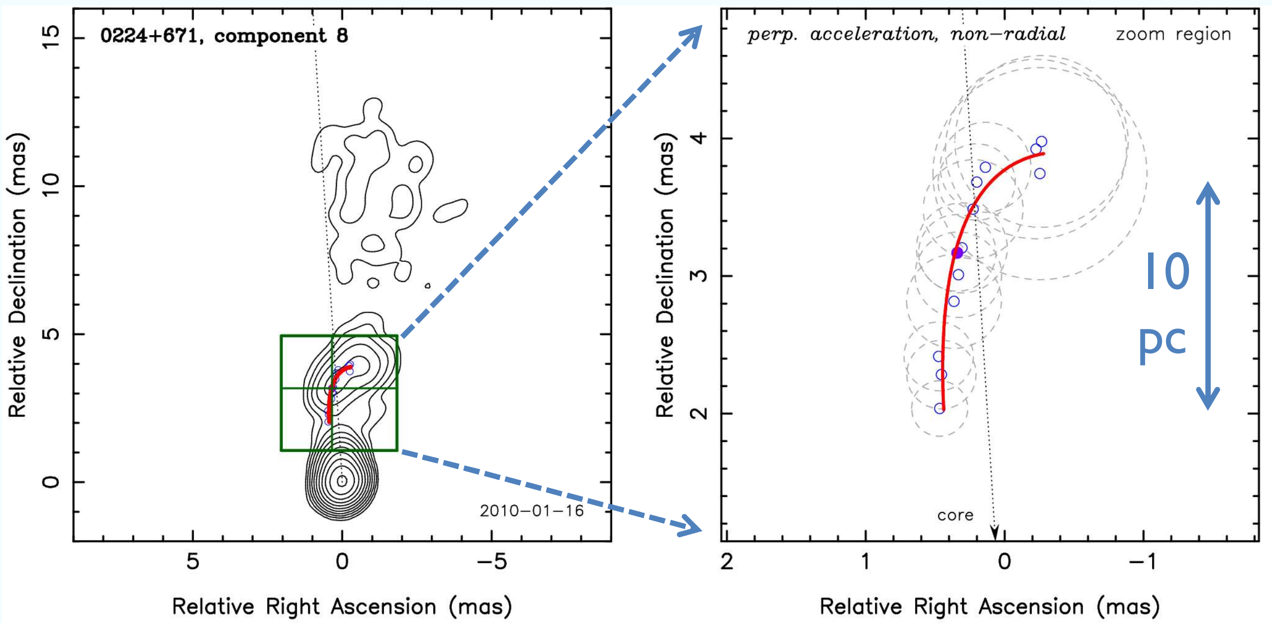
Parsec-Scale Studies of Blazar Jet Kinematics

Matt Lister

Department of Physics & Astronomy

Purdue University, USA



Turin, June 2018

MOJAVE Collaboration

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

The MOJAVE Program is supported under NASA Fermi Grant NNX15AU76C

Monitoring
Of
Jets in
Active Galaxies with
VLBA
Experiments

Very Long Baseline Array

Talk Outline

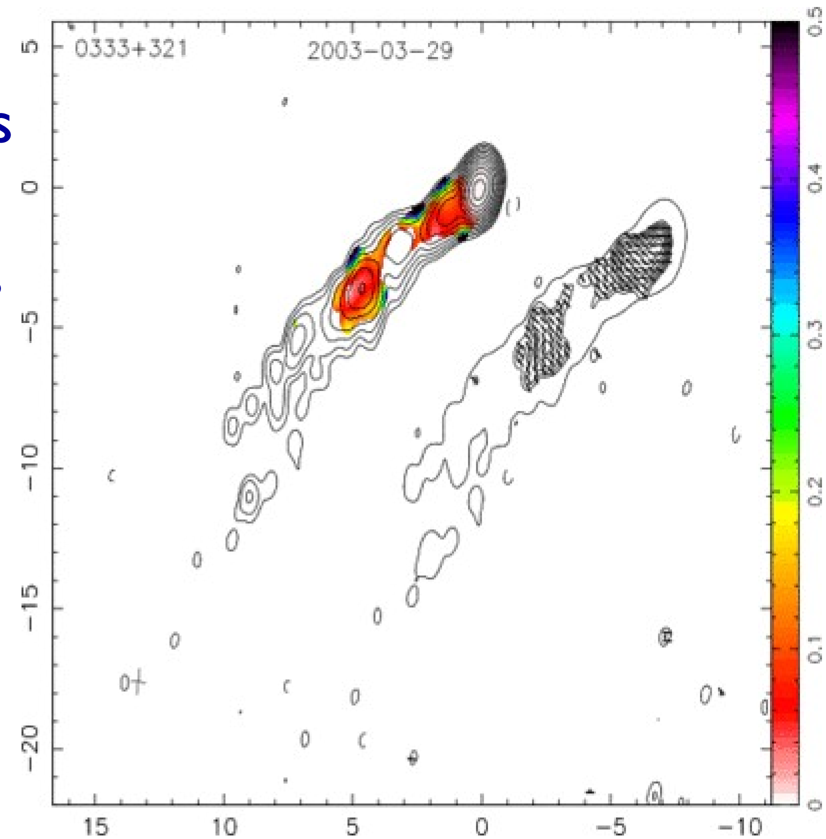
- **AGN jet kinematics:**
  - – MOJAVE, Walker M87, Boston U, Piner & Edwards
  - – slow, non-radial, inward, & superluminal features
  - – accelerations and trends down the jet
- **Demographics and Statistical Trends**

MOJAVE VLBA Program

- Milliarcsec-resolution 15 GHz images of over 400 AGN jets
  - 25 year baseline on many sources
  - full polarization since 2002

- 30 AGN observed per month, chosen from list of ~100 targets:
  decl. > - 30° and > 0.1 Jy

- Results published in series of papers, see list and data archive at www.astro.purdue.edu/MOJAVE

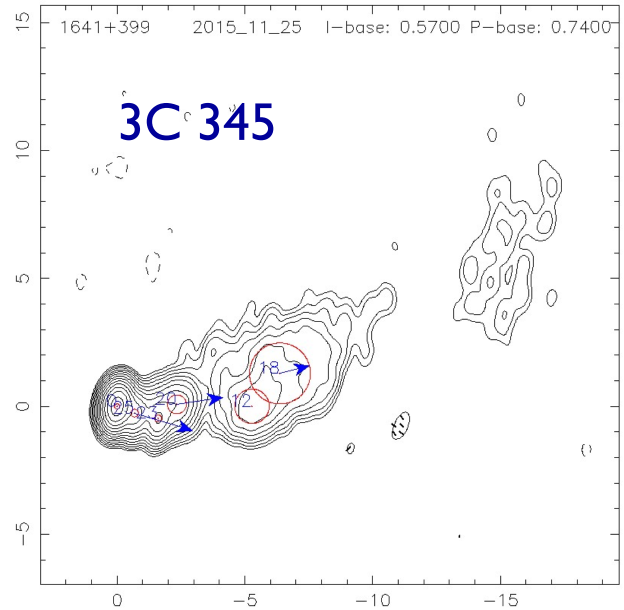


Blazar NRAO 140 at 15 GHz

Colors: fractional linear polarization

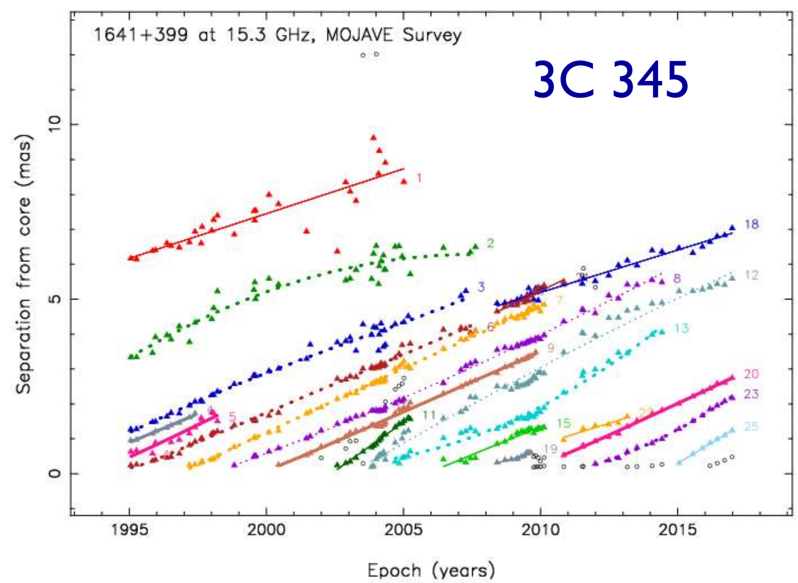
MOJAVE Kinematics Studies

- Gaussian models fit to visibilities at each epoch (at least 5 epochs per AGN).
  - rms positional accuracy: ~ 0.06 mas
  - track trajectories of bright jet features
  - probing jet kinematics at 10-1000 pc (de-projected) from central engine



- Latest analysis covers 1744 jet features in 382 AGNs, based on 7173 VLBA epochs from 1994 Sept to 2017 Jan 1.

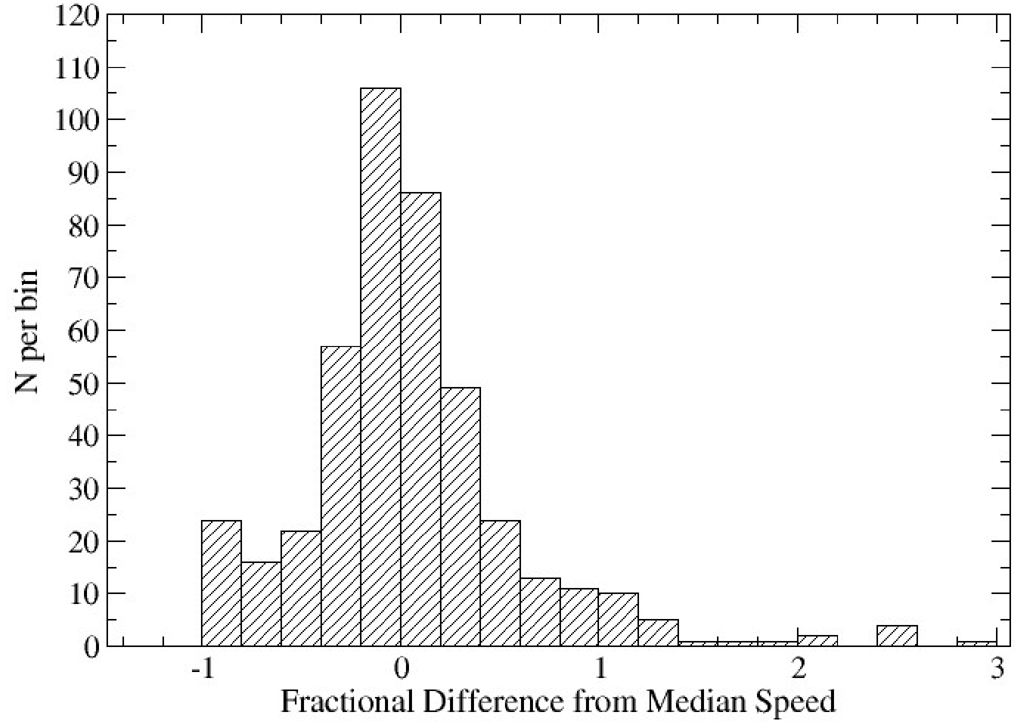
- Typical angular speeds are ~ 0.1 mas/y, range from a few μas/y to 3 mas/y



