The latest *Fermi*-LAT catalogs and SKA prospects for high energy studies

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What are LAT catalogs good for?

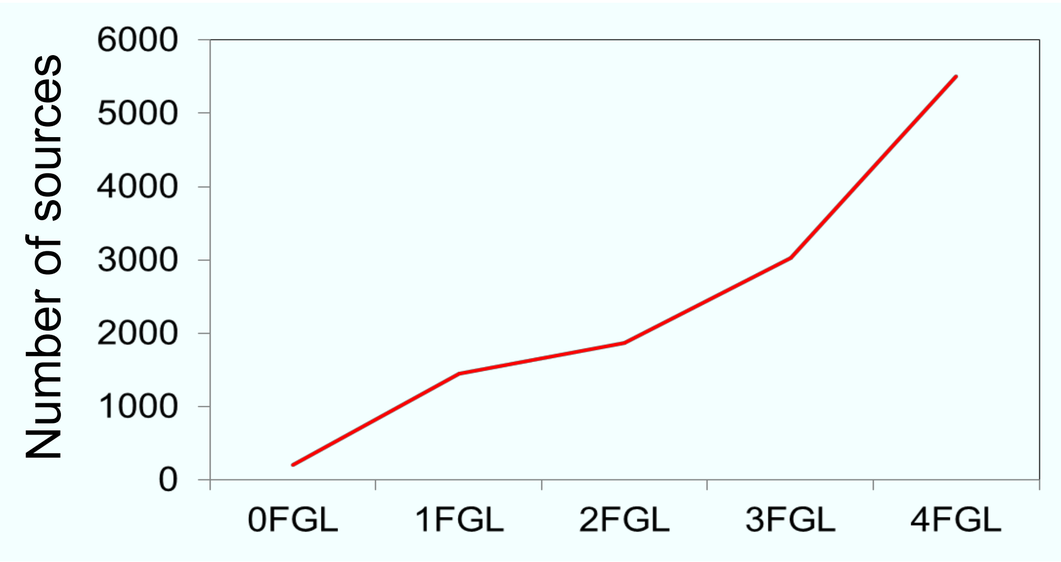
- **Predictions/optimisation of future observatories: CTA, SKA, LHAASO, …**
- **Sky model for data analysis**
- **Reference for studies on:**
  - **individual sources**
  - **source populations**
  - **MW analyses**
- **Source samples to investigate**
  - **Extragalactic Background Light**
  - **Extragalactic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

1+2+3FGL

2774 citations

(NASA ADS)

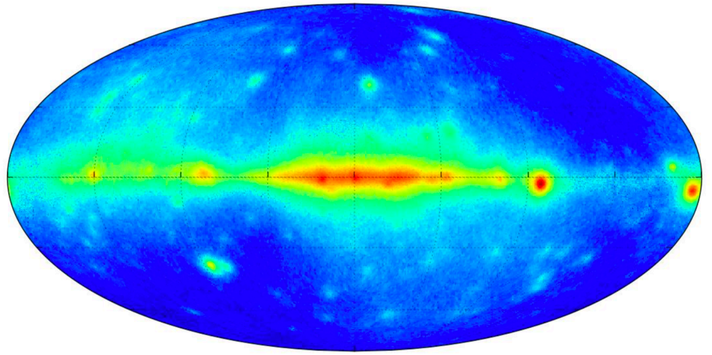
Fermi-LAT general catalogs



Catalog	Energy Range (GeV)	Data Interval (months)	Sources	Unassociated	Release Date
0FGL	0.2-100	3	205	37 (18%)	Feb. 2009
1FGL	0.1-100	11	1451	630 (43%)	Feb. 2010
2FGL	0.1-100	24	1873	649 (35%)	Aug. 2011
3FGL	0.1-300	48	3033	992 (33%)	Jan. 2015
4FGL	0.05-1000	96	~5500	~1800 (33%)	Early 2019
1FHL	10-500	36	511	65 (13%)	Jun. 2013
2FHL	50-2000	80	360	48 (14%)	Aug. 2015
3FHL	10-2000	84	1556	176 (11%)	Mar. 2017
1FLE	0.03-0.1	104	198	28 (14%)	Oct. 2018

Each “FGL” catalogue is accompanied by a sibling “LAC” catalogue of gamma-ray active galactic nuclei

