The connection between radio and gamma-ray emission in AGN

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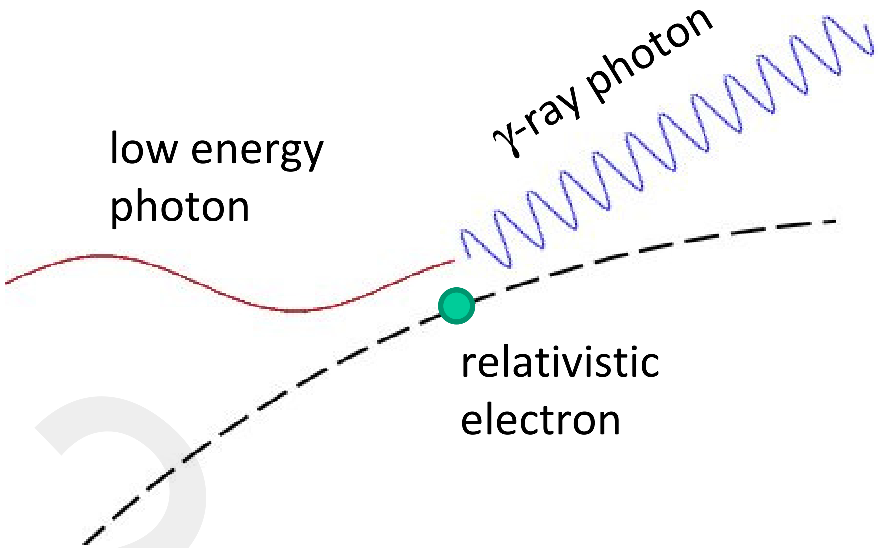
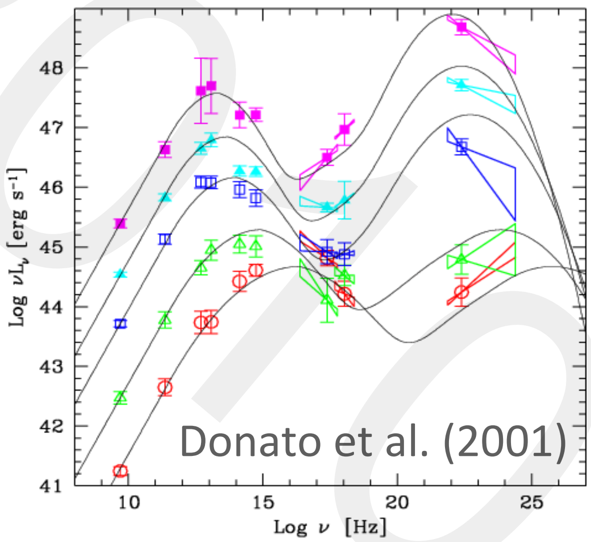
Pre-Fermi Background

- **synchrotron radio emission originates from relativistic electrons that can upscatter photons to high energy**
  - **some connection between radio and γ-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.**
- **is there a correlation? do radio and γ-ray fluxes in BL Lacs and FSRQs behave in the same way?**



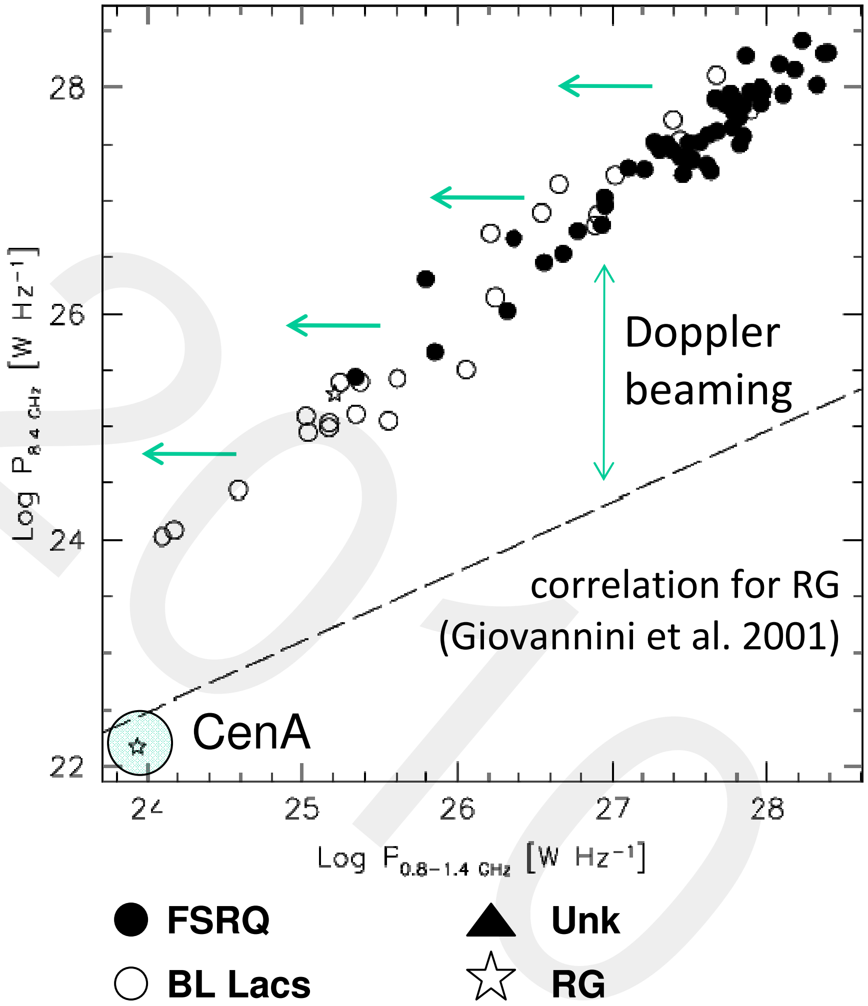


LAT Bright AGN Sample (LBAS, Abdo et al. 2009, ApJ 700, 597)