Speed Dispersion Within the Jet

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

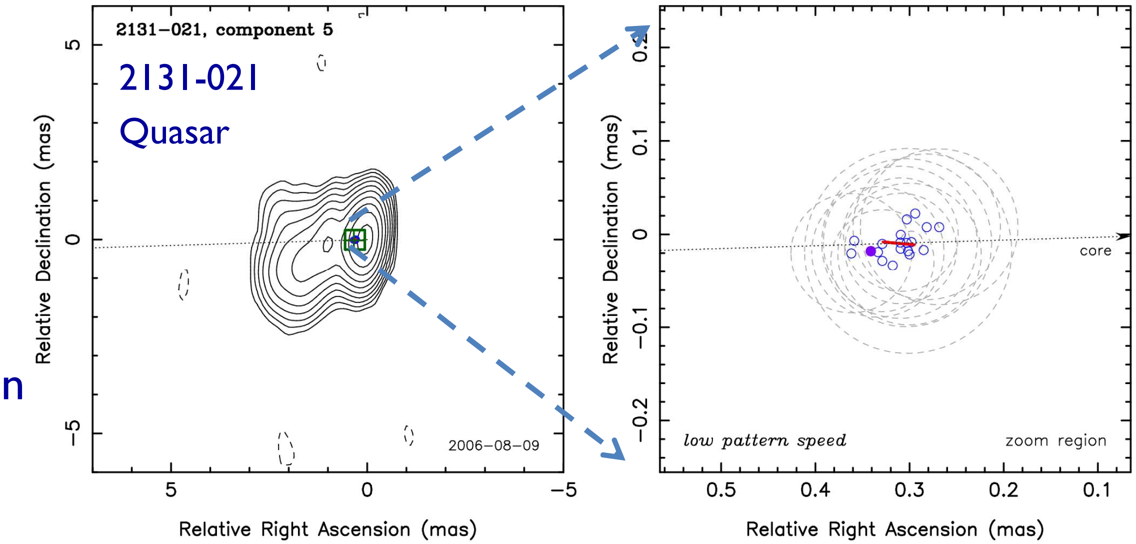
- A ***characteristic median speed*** exists for each jet



Normalized speed distribution within 26 jets, each having at least 10 moving features.

Slow Pattern (‘Stationary’) Features

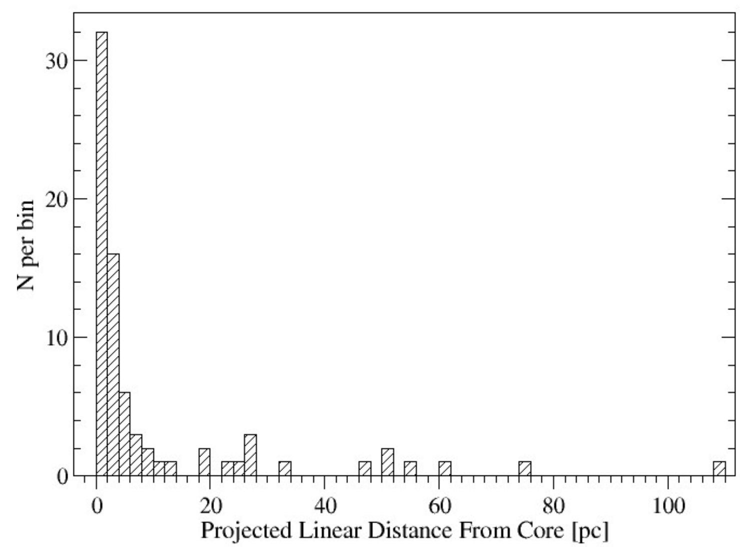
- Features that have:
  - i. speed < 20 μas/y
  - ii. < 1/10th of max speed seen in the jet
  - iii. no significant acceleration



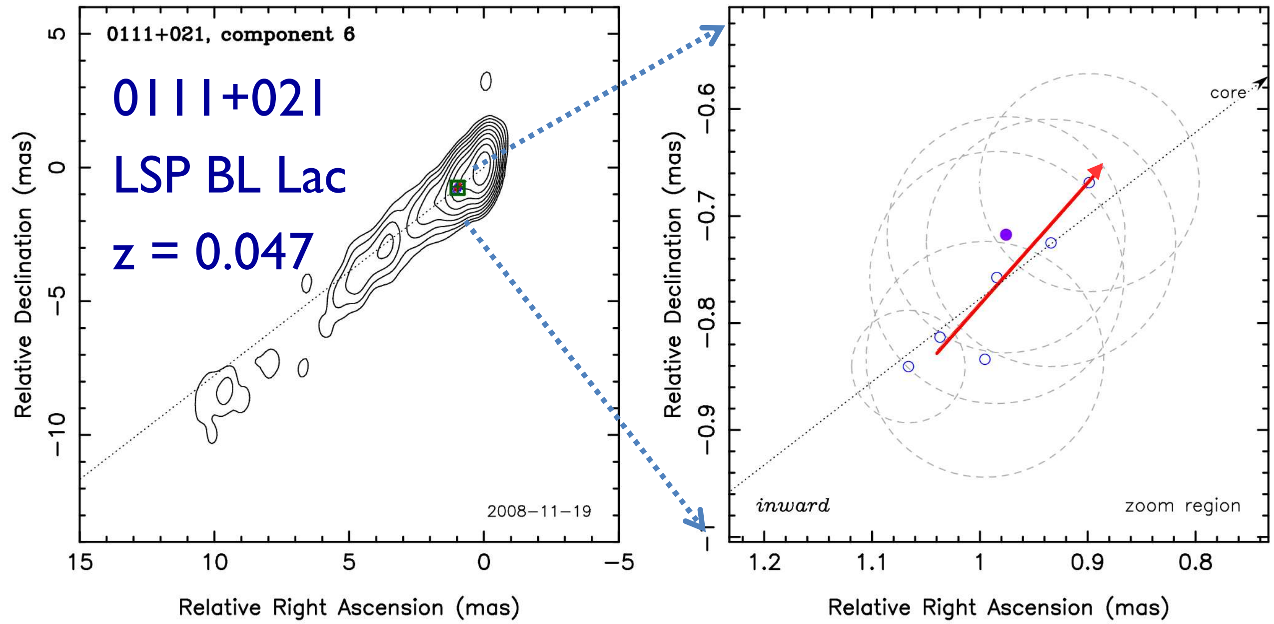
- 6% of all jet features

- Present in 25% of quasar and 24% of BL Lac jets

- Majority are located close to the base of the jet



Apparent Inward Motions

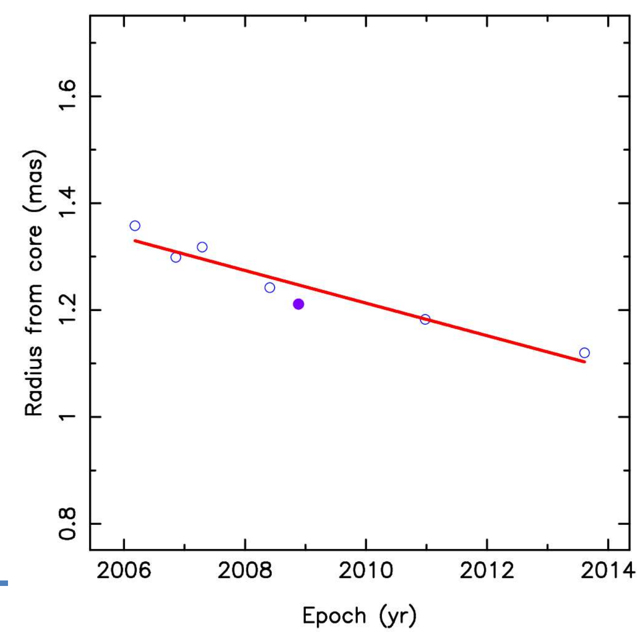


Statistics:

- Only 2.5% of all features are inward
- Seen in 9% of quasar and 10% of BL Lac jets

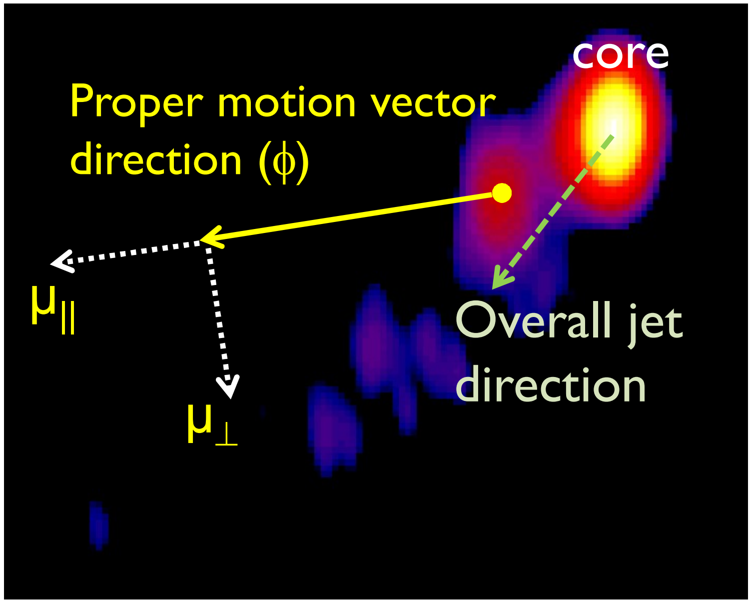
Likely explanations:

- Accelerated motion across the line of sight
- Inward pattern speed (e.g., reverse shock)
- Misidentification of true core feature



Acceleration Analysis

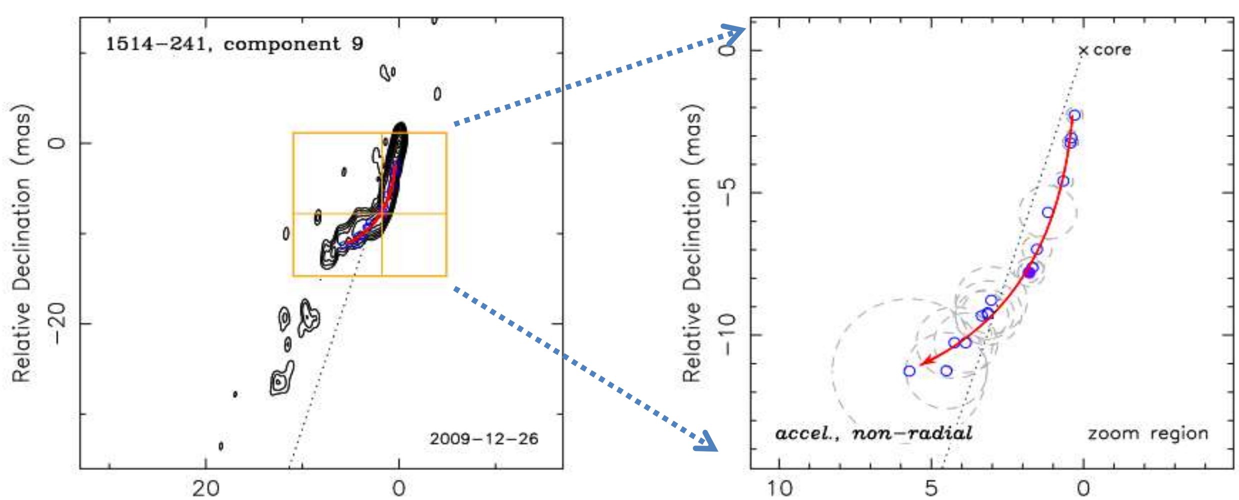
- Analyzed 880 features in 206 blazar jets which had at least ten VLBA epochs and known redshift.
- Measured accelerations in || and ⊥ directions to fitted apparent motion vector on the sky.



