The radio/gamma-ray connection in Active Galactic Nuclei in the Fermi era

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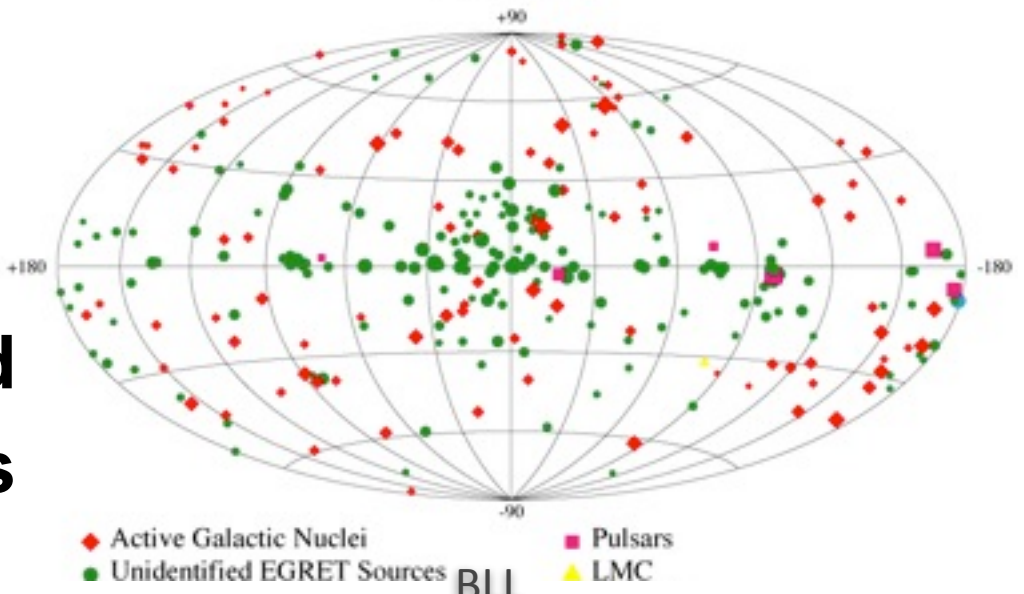
Outline

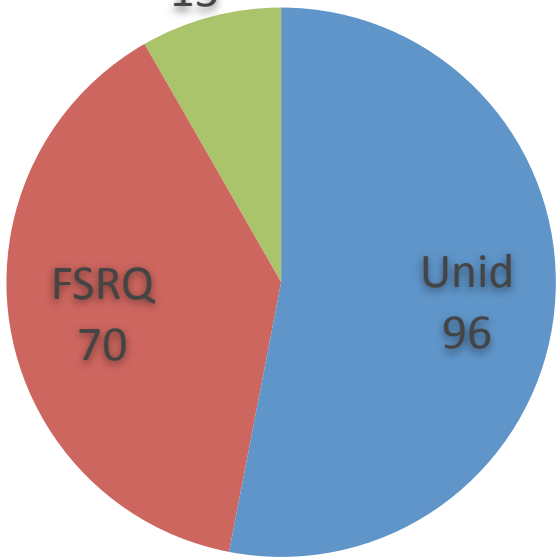
1. General background – EGRET and Fermi
2. Open questions
3. Dataset and method
4. Results
5. Summary

EGRET status

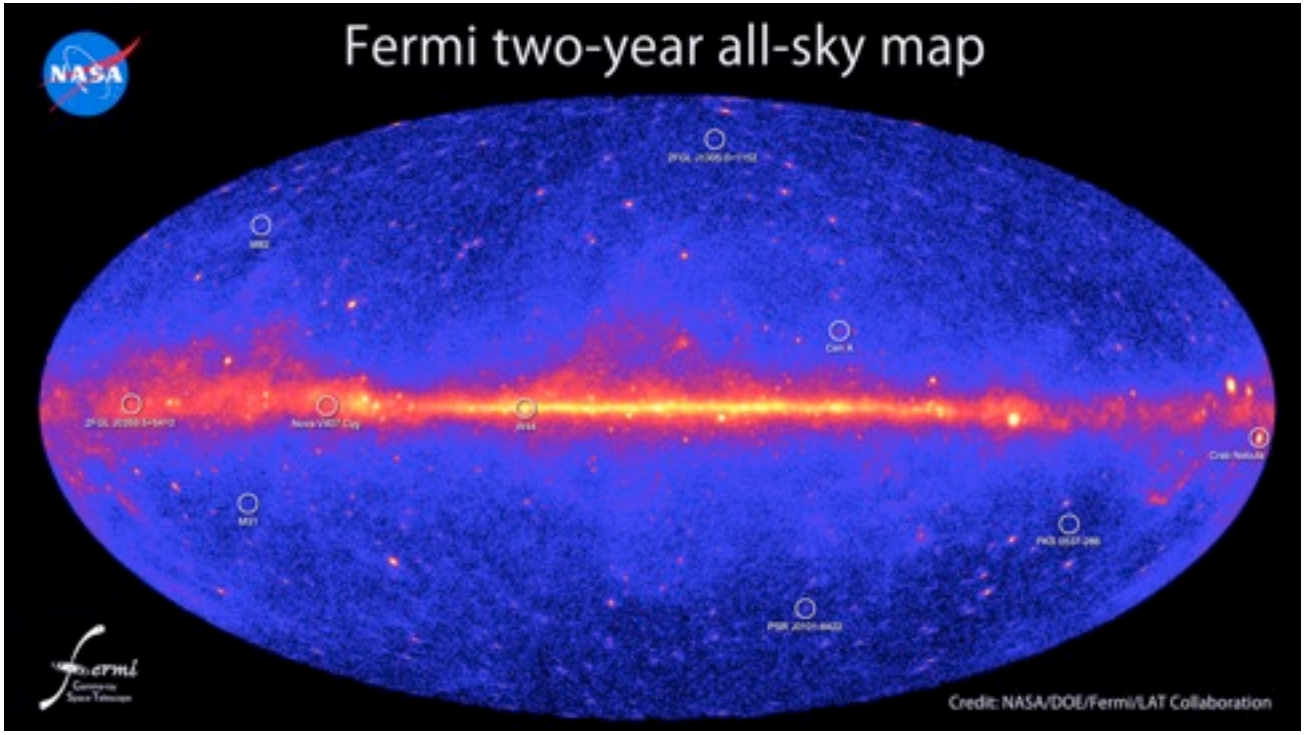
- **EGRET 1991-1999**
- **Most high galactic latitude sources remained unidentified**
- **All the identified ones were radio loud, almost all blazars, and mostly FSRQ; very few BL Lacs, only 2 HBLs**



