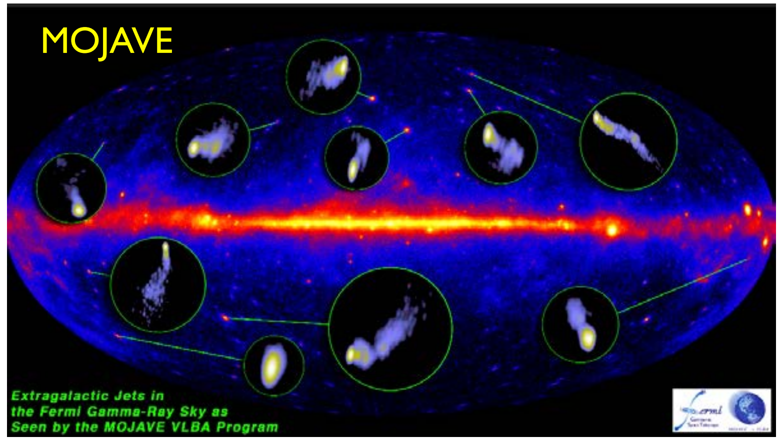
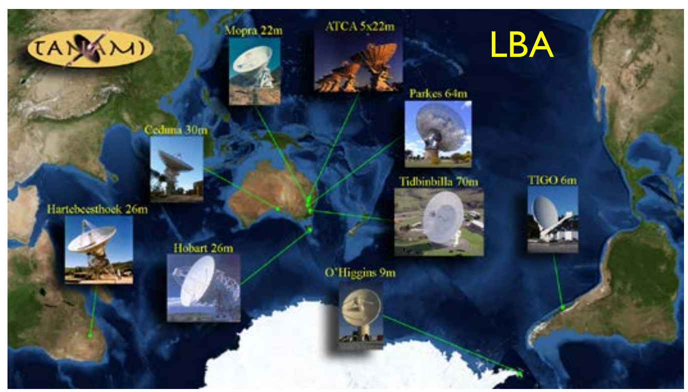
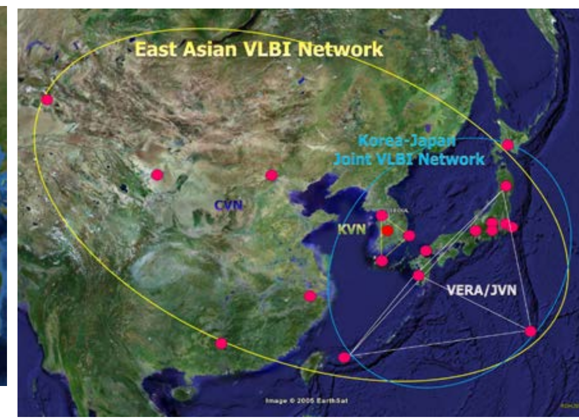
Large AGN Surveys With VLBI

Prof. Matthew Lister, Purdue University







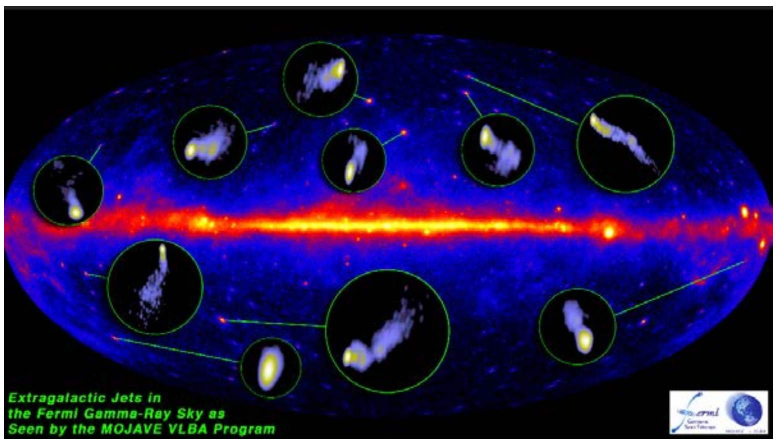
Outline

- Science motivations and applications for VLBI
- Large VLBI Surveys from Earth and Space: past and present
- Investigating radio and γ-ray properties of powerful AGN jets with MOJAVE and *Fermi*

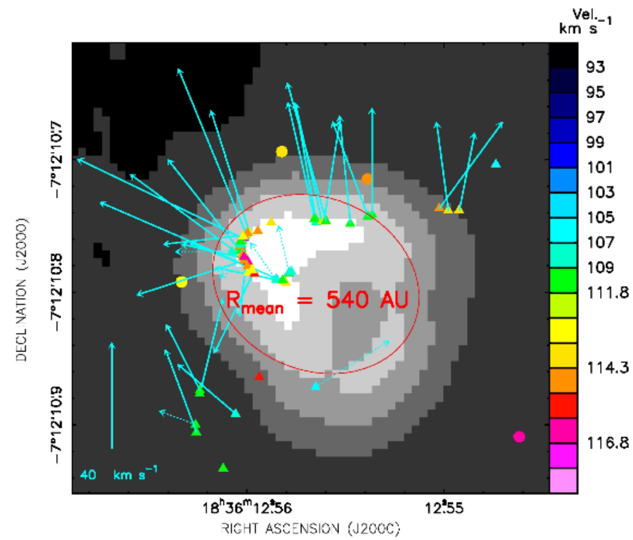
Why VLBI?

1. Ultrahigh angular resolution (sub-milliarcsecond scale).

2. Precise (microarcsecond scale) positional accuracy for astrometry.



1 million factor zoom-in views of γ-ray-loud AGNs (MOJAVE program)



Maser proper motions in HII region G24 (L. Moscadelli)

Limitations of VLBI

- **Too much resolution**

  → Sensitivity limits require target sources to be very compact ($T_b > 10^6$ K)

- **Not enough resolution**

  →Many target sources are too compact (!)

- **Interferometric coverage can be sparse**

  → Limited image fidelity, lack of short spacings

- **Very limited field of view (≤ 1 arcsec^2)**

  → but multiple correlation sky positions possible

Early VLBI Surveys

- Limited by availability of ad-hoc antenna arrays, small recording bandwidth, correlator capabilities

- Strategy was to identify and observe suitable targets from single-dish catalogs (bright, flat spectrum)

- **VLBI surveys are an excellent filter for finding AGN**

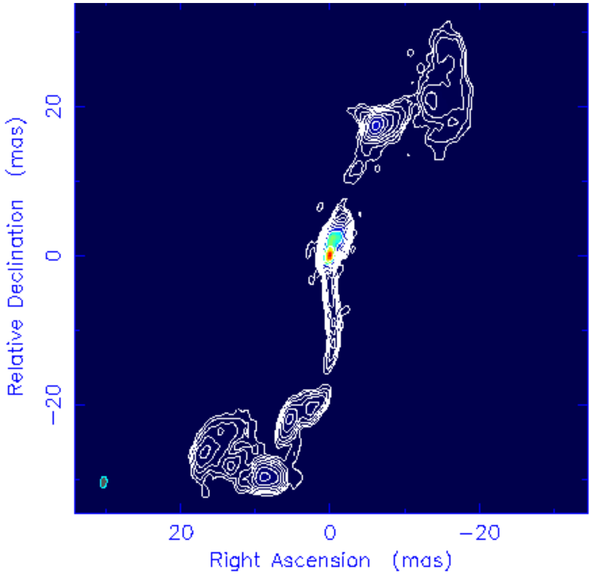
- **Pearson-Readhead Survey** (Pearson & Readhead 1981, 1988)
  - Complete sample of 64 AGN with:

    5 GHz flux density > 1.3 Jy, $\delta > +35^{\circ}$, $|b| > 10^{\circ}$
  - Roughly 75% were compact enough for VLBI observations
  - Extensive follow-up studies at other wavelengths and resolution scales

Pearson-Readhead Survey

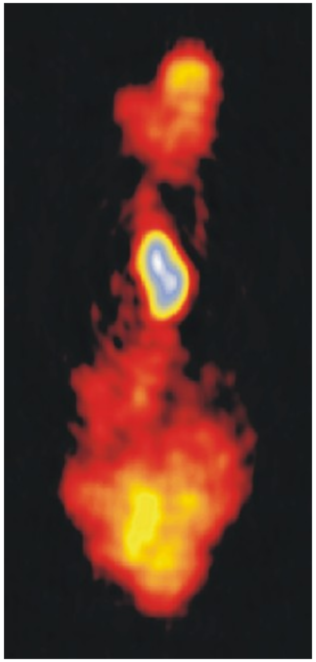
2352+495:

Young Radio Jets



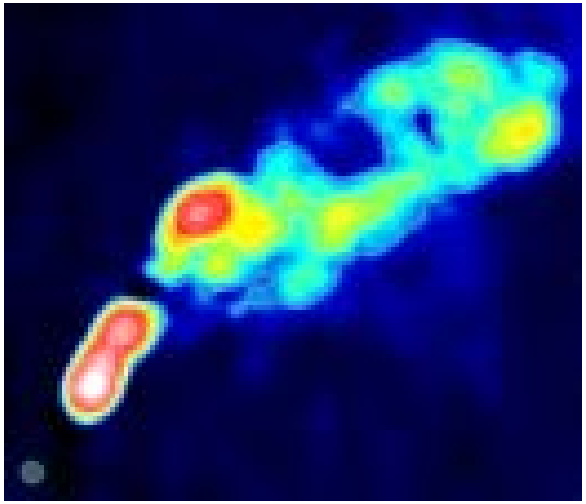
Owsianik et al.

