Kinematics of Parsec-Scale Jets of Gamma-Ray Blazars: Ten Years of the 43 GHz VLBA-BU-BLAZAR Program

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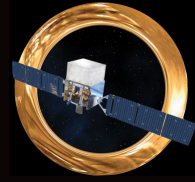
EHT Image of 3C279

VLBA-BU-BLAZAR



- Roughly monthly observations with the Very Long Baseline Array (VLBA) at 43 GHz (7 mm)
- 38 sources, all detected with Fermi:
  - 22 FSRQs
  - 13 BLs
  - 3 RGs (3C 84, 3C 111, and 3C 120)
- Calibrated, cleaned intensity maps and fits files available online https://www.bu.edu/blazars/BEAM-ME.html
- 2007—2013 data published in Jorstad et al. 2017
- Current work = 2007—2018, but not simply a data update!

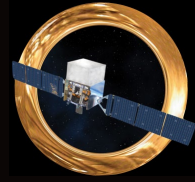
FSRQs

CTA 26	1127-145	1406-076	1730-130
0420-014	1156+295	1510-089	3C 446
0528+134	1222+216	1611+343	CTA 102
0827+243	3C 273	1622-297	3C 454.4
0836+710	3C 279	1633+382	
1055+018	1308+326	3C 345	

BLs

3C 66A	Mkn 421
A0 0235+164	WCom
S5 0716+71	Mkn 501
PKS 0735+17	1749+096
0829+046	1ES 1959+650
OJ 287	BL Lac
0954+658	