Hartmann et al. 1999



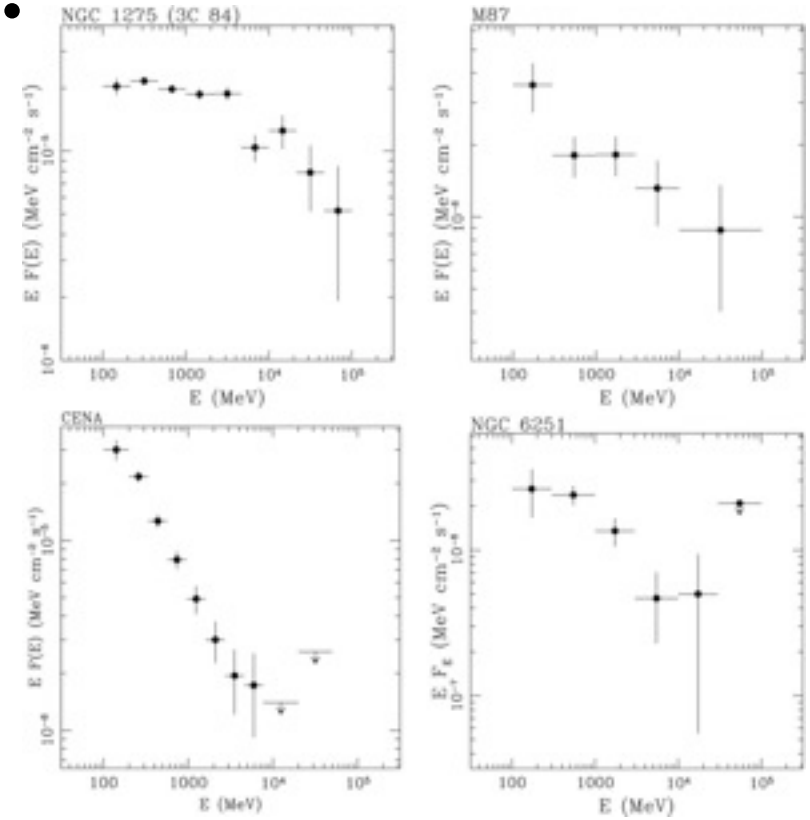
From EGRET to Fermi



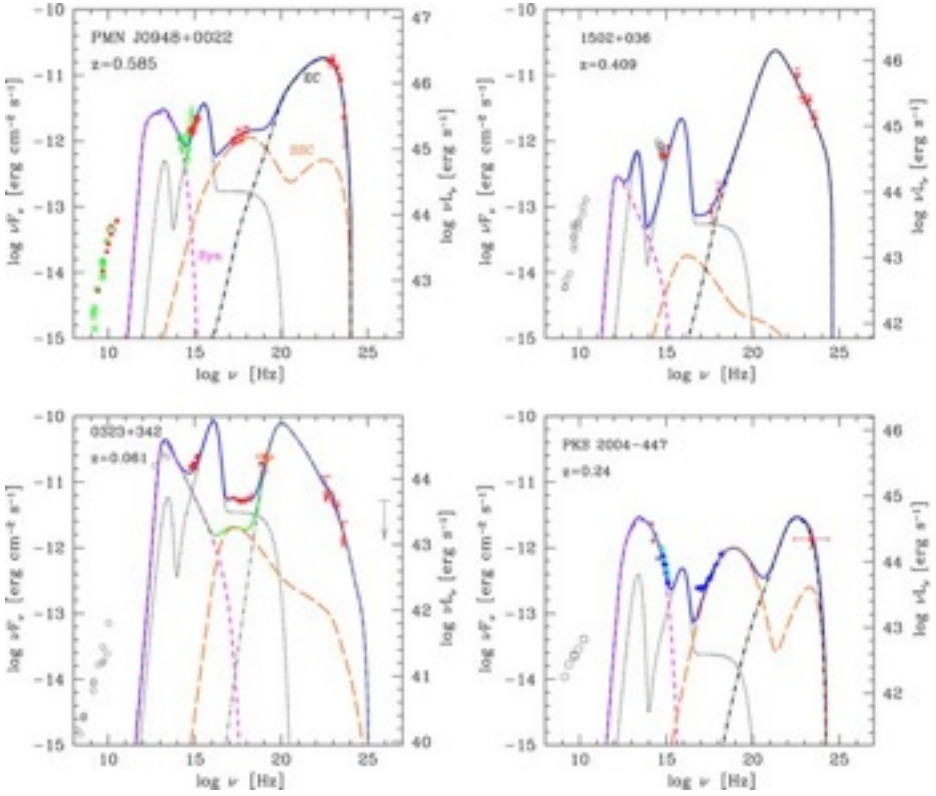
- EGRET: 66 blazar (+27 l.c., FSRQ:BLL=4.7)
- LBAS: 106 AGN (FSRQ:BLL=1.4)
- 1LAC: 709 AGN (FSRQ:BLL=1.0)
- 2LAC: 1017 AGN (FSRQ:BLL=0.8)
- Only a few unidentified sources remain at high fluxes
- Gamma-ray sources continue to be associated to radio loud objects

Blazars, blazars, blazars, and more blazars

- **Vast majority (97.3%) of Fermi h.l. associated sources are blazars**
- **Non blazar sources are typically misaligned blazars (MAGN), or very blazar-like sources (RL NLS1)**
- **Only truly non blazar sources are Cen A lobes and 2 starbursts**
-



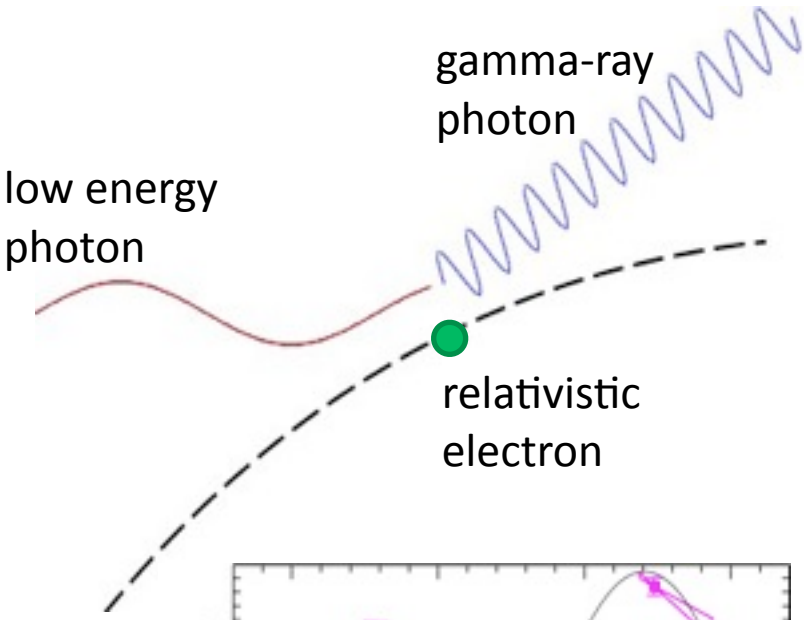
Abdo et al. (2010b, CA: P. Grandi)

