Max-Planck-Institut
für Radioastronomie

VNIVERSITAT DE VALÈNCIA

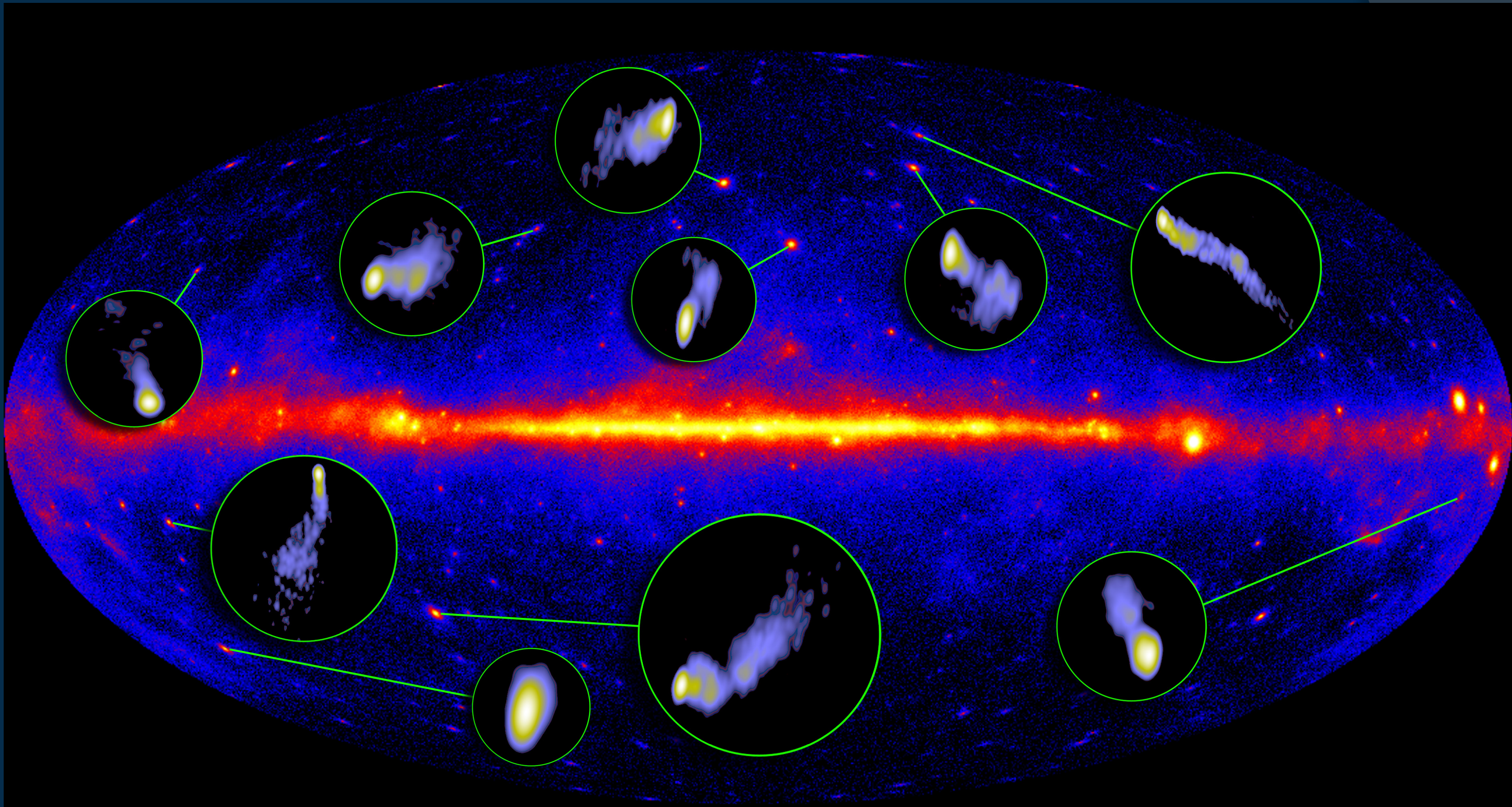
November 10th, 2011

Fermi and Jansky Meeting, St. Michaels, MD, USA

Eduardo Ros (Univ. Valencia & MPIfR)

HIGH-RESOLUTION MONITORING OF PC-SCALE JETS IN THE *FERMI* ERA

Gamma and radio sky

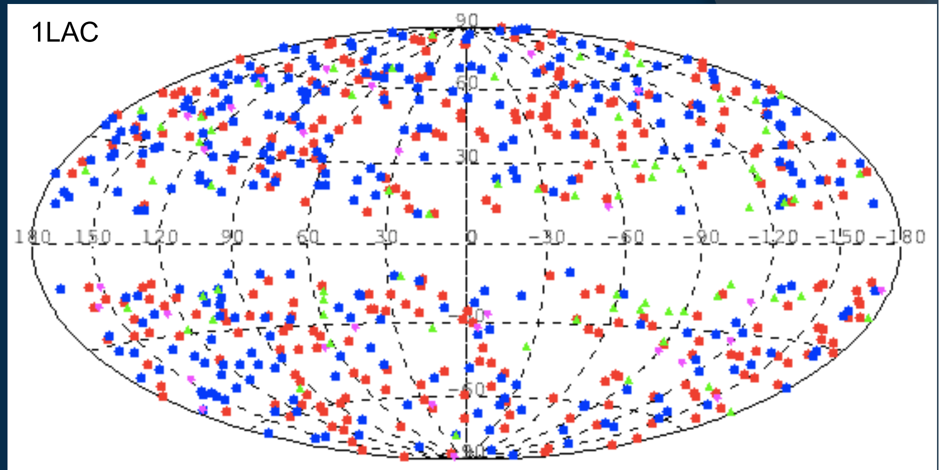


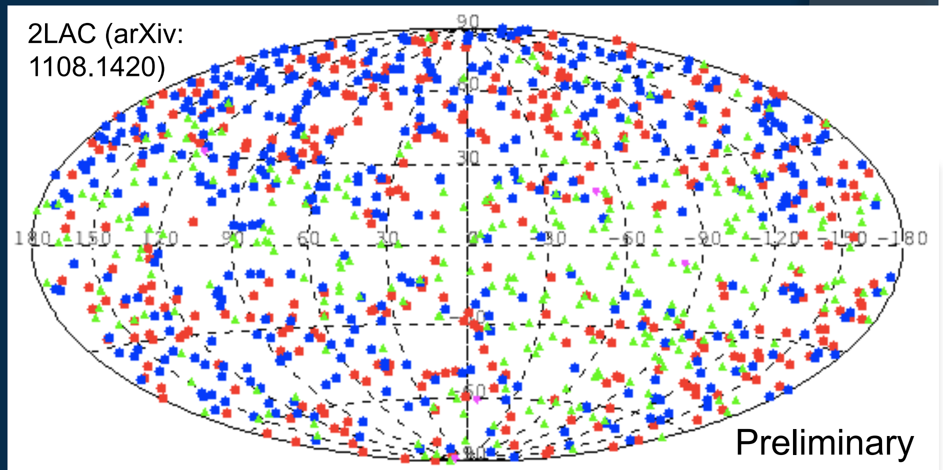
Collage: M. Kadler (images by MOJAVE & NASA)

See Lott's Talk

Fermi/LAT catalogs

- Since EGRET we know that the gamma-sky is dominated by the Galactic Plane, PSR, and Blazars
- The 1st Fermi-LAT catalog (Abdo+'10) contains 1400 sources, from which ½ are AGN
- 2nd Fermi-LAT catalog (2LAC, submi.) contains 1749 sou.*
  - 950 are AGN
    - 360 FSRQ
    - 420 BL Lac (60% have z)
    - 160 unkown
    - 20 other AGN





* Numbers from Lott's talk at CTA meeting

The gamma sky is extragalactic

- *Fermi*/LAT shows that BL Lacs are the most common γ-emitters, over flat spectrum radio quasars
- Big biases are present, both in γ and radio:
  - Doppler beaming: orientation bias
  - Luminosity grows with redshift: Malmquist bias
  - Spectral Energy Distribution (jet contribution, directly probed by radio)

VLBI capabilities

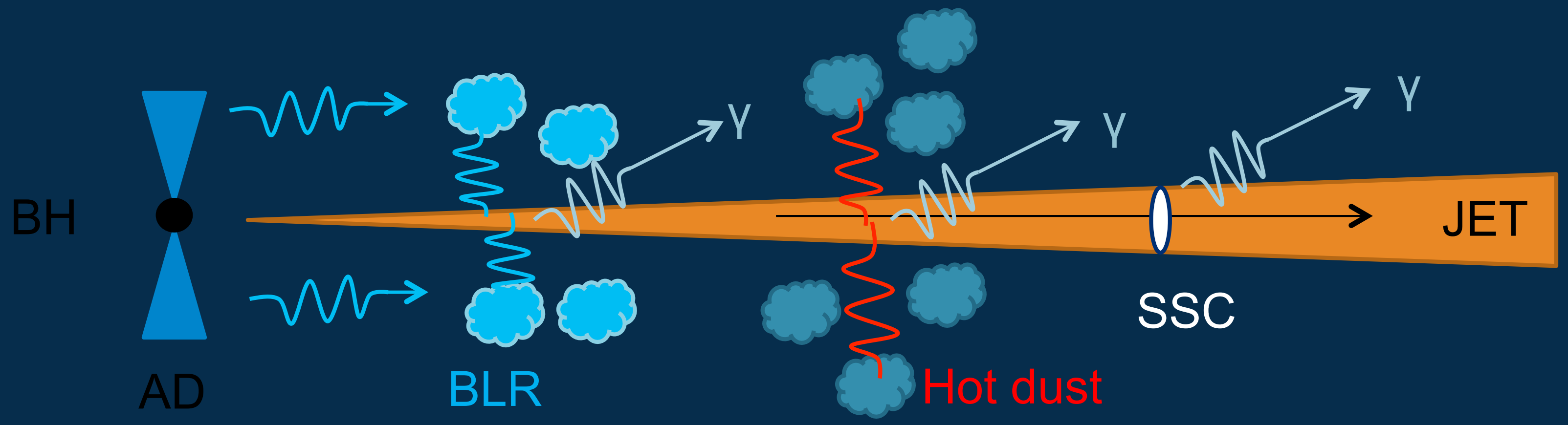
- VLBI shows beamed sources:
  - Superluminal speeds
  - One-sided core-jet structure
  - Compact core emission (high T_b)
  - Rapid variability in jets

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

Blazars in radio and gamma-rays



Cartoon: T. Savolainen

- Major open questions:
  - What makes a particular blazar gamma-ray loud?
  - Where in the jet do gamma-rays originate?
  - What is the gamma-ray production mechanism?

Observing

- Blazars are being detected and observed by
  - Fermi/LAT
  - AGILE
  - VHE telescopes (VERITAS, MAGIC, HESS)
- Radio-γ-connection
- Blazars are imaged and monitored by VLBI arrays
  - Ideally: multi-wavelength, multi-epoch, polarization

Properties probed by VLBI

- Multifrequency/phase-referencing → core-shift → magnetic field, pressure gradients, etc.
- T_b (usually of ≈10^{12} in core, dropping to ≈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 from moving with standing shocks

VLBI today

- Astronomy:
  - Antennas worldwide
    - Predominantly at the Northern Hemisphere
    - Hardly present in South Africa or South America
  - Frequencies from 330 MHz (λ90cm) to 86 GHz (λ3.6mm)
  - Australian, European, North American and East Asian arrays
- Trend towards telescopes connected by optical fibre (eVLBI)
- Geodesy:
  - Sparse network in all continents, operation at 2.3/8.4 GHz
    - Preliminary plans for a continuous 1-14 GHz receiver system

VLBI Arrays

The quest for resolution

Resolution = Observing wavelength / Telescope diameter

Angular Resolution	Optical (5000A) Diameter	Optical (5000A) Instrument	Radio (4cm) Diameter	Radio (4cm) Instrument
1’	**2mm**	**Eye**	**140m**	**Effelsberg**
1"	**10cm**	**Amateur Telescope**	**8km**	**VLA-B**
0.”05	**2m**	**HST**	**160km**	**MERLIN**
0.”001	**100m**	**Interferometer**	**8200km**	**VLBI**

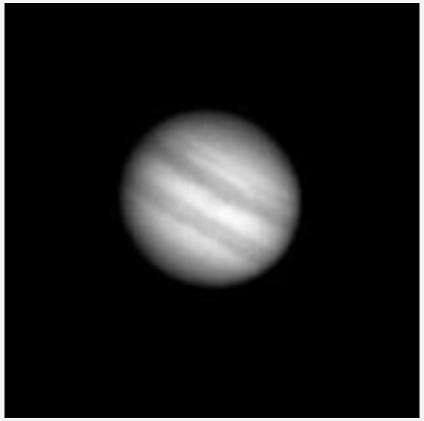
Atmosphere gives 1" limit without corrections which are easiest in radio

Table & Graphics: NRAO

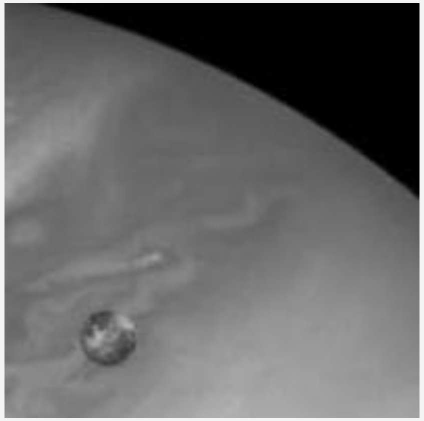
Jupiter and Io as seen from Earth

1 arcmin

1 arcsec



0.05 arcsec



0.001 arcsec

Simulated with Galileo photo

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

γ-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 νIC factor ν_{IC}

Basic relations

- Lorentz factor and apparent speed

$$\Gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$\beta_{\mathrm{app}} = \frac{\beta \sin\theta}{1-\beta\cos\theta}$$

$$\beta_{\mathrm{app,max}} = \beta\Gamma$$

$$\cos\theta_{\mathrm{max}} = \beta$$

- Doppler factor

$$\delta = \frac{1}{\Gamma\sqrt{1-\beta\cos\theta}}$$

- Intrinsic and apparent opening angles ψ

$$\psi_{\mathrm{int}} = \psi_{\mathrm{app}} \sin\theta$$

- Intrinsic and observed Tb and luminosity

$$L_{\mathrm{obs}} = L_{\mathrm{int}} \times \delta^{n+\alpha} \, (n = 2,3)$$

$$T_{\mathrm{b,obs}} = T_{\mathrm{b,int}} \times \delta$$

Basic relations (ii)

