The Fermi-LAT Fourth Source Catalog (4FGL)

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on behalf of the Fermi-LAT collaboration

National Aeronautics and Space Administration

Fermi

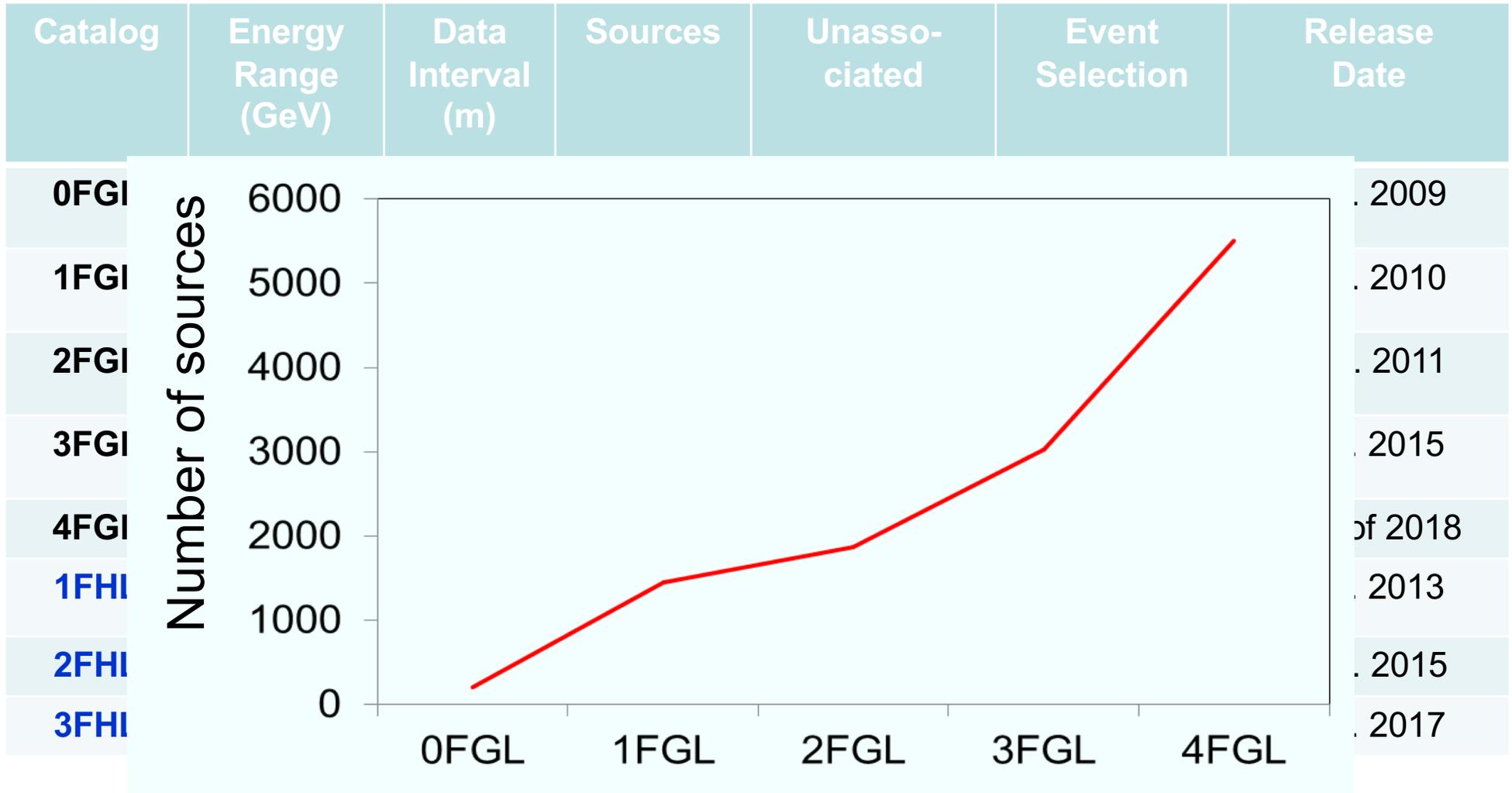Gamma-ray Space Telescope

www.nasa.gov/fermi

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Outline

- **Recap on released catalogs/lists**
- **Analysis procedure in a nutshell – novel features**
- **Interplay with Diffuse Emission Model**
- **Association procedure**
- **Updated results on Cat 8 (E>50 MeV)**
- **Galactic unassociated sources**
- **Towards 4LAC**
- **Summary**

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Catalog	Energy Range (GeV)	Data Interval (m)	Sources	Unasso-ciated	Event Selection	Release Date
0FGL						2009
1FGL						2010
2FGL						2011
3FGL						2015
4FGL						of 2018
1FHL						2013
2FHL						2015
3FHL						2017

What are LAT catalogs good for?

3FGL: *838 citations* (NASA ADS)

- **Predictions/optimization of future observatories: LHAASO, CTA, SKA…**
- **Sky model for data analysis**
- **Reference for studies on:**
  - **individual sources**
  - **source populations**
  - **MW analyses**
- **Source samples to investigate**
  - **Extragalactic Background Light**
  - **Extragalactic Diffuse Gamma-ray Background**
- **Exploration of new classes: stars, galaxy clusters…**
- **Nature of unassociated sources via follow-up observations**
- **Classification of unassociated sources**

FL8Y

Preliminary LAT 8-year Point Source List, 5523 sources, released early January 2018

Meant to help in writing 2018 NASA Fermi Guest Investigator proposals.

Similar to 4FGL in many aspects (data+analysis procedure) but 4FGL will use a Pass8 diffuse emission model (see Seth Digel's talk)

Caveats

"The FL8Y list is meant to provide researchers analyzing Fermi data with an updated description of the gamma-ray sky with respect to 3FGL. It contains nearly 2500 new sources which can be used as a starting point for new works. It can also be used for modelling the source background in a region of interest.

Being a courtesy effort, FL8Y is neither published nor posted on the arXiv. We request the community users to refrain from publishing works (in particular population studies) using directly material from FL8Y, and wait for the future 4FGL catalog that will supersede FL8Y."

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Methodology of the LAT source catalogs

3D maximum likelihood (x,y,E)

Point sources on top of isotropic, interstellar model and extended sources

Report position, significance, association, basic SED and light curve, flags

pointlike

Refit spectrum of diffuse components

Source detection

Source localization

Comparison for spectra

pyLikelihood

Official Science Tools and diffuse model

Thresholding

Spectral characterization

Light curves

Comparison for localization

Run with alternative diffuse model

Catalog

With flags

Associations

Bayesian + Likelihood ratio

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Diffuse Emission Modeling Improvements for 4FGL

- ## On large scales:
  - Refined decomposition of CO (H_2 tracer) and H I into 'rings' of Galactocentric distance
  - Decomposition of inverse Compton model into 'rings'
  - P305 event selection (Bruel et al. poster) removes structure in residual charged particle background
  - Re-evaluated 'non-template' gamma rays (Fermi bubbles + Loop I + etc.)

- ## On finer scales:
  - Factored the CMZ from the innermost ring
  - Better angular resolution for H I with the new HI4PI survey (16')
  - Better angular resolution (6') and linearity for Dark gas (Planck data)
  - Used 8-year source list derived for >50 MeV

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Diffuse Emission Model Status

- We have implemented the improvements noted. Final stages are:
    1. Tuning/iterating the non-template template;
    2. Checking against an iteration of source detection for the Catalog analysis

- We anticipate finalizing the model in time to support release of the 4FGL source list by the end of the year

