AGN Jet Kinematics on Parsec Scales

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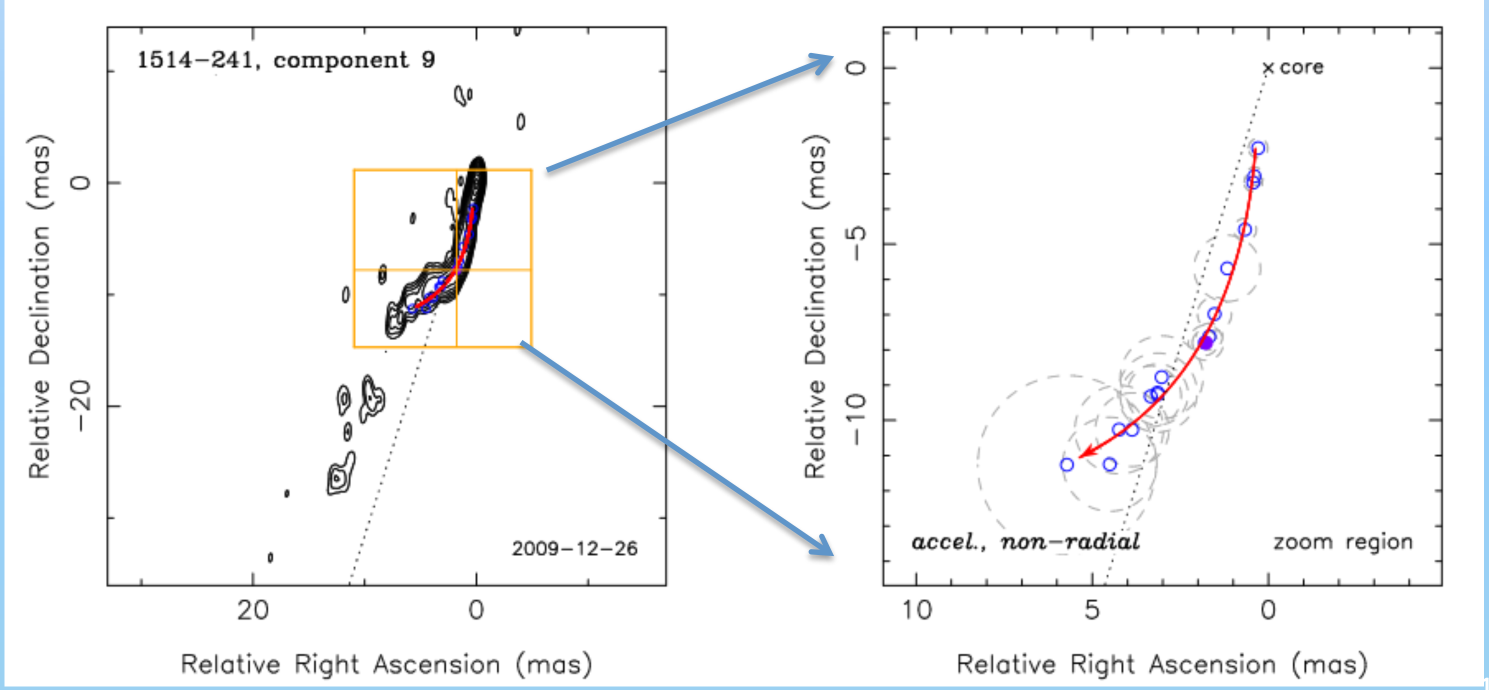
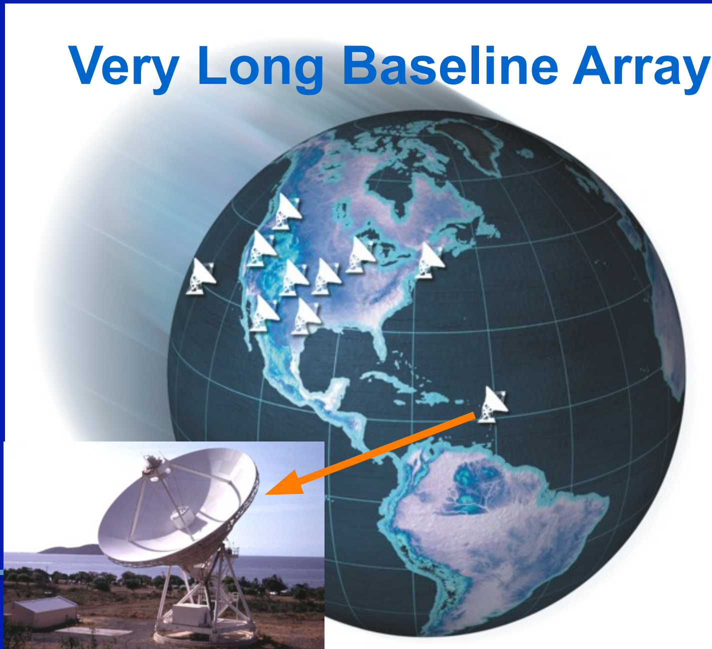


Malaga, May 2016

MOJAVE Collaboration

- M. Lister (P.I.), E. Stanley, M. Hodge (Purdue, USA)
- T. Arshakian (U. Cologne, Germany)
- M. and H. Aller (U. Michigan, USA)
- M. Cohen, J. Richards (Caltech, USA)
- D. Homan (Denison, USA)
- M. Kadler, J. Trüstedt (U. Wurzburg, Germany)
- K. Kellermann (NRAO, USA)
- Y. Y. Kovalev (ASC Lebedev, Russia)
- J.A. Zensus (MPIfR, Germany)
- A. Pushkarev (Crimean Observatory)
- E. Ros (MPIfR, Germany & U. Valencia, Spain)
- T. Savolainen, T. Hovatta (Metsăhovi Obs., Finland)

Monitoring
Of
Jets in
Active Galaxies with
VLBA
Experiments



The MOJAVE Program is supported under NASA Fermi Grant NNX15AU76C

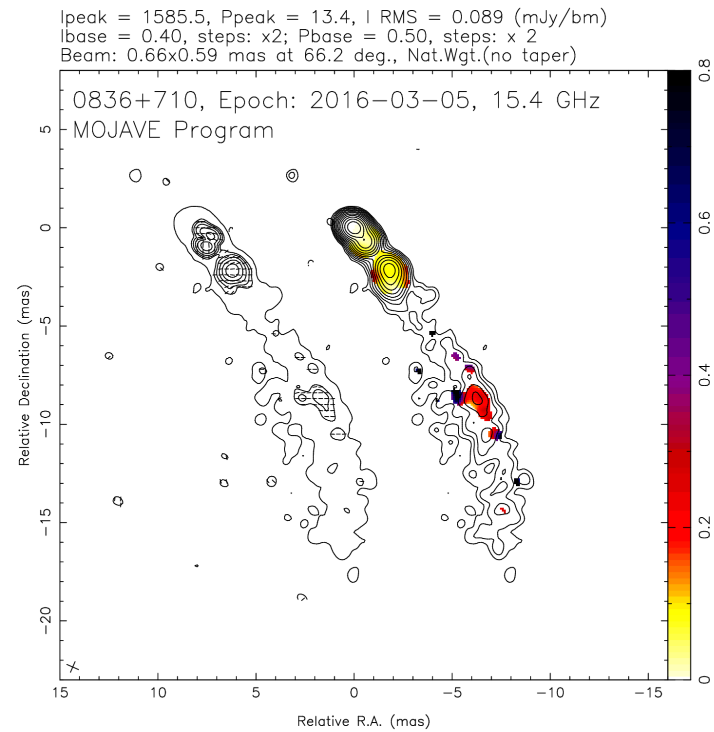
MOJAVE VLBA Program

- Milliarcsec-resolution 15 GHz images of over 400 AGN jets
  - continuous time baselines on many jets back to 1994
  - full polarization since 2002

- 22 AGN observed per month, chosen from list of ~100 targets:

  decl. > - 30°and > 0.1 Jy

- Results published in series of papers, full list is available at www.physics.purdue.edu/astro/MOJAVE



Blazar 0836+710 at 15 GHz

Colors: fractional linear polarization

MOJAVE AGN Samples

1.5 Jy :

all 181 AGN above δ = -30 known to have exceeded 1.5 Jy in 15 GHz VLBA flux density (1994.0 - 2010.0; Lister et al. 2015, ApJ 810, L9).

1FM γ-ray :

complete 1FGL *Fermi*-selected sample (116 AGN) above 100 MeV (Lister et al. 2011, ApJ 742,27).

Low-luminosity :

representative sample of 43 AGN with 15 GHz luminosity < 10^{26} W Hz^{-1} from the Radio Fundamental Catalog http://astrogeo.org/rfc/.