- Variability Doppler factor from flux density variations:

$$\tau_{\rm obs} = \frac{dt}{d(\ln S)}$$

$$T_{\rm b,obs(var)} = 5.87\times10^{21} h^{-2} \frac{\lambda^2 S_{\max}}{\tau_{\rm obs}^2}\left(\sqrt{1+z}-1\right)^2$$

$$\delta_{\rm var} = \sqrt[3]{\frac{T_{\rm b,obs(var)}}{T_{\rm b,int}}} \quad (T_{\rm b,int} = 5\times10^{10} K)$$

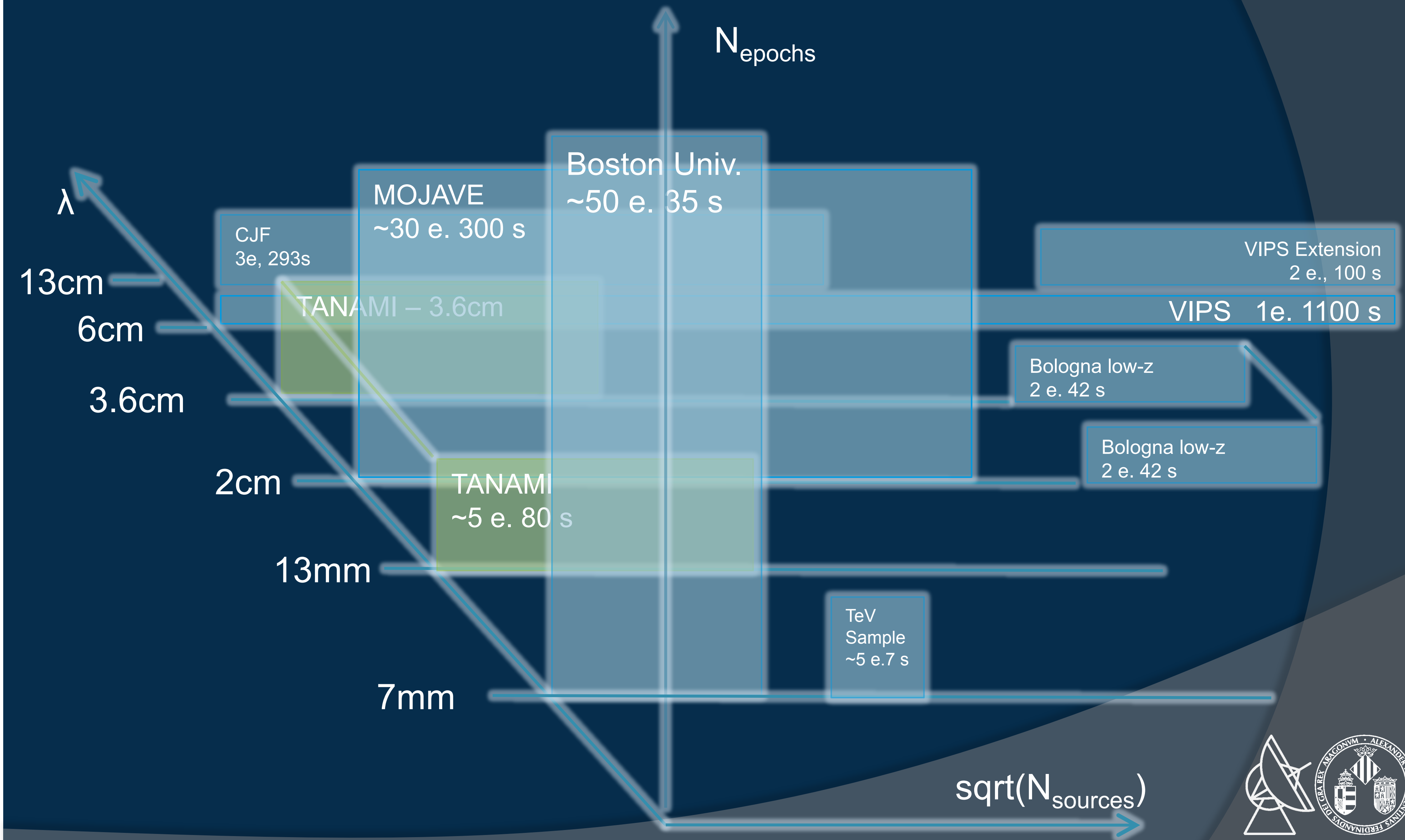
- β_{app} & δ_{var} provide viewing angle θ and bulk Lorentz factor Γ:

$$\theta = \arctan\frac{2\beta_{\rm app}}{\beta_{\rm app}^2+\delta_{\rm var}^2-1}$$

$$\Gamma = \frac{\beta_{\rm app}^2+\delta_{\rm var}^2+1}{2\delta_{\rm var}}$$

Hovatta et al. 2009 A&A 494 527

Surveys: an overview



Main survey programs (tabulated)

Program	λ	$N_{sources}$	N_{epochs} & Obs.	Ref.
Boston Univ.	7mm	35	50 (2007-now)	Marscher, Jorstad +
TeV Sample	7mm (+1.3/3.6cm)	7	5 (2006-now)	Piner+ 2010 ApJ 723 1150
MOJAVE	2cm	300	20 (1994-now)	Lister+ 2009 AJ 138 1874
Bologna low-z	2/3.6cm	42	2 (2010-now)	Giroletti+'11
TANAMI	1.3/3.6cm	80	5 (2008-now)	Ojha+'10, Kadler+'11
VIPS	6cm	1127	1 (2007)	Hemboldt+'07
VIPS subsample	6cm	100	2 (20010-now)	Linford+'11
CJF	6cm	293	3 (1990s)	Taylor+'96, Pearson+'98
VCS & Co.	3.6/13cm	10^2	10^{0-3} (1990s-now)	Kovalev+'09 & Co.

Selection criteria: usually flux and spectrum based

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?
- Gamma ray emission and jet activity correlation?

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

VLBI Imaging and Polarimetry Survey (VIPS)

See Linford's Talk

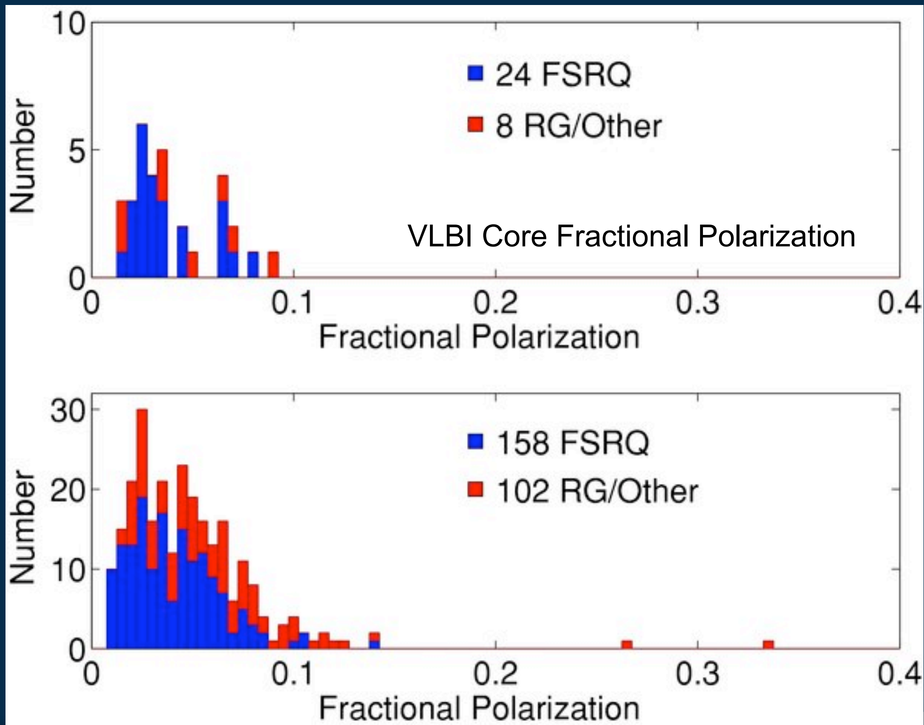
- 1127 sources at 5 GHz
- One epoch, pre-Fermi era
- Polarisation included
- Helmboldt et al. 2007 ApJ 658, 203
- Followed by VLBA observations of 100 blazars (at least two epochs) – P.I. G.B. Taylor

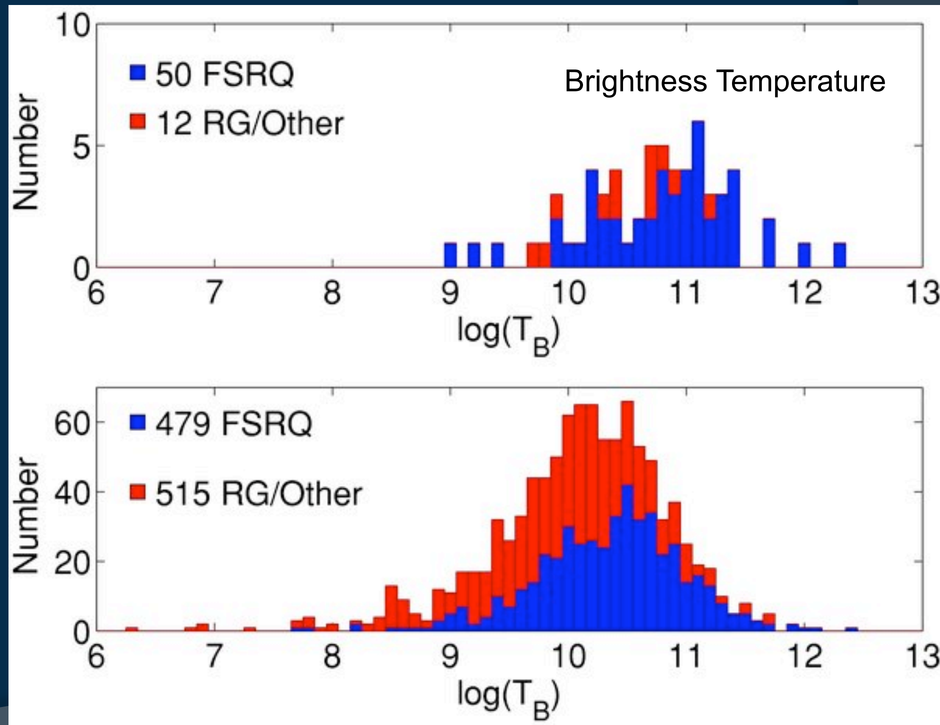
VIPS Extension

See Linford's Talk

- Median value in core fractional polarization is 3.5% for γ-detected and 4.4% for non-γ
- Brightness temperature of γ-bright higher than non-γ

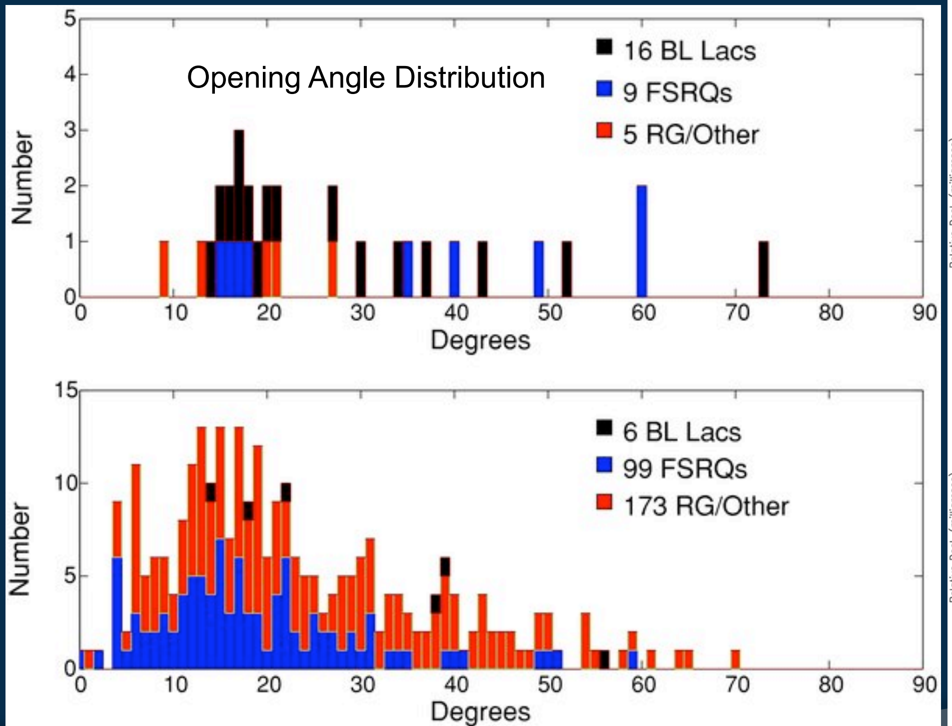
Linford et al. (2011 ApJ 726 16)



