The radio/gamma-ray connection from 120 MHz to 230 GHz

M. Giroletti, F. D’Ammando, M. Orienti on behalf of the *Fermi*-LAT collaboration

Blazars through Sharp Multi-Wavelength Eyes

Málaga, Spain, June 3, 2016

Outline

- **Background and motivation**

- **Recap on radio-gamma ray connection with GHz data**
  - **Ackermann et al. (2011, ApJ 741 30)**

- **Extensions**
  - **to VLBI and E>10 GeV data (Lico et al., submitted & PhD Th.)**
  - **to low frequency ~100 MHz radio data (Giroletti et al. 2016)**
  - **to high frequency 230 GHz ALMA data (Giroletti et al. in prep.)**

Date: Thu, 17 Apr 2003 15:37:10 -0400
From: Alan Marscher <marscher@bu.edu>
To: Marcello Giroletti <giroletti@ira.cnr.it>
Subject: Re: Mkn 501 paper, final draft

Hi, Marcello,

I've made numerous minor changes to the wording - usually adding or deleted a "the" or "a"

...mistakes are usually because the English way of saying something is either illogical or completely arbitrary. It's a real pity for all of you with better languages that English has become the standard language for scientists.

...
OK, you've answered my scientific comments, so now all that remains is to see what the referee thinks.

Good job!

With best wishes,
Alan

The Astrophysical Journal, 600:127–140, 2004 January 1

PARSEC-SCALE PROPERTIES OF MARKARIAN 501

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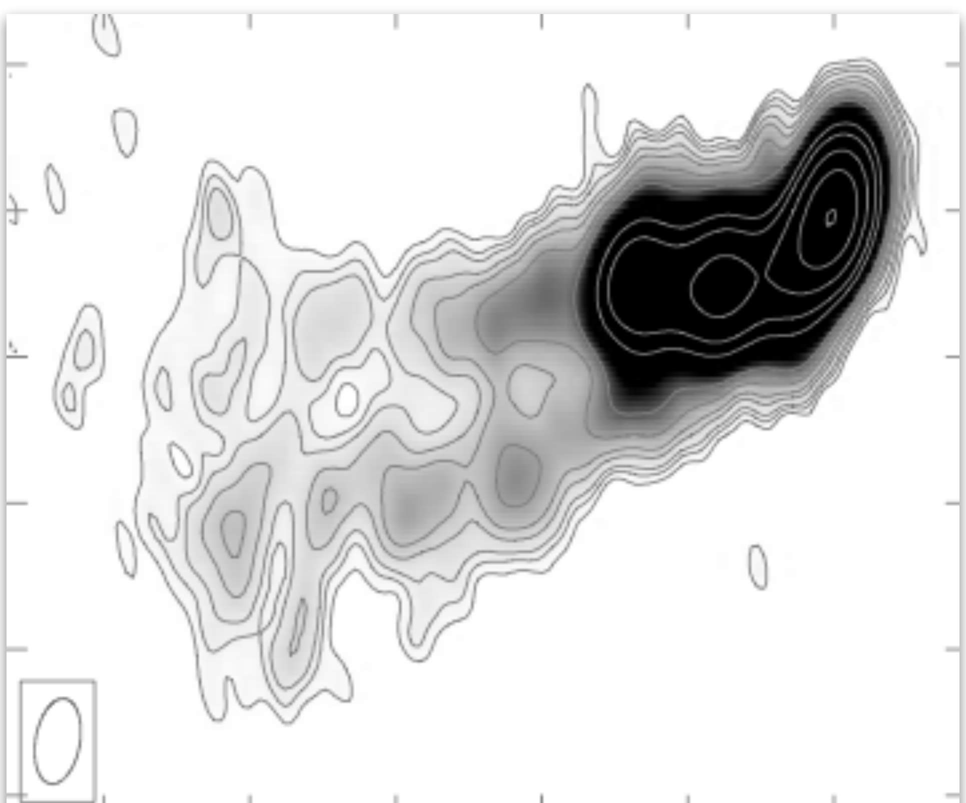
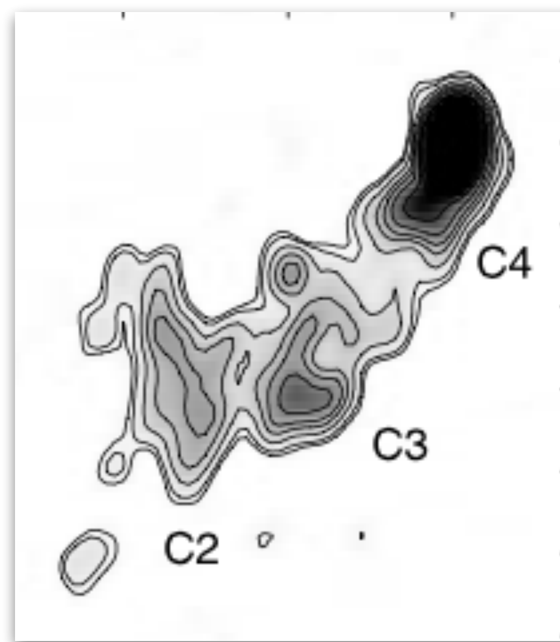
ABSTRACT

We present the results of a high angular resolution study of the BL Lac object Markarian 501 in the radio band.





My #1 most highly cited (non Fermi) paper

(Alan's #18)

Thank you Alan,

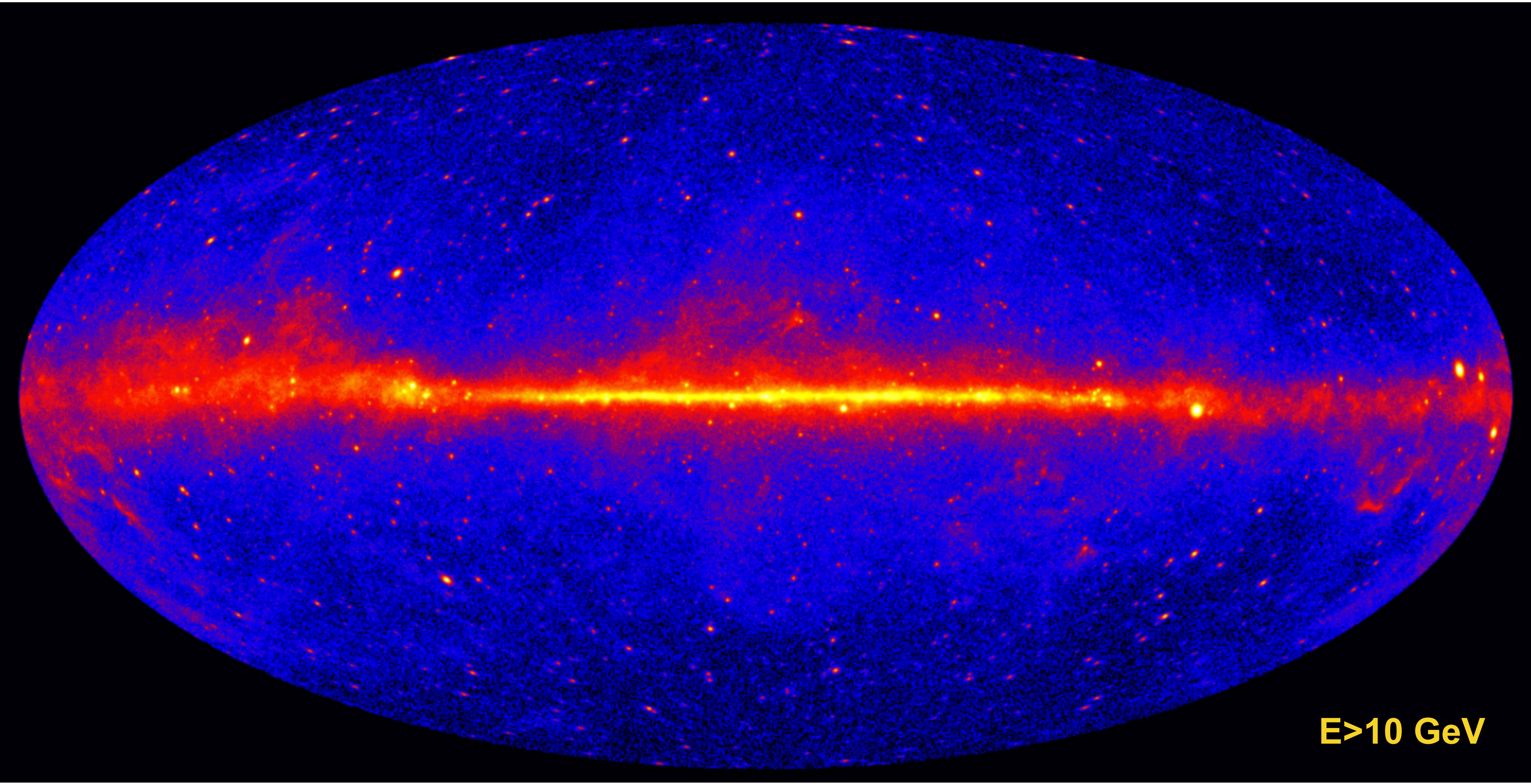
Happy birthday!

Background and motivation

- Reasons favoring a radio-γ connection
  - both require a population of relativistic particles
  - radio loud AGN dominate γ-ray catalogs
  - *blazars* dominate γ-ray catalogs
    - radio and γ rays are both produced in relativistic beamed jets
  - similarity in light curves on short and long timescales
  - one zone (SSC) models successfully reproduce basic SED features
  - radio luminosity determines γ-ray properties ("old" blazar sequence)
- Reasons against a radio γ connection
  - γ rays show rapid variability
    - γ ray region must be self absorbed in radio band
  - most radio loud sources are not detected in γ rays
  - many *blazars* are not detected in γ rays
    - radio emission and beaming are not sufficient conditions
  - orphan flares

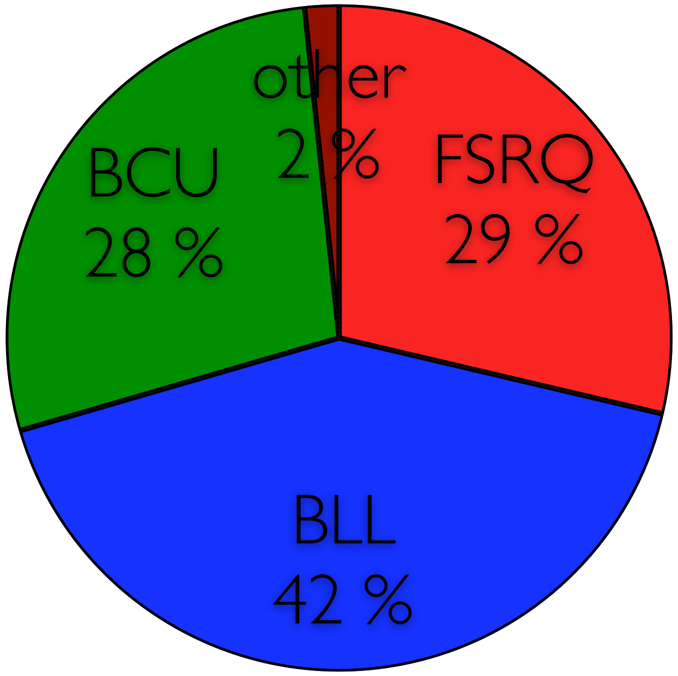
Fermi catalogs

- four main catalogs (0FGL/1FGL/2FGL/3FGL), each one accompanied by an AGN catalog (nLAC)
  - most recent is 3FGL, 4 years, 3033 sources, E>100 MeV
- two hard source catalogs:
  - 1FHL (years, E>10 GeV), 2FHL (5 years, E>50 GeV)



