Fermi-LAT Catalogs

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(with the help of past LAT speakers)
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Why to build a catalog

Catalogs as drivers for other studies

- Population studies: LogN – LogS, Luminosity Function
- Long term studies
- Reference for works on individual sources (included provides starting source model for any ROI)
- Timing correlations between the activity in the gamma-ray bands and other bands
- Dichotomy between gamma-ray detected and gamma-ray non-detected blazars at other wavelengths
- Correlation between gamma-ray AGNs and the sources of ultra high-energy cosmic rays / high-energy neutrinos
- Sample to probe the Extragalactic Background Light / InterGalactic Magnetic Field
- Contribution of AGNs to the extragalactic diffuse gamma-ray background
- Finding new MSPs
- Triggering dedicated studies of SNRs
- Constrain the population of unresolved Galactic sources
- Build the next generation model for diffuse Galactic emission

How to build a catalog

Source detection and source list

Given a collection of gammas described by, after reconstruction:

energy, incoming direction, time

-> construct a model of the gamma-ray sky for a given time period

BLIND SEARCH:

Look for patterns in the data indicating presence of a point source, hopefully discriminating against diffuse, relatively smooth background

Techniques:

- **Image-based techniques**: wavelet (PGWAVE), Maximum Likelihood (pointlike)
- **Photon-based techniques**: clustering Minimal Spanning Tree (MST)

All provide candidates, or "seeds" for the full likelihood calculation including localization that is required to define it as a source. This is the stage at which the full information about the data is used: the background, PSF, nearby sources.

Significance and Thresholding:

Maximum Likelihood keeping only sources with significance > 4σ

General procedure for FGL catalogs

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

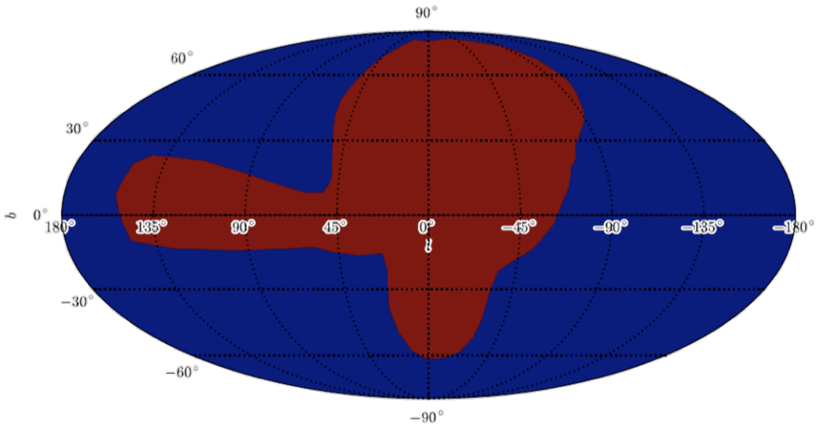
3. Evaluate spectral parameters and source significances
   – This is an all-sky analysis but in 'regions of interest' (ROIs) with the LAT likelihood analysis Science Tools
   – Iteration among the ROIs is required to allow for influences of sources on adjacent ROIs
   – The iteration also includes evaluation 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

Diffuse Gamma-Ray Background

Modelled as:

- a linear combination of templates tracing the interstellar medium (hadronic interactions+ bremsstrahlung)
- an inverse-Compton component
- templates for large features like the radio continuum Loop
- an isotropic component (sub-threshold celestial sources plus residual charged particles misclassified as gamma-rays)
- contributions from Sun+Moon passive emissions
- an Earth-limb component

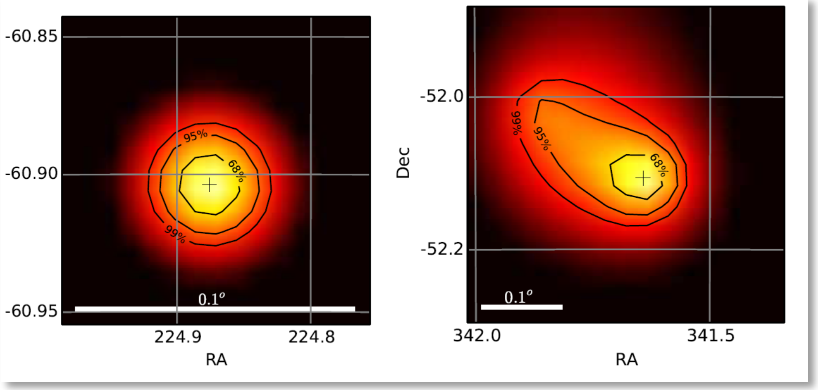


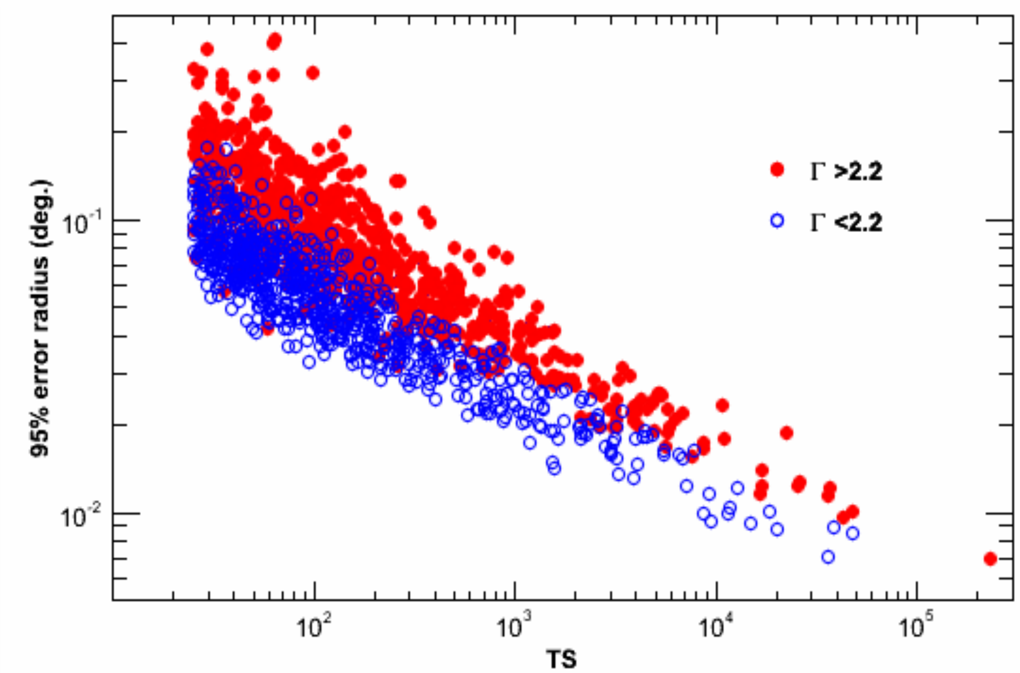
Remaining structures modeled from positive residuals
Features with extension >2° included in the model

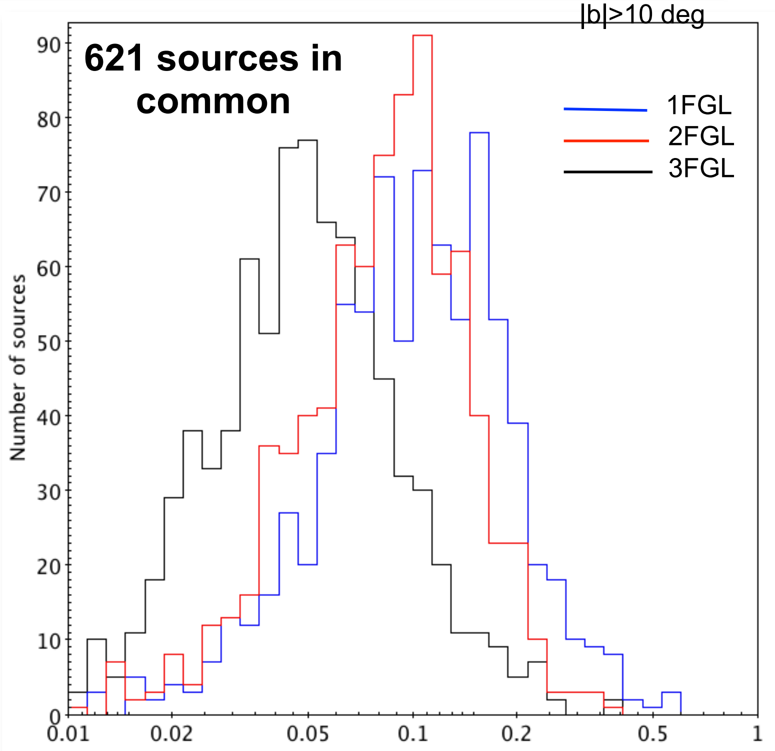
Localization

Good localization is crucial to performing associations.

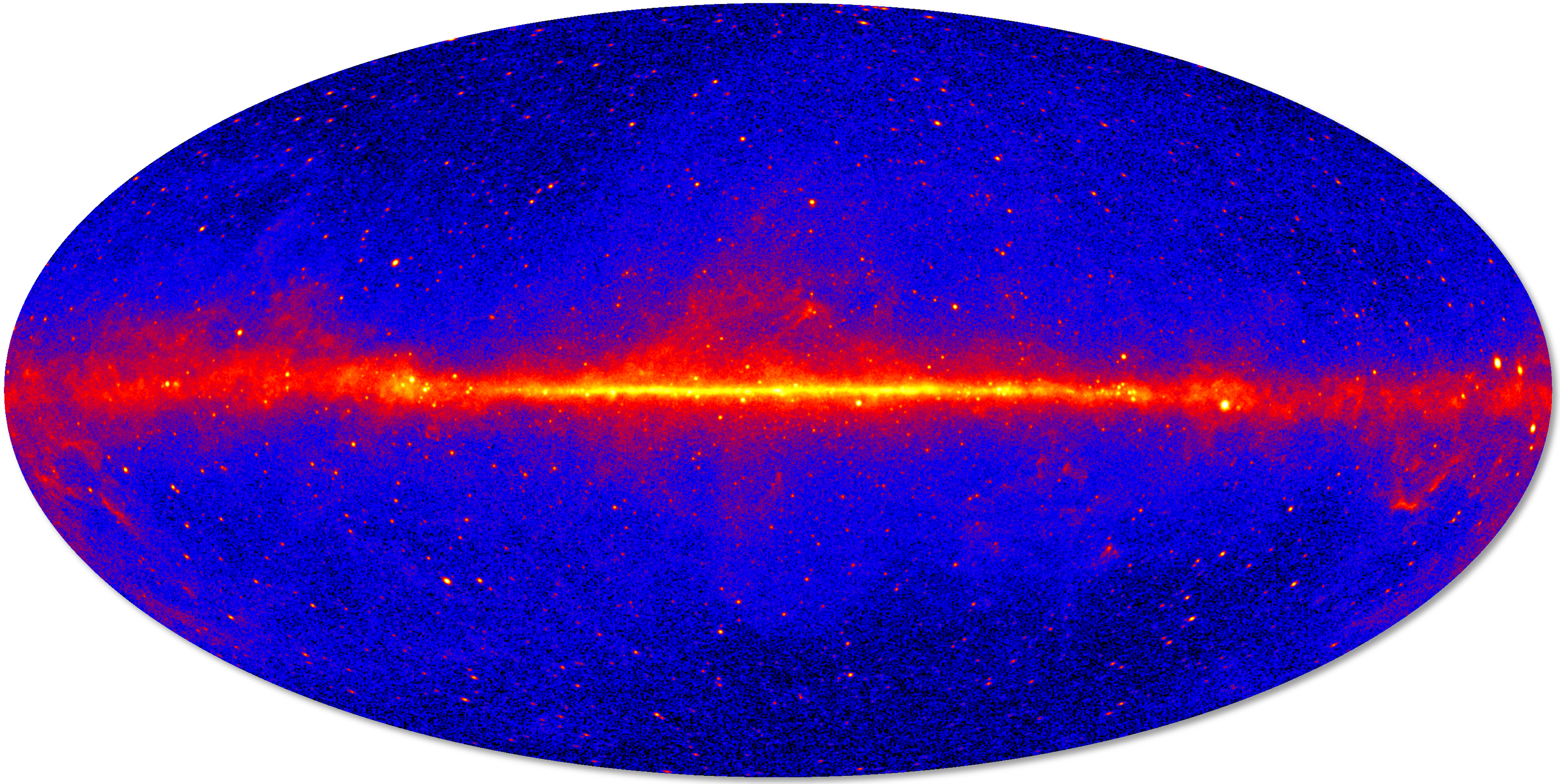
Sources with high TS / hard spectra are better localized.