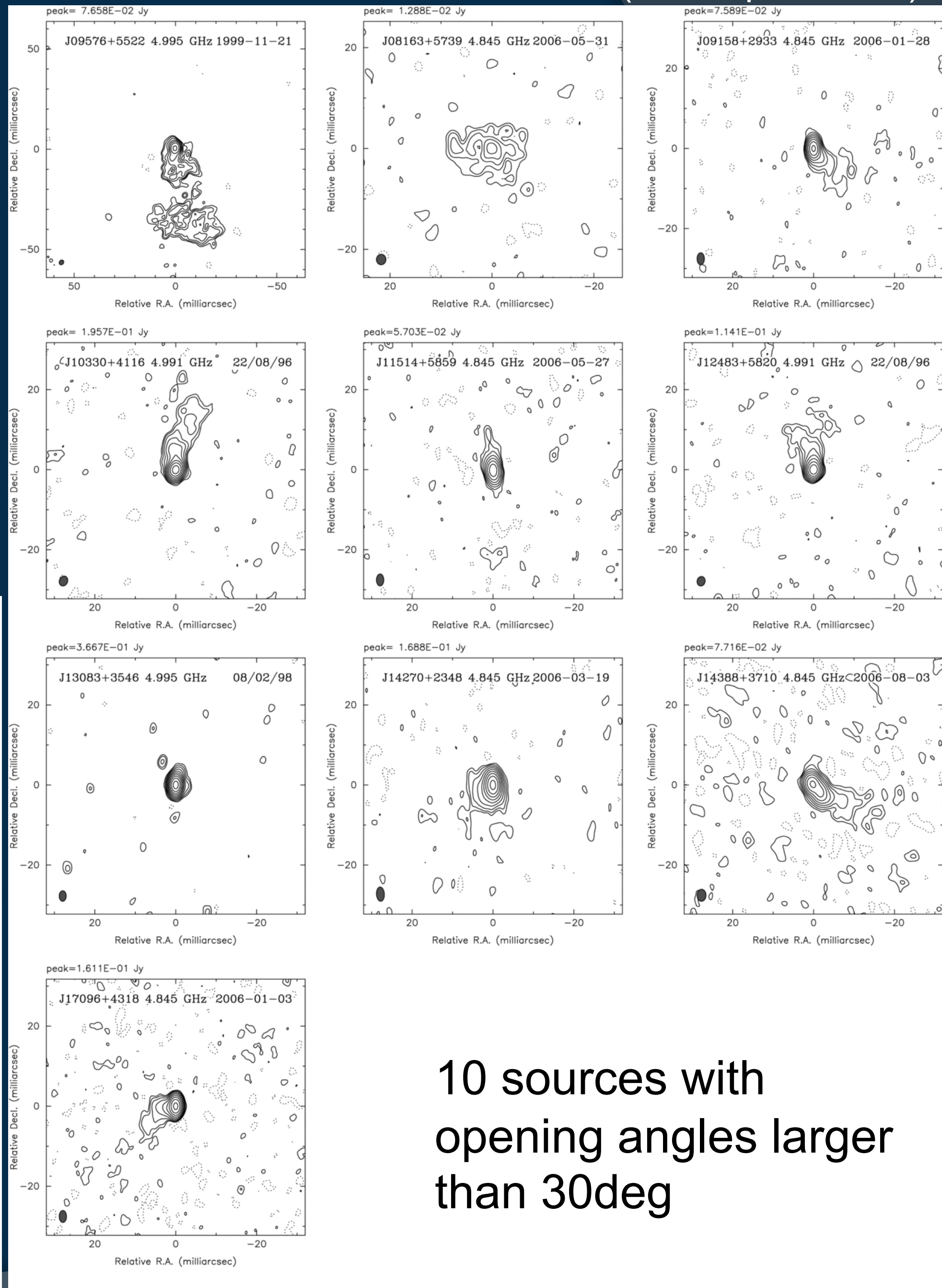


VIPS Extension

- LAT sources have unusually large opening angles



Linford et al. (2011 ApJ 726 16)



10 sources with opening angles larger than 30deg

TeV Blazars VLBA Monitoring

- VLBA images of TeV Blazars including polarimetry
- Mostly at 43 GHz
- Sampled sources:
  - Mrk 421, Mrk 501, H 1426+428, 1ES 1959+650, PKS 2155−304, 1ES 2344+514
- New, recent additions (AAS#218 #327.05):
  - 1ES 1101−232, Mrk 180, 1ES 1218+304, PG 1553+113, H 2356−309
- All new detected components have β_{app}<2c

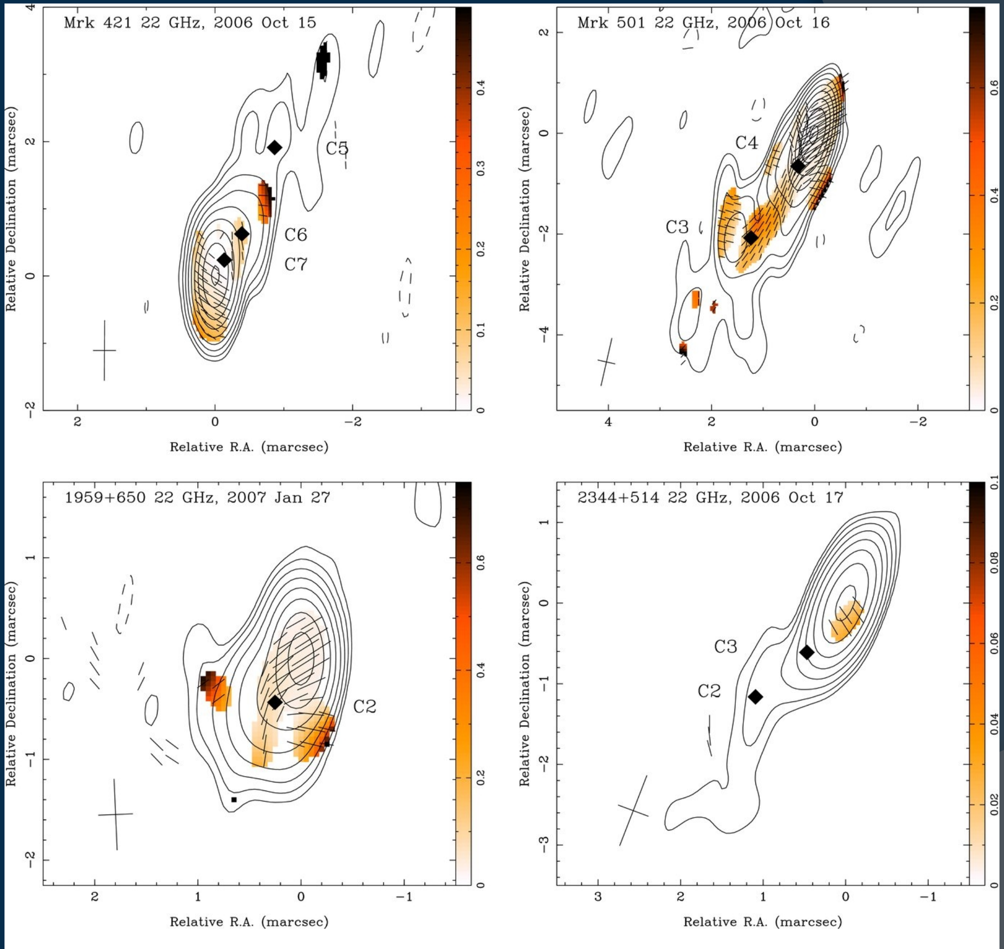
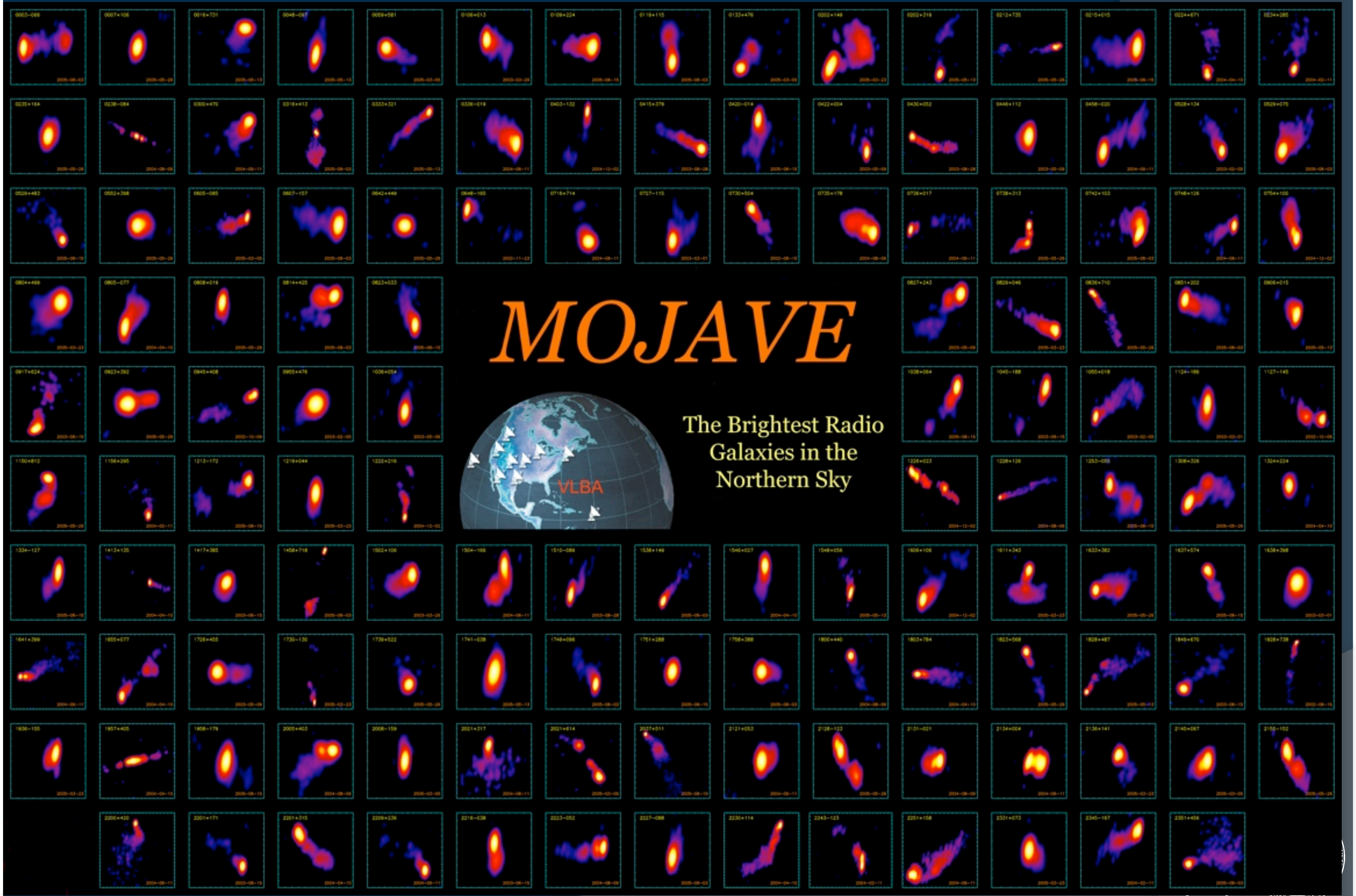


Fig. 8 in Piner, Pant & Edwards 2010 ApJ 723 1150

Note: several of these sources are being also observed by Giroletti et al. with the EVN


MOJAVE
The Brightest Radio
Galaxies in the
Northern Sky
VLBA

MOJAVE:

- 28% overlap in samples of bright γ-rays and radio-selected AGN
- 1FM:
  - 118 sources bright at γ-rays
- 1FM-matching sample
  - 105 left ($S_{VLBA} \geq 1.5$ Jy)

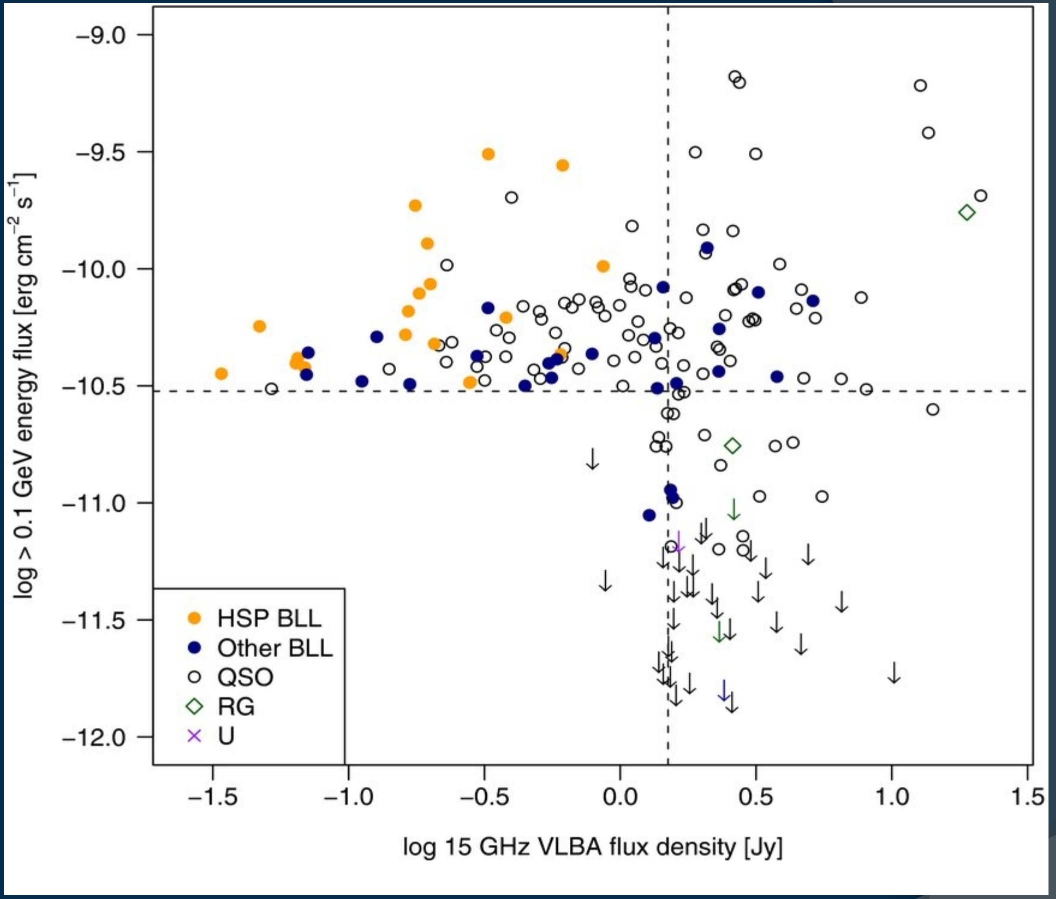


Fig. 1 in Lister et al. 2011 ApJ 742 27

MOJAVE program

See Lister's Talk

See Hovatta's Talk

- Milliarcsecond-resolution, full Stokes images
- Currently ~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/

