Parsec-Scale Radio Properies of Gamma-ray Emitting Blazars

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FERMI AND JANSKY - OUR EVOLVING UNDERSTANDING OF AGN
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Image by Aurore Simonnet
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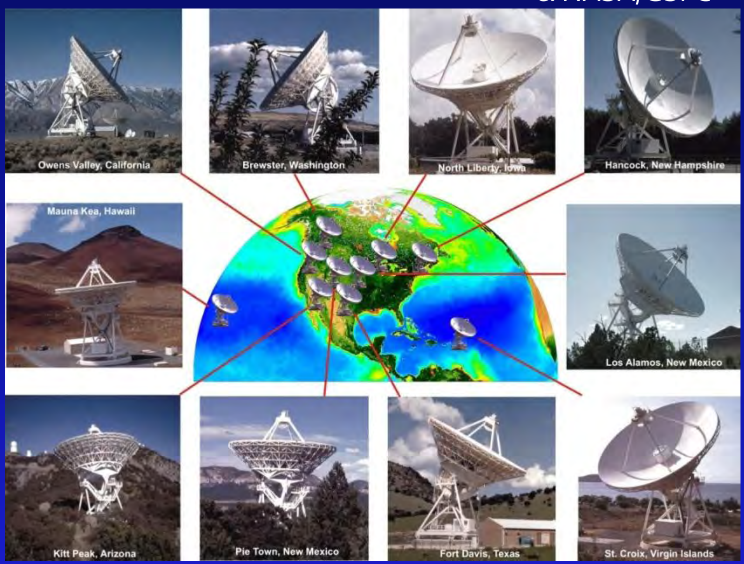
The Tools: Fermi & VLBI

- The Fermi Gamma-ray Space Telescope
  - Large Area Telescope (LAT)
  - Wide-field
  - Covers ~20 MeV to 300 GeV

NASA

- VLBI

NRAO/AUI & NASA/GSFC



Paul Boven & NASA

Tasso Tzioumis, ATNF

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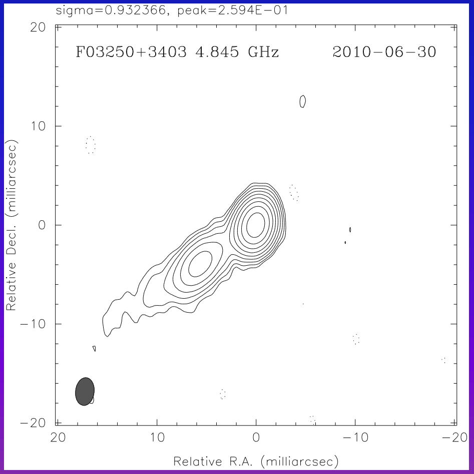
Our Sample

LAT-detected

- 244 sources from 1LAC catalog
  - 102 VIPS sources (90 observed in 2 epochs)
  - 7 MOJAVE sources
  - 135 sources not in VIPS or MOJAVE
- VIPS observations made prior to and during 2006
- New observations made between Nov. 2009 and July 2010

Non-LAT

- VIPS: VLBA Imaging and Polarimetry Survey (Helmboldt et al. 2007)
- 1018 non-LAT sources
- 5 GHz (6 cm)



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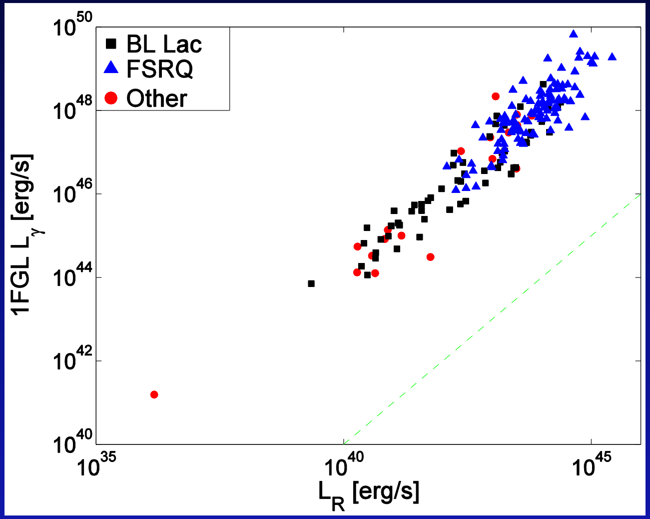
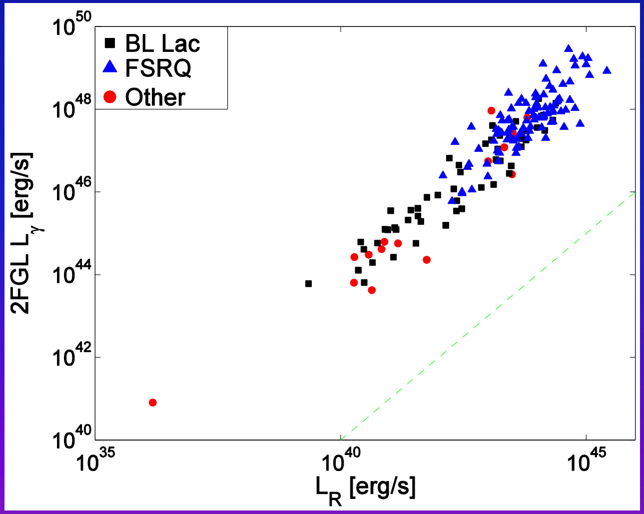
Gamma-ray Loudness