Fermi AGN demographics

- 3FGL (Acero+15): 3033 sources, 1010 not associated
- 3LAC (Ackermann+15): 1563/2192 high galactic latitude are AGN
  - grand total of 1773 gamma-ray AGN
    - including duplicate associations and low latitude “affiliations”
  - 98% are blazar, or blazar candidates
- In “clean” sample of 1444 sources
  - FSRQ: 414 (28%)
  - BLL: 604 (42%)
  - BCU 402 (29%)
  - other 24 (2%)

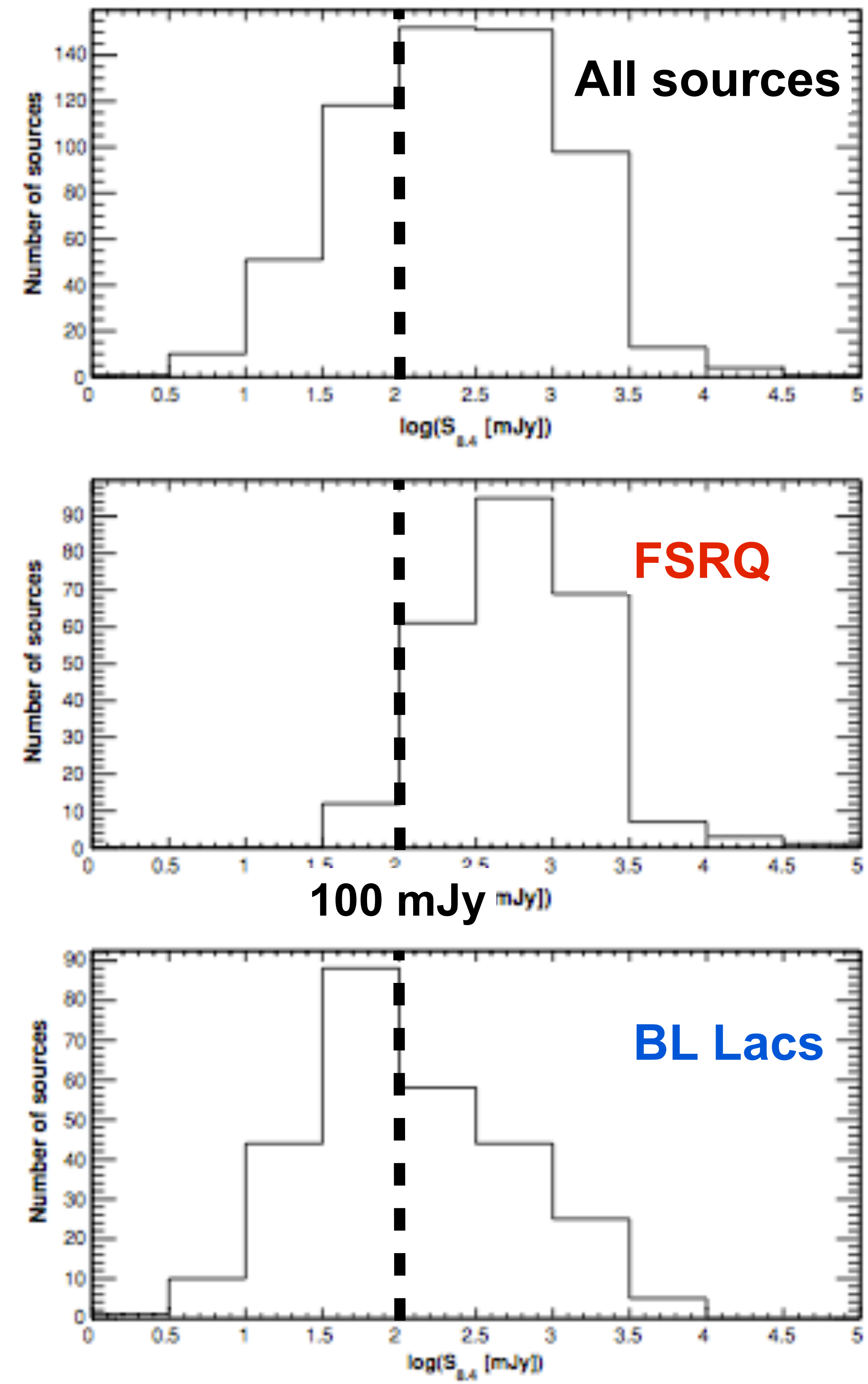


- Only a few unidentified sources remain at high fluxes
- Gamma-ray sources continue to be associated with radio loud objects
- Vast majority of associated sources are blazars
  - and non blazar sources are typically misaligned blazars (MAGN), or very blazar-like sources (RL NLS1, talk by F. D’Ammando)

Previous catalogs

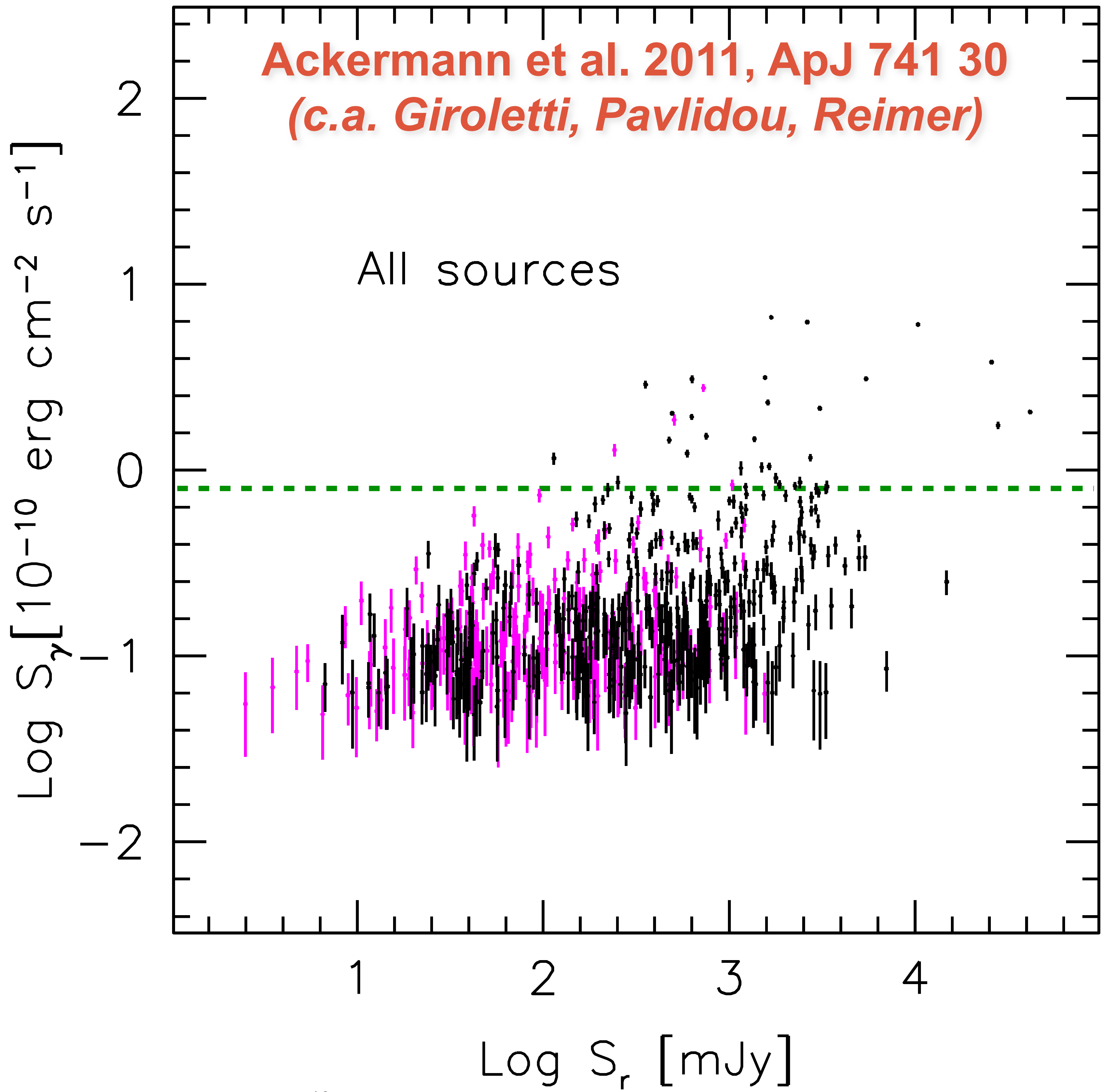
- “clean” 1LAC contained 599 sources
  - >40% of clean 3LAC, >900% of high confidence EGRET
- FSRQ and BLL ~equally represented
- sources well characterized in γ rays by *Fermi*
  - flux, photon index, and flux in bands
- interferometric core flux density available for ALL sources
- simultaneous data from intensive OVRO monitoring available for 199 sources
  - northern and brightest (talk Pearson)
- dedicated statistical analysis method to assess significance (Pavlidou+12)
  - many well known biases
  - strength and significance are different things

8.4 GHz flux density



Results

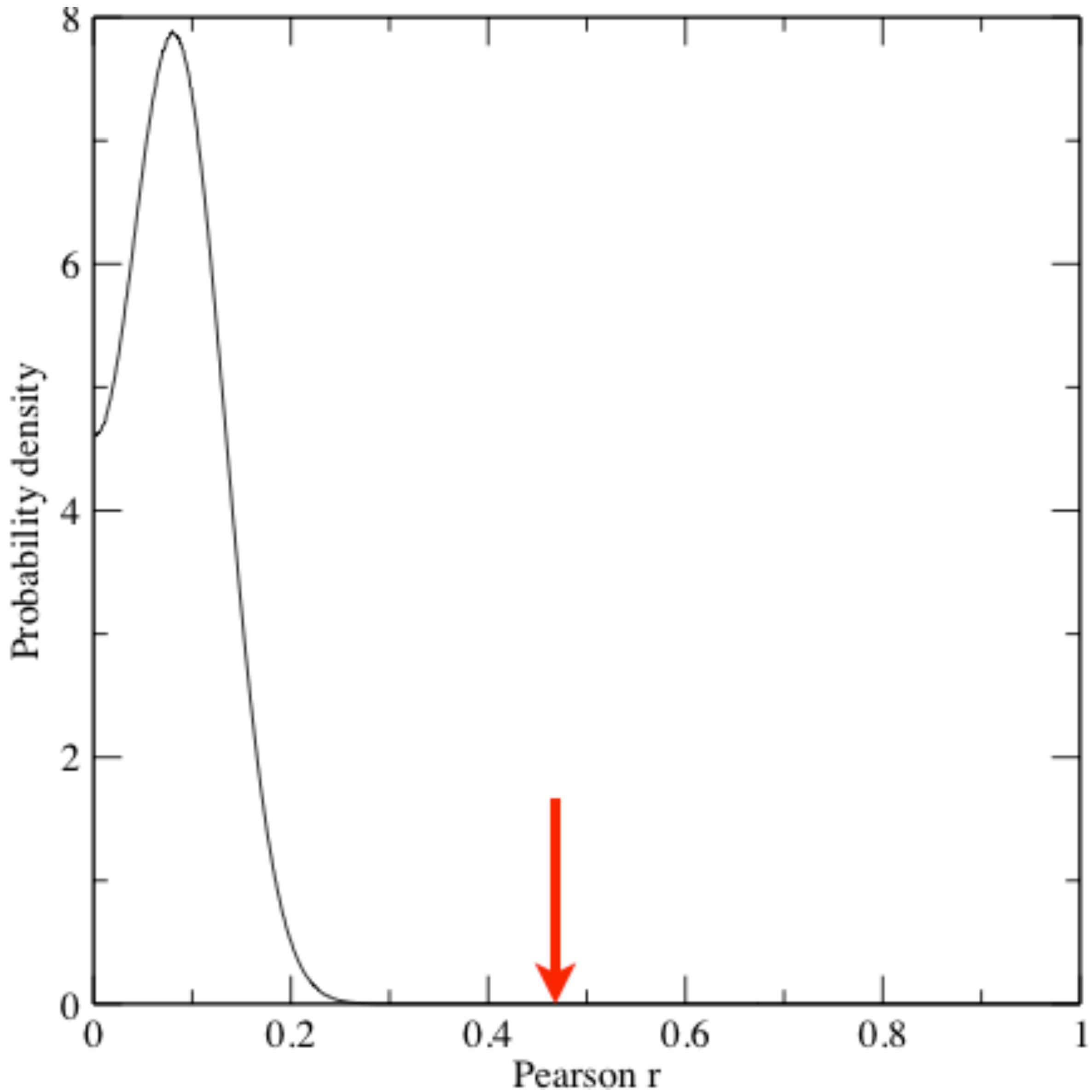
- **All 599 1LAC clean sources**
- **black: with redshift**
- **magenta: without redshift**
- **correlation coefficient: *r=0.47***



