The connection between radio and gamma-ray emission in relativistic jets in the *Fermi* era and beyond

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on behalf of the *Fermi*-LAT collaboration
and R. Lico, H. Bignall, C. Reynolds, et al.

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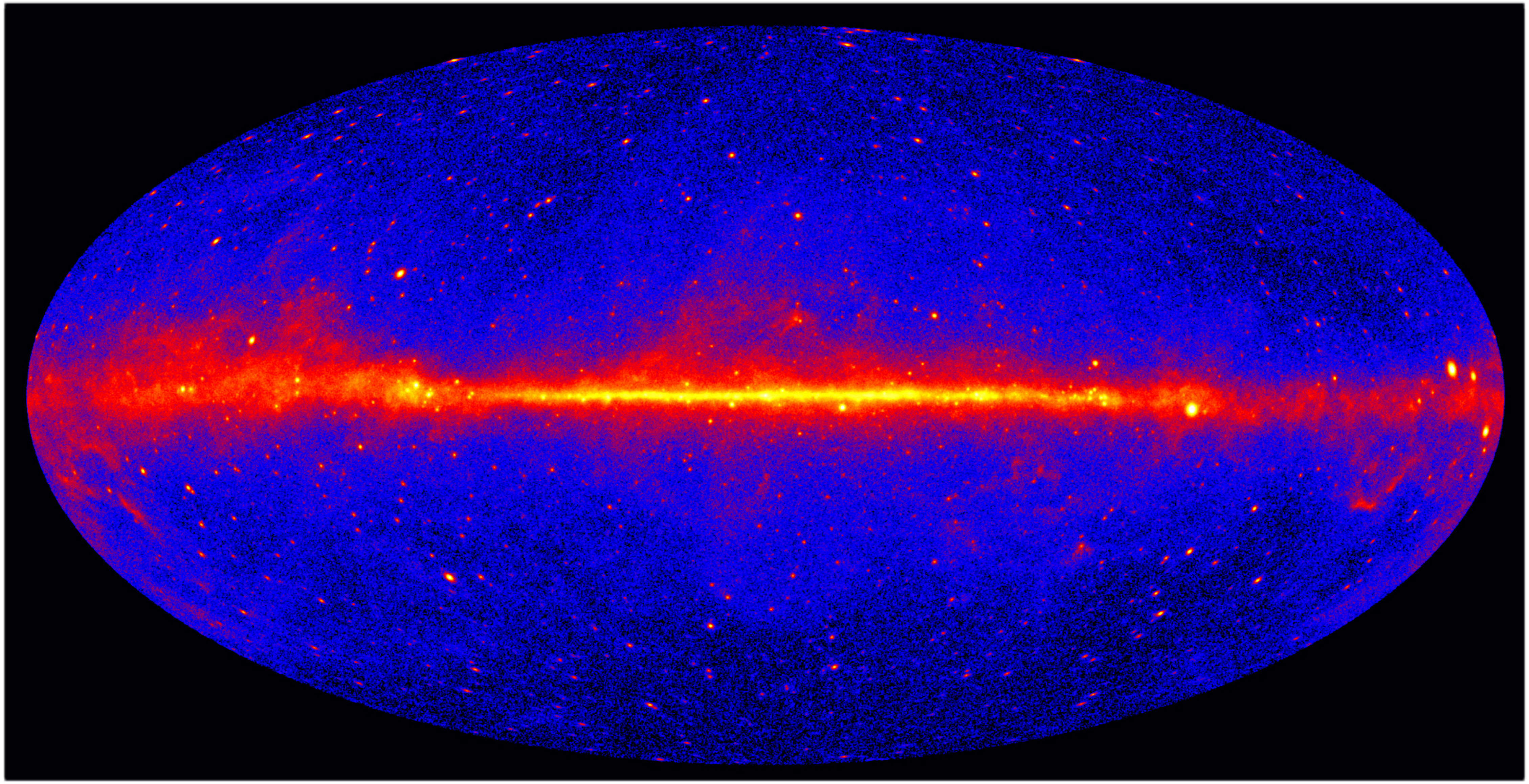
Outline

- *Fermi* & gamma-ray emission
- radio-gamma connection with MeV/GeV data
- radio-gamma connection with E>10 GeV data
- future
- references at the end

Fermi catalogues

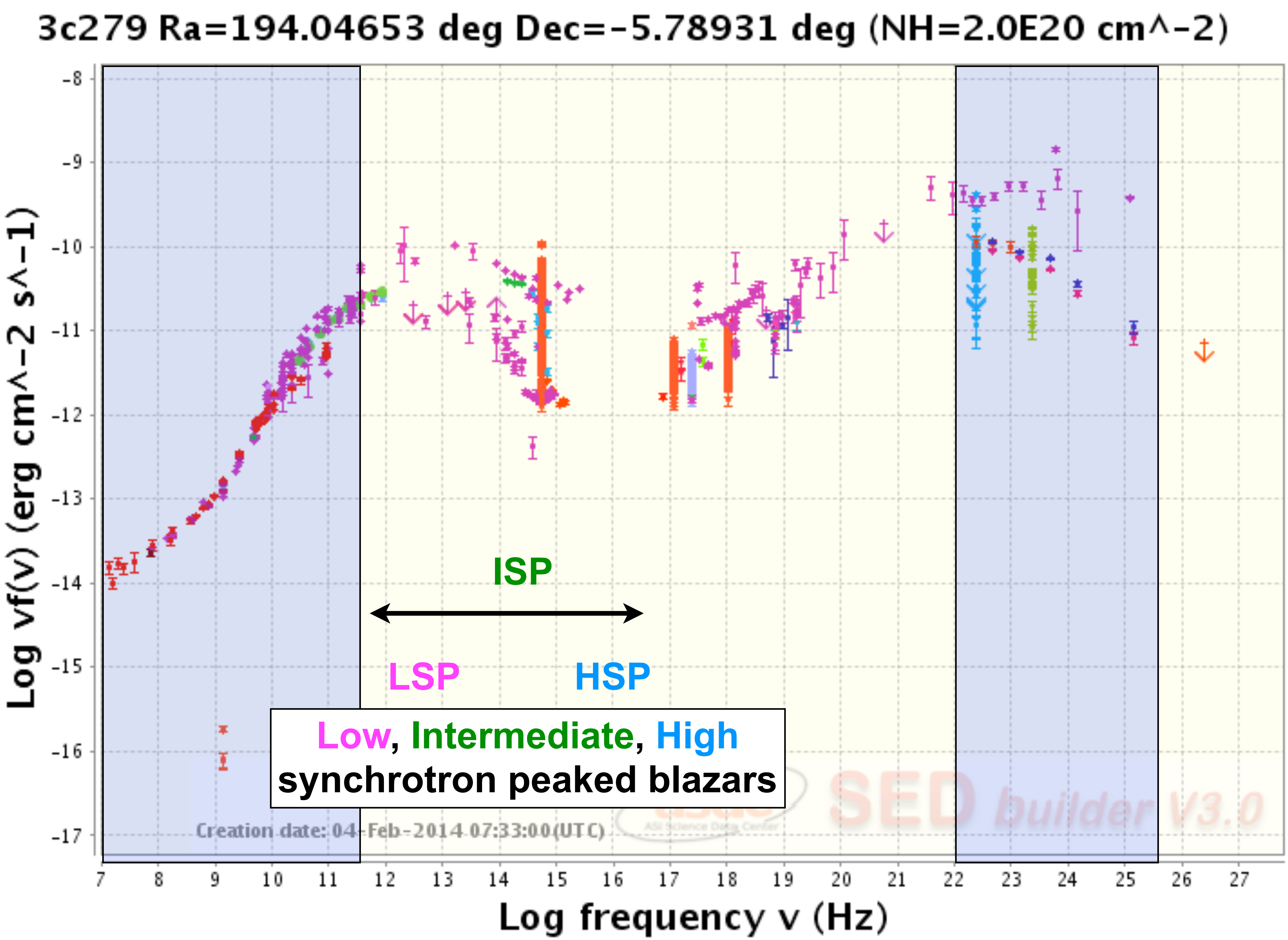


- four main catalogues: 0FGL (3 months of data, 205 sources), 1FGL (11 months, 1451 src), 2FGL (2yr, 1873 src), 3FGL (4yr, 3033 src)
  - each one accompanied by a dedicated AGN catalogue (LBAS, 1LAC, 2LAC, 3LAC, talk by Lott)