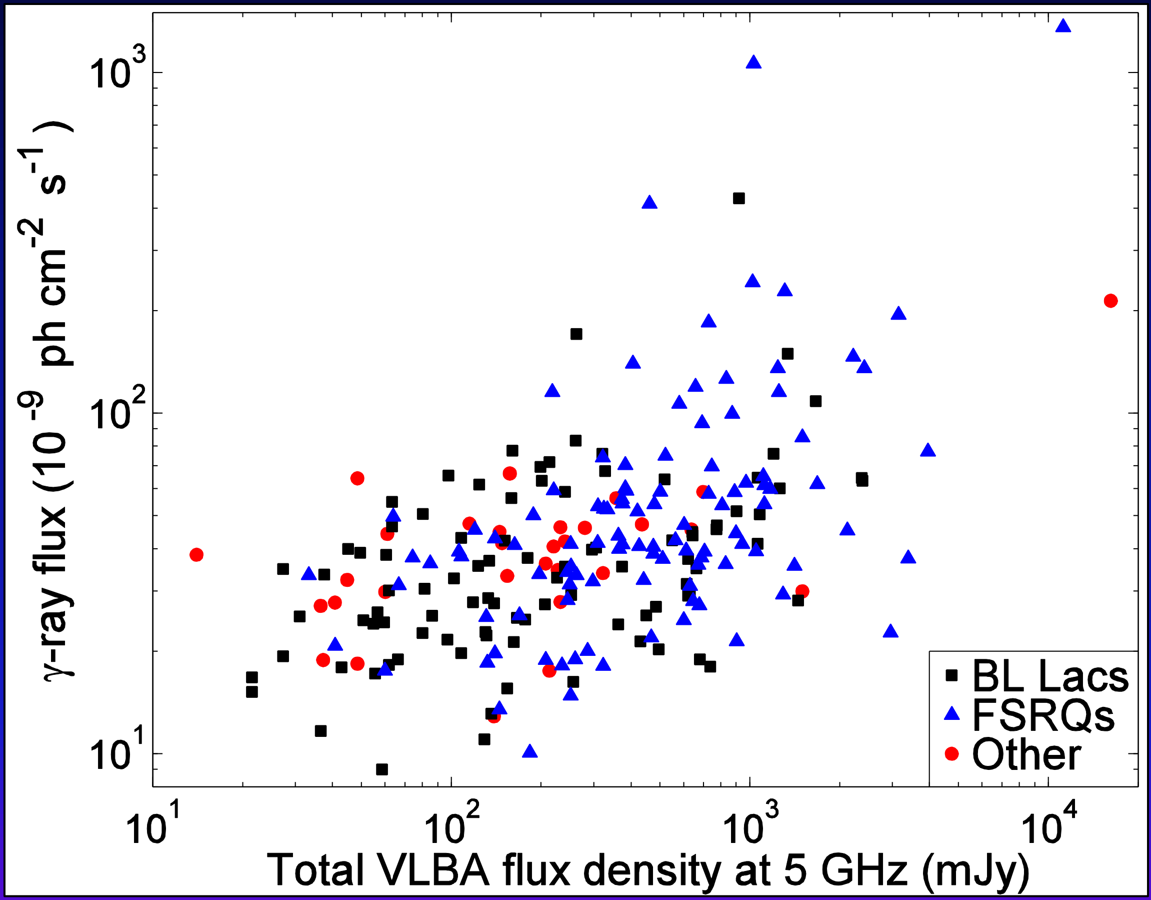




- Lister et al. (2011) used the ratio of γ-ray to radio luminosity as a measure of γ-ray loudness
- All of our LAT sources are γ-ray loud

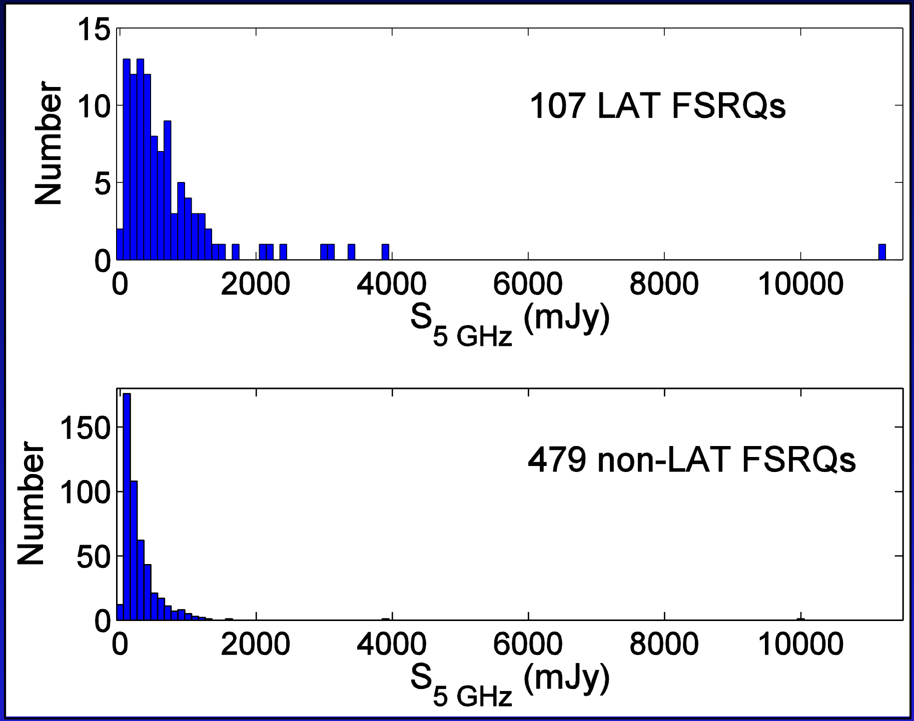
Flux-Flux Correlation

- BL Lacs
  - Rho = 0.467
  - P = $2x10^{-6}$
  - Correlation
- FSRQs
  - Rho = 0.510
  - P = $2x10^{-8}$
  - Correlation
- AGN/Other
  - Rho = 0.443
  - P = 0.014
  - Tentative correlation
- **Radio and γ-ray emission are probably related**