★ = Changed process, new analysis, or new definition since 2017



All for individual sources
and for the three subclasses

Clean-ed VLBA Images

Difmap: Use Gaussians to model total intensity

Connect "knots" across epochs, calculate kinematics ★

Jet Structure

Knots

Brightness Temperatures

Jet PA vs. Time ★

Jet Physical Parameters

Opening Angles ★

Doppler Factors

Bulk Lorentz Factors

Viewing Angles

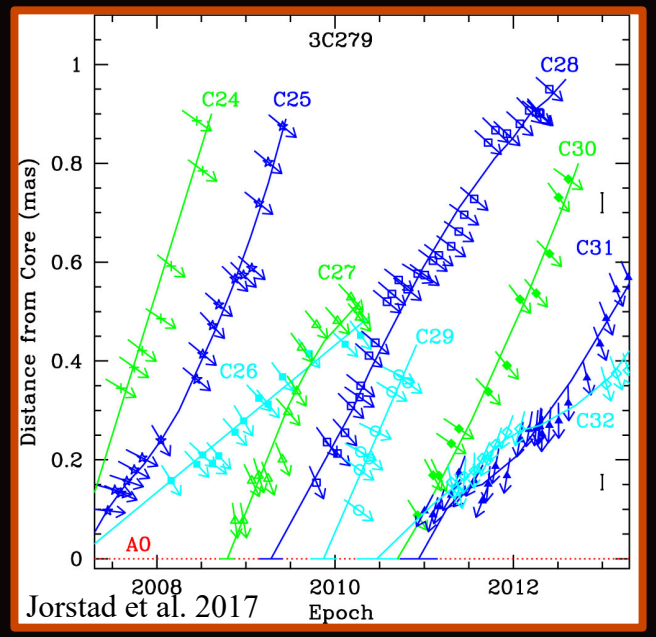
Knot Motions

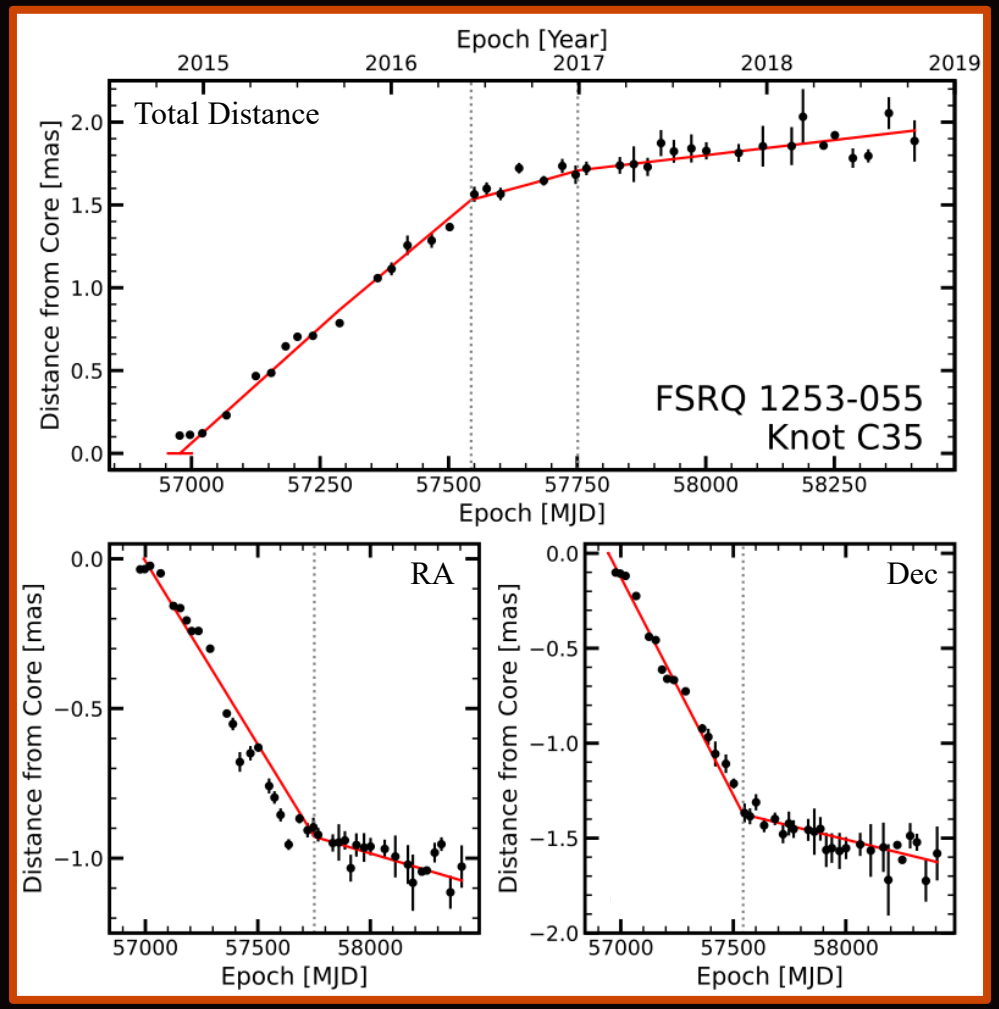