Gamma-ray AGN demographics

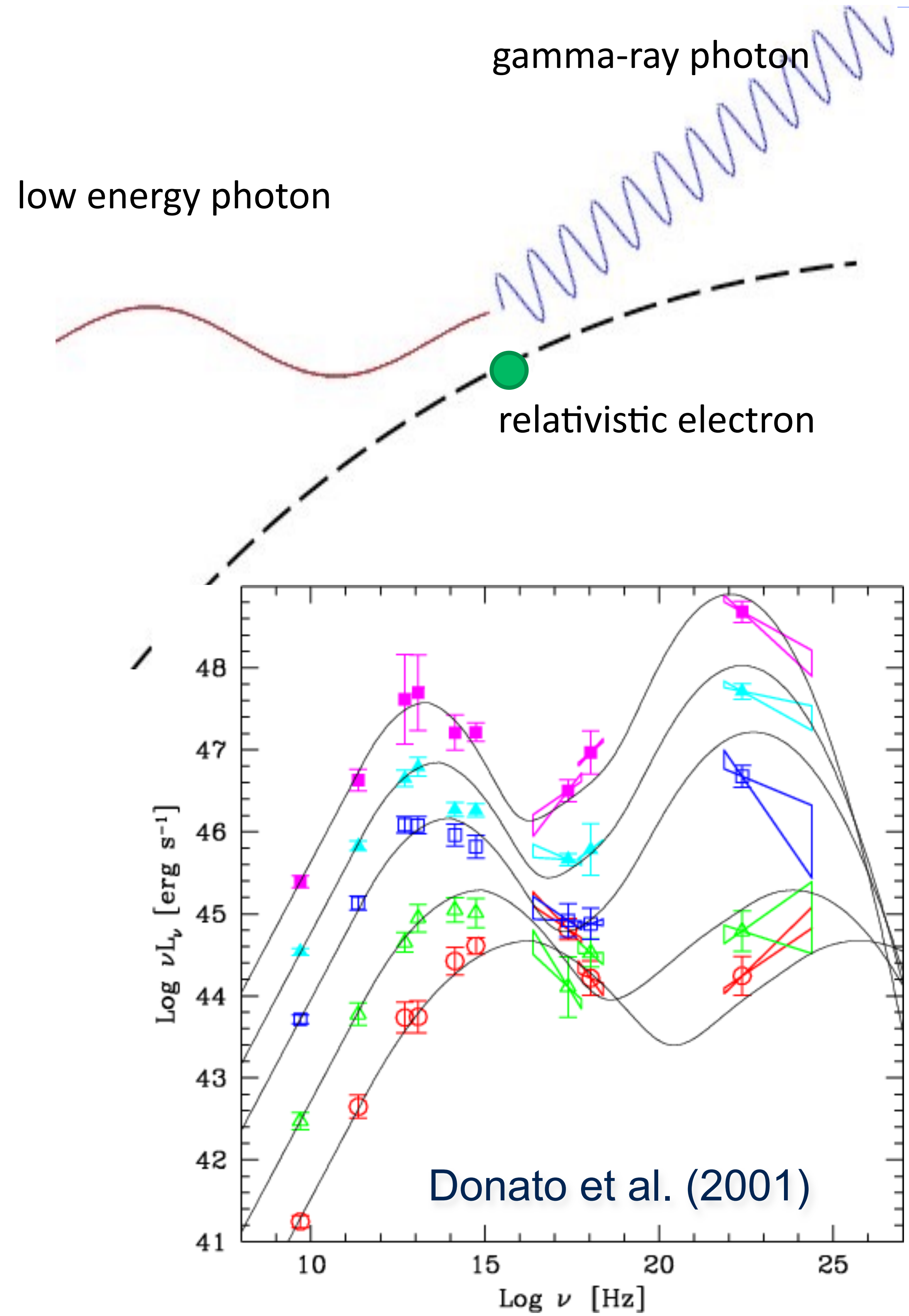
- EGRET: 66 blazar (+27 low conf., FSRQ:BLL=4.7)
- LBAS: 106 AGN (FSRQ:BLL=1.4)
- 1LAC: 709 AGN (FSRQ:BLL=1.0)
- 2LAC: 1017 AGN (FSRQ:BLL=0.8)
- 3LAC: 1591 AGN (FSRQ:BLL=0.7)
- Only a few unidentified sources remain at high fluxes
- Gamma-ray sources continue to be associated to radio loud objects
  - Vast majority (97.3%) of *Fermi* high-*b* associated sources are blazars
  - Non blazar sources are typically misaligned blazars (MAGN, Abdo et al. 2010c), or very blazar-like sources (RL NLS1, Abdo et al. 2009b)
  - Only truly non blazar sources are Cen A lobes and a handful of starbursts

Radio and gamma-ray emission in blazars: Spectral Energy Distribution



Radio and gamma-ray emission in blazars

- **synchrotron radio emission originates from relativistic e$^-$ that can upscatter photons to high energy**
  - **leptonic models naturally predict some connection between radio and gamma-ray emission**
  - **all EGRET AGNs were radio loud, differently from most X-ray QSOs**
- **the blazar sequence was originally devised on the basis of the radio luminosity**
- **evidence or not of flux-flux, Lum-Lum correlations is a debated issue**
  - **Stecker et al. (1993), Mücke et al. (1997), Bloom (2008), etc.**
  - **bias, variability, number of sources, etc.**



Radio/gamma-ray connection with *Fermi*

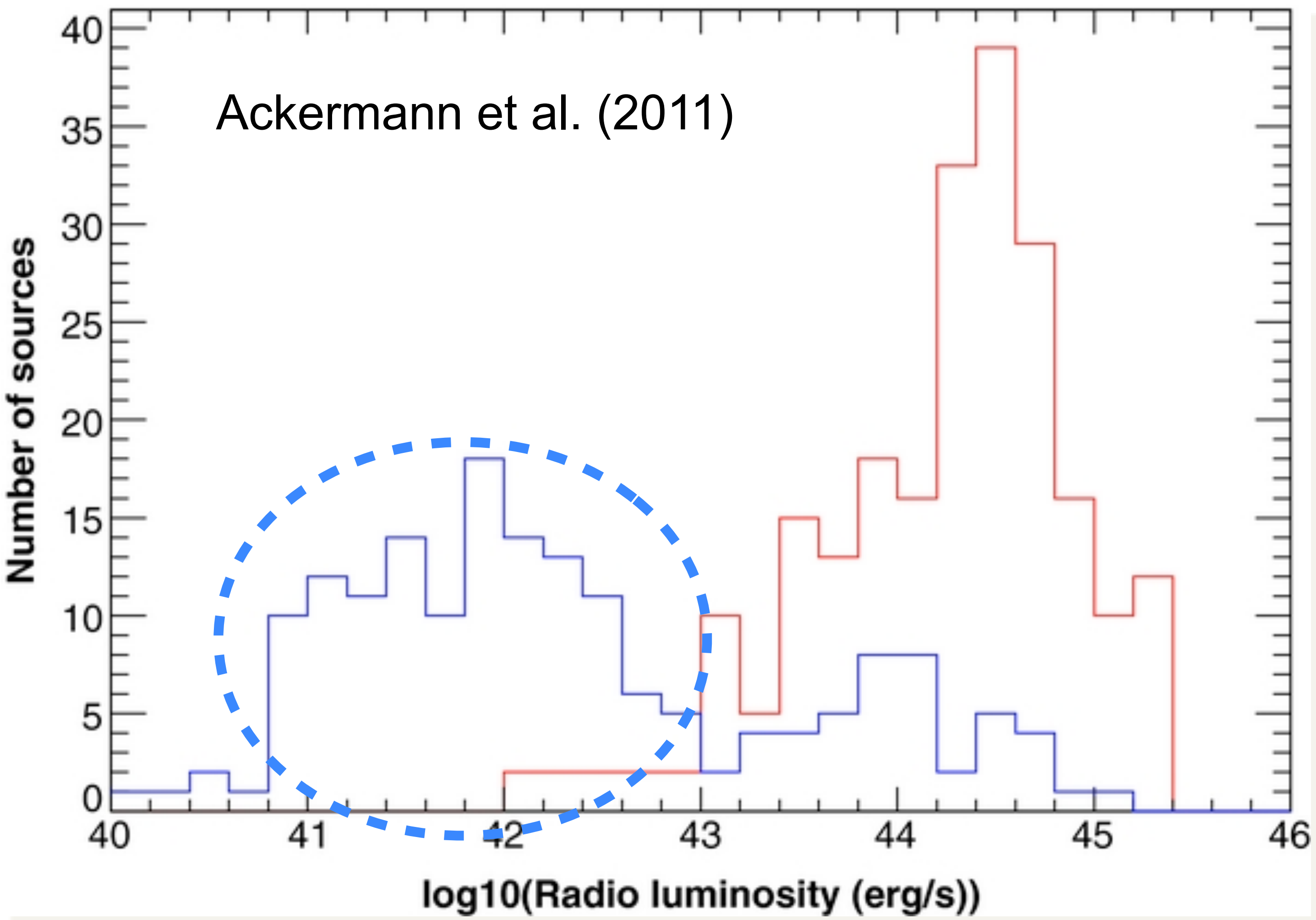
- Big questions
  - is there a correlation between radio and gamma-ray emission in AGNs?
  - is it also significant?
  - does it depend on simultaneity?
  - does it depend on blazar type?
  - does it depend on energy band?

