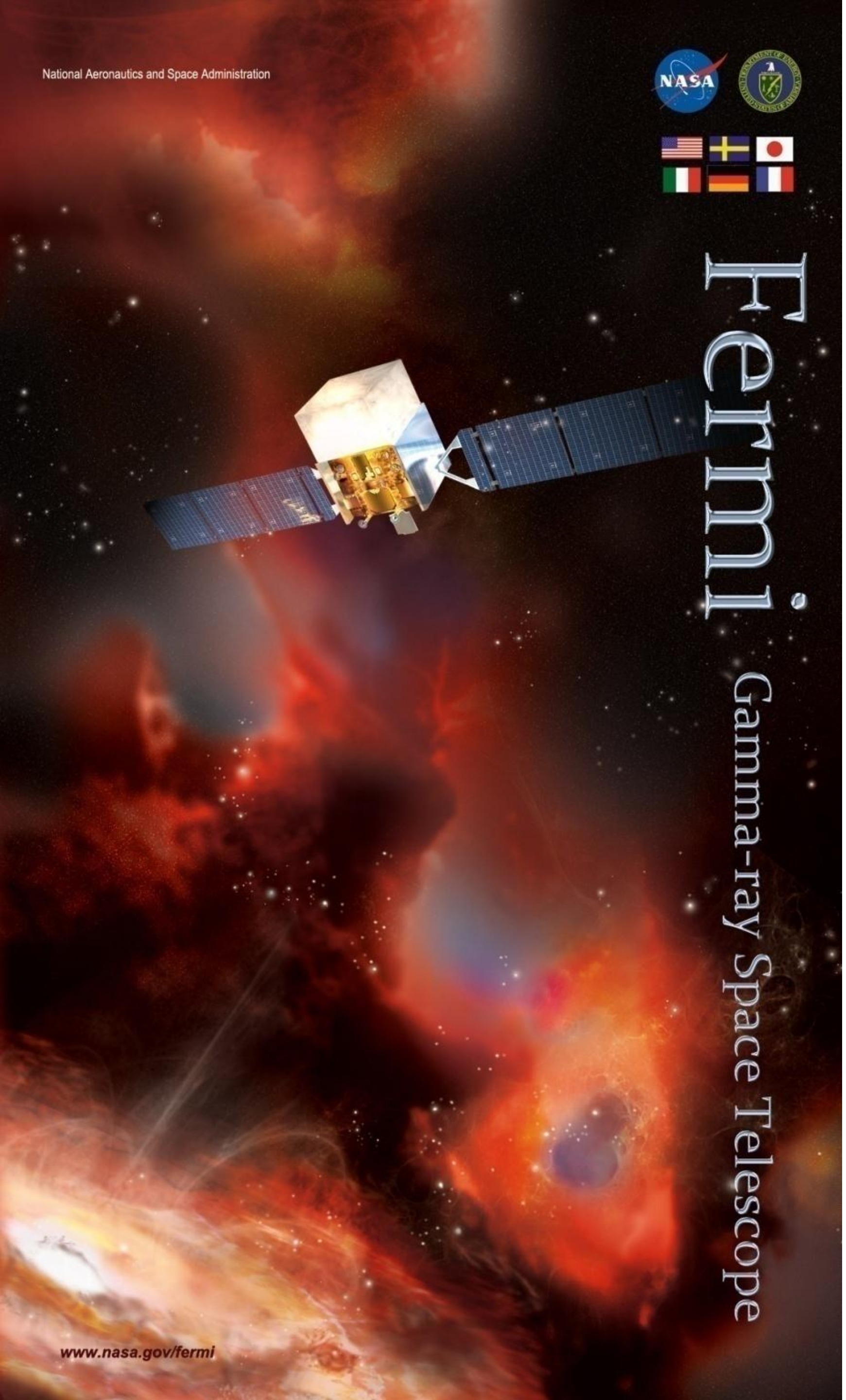

Faint blazars and their impact on the radio/gamma-ray connection

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with acknowledgments to… cospar 10

Outline

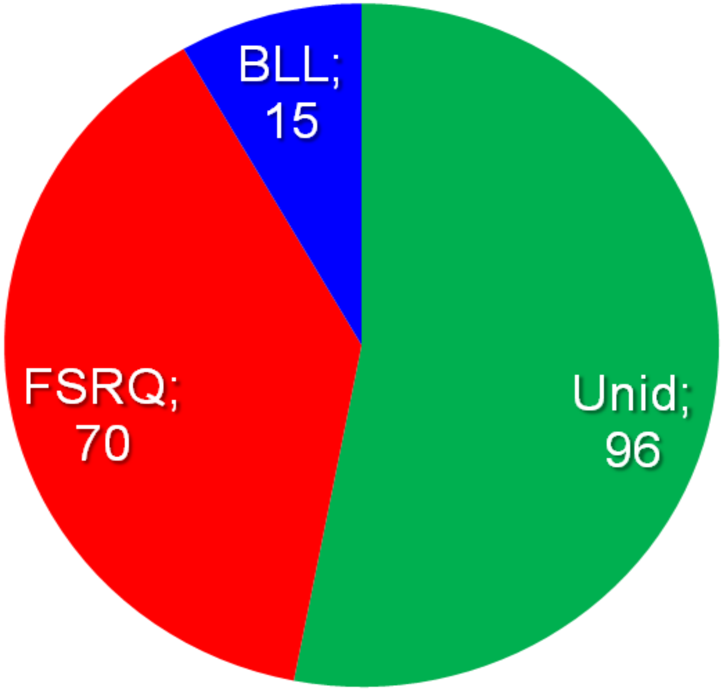
1. General background
2. Faint BL Lacs
   - new sample introduction and observations
   - preliminary results
3. Radio-gamma ray connection
   - BL Lacs and FSRQs in radio and gamma
   - correlation(?) and other questions…
4. Summary