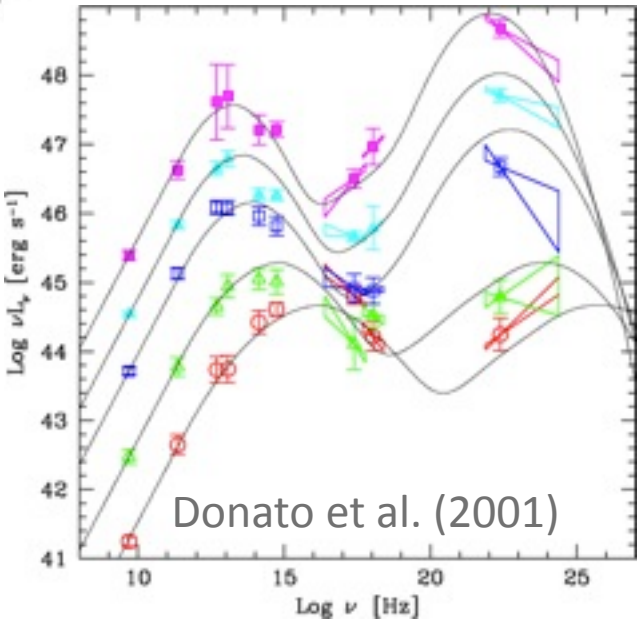


Abdo et al. (2009b, CA: L. Foschini)

Radio and gamma-ray emission in blazars

- **synchrotron radio emission originates from relativistic electrons that can upscatter photons to high energy**
  - **some connection between radio and gamma-ray properties is expected!**
  - **observationally, all EGRET AGNs are 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 in the Fermi era

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

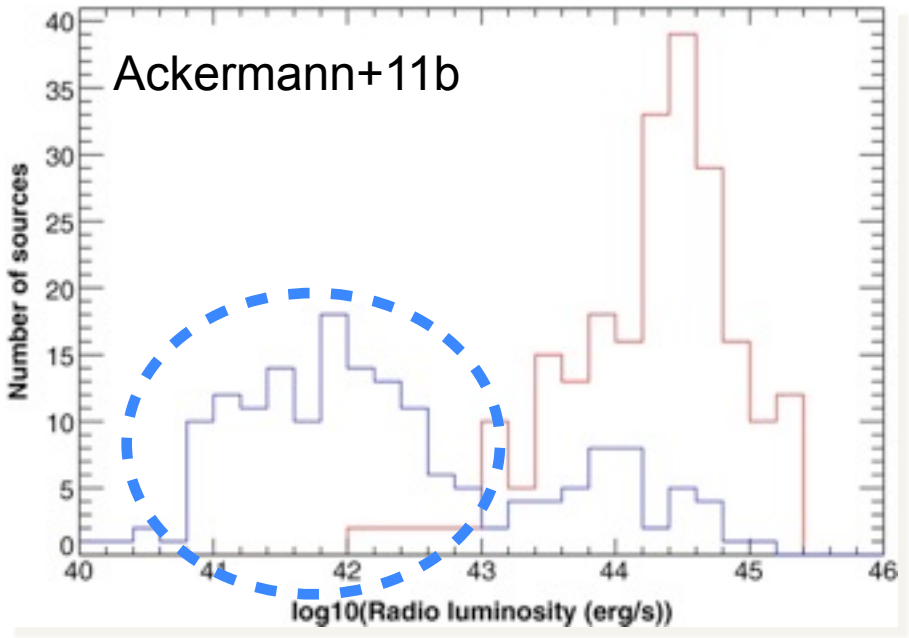
- **See also works from Kovalev et al. (2009), Ghirlanda et al. (2010, 2011), Mahony et al. (2010)**

Radio/gamma-ray connection in the Fermi era

- **Ingredients**
  - **Gamma-rays**
    - **599 sources characterized in gamma rays by LAT in the 1LAC (flux, photon index, and flux in bands)**
  - **Radio**
    - ***ALL SOURCES* with *ARCHIVAL* radio data of *CORE REGION* (freq. 8.4 GHz, ang. resolution ~ 0.2”, e.g. from CRATES, Healey et al. 2007)**
    - **199 brightest and northern also with *REGULAR AND SIMULTANEOUS* monitoring (~twice per week) at 15 GHz (from OVRO radio telescope, see Richards et al. 2011)**
  - **machinery to assess significance of flux-flux correlations – NB: significance and strength are different things! (Pavlidou et al., 2012)**

