted)
- Briefly, the diffuse gamma-ray emission from cosmic-ray interactions in the Milky Way can be modeled to first order as a linear combination of templates tracing the interstellar medium, a model for the inverse Compton component, and templates for large features like the radio continuum Loop I
- However, the LAT has revealed in increasing detail a number of aspects of diffuse gamma-ray emission that are not 'template-able'
  - Most famously the Fermi Bubbles (hard spectrum, large lobes)
  - But additionally over much of the inner Galaxy

More on Galactic Diffuse Emission Modeling

- **So we are faced with the issue of defining the ‘extra’ diffuse emission based solely on LAT observations**
- **The procedure adopted filters the residuals to few-degree angular resolution and re-injects them as a template with independent spectrum**
- **The unavoidable consequences are that in regions with this re-injection extended sources are subsumed into the model and real structure in these extra diffuse components could be detected as point sources**

Region covered by filtered residual diffuse emission

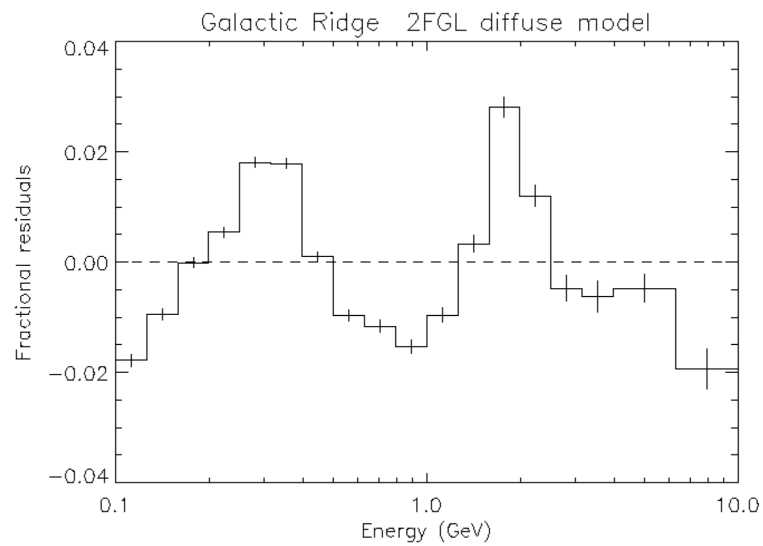


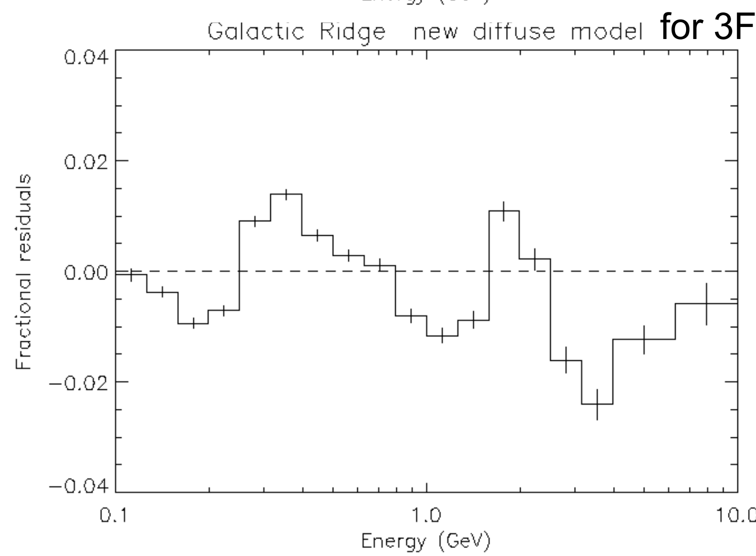
http://fermi.gsfc.nasa.gov/ssc/data/access/lat/Model_details/FSSC_model_diffus_reprocessed_v12.pdf

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 (although not with the 2FGL-era model and flag now also includes analysis dependence)**

* 44 of the 2FGL sources had fluxes change by >3σ by this method





for 3FGL

|*b*| < 10°, |*l*| <60°

3FGL Performance

- **Localization**

Good (typical) and Not-so-good

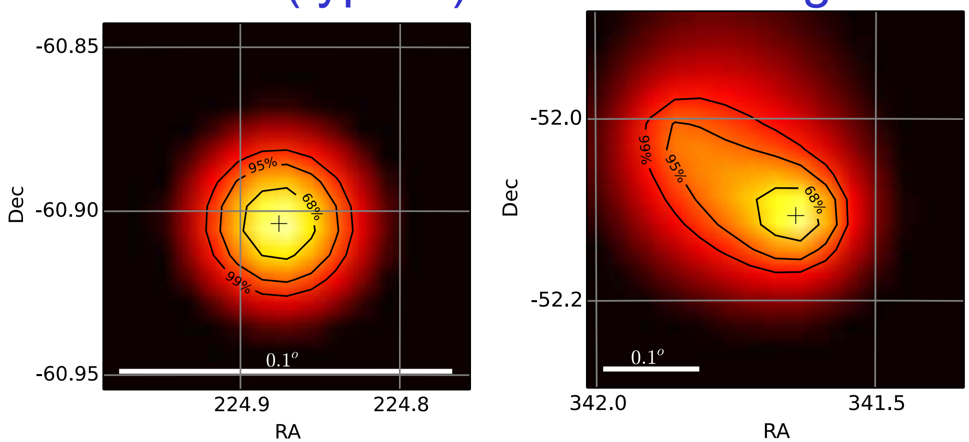
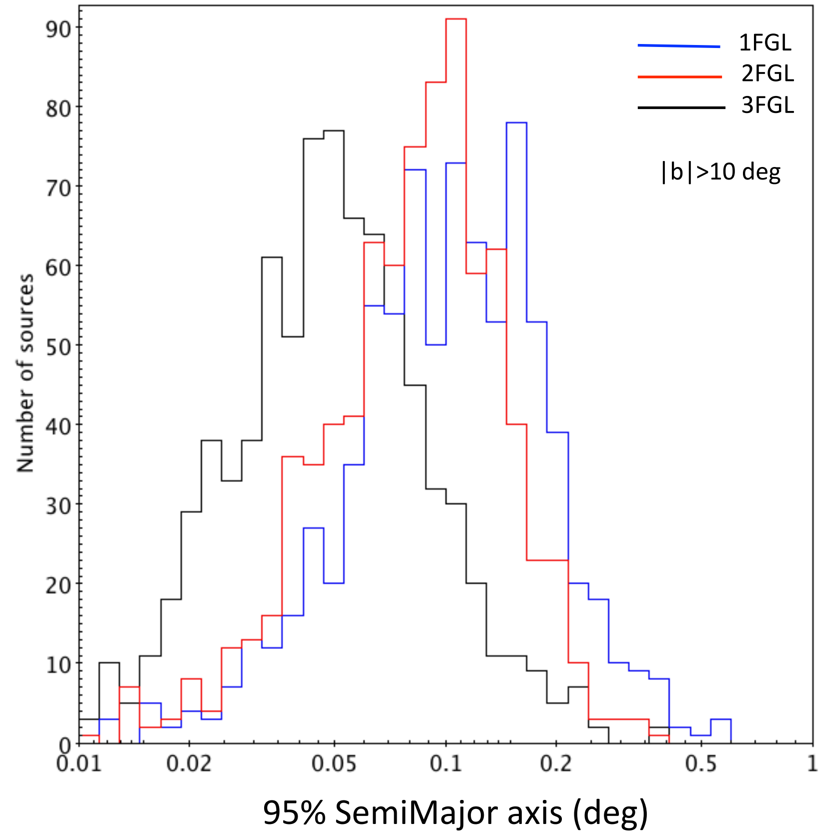