Moving Knots

Accelerations ★

Quasi-Stationary Features ★

Polynomial vs. Piecewise Kinematics

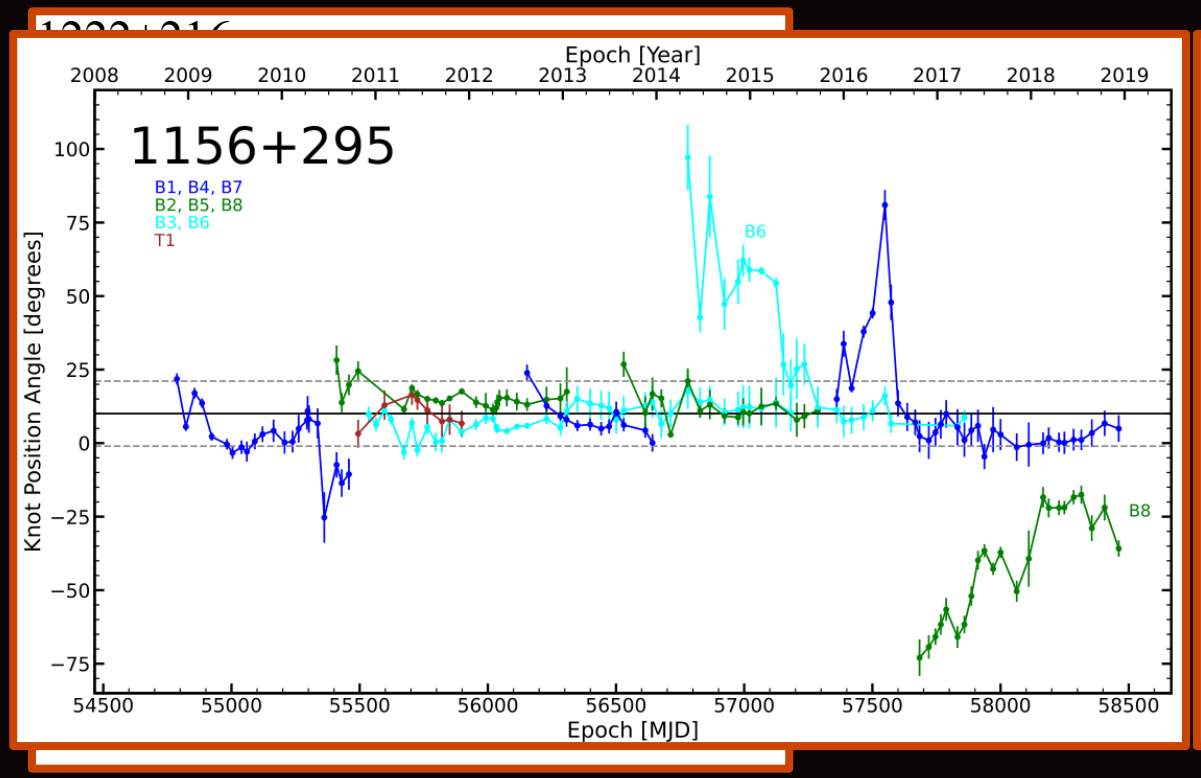


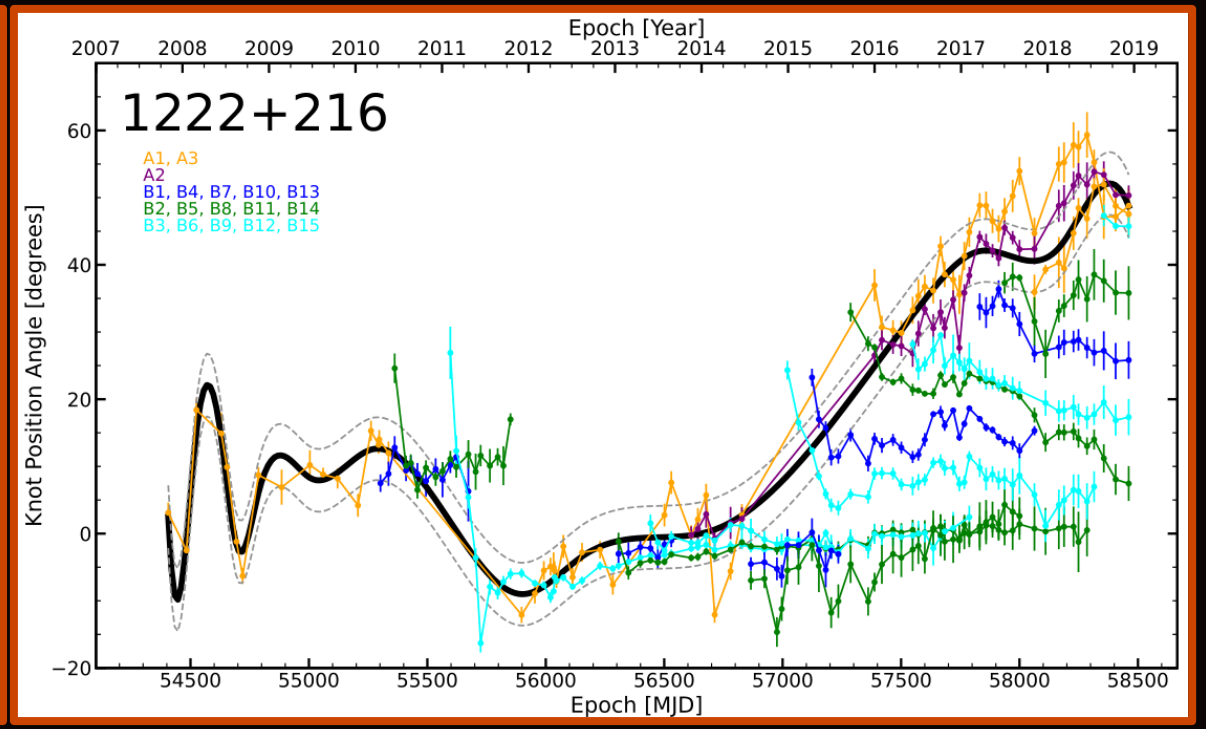


- Advantages of Piecewise Fitting:
  - Simpler to get knot speeds, trajectories
  - More accurately defines time of acceleration
  - Can get distance along jet to acceleration region
  - Easy to separate acceleration in different motion directions
  - Better tracing of time of ejection
- Disadvantage:
  - Discontinuous*