3C 84: Radio Galaxy



Walker et al.

3C 380: Radio Quasar



VSOP program

- Three main morphological classes of radio AGN jets
- Observed jet emission strongly affected by relativistic beaming
- Flat-spectrum AGN tend to be more compact

Caltech-Jodrell Bank Surveys

- CJ1: lowered the PR survey flux density limit to 0.7 Jy at 5 GHz
- CJF (flat-spectrum survey; Taylor et al. 1996)
  - complete sample w.r.t flux density and spectral flatness (293 AGN)
- Jet kinematics: (Britzen et al. 2008)
  - 3 to 5 VLBI epochs per source at 5 GHz;
  - superluminal speeds up to 30c
  - some inward motions seen
  - speeds positively correlated with radio luminosity

Frequency(MHz)	4850
Flux lower limit @5 GHz	350 mJy
Spectral Index	$\alpha_{1400}^{4850} \geq -0.5$
Declination	$\delta \geq 35°$
Galactic latitude	$\|b\| \geq 10°$
# Quasars	198
# BL Lac	32
# Radio galaxies	52
# Unclassified	11
# Total	293

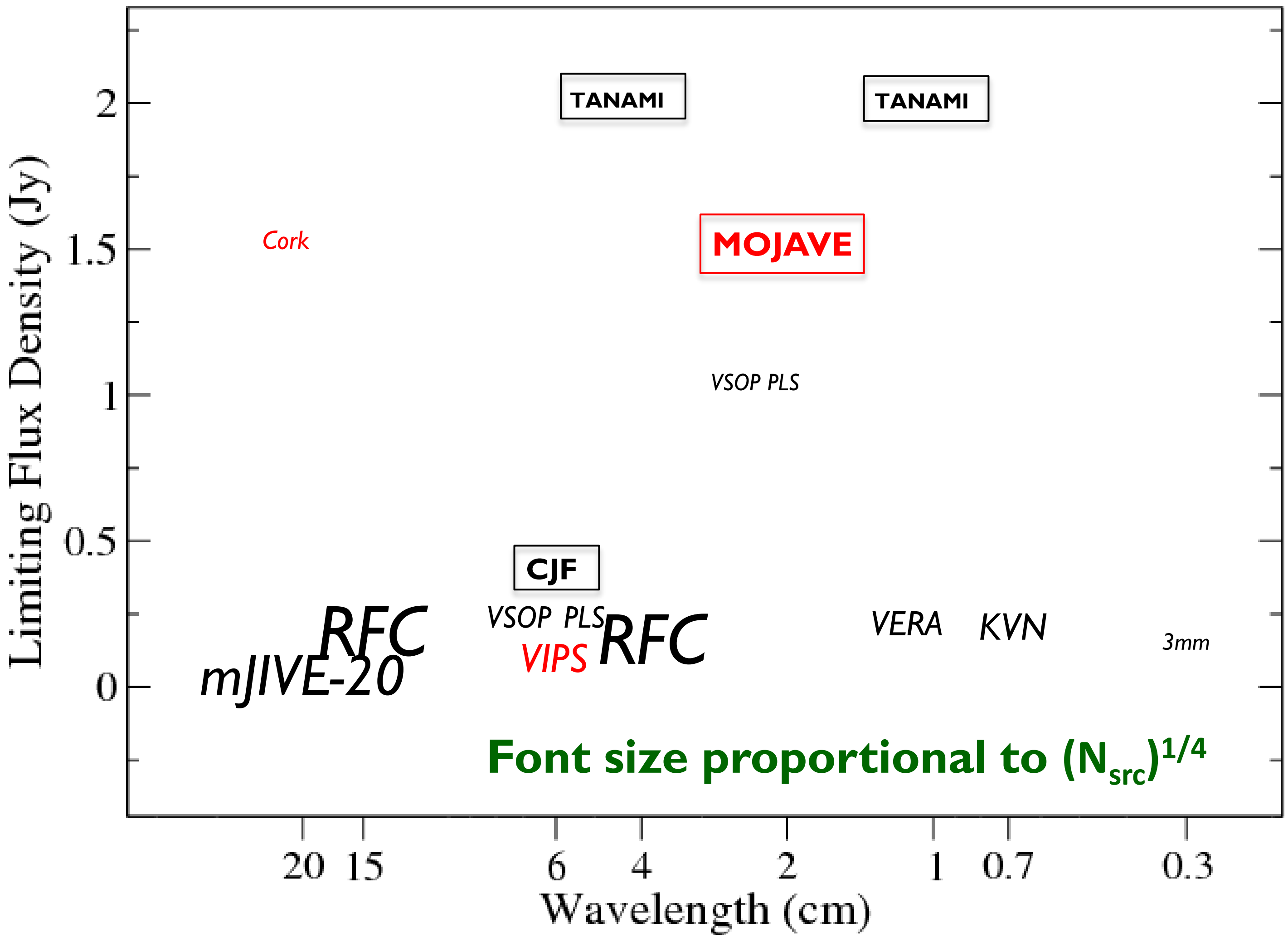
Karouzos et al. 2012

Large VLBI AGN Surveys: Modern Era

1994: Advent of VLBA greatly facilitates large monitoring programs, polarimetry, & multi-frequency studies

Survey	λ (cm)	Flux Lim. (Jy)	Nsrc	Reference / Website
mJIVE-20	20	0.001	~4300	safe.nrao.edu/vlba/mjivs/
Cork	20	1.5	135	physics.ucc.ie/radiogroup/
RFC	15, 4	0.2	~9500	astrogeo.org/rfc/
VIPS	6	0.085	1100	www.phys.unm.edu/~gbtaylor/VIPS/
VSOP PLS	6	0.3	374	www.vlba.nrao.edu/astro/obsprep/sourcelist/6cm/
CJF	6	0.35	300	www.astro.caltech.edu/~tjp/surveys.html
TANAMI	4, 1	2	80	pulsar.sternwarte.uni-erlangen.de/tanami/
MOJAVE	2	1.5	400	www.astro.purdue.edu/MOJAVE
VSOP PLS-22	2	1	140	G. Moellenbrock et al. 1996
VERA	1	0.2	551	L. Petrov et al. 2011
KVN	0.7	0.2	900	L. Petrov et al. 2012
Global 3mm	0.3	0.1	127	S. Lee et al. 2008