NB only two unassociated sources have gamma-ray flux larger than 8×10^{-10} erg cm^{-2} s^{-1} (green dashed line)

Significance

- how many times can we get such *r* from random datasets, with the same flux density and luminosity dynamic ranges?



–well, less than once every ten million times!

- probability of chance correlation: P<1e-7

The correlation, blazar types, energy bands, and time dependence

- **Blazar types**
  - **FSRQ and BLL independently still show very high significance of a correlation (chance *P*<1e-7)**
  - **BL Lacs show moderately stronger correlation than FSRQs**
  - **HSP blazars have the strongest correlation among the various SED-peak-defined classes**
- **Energy bands**
  - **not all LAT energy sub-bands correlate with radio with the same strength**
  - **the strongest correlation is found for increasing energy bands as we move from LSP to ISP to HSP**
    - **and HSP blazars are in general the subclass with the highest r**
- **Timing**
  - **Considering the subset of OVRO-monitored sources, *r* and *P* improve when considering simultaneous vs archival data (1.9×10^{-6} to 9×10^{-8})**
    - **caveat sample size is “only” 161 sources**

Discussion

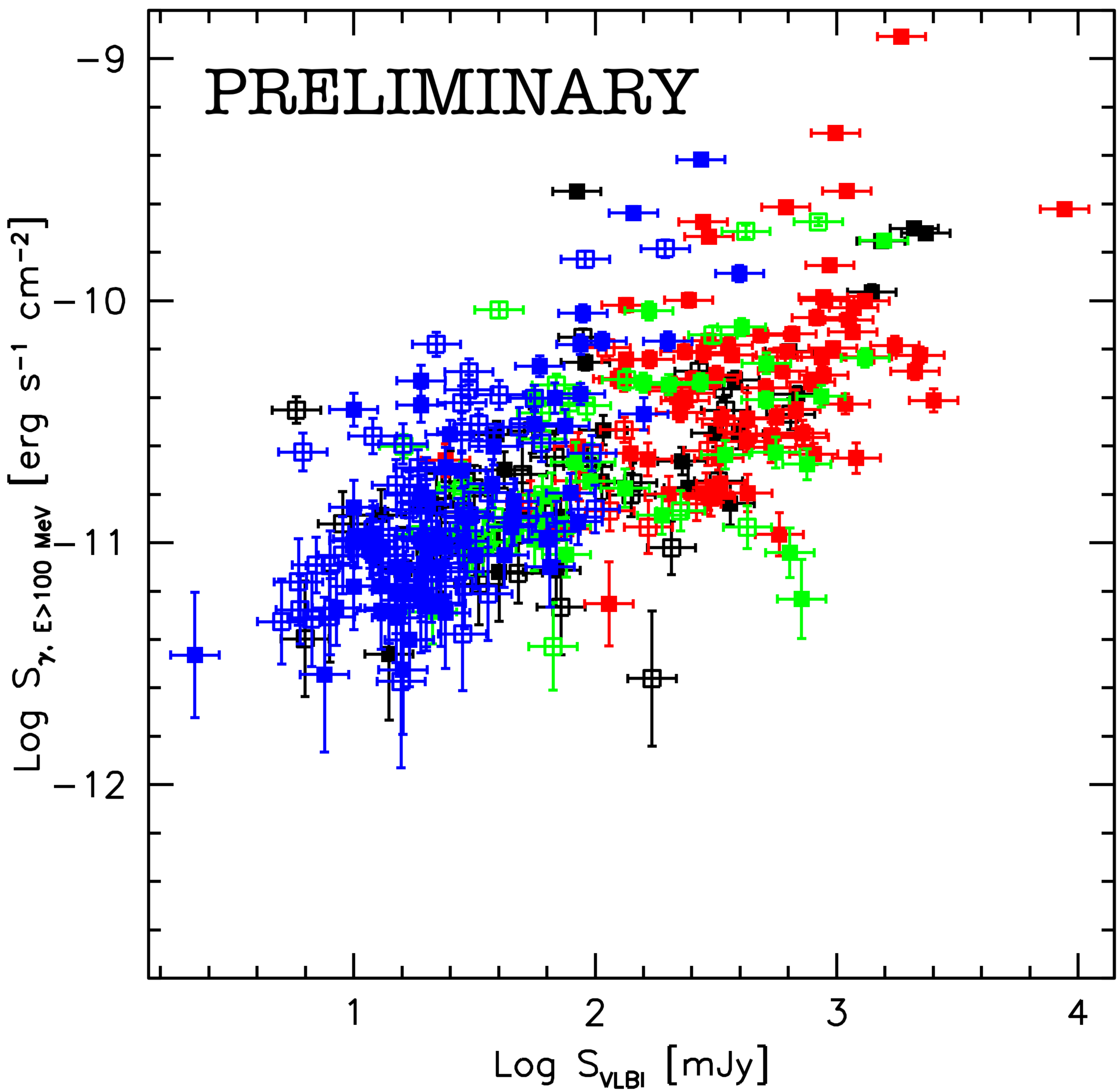
- Correlation is very significant, but scatter is large
  - connected but different emitting regions and physical processes
  - connected but different time domains
    - study of light curves (and SEDs) remains very valuable for single sources
    - concurrent data do correlate better
- Leptonic processes contribute to γ-ray emission
  - synchrotron self-Compton processes are favored in BL Lacs and particularly in HSP blazars (stronger correlation)
  - additional processes/elements play a role in FSRQs
    - external Compton/redshift range/variability

The extension towards higher energy

- Motivation: observations above ~100 GeV based on detection of Cherenkov atmospheric radiation (IACT) are quite different from LAT surveys:
  - limited field of view, limited observing time, limited (integrated) sensitivity
  - census: 47 AGNs over 151 detection (with 25 UNID and many galactic sources); mostly HSP-blazars
  - bias: plenty of! no systematic survey, observations in flaring state, ...
- 1FHL: first *Fermi* catalog of high energy sources (E>10 GeV, Ackermann et al. 2013)
  - three years of survey data, as uniform and unbiased as possible
  - 514 sources, 76% of which are AGN, 13% unassociated
  - AGN fraction larger than in 2FGL, census leaning towards extreme spectral type blazars (HSP, 41%)
  - still significant fraction of unidentified sources
    - remarkable, given generally smaller positional ellipses

1FHL sources: radio vs E>100 MeV

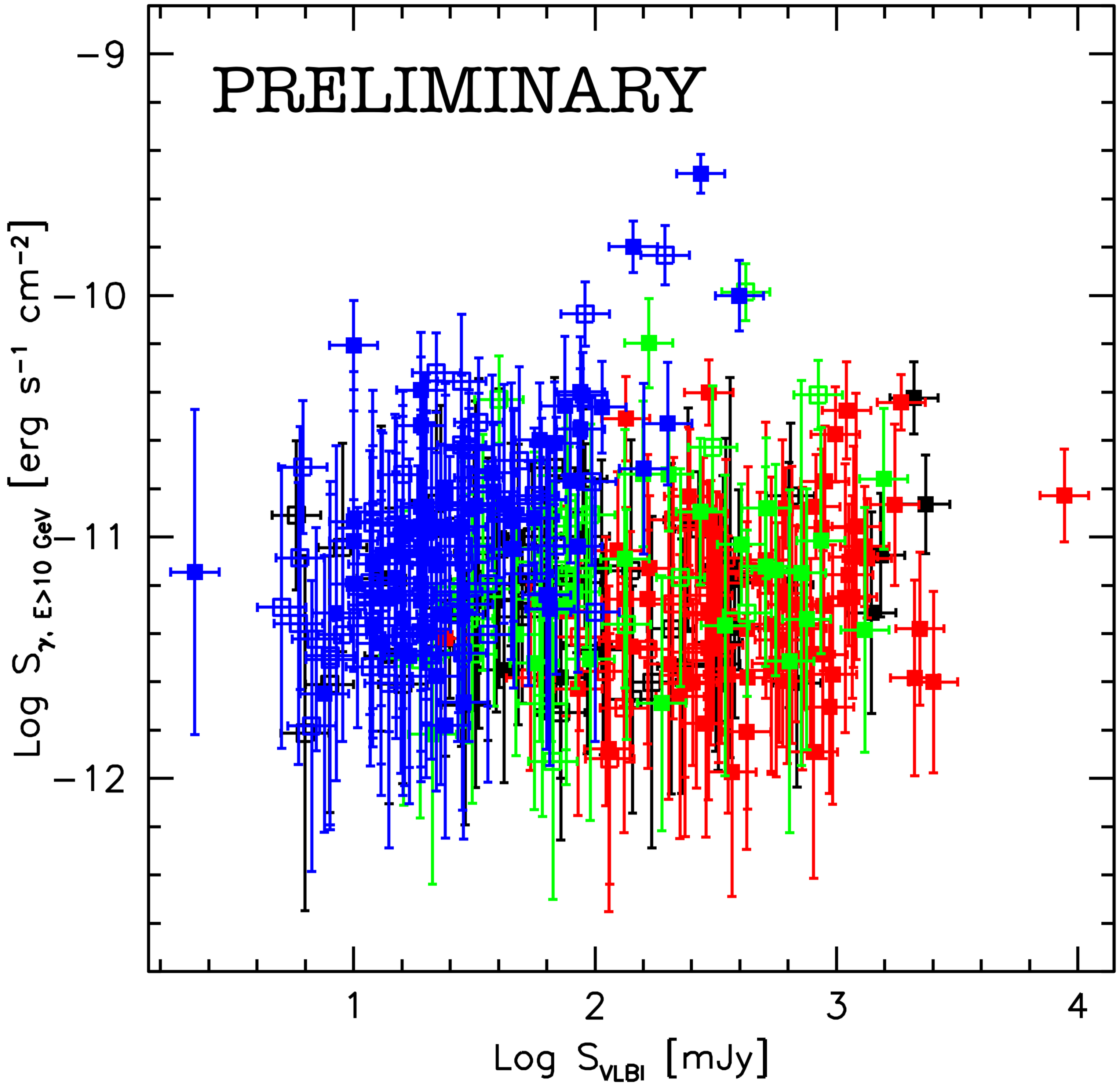
- radio from VLBI (Lico et al., submitted)
- gamma ray from 3FGL
- clear correlation
  - $r = 0.73$
  - $P < 10^{-6}$
- R. Lico PhD Thesis



- BLL
- FSRQ
- BCU
- others
  - filled: with z
  - empty: no z

1FHL sources: radio vs E>1 GeV

- **gamma ray from 1FHL**
- **correlation vanishes**
  - **– *r* = -0.02**
  - **– *P* = 0.8**
    - **largely because of drop in FSRQ gamma-ray flux**



The extension towards low frequency

- The Murchison Widefield Array is the first operational SKA precursor. It paves the way towards low frequency (<300 MHz) radio astronomy
- Hurley-Walker et al. (2014) published a commissioning survey catalogue, including ~14,000 sources over 6,100 deg^2 in the southern sky
  - 3σ sensitivity of ~120 mJy
  - positional accuracy ~3’
  - flux density at 120, 150, 180 MHz, and corresponding α

- Massaro et al. (2013a,b), Nori et al. (2014) showed that low frequency is useful to study (gamma-ray) blazars
  - the core continues to dominate the radio flux density as shown by the flat spectra
  - low frequency surveys are a relatively cheap resource to search for blazar candidates
    - counterintuitive, but practical!

