Unveiling the blazar region with mm-wavelength observations: the ALMA-*Fermi* connection

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Gamma-ray Space Telescope

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ALMA

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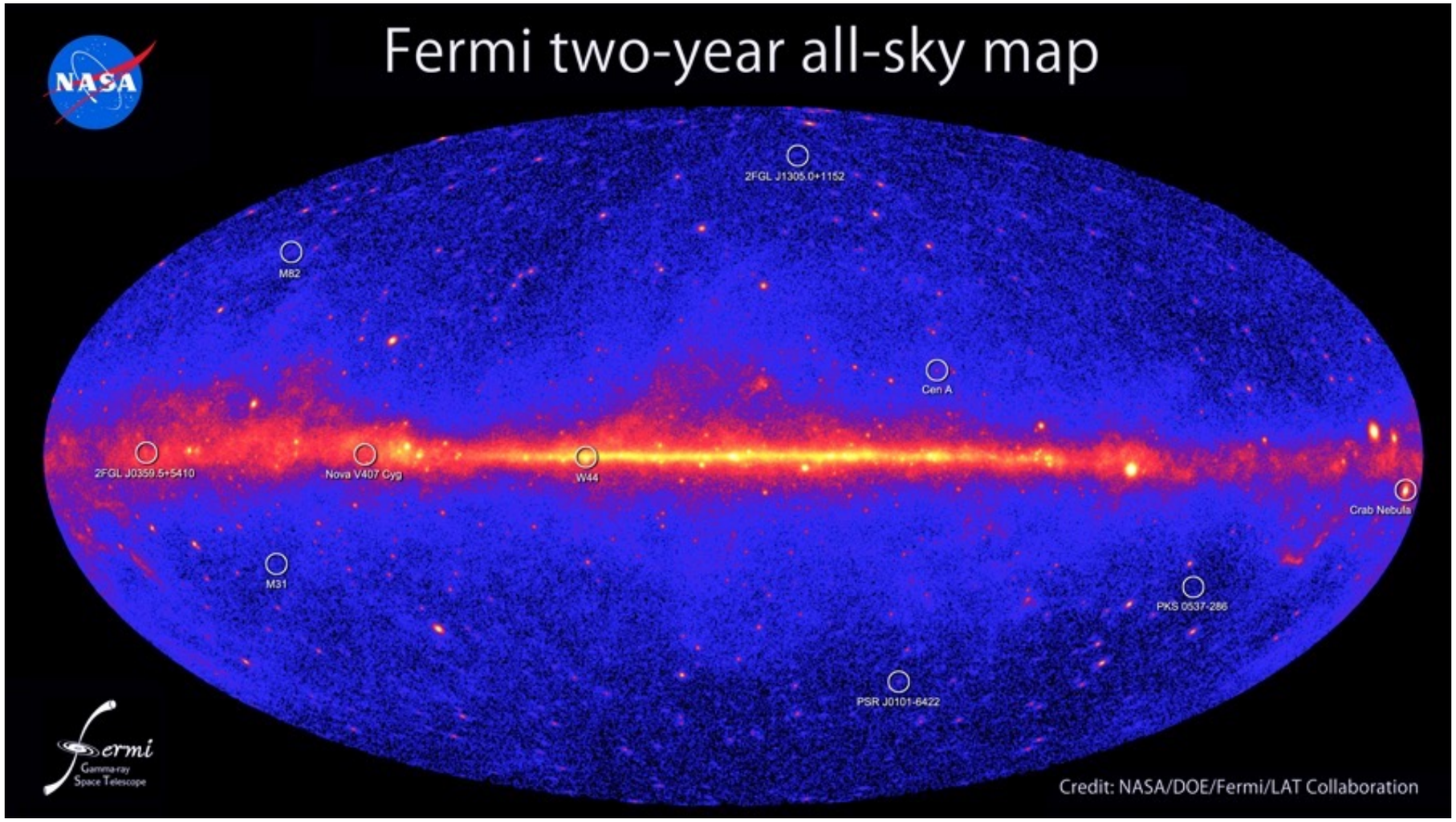
Outline

- broadband emission in blazars
- radio-gamma connection
- recent history
- open questions
- the *Fermi*-ALMA synergy

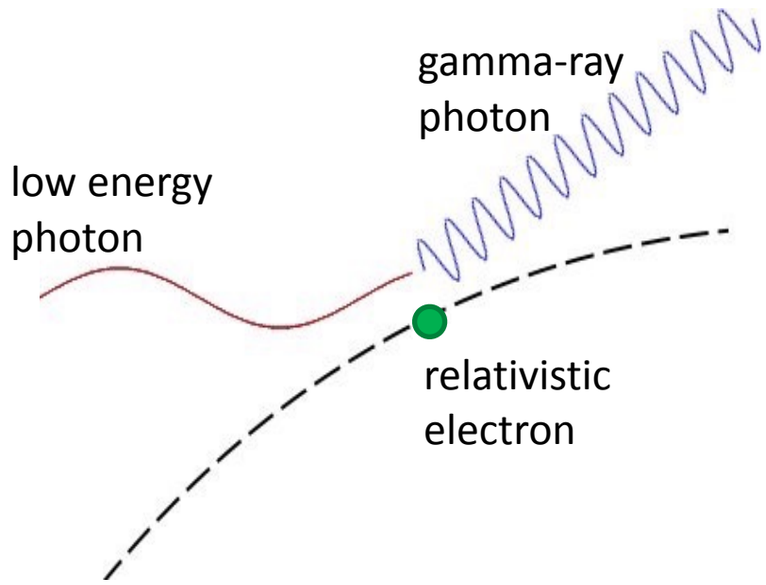


- blazars are very rare compared to other AGNs - but they dominate the census of gamma-ray detected sources