- See also works from Kovalev et al. (2009), Ghirlanda et al. (2010, 2011), Mahony et al. (2010)

- We base our work on
  - 0.2” angular resolution archival 8.4 GHz for all 599 AGNs
  - 15 GHz single dish simultaneous data for 199 AGNs
  - 1LAC data in 5 energy sub-bands between 0.1-100 GeV

Main novelties

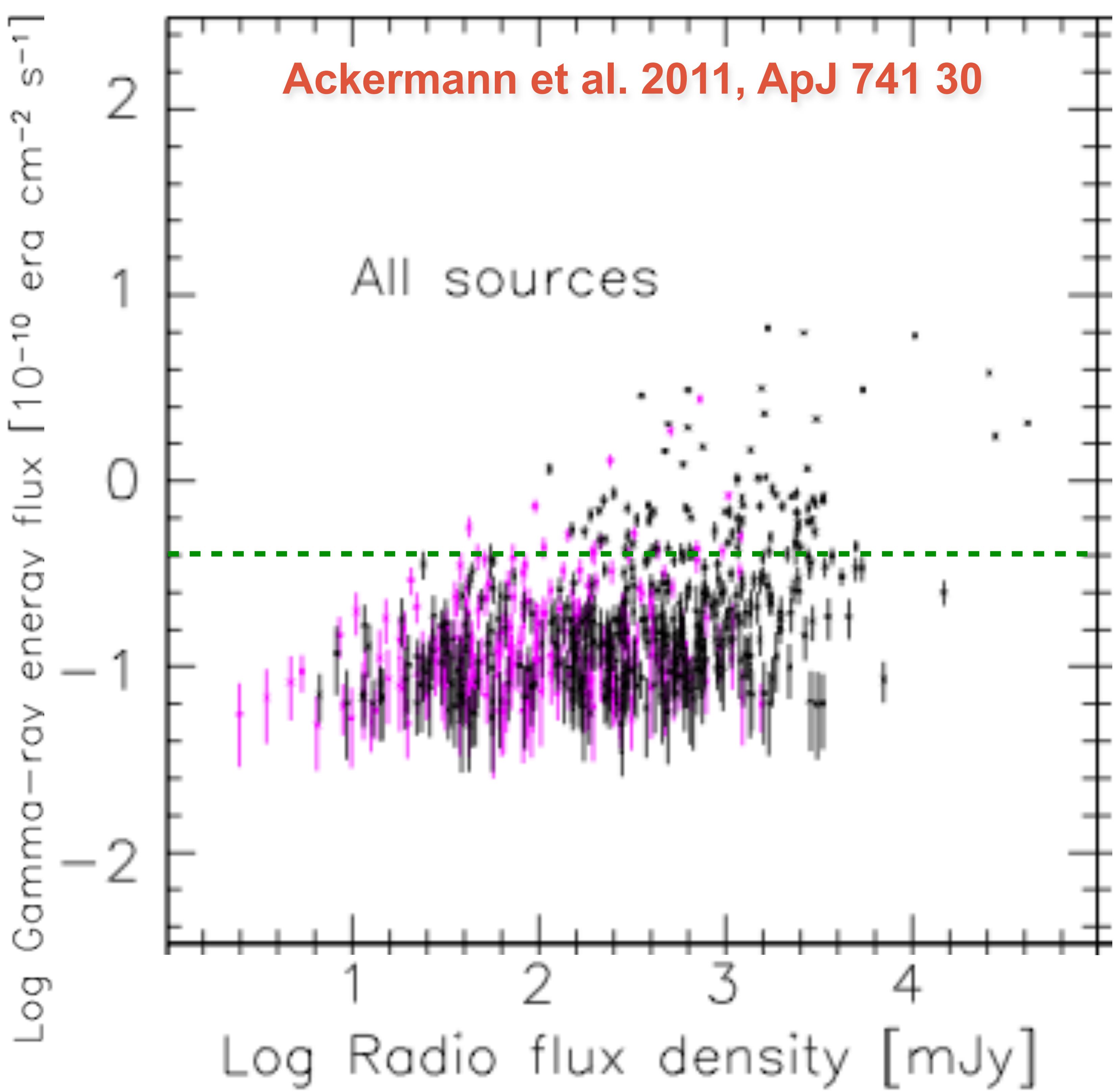
1. Include ALL gamma-ray AGNs
   – faintest ones (typically, BL Lacs) are not included in most other works
2. Use both archival and simultaneous radio data
3. Assess statistical significance with dedicated tools
   – Pavlidou et al. (2012)