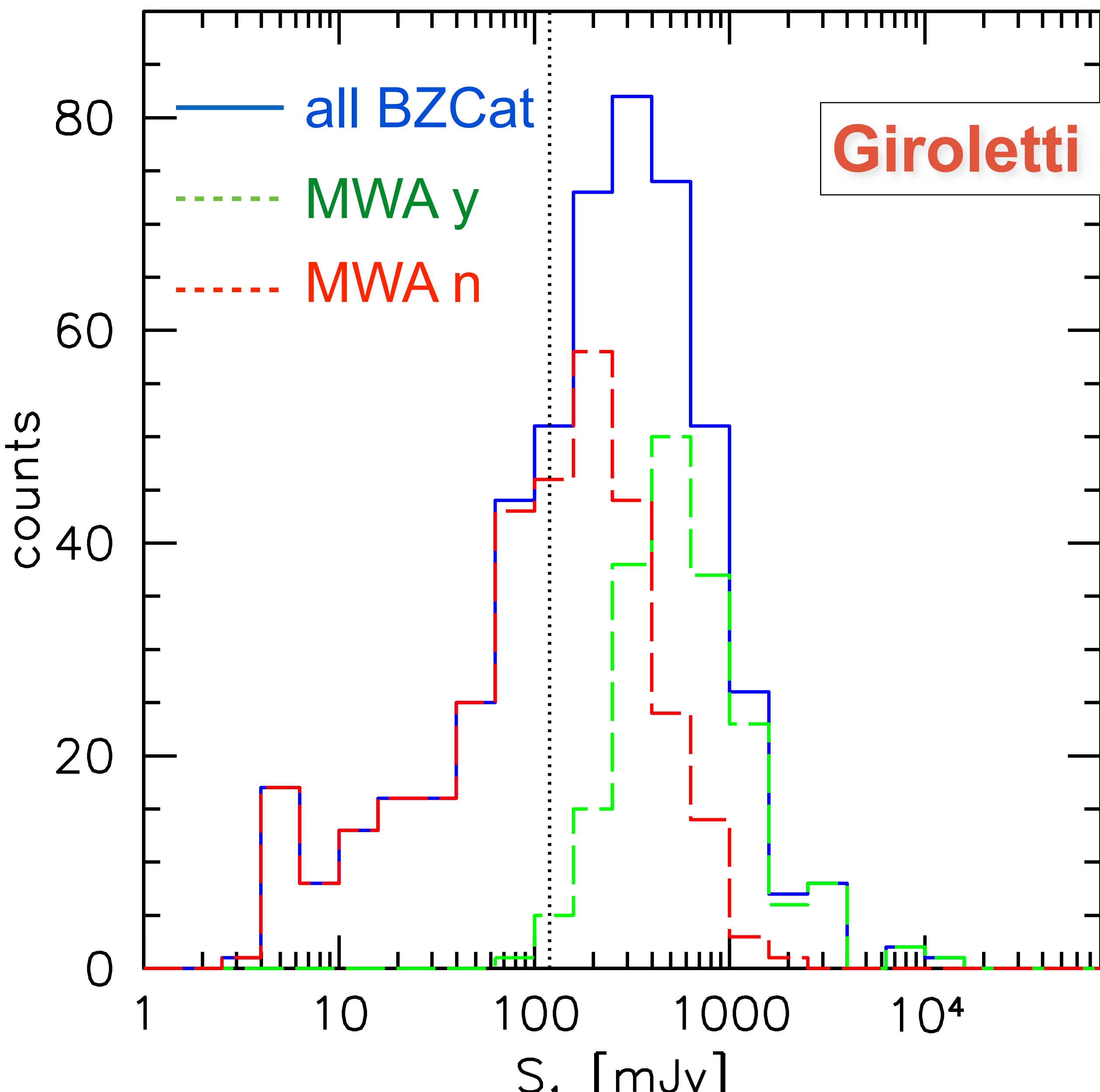
Sample construction

- In the whole MWACS footprint we searched for
  - counterparts to all known blazars from BZCat
  - counterparts to all gamma-ray blazars from clean 3LAC
  - counterparts to unidentified gamma-ray sources from 3FGL
    - affected by large positional uncertainty

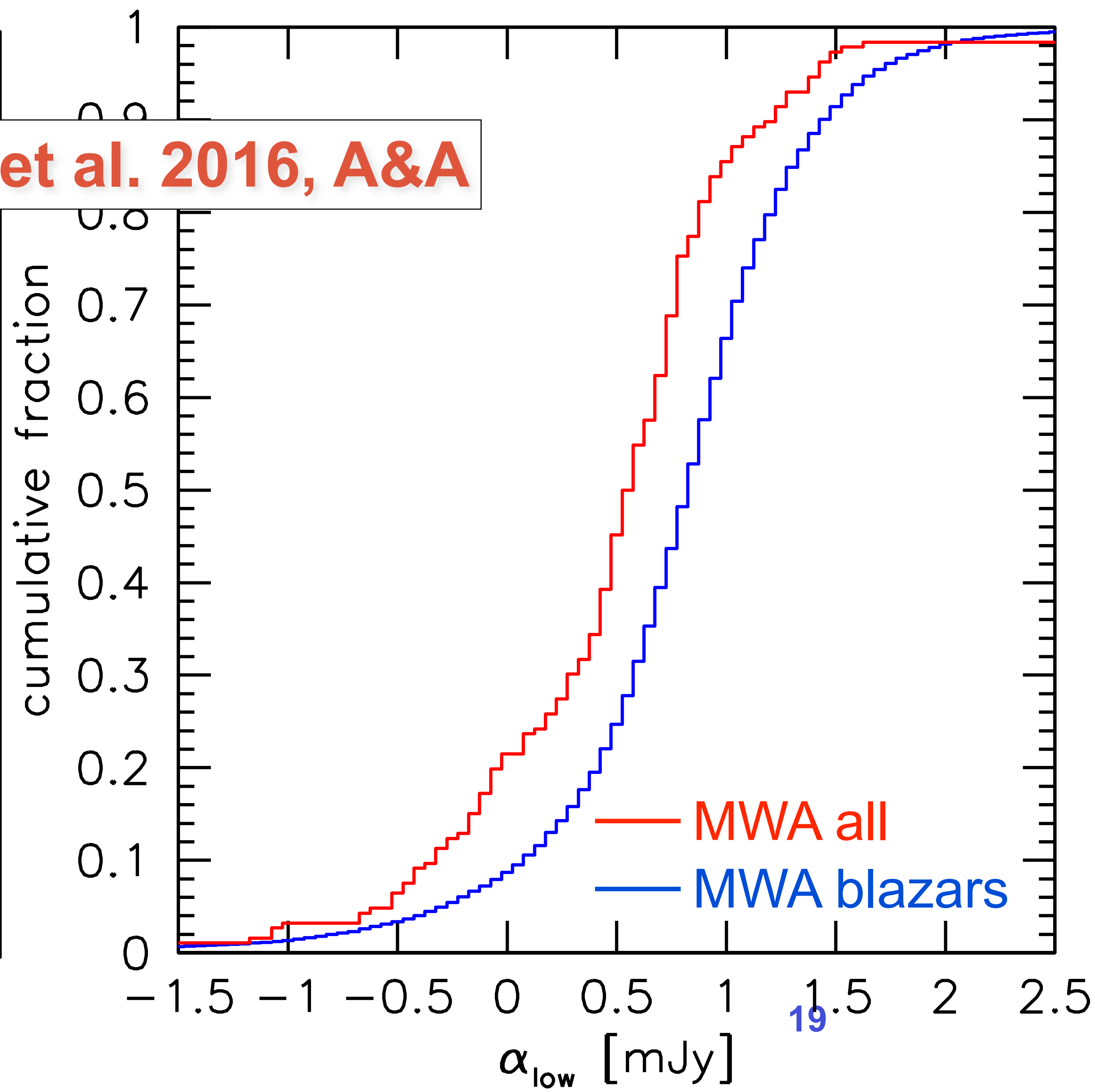
Class	ratio	%BZC	ratio	%3LAC
Total	186/517	36 %	80/164	46 %
FSRQ	147/327	45 %	52/71	73 %
BLL	23/153	15 %	19/87	22 %
BCU	16/37	43 %	8/16	11 %

Blazars at low frequency

- **Blazar flux density distributions at 1 GHz**
  - **MWACS detected blazars are brighter**
  - **many (most of the) MWACS undetected blazars must have flat/inverted spectrum**
- **Low frequency spectra are less steep for blazars than for other sources:**
  - **0.51 ± 0.05 vs 0.81 ± 0.01**