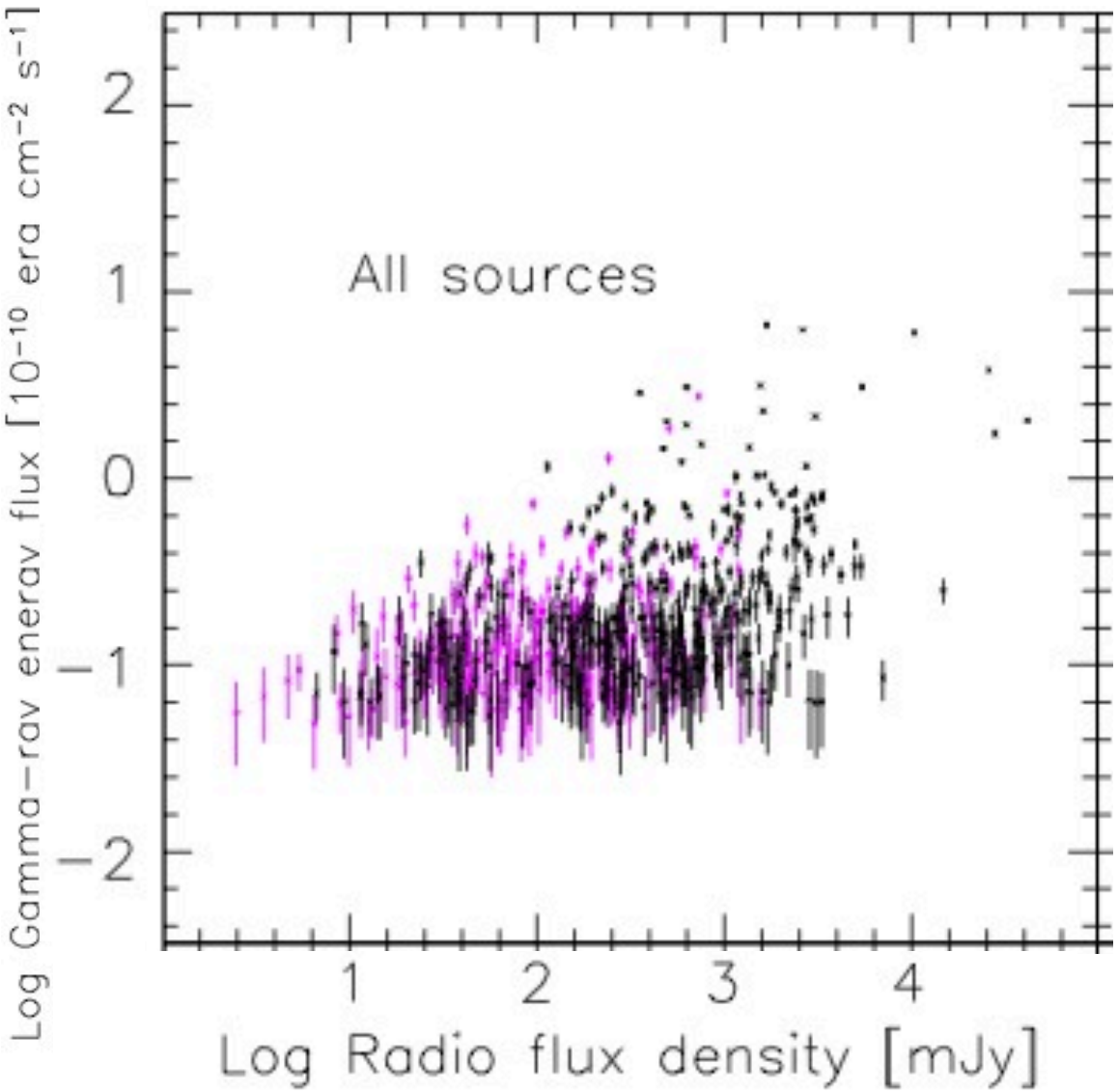
Main novelties

1. **Include ALL gamma-ray AGNs (typically, the faintest ones were not considered in previous works)**
2. **Use both archival and simultaneous radio data**
3. **Assess statistical significance with dedicated tools**

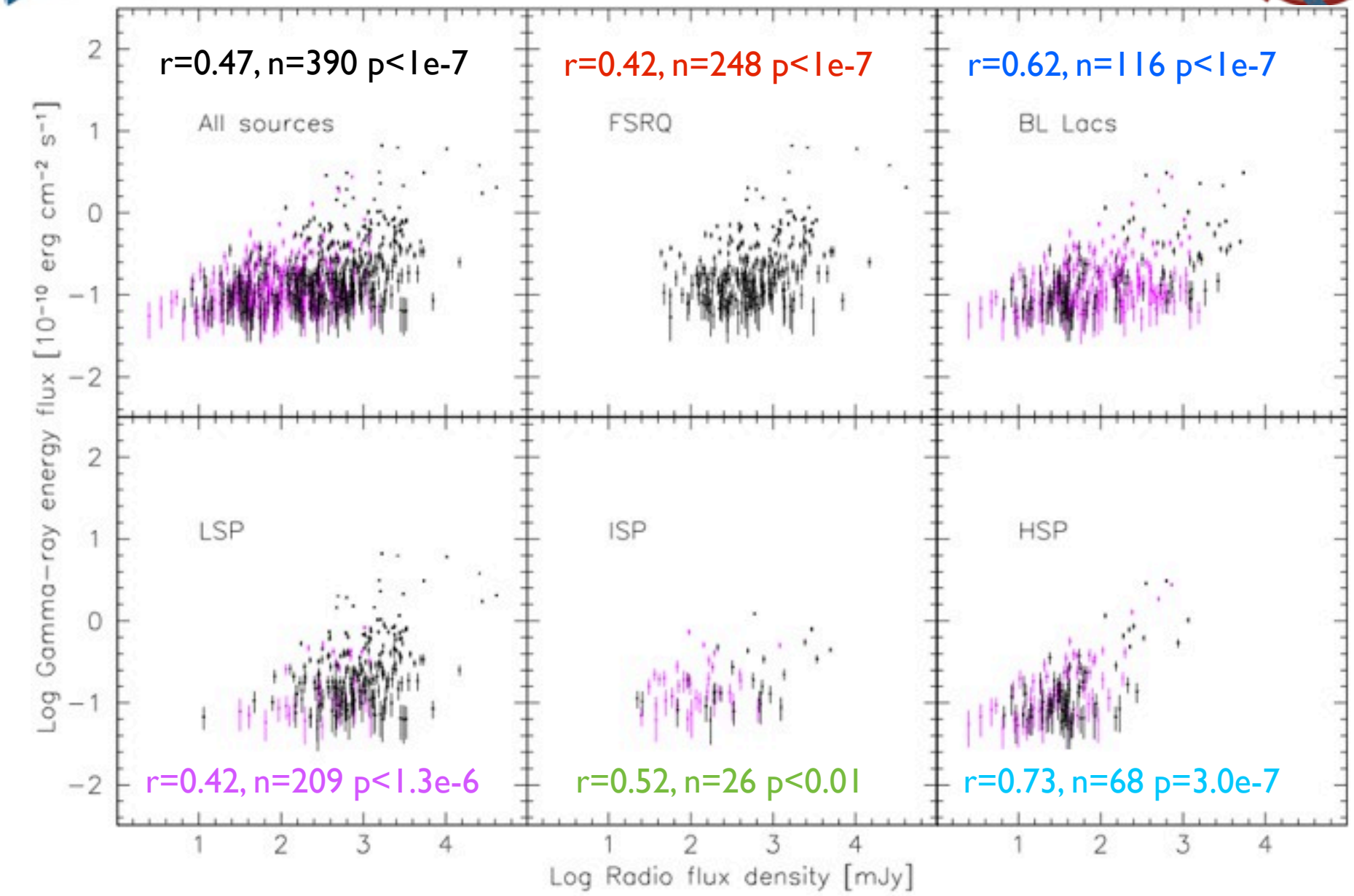


Results: Ackermann et al. 2011, ApJ 741 30

- **All 599 1LAC clean sources**
- **black: with redshift**
- **magenta: without redshift**
- **r=0.47**
- **P<1e-7**