Results

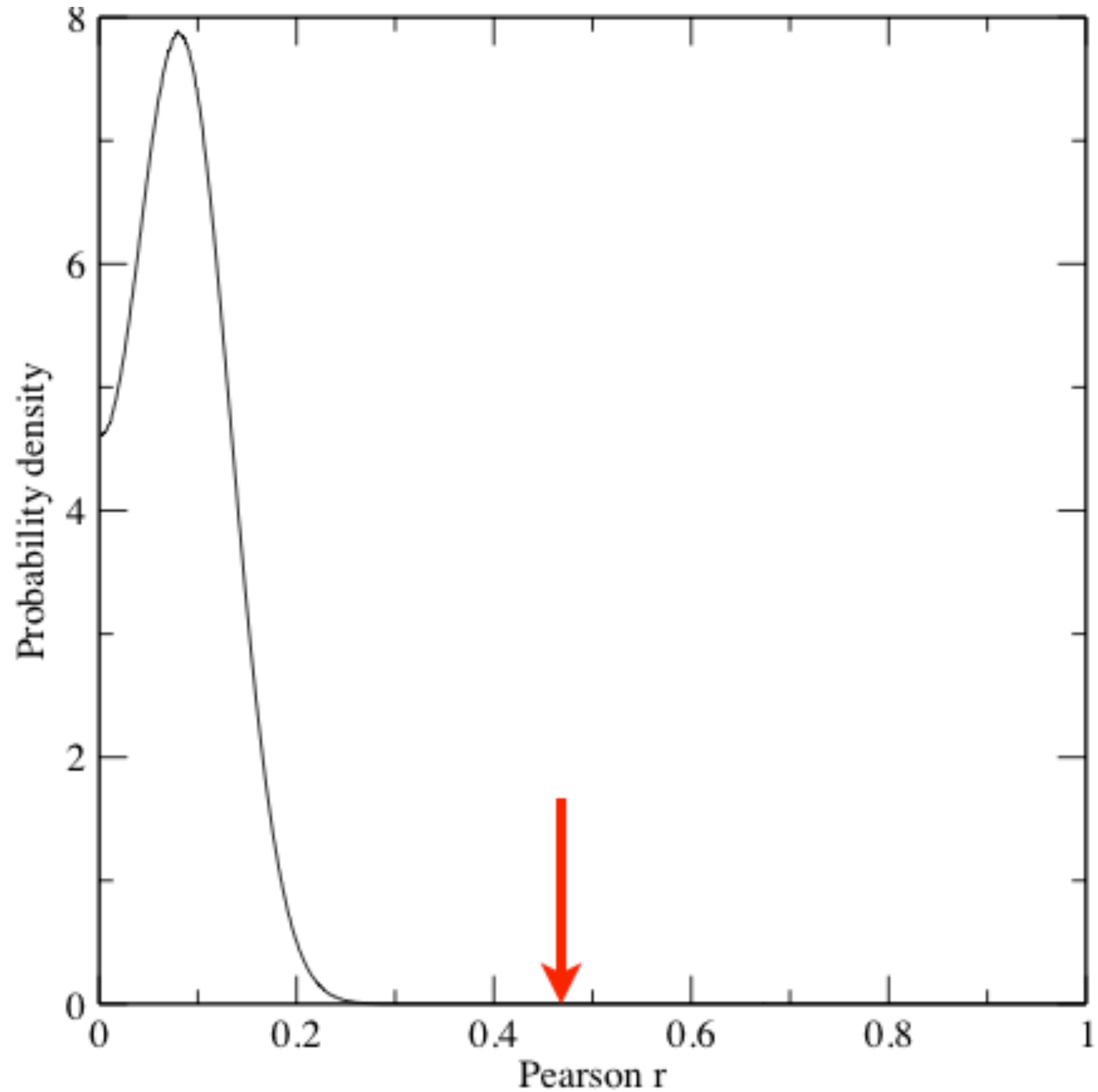
- **All 599 1LAC clean sources**
- **black: with redshift**
- **magenta: without redshift**
- **correlation coefficient: *r=0.47***

NB no unassociated sources have gamma-ray flux larger than 4×10^{-11} 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 in ten million cases!
    - probability of chance correlation: P<1e-7

Additional tests: 1 - 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 <u>non concurrent</u> data:
    - Spearman's rho=0.36 , Pearson's r=0.42, <u>significance=1.9×10^{-6}</u>
  - gamma-ray vs 15 GHZ <u>concurrent</u> data:
    - Spearman's rho=0.39 , Pearson's r=0.46, <u>significance=9×10^{-8}</u>
  - number of sources considered: 160

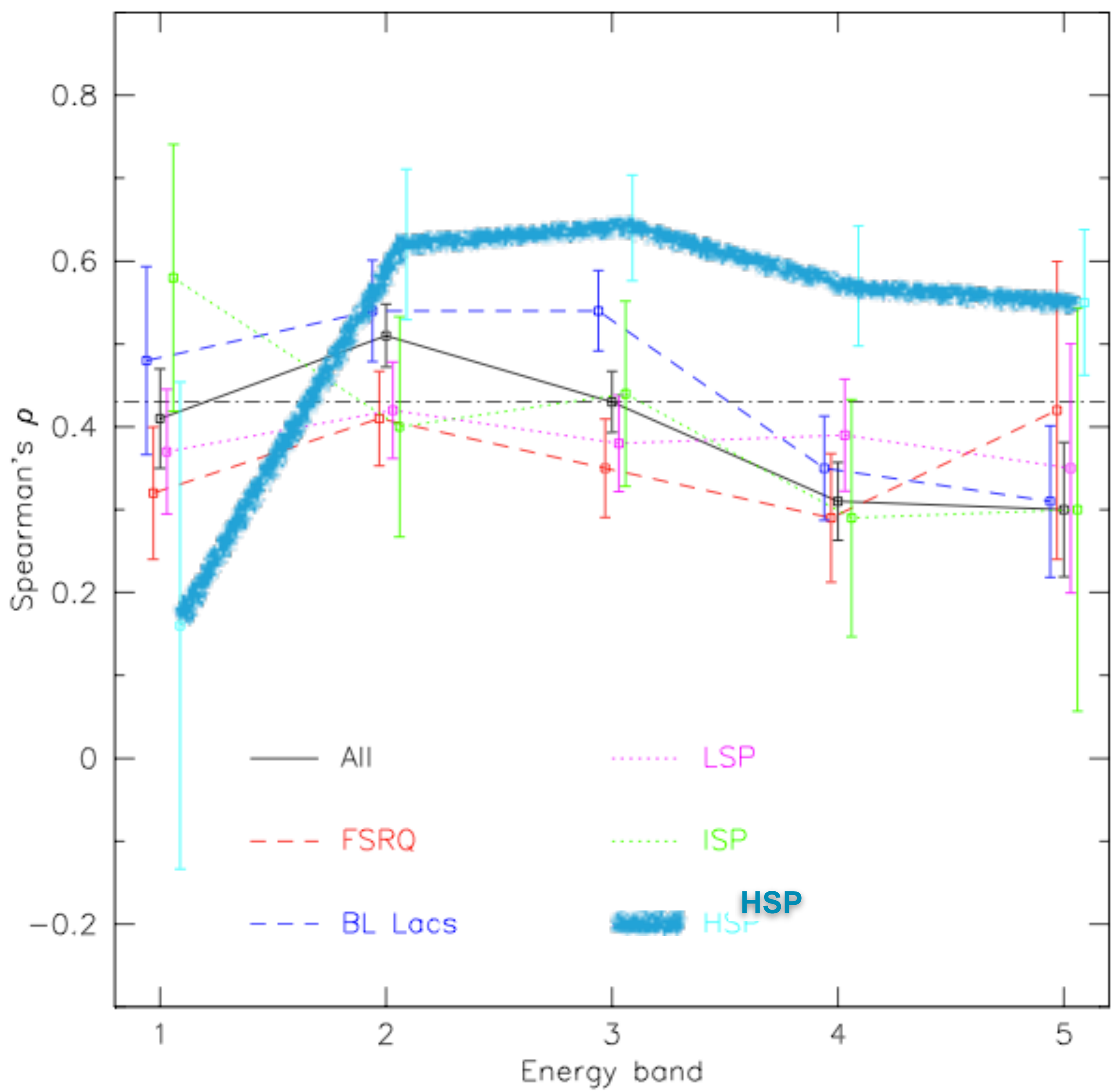
Additional tests: 2 - blazar types

- **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

Additional tests: 3 - energy bands

- not all LAT energy bands correlate with radio with the same strength...
  - for the whole 1LAC, the strongest correlation is found using Band 2 (0.3-1 GeV)
- in every band, 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