Hard Spectrum :

complete sample of 110 hard -ray spectrum, radio bright AGN from Fermi 2-year catalog

Upcoming MOJAVE VLBA Program

Approved at high scheduling priority for Sept 2016 - 2019

- 12 VLBA sessions per year, each 24 hrs long
- 30 AGN observed per session, from list of 124 AGN

Goals:

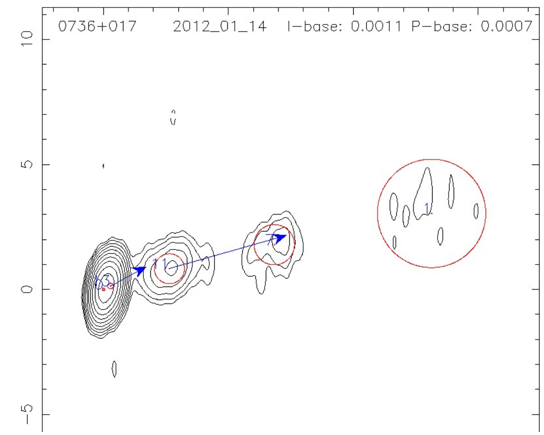
- Continue studying long term kinematic behavior of 30 accelerating jets

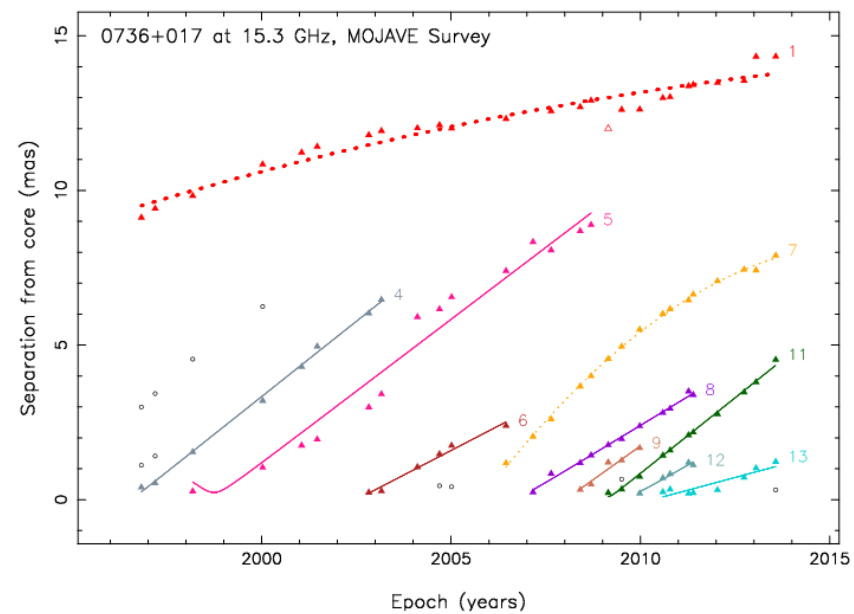
- Complete the kinematic statistics for MOJAVE radio and γ-ray samples:
  - 43 GHz monitoring of 14 ultra-compact jets to get speeds
  - Increase VLBA time baseline on 5 jets with very slow expansion rates

- Support for multi-wavelength campaigns with 50 new targets from:
  - *Fermi* LAT monitored list of flaring AGN
  - RoboPol optical polarization monitoring sample
  - Hard spectrum AGN from 2FHL and 3FGL *Fermi* catalogs

MOJAVE Kinematics Studies

- Gaussian models fit to visibilities at each epoch (at least 5 epochs per AGN).
  - rms accuracy: 0.05 - 0.1 mas
- Two dimensional sky motion fits made to individual jet features
  - probing jet kinematics at 10-1000 pc (de-projected) from central engine
- MOJAVE X, XI, XIII studies cover 1295 jet features in 307 AGNs, based on 5837 VLBA epochs from 1994 Sep-2013 Aug.
  - most recent paper XIII adds 122 new jets, most are Fermi LAT γ-ray associations:



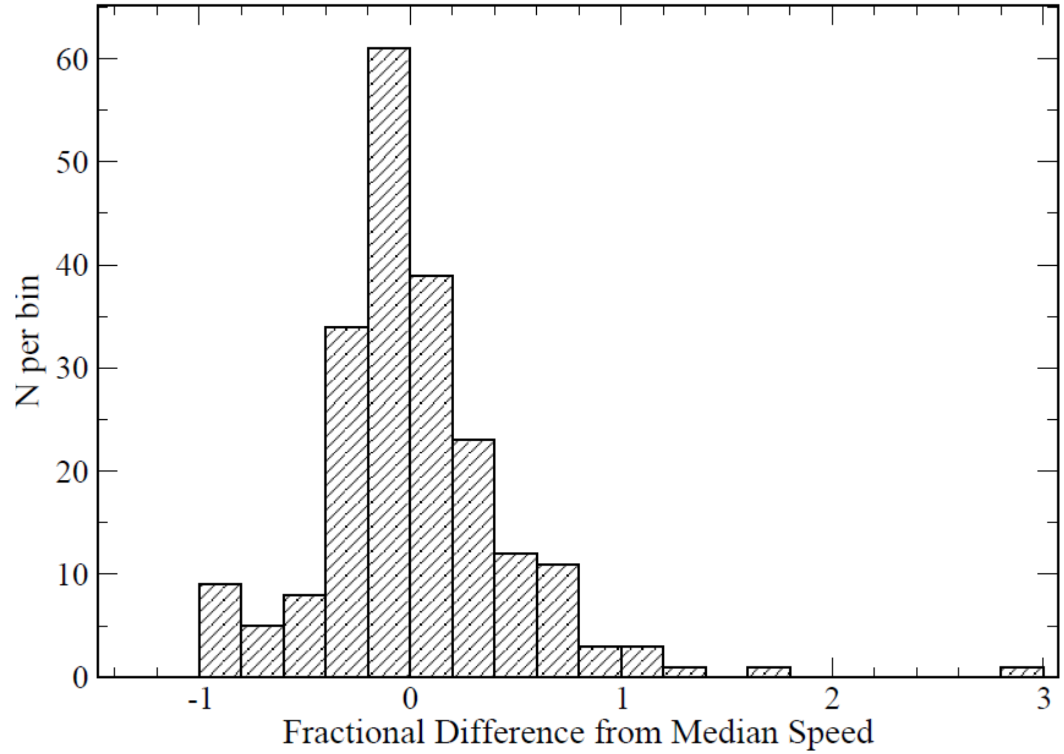


Lister et al. arXiv1603.03882

Speed Dispersion Within the Jet

- An AGN jet typically contains features with a range of bulk Lorentz factor and/or pattern speed

- A ***characteristic median speed*** exists for each jet

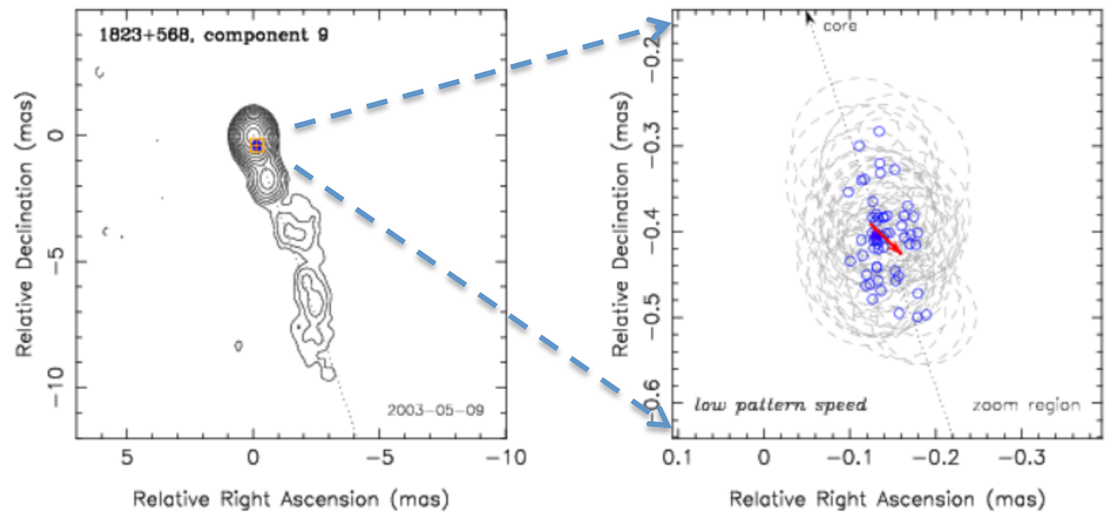


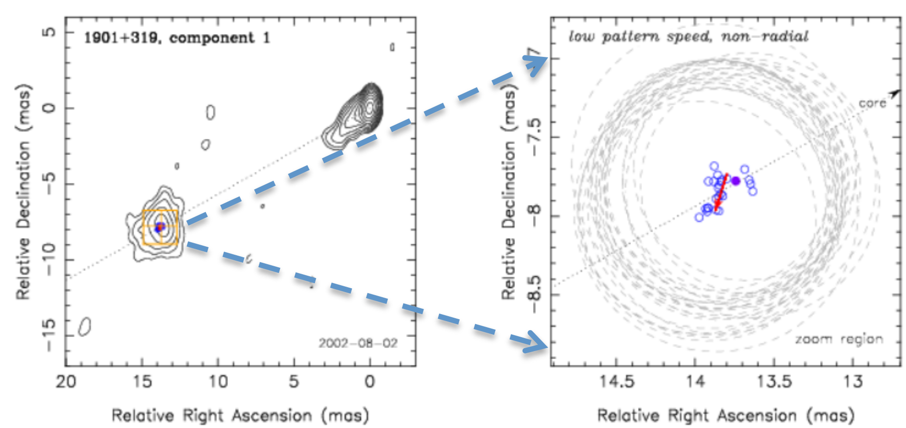
Normalized speed distribution within 12 jets each having at least 10 moving features.