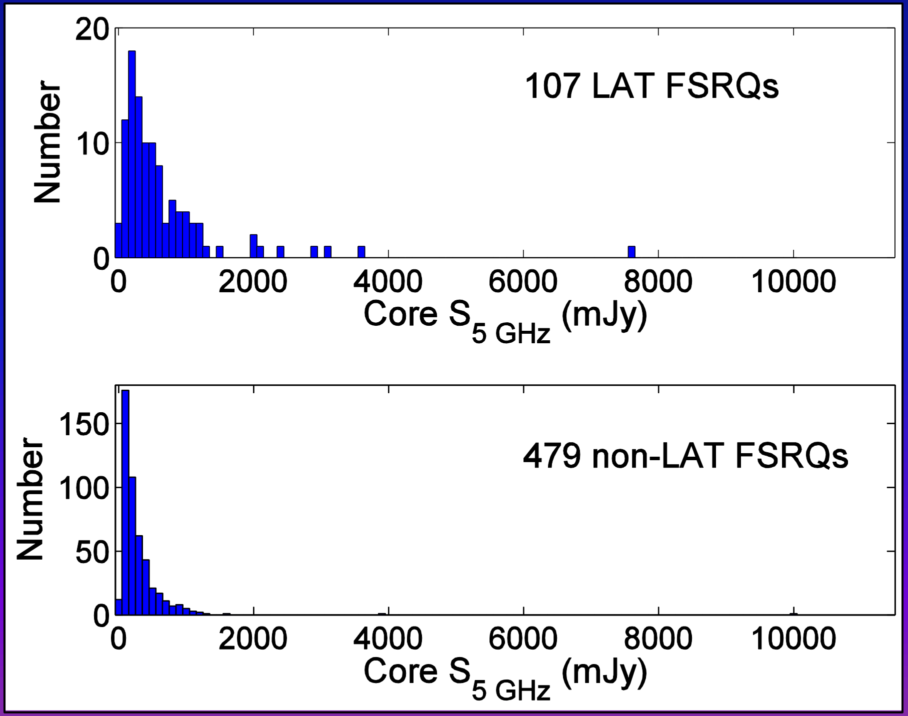


LAT fluxes: 100 MeV – 100 GeV

Flux Densities

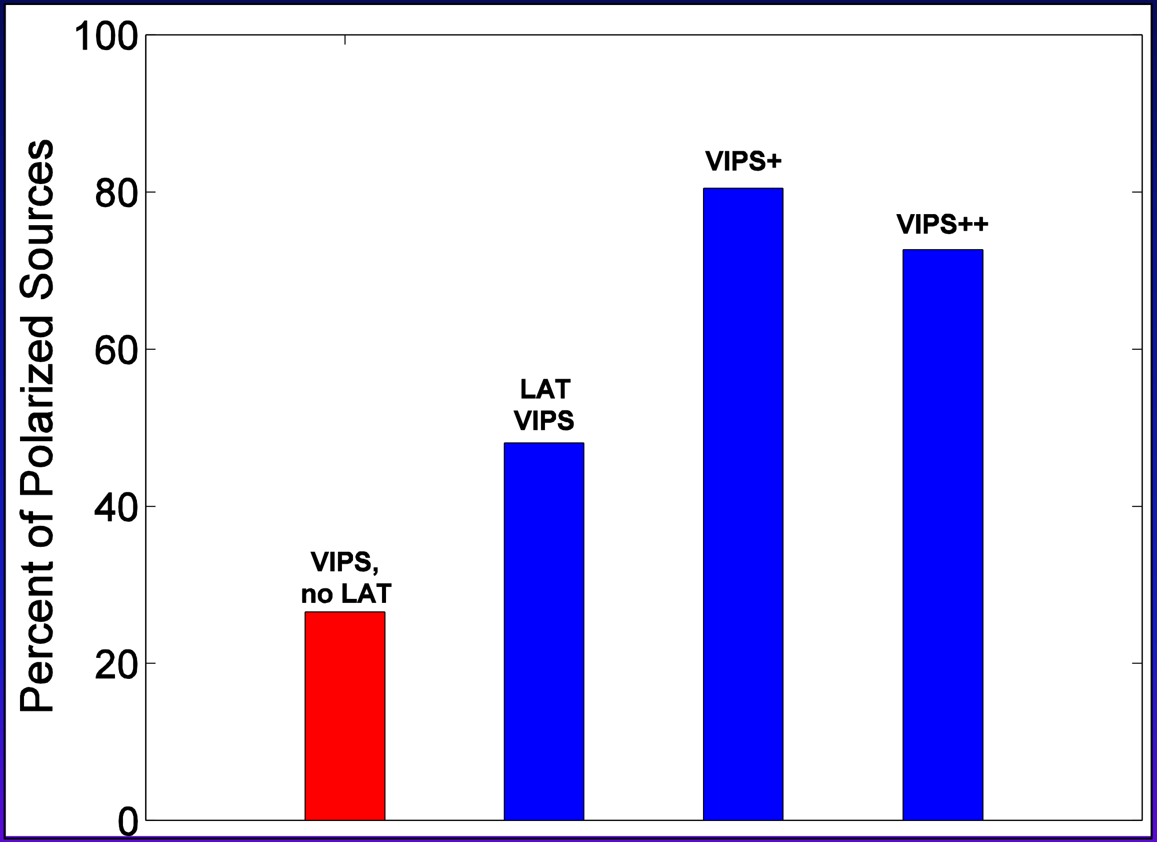


- LAT FSRQs have higher core and total 5 GHz flux densities than non-LAT FSRQs



LAT FSRQs appear to be extreme sources

Core Polarization

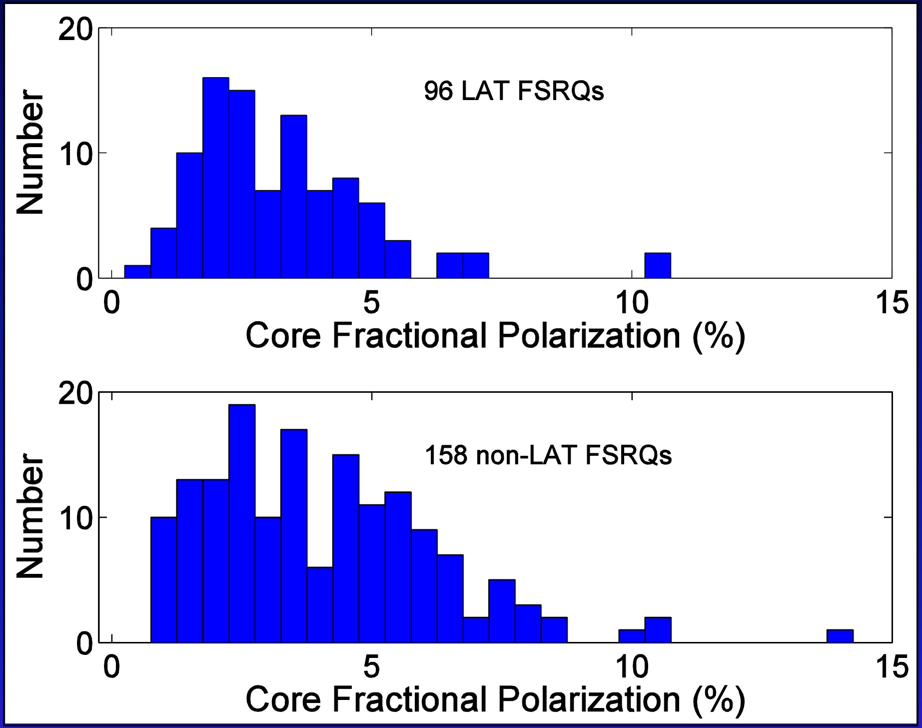


VIPS: data taken prior to or during 2006
VIPS+: Follow-up on 90 VIPS/LAT sources plus 7 MOJAVE/LAT sources, 2009-2010
VIPS++: 135 LAT sources not in VIPS or MOJAVE, 2010

