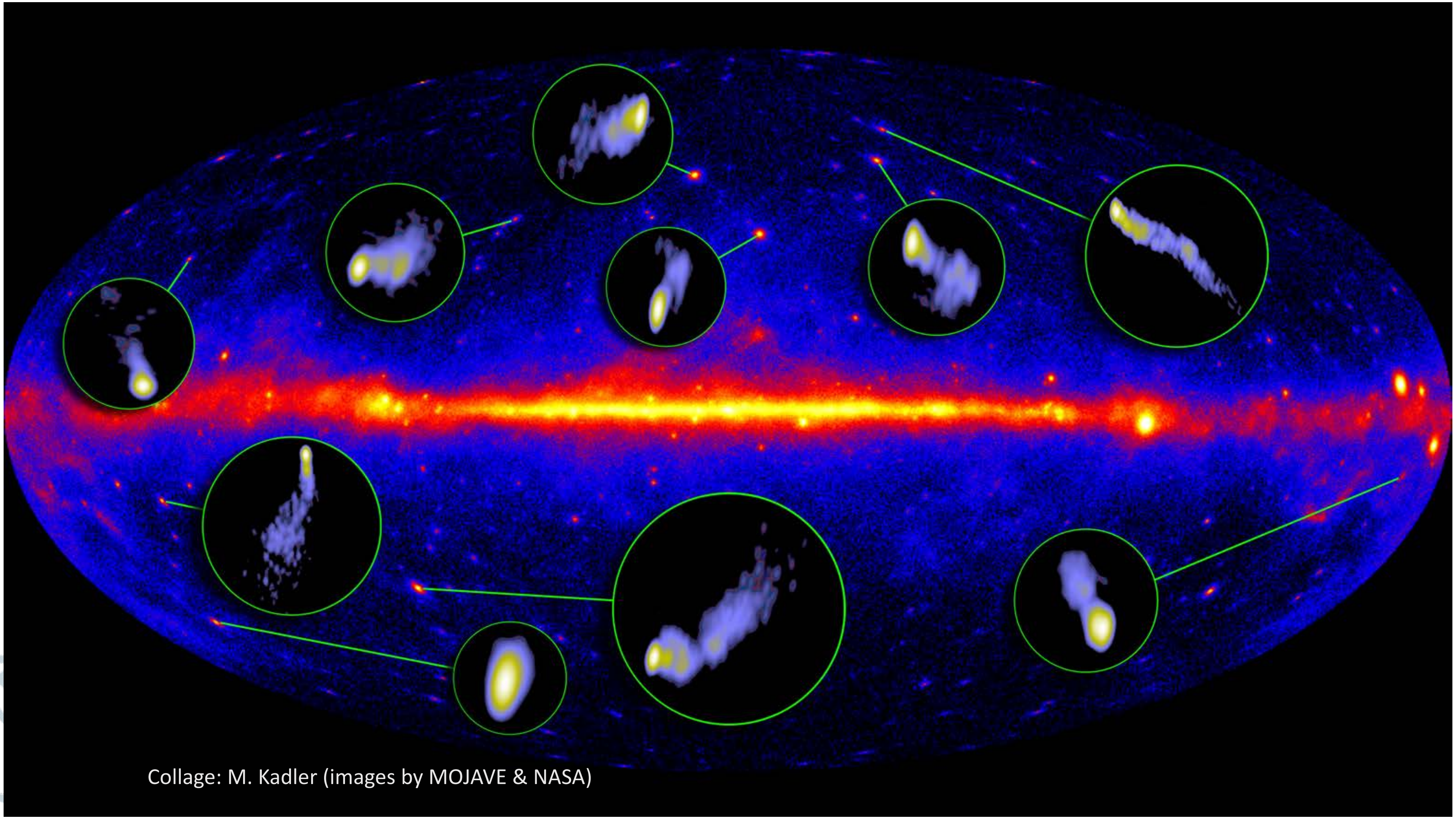
AGN Monitoring with VLBI

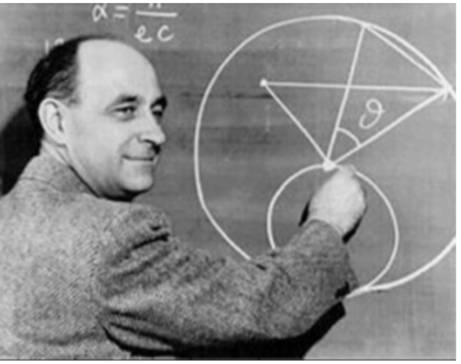
Eduardo Ros (MPIfR)

Monitoring the Universe

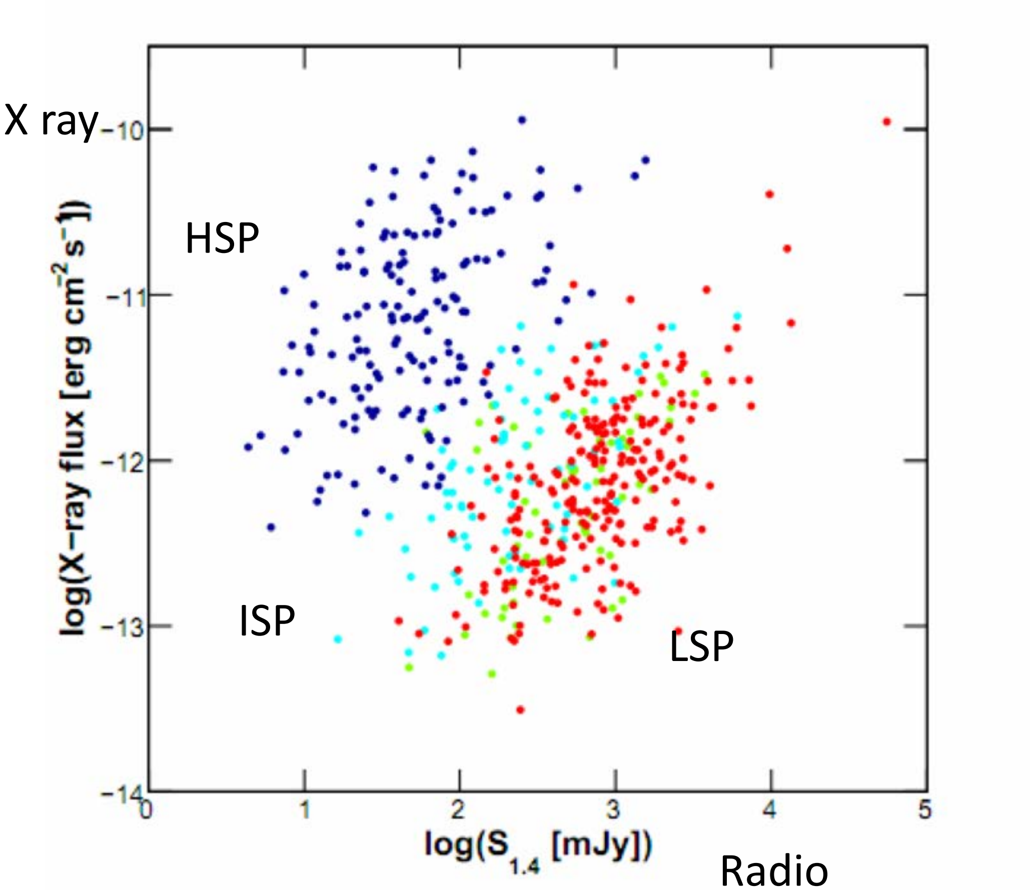
Cochem, September 20th, 2018

Gamma and radio sky





The radio-γ connection



Fermi LAT Coll 2012 ApJ 743 171

- Fermi is an excellent AGN survey instrument:
  - jet flux only, no contamination from host galaxy
- Quasars are all low-spectral peaked
- IC scattering of broad line region photons quenches high energy electron population
- Highest spectral peaked (HSP) jets are the less powerful BL Lac class (no broad line region)

Why VLBI?

- Extremely high angular resolution (sub-milliarcsecond corresponding to parsecs)
- Precise positional accuracy for astrometry

- Too much resolution
  - Sensitivity limits require compactness $T_b > 10^6$ K
- But also limited resolution
  - Some sources still too compact
- Interferometric coverage
  - Sparse Fourier sampling limits image fidelity
- Limited field of view
  - Multi-sky position correlated possible, but challenging

Blazar Characteristics

- Powerful jets oriented towards the observer
- High T_b (VLBI targets)
- Smaller apparent speeds than QSOs, especially for TeV sources (smaller viewing angles?)
- Predominantly high-synchrotron-peaked (HSP) sources

Note: HSP ➔ $\nu_p > 10^{15}$ Hz; ISP ➔ 10^{14} Hz $< \nu_p < 10^{15}$ Hz; LSP ➔ $\nu_p < 10^{14}$ Hz

Properties probed by VLBI

- Multifrequency/phase-referencing ➔ core-shift ➔ magnetic field, pressure gradients, etc.
- T_b (usually of $\approx 10^{12}$ in core, dropping to $\approx 10^{10}$ or lower in jet)
- Shocks and/or instabilities (components/features)
- Linear and circular polarization ➔ magnetic field orientation
- Structural changes ➔ helical jets, binary BH hypothesis
- Ejection times for traveling components, related to core flux density outbursts
- Interaction of moving and standing shocks

VLBI surveys

- Limitation by the availability of ad-hoc antenna arrays, small recording bandwidth, correlator capabilities
- Identification of suitable targets from single-dish catalogs and then pointed VLBI observations
- VLBI surveys filter AGN from other radio-loud objects
- Pearson-Readhead Survey (P&R 1981, 1988)

Pictures: Stamping Through Astronomy

Survey goals
(e.g. MOJAVE)

- Overall distribution of superluminal speeds and intrinsic velocities in jets?
- Location of acceleration and collimation area
- Trajectories of components within jets?
    - Same speeds?
    - Curved or straight?
    - Accelerations or deccelerations present?
- Velocity relation to nature of host galaxy?
- Differences between bulk flow and pattern velocity?
- Nature of material responsible of polarization alterations?
- Mechanism of production of circular polarization?
- High-energy emission and jet activity correlation?