Part 1

GENERAL BACKGROUND

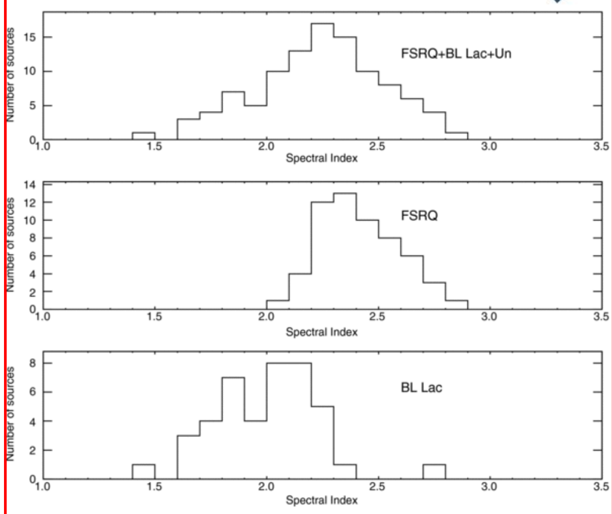
EGRET status

- EGRET 1991-1999
- Most high galactic latitude sources remained unidentified
- Among the identified ones, BL Lacs were a minority
  - And High-Frequency Peaked BL Lacs a negligible fraction!
- VHE observatories detect preferably BL Lacs, though!
- In radio, BL Lac jets are less extreme than FSRQs, but also much less studied!

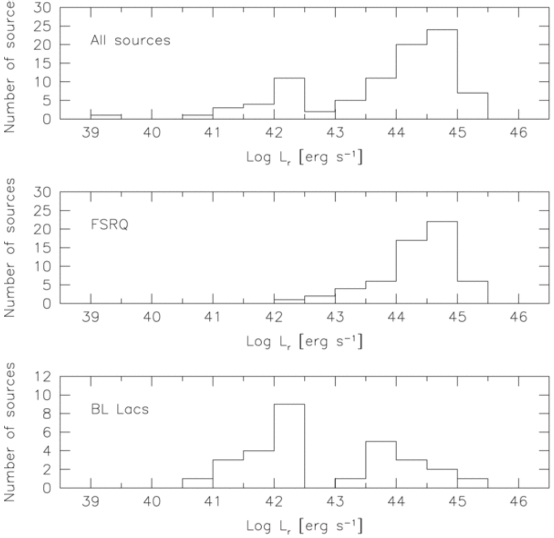


LAT Bright AGN Sample (LBAS, Abdo et al. 2009, ApJ 700, 597)

- **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



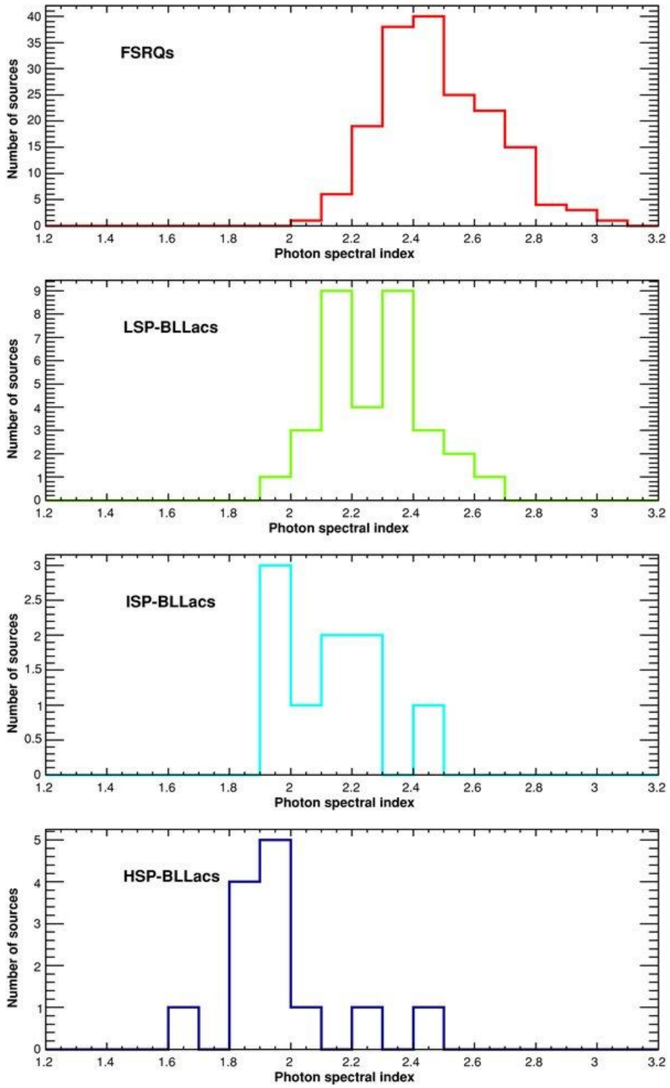
radio luminosity

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)**

Blazars in the 1LAC

- **BL Lacs outnumber FSRQs!**
  - 275 vs 248 in clean sample
- **Markedly different spectral properties**
  - In gamma-rays
  - In synchrotron component
- **Different redshift and flux distributions**
  - Significant separation in luminosity
  - Both radio and gamma



(Abdo et al. 2010, 1LAC)