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

AGN Jets Are Accelerating

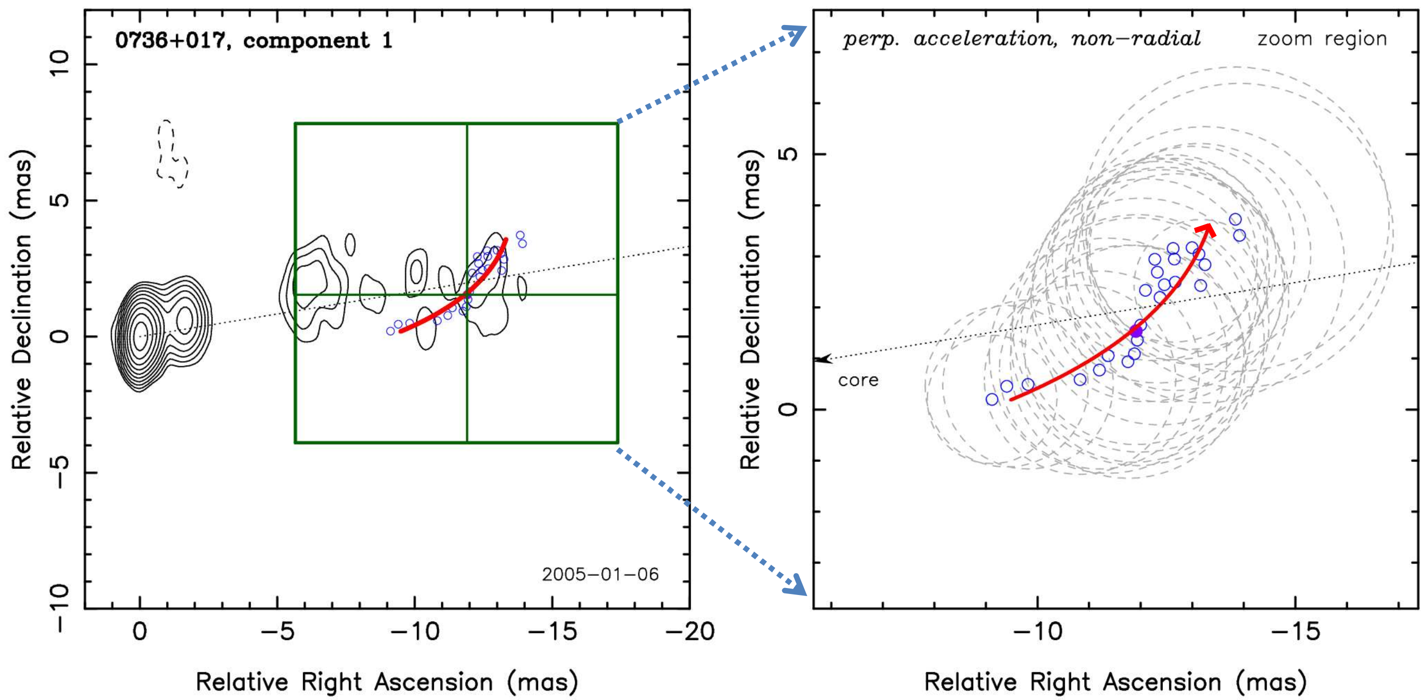
- 60% of AGN jets studied have at least one feature with >3σ acceleration.
- 37% of all individual jet features show evidence of acceleration.
- Parallel accelerations are of larger magnitude and more prevalent than ⊥ accelerations.
  - primarily due to changes in Lorentz factor, not bending
- Similar results seen by Piner et al. 2012 (8 GHz) and Jorstad et al. 2017 (43 GHz)



Acceleration of Non-Radial Features

- Overall jet axis direction determined using stacked-epoch image.
- Most off-axis features have perpendicular accelerations that are steering them back towards the jet axis.

- We are seeing jet collimation at scales up to 50 pc

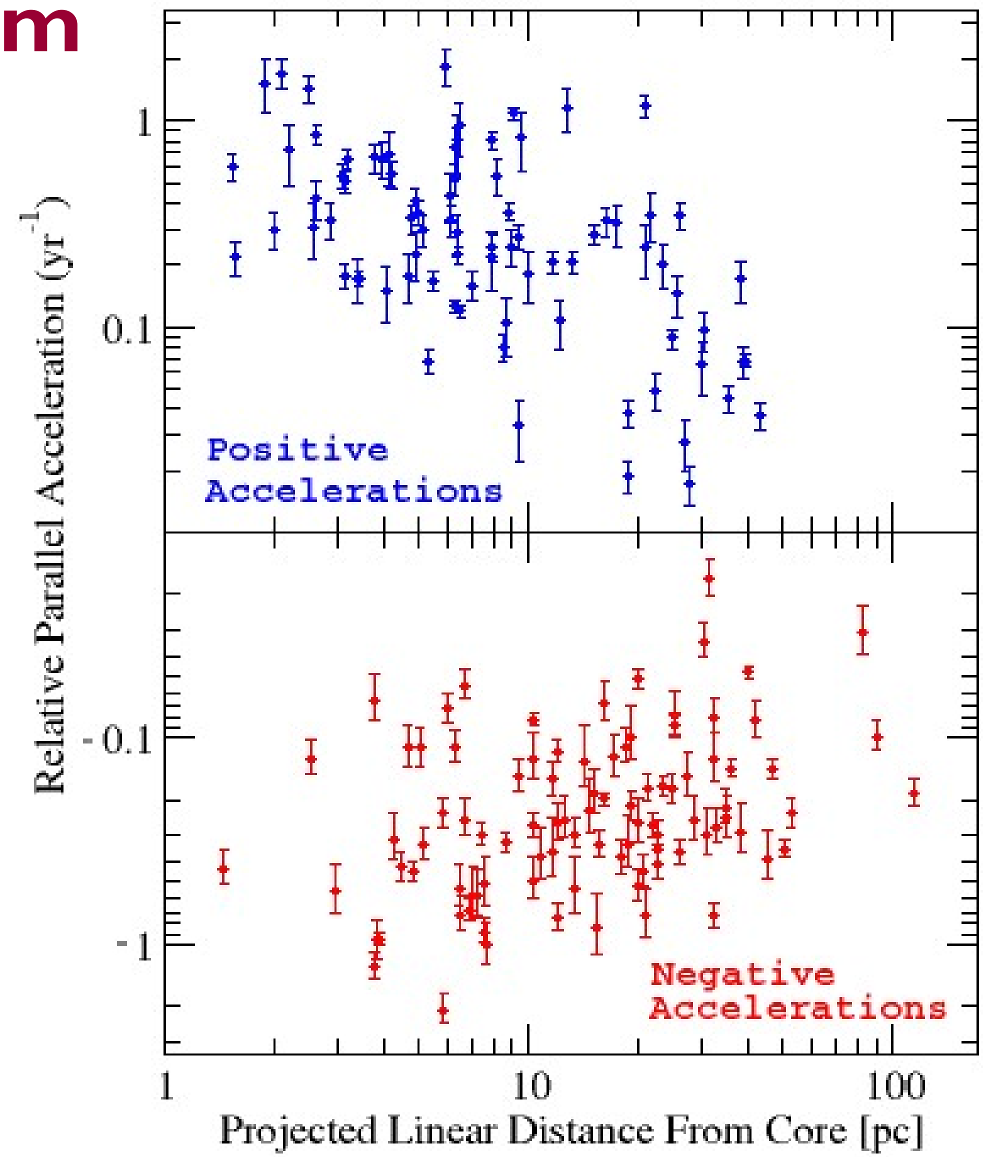


Trends Downstream

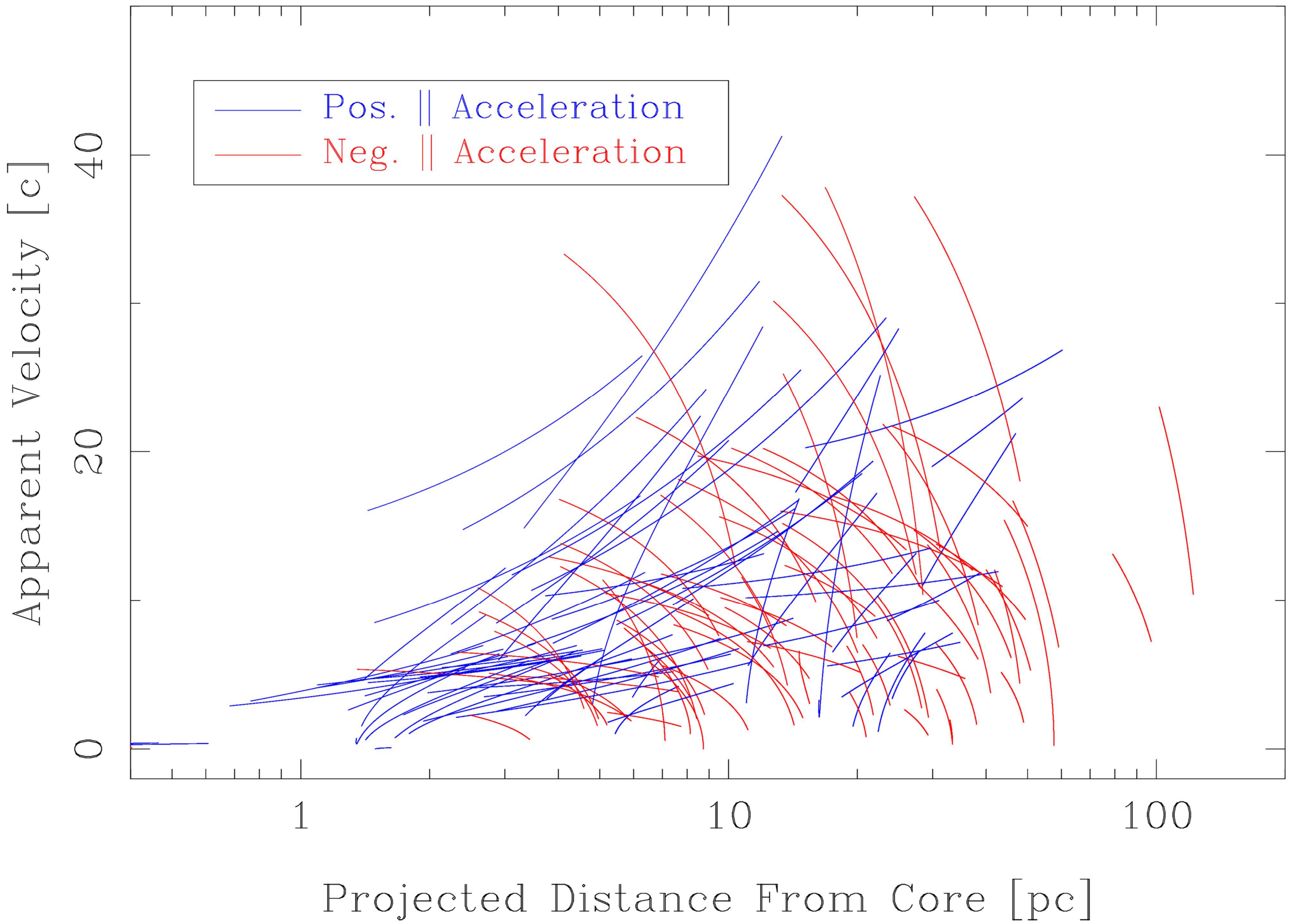
- Features tend to speed up near the core, and slow down further out.