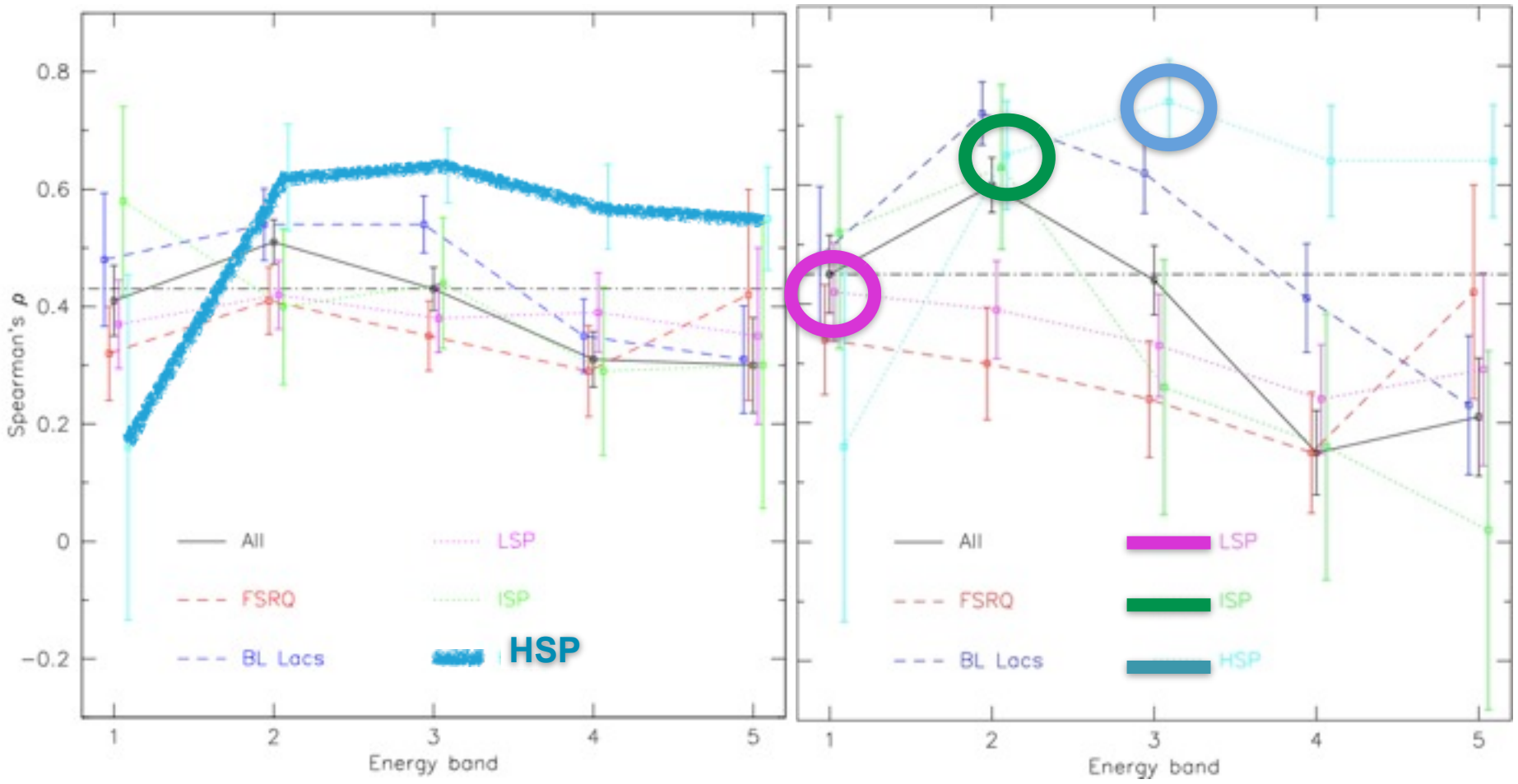
dividing by class…



Additional tests…

- **Timing**
  - Considering the subset of sources regularly monitored by OVRO, the correlation coefficient and the significance improve when considering simultaneous vs archival data
- **Blazar types**
  - BL Lacs (r=0.46) show a moderately stronger correlation than FSRQs (r=0.39)
  - each sub-class (FSRQ and BLL) independently still shows very high significance of a correlation ($p<1e-7$)
  - HSP blazars have the stronger correlation among the various SED-based classification
- **Energy bands**
  - Not all LAT energy bands correlate with radio with the same strengths
  - LSP have strongest correlation in band 0.3-1 GeV, ISP in 1-3 Gev, HSP in 3-10 GeV
  - …but significance is marginal so far

Correlation coefficient vs energy band, divided by blazar type



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?
    - maybe YES
  - does it depend on energy band?
    - maybe YES

References

- Abdo, A. A. et al. 2009a, ApJ 700, 597 (LBAS)
- Abdo, A. A. et al. 2009b, ApJ 707, L142 (NLS1)
- Abdo, A. A. et al. 2010a, ApJ 715, 429 (1LAC)
- Abdo, A. A. et al. 2010b, ApJ 720, 912 (MAGN)
- Ackermann, M. et al. 2011a, ApJ 741, 30 (Radio-gamma connection)
- Ackermann, M. et al. 2011b, ApJ 743, 171 (2LAC)
- Bloom S. D. 2008, AJ, 136, 1533
- Donato, D. et al. 2001, A&A 375, 739
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- Hartman, R. C., et al. 1999, ApJS, 123, 79
- Healey, S. E. et al. 2007, ApJS 171, 61
- Kovalev, Y. Y. et al. 2009, ApJ 696, L17
- Mahony, E. K. et al. 2010, ApJ 718, 587
- Mücke, A. et al. 1997, A&A 320, 33
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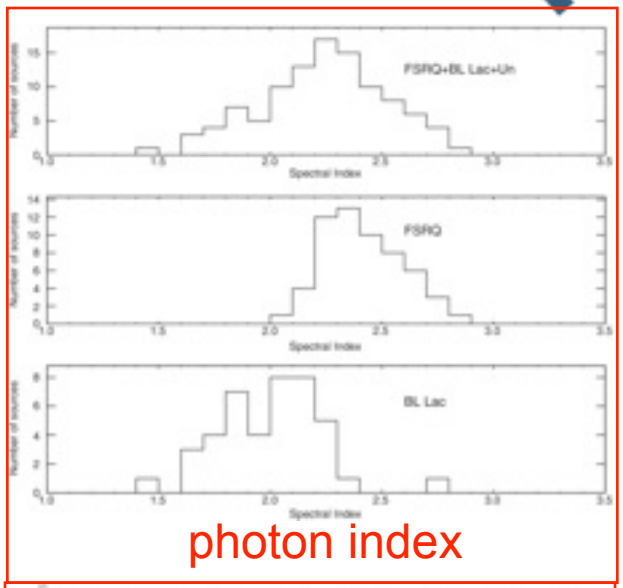
- Pavlidou et al., 2012, ApJ 751, 149