Adapted from http://www.physics.purdue.edu/astro/MOJAVE/project.html

Parsec-scale properties

- Directly measured:
  - Apparent speed β_{app}
  - Comp. flux density S
  - Brightness temperature T_b
  - Apparent opening angle ψ
  - Luminosity L_R
  - P.A. misalignment with kpc $\Delta\phi$
  - Spectral index α
  - Lin. polarisation angle χ
  - Lin. polarisation level m
- Indirectly:
  - Viewing angle θ
  - Lorentz factor Γ
  - Doppler factor δ
  - Component ej. epoch t_0

	β_{app}	S	T_b	α	δ	θ	L_R	Δϕ	ψ	χ	m
Det	**Histograms**, selecting by opt. class ad HBL/IBL/…										
Fl.											
S_γ											
L_γ											
Γ											
G_r											
ν											

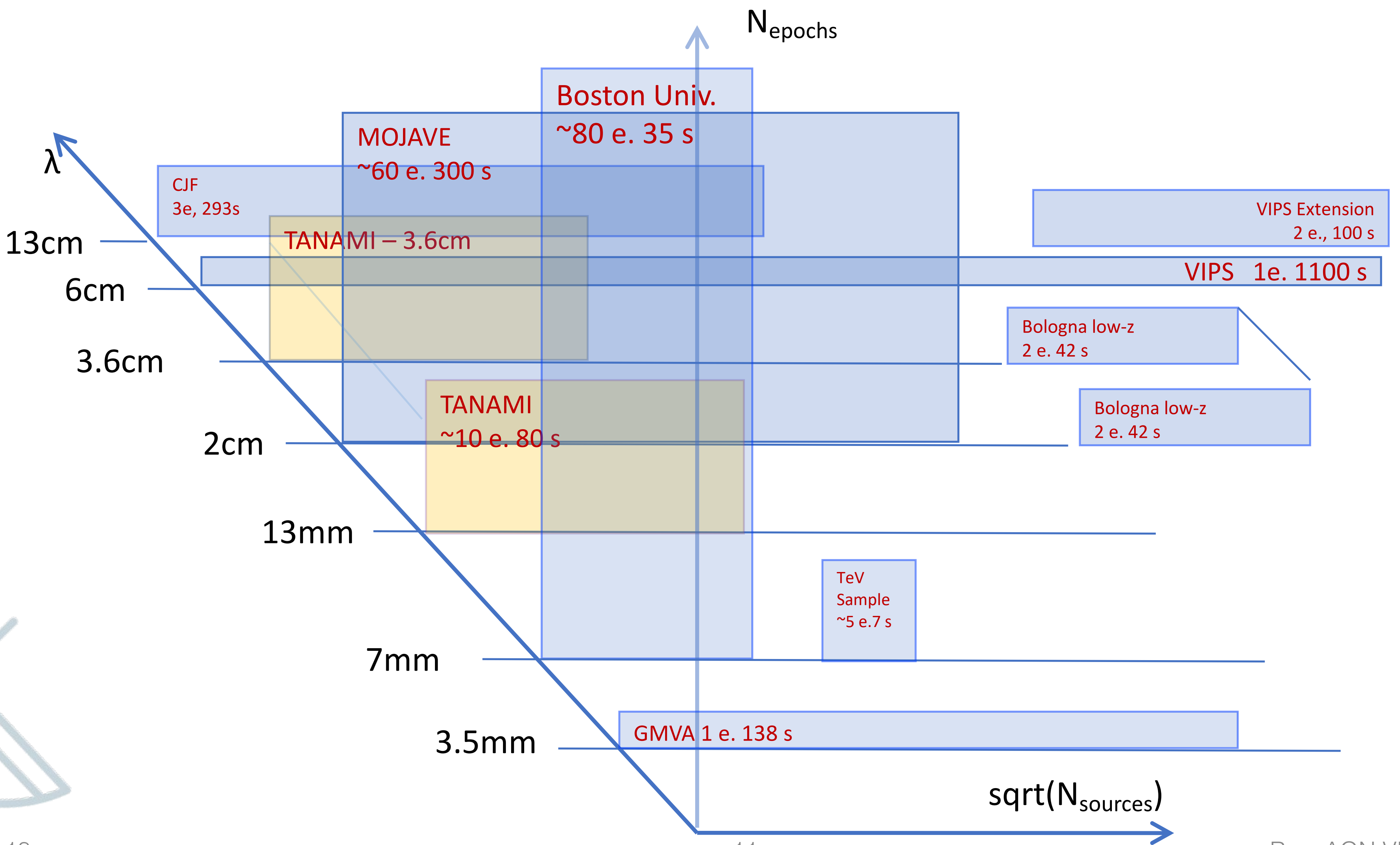
CORRELATION PLOTS

High-energy properties

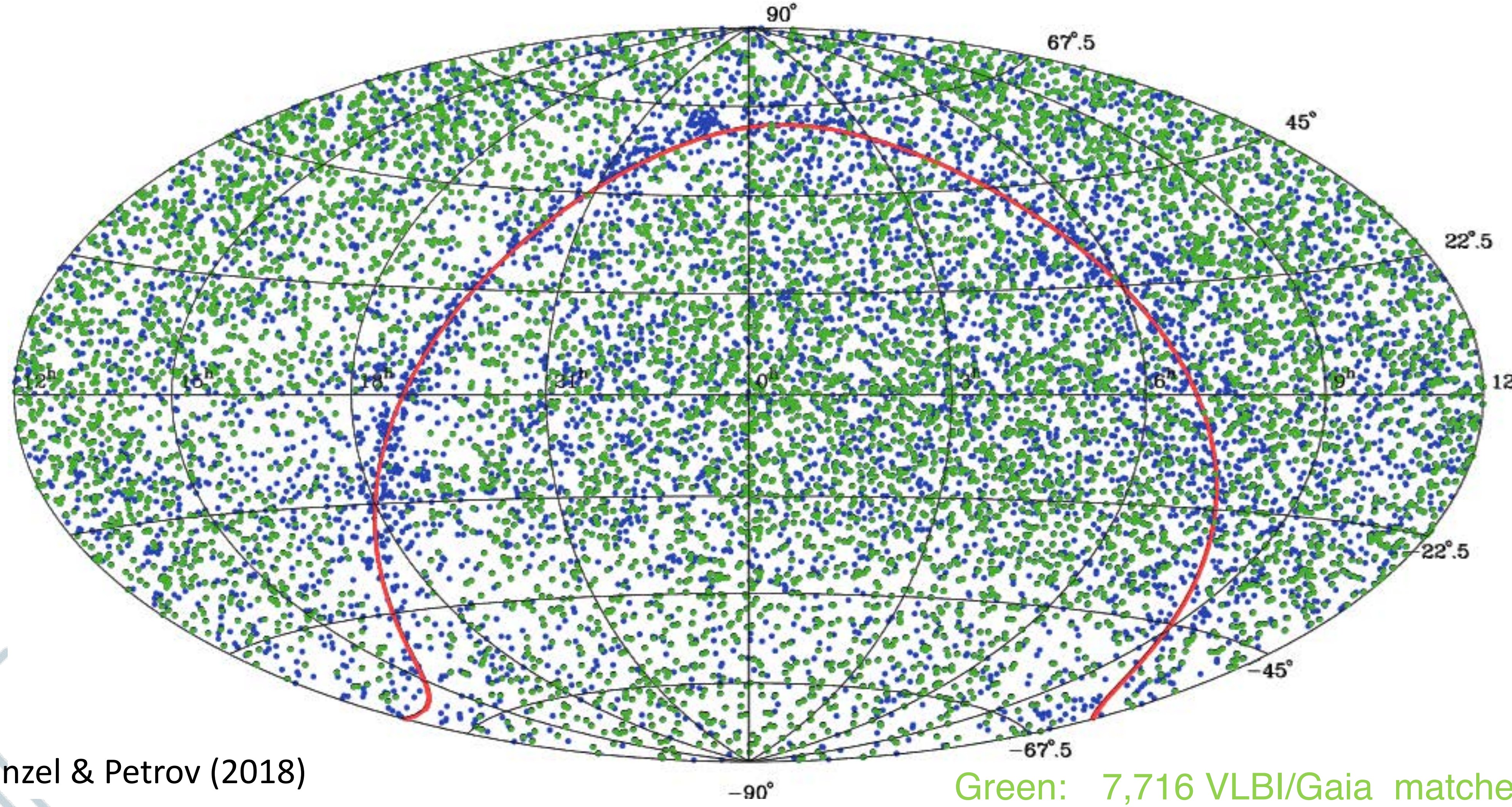
- Direct properties:
  - Detection (yes/not)
  - Flaring activity
  - Flux S_γ
  - Luminosity L_γ
  - Photon index Γ
- SED properties:
  - Gamma-radio loudness G_r
  - High-energy peak frequency ν_{IC}

Survey	λ (cm)	S (Jy)	# sou	#ep	Reference/webpage
mJIVE-20	20	0.001	4300	1	https://safe.nrao.edu/vlba/mjivs/
Cork	20	1.5	135	1	http://physics.ucc.ie/radiogroup/18-22cm_observations.html
RadioAstron	20/6	0.6	240	1	Kovalev+ in prep
RFC	15/4	0.2	9500	1	http://astrogeo.org/rfc/ Deller & Middelberg'14
VIPS	6	0.085	1127	1/2	http://www.phys.unm.edu/%7Egbtaylor/VIPS/ Hemboldt+'07, Linford+'11
VSOP PLS	6/2	0.3/1	374/140	1	http://www.vlba.nrao.edu/astro/obsprep/sourcelist/6cm/ Moellenbrock+'96
CJF	6	0.35		3	https://www3.mpifr-bonn.mpg.de/staff/sbritzen/cjf.html Taylor+'96 Pearson+'98 Britzen+'07
TANAMI	**4/1**	**2**	**80**	**10**	**http://pulsar.sternwarte.uni-erlangen.de/tanami/ Ojha+'08 Müller+'16**
Bologna low-z	4/2		42	2	Giroletti+'11
MOJAVE	**4**	**1.5**	**400**	**40**	**http://www.astro.purdue.edu/MOJAVE/ Lister+'09**
VERA	1/0.7	0.2	551	1	http://astrogeo.org/kj-qcal1/ Petrov+'11
TeV	0.7		20	10	http://whittierblazars.com/ Piner+ 2010, Piner & Edwards 2018
BU Blazar	**0.7/0.3**		**35/17**	**80/5**	**https://www.bu.edu/blazars/VLBAproject.html**
KVN	0.7	0.2	900	1	http://astrogeo.org/qcal1/ Petrov+'12
GMVA	0.3	0.1	138	1	Lee+'08 Nair+'18

Surveys: an overview



VLBI Radio Fundamental Catalogue (**14,786 sources**) on 01/01/2018 and *Gaia* DR1 ($1.14 \cdot 10^9$ objects)



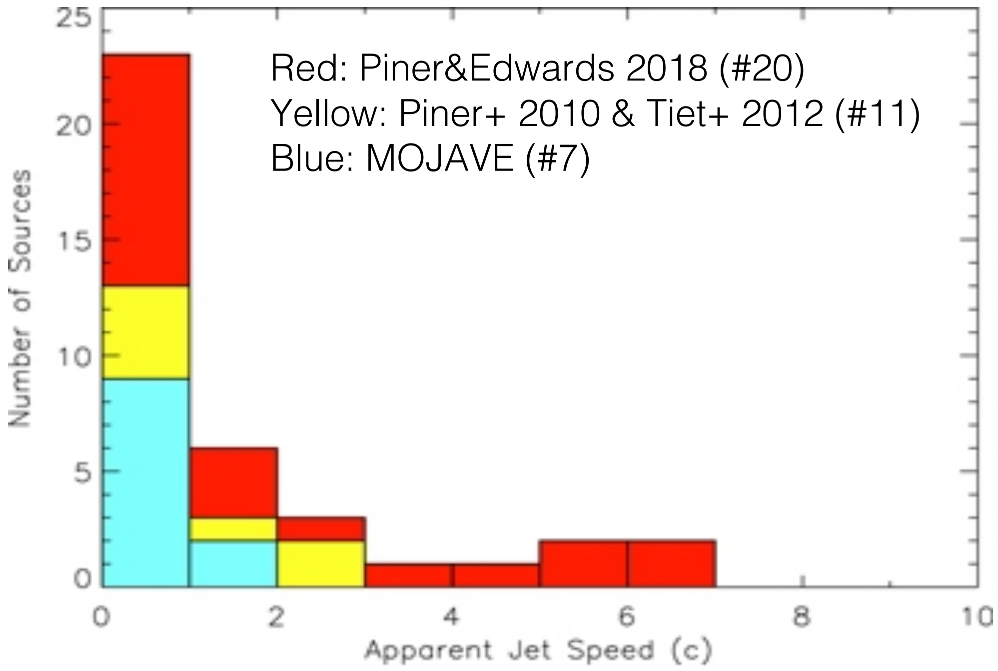
Source: Schinzel & Petrov (2018)