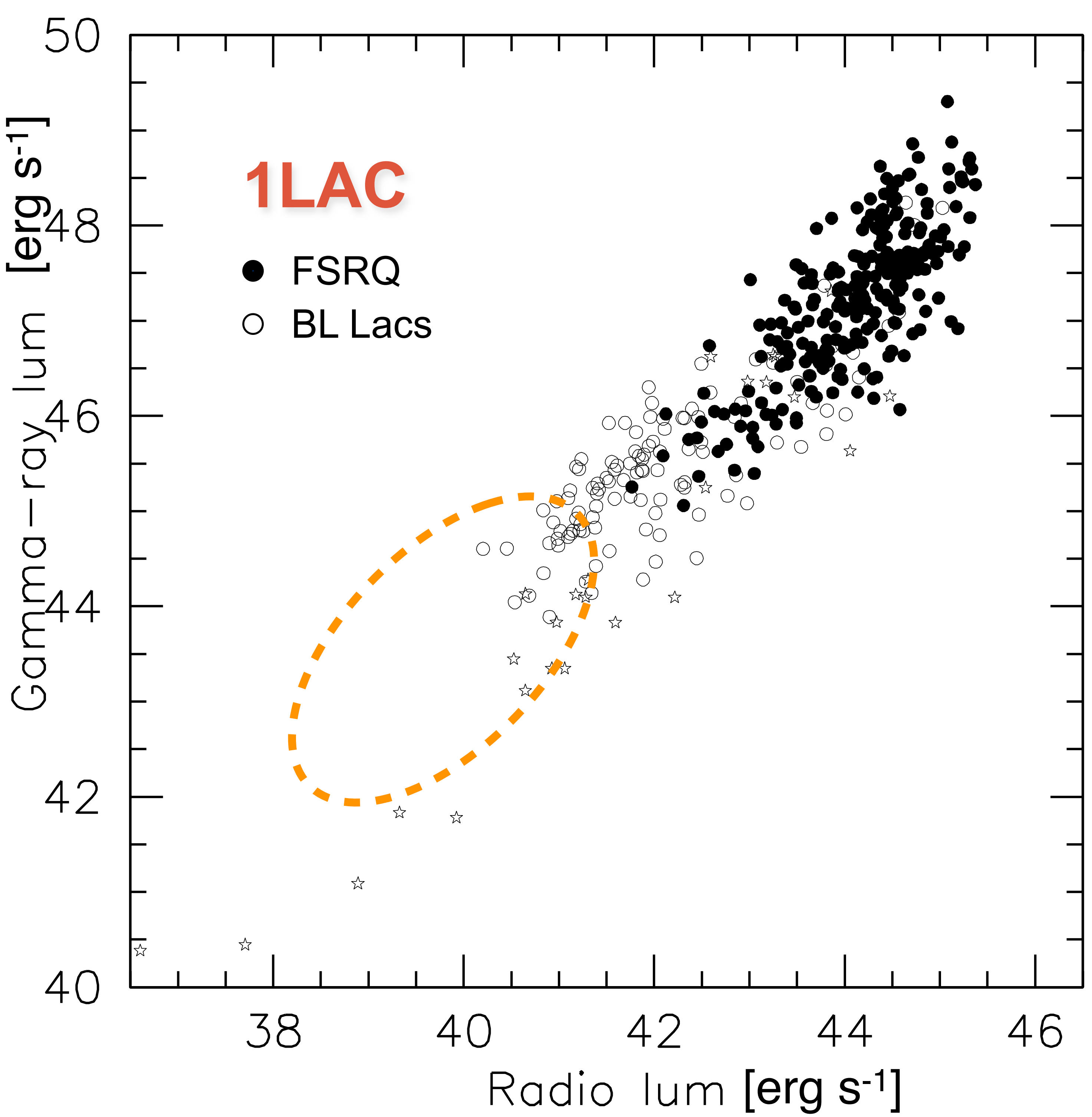


Discussion #1

- Correlation is highly significant, but scatter is large
  - connected but different physical processes
    - leptonic contribution generally present
  - connected but different time domains (and emitting regions)
    - study of light curves, SEDs, and jet structure evolution remains very valuable for single sources (Hovatta, Lister, Jorstad talks)
    - concurrent data do correlate better
  - gamma-ray flux/luminosity can not be predicted on the basis of the radio flux density/luminosity
    - caveat for gamma-ray background studies
    - and many (moderately) bright FSRQs are still undetected in 1LAC/2LAC/3LAC

Discussion #2

- 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^{39-41} erg s^{-1}) for intrinsically weak and/or misaligned blazars



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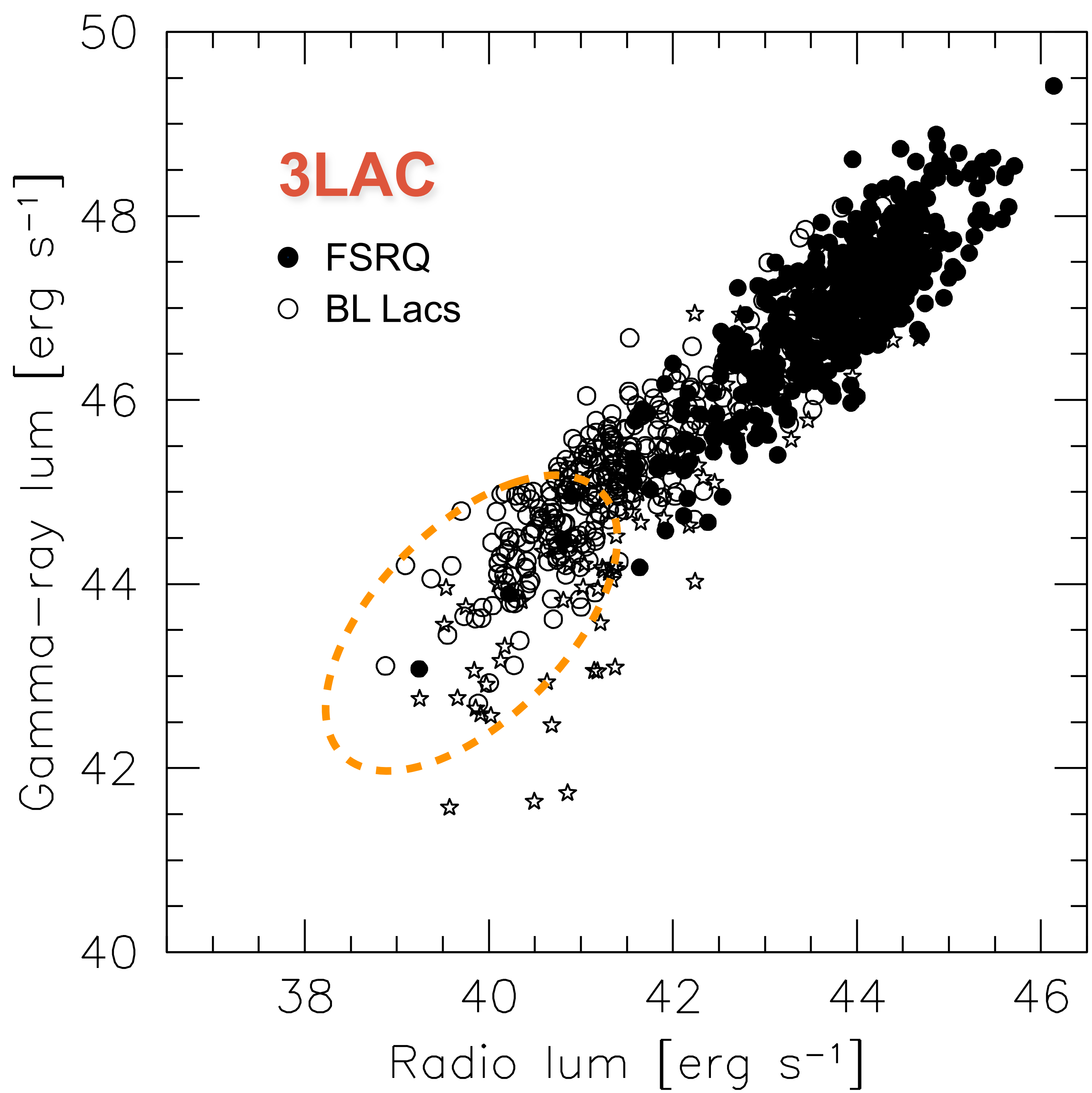


Discussion #3

- Physical implications of these results:
  - there must be some connection between radio and gamma-ray processes and emission regions
  - leptonic processes contribute to gamma-ray emission
    - synchrotron self-Compton processes are favoured in BL Lacs and particularly in HSP blazars (stronger correlation)
    - additional effects play a role in FSRQs (external Compton? evolution?)
  - gamma rays and main radio emitting regions are within <1pc

Conclusions, part 1

- Big ~~*questions*~~ answers:
  - is there a correlation between radio and gamma-ray flux in AGNs?
    - YES
  - is it also significant?
    - YES
  - does it depend on simultaneity?
    - YES
  - does it depend on blazar type?
    - ~yes
  - does it depend on energy band?
    - ~yes

Very High Energy (VHE) gamma rays and lack of radio-VHE connection

- observations above ~100 GeV based on detection of Cherenkov atmospheric radiation (IACT)
- 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, ...
- physical issues
  - anti-correlation between SED peak and source power (blazar sequence)
  - extragalactic background light (EBL) attenuation
  - complex framework!