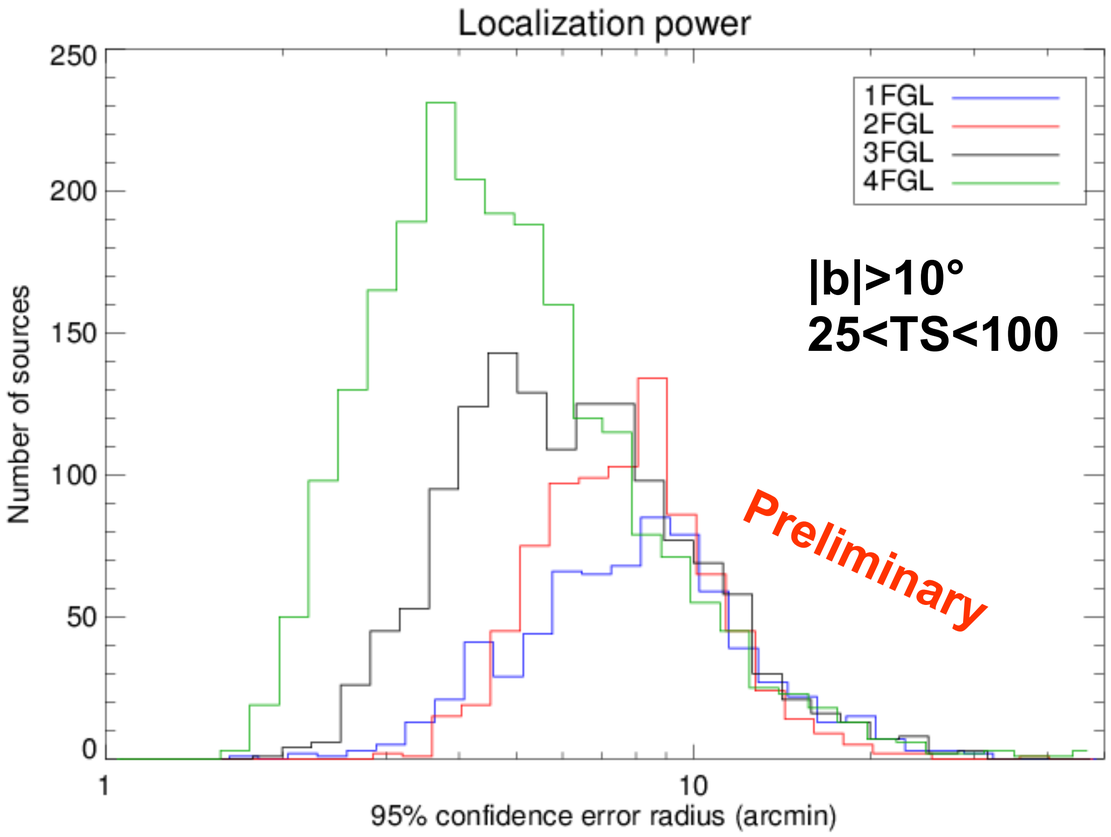
Principe et al. (2018)

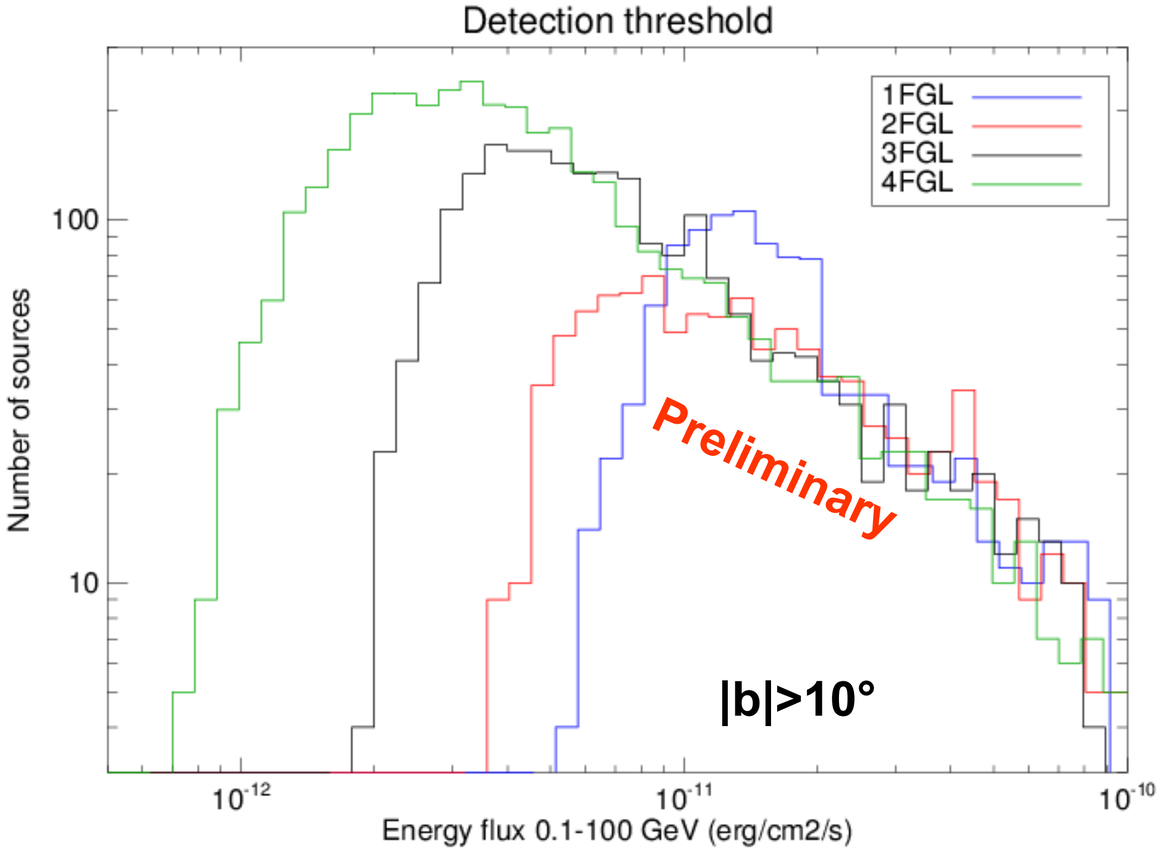


FL8Y

- **Preliminary LAT 8-year Point Source List, 5523 sources, released early January 2018**
  - **it was meant to help in writing 2018 NASA Fermi Guest Investigator proposals.**
  - **it will be similar to 4FGL in many aspects (data+analysis procedure) but 4FGL will use an updated diffuse emission model**
- **Caveats**
  - *The FL8Y list is meant to provide researchers analysing 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.*

FL8Y characterisation





Improved localisation (important for association):
median error radius (at 25<TS<100) 4.4 arcmin