Effect of diffuse emission model on source detection

4-year Pass7

Vela

8-year Pass8

Vela

Preliminary

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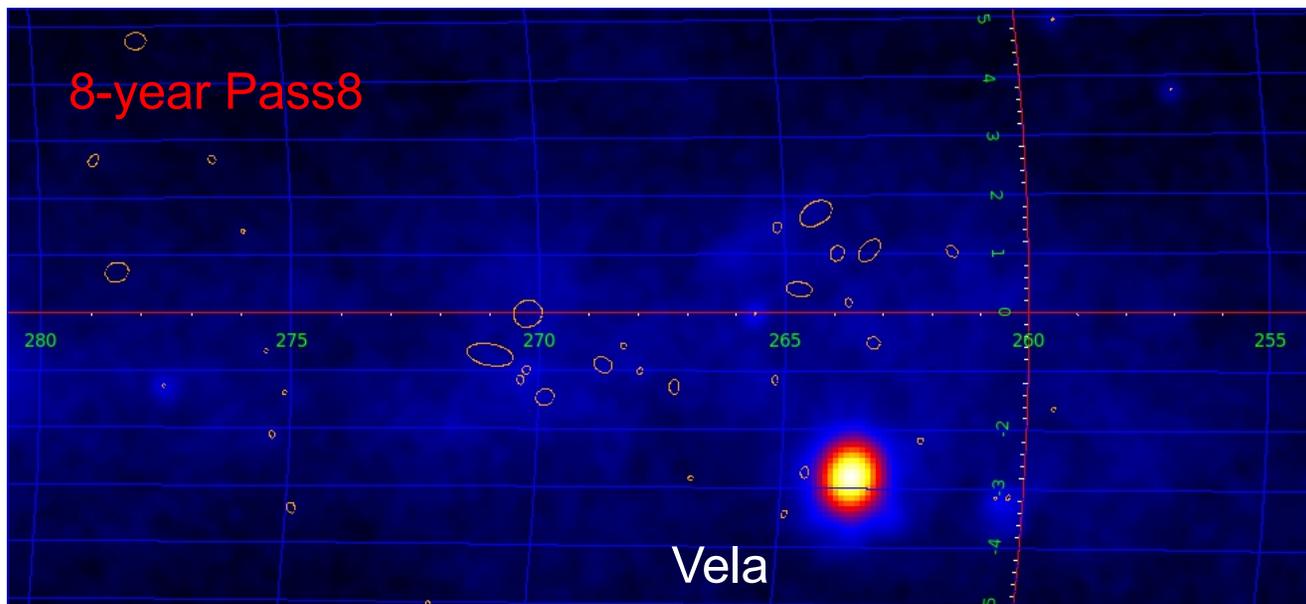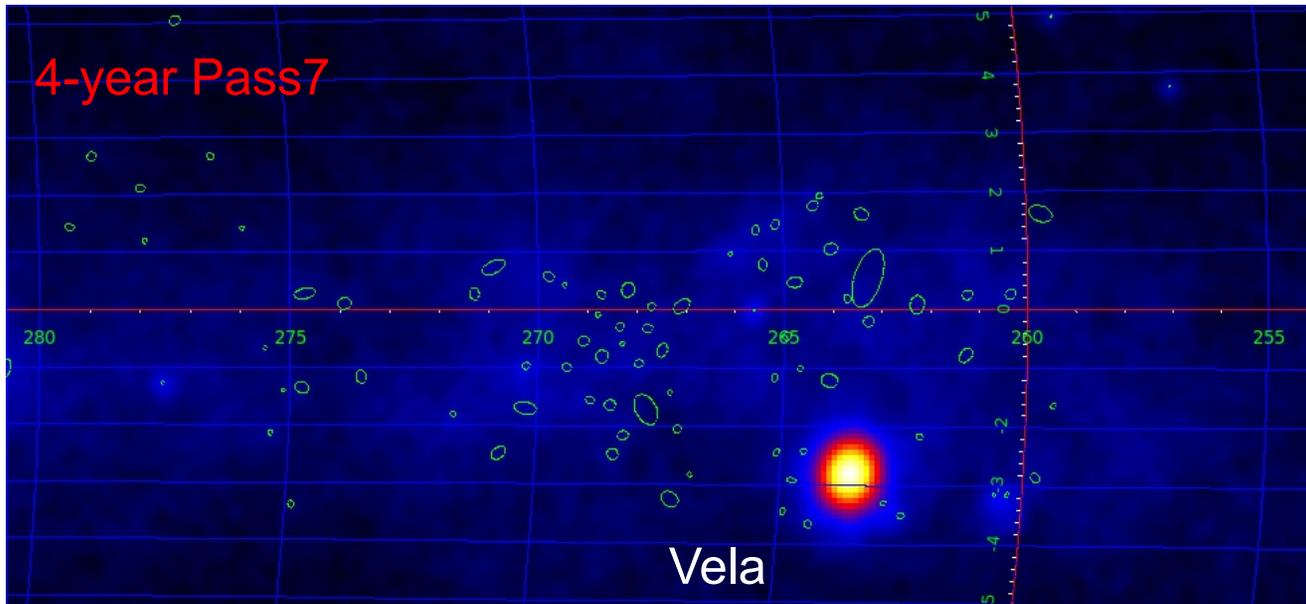
3FGL   vs   FL8Y/4FGL

| 3FGL		FL8Y/4FGL
4 years P7Rep	Data	8 years **P8**, TS x 2.3 (acceptance)
Front/Back, z < 100°	Selection	PSF types, zmax depend on energy
100 MeV – 300 GeV	Main fit	100 MeV – 1 TeV
No weights or energy dispersion	Method	**Weights**, energy dispersion
gll_iem_v06	Interstellar	Idem (**will be updated in 4FGL**)
25	Extended sources	58
Cutoff as $\exp\left(-E/E_{\text{cut}}\right)$	Pulsars	Cutoff as $\exp\left(-a\,E^{2/3}\right)$
Used for PL, PLEC, LP	Spectral_Index	PL_Index, LP_Index, PLEC_Index
beta, Exp_Index	Spectral params	LP_beta, PLEC_Exp_Index
Test either LP or PLEC	Spectral shapes	Always report PL, LP, PLEC params

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FL8Y characterization

Improved localization (important for association)
Median error radius at 25<TS<100
4.4 arcmin

Detection theshold for extragalactic sources: energy flux ~2.10^{-12} erg cm^{-2}s^{-1} (depends slightly on spectral shape)

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Association methods
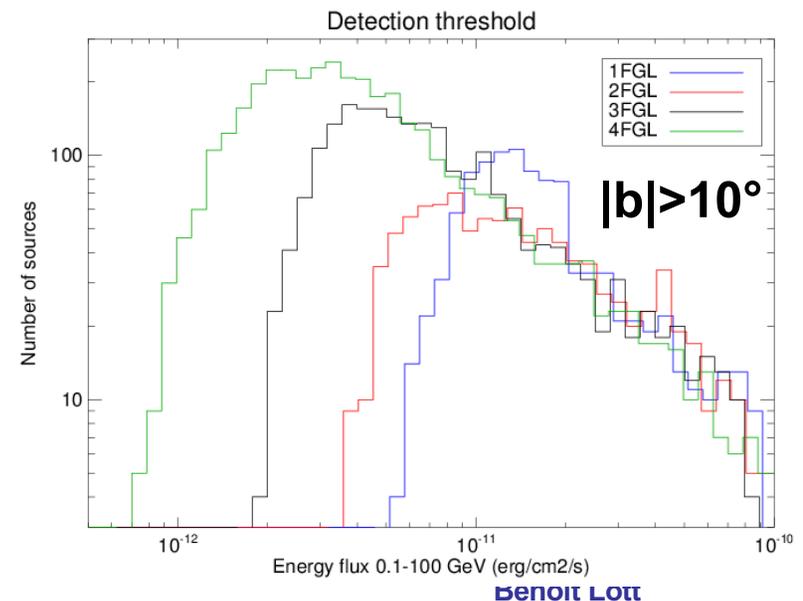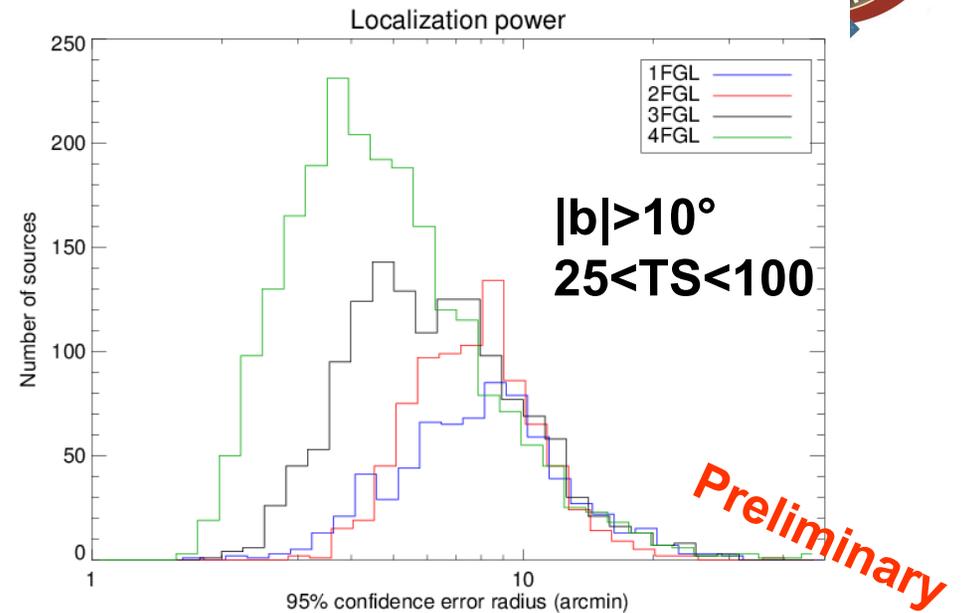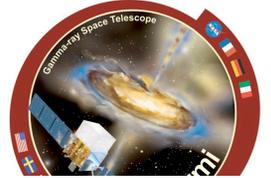
Bayesian method *(general), J. Knödlseder*