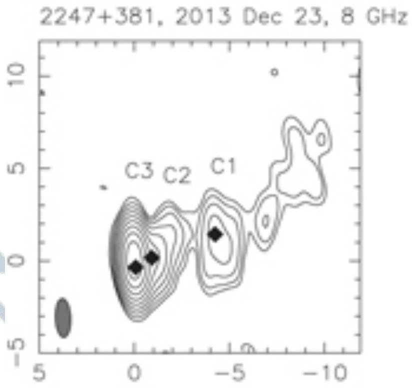
Green: 7,716 VLBI/Gaia matches (P<0.0002)
Blue: VLBI sources without Gaia matches

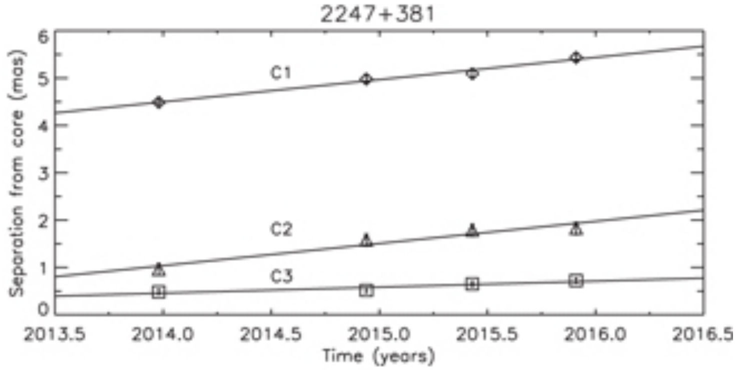
TeV BL Lac VLBA monitoring

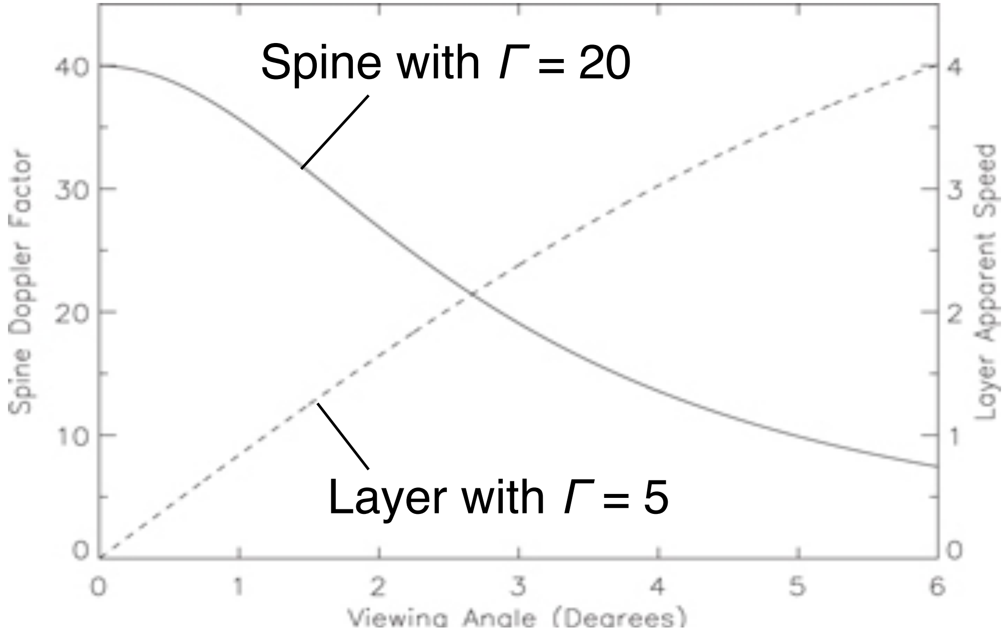
Piner et al.

- TeV emitting sources have low speeds
- Out of 38 HBLs, 2/3 consistent with no motion, highest speed 3.6c
- Bulk Lorentz factors up to 4: fast central spine and slow outer layer







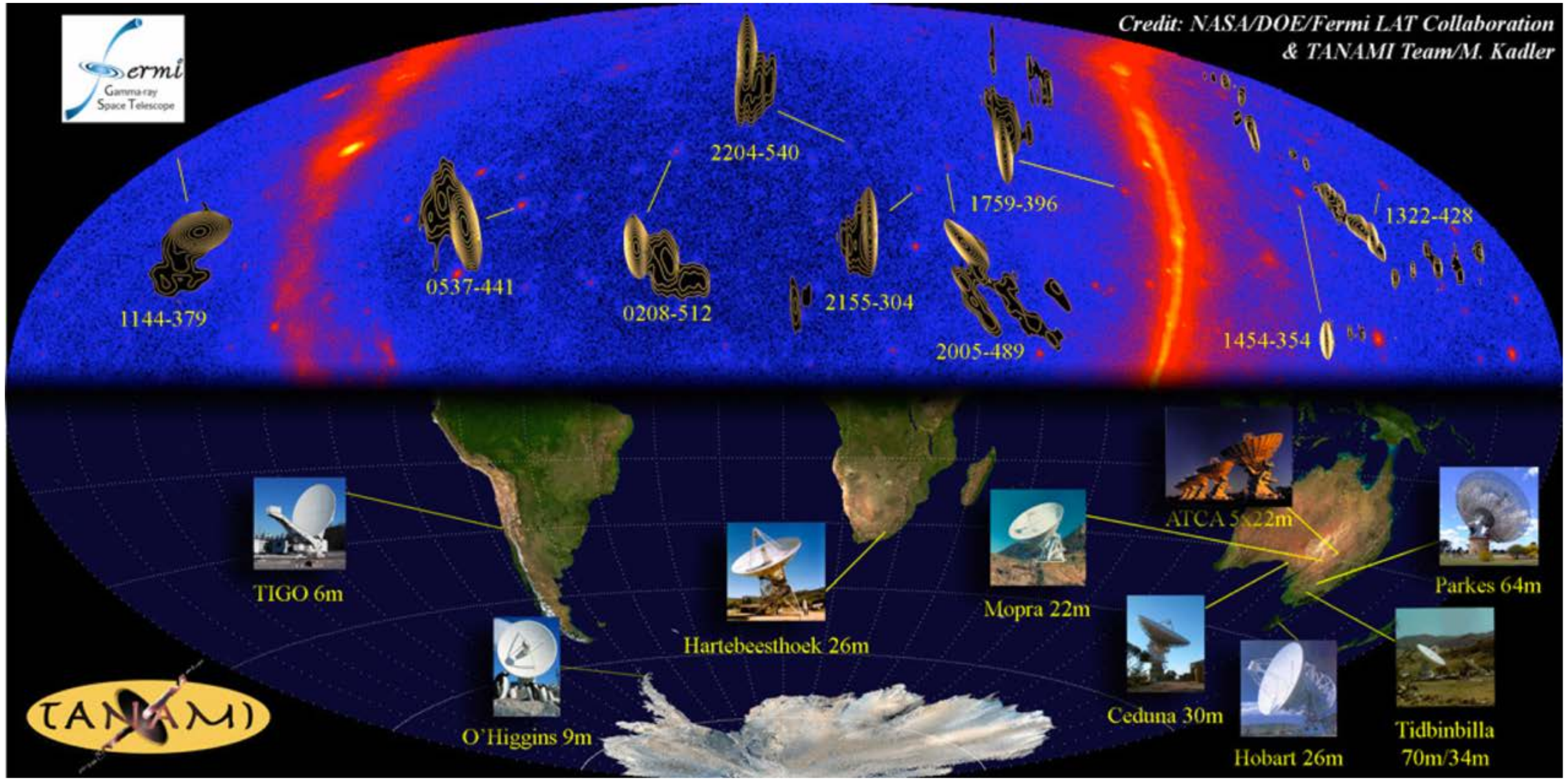


Multi-epoch VLBA Imaging of 20 New TeV Blazars: Apparent Jet Speeds

B. Glenn Piner and Philip G. Edwards 2018 ApJ 853 68 doi:10.3847/1538-4357/aaa425 http://pulsar.sternwarte.uni-erlangen.de/tanami/

TANAMI Project

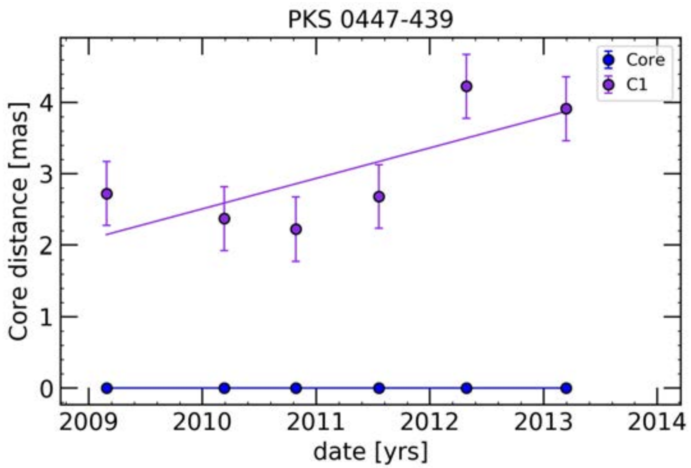
Tracking AGN with Austral Milliarcsecond Interferometry

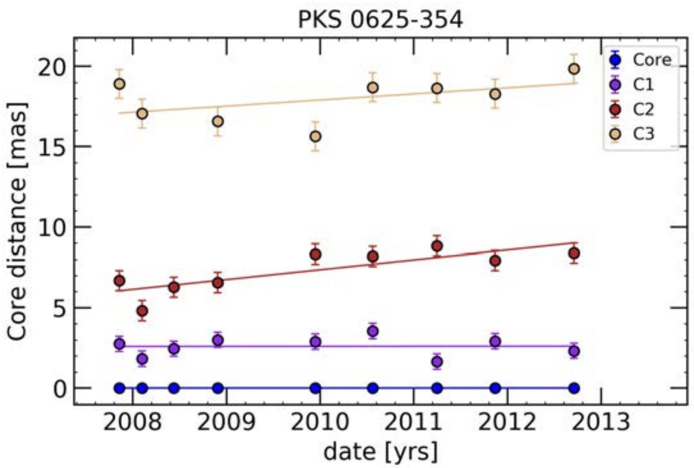


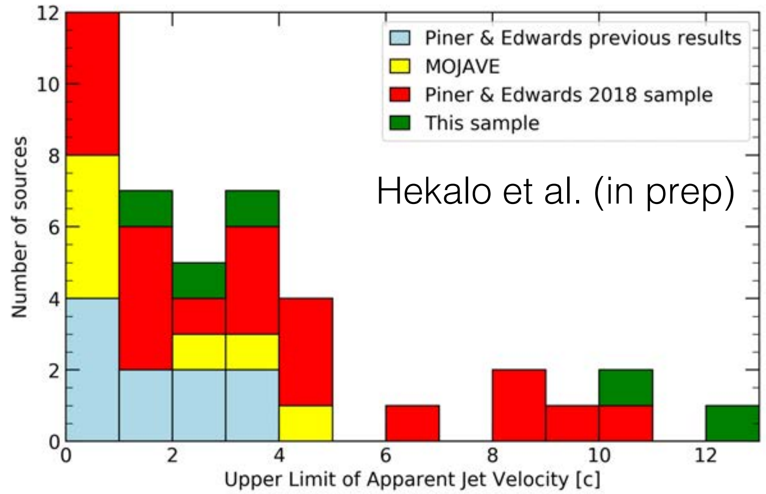
Ojha et al. A&A 2010

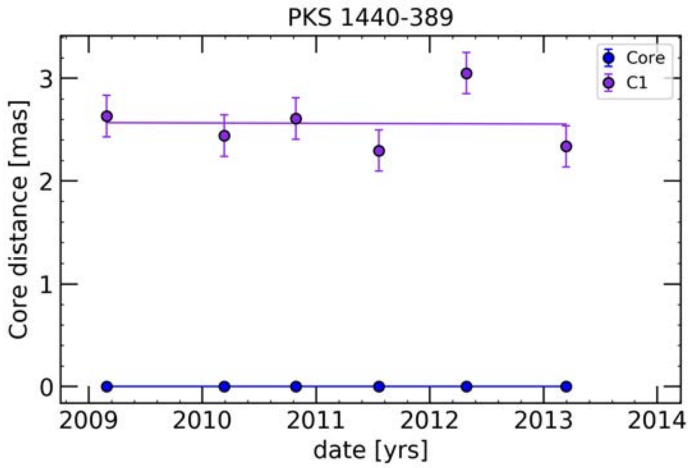
- Monitoring of ~80 Southern Sources at 8.4 GHz and 22 GHz
- Addition of antennas in Chile and Antarctica provide unprecedented austral resolution at 8.4 GHz
- Observations since November 2007, 2-month cadence