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

Association methods

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

(following Mattox et al. 1997)

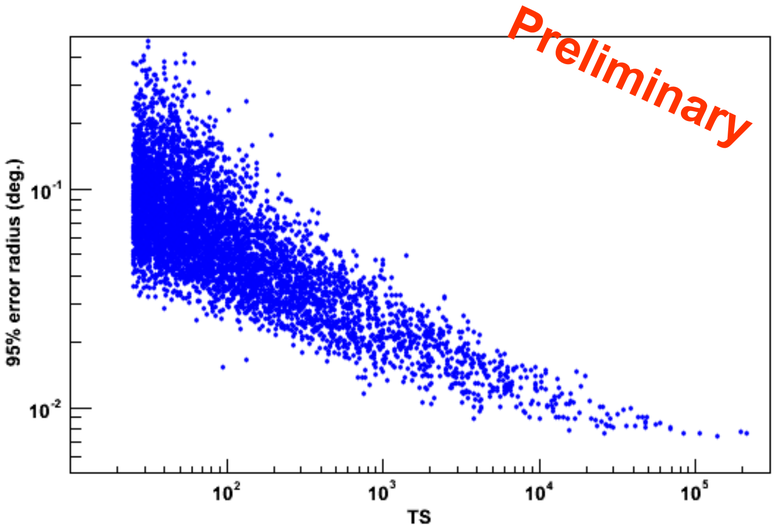
- true association: offset determined by position uncertainty (Rayleigh distribution)
- false association: offset determined by counterpart local density
- Prior via Monte-Carlo

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

$$P_{thr} = 0.8$$

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

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



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

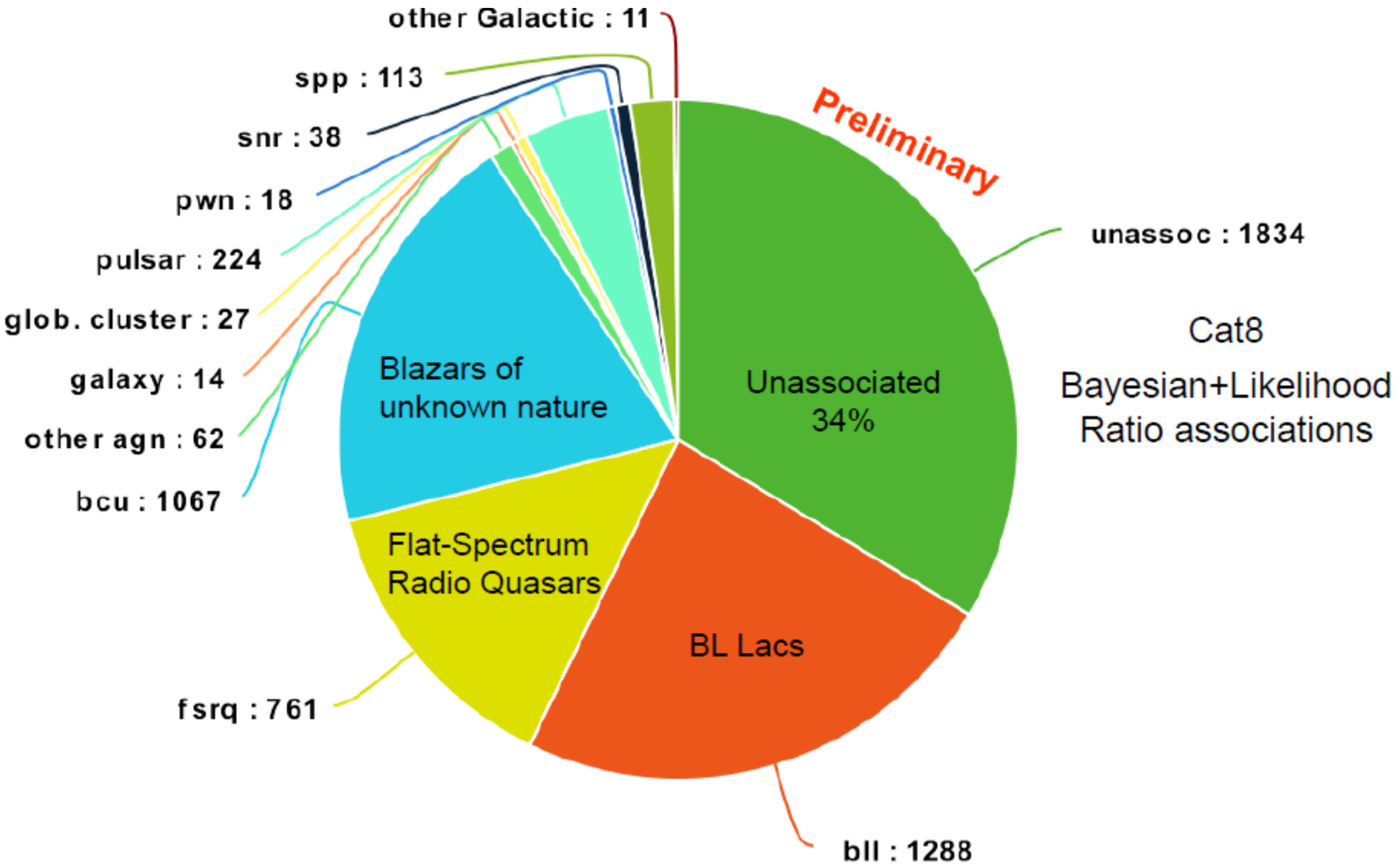
(following de Ruiter 1977)