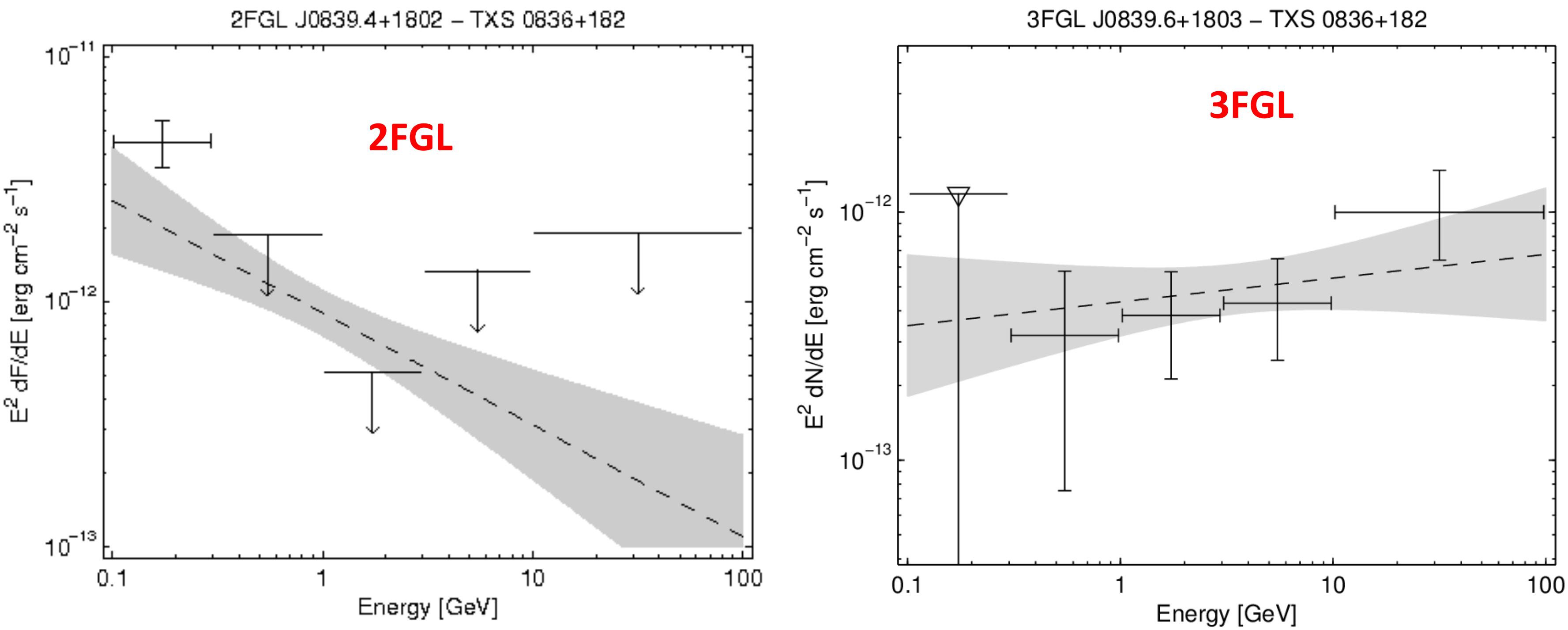
Fig. 5.— Examples of localization TS maps. The contours for 68%, 95%, and 99% tainment are shown. The scale (in decimal degrees) is not the same in both plots. PSR J1459−6053, a good localization with LQ = 0.63. Right: 3FGL J2246.7−5205, a localization with LQ = 14.

For 621 sources in common



3FGL Performance 2

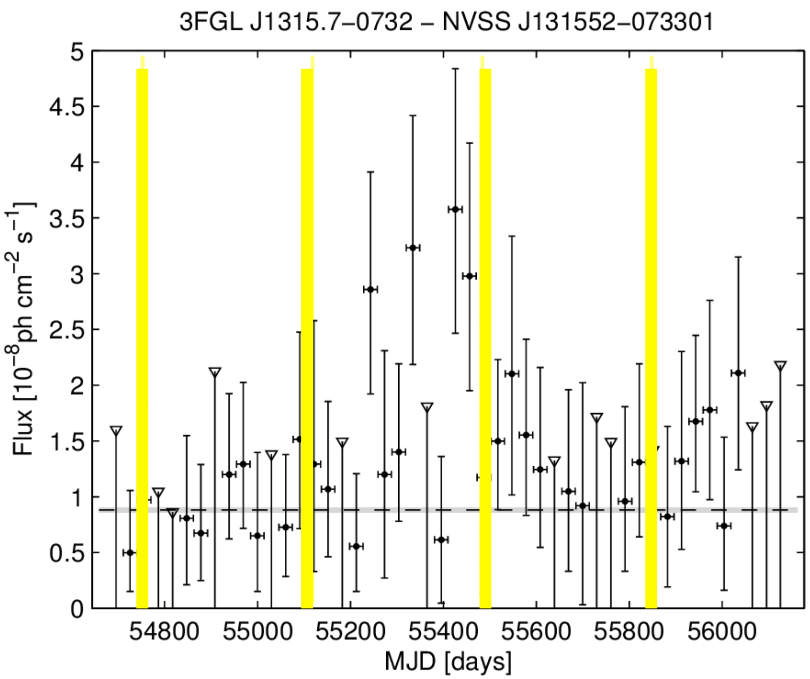
- **Spectra**



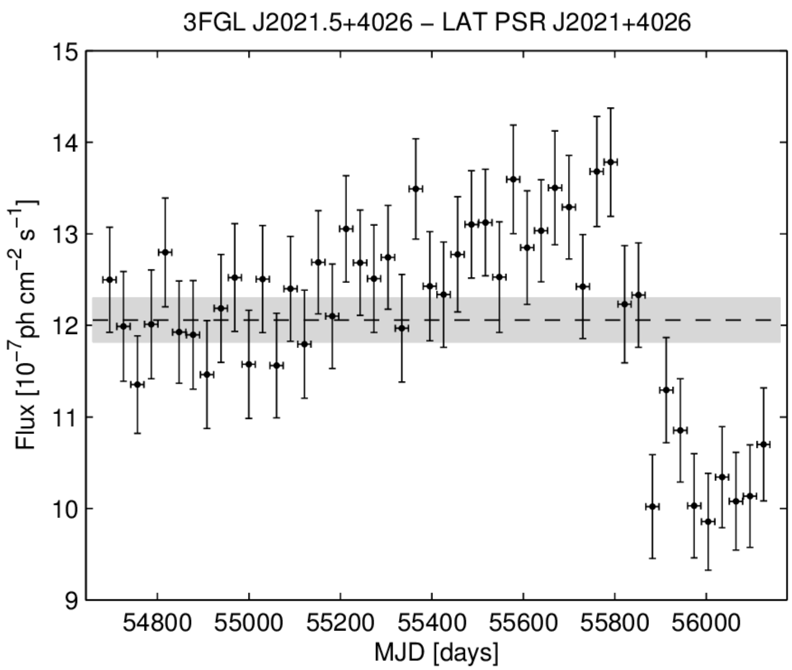
Example for the same source: This source at low ecliptic latitudes had been polluted in the 2FGL analysis by close passages of the Sun

3FGL Performance 3

- **Light curves**



A source at low ecliptic latitude no longer affected by the passage of the Sun



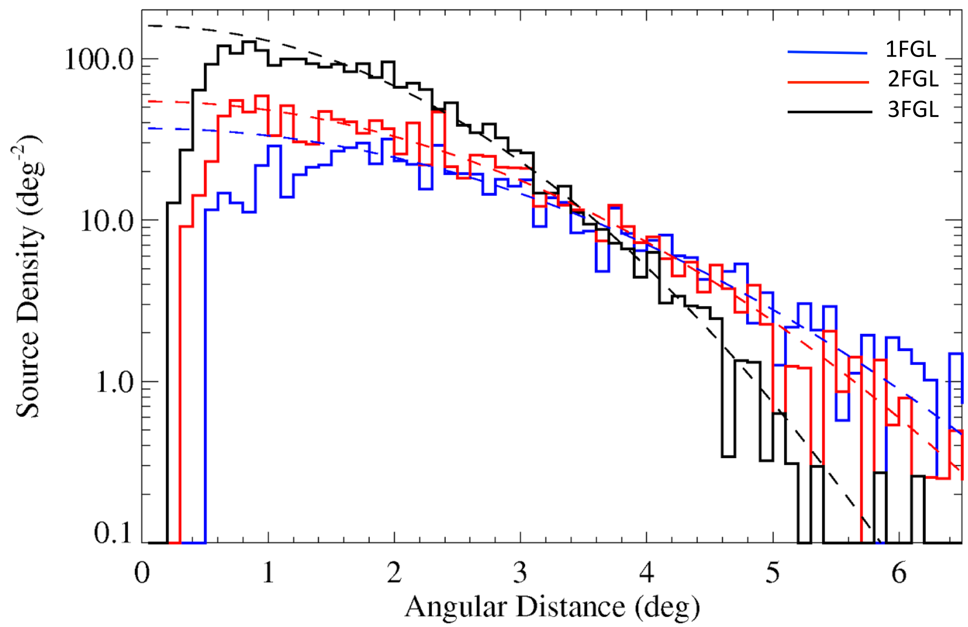
The **variable pulsar** LAT PSR J2021+4026 (Allafort et al. 2013, ApJL 777, L2)

see T. Johnson’s talk on Tuesday

3FGL Limitations

- **Source confusion: The distribution of nearest neighbors indicates a deficit at small separations**
  - **For 3FGL the deficit is approximately 140 sources at |*b*| > 10°**
  - **In some cases closely-spaced sources are effectively merged**
- **As mentioned, uncertainties in the Galactic diffuse emission are an important systematic**