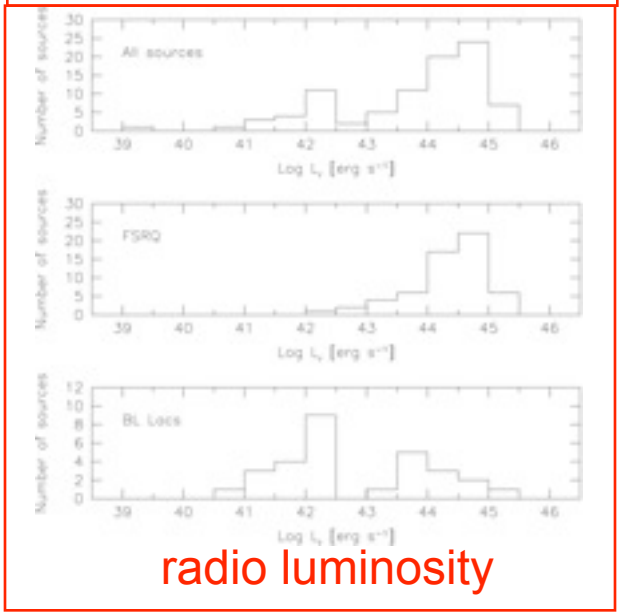
EXTRA SLIDES

LAT Bright AGN Sample
(LBAS, Abdo et al. 2009, ApJ 700, 597)

- 125 non-pulsar sources at |b|>10°
  - Only 9 unassociated (3EG: 96/181 at |b|>10°)
  - Much more balanced FSRQ/BLL ratio: 58/42 (including 7 HBLs)
  - (plus 4 of uncertain type and 2 radiogalaxies: Cen A, NGC1275)
- Unique Fermi features and FSRQ/BLL characterizations:
  - energy range: different spectral properties
  - Sensitivity: confirms different redshift distributions
  - Positional accuracy: counterparts identification and MWL properties



photon index



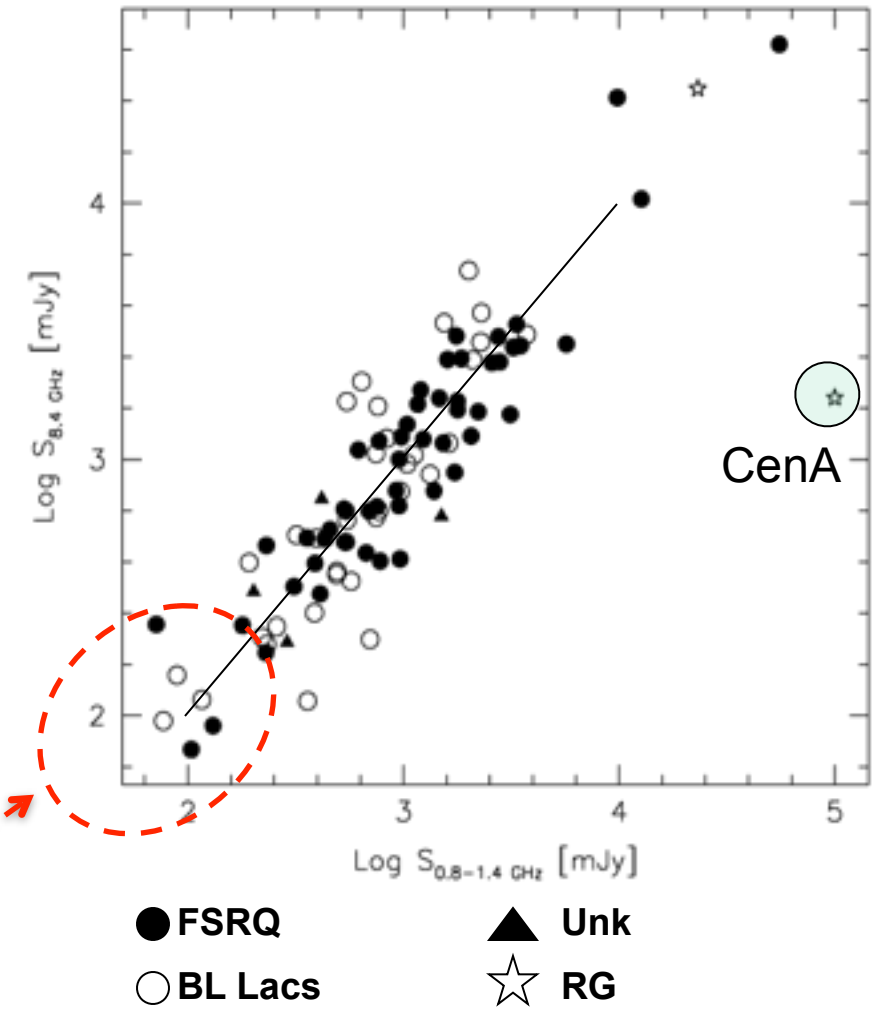
radio luminosity

Beyond the LBAS: 1FGL and 1LAC

- LBAS results were restricted to
  - 3 months of gamma-ray data
  - TS>100 (highest confidence gamma-ray sources)
- Fermi has continued its operation in survey mode with unique characteristics:
  - Sensitivity: include the weakest gamma-ray (and radio?) sources
  - Field of view: gather data from as large sky area as possible
  - Spectral range: collect and discuss soft (radio bright?) and hard (radio weak?) sources
- Milestones after 11 months of data collection
  - the 1FGL (first Fermi-LAT catalog), which contains and characterizes 1451 sources (Abdo et al. 2010, ApJS 188, 405)
  - the 1LAC (first catalog of Fermi-LAT detected AGNs), which includes 671 gamma-ray sources statistically associated to high latitude AGNs (Abdo et al. 2010, ApJ 715, 429)