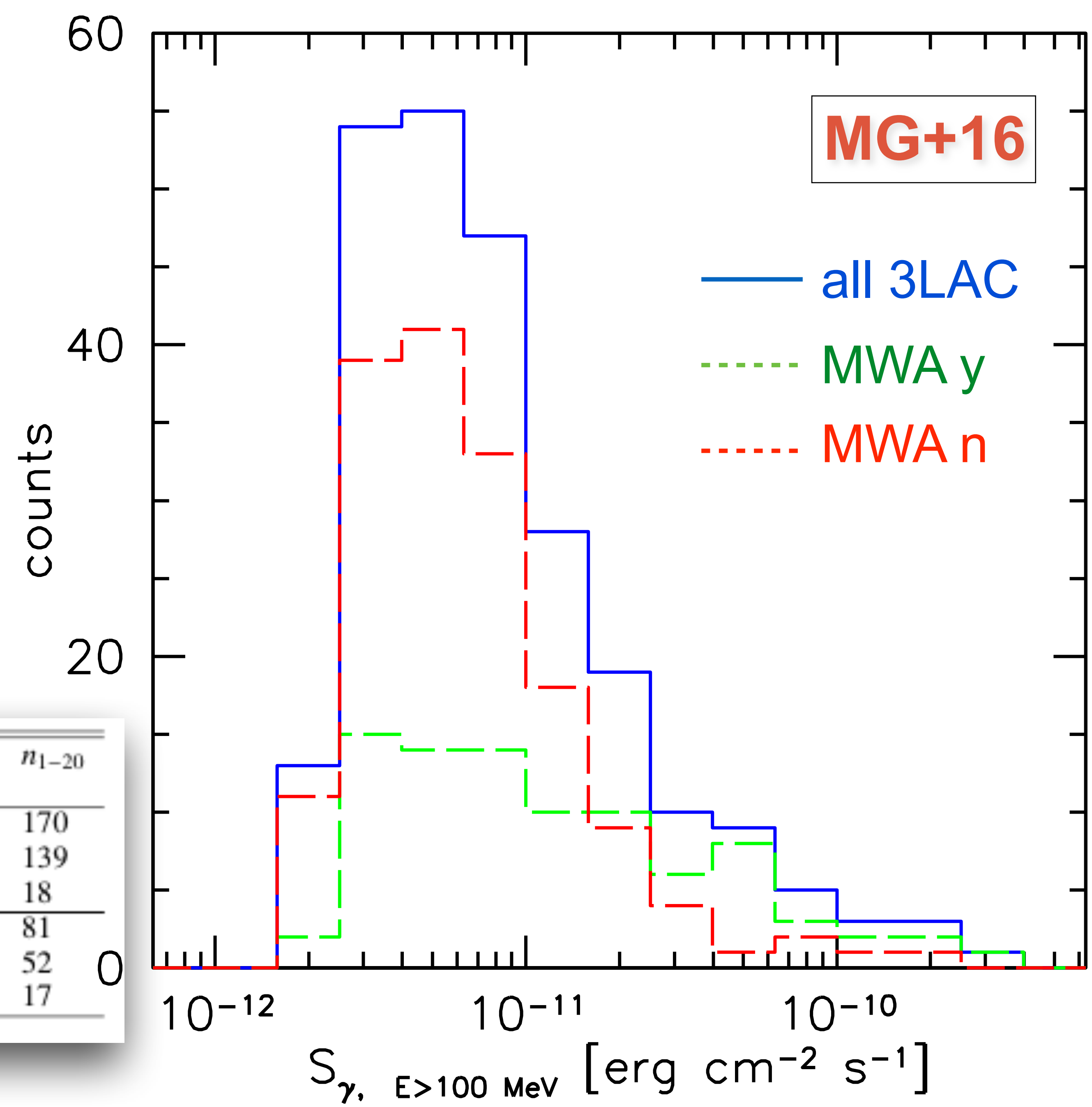
Giroletti et al. 2016, A&A



gamma-ray blazars at low frequency

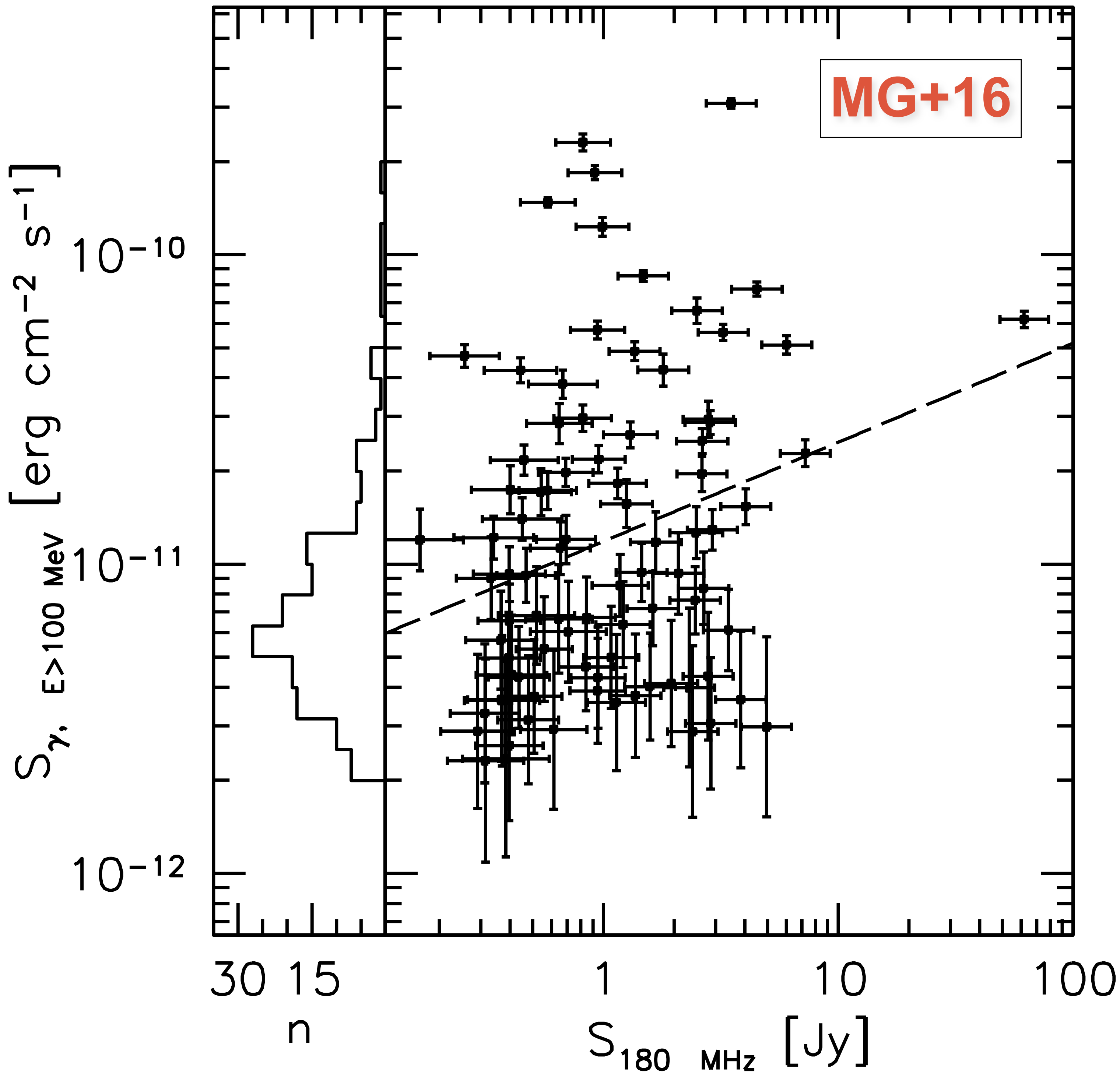
- **Bright gamma-ray sources are more easily detected in MWACS**
  - **76% above 4×10^{-11} erg cm^{-2} s^{-1}**
  - **BL Lacs have lower detection rate**
- **Low-frequency α similar to all blazars, low-mid frequency α somewhat flatter**

Sample (1)	Class (2)	$\langle\alpha_{\mathrm{low}}\rangle$ (3)	$\langle\alpha_{0.18-1}\rangle$ (4)	$n_{\mathrm{low},\,0.18-1}$ (5)	$\langle\alpha_{1-20}\rangle$	n_{1-20}
BZCat-MWACS	Total	0.51 ± 0.05	0.26 ± 0.02	186	0.10 ± 0.02	170
	FSRQ	0.48 ± 0.06	0.23 ± 0.03	147	0.10 ± 0.02	139
	BLL	0.55 ± 0.10	0.41 ± 0.07	23	0.12 ± 0.05	18
3LAC-MWACS	Total	0.47 ± 0.09	0.27 ± 0.04	87	0.08 ± 0.03	81
	FSRQ	0.40 ± 0.12	0.13 ± 0.04	52	0.04 ± 0.03	52
	BLL	0.56 ± 0.13	0.32 ± 0.07	19	0.15 ± 0.06	17



Radio/gamma-ray correlation

- **MWACS flux density and *Fermi* energy flux are only weakly correlated**
  - ***r*=0.26, chance *P*=0.27**
- **Markedly different from stronger and very significant (p<10^{-7}) correlation found using GHz data**
  - **unbeamed lobes contribute!**
  - **how much?**