Part 1

FAINT BL LACS AND RADIO OBSERVATIONS

Open questions

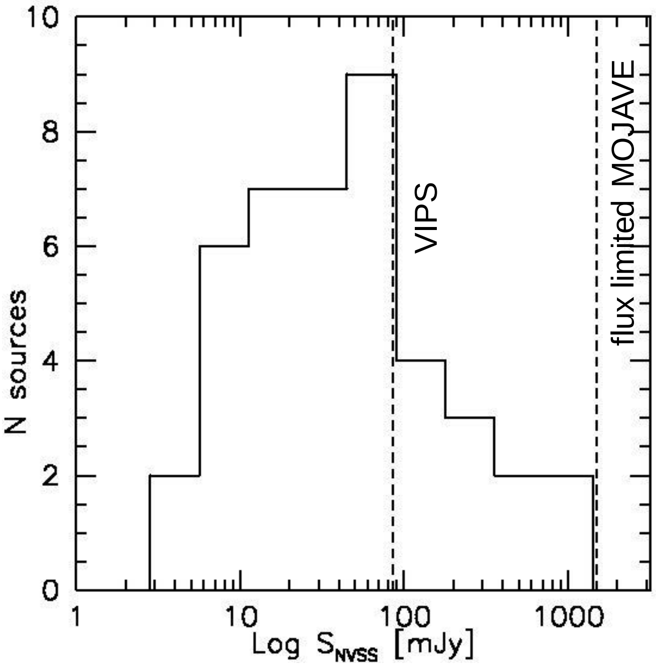
- Are the jets in FSRQs and BL Lacs the same?
    - Accretion/ejection coupling…
    - Doppler factors? Jet structure?
    - No radio quiet BL Lacs, but BL Lacs generally fainter than FSRQ!
- Observations have tried to collect evidence
    - Lower apparent velocities in BL Lac jets than in FSRQ (Gabuzda et al., 1994; Jorstad et al., 2001; Kellermann et al., 2004)
    - Even more prominent in TeV blazars (Giroletti et al. 2004, 2006, Piner et al. 2008)
- …now it is time for a systematic study

A new sample of nearby BL Lacs

- **An unbiased sample of BL Lacs?**
  - **Nearly impossible but…**
  - **Start from ASDC Catalog of known blazars**
    - **`http://www.asdc.asi.it/bzcat`**
  - **Limit to SDSS sky area**
    - **Sizeable sample, good optical characterization**
  - **Limit to z<0.2**
    - **Include ALL sources, even the weakest ones (eg HBLs?), and with great linear resolution (1 pc = 0.5 mas at z=0.1)**
- **Final list: 42 sources**
  - **Fermi all sky monitor**
  - **SWIFT, Chandra, XMM-Newton, INTEGRAL archives**
  - **Optical from SDSS and other telescopes (eg Vallinfreda)**
  - **Radio: NVSS, FIRST, and…**

VLBI: Observational strategy

- **Most of these blazars are well below the MOJAVE or even VIPS flux density limits**
- **8 and 15 GHz VLBA observations**
  - **spectral index information**
  - **great linear resolution**
  - **complementary and comparable to MOJAVE**
- **Ongoing observations**
  - **starting from brightest sources (PC recommendation)**
  - **30 observed so far (24 analysed)**

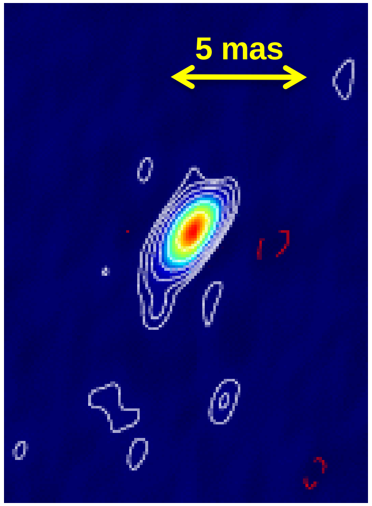


VLBA observations – details

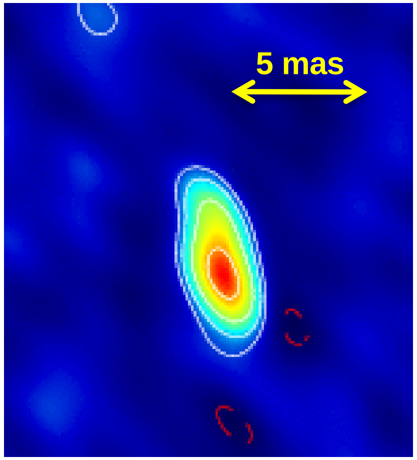
- ~1 hour per target
  - with a 1:3 ratio between 8 and 15 GHz integration time.
- Targets with S_8<30 mJy and S_{15}<50 mJy observed in phase reference mode
  - which also provides absolute positions, often for the first time
- Observations used 256 Mbps with 9 VLBA telescopes (no SC) – in some cases 8 because of weather conditions.
- Good data quality: rms noise ~0.2 mJy beam^{-1} (close to theoretical one)
- Typical restoring beam: ~1.2 x 1.8 mas at 8 GHz and ~0.6 x 0.9 mas at 15 GHz (natural weights).