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

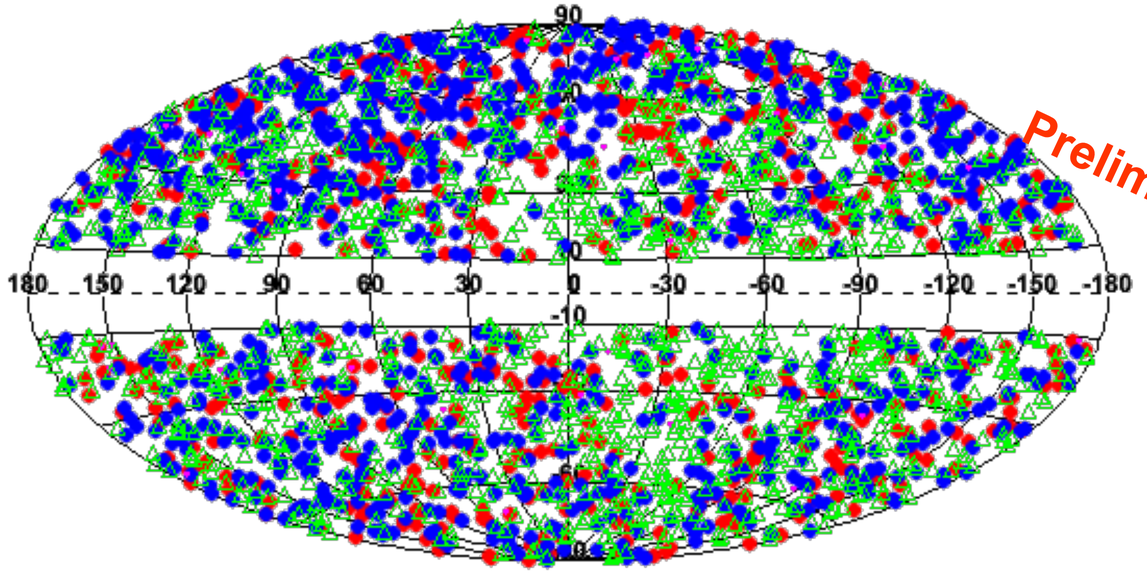
  + inspection of SEDs for « blazarness ».
- Can handle large surveys: NVSS, SUMSS, ROSAT
- Overlap between Bayesian and LR methods for AGNs ~75%.

Association summary

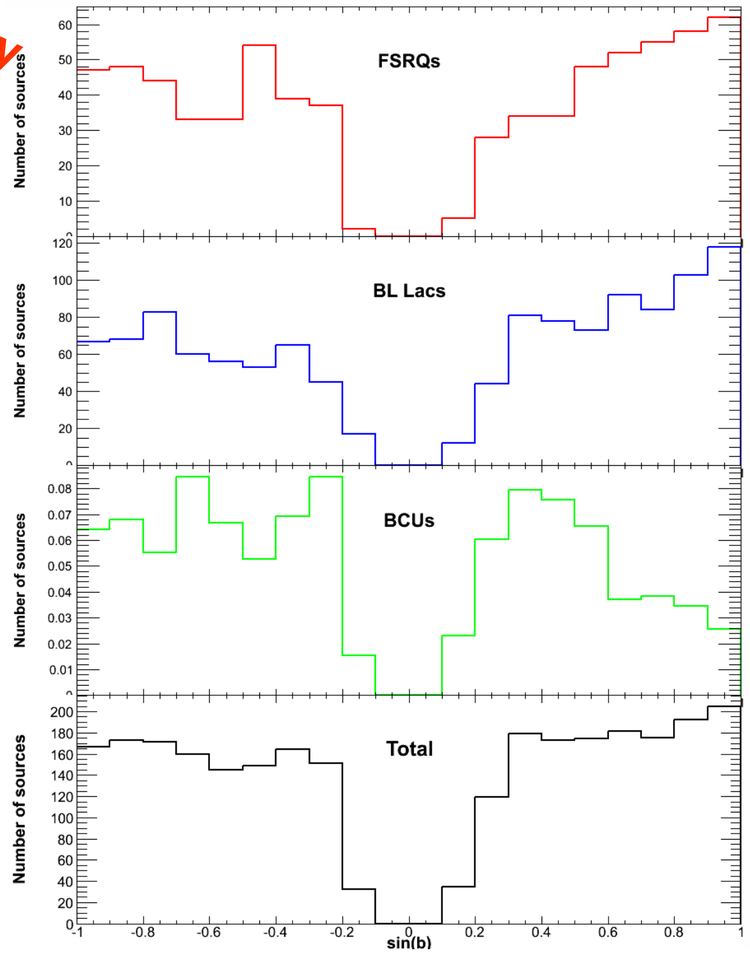
Class	3FGL	FL8Y (E>50 MeV)
Total	3034	5457
Pulsar*	143+24	210+14 (+34%)
PWN	11	18 (+63%)
SNR	23	38 (+65%)
HMB	3	6 (+100%)
SPP†	49	113 (+122%)
Glob. Cluster	15	27(+80%)
AGN	1751	3184 (+81%)
Associated	2041	3621 (+77%)



Towards 4LAC



Preliminary



Bayesian- +LR- method associations in Cat8
2750 sources |b|>10° *(3LAC: 1591 sources)*
- **number of FSRQs:** **714** ***(+53%)***
- **number of BLLs:** **1223** ***(+92%)***
- **number of BCUs:** **759** ***(+68%)***

3184 sources (all sky)

