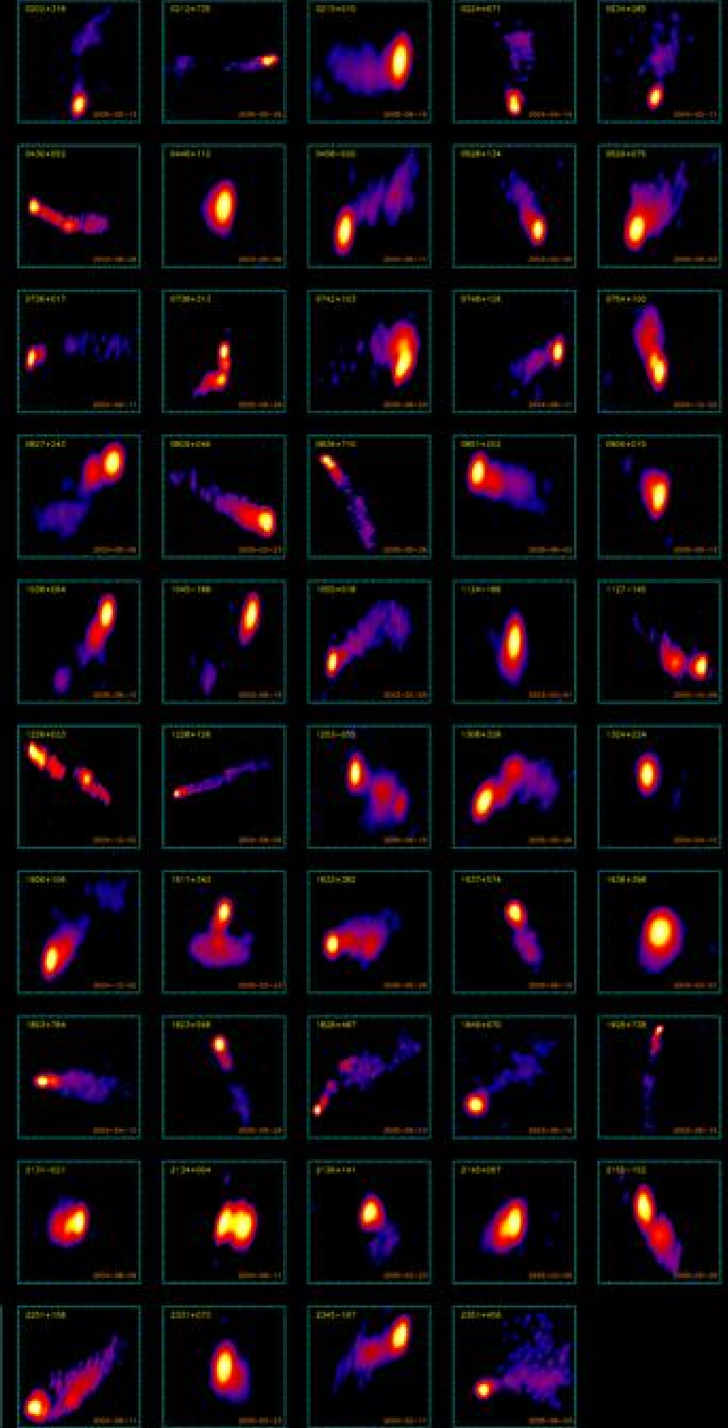


The MOJAVE Program:

Investigating Evolution in AGN Jets

Matthew Lister, Purdue University, USA

Collaborators:

M. Cara, N. Cooper, S. Kuchibhotla, S. Nichols,
A. Lankey, N. Mellott, K. O'Brien (Purdue)
M. and H. Aller (Michigan)
M. Cohen (Caltech)
D. Homan (Denison)
M. Kadler (GSFC)
K. Kellermann (NRAO)
Y. Kovalev (Lebedev)
T. Arshakian, A. Lobanov, E. Ros, J. A. Zensus (MPIfR)
R. Vermeulen (ASTRON)

Outline

I. Project Goals and Rationale

III. MOJAVE Science Highlights

- Statistical results:
    - AGN jet speeds and luminosities
    - pc- jet polarization (Lister & Homan 2006 AJ 130,1389)
- Grab-bag of individual source results:
    - nozzle precession
    - rapid flux variability
    - conical shocks

V. Upcoming work

MOJAVE Science Goals

- **Approaches to understanding blazar jets:**
  1. Individual source studies (e.g., 3C120)
  2. Large statistical studies

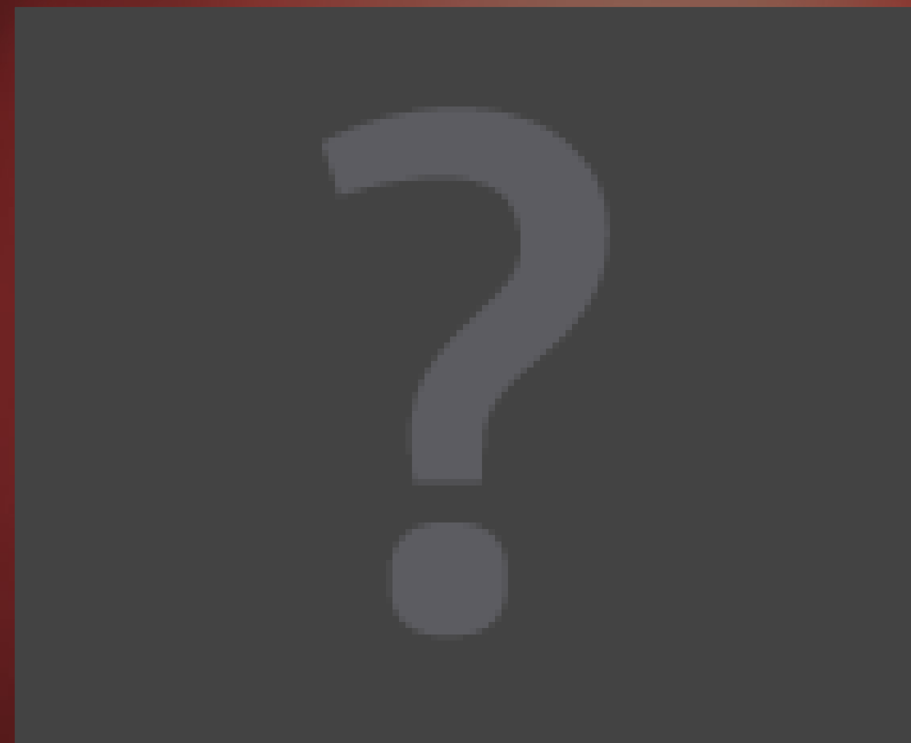
- **Blazar samples contain huge biases**
  - relativistically beamed emission
  - need large sample with well-defined selection criteria