- 125 non-pulsar sources at $|b|>10°$
  - 106 high-confidence (P>90%) associations with AGNs: (LBAS)
  - 10 lower-confidence associations
  - 9 unassociated (3EG: 96/181 at $|b|>10°$)
- High-confidence associations:
  - FSRQs: 58
  - BL Lacs: 42 (including 7 HBLs)
  - Uncertain class: 4
  - Radiogalaxies: Cen A, NGC1275
- LBAS sources are associated to CRATES/BZ Cat sources:
  - CRATES: Healey et al. (2007, 8.4 GHz VLA data)
  - BZCAT: Massaro et al. (2009, multifrequency catalog)
- Radio properties typical of compact self-absorbed components
  - relatively bright: 98/106 (92%) have $S_{8.4}$>100 mJy
  - flat spectral index: α=0.02±0.27, with $S(\nu) \sim \nu^{-\alpha}$

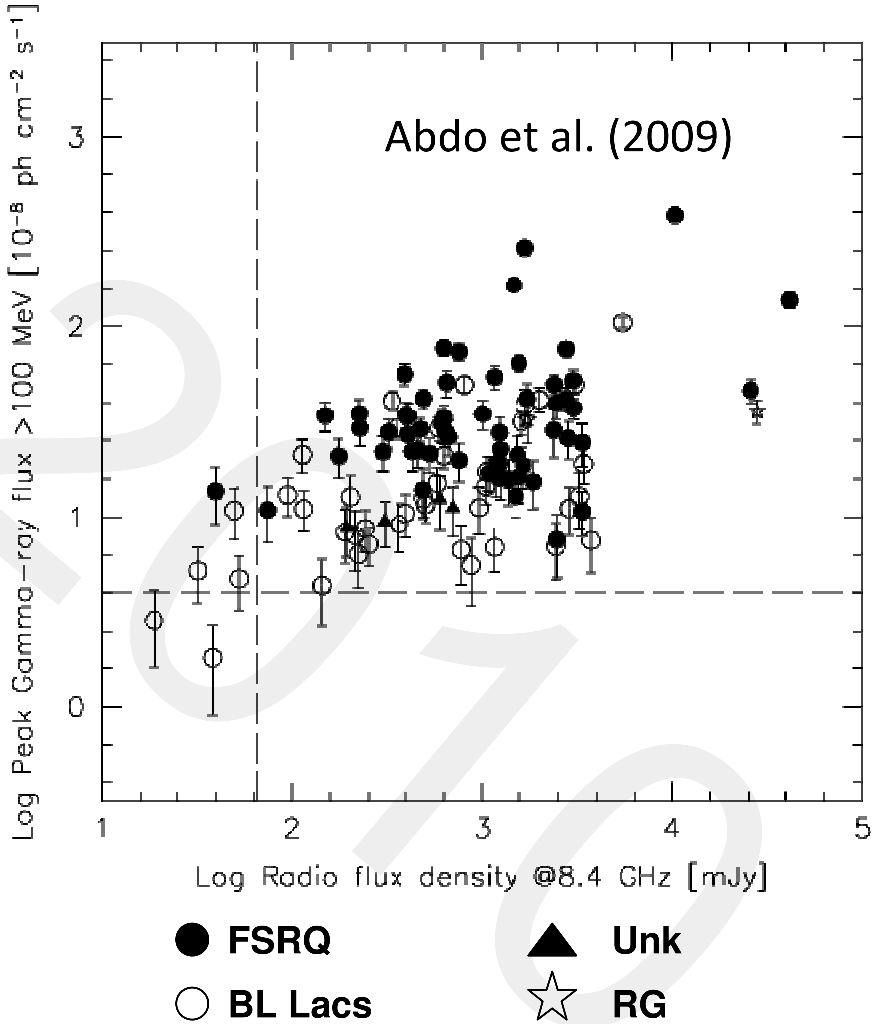
Low vs high radio frequency: luminosity plane

- 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)
- BL Lacs and FSRQ follow different distributions:
  - FSRQ: $LogL_r$=44.4±0.6 [erg s^{-1}]
  - BL Lacs: $LogL_r$=42.8±1.1 [erg s^{-1}]