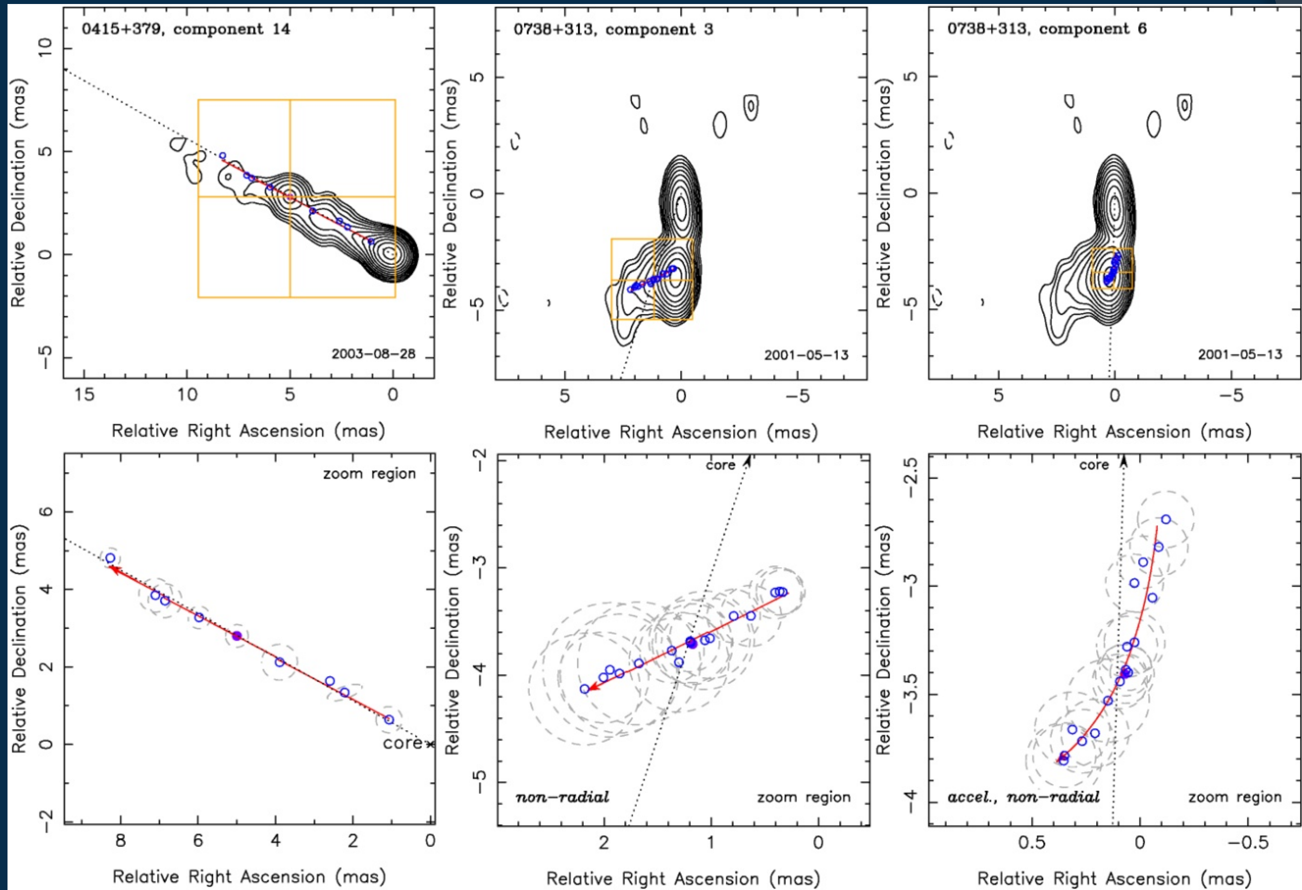
See Lister’s Talk

MOJAVE results on jet kinematics

Accurate kinematics of 526 features in 127 jets over 12 years:

Image of the jet:

Trajectory of the moving feature:



Lister et al. 2009, AJ 138, 1874

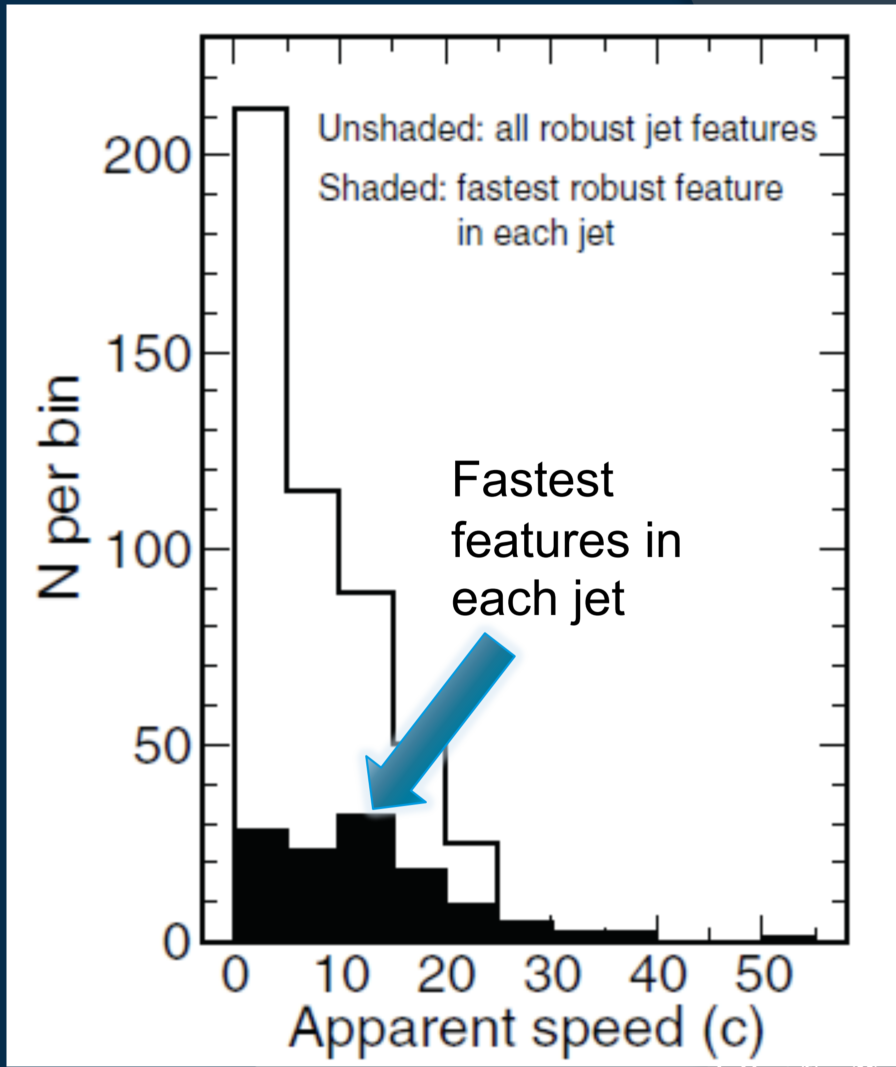
MOJAVE results on jet kinematics

See Lister's Talk

- Dispersion of β_{app} within indivual jet is >3 times smaller than the overall dispersion among all jets ➔ characteristic speed describing each jet, reflected by obs. proper motions
- Max(β_{app}) distribution peaks at ~10c and ranges up to 50c

  ➔ Lorentz factors >10 are common

  ➔ maximum Lorentz factor of the parent population is ~50

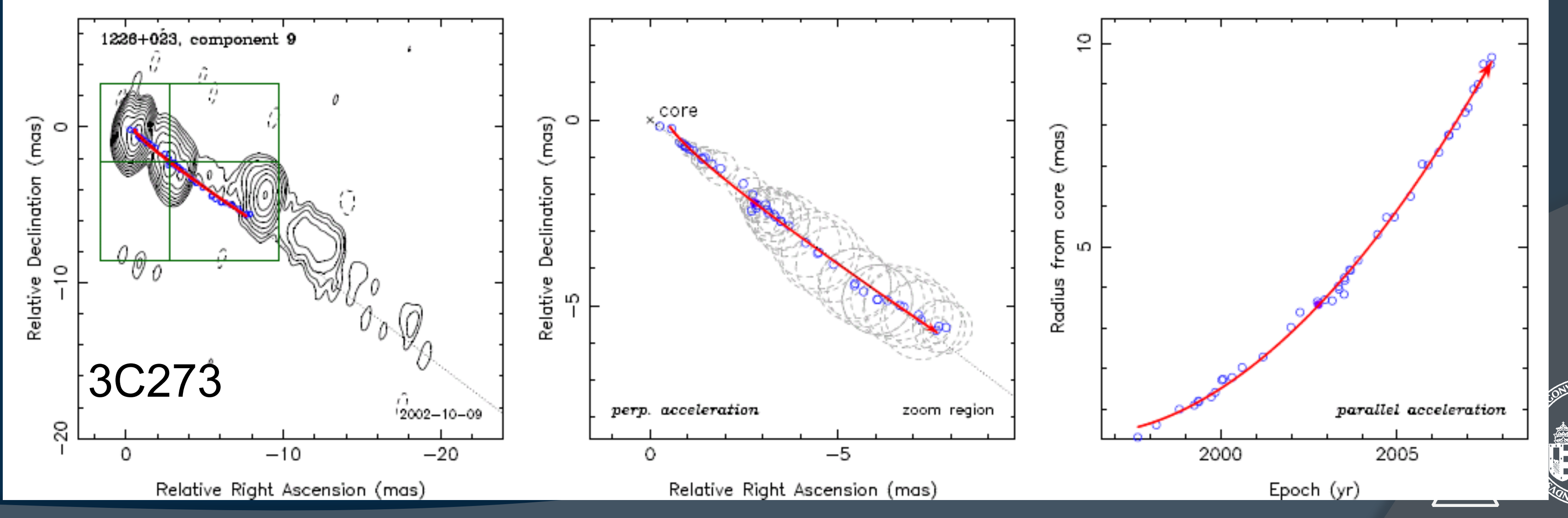


MOJAVE results on jet kinematics

See Lister's Talk

Over 1/3 of the bright features show acceleration:

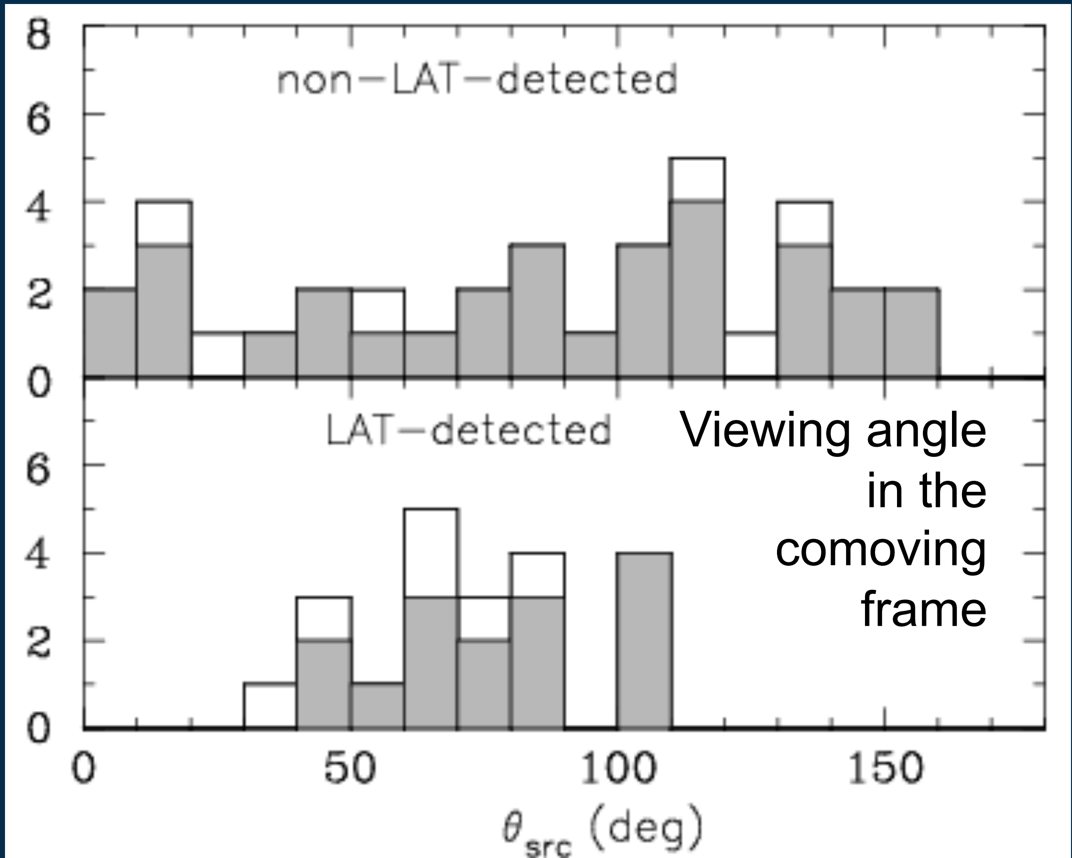
- Parallel accelerations are generally larger than perpendicular accelerations → changes in intrinsic speed are common – not only changes in jet direction
- Prevalent positive acceleration (speeding up) close to the core (within 15 pc) → jets are still becoming organized in parsec scales. ➔ see jet launching models.