- The percentage of sources found to be polarized is higher for LAT blazars than for non-LAT blazars.
- **Strong, uniform magnetic fields in the cores are tied to γ-ray emission.**

Core Polarization

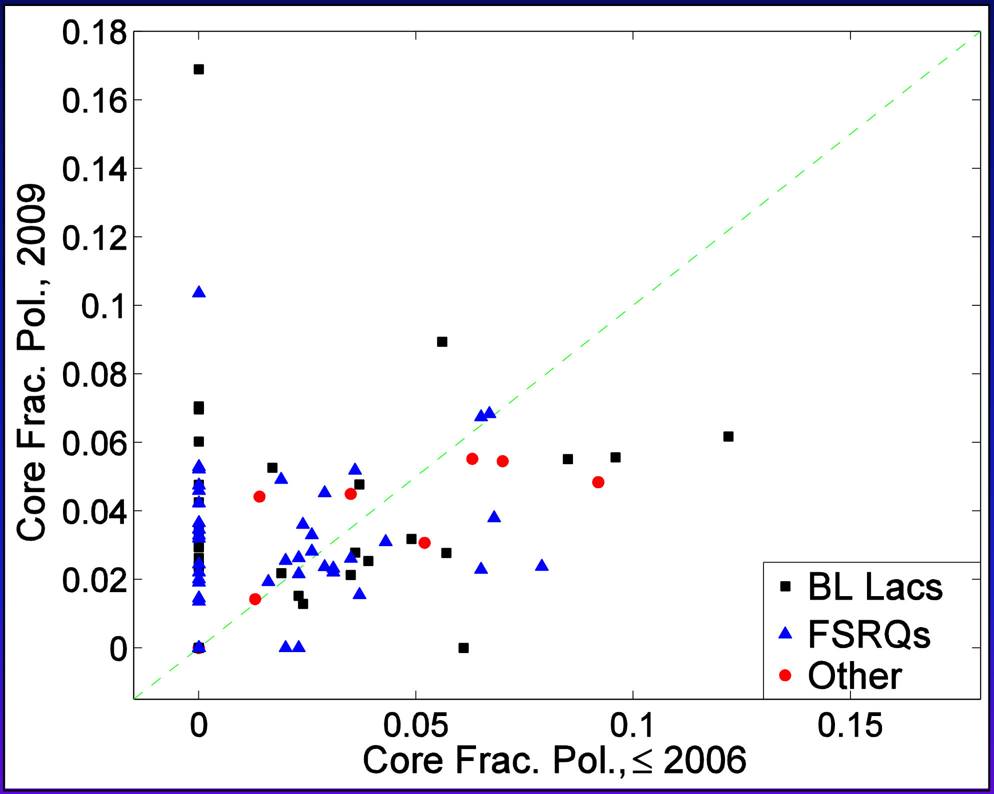
- LAT sources are more likely to be polarized.
  - LAT: 176/232 (75.9%)
  - Non-LAT: 270/1018 (26.5%)
- Fractional polarization is slightly less for LAT sources.
  - LAT median: 3.3%
  - Non-LAT median: 4.4%
  - This is different from other studies (e.g. Hovatta et al. 2010)
- FSRQ core fractional polarization may be different for LAT and non-LAT
  - K-S test: 0.4% probability that they are drawn from same parent population



LAT sources are polarized more often, but do not appear to be more strongly polarized

Core Polarization:

New vs. Old



- 48 of 90 sources showed higher core fractional polarization during LAT detection
- 15 sources had no detectable core polarization in both epochs
- Only 3 sources went from polarized in archival data to unpolarized in new data

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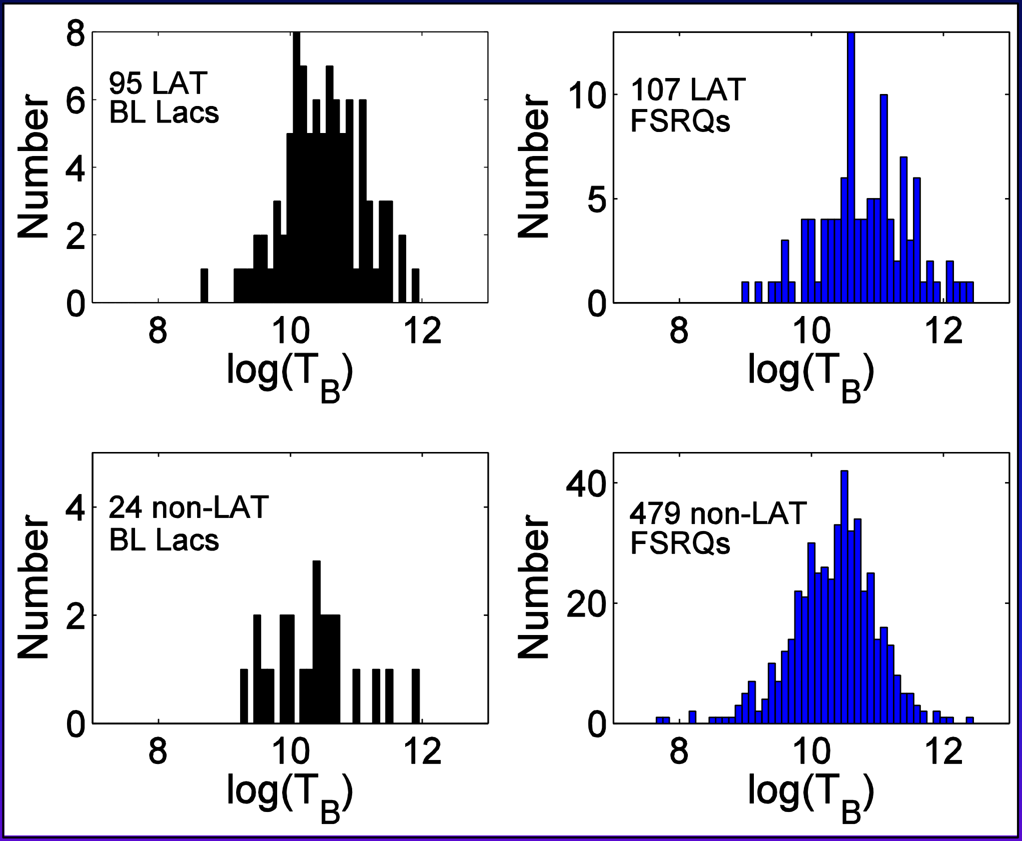
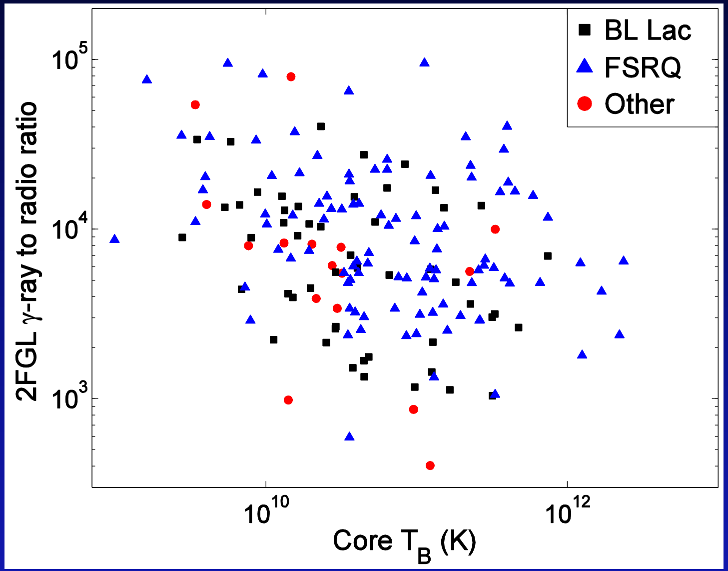
Core Brightness Temperatures