Preliminary results – images

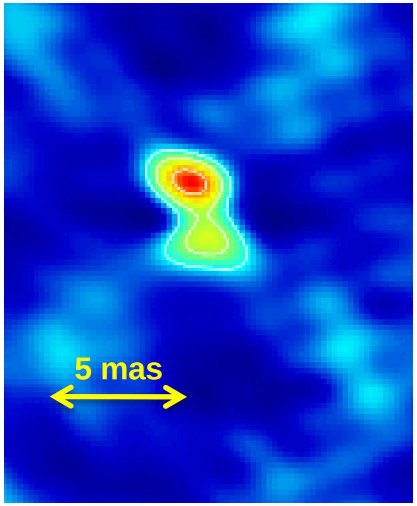
- **Overall good detection rates at both 8 and 15 GHz (see next slide)**
  - **and with interesting substructures too!**



J0754+3919
P=23.2 mJy/b



J0916+5238
P=20.0 mJy/b



J1033+4929
P=16.7 mJy/b

  - **low flux density complicates self calibration and imaging/modeling at 15 GHz, but structures are there too**

Preliminary results – statistics

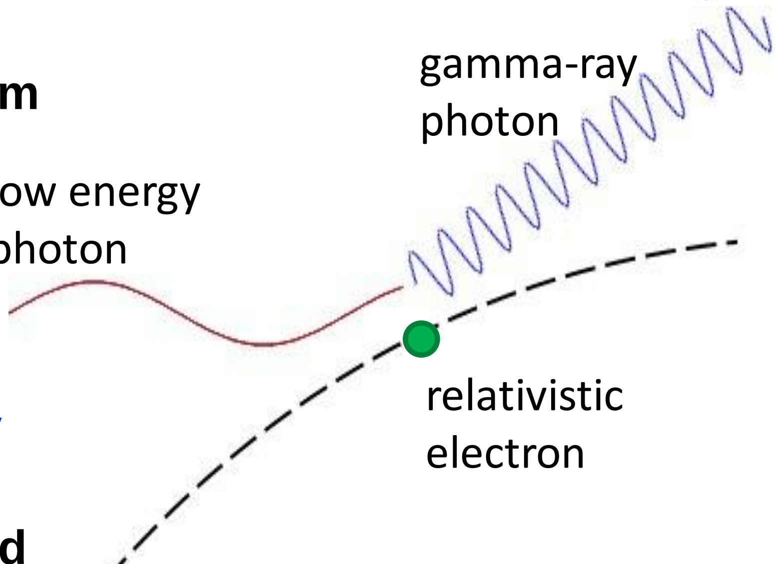
- Detection rate (goal): 22/24 (92%)
  - some not imaged yet
  - 8 GHz slightly more successful
- Average spectral index is moderately steep
  - α ~ 0.5-0.7
  - additional evidence of jet structure
- γ-rays detection rate (based on 1FGL)
  - ~58% for the sources observed so far
  - ~38% in the full sample
- photon indices in range Γ=1.3-2.0
  - typical of BL Lacs
  - hardest index (Γ=1.3) for the TeV source J1428+4240
- radio-gamma
  - all 1FGL sources are VLBA detected
  - VLBA non detections are gamma-ray quiet
    - misclassification?