(following Mattox et al. 1997)

- true association: offset determined by position uncertainty (Rayleigh distribution)
- false association: offset determined by counterpart local density
- Prior via Monte-Carlo

$$N_{false} = \sum_{p_{ik} \geq P_{thr}} (1 - p_{ik})$$

$$P_{thr} = 0.8$$

$$N_{assoc} = \sum_{p_{ik} \geq P_{thr}} 1$$

- *New features*: provide low-confidence *(P>0.1)* associations

Preliminary
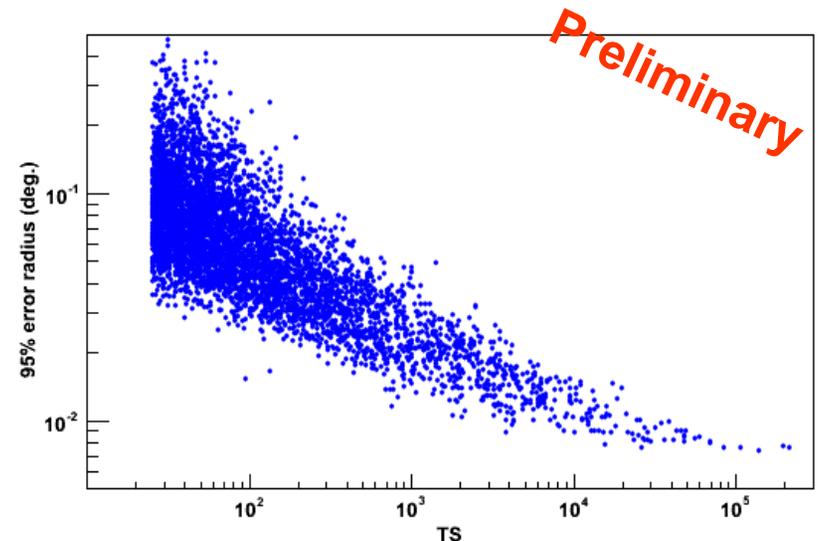
Likelihood-ratio method *(AGNs),* **ASDC**

(following de Ruiter 1977)

- Similar to Bayesian-method, false associations from density of objects brighter than considered candidate.

  + inspection of SEDs for « blazarness ».

- Can handle large surveys: NVSS, SUMSS, ROSAT
- Overlap between Bayesian and LR methods for AGNs ~75%.

Counterpart catalogs

| Name	Objects[a]	Ref.
High $\dot{E}/d^2$ pulsars	313	
Other normal pulsars	2248	
Millisecond pulsars	240	
Pulsar wind nebulae	69	
High-mass X-ray binaries	137	
Low-mass X-ray binaries	187	
Point-like SNR	295	
Extended SNR[†]	274	
O stars	378	
WR stars	226	
LBV stars	35	
Open clusters	2140	
Globular clusters	160	
Dwarf galaxies[†]	100	
Nearby galaxies	276	
IRAS bright galaxies	82	
BZCAT (Blazars)	3561	
Supplement to BZCAT	102	A
BL Lac	1371	
AGN	10066	
QSO	129,853	
Seyfert galaxies	27651	
Radio loud Seyfert galaxies	29	
Radio-loud Seyfert galaxies	556	
FRICAT (Radio galaxies)	233	
FRIICAT (Radio galaxies)	123	
Giant Radio Sources	1616	
2WHSP	1691	
WISE blazar catalog	12319	
Radio Fundamental Catalog	14786	
CGRaBS	1625	
CRATES	11499	
VLBA Calibrator Source List	5776	http://
ATCA 20 GHz southern sky survey	5890	
ATCA follow up of 2FGL unassociated sources	424	
70-month BAT catalog	1092	
IBIS catalog of soft gamma-ray sources	939	
1st AGILE catalog*	47	
3rd EGRET catalog*	271	
EGR catalog*	189	
0FGL list*	205	
1FGL catalog*	1451	
2FGL catalog*	1873	
3FGL catalog*	3033	
1FHL catalog*	514	
2FHL catalog*	360	
3FHL catalog*	1556	
TeV point-like source catalog*	108	
TeV extended source catalog[†]	72	
LAT pulsars	209	
LAT identified	143	

known or plausible γ-ray-emitting source classes
AGNs
Galaxies
Pulsars
PWNs
SNRs
Globular Clusters
O, WR, LBV stars
Binaries

surveys at other frequencies
Radio,
IR,
X-rays

GeV/TeV sources

identified γ-ray sources

Association: based on spatial coincidence only
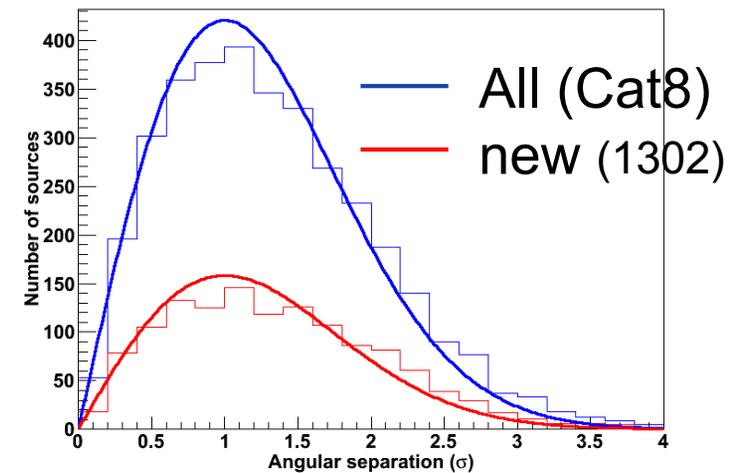
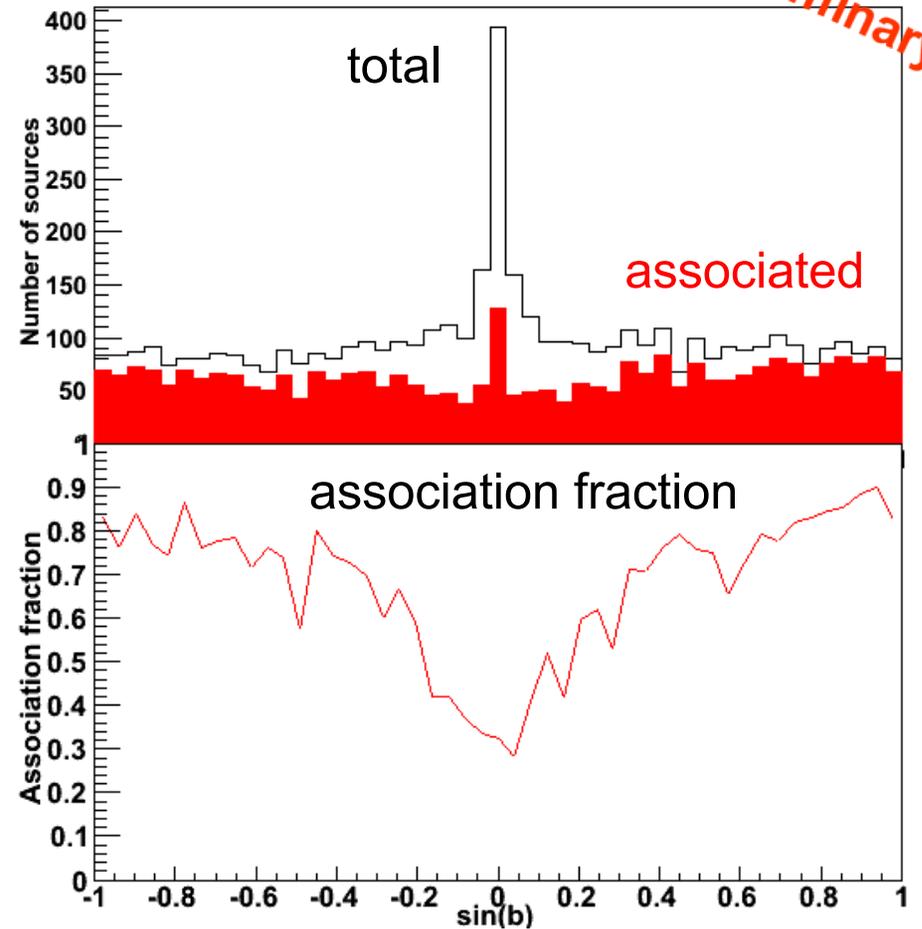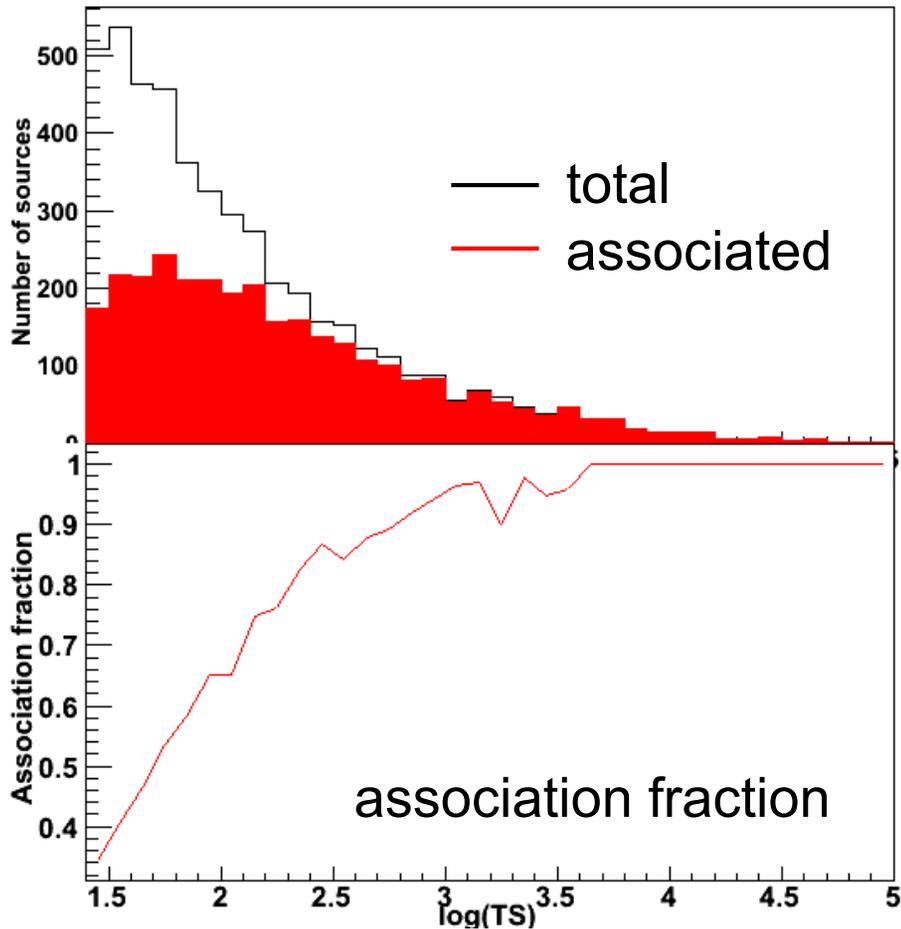**Identification:** based on angular extent or correlated variability (periodic or otherwise) at other wavelengths