  - e.g. ~60% of the 1800 sources in the 2nd *Fermi* all-sky catalog

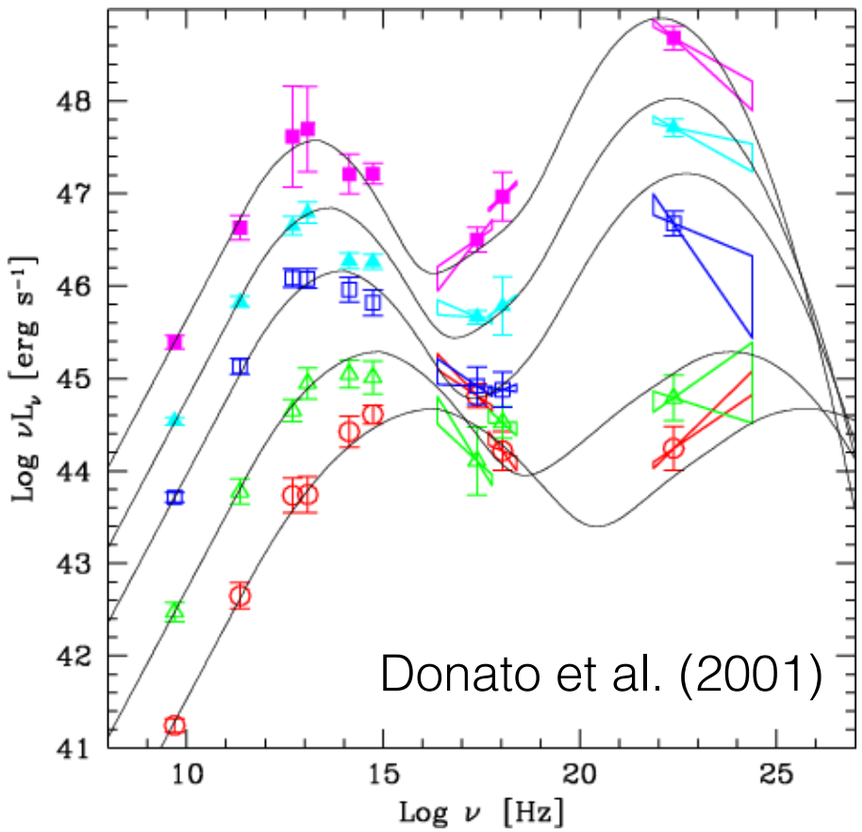
gamma-ray blazars in a nutshell

- a relativistic, beamed jet seems a pre-requisite for gamma-ray emission
  - very much UN-like, e.g., X-rays
- simple physical interpretation is based on relativistic electrons emitting synchrotron radiation and up-scattering seed photons to high energy
  - but how about the details?



Open topics

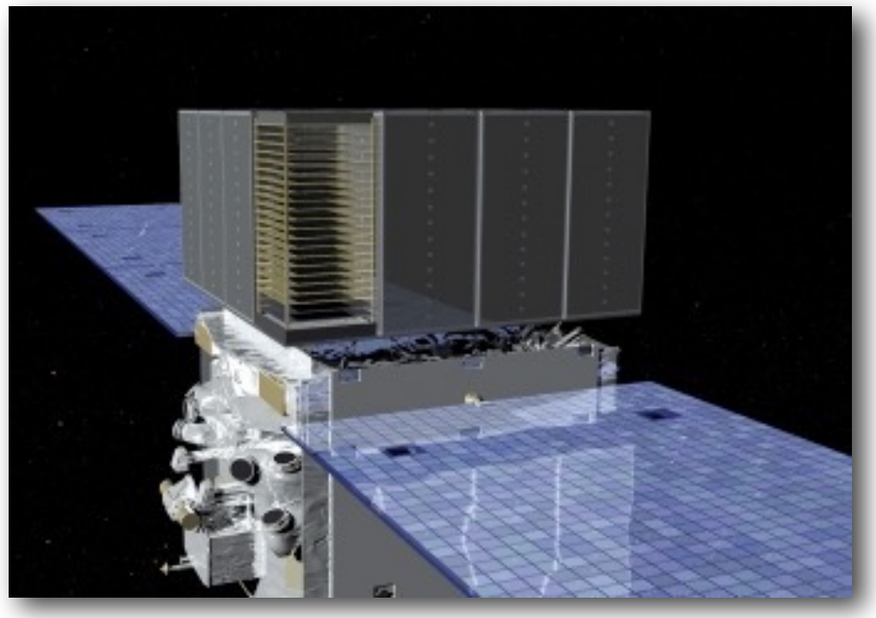
- blazar sequence, real or artefact?
- not all beamed radio sources are gamma-ray detected
- emission regions are probably not co-spatial
- additional mechanisms have been proposed

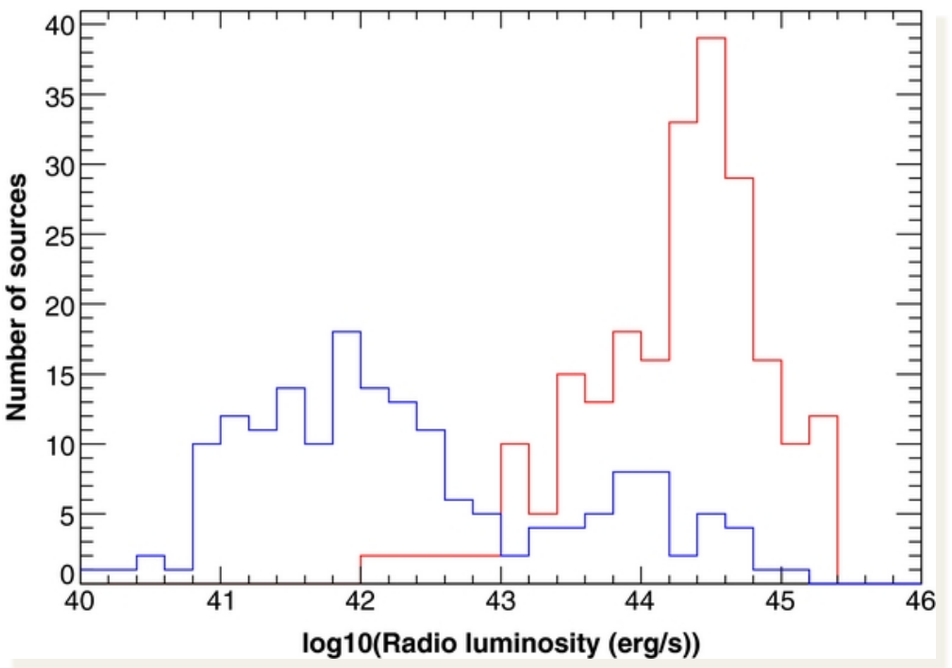


- and this is of interest also for the gamma-ray diffuse background
  - Stecker et al. (1993), Muecke et al. (1997), …

The radio/gamma-ray connection in the *Fermi* era

- Gamma-rays
- 599 sources characterized in gamma rays by LAT in the 1LAC (flux, photon index, and flux in bands)
- 248 flat spectrum radio quasars (brighter, softer, more distant)
- 275 BL Lac type objects (fainter, harder, lower or no redshift)
- 75 other/uncertain (including a handful of radio galaxies and narrow-line Sy1s)