MOJAVE Paper X

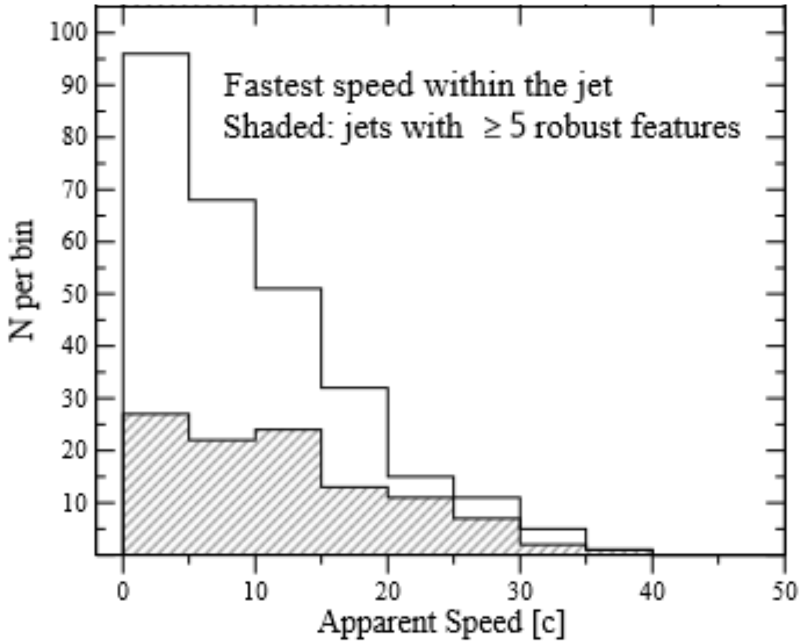
Slow Pattern (‘Stationary’) Features

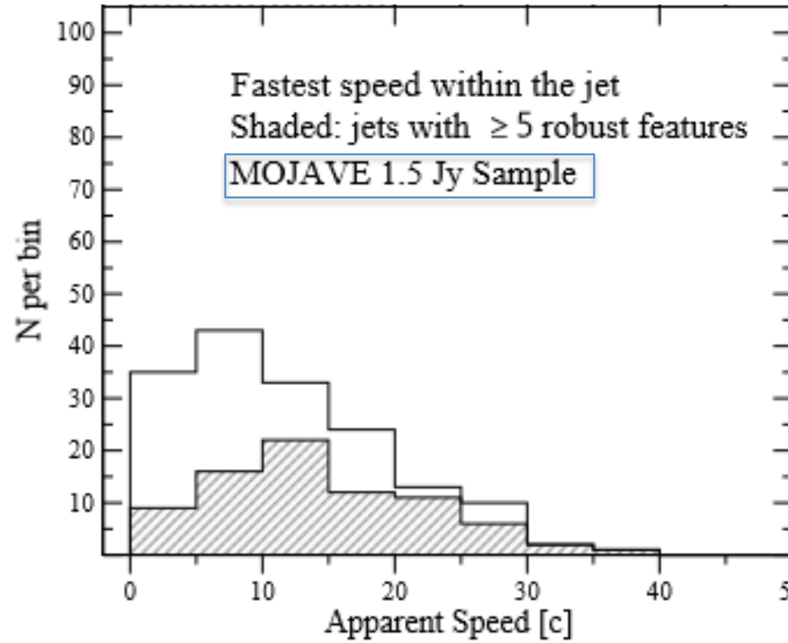
- Defined as:
  - i. < 20 μas/y
  - ii. < 1/10th of max speed seen in the jet
  - iii. Non-accelerating
- 6% of all jet features
- Majority are located close to the base of the jet
- Present in 15% of quasar and 25% of BL Lac jets





Maximum Jet Speed Distribution (301 AGNs)



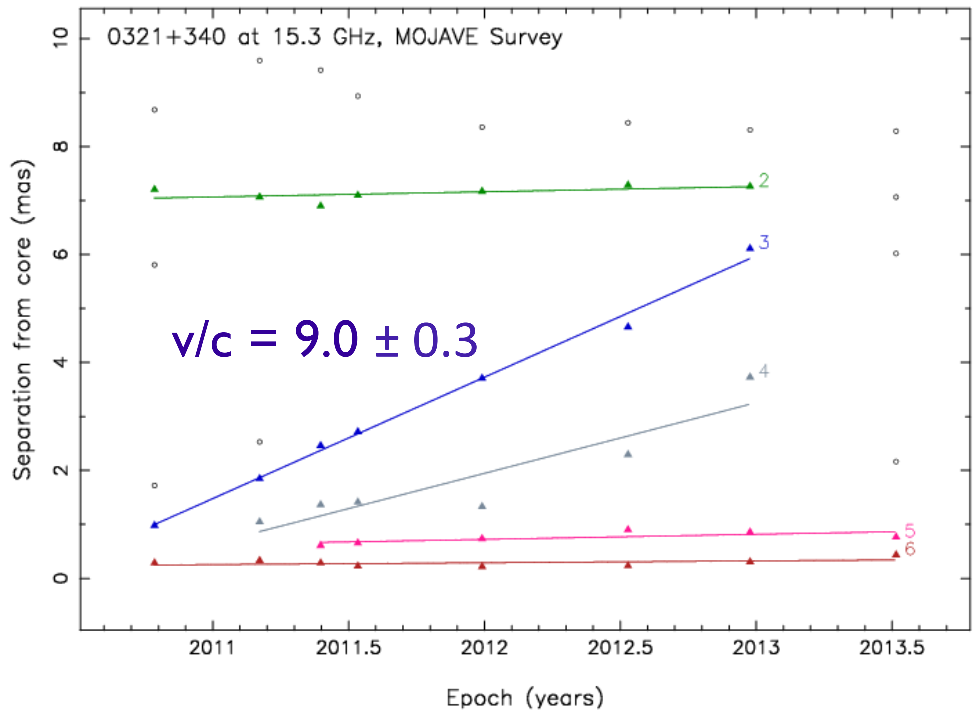


Lister et al. arXiv1603.03882

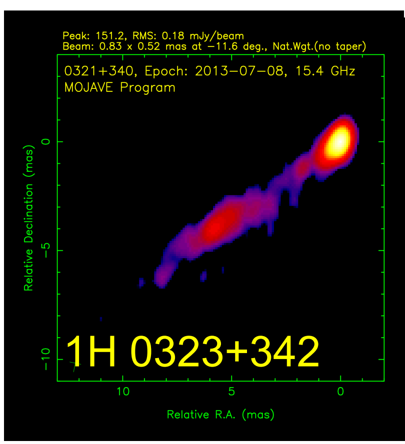
- Peaked at low values
  - only 6 jets with β_{app} > 30, distribution implies Γ_{max} = 50
  - parent population can't all have the same Lorentz factor (Vermeulen & Cohen 1995)
- Blazars are not typical jets!
  - most AGN jets in the parent population have much lower synchrotron power and a Lorentz factor << 10.

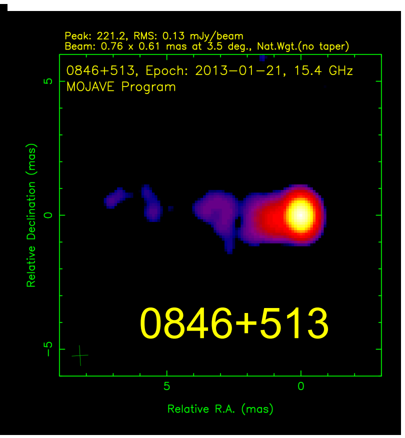
Narrow-Line Seyfert I Jets

- Have low black hole mass and near-Eddington accretion rate
- Likely hosted in spirals
- Rare sub-population (< 7%) are radio loud, and a scarcer few are γ-ray loud
- 3rd class of γ-ray AGN
- Low detection #s may indicate young jets (Foschini et al. 2014)

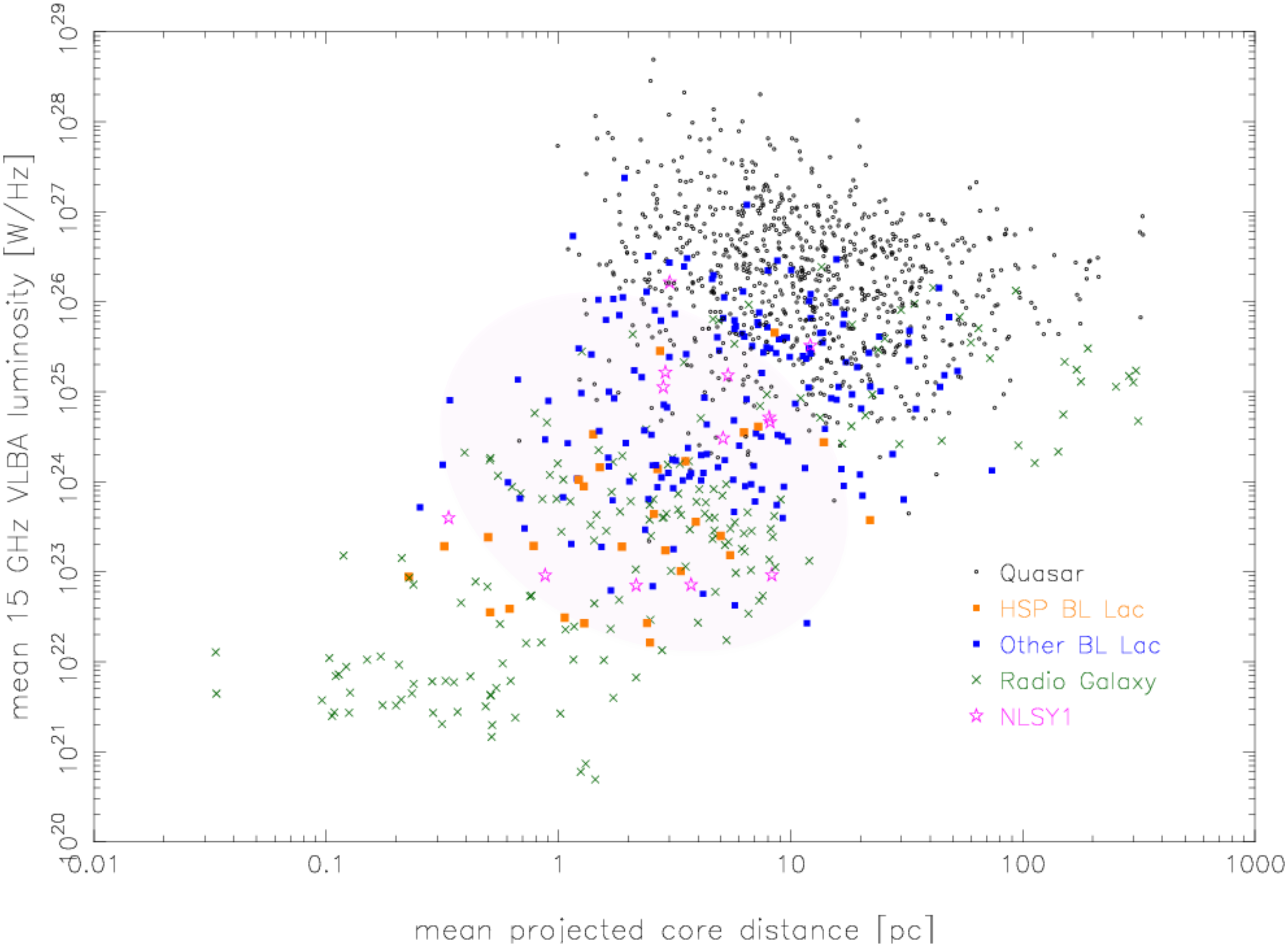


MOJAVE Paper XIII



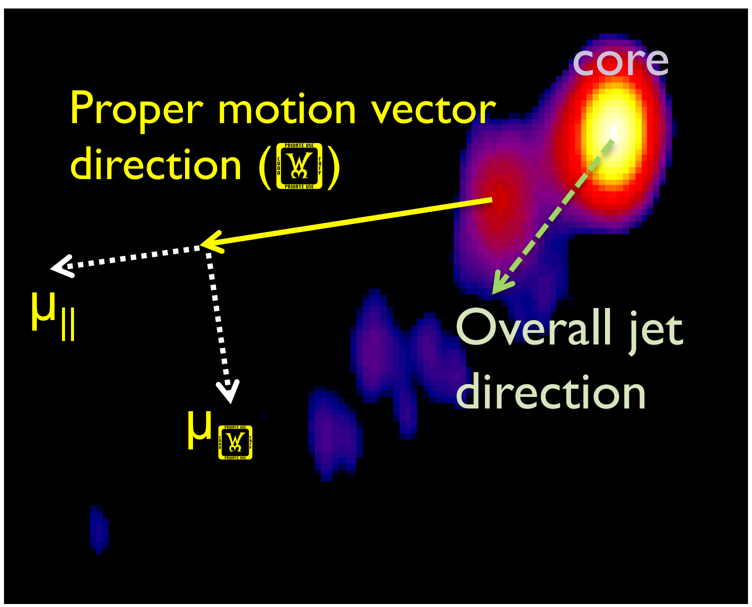


- 3 of 5 NLSY1 in MOJAVE have $v_{app} > 6$ c
- NLSY1 Jets are much weaker than quasars, similar to BL Lacs