The LAT gamma-ray sky in 8 years



Flags!

Table 3. Definitions of the Analysis Flags

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 $TS < 25$.
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).
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.
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 ($2\,r_{68}$).
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).
7	Unstable position determination; result from *gtfindsrc* outside the 95% ellipse from *pointlike*.
8	Not used.
9	Localization Quality > 8 in *pointlike* (§ 3.1) or long axis of 95% ellipse > 0°.25.
10	Spectral Fit Quality > 16.3 (Eq. 3 of Nolan et al. 2012, 2FGL).
11	Possibly due to the Sun (§ 3.6).
12	Highly curved spectrum; `LogParabola` β fixed to 1 or `PLExpCutoff` `Spectral_Index` fixed to 0.5 (see § 3.3).

Flags reflect potential analysis issues in assessing the TS, flux, spectrum, position… of a particular source.

Some sources are flagged as "confused" and designated with "c" in their names.

Read caveats, legends, captions ... !

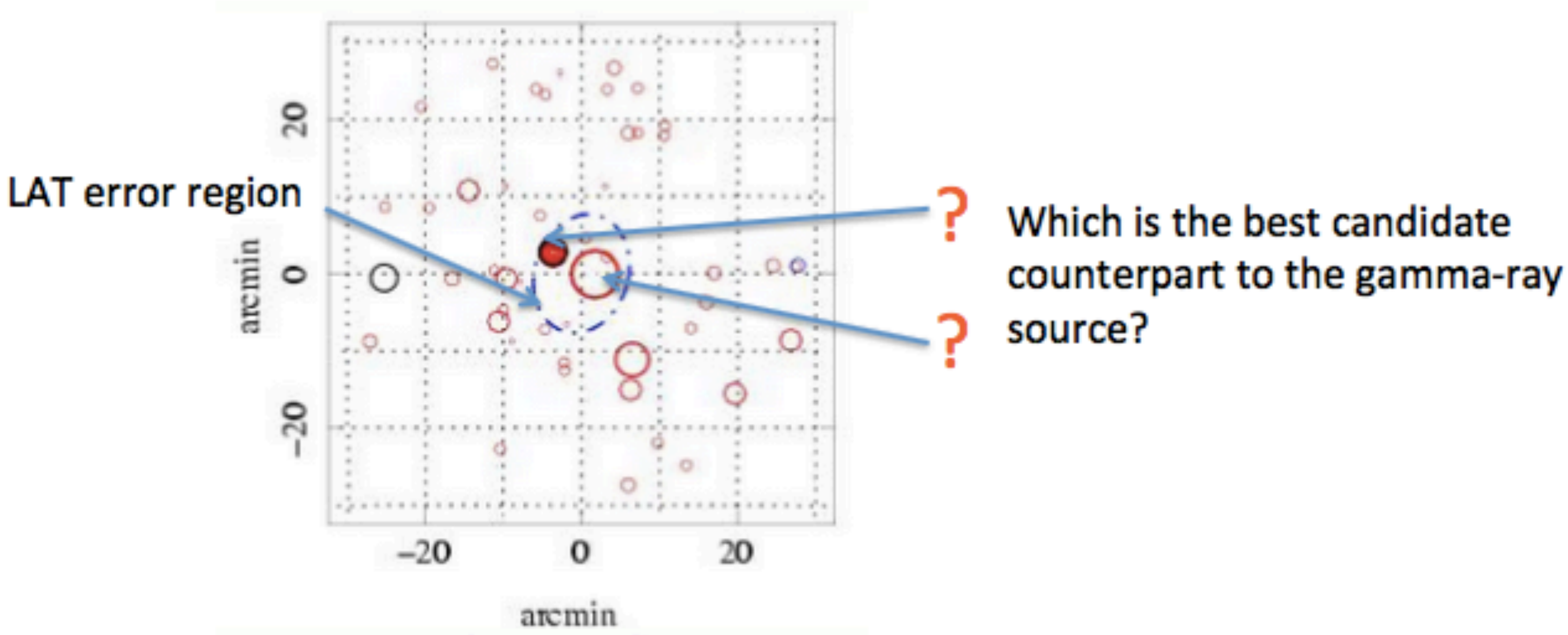
Association methods

- **Bayesian method**

It uses Bayes theorem to calculate posterior probability (given an ‘a priori’ knowledge) that a sources from a candidate catalog is truly a gamma-ray counterpart

- **Likelihood-ratio method**

It makes use of counterpart densities through LogN-LogS from large surveys in order to search for possible counterparts among faint radio and X-ray sources



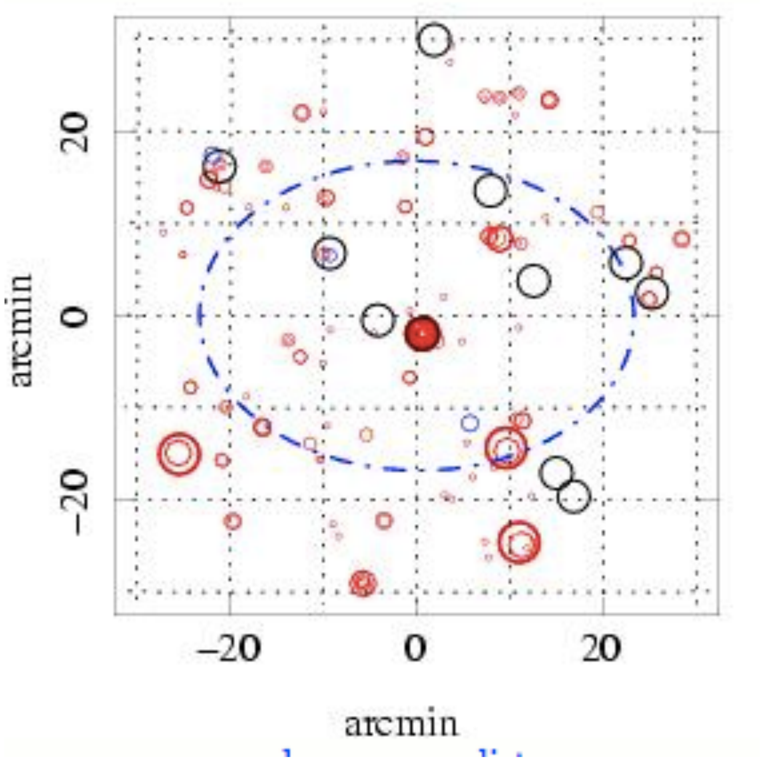
PMN J0004-1148

Counterpart catalogs

known or plausible γ-ray-emitting source classes	High $\dot{E}/d^2$ pulsars	213	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
surveys at other frequencies	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)
GeV sources	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)
	TeV point-like source catalog*	82	http://tevcat.uchicago.edu/
	TeV extended source catalog†	66	http://tevcat.uchicago.edu/
Identified gamma-ray sources	LAT pulsars	147	Collaboration internal
	LAT identified	137	Collaboration internal

How do the association methods work?

3FGL J1659.4+2631 - 4C +26.51 - FSRQ



For an AGN type source, association methods combine:

- Counterpart distance
- Counterpart flux

For **each** candidate counterpart, an association probability is calculated.

The counterpart is associated to the gamma-ray source if the association probability > 80%

Identified, associated and unassociated sources

Identified γ-ray source: it shows correlated variability with candidate counterparts

Associated γ-ray source: it has a counterpart with association probability > 80%

Unassociated γ-ray source: it has NOT a counterpart with assoc probability > 80%

Gold mine

70% of 3FGL unassociated sources have at least a radio or X-ray source within their error ellipse

Unassociated source does not mean totally unknown source or empty field

We 'simply' have a lack of information which prevent us to associate a candidate counterpart

=> MW studies, campaigns, follow up etc

Read caveats, legends, captions ... !