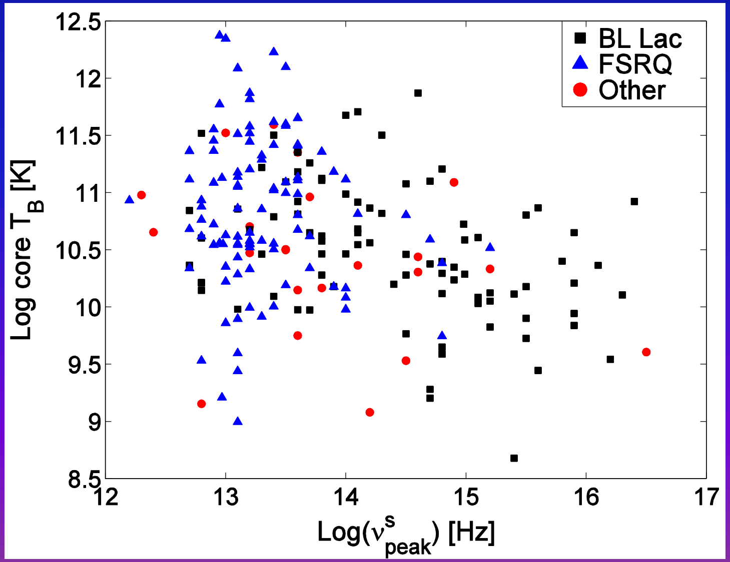


- K-S tests indicate that the FSRQs are very different, but BL Lac objects are similar.
- Median core T_Bs for FSRQS:
  - LAT: 6.4×10^{10} K
  - Non-LAT: 2.5×10^{10} K
- **LAT FSRQs are extreme sources**

Core Brightness Temperature Correlations

- We found a significant correlation between core T_B and γ-ray loudness
  - 1FGL: ρ=-0.3, $p=2x10^{-6}$
  - 2FGL: ρ=-0.3, $p=8x10^{-5}$
- We also found a correlation between core T_B and peak synchrotron frequency, but only for BL Lacs
  - ρ=-0.4, $p=10^{-4}$





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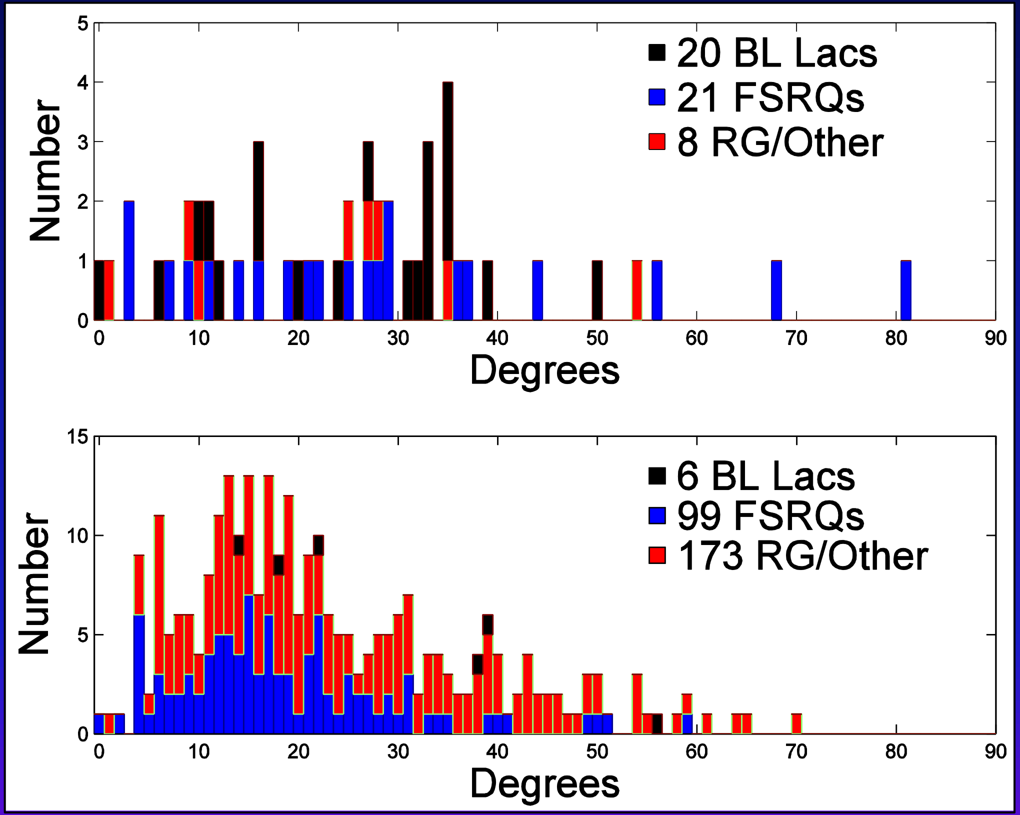
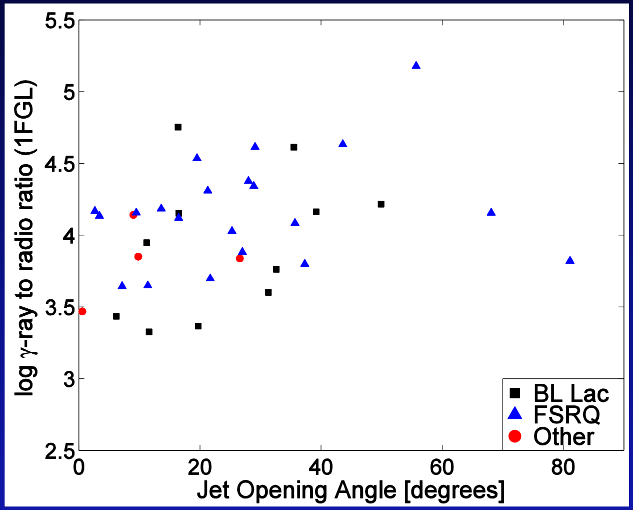
Jet Opening Angle