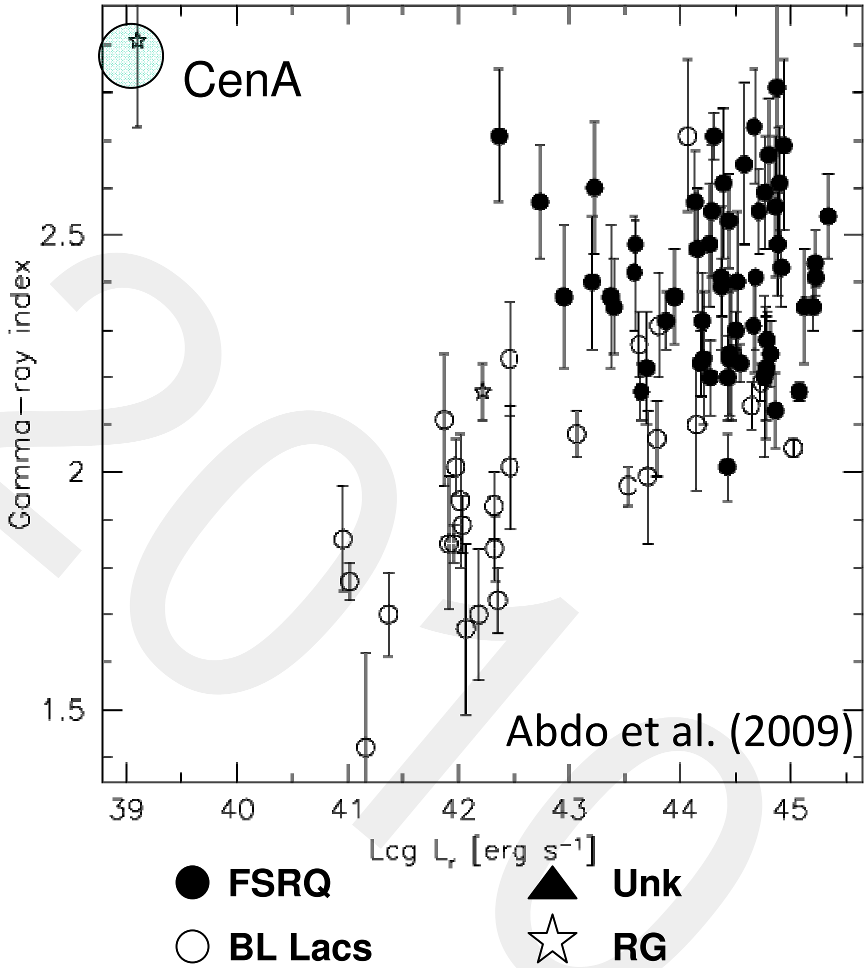
Radio vs gamma-ray flux

- 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

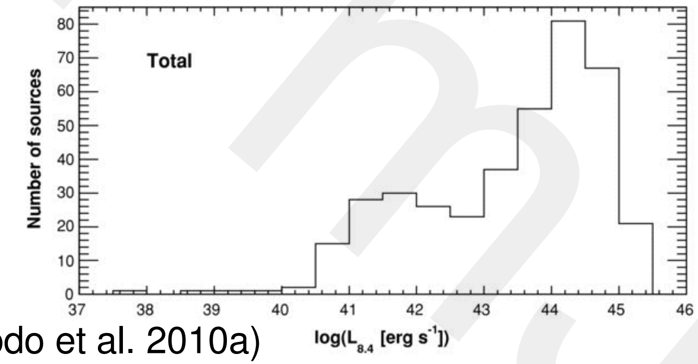
- **Only sources with known redshift**
  - **K-corrected**
- **FSRQs**
  - **largest Lr, softer indices**
- **BL Lacs**
  - **lower Lr, harder indices**
- **Radio galaxies**
  - **3C84 BL Lac-like, Cen A well displaced**



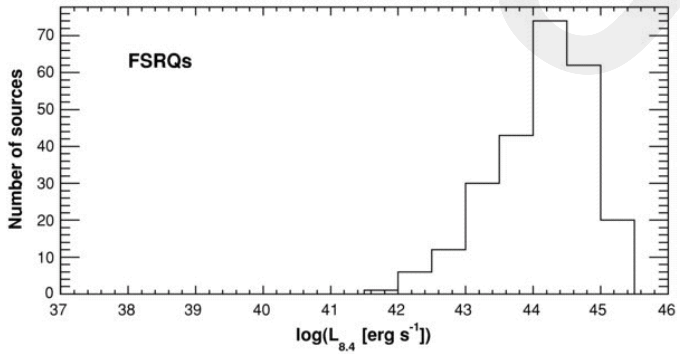
Beyond the LBAS: 1FGL and 1LAC

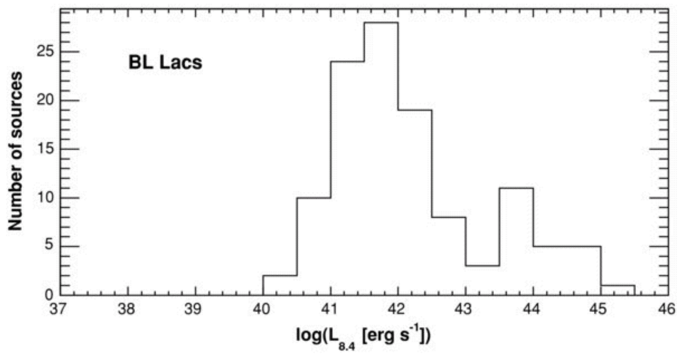
- LBAS results were restricted to
  - 3 months of γ-ray data
  - TS>100 (highest confidence γ-ray sources)
- Fermi has continued its operation in survey mode with unique characteristics:
  - Sensitivity: include the weakest γ-ray (and radio?) sources
  - Field of view: gather data from as large sky area 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. 2010b)
  - the 1LAC (first catalog of Fermi-LAT detected AGNs), which includes 671 γ-ray sources statistically associated to high latitude AGNs (Abdo et al. 2010a)

Radio luminosity



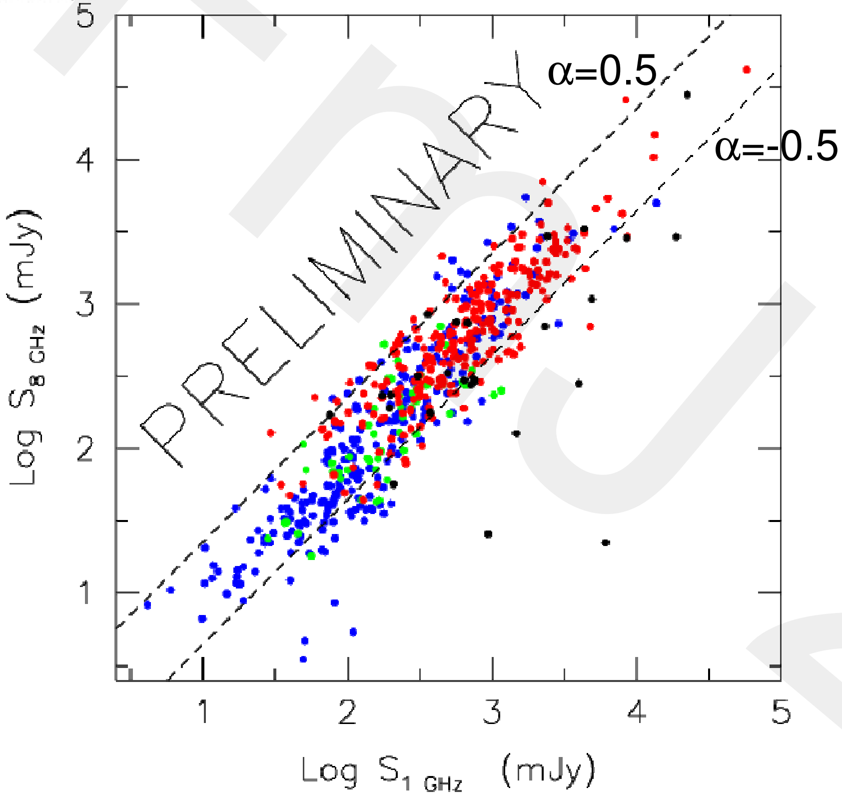
(Abdo et al. 2010a)