Unknown sources and the MW mine

AGN classification strategy

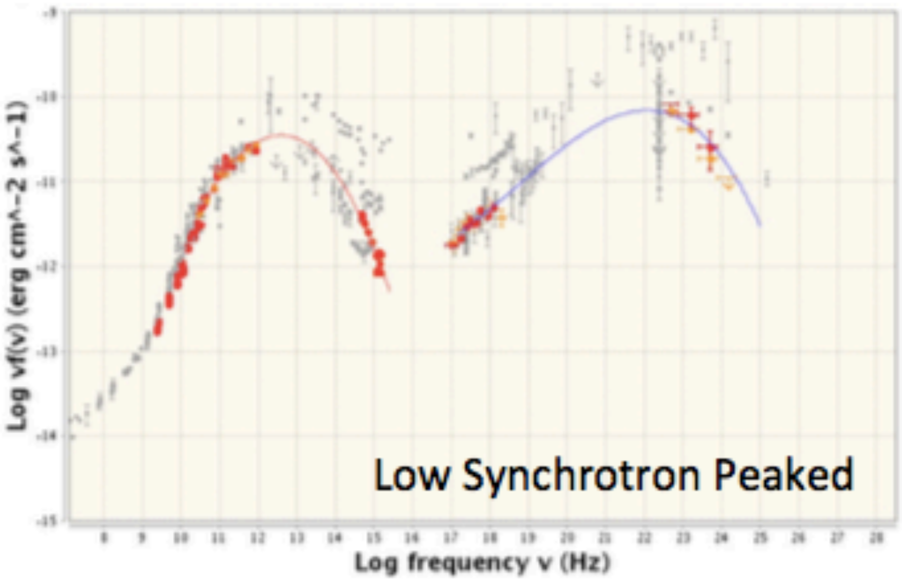
Building spectral energy distributions of unclassified sources:

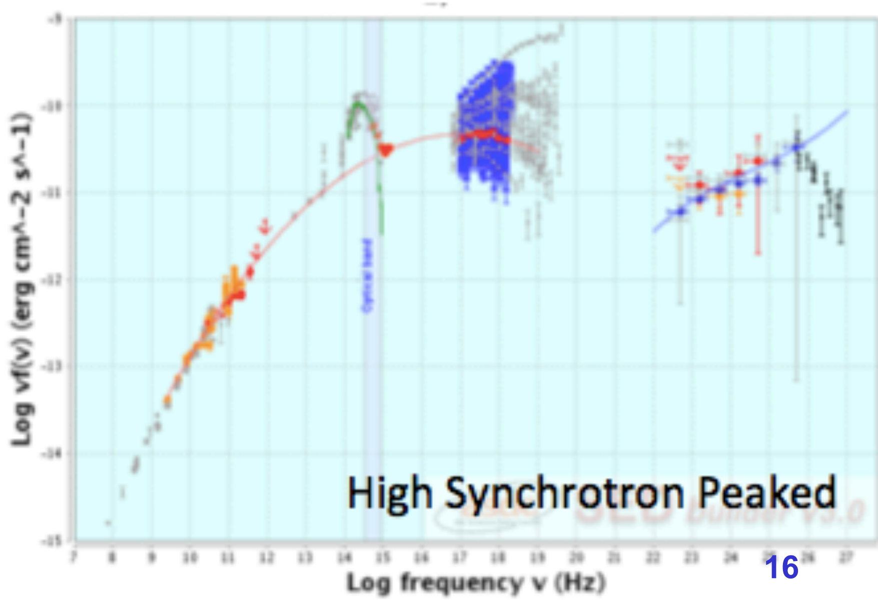
Individuating if the source has a flat radio spectrum (at least between 1.4 GHz and 5 GHz) <- radio follow-up

Broad band emission, double humps SED, fit within the WIE blazar strip

Searching for an optical spectrum:

Via SDSS, NED, spectra published in large and methodic optical follow-up





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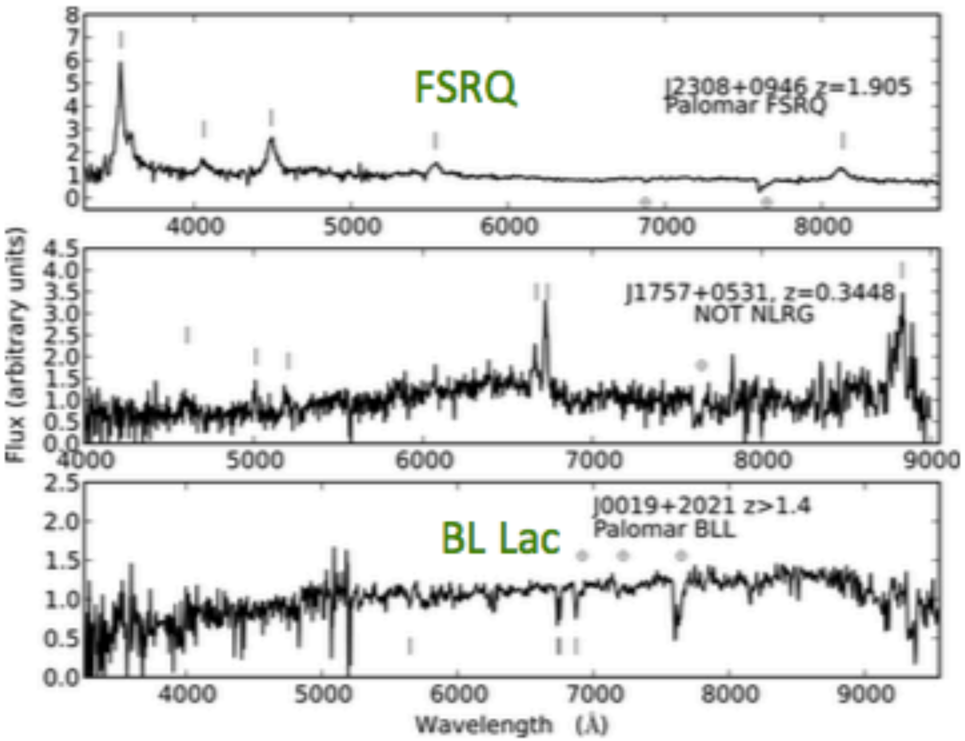
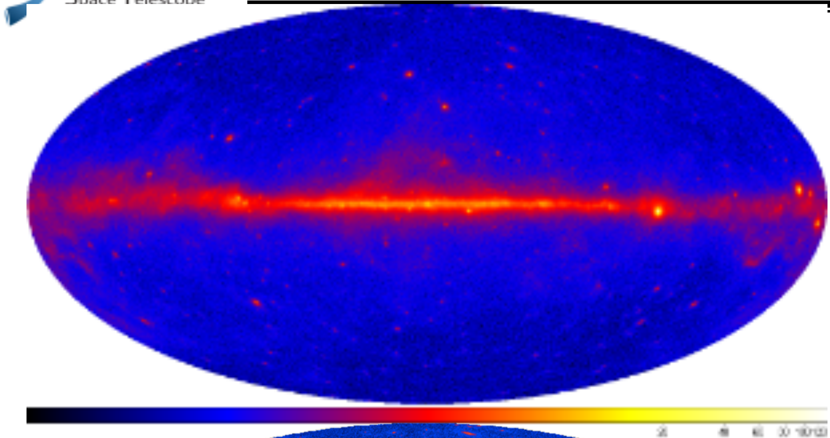
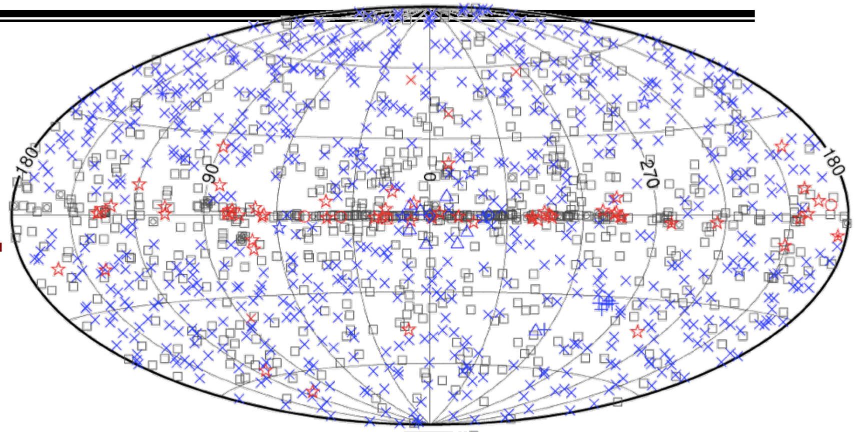


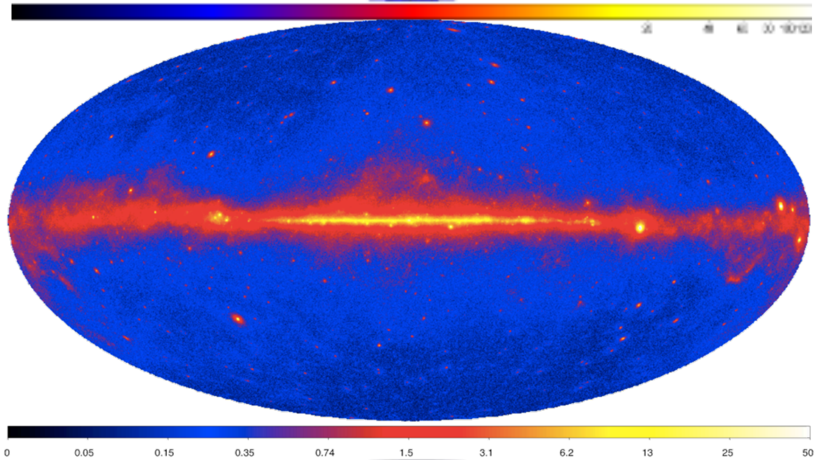
How did LAT catalogs evolve?