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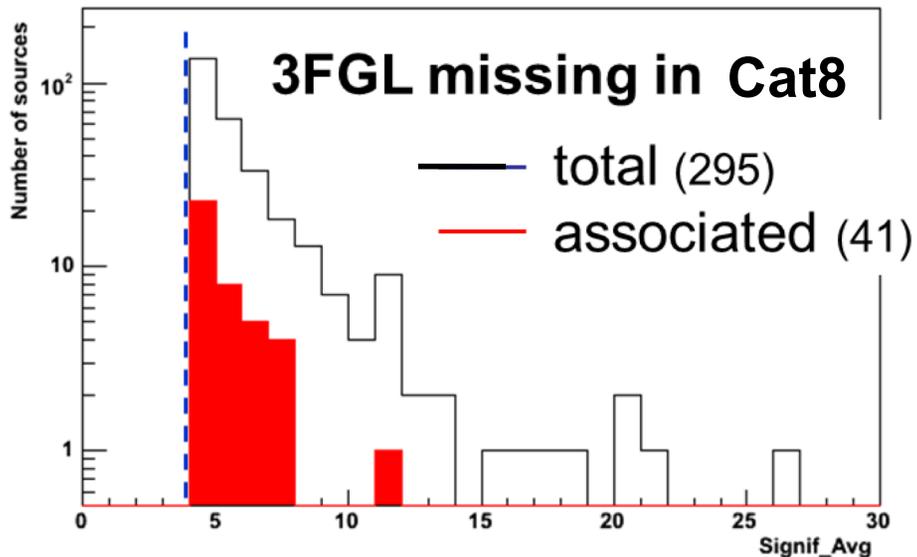# Association performance

Cat8 (E>50 MeV)
Bayesian+LR

Preliminary

Overall association rate: 66%
False associations: ~ 70 sources

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Association summary (I)

Class	3FGL (Bay.+LR)	FL8Y (Bay.)	Cat8 (E>50 MeV) (Bay.+LR)
Total	3034	5523	5457
Pulsar*	143+24	183+34	210+14 (+34%)
PWN	11	19	18 (+63%)
SNR	23	38	38 (+65%)
HMB	3	6	6 (+100%)
SPP†	49	96	113 (+122%)

- non-assoc.
- assoc.

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other Galactic : 11
spp : 113
snr : 38
pwn : 18
pulsar : 224
glob. cluster : 27
galaxy : 14
other agn : 62
bcu : 1067
fsrq : 761
bll : 1288

Blazars of unknown nature
Flat-Spectrum Radio Quasars
BL Lacs
Unassociated 34%

Preliminary

unassoc : 1834

Cat8
Bayesian+Likelihood
Ratio associations
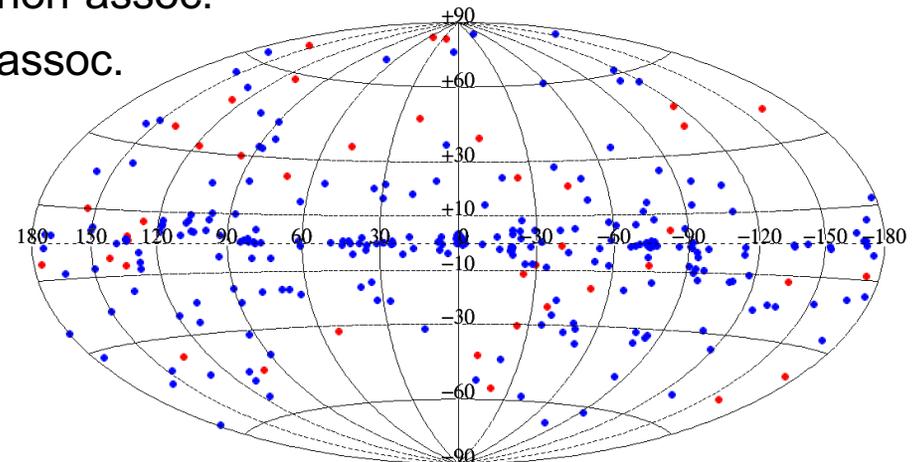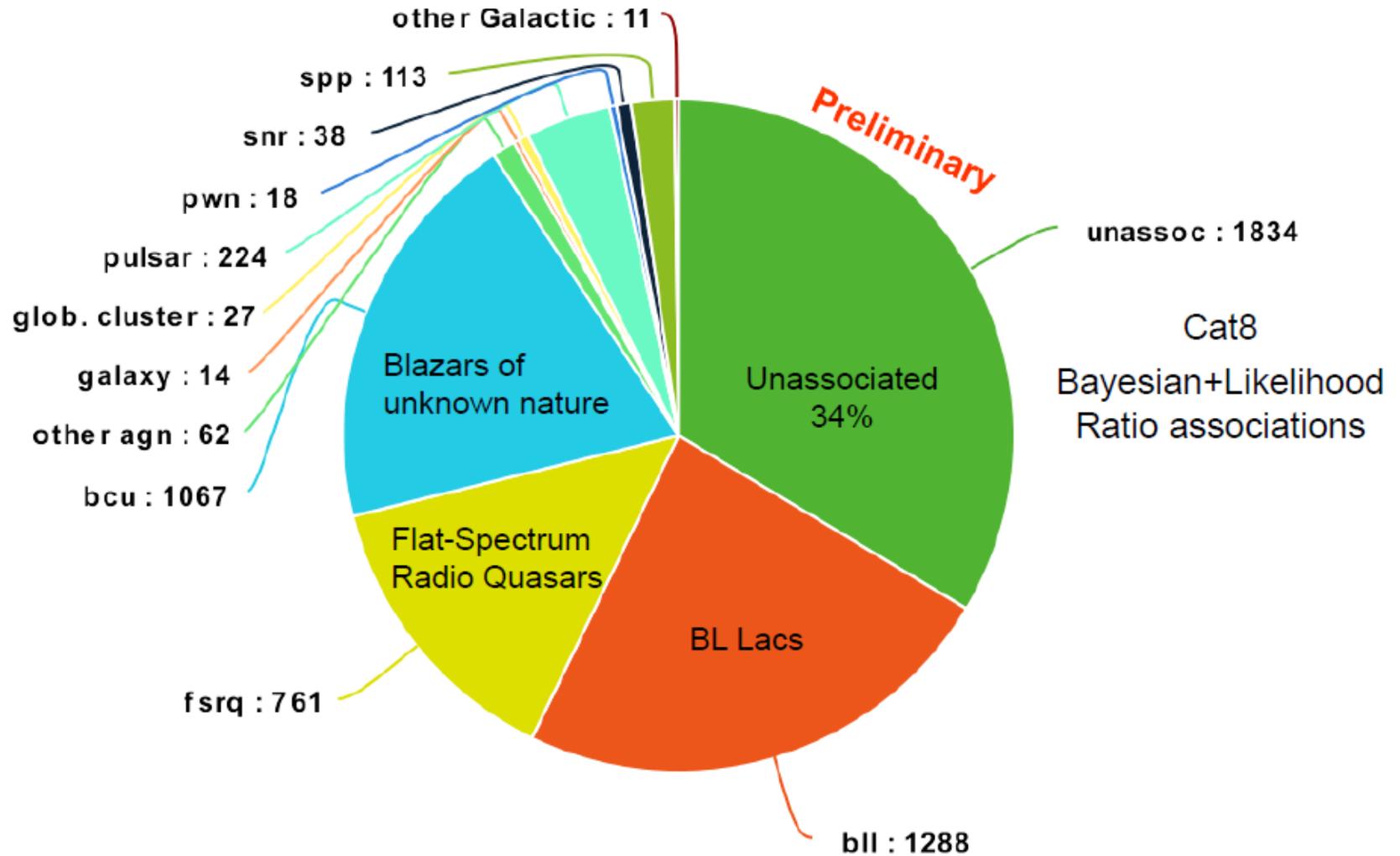
Variability

