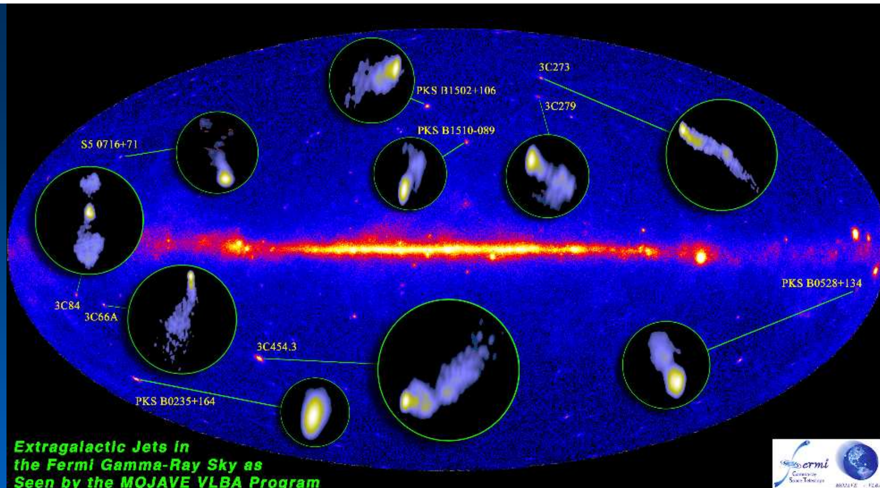
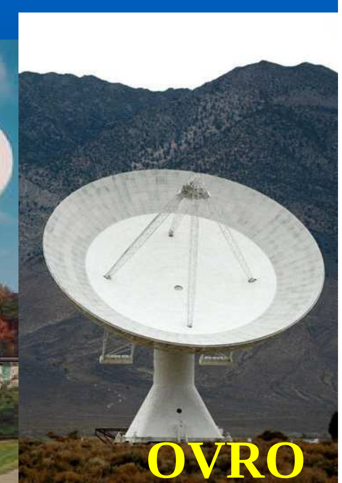


Blazars at High Resolution:
What large multi-epoch VLBI studies can tell us

Matt Lister

Purdue University



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Monitoring
Of
Jets in
Active Galaxies with
VLBA
Experiments

The MOJAVE Program is supported under NASA Fermi Grant NNX08AV67G

Very Long Baseline Array

Outline

- Sampling biases in blazar studies
- Understanding blazar demographics with large surveys: Fermi (2LAC) and VLBA (MOJAVE)
- Latest kinematics results from MOJAVE

Goals of Blazar Population Studies

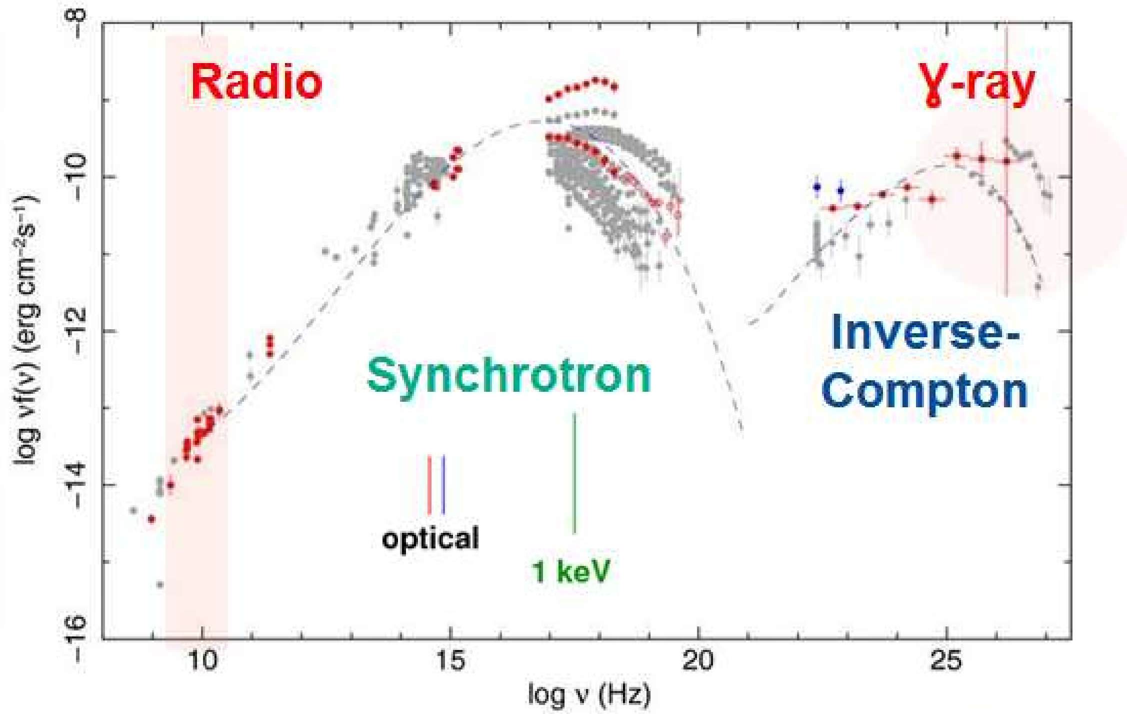
- What fundamental parameter(s) dictate blazar characteristics?
  - observables: SED peak location, line widths, jet speed, synchrotron power, Compton dominance
  - intrinsic quantities: accretion rate, BH mass & spin, jet power & B field, host galaxy properties

- How are specific blazar classes unified with their un-beamed counterparts?

Blazar Sample Biases

- Inconvenient truth: ***No blazar sample can ever be truly complete***

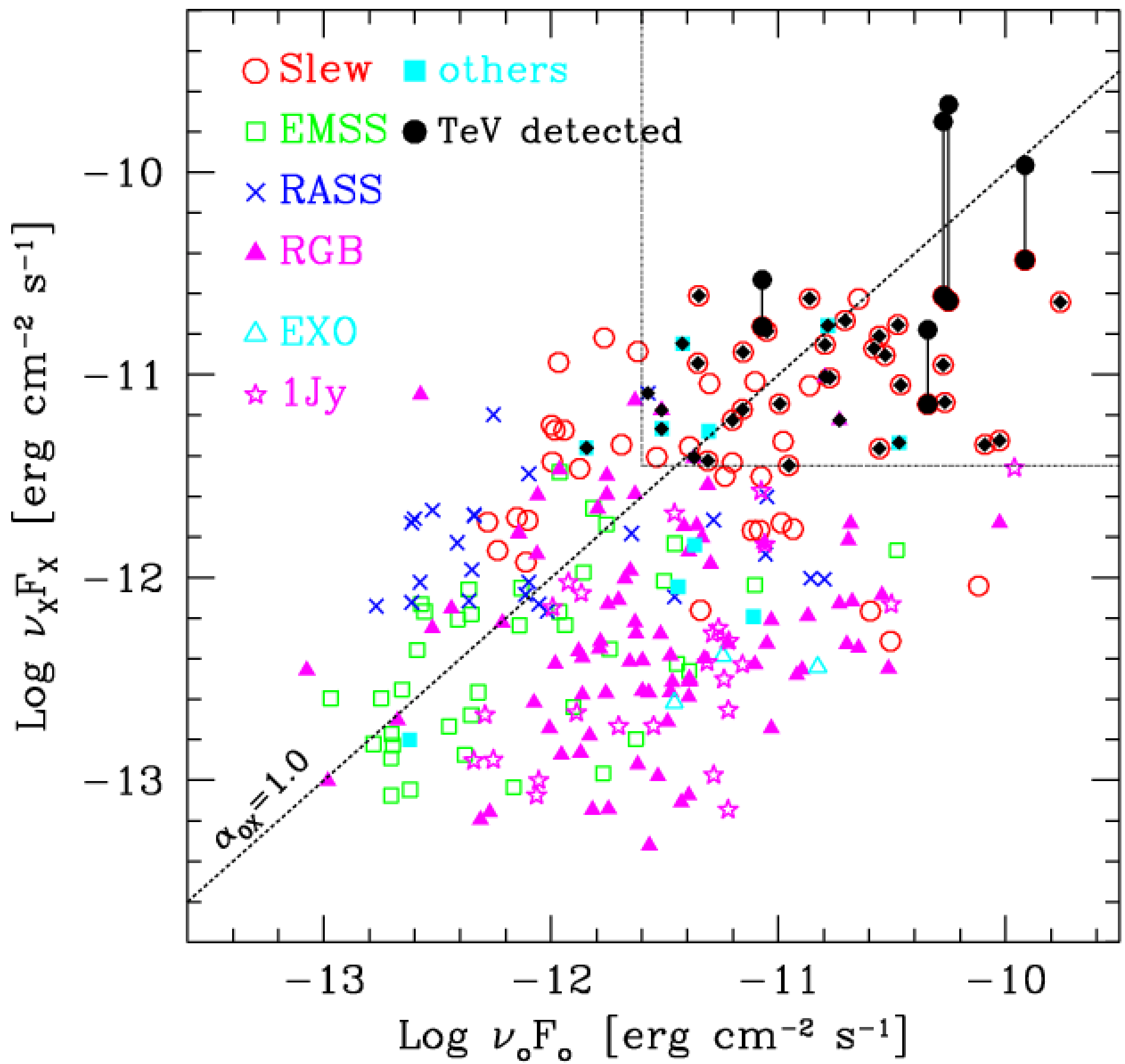
- Flux density is dependent on jet activity state, speed & orientation, and blazar SED characteristics