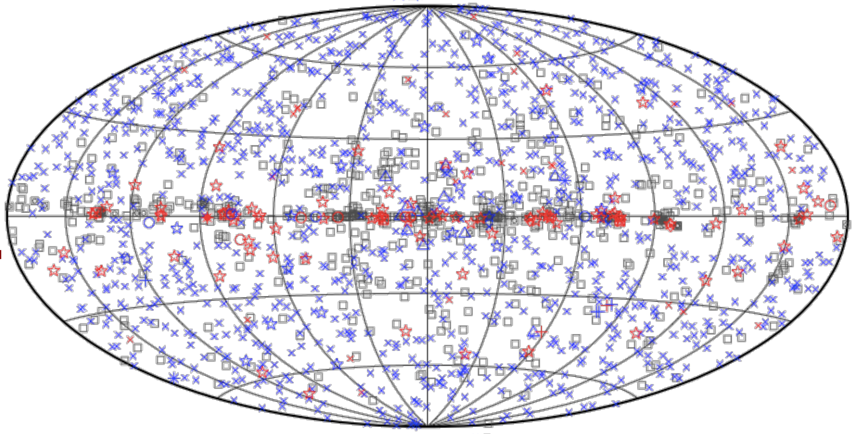
100 MeV – 300 GeV surveys evolution



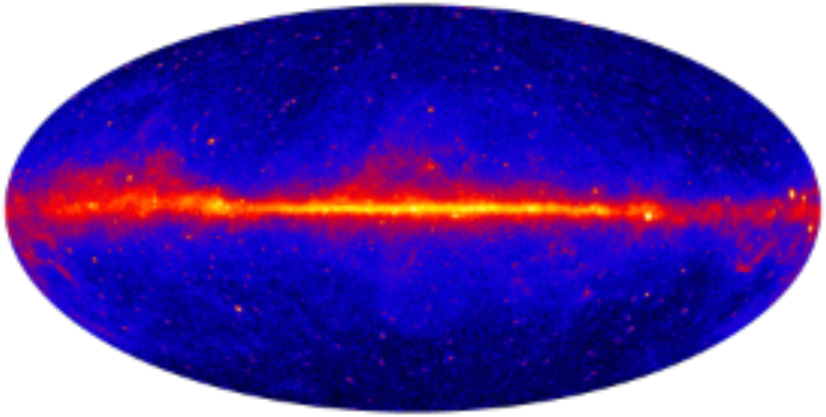


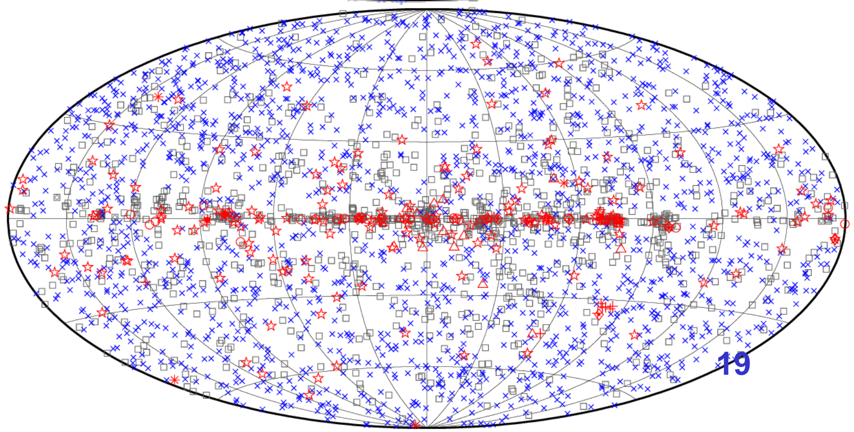
1FGL
11 m





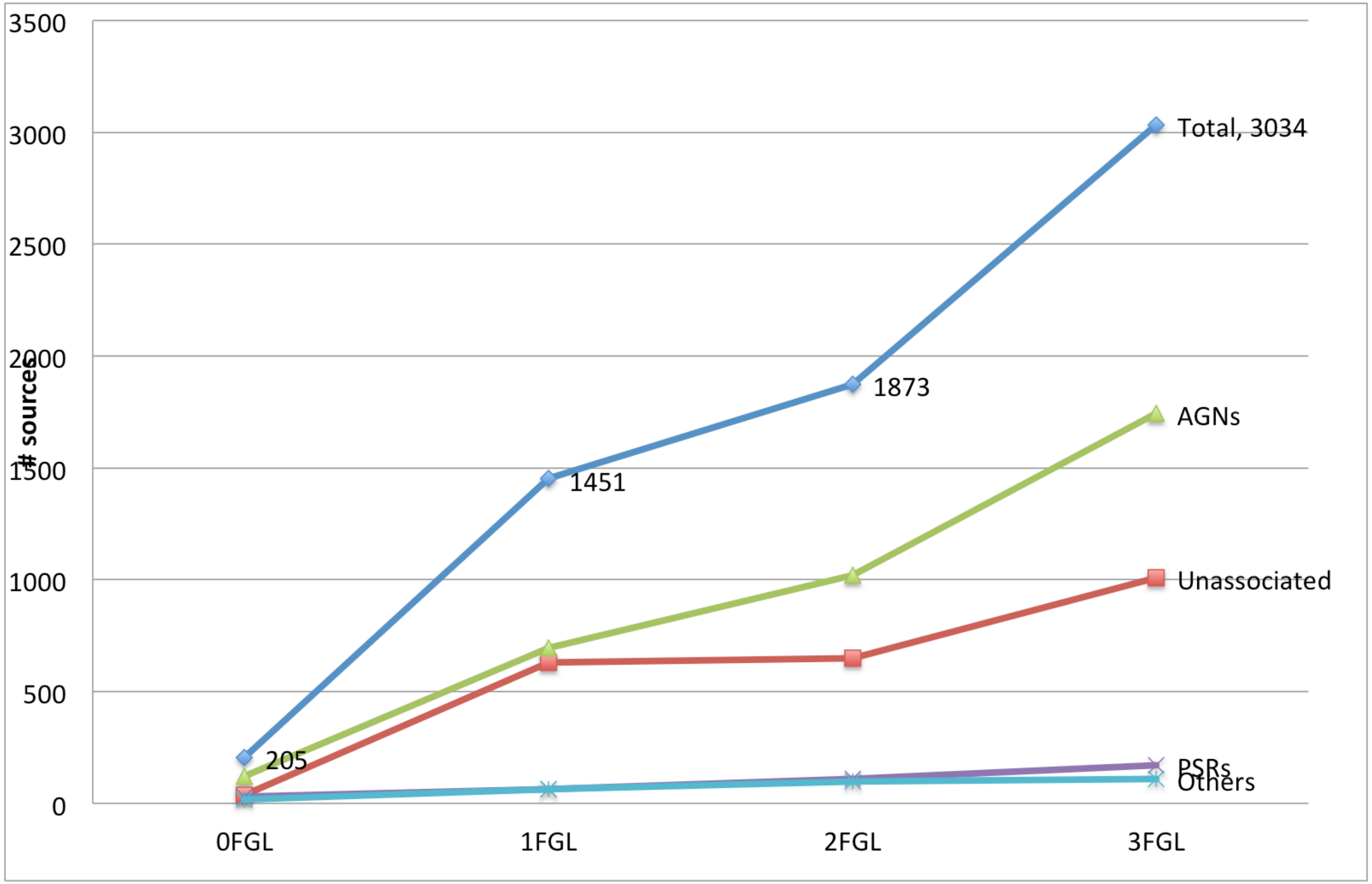
2FGL
2 y





3FGL
4 y

How did the source counts change?



PSR are the vast majority of the Galactic counterparts
AGN are the vast majority of the extragalactic counterparts

Identified, associated and unassociated sources

What happened to the sources which were unassociated in previous LAT catalogs?

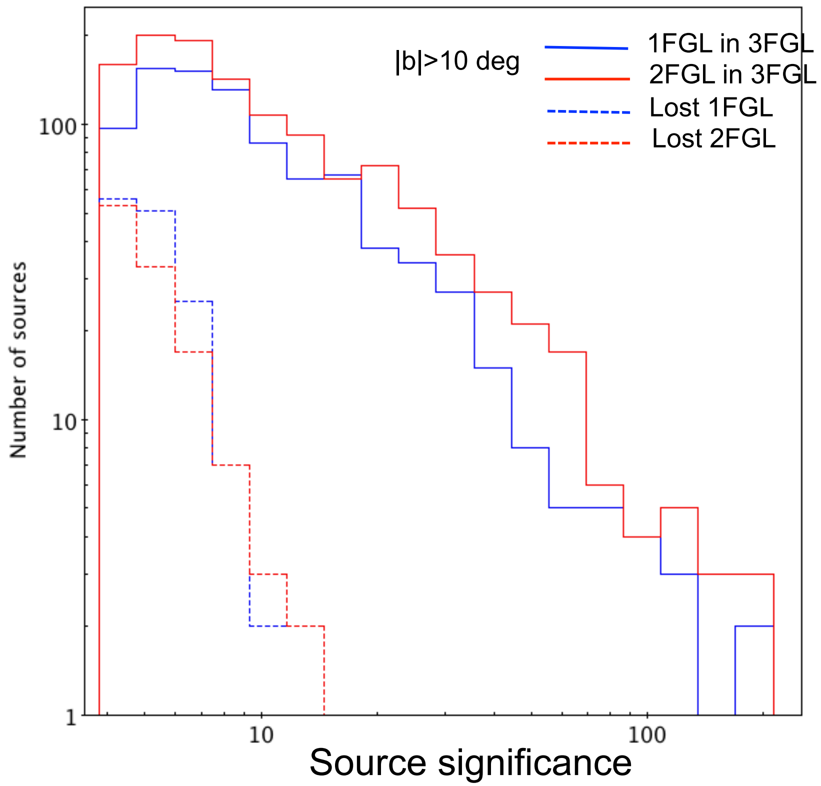
	0FGL	**1FGL**	**2FGL**
Unassoc in LAT catalog	37	630	649
Also in 3FGL	30	366	415
Associated in 3FGL	24	218	149
Still unassoc in 3FGL	**6 (16%)**	**148 (23%)**	**266 (41%)**

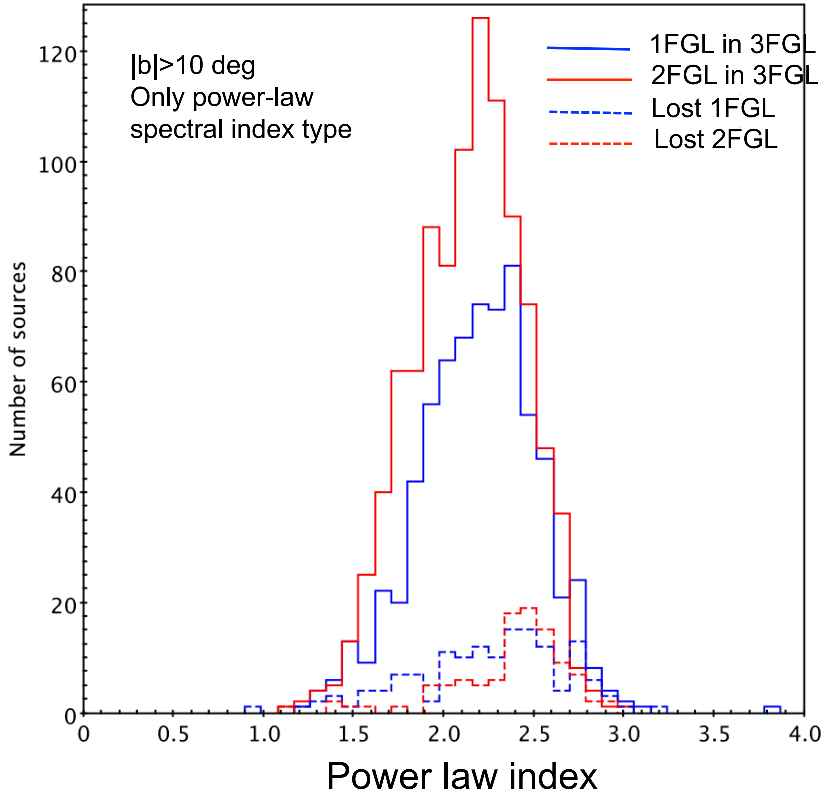
Sources no longer detected in the next LAT catalogs

	0FGL not in 3FGL	1FGL not in 3FGL	2FGL not in 3FGL	1FHL not in 3FGL
All	12	310	300	17
With flags	-	131	211	-
Name-FGL c [(a)]	-	104	87	-
AGN	1	22	27	1
PSR	0	1	3	0
Unassociated	11	264	234	16
Within 1° of a 3FGL e [(b)]	3	27	33	4
sources in other FGL catalogs				
0FGL	-	5	5	0
1FGL	4	-	56	1
2FGL	3	67	-	1
1FHL	0	2	8	-
Not in any other *Fermi* catalog	7	237	237	15

- The vast majority is **unassociated** or with analysis flags or of 'c' type
- The vast majority is not in any other LAT catalog
- Many are resolved in more than one source (3FGL sources and/or initial seeds)
- Many of them are within the 99.9% confidence error radius (or 1 deg) of a 3FGL source or of a seed in the initial list
- Some of them are within 1 deg from an extended 3FGL source
- Among associated sources: we are losing the same number of AGN from one FGL to another

Some properties of the sources no longer detected





Highly significant sources in 1FGL and 2FGL are also seen in 3FGL.