mean 15 GHz VLBA luminosity [W/Hz]
mean projected core distance [pc]
Quasar
HSP BL Lac
Other BL Lac
Radio Galaxy
NLSY1
0.01
0.1
1
10
100
1000

Jet Acceleration Studies (MOJAVE XI, XIII)

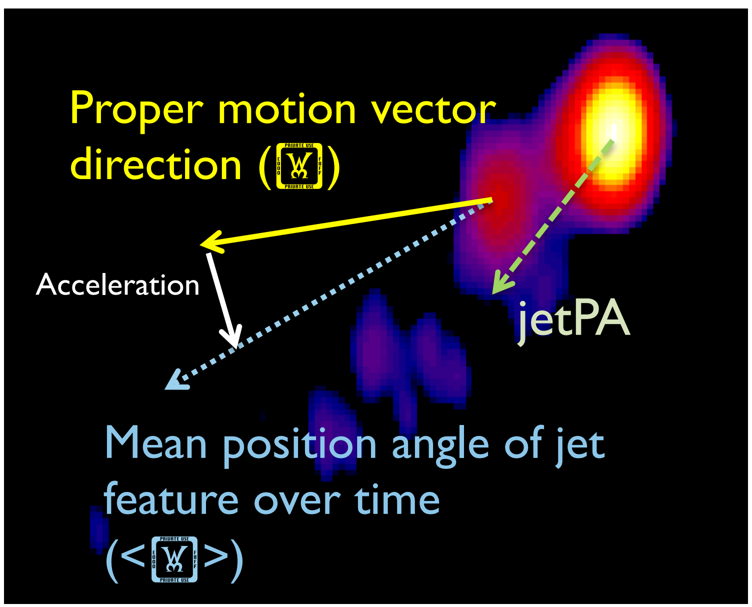
- Analyzed 651 features in 295 blazar jets which had at least ten VLBA epochs.
- Measured accelerations in directions || and $\perp$ to fitted apparent motion vector on the sky.

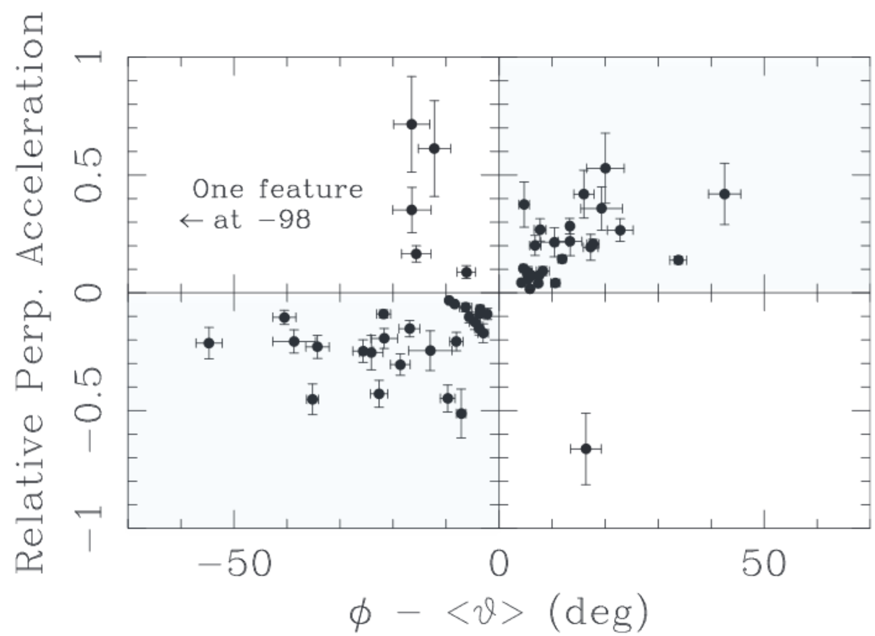


Non-radial = proper motion vector does not point back to the core feature

Acceleration of Non-Radial Features

- Determine main jet axis direction using stacked-epoch image.
- Most off-axis features have accelerations that are steering them back towards the jet axis.
- We are seeing jet collimation at scales up to 50 pc

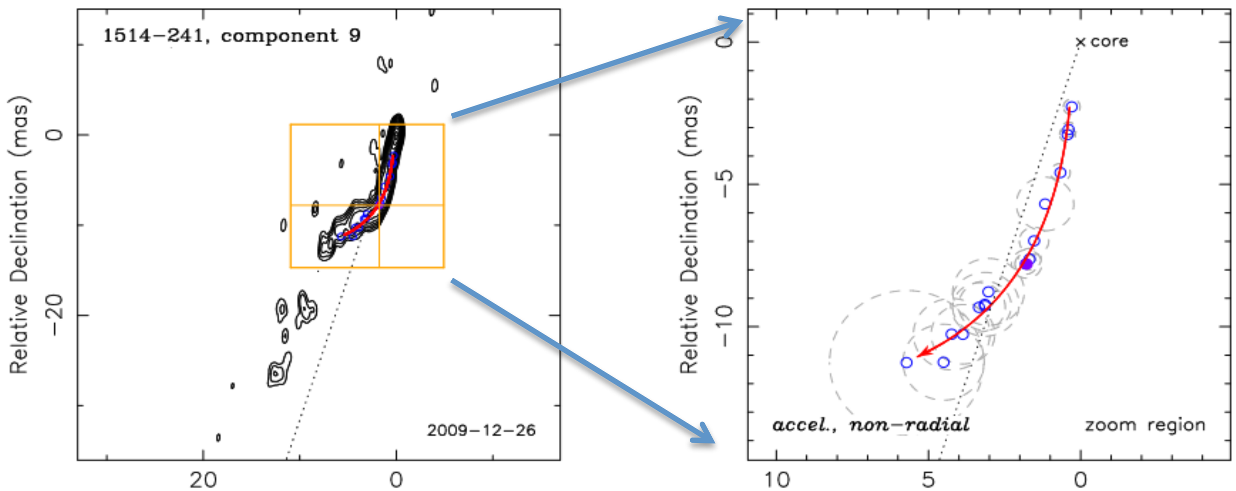




MOJAVE Paper XI

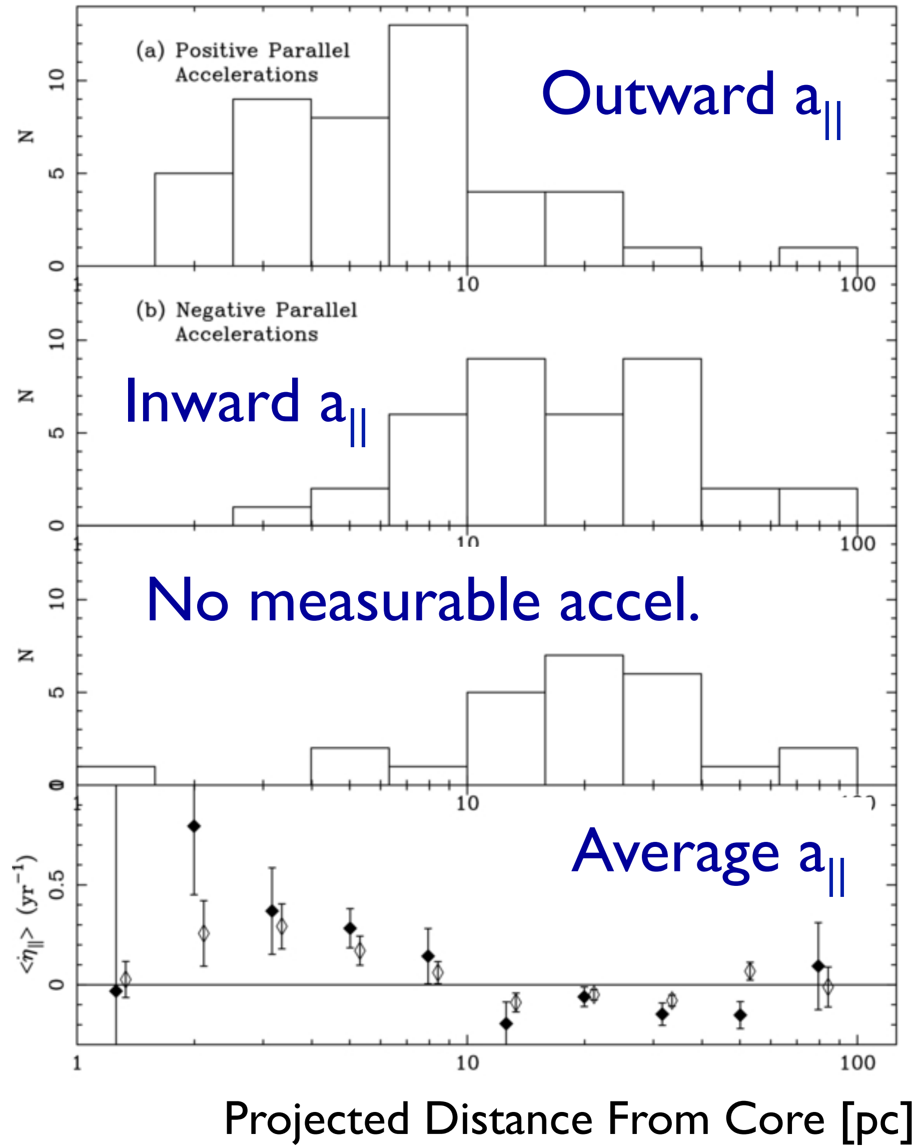
AGN Jets Accelerate

- 82% either have at least one accelerating or non-radially-moving feature.
- Half of all individual jet features show evidence of acceleration.
  - ejection times can be reliably estimated for only ¼ of all moving features.
- Parallel accelerations are of larger magnitude and more prevalent than perpendicular accelerations.
- Similar results seen at 8 GHz in AGN sample of Piner et al. 2012 ApJ 758, 84