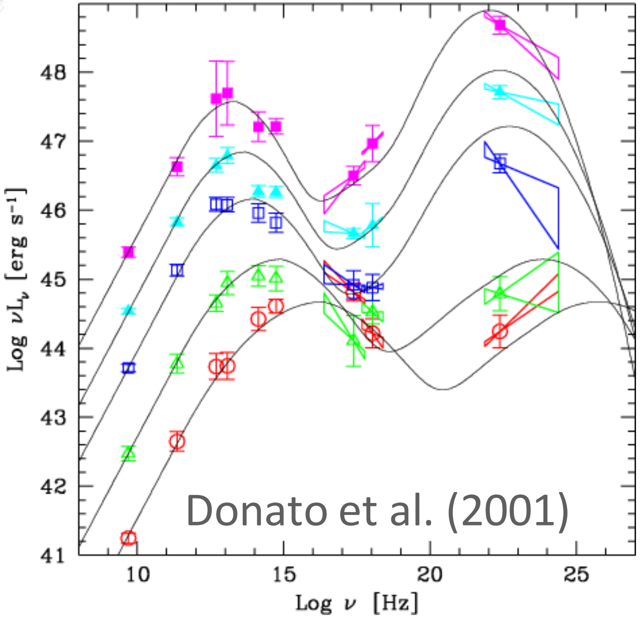
Part 3

FERMI AGN AND THE RADIO/GAMMA-RAY CONNECTION

Pre-Fermi Background

- **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.**

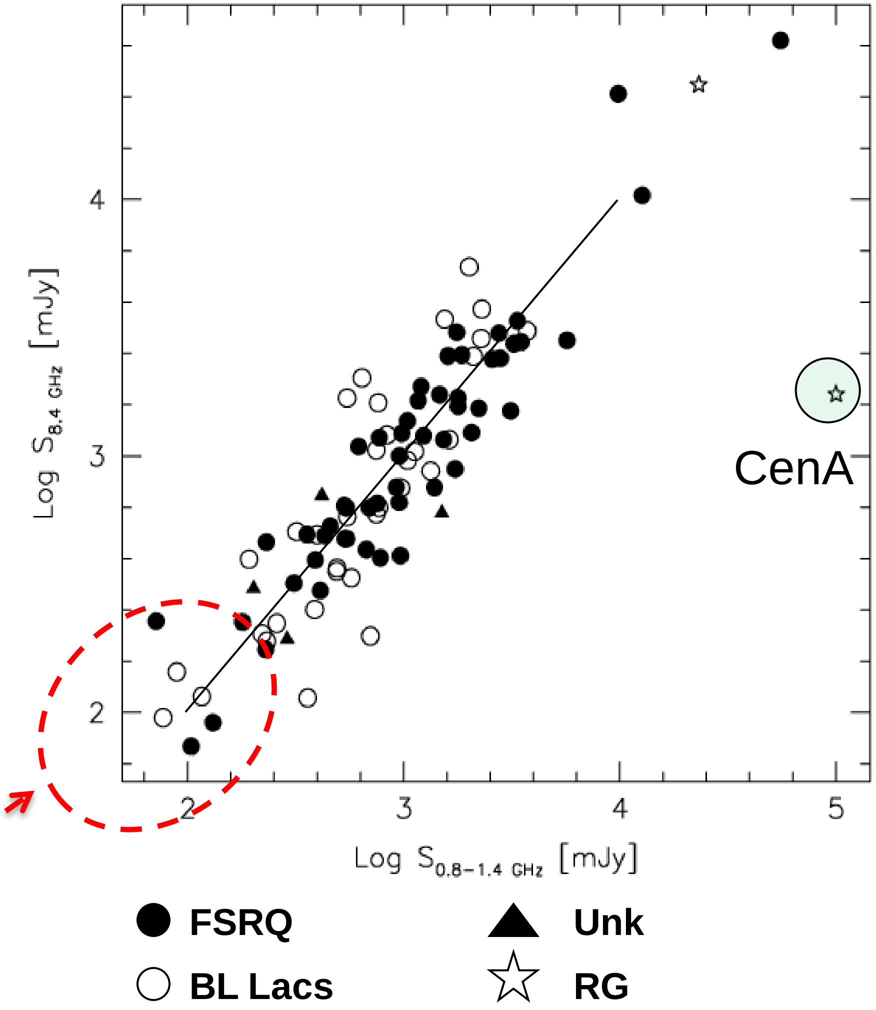




Donato et al. (2001)

Low vs high radio frequency: flux-flux

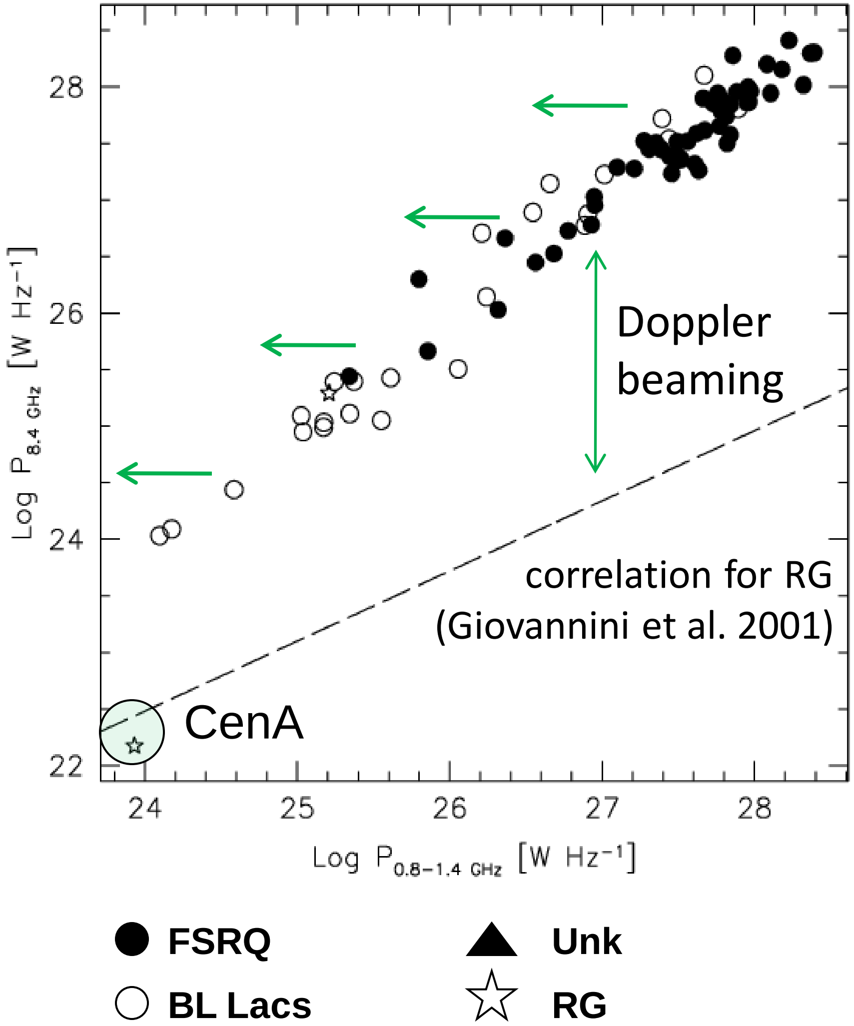
- **Based on LBAS (bright Fermi AGNs)**
- **Flux plane is not subject to distance bias**
    - **Low frequency from NVSS (1.4 GHz) or SUMSS (0.8 GHz)**
    - **High frequency typically from CRATES (8.4 GHz, or NED)**
- **another representation of the spectral index flatness**
    - **little to none extended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



