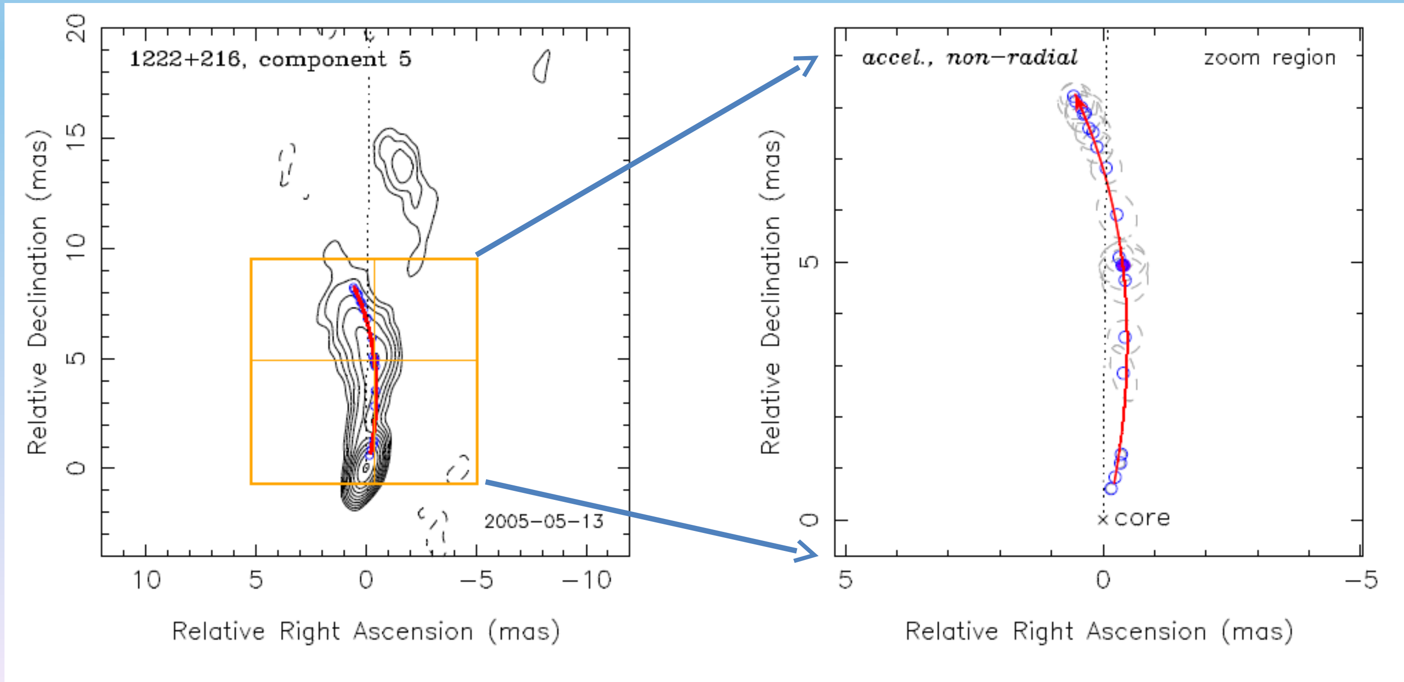
Long Term Kinematic Behavior of Parsec Scale Blazar Jets

Matt Lister

Dept. of Physics & Astronomy

Purdue University, USA



Krakow, April 2015

Outline

- Time domain studies of AGN jets with the MOJAVE VLBA survey

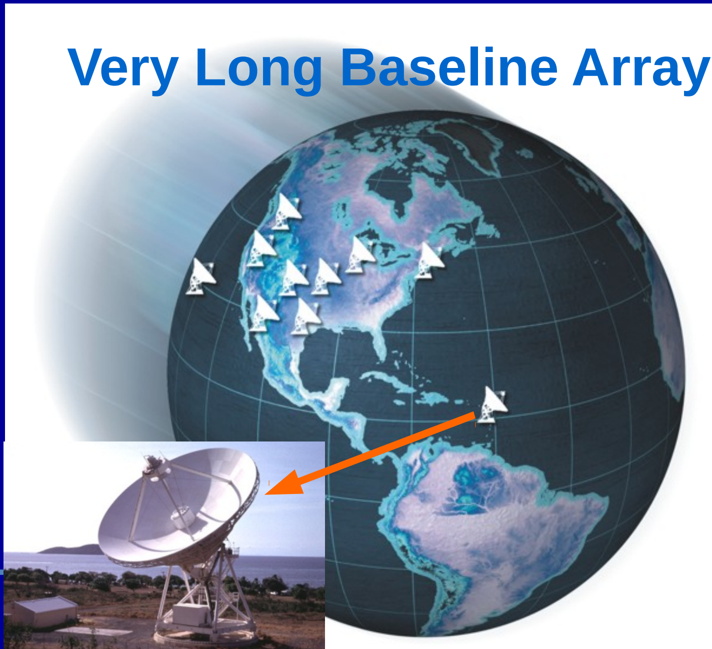
- Statistical trends and implications for TeV blazars

- Kpc-scale radio structure of blazar jets

MOJAVE Collaboration

- M. Lister (P.I.), J. Richards, E. Stanley, M. Hodge (Purdue, USA)
- T. Arshakian U. Cologne, Germany
- M. and H. Aller (U. Michigan, USA)
- M. Cohen (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



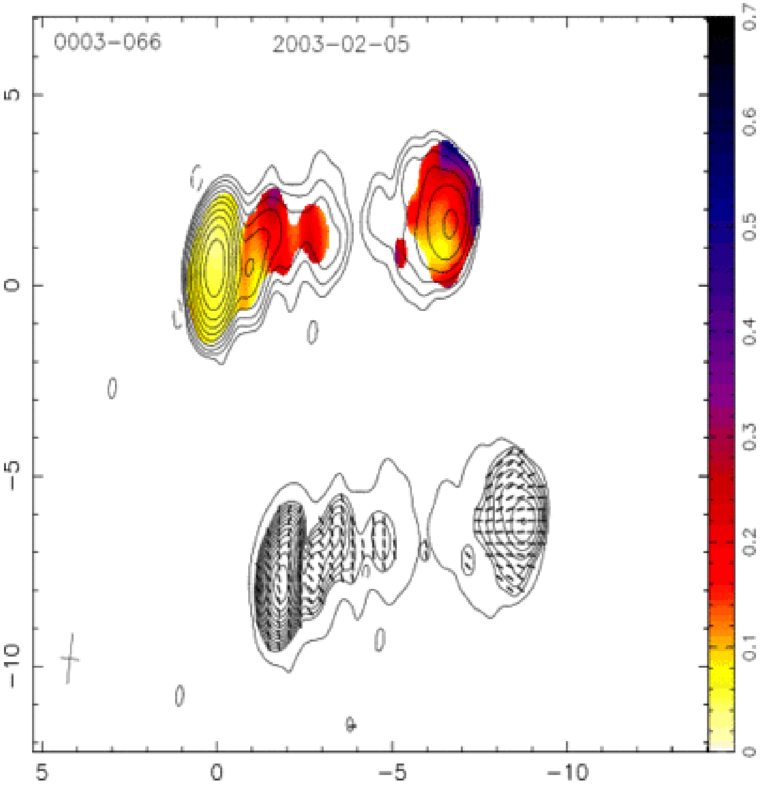
The MOJAVE Program is supported under NASA Fermi Grant **NNX12A087G**

MOJAVE VLBA Program

- Regular observations of radio-bright AGN
  - VLBA Key Science project

- 24 hour observing session every month
  - cadences tailored to individual jets

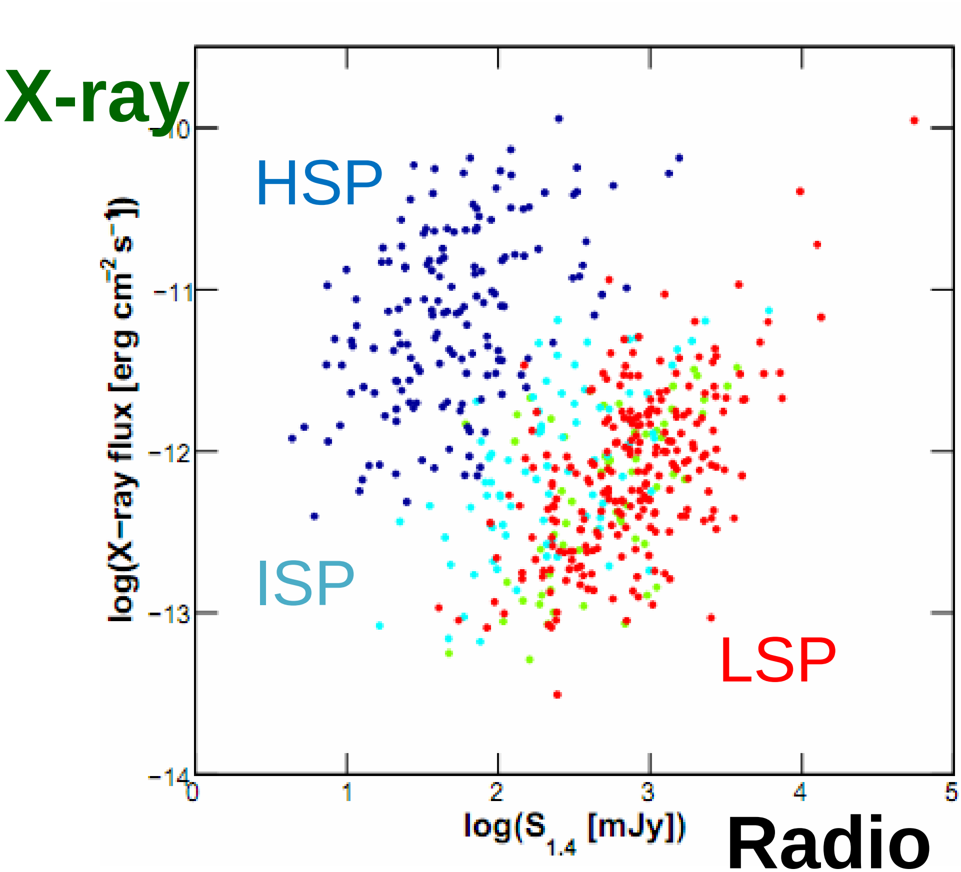
- Milliarcsec-resolution images at 15 GHz
  - continuous time baselines on many sources back to 1994
  - full polarization since 2002



Blazar 0003-066 at 15 GHz

Colors: fractional linear polarization

Investigating *Fermi* blazar jets



Fermi LAT Collab, 2012, ApJ 743, 171

- *Fermi* is an excellent AGN survey instrument:
  - 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)

MOJAVE AGN Monitoring Samples

1.5 Jy :

all AGN above δ = -30° known to have exceeded 1.5 Jy in 15 GHz VLBA flux density (1994.0 - 2010.0; Lister et al. 2013, AJ 146, 120).

Low-luminosity :

representative sample of 43 AGN with 15 GHz luminosity below 1026 W Hz-1 selected from the Radio Fundamental Catalog http://astrogeo.org/rfc/.

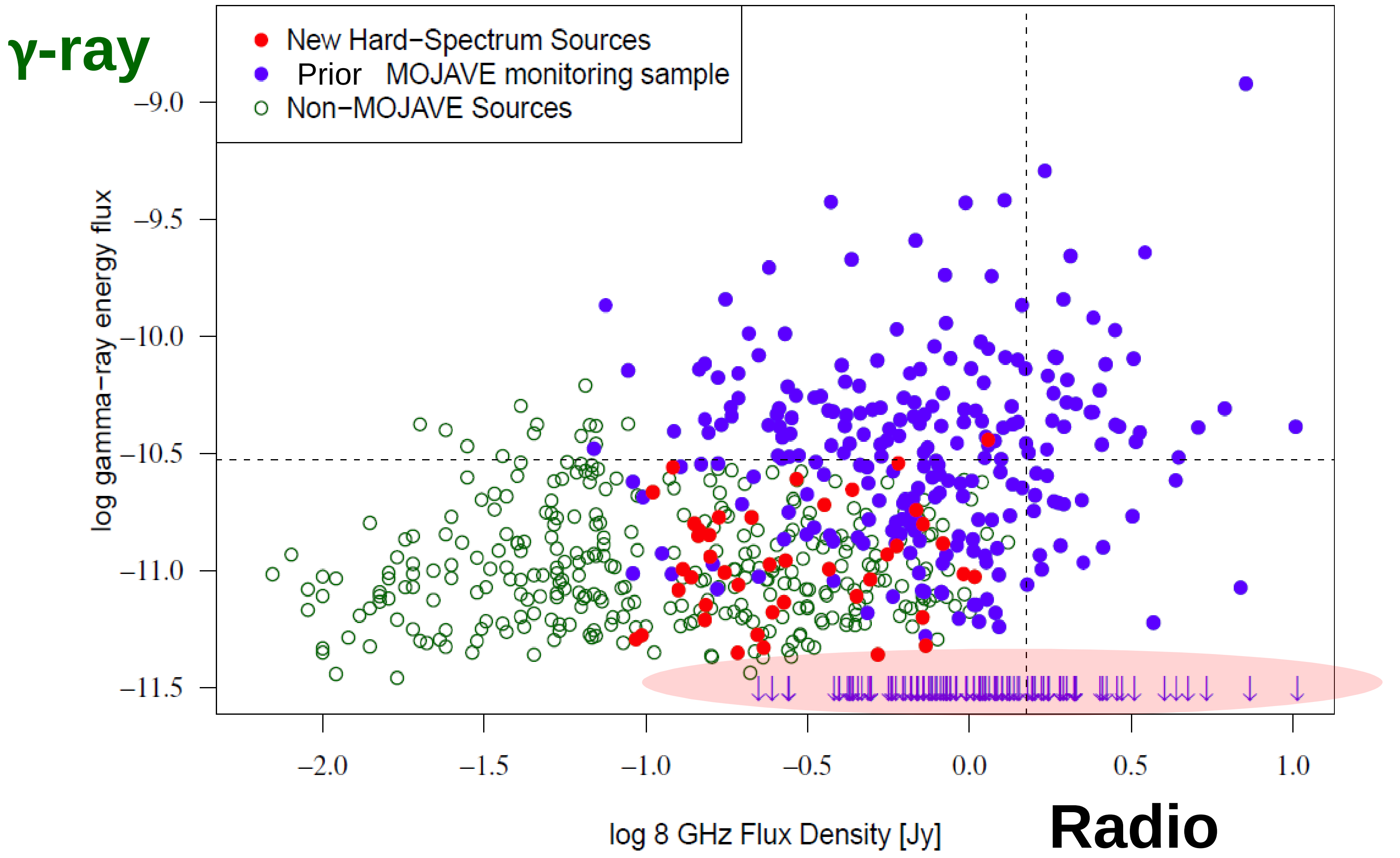
1FM γ-ray :

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

Hard Spectrum :

representative sample of hard γ-ray spectrum, radio bright AGN from Fermi 2-year catalog

Coverage of radio/γ-ray flux plane



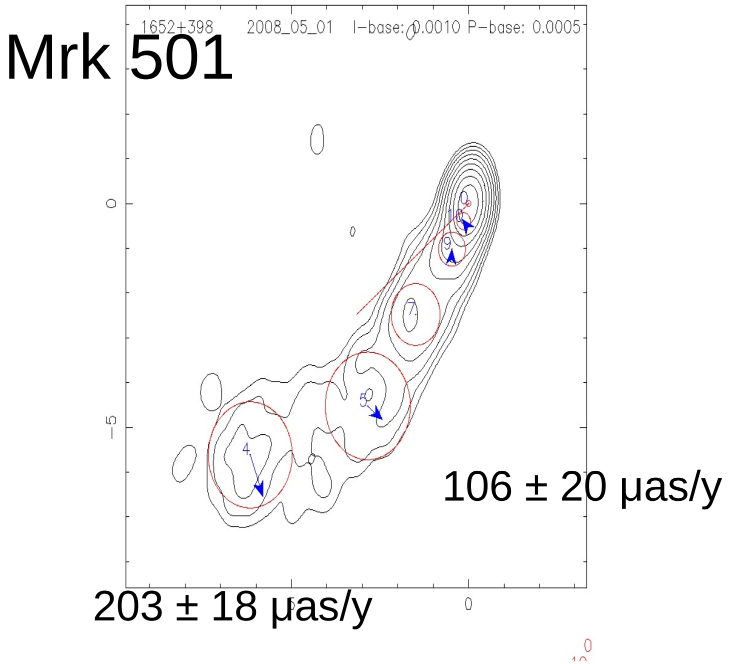
Most Recent MOJAVE Kinematics Analysis

- 4366 VLBA epochs of 200 AGNs from 1994 Sept - 2011 May.
- Gaussian models fit to visibilities at each epoch.
- Image restoring beam:

  ~0.5 to 1 mas
- Image sensitivity:

  0.1 - 0.3 mJy/beam
- Positional rms accuracy:

  0.05 - 0.1 mas



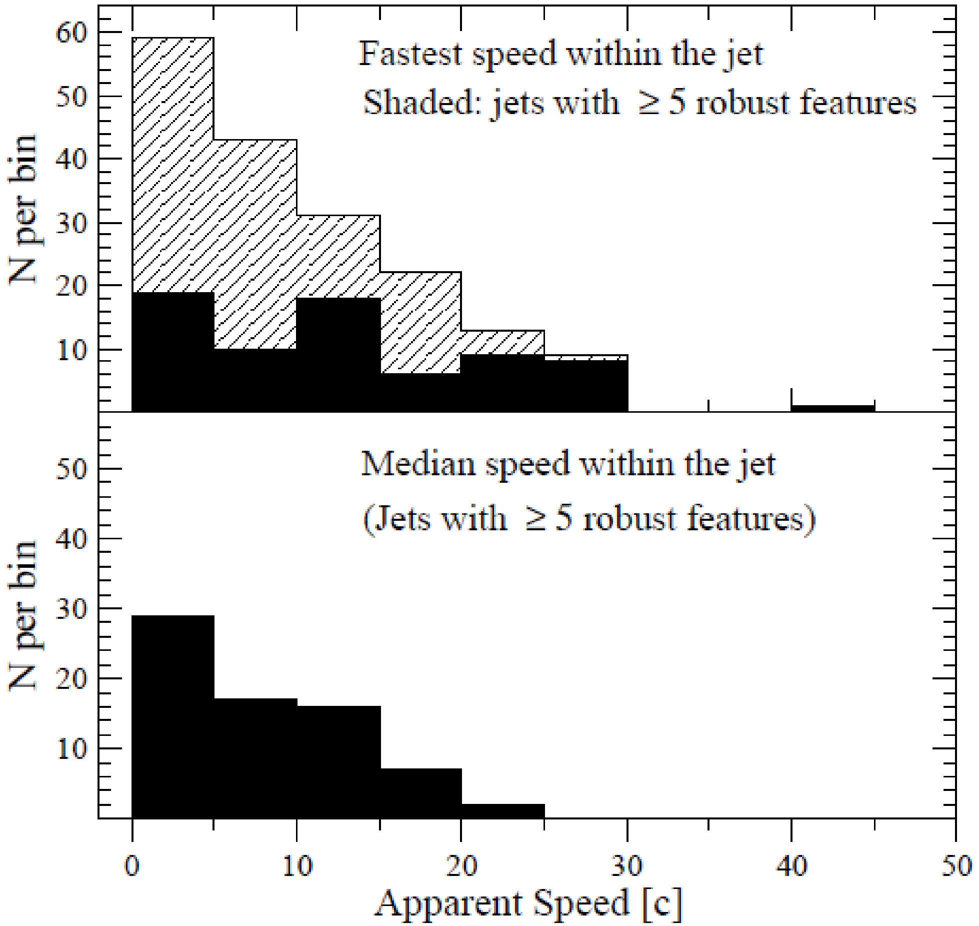
Lister et al. 2013, AJ 146, 120

Homan et al. 2015, ApJ 798,134

Probing jet kinematics and polarization in region 10-1000 pc (de-projected) from central engine.

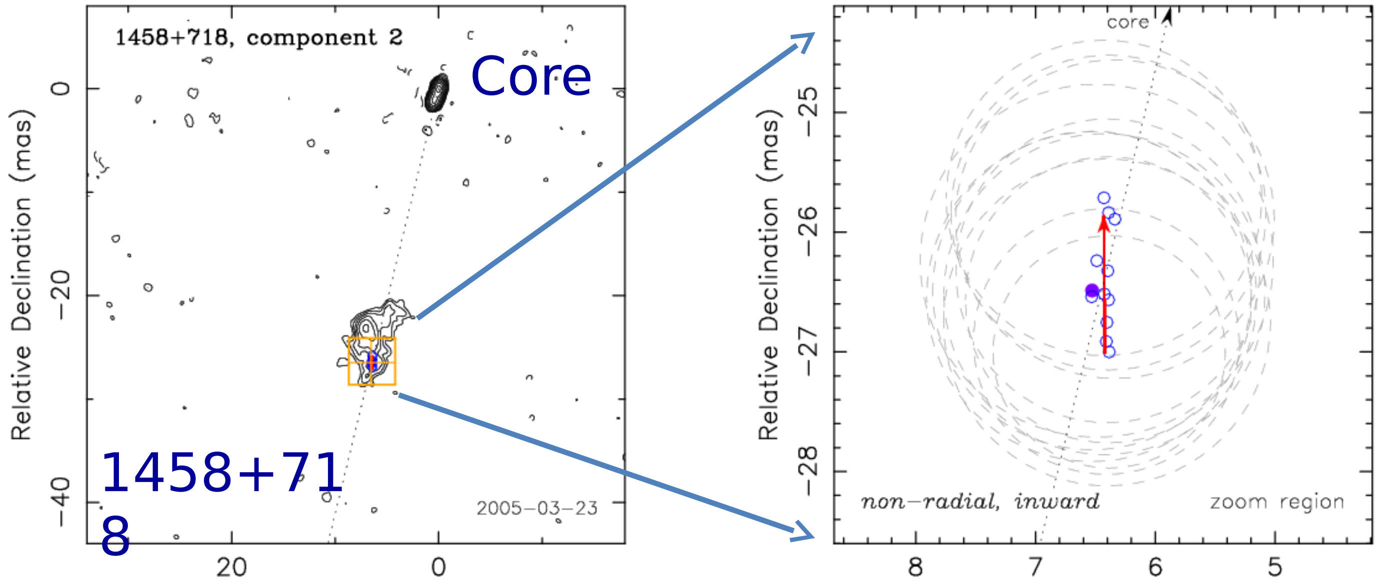
Overall Jet Speed Distribution

- Peaked at low values
  - only 2 jets with βapp > 30
  - high Γ jets are very rare in blazar parent population
- Lorentz factors of the most luminous/powerful jets range up to ~50
- The typical AGN jet is weak and has a Lorentz factor of only ~ a few



Lister et al. 2013, AJ 146, 120

Apparent Inward Motions



Statistics:

- Rare: only 2% of all moving features
- Seen in only 10 of 200 jets (6 of these are BL Lac jets)

Possible causes:

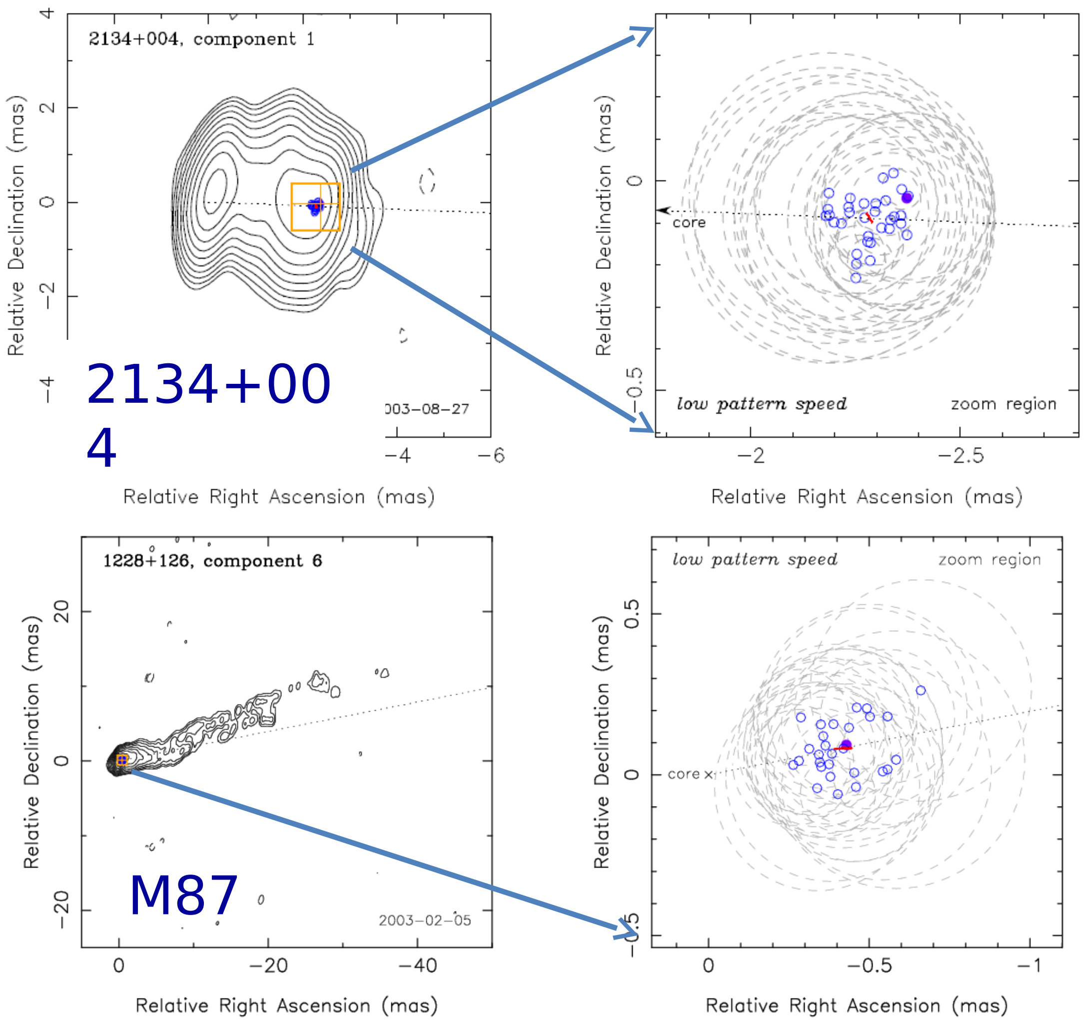
- Accelerated motion across the line of sight
- Inward pattern speed (e.g., reverse shock)
- Misidentification of true core feature

Slow Pattern Speeds

- Defined as:
  - < 20 μas/y ,
  - non-accelerating ,
  - < 1/10th of max speed seen in the jet

- Only 4% of all features

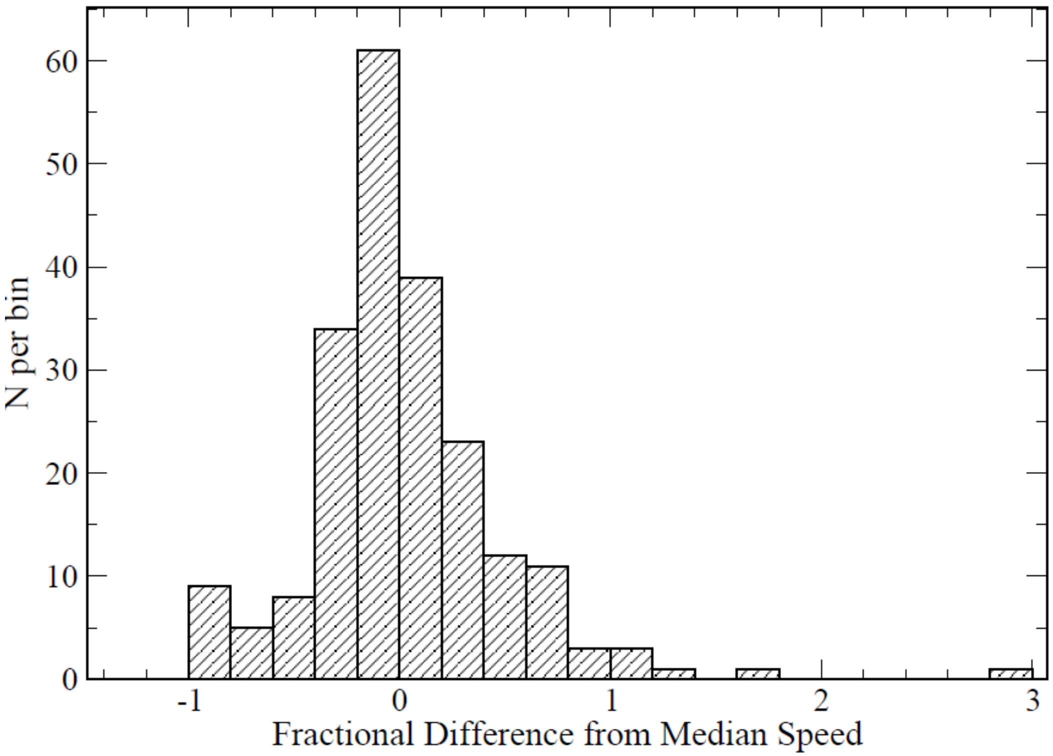
- Found in 10% of quasar jets and 25% of BL Lacs



Speed Dispersion Within the Jet

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

- Characteristic median speed exists for each jet



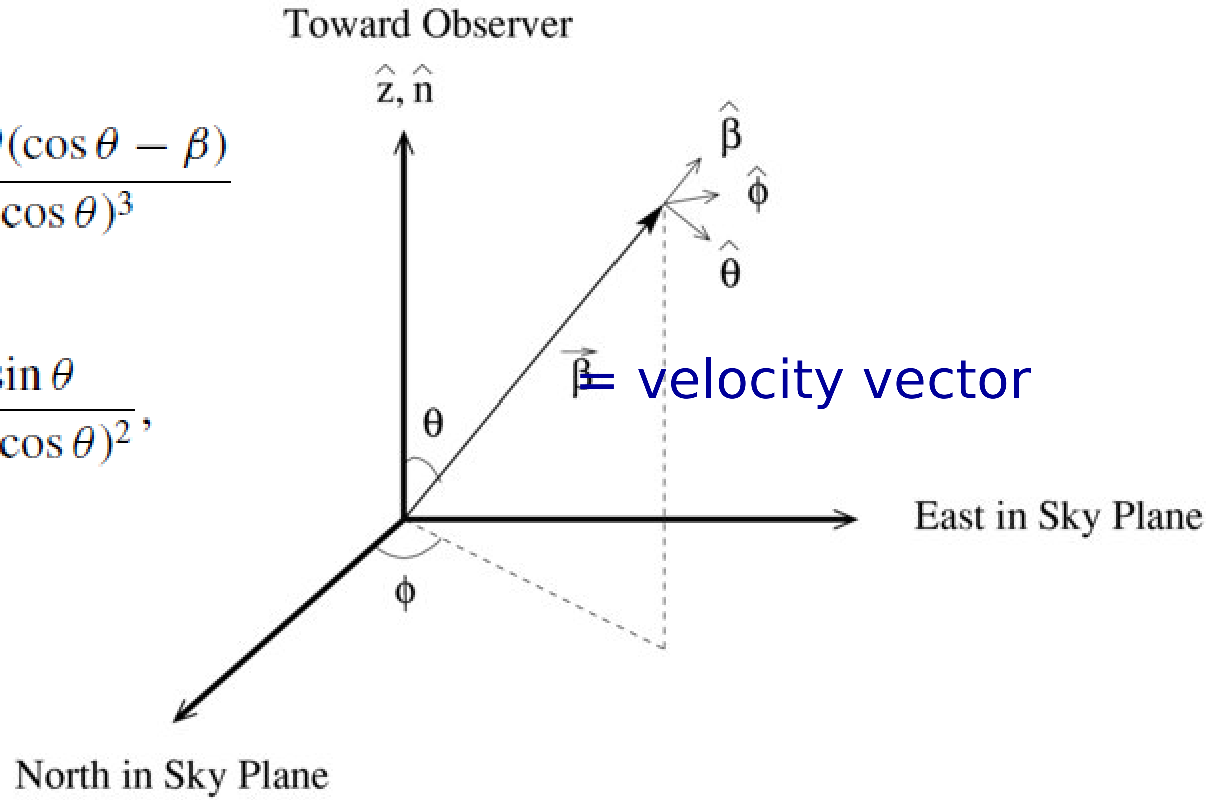
Normalized speed distribution within 12 jets each having at least 10 moving features.

MOJAVE Jet Acceleration Study

- Homan et al. 2015 (ApJ 798,134) analyzed 329 features in 95 blazar jets
- All features had at least ten VLBA epochs.
- Analyzed accelerations in directions || and ⊥ to apparent motion vector.

$$\dot{\beta}_{\parallel \mathrm{app}} = \frac{d\beta_{\parallel \mathrm{app}}}{dt_{\mathrm{app}}} = \frac{\dot{\beta}\sin\theta + \beta\dot{\theta}(\cos\theta - \beta)}{(1-\beta\cos\theta)^3}$$

$$\dot{\beta}_{\perp \mathrm{app}} = \frac{d\beta_{\perp \mathrm{app}}}{dt_{\mathrm{app}}} = \frac{\beta\dot{\phi}\sin\theta}{(1-\beta\cos\theta)^2},$$

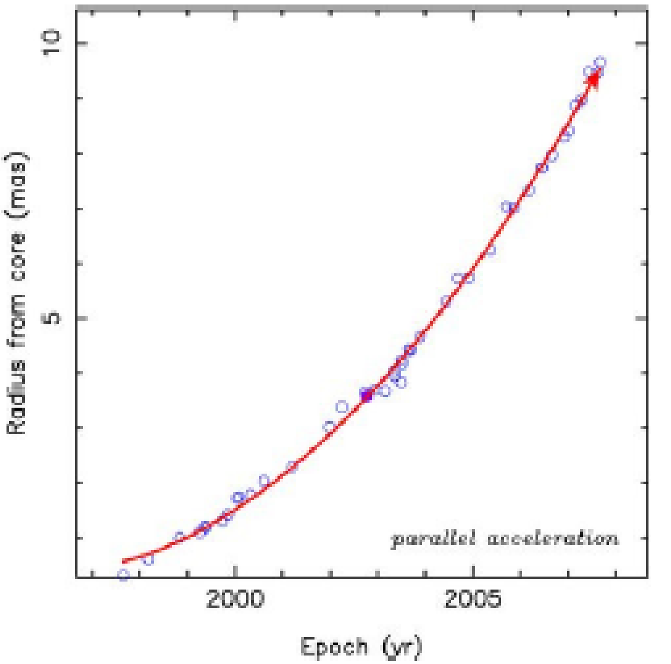


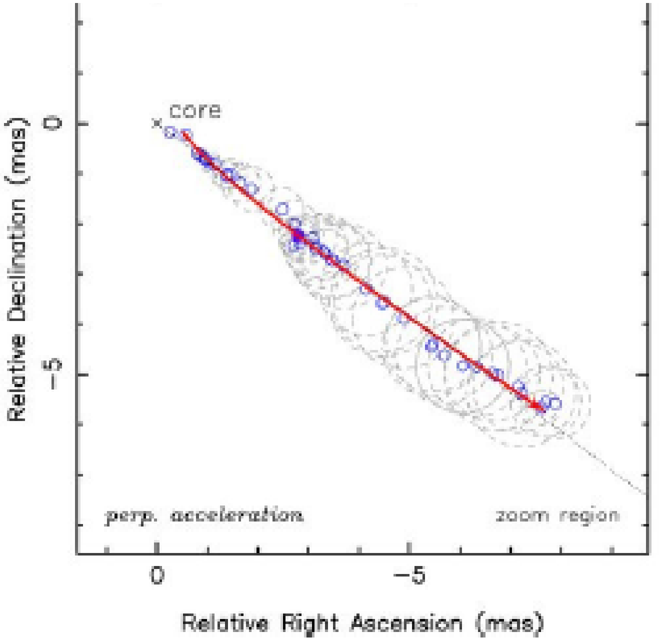
- No perpendicular acceleration is expected in cases of changes in speed along a straight trajectory.

- If jet features are moving with constant speed on a curved trajectory, should expect to see accelerations both <u>parallel</u> and <u>perpendicular</u> to mean velocity vector.

AGN Jets are Accelerat

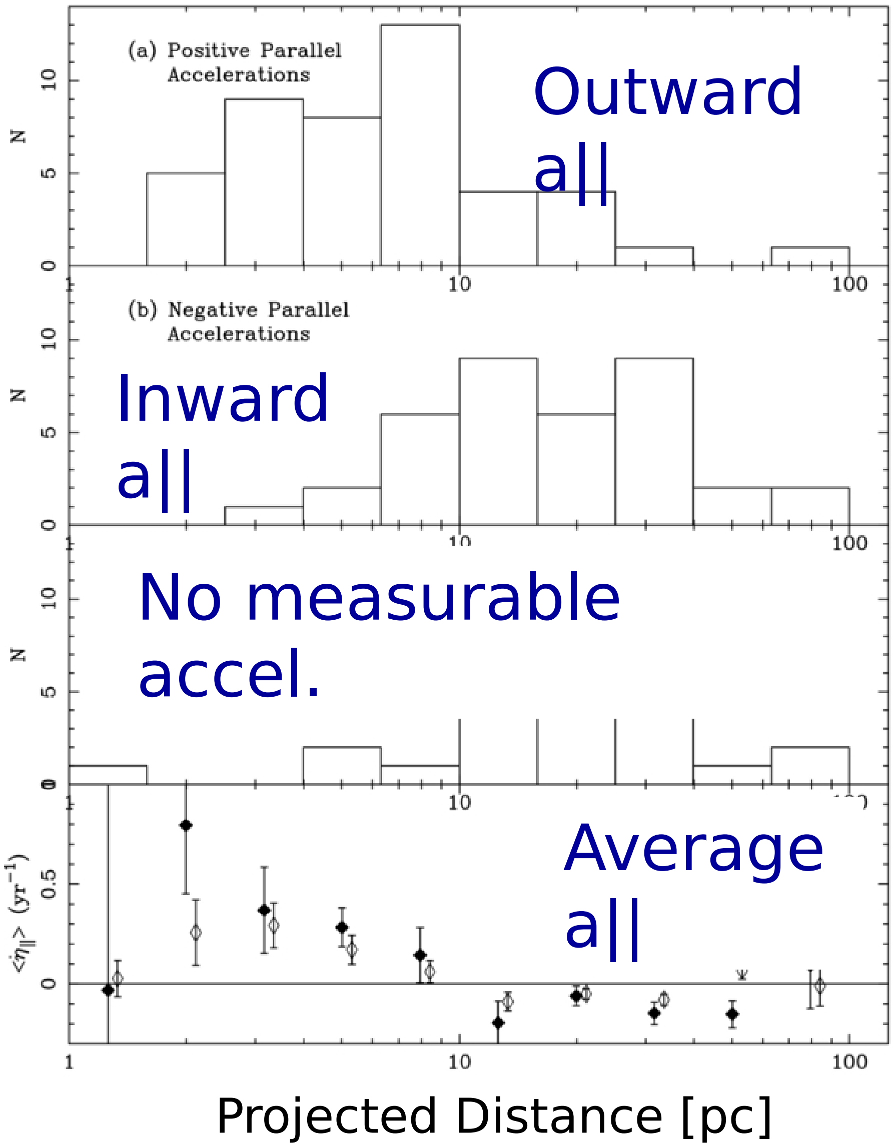
- 75% of the jets studied have at least one accelerating feature.
- Half of all the jet features show significant acceleration.
- Parallel accelerations are of larger magnitude and more prevalent than perpendicular accelerations.
- Results confirmed at 8 GHz in AGN sample of Piner et al. 2012 ApJ 758, 84





Evidence for changing Lorentz factors

- Overall statistics show that observed accelerations cannot be solely due to bending
  - most features have a **high** || / ⊥ acceleration ratio.
- Positive parallel accelerations are most common within 10 pc of the core
- 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.



Rate of Jet Speed Changes

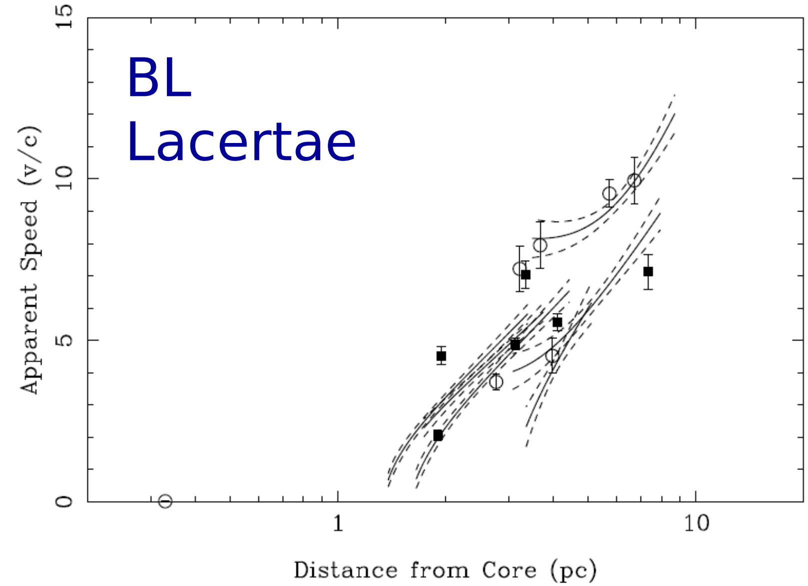
Inner jet:

$\dot{\Gamma} / \Gamma = 10^{-3}$ to 10^{-2} per y

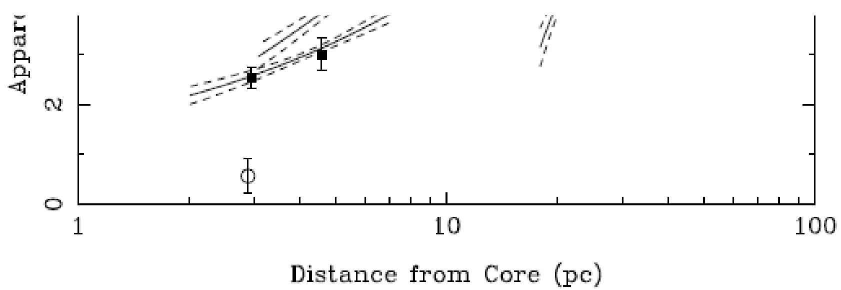
(rate is slower in the jet frame)

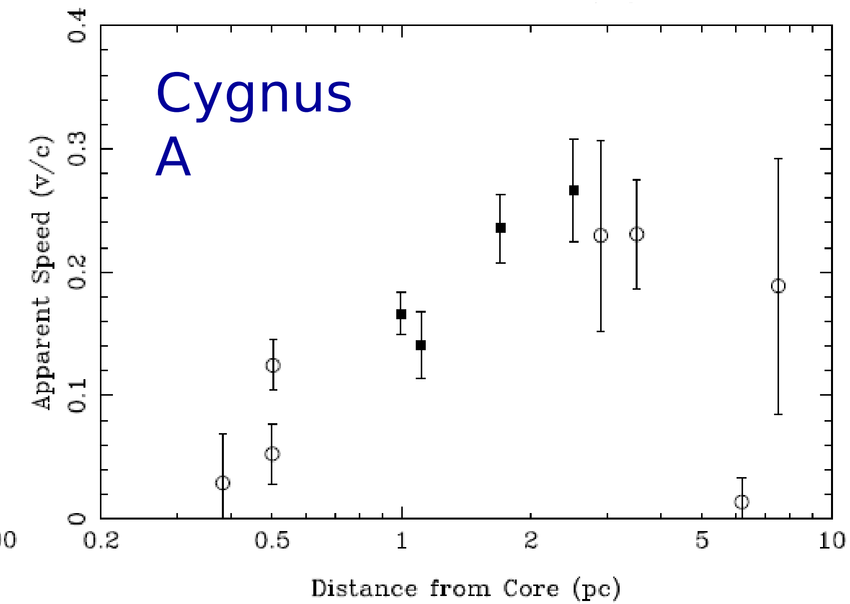
At > 100 pc downstream:

$\dot{\Gamma} / \Gamma = -10^{-3}$ per y; enough to completely decelerate the jet by ~100 kpc, but ISM density drops off