Jet Structure: Position Angle over Time

10 years allows us to see long-term changes in jet orientation



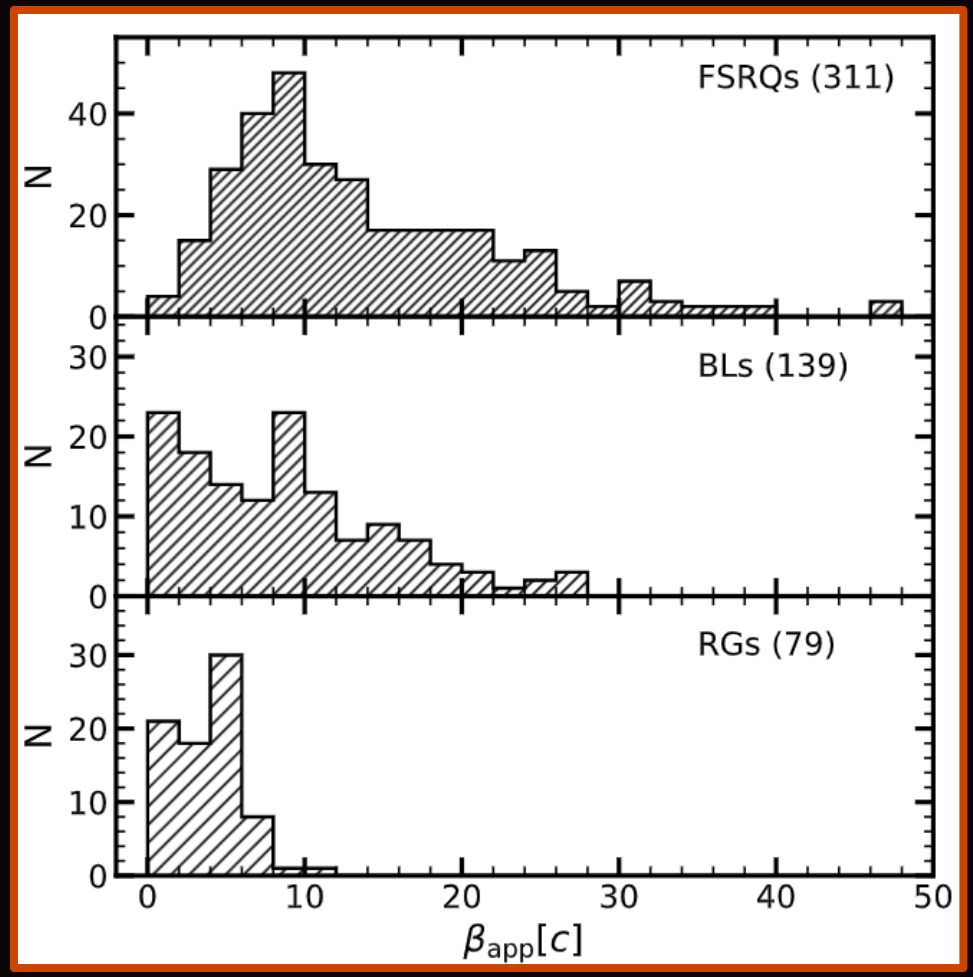


29 sources = Constant PA

9 sources = Changing PA

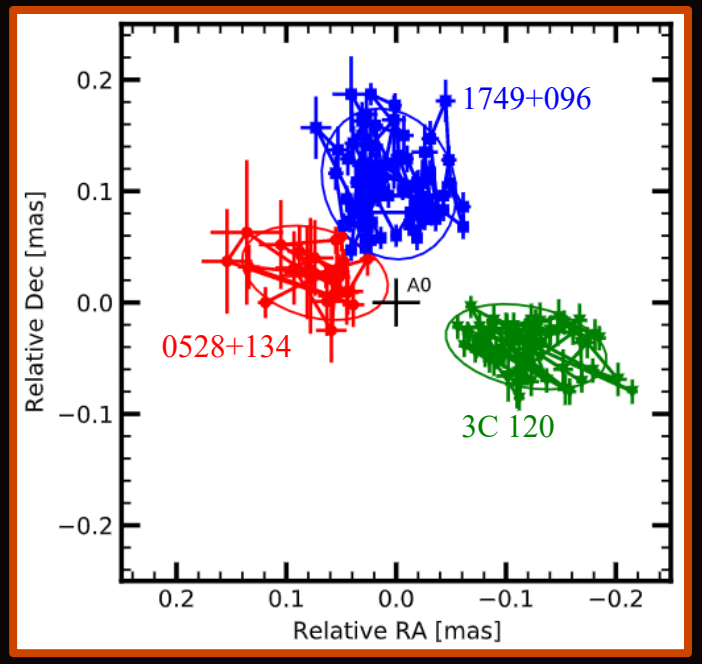
Moving Knots

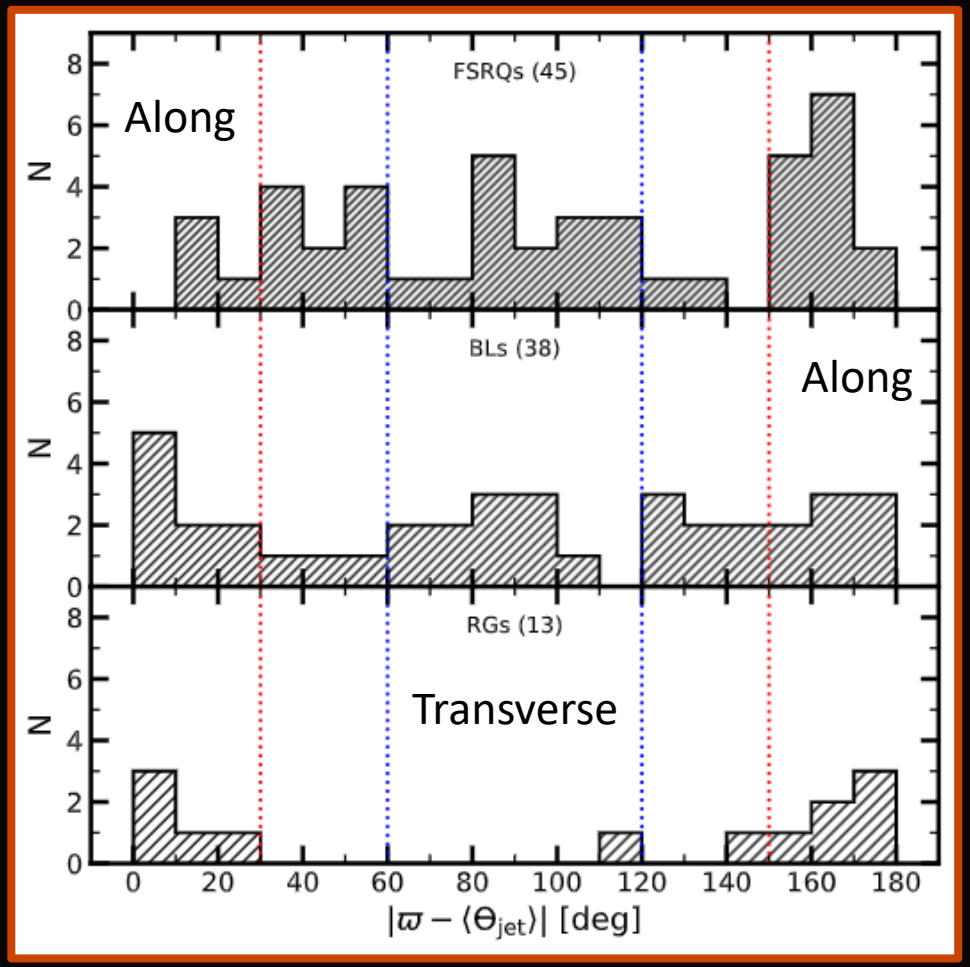
- 529 distinct knot speeds seen in 426 total knots
- FSRQ knots move fastest ($\beta \sim 0.5c - 50c$)
- RGs slowest and narrowest distribution
  - Fastest speeds in 3C 111 and 3C 120, slowest in 3C 84
  - 1 reliable knot with a speed $\beta = 1.4c$ in 3C 84
- All distributions statistically different according to KS test