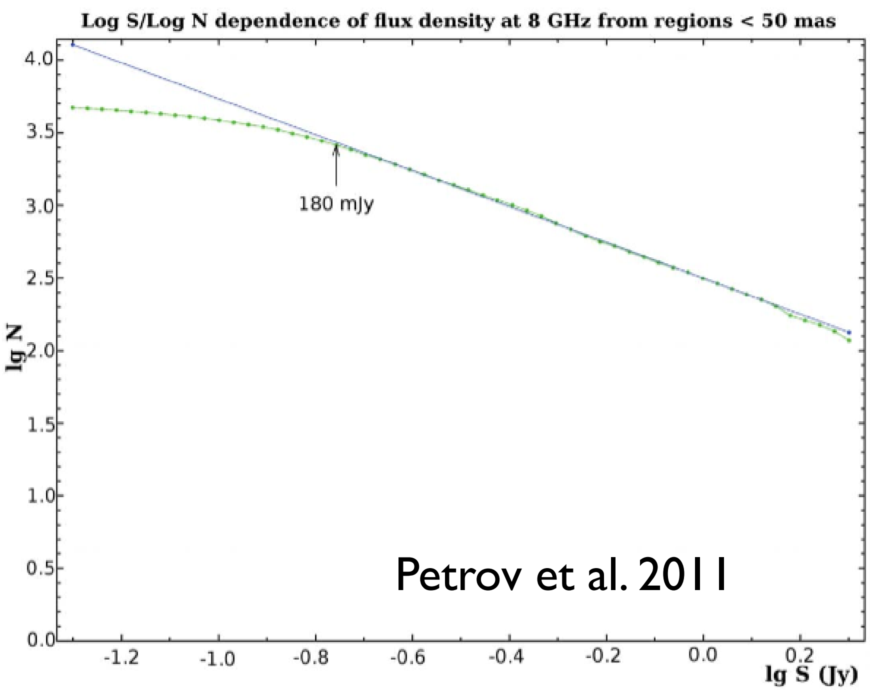
Large VLBI Surveys (> 80 AGN)



Boxed = Multiepoch monitoring   Red = Full polarization

Geodetic VLBI Surveys

- Large database of VLBI 2 and 8 GHz observations made of several hundred AGN for calibration of **International Celestial Reference Frame (ICRF)**
- The **Radio Fundamental Catalog** is a compendium of VLBI data on nearly 10000 objects (nearly all AGN) at 2, 5, 8 and 22 GHz: astrogeo.org/rfc/

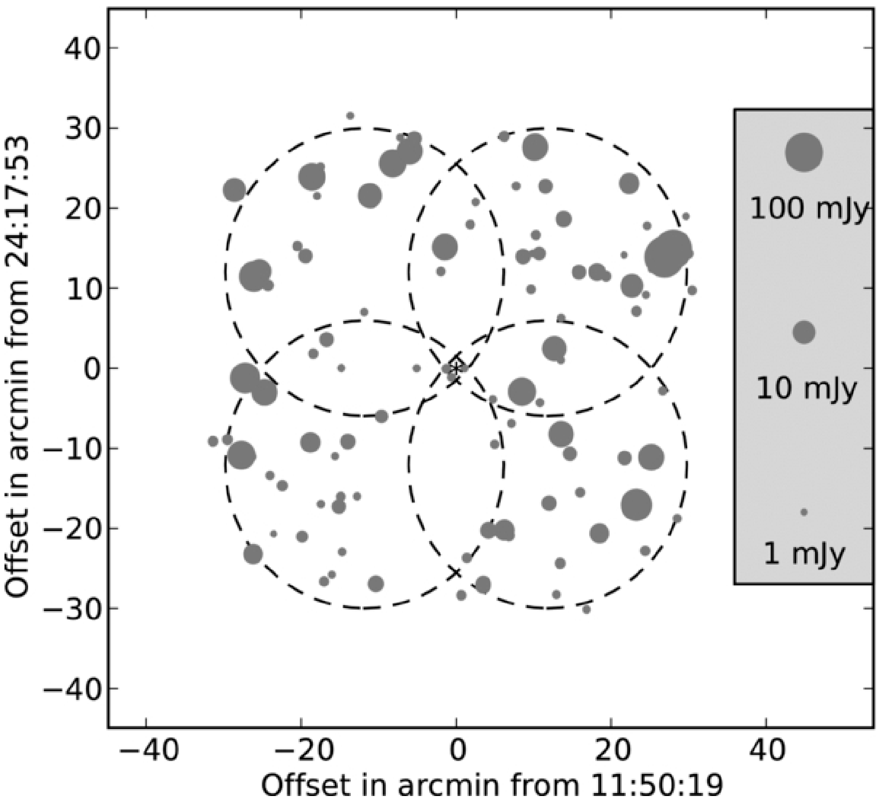


- Virtually every cm-wave VLBI source above ~150 mJy is now catalogued
- Catalog is overwhelmingly dominated by AGN

mJIVE-20

- 20cm VLBA survey of FIRST survey sources
- Short pointings during VLBA filler time yields peak flux density and approximate T_b
- Exploits multiple-phase center capability of VLBA software correlator

  ~100 sources/sq. deg./hour
- ~4300 VLBI detections so far in the range 1 to 100 mJy



Deller & Middelberg 2014

mJIVE-20: Preliminary Findings

1. Fainter FIRST sources show higher likelihood of VLBI detection

- If more luminous jets have higher Lorentz factors, de-boosting effect of VLBI core luminosity is higher for arbitrary jet orientations.

- Slower, less luminous jets less affected by orientation, so their ratio of VLBI core to total (FIRST) flux density is higher.

2. Stellar/point like SDSS sources show much higher VLBI detection likelihood than either galaxies or sources with no SDSS counterpart.

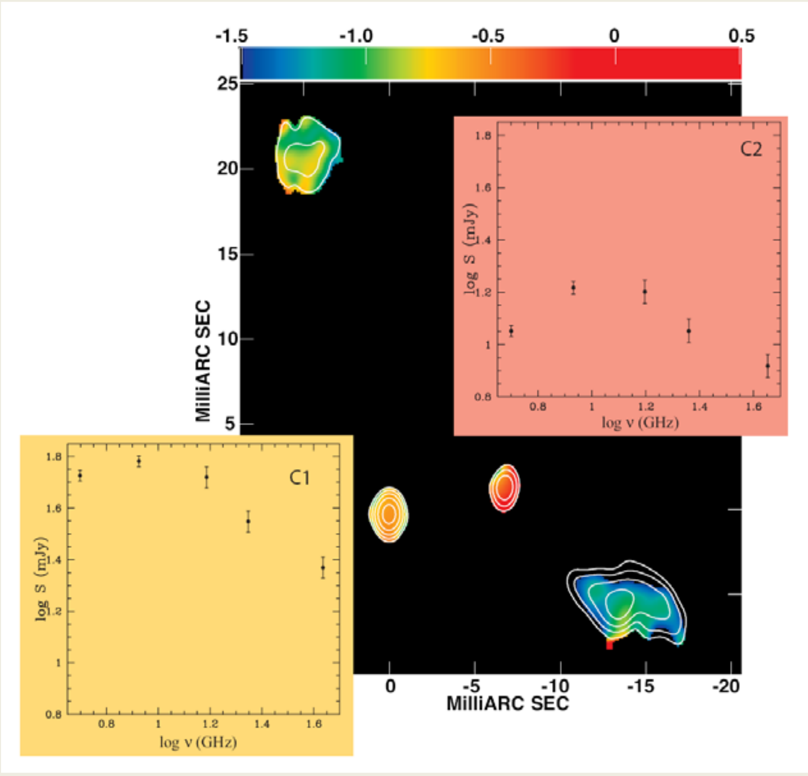
- VLBI detection likelihood trend w.r.t. FIRST flux density (point 1) is even stronger in galaxies and no-SDSS-counterpart sources.

Deller & Middelberg 2014

VLBA Imaging and Polarimetry Survey (VIPS)

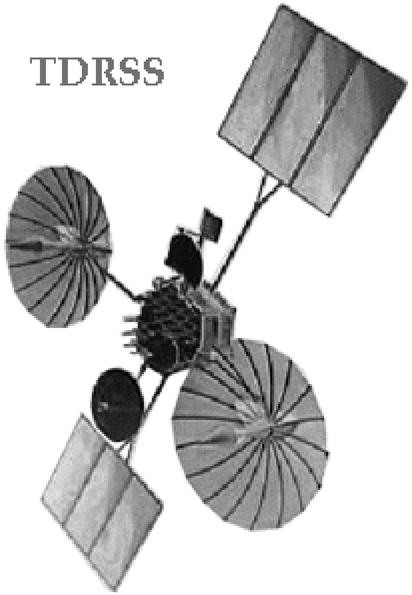
- 1127 flat-spectrum AGN imaged at 5 &15 GHz in SDSS northern cap
  - all CLASS survey sources with 8 GHz VLA flux density > 85 mJy