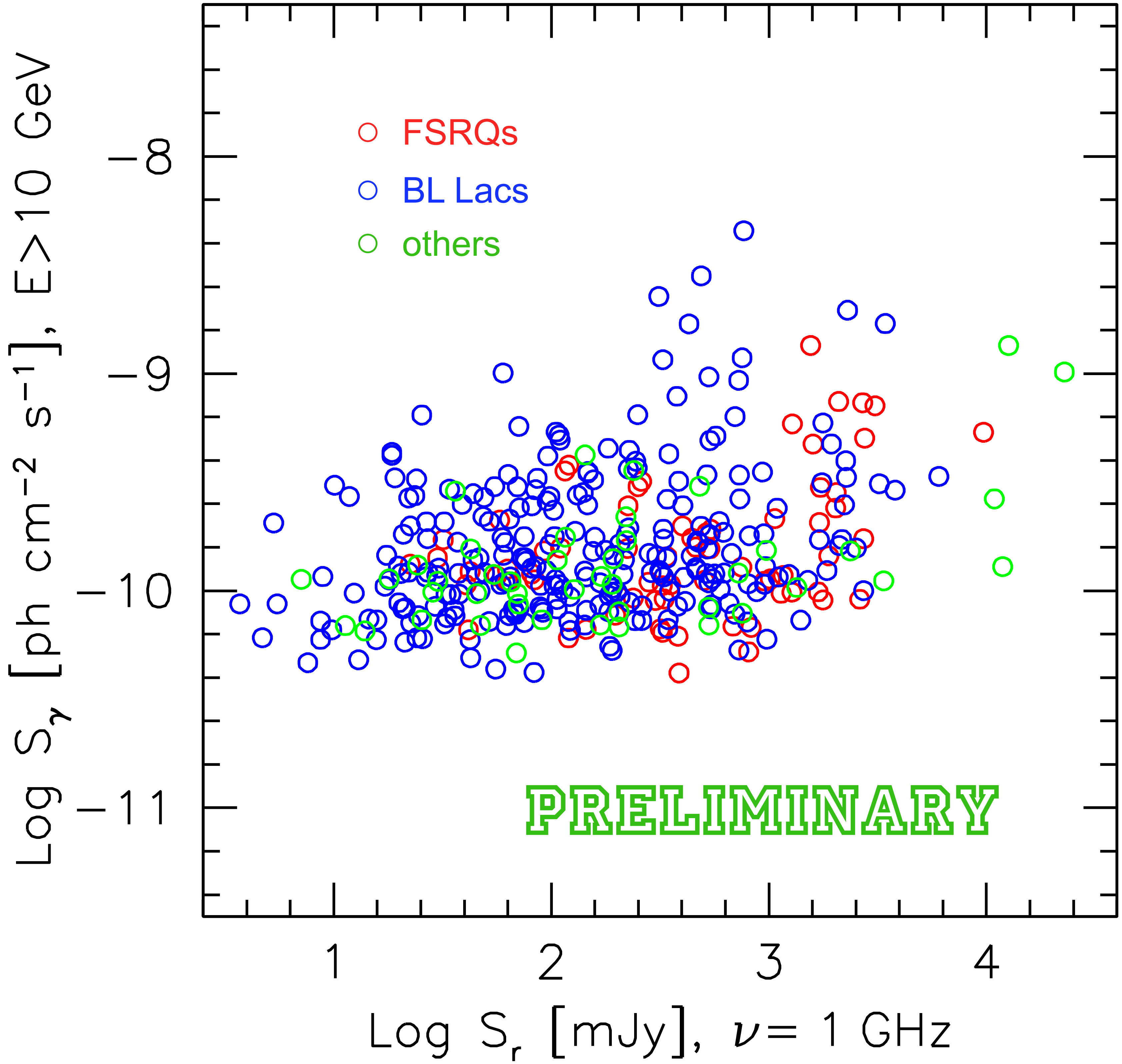
The 1FHL

- 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 vs radio flux density

- **375 associated AGNs**
  - **radio data from NVSS/SUMSS**
  - **(<α>=0)**

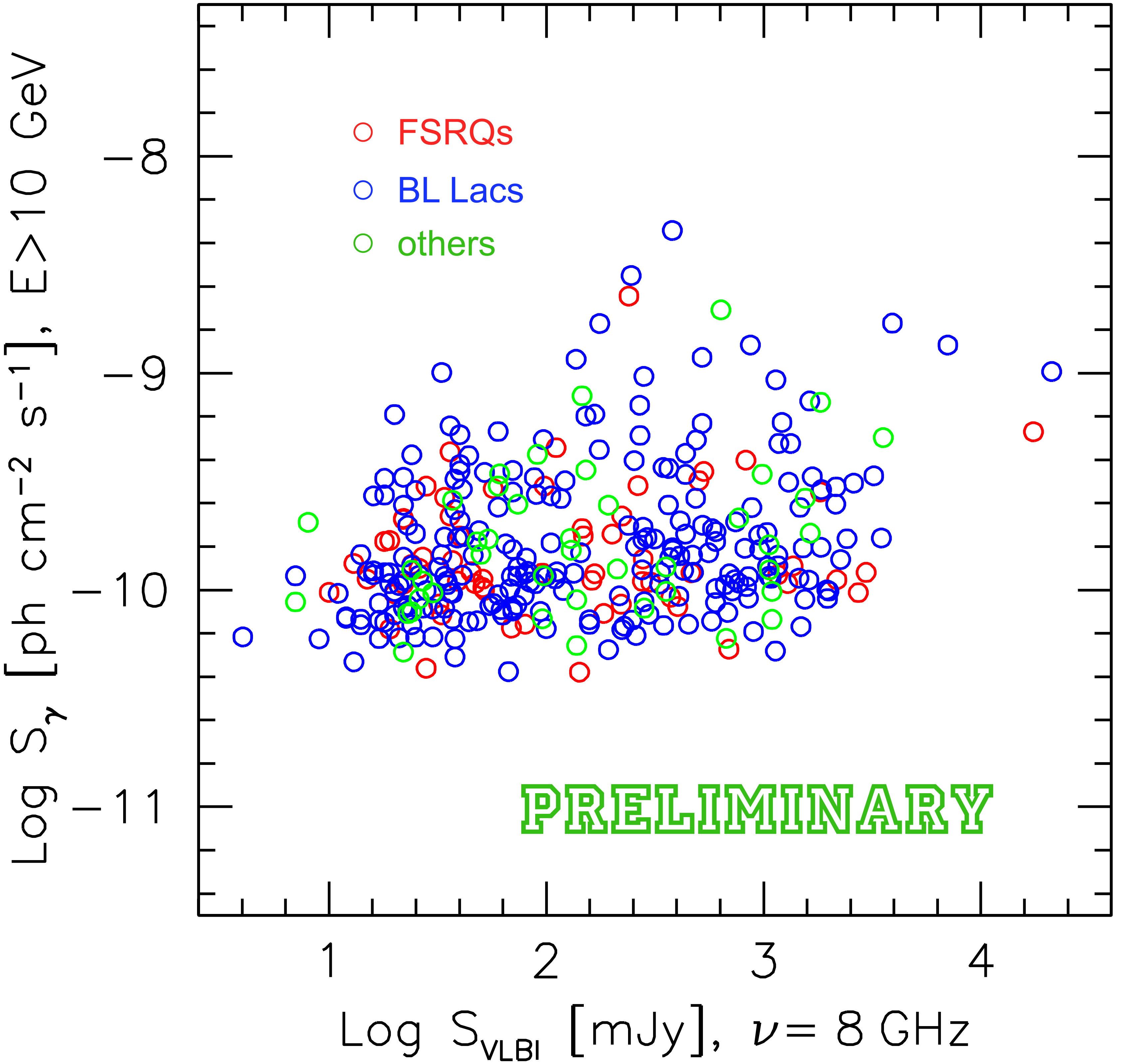
- **r=0.32**
- **chance probability <1e-6**