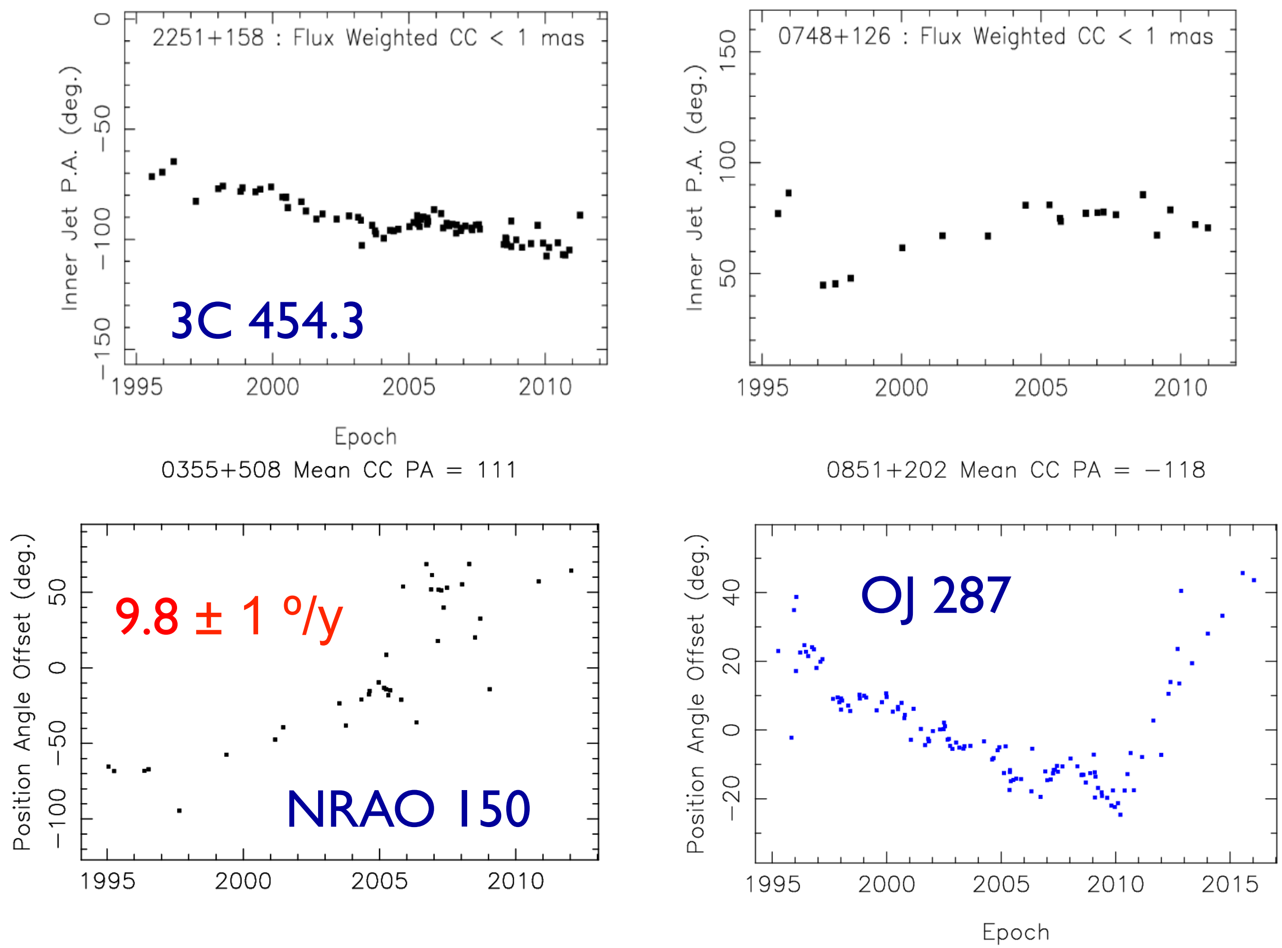
Evidence for changing Lorentz factors

- Overall statistics show that observed accelerations cannot be solely due to bending.
- Features tend to speed up near the core, and slow down at ~ 100 pc (deprojected) farther downstream.
- Changes in Lorentz factor must be the primary cause of the observed accelerations.

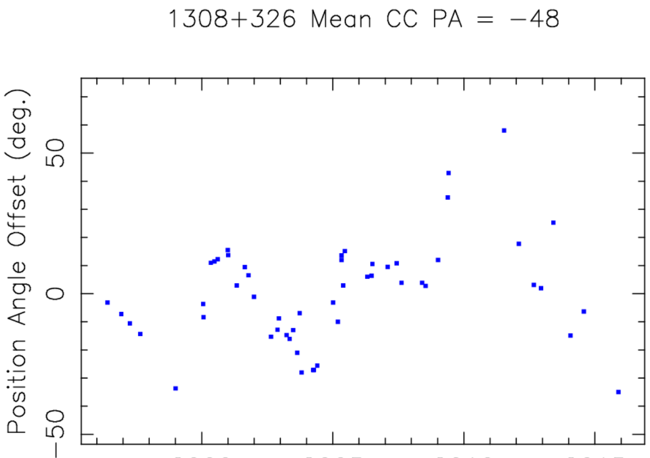


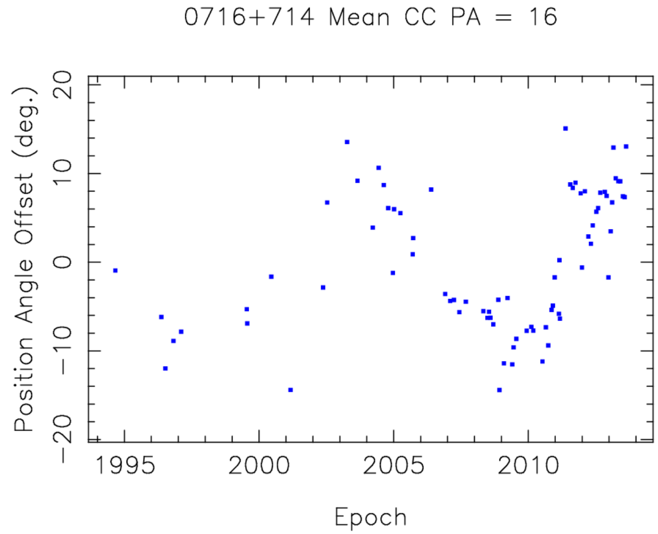
Changes in Inner Jet Direction

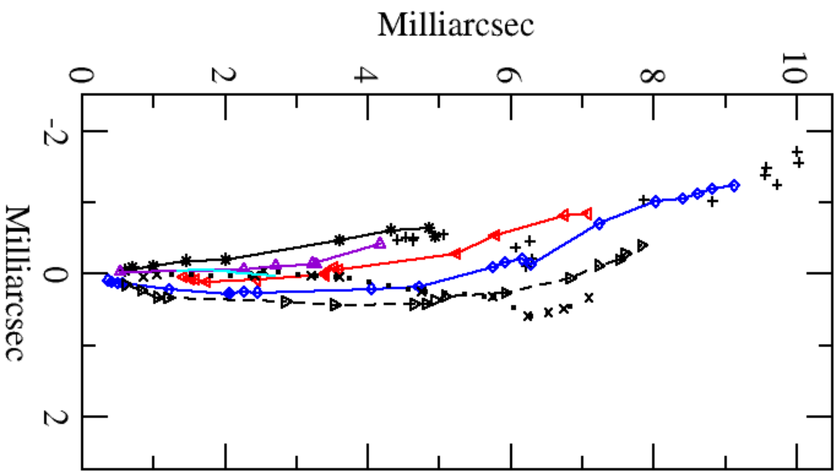
- Half of best monitored MOJAVE jets show changes in their innermost jet position angle, at rate of ~1- 3°per yr

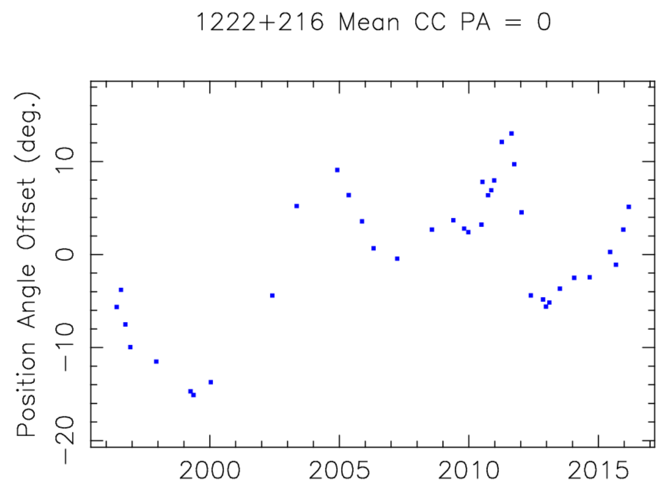


- Sinusoid-like jet position angle variations seen in a few jets
- Variations are too slow (decade-long) to claim periodicity