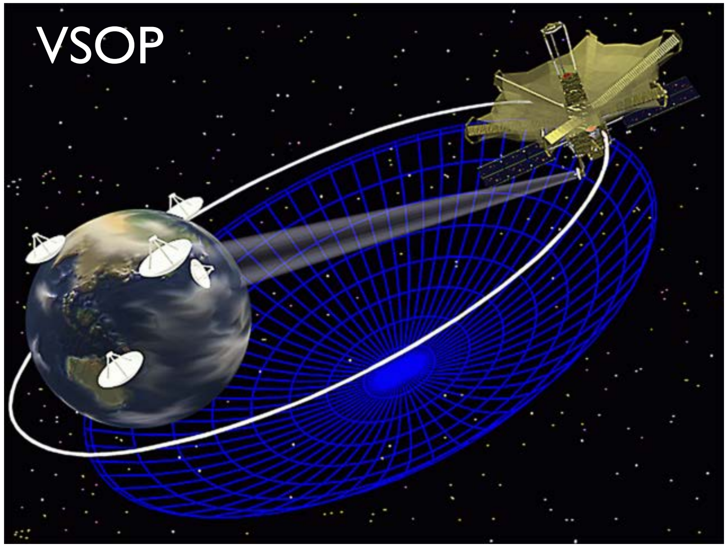
- Major results:
  - No trend between optical magnitude and 5 GHz flux density
  - 37% of AGNs had detectable linear polarization, ranging from 1% - 20%, (typically 5%)
  - B field near core is typically aligned with the jet, and becomes more ordered downstream
  - Discovery of binary black hole candidate 4C +37.11: contains two flat spectrum cores separated by 7 pc

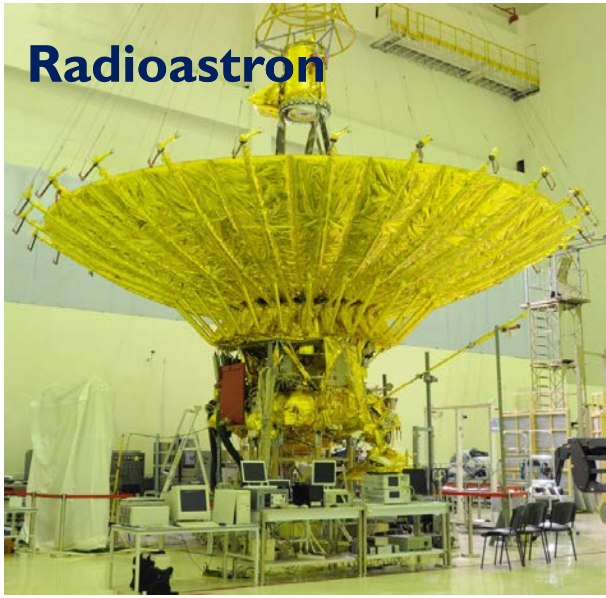


Rodriguez et al. 2006

Space VLBI Surveys







USA (1986-88)
2.2 Earth Diam.
~20 AGN at
2 & 15 GHz

Japan (1997-2003)
3 Earth Diam.
~200 AGN at 1 and 5 GHz

Russia (2011-present)
30 Earth Diam.
0.3, 1.6, 5, & 22 GHz
Surveying >200 AGN

Why Space-VLBI?

A Gaussian region of FWHM diameter at a (radio) wavelength λ has an equivalent blackbody temperature

Kelvin

The maximum resolving power of an interferometer is

Therefore,

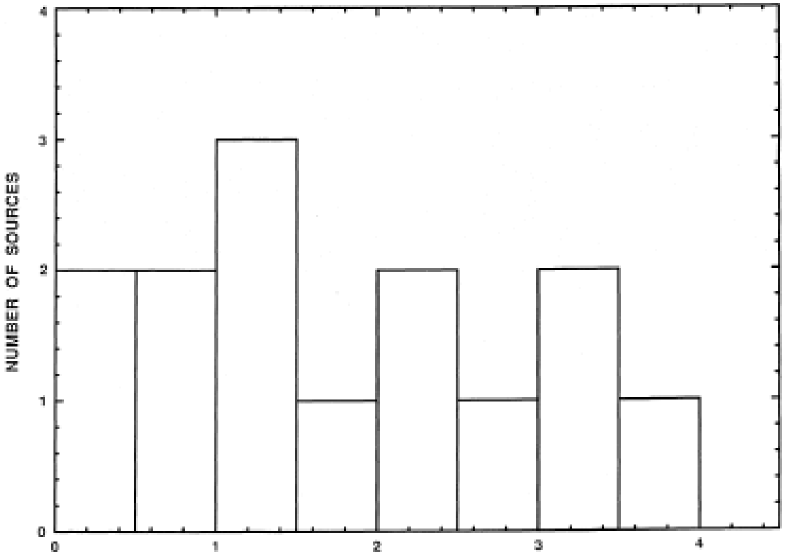
Kelvin

But hardly any AGN have flux densities S > 10 Jy, therefore

→ With Earth-based VLBI we can only directly measure AGN brightness temperatures below ≈10^{12} K

TDRSS Survey

Linfield et al. 1990



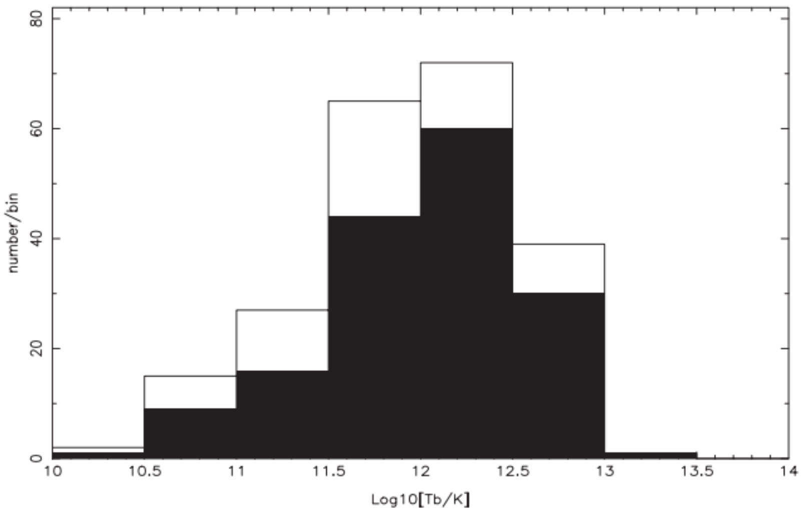
$T_b / 10^{12}$ K

Detected AGN up to

$T_b = 4 \times 10^{12}$ K

VSOP AGN Survey

Dodson et al. 2008



Log 10 [T_b / K]

56% of AGN have $T_b > 10^{12}$ K
(30% in observer frame)

Radioastron AGN Survey (Kovalev et al.)

- Key science program to measure T_b in jet cores selected from a list of 240 AGN with correlated 8 GHz flux density exceeding 0.6 Jy at longest ground-based baselines
- Successfully detected fringes to more than 30 AGN at projected baselines 5-23 Earth diameters at 1.6 and 5 GHz.
- Fringes also found at 22 GHz over baseline lengths between 2.5 and 8 Earth diameters for at least 10 AGN
- Target detection rates as of Jan. 2014:

  1.6 GHz: 75%, 5 GHz: 70%, 22 GHz: 30%

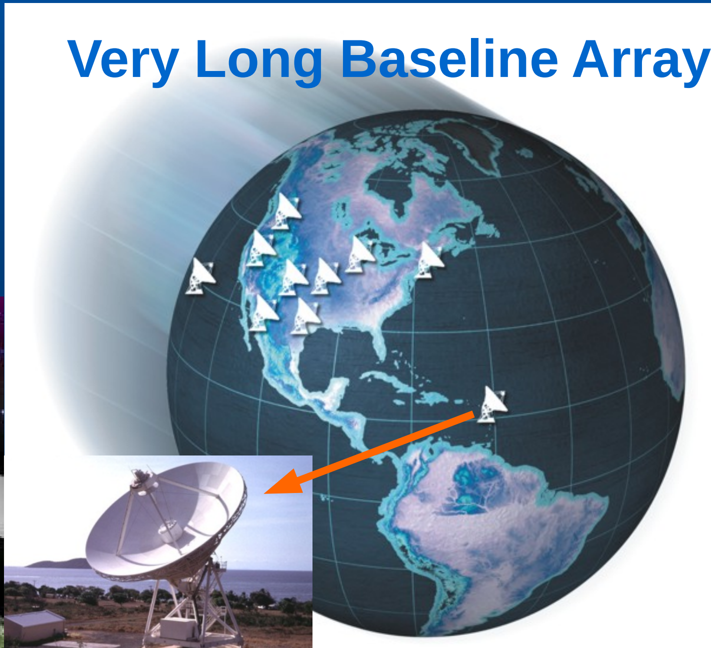
→ All of these detections give 10^{12} K < T_b < 10^{14} K