Nearest Neighbor Distance (|*b*| > 10°)



Systematic Uncertainties from the Diffuse Model

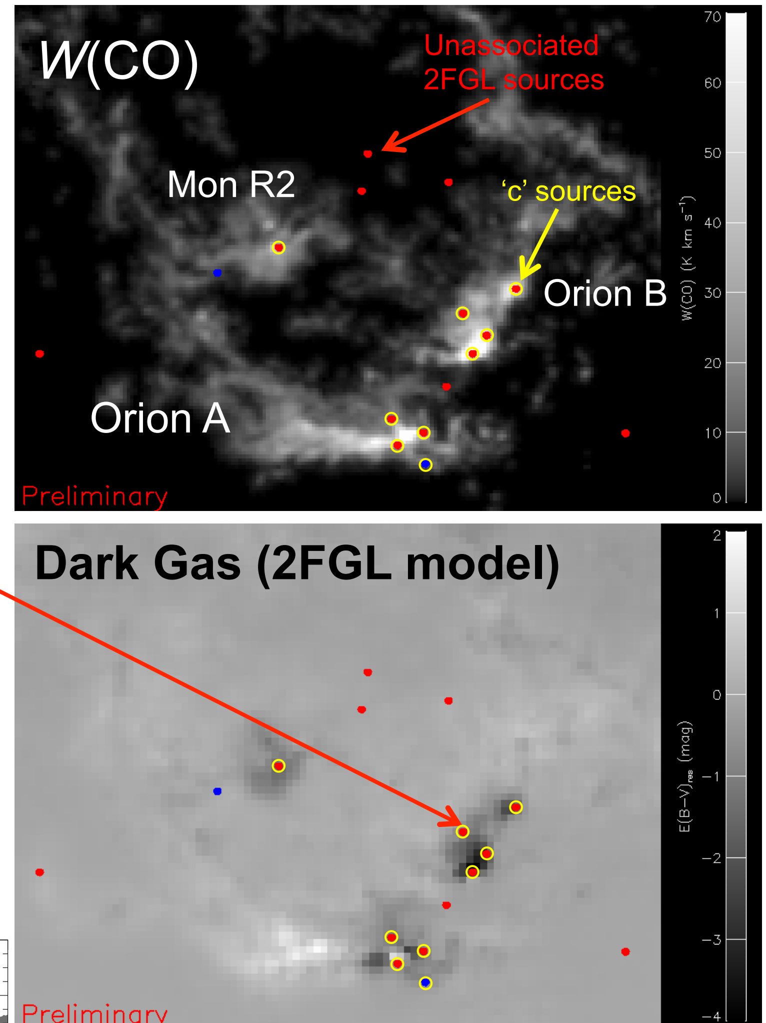
- **Diffuse model-related flags**
  - **Large impacts on significance (1), location (2), or flux (3)**
- **Also, location of sources with respect to likely defects in the model for Galactic diffuse emission (6)**

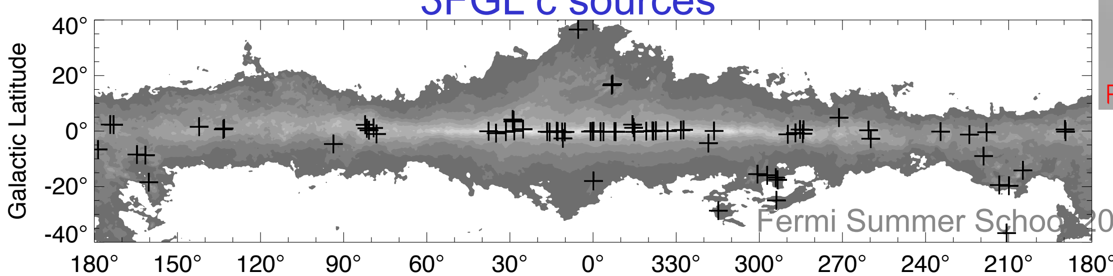
Flag[a]	Meaning	
1	Source with $TS > 35$ which went to $TS < 25$ when changing the diffuse model (§ 3.7.3) or the analysis method (§ 3.7.4). Sources with $TS \leq 35$ are not flagged with this bit because normal statistical fluctuations can push them to $TS < 25$.	213
2	Not used.	
3	Flux (> 1 GeV) or energy flux (> 100 MeV) changed by more than 3σ when changing the diffuse model or the analysis method. Requires also that the flux change by more than 35% (to not flag strong sources).	200
4	Source-to-background ratio less than 10% in highest band in which $TS > 25$. Background is integrated over πr_{68}^2 or 1 square degree, whichever is smaller.	145
5	Closer than $\theta_{\rm ref}$ from a brighter neighbor. $\theta_{\rm ref}$ is defined in the highest band in which source $TS > 25$, or the band with highest TS if all are < 25. $\theta_{\rm ref}$ 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 ($2\,r_{68}$).	164
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 (§ 3.8).	78
7	Unstable position determination; result from *gtfindsrc* outside the 95% ellipse from *pointlike*.	24
8	Not used.	
9	Localization Quality > 8 in *pointlike* (§ 3.1) or long axis of 95% ellipse > 0°.25.	64
10	Spectral Fit Quality > 16.3 (Eq. 3 of Nolan et al. 2012, 2FGL).	42
11	Possibly due to the Sun (§ 3.6).	0
12	Highly curved spectrum; `LogParabola` β fixed to 1 or `PLExpCutoff` `Spectral_Index` fixed to **0.5** (see § 3.3).	45

On Analysis Flag 6 & ‘c’ sources

- The dark gas component of the interstellar medium is inferred from IR observations + CO and H I surveys
- In the 2FGL model, the dark gas component around bright IR sources like the Orion Nebula had deficits
  - Unassociated LAT point sources tended to congregate there
- These were many of the 2FGL ‘c’ sources
- Filtering of these small-scale defects is greatly improved for the diffuse emission modeling for 3FGL

Molecular and Dark Gas in Orion

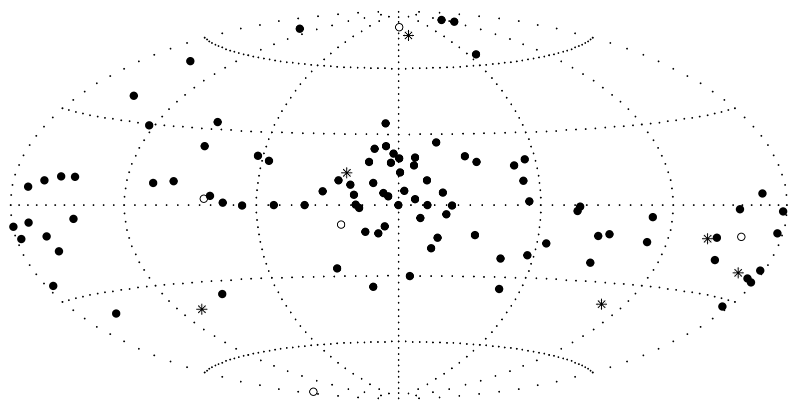




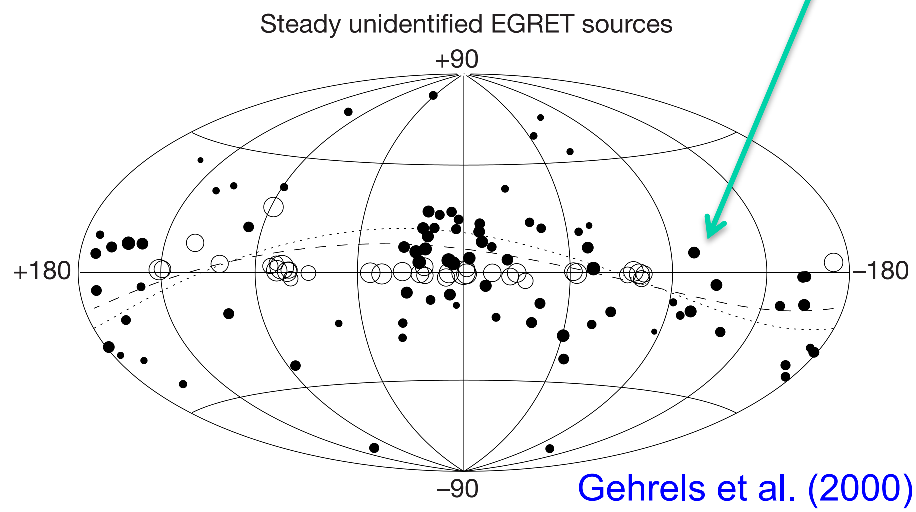
EGRET 'Faint Persistent Sources'

- The potential for confusion with diffuse emission is real
- The 3EG catalog has a population of faint, persistent (i.e., steady as far as EGRET could tell) sources at moderate latitudes

3EG sources not in EGR



belt[3,4] of massive stars and gas clouds at ~600 light years distance, as has been previously suggested[5].