Abdo et al., ApJ 716, 30 (2010)

Mrk 421
High
Spectral-
Peaked
(HSP) blazar

X-ray
Flux



Optical Flux

Costamante 2002, A&A 384,56

Blazar Sample Biases

- Challenges present in every band:
  - obscuration in optical and X-ray
  - spectral contamination from accretion disk and host galaxy
  - spectral contamination from lobe (non-beamed) emission
  - source localization in gamma-rays
  - photon attenuation in TeV gamma-rays
  - non-simultaneous, incomplete or uneven survey sky coverage

Addressing Blazar Sample Biases

- Concentrate on 'uncontaminated' bands:
  - radio, sub-mm, γ-rays
- Discriminate based on compactness
  - radio spectrum, brightness temperature
- Stick to bright flux cutoffs
  - avoids contamination from nearby low-luminosity AGNs
- Use multi-epoch, wide-area surveys
  - catch both active and quiescent states

Fermi 2nd LAT AGN Catalog

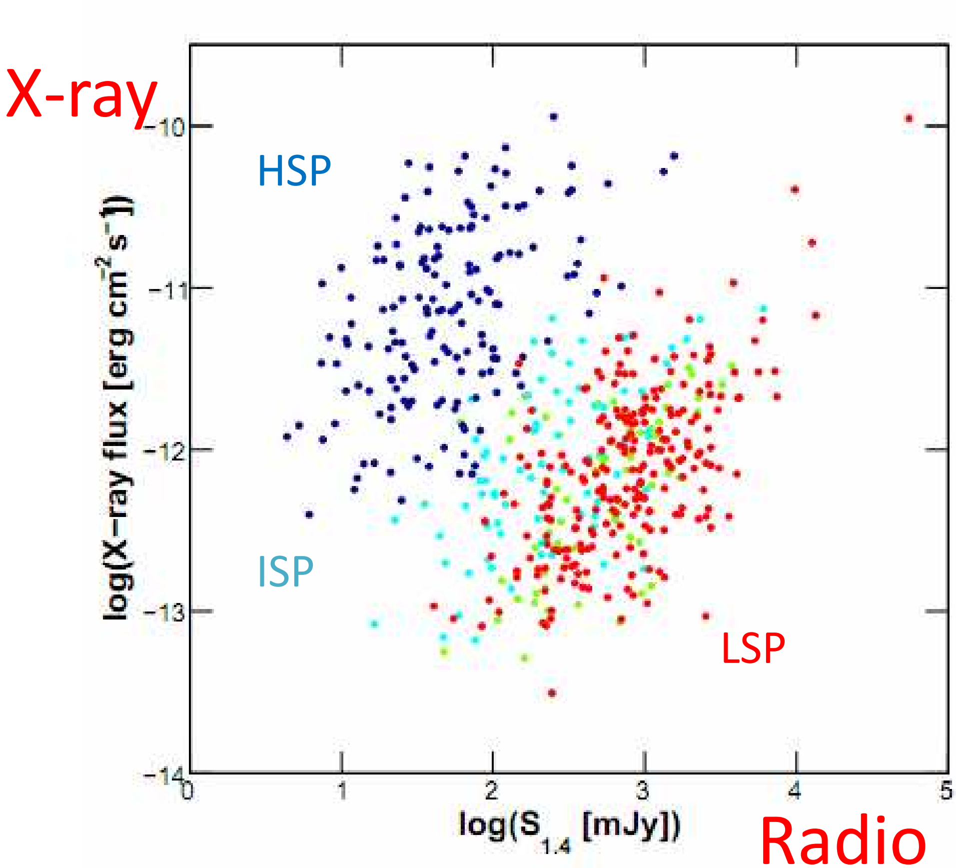


Fig. 8.— X-ray flux versus radio flux for blazars in the Clean Sample. Red: FSRQs, green: LSP-BL Lacs, light blue: ISP-BL Lacs, dark blue: HSP-BL Lacs.

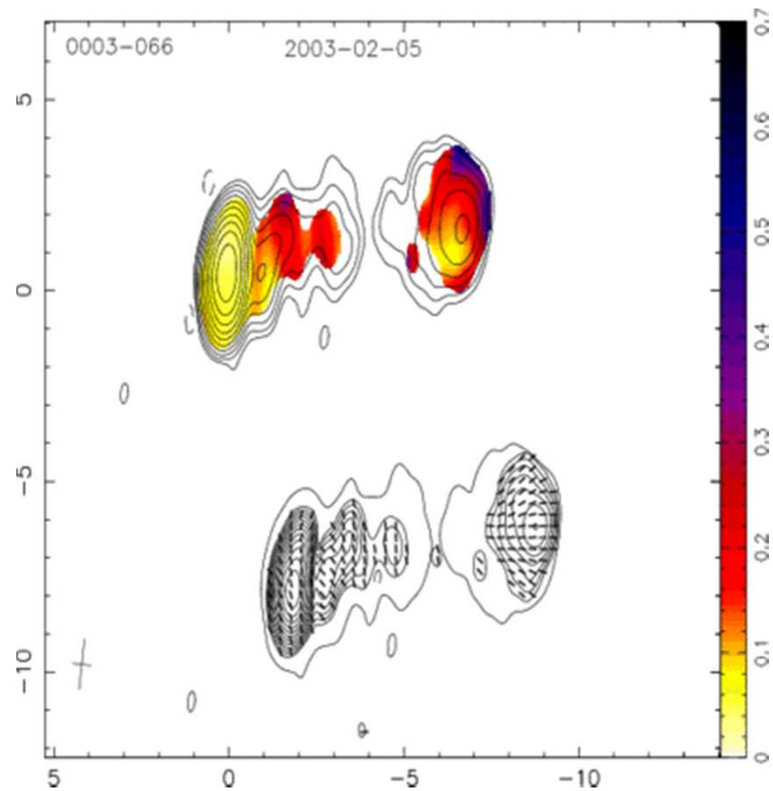
Fermi LAT Collab, 2012, ApJ 743, 171

- Broadband (> 0.1 Gev), multi-epoch (2yr long) selection
- No contamination from host galaxy
- Still incomplete due to association issues
  - 886 'clean' 2LAC blazars
  - 302 unassociated 2FGL

MOJAVE VLBA Program

- Regular observations of radio-bright AGNs
  - NRAO VLBA Key Science project
- 24 hr observing session every 3 weeks
  - cadence tailored to individual jets: once every 3 weeks to once every 3 years
- mas-resolution images at 15 GHz
  - continuous time baselines on many sources back to 1994
  - full polarization since 2002

www.physics.purdue.edu/MOJAVE



MOJAVE images of 0003-066

Colors: fractional linear polarization

MOJAVE Monitoring Samples ($\delta > -30°$)

- **1.5 Jy** → All 184 AGNs known to have exceeded 1.5 Jy at 15 GHz (VLBA) between 1994.0-2010.0
- **1FM** →complete set of 116 γ-ray selected AGNs from *Fermi* 1LAC
- **Low-Luminosity** → Representative sample of AGNs with pc-scale 15 GHz luminosity below 10^{26} W/Hz (mainly radio galaxies)
- 272 AGNs total, dominated by blazars, redshifts are 90% complete:
  - 179 flat spectrum quasars
  - 67 BL Lacs (41 of which have a SED peak above 10^{14} Hz)
  - 21 radio galaxies
  - 5 unknown optical classification