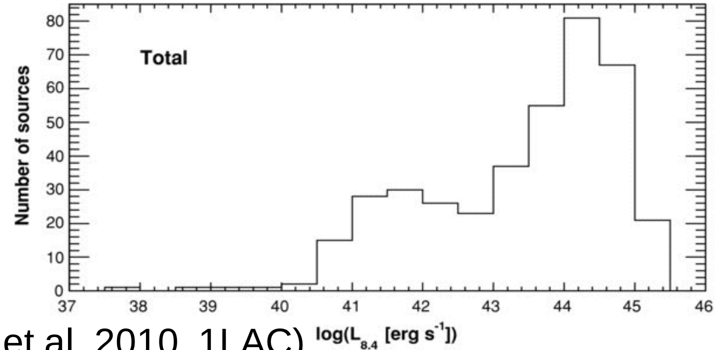
New BL Lacs sample fills in here

Low vs high radio frequency: luminosity-luminosity

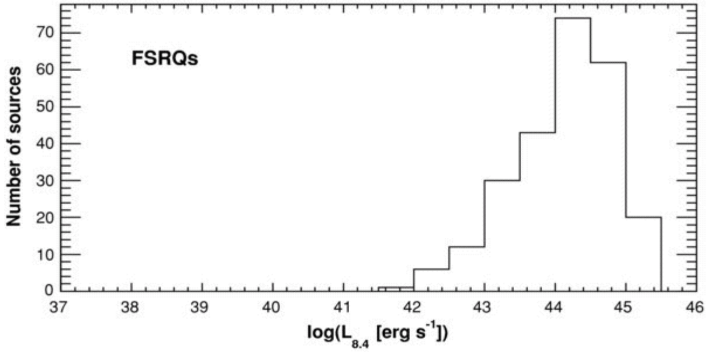
- **Caveat: Distance dependence stretches distribution**
- **All cores more luminous than expected for RG of same P_{low}**
  - **Doppler boost!**
  - **even more if one could subtract core from truly extended emission**
  - **indeed, extended radio emission of LBAS sources could be as low as 10^{23} 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: $\log L_r = 44.4 \pm 0.6$ [erg s^{-1}]**
  - **BL Lacs: $\log L_r = 42.8 \pm 1.1$ [erg s^{-1}]**

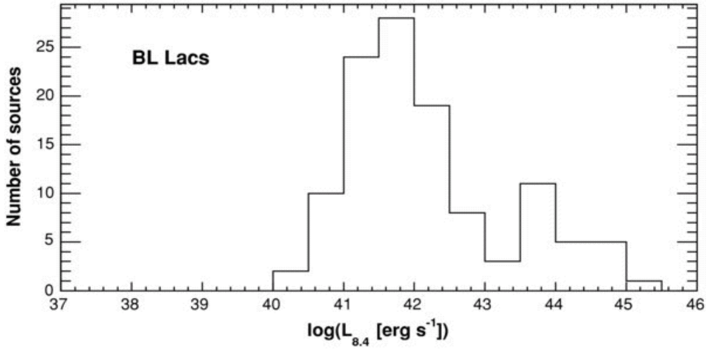


1LAC: Radio luminosity



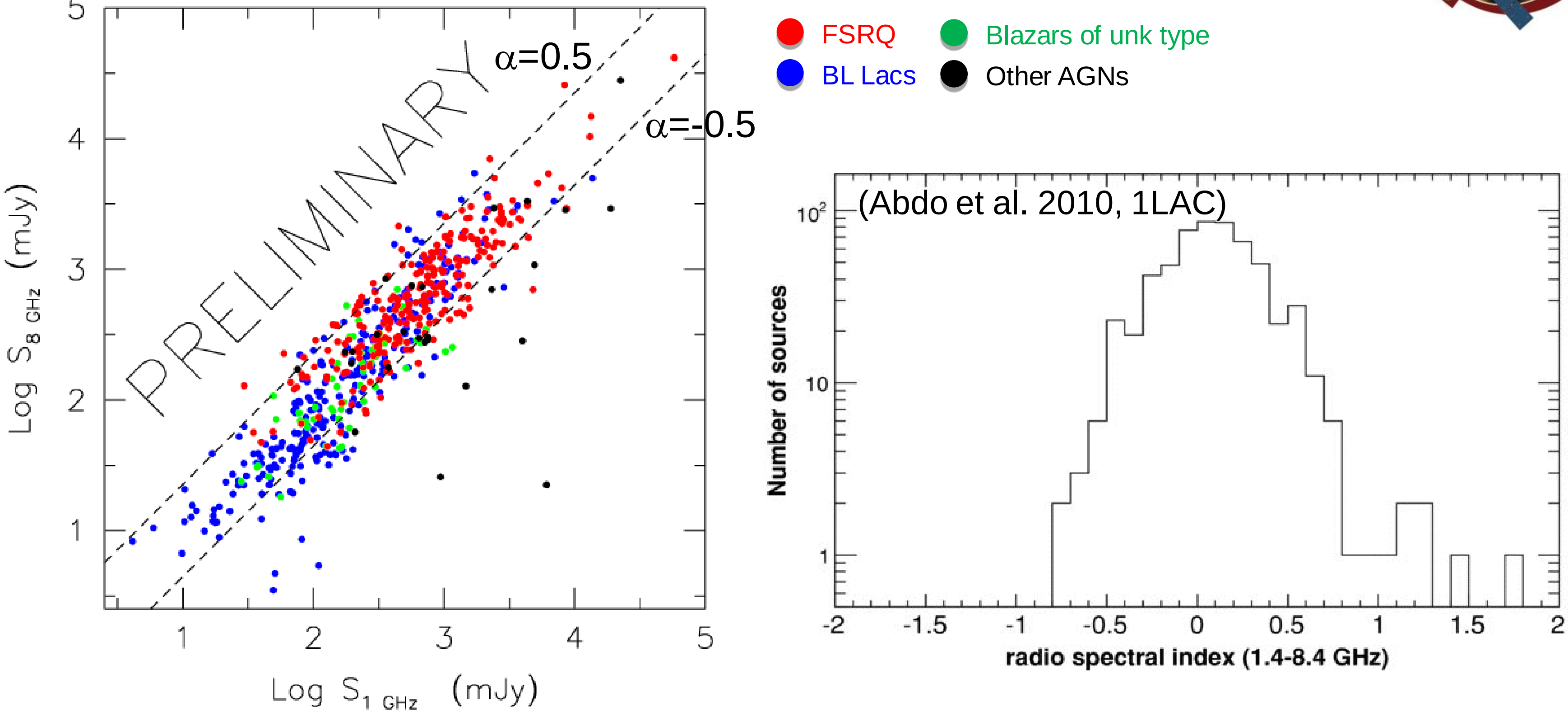
(Abdo et al. 2010, 1LAC)