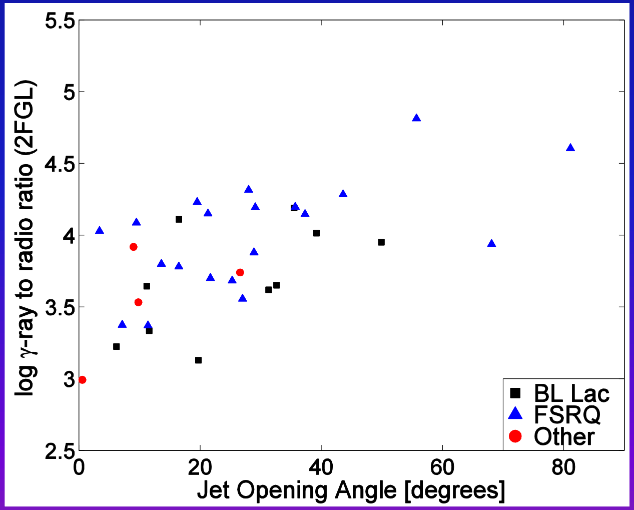
- Only had opening angle measurements for 49 LAT sources.
- There is evidence that LAT sources have larger opening angles, especially FSRQs.
- K-S test done on combined BL Lac-FSRQ samples showed 0.4% chance that LAT and non-LAT distributions are related



Stacked histograms

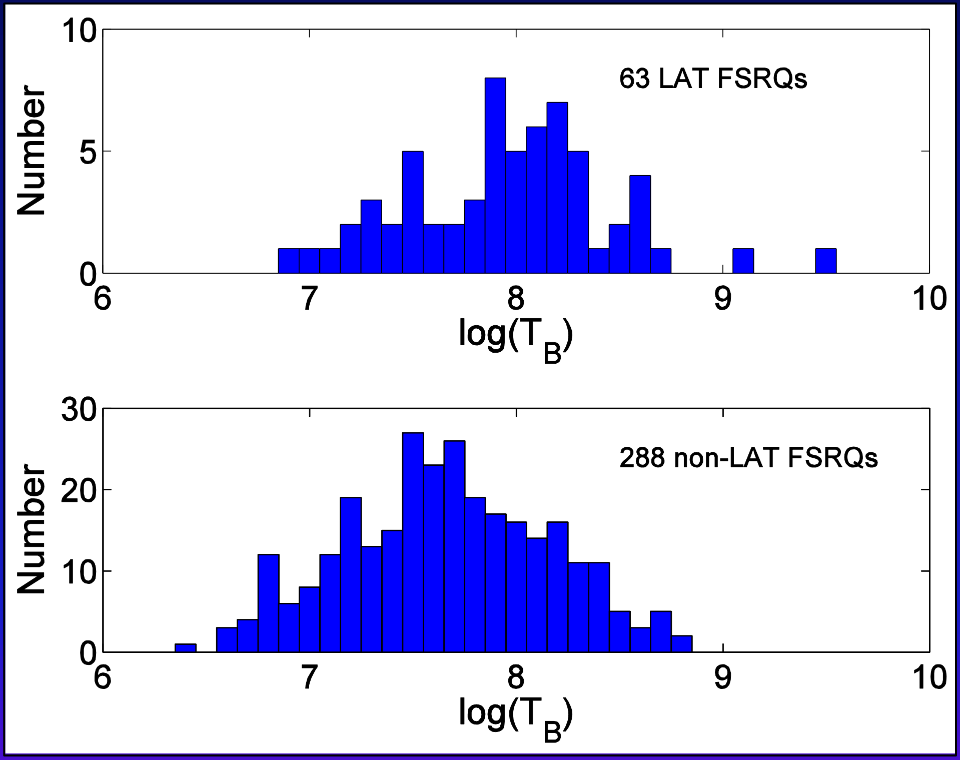
Jet Opening Angle





- Lister et al. (2011) reported a non-linear relation between jet opening angle and γ-ray loudness
- We also found a hint of a correlation, but only for FSRQs and only in the 2FGL data
  - 1FGL: $\rho=0.2$, $p=0.34$
  - 2FGL: $\rho=0.6$, $p=0.009$

Jet Characteristics



FSRQ jet brightness temperatures

- Jet bending (ΔPA) and jet length distributions are very similar for LAT and non-LAT sources.
- LAT FSRQs appear to have higher jet brightness temperatures than non-LAT FSRQs (K-S test: 10^{-5})

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BL Lacs

- Our LAT BL Lac sample is almost 4 times the size of our non-LAT sample
  - Possibly a selection effect – could there be a population of dim BL Lacs that do not produce γ-rays?
- 3 small differences between LAT and non-LAT BL Lac populations:
  - LAT BL Lacs have core polarization more often (70% LAT vs. 42% non-LAT)
  - LAT BL Lacs are more often "long-jet" morphology
  - LAT BL Lacs *may* have larger opening angles
- It seems likely that all BL Lacs are producing γ-rays, but some are just below the LAT threshold

FSRQs

- LAT FSRQs appear to be very different from the non-LAT FSRQs
  - Higher radio flux densities
  - Higher core and jet brightness temperatures
  - More often polarized (90% LAT,33% non-LAT)
  - *May* have larger opening angles
- 28 of 44 LAT FSRQs with observations in 2 epochs showed an increase in core polarization during LAT detection

FSRQs

- It seems that the LAT FSRQs are extreme sources.
- The LAT FSRQs can be explained with Doppler boosting, but they require a substantially higher Doppler factor than the LAT BL Lacs.
- Lister et al. (2009) reported that the median jet speeds for LAT FSRQs were more than a factor of 2 faster than for the LAT BL Lacs.

