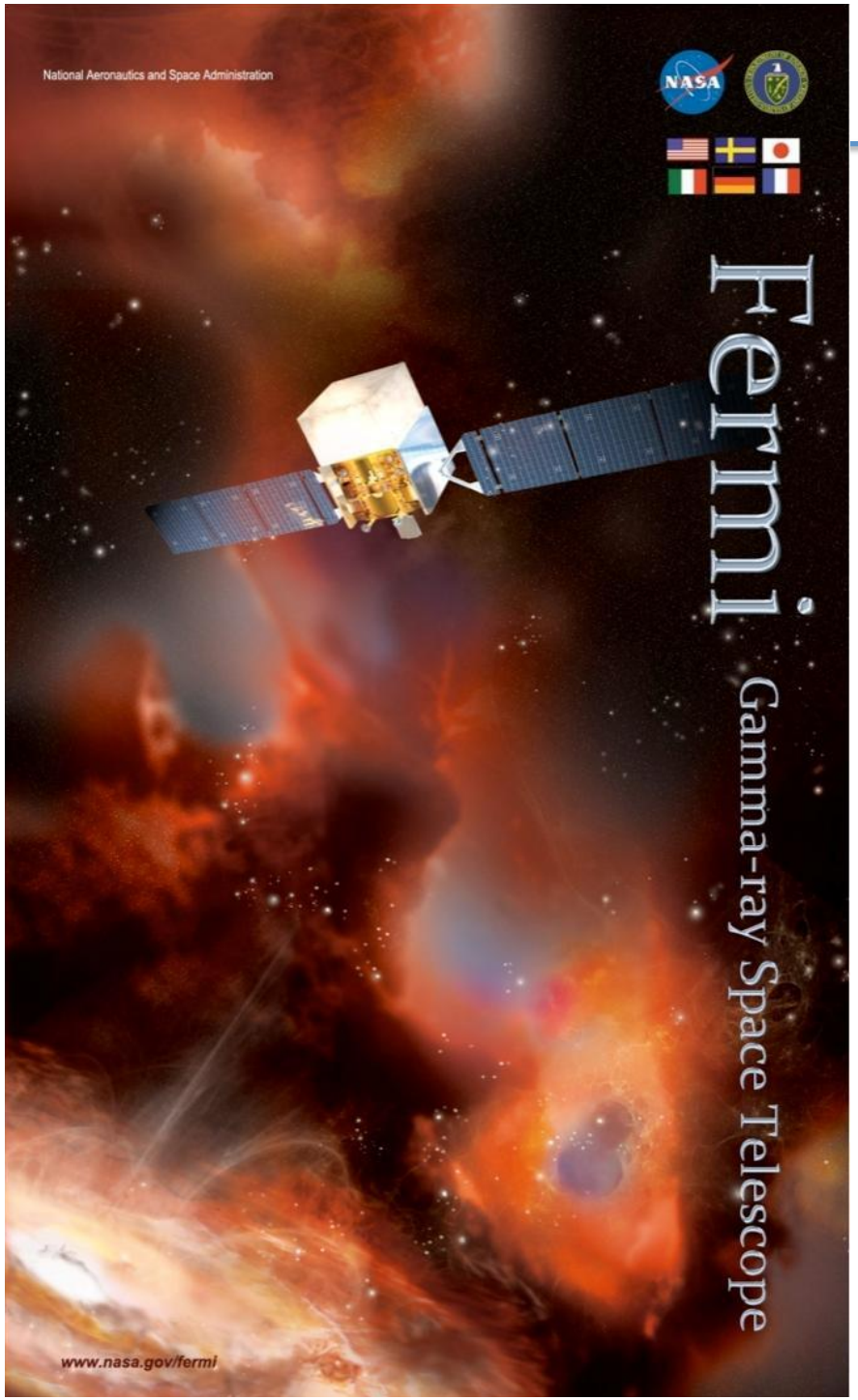


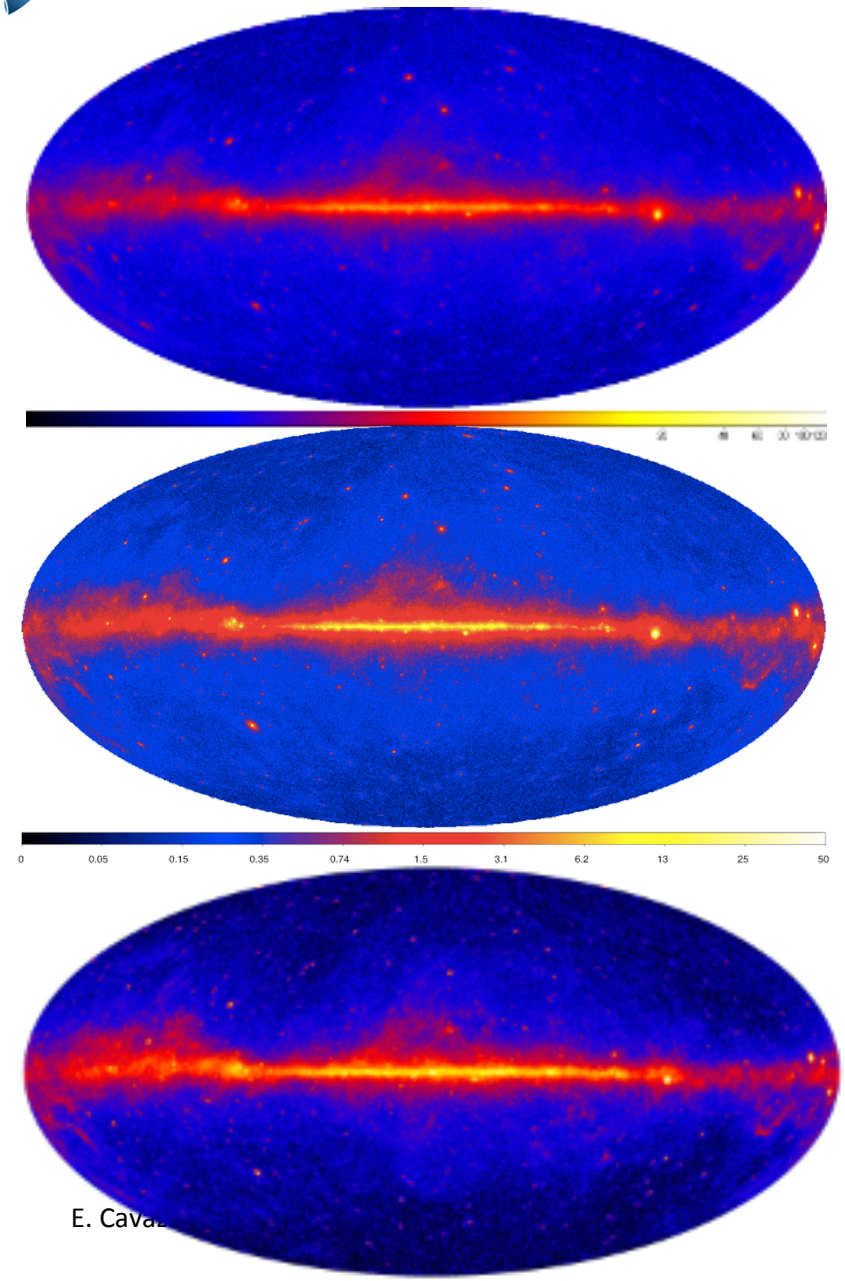
Overview of the *Fermi* LAT Catalogs

Elisabetta Cavazzuti
(Italian Space Agency Data Center)