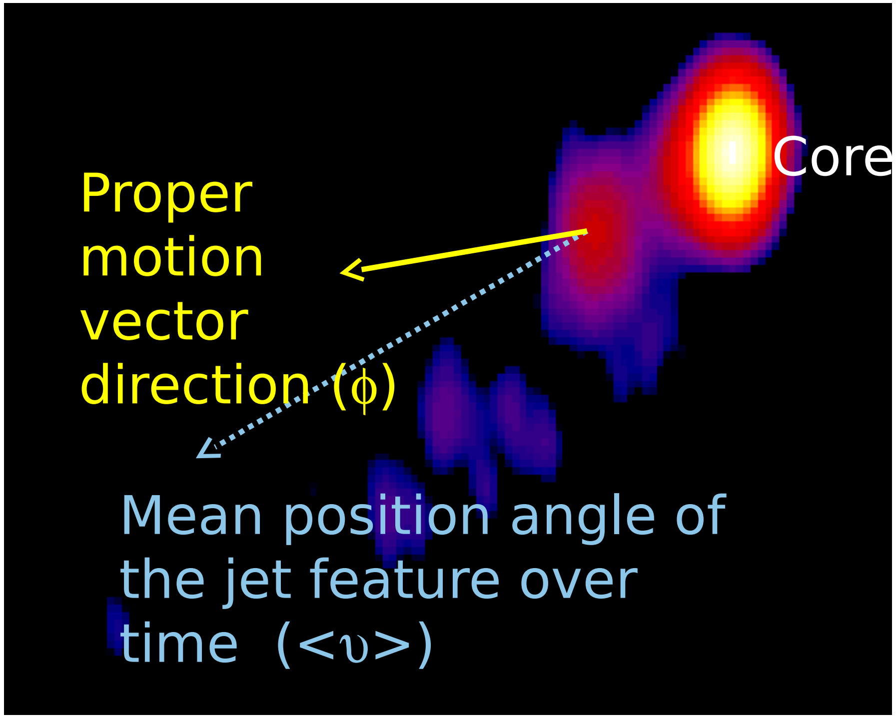
1928+7
38

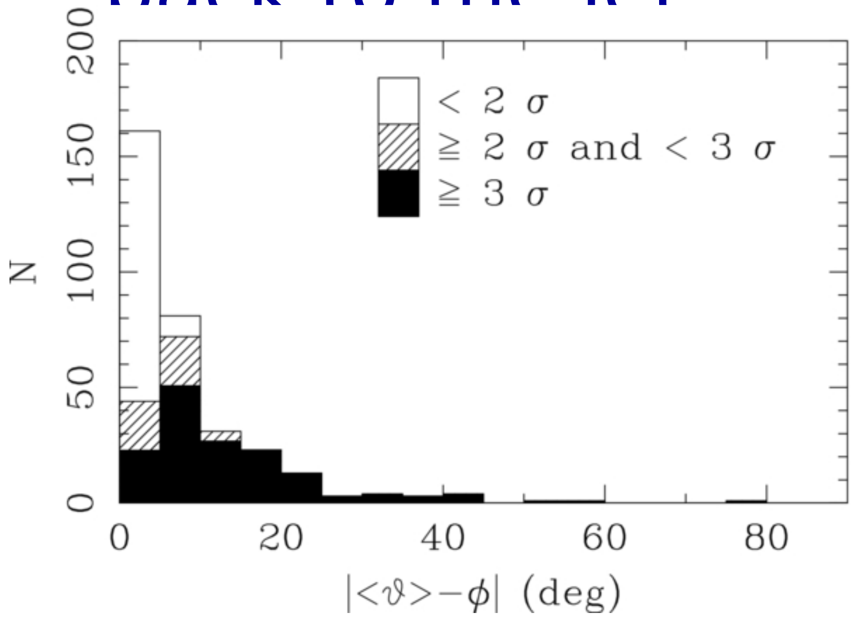




Curved Motions

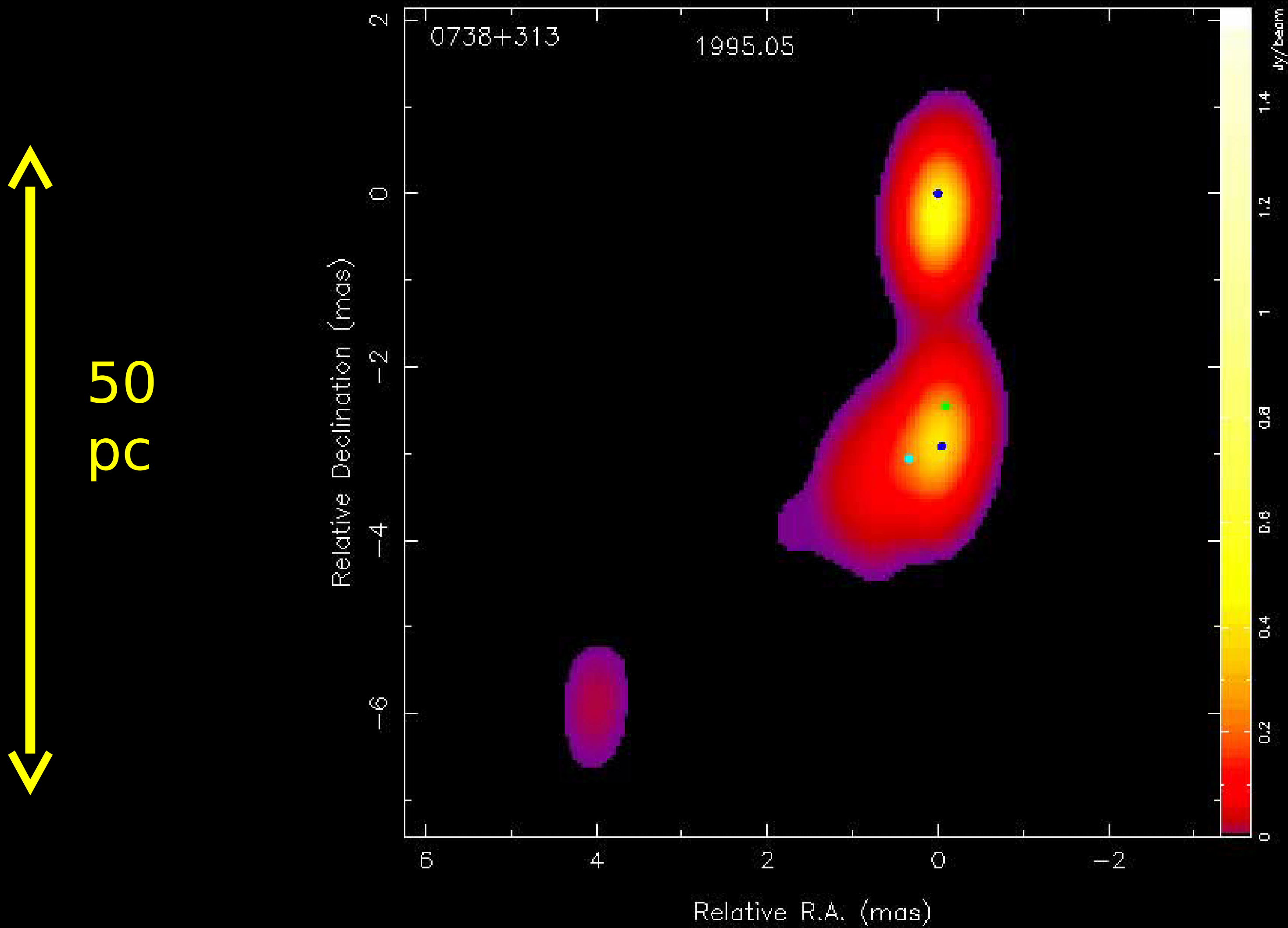
- A jet feature is **non-radial** if its proper motion doesn't point back to the jet





- Half of all the jet features are non-radial.
- Many trajectories are highly curved on the sky

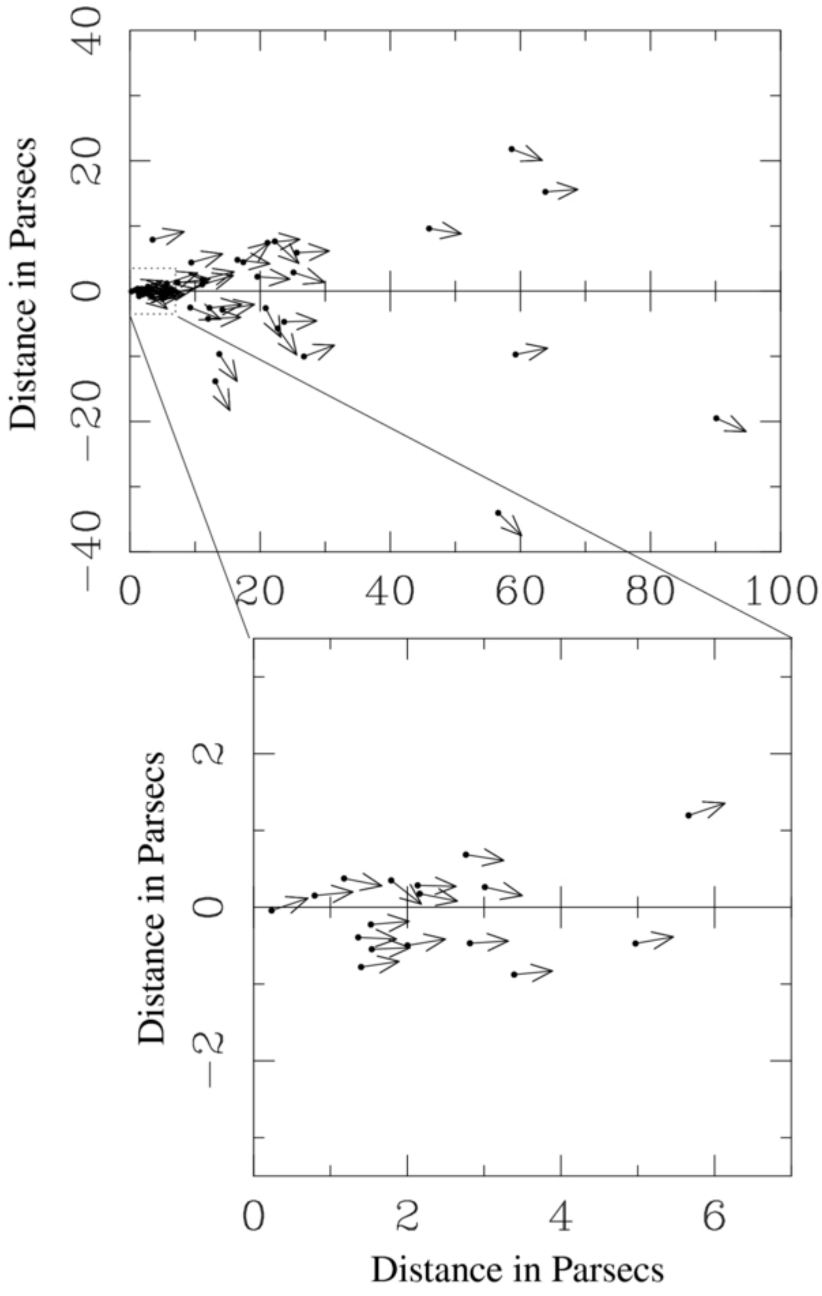
MOJAVE Time Lapse: 20 yr of Quasar 0738+313 at z =



Inner Jet Collimatio

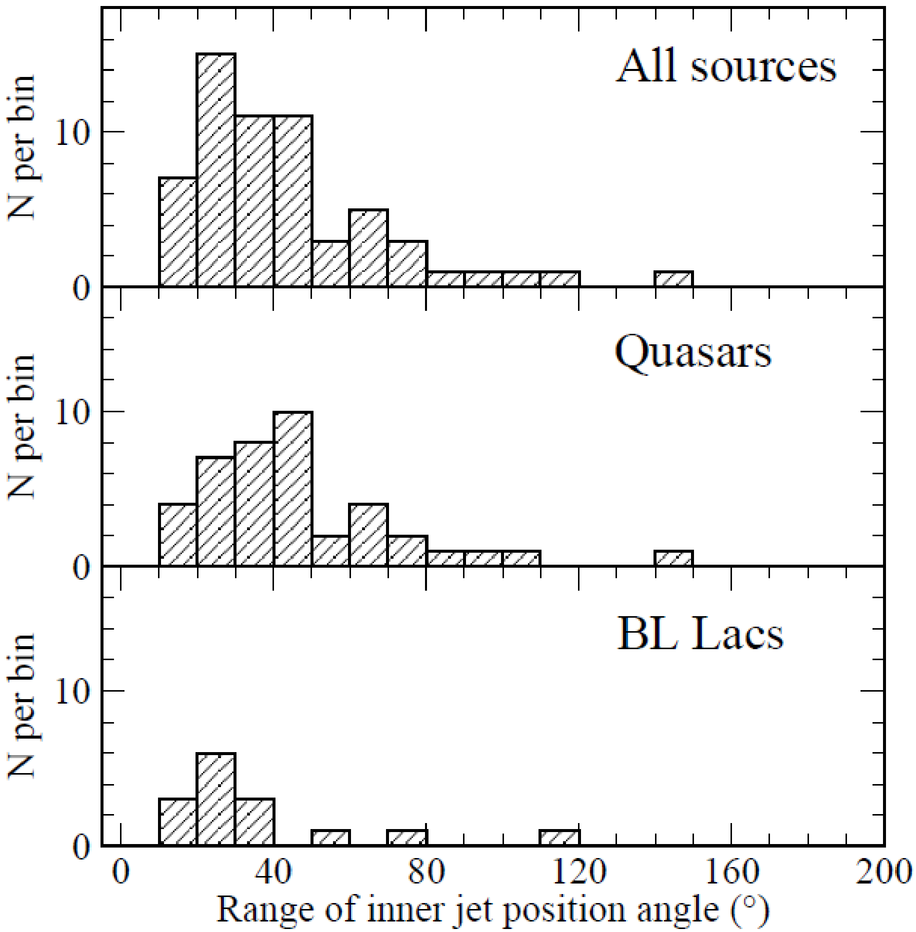
- Proper motion vector directions within ~50 pc (deprojected) of jet core indicate collimation.

- No apparent collimation seen further out. (Major exception: 3C 279 in 1999 ; Homan et al. 2003)



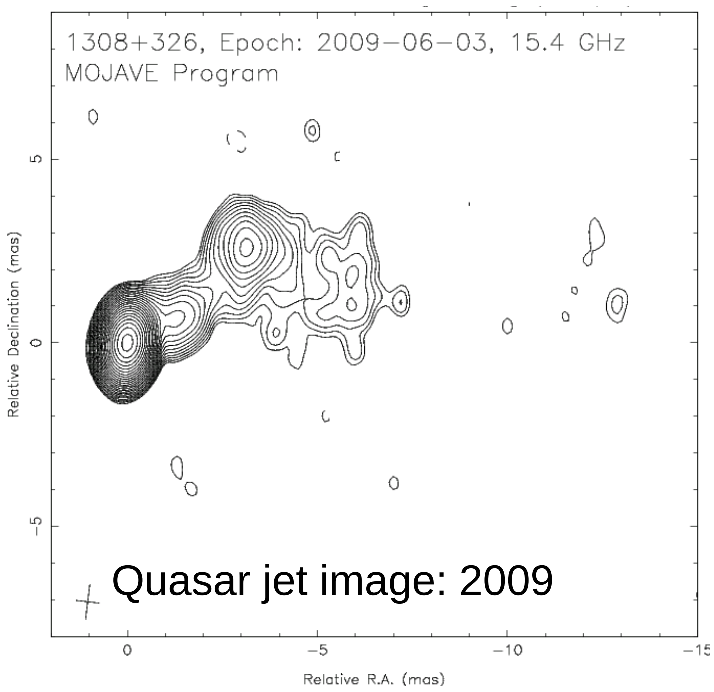
Inner Jet Orientation Variations

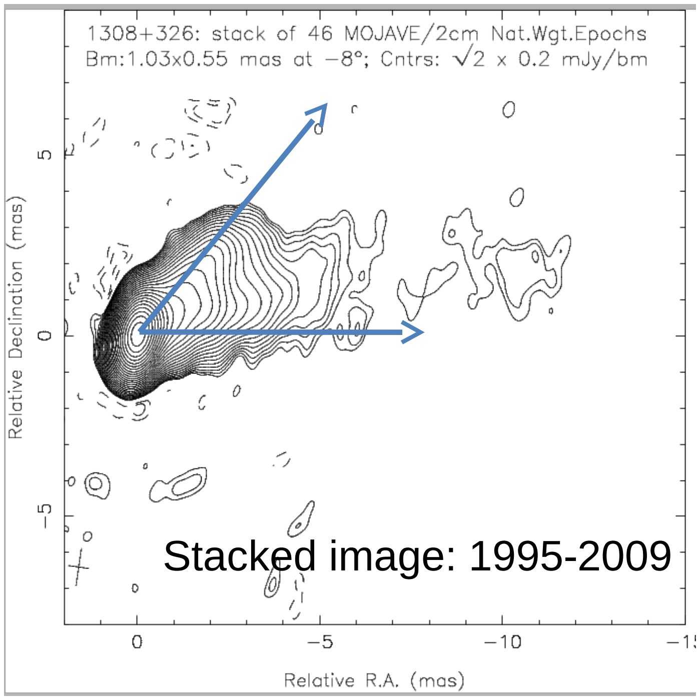
- Analyzed 60 jets with 12-15 years of VLBA coverage
- Half show significant changes in inner jet position angle, up to several degrees/yr ; possible sinusoidal variations; large jumps also occur
- Jets of weak-lined blazars (BL Lacs) typically show smaller variations than quasars



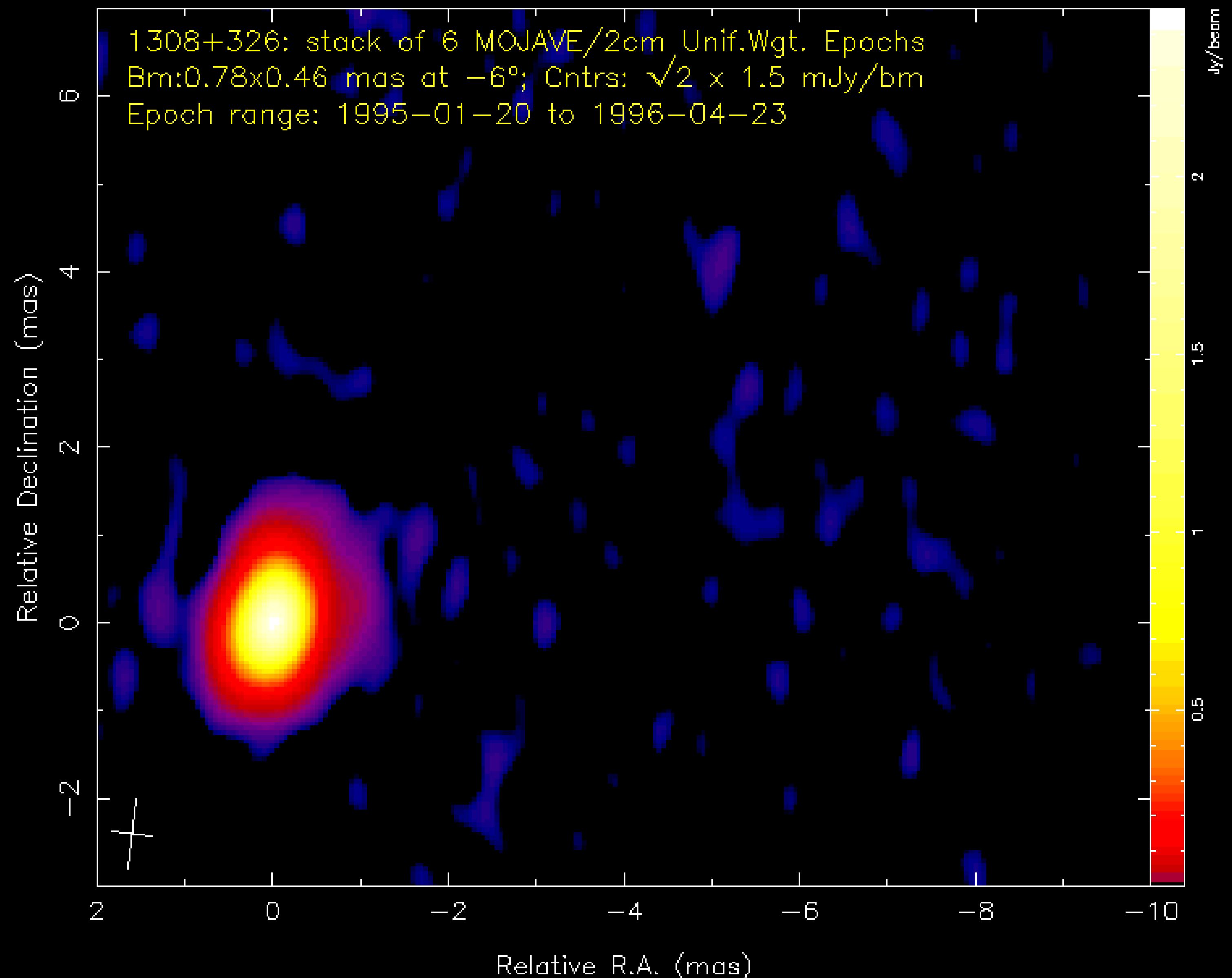
Lister et al. 2013, AJ 146, 120

Energized Jet Channels



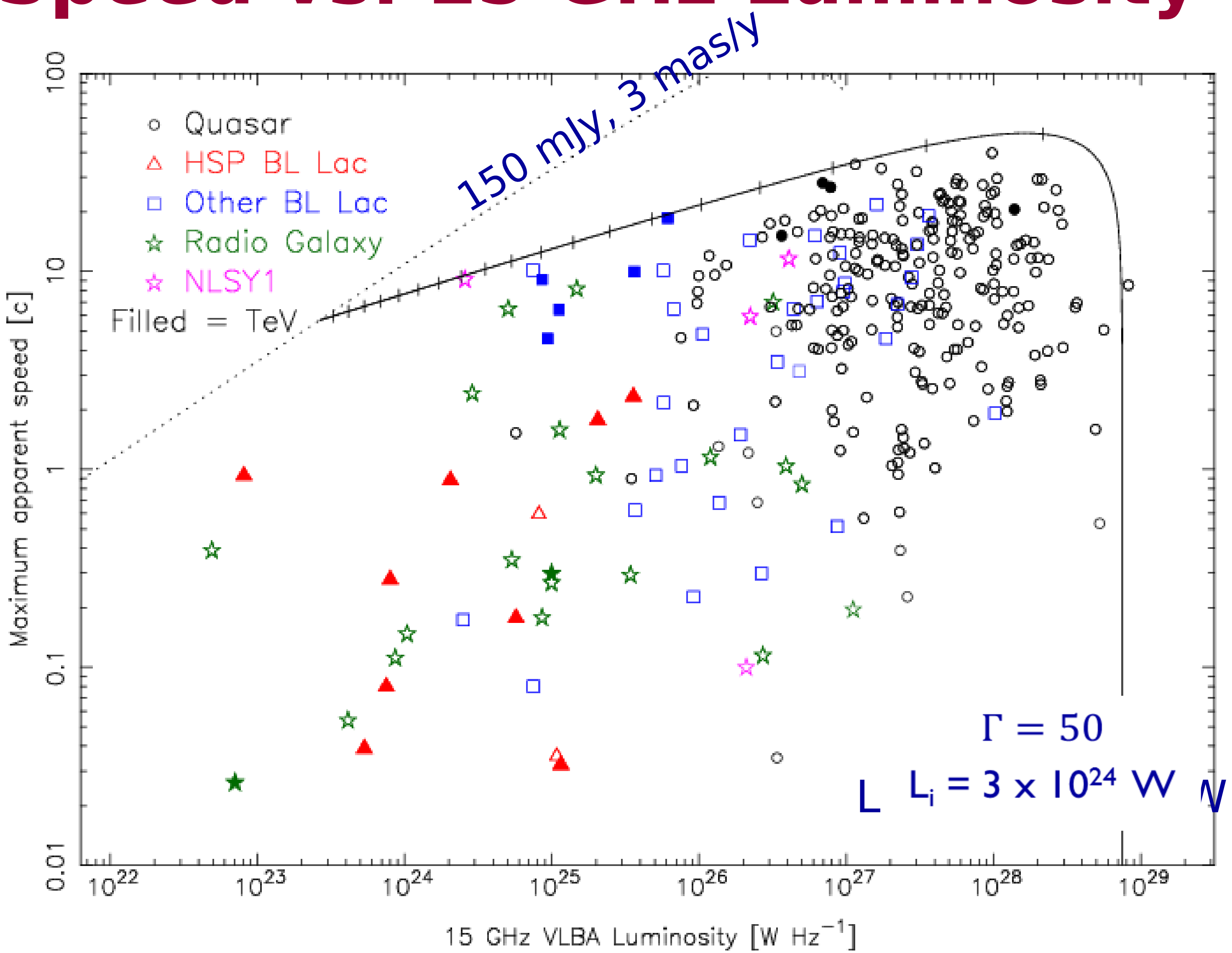


- Newly ejected jet features move out on successively different trajectories
- At any given time, typically only a portion of the full (conical) outflow is energized/visible in a VLBA image


1308+326: stack of 6 MOJAVE/2cm Unif.Wgt. Epochs
Bm:0.78x0.46 mas at −6°; Cntrs: √2 x 1.5 mJy/bm
Epoch range: 1995−01−20 to 1996−04−23
Relative Declination (mas)
Relative R.A. (mas)
Jy/beam