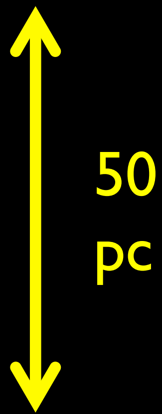


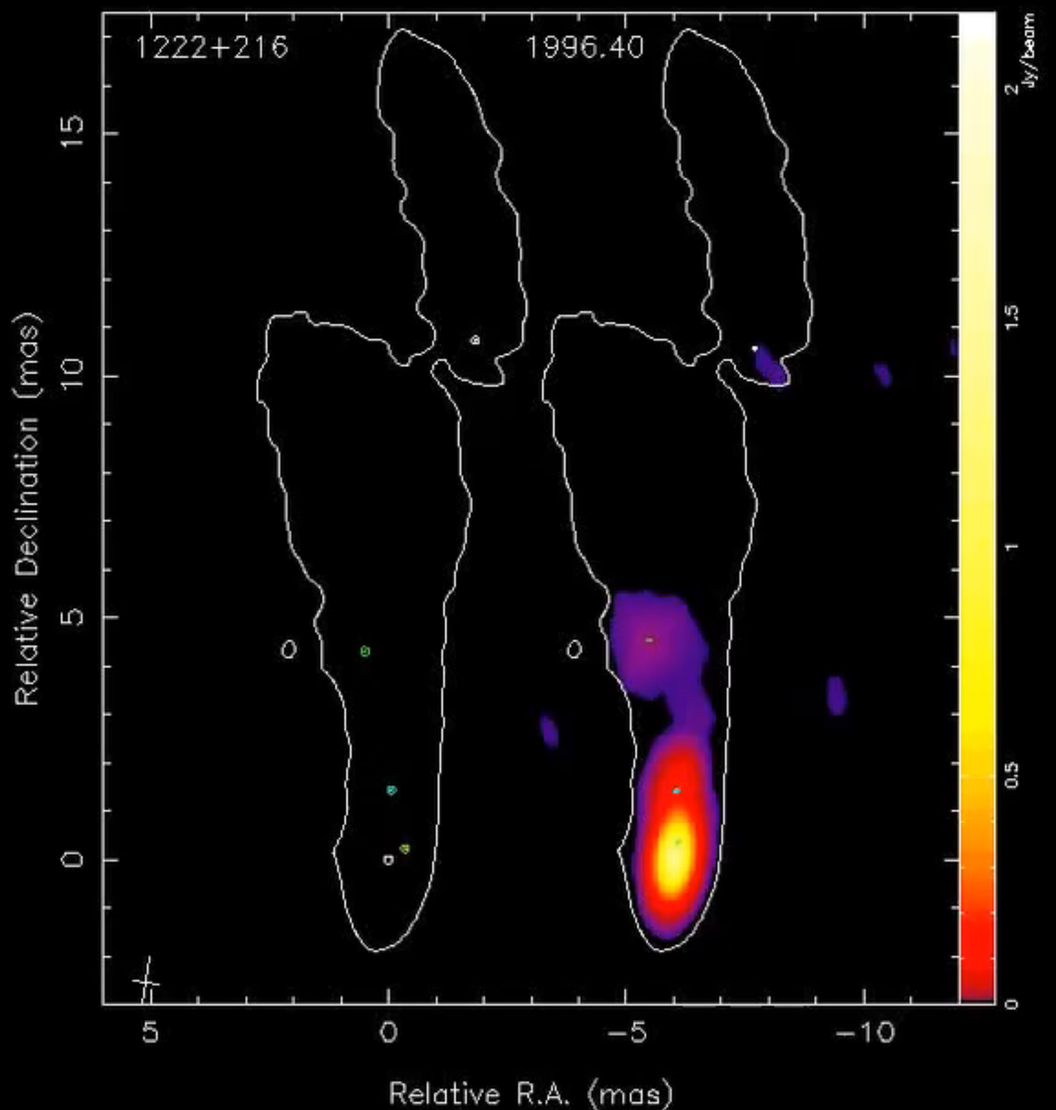




TeV-detected Quasar 1222+216 at z = 0.43

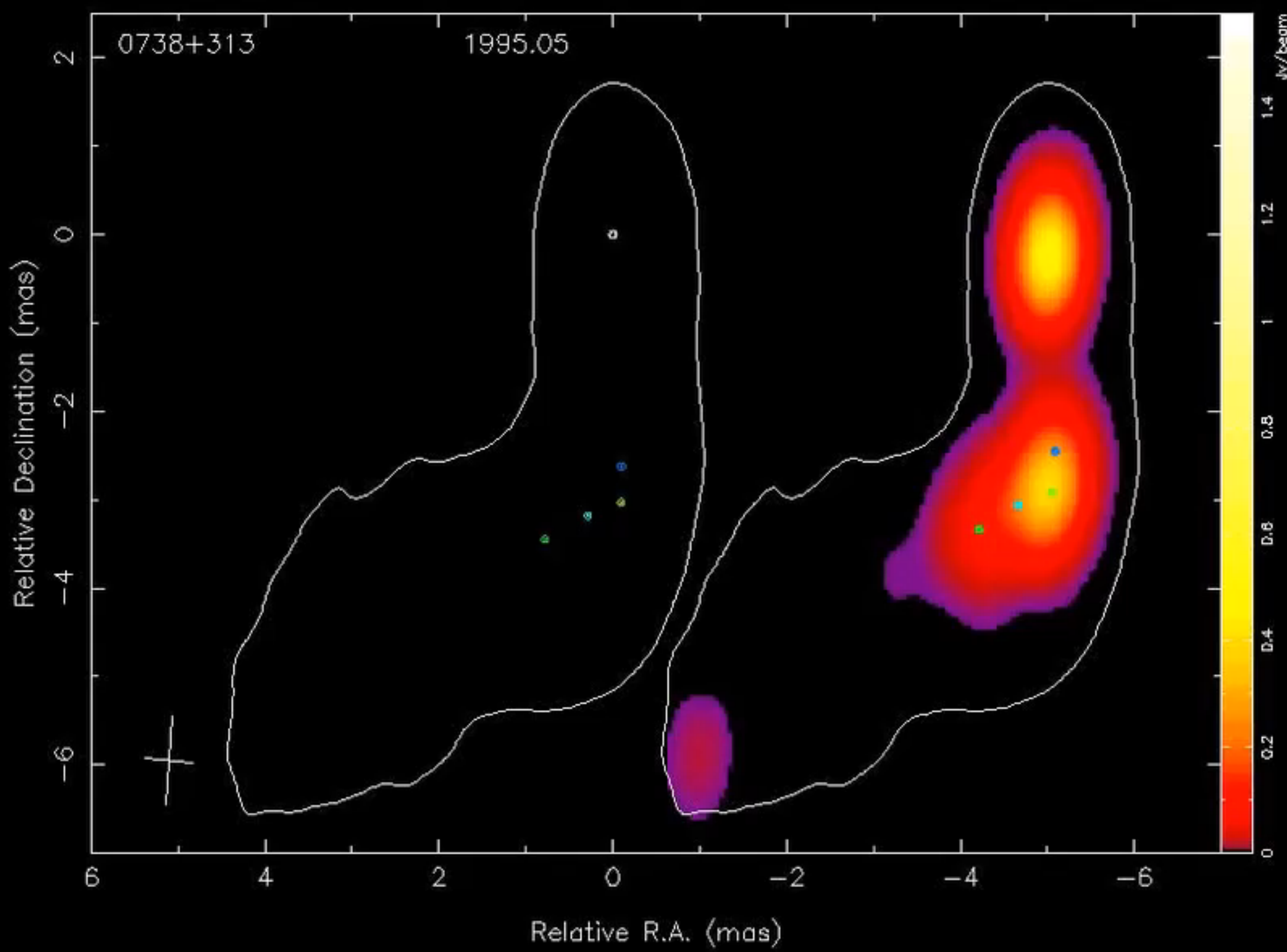
- Max speed = 27 c
- Viewing angle < 4°
- Deprojected opening angle < 1.6°