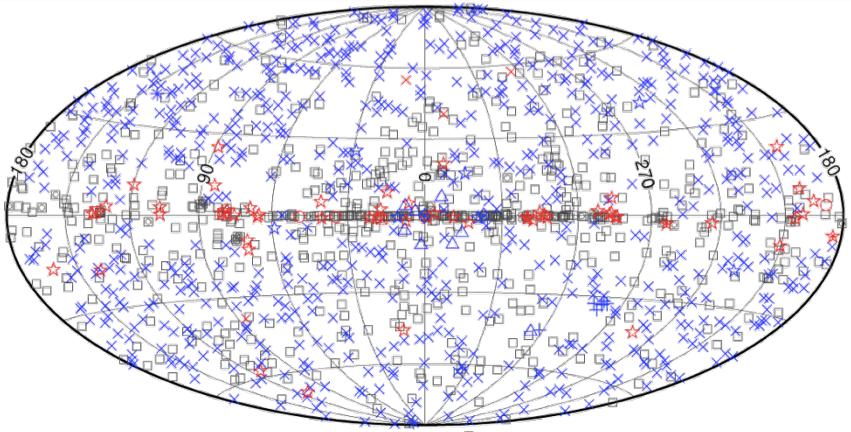
on behalf of the LAT Collaboration

5th Fermi Symposium
Nagoya

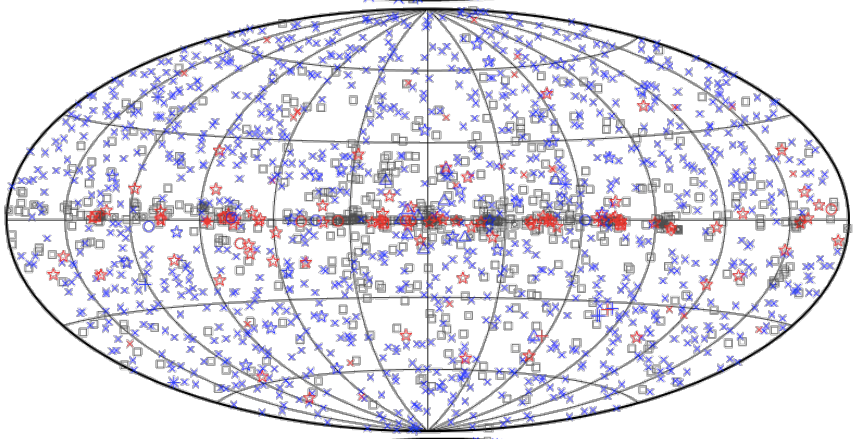
Intensity and source counts maps evolution



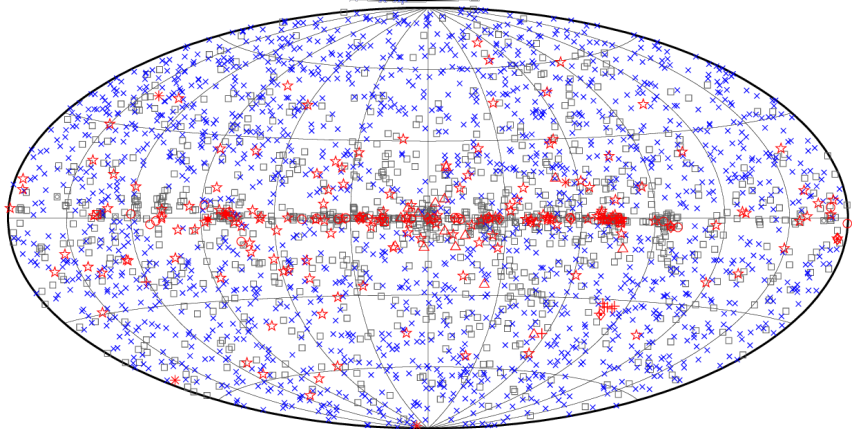
1FGL
11 m



2FGL
2 y



3FGL
4 y



3FGL updates relative to 2FGL

- **4 years of data**
- **Pass 7 Reprocessed data**, **improved PSF above 10 GeV by ~30%** improving the localization of hard sources
- **Improved model of the diffuse Galactic and isotropic emission**
- Improvements in the characterization and localization of the source 'seeds': most marked at low Galactic latitudes, i.e**. improved sensitivity in the Galactic plane**
- **Deepest catalog** in the energy range 100 MeV - 300 GeV
- **Unbinned likelihood used at high energy (> 3 GeV)** where keeping track of the exact direction of each event helps; **Binned likelihood used at low energy (< 3 GeV)**. Both data sets were split between Front and Back.
- Models of gamma-ray emission related to the **Sun and Moon calculated for each time interval analyzed**.

Spectral shapes and Extended sources

3 Spectral shapes

- spectral representation of sources was mostly the same as in 2FGL, with the addition of a parameter modelling the super or subexponential cutoff power law:
  - a **log-parabola** representation for all significantly curved spectra except for pulsars and 3C 454.3
  - an **exponentially cutoff power law** for all significantly curved pulsars and a **super or subexponentially cutoff power law** for the bright pulsars and 3C 454.3
  - a **simple power law** for all sources not significantly curved
  - Crab's complex spectrum was represented as three components
- Overall: 6 sources were fit with PLSuperExpCutoff, 111 pulsars were fit with PLExpCutoff, 395 sources were fit with LogParabola and the rest were fit with power law.

25 Extended sources

- 12 SNR
- 9 PWN
- Cygnus Cocoon
- LMC and SMC Clouds
- Lobes of radio galaxy Centaurus A

How did the source counts change?