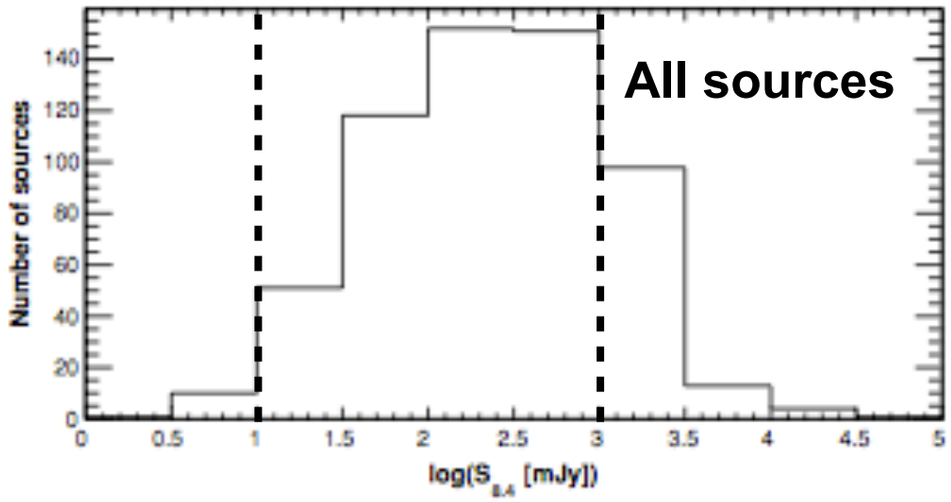


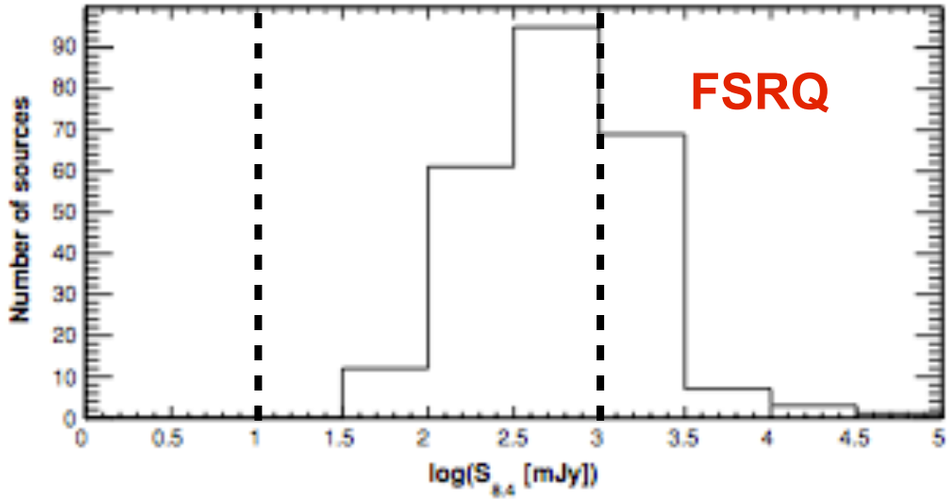
Radio data

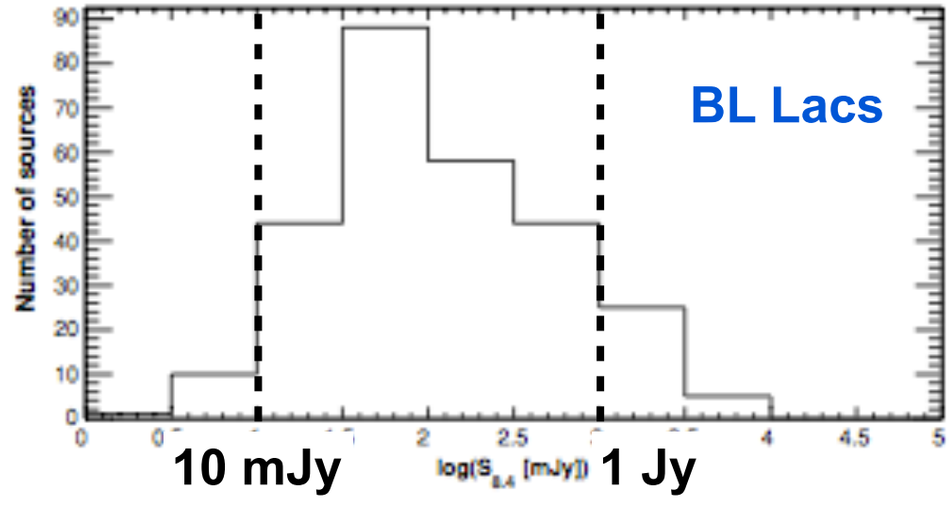
- For **all sources**
  - **archival** radio data of **core** region (freq. 8.4 GHz, ang. resolution ~ 0.2”, e.g. from CRATES, Healey et al. 2007)
- For 199 brightest and northern sources
  - regular and **simultaneous** monitoring (~twice per week) at 15 GHz (from OVRO radio telescope, see Richards et al. 2011, ApJS)