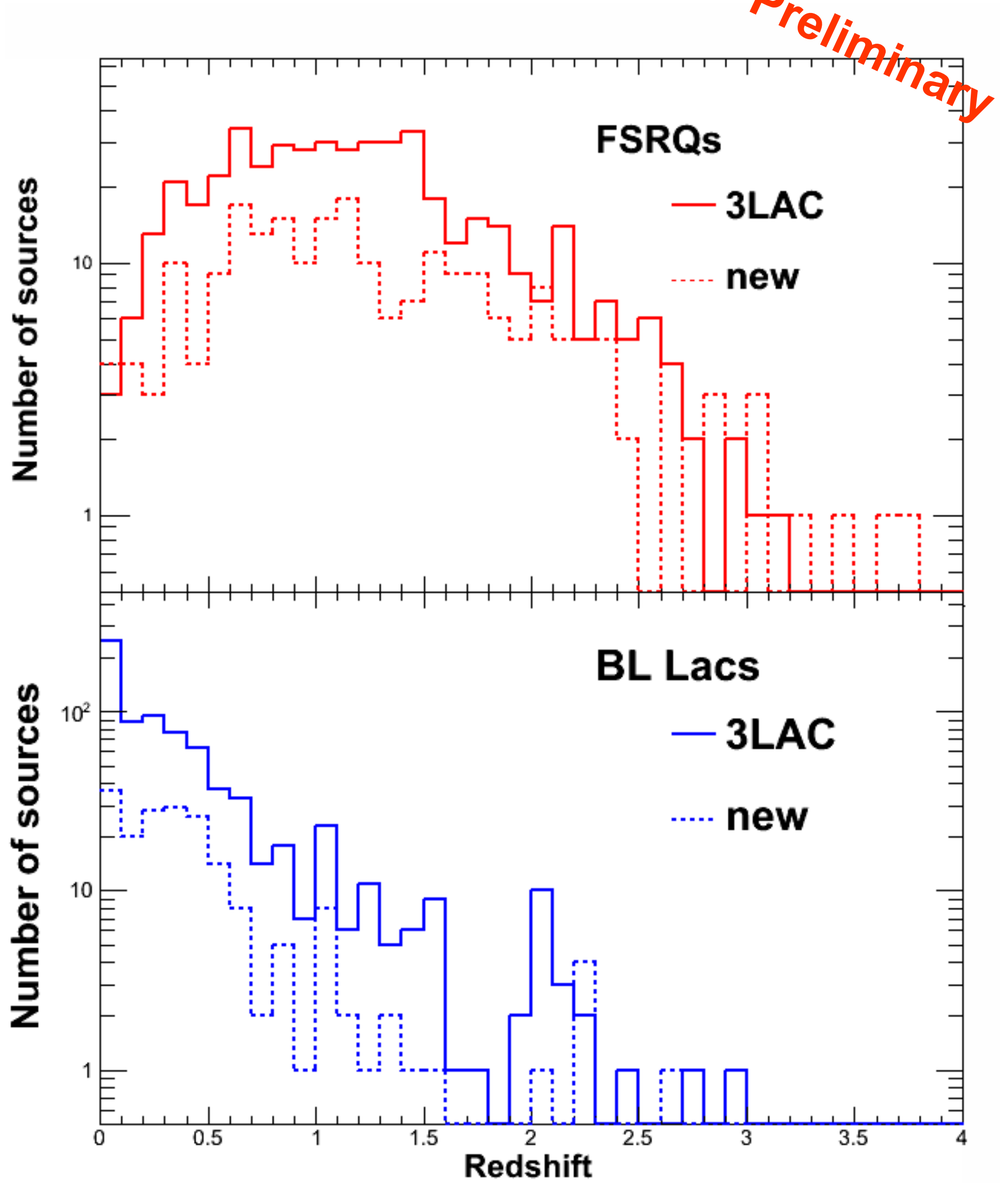
9 NLSy1 (4 new), 34 radio galaxies, 16 other AGNs
1422 sources in BZCAT
69 TeV sources