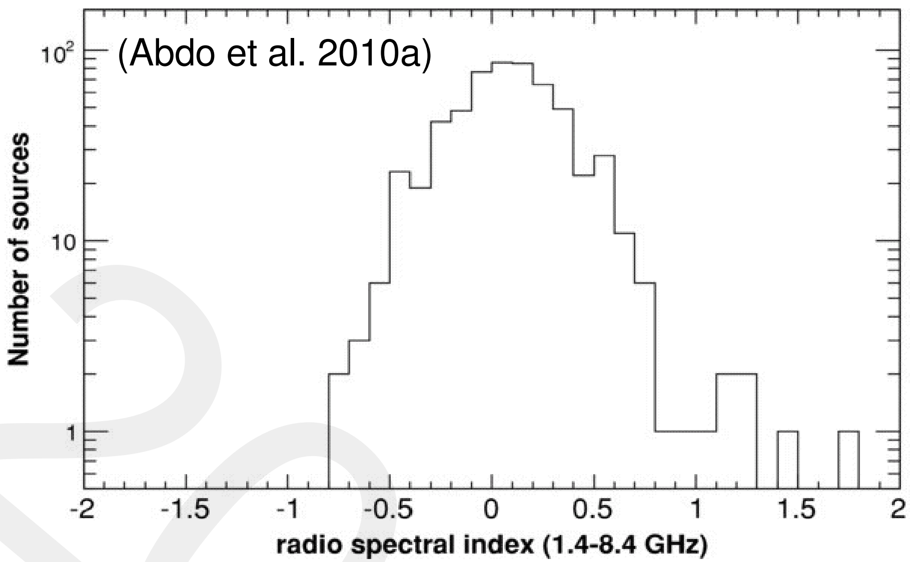




- $L_r = \nu L(\nu)$, ν=8.4 GHz
- Radio luminosity L_r is typically 10^{41}-10^{45} erg s^{-1}
  - but it can be as low as 10^{37} erg s^{-1}
- FSRQ are clustered at higher luminosities
  - $LogL_{r,\ FSRQ}$= 44.1 ± 0.7 [erg s^{-1}]
- BL Lacs follow a broader distribution down to 10^{40} erg s^{-1}
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