Constraints on Gamma-ray Emitting Region

- Correlation between radio flux density and LAT flux implies synchrotron and inverse Compton emission are related
  - γ-rays should be coming from jets
- Most of the differences between LAT and non-LAT samples are related to the cores
  - γ-rays should be coming from the BASE of the jets
- It is possible that BL Lacs and FSRQs have different γ-ray production mechanisms
  - BL Lacs may be synchrotron self-Compton (SSC)
  - FSRQs may be external inverse Compton (EC) – seed photons may come from broad-line region (BLR)

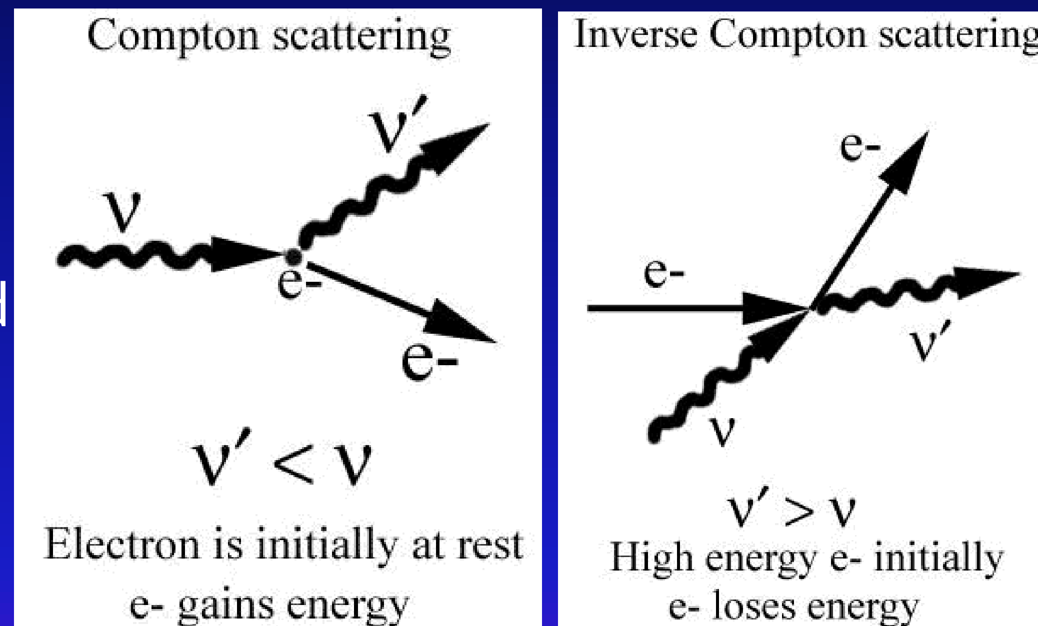
Conclusions

- BL Lacs are probably all producing gamma-rays, but we don't detect some because of low Doppler factors and/or variability.
- Gamma-ray loud FSRQs are extreme sources with high radio flux densities and high brightness temps.
- There is a hint that LAT blazars have larger jet opening angles than non-LAT blazars.
- Strong, uniform magnetic fields in the cores/at the base of the jets play a role in γ-ray emission.
- The γ-rays are probably coming from the base of the jets.

Backup slides

γ-ray Production Mechanism

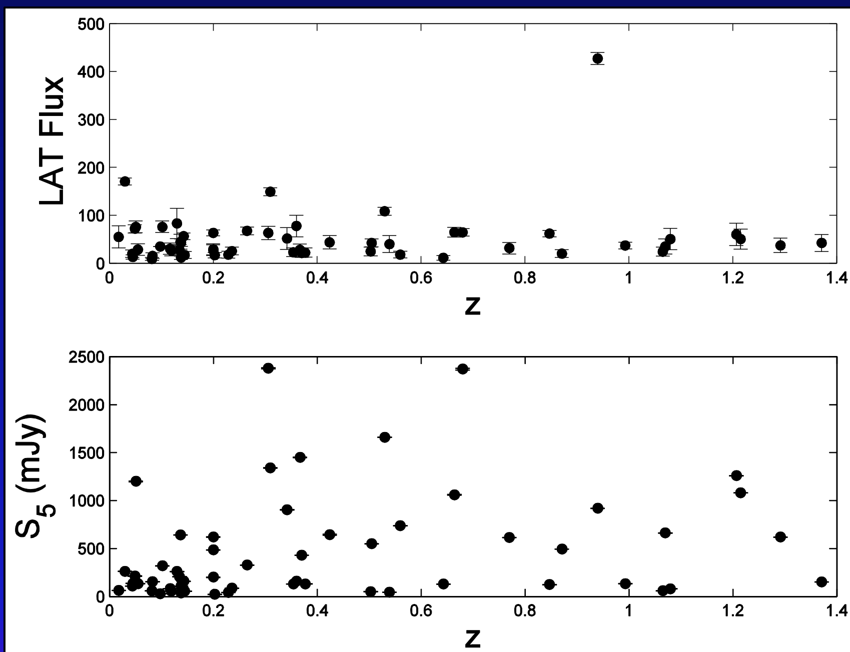
- Inverse Compton scattering
- 2 possibilities
  - Synchrotron Self-Compton (SSC) – seed photons are from the electrons’ own synchrotron emission
  - External Inverse Compton (EC) – seed photons are from some external source