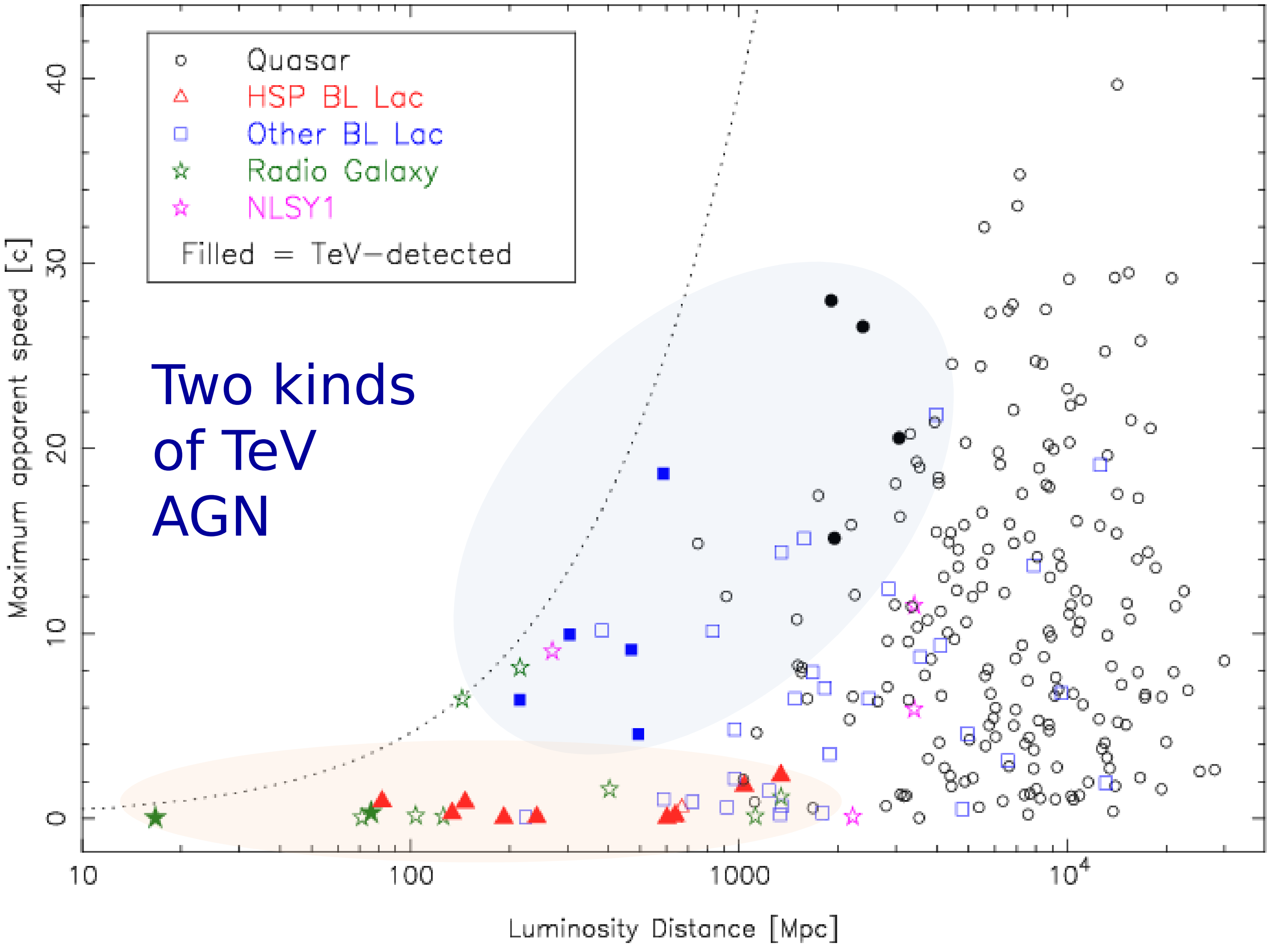
Statistical Trends

Jet Speed vs. 15 GHz Luminosity

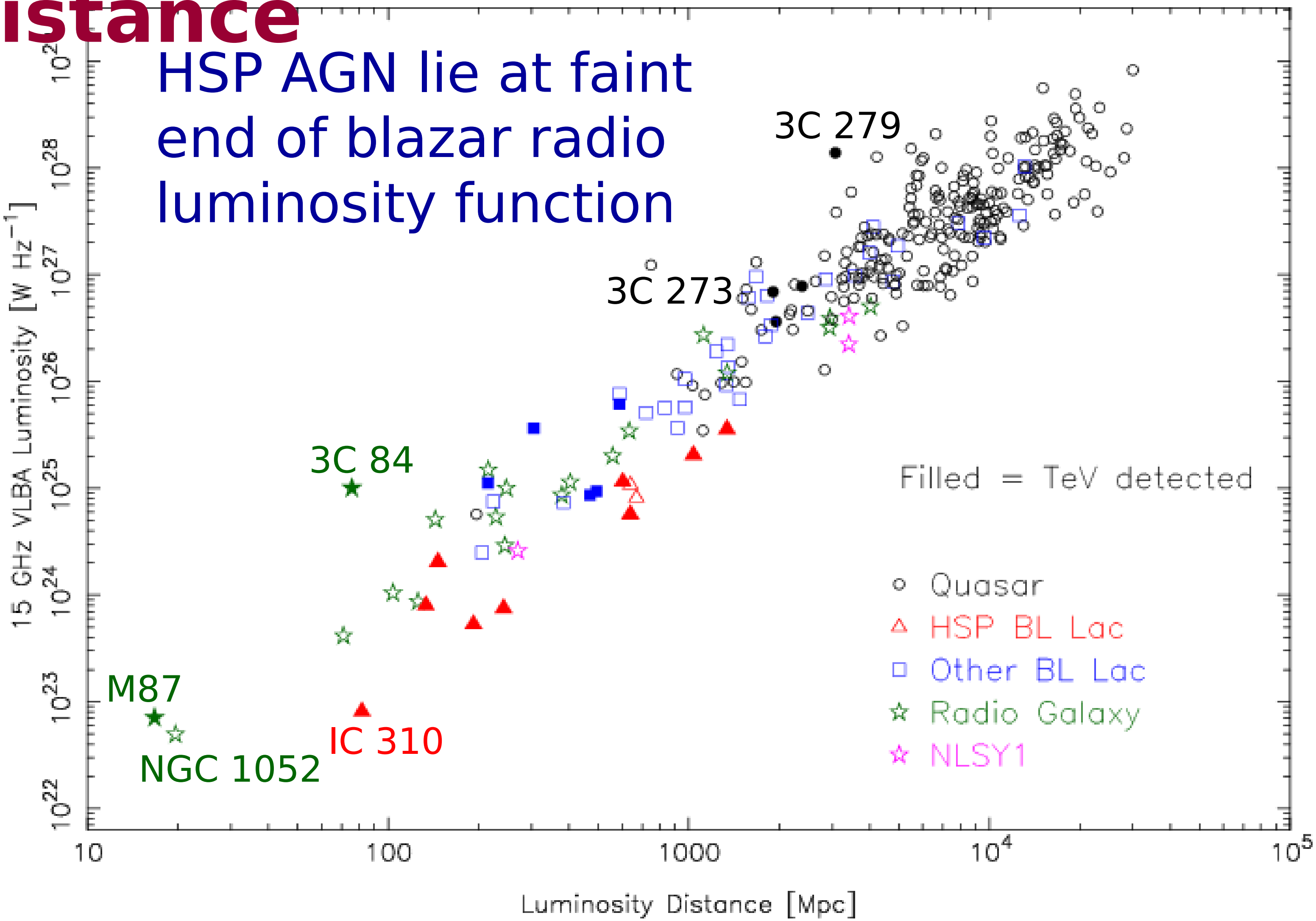


Only the most luminous jets can attain high Lorentz factors

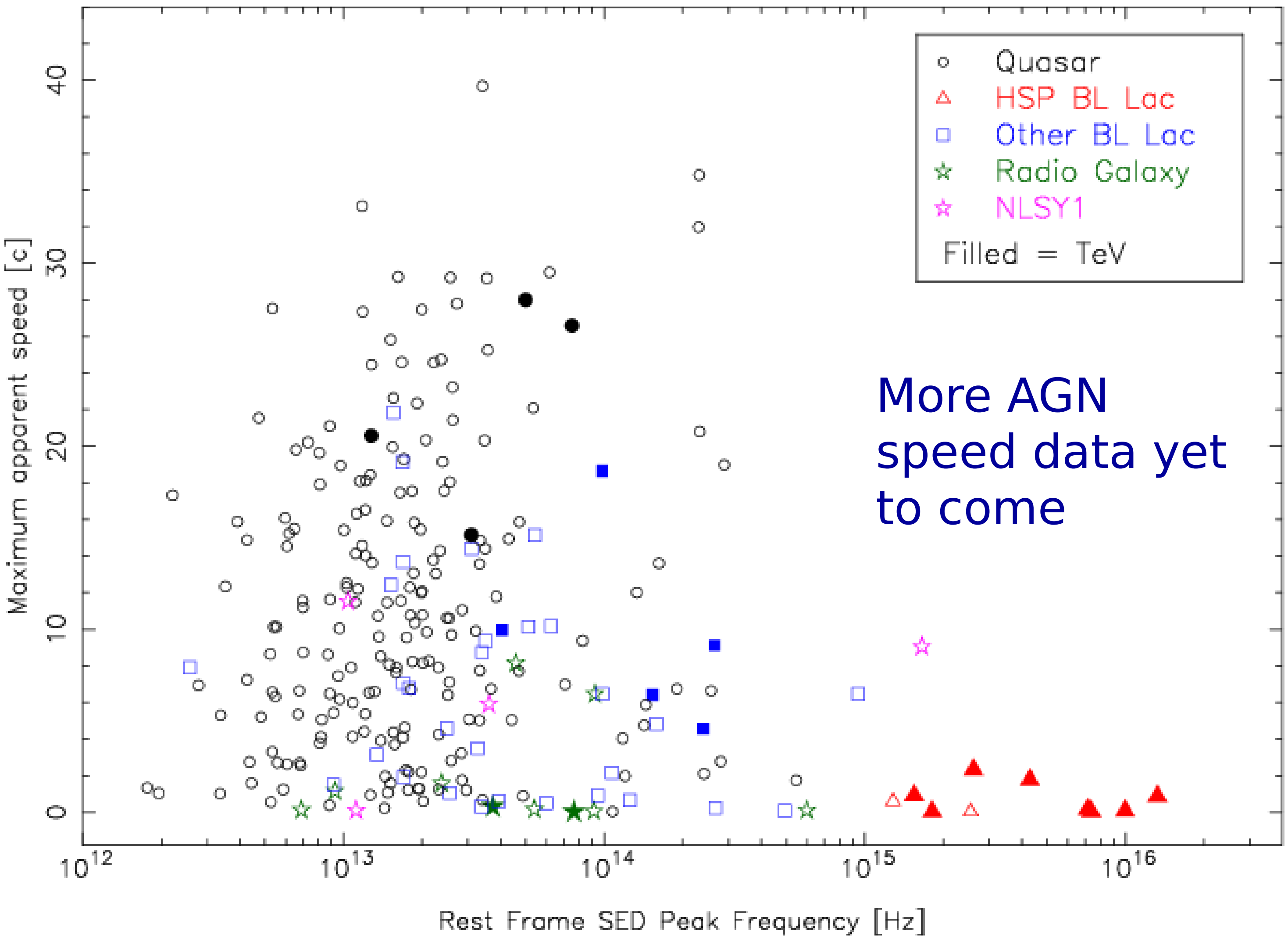
Jet Speed vs. Cosmic Distance



Radio Jet Luminosity vs. Cosmic Distance



Jet Speed vs. Synchrotron Peak Fr

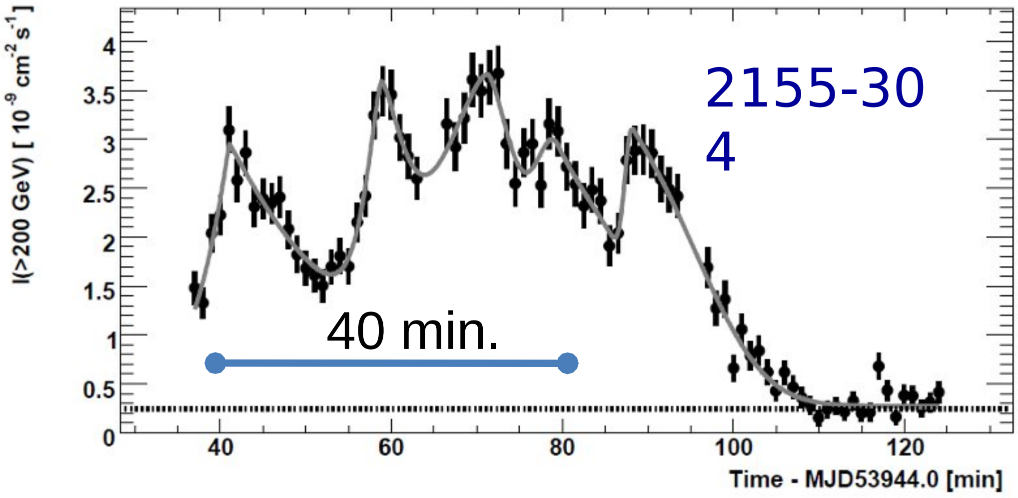


More AGN speed data yet to come

The HSP Doppler Beaming Crisis

- Extreme variability of TeV ɣ-rays imply very small emission regions

- ɣ-rays suffer huge pair losses unless HSP jets have very high beaming factors

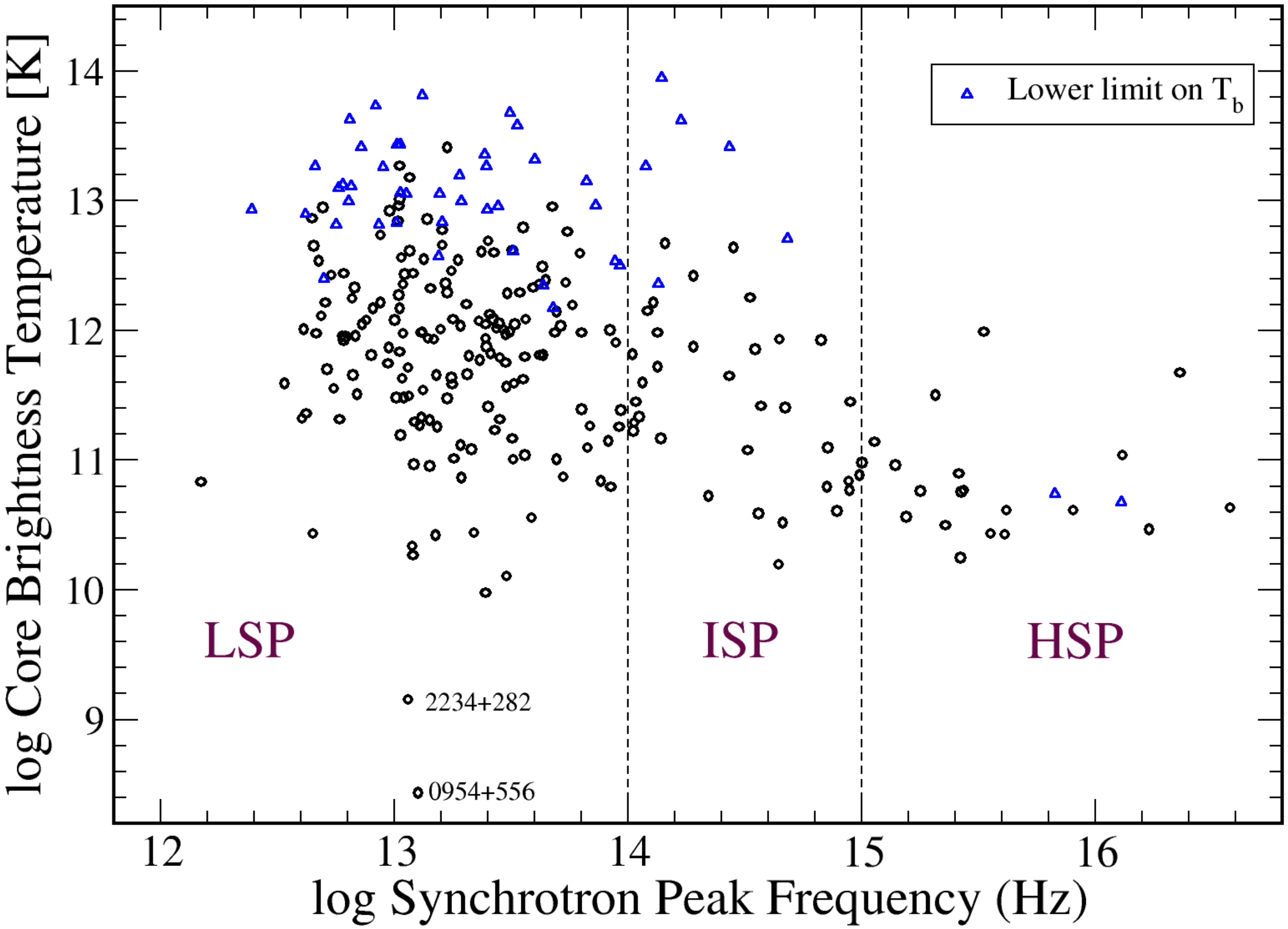


Aharonian et al. 2007 (H.E.S.S. Collaboration)

- Possible explanations:
  - Fast spine / slow sheath structure (e.g., Tavecchio et al. 2008)
  - Reconnection regions or misaligned 'mini-jets' (Giannios et al. 2010,2013)
  - Fast leading edges of intermittent outflows (Lyutikov & Lister 2010)

Relativistic Beaming Levels

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

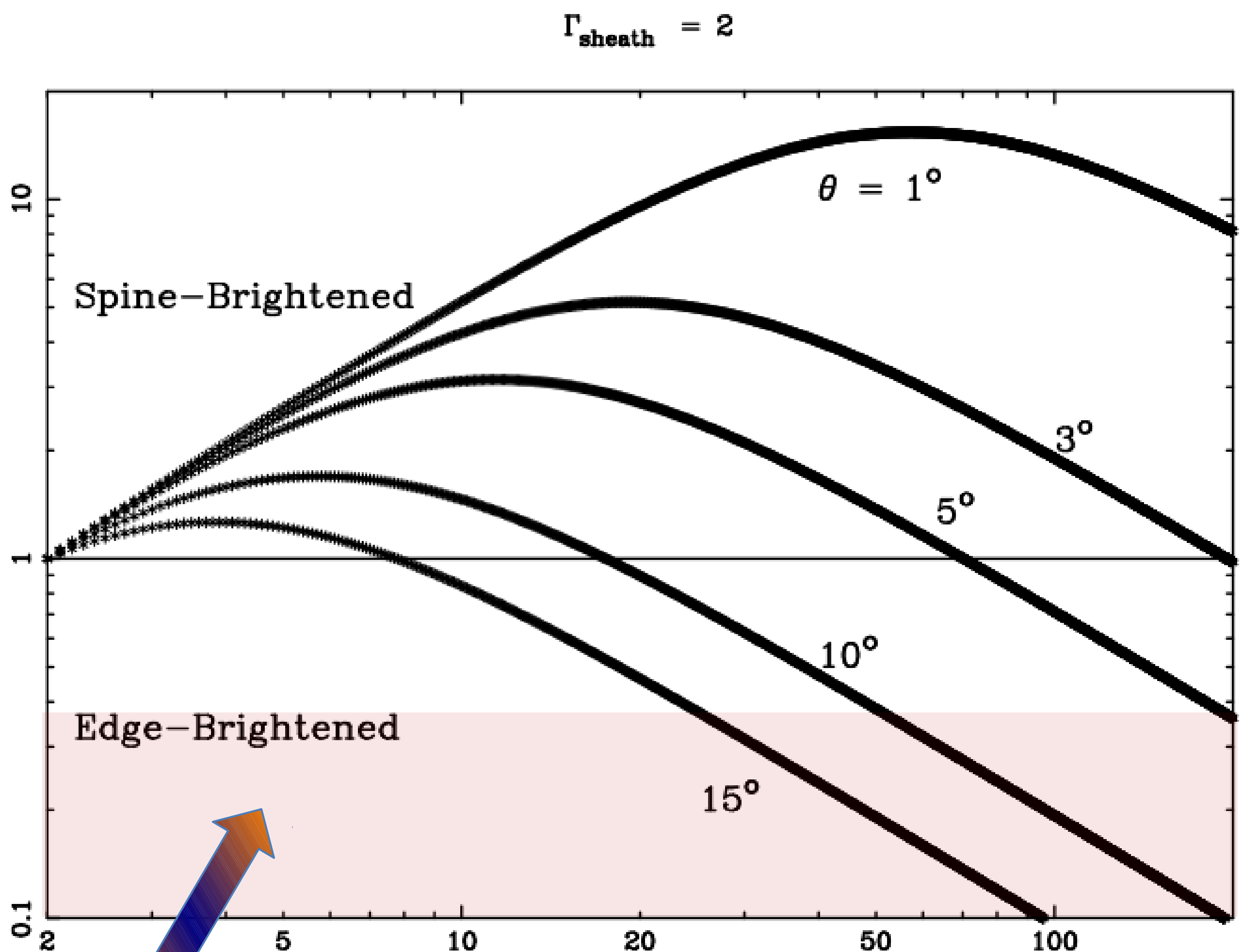


- **Lower VLBI brightness temp. and variability of HSP radio cores are indicative of low radio relativistic beaming factors**

Ramifications of a Very Fast-TeV Jet Spine

- Let's assume $\delta_{TeV} > 100$, which implies
  → viewing angle < 0.6° $(\sin\theta < 1/\delta)$
  → Lorentz factor > 50 $(\Gamma > \delta/2)$

- Large flux-limited jet surveys will always include some jets with $\Gamma \sim \Gamma_{max}$ (Lister et al. 1997), so fast spine model implies:
  - TeV emitting region is much faster than all known radio jets
  - Bright TeV jet population is heavily orientation biased
  - Parent TeV jet population must be very large
  - TeV-emitting jet region has to be intrinsically radio weak



$\frac{\delta_{spine}}{\delta_{sheath}}$

Γ_{spine}

“Sometimes the fast spine is invisible since it is beamed away from you”

works only if jet viewing angle > 10º or spine δ >> 100

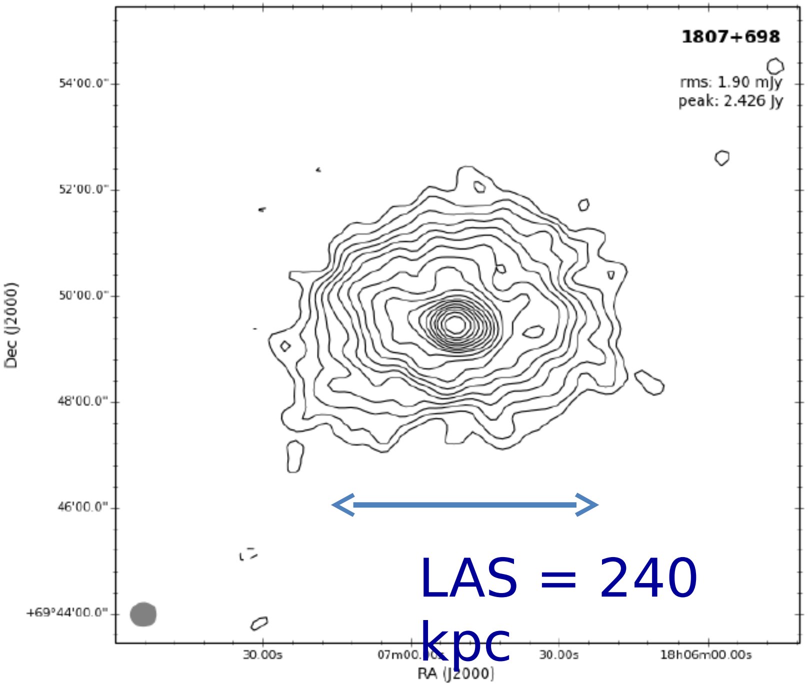
Radio Jets of HSPs in Fast Spine Scenario