Soft and/or variable sources tend not to be found across all catalogs.

e.g. FSRQ are soft gamma-ray sources AND variable

Lesson learned

Lesson learned about association and classification

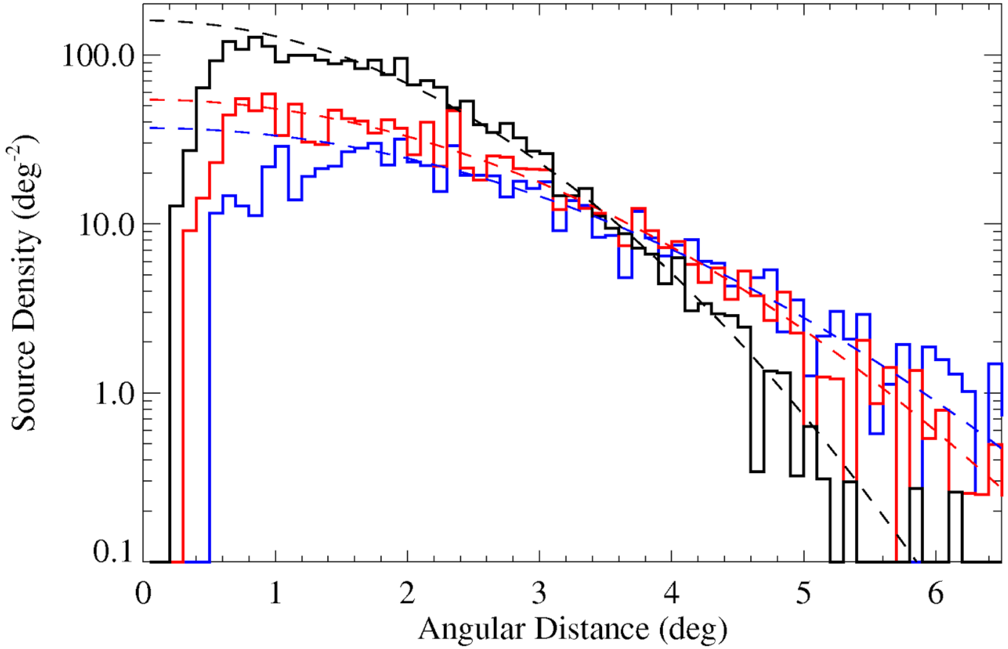
- Improved or new algorithms for associations which take into consideration:
  - MW information
  - Time domain studies of both the gamma-ray sources and the candidate counterparts

- Improved MW data where to look for candidate counterparts:
  - X-ray deep survey (at least)
  - New MW catalogs involved in the association procedures
  - Optical and radio follow-up based on candidate **unclassified** counterparts -> **PERIODIC UPDATES OF THE ASSOCIATIONS IN THE LAST PUBLISHED FGL CATALOG**

Improving the associations also has implications for the study of the cosmological parameters, contribution to the unresolved gamma-ray background etc.

Distance to the nearest neighbors

|b|>10 deg



For 3FGL the implied **number of missing closely-spaced sources is ~140**, or about **6%** of the estimated true source count. For the **2FGL** catalogue the fraction was only **3.3%.**

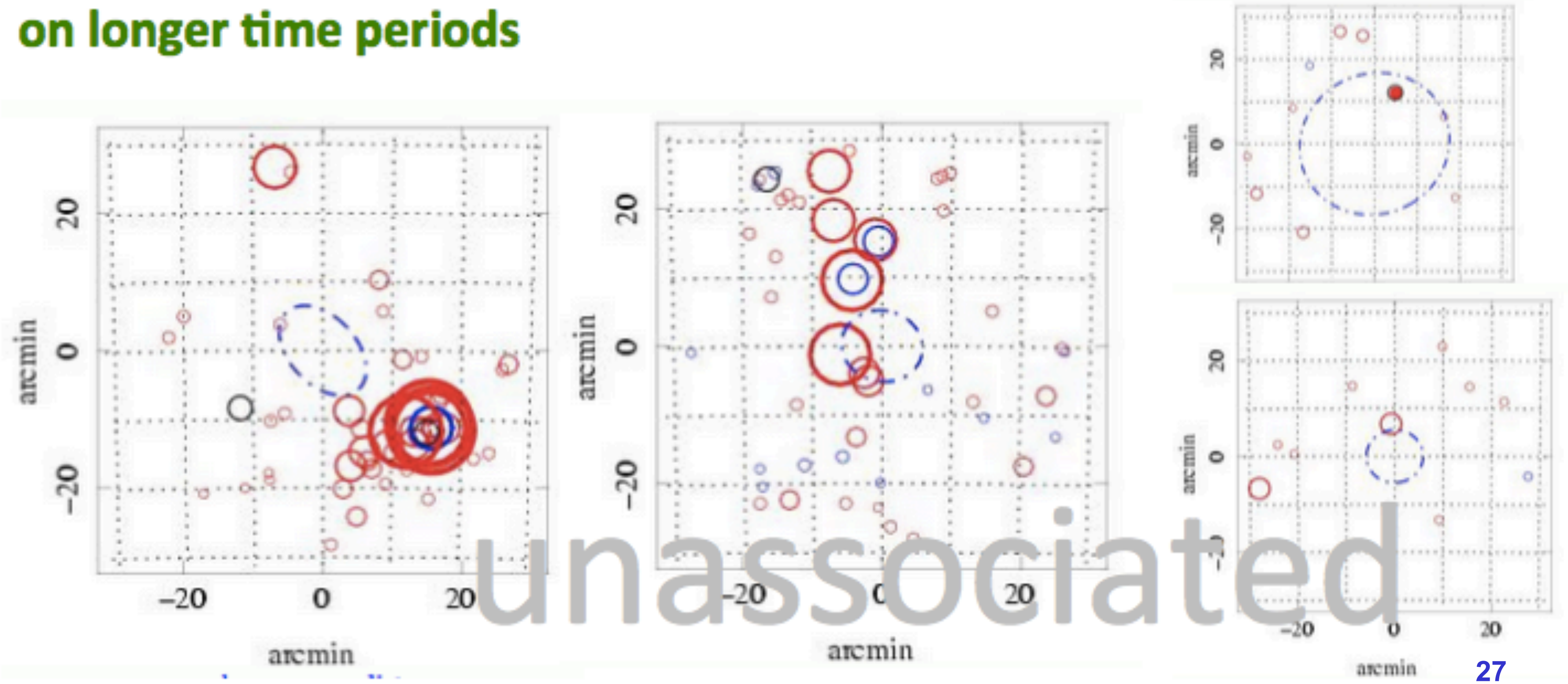
larger number of detected sources is now pushing the main LAT catalogue into the confusion limit even outside the Galactic plane.

Because the effect of confusion goes as the square of the source density, the expected **number of sources above the detection threshold within 0°.5 of another one (most of which are not resolved) has increased by a factor 3 between 2FGL and 3FGL.**