Quasi-Stationary Features

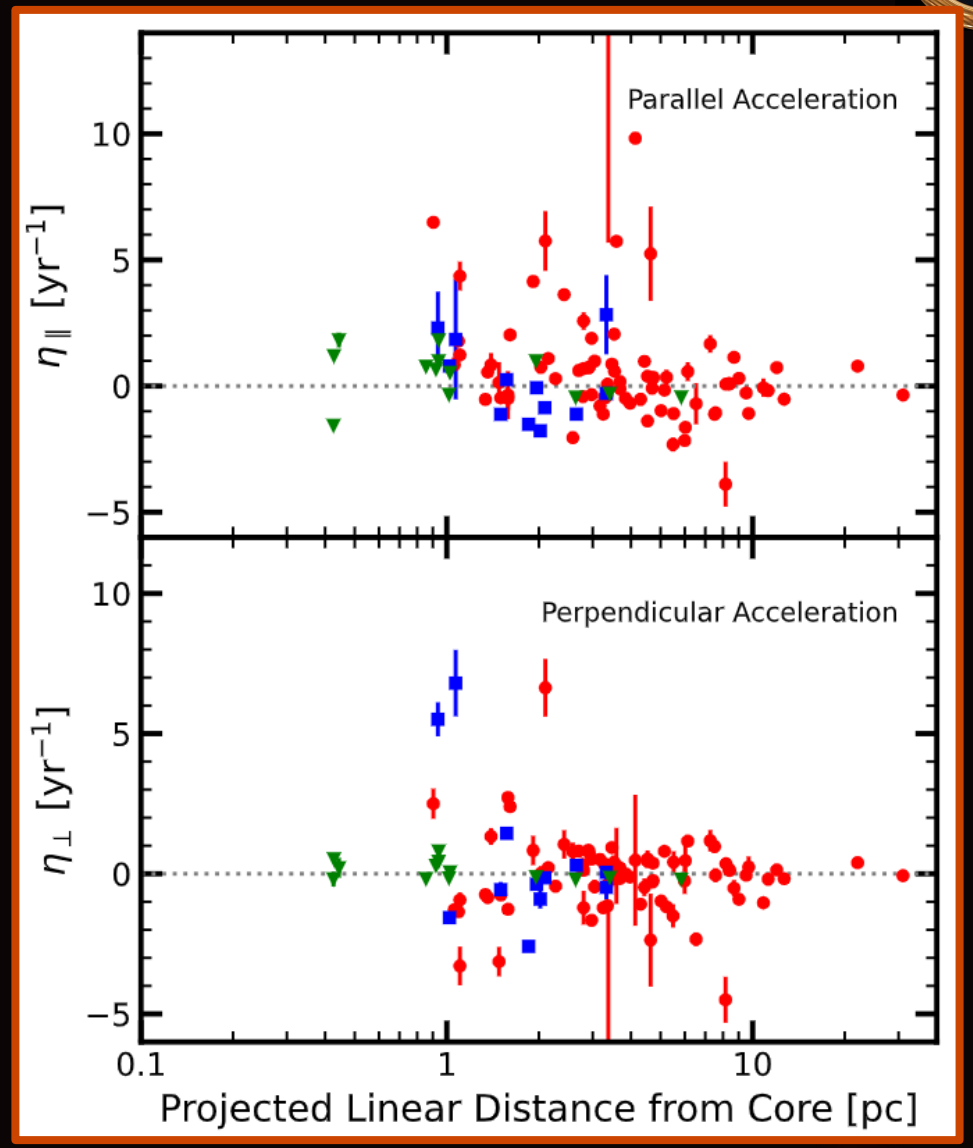
- 96 knots show no significant motion
- On average:
  - 2 knots per FSRQ jet
  - 3 knots per BL jet
  - 6 knots per RG jet
- At least half appear or disappear with time → not permanent features!
- Fluctuate in position more than can be explained by errors