- **Select on the basis of beamed jet flux:**
  - 133 brightest AGN seen by VLBA at 15 GHz above declination -20°
  - 95% are blazars (heavy jet orientation bias)

MOJAVE Science Goals

Long term VLBA monitoring essential for understanding:

- kinematics of bright jet features:
  - curvature, accelerations, stationary/slow features
  - 3-d geometry of jets
- decay of magnetic field and particle energy
- jet collimation/opening angles
- nozzle precession



7 year movie of 3C 279 by M. Kadler

The Data

- Large archive of submilliarcsecond-resolution AGN jet images:
  - VLBA 2 cm survey ('94 – '02):
    - over 200 AGN observed once/yr
  - MOJAVE-I (’02 – ’05):
    - complete sample of 133 AGN (96 in 2 cm survey)
    - 4 to 6 full polarization VLBA epochs/source

2 pc

Quasar 1222+216

- Everything available online at

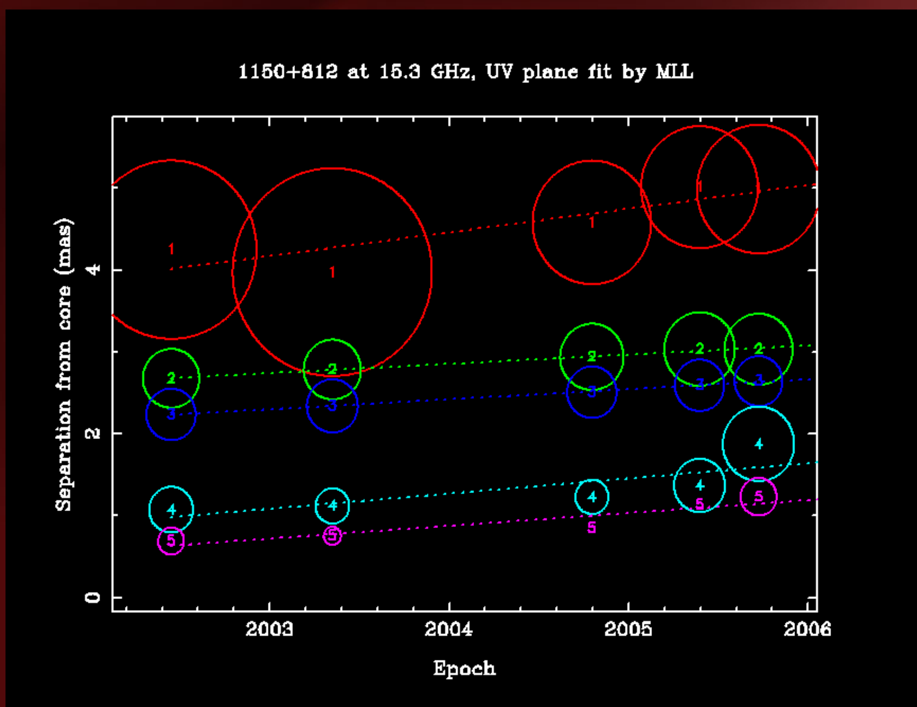
  www.physics.purdue.edu/astro/MOJAVE

Statistical Results

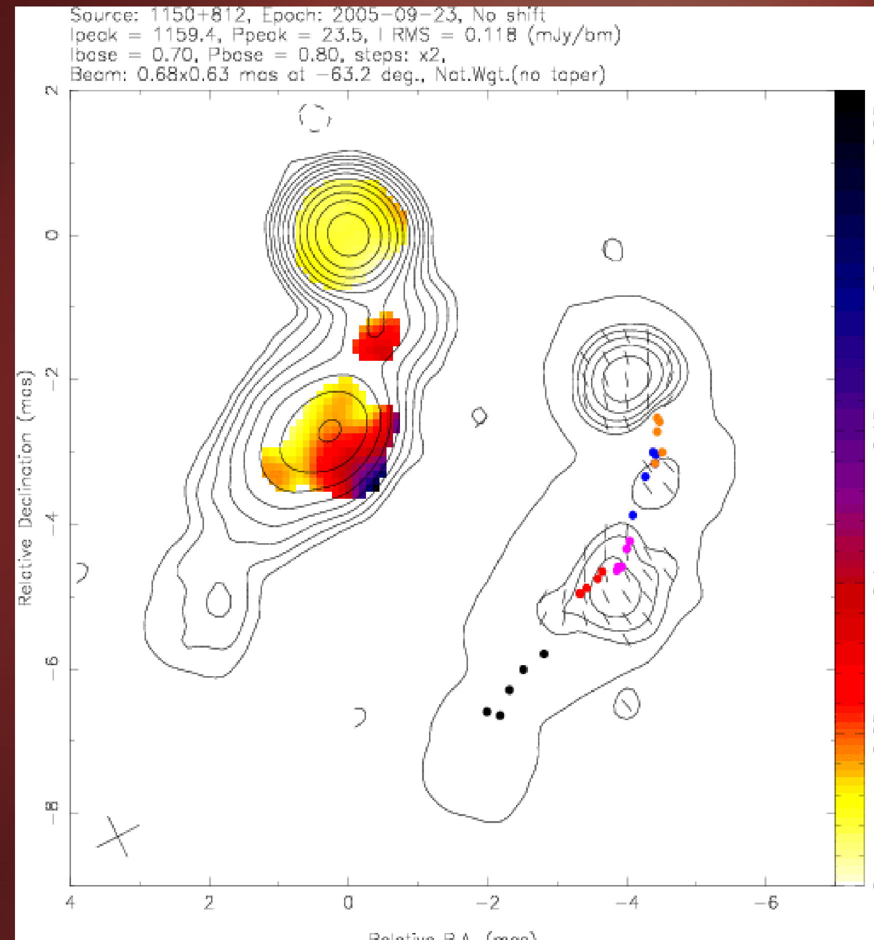
Jet Kinematics

To date: apparent speeds determined for 61 MOJAVE jets

- Gaussians fit to bright features
- data stored in MySQL database



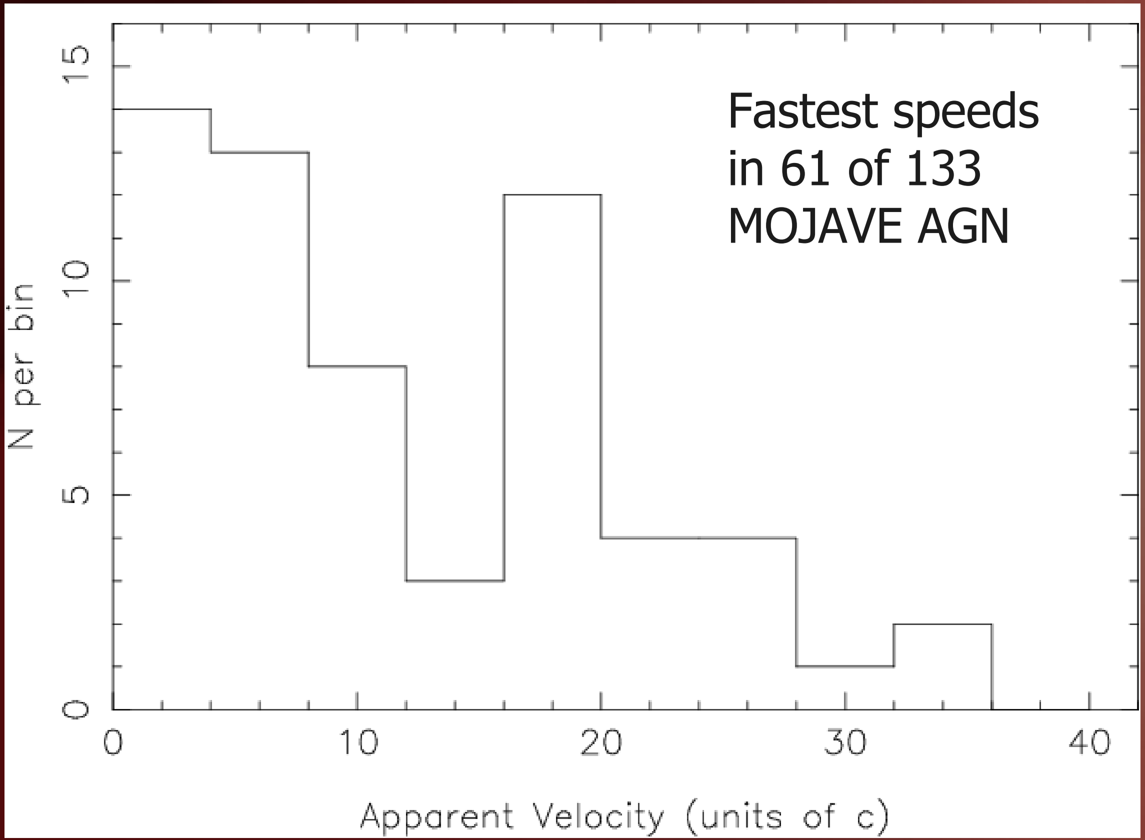
Apparent speeds of 7-18 c in 1150+812



Total intensity + fractional pol (left)

Polariz. intensity with E vectors (right)

Apparent Speed Distribution



- **Superluminal speeds above 30 c are rare**
  - **blazar parent population mainly have Lorentz factors < 5**
  - **very few AGN in the Universe with jet Lorentz factor > 30**
    - **fast jets can run but they can't hide...**