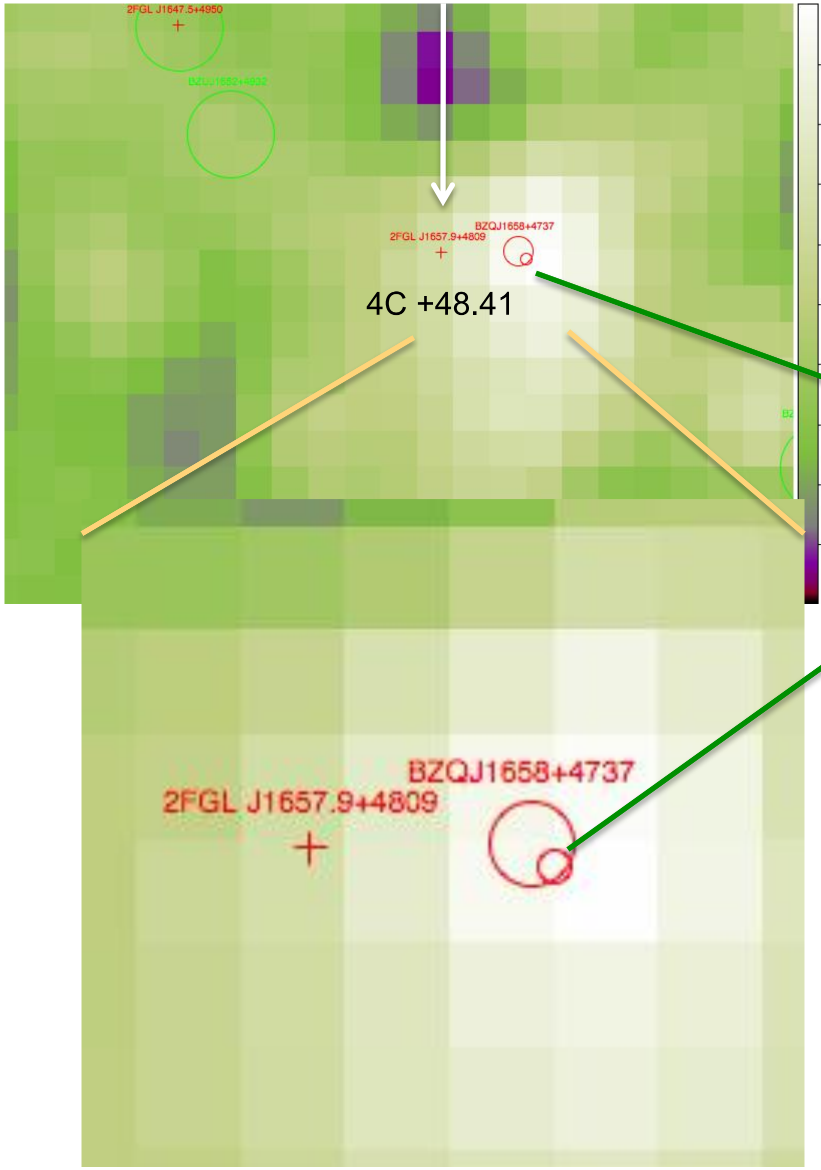
Lesson learned about source detection

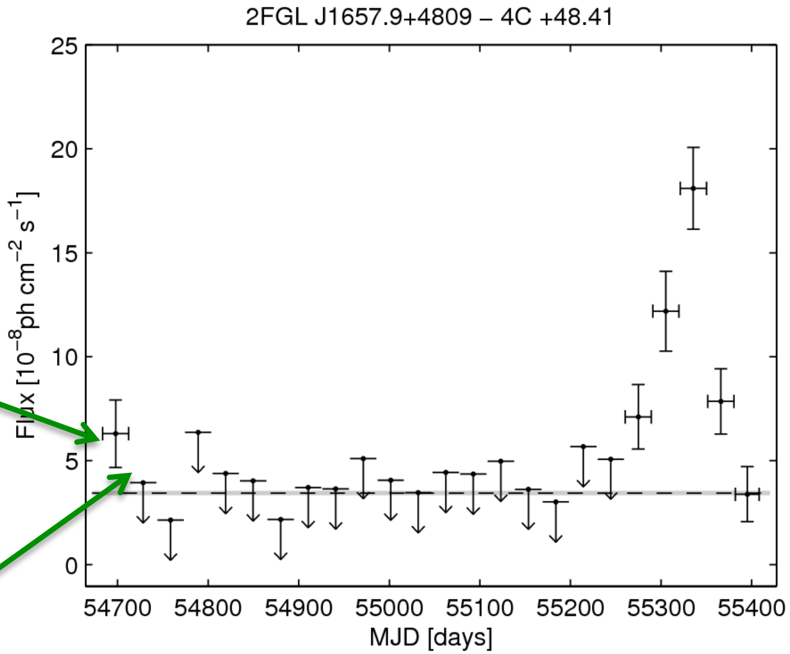
- Improved or new algorithms for localization which take into consideration:
  - MW information
  - Time domain studies of both the gamma-ray sources and the candidate counterparts

Short transient could influence source localization or source detection on longer time periods



Confusion?