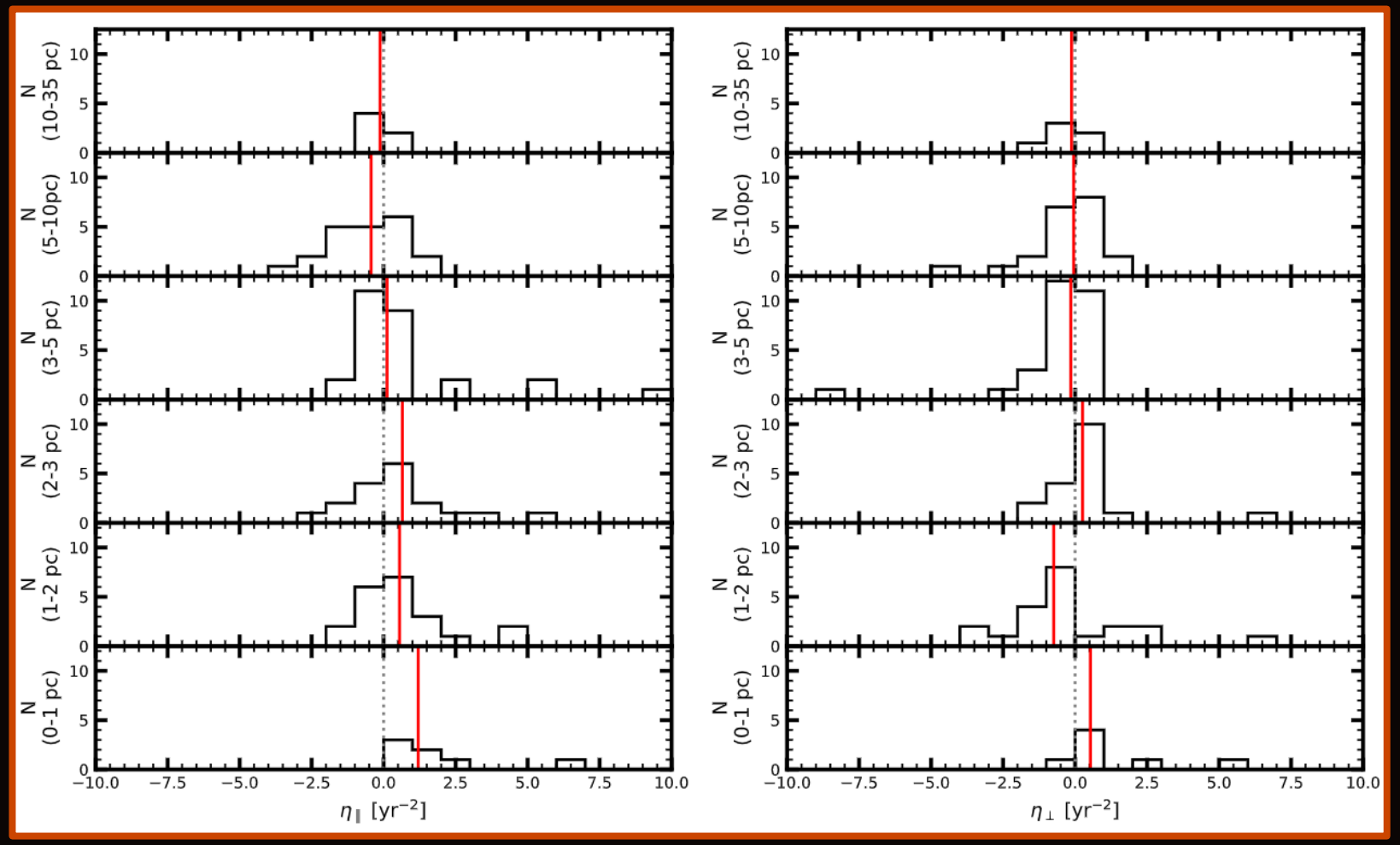
Accelerations

- 75 knots required non-linear fits (17.6%)
- Some knots have >1 acceleration region – 104 accelerations
- Normalize accelerations with redshift, knot speed (Homan et al. 2009)
- No distinction between accelerations in each class



Accelerations

- Piecewise linear fitting advantage: Get accurate distances to acceleration regions