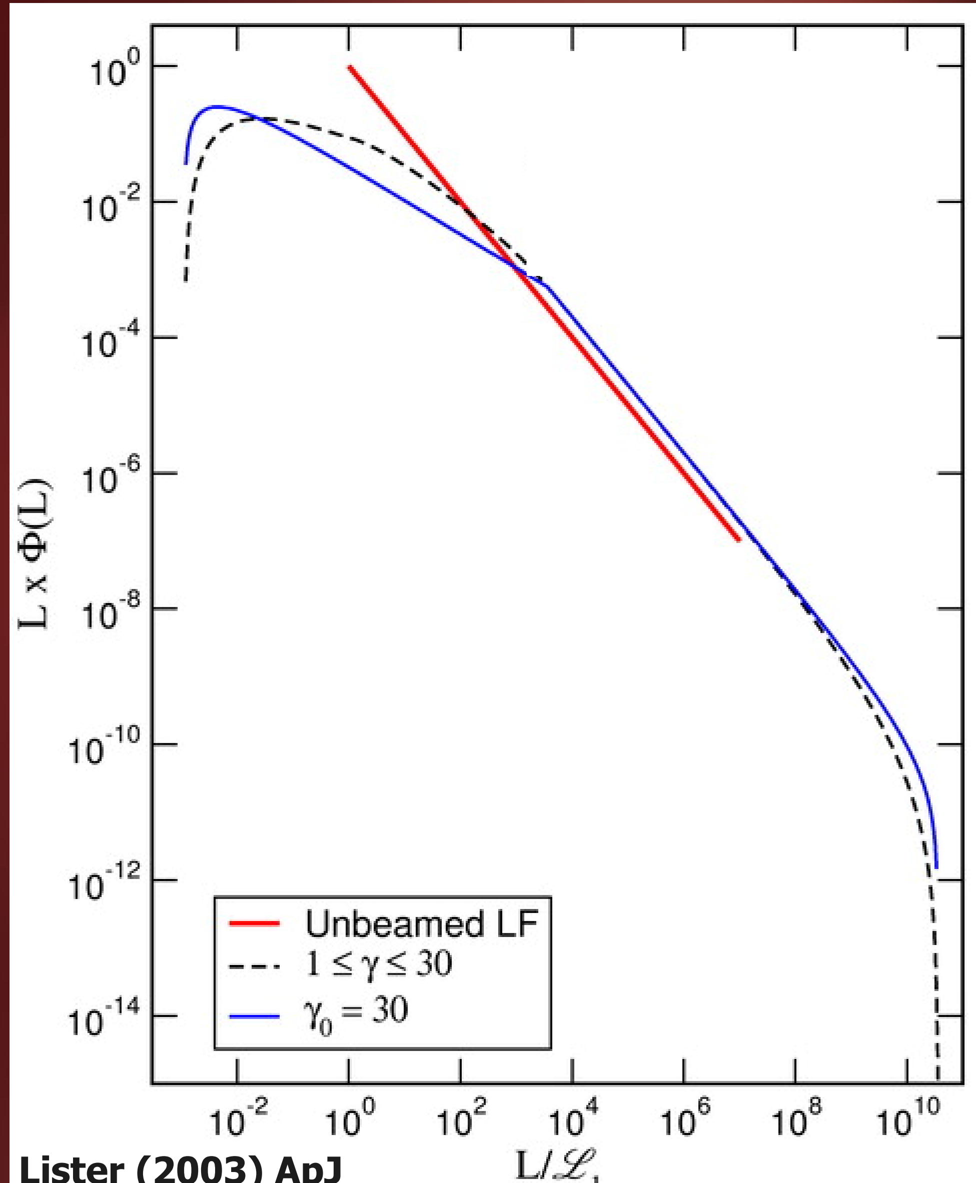
Parent Luminosity Function

Blazar luminosity functions are strongly affected by beaming

- what is their intrinsic LF?
- 'deconvolution' possible if parent speed distribution is known

Method:

- assume a simple intrinsic power law LF
- assume Γ distribution
- add beaming and evolution
- use maximum likelihood to determine best-fit LF



Lister (2003) ApJ

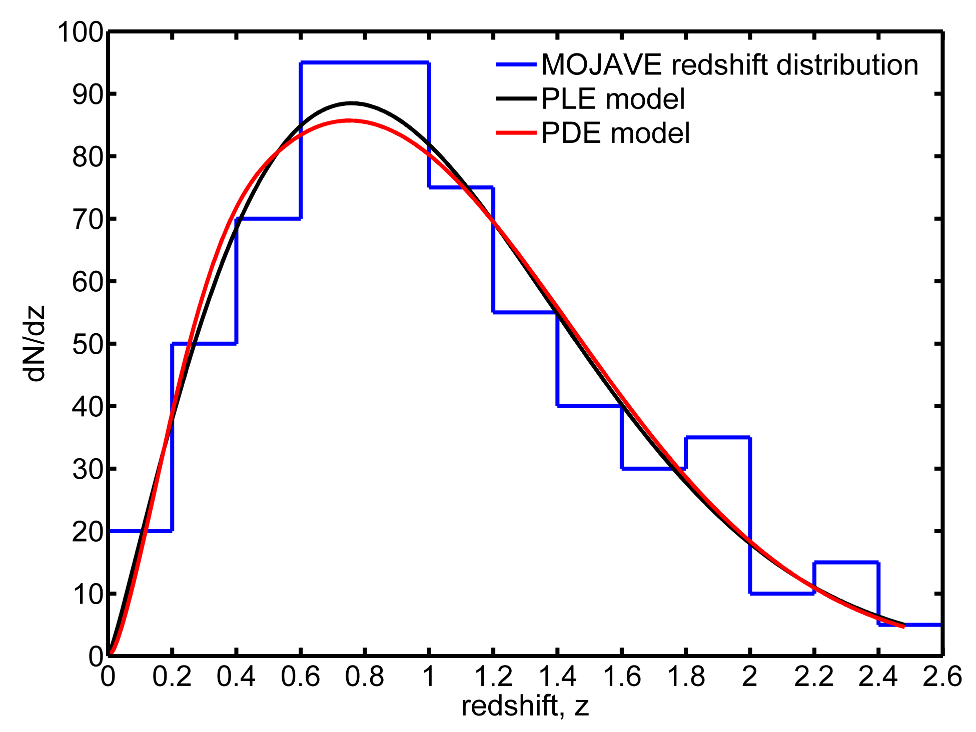
MOJAVE Parent Luminosity Function

Best LF fit for pure density evolution:

- $n(L,z)dL \sim L^{-2.7}\ f(z);\ L > 10^{23.5}$

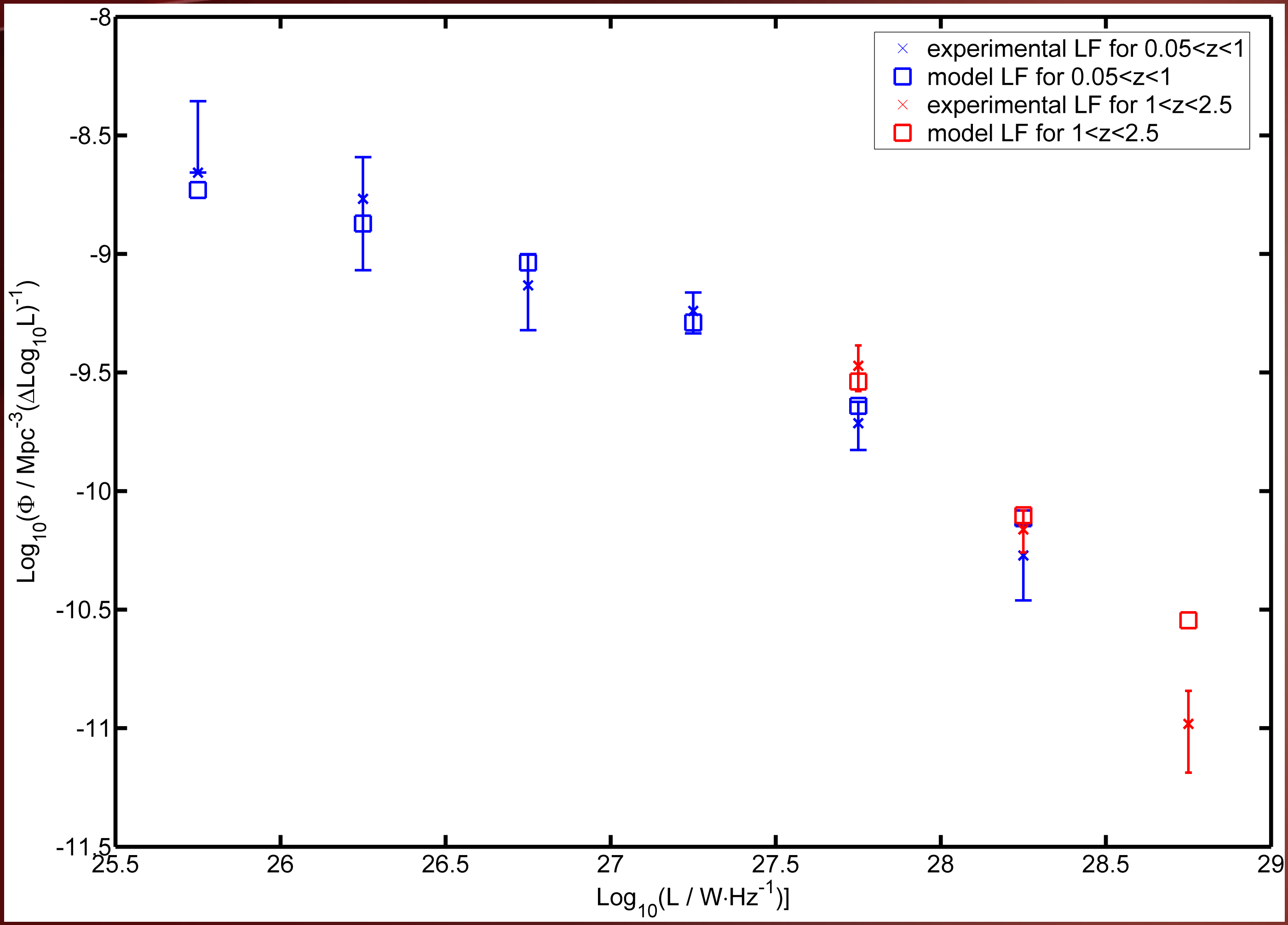
  $f(z) = z^{1.8} \exp[-(1-z)^2]$

(pure luminosity evolution also provides good fit)