	0FGL	1FGL	2FGL	3FGL	1FHL*
Total	**205**	**1451**	**1873**	**3033**	**514**
Unassociated	37 (18%)	630 (43%)	649 (35%)	992 (33%)	65 (13%)
AGNs	121 (59%)	689 + 4 (ID) (48%)	991 + 28 (ID) (57%)	1691 + 66 (ID) (58%)	371 + 22 (ID)
PSRs	15 + 15 (ID)	7 + 56 (ID)	25 + 83 (ID)	29 + 137 (ID)	1 + 26 (ID)
PWN	-	2	3 (ID)	2+9 (ID)	3 + 3 (ID)
SNR	-	3 (ID)	4 +6 (ID)	11+12 (ID)	5 + 6 (ID)
GLC	1	8	11	15	-
SBG	-	2	4	4	-
HMB	1 + 1 (ID)	2 (ID)	4 (ID)	3 (ID)	3 (ID)
spp	13	41	58	51	6
Others	1	7 (gal+MQO+...)	7 (gal+Nova+…)	11 (gal+Nova+BIN…)	3 (gal, sfr, lbv)
Extended			12	25	18
High/Low |b|	132/73	1043/408	1319/554	2193/841	399/115

preliminary

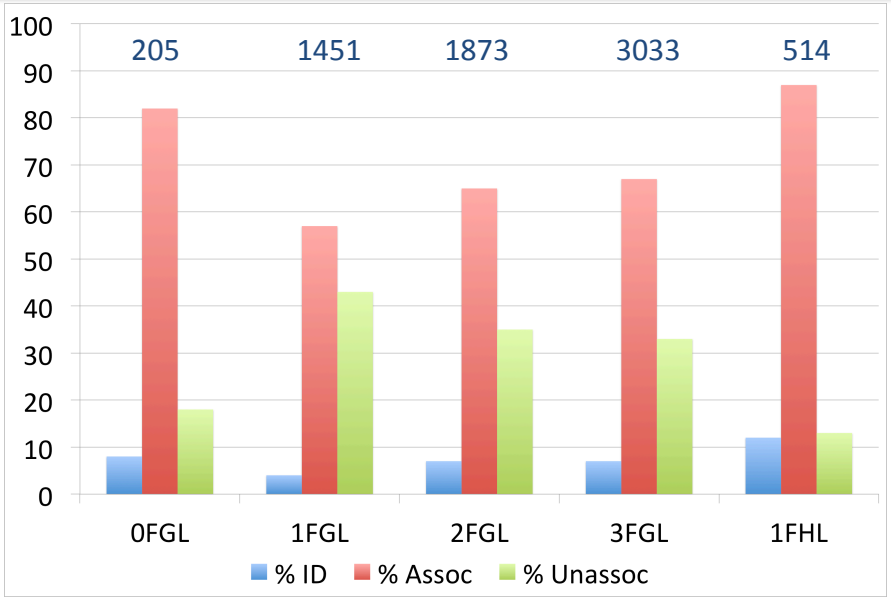
(Low |b|: |b| <10 deg); *1FHL: >10 GeV, 3 yrs

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

E. Cavazzuti

See also talks:
> 50 GeV sources – M. Ajello
3LAC – B. Lott
PSR – M. Kerr
SNR – J. Hewitt
and poster:
Unassociated sources – E. Ferrara

Identified, associated and unassociated sources



Number of sources in the catalog

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

	0FGL	**1FGL**	**2FGL**	**1FHL**
Unassoc in LAT catalog	37	630	649	65
Also in 3FGL	30	366	415	49
Associated in 3FGL	24	218	149	30
Still unassoc in 3FGL	**6 (16%)**	**148 (23%)**	**266 (41%)**	**19 (29%)**

Out of 54 1AGL sources, 44 are in 3FGL and 19 of these 1AGL are unassociated in 3FGL

E. Cavazzuti

How can we improve the association rate?

- Improved or new algorithms for localization and 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

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

Sources no longer detected from previous LAT catalogs

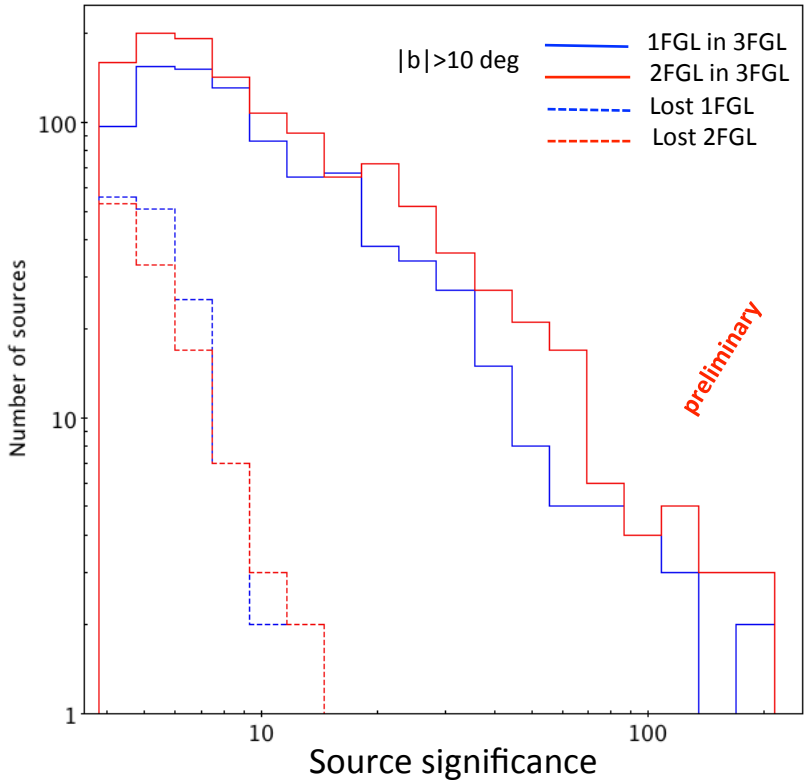
	0FGL not in 3FGL	1FGL not in 3FGL	2FGL not in 3FGL	1FHL not in 3FGL
All	12	310	299	17
with flags	-	131	210	-
with 'c'	-	104	87	-
AGN	1	22	27	1
PSR	0	1	3	0
Unassoc	11	264	234	16
within 1 deg from a 3FGL'e'	3	18	15	4
		sources in other FGL catalogs		
0FGL	-	5	5	0
1FGL	4	-	56	1
2FGL	3	67	-	1
1FHL	0	2	7	-
not in any other *Fermi* catalog	7	237	238	15