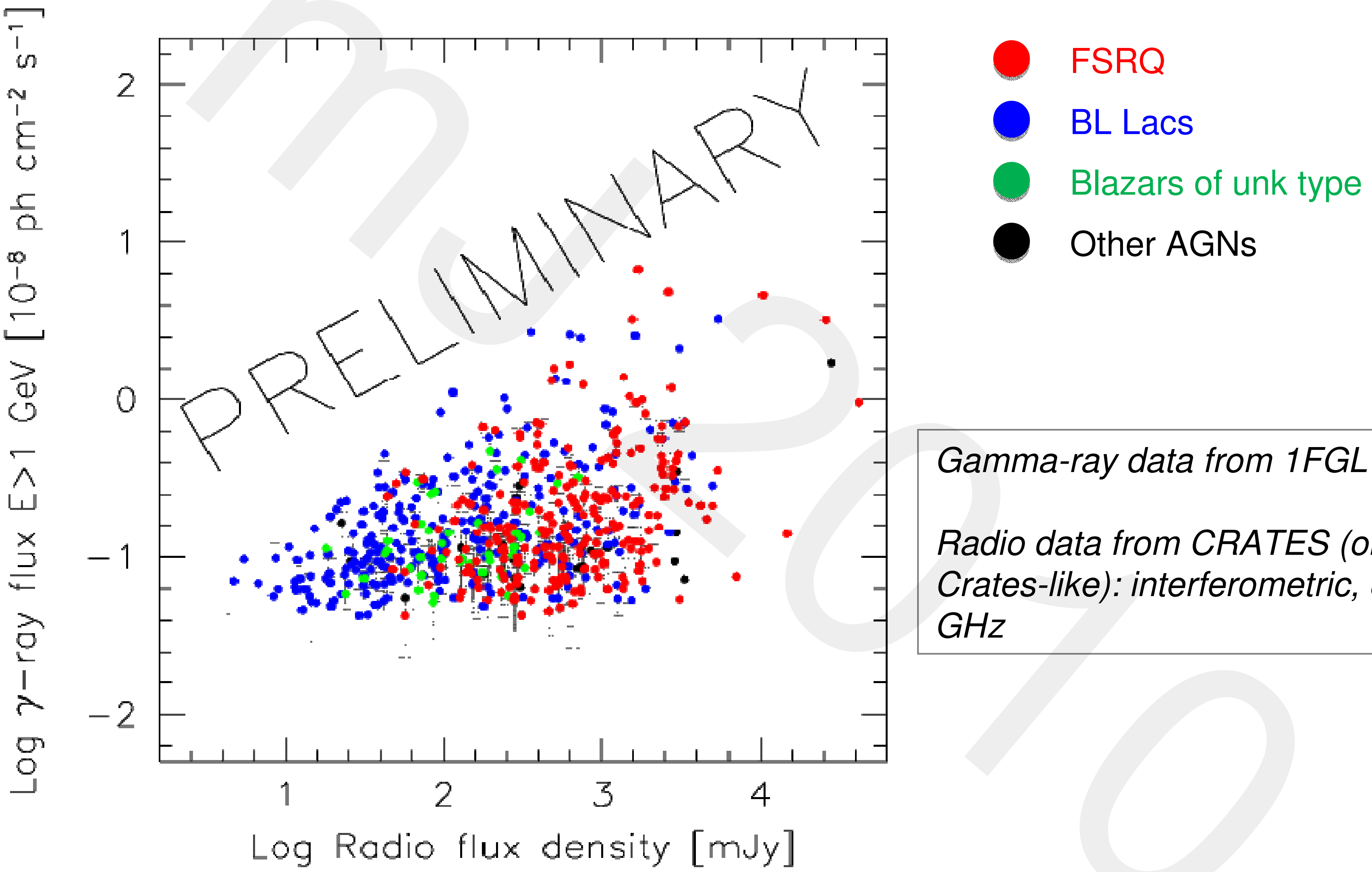
Radio spectral index





- Sources with radio data at
  - 1.4 GHz from NVSS: extended, optically thin radio emission
  - 8.4 GHz from CRATES/NED: nuclear, self-absorbed emission
- Most sources with typical flat spectrum ($<\alpha> = 0.06+/-0.23$)
- However, a small but non negligible fraction has $\alpha>0.5$
  - see T. Cheung's talk on Wed