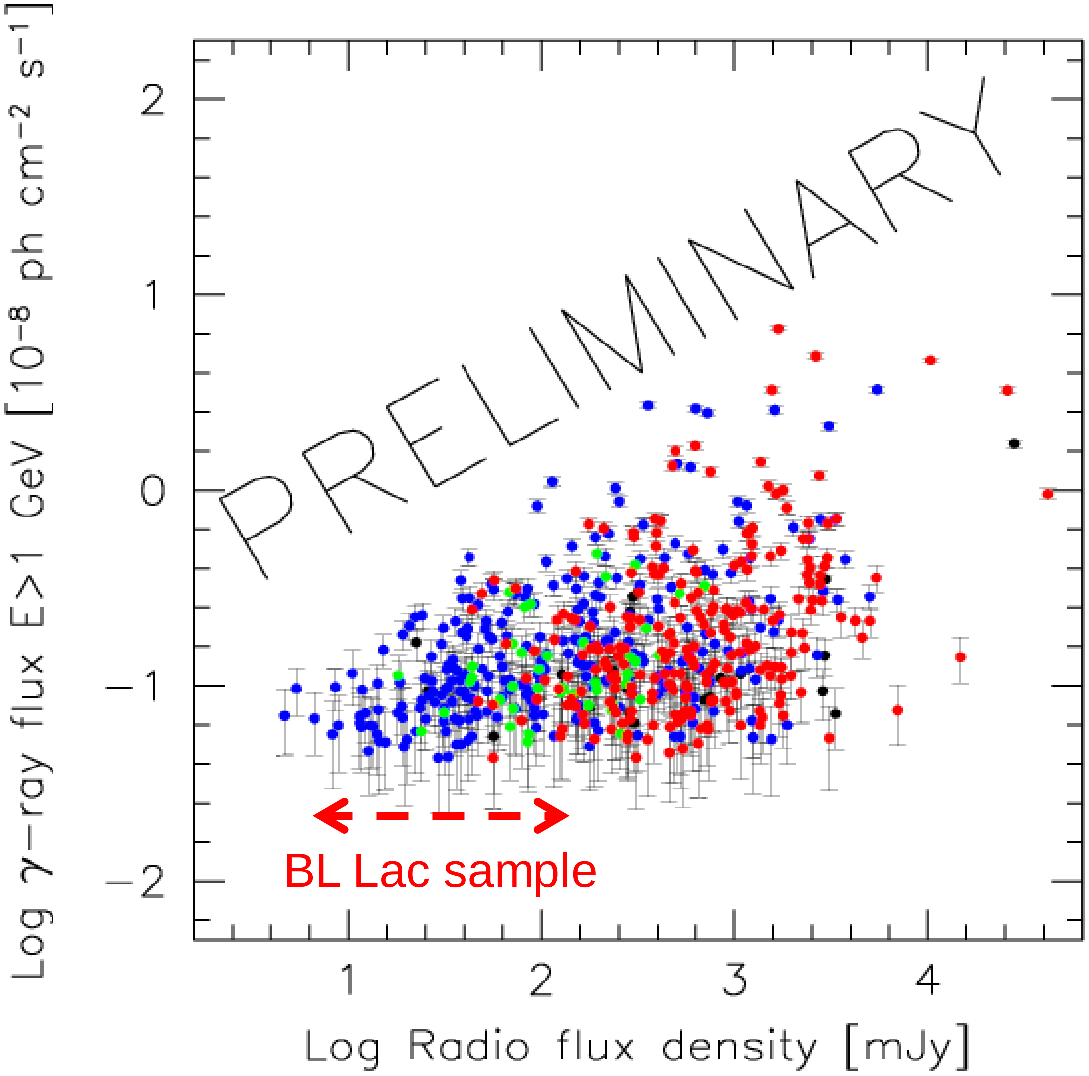
- **$L_r = \nu L(\nu)$, $\nu = 8.4$ GHz**
- **Radio luminosity L_r is typically 10^{41}-10^{45} erg s^{-1}**
  - **but it can be as low as 10^{37} erg s^{-1}**
- **FSRQ are clustered at higher luminosities, while BL Lacs follow a broader distribution down to 10^{40} erg s^{-1}**
  - **FSRQ: 44.1 +/- 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**

Radio spectral index/core dominance



- **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 (<α> = 0.06+/-0.23)**
- **However, a small but non negligible fraction has α>0.5**
  - **misaligned AGNs (Abdo et al. 2010, arXiv:1007.1624v1)**