Low vs high radio frequency: flux-flux

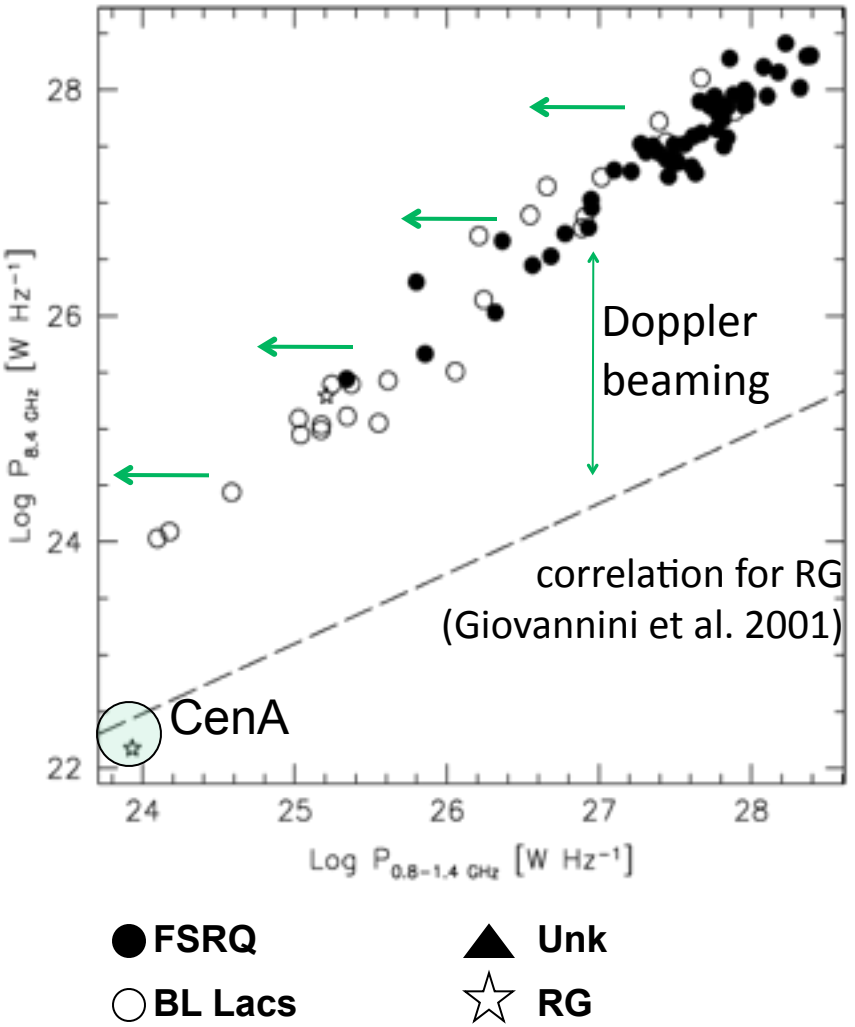
- Based on LBAS (bright Fermi AGNs)
- Flux plane is not subject to distance bias
  - Low frequency from NVSS (1.4 GHz) or SUMSS (0.8 GHz)
  - High frequency typically from CRATES (8.4 GHz, or NED)
- another representation of the spectral index flatness
  - little to none extended radio emission
  - except Cen A!



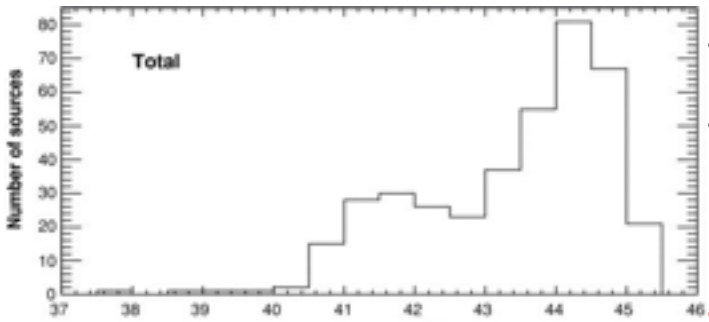
New BL Lacs sample fills in here

Low vs high radio frequency: luminosity-luminosity

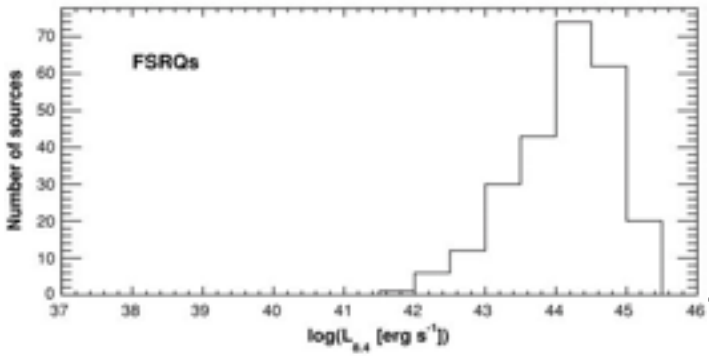
- Caveat: Distance dependence stretches distribution
- All cores more luminous than expected for RG of same P_{low}
  - Doppler boost!
  - even more if one could subtract core from truly extended emission
  - indeed, extended radio emission of LBAS sources could be as low as 10^{23} W Hz^{-1}
  - CenA well behaved: fair amount of extended radio emission
- Radio luminosity $L_r=\nu L(\nu)$ span a broad range $10^{39.1} < L_r < 10^{45.3}$ erg s^{-1}, (ν=8.4 GHz)
  - with different distributions for BL Lacs and FSRQ:
  - FSRQ: $\log L_r=44.4\pm0.6$ [erg s^{-1}]
  - BL Lacs: $\log L_r=42.8\pm1.1$ [erg s^{-1}]

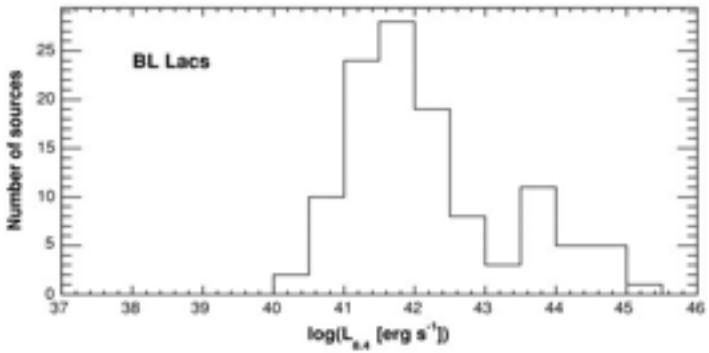


1LAC: Radio luminosity

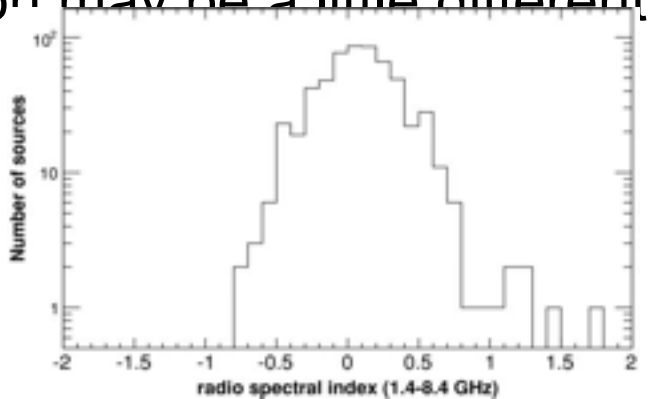


(Abdo et al. 2010, 1LAC)