(Homan et al. 2009, ApJ 707, 1253)

MOJAVE – Viewing angle

See Lister's Talk



Savolainen et al. A&A 2010 512 A24

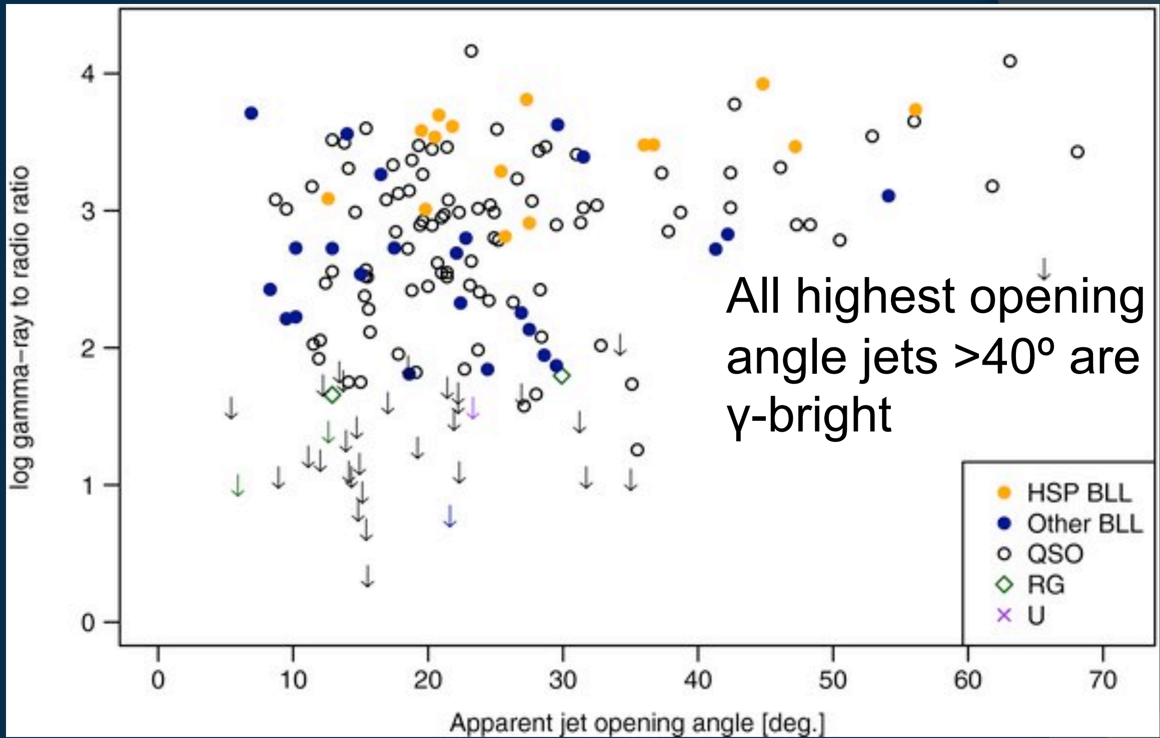
- γ-ray bright sources have a narrower viewing angle than γ-quiet
- (LBAS: 3-months AGN list)

See Lister's Talk

MOJAVE pc-scale properties

- AGN with wide apparent opening angles tend to have high γ-ray loudness values
- HSP BL Lac objects have low core T_b
- No trend between radio core polarization degree or vector offset and γ-loudness

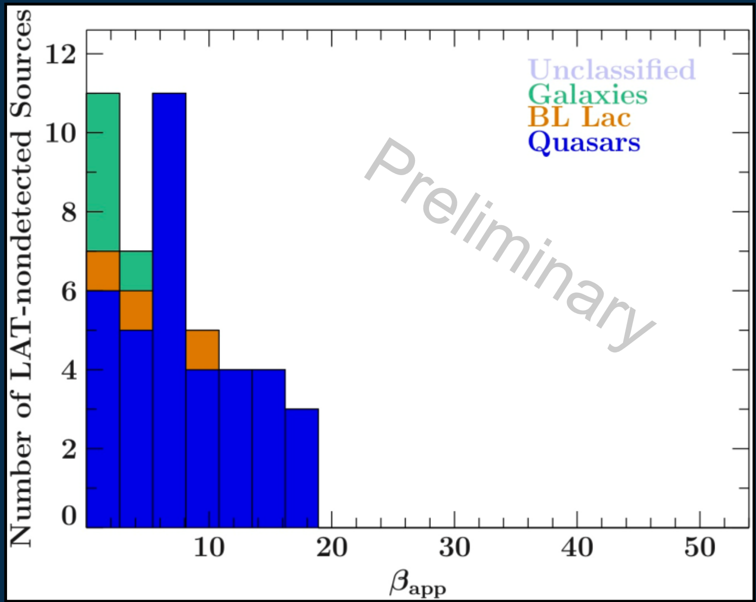
Fig. 9 in Lister et al. 2011 ApJ 742 27

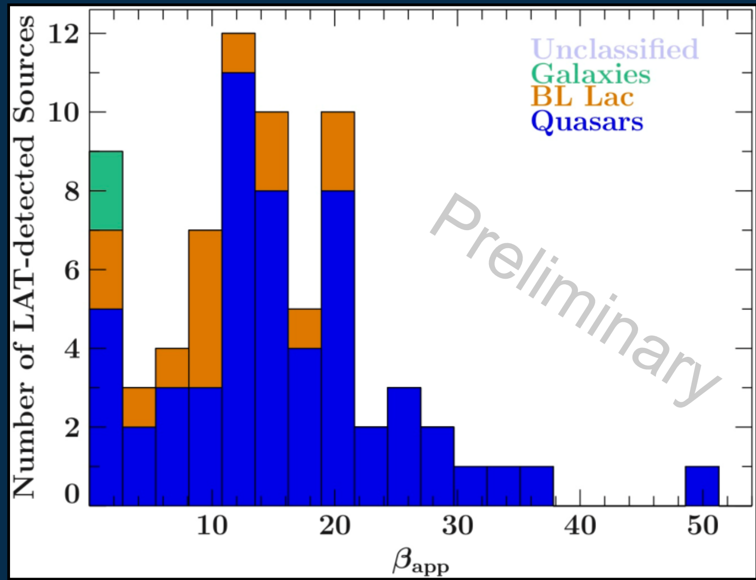


Similar result obtained by the TANAMI team (Ojha et al. 2010 A&A 519 A45) and by the VIPS γ-sample (Linford et al. 2011 ApJ 726 16)

MOJAVE-*Fermi* results

See Lister's Talk





- LAT-detected AGN have higher apparent speeds

See Jorstad & Marscher Talks

BU Blazar Monitoring

- Study of 35 blazars at 43 GHz, observed monthly by the VLBA
- 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

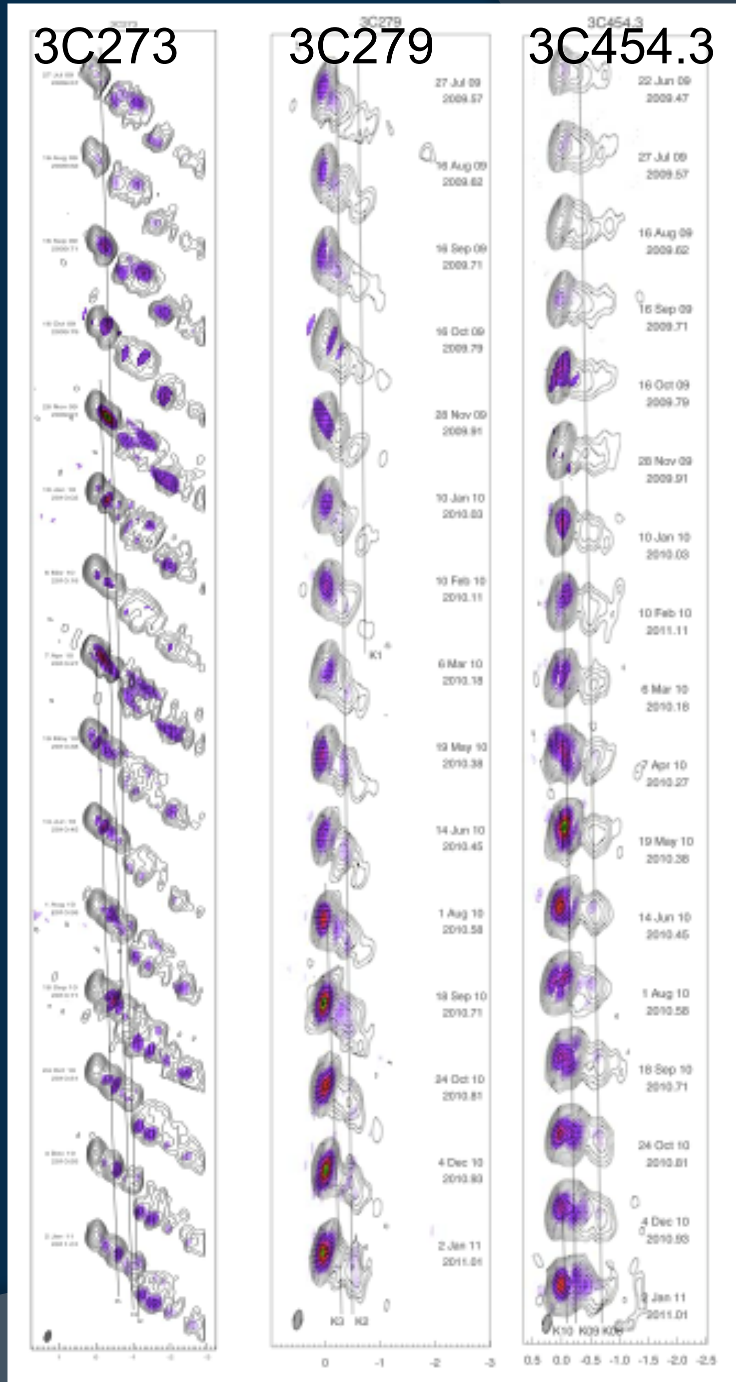
http://www.bu.edu/blazars/

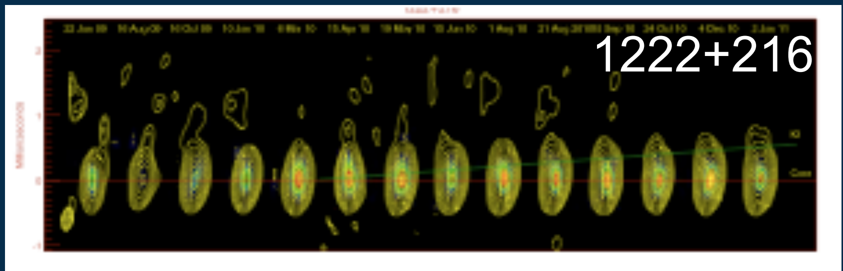
BU Blazar Monitoring

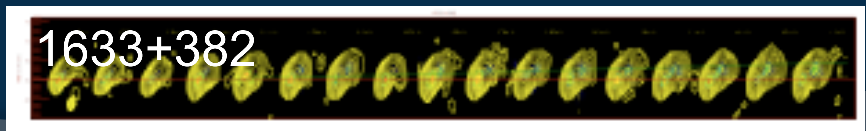
See Jorstad & Marscher Talks

- High levels of γ-ray activity coincide with the production of superluminal knots and their passage through stationary features in the jet
- Outburst in γ-rays occur parsecs downstream of the central engine