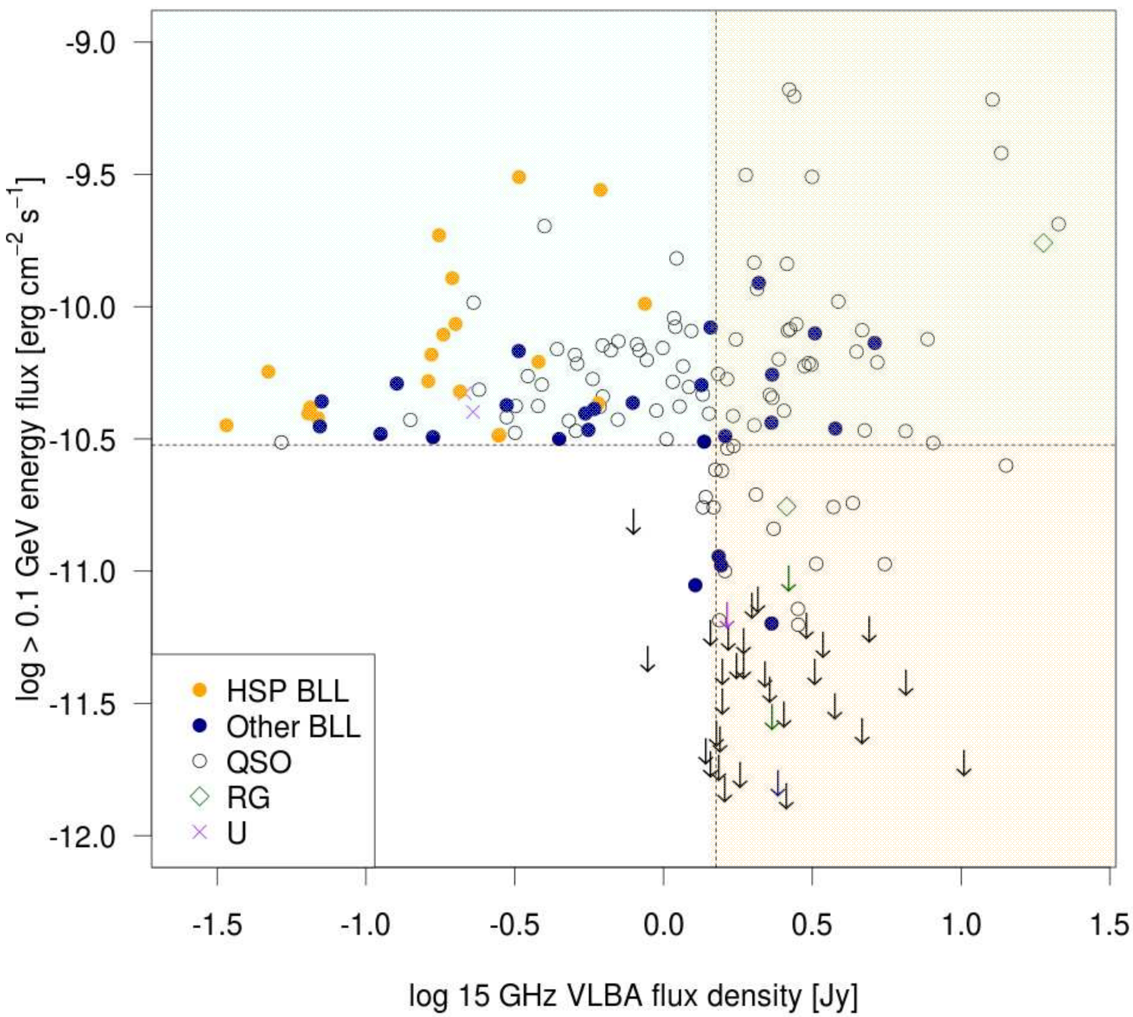
MOJAVE Bright AGN Sample

All known dec. > -30°, |b| > 10° AGNs with:

- 1LAC >100 MeV energy flux above 3×10^{-11} erg s^{-1} cm^{-2}

OR

- 15 GHz VLBA flux density has exceeded 1.5 Jy at any time during 11month Fermi 1LAC period

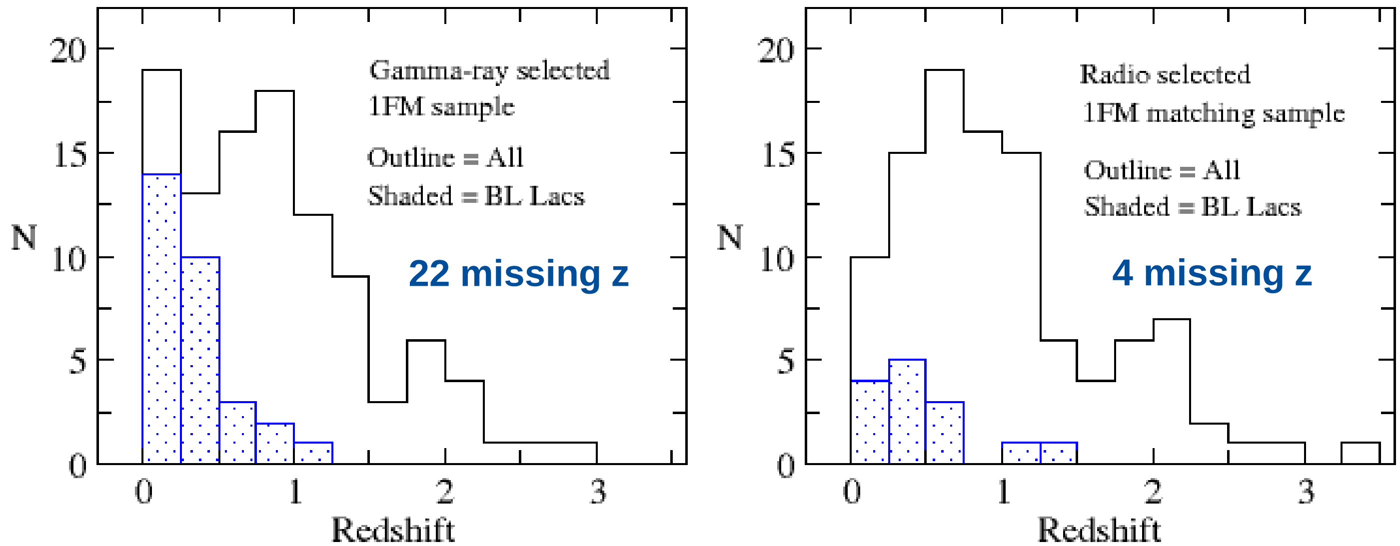


- Only one missing (unassociated) source: in top left corner region
- 173 AGNs in total, 48 are both radio- and γ-ray selected (top right corner)

Lister et al. 2011, ApJ 742, 27

Redshift distributions

ɣ-ray selected | **Radio selected**

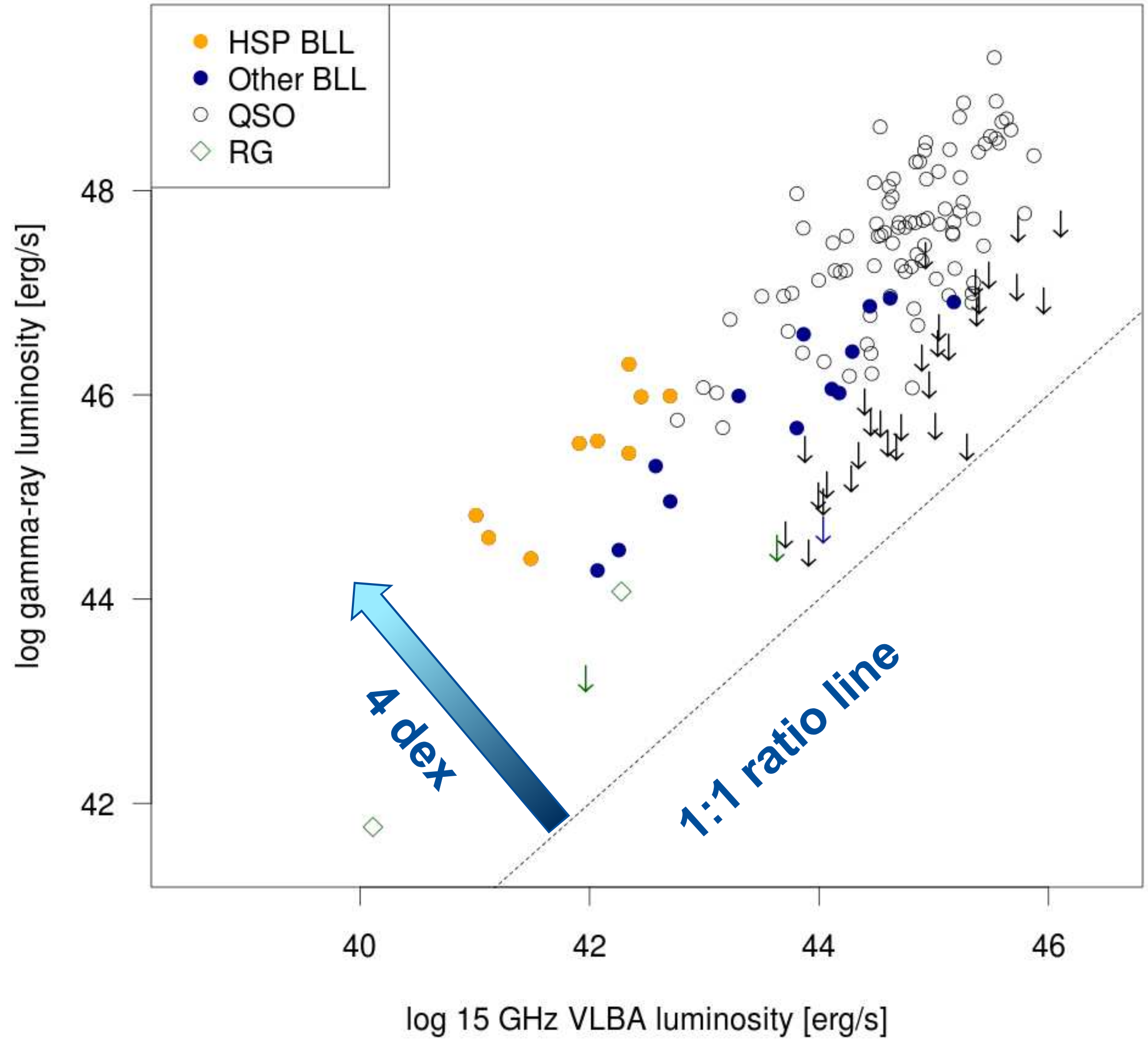


- the brightest ɣ-ray and radio-selected quasars have similar redshift distributions.