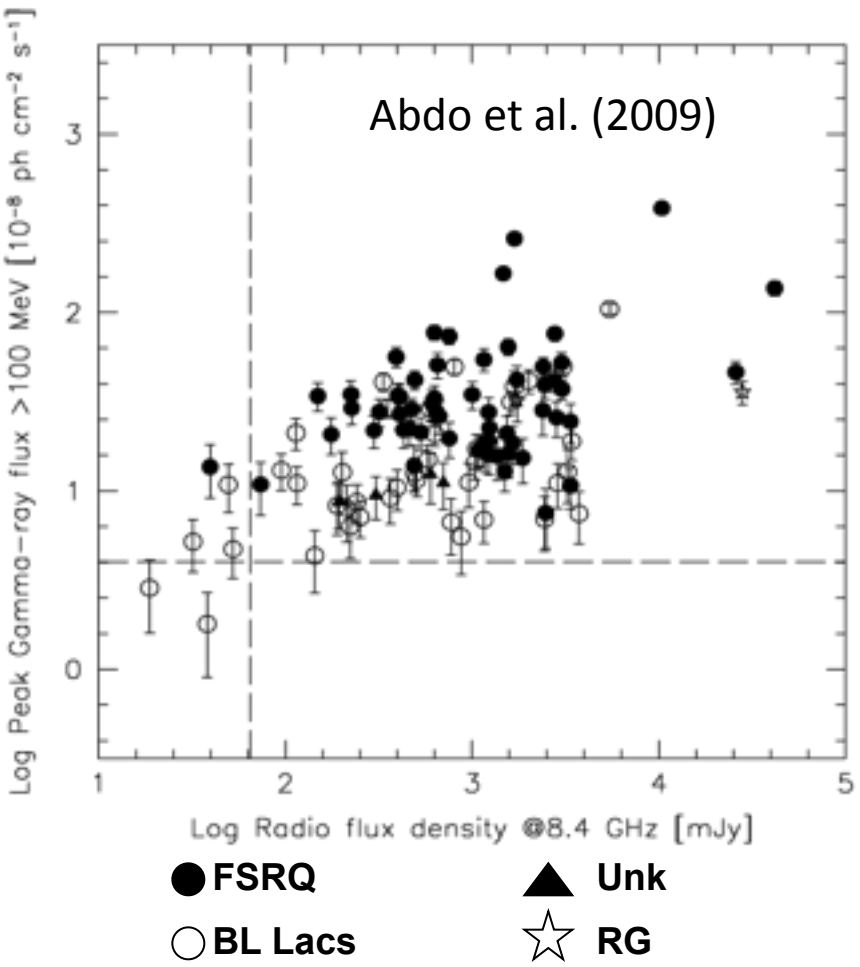


- $L_r = \nu L(\nu)$, ν=8.4 GHz
- Radio luminosity L_r is typically 10^{41}-10^{45} erg s^{-1}
  - but it can be as low as 10^{37} erg s^{-1}
- FSRQ are clustered at higher luminosities, while BL Lacs follow a broader distribution down to 10^{40} erg s^{-1}
  - FSRQ: 44.1 +/- 0.7 [erg s^{-1}]
  - BLLacs: 42.2 +/- 1.1 [erg s^{-1}]
- Unknown type blazars and some BL Lacs lack redshift so actual distribution may be a little different



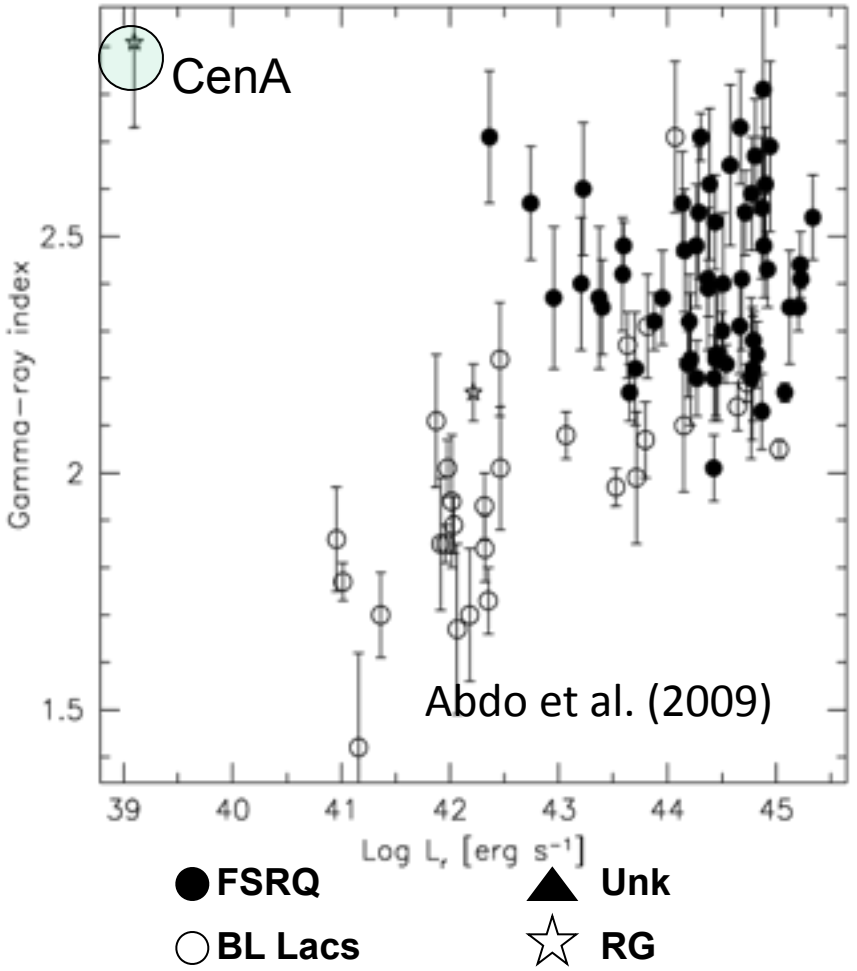
LBAS: Radio vs gamma-ray flux

- Radio: CRATES/NED flux density at 8.4 GHz
- Gamma-ray: Fermi-LAT peak flux at E>100 Mev in 3 months
- Spearman's rank correlation coefficient: r=0.42, for 106 elements, but…
  - Do few data points drive correlation?
  - BL Lacs and FSRQ sample rather different regions
    - FSRQ: 57 sources, r=0.19, BL Lacs: 42 sources, r=0.49
  - Total without the most extreme data points goes down to r=0.24 (12% of the sample)
- Significance difficult to claim. Issues:
  - Variability, extended radio emission
  - Selection effects?



Photon index vs radio luminosity

- Only sources with known redshift
  - K-corrected
- FSRQs: largest Lr, softer indices
- BL Lacs: lower Lr, harder indices
- RGs: 3C84 BL Lac-like, Cen A well displaced



Simpson's paradox

- Two groups showing some correlation when considered independently, show the opposite behavior when considered as one set.