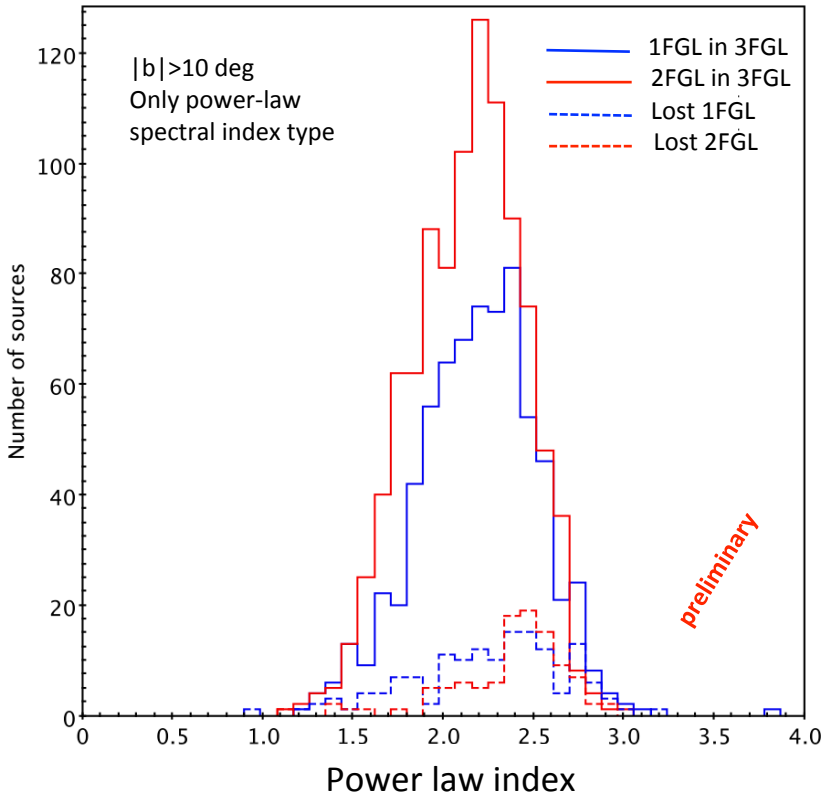
preliminary

- 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

E. Cavazzuti

Some properties of the sources no longer detected





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

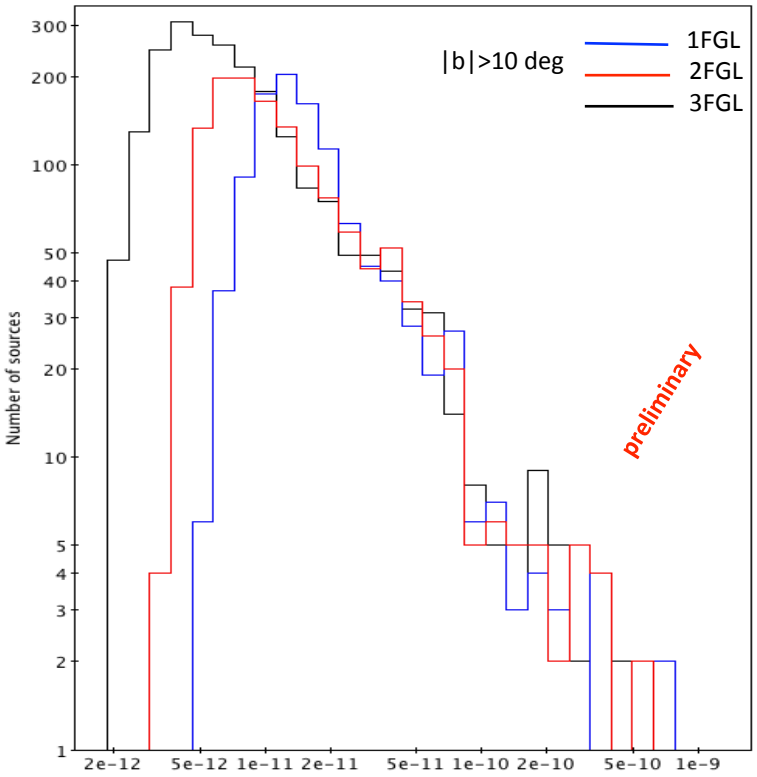
Soft and/or variable sources tend not to be found across all catalogs.

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

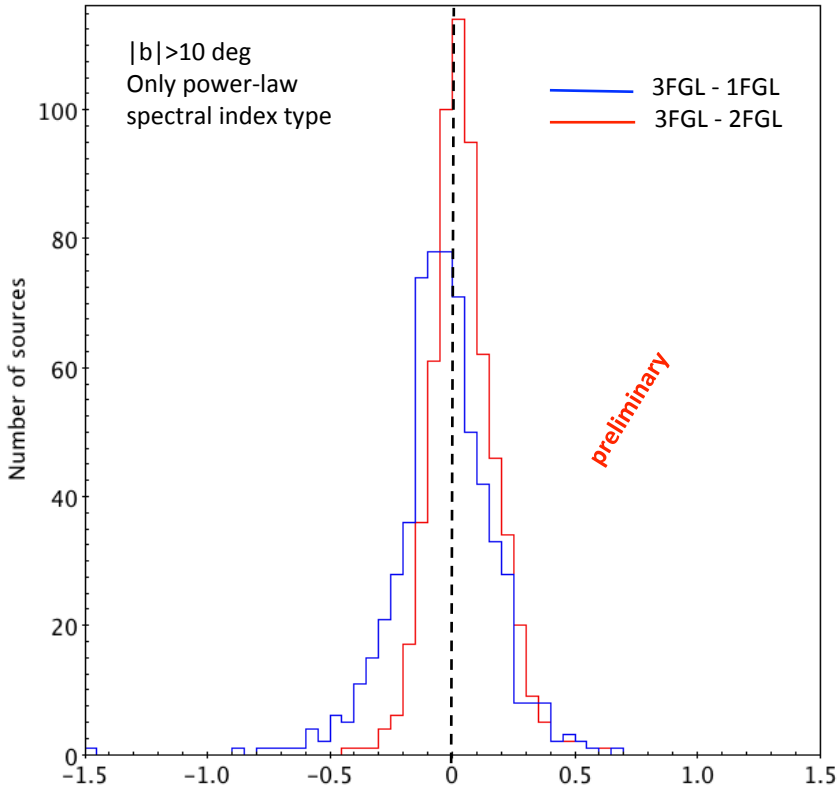
Flux threshold and spectral index evolution

The **flux threshold is down to** 3×10^{-12} **erg cm^{-2} s^{-1}**
(from 5×10^{-12} erg cm^{-2} s^{-1} in 2FGL)

621 **sources in common** among 1/2/3FGL



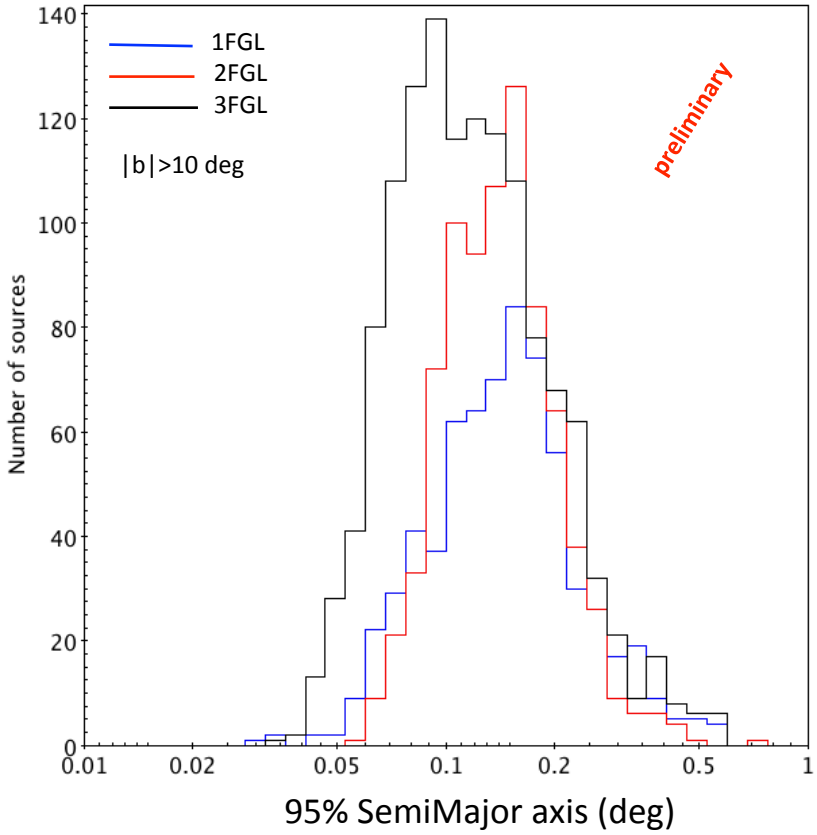
Energy flux 100 MeV – 100 GeV (erg/cm^2/s)