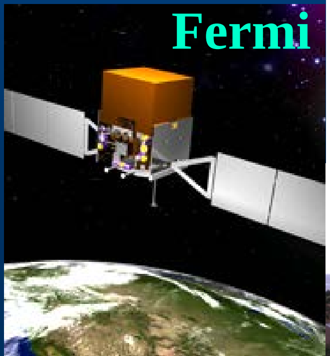
→ 22GHz 3C 273 fringe detection at 8.1 D_E is the highest directly achieved angular resolution in the history of astronomy (27 μas)

MOJAVE Collaboration

- M. Lister (P.I.), J. Richards (Purdue)
- T. Arshakian (Byurakan Observatory, Armenia)
- M. and H. Aller (Michigan)
- M. Cohen, T. Hovatta, A. Readhead (Caltech)
- N. Gehrels (NASA-GSFC)
- D. Homan (Denison)
- M. Kadler (U. Wurzburg, Germany)
- K. Kellermann (NRAO)
- Y. Kovalev (ASC Lebedev, Russia)
- A. Lobanov, T. Savolainen, J. A. Zensus (MPIfR, Germany)
- A. Pushkarev (Crimean Observatory, Ukraine)
- E. Ros (Valencia, Spain)
- G. Tosti (INFN Perugia, Italy)

Monitoring
Of
Jets in
Active Galaxies with
VLBA
Experiments





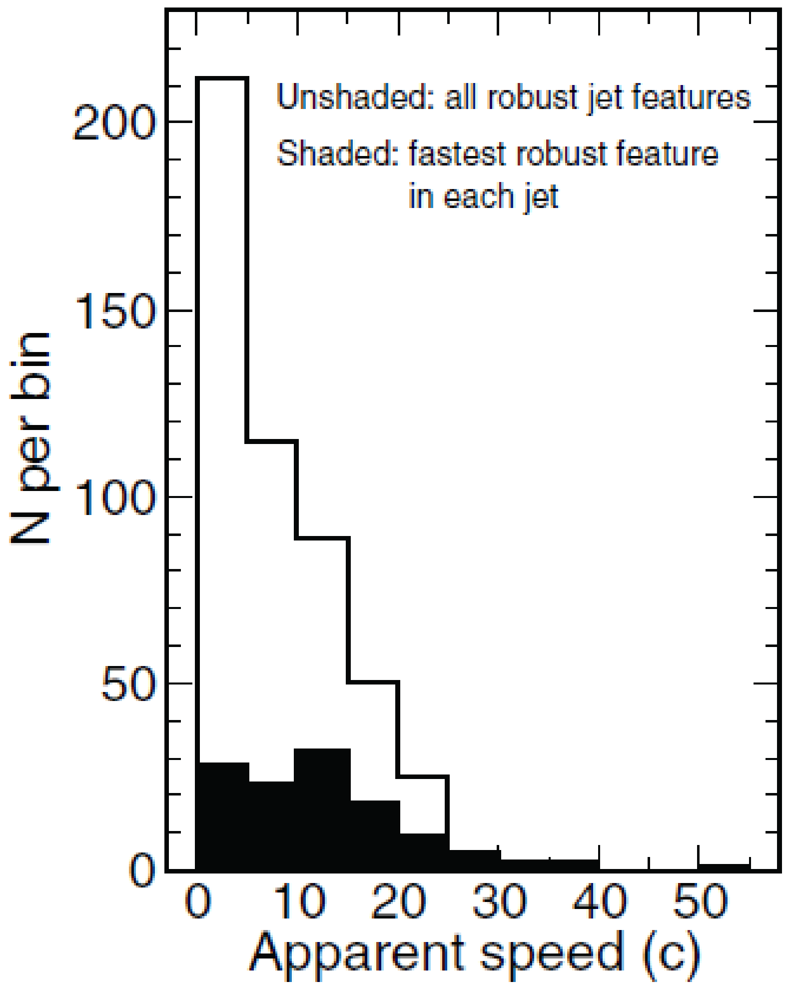
The MOJAVE Program is supported under NASA Fermi Grant 11-Fermi11-0019

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)
- 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 numerals refer to MOJAVE paper series, full list at http://www.cv.nrao.edu/2cmsurvey/publications.html

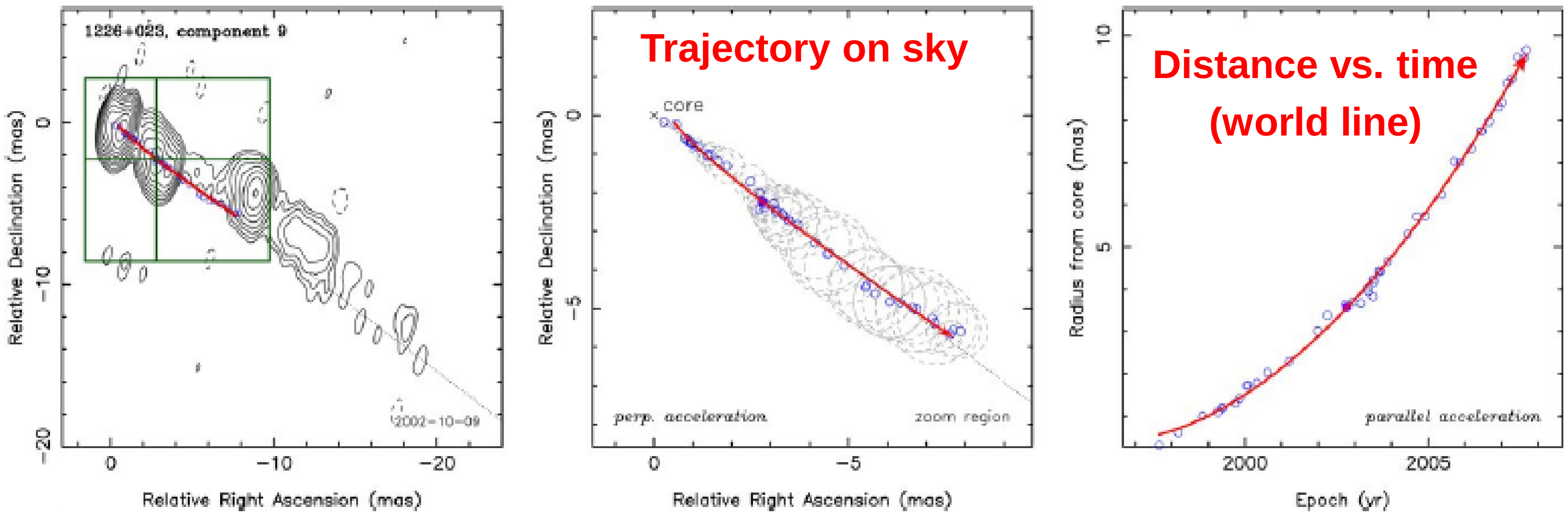
1. Jet Speeds



Lister et al., 2009, AJ, 138, 1874

- Speed distribution:
  - peaked at low values
  - only 2 jets with $\beta_{app} > 30$
  - high Γ jets are very rare in blazar parent population
- Lorentz factors of the most luminous/powerful jets range up to ~40
  - weaker jets have Lorentz factors of a few
- 98% of motions are outward from core
- Speeds of features increase down the jet