- Within ~10 pc (projected), for δ ~ 10, in observer frame: $\dot{\Gamma}/\Gamma \sim 10^{-3} - 10^{-2}$ per year

- Past 10 pc (projected), for δ ~ 10, in observer frame: $\dot{\Gamma}/\Gamma \sim -10^{-3}$ per year

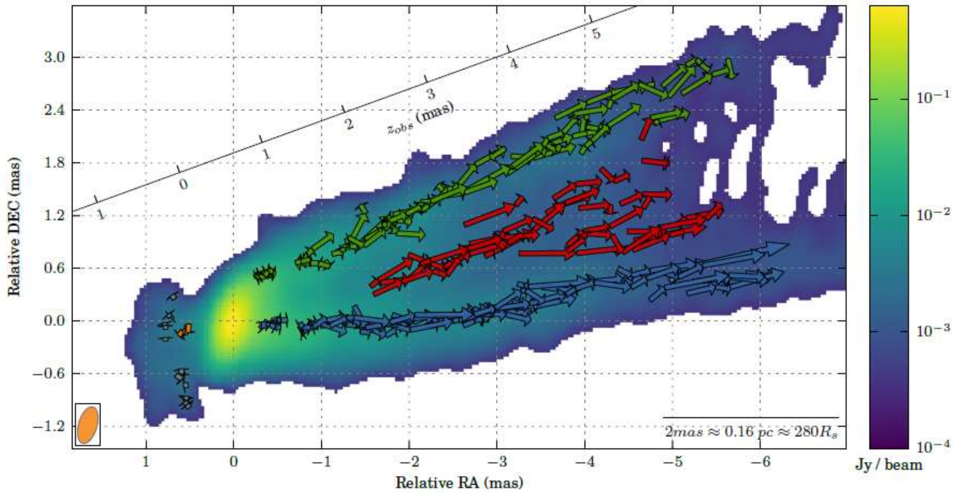


Do the observed motions reflect the underlying jet flow?

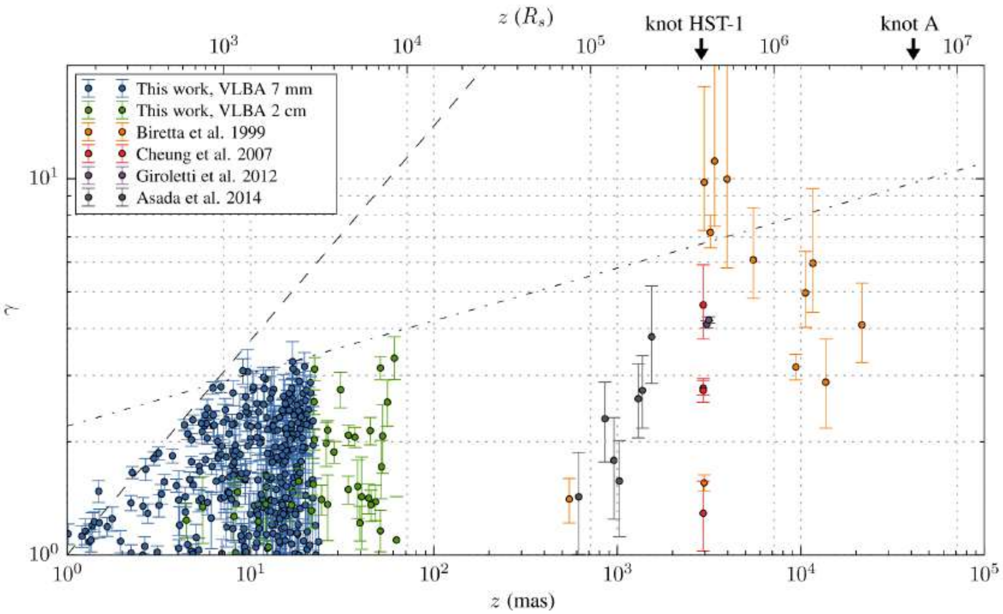


- Any intrinsic shock speeds are added relativistically to the flow speed.
- Statistical trends in MOJAVE jet sample are impossible to reproduce with a random collection of inward & outward moving shocks.

Acceleration in M87 Jet

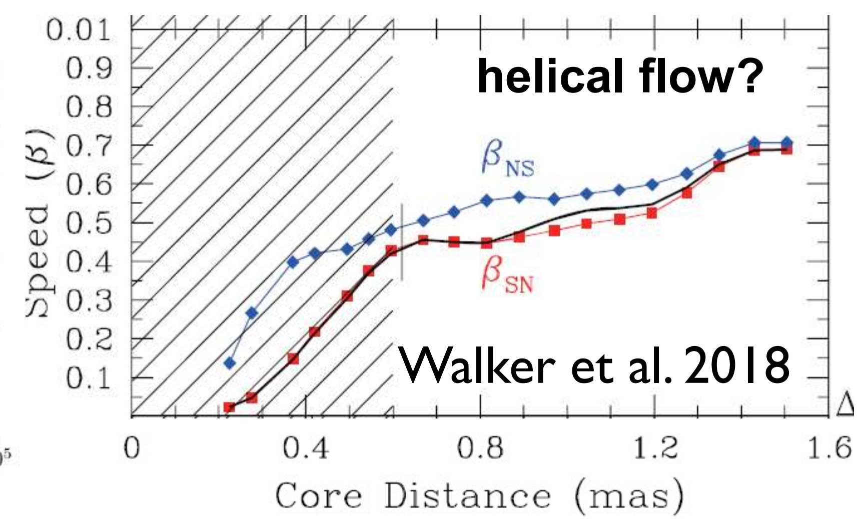


- Wavelet + cross-correlation image analysis of C. Walker 43 GHz VLBA M87 movie project and 15 GHz MOJAVE images



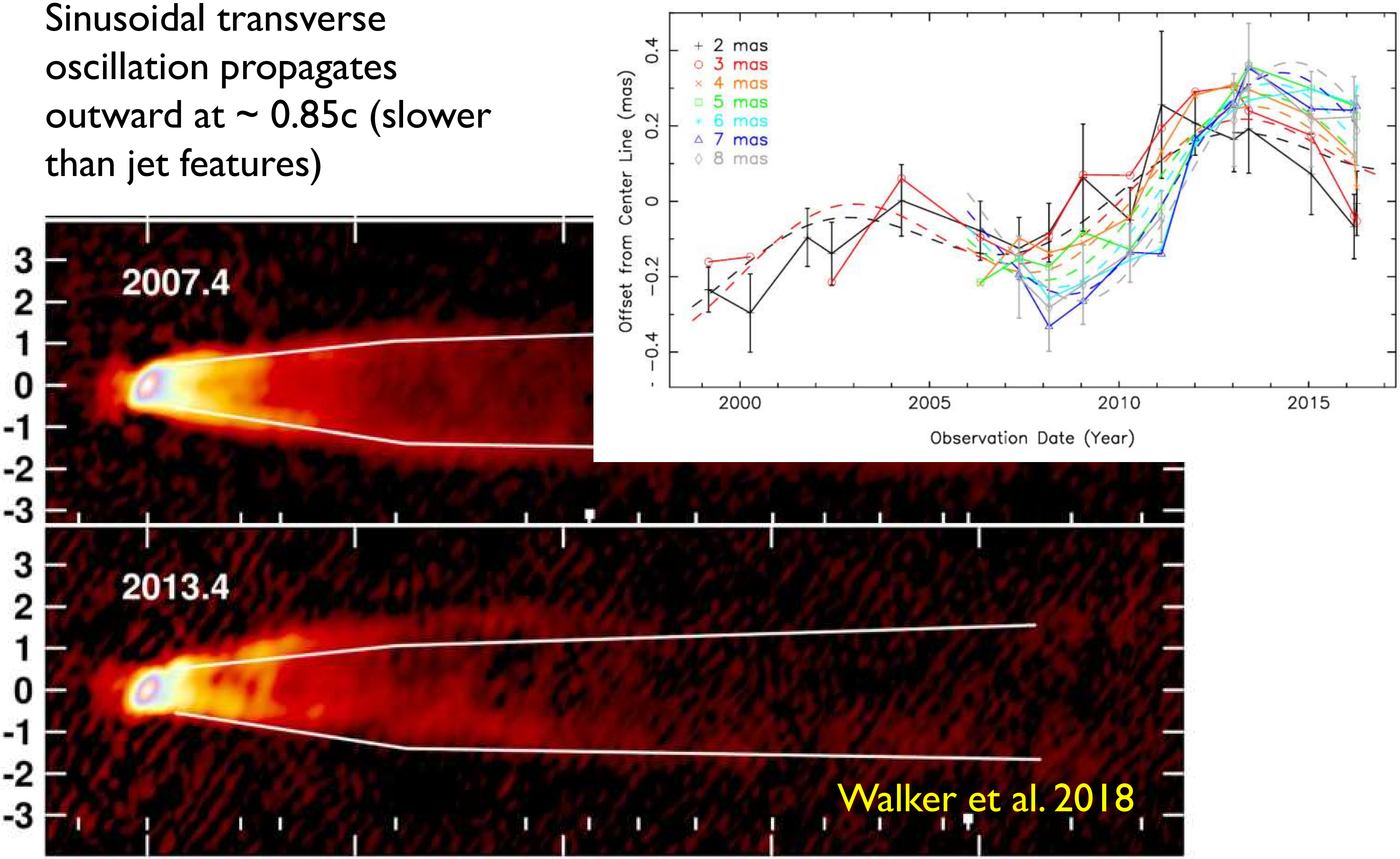
Mertens et al. 2016

Speeds of N and S jet sheaths:



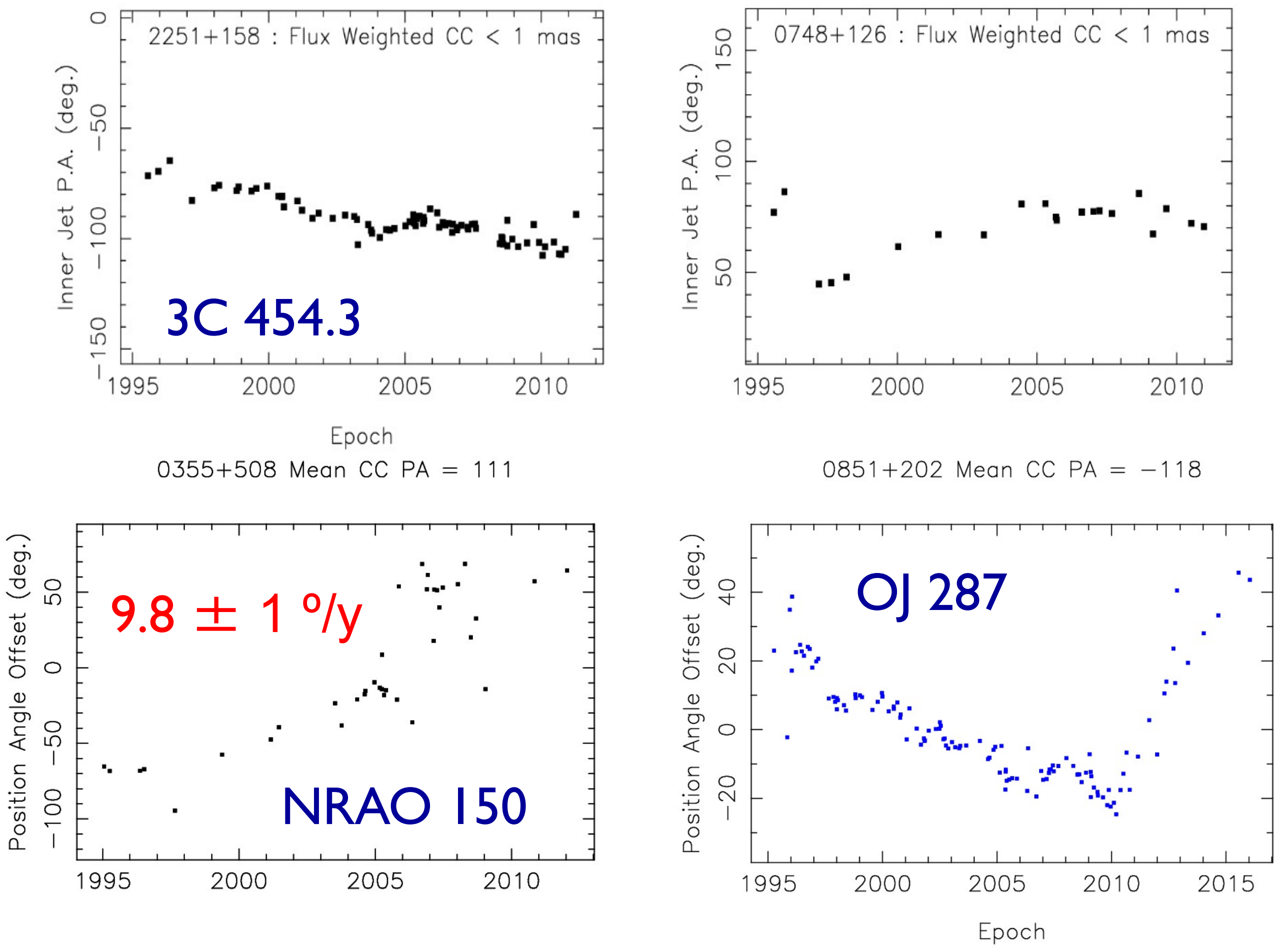
Side-to-Side Motion of M87 Jet

Sinusoidal transverse oscillation propagates outward at ~ 0.85c (slower than jet features)

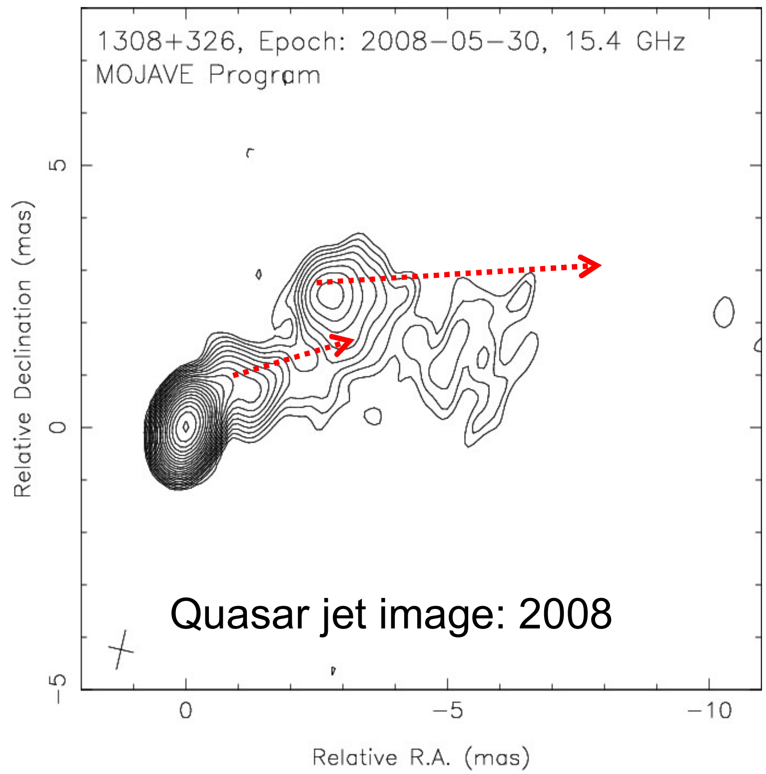


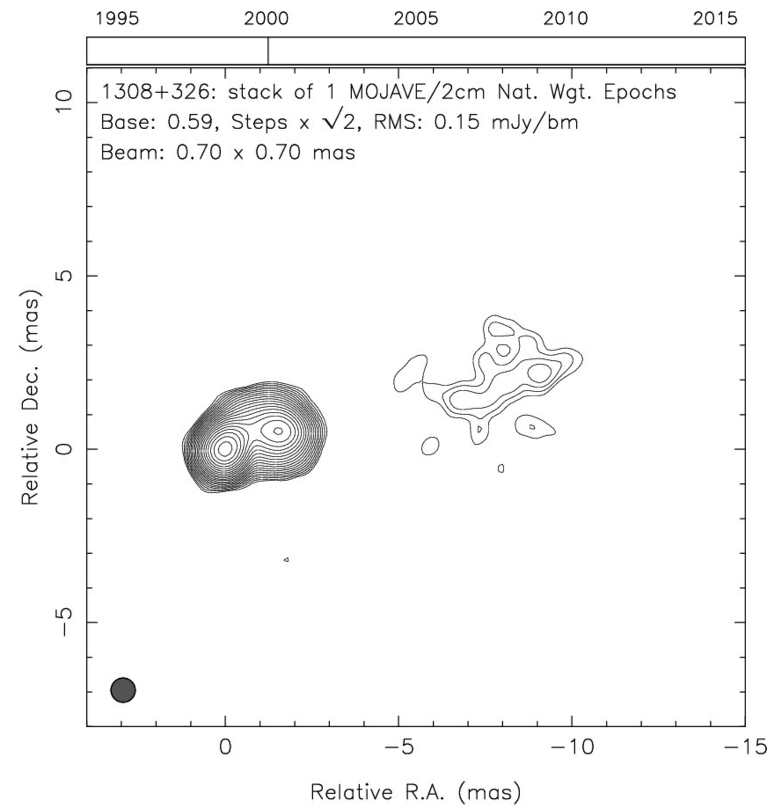
Changes in Inner Jet Direction

- Half of best monitored MOJAVE jets show changes in their (projected) innermost jet position angle, at rate of ~1- 3° y^{-1}



Energized Jet Channels



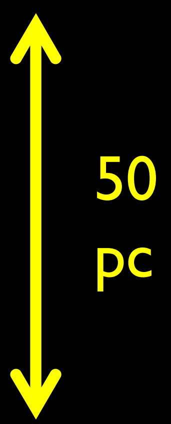


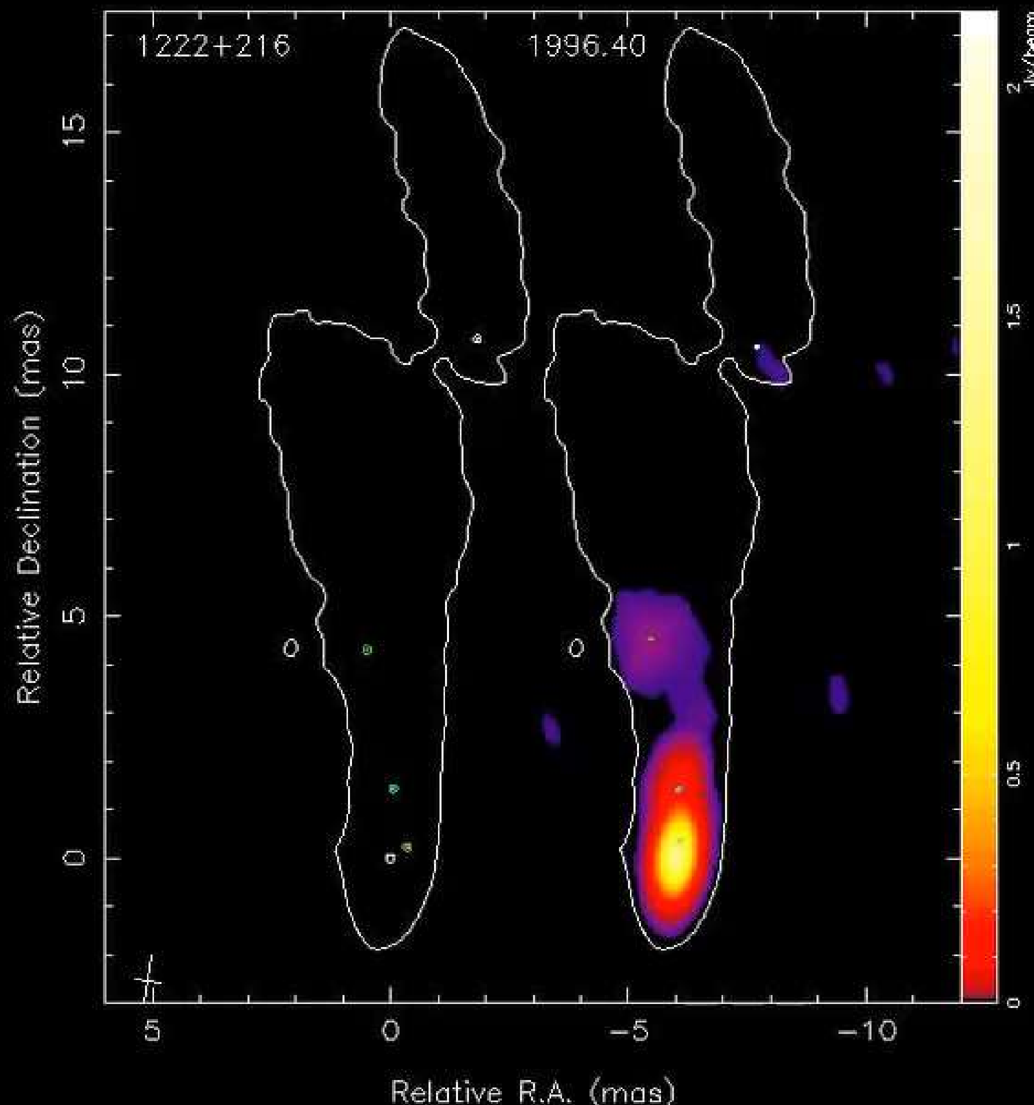
MOJAVE Paper XIV

- At any given time, typically only a portion of the full (conical) outflow is energized/visible in a VLBA image