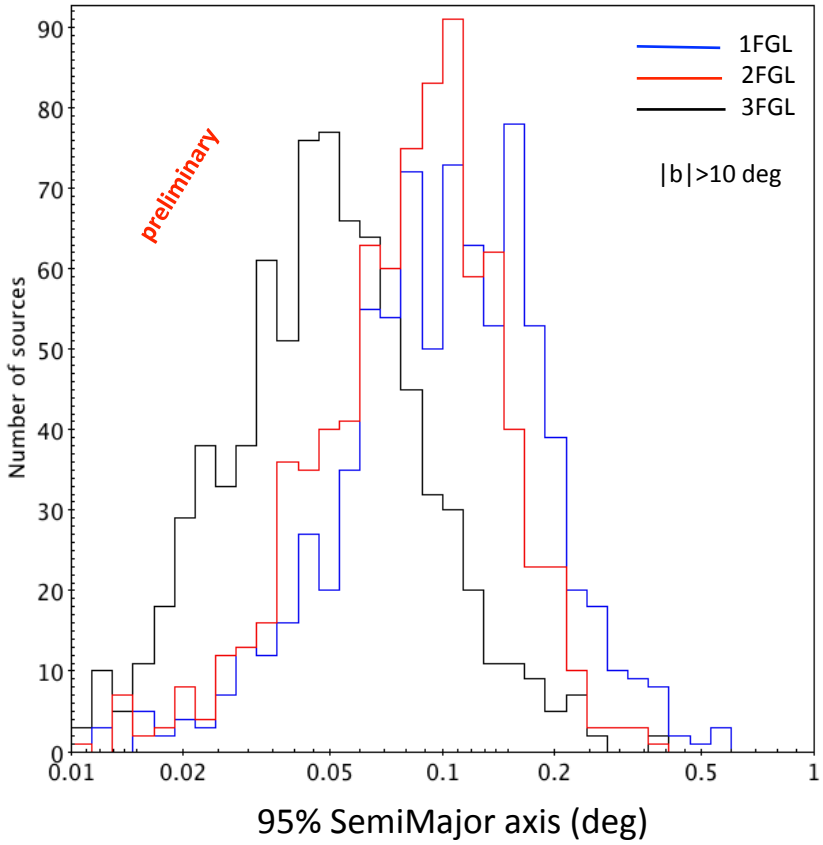
Delta power-law index

95% confidence error ellipse evolution

Sources with **25<TS<100**
(TS= Likelihood test statistic)



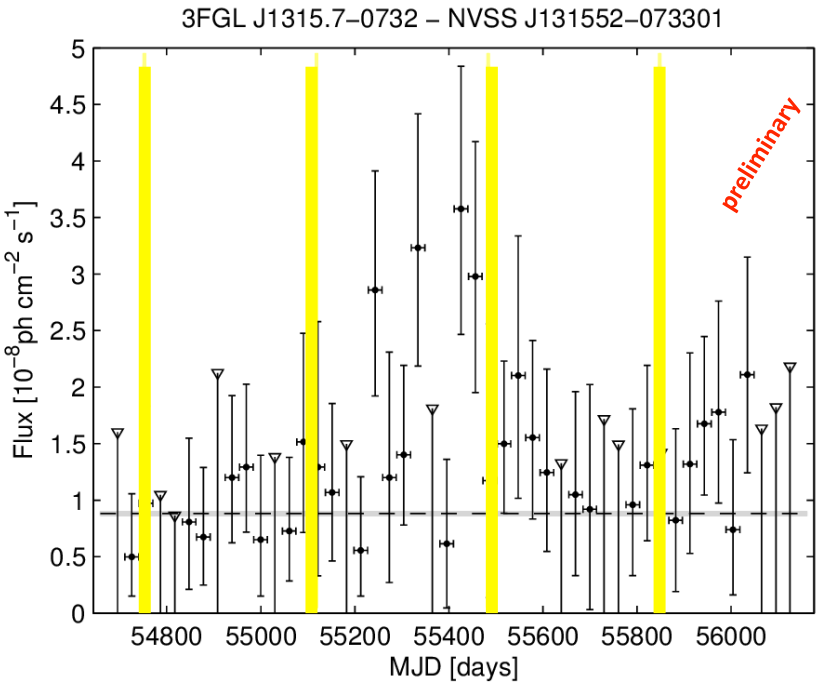
621 **sources in common** among 1/2/3FGL