Observed distributions

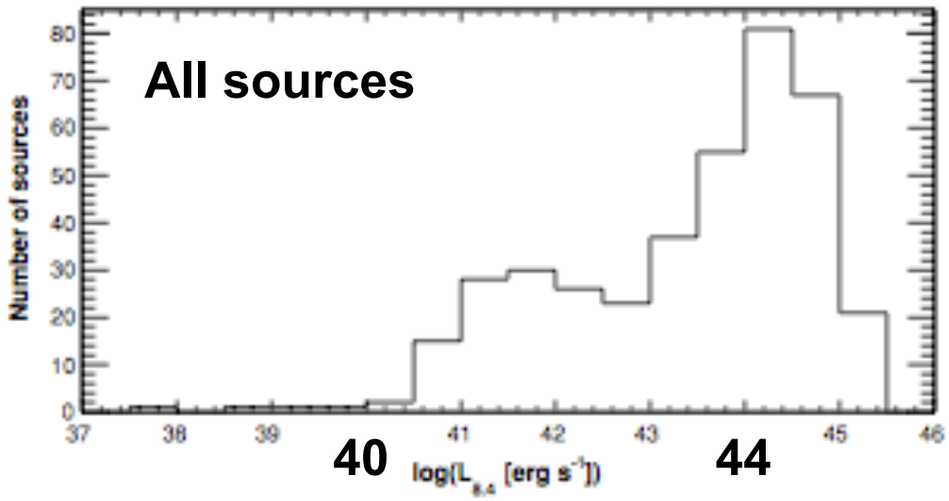
8.4 GHz flux density

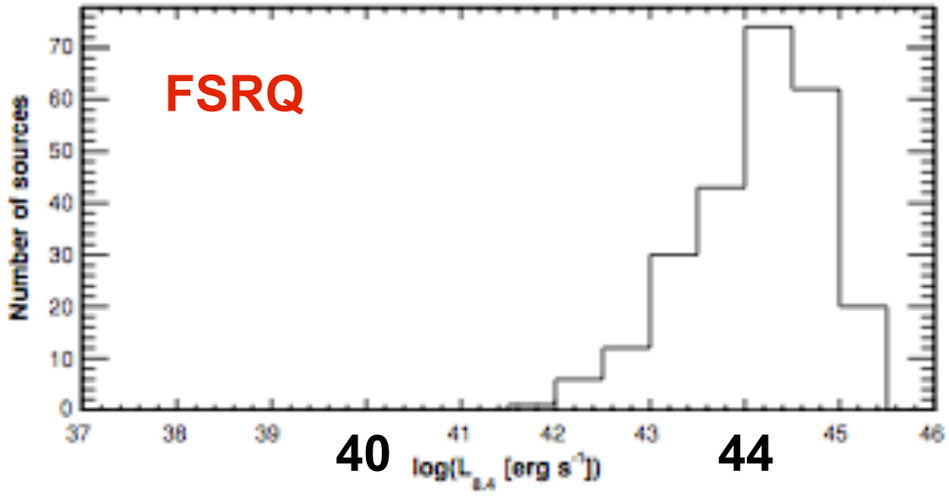


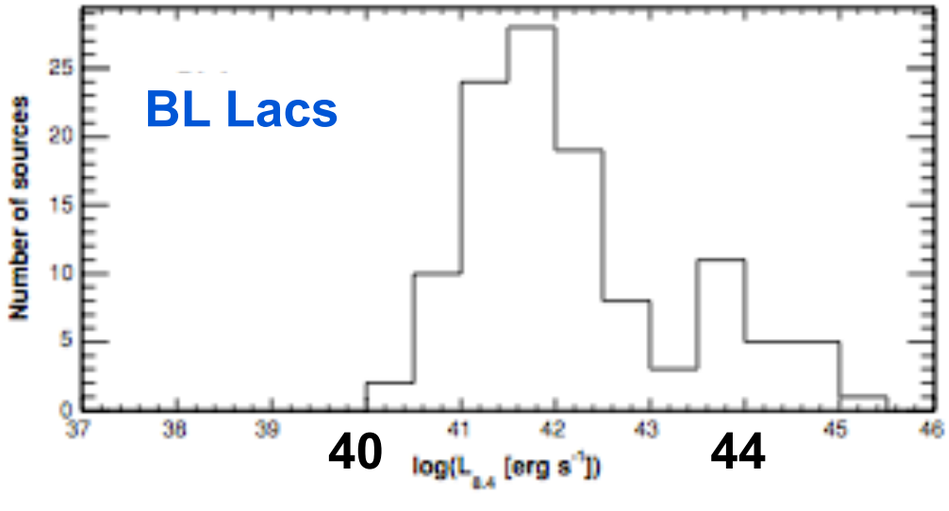




vL(v) Luminosity







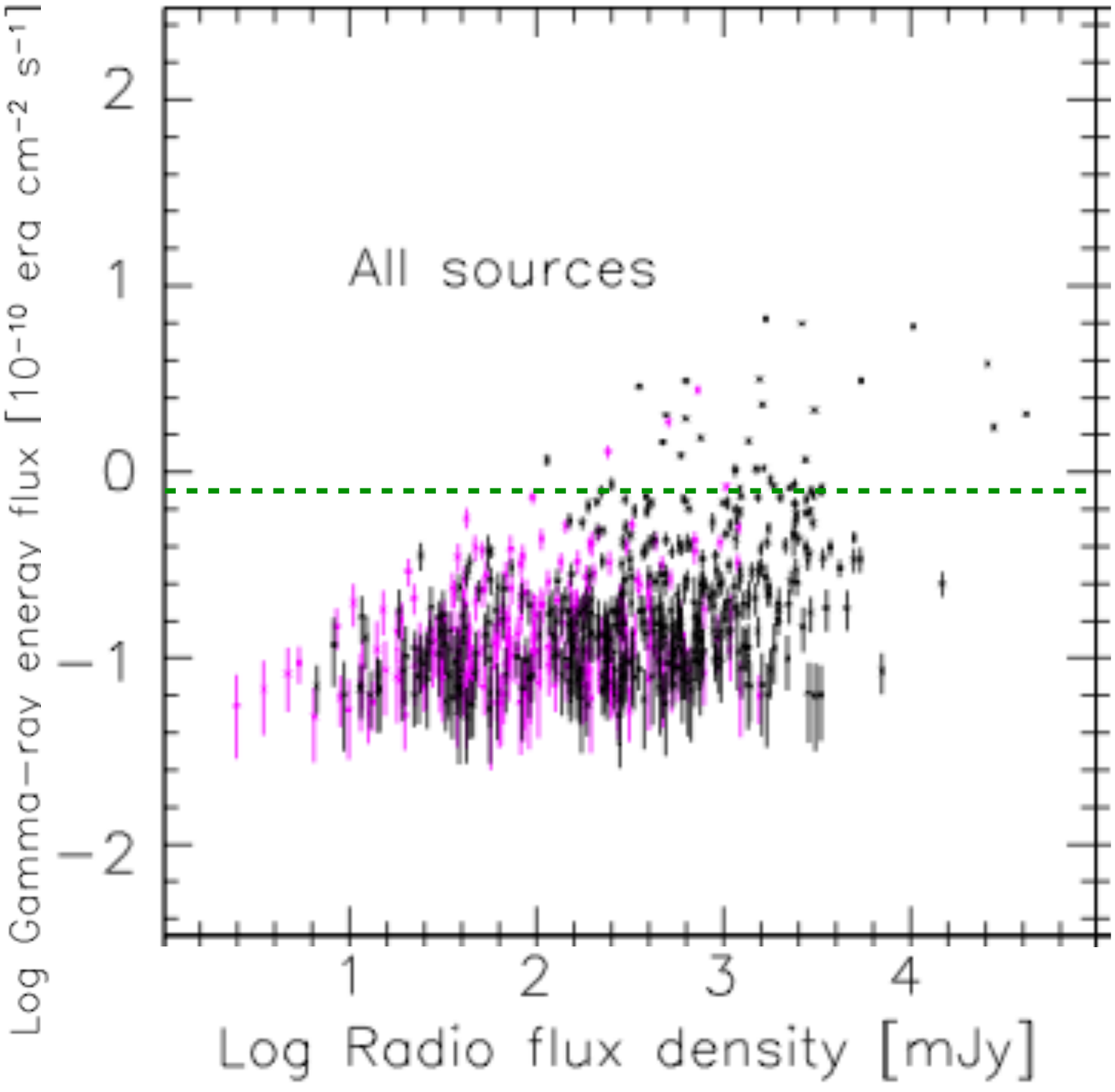
Our significance assessment method (Pavlidou et al. 2012)

- 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?