Jorstad et al. Fermi Symp 2011 arXiv 1111.0110



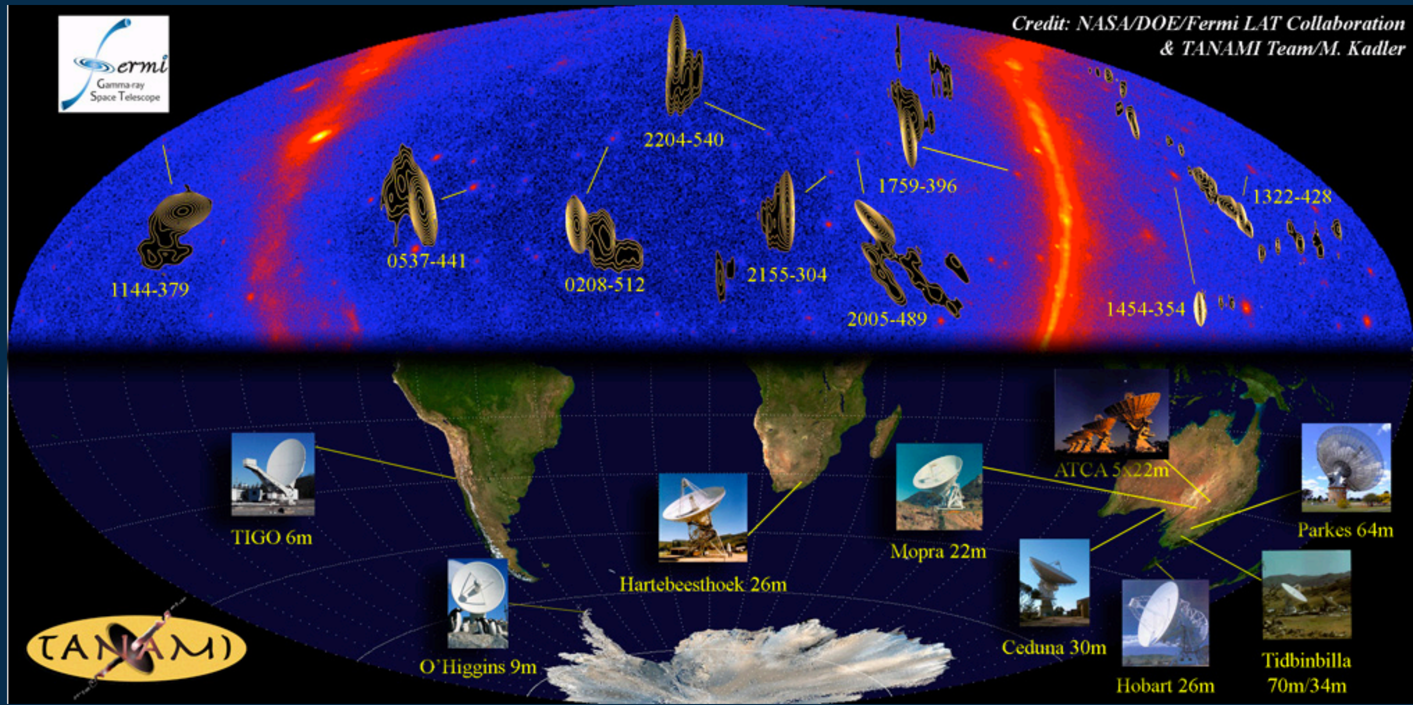




TANAMI Project

Tracking AGN with Austral Milliarcsecond Interferometry

See Müller's Talk



(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

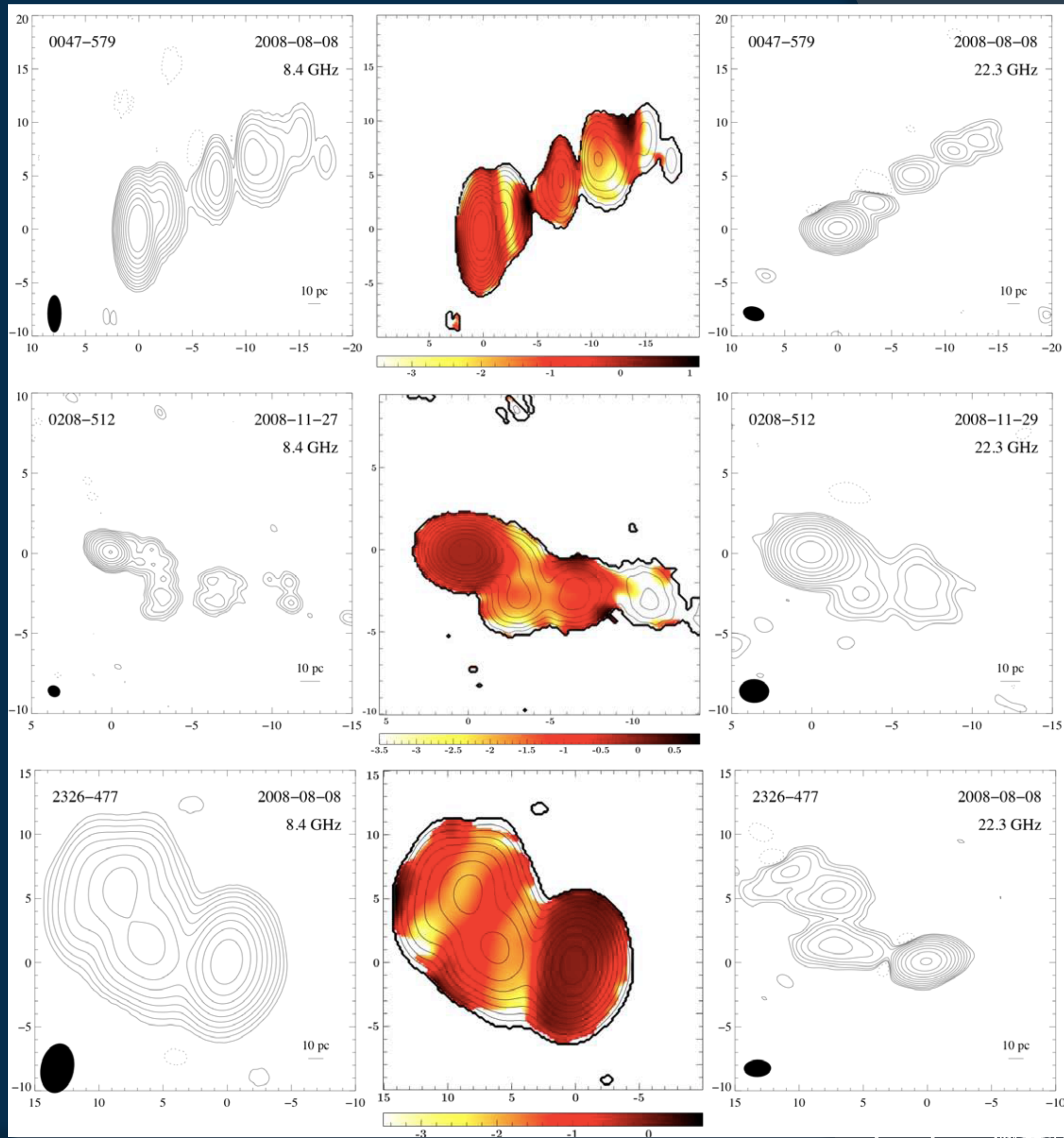
http://pulsar.sternwarte.uni-erlangen.de/tanami/

TANAMI results

See Müller's Talk

- Several 'terra incoginta' sources
- SPIX images are being produced
- In data collection phase, first proper motions coming
- Individual source studies being processed

Spectral index images



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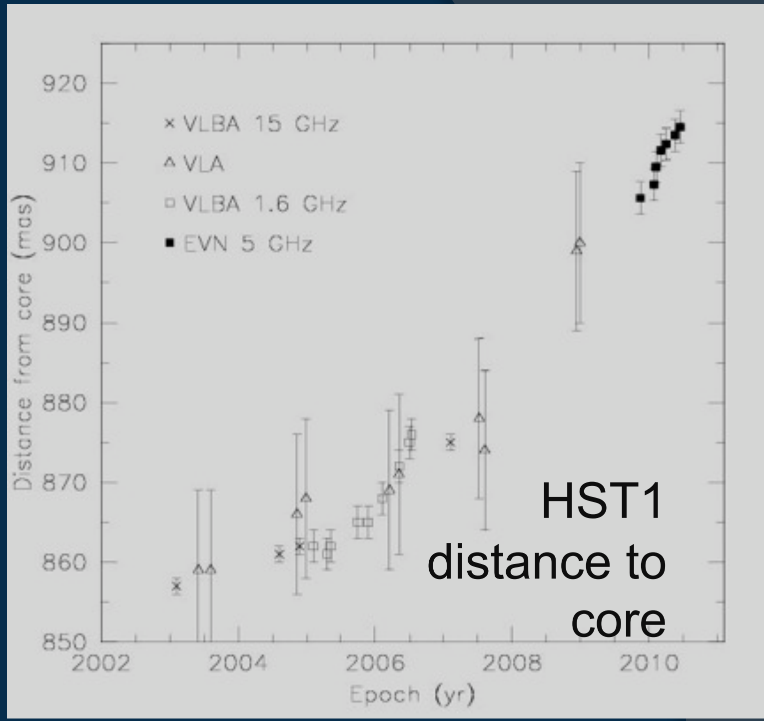
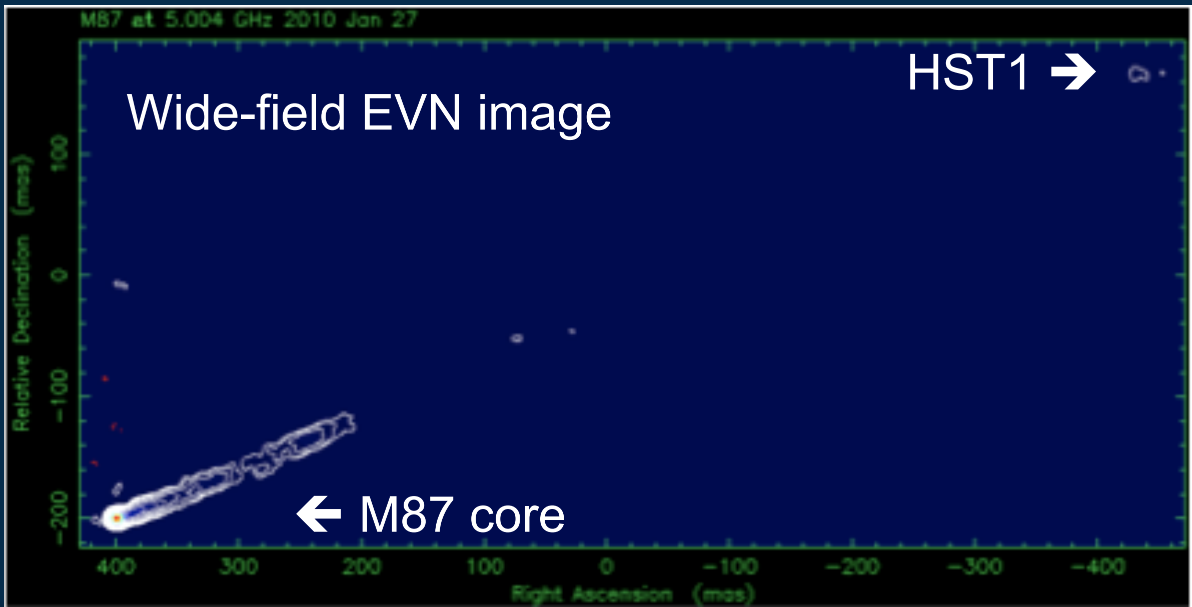
Individual Source Studies

M 87

- eEVN observations by M. Giroletti after a TeV flare (09feb2010, ATel2431)



Giroletti et al. EVN Symp 2010 (PoS 047)

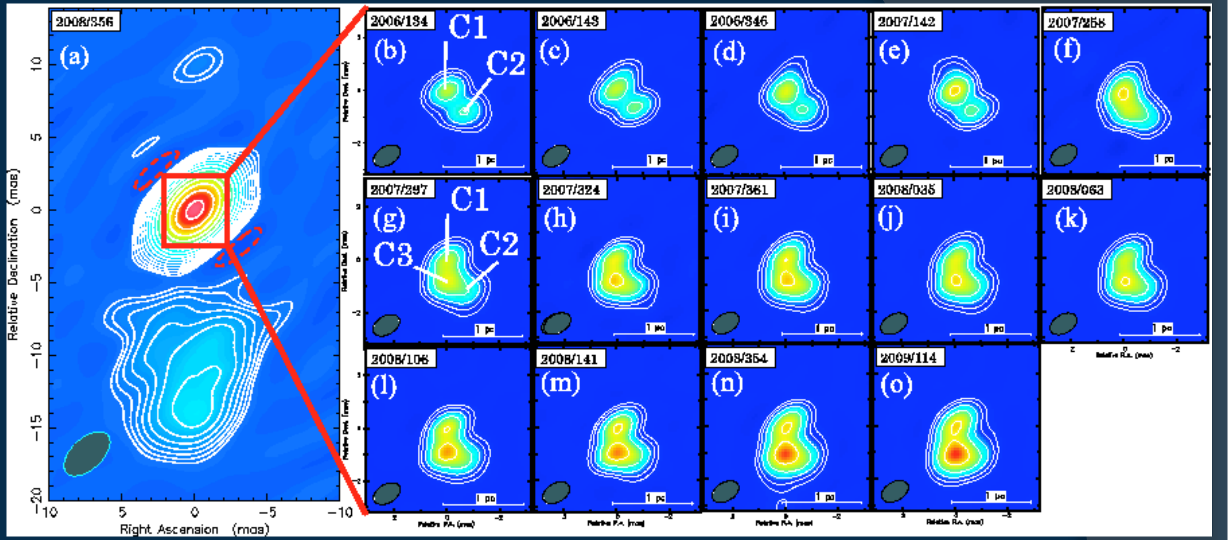


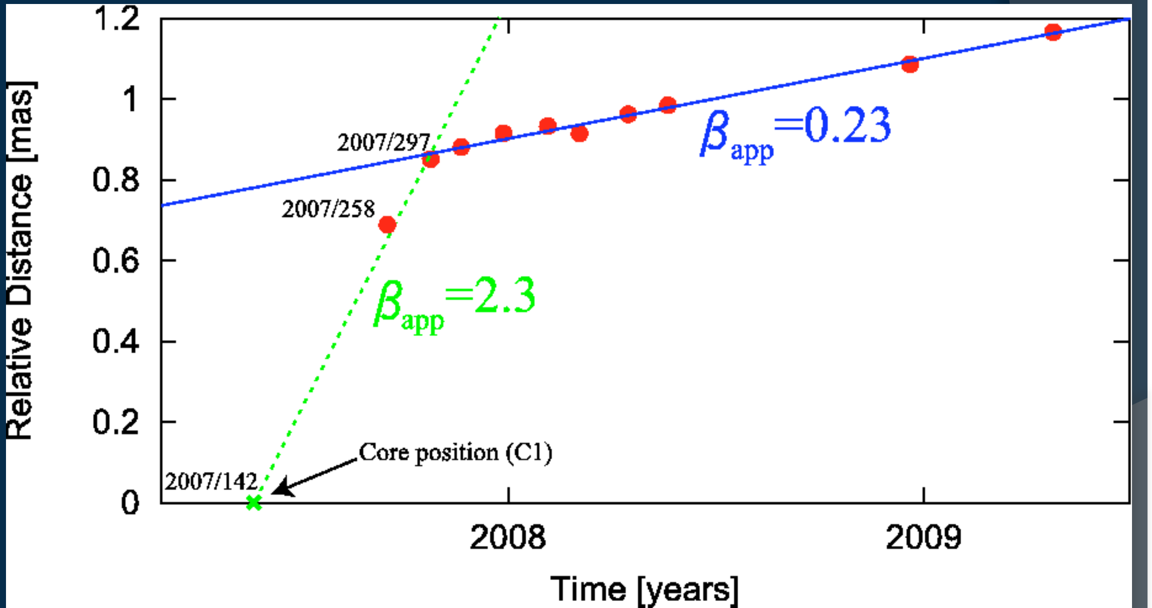
- Role of HST1 is unclear (see Cheung et al. 2007 and Chang et al. 2010)