- Pc-scale radio jets have intrinsic opening angles ~ 1° to 2° (Pushkarev et al., arXiv 1205.0659).
  - radio jet viewing angle of an HSP would have to be $\lesssim 3°$
  - implies $\Gamma_r \lesssim \delta_r/2$ (well inside $1/\Gamma_r$ cone)
- VLBI core brightness temperatures, one-sided morphology, and radio variability all indicate $3 \lesssim \delta_r \lesssim 10$.
- Radio jets of HSP AGNs would therefore have:
  $1.5 \lesssim \Gamma_r \lesssim 5$ and $10^{21} \lesssim L_r \lesssim 10^{24}$ W Hz^{-1} (unbeamed)
- This puts them at the very low end of the intrinsic luminosity range for blazar jets.
  → kpc-scale radio emission should be weak & foreshortened

MOJAVE Kpc-Imaging Campaigns

- VLA imaging of 300 MOJAVE AGN in A and B configurations at 1.4 and 5 GHz (Ethan Stanley, Ph.D. thesis)

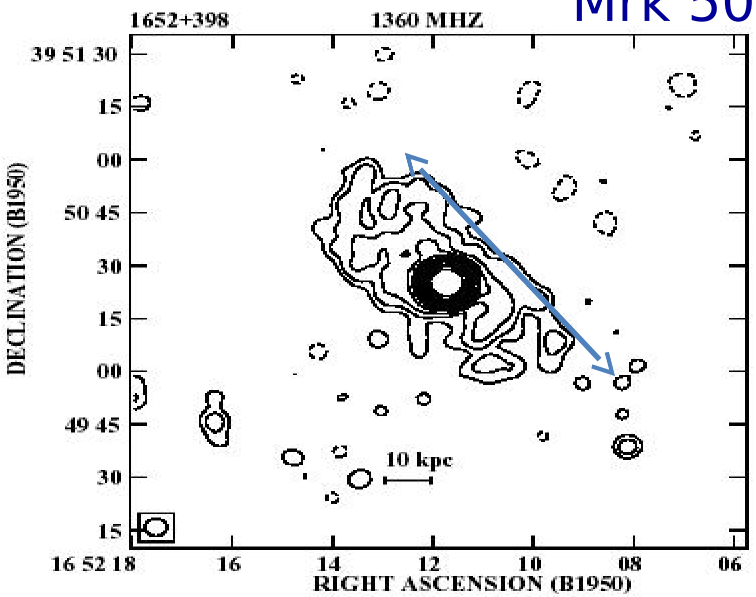
- LOFAR imaging of MOJAVE 1.5 Jy sample (Jonas Trüstedt, Ph.D. thesis)
  - using international baselines to achieve 1 arcsec resolution at 140 MHz
  - 610 MHz GMRT observations have also been proposed



LOFAR image of giant radio halo of ISP BL Lac 1807+698 courtesy Jonas Trüstedt

Deprojected size $\geq \; \delta \cdot LAS$

Mrk 501

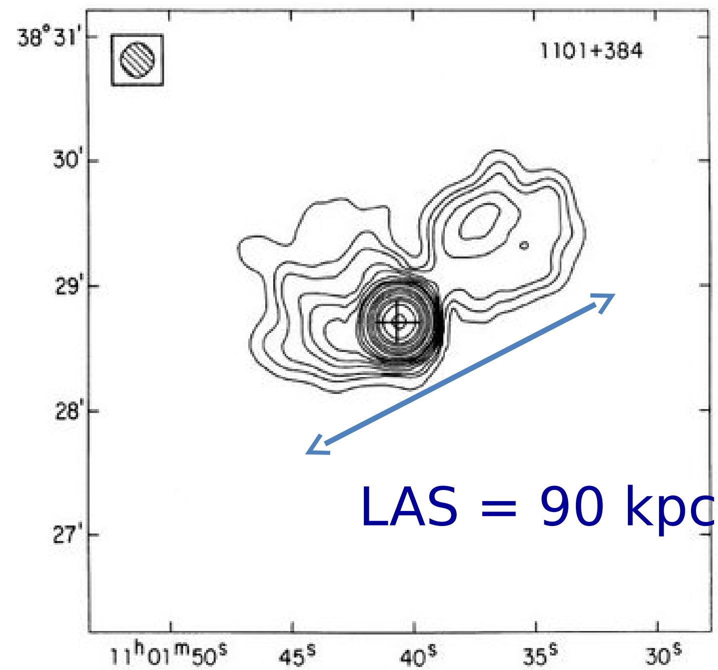


LAS = 50 kpc

Fig. 24. 1652+398, VLA B configuration, 1.36 GHz. The restoring beam is 3.5 × 3.0 arcsec in PA −84°. The peak flux density is 1383 mJy/beam and the rms noise on the image is 0.13 mJy/beam

Cassaro et al. 1999

Mrk 421



LAS = 90 kpc

Machalski & Condon 1985

Deprojected size $\geq \; 500 \left(\frac{\delta}{10}\right)$ kpc

Deprojected size $\geq \; 900 \left(\frac{\delta}{10}\right)$ kpc

>500 kpc is considered a ‘giant’ radio galaxy (see Machalski et al. ApJ 679, 149 and poster upstairs)

Summary

- **The MOJAVE program has revealed important aspects of AGN jets:**
  - the most powerful blazar jets have a wide range of Lorentz factors up to ~50, while typical AGN jets have Lorentz factors of ~a few.
  - jet features are speed up within ~50 pc of the jet base where jet is still collimating, and decelerate further out
  - at any given time, only a small portion of a broader pc-scale conical outflow is highly energized ⇒ *be careful interpreting single-epoch images*
  - a very fast-spine interpretation for TeV HSPs would imply that they have very weak and slow radio jets at implausibly small viewing angles.

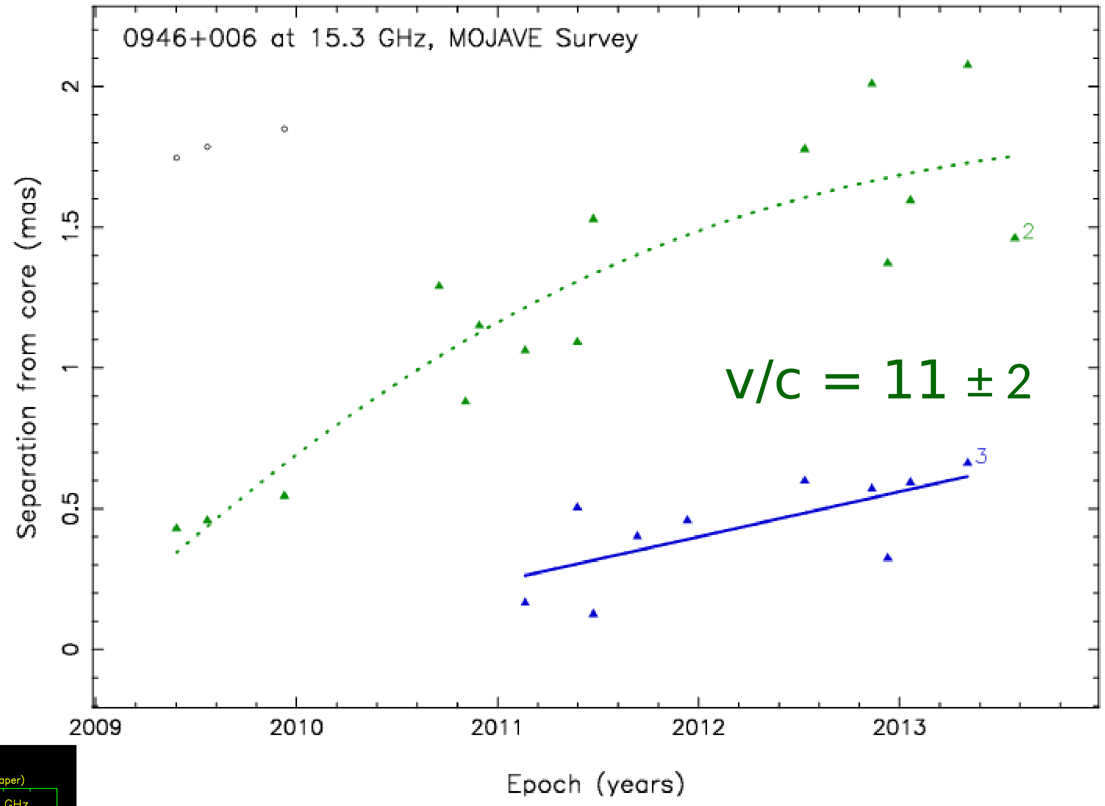
- **MOJAVE VLA and LOFAR campaigns are also investigating kpc-jet morphology and trends between pc-scale properties and jet power**

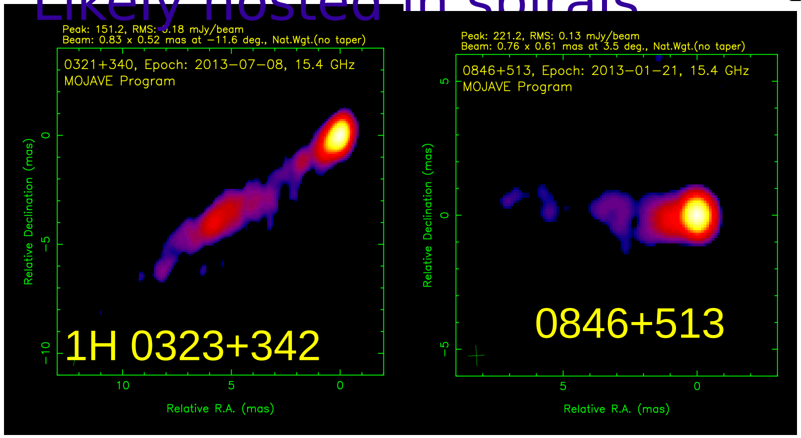
www.astro.purdue.edu/MOJAVE

Backup slides

Superluminal Narrow-Lined Seyfert I Jets

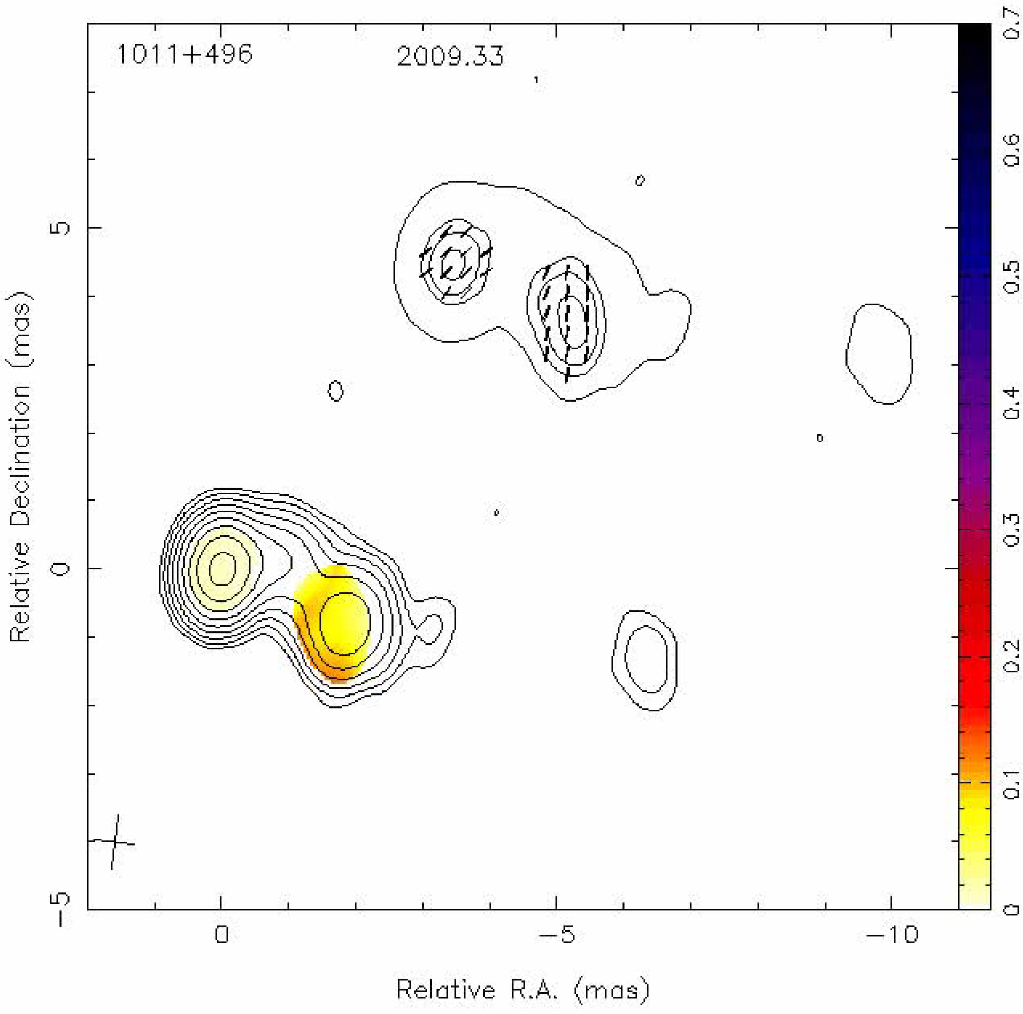
- NLSY1 have high low black hole mass and near-Eddington accretion rate
- Rare sub-population (< 7%) are radio loud, and a scarcer few are γ-ray loud
- Likely hosted in spirals



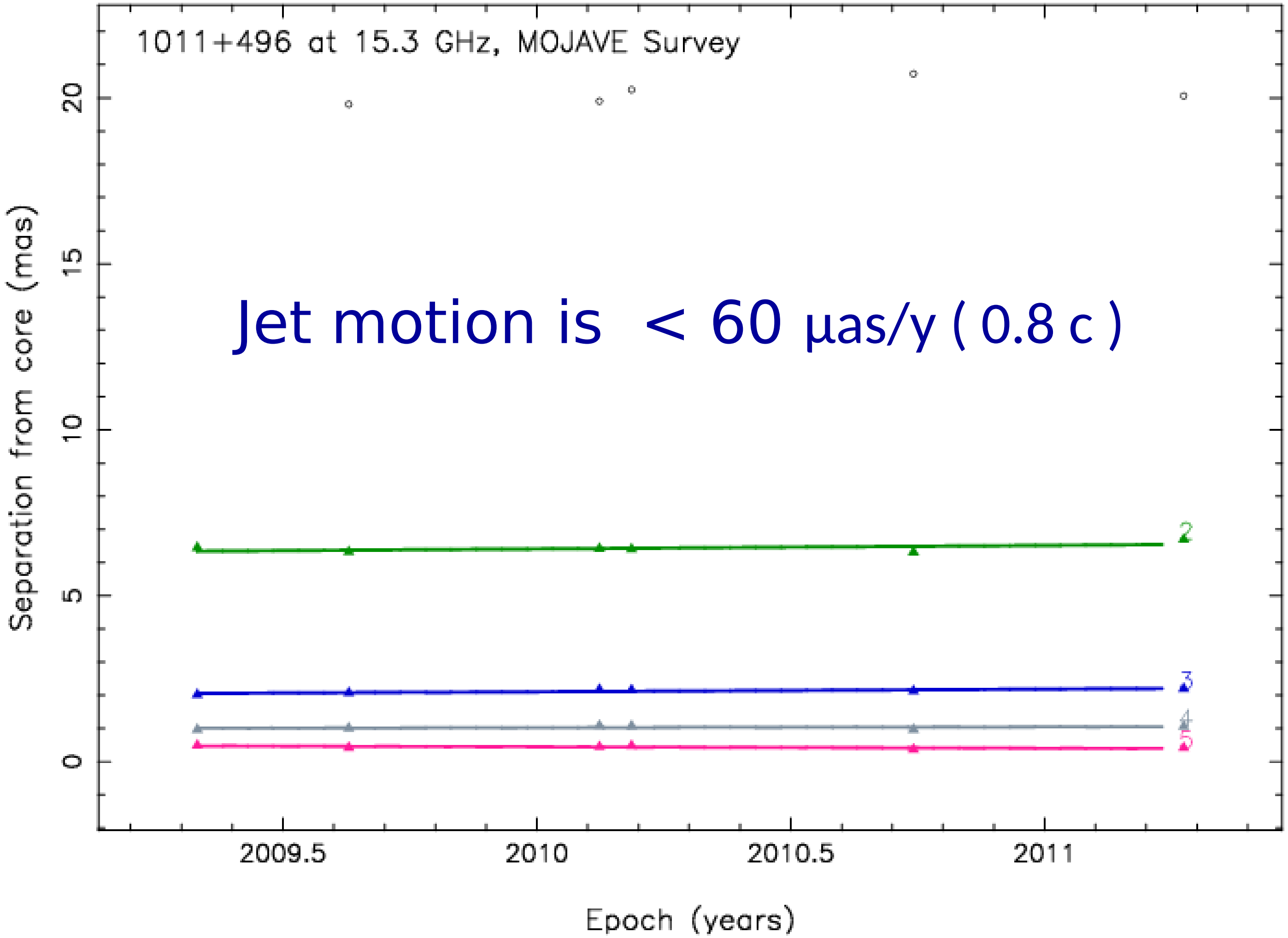


- 3 of 4 NLSY1 in MOJAVE have vapp > 6 c
- Pc-scale radio jets similar to LSP BL Lacs
- Low detection #s may indicate young jets (Foschini et al. 2014)

Trackable features in jets of TeV AGN



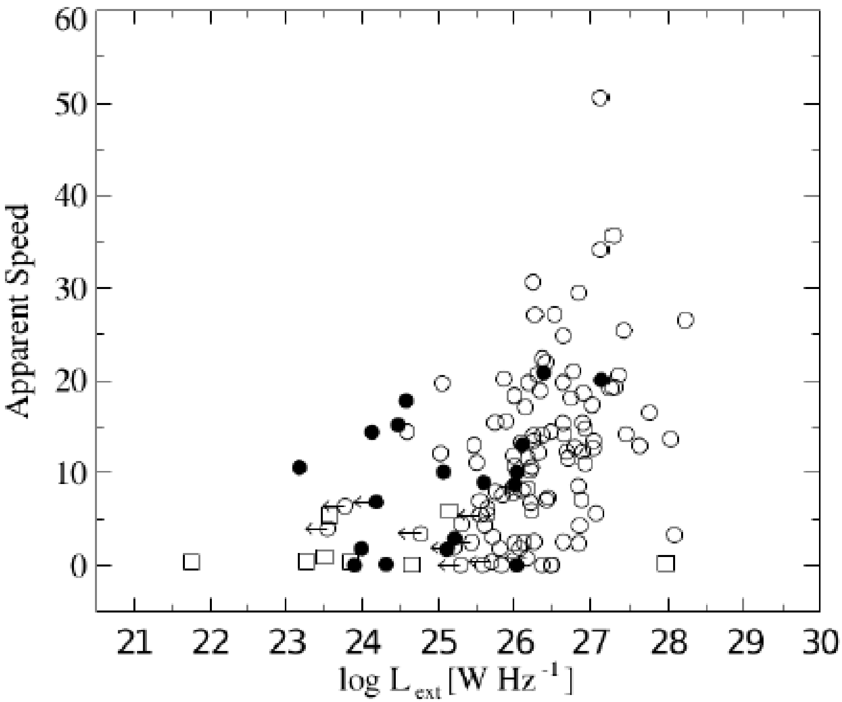
Trackable features in jets of TeV AGN?



Jet motion is < 60 μas/y (0.8 c)

Extended Jet Power

- MOJAVE VLA campaign in 2007 revealed trend between apparent speed and extended lobe emission
- Are the kinetic powers of high and low-spectral peaked BL Lacs consistent with the predictions of the unified model?
- What are the implications for the Doppler beaming crisis?

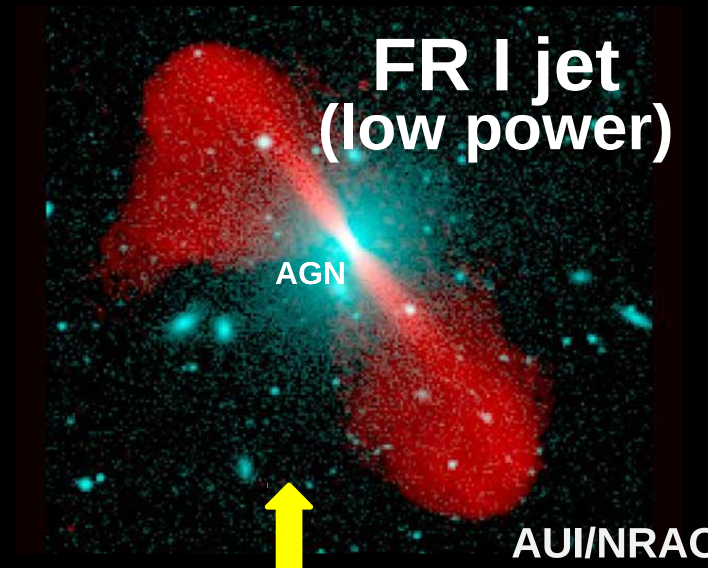


Kharb et al. 2010, ApJ 710, 764

Blazar Flavors: Quasars and BL Lacs

Quasars:

- broad optical emission lines
- high power jets seen end-on
- synchrotron peak in



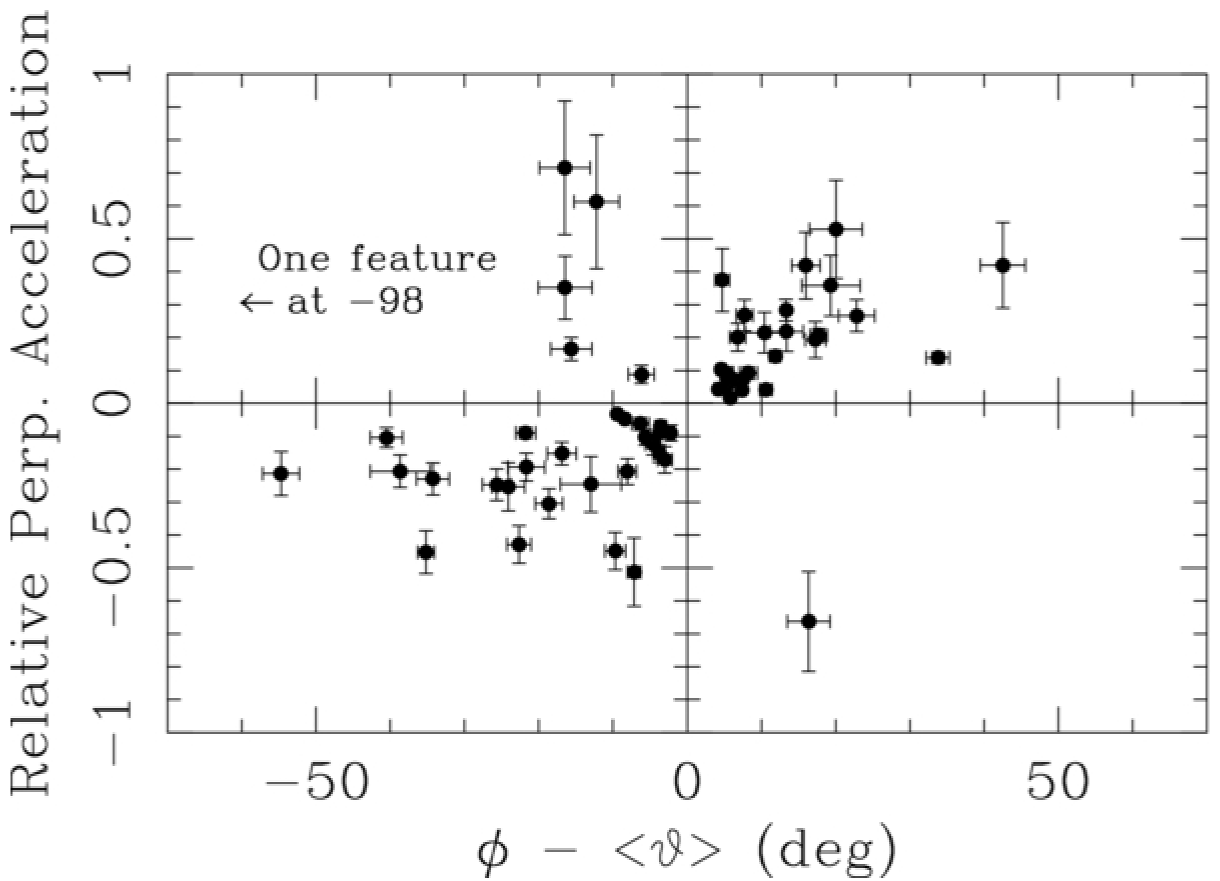
BL Lacertae objects:

- weak/absent broad emission lines
- low power jets seen end-on
- synchrotron peaks range from infrared to

Current BL Lac Paradigm

- Lower jet power implies low accretion rate onto black hole:
  - inflow radiates inefficiently, thus no optically thick accretion disk or broad line region

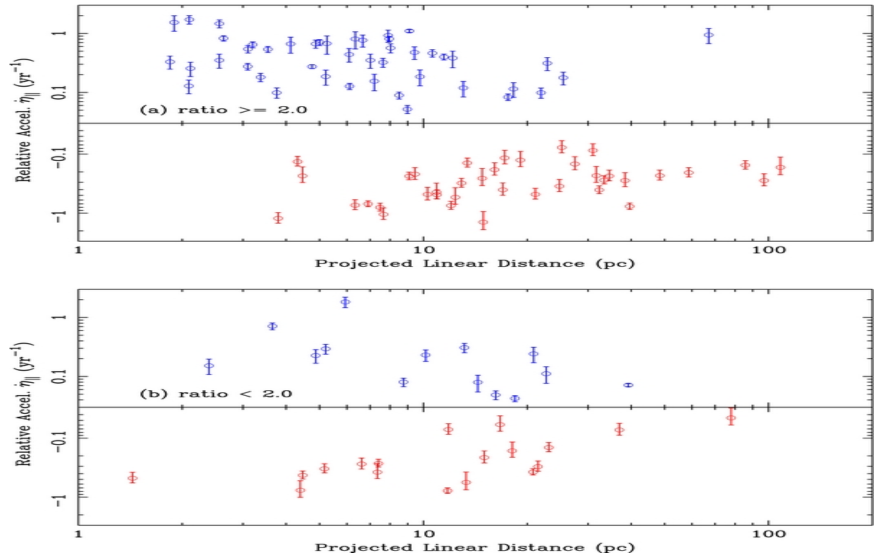
- No broad line photons are available for external Compton scattering
  - less Compton cooling of synchrotron electrons
  - synchrotron can peak up to optical/UV regime


Relative Perp. Acceleration
1
0.5
0
−0.5
−1
One feature
← at −98
−50
0
50
$\phi - \langle\vartheta\rangle$ (deg)

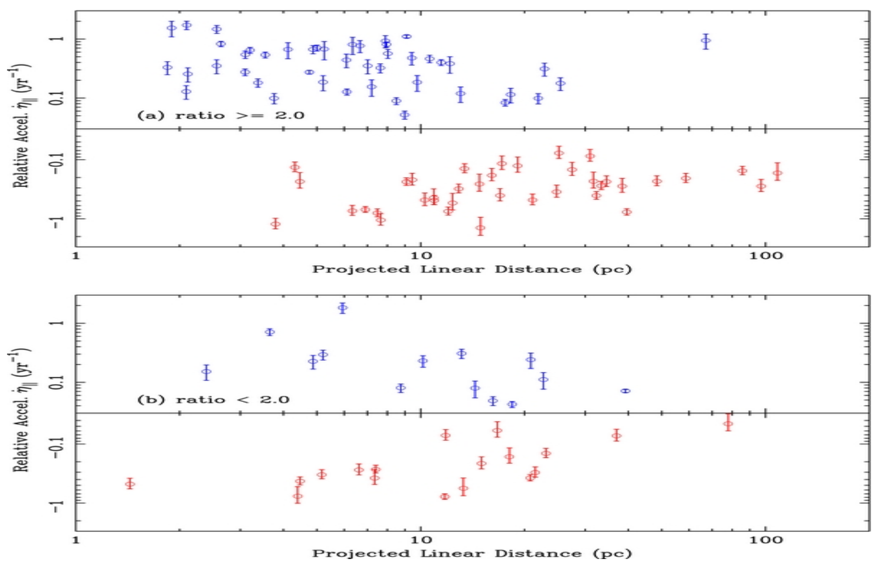
Are these trends solely due to jet bending?

Predictions:

- no inward/outward acceleration trend expected with distance
- parallel accelerations should be ~60% magnitude of ⊥ accelerations
- features with large parallel accelerations should also show large perpendicular accelerations

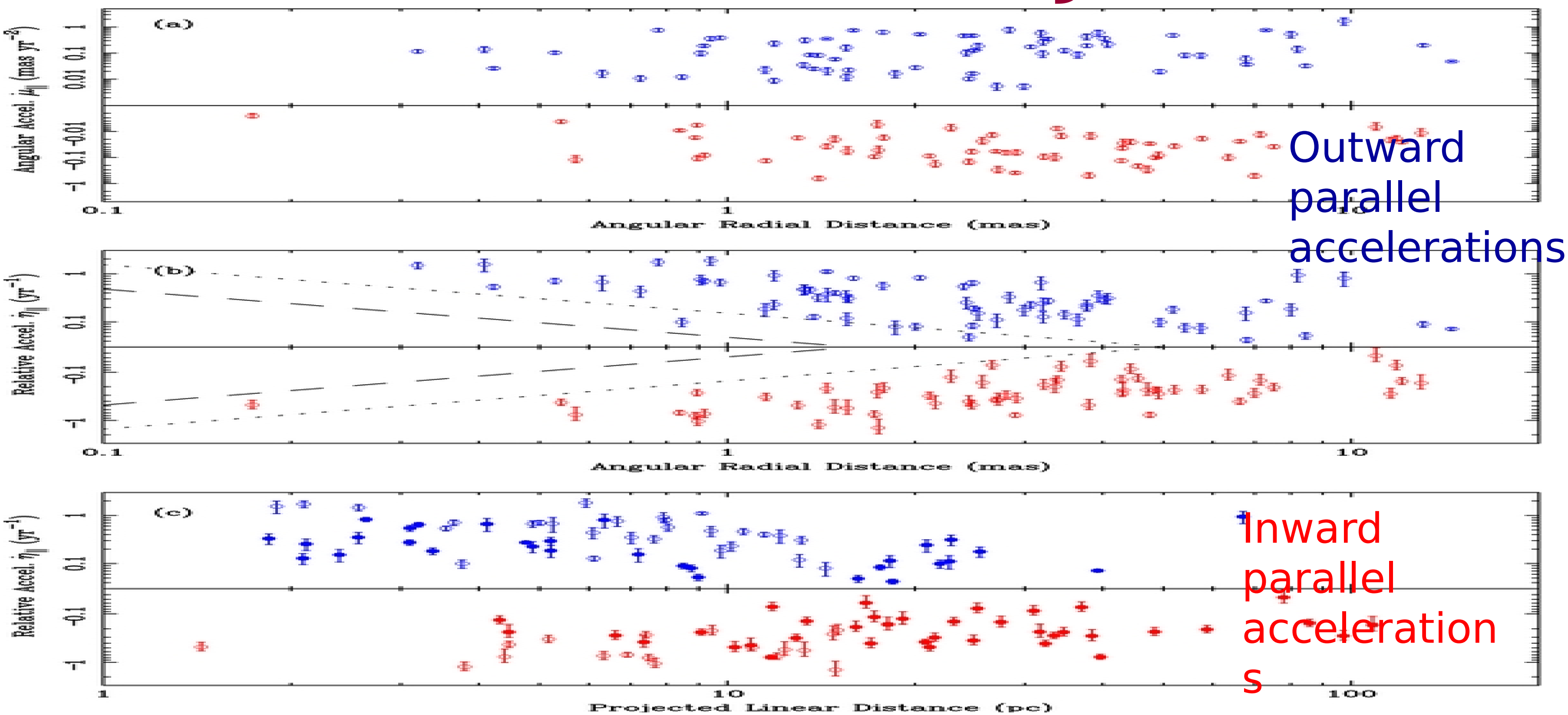


- Most features have a **high** || / ⊥ acceleration ratio.



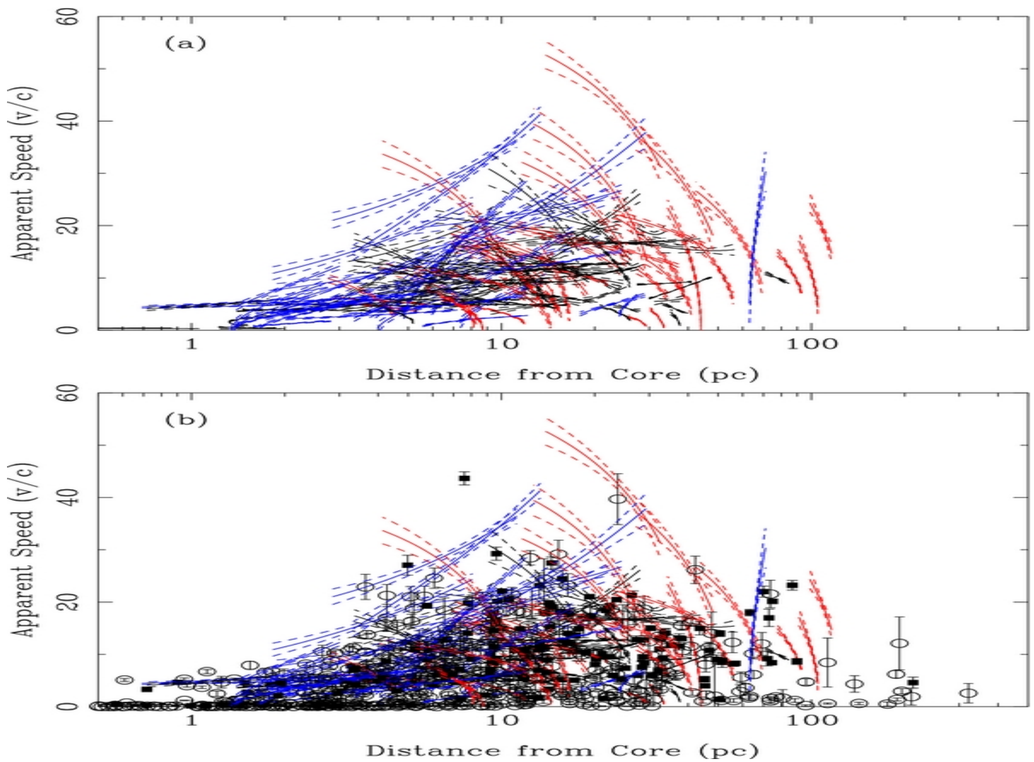
- Speed increase/decrease trend is more evident in these features.

Acceleration Down the Jet



- Features tend to speed up near the core, and slow down at ~ 100 pc (deprojected) farther downstream.

Do the observed motions reflect the underlying jet flow?

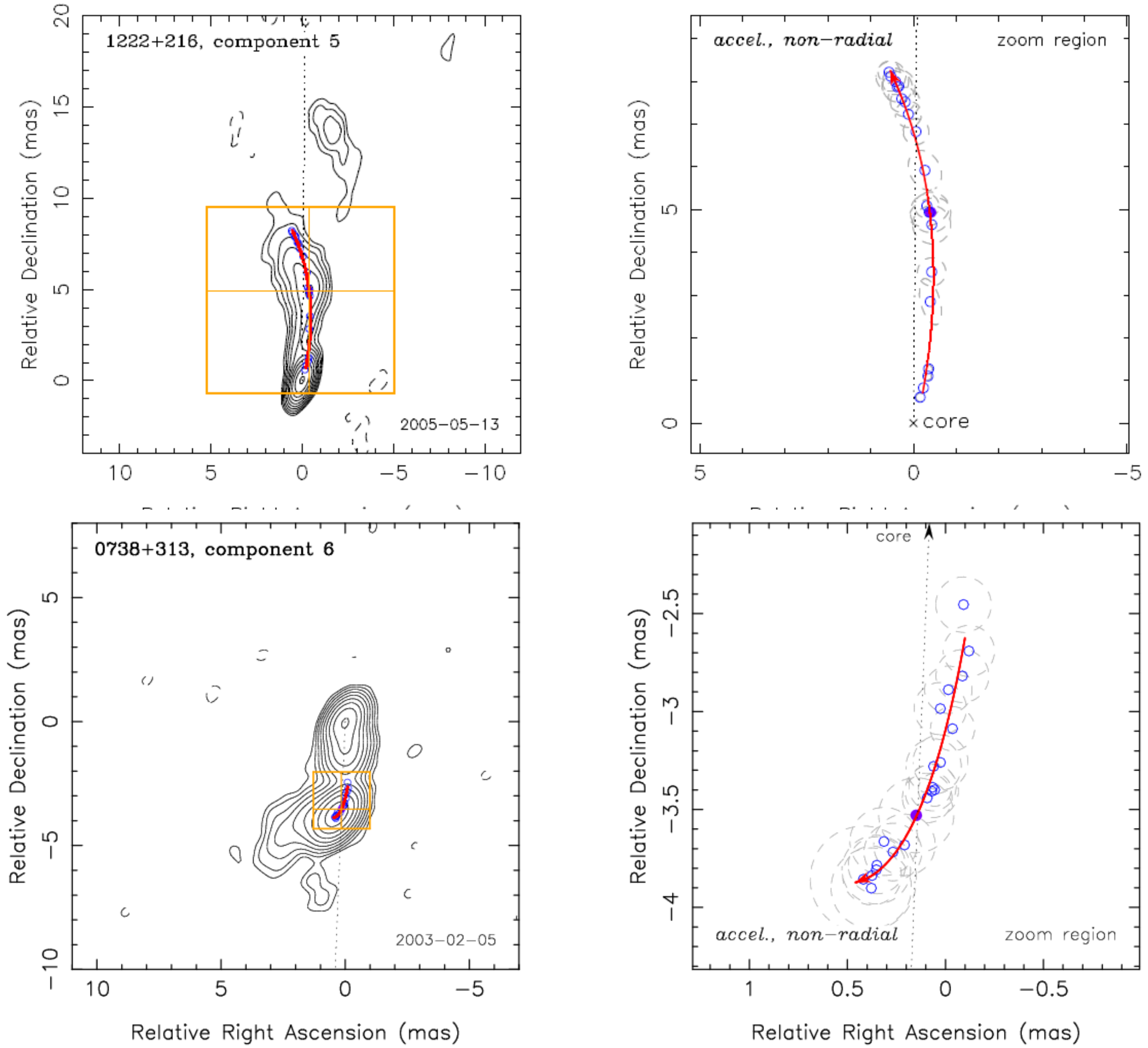


Red: inward acceleration

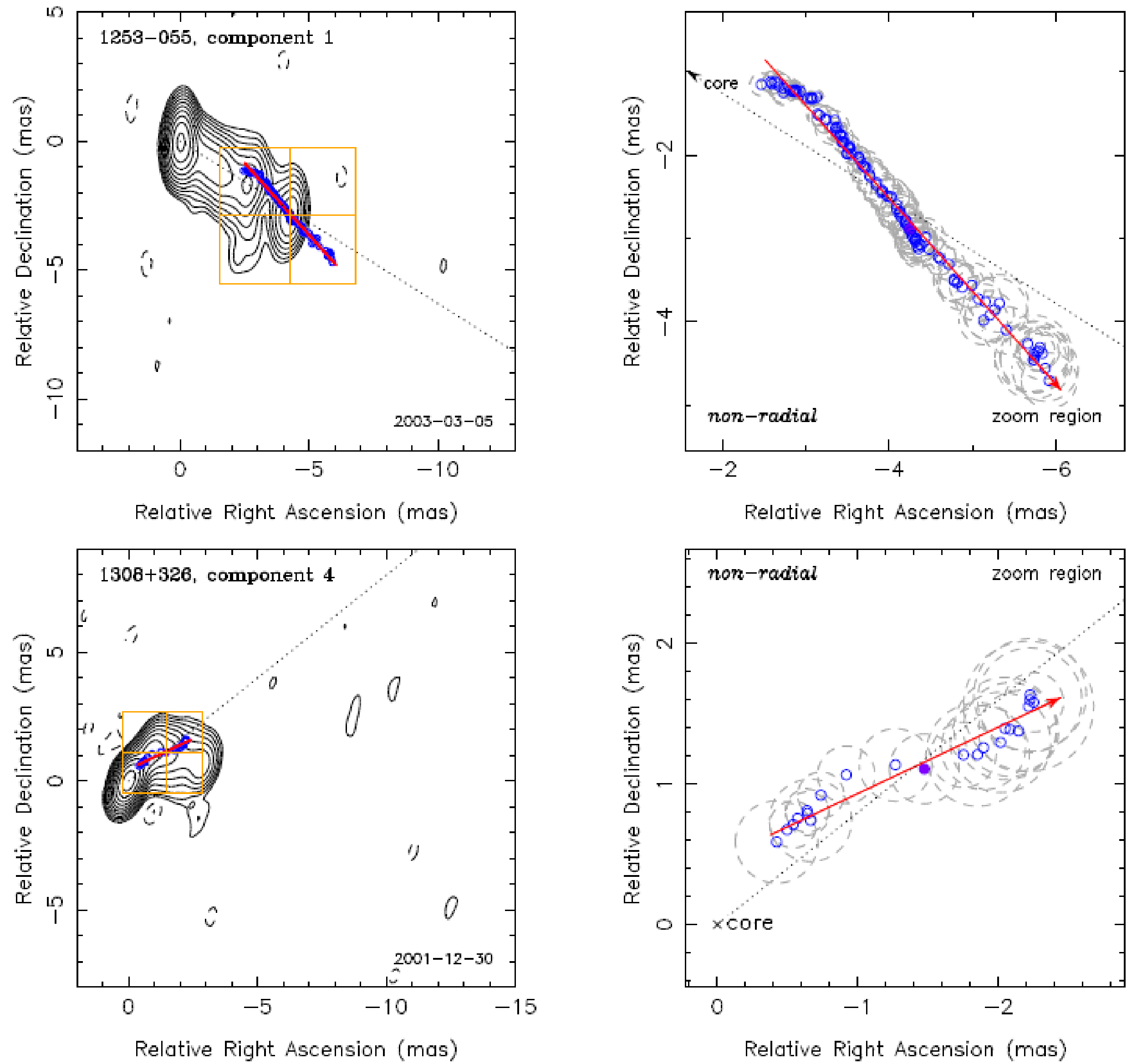
Blue: outward acceleration

Black: no significant acceleration

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



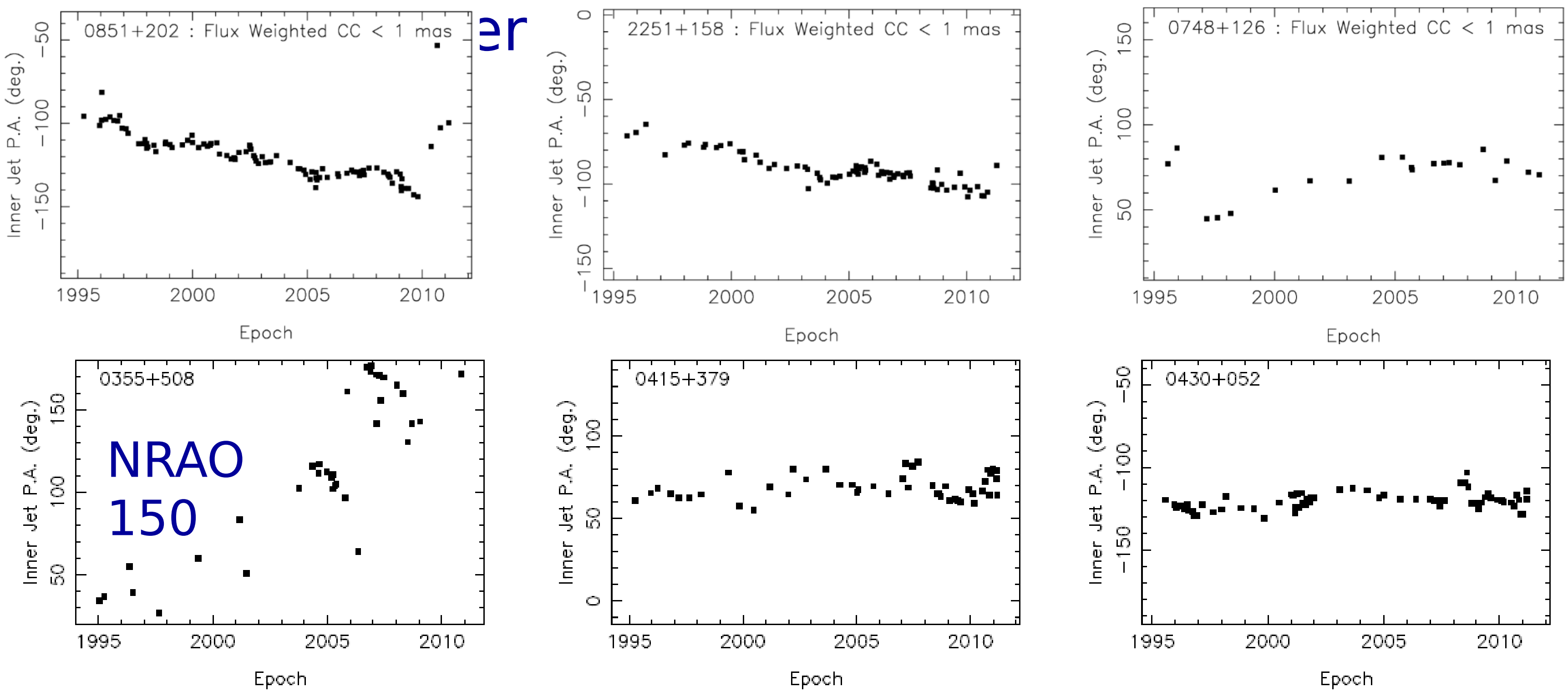
- In most cases a constant acceleration model provides a good fit to the observed motions



- Some of the best-sampled features, however, show <u>variable</u> acceleration

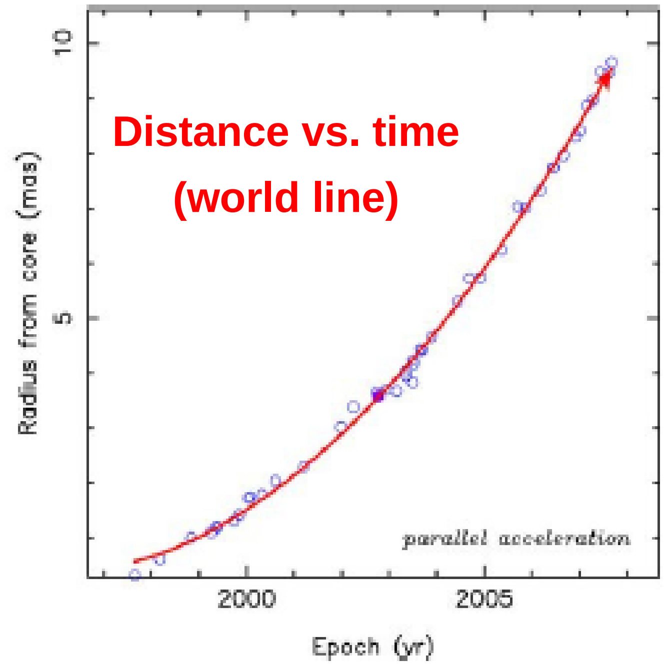
- 50% of jets show no trend/changes in position angle with time