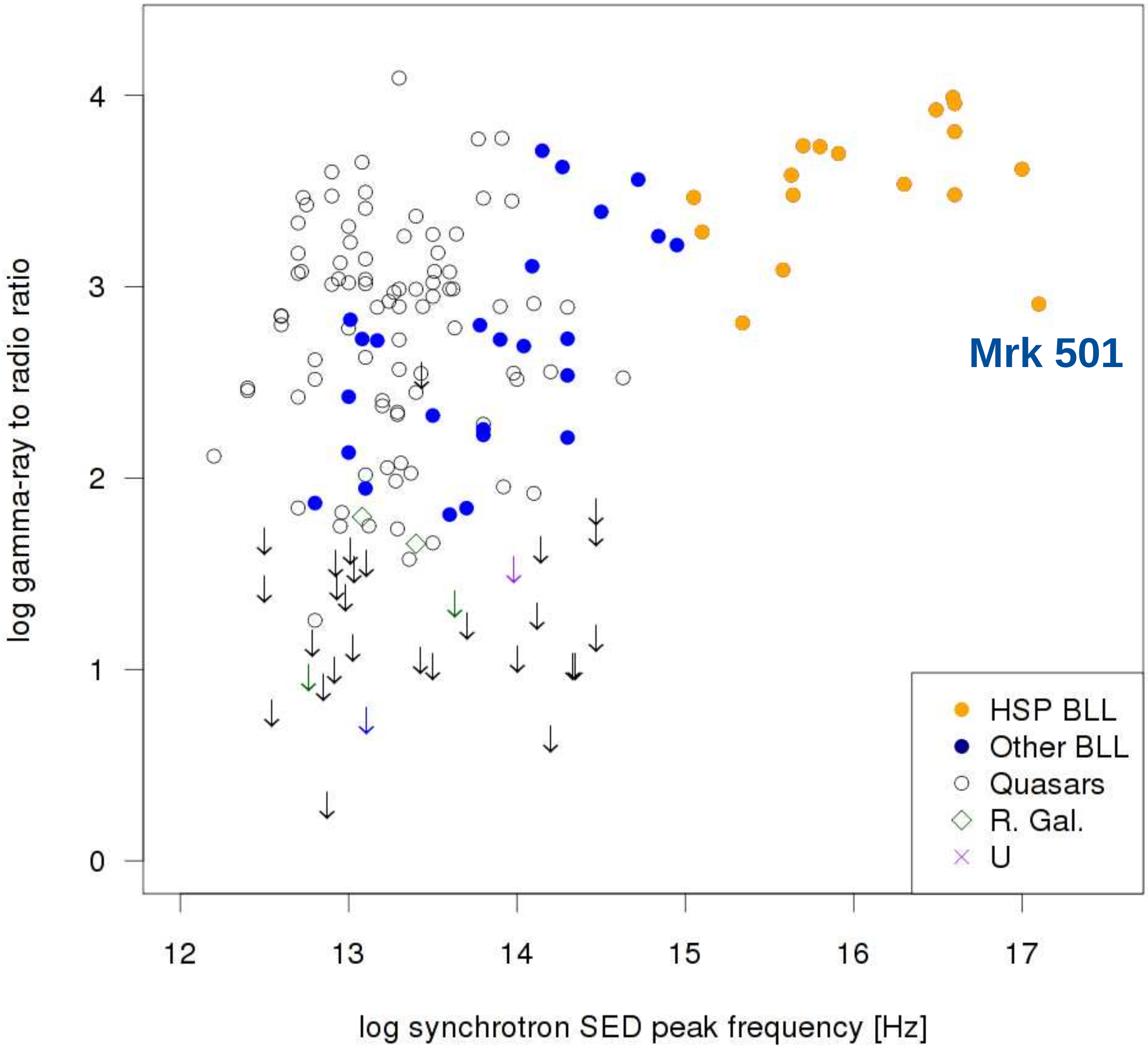
- ɣ-ray selected blazars have an additional sub-population of low-z HSP BL Lacs that are intrinsically very bright in ɣ-rays

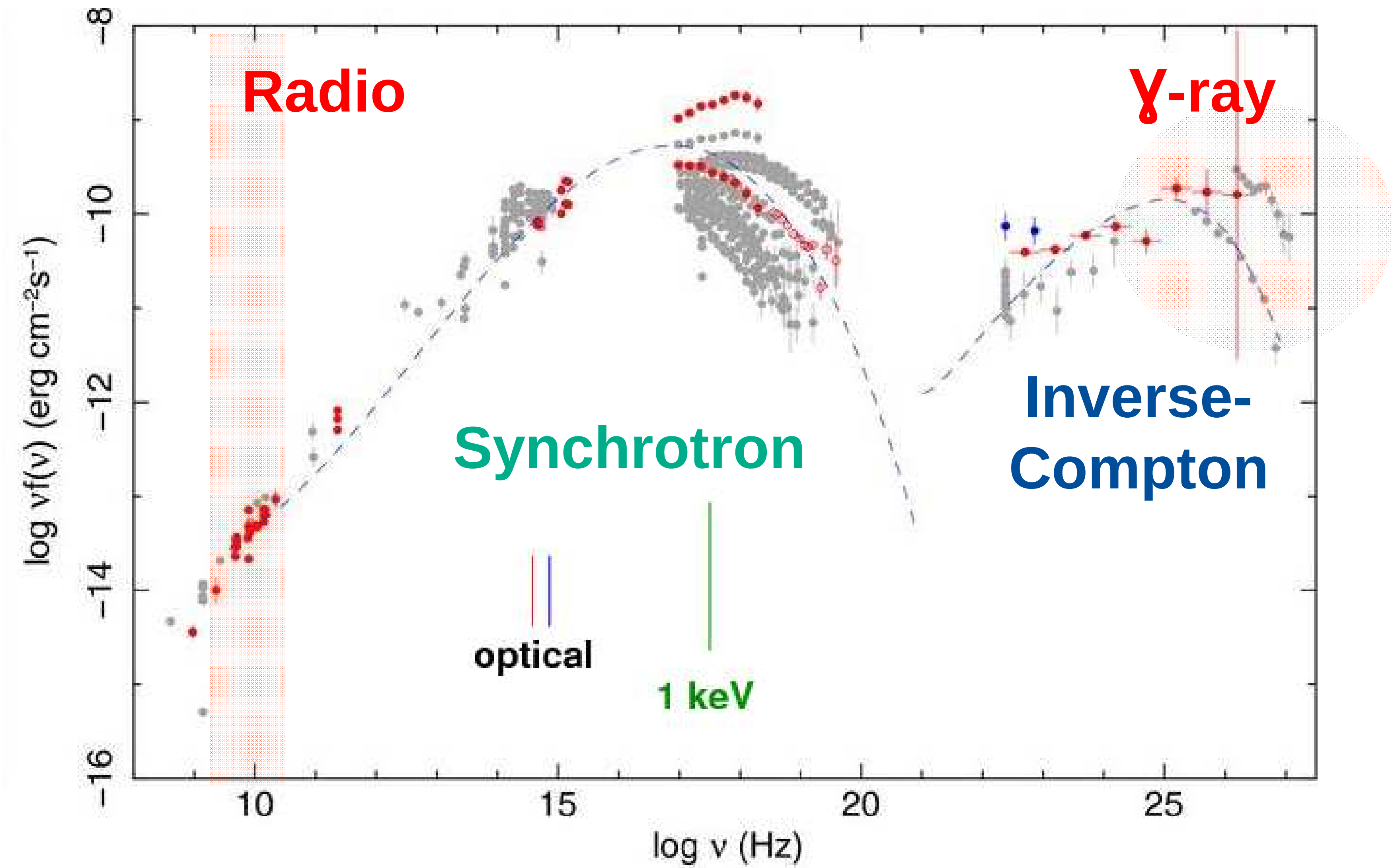
ɣ-ray Loudness

- Ratio of ɣ-ray to 15 GHz VLBA radio luminosity
- Lowest luminosity BL Lacs (HSPs) all have high ɣ-ray loudness (due to SED peak location)
- Fermi upper limit AGNs all have low ɣ-ray loudness due to sample selection bias (omits radio-weak--ɣ-ray weak sources)



ɣ-ray loudness increases with ν_{peak} for BL Lacs





Abdo et al., ApJ 716, 30 (2010)