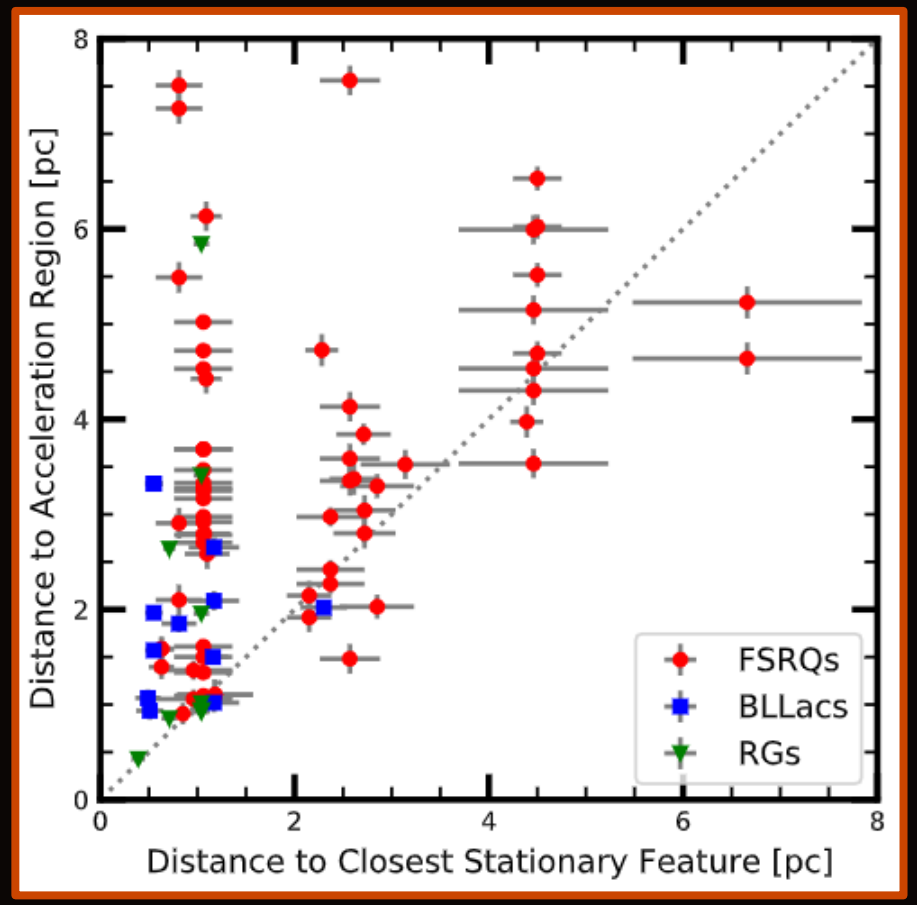
Parallel to jet direction

Perpendicular to jet direction

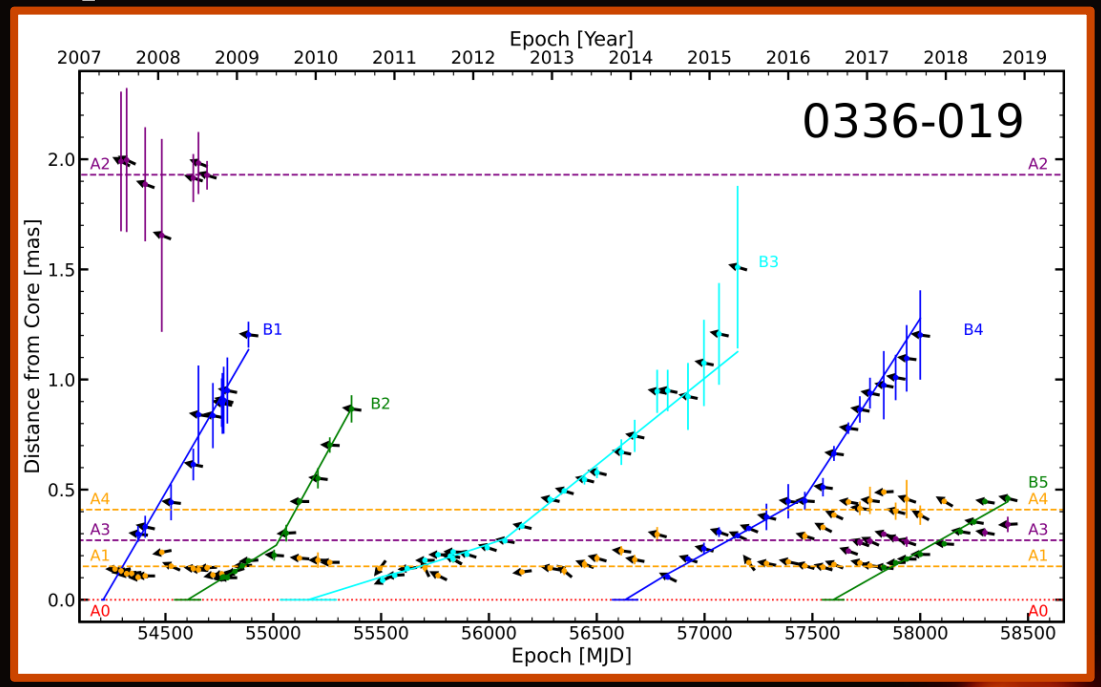
- Parallel to Jet Direction:
  - Initially acceleration
  - Over the length of the jet, turns into deceleration
- Perpendicular:
  - Initial positive acceleration
  - Quickly turns negative
  - Stacking of radio images can help identify if acceleration related to jet width (e.g., Casadio et al. 2021)

Accelerations

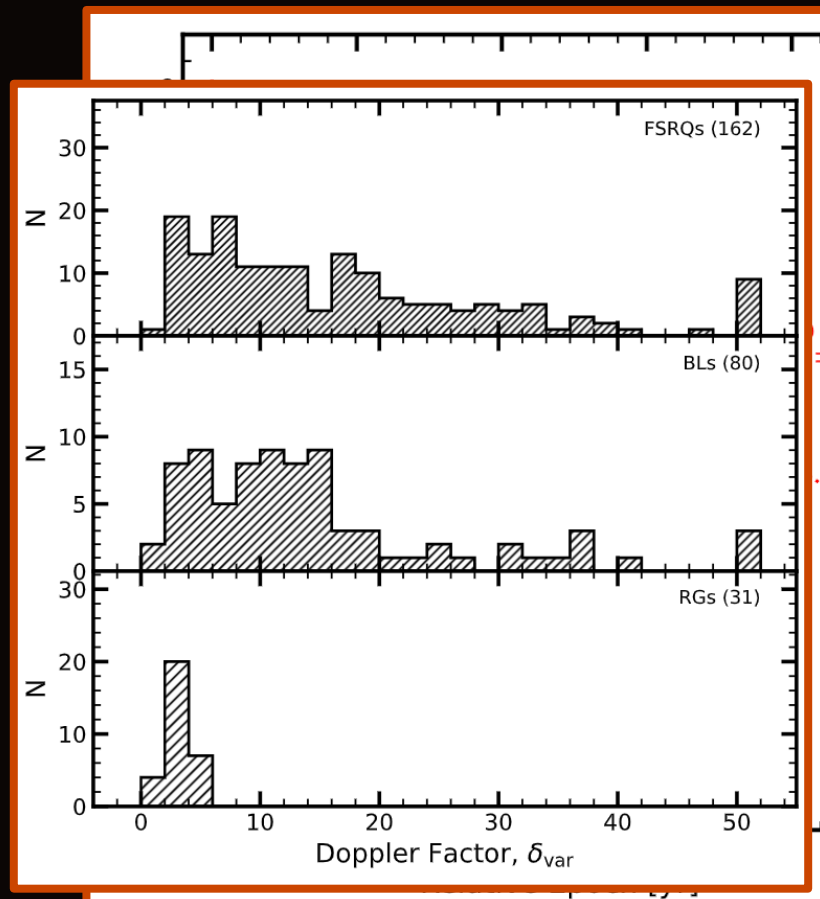
- Piecewise linear fitting advantage: Get accurate distances to acceleration regions