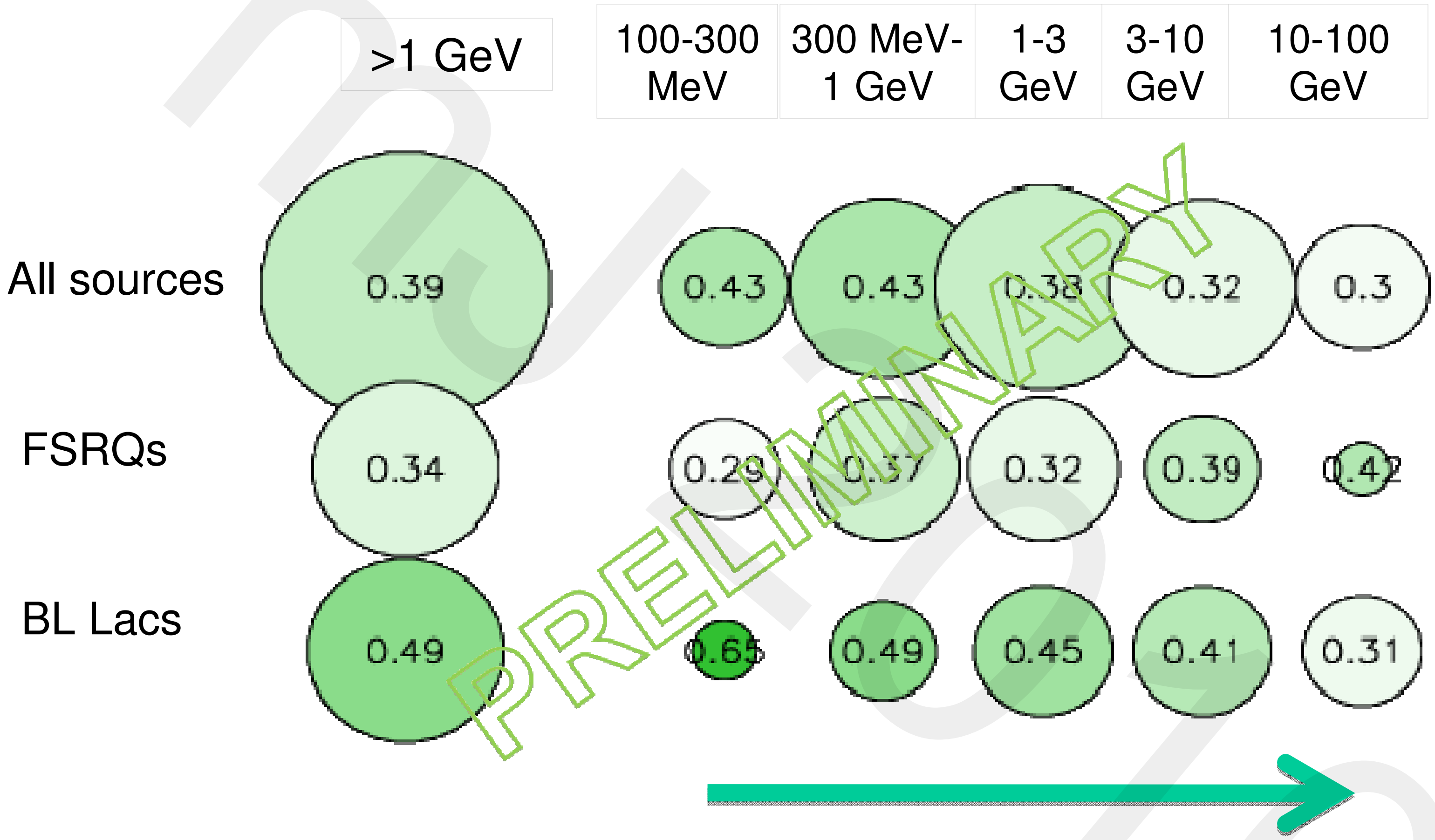
Radio vs gamma-ray fluxes



Gamma-ray data from 1FGL

Radio data from CRATES (or Crates-like): interferometric, 8 GHz

Correlation coefficient by source type and energy

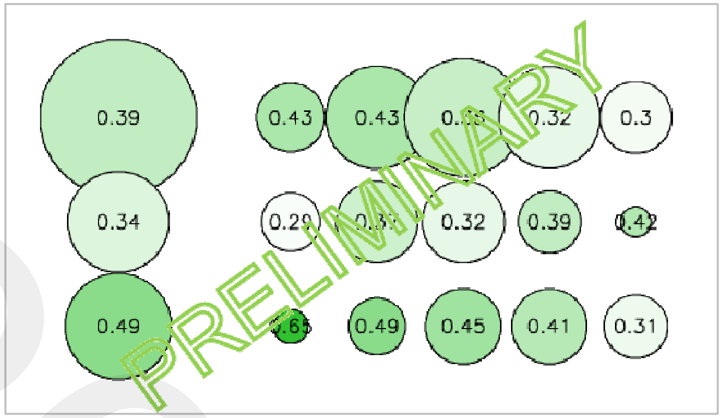


numbers give correlation coefficients,
symbol size is proportional to number of sources

Energy band

Main findings - summary

- Correlation coefficient for all sources, E>1 GeV is r=0.39
- R>0 for all 18 source type/energy band combinations
- $r_{BLL} > r_{FSRQ}$, except for highest energy band
- r_{BLL}> decreases with increasing energy band (0.65->0.31)
- r_{FSRQ} is more stable, slightly increasing (0.29->0.42)



– **Owens Valley Radio Observatory provides also simultaneous radio data for a sub-sample of radio bright sources (see Max-Moerbeck talk)**

See also next talk (Mahony, AT20G), Ghirlanda et al. (2010, AT20G), Kovalev et al. (2009, LBAS), Pushkarev et al. (2010, Mojave)

What about significance?

- Strong apparent correlation ≠ significant intrinsic correlation
- Need to simulate MANY samples with intrinsically uncorrelated flux densities and see how often we can get as high a *'r'* as the observed one
  - with the same distance and dynamic range of our sample
  - spectroscopic information is very important!
- Preliminary results:
  - Prob(FSRQ, E>1 GeV) ~ 2×10^{-3}
  - Prob(BLL, E>1 GeV) < 1×10^{-7}
  - distance range does make a big difference – and so will the assumption on d_L for the sources without z
    - only BL Lacs with measured z considered so far

Take home notes

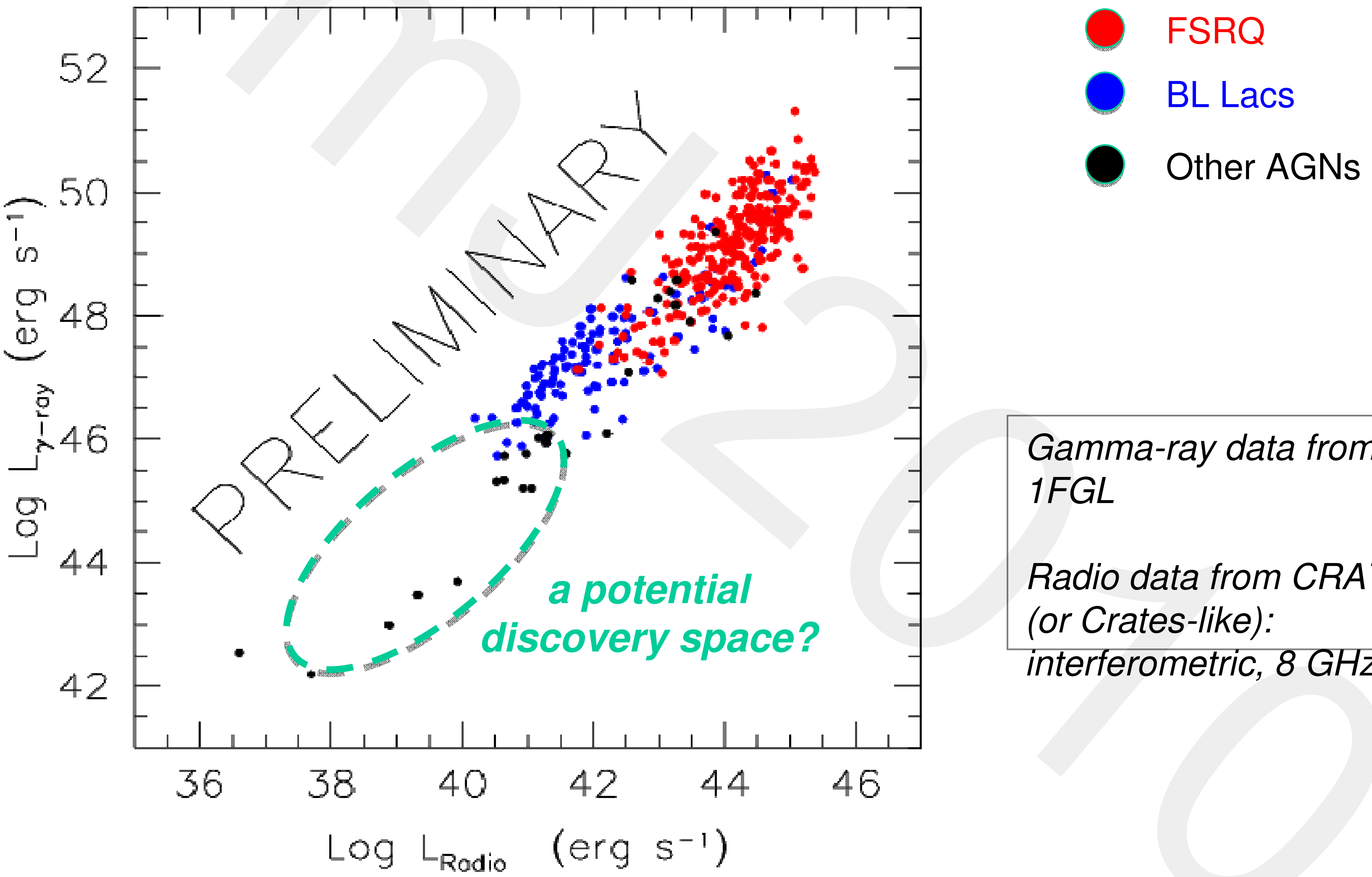
1. The bright gamma-ray extragalactic sky remains dominated by radio loud AGN
   – mostly blazars but also some steep spectrum radio sources are there
2. Radio and gamma-ray fluxes appear to correlate over 4 magnitudes
   – with some possible difference between FSRQs and BL Lacs
3. Monte-Carlo simulations provide an estimate of the correlation significance
   – significance is high but sensitive to source distance distribution and other assumptions