Results: Ackermann et al. 2011, ApJ 741 30

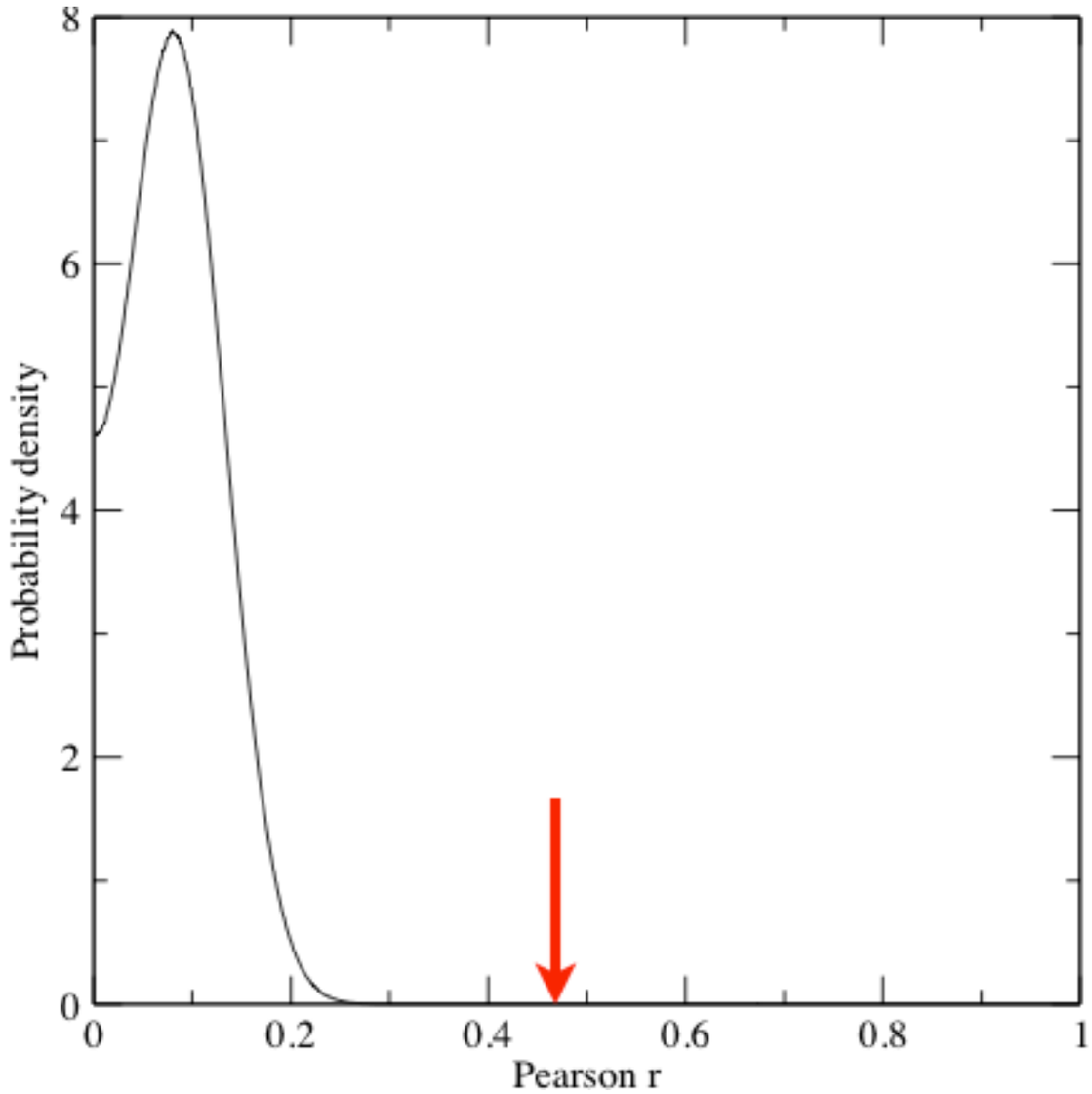
- All 599 1LAC clean sources
- black: with redshift
- magenta: without redshift
- correlation coefficient: *r=0.47*

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**

However…

- Correlation is very significant, but scatter is large
  - connected but different emitting regions and physical processes
  - connected but different time domains
    - NB 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

New approach

- Third *Fermi*-LAT catalogue (3FGL), characterises larger population, and extends gamma-ray flux dynamic range

- Most importantly: mm-wavelength emission from most compact regions, and hopefully nearly free from contamination from jets/lobes

- Possibility to consider simultaneous mm and gamma-ray data

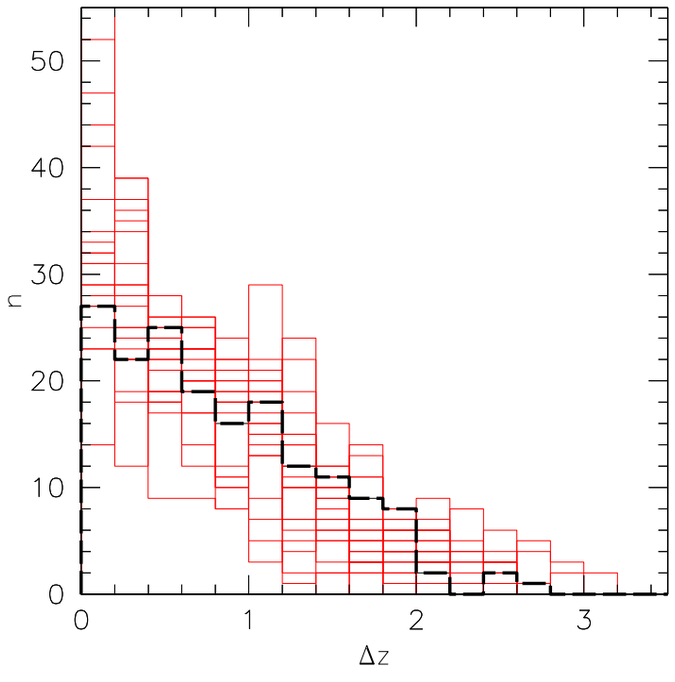
Welcome ALMA!