8% deficit in the Southern hemisphere

Redshift distributions

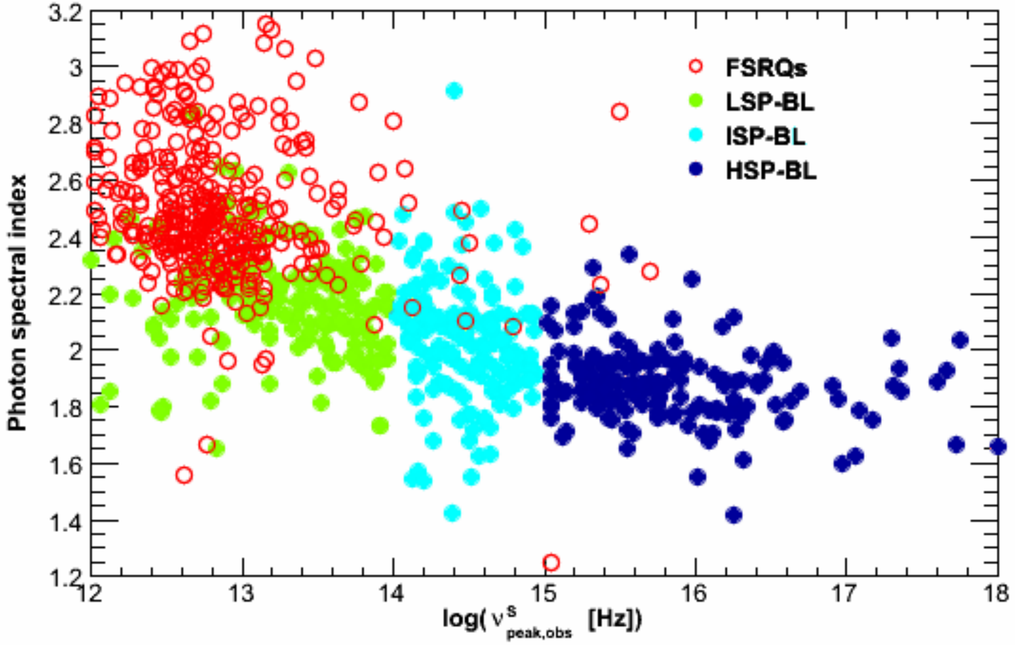
1628 redshifts in Cat8

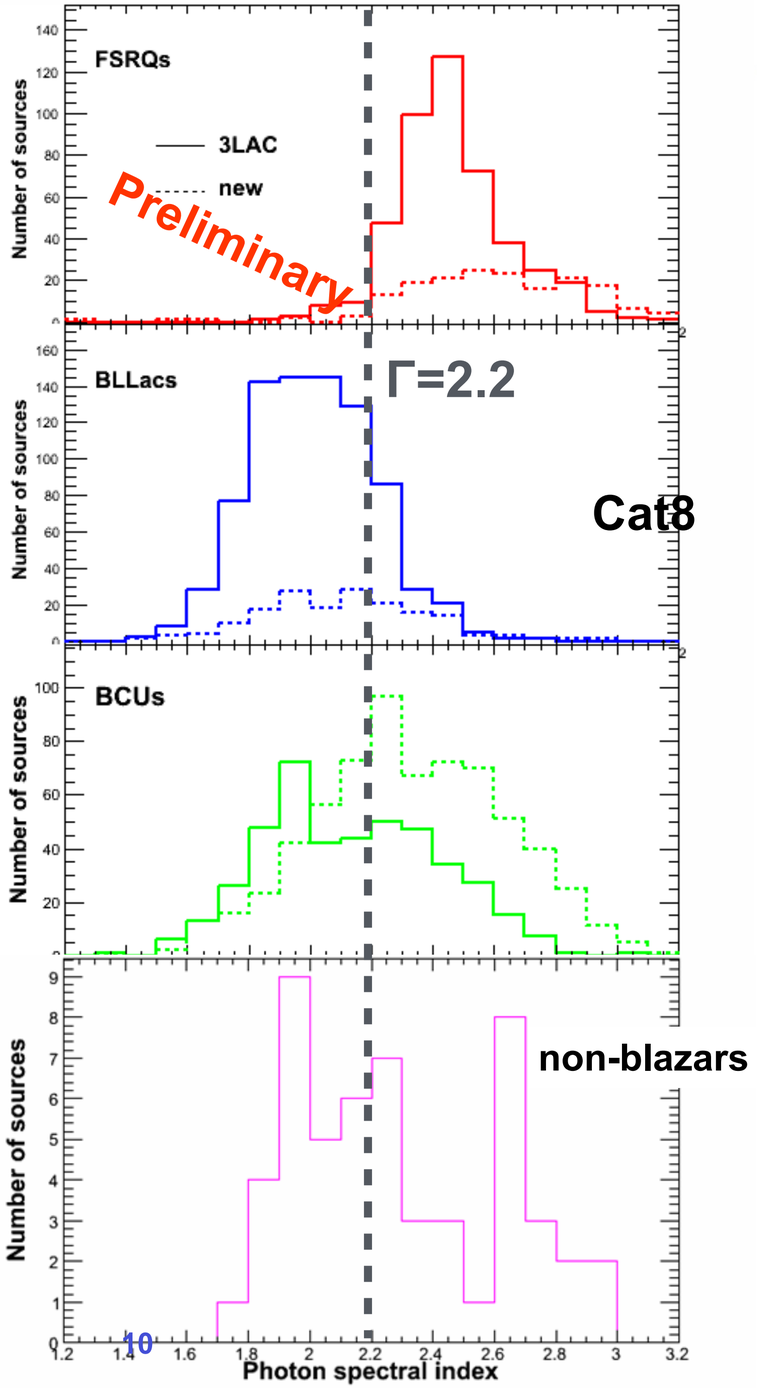
- several new z>3 FSRQs
- maximum redshift z=3.9
- 468/1233 (38%) BL Lacs have no measured redshifts