TeV-detected Quasar 1222+216 at z = 0.43

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

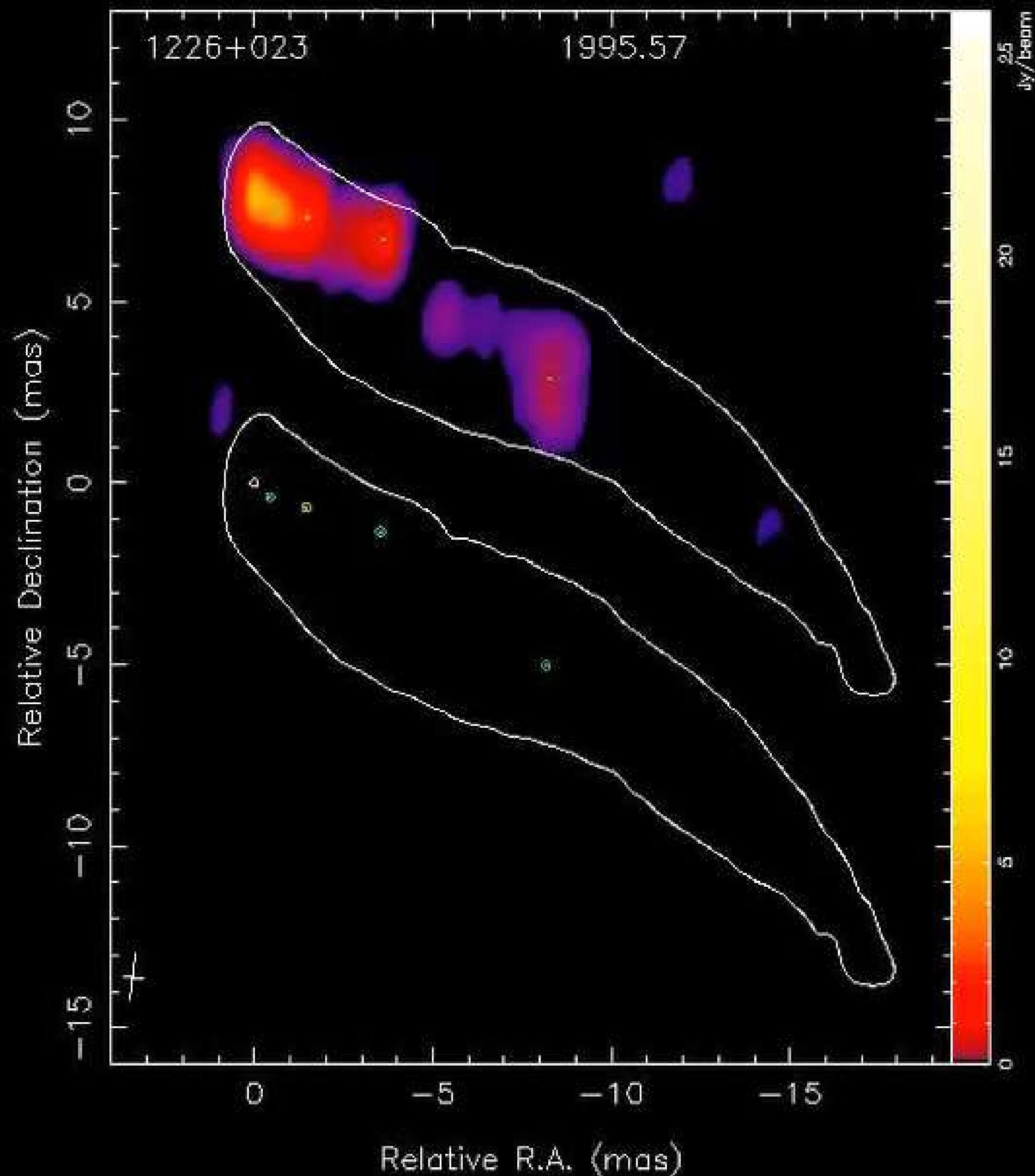




3C 273 at
z = 0.16

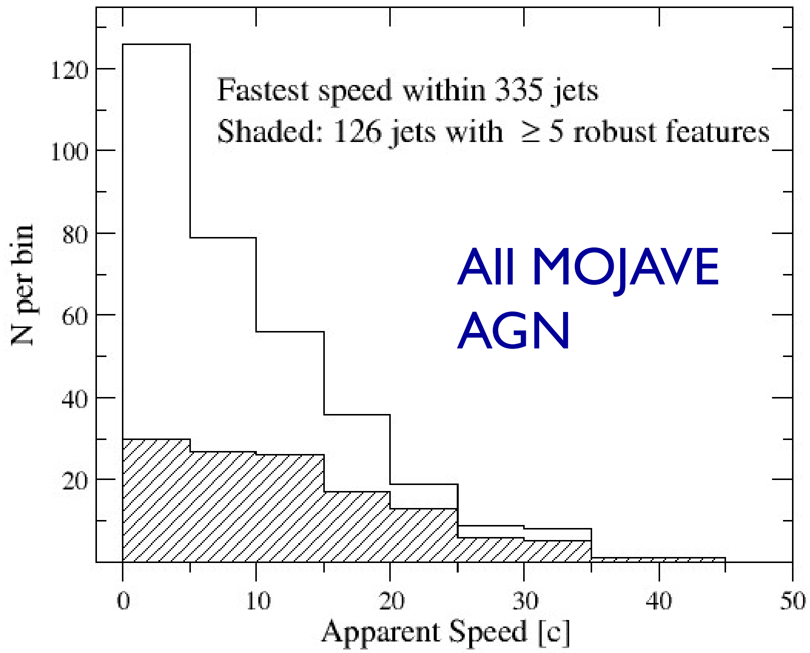
25
pc

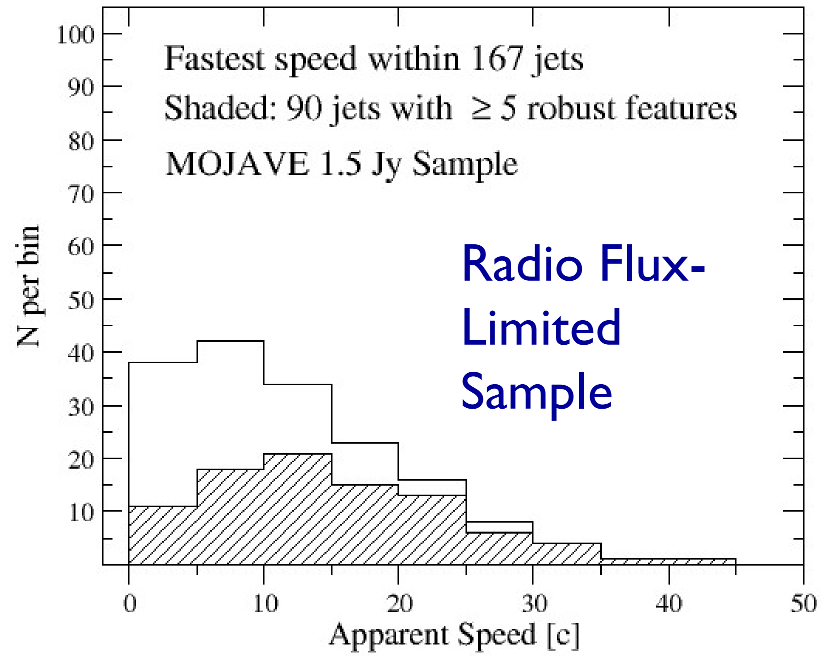
- Max speed 15 c



Statistical Trends

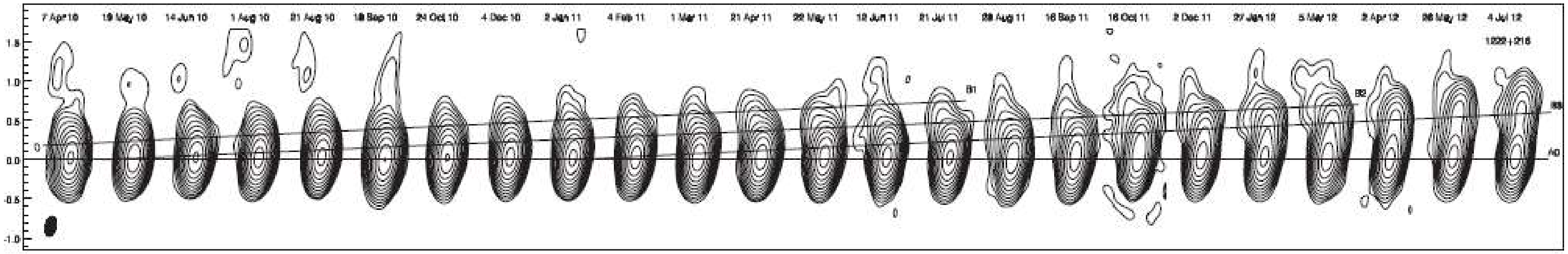
Maximum Jet Speed Distribution





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

Boston U. Blazar Monitoring Program



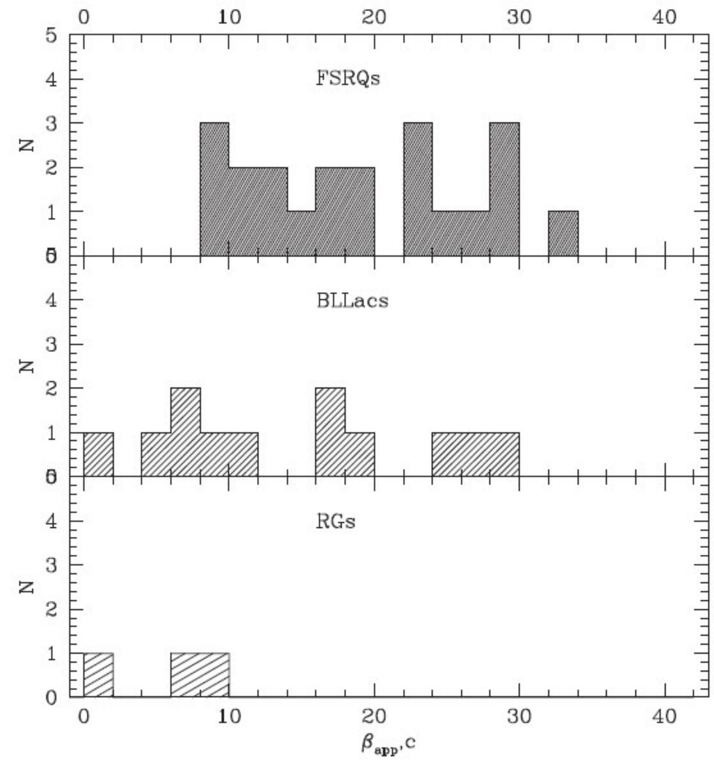
1222+216

Monthly VLBA 43 GHz obs. of 36 AGN

- samples rapidly-fading features within ~1 mas of the jet base.