M. Cara (PhD. Thesis, in prep)

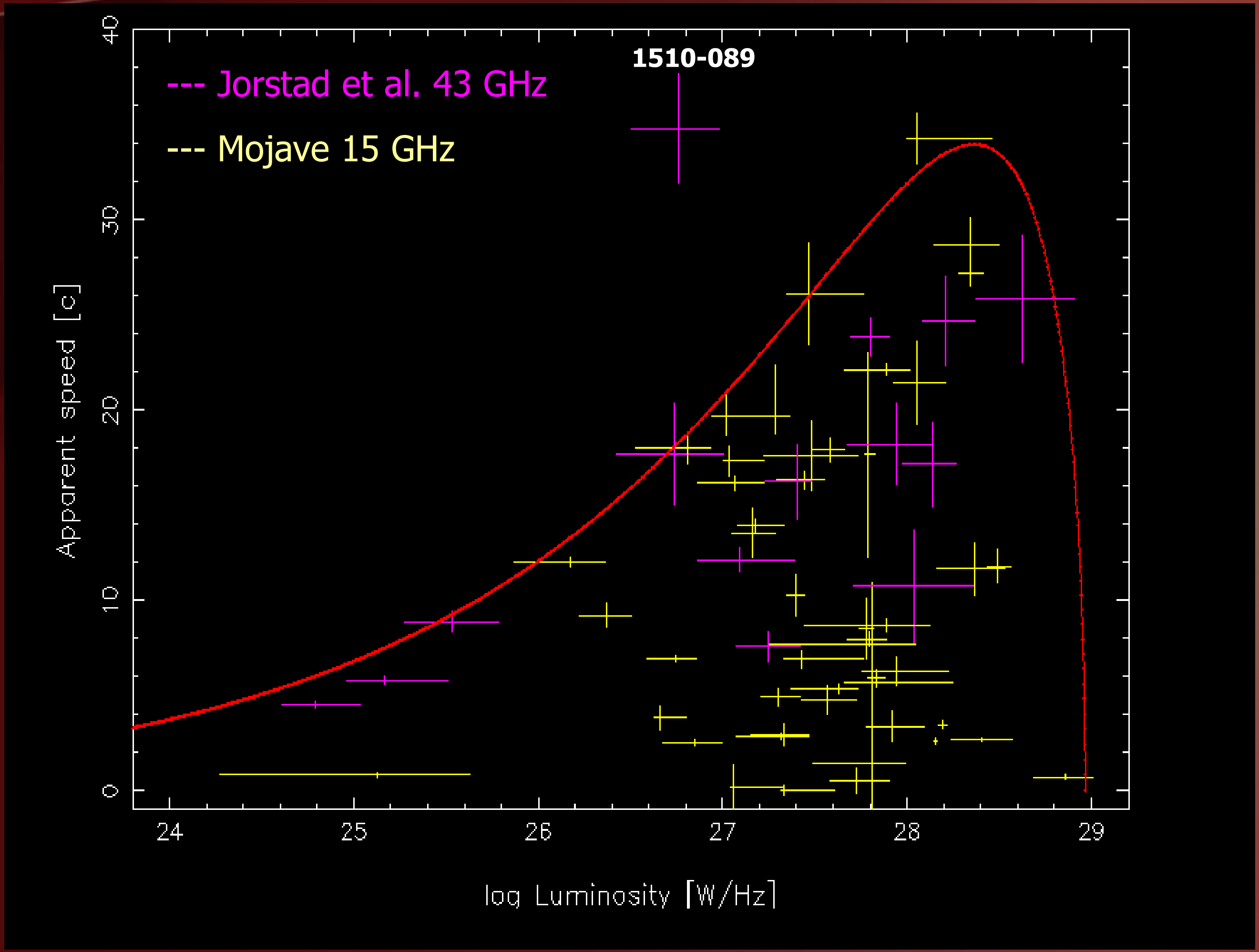
MOJAVE Parent Luminosity Function



- **100 MOJAVE blazars require ~ 10^8 parent AGN**
- **mean space density = 1.4 x 10^{-4} Mpc^{-3}**
  - **comparable to AGN with L_{xray} ~ 10^{44} erg/s**

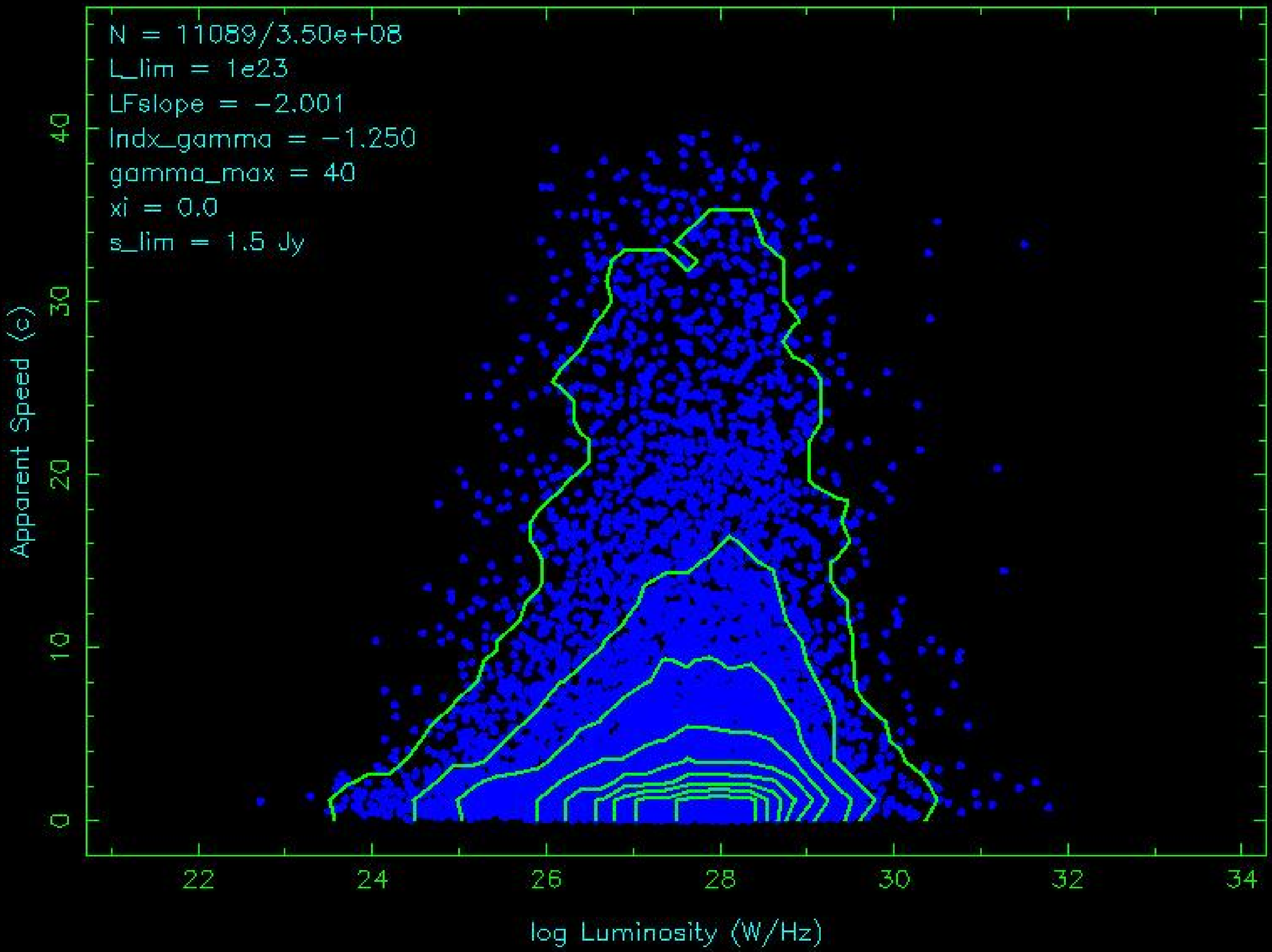
(Silverman et al. 2005)