2. Jet Accelerations

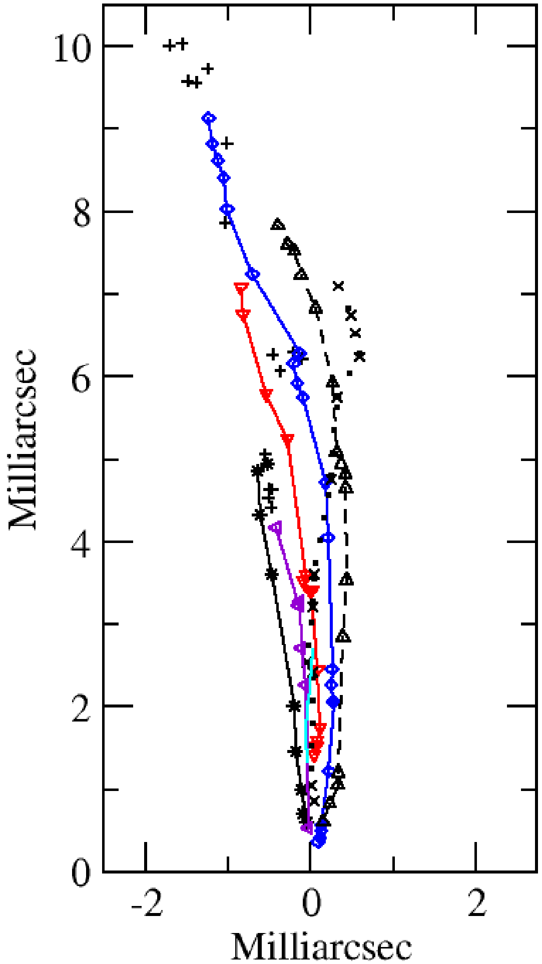


Homan et al. 2009

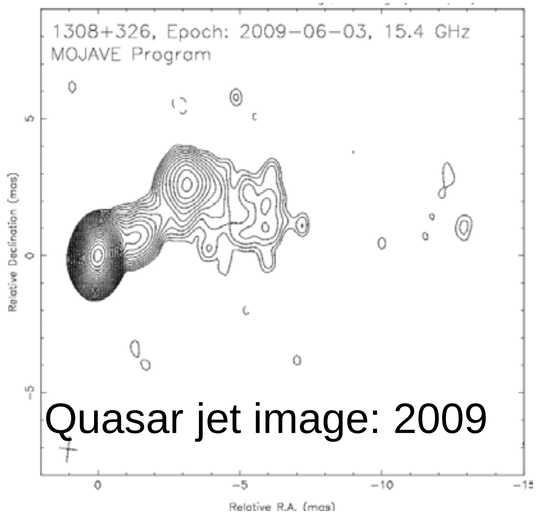
- Moving features have complex curved trajectories and are usually accelerating (70% are non-ballistic)

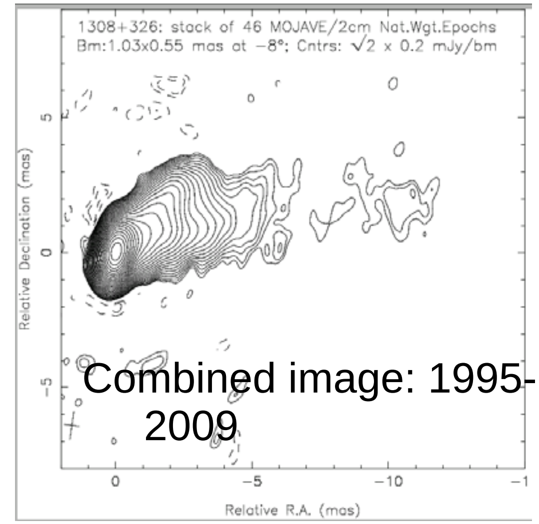
- Close to the base of the jet, accelerations are more common than decelerations
  - jet flow is still being organized on scales of tens of light years from the black hole

3. Energized Jet Channels



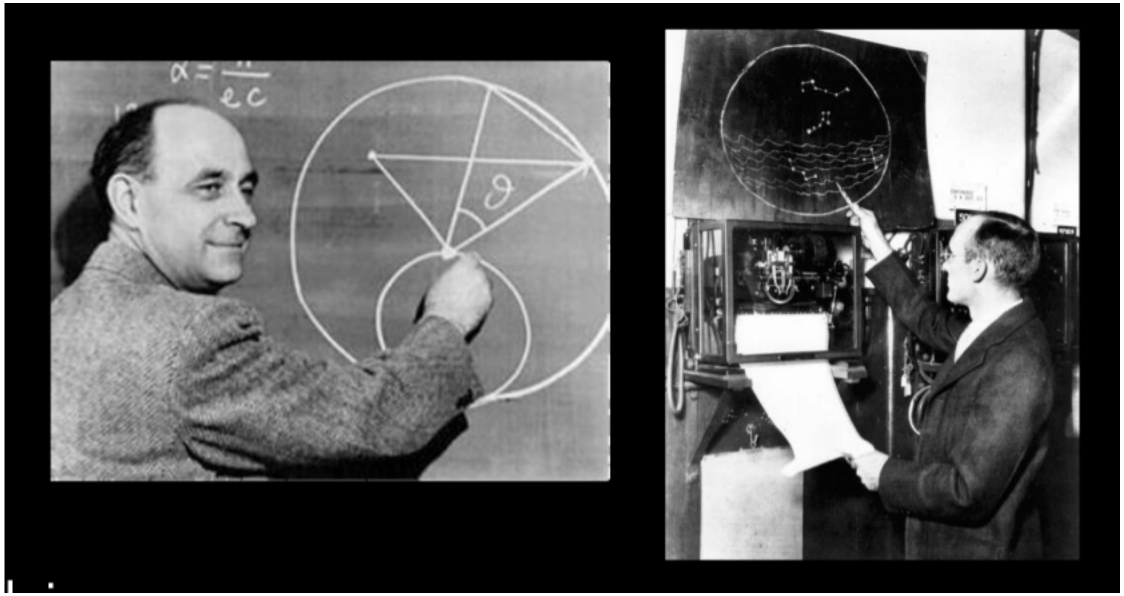
Lister et al. 2013





- Newly ejected jet features move out on successively different trajectories

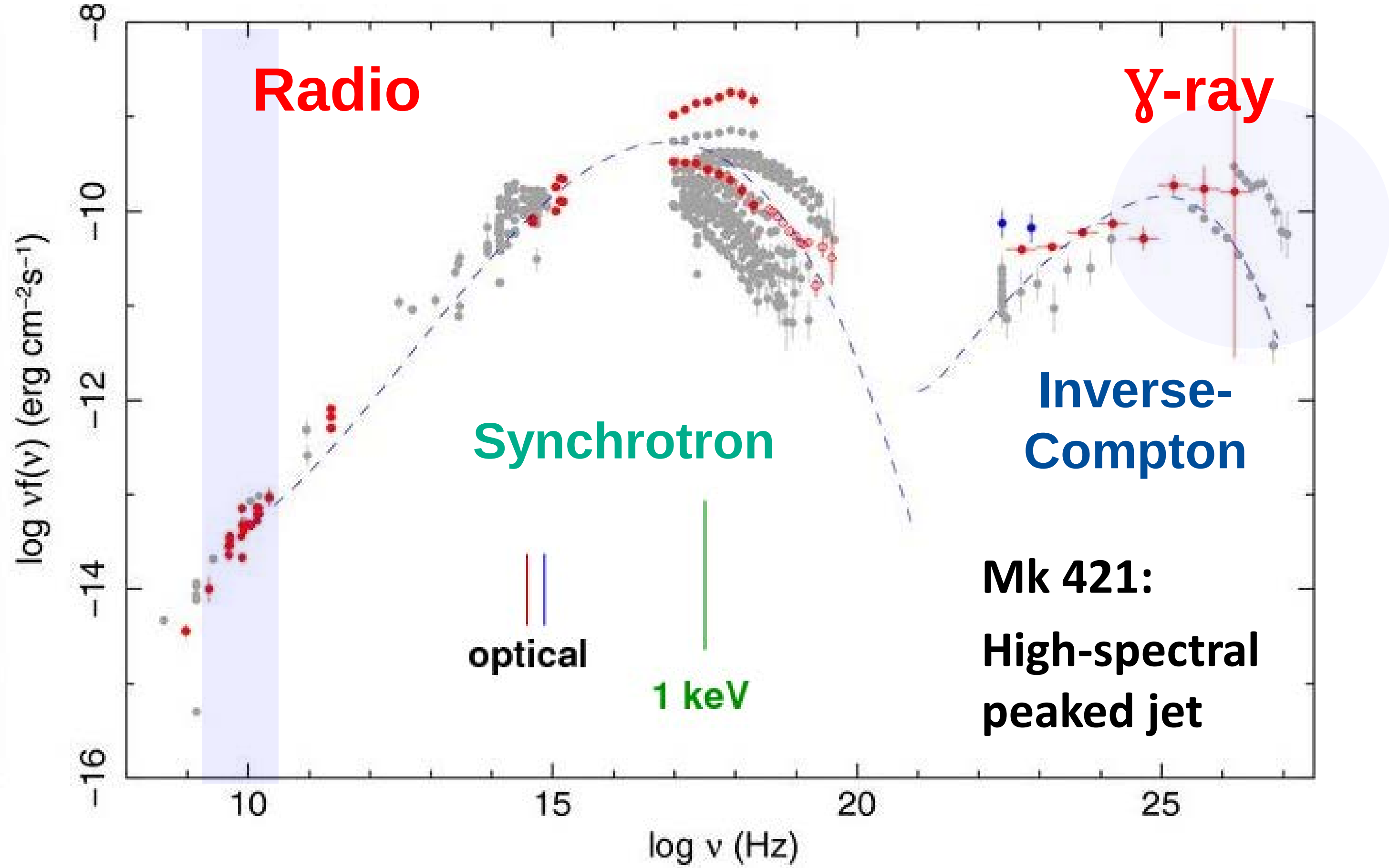
- At any given time, only a portion of the (conical) jet is energized/visible