1FHL vs VLBI flux density

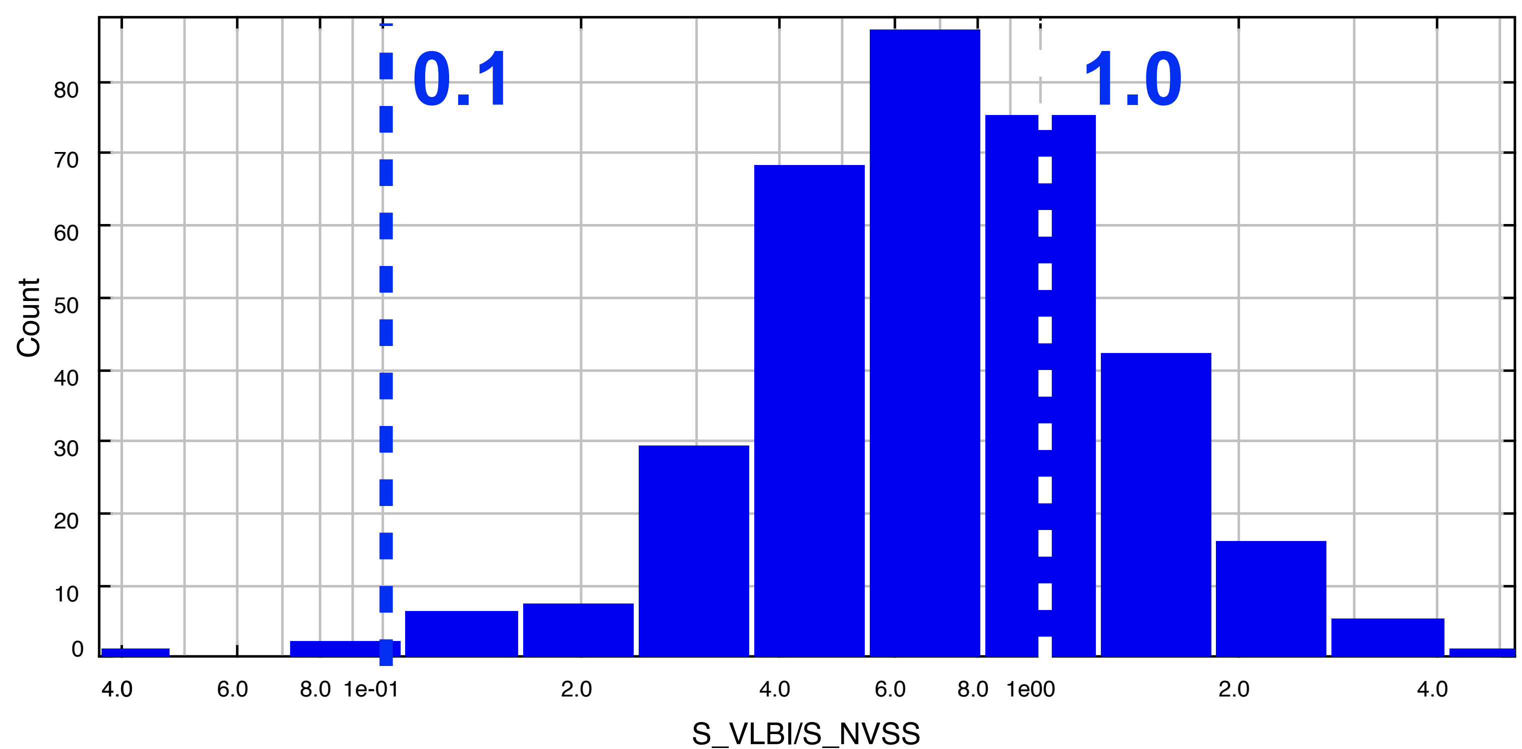
- mas resolution data from radio fundamental catalogue (RFC)
  - VLBI @8GHz
  - 340 sources

- r=0.29
- chance probability <1e-6



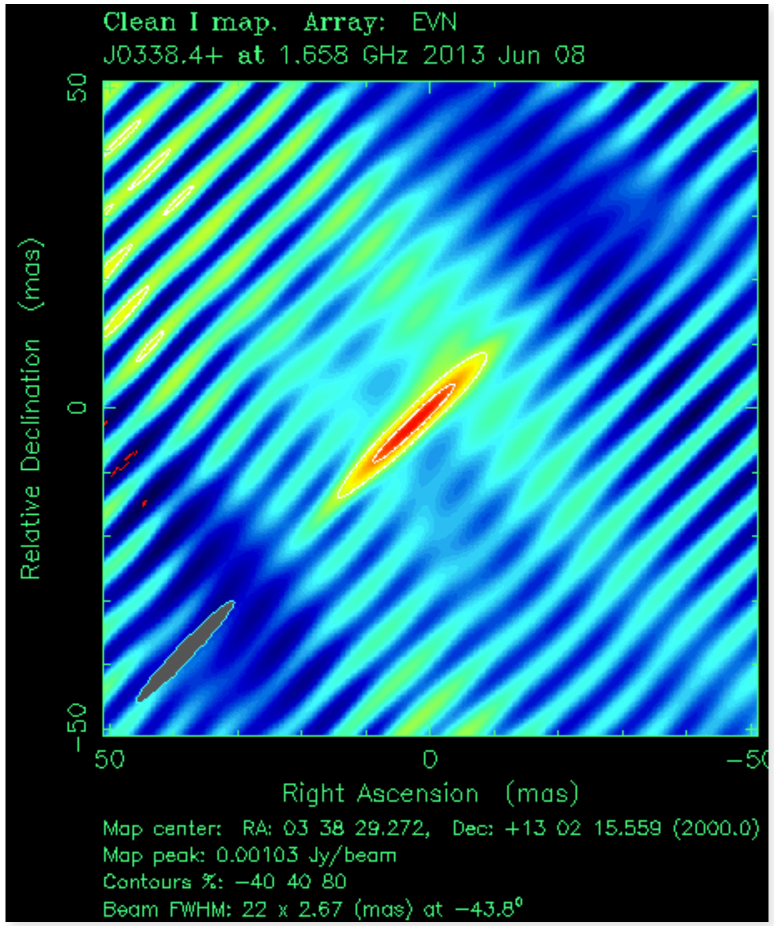
radio-gamma correlation at E>10 GeV

- correlation is
  - scattered
  - weaker than for lower energy gamma rays
    - r=0.66 using NVSS+3FGL data for the same population
  - but still very highly significant
- even at E>10 GHz, radio and gamma-ray regions “know” about each other
- large scale and VLBI data give similar results
- yet, VLBI important to associate sources