18 yr time lapse of Quasar 0738+313 at z = 0.63

25
pc

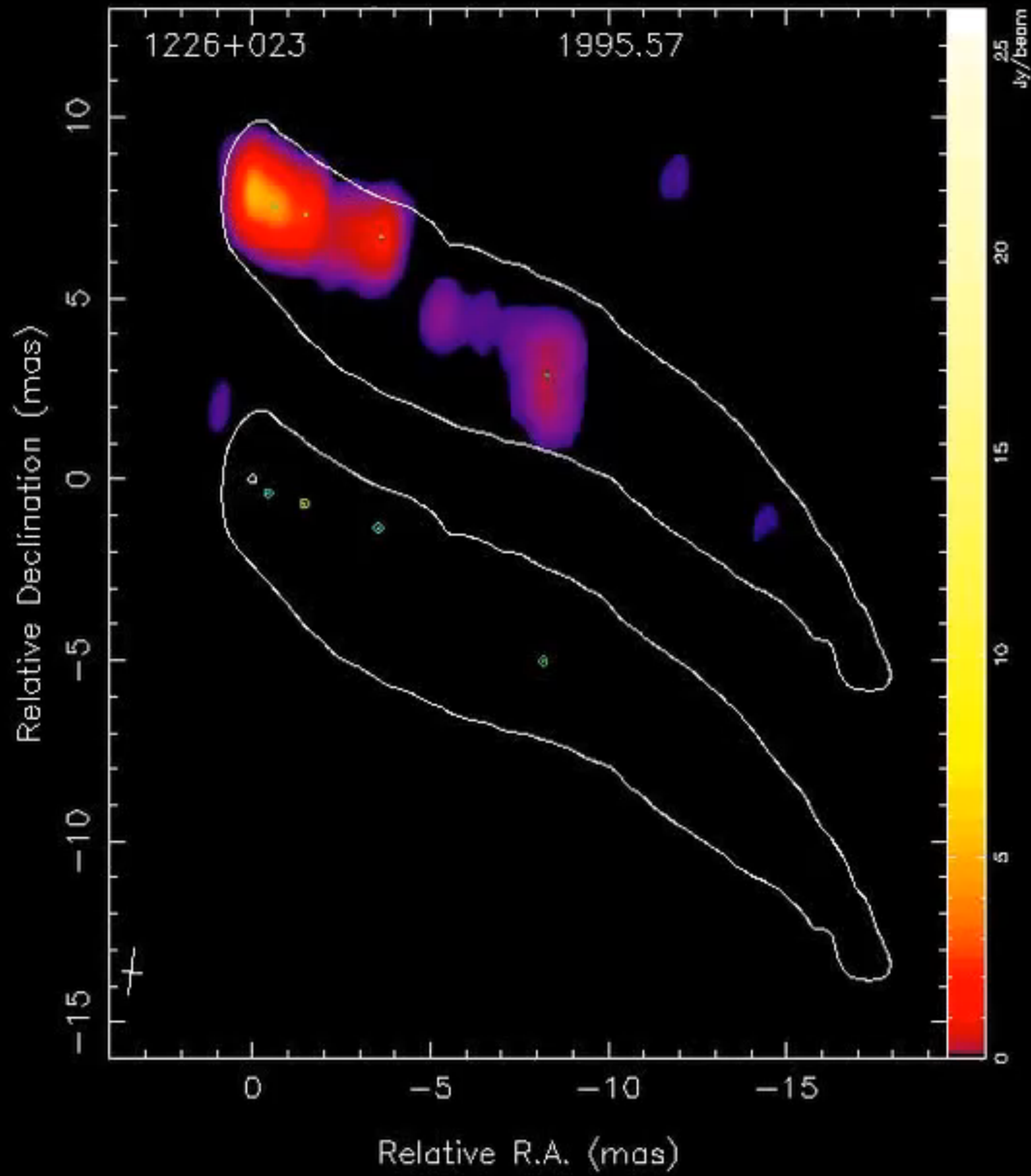


- Max speed 11 c
- Viewing angle < 11°
- Deprojected opening angle at 100 pc is < 2°

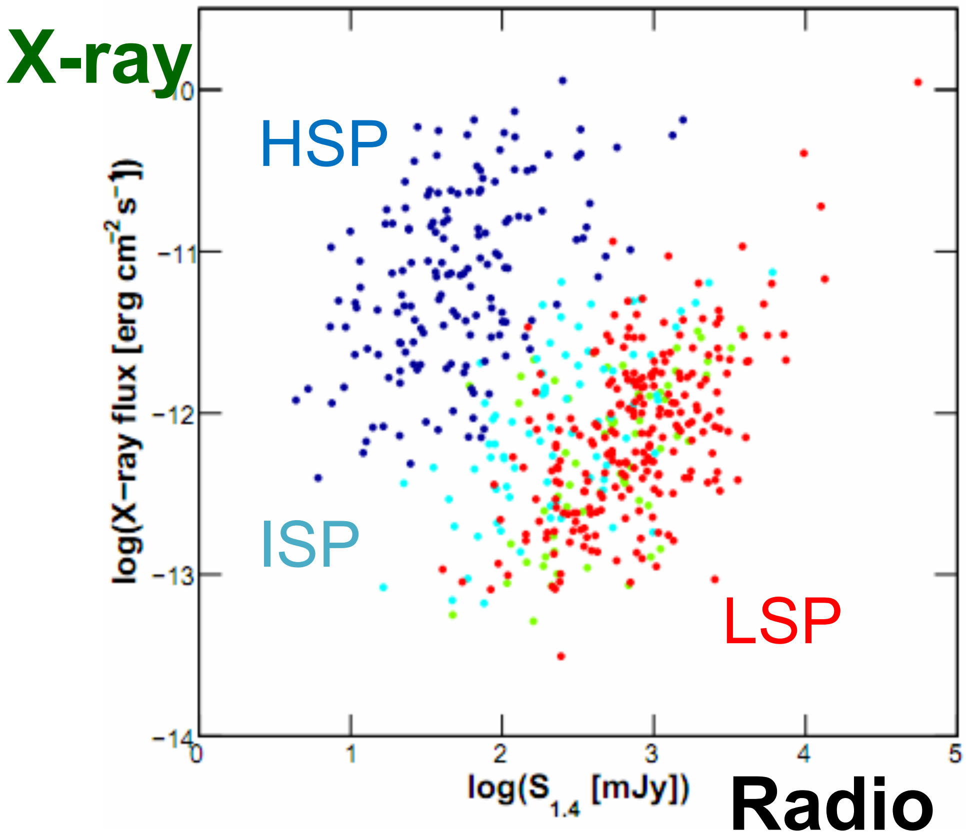
3C 273 at z = 0.16

25 pc

- Max speed 15 c



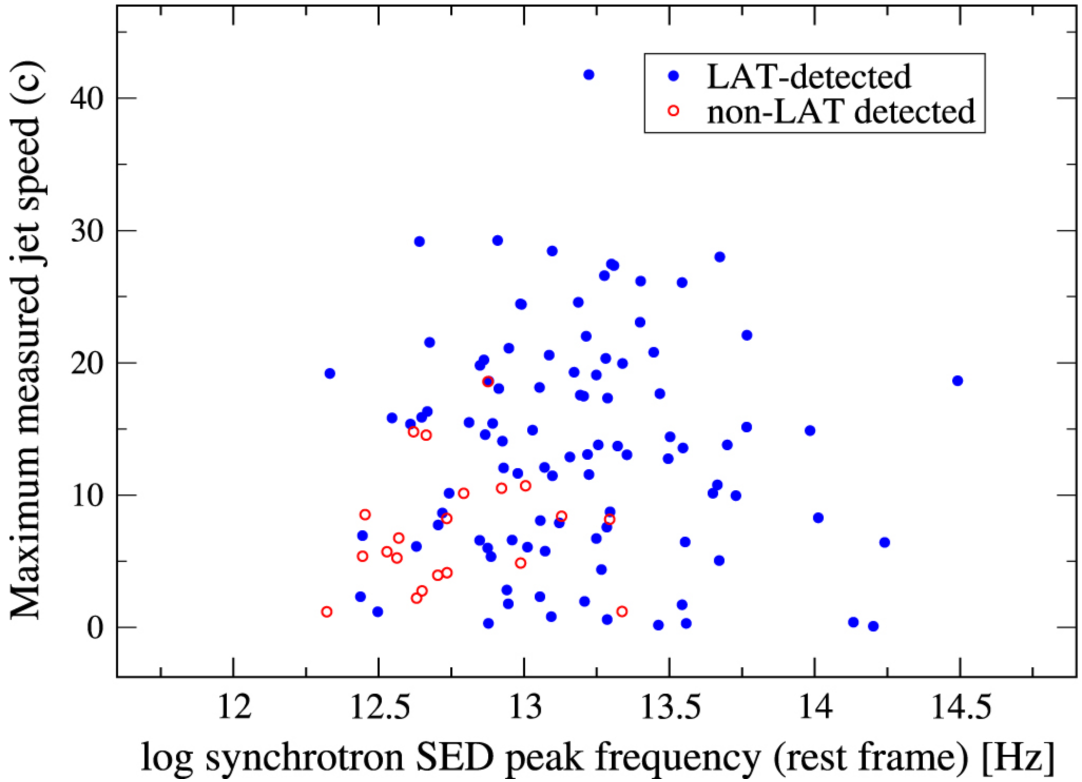
Investigating *Fermi* γ-ray blazar jets



Fermi LAT Collab, 2012, ApJ 743, 171

- *Fermi* is an excellent instrument for blazar demographic studies:
  - broadband coverage, sees jet flux only, no contamination from host galaxy
- Quasars (red points) have low-spectral peaked SEDs
- IC scattering of broad line region photons quenches high energy electron population in the jet
- Highest spectral peaked (HSP) jets are of the less powerful BL Lac class (no broad line region)

The Role of Doppler Boosting

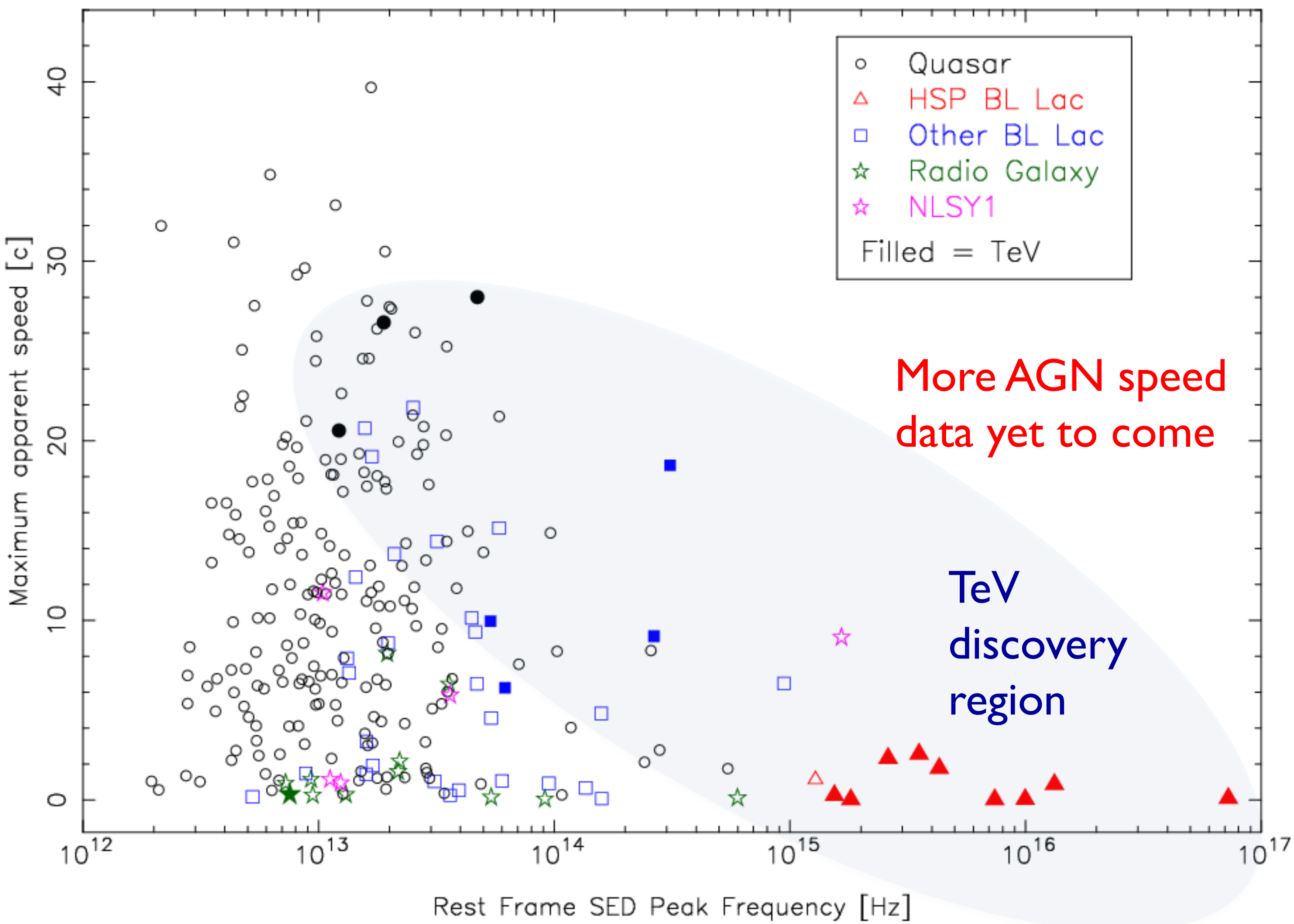


All of the fastest jets in the 1.5 Jy sample have Fermi-LAT detections.