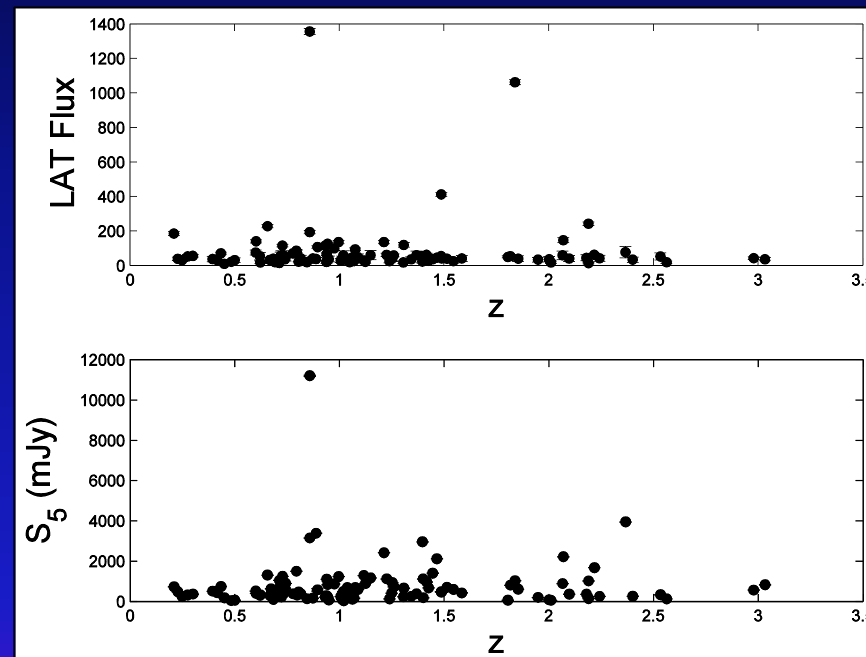
Diagrams from venables.asu.edu

No Strong Redshift Correlations

BL Lacs



FSRQs

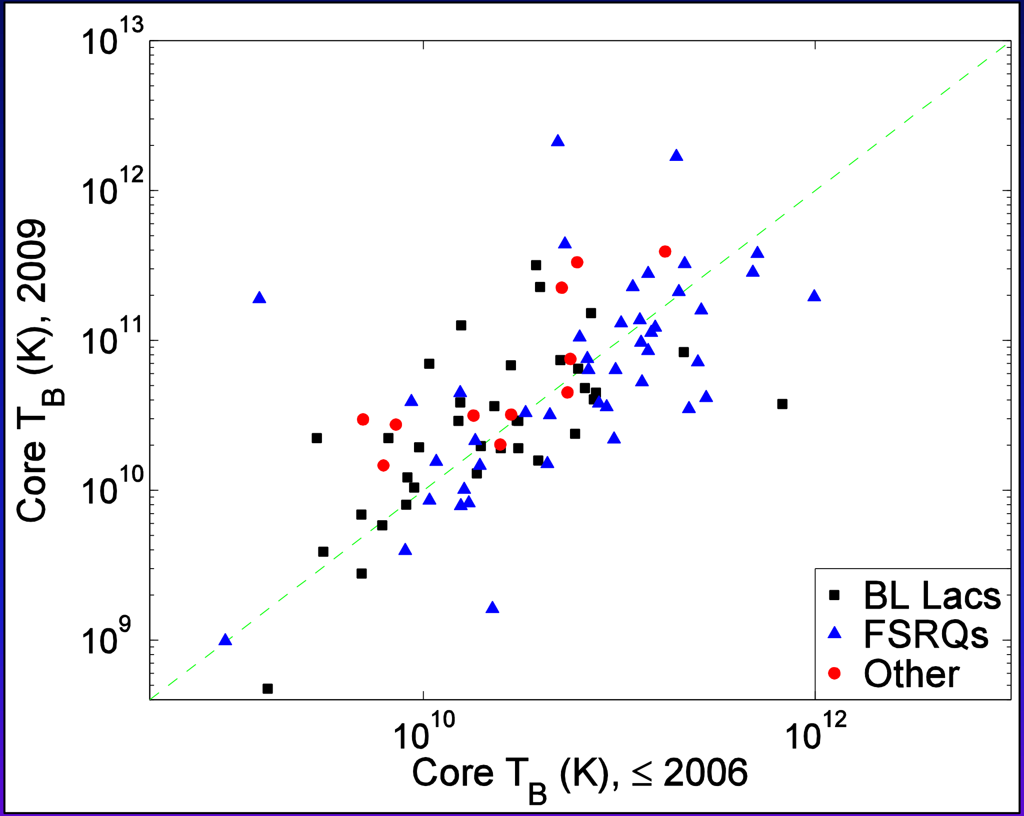


LAT-z: rho = 0.08, P=54%
S_5-z: rho = 0.31, P=2.1%

LAT-z: rho = 0.02, P=87%
S_5-z: rho = 0.11, P=26%

γ-ray flux is in units of 10^{-9} ph cm^{-2} s^{-1}

Core Brightness Temperatures (New vs. old)



- Nearly all of the sources had new core T_B measurements within 5% of the old measurement, or showed an increase in core T_B

Source Morphology

LAT/ non-LAT	Opt Type	LJET (>6mas)	SJET (<6mas)	PS	CPLX	CSO	N/A
LAT							
	BL Lac	55 (58%)	25 (26%)	12 (13%)	5 (3%)	…	…
	FSRQ	54 (50%)	30 (28%)	21 (20%)	2 (1%)	…	…
	Other	21 (70%)	5 (17%)	4 (13%)	…	…	…
Non-LAT							
	BL Lac	11 (46%)	7 (29%)	6 (25%)	…	…	…
	FSRQ	188 (39%)	121 (25%)	136 (28%)	2 (~1%)	30 (6%)	2 (~1%)
	Other	214 (42%)	98 (19%)	111 (21%)	11 (2%)	71 (14%)	10 (2%)

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Non-Blazar AGN

- The major difference between the LAT and non-LAT AGN/Others is that 43% of the LAT sources have polarization in their cores, compared to only about 20% for the non-LAT AGN/Others.
- Note: we used the optical classification system from the 1LAC (Abdo et al. 2010). There is controversy about the classification of several of the objects we call AGN/Other.

Compact Symmetric Objects

- Stawarz et al. (2008) predicted there should be many CSOs among LAT detections due to inverse Compton scattering of ultrarelativistic electrons in their lobes.
- However, there are no compact symmetric object candidates among the LAT sources in our sample or any other survey, to date.

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