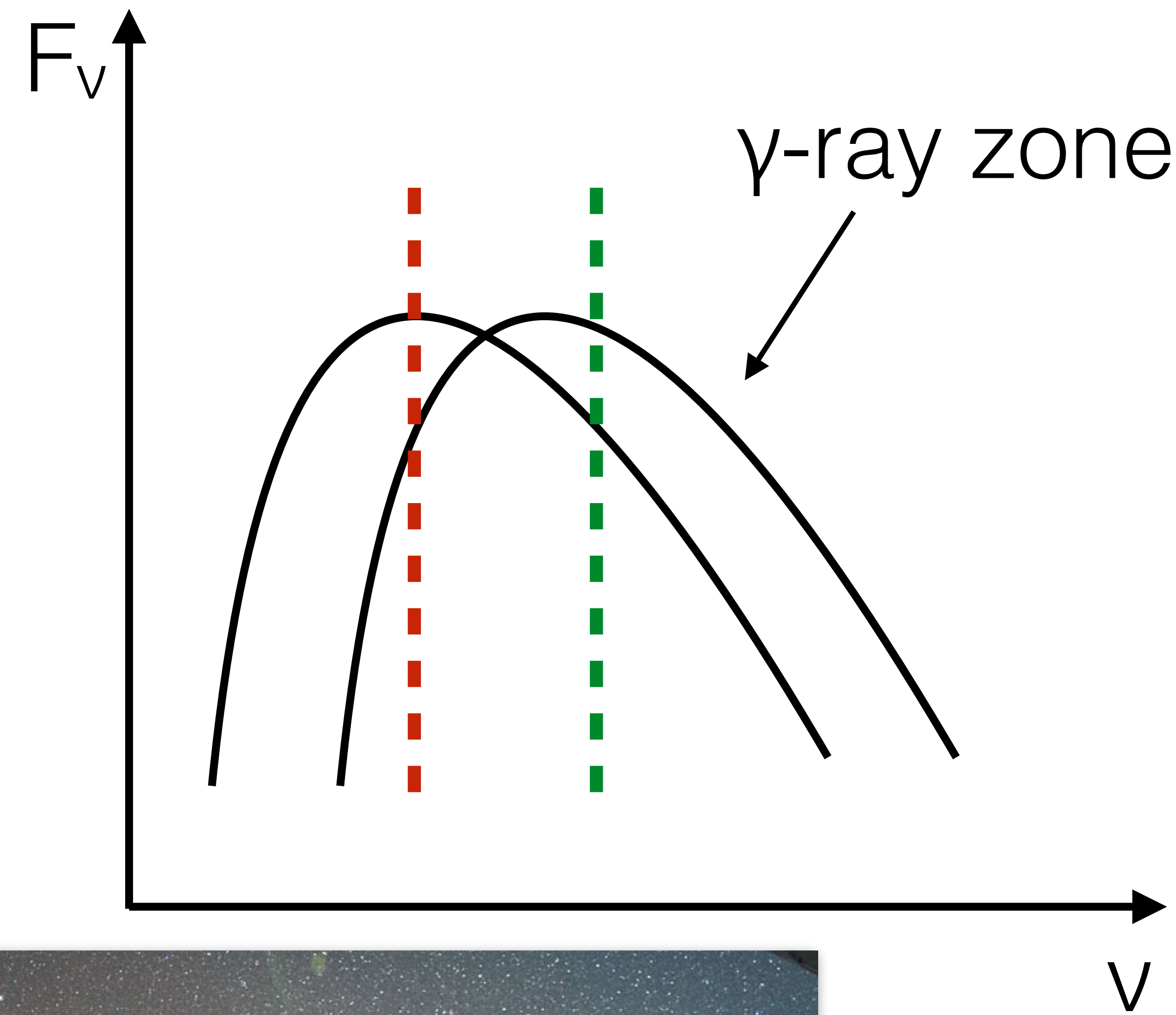


$$S(\nu) = k_c \nu^{-\alpha_c} + k_l \nu^{-\alpha_l}$$

- **S_c/S_l~0.6 @120 MHz, S_c/S_l~24 @20 GHz**

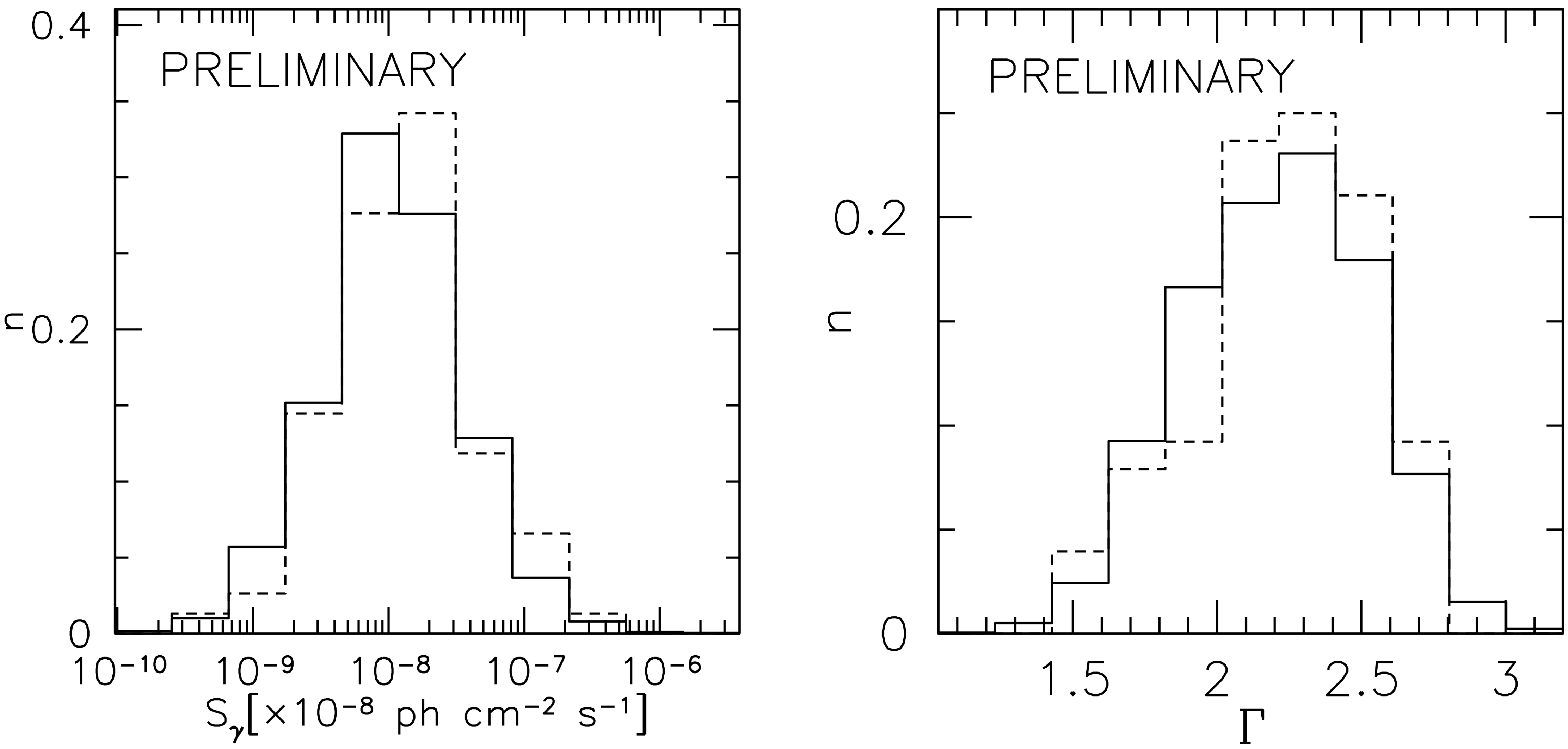
The extension towards mm-λ

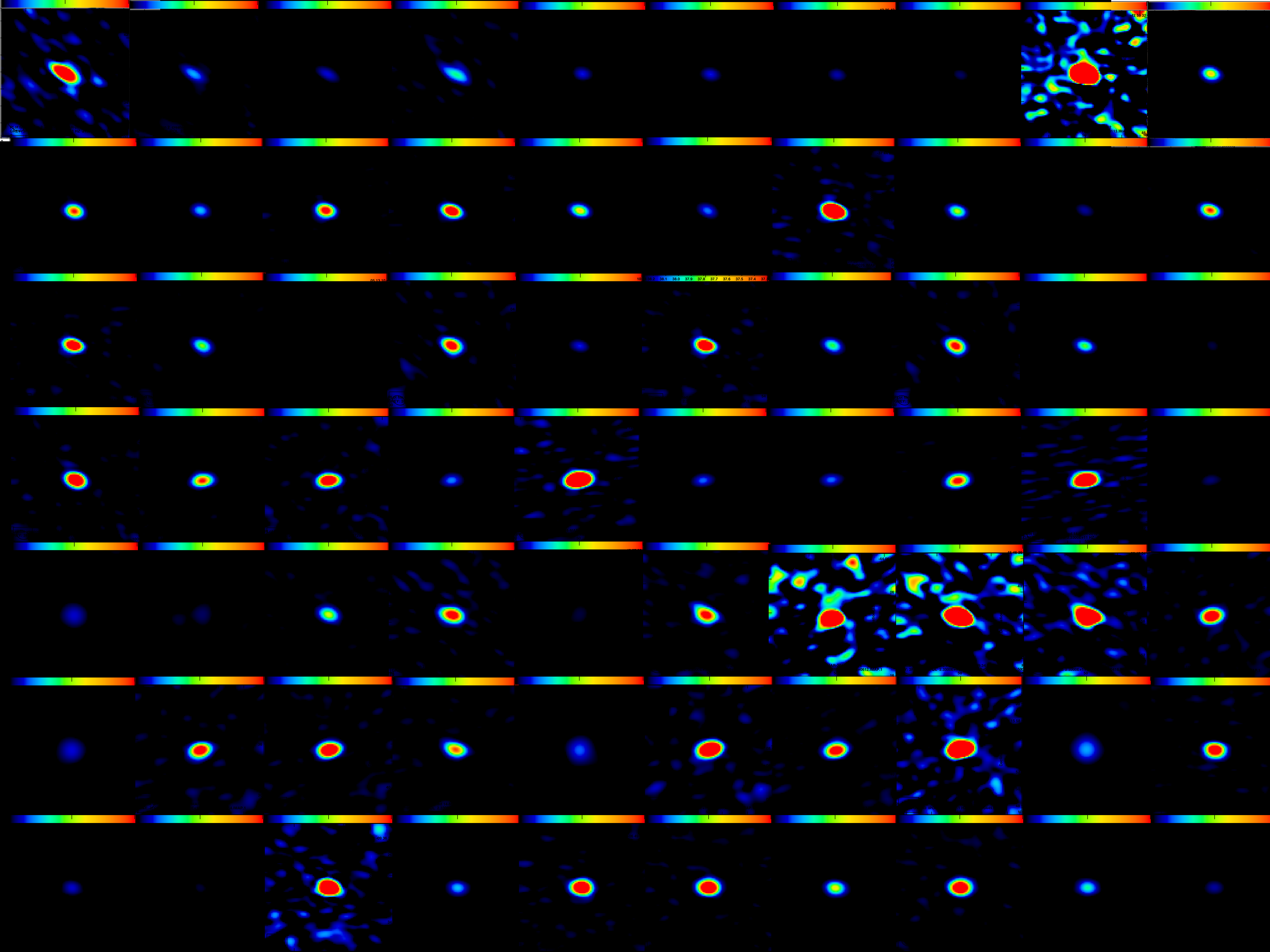
- **mm-λ emission: less opacity in compact regions, less contamination from extended emission**
- **ALMA sensitivity permits to observe a sizable sample in reasonable time**
  - **77 representative 3LAC sources observed**
  - **reasonable compromise between statistically significant sample size and telescope time request**



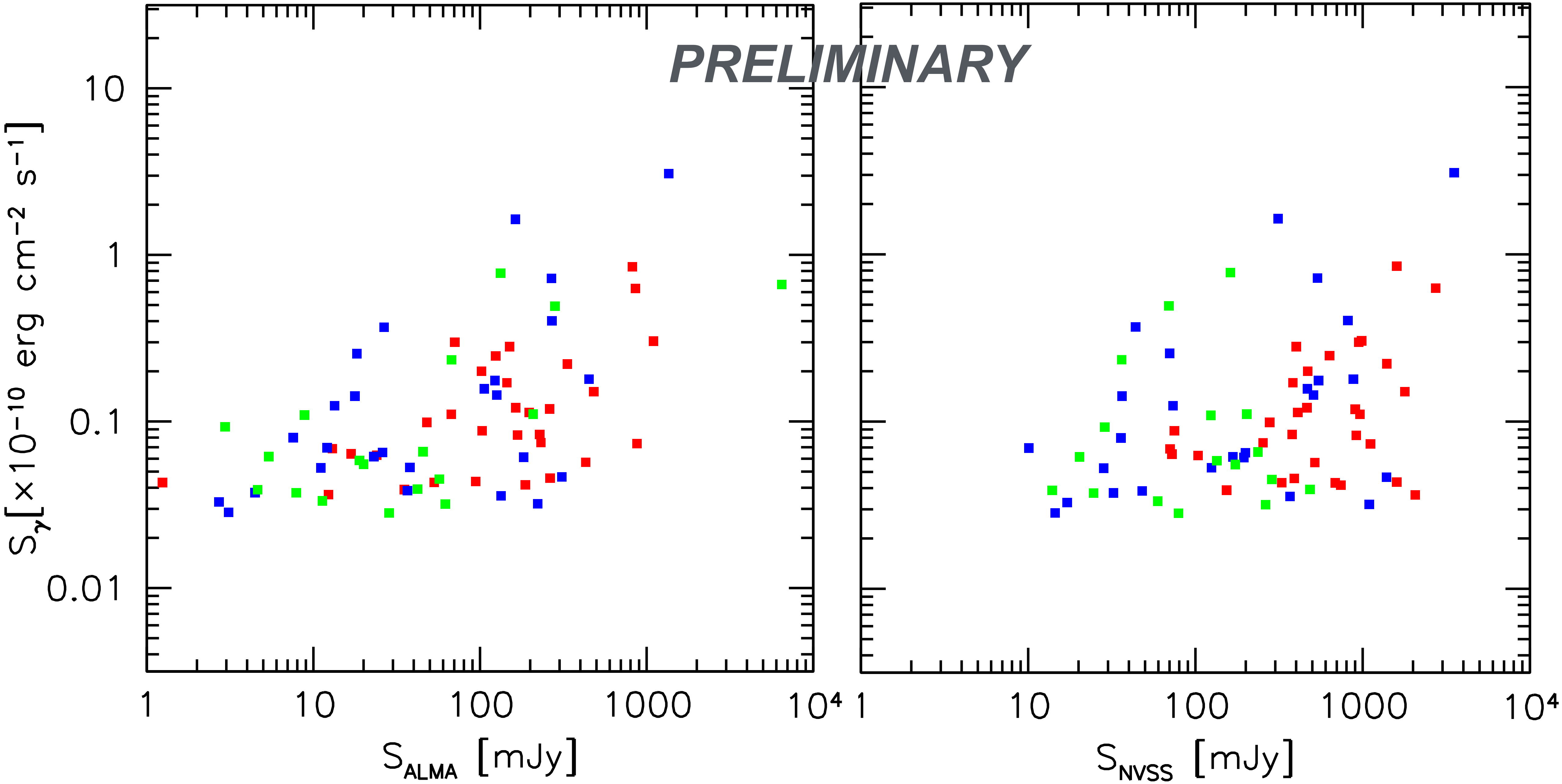
a representative 3LAC sample?