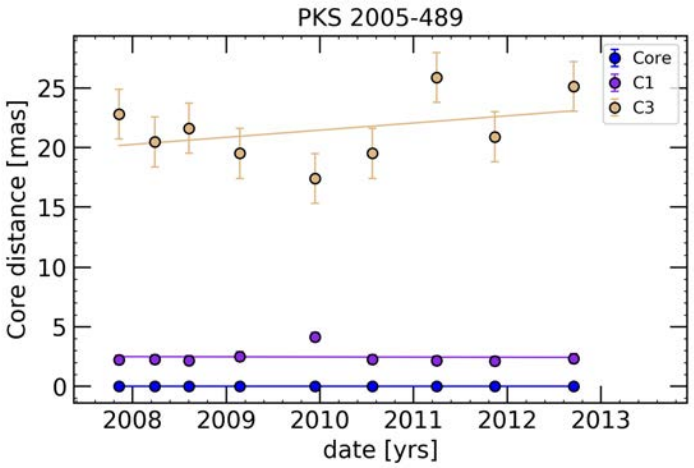
TANAMI monitoring of TeV sources

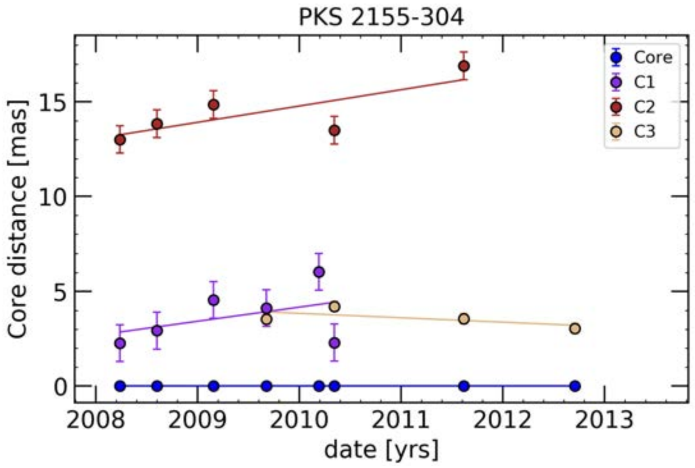








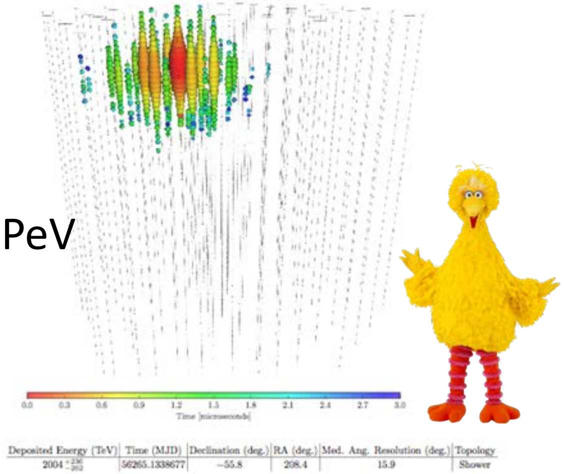


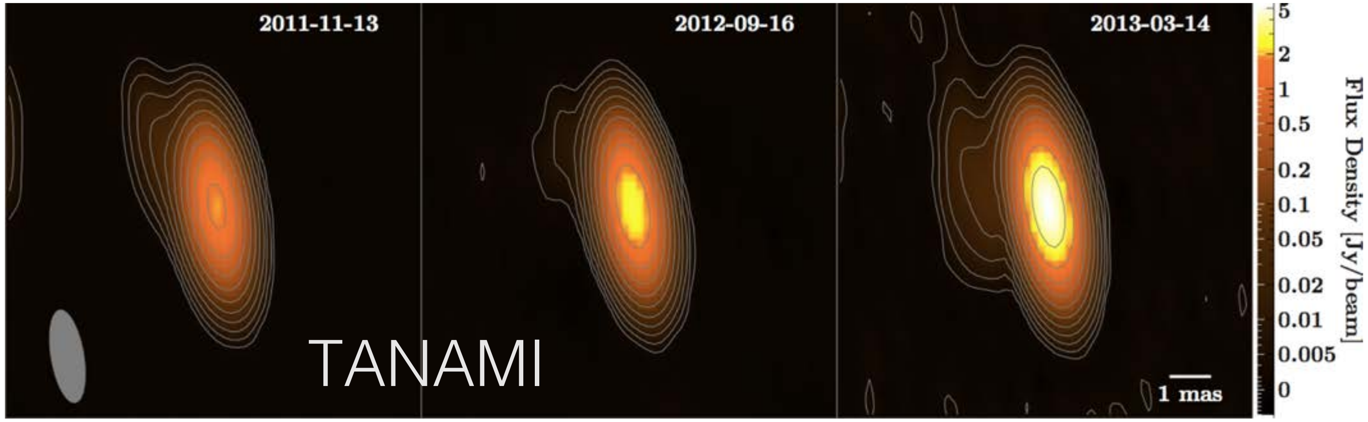


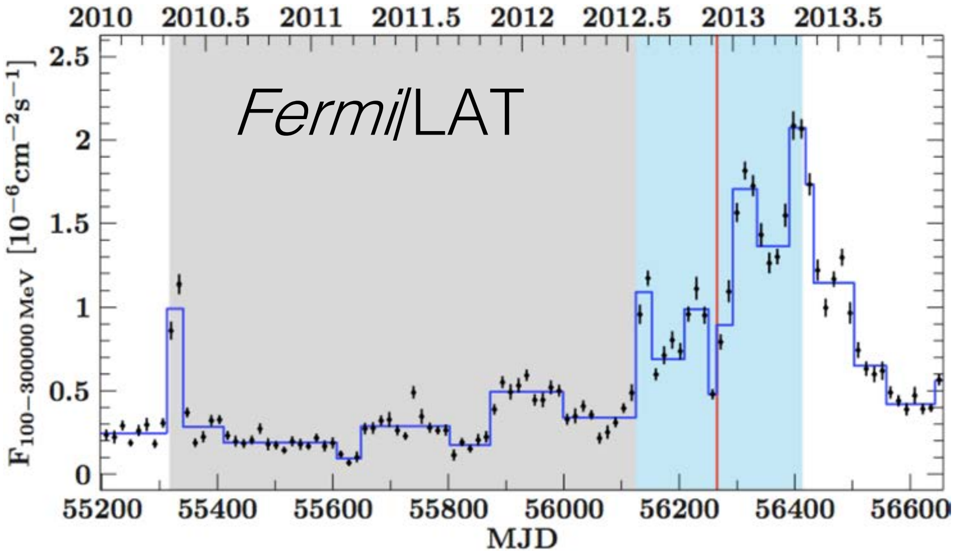
- For Radio Galaxy monitoring, see Angioni's talk

TANAMI Neutrino association PKS B1424–248

E~2PeV





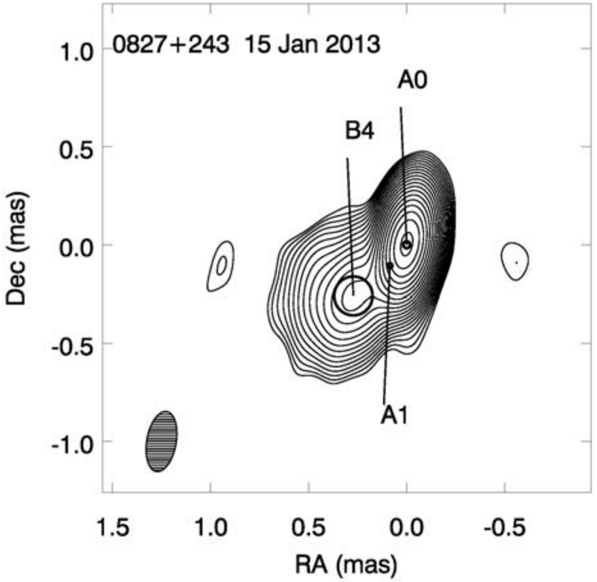


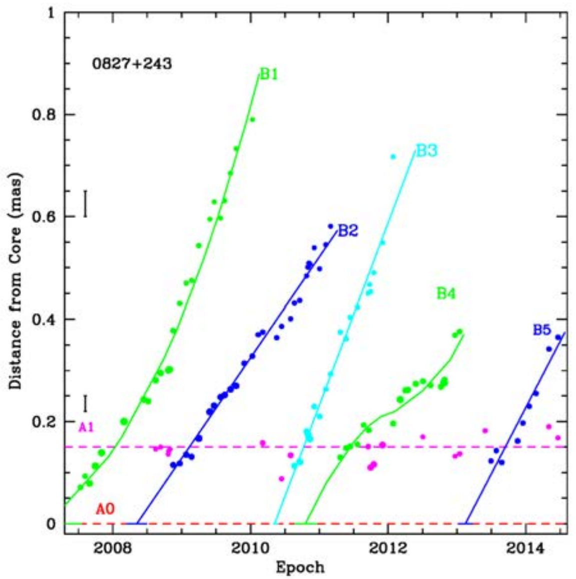
- Major Radio Outburst:
- Radio core flux density increased from 1.5Jy to 6Jy in late 2012 to early 2013
- Strongest outburst ever seen by TANAMI

BU Blazar Monitoring

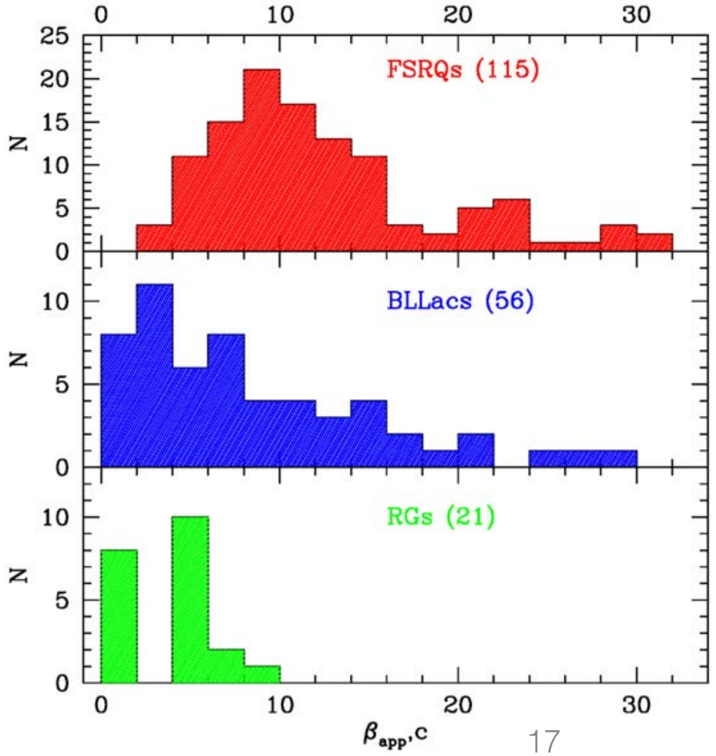
- Study of 35 blazars at 43 GHz monthly w/ VLBA (17 at 86 GHz w/ GMVA bi-annually)
- High spatial and time resolution, with polarimetry
- (Lack of) opacity: closer view the core region and the birth of new features traveling downstream
- Several studies presented individually in publications
- Calibrated data are made public