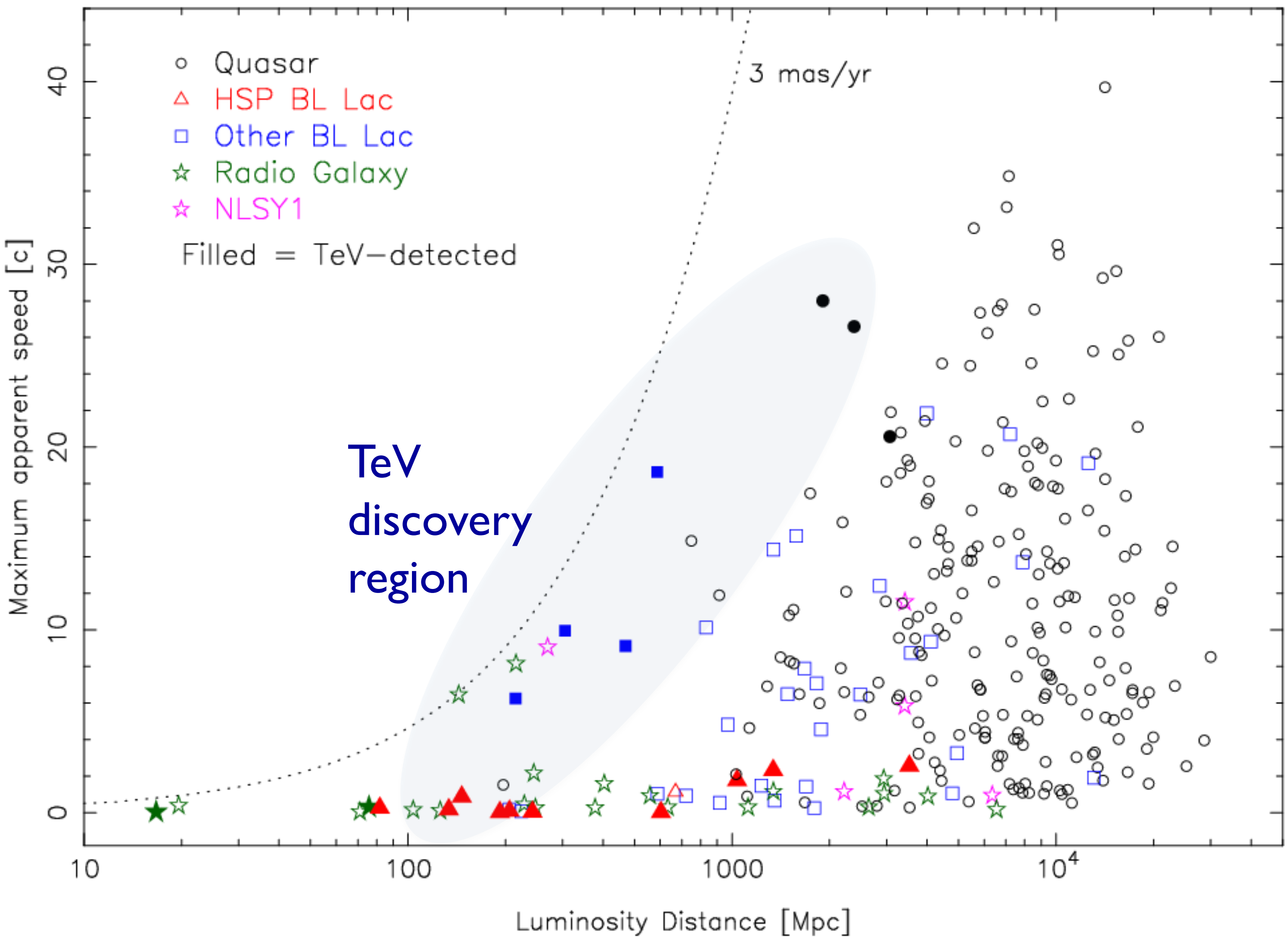
Lister et al. 2015, ApJ L., 810, 1

- External IC model predicts higher effective flux boosting in gamma-rays than radio, due to blue-shifting of external seed photons in jet frame.
- 100 MeV lower cutoff and sensitivity of *Fermi* LAT biases it against detecting low-spectral peaked, low Doppler factor blazars

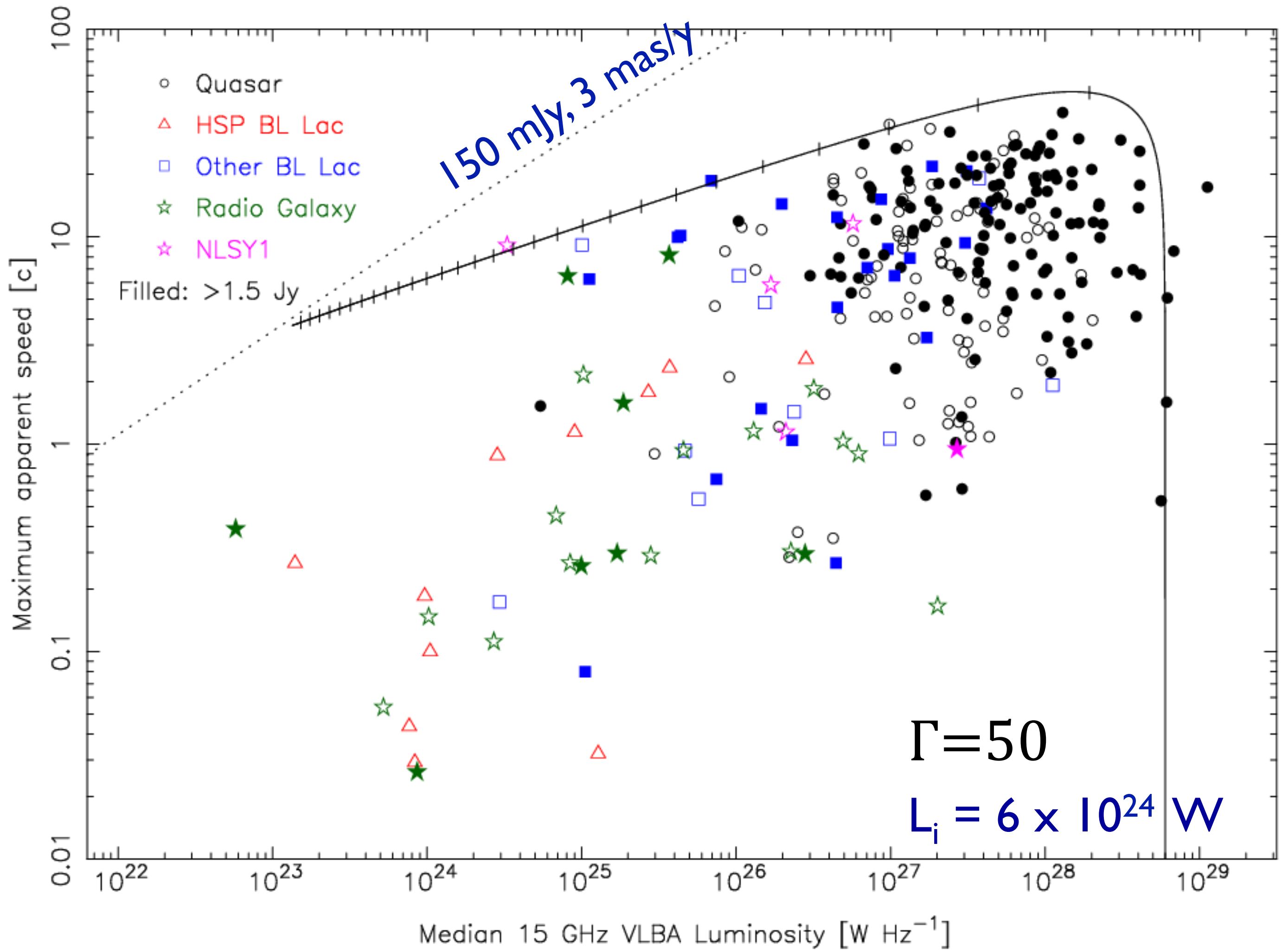
Jet Speed vs. Synchrotron Peak Frequency



Jet Speed vs. Cosmic Distance



Jet Speed vs. 15 GHz Luminosity



Only the most intrinsically powerful AGN jets attain high bulk Lorentz factors

Summary

- **The MOJAVE program is probing statistical aspects of AGN jets:**
  - the most powerful blazar jets have a wide range of bulk Lorentz factors up to ~50, while typical AGN jets have Lorentz factors of ~a few.
  - jet features speed up within ~100 pc of the jet base where jet is still collimating, and decelerate further out
  - VLBI images trace out only the currently energized emission regions, which don't fill the entire jet cross-section.
  - Current gamma ray blazar surveys are biased against low-spectral peaked, low-Doppler factor AGN jets.

- **Still to come: kinematics of lower-luminosity, hard-spectrum gamma-ray jets, and investigations of long term jet accelerations and nozzle variations.**

www.astro.purdue.edu/MOJAVE