Photon-index distributions

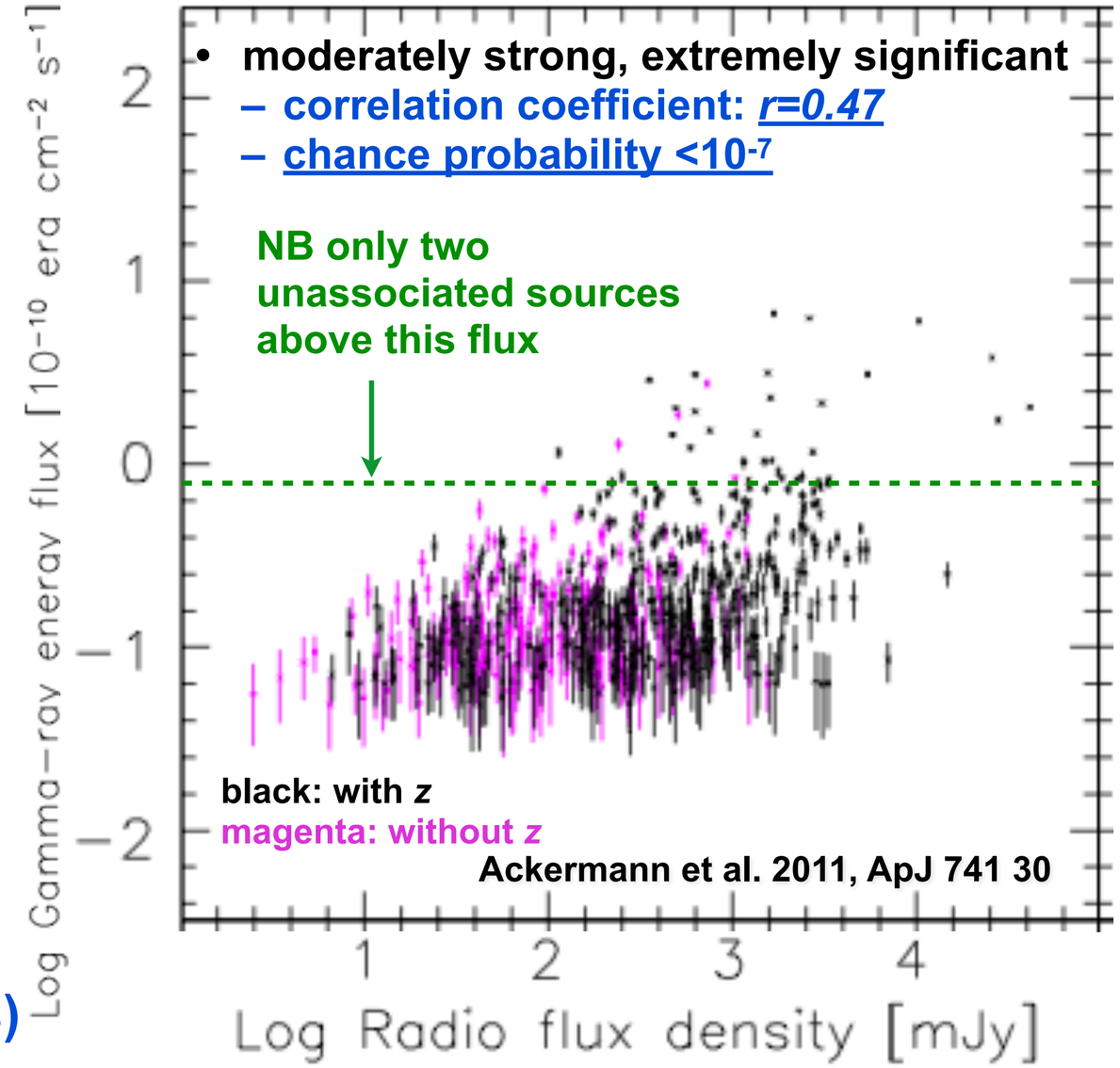
- Little overlap between FSRQs and BL Lacs, limit at Γ=2.2
- New FSRQs notably softer than 3LAC ones
  – <Γ>=2.60 vs. 2.46
- New BL Lacs notably softer than 3LAC ones
  – <Γ>=2.19 vs. 2.04
- BCUs index distribution straddling the two classes and extending beyond 2.6. New BCUs softer than 3LAC ones
  – <Γ>=2.32 vs. 2.11





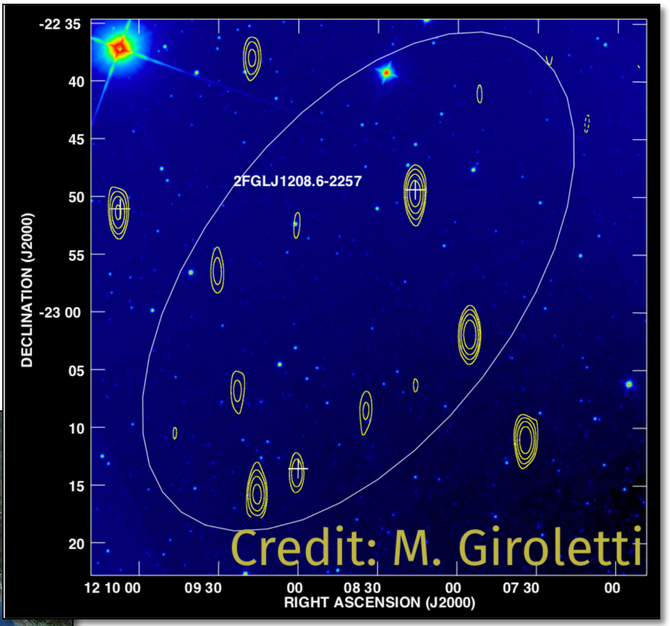
The *Fermi* view of the radio-gamma ray connection