- Band 6 project: 7.5 GHz bandwidth centered at 233 GHz

  - core emission dominance, in relatively favourable atmospheric transmission condition

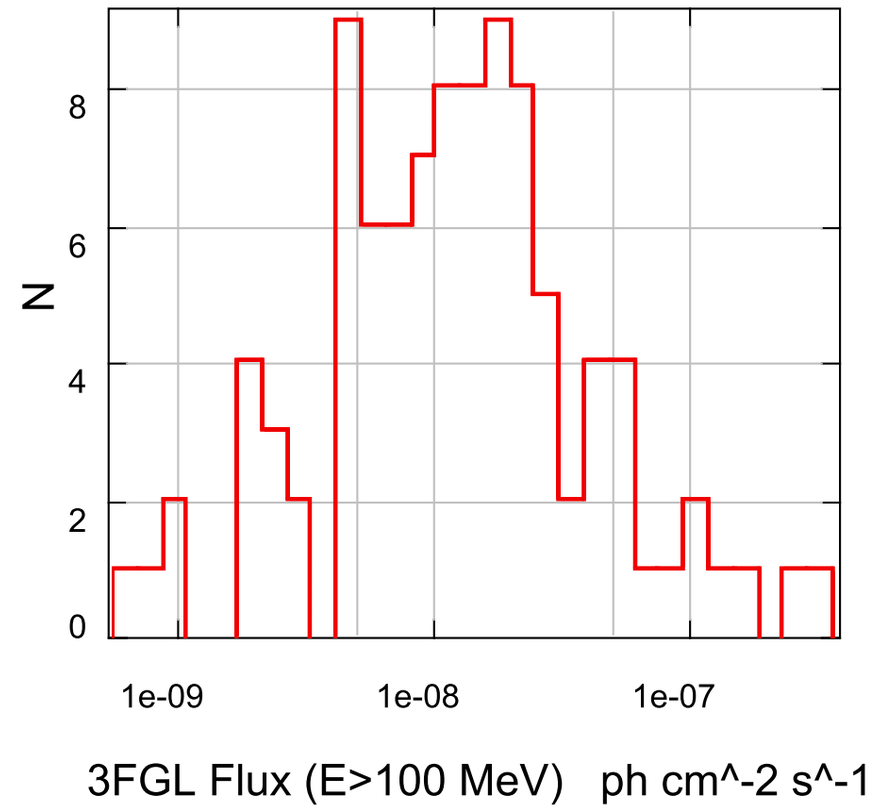
- due to limitations in AO2, select randomly the 10 most gamma-ray crowded 10^{o} radius regions centred on 3FGL AGNs

- total number of sources: 97



An ideal Cycle2/Early Science project

- total number of sources: 97
  - with ~80 sources we already get >5sigma c.l. results
- we can complete the entire project with less than 5 hours! …even with an Early Science configuration



- we can facilitate the characterisation of ALMA systems (one of the purposes of Early Science phase)
- and we can do it simultaneously to *Fermi* operations

The story so far…

- The proposal was approved for ALMA time and ranked within the top 20-40%

- 10 scheduling blocks were generated with support from ARC-IRA-BO last December

- 2 fully observed

- 5 partially observed

- 3 ready for observations

2013.1.01342.S - Unveiling the blazar region with mm-wavelength ob

Entity	Status
2013.1.01342.S	InProgress
Proposal	
ObsUnitSet	PartiallyObserved
SG OUS (Group 1)	PartiallyObserved
SG OUS (Group 2)	PartiallyObserved
SG OUS (Group 3)	Ready
SG OUS (Group 4)	FullyObserved
SG OUS (Group 5)	PartiallyObserved
SG OUS (Group 6)	Ready
SG OUS (Group 7)	FullyObserved
SG OUS (Group 8)	PartiallyObserved
SG OUS (Group 9)	PartiallyObserved
SG OUS (Group 10)	Ready

…so stay tuned!