Two sets of lightcurves created for 4FGL:

Cat 8

- **Yearly light curves (8 points)**

  - variability index (χ^2 with 7 d.o.f., 99% confidence limit: 18.48)

  Ex: exercise on Cat8

  1380 variables sources, 1267 AGNs, 21 Gal., 92 unassociated

  - fractional variability

- **Bimonthy light curves (48 points)**

- AGNs
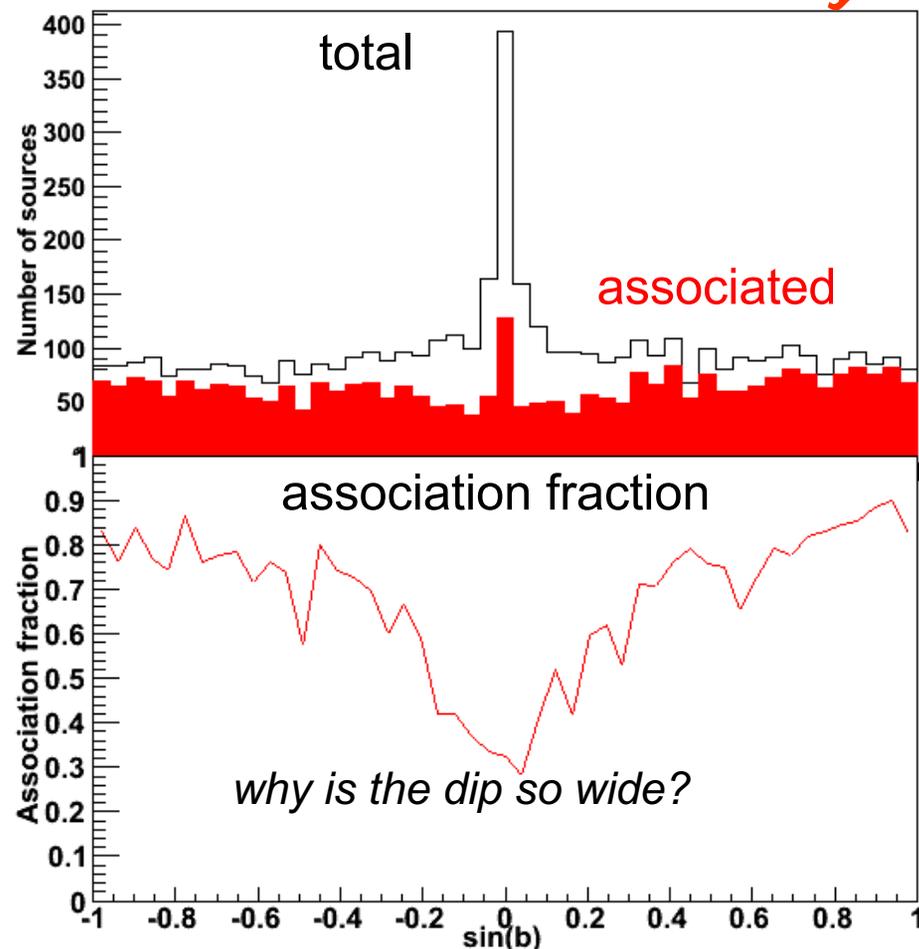- Unassoc..
- Gal.

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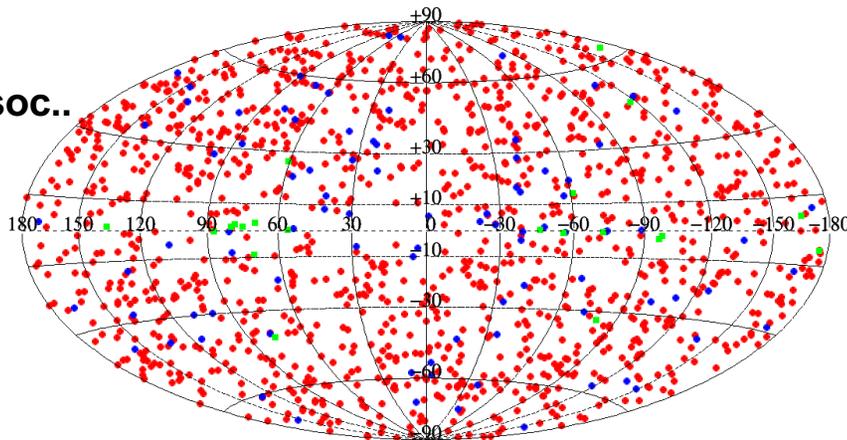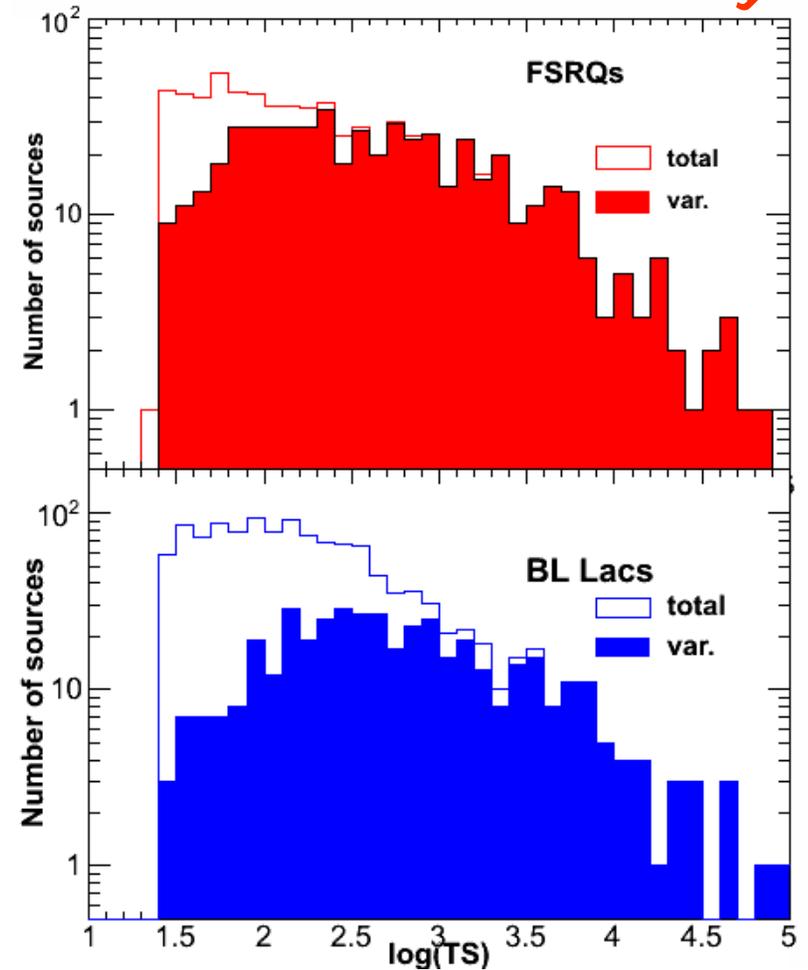
Association performance