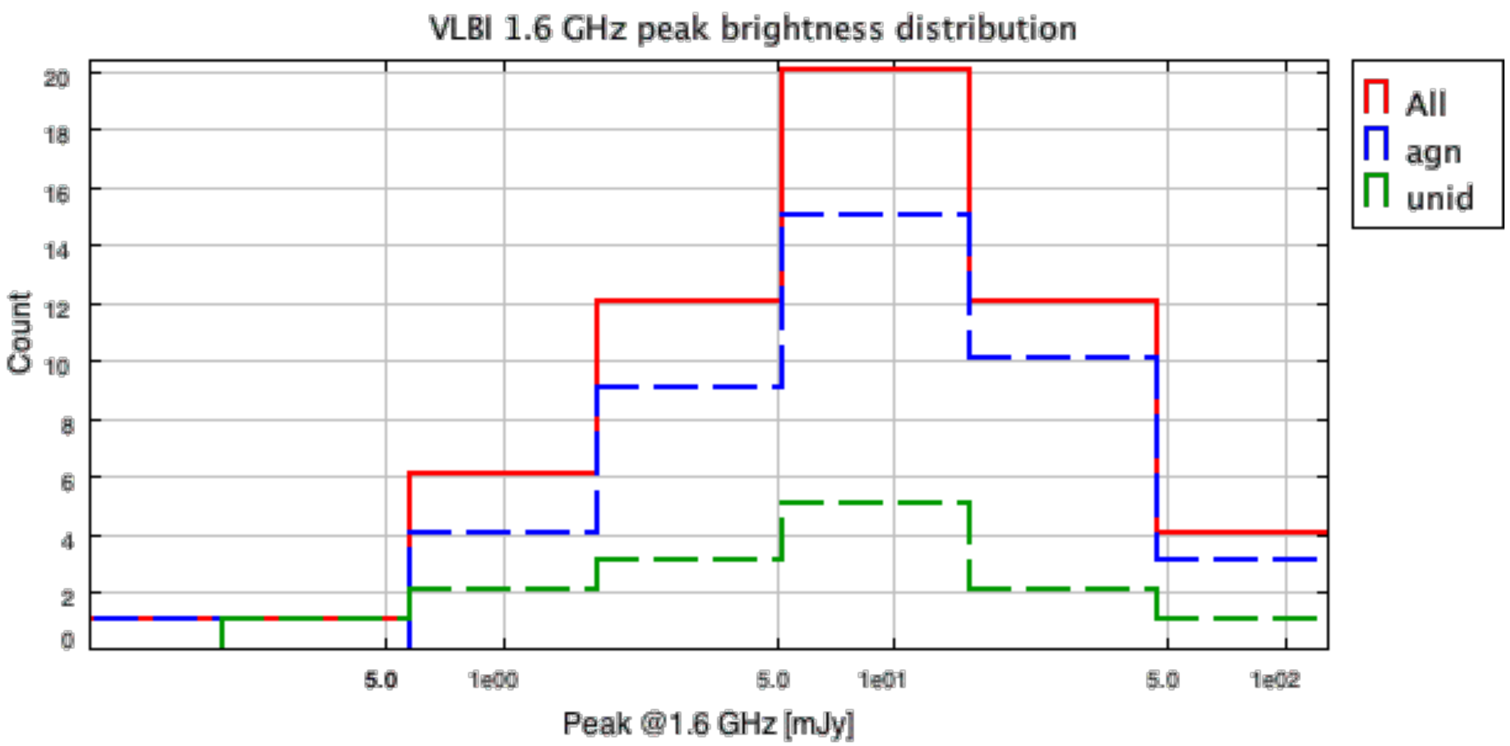


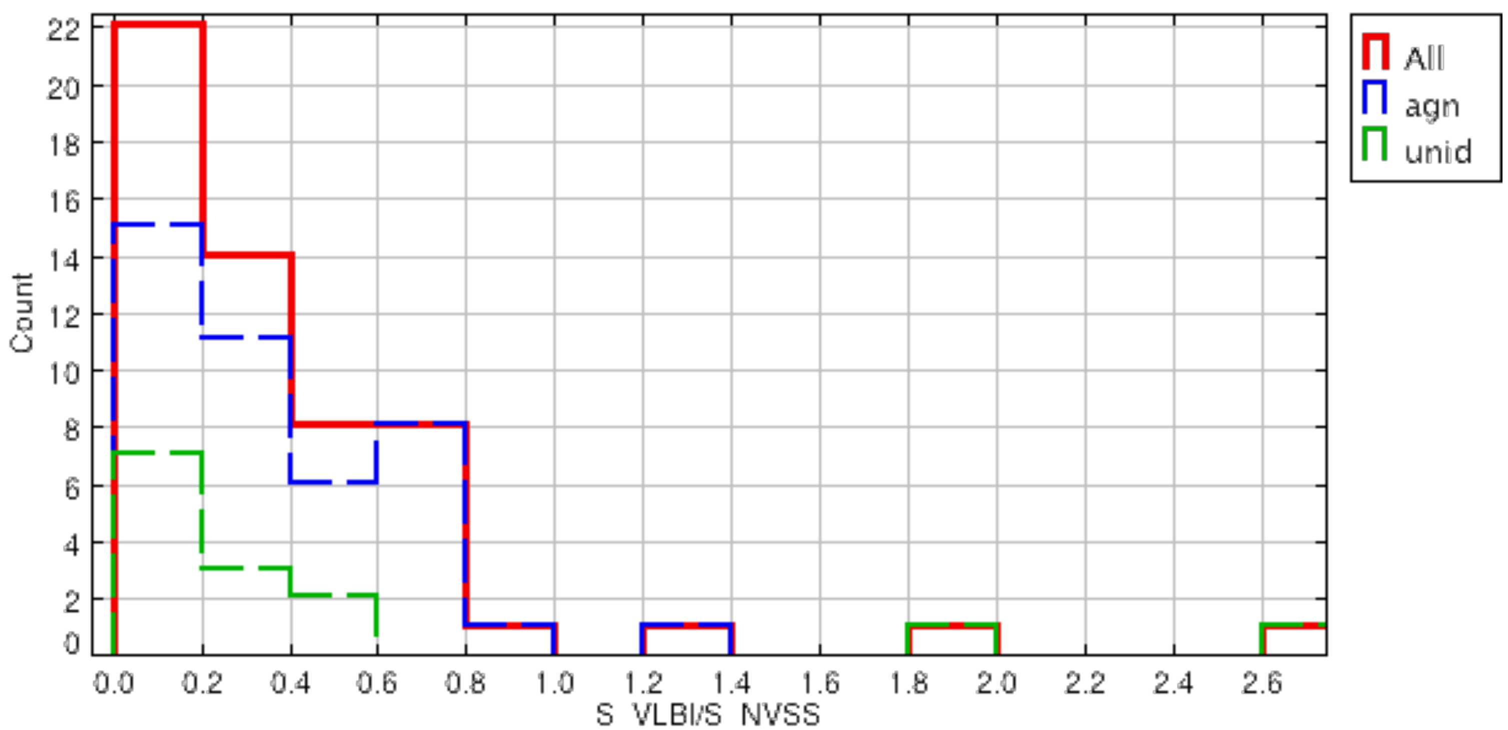
VLBI observations

- goal: complete the VLBI observations for entire 1FHL
  - and address the bias against weak and unassociated sources
- EVN & VLBA observations of ~70 sources
  - 1.6 GHz e-EVN
  - 5 GHz VLBA
- phase reference, no known position
  - found offsets as large as 6” from NVSS centroid
- detection rate
  - 83% overall
    - 100% for blazar candidates
    - 70% for unassociated sources



Radio flux densities





- Sources are generally weak (VLBI brightness distribution peaks ~10mJy)
- a fair amount of resolved flux is present (S_{vlbi}/S_{nvss}~0.1)
- 1FHL AGNs and UNID behave ~similarly
  - UNID sources classified as blazar candidates (D'Abrusco et al. 2013, Massaro et al. 2014) are confirmed as compact radio sources

Take home notes

1. radio-MeV/GeV connection very strong but very scattered
   - work needed to constrain blazar physics

2. radio-VHE connection not as strong, but still there
   - pc scale radio cores are confirmed
   - towards a complete dataset of VLBI images for VHE blazars (Lister talk, Piner poster)

3. *Fermi* operation continues, CTA will become operational soon, SKA pathfinders/precursors are active
   - let's use them all!

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