improvement at a given significance level

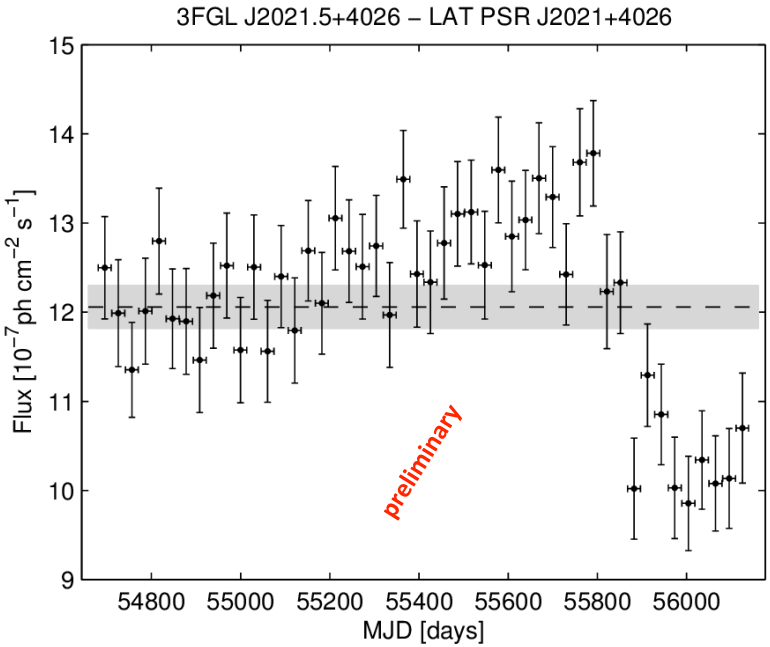
improvement for a given set of sources

Improved light curves

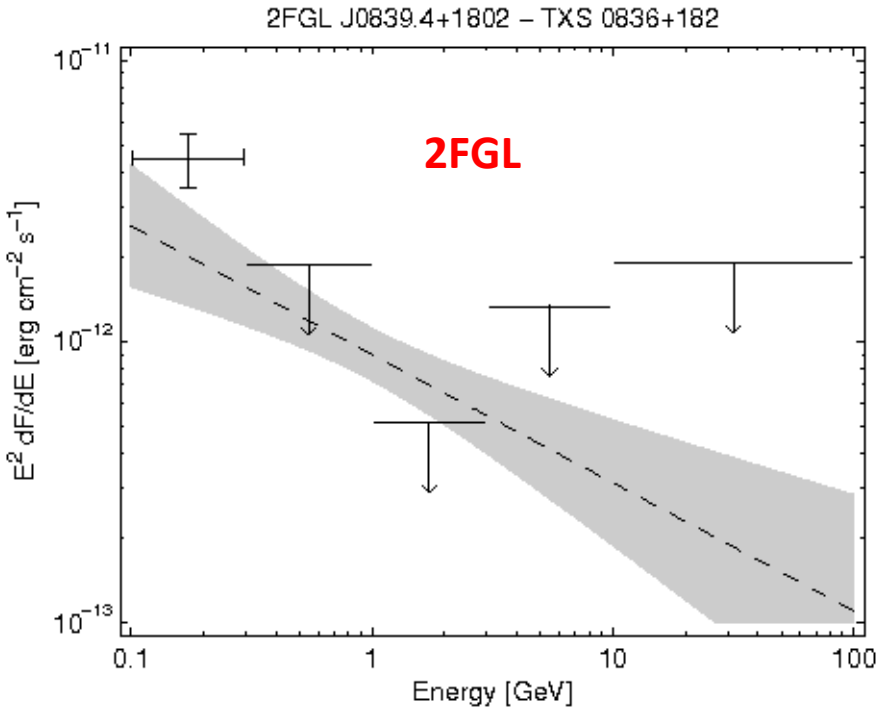


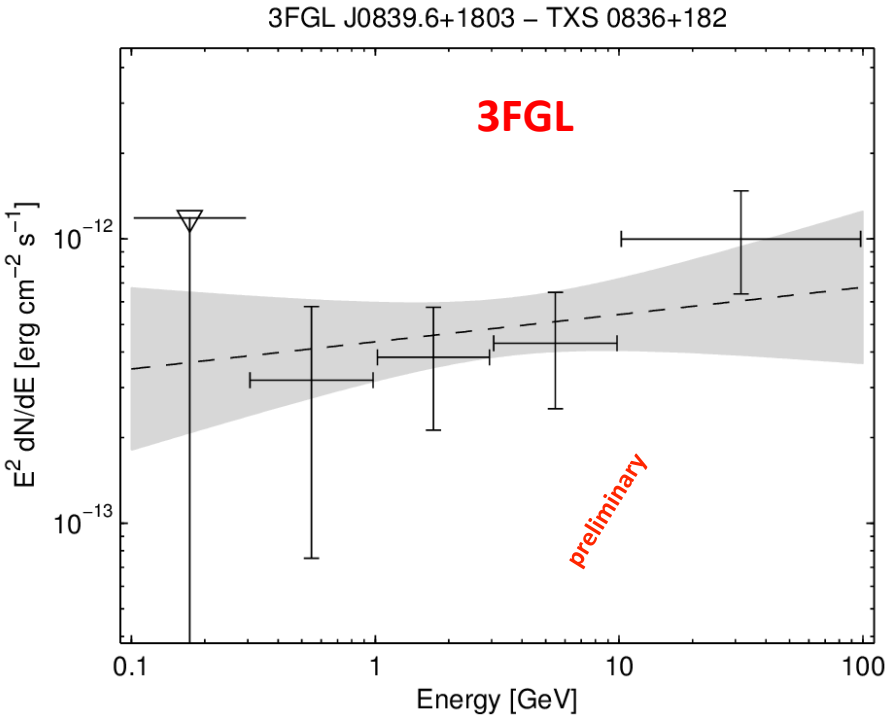
Light curve of a source on the Sun track, showing that the peaks corresponding to **the Sun passages (yellow) are gone** (updated analysis procedure since 2FGL).

Light curve of the **variable pulsar**
LAT PSR J2021+4026
(Allafort, A. et al. 2013, ApJL, 777, L2)
as seen by the automatic pipeline for 3FGL