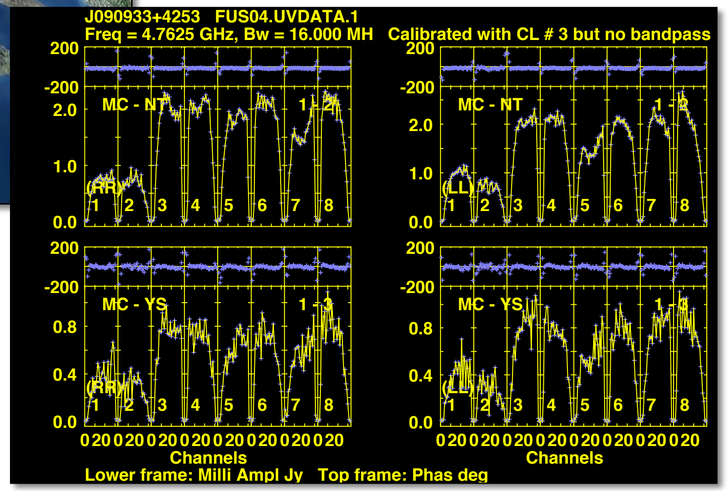
- **All associated gamma-ray sources are radio emitters**
- **Specific radio properties are a defining characteristic of blazars**
  - **flat radio spectrum at all frequencies (work with SKA precursors/pathfinders)**
    - **Massaro+13, Giroletti+16, Mooney+18**
  - **compactness/strong core dominance**
  - **superluminal motion in parsec scale jets**
  - **variability**
- **large scatter and flux density limits prevent simple linear fit - questions:**
  - **can we improve our understanding of this correlation to finally constrain physics (in blazars, and not only - eg EGRB)?**
  - **what about UGS (~30% of total, ie many 100's)**



Characterizing UGS

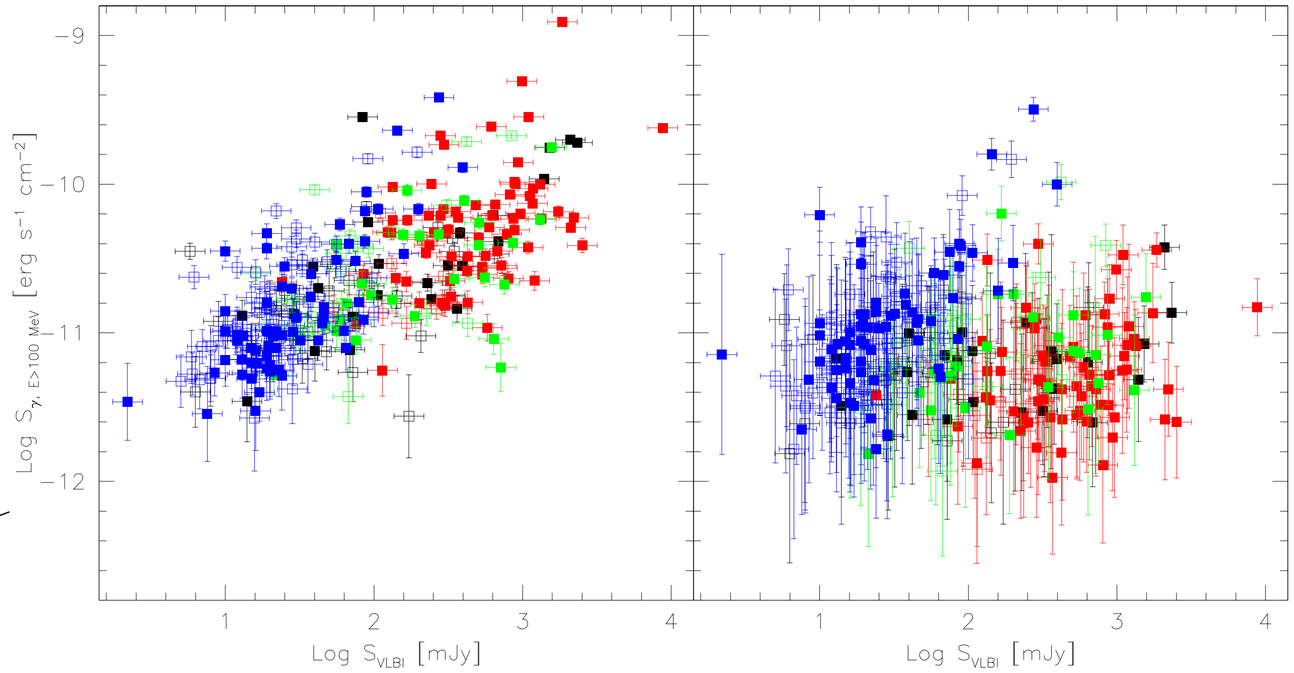
- most UGS have relatively low gamma-ray flux
  - positional uncertainty is larger
  - low F_r sources have higher spatial density
    - it gets nearly impossible to associate counterparts only on the basis of pure spatial coincidence
- yet, these sources could be very important, eg low F_r could stem from
  - low luminosity
    - and large ν_{peak}: extreme accelerators
    - and low ν_{peak}: blazar sequence outliers
  - or high distance
    - early blazars: constraints on massive BH formation history
  - and if they are not blazars, it could even be more fun!
- need VLBI to filter out extended emission!





SKA prospects

- **The final *Fermi* catalog will likely be one magnitude deeper than 1LAC**
  - **not only longer exposure but also better characterisation of detector, diffuse model, etc.**
  - **weakest known 3LAC blazar is 4.2 mJy, 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, polarisation sensitive**
  - **high frequency bands desirable to get closer to gamma-ray emission region**
- **Even more intriguing when very high energy gamma rays are considered**
  - **the radio-gamma connection breaks down if we consider the hard source *Fermi* catalogues**
  - **CTA will come online, too!**



Lico et al. (2017)

radio vs E>100 MeV **radio vs E>10 GeV**

Take home notes

1. radio and gamma rays, despite being the most distant parts of the EM spectrum, are connected in many important astrophysical contexts
   - jets, pulsars, SNe, SNR, ...

2. large improvements are happening/going to happen in both bands
   - with *Fermi*, SKA, and its pathfinders/precursors
   - and the Cherenkov Telescope Array (CTA)

3. we should organize operations in order to maximize scientific return
   - improving also connection with UHECRs studies