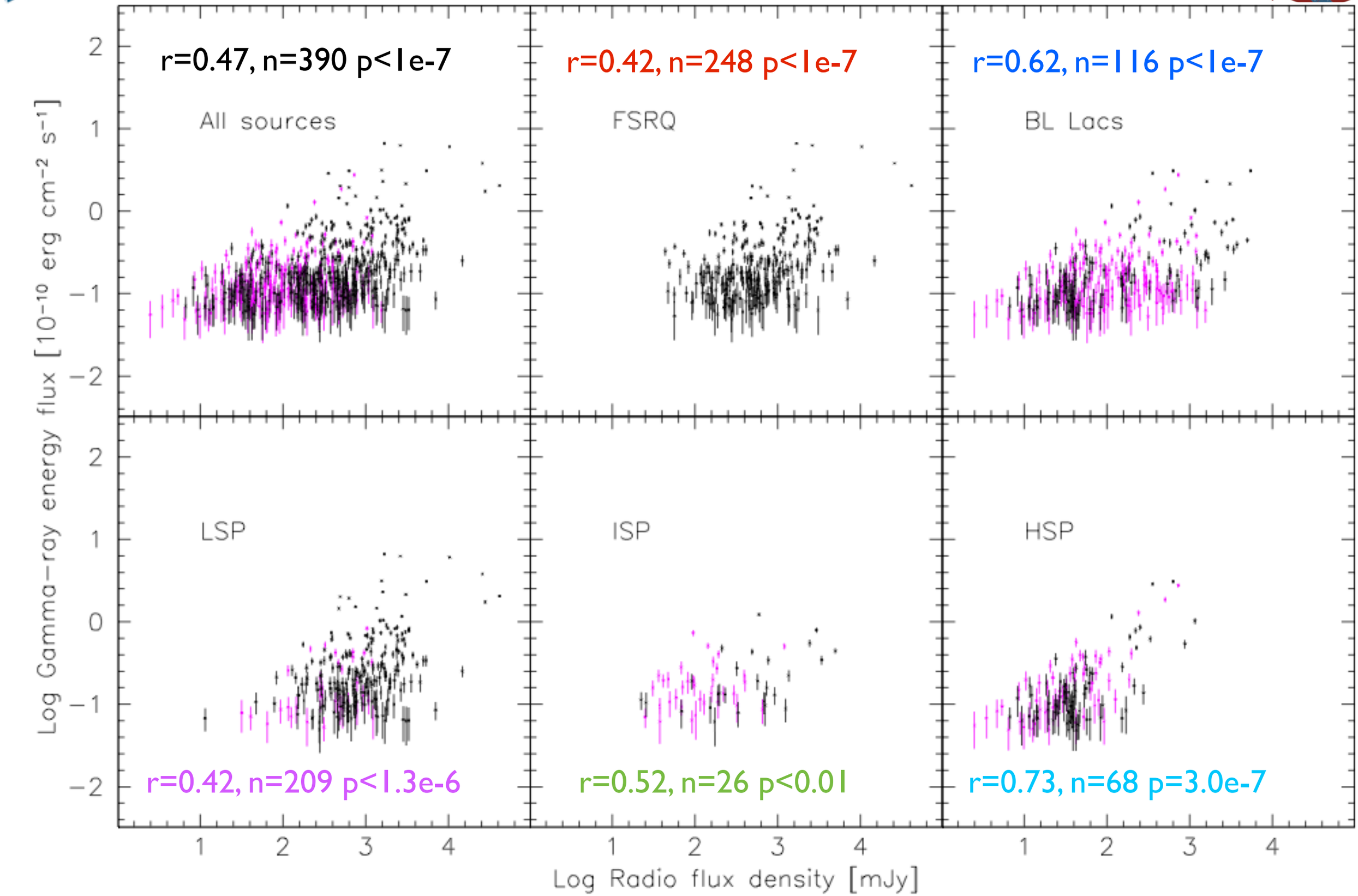
Additional tests: 1 - timing

- **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 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: 2 - blazar types