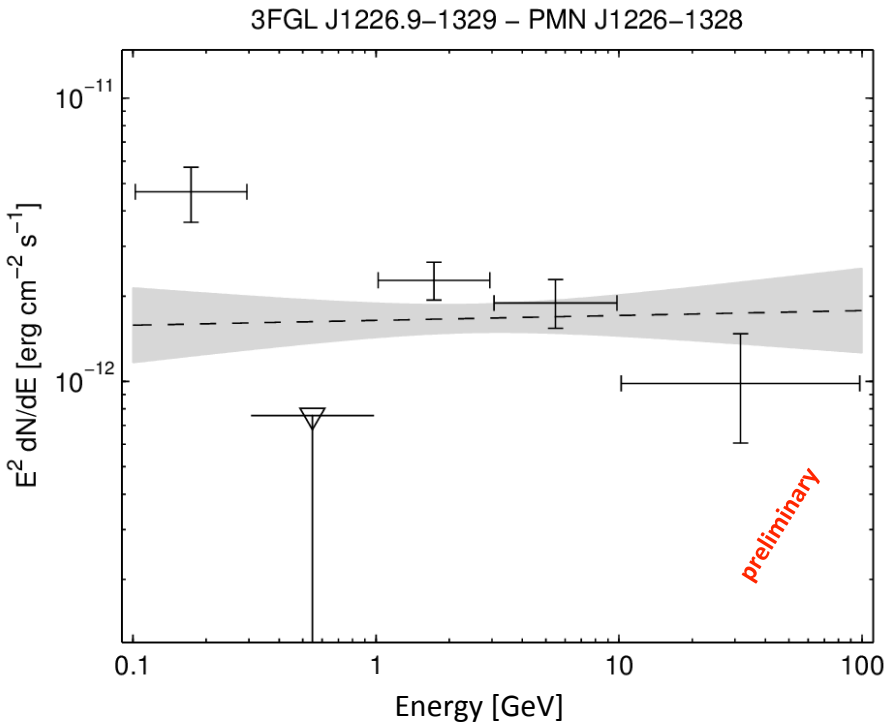
Spectral characterization in 3FGL

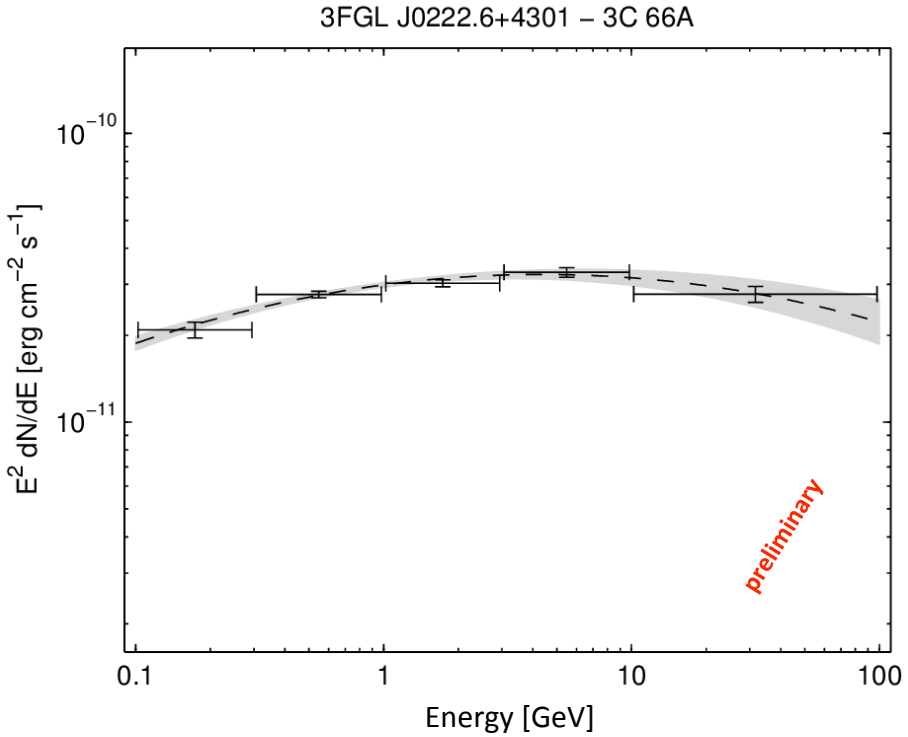




SED of the same source seen in 2FGL (Sun contamination) and in 3FGL (**removed Sun contamination**)

Spectral characterization in 3FGL



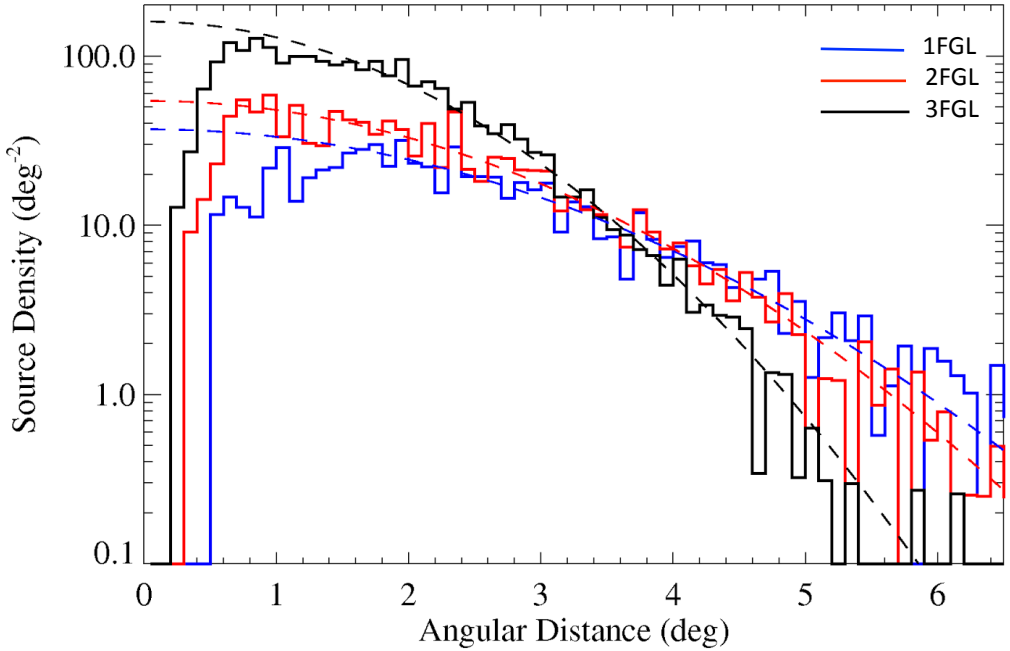


Example of **a source flagged with bad spectral fit quality**. This is a relatively typical case for sources with this flag with conflict between the first two band fluxes. This source is close to the brighter PSR J1231-1411.

Source with LogParabola spectrum **(TSCurve > 16) but Signif_Curve < 3** because the systematic error on the high-energy point (10%) makes it nearly compatible with a power-law. This is a TeV source which has indeed a softer spectrum beyond 100 GeV.

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%.**

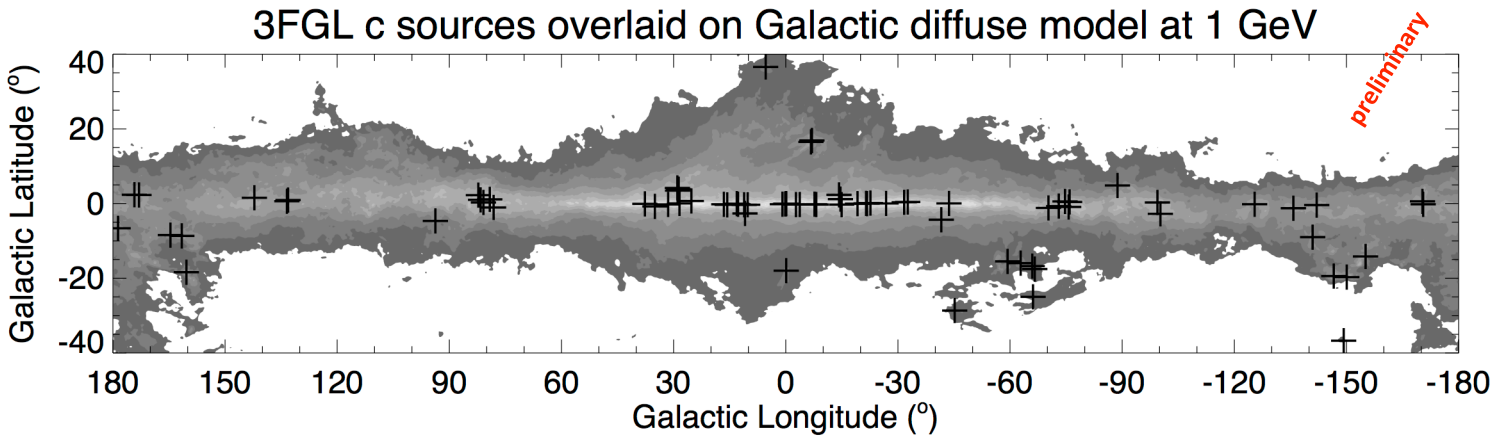
→ **even though the PSF improved** after the Pass7 reprocessing, the **larger number of detected sources (2193 vs 1319 above |b| = 10 deg) is now pushing the main LAT catalogue into the confusion limit** even outside the Galactic plane.