References

- Abdo, A. A. et al. 2009, ApJ 700, 597
- Abdo, A. A. et al. 2010a, ApJ 715, 429 (1LAC)
- Abdo, A. A. et al. 2010b, ApJS 188, 405 (1FGL)
- Bloom S. D. 2008, AJ, 136, 1533
- Donato, D. et al. 2001, A&A 375, 739
- Ghirlanda, G. et al. 2008, arXiv:1003.5163
- Giovannini, G. et al. 2001, A&A
- Healey, S. E. et al. 2007, ApJS 171, 61
- Kovalev, Y. Y. et al. 2009, ApJ 696, L17
- Mahony, E. K. et al. 2010, arXiv:1003.4580
- Massaro, E. et al. 2009, A&A 495, 691
- Mücke, A. et al. 1997, A&A 320, 33
- Stecker, F. W., Salamon, M. H., & Malkan, M. A. 1993, ApJ, 410, L71

EXTRA SLIDES

Radio and Gamma-ray Luminosity

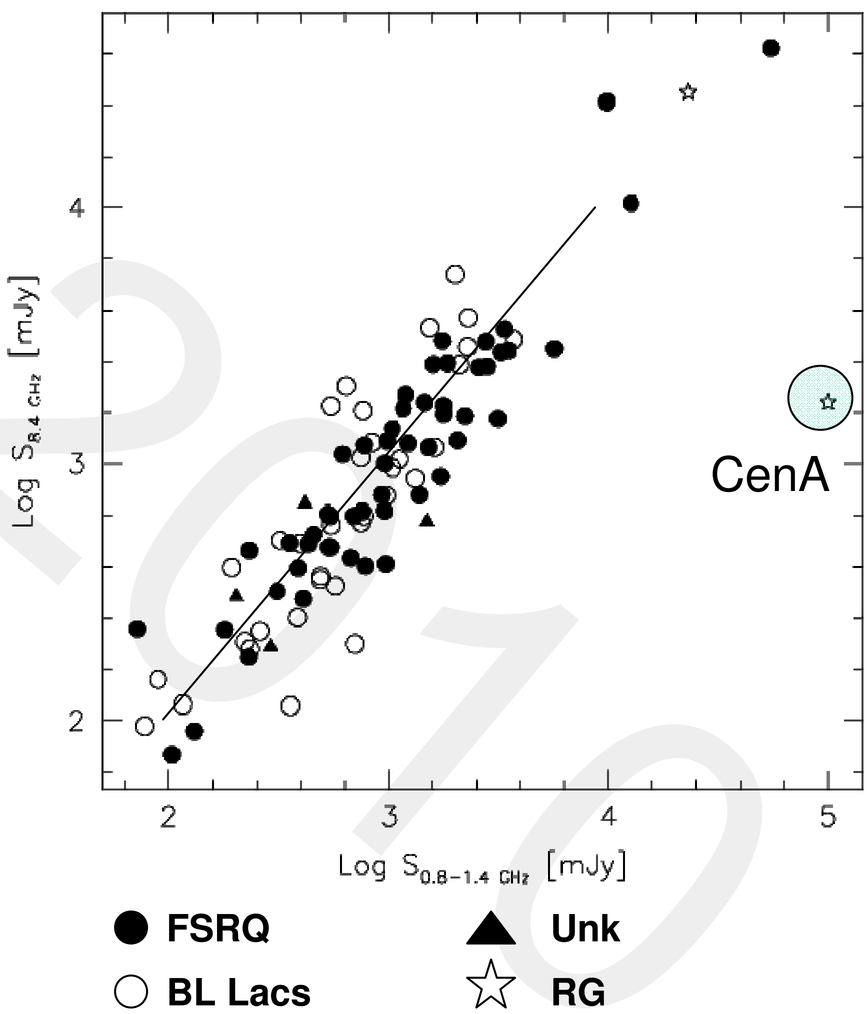


Gamma-ray data from 1FGL