Gehrels et al. (2000)

- These were hypothesized to be related to massive star formation in the Gould Belt
- In a later analysis taking into account new understanding of the interstellar gas (so-called 'dark gas') many of them were no longer detected (EGR catalog, Casandjian & Grenier 2008)

Identification vs. Association

- Identification is a strong term
  - For the LAT, based on correlated variability or spatial extent
  - For 3FGL we included 25 extended sources (necessarily as input to the analysis) and overall had 232 identified sources (132 of which were pulsars)
- Association is generally the strongest statement that we can make
- And the approach needs to be considered carefully

- For LAT catalogs we have converged on two quantitative methods for assignment of associations
  - We report the union of the results

Source Populations and Source Association

- Both Population protocol and Source-by-source association approaches; the former only for 1FGL
- For Population protocol: before launch we defined representative (physically motivated) members of each of a number of source classes, and a simple definition of source association, and the budget for association probabilities
  - Has some challenges in application – needing to guess correctly about representative members of classes in terms of detectability; separability of populations (a 1FGL source lining up with a representative SNR could be LAT pulsar)
- The Source association is like calibrated cross correlation between catalogs – the goal being quantitative probabilities of association and to controlled false association rate
  - For FGL catalogs we adopted *P* = 0.8 threshold

1FGL Population Protocol Results

Table 8. Results from Application of the Population Protocol

Test Population	N_p	b	$\mathcal{C}$	CP	P	(CP $<$ P)?	CL
Galactic Populations							
Pulsars	215	1.440	30	5.3×10^{-29}	1.0×10^{-9}	yes	$>$ 99.999%
Millisecond Pulsars	23	0.050	7	1.5×10^{-13}	1.0×10^{-8}	yes	99.89%
EGRET SNRs	23	1.590	13	1.5×10^{-8}	1.0×10^{-8}	no	...
TeV SNRs	4	0.920	3	6.6×10^{-2}	9.9×10^{-7}	no	...
Magnetars	13	0.120	0	...	9.9×10^{-7}	...	...
WR-binaries	41	0.260	0	...	9.9×10^{-7}	...	...
MQ/γ-ray bin.	17	0.140	3	4.1×10^{-4}	9.9×10^{-7}	no	...
Binary pulsars	10	0.040	0	...	9.9×10^{-7}	...	...
Globular clusters	29	0.240	4	1.1×10^{-4}	9.9×10^{-7}	no	...
Extragalactic Populations							
Blazars	215	0.480	61	0.0	1.0×10^{-9}	yes	$>$ 99.999%
Misaligned jet sources	53	0.150	5	5.5×10^{-7}	9.9×10^{-7}	yes	99.25%
Starbursts	15	0.050	4	2.5×10^{-7}	9.9×10^{-7}	yes	97.89%
Galaxy clusters	48	0.150	0	...	9.9×10^{-7}	...	...
Dwarf spheriodals	18	0.070	0	...	9.9×10^{-7}	...	...

In 3FGL we now have all of these classes

But still neither of these

Counterpart Catalogs: Bayesian Method

- These were used in searching for associations with LAT sources
- For catalogs of point-like sources the chance association probabilities were evaluated locally from simulations
- For extended counterparts (e.g., SNRs) or for catalogs with large location uncertainties (e.g., 3EG) the chance probability could not be calibrated
  - We note overlaps with SNRs in a separate table

Table 12. Catalogs Used for the Automatic Source Association Methods

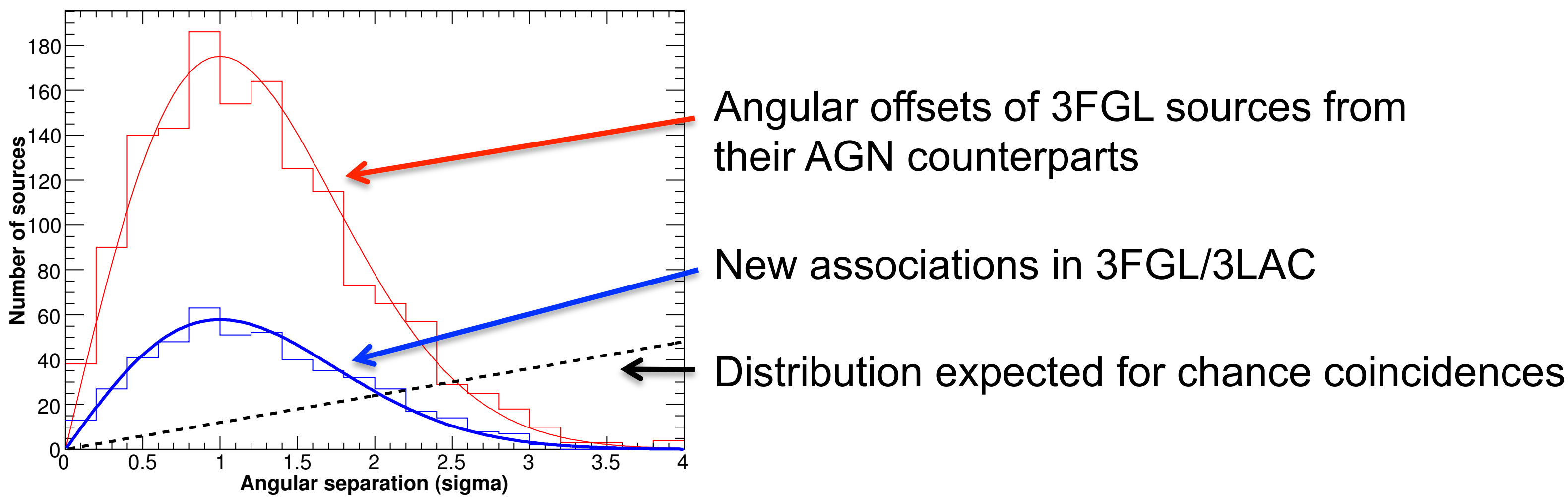
Name	Objects[a]	Ref.
High $\dot{E}/d^2$ pulsars	213	Manchester et al. (2005)[b]
Low $\dot{E}/d^2$ pulsars		Manchester et al. (2005)[b]
Other normal pulsars	1657	Manchester et al. (2005)[b]
Millisecond pulsars	137	Manchester et al. (2005)[b]
Pulsar wind nebulae	69	Collaboration internal
High-mass X-ray binaries	114	Liu et al. (2006)
Low-mass X-ray binaries	187	Liu et al. (2007)
Point-like SNR	157	Green (2009)
Extended SNR†	274	Green (2009)
O stars	378	Maíz-Apellániz et al. (2004)
WR stars	226	van der Hucht (2001)
LBV stars	35	Clark et al. (2005)
Open clusters	2140	Dias et al. (2002)
Globular clusters	160	Harris (1996)
Dwarf galaxies†	100	McConnachie (2012)
Nearby galaxies	276	Schmidt et al. (1993)
IRAS bright galaxies	82	Sanders et al. (2003)
BZCAT (Blazars)	3060	Massaro et al. (2009)
BL Lac	1371	Véron-Cetty & Véron (2010)
AGN	10066	Véron-Cetty & Véron (2010)
QSO	129,853	Véron-Cetty & Véron (2010)
Seyfert galaxies	27651	Véron-Cetty & Véron (2010)
Radio loud Seyfert galaxies	29	Collaboration internal
1WHSP	1000	Arsioli et al. (2014)
WISE blazar catalog	7855	D'Abrusco et al. (2014)
* NRAO VLA Sky Survey (NVSS)[c]	1,773,484	Condon et al. (1998)
* Sydney University Molonglo Sky Survey (SUMSS)[c]	211,050	Mauch et al. (2003)
* Parkes-MIT-NRAO survey[c]	23277	Griffith & Wright (1993)
CGRaBS	1625	Healey et al. (2008)
CRATES	11499	Healey et al. (2007)
VLBA Calibrator Source List	5776	http://www.vlba.nrao.edu/astro/calib/vlbaCalib.txt
* ATCA 20 GHz southern sky survey	5890	Murphy et al. (2010)
ATCA follow up of 2FGL unassociated sources	424	Petrov et al. (2013)
* ROSAT All Sky Survey (RASS) Bright and Faint Source Catalogs[c]	124,735	Voges et al. (1999),[d]
58 months BAT catalog	1092	Baumgartner et al. (2010)
4^{th} IBIS catalog	723	Bird et al. (2010)
TeV point-like source catalog*	148	http://tevcat.uchicago.edu/
TeV extended source catalog†	66	http://tevcat.uchicago.edu/
1st AGILE catalog*	47	Pittori et al. (2009)
3rd EGRET catalog*	271	Hartman et al. (1999)
EGR catalog*	189	Casandjian & Grenier (2008)
0FGL list*	205	Abdo et al. (2009d, 0FGL)
1FGL catalog*	1451	Abdo et al. (2010d, 1FGL)
2FGL catalog*	1873	Nolan et al. (2012, 2FGL)
1FHL catalog*	514	Ackermann et al. (2013a, 1FHL)
LAT pulsars	147	Collaboration internal