Apparent Speeds vs. Luminosities

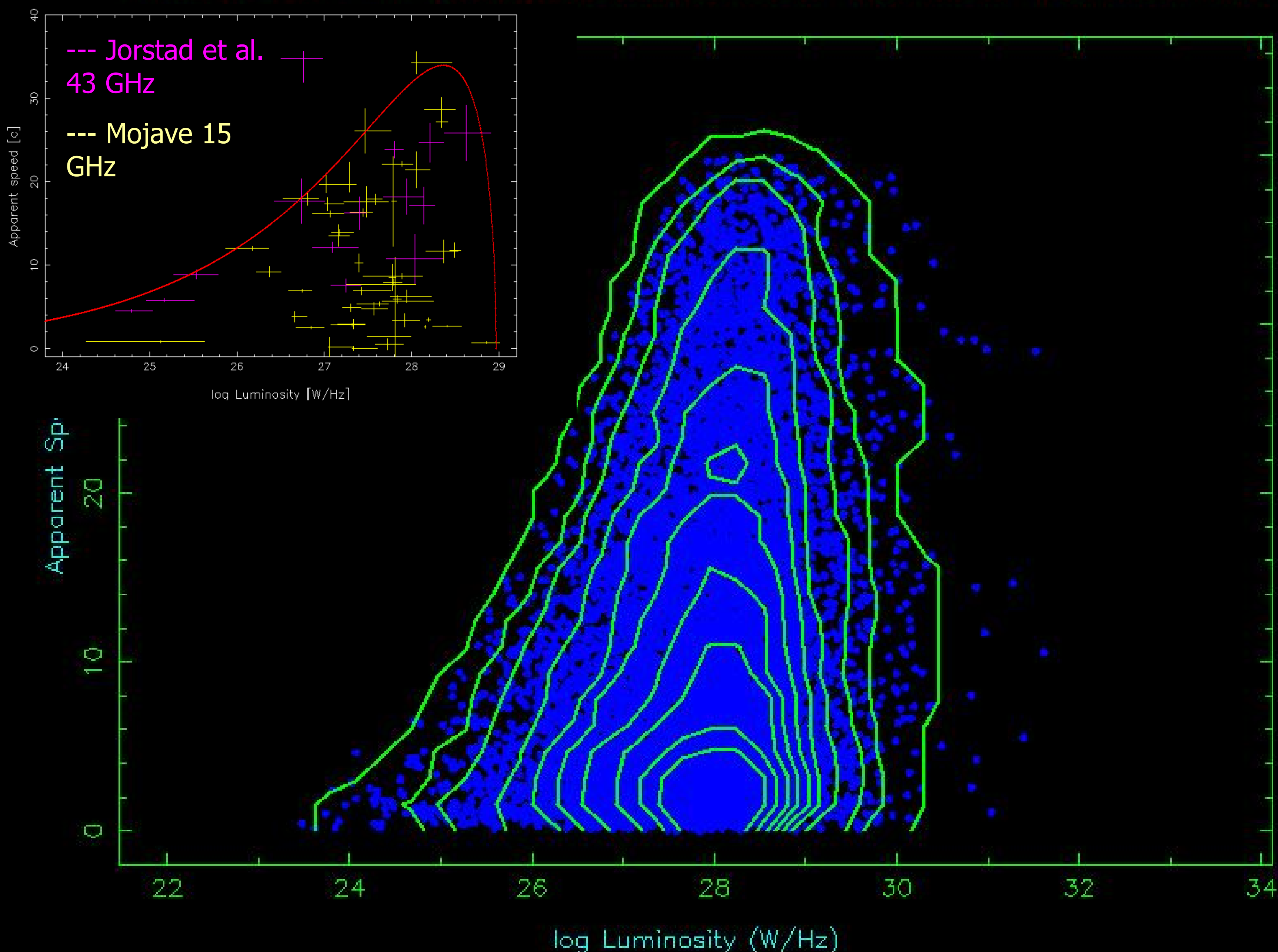


- Red curve: intrinsic L = $10^{25.3}$ W/Hz, Lorentz factor = 35
- Envelope means speeds cannot be random patterns
- Low-luminosity sources can’t have high Lorentz factors

Model A: Intrinsic synchrotron luminosities independent of jet Lorentz factor



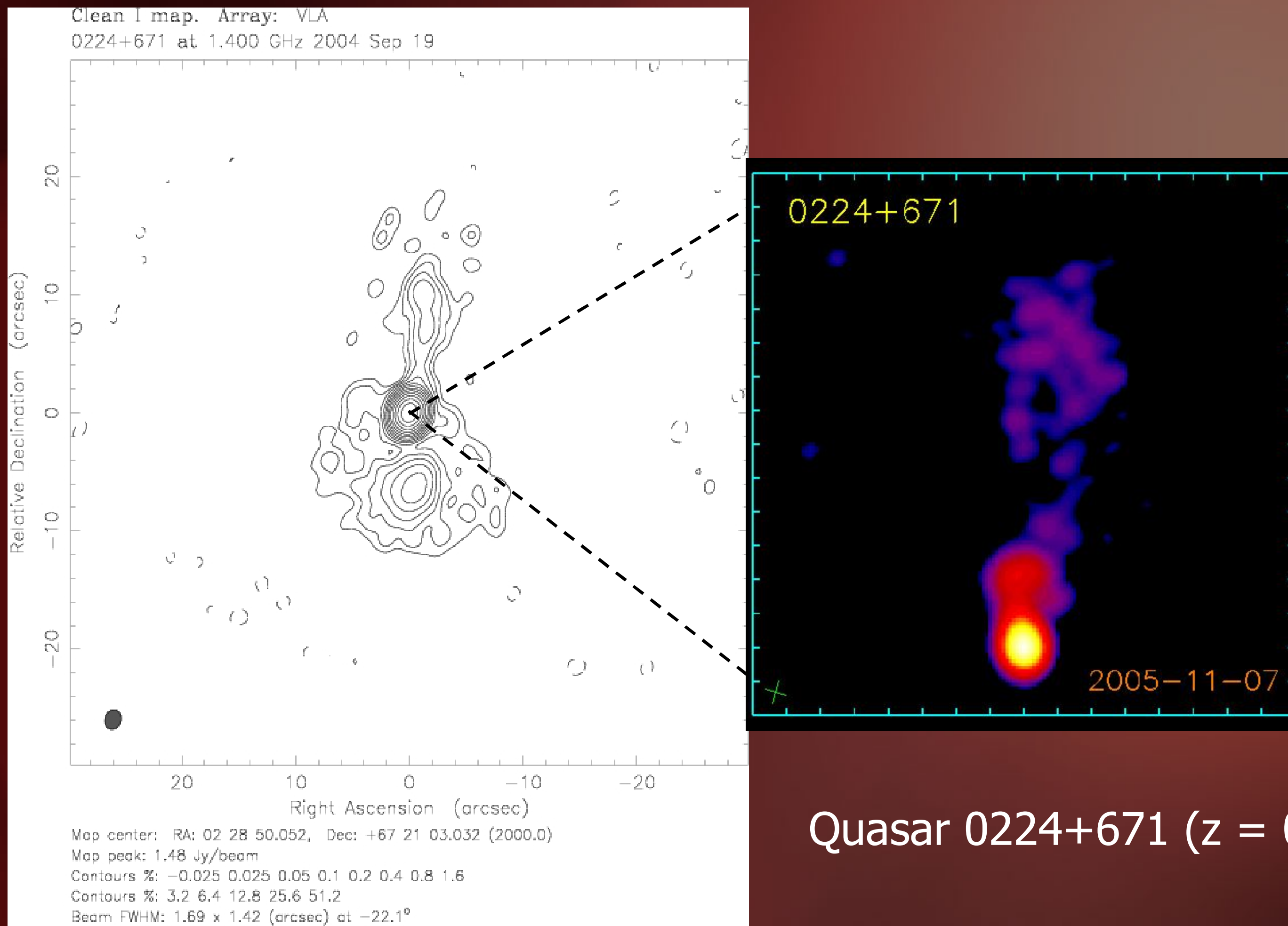
Model B: Intrinsic synchrotron luminosities scale with jet Lorentz factor