Radio data from CRATES (or Crates-like): interferometric, 8 GHz

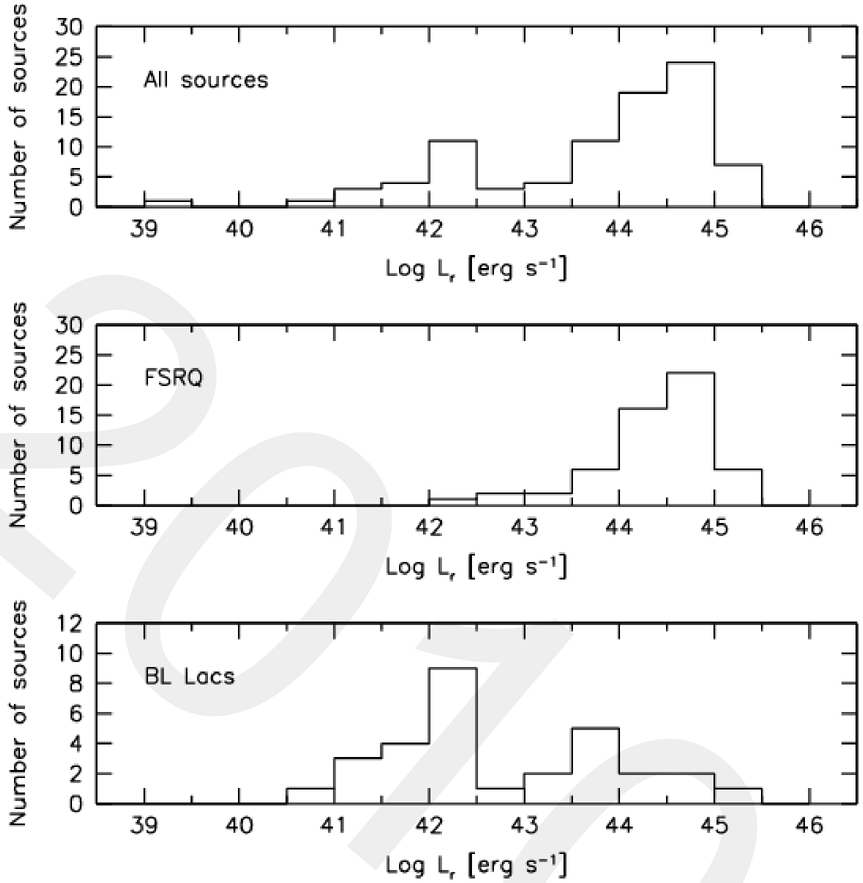
Low vs high radio frequency: flux-flux

- 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!

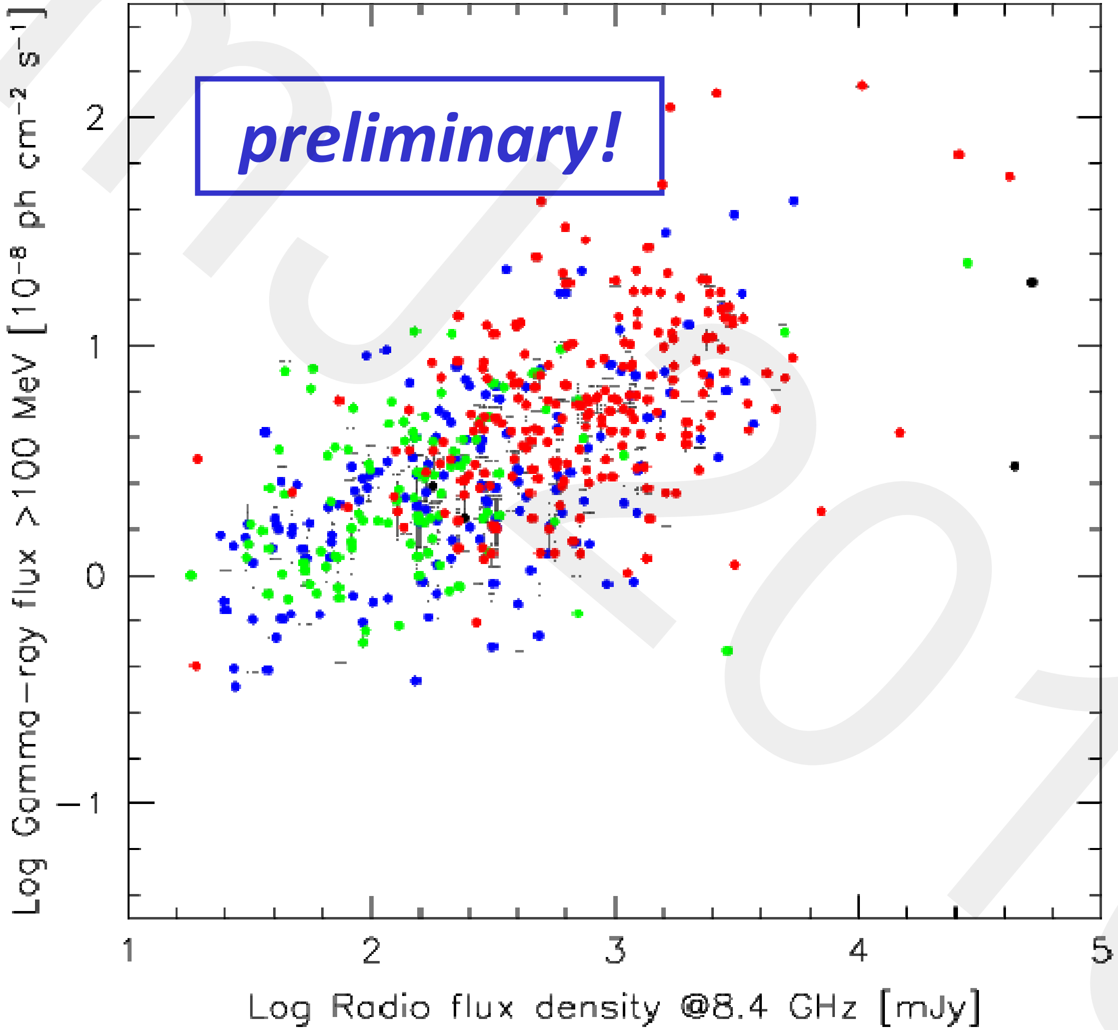


Radio luminosity according to type

- $L_r = \nu L(\nu)$, $\nu = 8.4$ GHz
- range $10^{39.1} < L_r < 10^{45.3}$ erg s^{-1}
- BL Lacs and FSRQ follow different distributions:
  - FSRQ: LogL_r=44.4±0.6 [erg s^{-1}]
  - BL Lacs: LogL_r=42.8±1.1 [erg s^{-1}]
- 2 RGs:
  - NGC1275 similar to BL Lacs: $L_r = 10^{42.2}$ er s^{-1}
  - CenA lies at the very lower end of the radio power distribution, with $L_r = 10^{39.1}$ erg s^{-1}.



Radio vs gamma-ray fluxes



with more sources than in the LBAS, r=0.60