*Also used for Likelihood Ratio method

Likelihood Ratio Method

- This was applied using uniform radio and X-ray surveys, for AGN associations
- In this approach the counterpart densities are (reasonably) assumed to be spatially uniform over the areas of the surveys
- And their flux distribution is also considered

Sanity check



- For 3FGL the Bayesian method finds 1663 AGN associations (405 unique to this method). The Likelihood Ratio method finds 1340 (82 unique)

Associated Source Classes

- **Blazars and pulsars dominate**
- **Only one Galactic nova of ~4 detected by the LAT**
  - **Briefer transient classes of LAT sources (GRBs, solar flares) are not represented at all***
- **The fraction of unassociated sources is about 1/3**
  - **This has not decreased appreciably as the FGL catalogs have deepened and counterpart catalogs have grown**

Table 6. LAT 3FGL Source Classes

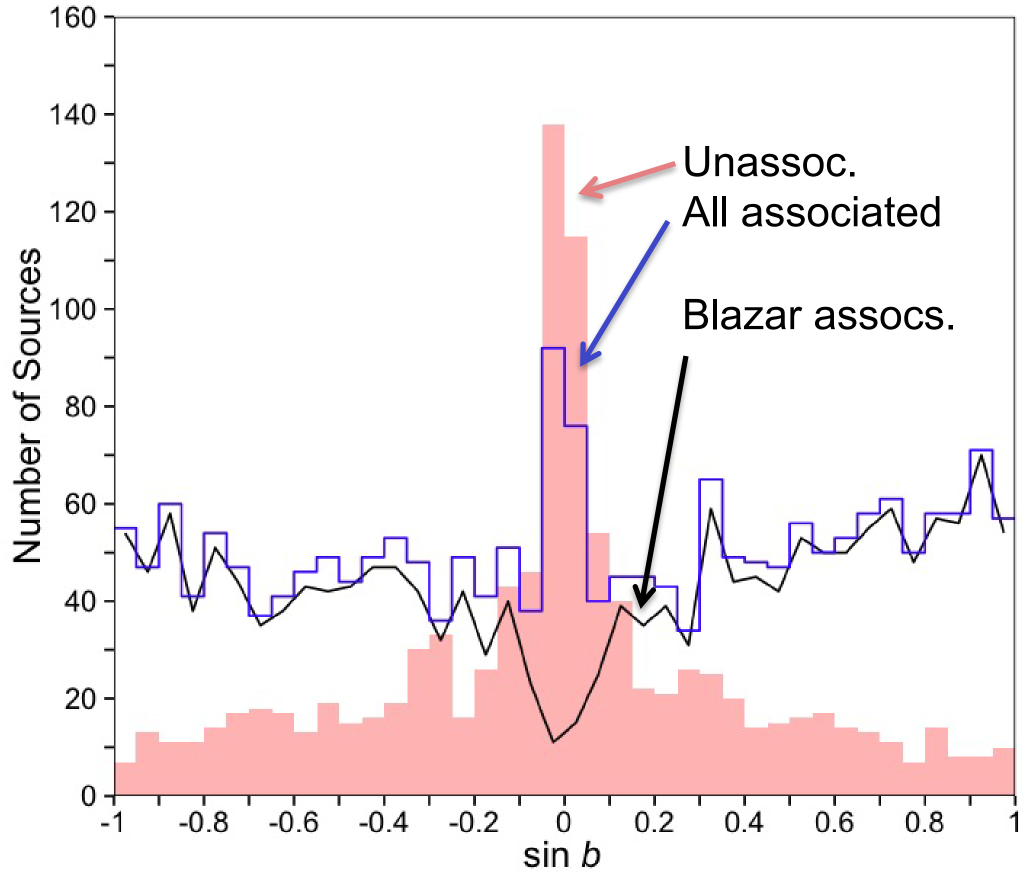
Description	Identified		Associated	
	Designator	Number	Designator	Number
Pulsar, identified by pulsations	PSR	143	...	...
Pulsar, no pulsations seen in LAT yet	...	...	psr	24
Pulsar wind nebula	PWN	9	pwn	2
Supernova remnant	SNR	12	snr	11
Supernova remnant / Pulsar wind nebula	...	...	spp	49
Globular cluster	GLC	0	glc	15
High-mass binary	HMB	3	hmb	0
Binary	BIN	1	bin	0
Nova	NOV	1	nov	0
Star-forming region	SFR	1	sfr	0
Compact Steep Spectrum Quasar	CSS	0	css	1
BL Lac type of blazar	BLL	18	bll	642
FSRQ type of blazar	FSRQ	38	fsrq	446
Non-blazar active galaxy	AGN	0	agn	3
Radio galaxy	RDG	3	rdg	12
Seyfert galaxy	SEY	0	sey	1
Blazar candidate of uncertain type	BCU	5	bcu	568
Normal galaxy (or part)	GAL	2	gal	1
Starburst galaxy	SBG	0	sbg	4
Narrow line Seyfert 1	NLSY1	2	nlsy1	3
Soft spectrum radio quasar	SSRQ	0	ssrq	3
Total	...	238	...	1786
Unassociated	...	...	...	1010

Note. — The designation 'spp' indicates potential association with SNR or PWN (see Table 7). Designations shown in capital letters are firm identifications; lower case letters indicate associations. In the case of AGN, many of the associations have high confidence. Among the pulsars, those with names beginning with LAT were discovered with the LAT.

* This is by design; time intervals of the brightest flares were excluded from the analysis

On the Unassociated Sources

- Clearly concentrated toward the Galactic equator
- Source density is greatest there but so is the fraction of 'flagged' sources
- And blazar counterpart catalogs tend to be incomplete at low latitudes



Automatic Classification of Unassociated Sources

- **Classification Tree and Logistic Regression approaches were studied using the 1FGL catalog***
- **This included studying what intrinsic source properties were the best discriminators between ‘AGN-like’ and ‘pulsar-like’**
  - **And minimizing dependence of these quantities on source significance**
- **Most important were fractional variability and some measure of spectral hardness**
- **The firm associations/identifications provided training samples**

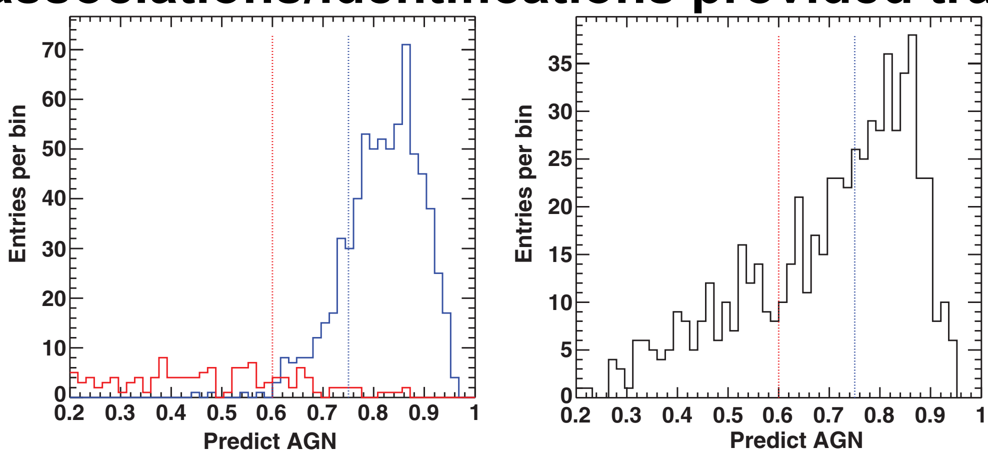


Figure 8. Distribution of the Classification Tree predictor. Vertical lines indicate the value of the thresholds we set to identify AGN candidates (Predictor >0.75) and pulsar candidates (Predictor <0.6). Left: sources of the 1FGL catalog identified as pulsar (red) and AGN (blue). Right: distribution of the predictor for unassociated sources.