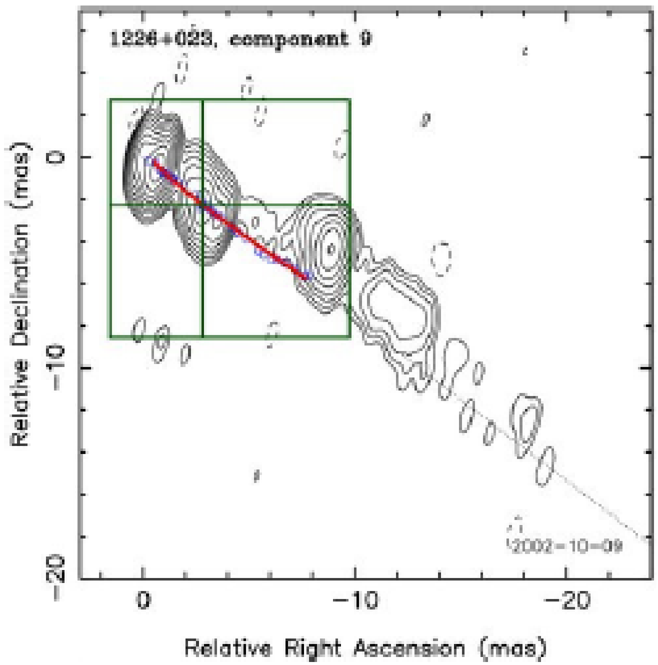
- 43% show monotonic swings in position angle
  - Typically 1 to 3 degrees per year
  - Fastest case: quasar NRAO 150 (9.8 ± 1
    er

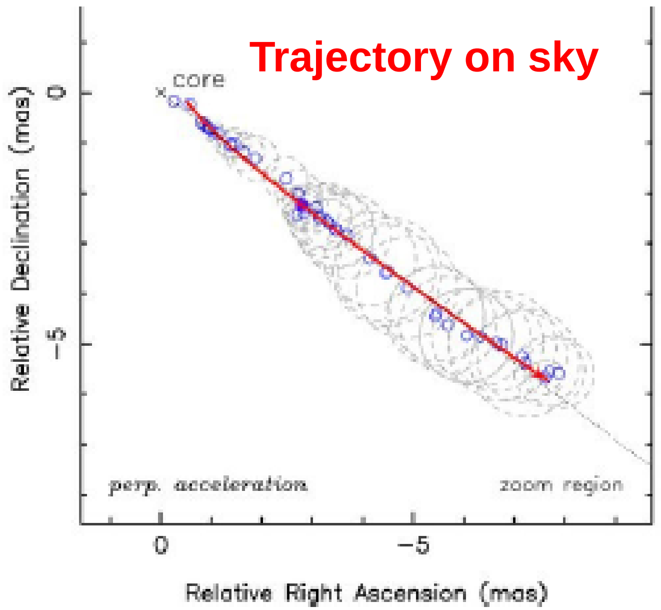


Jet Accelerations

- Many of the features move on complex curved trajectories and most are accelerating (non-ballistic)

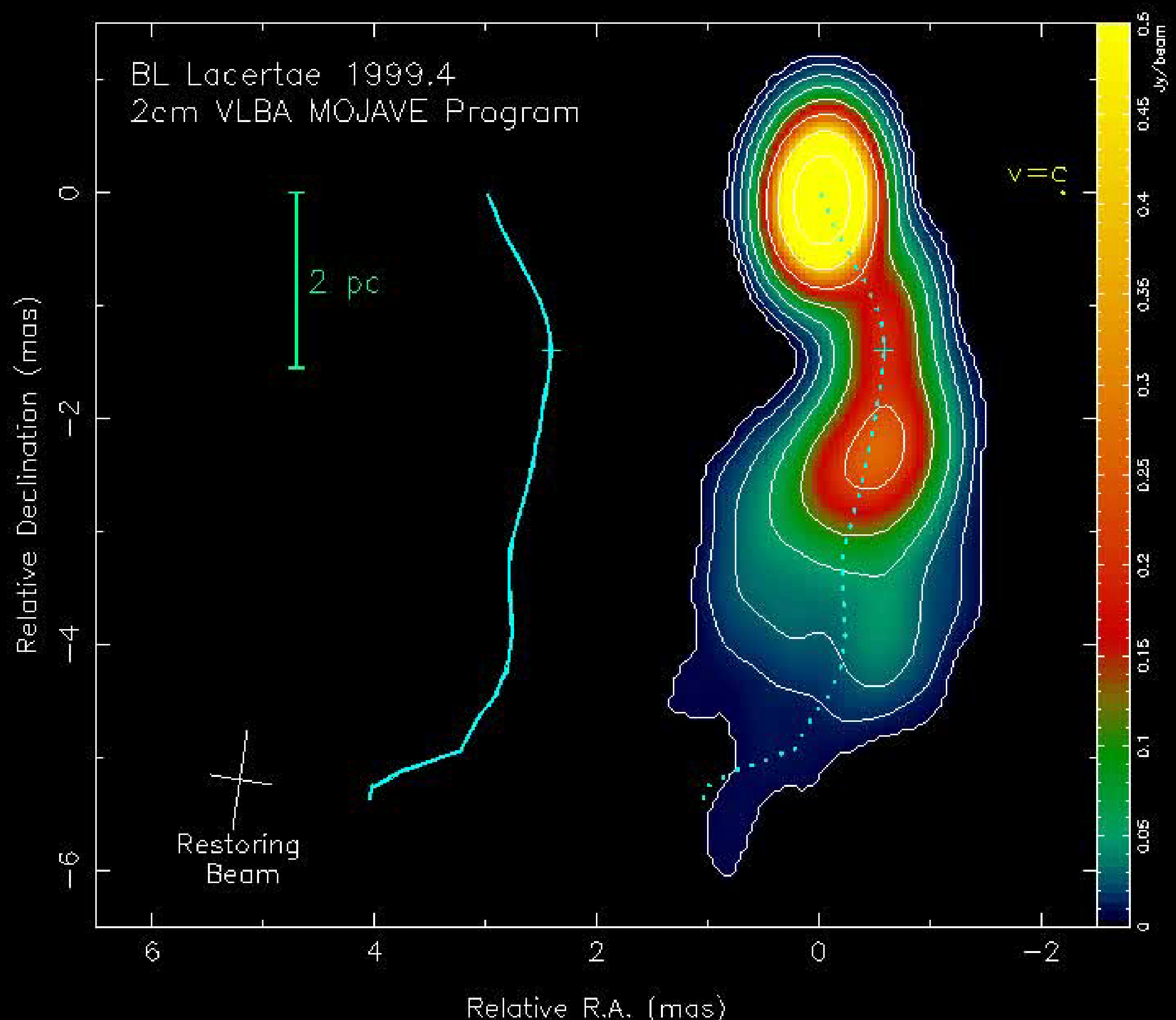




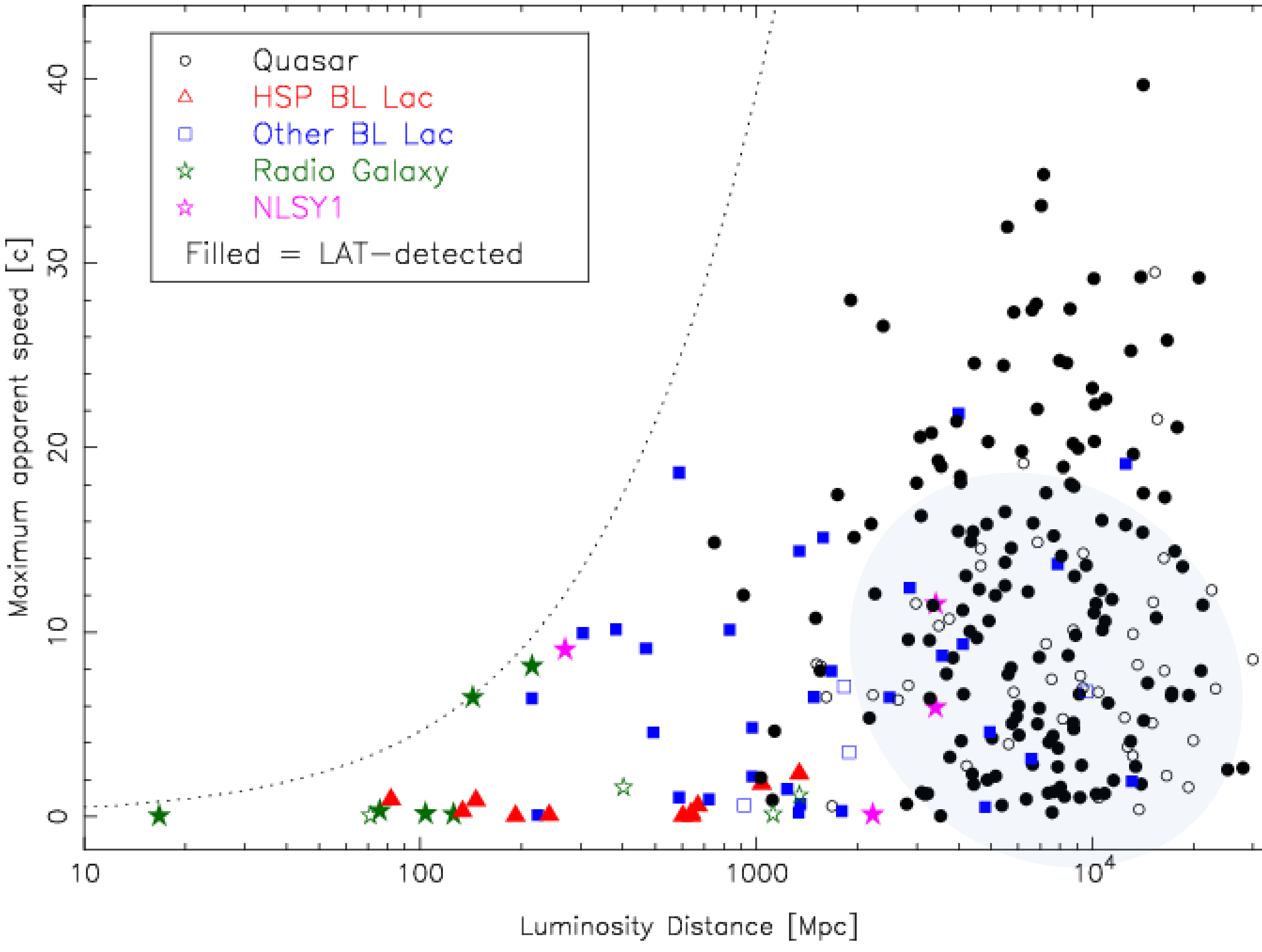


MHD Plasma Waves in BL Lacertae

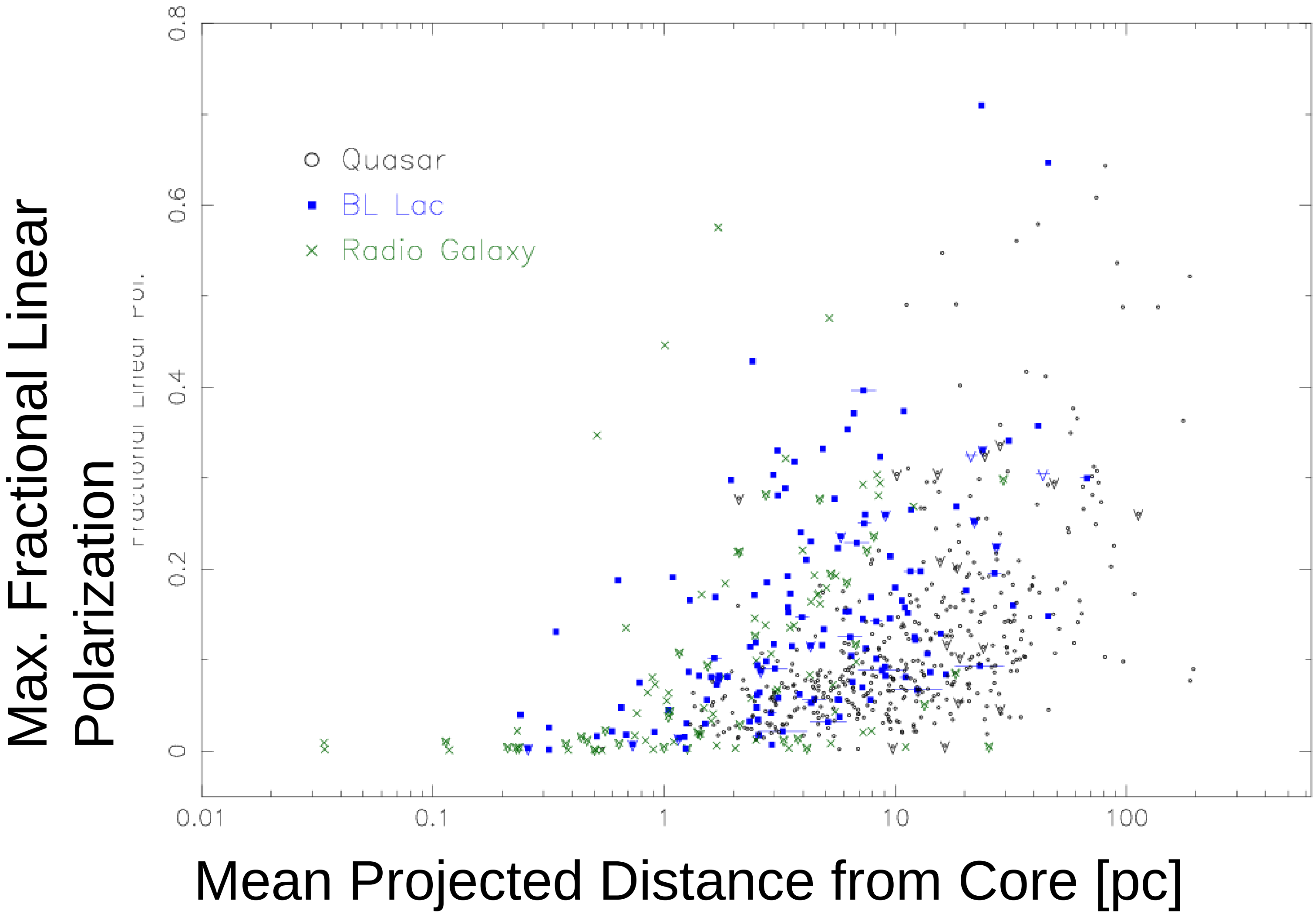
M. Cohen et al. ApJ, 2014, 2015

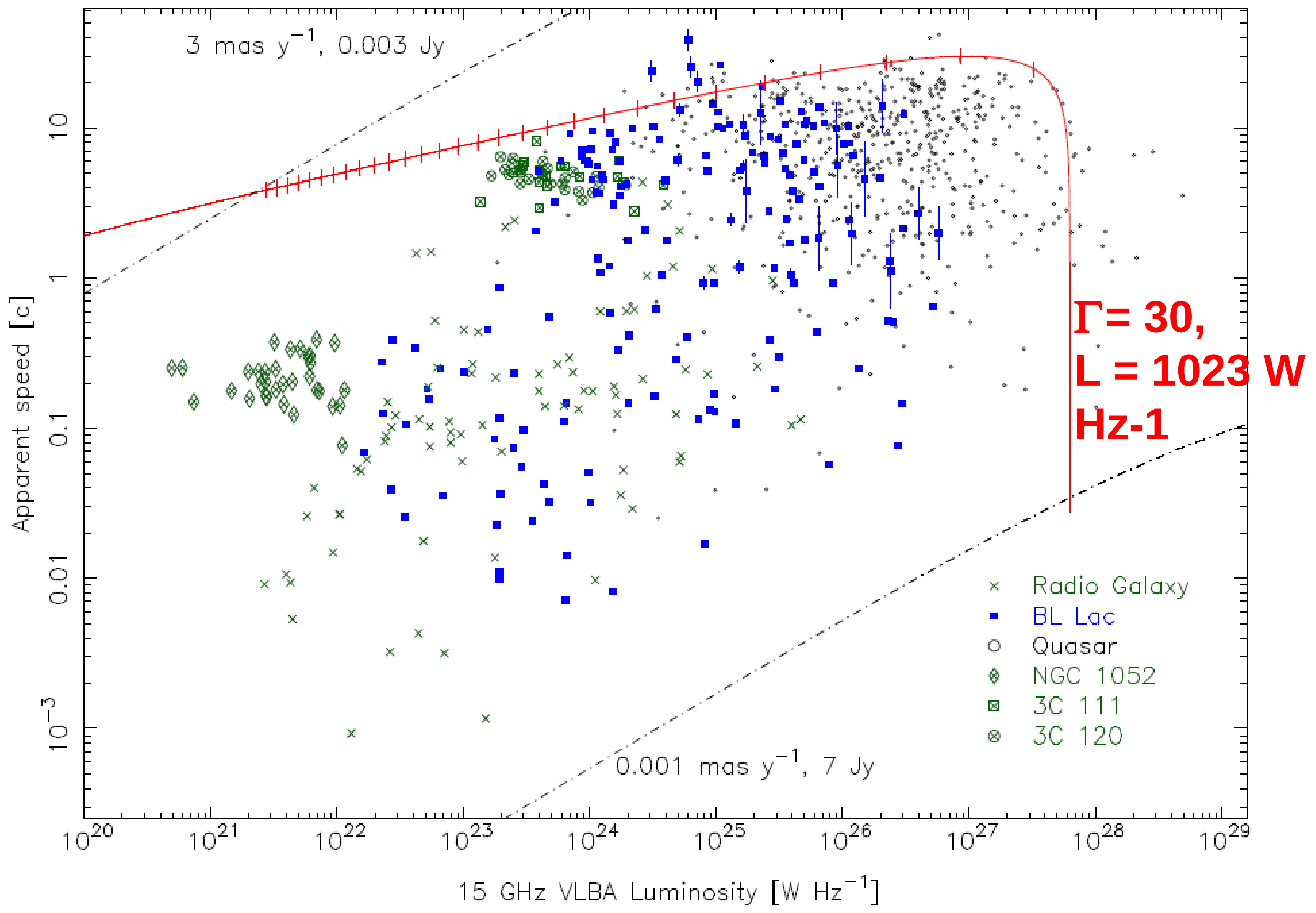


Jet Speed vs. Luminosity Distance



Evolution of Magnetic Field Order

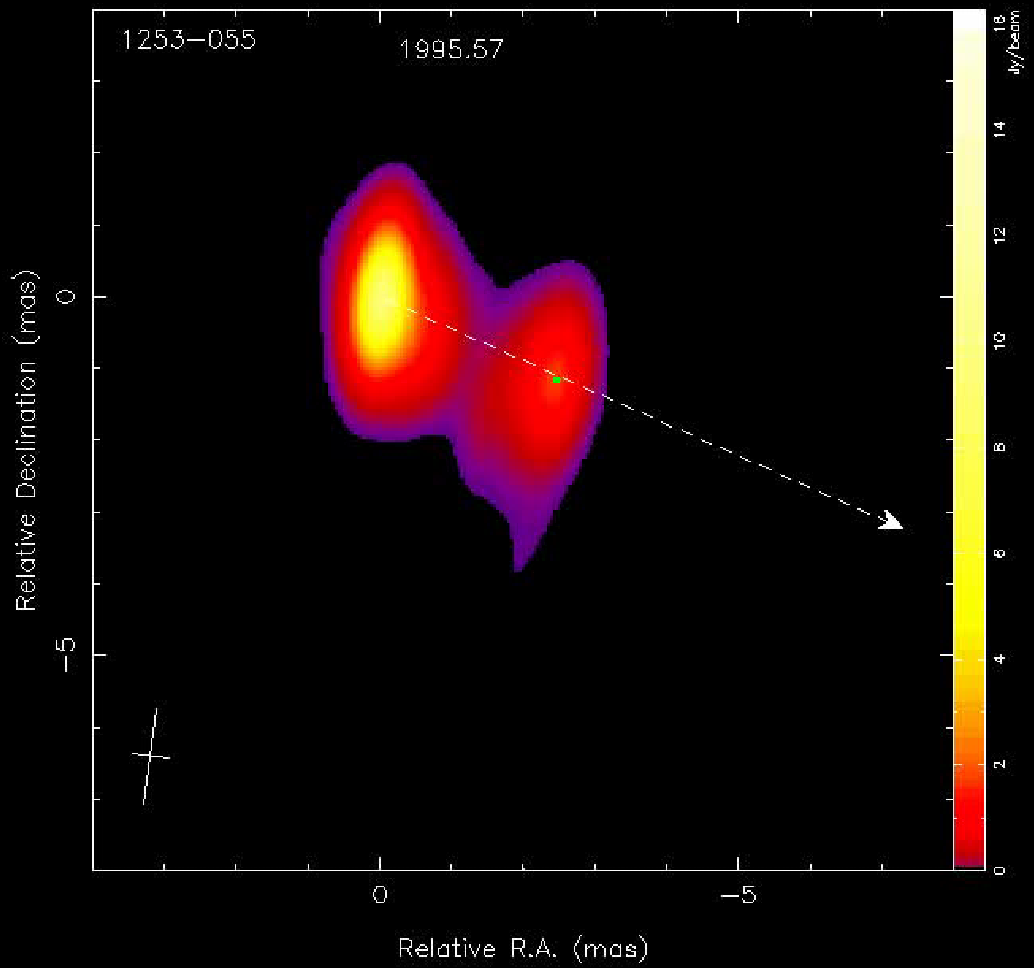




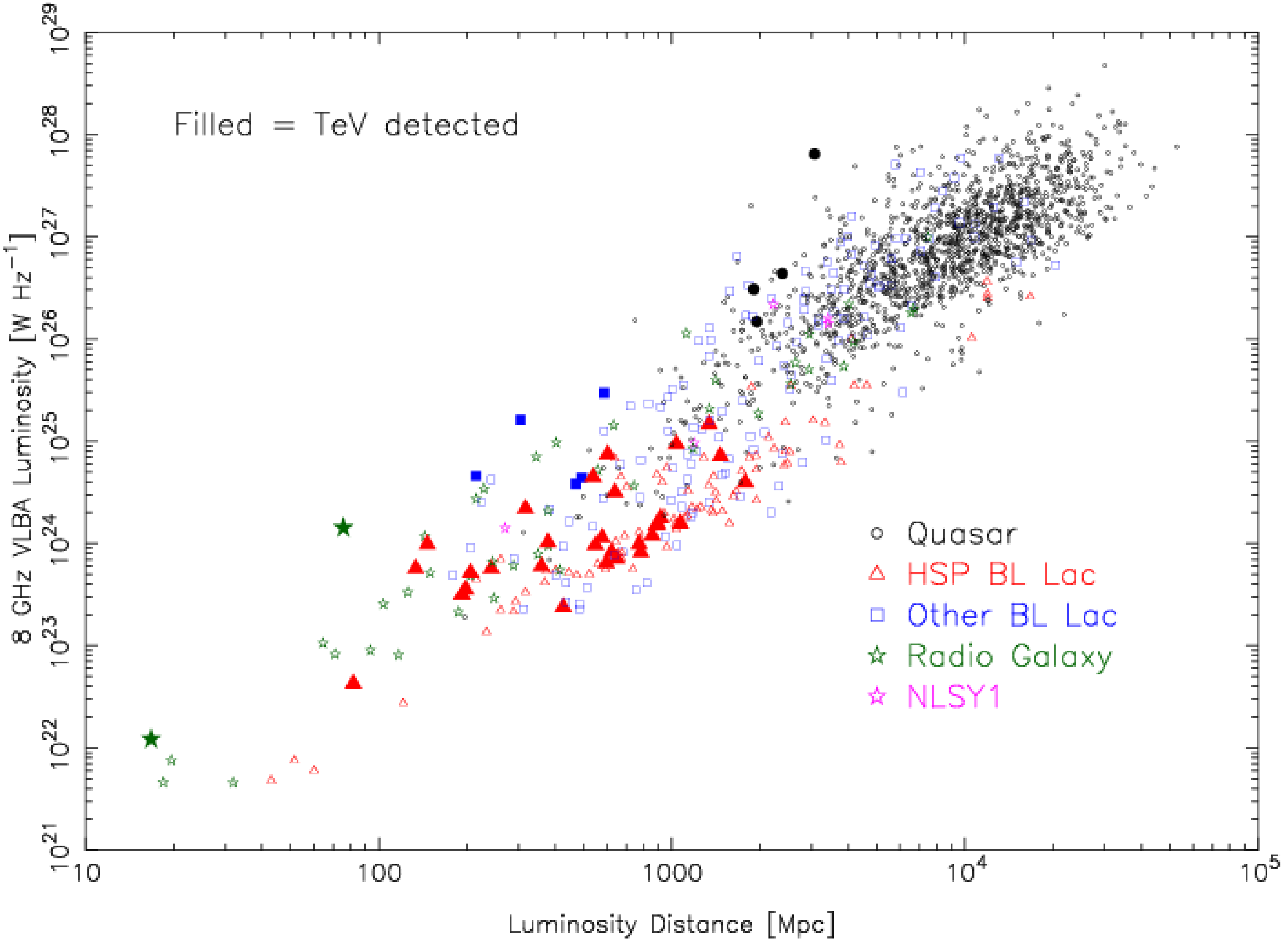
- No examples of fast, low-synchrotron luminosity features.
- Only the most luminous jets can attain high Lorentz factors