Fermi Meets Jansky:

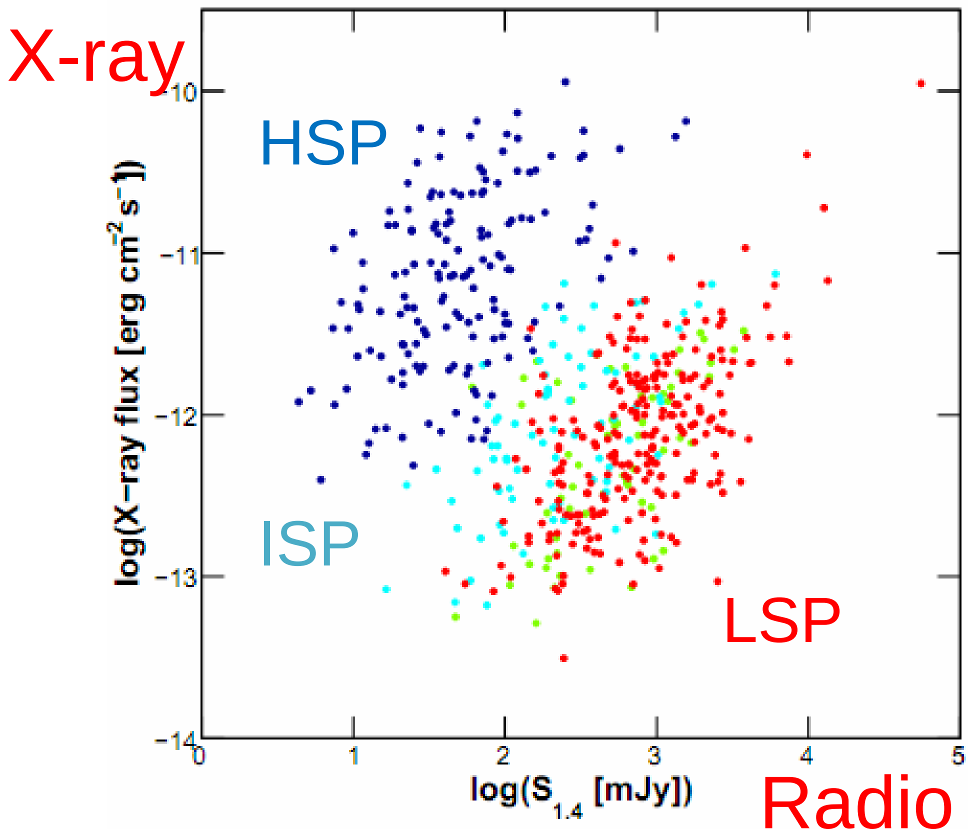
The AGN radio/γ-ray connection

Synchrotron Peak Location



Abdo et al., ApJ 716, 30 (2010)