Nagai et al. 2010 PASJ 62 L11

3C84

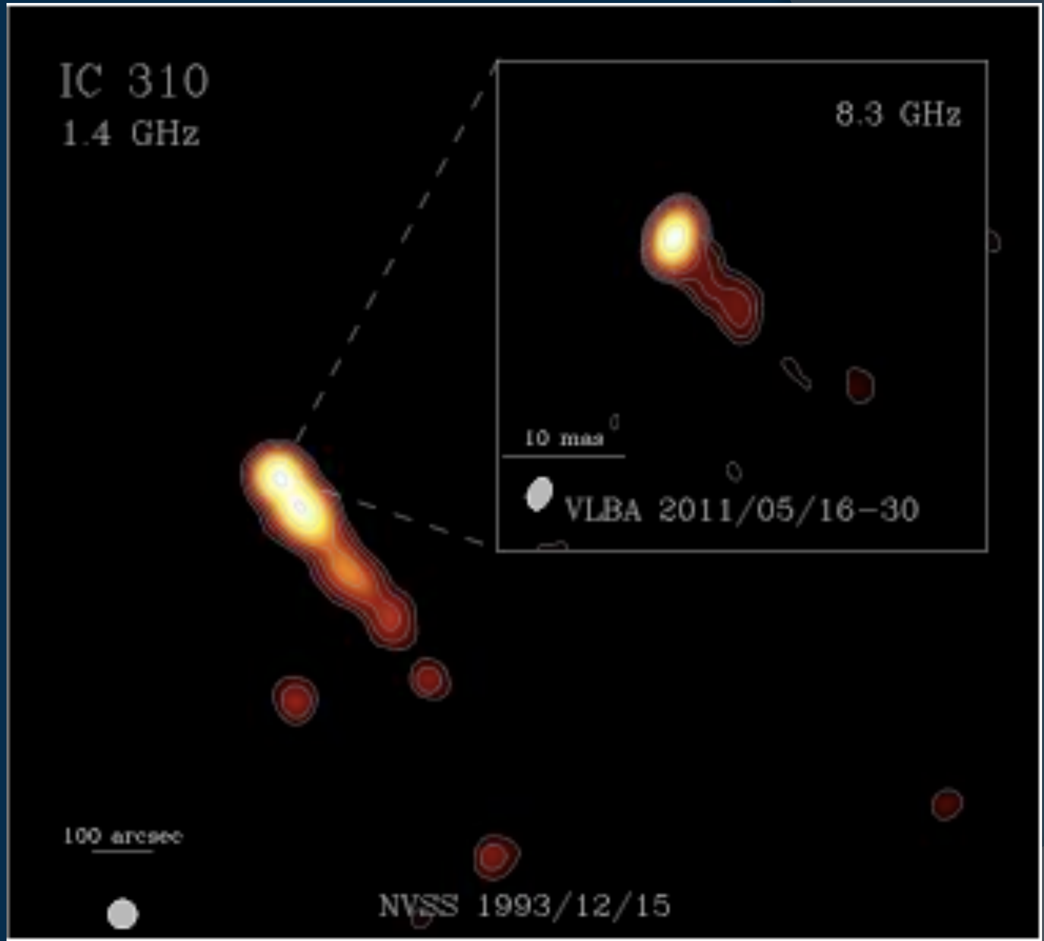
- At the Perseus cluster, z=0.017559
- VERA observations report a jet component (β_{app}~0.23c) getting brighter during a γ-flare





IC310

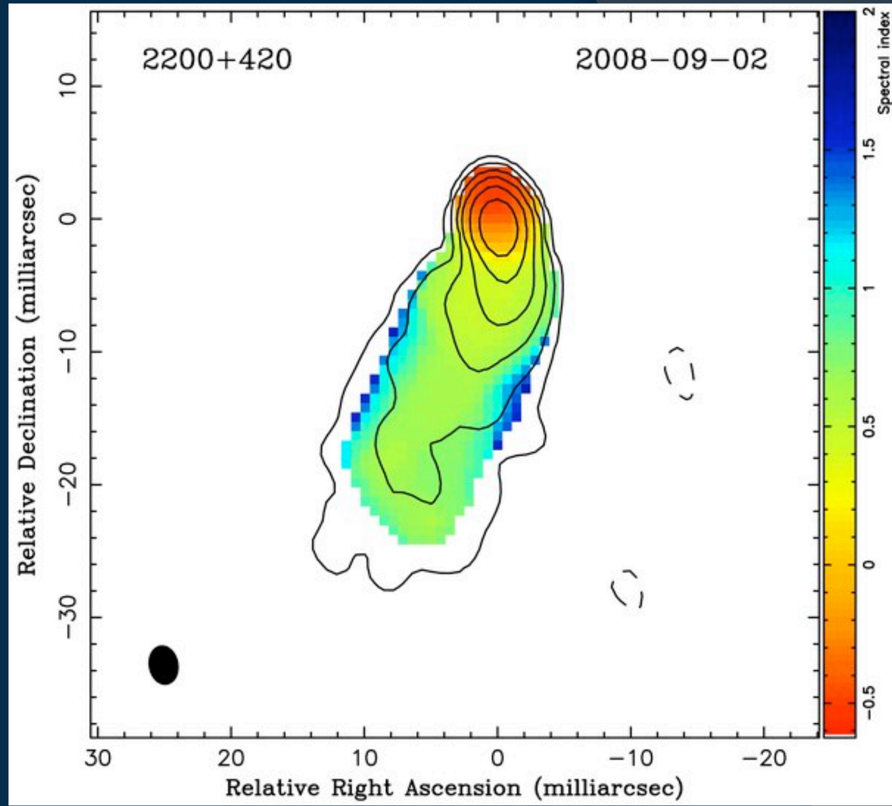
- Close galaxy at the Perseus cluster (z=0.0189)
- VHE source detected by MAGIC, also detected by *Fermi*/ LAT
- 1st VLBI obs ever on May 2011, discovered the blazar-like parsec-scale, one-sided structure



Kadler et al. A&A submitted 2011

BL Lac

- 3 major γ-flares reported (25jan10, ATel2402; 16feb11, ATel3171; 22may11, ATel3368)
- Present in major surveys
  - MOJAVE β_{app} ~ 10.6c
- Frequent ejection of jet features



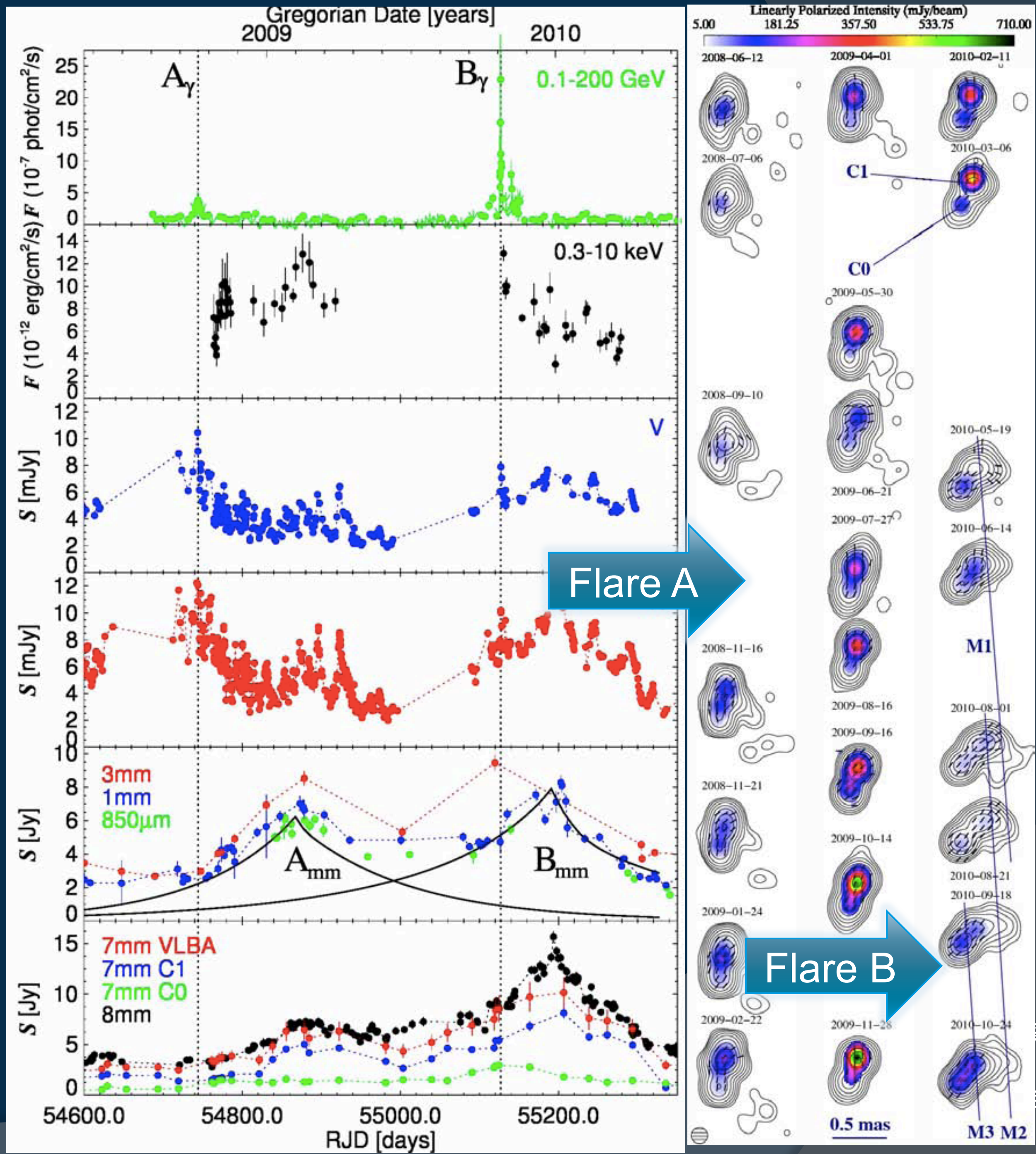
Abdo et al. 2011 ApJ 730 101

SPIX map from VLBA data: for δ~7.3, B<3G

OJ 287

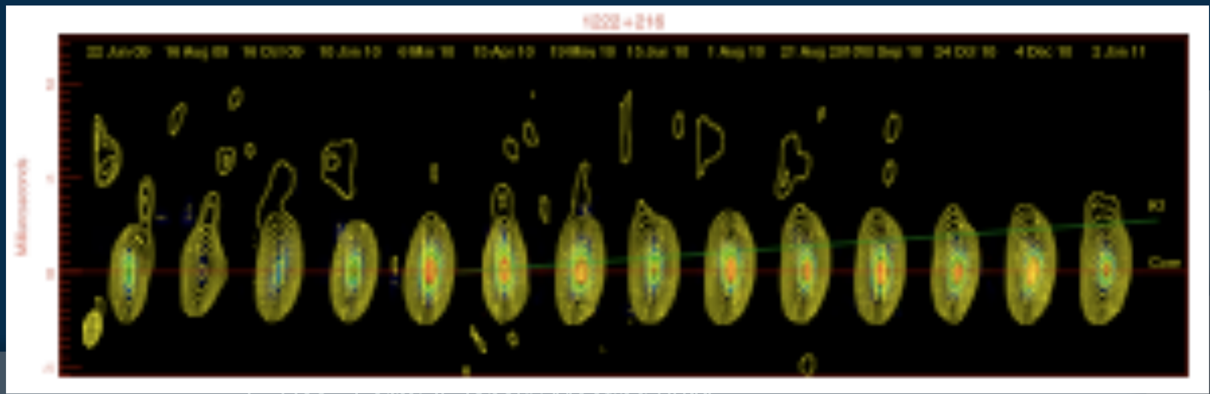
- Change in jet direction since 2005
- Flares A and B happen at the same time components pass through C1 (quasi-stationary shock?)