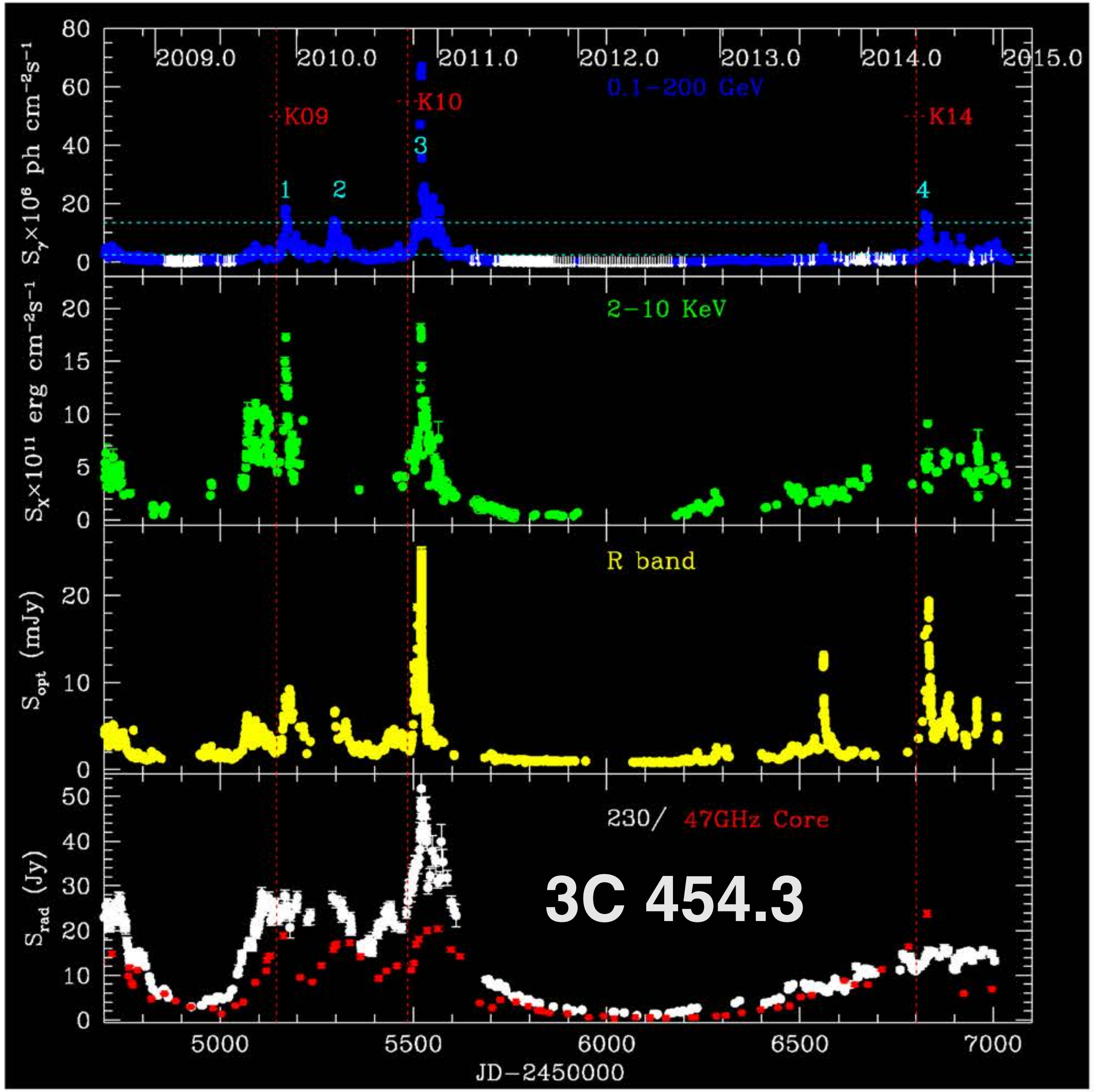
http://www.bu.edu/blazars/

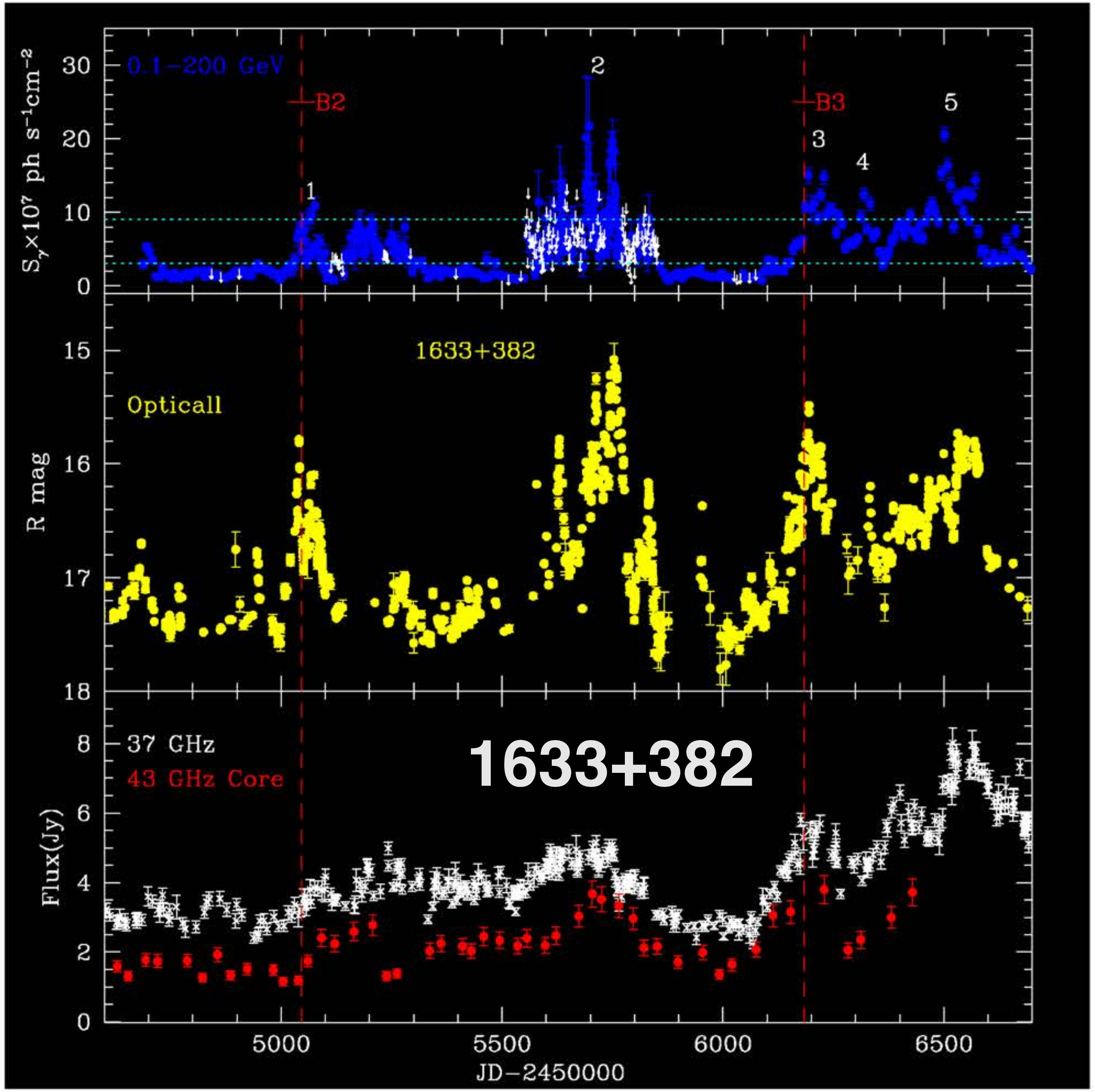




Jorstad, S.; Marscher, A. *The VLBA-BU-BLAZAR Multi-Wavelength Monitoring Program.* Galaxies 2016, **4**, 47







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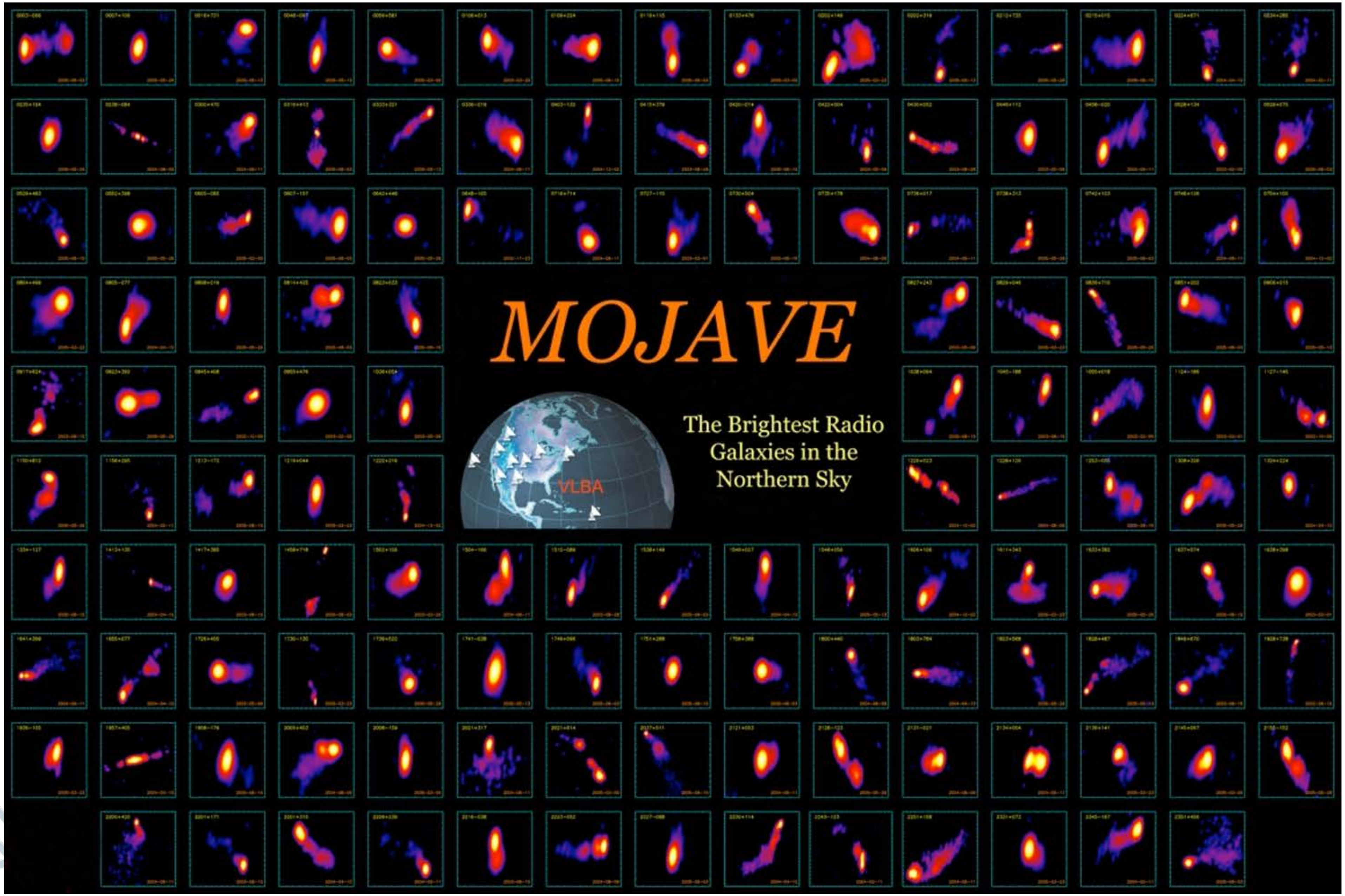