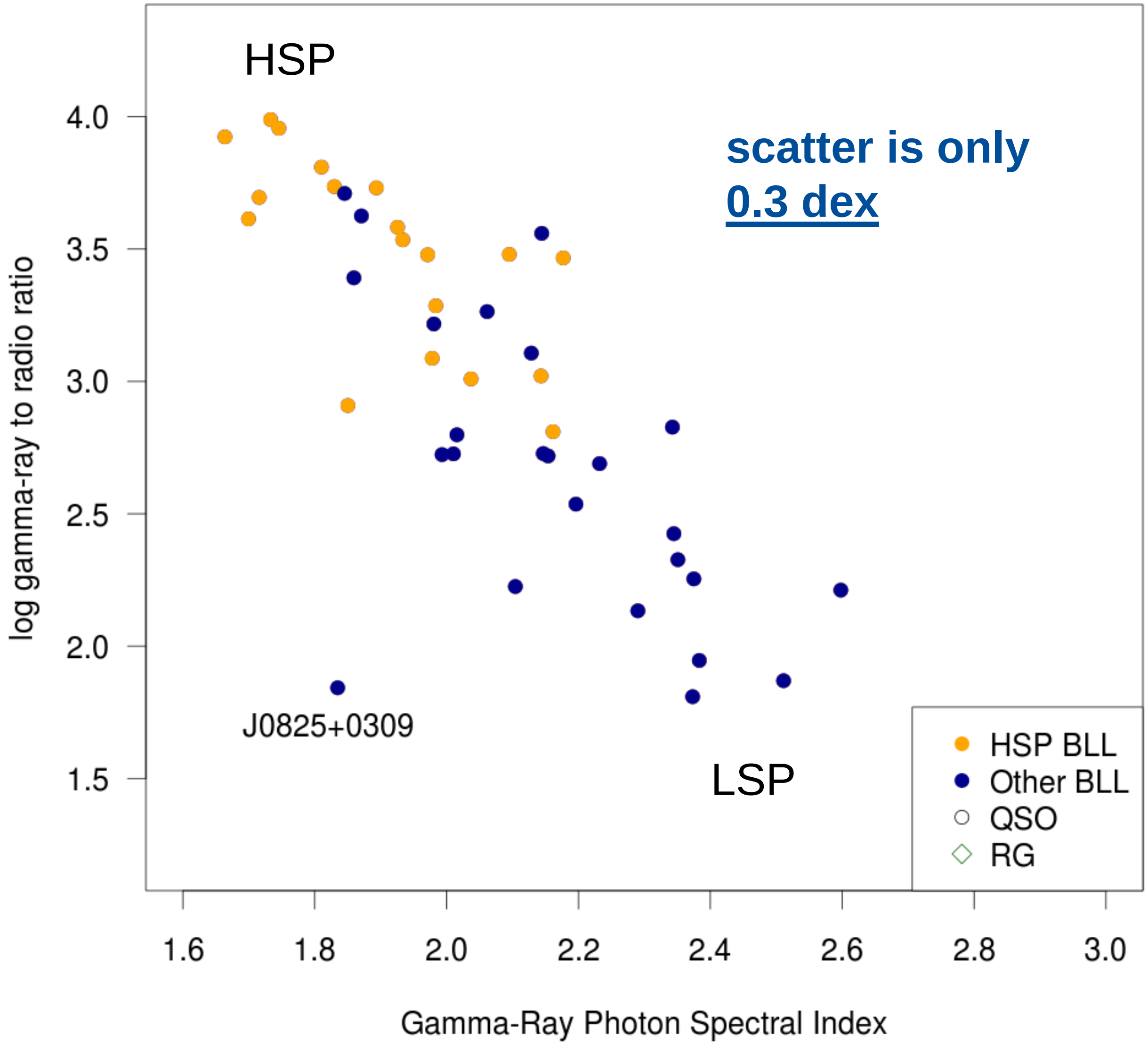
Mk 421: High-spectral peaked jet: high γ-ray to radio ratio

γ-ray loudness versus γ-ray hardness (BLL only)

- **Photon index is well correlated with Compton peak location *(LAT team, ApJ 716,30)***

- **Trend couldn't exist if the γ-ray and pc-scale radio jet emission were fully independent**

- **Trend is continuous from HSP through LSP**



Lister et al. 2011, ApJ 742, 27

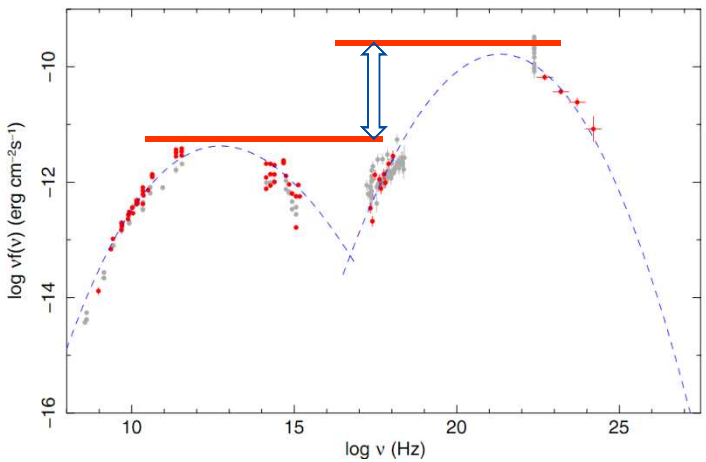
Bright BL Lac population:

- Must all have relatively similar intrinsic SED shapes
  - lower Compton dominance than quasars (Giommi et al. 2011)
  - ɣ-ray emission is primarily synchrotron self-Compton

- *Radio and ɣ-ray emission beamed by similar amounts*

- Likely not the case for quasars!

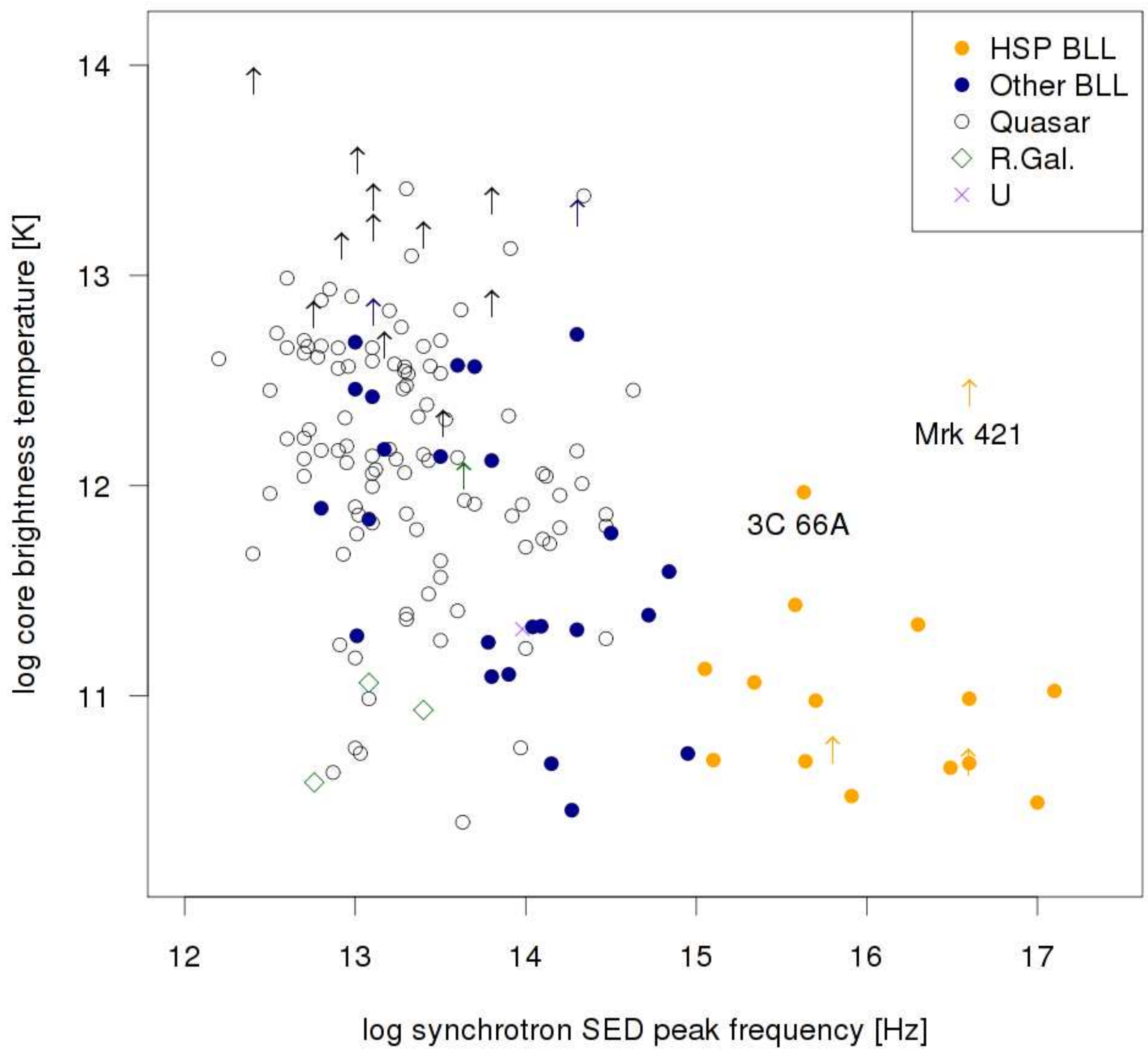
0528+134: Low-spectral peaked quasar



Doppler boosting levels in BL Lacs

- **Radio core compactness (brightness temperature) strongly increases with beaming and jet activity level**