- **Association fraction close to 85% at high Galactic latitude**

- **Photon index distribution of unassociated sources compatible with that of blazars of unknown types (BCUs)**

- **At low latitude, association rate ~40% with a wide « dip »**
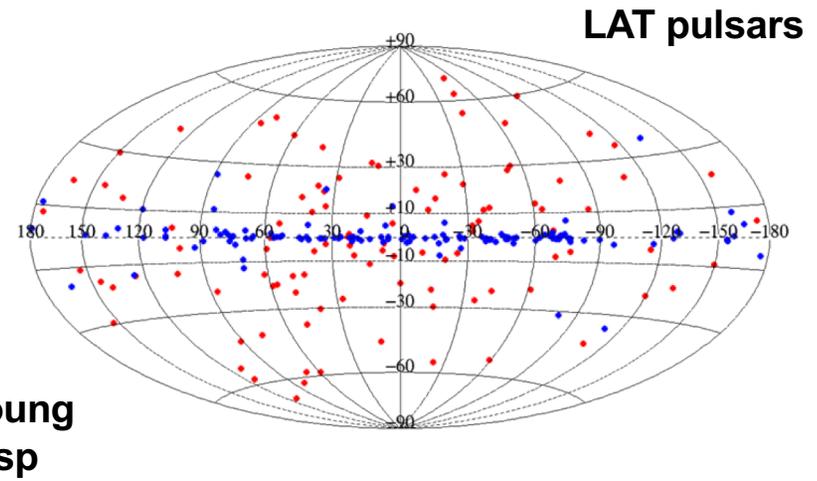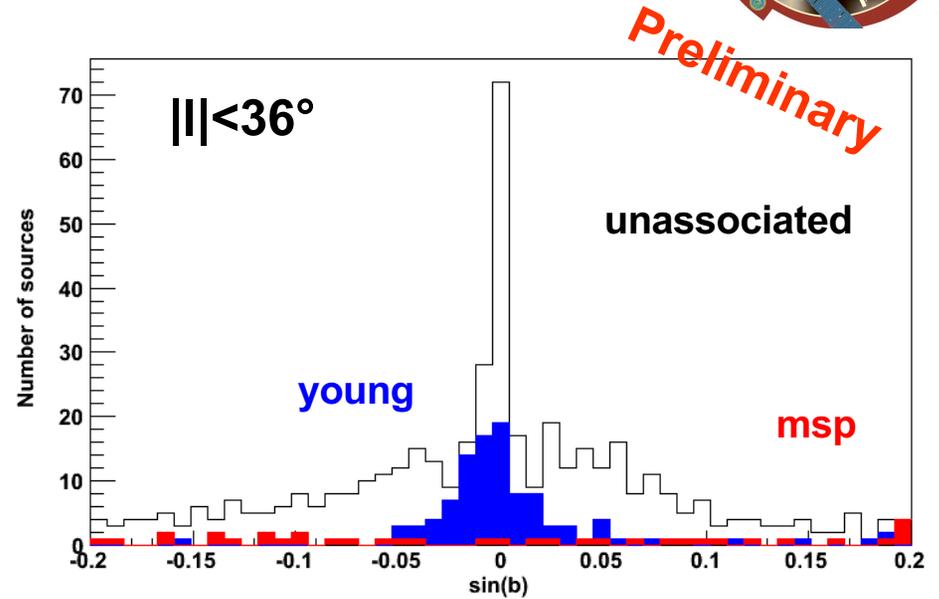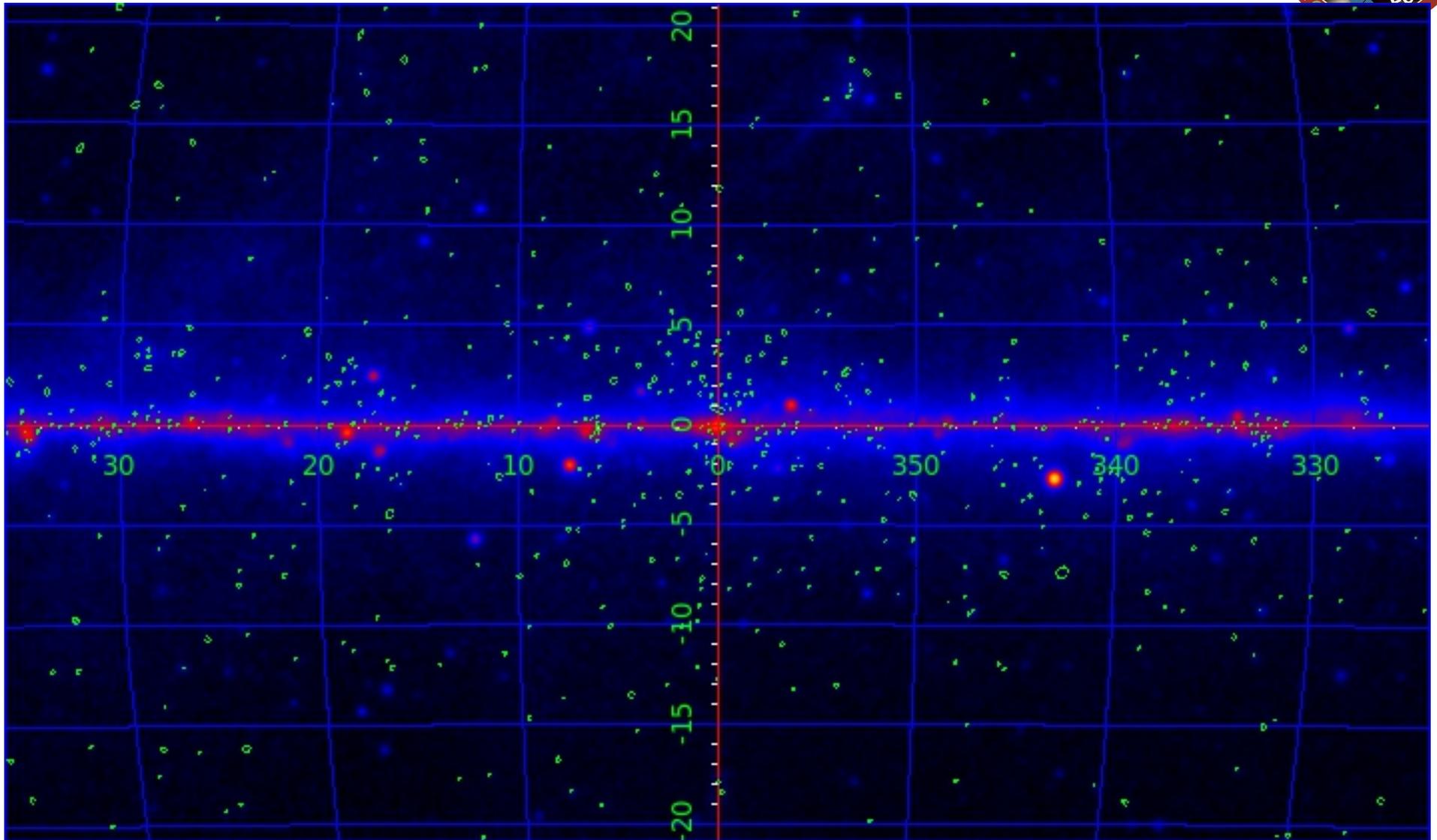
Cat8 (E>50 MeV)
Bayesian+LR

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Features of Galactic unassociated

- **229 unassociated sources located at |l|<36° and 2°< |b| <7°**

- **Galactic origin → pulsars?**

- **Spectral hardness (median index Γ=2.5) compatible with young pulsars (Γ=2.4) but not with MSP (Γ=2.2)**