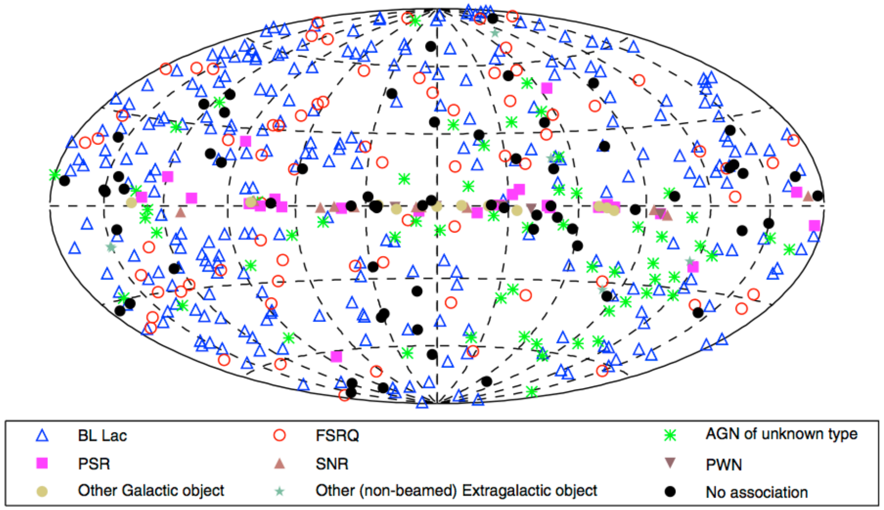


BZQ J1658+4737 flared in that time bin while 4C +48.41 was in a fainter state

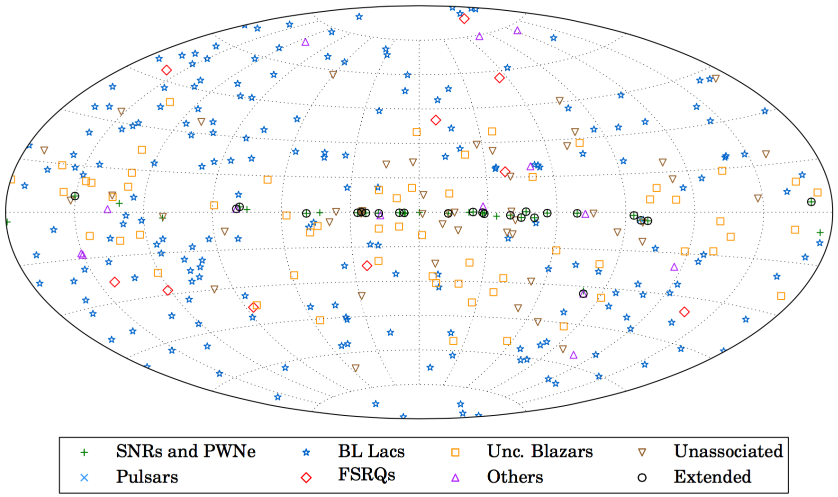
GeV – TeV connection

FHL catalogs

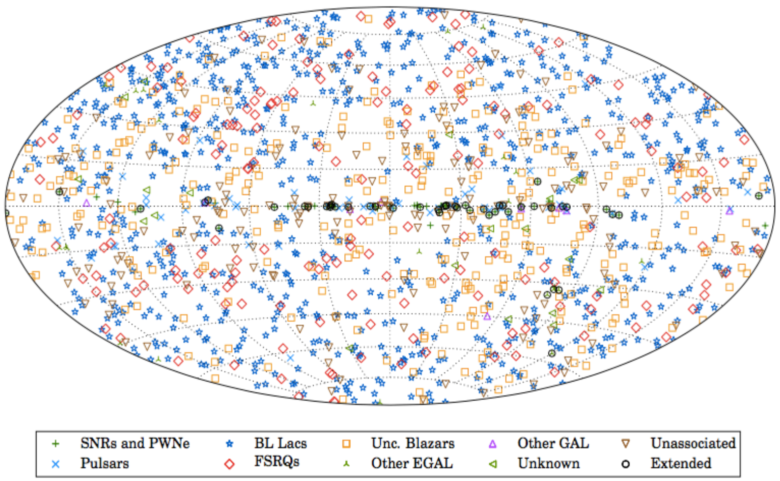
1FHL > 10 GeV, 3 years



2FHL > 50 GeV – 2 TeV, 6.7 years

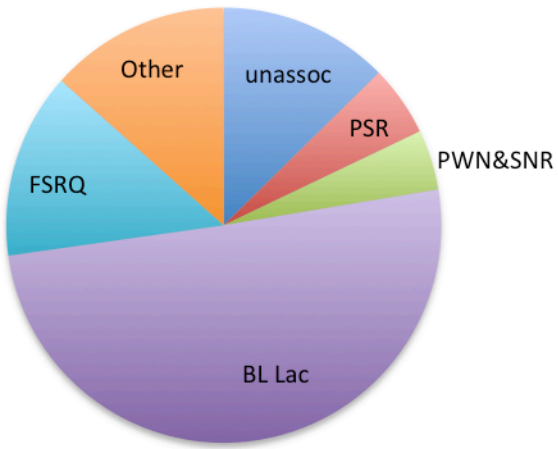


3FHL: 10 GeV – 2 TeV, 7 years

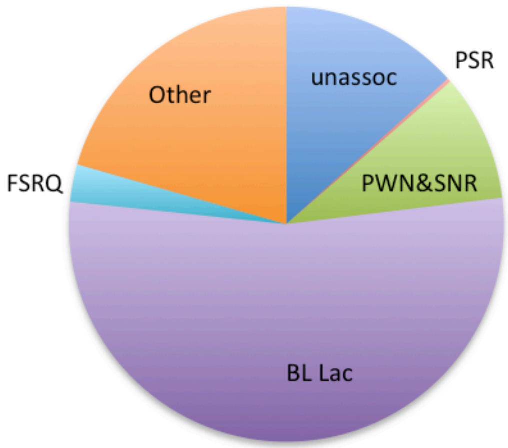


FHL classes

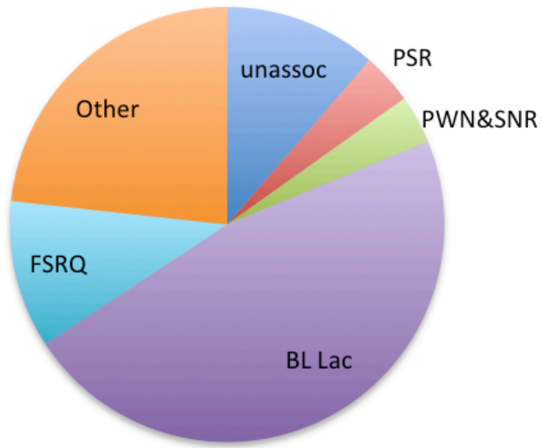
**1FHL > 10 GeV,
36 months years**



**2FHL, > 50 GeV,
80 months**

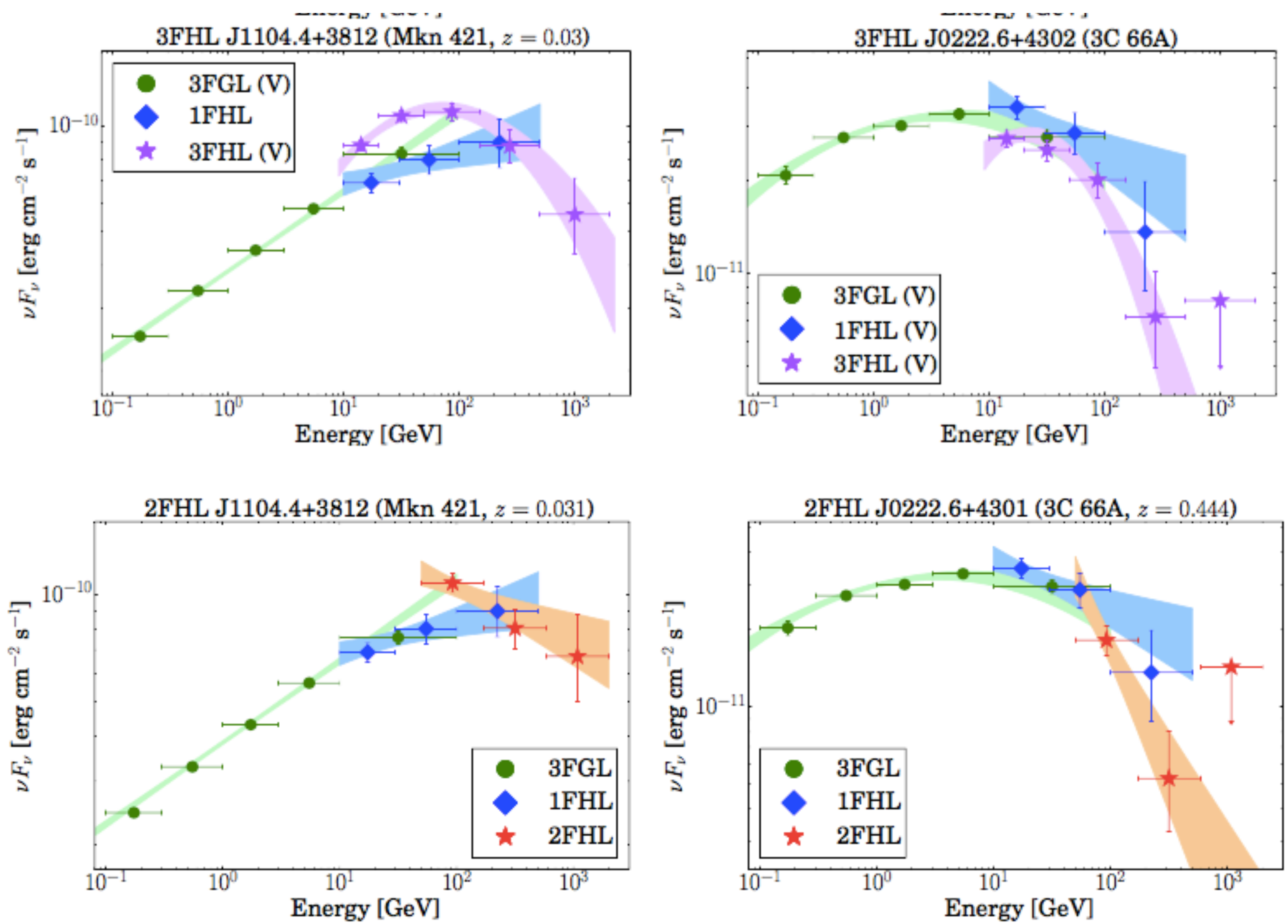


**3FHL, > 10 GeV
84 months**



Fermi Gamma-ray Space Telescope

Multi wavelength high energy SED



Blazars synchrotron peak distributions

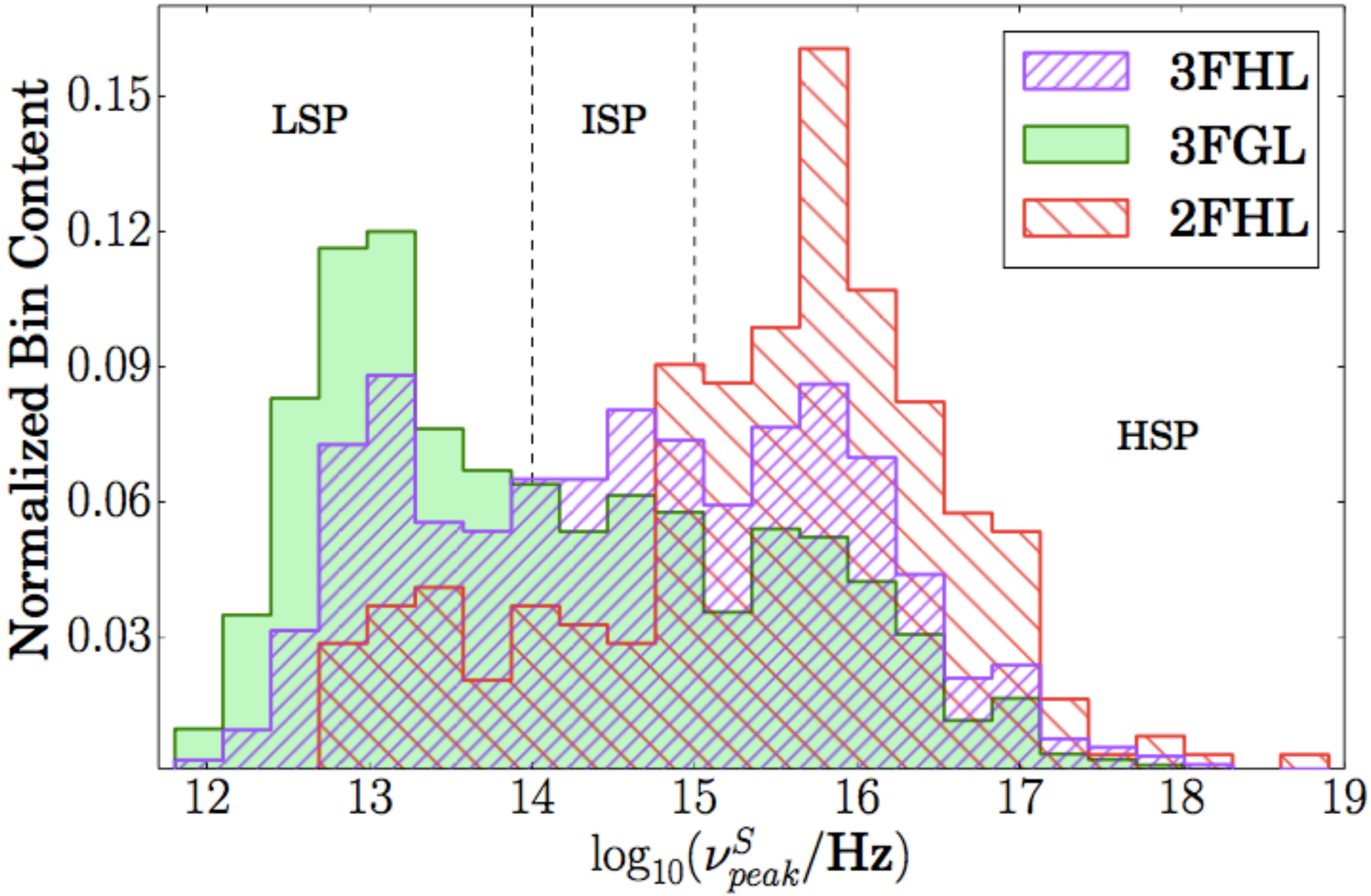


Fig. 14.— Normalized distributions of the frequency of the synchrotron peak for the blazars detected in the 3FGL (0.1–300 GeV), 2FHL (50 GeV–2 TeV), and 3FHL (10 GeV–2 TeV) catalogs.

BL Lac spectral index distributions

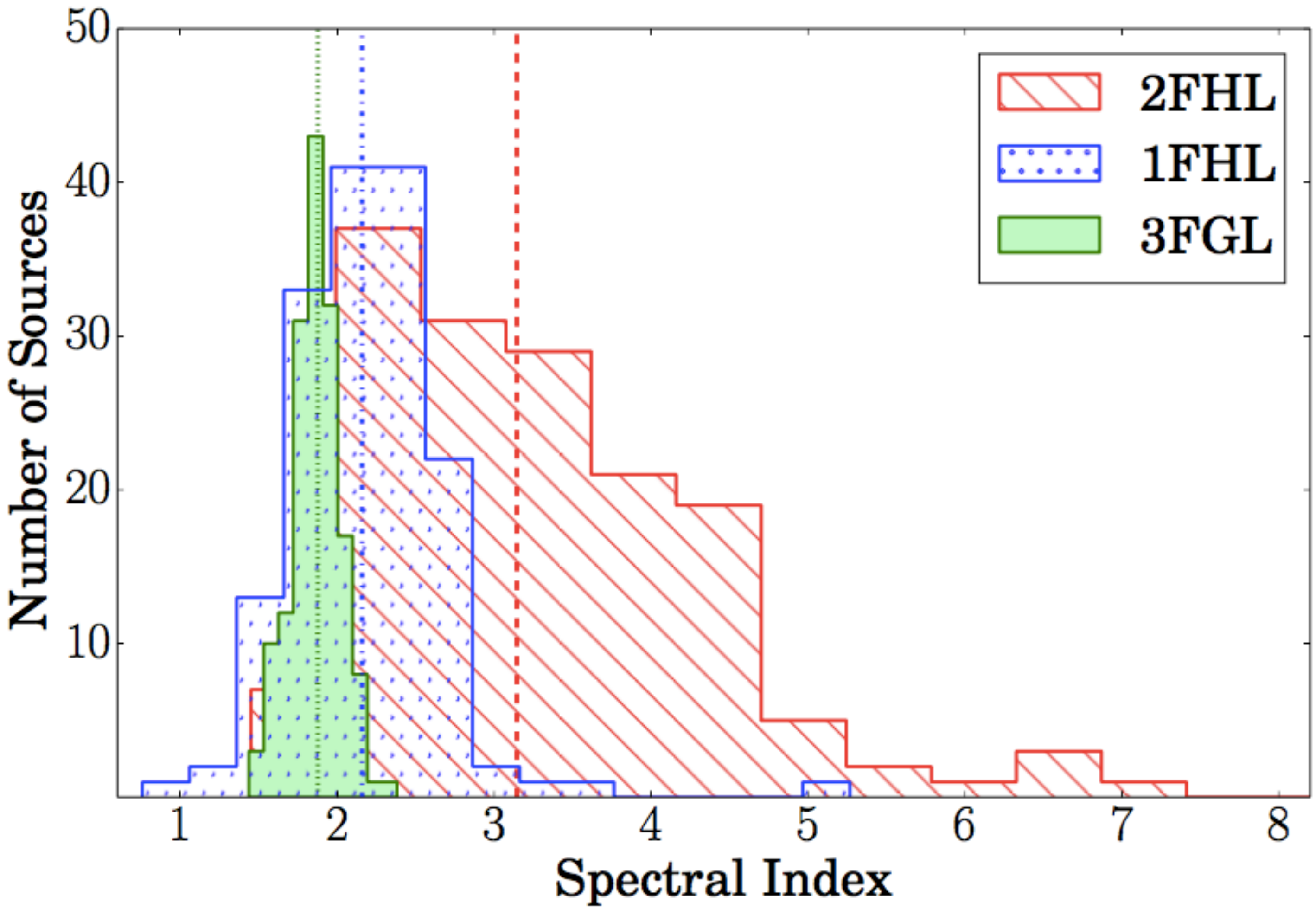


Fig. 10.— The distribution of spectral indices for a subsample of 158 BL Lacs that are in common among the 2FHL (backslash orange), 3FGL (slash green), and 1FHL (purple). The medians of the distributions are shown with vertical lines. The higher the energy band, the larger the index; therefore sources get softer with increasing energy. The scatter of the distribution is also larger with increasing energy, partly because of the lower statistics.