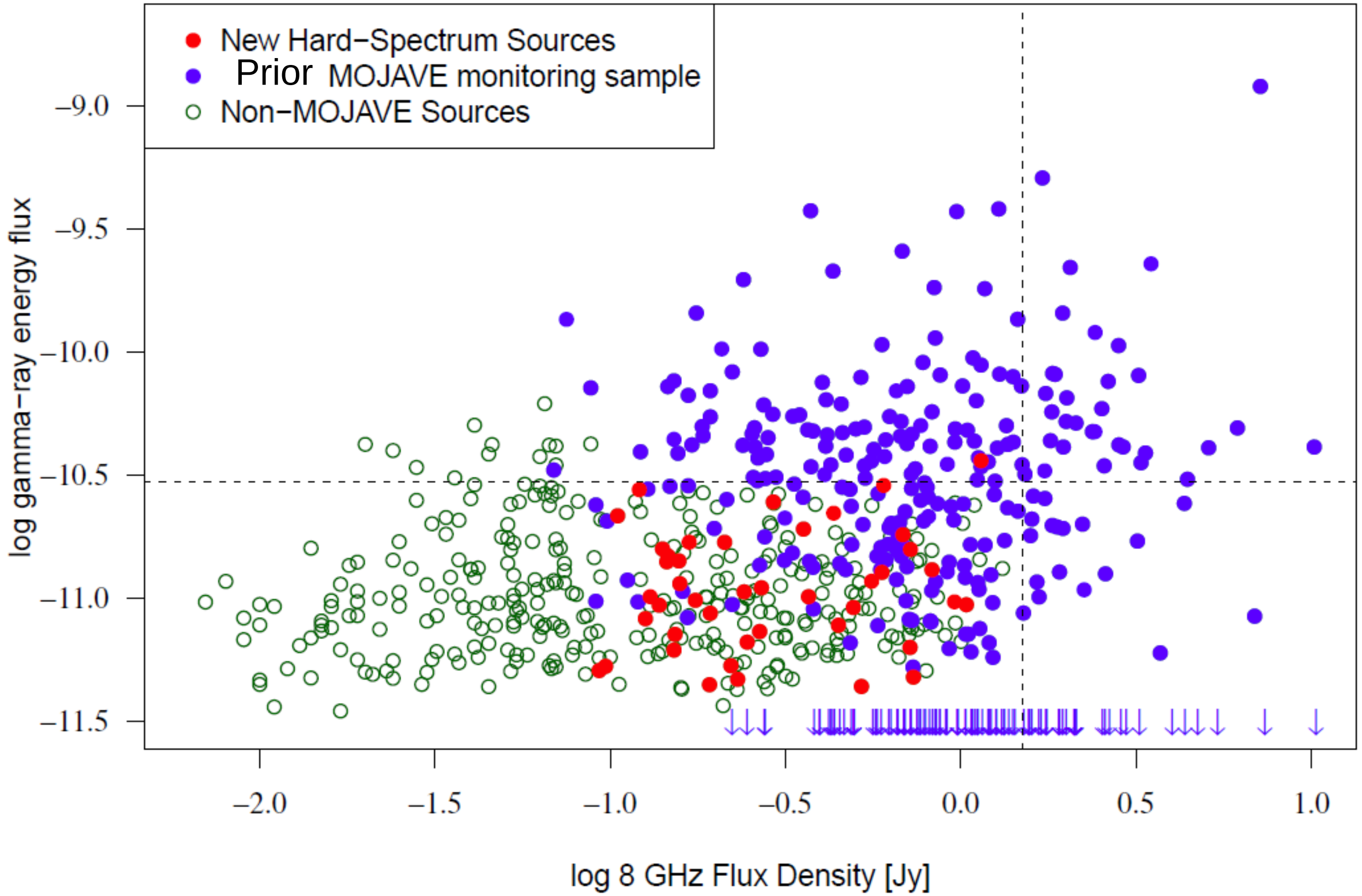
Fermi 2nd LAT AGN Catalog



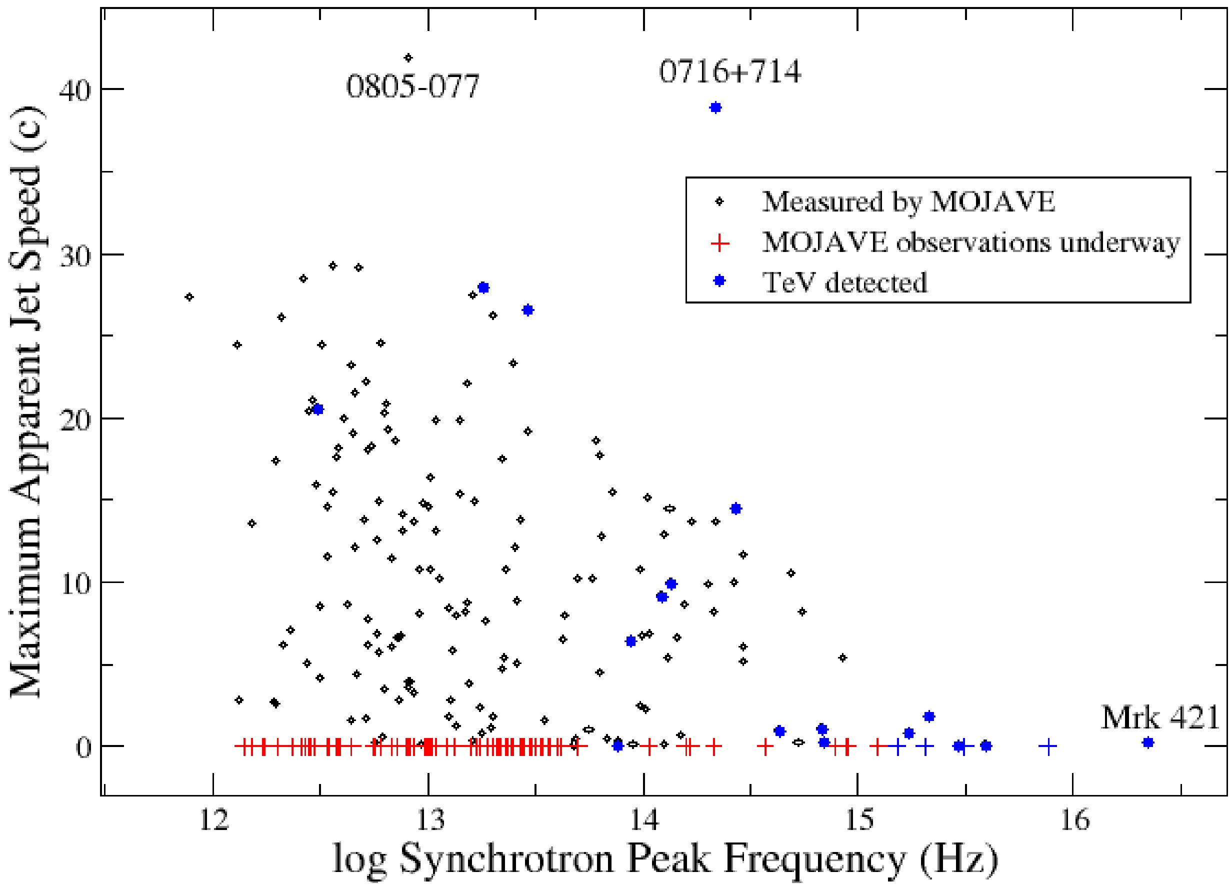
Fermi LAT Collab, 2012, ApJ 743, 171

- *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)

Radio vs. γ-ray flux correlation



Trends with Apparent Speed

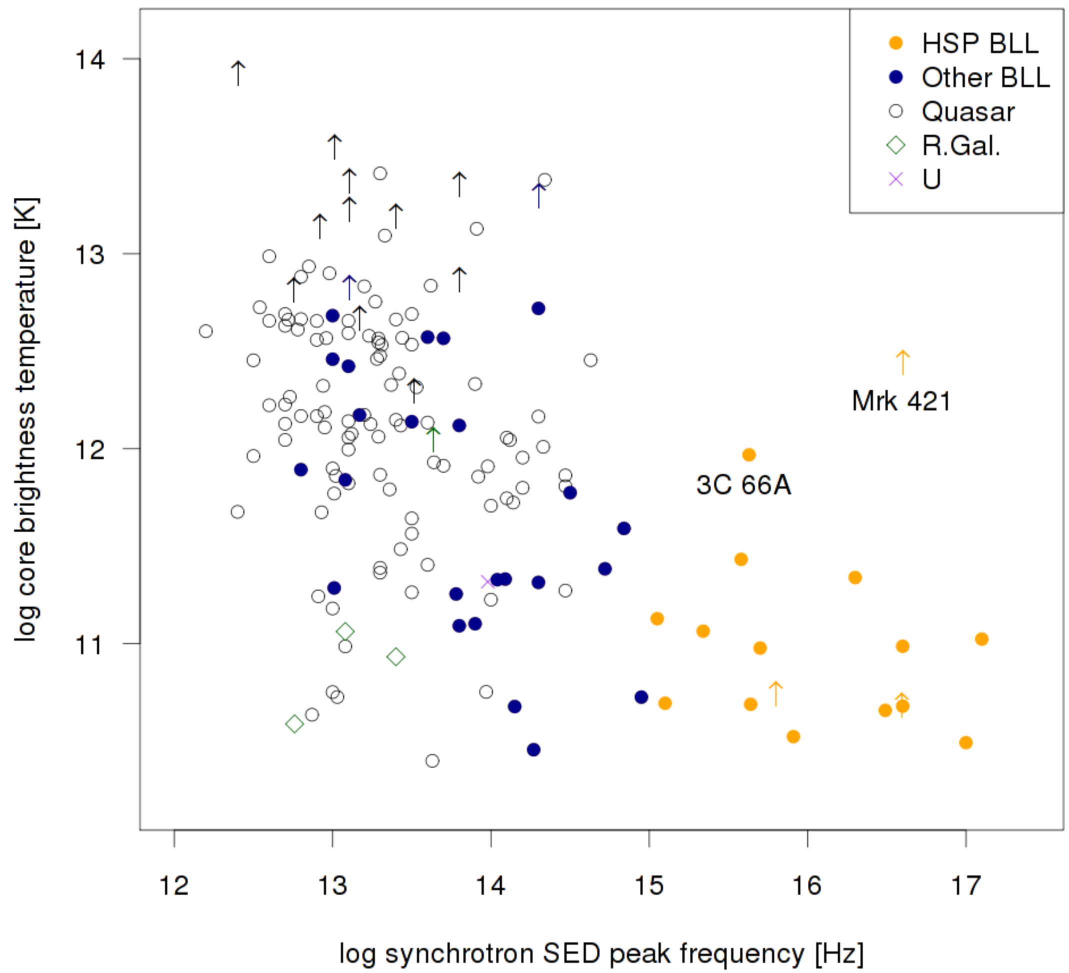


1. All of the fastest known jets have been detected in γ-rays
2. Highest spectral peaked blazars have small range of apparent speed

Relativistic Beaming Levels

- **Radio core compactness (brightness temperature) strongly increases with beaming and jet activity level**

- ***Lower radio compactness and variability of HSP radio cores is indicative of lower relativistic beaming factors***

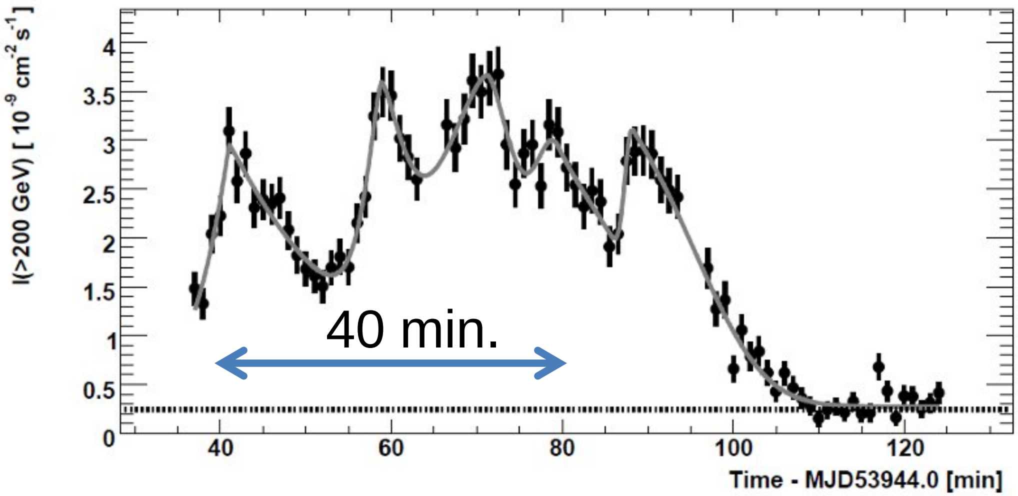


Lister et al. 2011

The Doppler Beaming Crisis for HSPs

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

- ɣ-rays cannot escape unless very high beaming factors are invoked



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

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

Summary

- Large VLBI surveys are responsible for much of our current understanding of relativistic outflows in active galaxies

- Dedicated arrays such as the VLBA are indispensable for probing the time evolution of jets and their overall characteristics via the study of large samples

- VLBI data have complemented many other AGN surveys such as SDSS, FIRST and *Fermi*.

- Continuous advances in VLBI data recording and correlator technology offer significant opportunities for new studies of AGN populations