- **Latitude dispersion compatible with that of >10^6 yr ATNF pulsars. Gamma-ray death line makes this possibility unlikely.**

- **No convincing evidence for other classes: LMXB, Be stars, O stars, X-ray stars, eclipsing binaries…**

- **Still there with new diffuse emission model but could still be related to missing diffuse component**

Preliminary

|l|<36°

unassociated

young

msp

Number of sources

sin(b)

LAT pulsars

- young
- msp

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Towards 4LAC

- FSRQs (red dots)
- BL Lacs (blue dots)
- BCUs (green triangles)
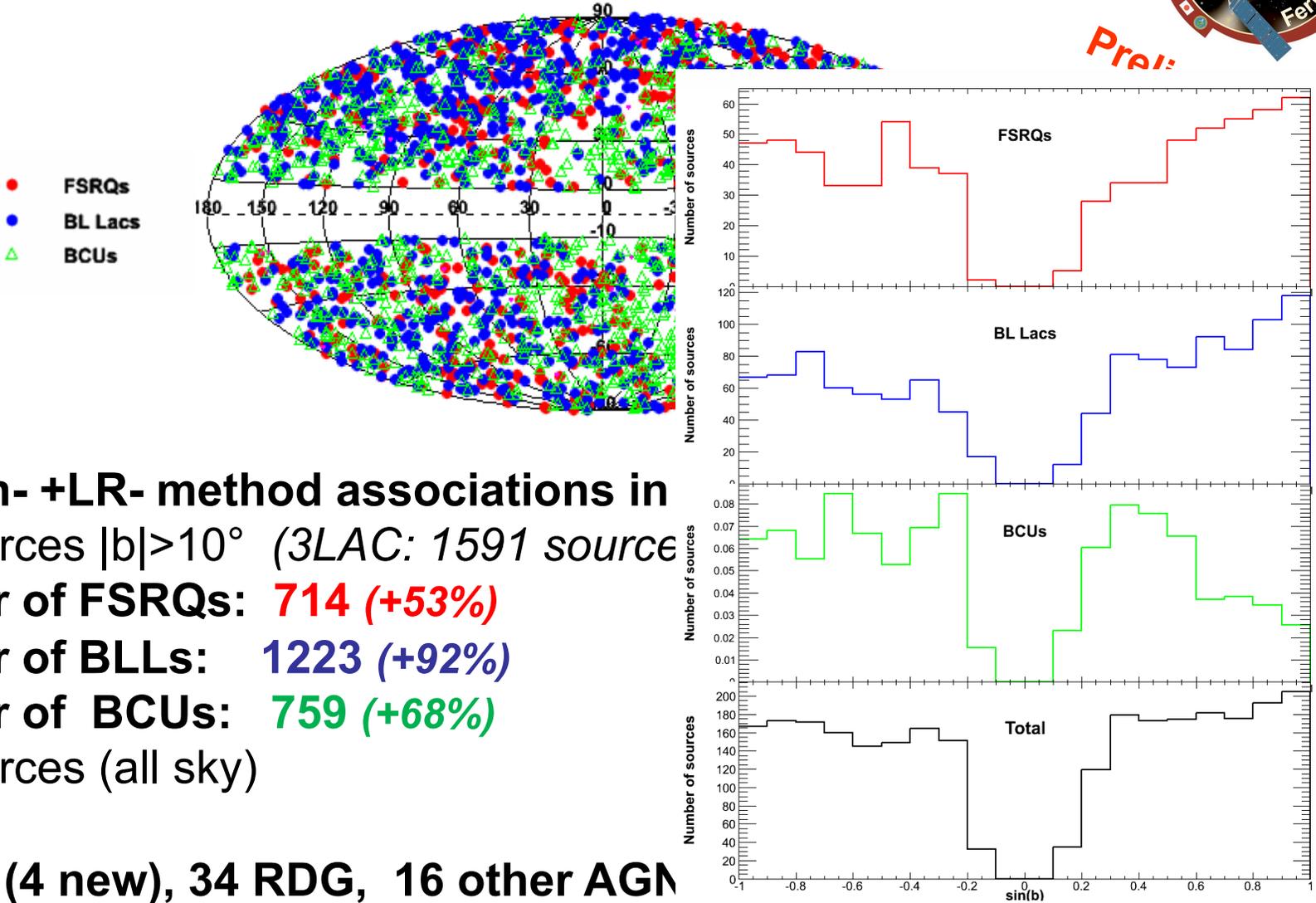
Bayesian- +LR- method associations in

2750 sources |b|>10° *(3LAC: 1591 source*

- **number of FSRQs:** **714** *(+53%)*
- **number of BLLs:** **1223** *(+92%)*
- **number of BCUs:** **759** *(+68%)*

3184 sources (all sky)

9 NLSy1 (4 new), 34 RDG, 16 other AGN
1422 sources in BZCAT
69 TeV sources

8% deficit in the Southern hemisphere

Synchrotron-peak positions

Two classification schemes:

- **Optically-based** (strength of broad lines): FSRQs, BL Lacs, BCUs (aka Sources of Unknown Type)

- **SED-based:** Low-, Intermediate-, High-Synchrotron-Peaked sources (LSPs, ISPs, HSPs resp.)

~75% blazars (87% for non-BCUs) have measured synchrotron-peak positions (fit manually by a team of 22 people)