* See Ackermann et al. (2012, ApJ 753, 83)

Multiwavelength Follow-up of Unassociated LAT Sources

- **Radio timing searches of LAT unassociated sources have been extremely successful for finding pulsars, especially millisecond pulsars (T. Johnson's talk on Tuesday)**

- **For blazars, typically blazar candidates have been selected based on LAT-measured properties and correlations with other catalogs**
  - **These provide more-precise locations and have guided optical spectroscopy to confirm blazar natures of sources**
  - **A very successful approach has been implemented by Massaro et al. (e.g., 2012, ApJ 757, L27), who defined the 'WISE Blazar Strip', a region of infrared color-color space where blazars congregate**
  - **The correspondences with LAT sources indicate blazar candidates, which they have followed-up with optical spectroscopy**

Population Studies: Extragalactic

- In terms of characterizing an extragalactic (isotropic) source population the flux distribution (log *N* – log *S*, or *N*(>*S*) in cumulative form) and the luminosity function are of direct interest

$$N(>S) = \int_{\Gamma_{\min}}^{\Gamma_{\max}} \int_{z_{\min}}^{z_{\max}} \int_{L_\gamma(z,S)}^{L_{\gamma,\max}} \Phi(L_{\gamma,z}) \frac{dN}{d\Gamma} \frac{dV}{dz} d\Gamma dz dL_\gamma, \quad (9)$$

where $L_\gamma(z, S)$ is the luminosity of a source at redshift z having a flux of S.

Ajello et al. (2012, ApJ 751, 108)

- To quantitatively determine these, the **detection efficiency** must be evaluated
- This involves running a Catalog analysis pipeline on many realizations of simulated sky-survey data
- The resulting quantitative distribution informs evaluation of the blazar contributions to the extragalactic background

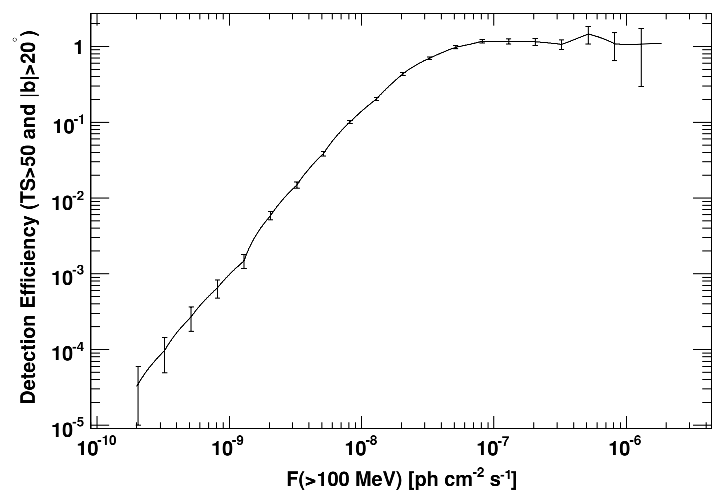


Figure 7. Detection efficiency as a function of measured source flux for $|b| \geqslant 20°$, TS $\geqslant$ 50, and a sample of sources with a mean photon index of 2.40 and dispersion of 0.28. The error bars represent statistical uncertainties from the counting statistic of our Monte Carlo simulations.

Abdo et al. (2010, ApJ 720, 435)

See talks by Y. Inoue next week for results

Population Studies: Galactic

- **With the 3FGL catalog sources we also studied the flux distribution and luminosity function of Galactic sources**
  - **One motivation was to estimate the unresolved source contribution to Galactic diffuse emission**
- **In this case the luminosity function is assumed to factor into spatial (*R, z*) and luminosity-dependent (L_γ) terms**
  - **We assumed a plausible spatial dependence (distribution like Lorimer's pulsar model in *R*, 500 pc scale height in z, and a power-law dependence on L_γ (index -1.8, for 2×10^{34}–2×10^{39} ph s^{-1}, >1 GeV)**
- **For this study we did not try to evaluate the detection efficiency – just kept in mind the approximate sensitivity thresholds**

Population Studies: Galactic (cont.)

- **Here is a comparison of source count distributions for different regions of the sky, for various source selections**
- **In this 'reference model' the Milky Way has about 29,000 sources**
  - **3FGL has about 1% of them**
- **The corresponding unresolved source fraction toward the inner Galaxy is about 3% of the total diffuse emission**

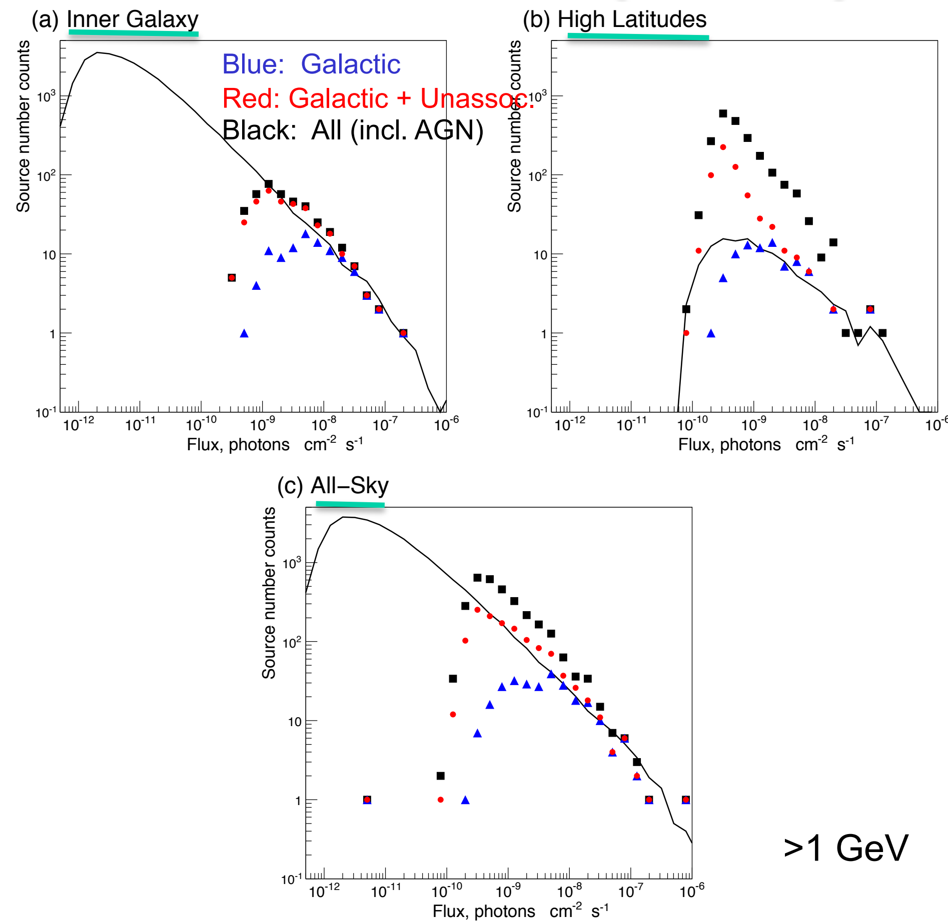


Fig. 24.— Dependence of source number counts (number of sources per 0.2 dex) on source photon flux S above 1 GeV. The markers are source number counts from the 3FGL catalog; blue triangles are identified and associated Galactic sources, red circles are identified and associated Galactic, and unassociated sources, and black squares are all sources including extragalactic (for reference). The curves are from the reference model described in the text. (a) inner Galaxy ($|b| < 10°$, $300° < l < 60°$); (b) high latitudes ($|b| > 10°$, all longitudes); (c) all-sky.