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.**

Many fewer ‘c’ sources

Relative to the 2FGL catalogue, far **fewer ‘c' sources** are flagged here (**162 vs. 78**) despite the much greater number of sources overall in the 3FGL catalogue.
The reduction of `c' sources:

- at high latitudes - **improvement of the representation of the dark gas component of the Galactic diffuse emission model in the vicinity of massive star-forming regions**.
- at low latitudes - **unassociated sources with very curved spectra are not flagged as ‘c’ any more**



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)
- Dichotomy between gamma-ray detected and gamma-ray non-detected blazars at other wavelengths
- Timing correlations between the activity in the gamma-ray bands and other bands
- 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

The importance of the MW data

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).

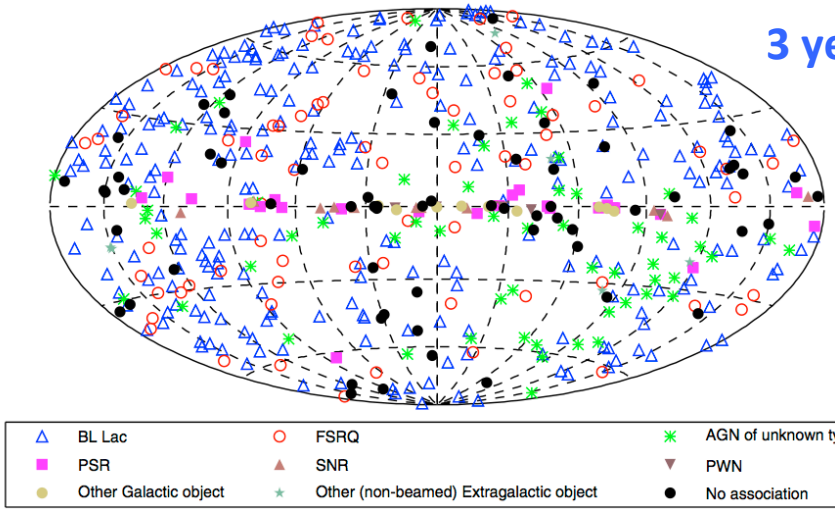
MW data are necessary to study broad band emission mechanisms, unified models, alternative models etc

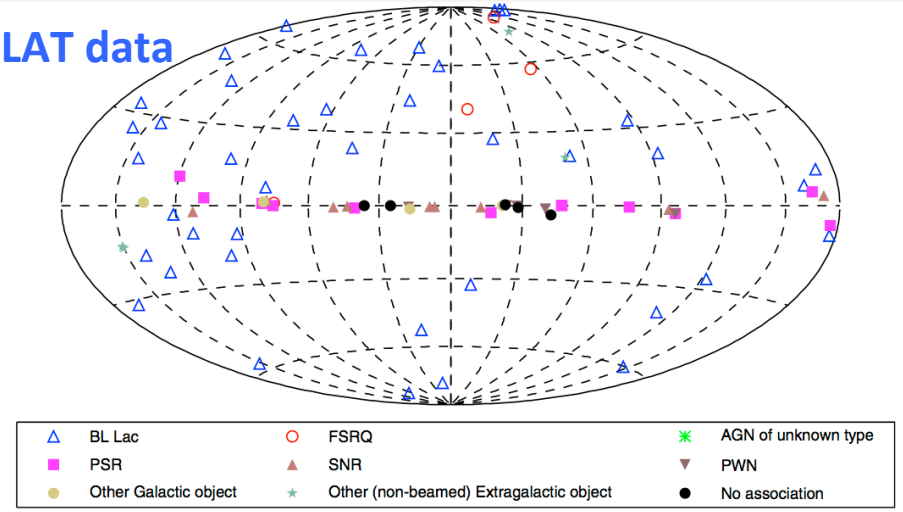
Which are the upcoming facilities which would contribute to exploit *Fermi* data?

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.**

Sources above 10 GeV and synergies with VHE obs.

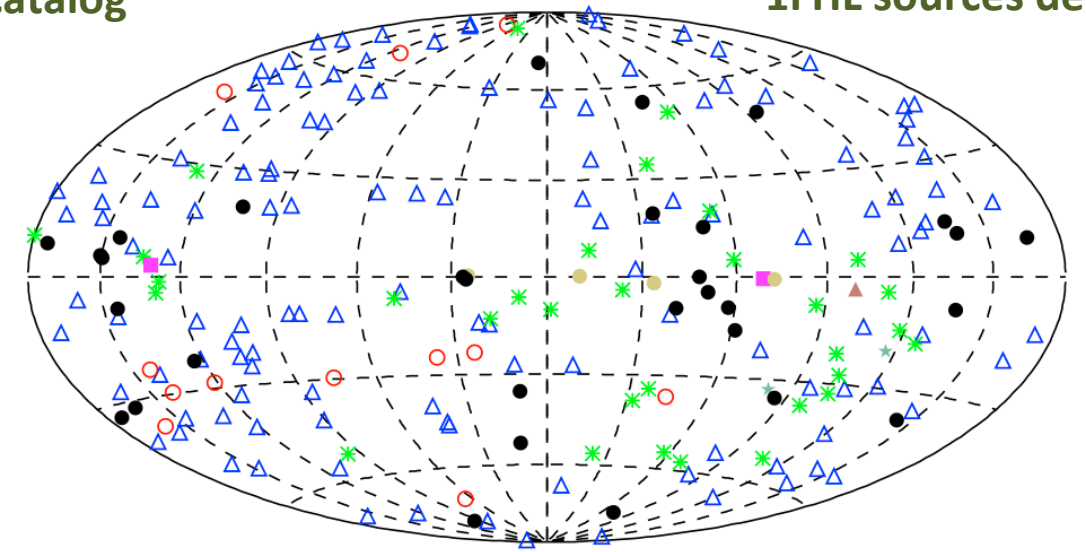
3 years of LAT data





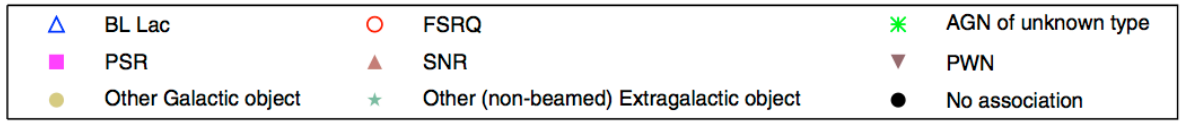
1FHL catalog

1FHL sources detected by IACT



1FHL sources as good candidates to be detected at VHE

M. Ajello talk on >50 GeV sources



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

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*

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
- Pass 8 is coming providing a completely new view of the telescope and certainly new results
- 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, will continue to contribute capitally to FGST success