MOJAVE
VLBA
The Brightest Radio Galaxies in the Northern Sky

MOJAVE program

- Milliarcsecond-resolution, full Stokes images
- Currently over ~300 sources monitored
- Continuous long-term monitoring, good sensitivity, source-specific observing cadences ➔ High-quality jet motions
- Large, well-defined sample ➔Statistics, properties of the parent population
- Calibrated data are made public

`https://www.physics.purdue.edu/astro/mojave/`

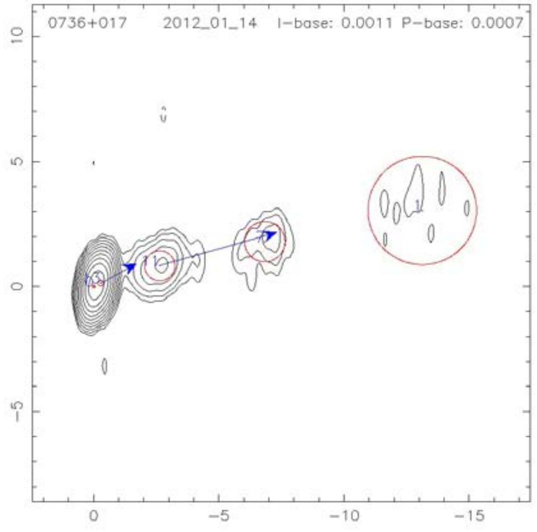
MOJAVE: Monitoring of AGN Jets

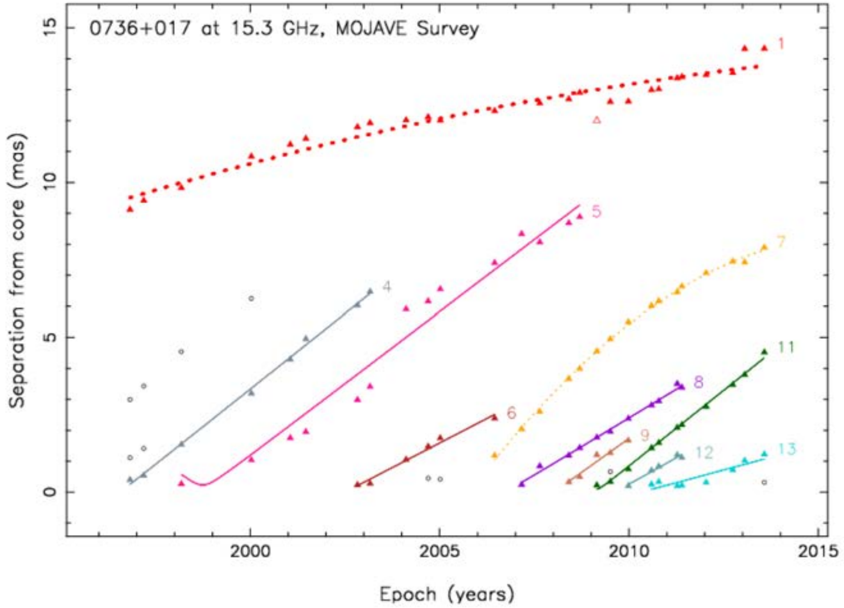
- Linear (I) and circular (II) polarization(also XVI)
- Kiloparsec radio (III, Kharb et al. 2010) and X-ray (Hogan et al. 2011)
- Parent population and luminosity function (IV)
- Faraday rotation measure (VII) and spectral index maps (XI)
- Nuclear opacity and magnetic fields (IX)
- Morphology and compactness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

Roman : paper series number, see details at http://www.cv.nrao.edu/2cmsurvey/publications.html

MOJAVE Kinematics Studies

- Gaussian models fit to visibilities at each epoch (at least 5 epochs per AGN).
  - rms accuracy: 0.05 - 0.1 mas
- 2D sky motion fits made to individual jet features
  - probing jet kinematics at 10-1000 pc (de-projected) from central engine
- MOJAVE X, XII, 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





MOJAVE XIII: Lister et al. AJ **152** 12 (2016)
https://doi.org/10.3847/0004-6256/152/1/12

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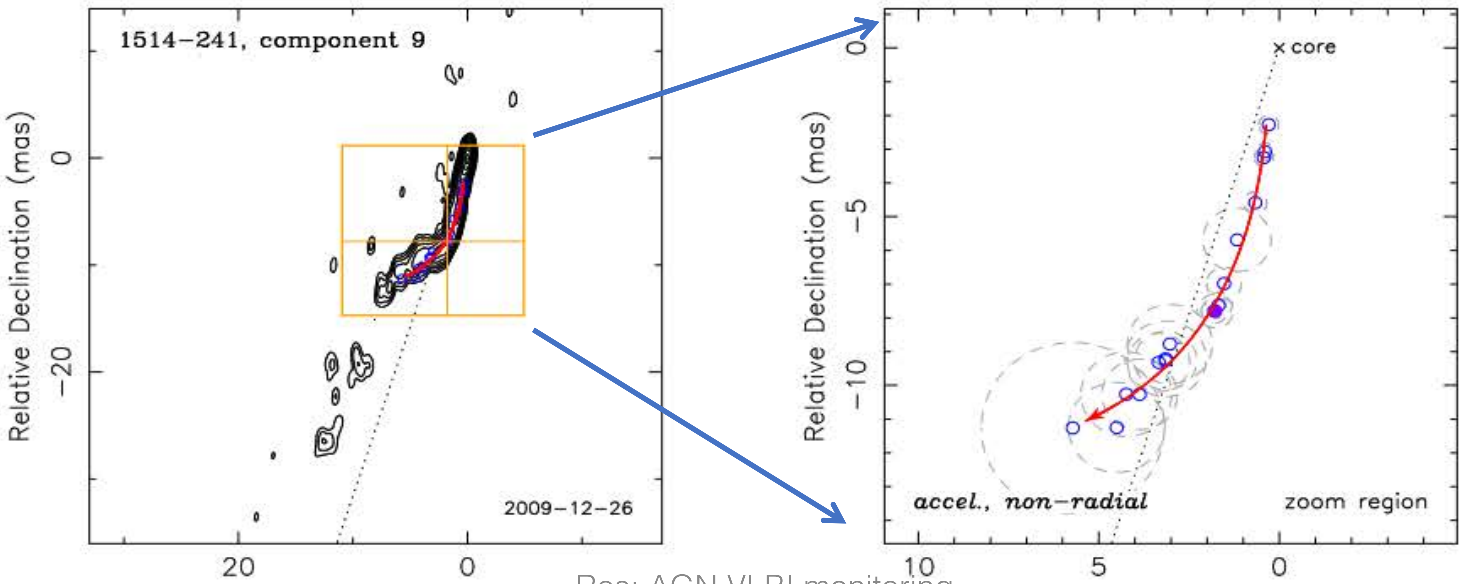
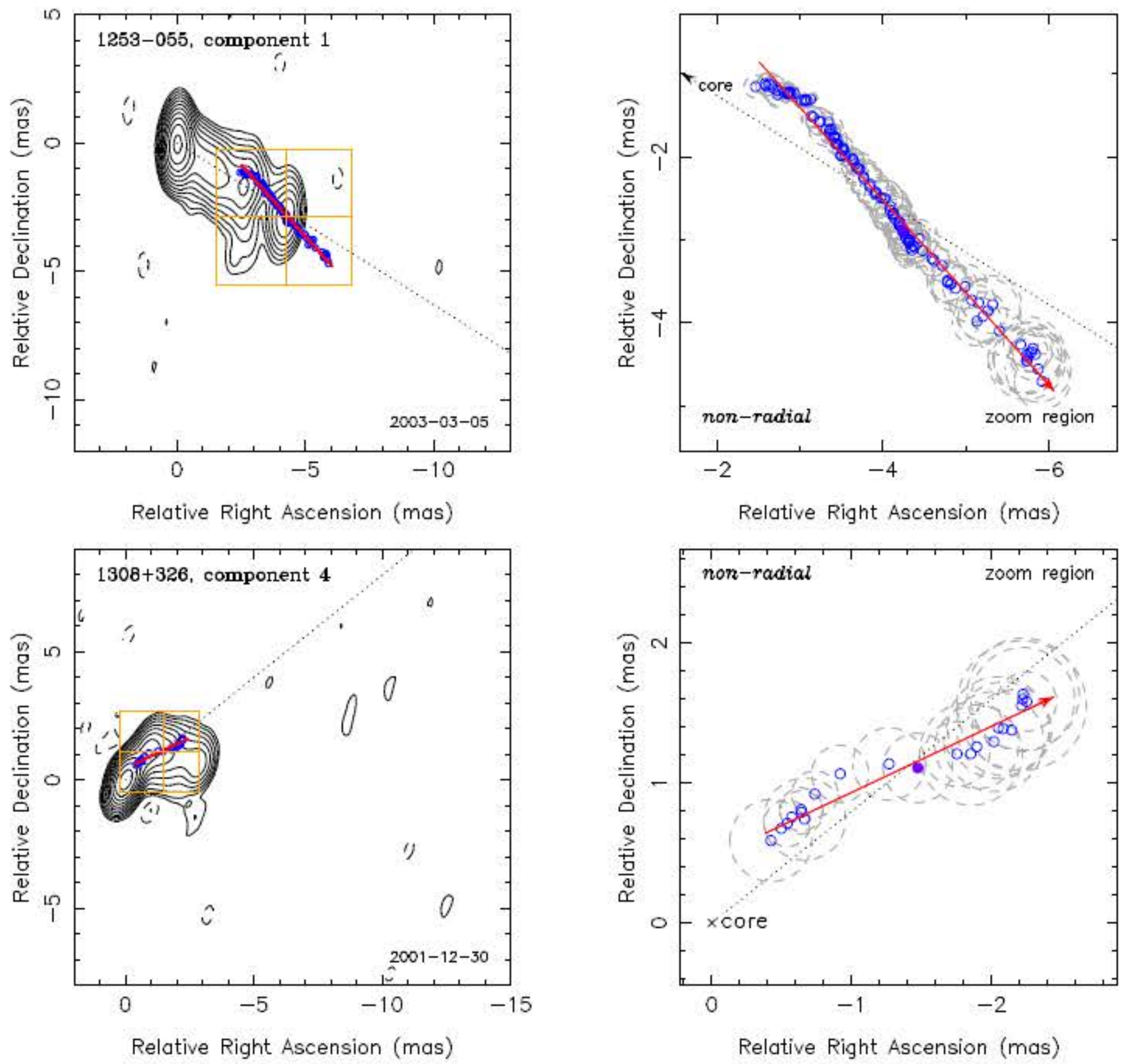
- New kinematics (Paper XVII) in preparation, to include
    - Data until 31dec2016
    - 135 new AGN (44 with no redshift)
    - 1744 features (vs 961 in paper XIII)
    - 880 features in acceleration analysis (vs 329 in XII)