Radio vs gamma-ray fluxes



● FSRQ

● BL Lacs

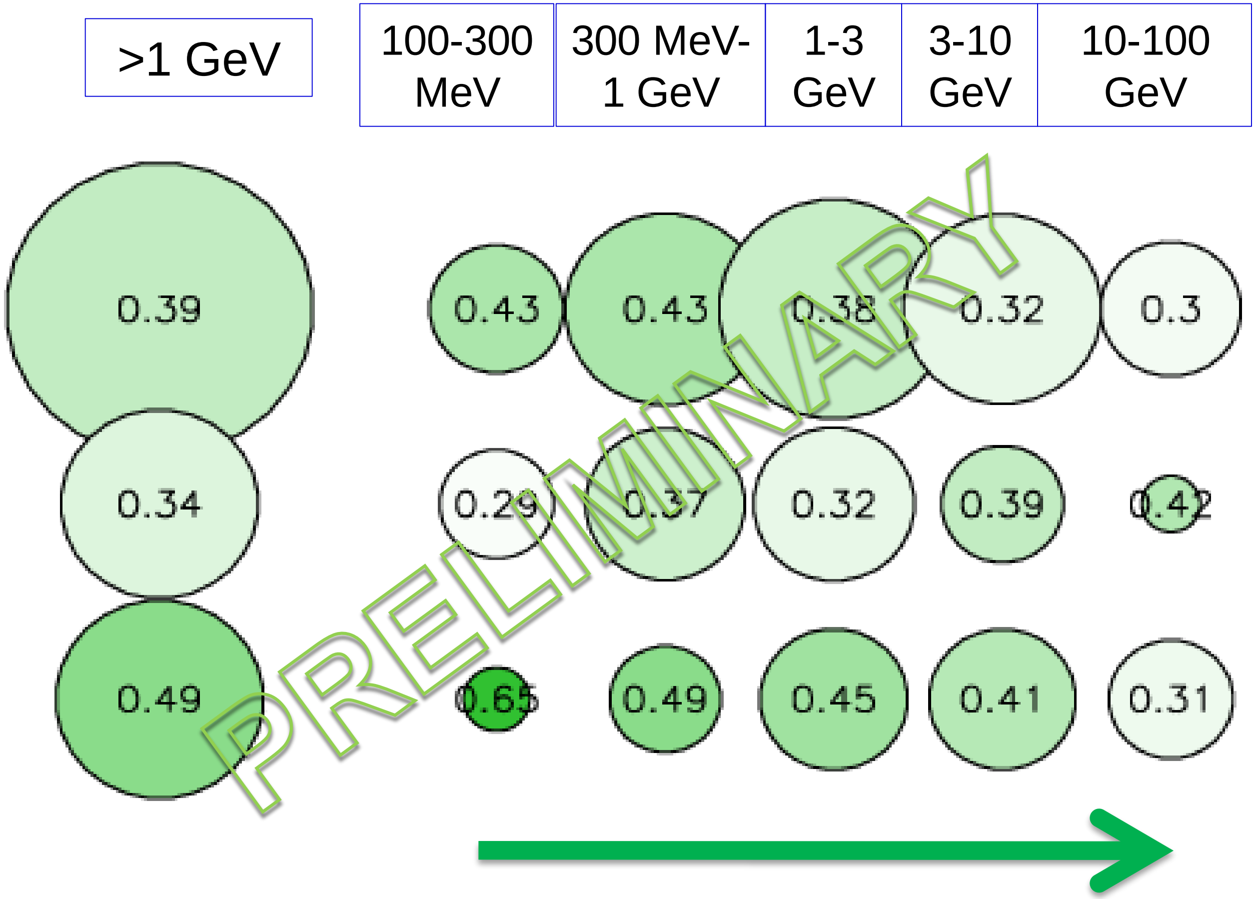
● Blazars of unk type

● Other AGNs

Gamma-ray data from 1FGL

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

Correlation coefficient by source type and energy



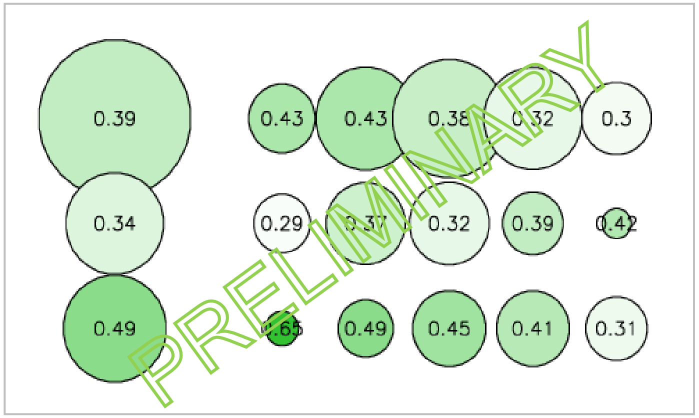
	>1 GeV	100-300 MeV	300 MeV-1 GeV	1-3 GeV	3-10 GeV	10-100 GeV
All sources	0.39	0.43	0.43	0.38	0.32	0.3
FSRQs	0.34	0.29	0.37	0.32	0.39	0.42
BL Lacs	0.49	0.65	0.49	0.45	0.41	0.31

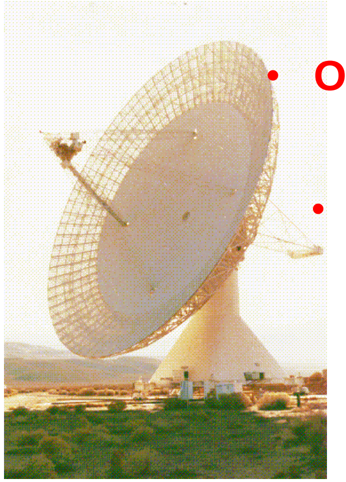
Energy band

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

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
- Time variability is significant – although general behavior is not affected

See also Mahony et al. (2010, 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

FINAL NOTES

Summary

- Compact VLBI cores are ubiquitous even in the least luminous BL Lacs
  - and they make up a significant fraction of the gamma-ray extragalactic sky
- Radio and gamma-ray fluxes appear to correlate over 4 magnitudes
  - with some possible difference between FSRQs and BL Lacs
- Monte-Carlo simulations provide an estimate of the correlation significance
  - which is high but sensitive to source distance distribution and other assumptions

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