SNRs and PWNs spectral index distributions

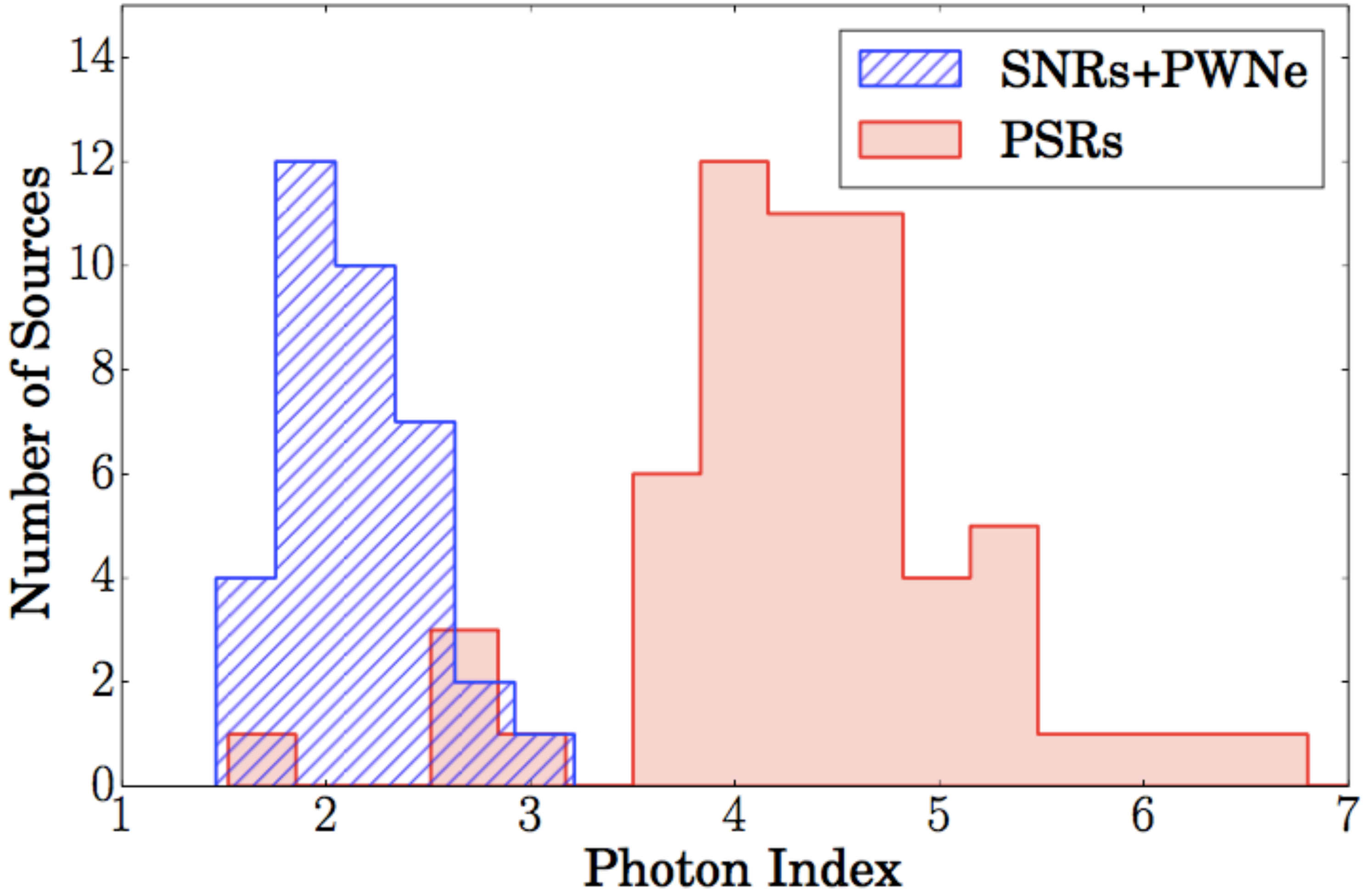


Fig. 12.— Distributions of γ-ray spectral indices of SNRs plus PWNe (dashed blue) and sources associated with PSRs (filled red). At the 3FHL energies, SNRs and PWNe tend to have smaller indices (harder spectra) than PSRs, for which the LAT measurement is sensitive to the exponential cutoff.

The importance of the multi-wavelength data

Multi-wavelength data from upcoming facilities

Fermi GST benefits enormously from synergies both with ground and space based telescopes/observatories.

In many LAT papers MW data contribute significantly.
There are a few cooperative agreements in place with radio astronomy community, X-ray satellites (Swift, NuSTAR etc), TeV collaborations (IACT).

MW data are necessary to study broad band emission mechanisms, unified models, alternative models etc

Which are the upcoming facilities which would contribute to exploit *Fermi* data?

eROSITA will be the primary instrument on-board the Russian "Spectrum-Roentgen-Gamma" (SRG) satellite which will be launched from Baikonur in 2016 and placed in an L2 orbit. It will perform the first imaging **all-sky survey** in the **medium energy X-ray range up to 10 keV with an unprecedented spectral and angular resolution.**

IACT and CTA

Current Imaging Atmospheric Cherenkov Telescopes (MAGIC, H.E.S.S., VERITAS) can **study individual regions of the VHE sky and survey relatively small areas**:

- bright sources
- observed in flaring states
- all experiments have discovered new sources

Cherenkov Telescope Array will offer a factor of 10 improvement

- higher sensitivity
- 1/4 sky survey off the plane in addition to a Galactic plane survey
- It will help us complete the spectrum of Fermi sources at energies above 100 GeV

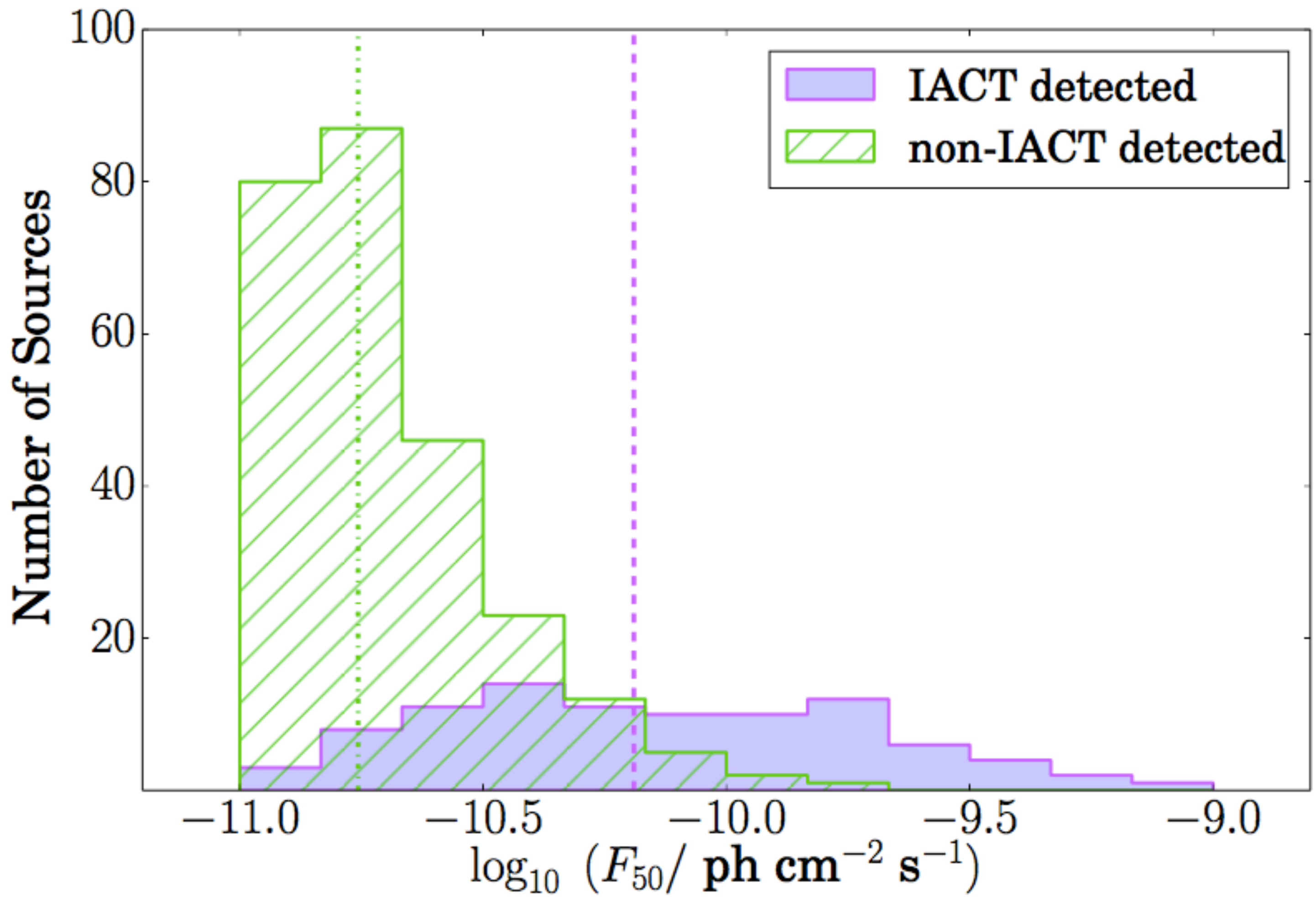


Fig. 15.— Photon flux distributions of the 2FHL population that has been detected already by IACTs (purple) and that has not yet been detected (green). The medians of the distributions are shown with vertical lines.

Square Kilometre Array

Sensitivity -> faint LAT sources are also faint radio sources
Polarization -> gamma-ray flux vs polarized radio flux
Variability -> it helps disentangle the candidate counterparts to LAT sources

high sensitivity in short time scales ->
Great discovery space for fast transients

The 10-yr *Fermi* catalog will be significantly deeper than the first LAT catalog

- not only longer exposure but also better characterization of detector, diffuse model, etc.
- weakest known 3LAC blazar is about 2.8 mJy (at 1.4 GHz NVSS), unassociated ones are probably fainter
- sub-mJy sources can certainly be expected

Radio catalogs will not only need to be deeper but also more physically informative

- multi-λ, multi-epoch, polarization sensitive
- high frequency bands desirable to get closer to gamma-ray emission region

Suitable, ideal project to be done in early science to maximize chance of overlap with *Fermi*

LAT catalogs

Besides the **general catalogs (FGL)**, the LAT team produces many other lists on specific source classes:

AGN (LAC)	**FHL (sources above 10 GeV or 50 GeV)**
PSR	**FGES (Extended sources in the Galactic plane)**
SNR	**FAV (All-sky Variability Analysis)**
GRB	

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

Conclusions

- Each LAT catalog has benefited from an always better knowledge of the instrument and of refined association methods: new skills are under investigation to further improve the future releases
- LAT catalogs are the drivers for many other studies which, in turn, will contribute to improve the future catalogs
- Unassociated sources remain a big discovery space which deserve to be continuously investigated
- MW data are fundamental to study and understand gamma-ray emission mechanisms
- Current and upcoming facilities at other wavelengths, both ground and space based, contribute capitally to LAT catalogs