BLLs: 381 LSPs, 326 ISPs, 271 HSPs (BCUs with SED-based classes are mainly LSPs)
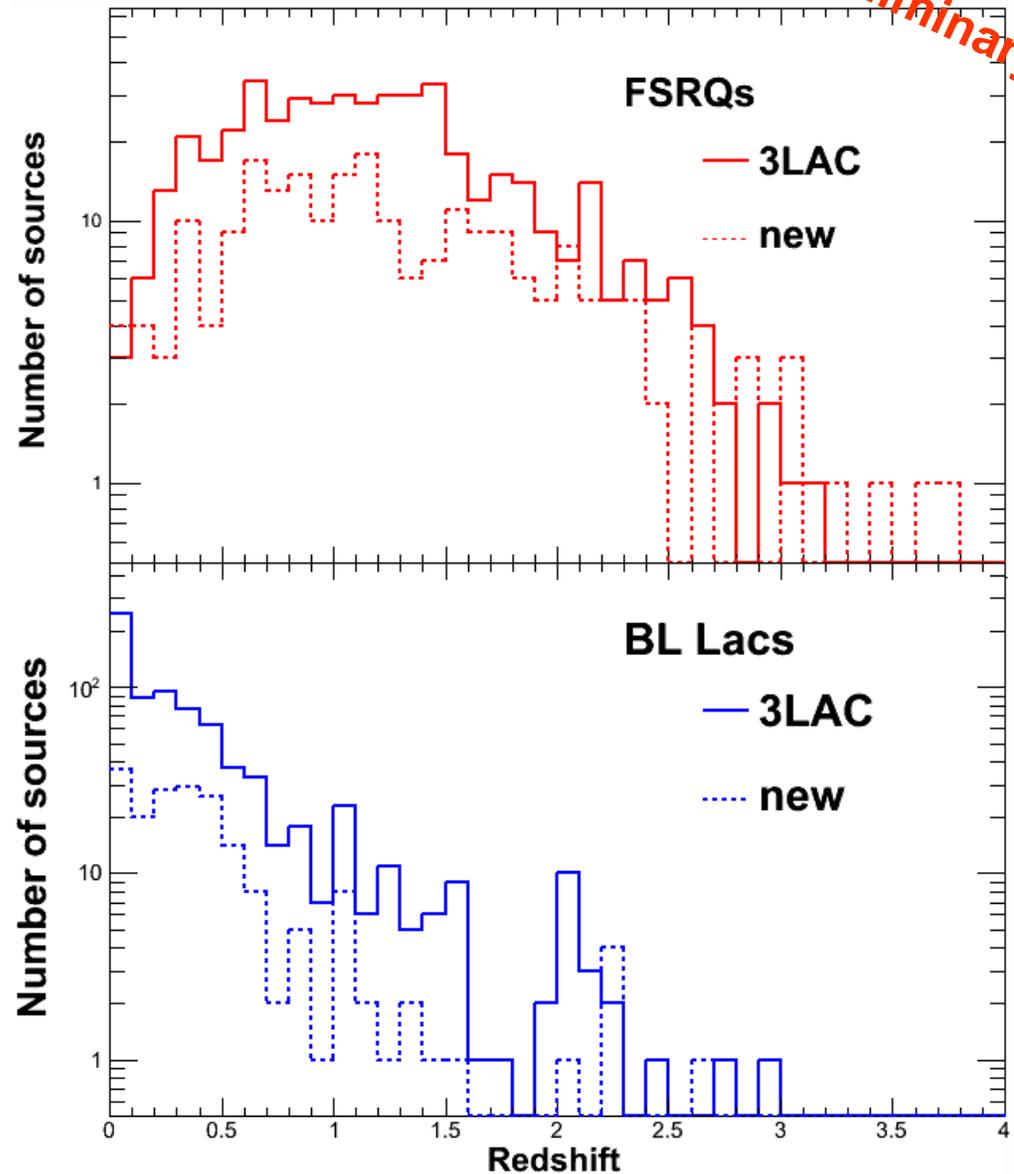
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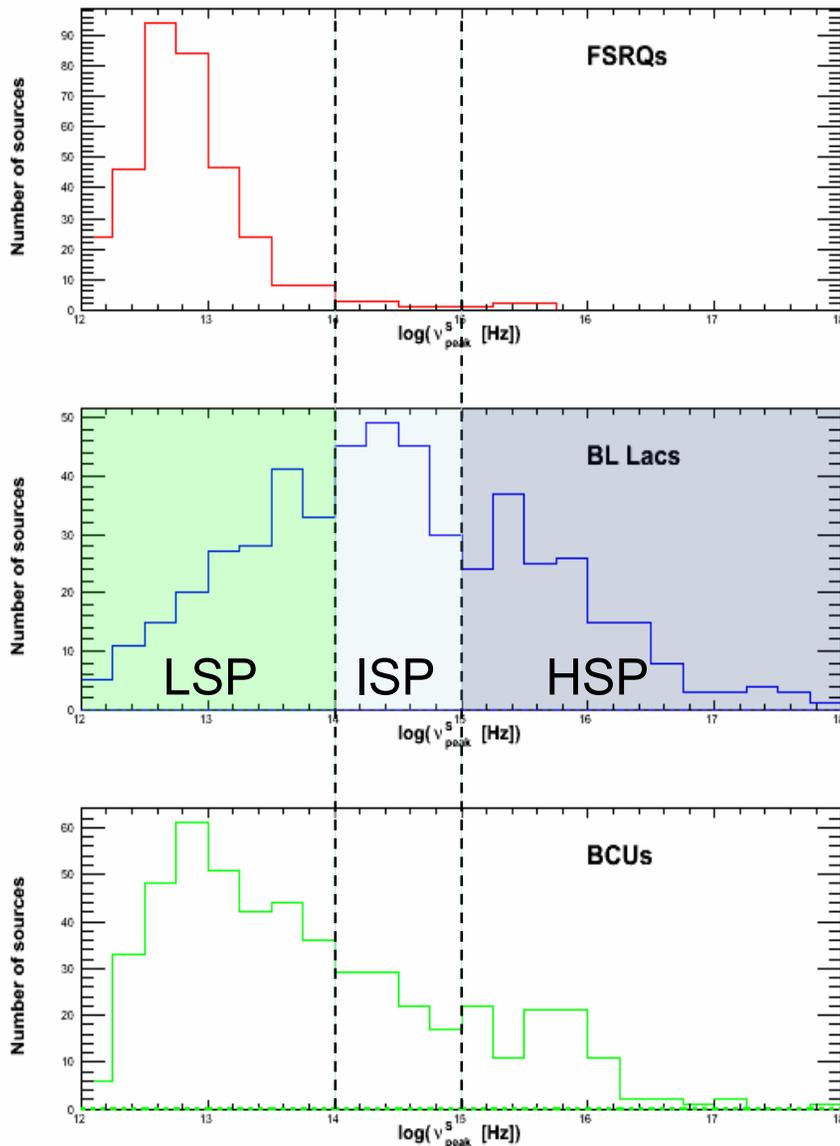
Redshift distributions

1628 redshifts in Cat8

- several new z>3 FSRQs

- maximum redshift z=3.9

- 468/1233 (38%) BL Lacs have no measured redshifts

Photon-index distributions

- **Little overlap between FSRQs and BL Lacs, limit at Γ=2.2**

- **New FSRQs notably softer than 3LAC ones: ($<\Gamma>$=2.60 vs. 2.46)**

- **New BL Lacs notably softer than 3LAC ones ($<\Gamma>$=2.19 vs. 2.04)**

- **BCUs index distribution straddling the two classes and extending beyond 2.6. New BCUs softer than 3LAC ones ($<\Gamma>$=2.32 vs. 2.11)**

Preliminary

Cat8

non-blazars

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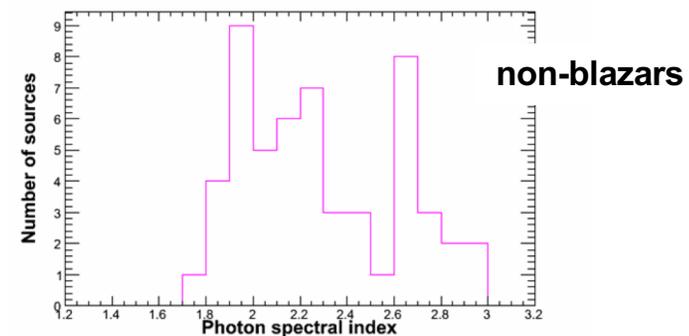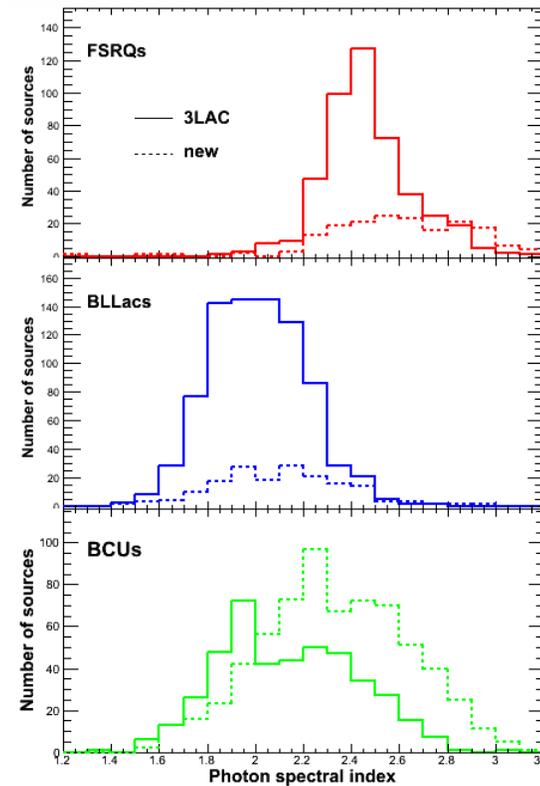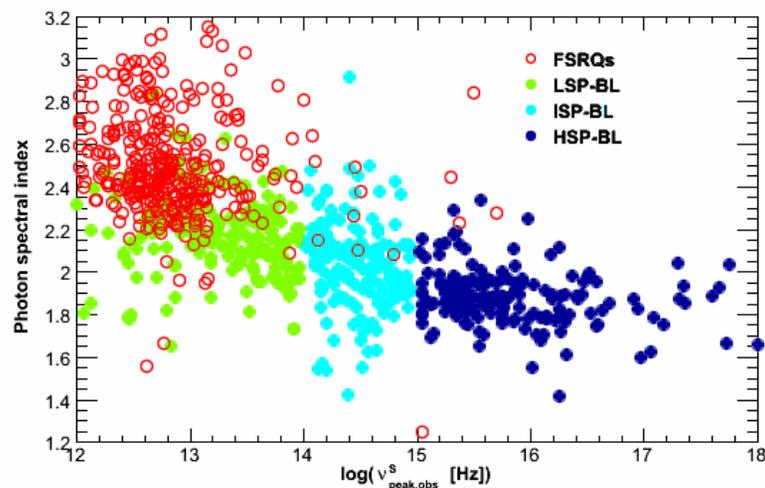
Summary

- The release of 4FGL is contingent on the Pass8 Diffuse Emission model, which is close to completion (see Seth Digel's talk on Wednesday). A better accuracy of the model is required relative to earlier catalogs as the analysis has become systematics limited, owing to large photon statistics.

- 4FGL will comprise about 5500 sources, with a ~66% association rate.

- We hope to release the list by the end of the year.

- A full-fledged catalog inluding SEDs and yearly- and bimonthly-lightcurves will require ~ 6 more months to produce.

- The 4LAC catalog (~2750 sources at |b|>10°) will be published back-to-back with 4FGL.

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