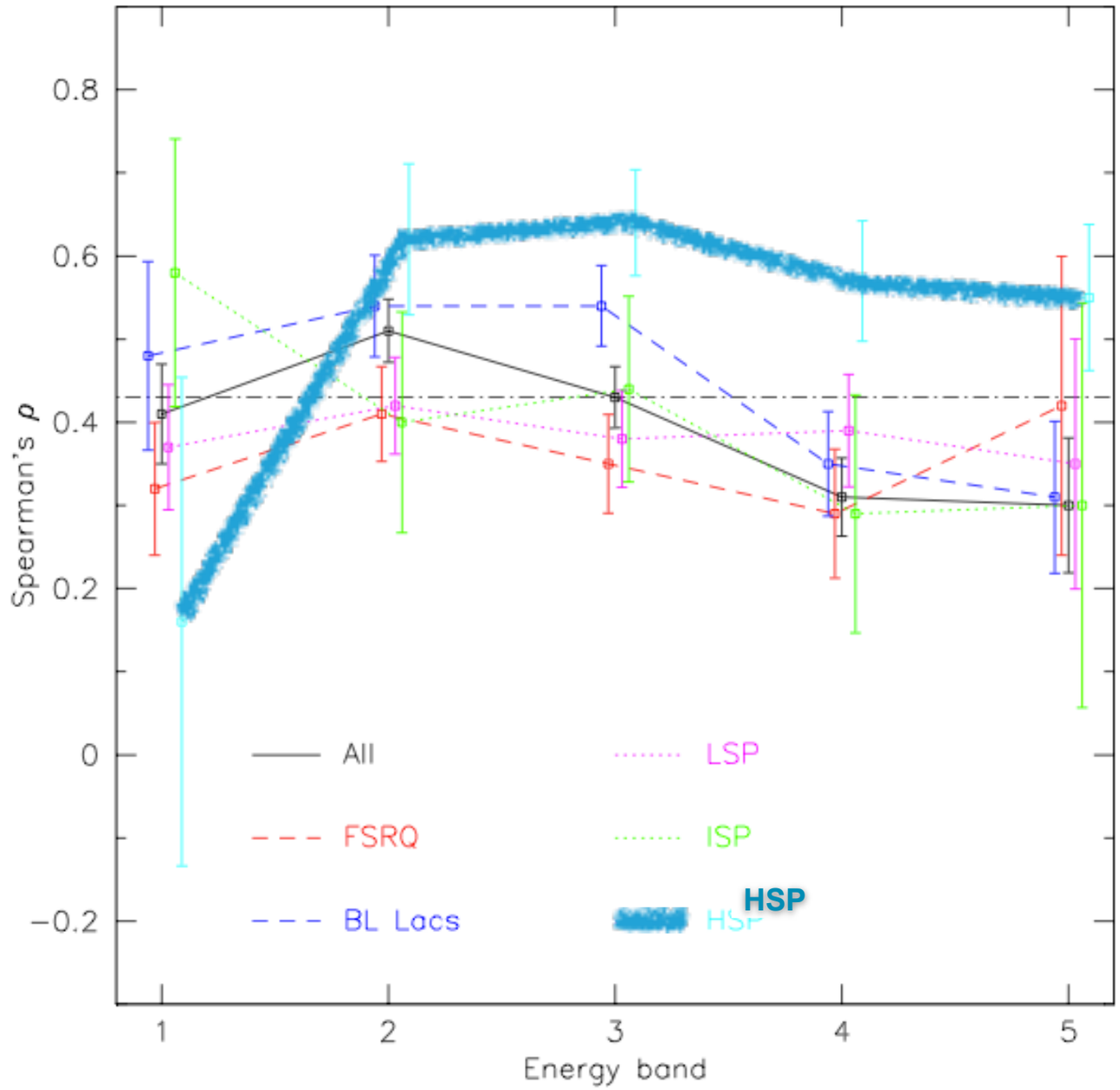
Additional tests: 2 - blazar types

- **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

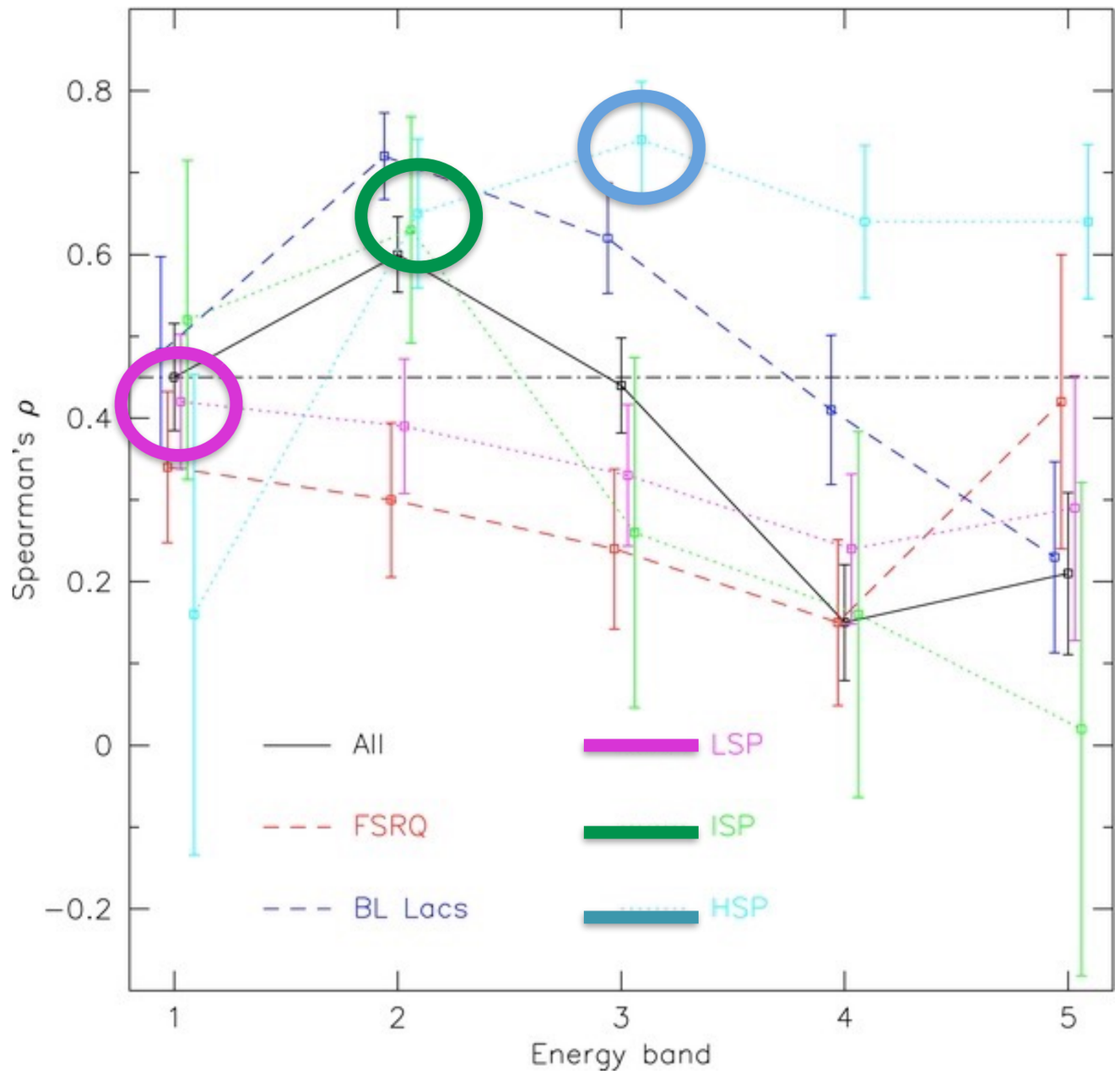
Additional tests: 3 - energy bands

- **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**



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**

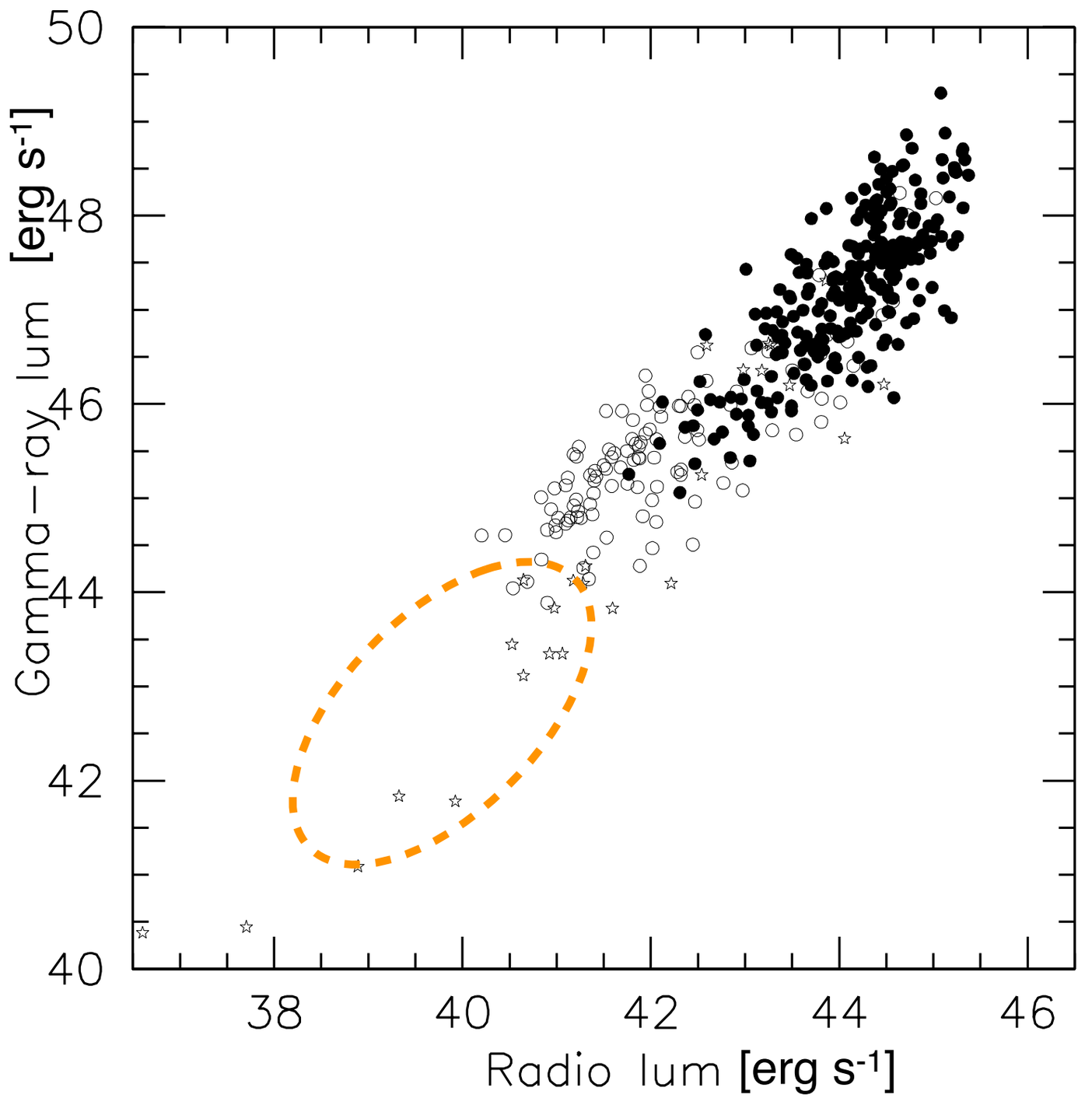


Discussion #1

- **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**
  - **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**

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 ($L_r \sim 10^{39\text{-}41}$ erg s^{-1}) for intrinsically weak and/or misaligned blazars**



Discussion #3

- **Some possible physical implications of our 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 processes play a role in FSRQs (external Compton?)**
  - **gamma rays and radio emitting regions are within <1pc**

Conclusions

- **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**