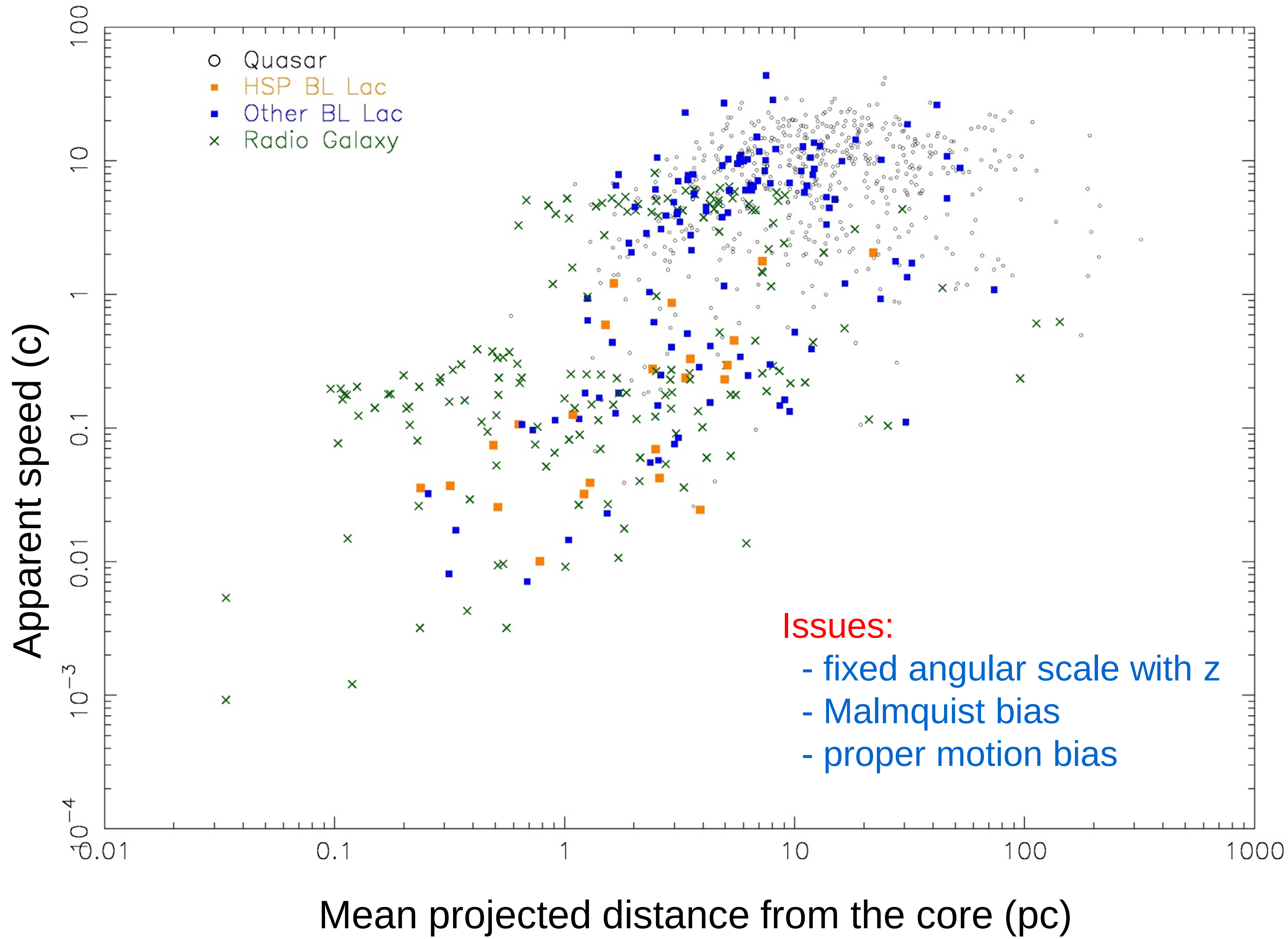
- ***Lower radio compactness and variability of HSP radio cores is indicative of lower Doppler beaming factors***



Trends in Joint MOJAVE Samples

- Analyzed kinematics of 889 discrete features in 201 jets, using data from 1994-2011
  - Apparent speeds & accelerations
  - Proper motion directions (jet opening angles)
  - Compactness, polarization properties

- N.B.: this set is not a complete sample
  - analysis of selection biases in progress

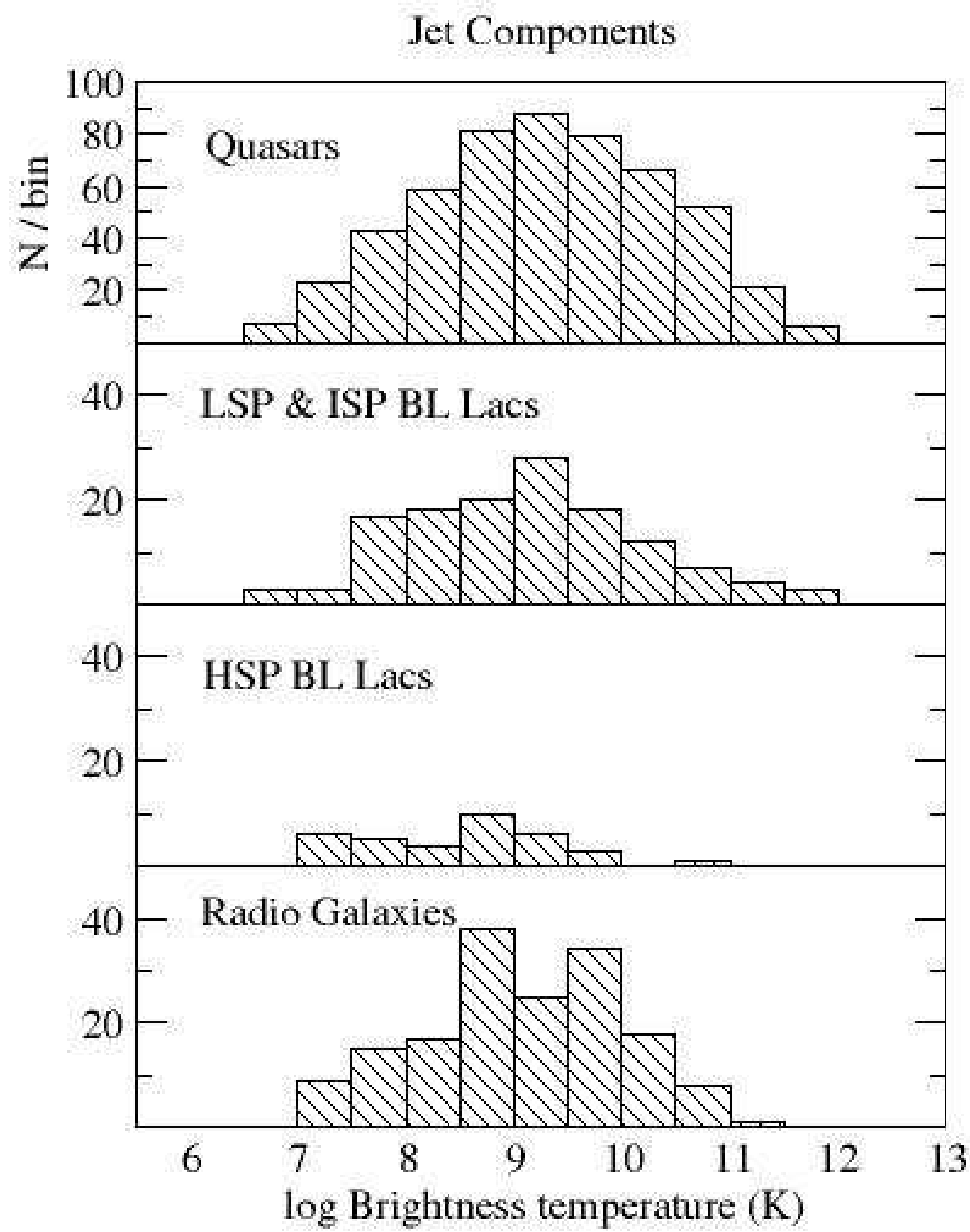


MOJAVE collaboration, in prep.