Jet accelerations

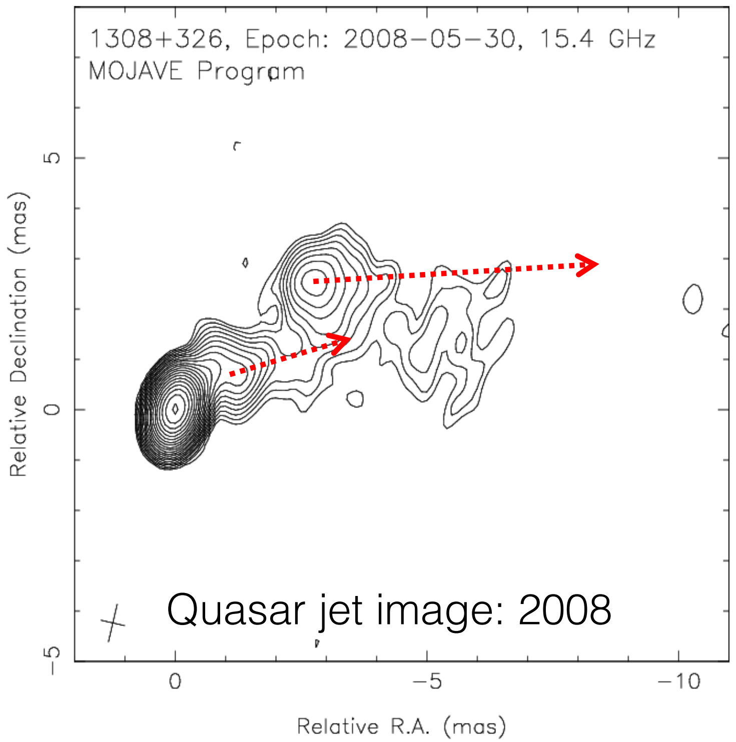
- 82% either have at least one accelerating or non-radially-moving feature.
- Half of all individual jet features show evidence of acceleration.
    - ejection times can be reliably estimated for only ¼ of all moving features.
- Parallel accelerations are of larger magnitude and more prevalent than perpendicular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

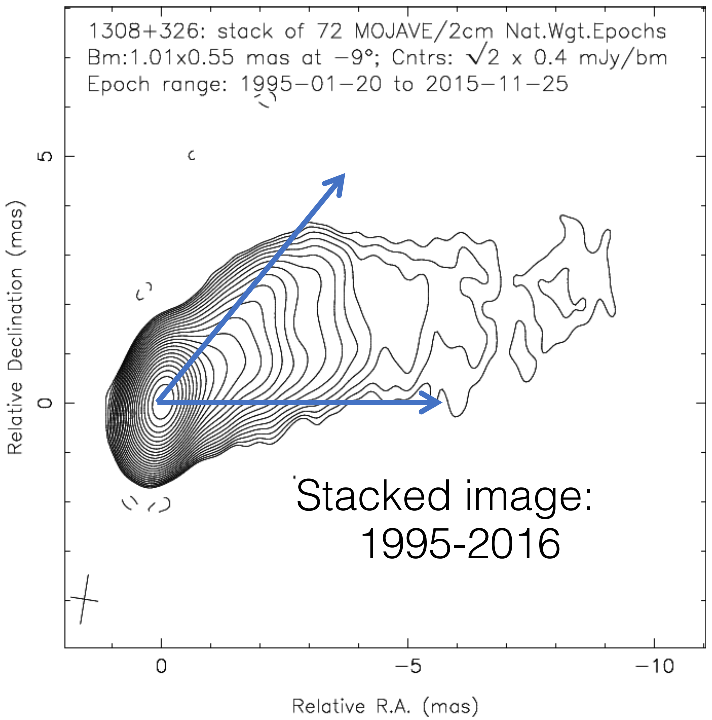


Best sampled features show variable acceleration



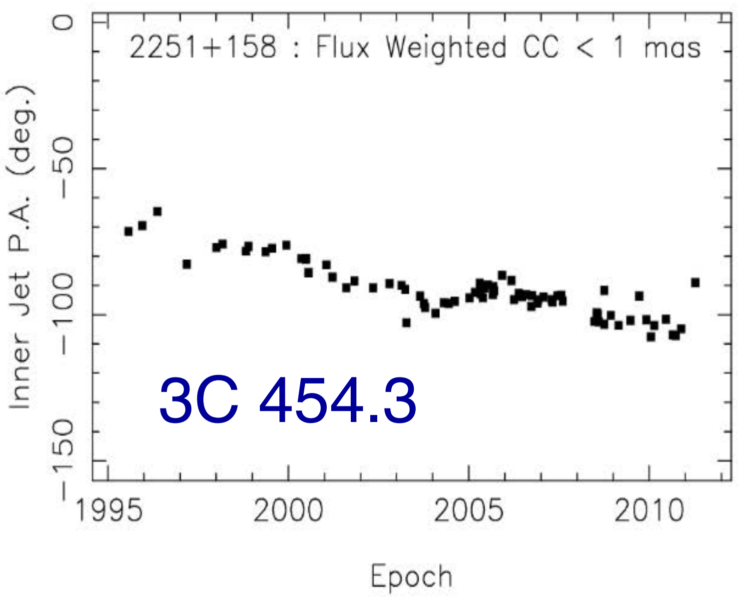
Energized jet channels

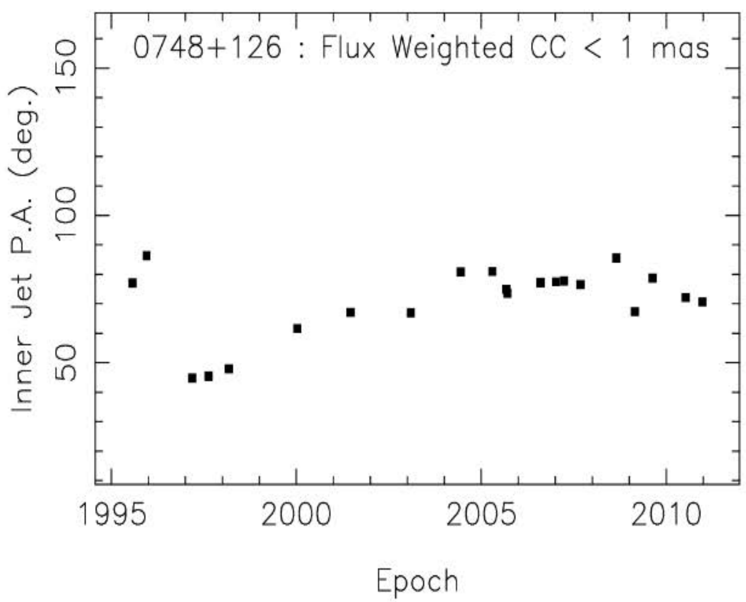


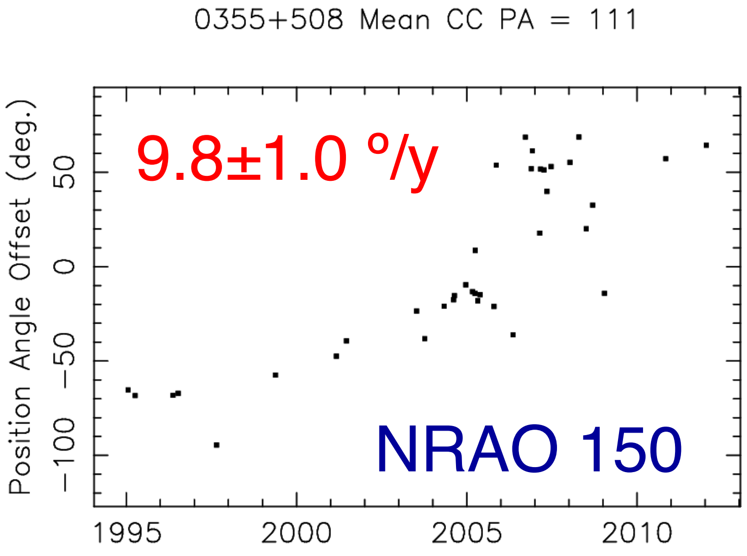


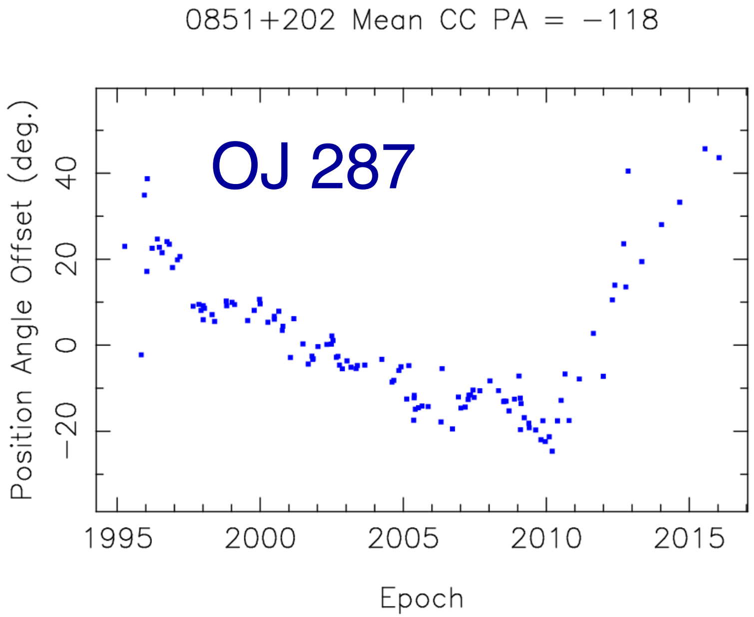
- At any given time, typically only a portion of the full (conical) outflow is energized/visible