Quasar 3C279

- z = 0.54
- Very bright jet feature emerged in early 1980s
- In early 1998: feature brightened and accelerated from 8c to 13c
- New motion vector is in the direction of the kpc-scale jet.
- Jet is undergoing collimation due to a sudden change in external gas pressure in the host galaxy (Homan et al. 2003)



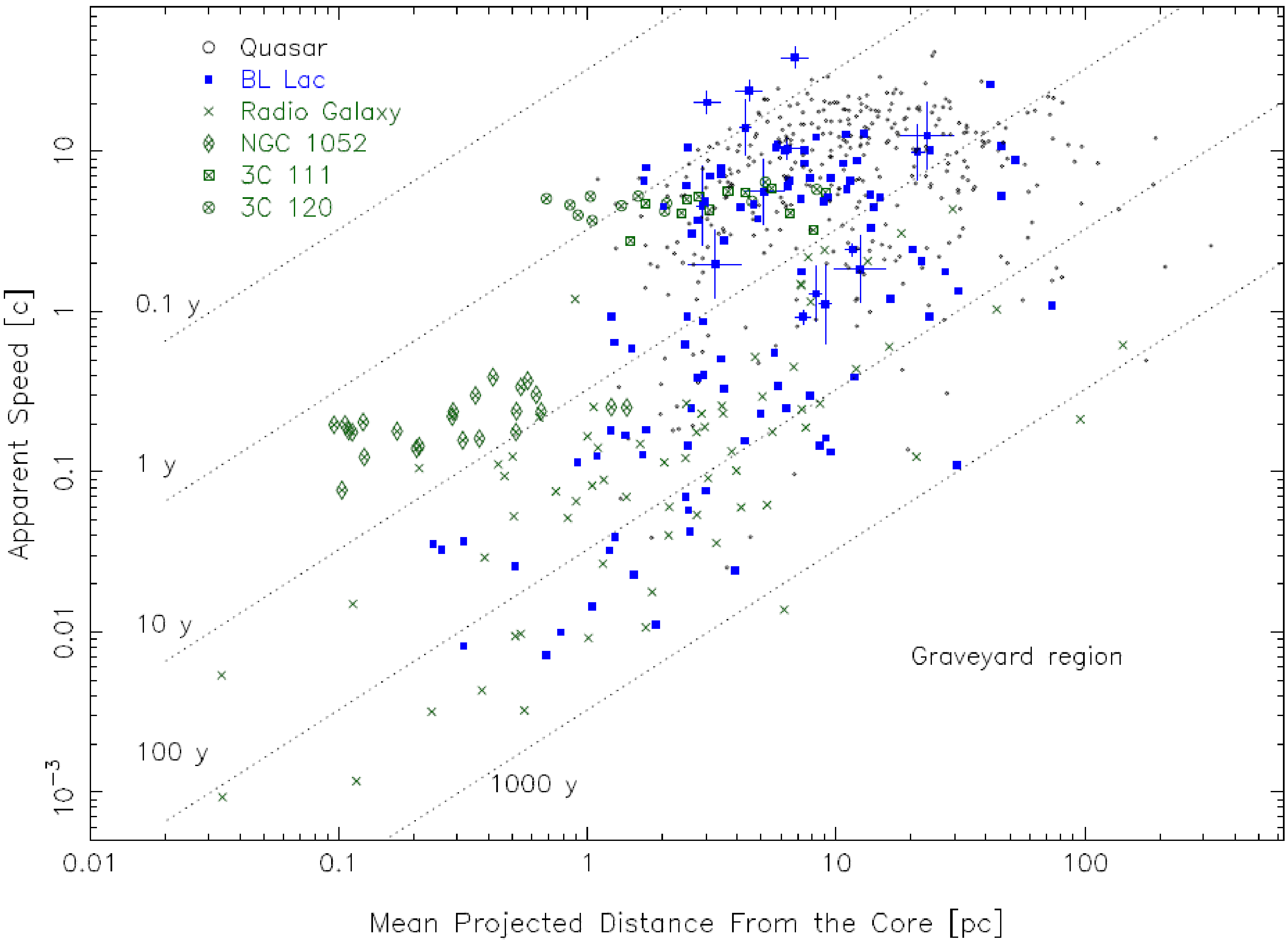
MOJAVE Time Lapse


Filled = TeV detected
8 GHz VLBA Luminosity [W Hz^{-1}]
Luminosity Distance [Mpc]
Quasar
HSP BL Lac
Other BL Lac
Radio Galaxy
NLSY1

MOJAVE Studies of AGN Jets

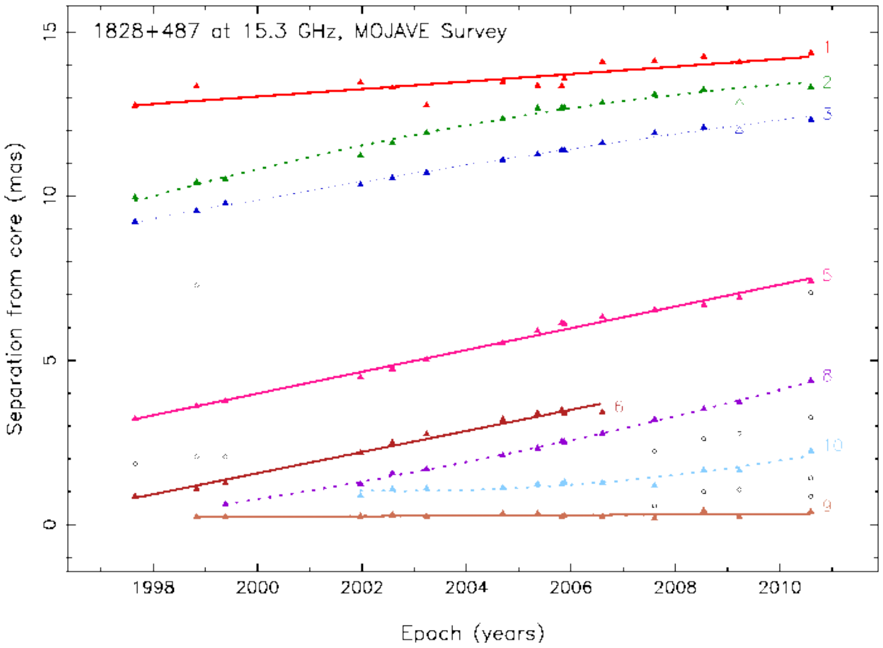
- Linear (I) and circular (II) polarization
- Kiloparsec radio (III, Kharb et al. 2010) and X-ray (Hogan et al. 2011)
- Parent population and luminosity function (IV)
- Faraday rotation measure (VII) and spectral index maps (XI)
- Nuclear opacity and magnetic fields (IX)
- Morphology and compactness (I,V, Homan et al. 2005)
- Kinematics (V, VI, VII, X, XI)
- Optical properties (Torrealba et al. 2012,; Arshakian et al. 2010, 2012)
- Gamma-ray properties (Lister et al. 2009, 2011, Pushkarev et al. 2010, Savolainen et al. 2010, Kovalev et al. 2009)

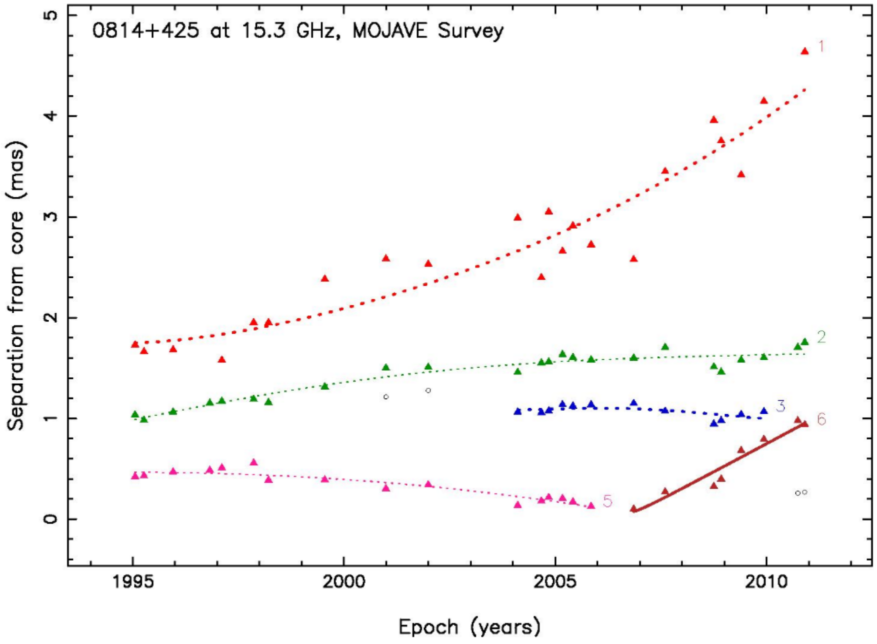
Roman numerals refer to MOJAVE paper series, full list at



- BL Lacs and radio galaxies show clear trend of increasing speed down the jet.
- Situation unclear for quasars, but we can directly measure the accelerations.

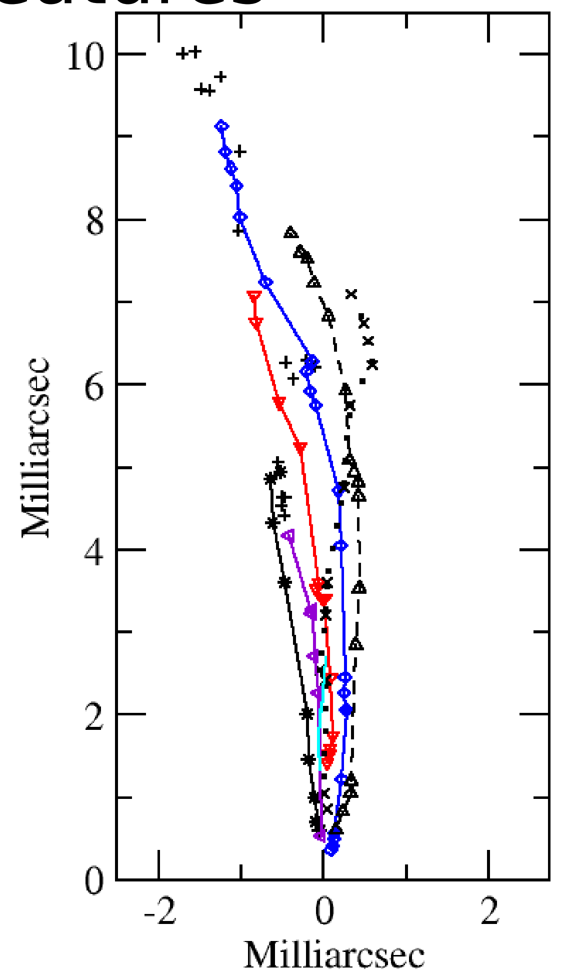
Kinematic Fits

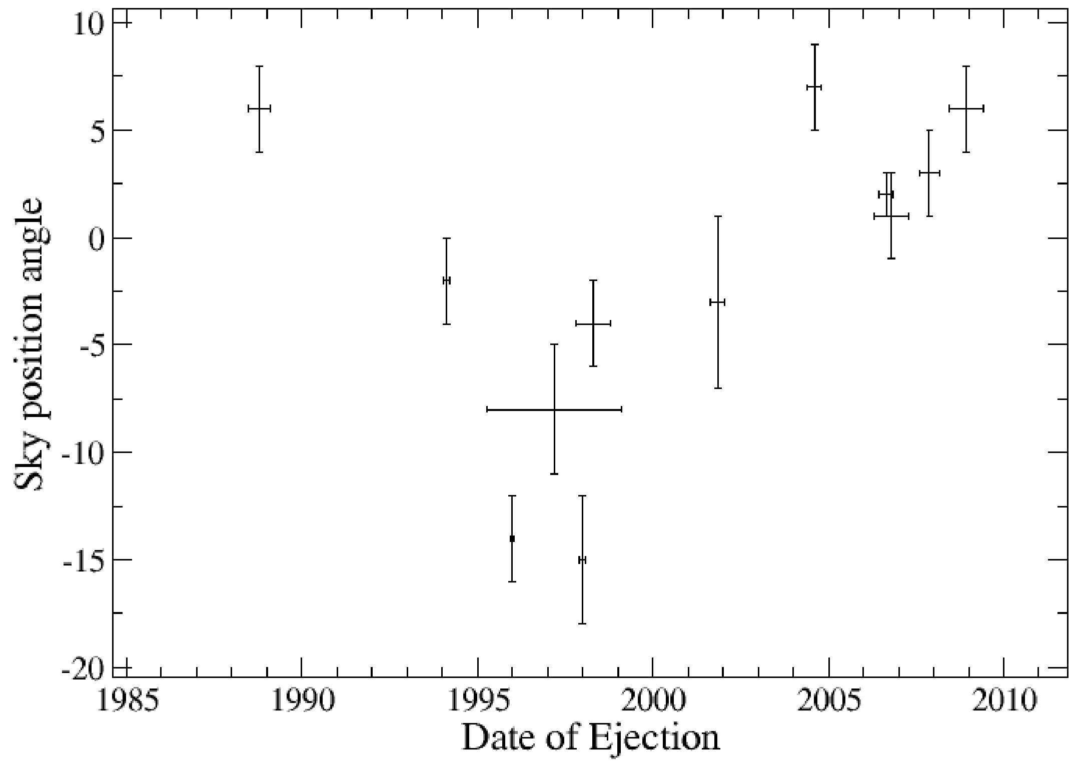




- Two-dimensional sky vector motion fits made to 887 bright features in 200 different AGN jets.
  - all features tracked over at least five VLBA epochs
  - many tracked for more than 10 years
  - optically thick jet ‘core’ used as a stationary reference point

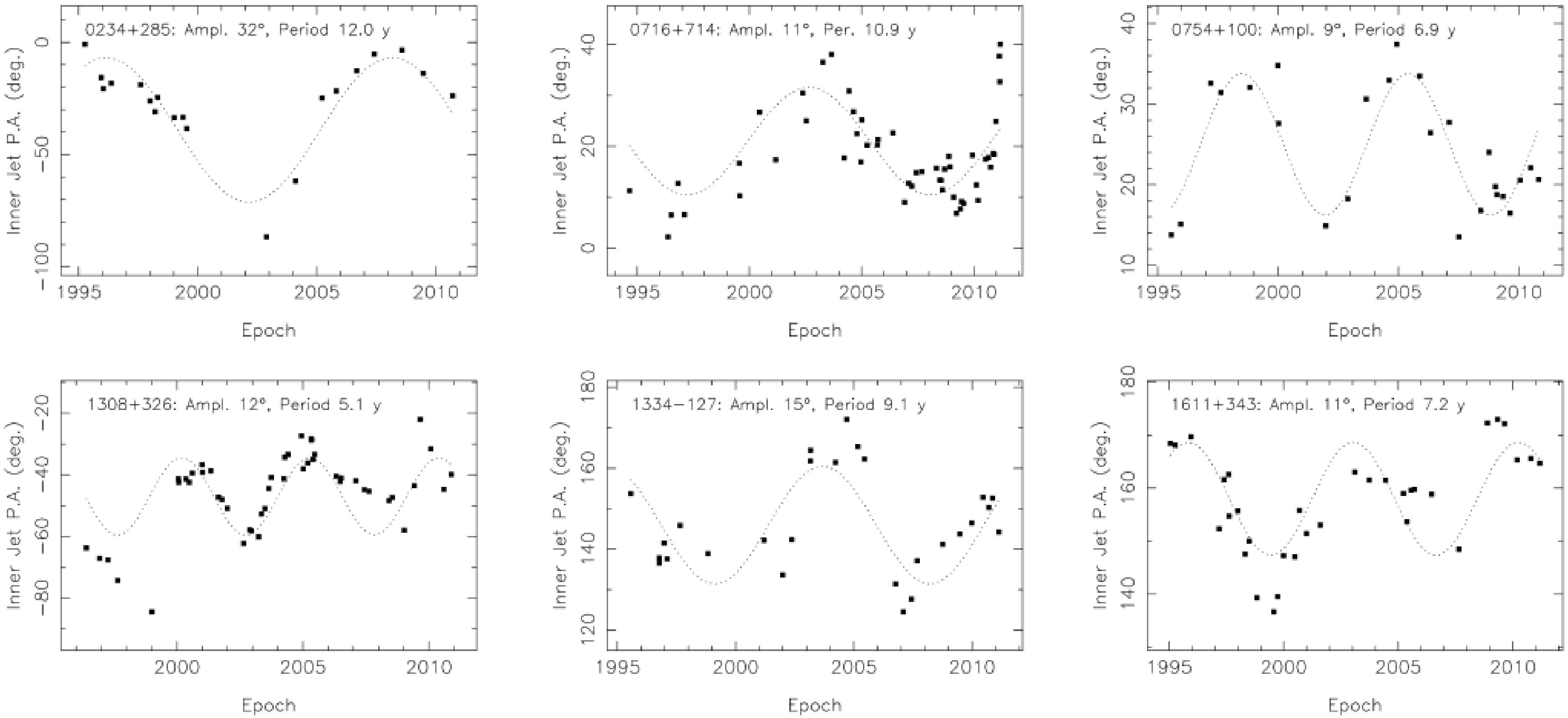
Inner jet position angle changes are primarily driven by the emergence of new bright features

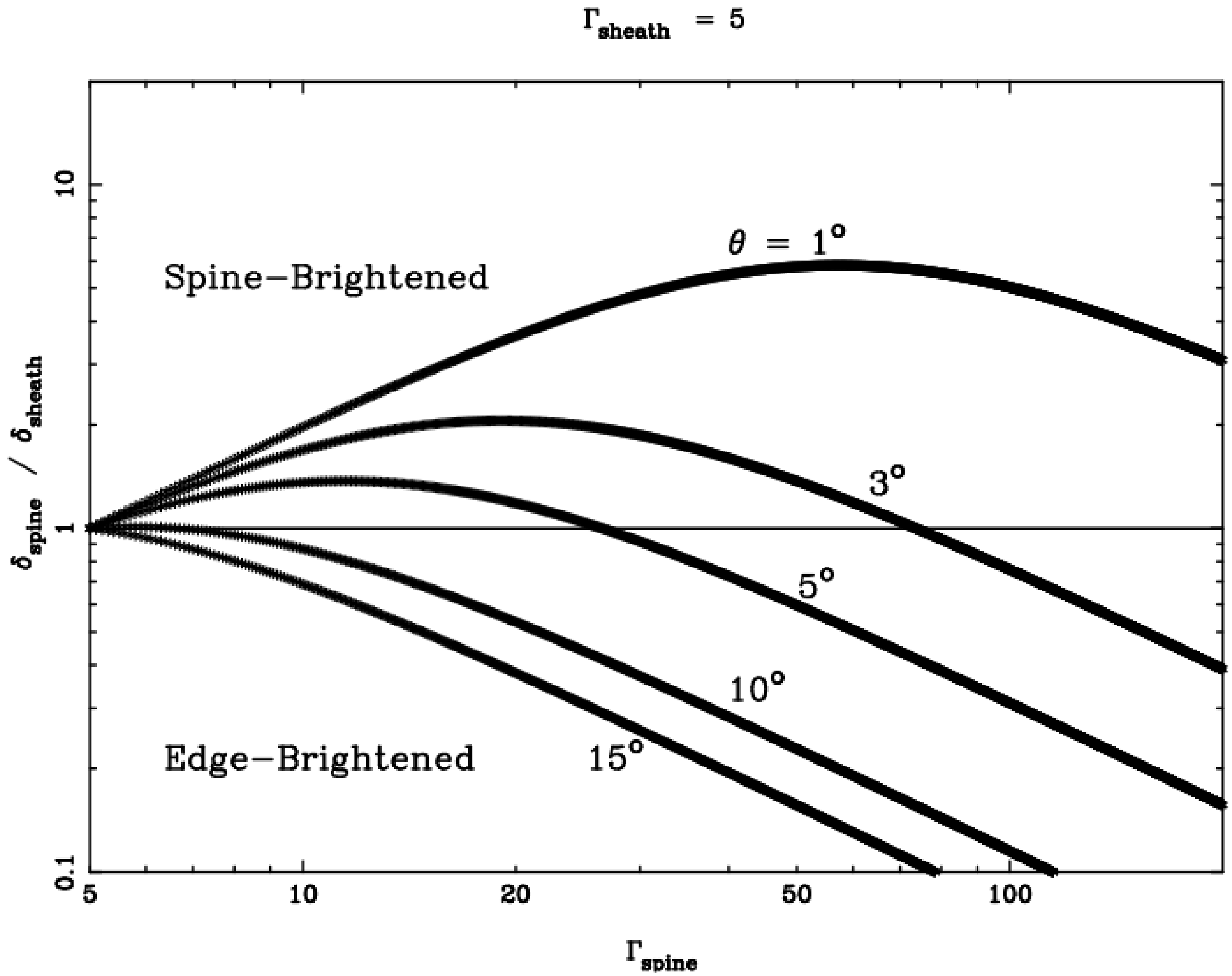




Initial sky position angle of new jet features in the quasar 1222+216

- Sinusoid-like jet position angle variations seen in 20% of jets
- Variations are too slow (decade-long) to claim




Γ_{sheath} = 5
θ = 1°
Spine−Brightened
3°
5°
10°
15°
Edge−Brightened
δ_{spine} / δ_{sheath}
10
1
0.1
5
10
20
50
100
Γ_{spine}

Acceleration of Non-Radial Features

- Define a main jet axis direction based on stacked-epoch images.
- 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