- **Jets of high spectral peaked BL Lacs characterized by lack of compact, superluminal features**

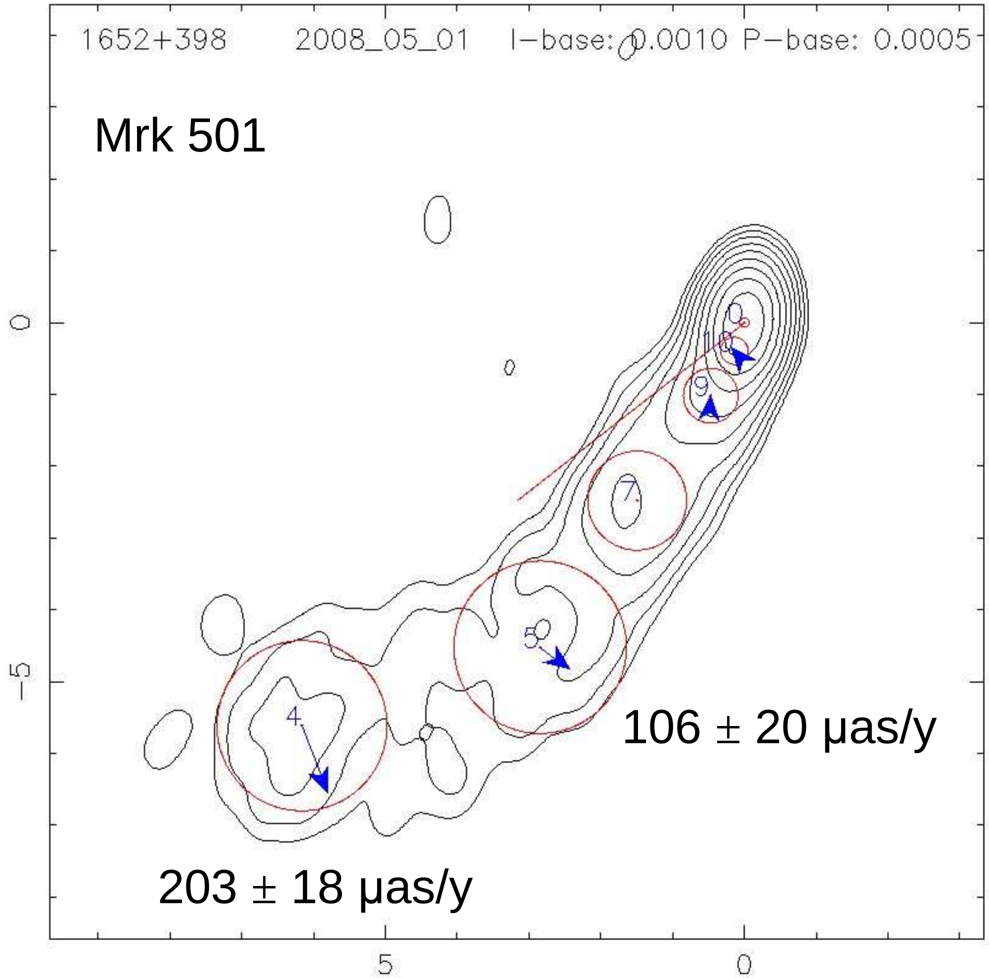
- ***Does this reflect an intrinsic difference in HBL jets?***

- **But what about the continuous trends for BLLs seen in MOJAVE 1FM sample?**

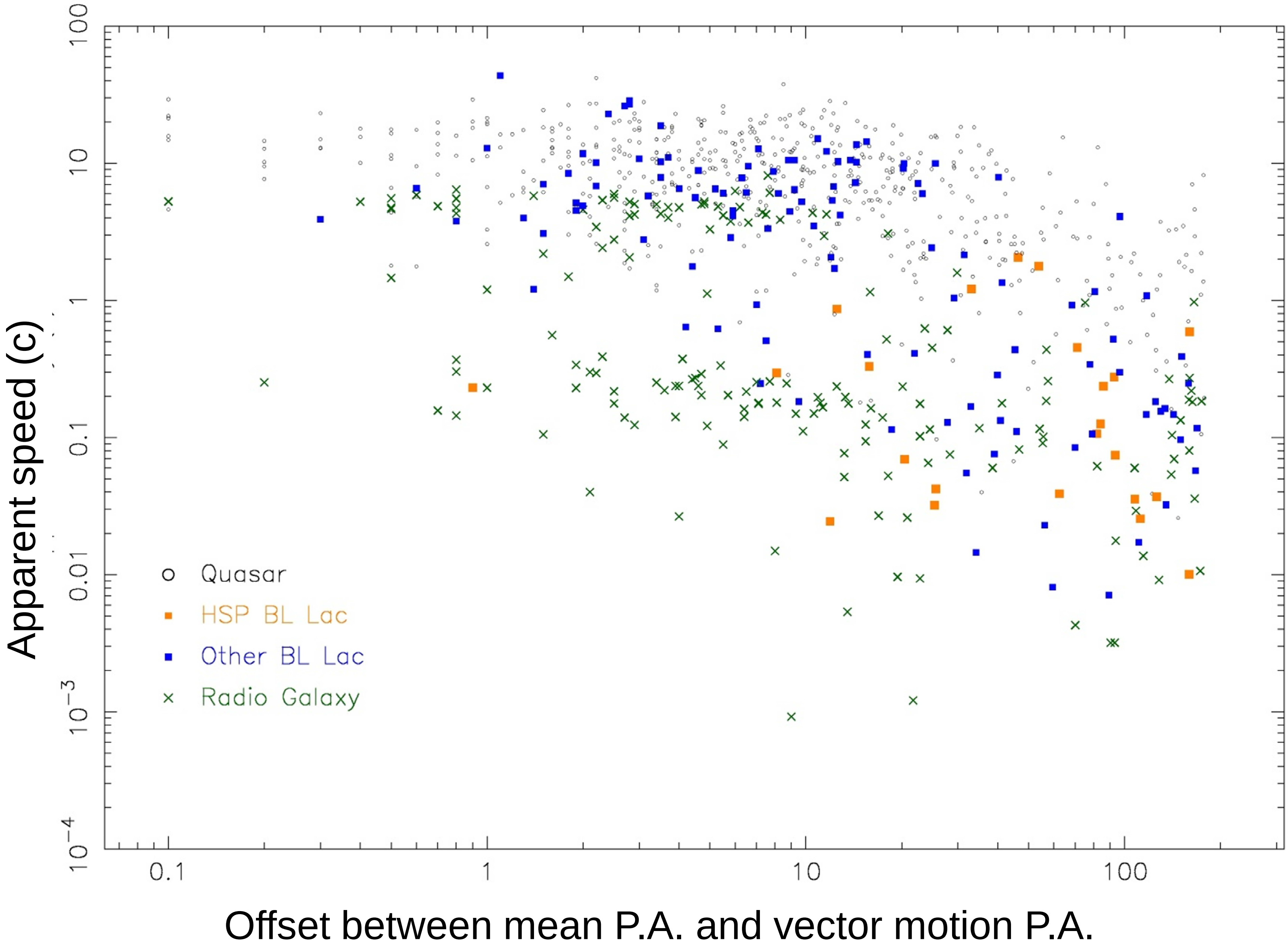


MOJAVE collaboration, in prep.