For the Next General LAT Catalogs

- We have an ongoing effort to improve/update associations analysis for any LAT catalog
  - With multiwavelength information
  - Accumulating results of follow-up studies
- 2FHL catalog of >50 GeV sources, 6 years of Pass 8 data, ~320 sources, ~60 new (not in 3FGL or 1FHL, a 3-year >10 GeV catalog), only ~70 in TeVCat
- Unnamed catalog of LAT transient sources, typically blazars that were bright only briefly
- 4FGL (6-7 years Pass 8), updating analysis procedure for Pass 8 (larger field of view), further refining the model of Galactic diffuse emission, investigating implications and challenges for going to lower energies, possibility of generalizing detection to include transient sources too faint on average

Source Class-Specific LAT Catalogs

- Active Galactic Nuclei: 1LAC, 2LAC, 3LAC have already been mentioned
  - These were developed in parallel with the #FGL catalogs
  - The Likelihood Ratio method was refined for these works and the resulting associations are folded back into the #FGL associations
- Pulsars: 1PC, 2PC (Abdo et al. 2013, ApJS 208, 17)
  - The latter has timing information for the first 117 LAT pulsars and includes, e.g., phase-selected spectroscopy, also upper limits for pulsars not detected by the LAT
- Extended Sources (Lande et al. 2012, ApJ 756, 5)
  - A systematic search for extended sources among the 2FGL sources
  - Reported 7 new extended sources

Source Class-Specific Catalogs 2

- First LAT GRB Catalog (Ackermann et al. 2013, ApJS 209, 11)
  - Searched 700+ GBM (hard X-ray) detections
  - Characteristics of 28 GRBs detected by the LAT in the first three years
- LAT SNR Catalog (in preparation)
  - Searched for all SNRs in Green's catalog, in 1-100 GeV range, three years
  - Found 30 likely likely counterparts based on overlap and significance, and robustness of results for a set of alternative diffuse emission models
  - Can start considering population studies of Galactic SNRs in gamma rays

FAVA: A Monitor + Catalog

- Fermi All-sky Variability Analysis (Ackermann et al. 2013, ApJ 771, 57)
- Systematic search for transient sources on weekly time scales by comparing sky maps with 'reference' maps for two energy ranges
  - Routine searches are run on LAT data run on 6-hour and 1-day time scales, so this was exploring a new time scale
- The location precision is not high but sensitivity is good
- In 47 months of LAT data, 215 FAVA flares were found
  - Some were new, not being associated with LAT catalog sources
  - No evidence for new Galactic transients was found
- FAVA is run routinely and automatically now, including follow-up likelihood analyses for detected transients

Summary

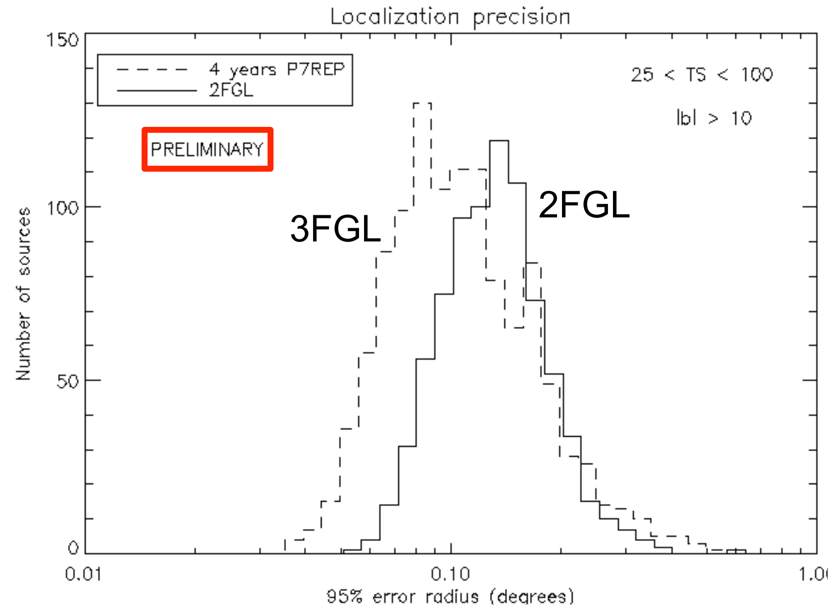
- The LAT catalog analysis procedure has been applied, with successive refinements, several times
- Uniform, systematic analysis has a number of useful objectives
- 3FGL has >3000 sources
- A number of class-specific catalogs also exist
- More LAT catalogs are in development

LAT catalogs and ancillary information are available from the Fermi Science Support Center

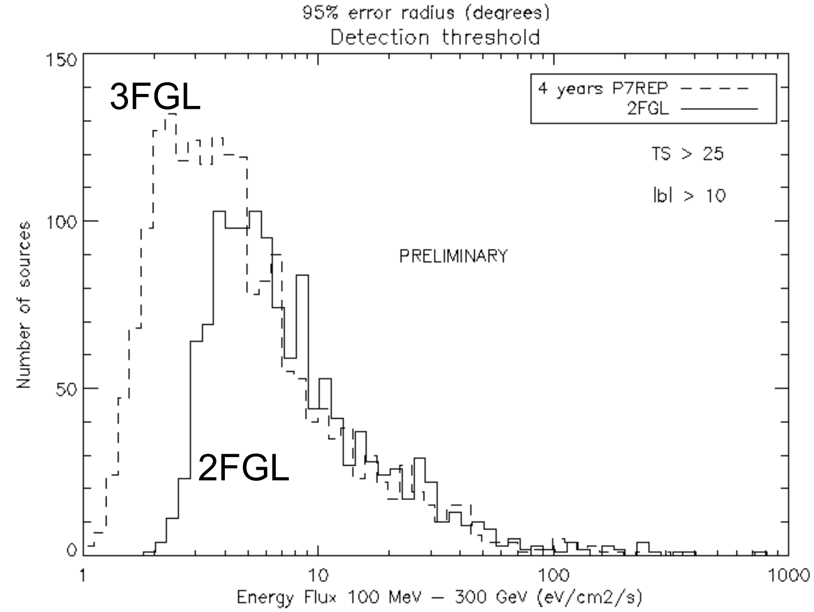
Backup Slides

3FGL Relative to 2FGL: Localization & Threshold

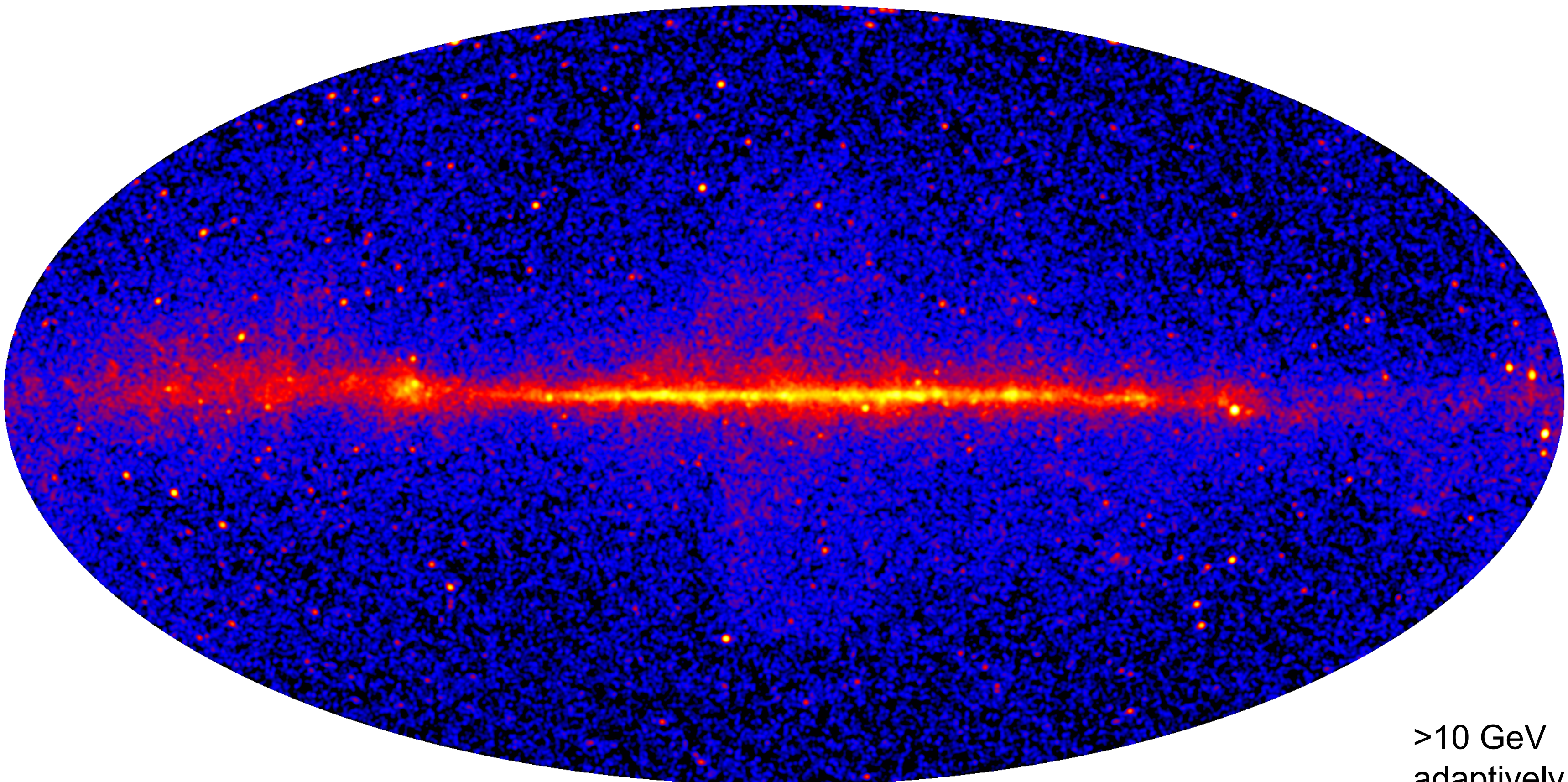
- Illustration of localization improvement, for sources of **similar significance** away from the Galactic plane
- The average localization region radius is 15% smaller