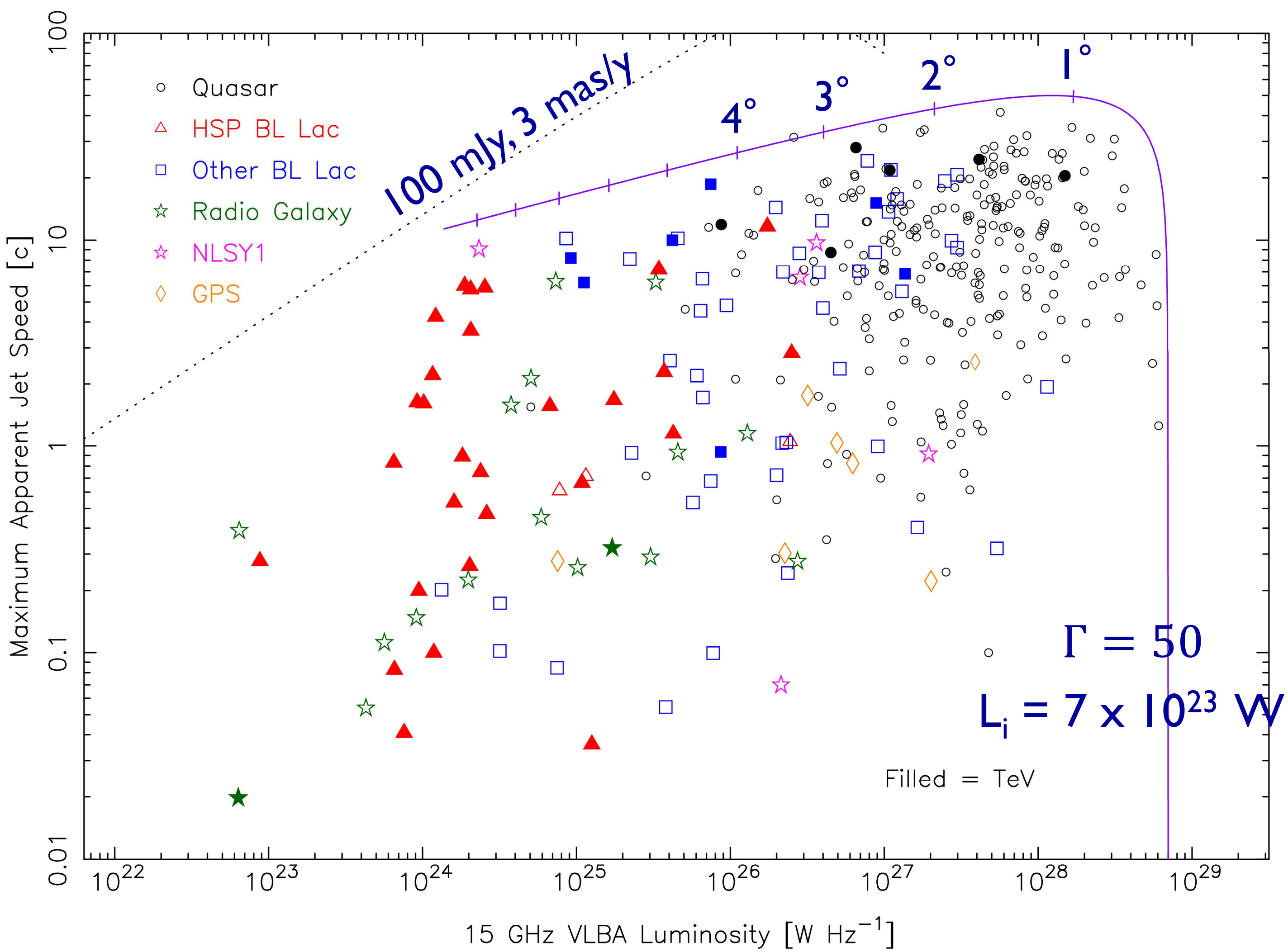
Results consistent with MOJAVE program:

- similar range of speeds
- 21% of features are stationary and most are within 3 pc of core
- 31% of features show accelerations
- parallel accelerations are larger and more common than perpendicular ones



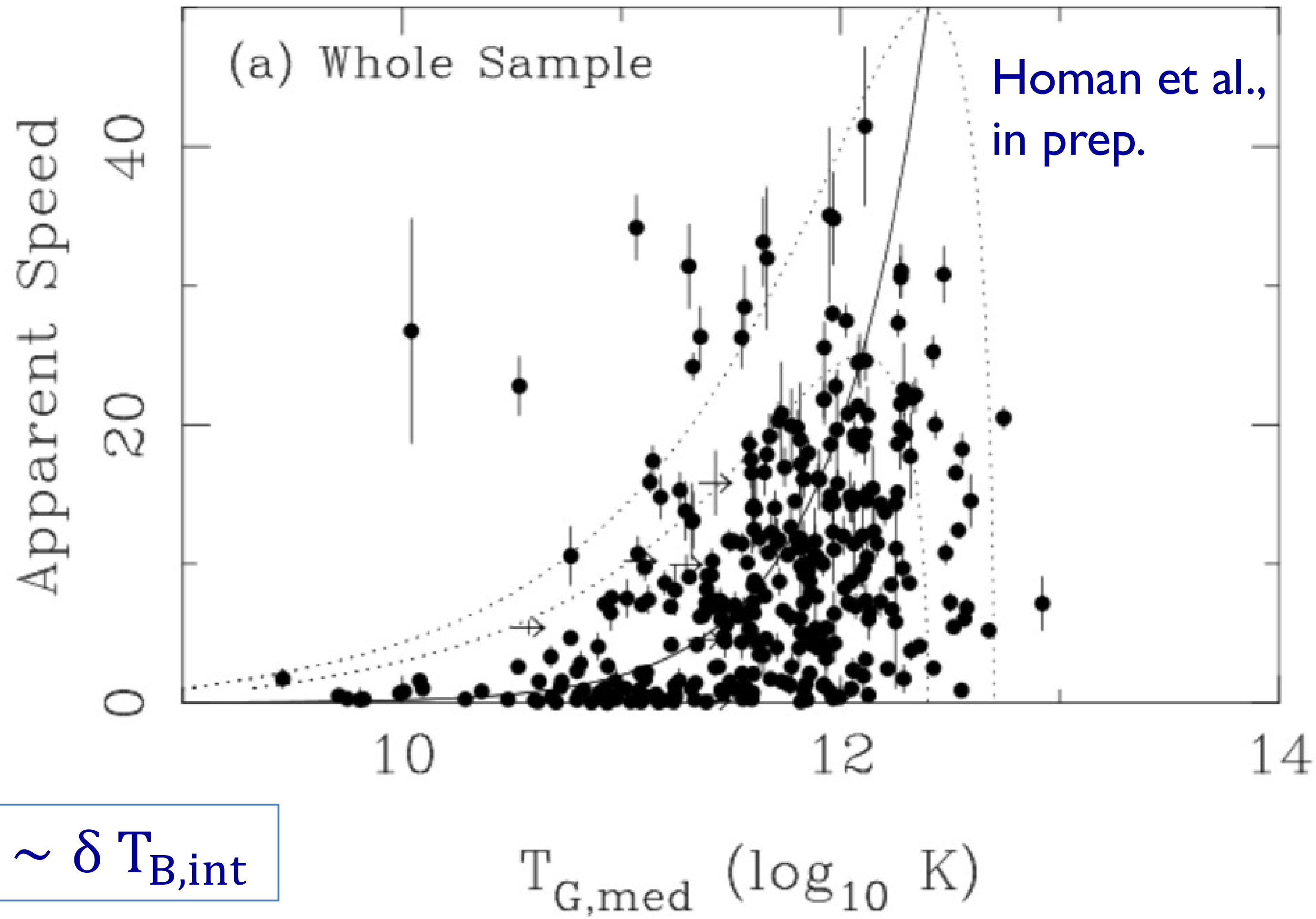
Jorstad et al. 2017

Jet Speed vs. 15 GHz Luminosity



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

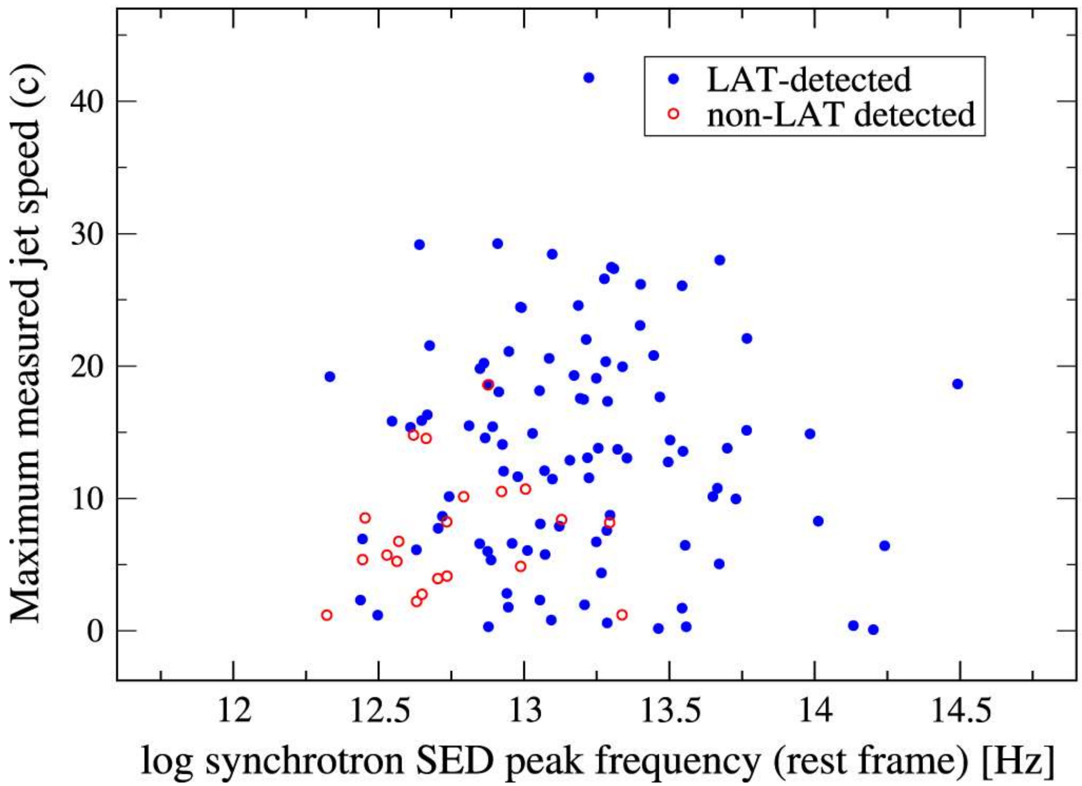
Maximum Jet Speed vs. Core Compactness



Homan et al., in prep.