Parsec-scale HSP Jet Properties

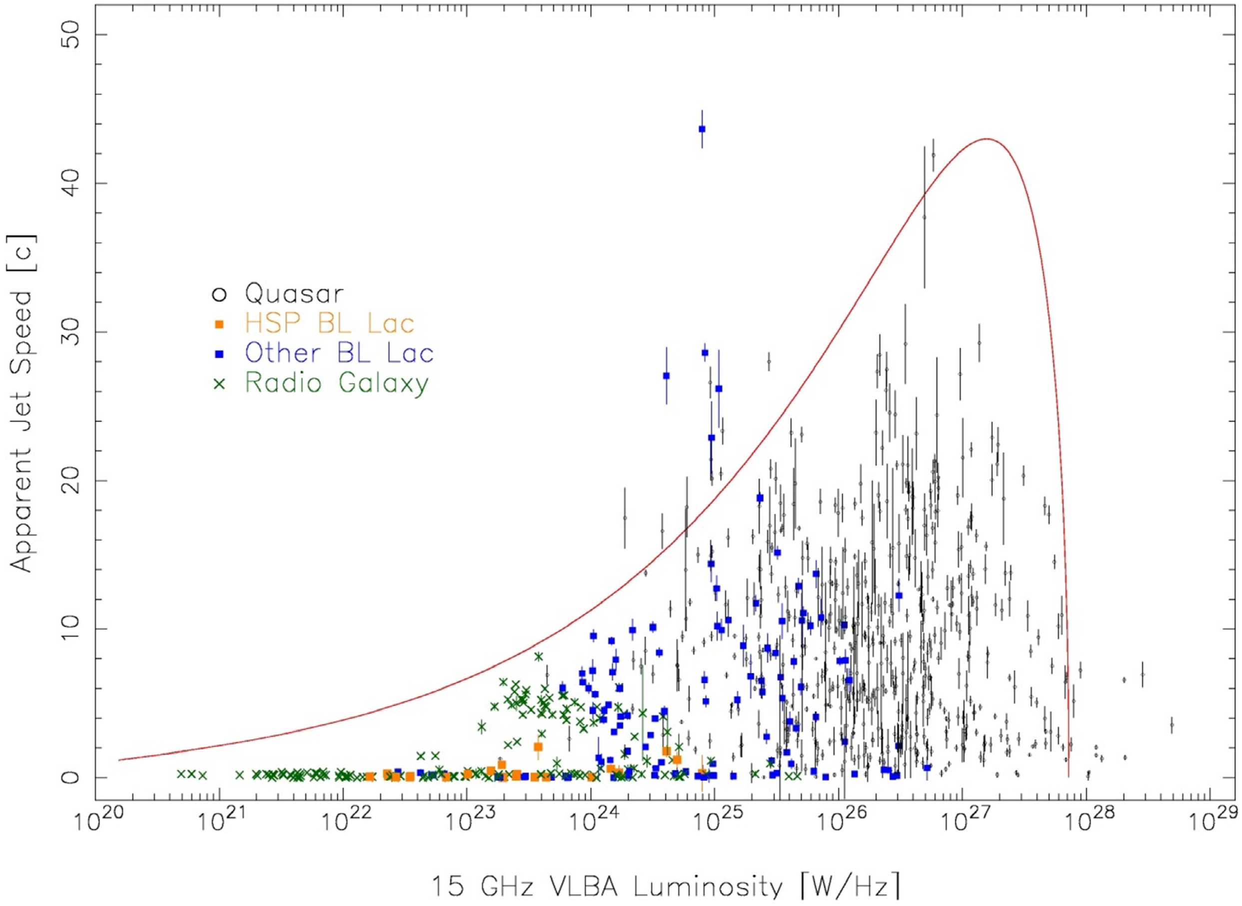


- **HSP jets are quite smooth**
  - slow non-radial drifts in centroid positions



MOJAVE collaboration, in prep.

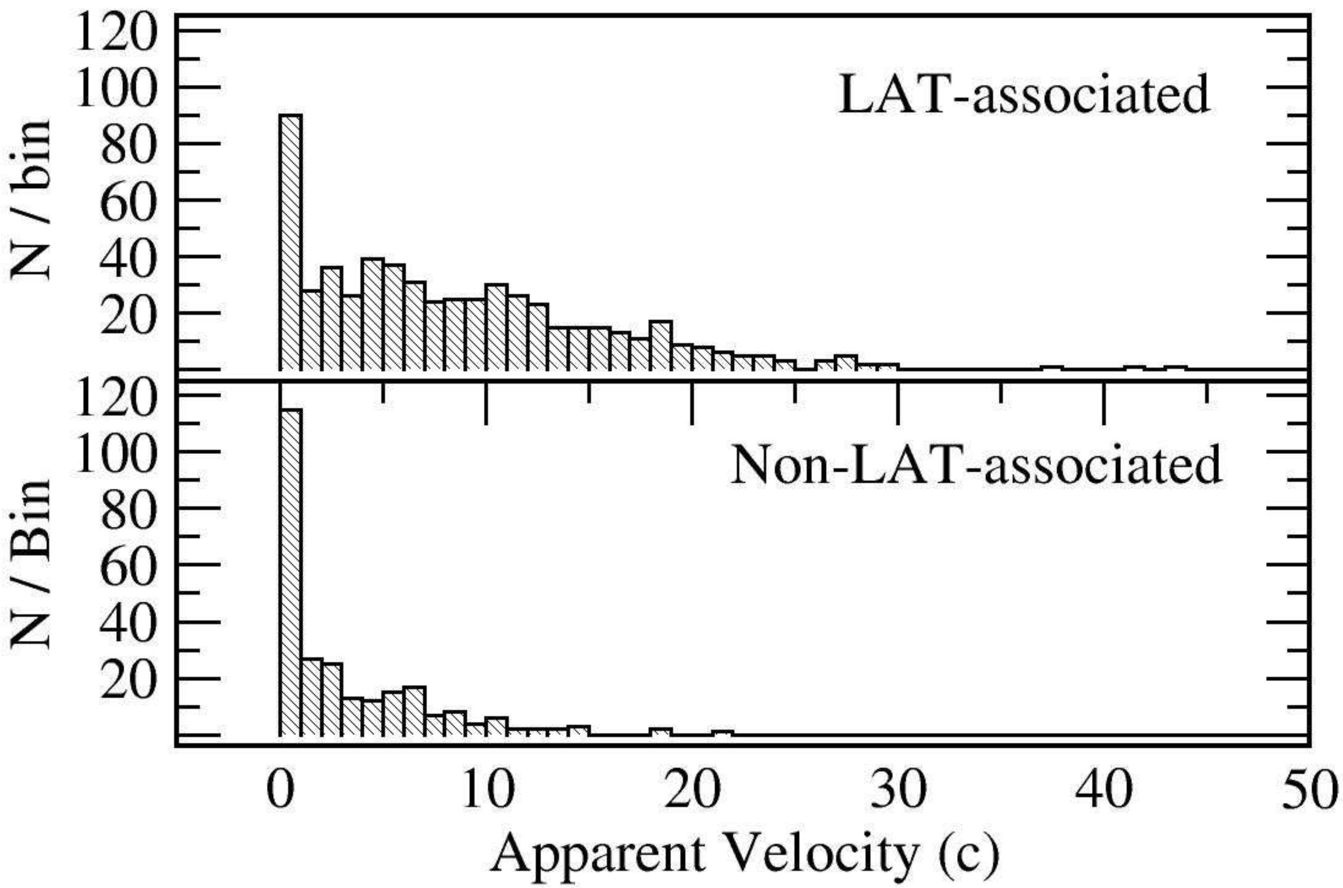
Speed – radio luminosity relation



- **BL Lac jets have lower radio synchrotron luminosity and slower speeds *(outlier: 0716+714)***
- **No fast speeds seen in HSP jets**

MOJAVE collaboration, in prep.

Apparent Jet Speeds



MOJAVE collab., in prep.

Jet opening angles

- **2FGL jets have larger mean opening angles than non-2FGL**
- **Analysis of intrinsic op. angles implies 2FGL jets viewed closer to the line of sight**

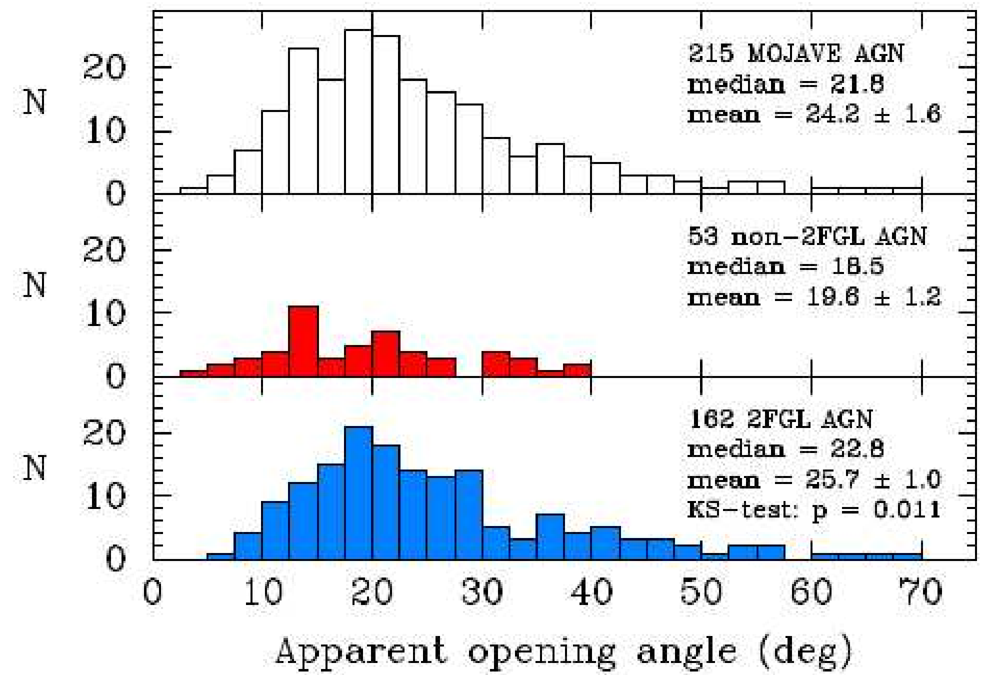


Figure 3: Distributions of the apparent opening angle from jet-cut analysis for 215 MOJAVE AGN (*top panel*), comprising 53 non-LAT-detected (*middle panel*) and 162 LAT-detected (*bottom panel*) sources.

Pushkarev et al., arXiv:1205.0659

Summary

- Studying blazar demographics requires a careful consideration of (many!) possible sampling biases.
  - censored data points shouldn’t be ignored!
- VLBA and Fermi have identified synchrotron peak frequency as a fundamental parameter for BL Lac jets.
- High spectral peaked BL Lacs show distinct characteristics:
  - typically smooth jets with lack of compact features
  - slow, non-radial motions and low radio variability
- The brightest BL Lacs have relatively similar SED shapes and a narrower range of Compton dominance than quasars.