- 77 sources
  - 65 clean
  - 16 BCU, 26 BLL, 31 FSRQ, 1NLSy1, 2 RGal
  - 43/14/18 LSP/ISP/HSP
    - distribution of subsample's (dashed) photon flux and spectral index similar to that of 3LAC (solid)





preliminary results



ALMA-3FGL, r=0.55

NVSS-3FGL, r=0.39

mm-γ correlation is stronger than cm-γ

Summary

- **Thanks to its large energy range, *Fermi* detects blazars over a wide range of luminosity and spectral types**
  - **strong and significant correlation between radio and gamma rays for the entire population** ← Ackermann et al. (2011)
- **The correlation strength decreases when we reduce the sample to**
  - **high energy detected sources (1FHL)** ← Lico et al. PhD. Th. (2016)
    - **because high power sources cool**
  - **low radio frequency detected sources (MWACS)** ← Giroletti et al. (2016)
    - **because radio lobes contaminate beamed components**
- **It should tighten with mm (ALMA) data** ← Giroletti et al. (in prep)
  - **stay tuned!**

BACKUP

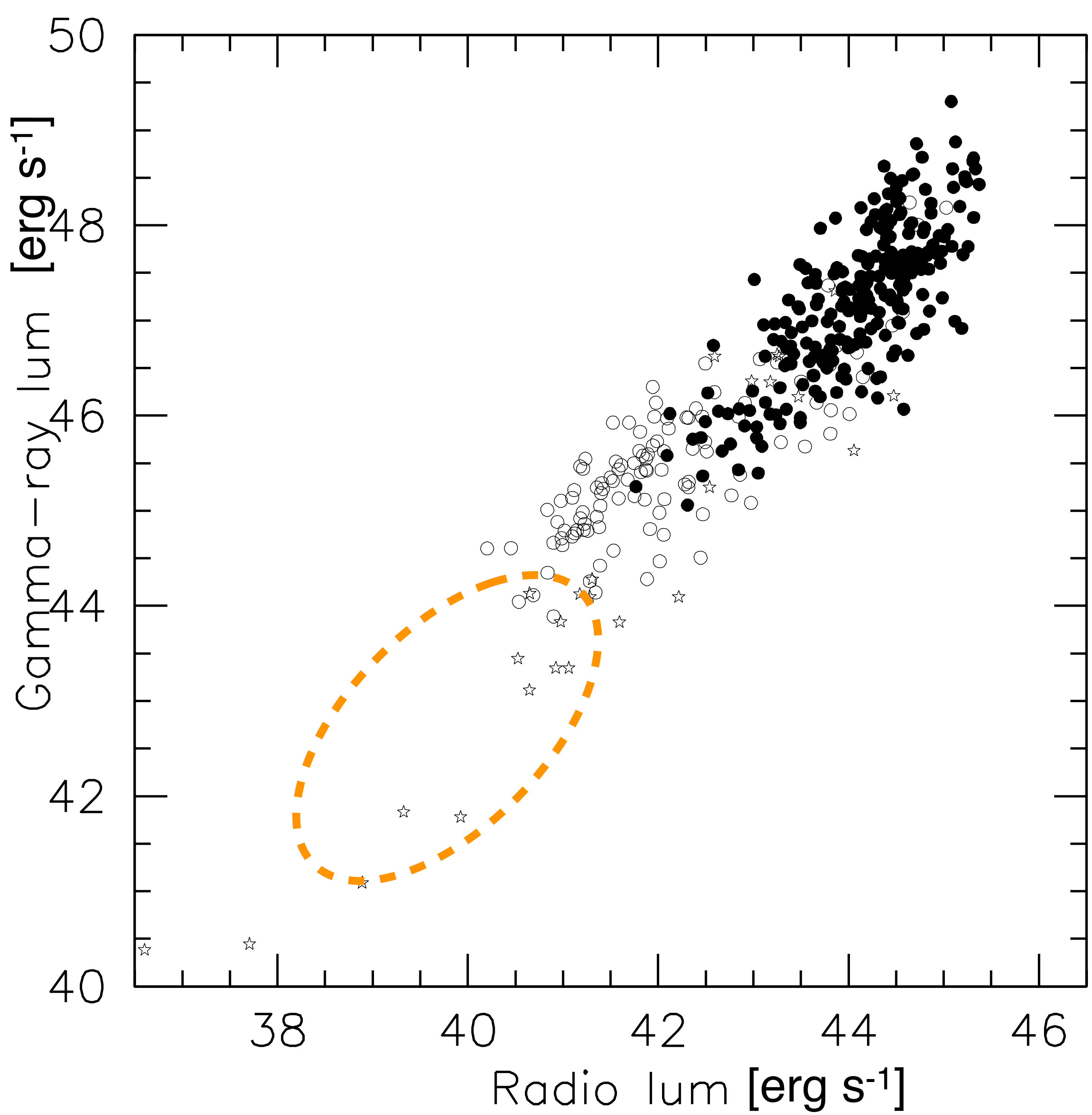
MATERIAL

Our significance assessment method (Pavlidou et al. 2012)

- split the sample in N redshift bins (N such that each bin has ~10 sources)
- for each bin:
  - –calculate radio and gamma-ray luminosity
  - –permute luminosities to obtain intrinsically uncorrelated data sets
    - permutation done on luminosities to keep dynamic range
  - –return to flux density plane with random z in bin
  - –reject pairs with flux densities out of initial range
- calculate *r* value for all pairs
- repeat MANY times
- how many times did we get $r > r_{obs}$ by chance?

The correlation & luminosity

- **We studied flux-flux correlations to avoid square-distance effects common for luminosity**
  - **–luminosities remain of great interest both at high and low values**
    - **great discovery space at low luminosity (L_r~$10^{39\text{-}41}$ erg s^{-1}) for intrinsically weak and/or misaligned blazars**

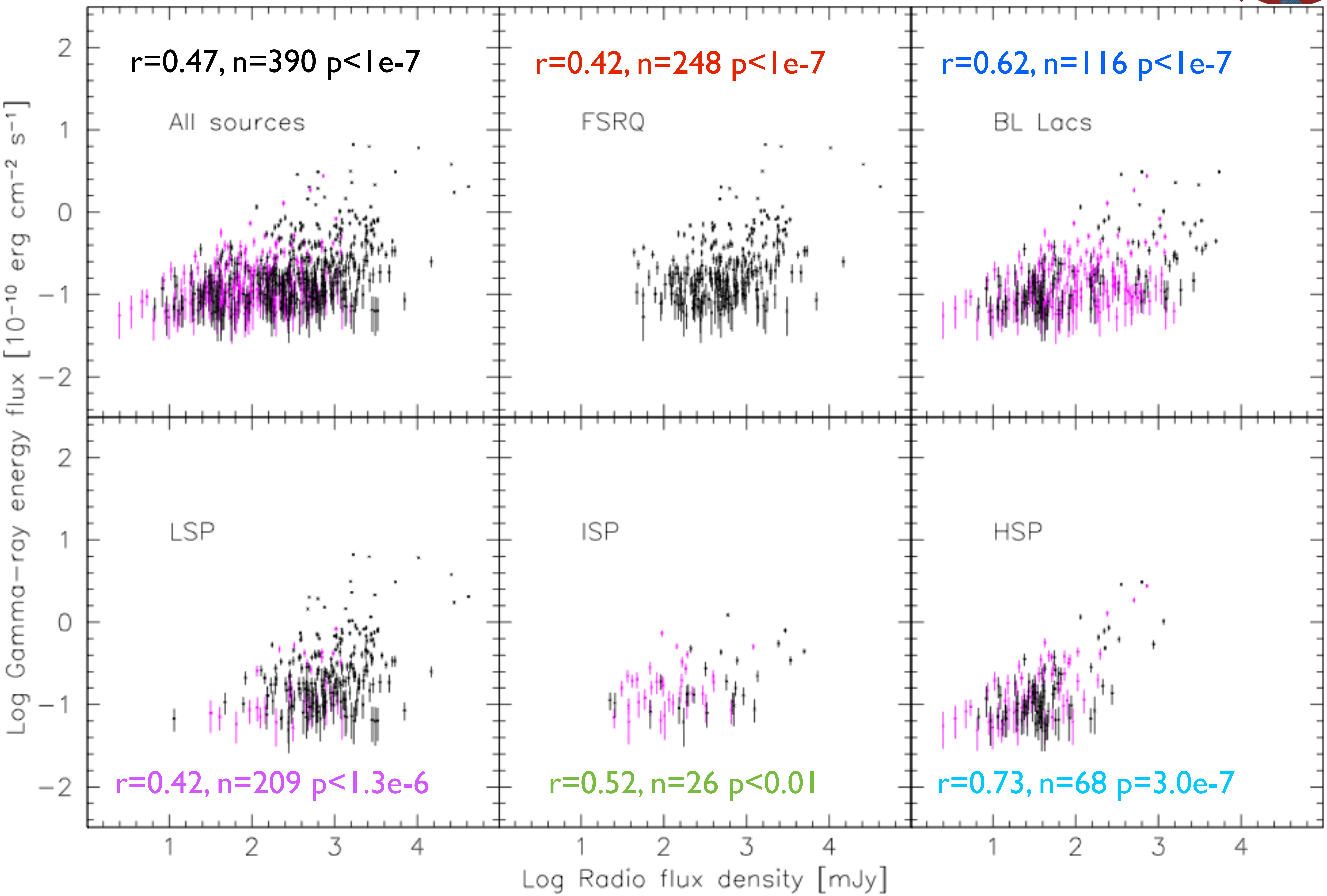


The correlation & blazar types

- **Comments:**
  - BL Lacs show a moderately stronger correlation than FSRQs
  - each sub-class (FSRQ and BLL) independently still shows very high significance of a correlation (chance prob.<1e-7)
  - HSP blazars have the stronger correlation among the various SED-based classification