Agudo et al. 2011 ApJ 726 L13



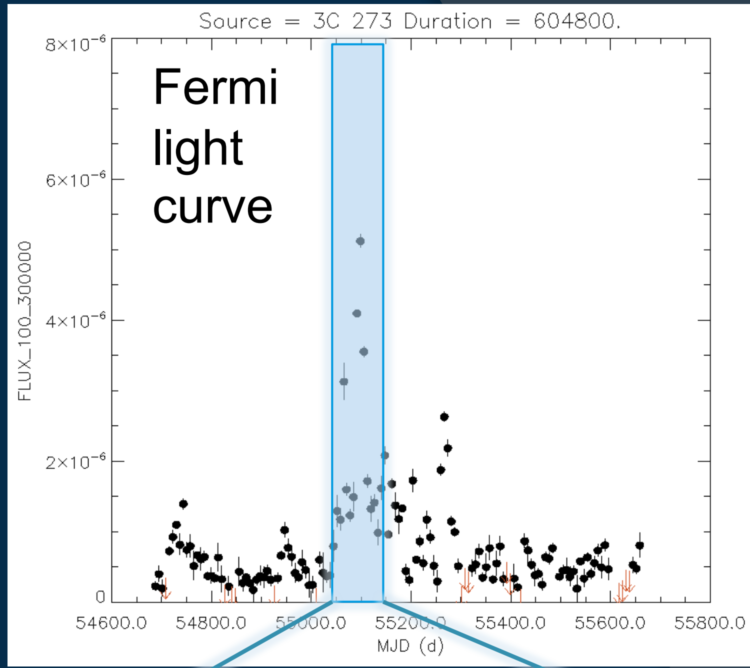
4C +21.35 (1222+216)

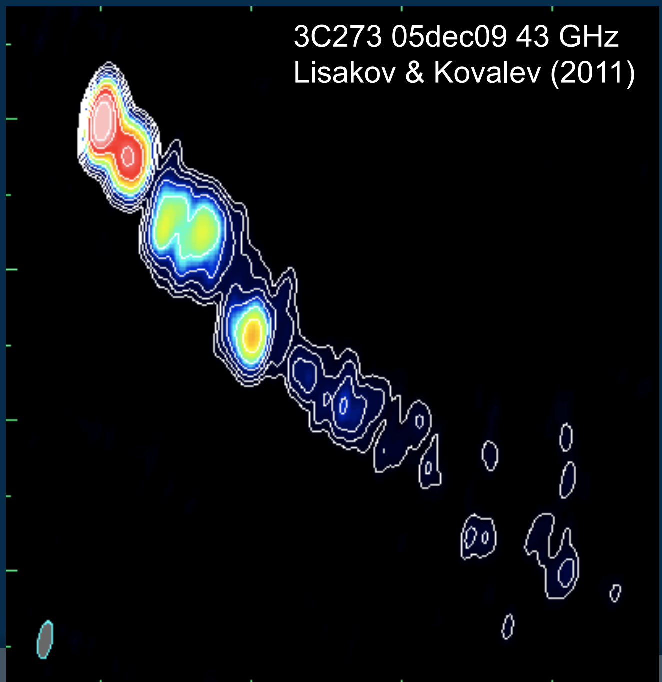
- Strong GeV gamma flare in Spring 2010 (Tanaka et al. ApJ 2011 733 19)
- Jorstad et al. 2011 eConf C110509 arXiv: 1111.0110 report a superluminal component K1 with 14c crossing a stationary jet simultaneously to the γ-high state



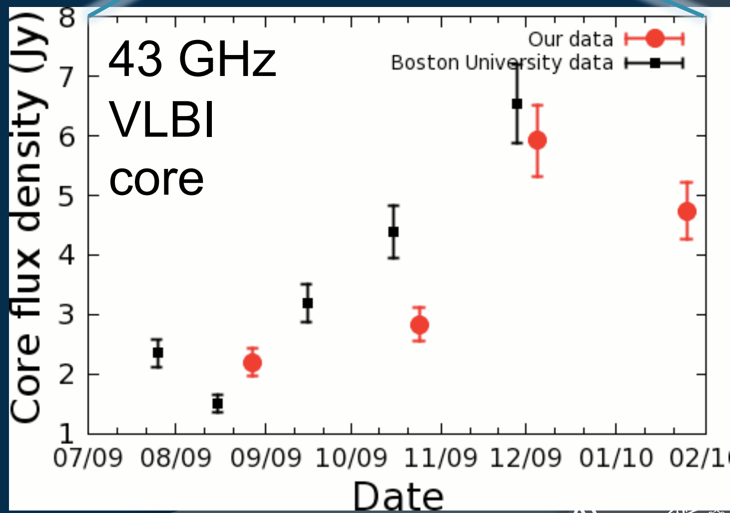
3C273

- Relationship between VLBI core and gamma-ray flare (delay implies location distance of 4-11 pc)





Also studied by the BU program, see below

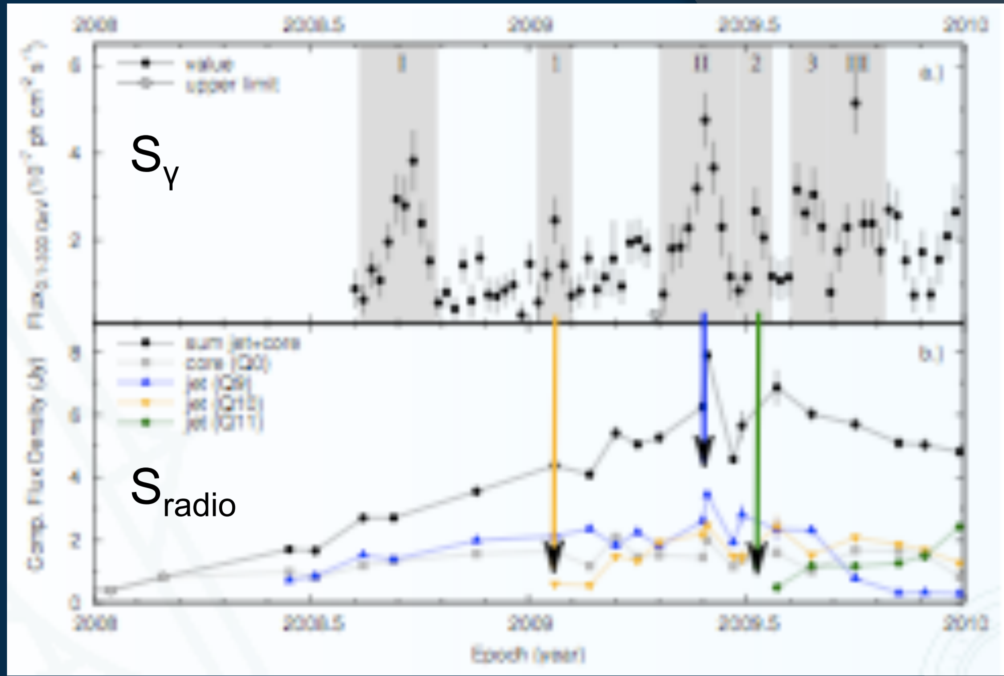


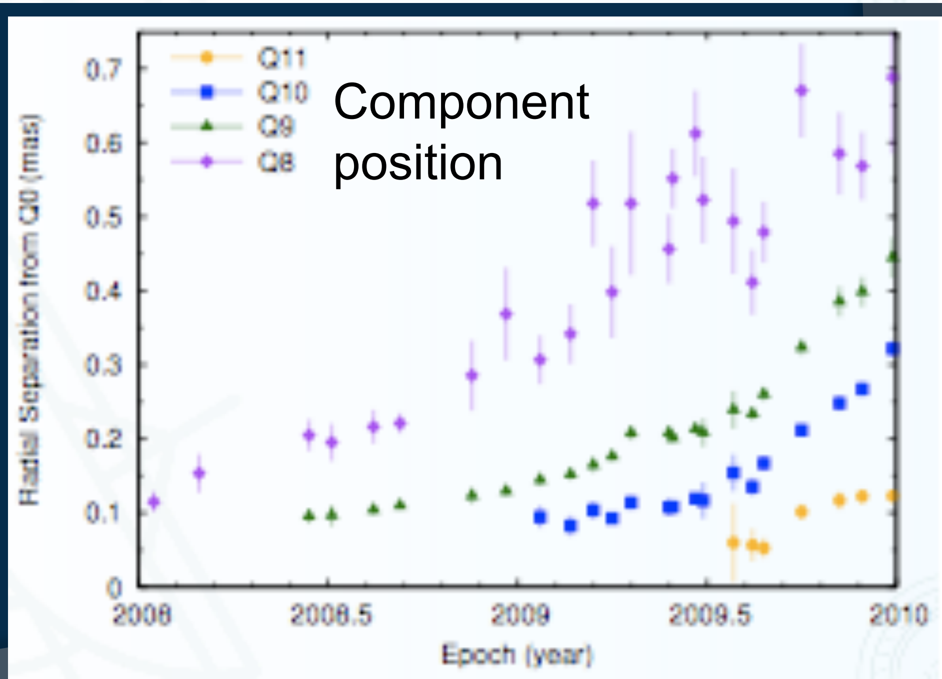
Lisakov & Kovalev (Fermi Symp. 2011)

3C 345

- QSO z=0.593, β_{app}≈20, δ≈8, θ=(2.6−6)°, ψ_{app}≈12.9°
- Radio flares in the jet have a γ-counterpart, 40pc away from core
- SSC should produce γ-emission

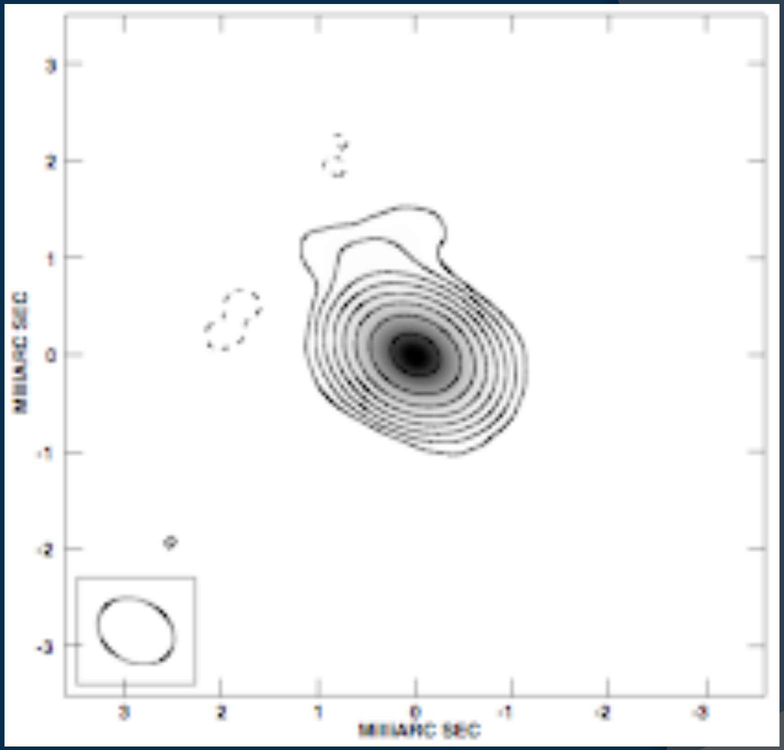
Schinzel, PhD Thesis 2011





RL-NSL1: PMN J0948+0022

Giroletti et al. (2011, A&A 528, L11)



- Radio-loud narrow-line Seyfert 1 Galaxy (RL NLS1) detected in gamma
- eEVN observations, 3 epochs so far
- $3.4{\times}10^{11}$ K
- Similar to flat-spectrum radio quasar

Other sources

- 3C 454.3
  - Several outbursts (early data on Abdo et al. ApJ 699 817; flares in Dec 2009 and April 2010 in Abdo et al. 2011 ApJ 721 721; and Nov 2010 in Abdo et a. 2011 ApJ 733 L26)
  - Intensively studied in VLBI
- Centaurus A
  - Only source with γ-emission beyond pc-scales
  - TANAMI results reported by Abdo et al. 2010 719 1433 and Müller et al. 2011 A&A 530 L11
- Mrk 421
  - Monitored by 2cmSurvey/MOJAVE (0.04-0.3c) and by Giroletti et al. at several frequencies
  - Reported also by Abdo et al. 2011 ApJ 736 13
- PKS 1510−089
  - Huge change in χ during a major γ-flare

See Jorstad's Talk

See Müller's Talk

See Giroletti's Poster

See Marscher's Talk

Other sources (ii)

- 3C 273
  - 4 new components since Fermi/LAT, with β_{app}~4−7 (0.7 knots/yr)
  - Fastest coincides with γ-flare
- 3C 279
  - 2 new knots, β_{app}~16−19, also related with γ-activity
- AO 0235+164
  - Claim of 70c component related to γ-flare

See Marscher's Talk

See Marscher's Talk

See Marscher's Talk

LSI+61º303 – a precessing microblazar

- Strong and variable γ-ray source (Fermi/LAT, MAGIC, VERITAS)
- Re-analysis of 2006 VLBA data (Massi, Ros & Zimmermann, A&A subm.):
  - Radio emission with double structure
  - Peaks of the image trace a defined ellipse in (27-30)d: precession period
- Model for emission processes in blazars?

Filling the table of γ--radio-pc-scale properties

MOJAVE
VIPS
BU
TANAMI

	β_{app}	S	T_b	α	δ	θ	L_R	Δϕ	ψ	Δχ	Δm	Acti-vity	Com-pact-ness
Det	✔	✔	✔		✔	✔			✔			✔	✔
Flaring												✔	
S_γ		✔ ✗	✗							✔	✔		
L_γ	✔						✔						
Γ		✗											
G_r			✔$_{inv}$				✔						
$\nu_{IC,SED}$													

TeV ➔ β_{app} ↘

TeV: transverse changes

PERMANENTLY UNDER CONSTRUCTION

Some evidences

- 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
- Warning: γ-samples are very biased, and the radio samples are usually flux-density selected
- No source with low L_γ has high β_{app}

VLBI-*Fermi* outlook

Answering some questions

1. Do the gamma-ray flares originate in relativistic shocks? *Probably.*
2. At what distance from the central engine is the main energy dissipation site? *It depends on who you are asking.*
3. What is the dominant emission mechanism? *Synchrotron in the radio, wait for talks and discussion*
4. What determines the ratio of gamma-ray luminosity to the synchrotron luminosity? *A conspiration of facts (modulated by Doppler!)*

What remains

- Collecting VLBI data at low and high frequencies at both hemispheres
- Intensive campaigns on selected sources
- Important connection to single-dish flux density monitoring results (not covered in this talk)
- Need for frequent mm-wavelength images, to address the core neighbourhood