Changes in the inner jet direction





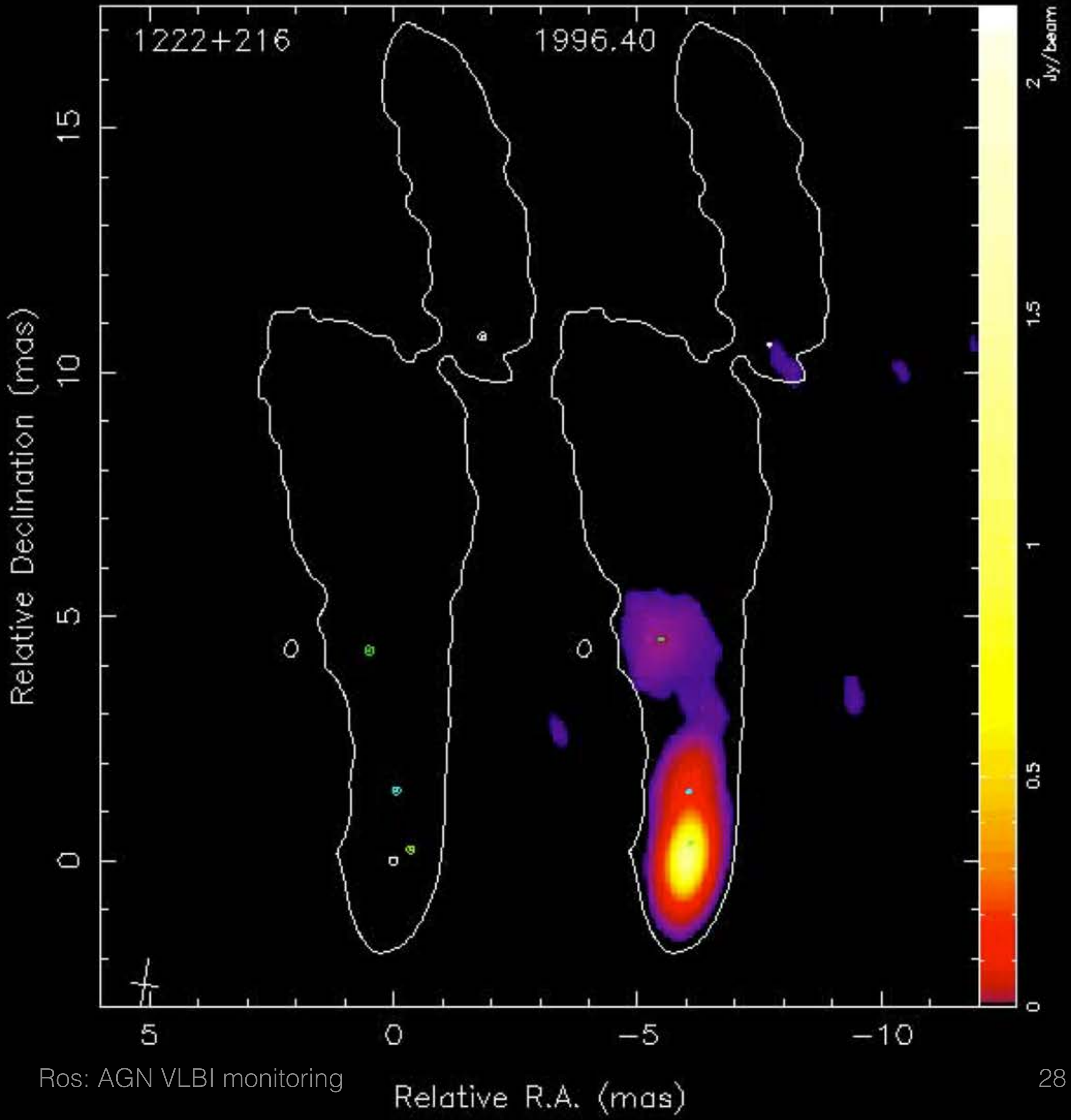




- ½ of best monitored sources show changes in their innermost jet position angle, at a rate of 1–3°/yr

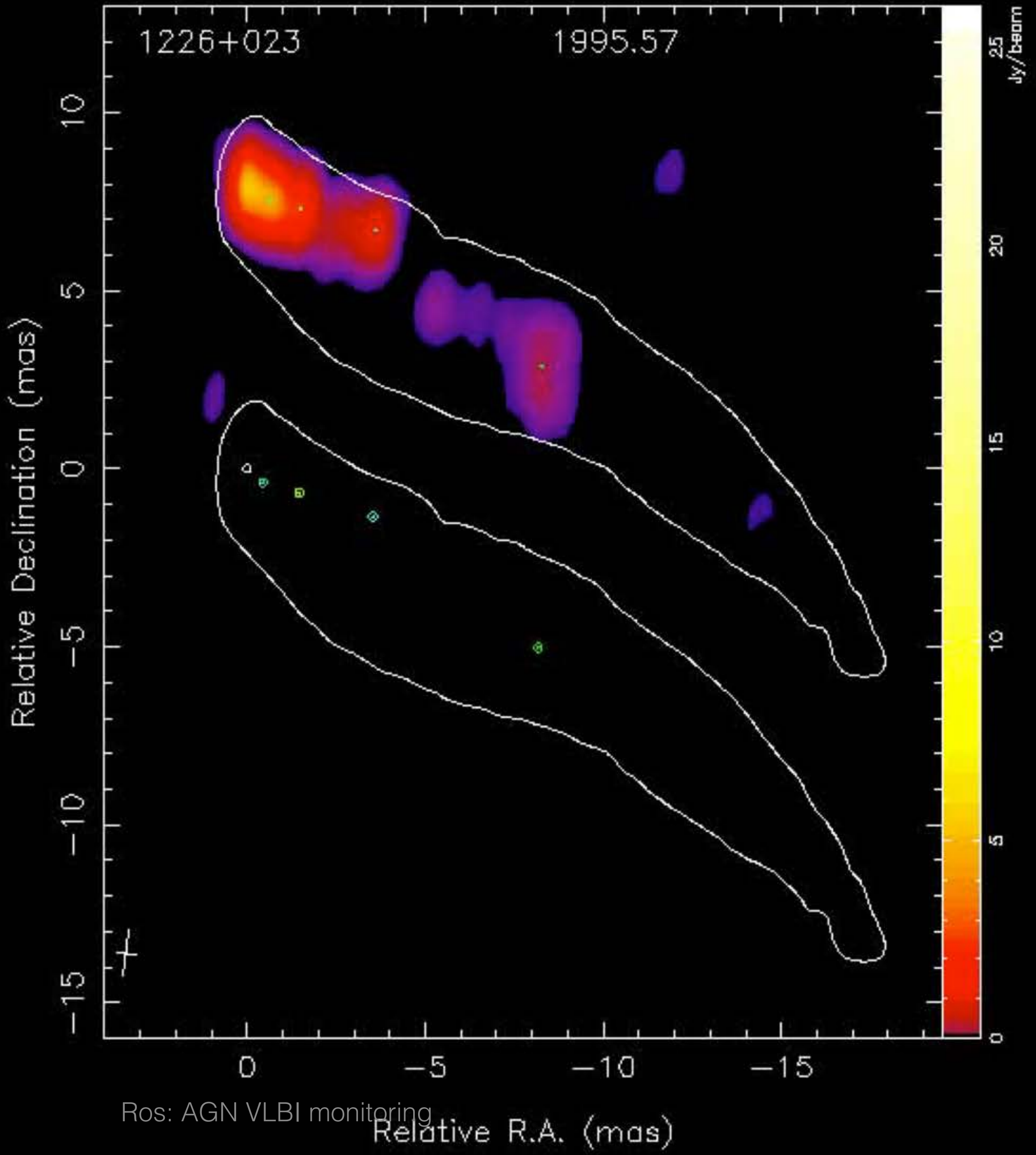
TeV-detected QSO 1222+216 at z=0.43

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



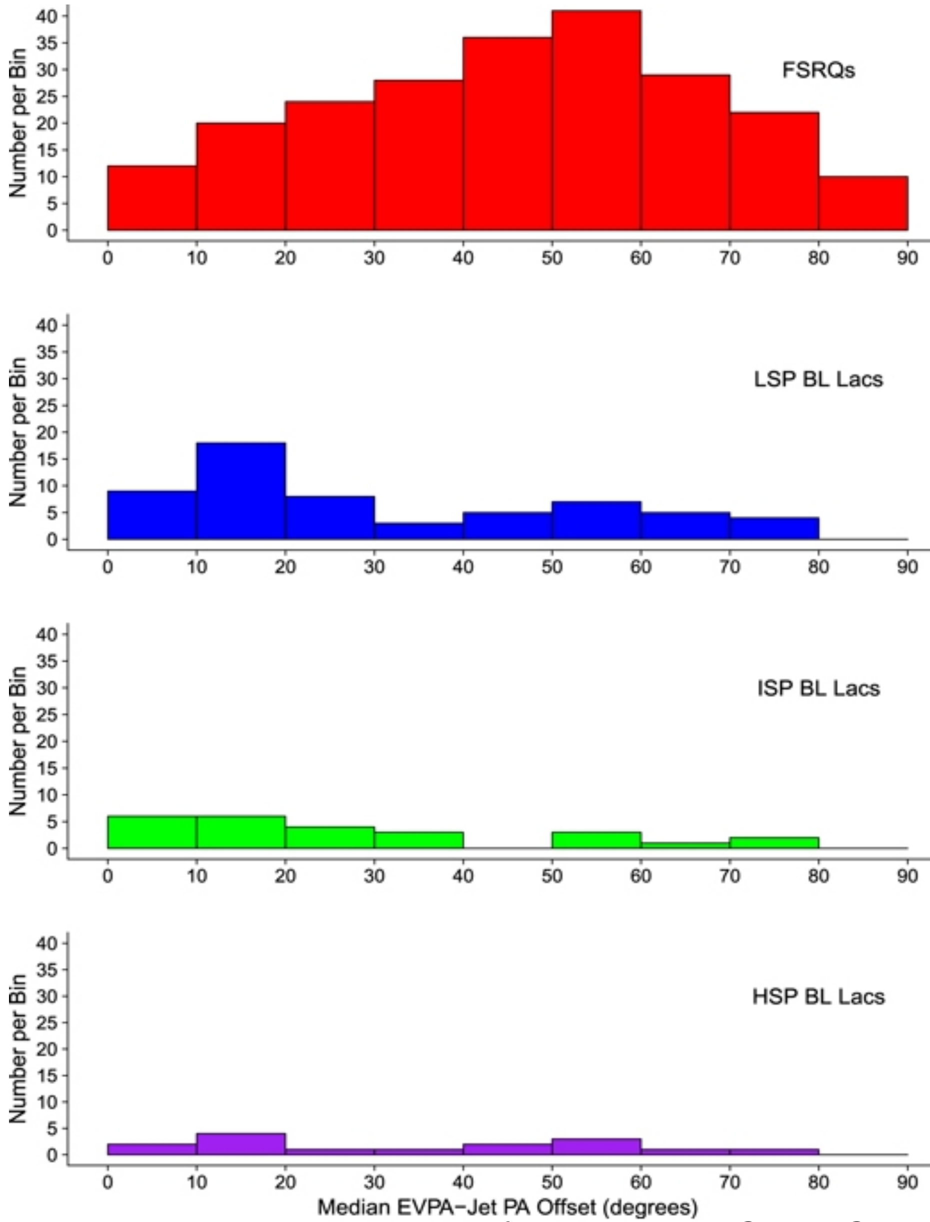
3C 273 at z=0.16

Max speed = 15 c



XVI: Linear Pol properties

- BL Lacs have $\chi \parallel$ jet direction, less variable
- AGN with ($m = P/I$) ↑ tend to have $\chi \parallel$ jet direction, χ less variable
- Interpretation: standing transverse shock at jet base collimates $B \perp$ jet direction, m↑, χ is stable over time
- HSP BL Lac have L↓ and m↓
- γ-loud AGN should have δ↑, but no dependence of m with γ detection
- γ-loud AGN have more variable χ



MOJAVE XVI: Multiepoch Linear Polarization Properties of Parsec-scale AGN Jet Cores
M. A. Hodge et al. 2018 ApJ 862 151 doi:10.3847/1538-4357/aacb2f

Some evidences

- Most powerful blazars have bulk $\Gamma \cong 50$, while typical AGN jets have $\Gamma \sim$a few
- Jet features speed up within 100 pc of the jet base where the jet is collimating, decelerate further out
- Gamma ray blazar surveys biased against LSP, low-δ AGN jets
- Changes in pc-scale emission are related to γ-activity
- γ-activity related to changes in polarization
- δ seems to be higher at γ-active stages
- No source with low L_γ has high β_{app}

Concluding remarks

- Large VLBI surveys are the key tool for our current understanding of relativistic outflows in AGN
- Dedicated arrays (VLBA) indispensable for probing the time evolution of jets and their characteristics
- VLBI data complement SDSS, FIRST, OVRO monitoring, *Fermi*, etc.
- Advances in VLBI recording and correlator technology open new opportunities for different AGN populations

Thank you!

Acknowledging material and comments from:

- M. Kadler
- M.L. Lister (China-USA Workshop 2016, Málaga jet meeting 2016, Brandeis Univ 2017, …)
- F. Schinzel & L. Petrov URSI 2018
- A. Hekalo, MSc Thesis U Würzburg 2018