- For **all sources with TS > 25** detected away from the Galactic plane, the distribution of energy fluxes extends down to ~2 eV cm^{-2} s^{-1} vs. ~3 eV cm^{-2} s^{-1} for 2FGL



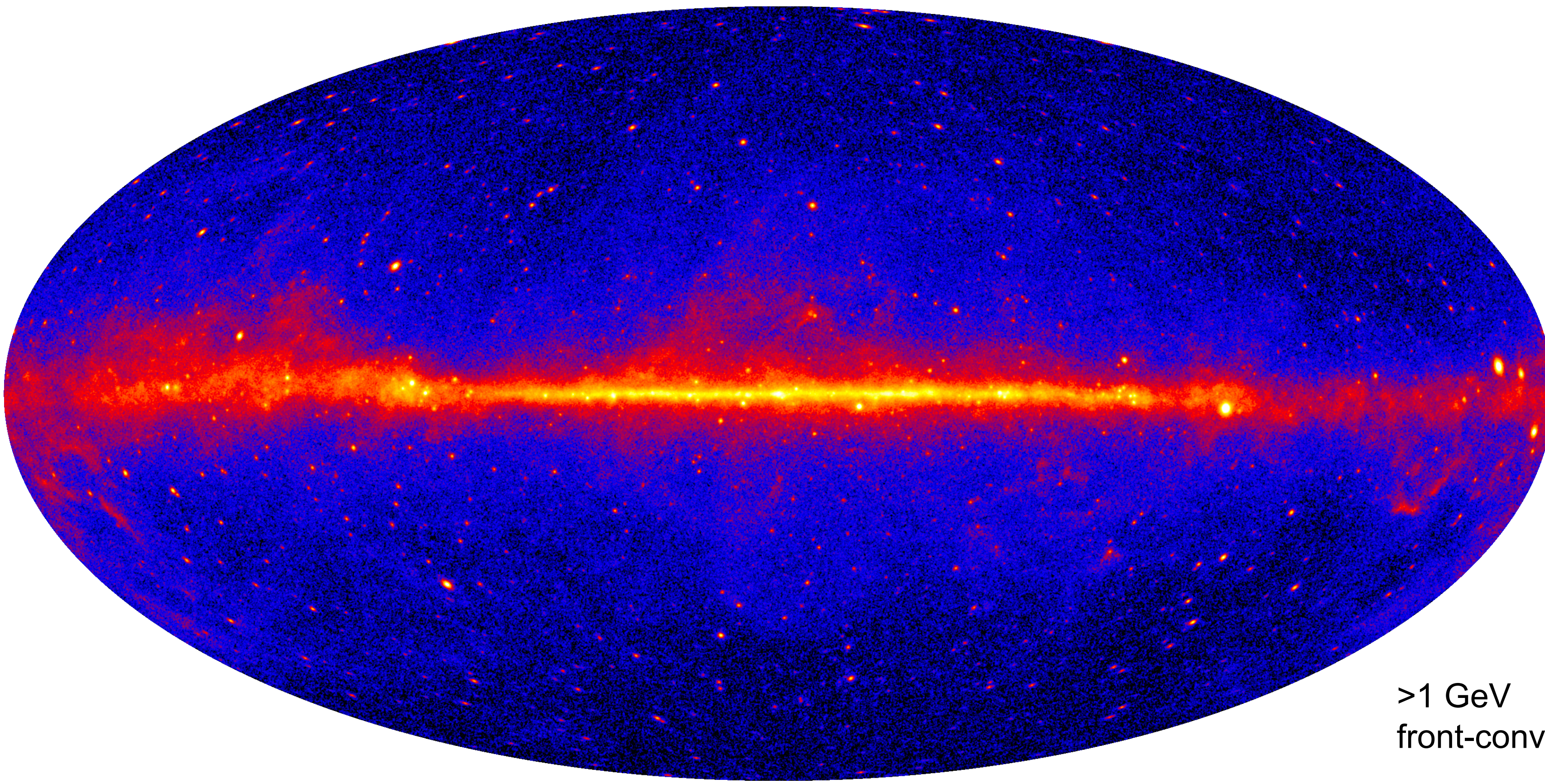
Highlights of 1FHL



>10 GeV
adaptively
smoothed

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

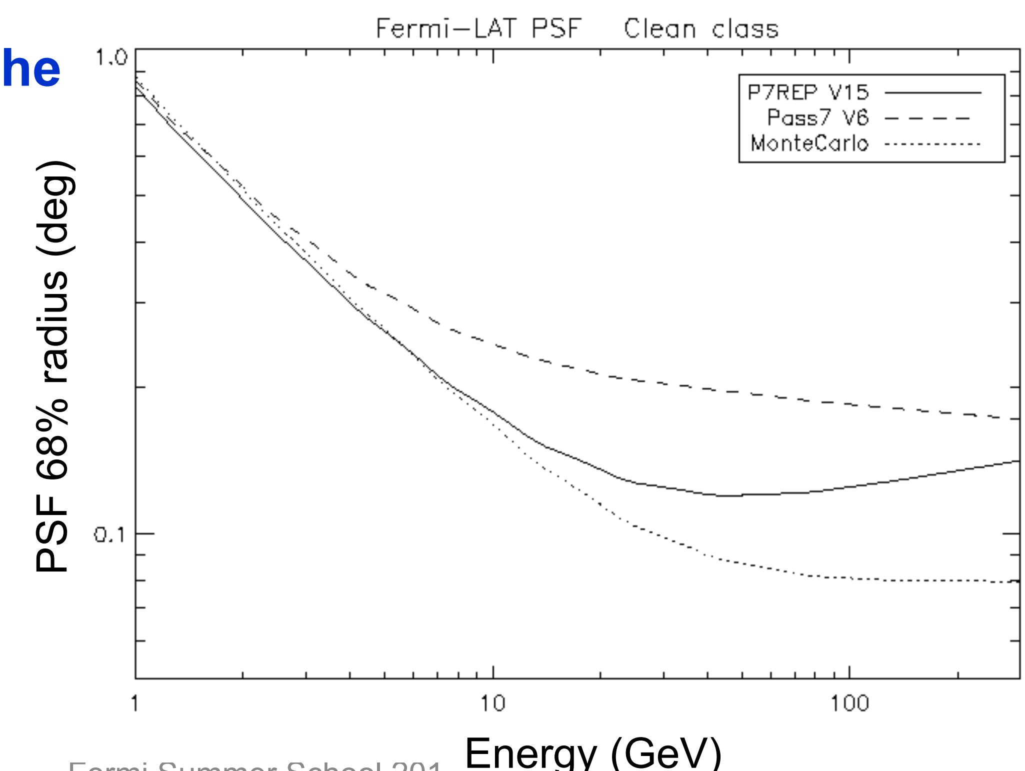
Highlights of 3FGL Development



- **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