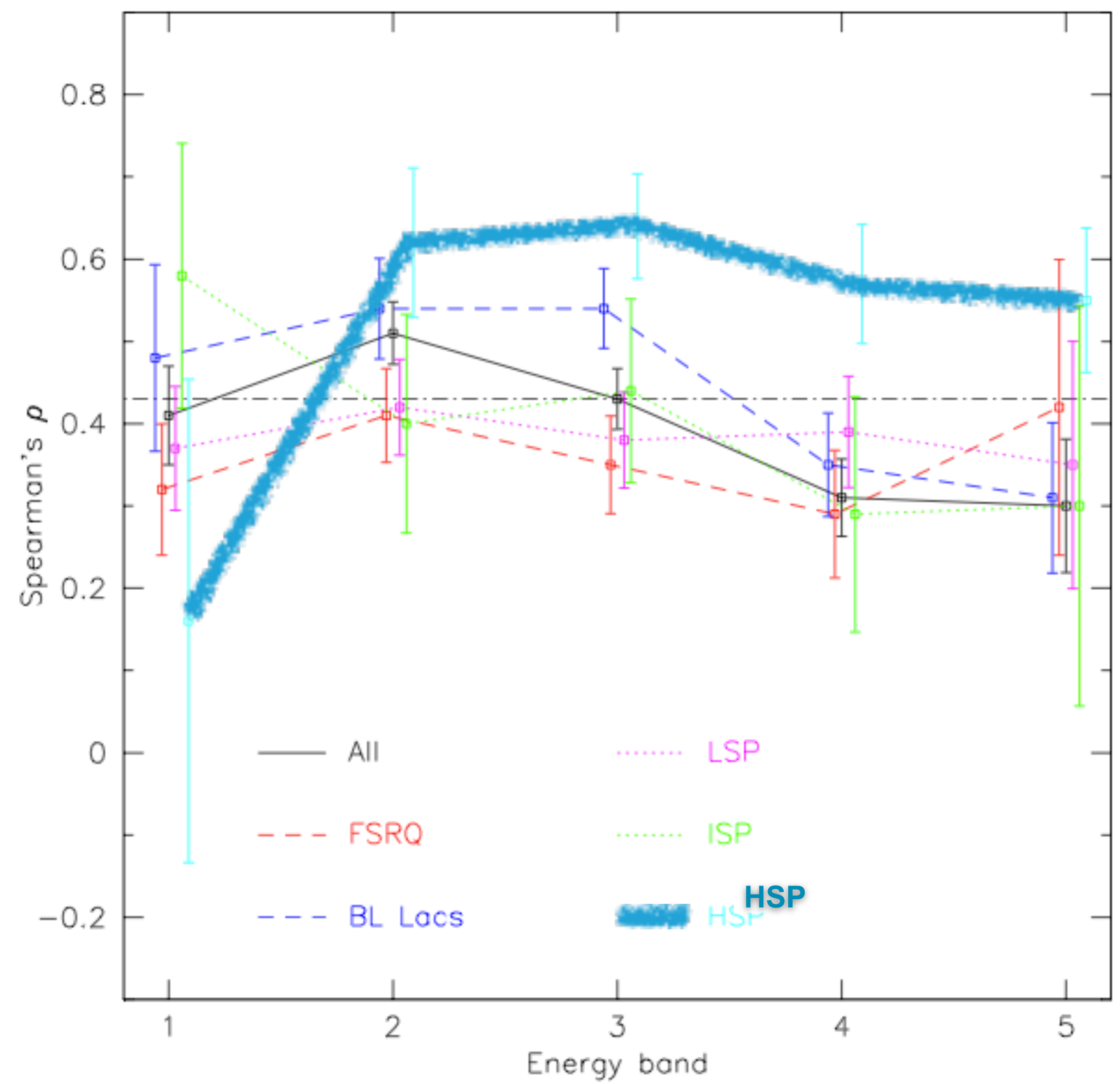
source type	corr. coeff.	# sources
All sources	0,43	599
FSRQ	0,39	248
BL Lacs	0,46	275
LSP	0,4	242
ISP	0,33	60
HSP	0,55	129

The correlation & blazar types



The correlation & energy bands

- not all LAT energy bands correlate with radio with the same strength...
  - –for the whole 1LAC, the strongest correlation is found using 0.3-1 GeV
- HSP blazars are the subclass with the largest correlation coefficient
  - –except for Band 1 (0.1-0.3 GeV), where there's very few of them

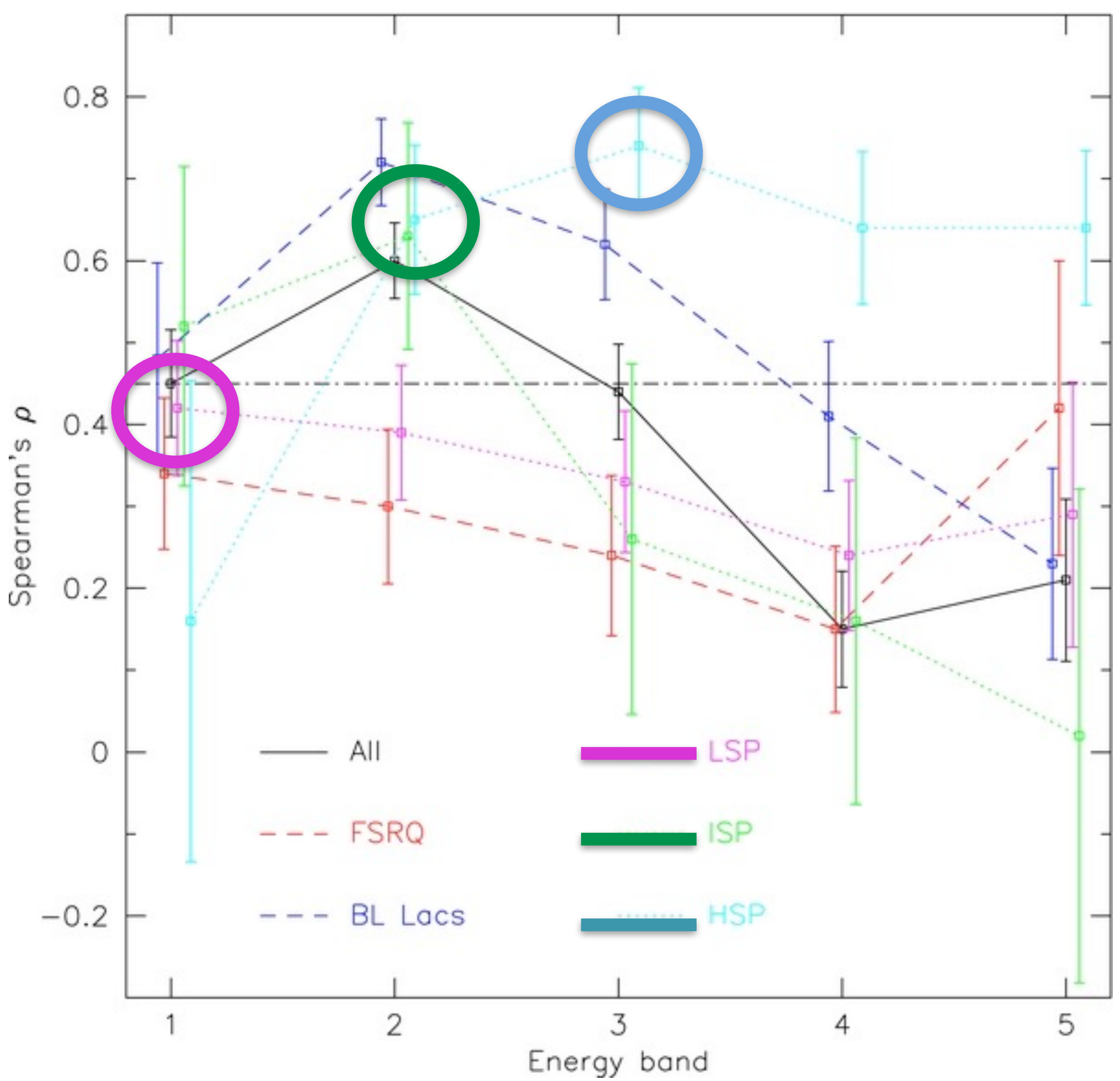


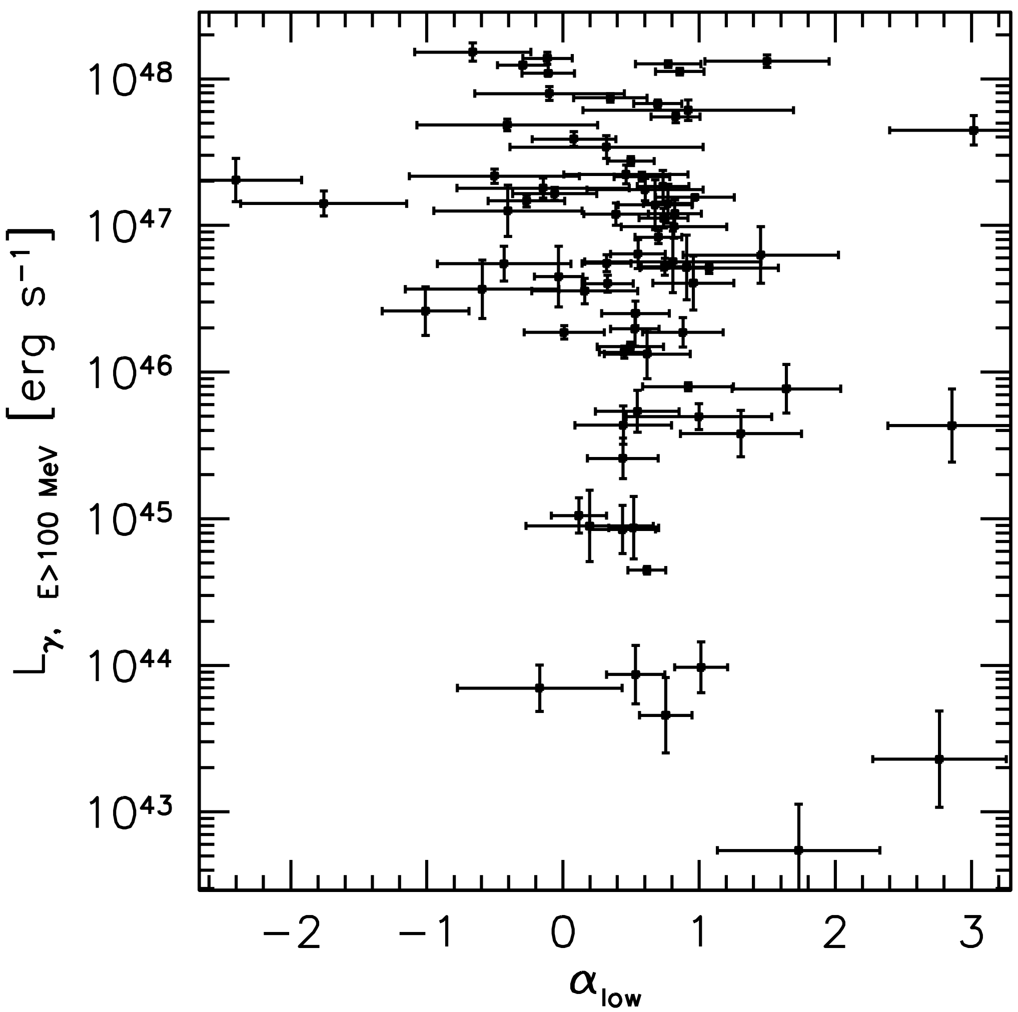
The correlation & timing

- Timing
  - Considering the subset of sources regularly monitored by OVRO, the correlation coefficient and the significance improve when considering simultaneous vs archival data
  - gamma-ray vs 15 GHz non concurrent data:
    - Spearman’s rho=0.36 , Pearson’s r=0.42, significance=1.9×10^{-6}
  - gamma-ray vs 15 GHZ concurrent data:
    - Spearman’s rho=0.39 , Pearson’s r=0.46, significance=9×10^{-8}
  - number of sources considered: 160

Additional tests: 4 - blazar type & energy band

- **Caveat: not all sources have a significant detection in all sub-bands**
  - –we defined a new sample consisting of sources detected in at least 4/5 energy bands: 138 sources
- **Source types behave somewhat differently in different energy bands**
  - –LSP have strongest correlation in Band1 (0.1-0.3 GeV)
  - –ISP in Band2 (0.3-1 GeV)
  - –HSP in Band3 (1-3 GeV)
    - …but significance is marginal so far

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10^{47}
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10^{45}
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$L_{\gamma,\ E>100\ MeV}$ [erg s^{-1}]
−2
−1
0
1
2
3
α_{low}