$T_{B,obs} \sim \delta \, T_{B,int}$

Jet Speed and γ-ray Emission



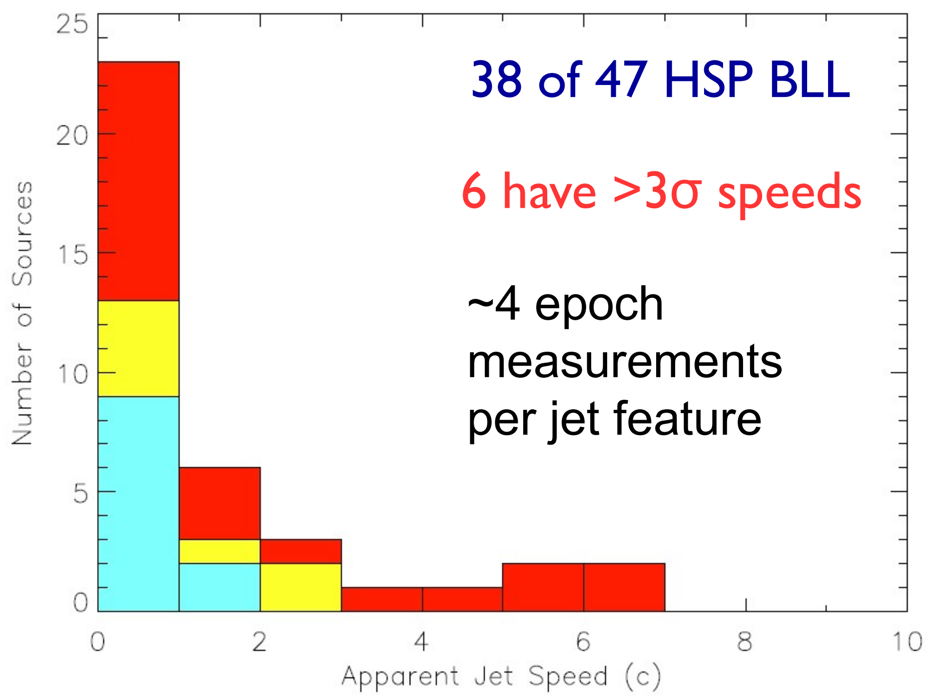
All of the fastest jets in the 1.5 Jy sample have Fermi-LAT detections.

Lister et al. 2015, ApJL., 810, 1

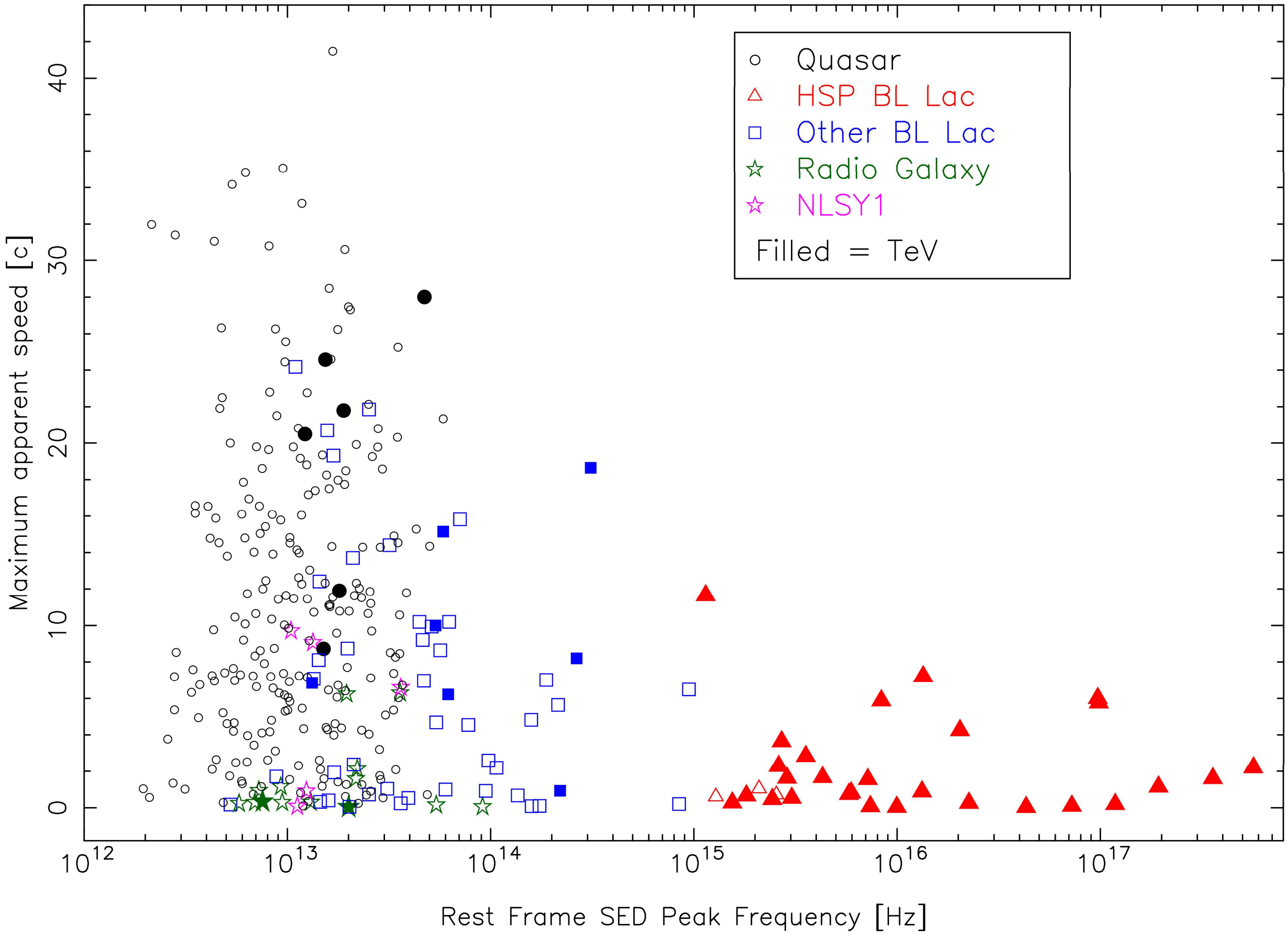
- External IC model: more boosting in gamma-rays than radio
- 100 MeV lower cutoff and sensitivity of *Fermi* LAT biases it against detecting low-spectral peaked, lower Doppler factor blazars

Piner and Edwards TeV AGN Study

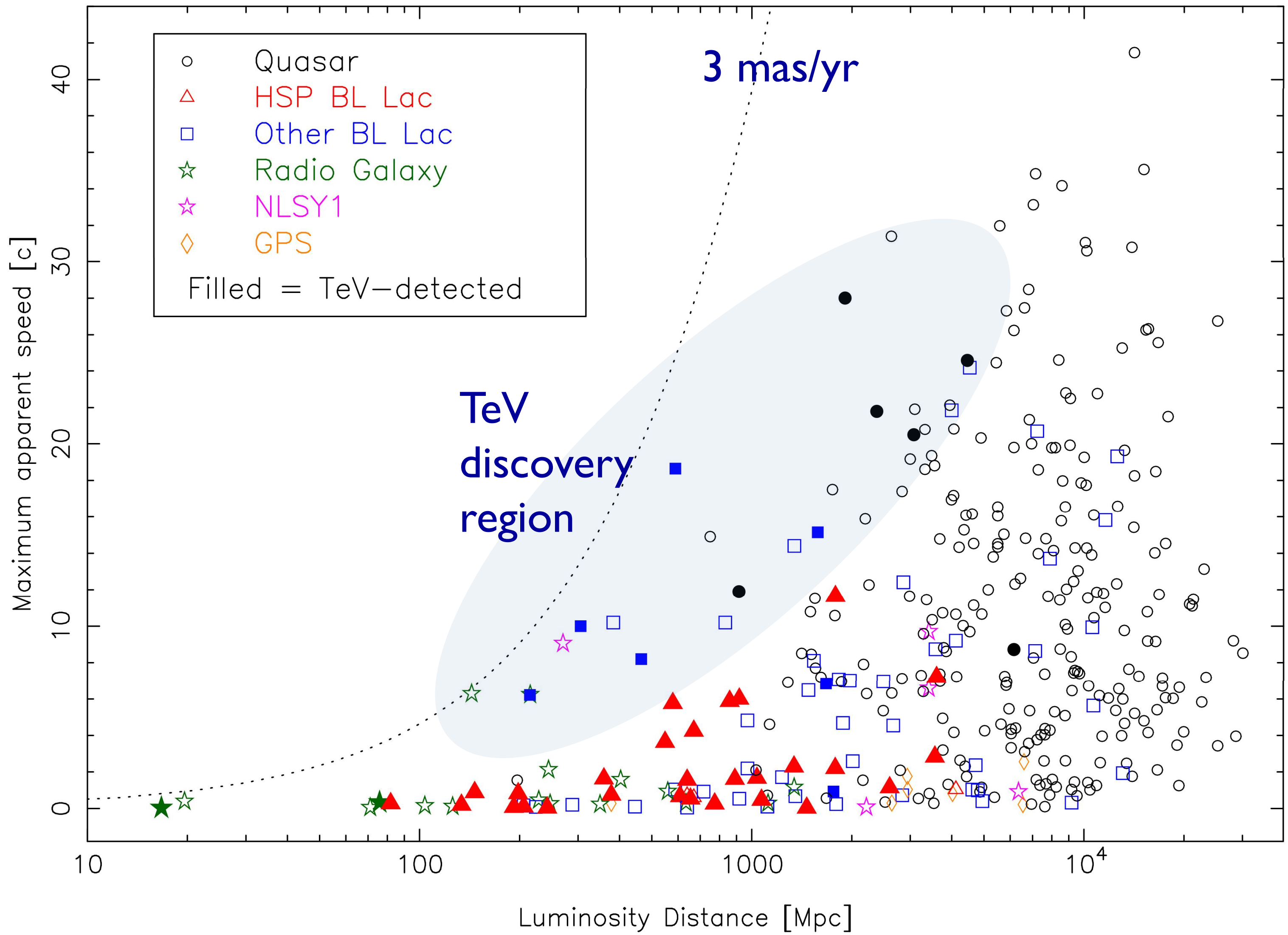
- Multiepoch 8 GHz VLBA study of 47 HSP BL Lacs in TeVCat catalog.
- Distribution implies $\Gamma \leq 4$
- Consistent with Doppler factor estimates from radio core brightness temperatures (MOJAVE, & Lico et al. 2016)
- Slow pattern speed features are rare, like MOJAVE blazars
- Very high Doppler factors (> 100) are typically required to fit SEDs and TeV variability timescales → fast TeV-emitting spine invisible in radio? break-out jet region? reconnection mini-jets?



Jet Speed vs. Synchrotron Peak Frequency



Jet Speed vs. Cosmological Distance



Summary

- **The VLBA is an unparalleled instrument for studying the pc-scale kinematics 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 only ~ a few.
  - jet features tend to increase their Lorentz factors 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.
  - *Fermi* LAT is biased against detecting low-spectral peaked, lower Doppler factor blazars
  - TeV-detected blazars have radio-emitting jets with Lorentz factors $\Gamma < 4$, while TeV emission indicates much higher Γ values.

www.astro.purdue.edu/MOJAVE