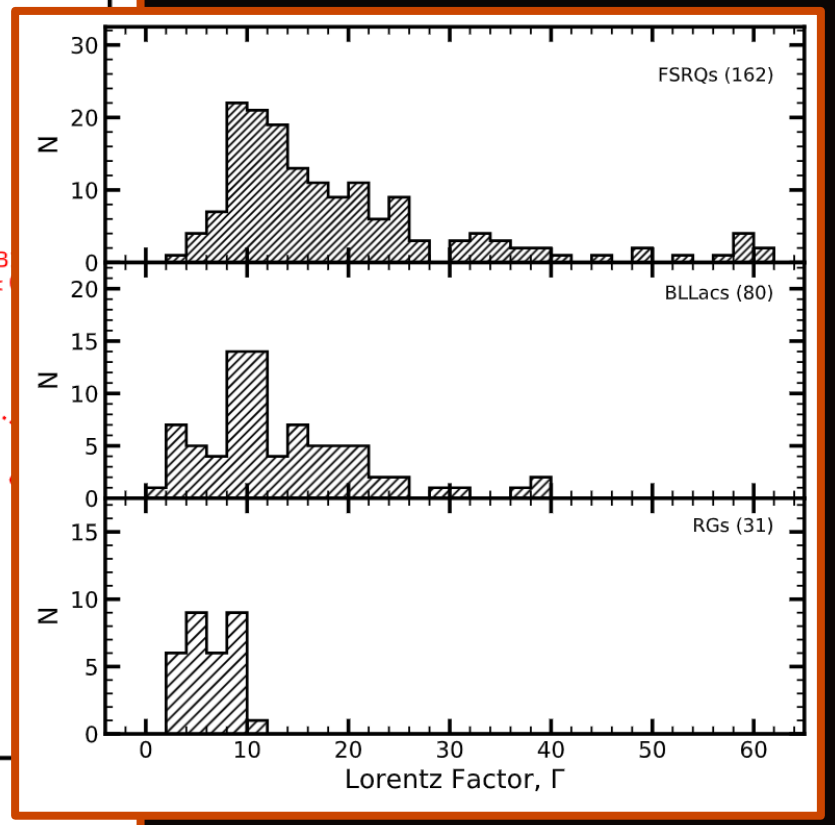


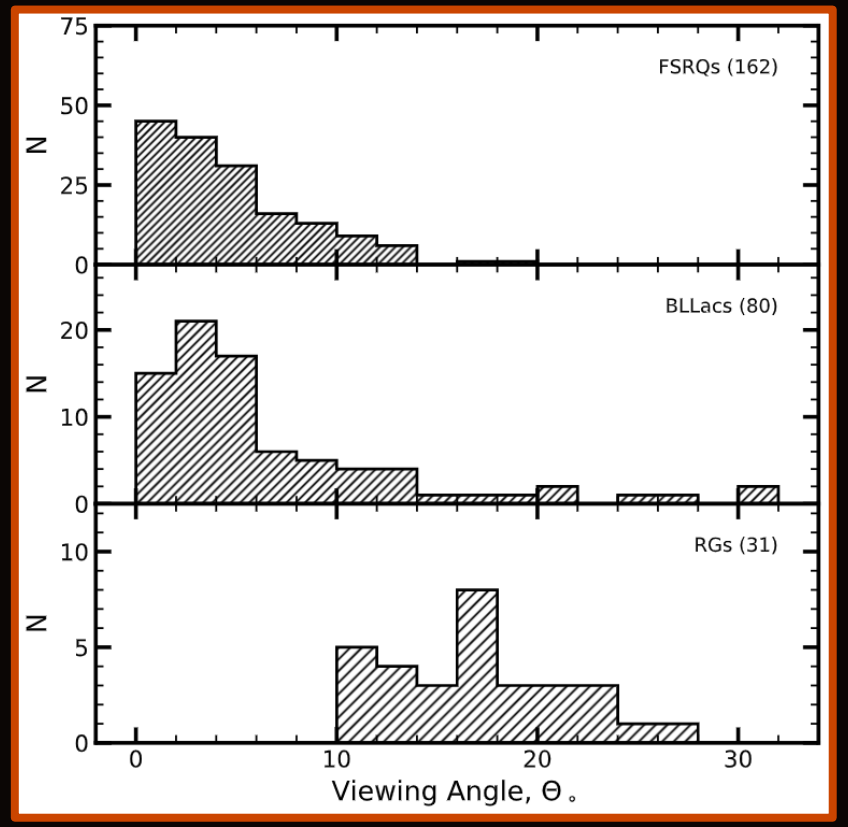
- Can compare acceleration locations with stationary feature locations!
  - Connect accelerations with closest stationary feature
- Most accelerations occur at, or beyond, the stationary features in a jet, regardless of subclass.
- Expected if stationary features are structural components, i.e. recollimation shocks



Physical Parameters

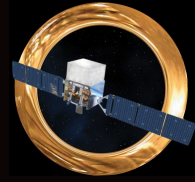






$$\Gamma = \frac{\beta_{app}^2 + \delta_{var}^2 + 1}{2\delta_{var}}; \quad \tan\Theta_\circ = \frac{2\beta_{app}}{\beta_{app}^2 + \delta_{var}^2 - 1}$$

Summary



- VLBA-BU-BLAZAR Program has been monitoring 38 blazars and radio galaxies for 10 years at 43 GHz
- We will publish 2007-2018 data this year, describing kinematics of >500 knots within several parsecs of the central black hole
- We have calculated apparent speeds, times of ejections, and physical parameters of the knots
- Typical parameters of the jets in the sample, average for each subclass will be provided in the paper
- Let us know if there is a source you are interested in!
- VLBA-BU-BLAZAR will continue as BEAM-ME
  - Add bi-monthly 86 GHz monitoring, circular polarization, compare with optical/X-ray polarization (IXPE), neutrino detections, etc.