Extended Radio Power

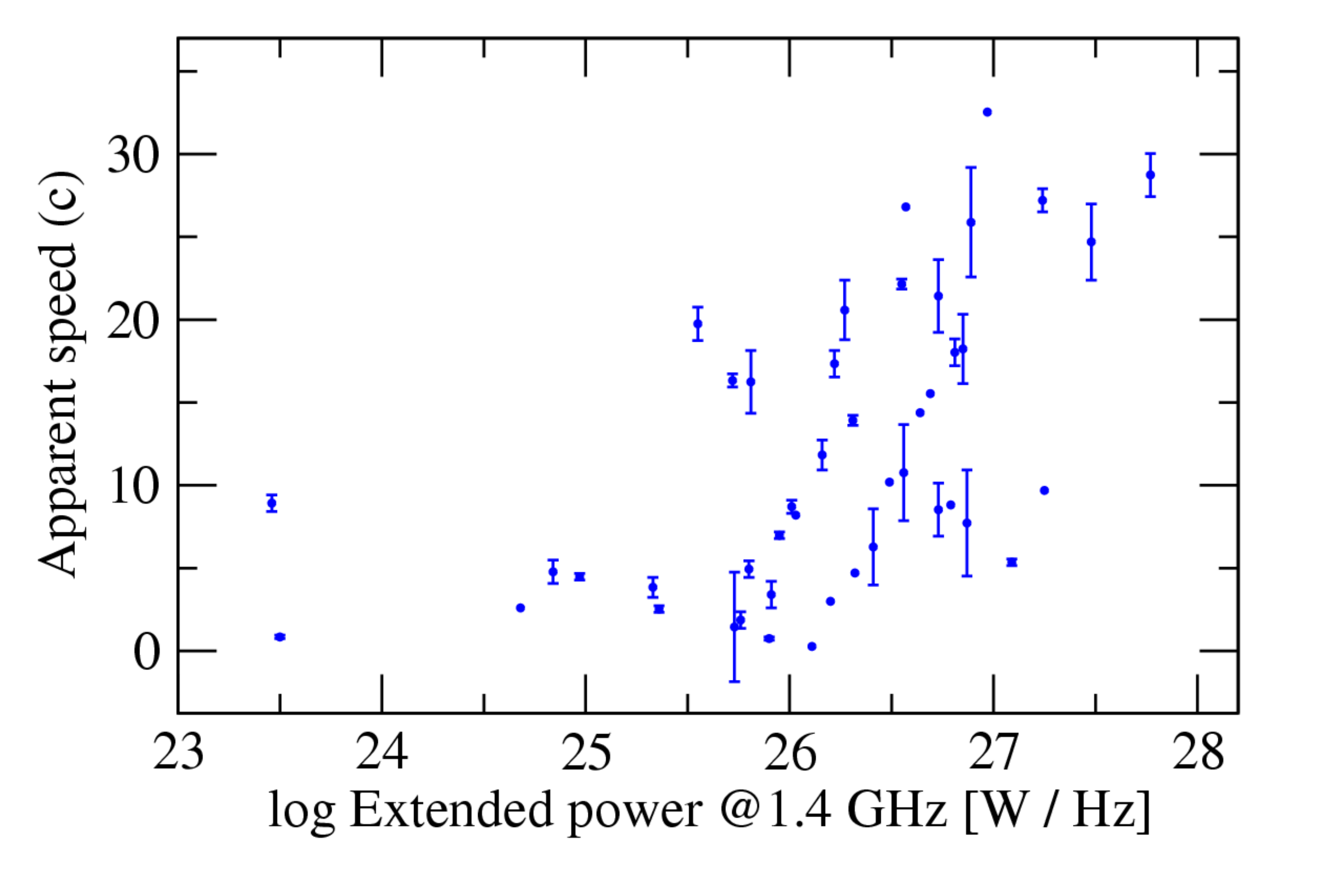
Deep VLA A-array 20 cm images of MOJAVE sample

- do faster jets have higher extended powers?



Quasar 0224+671 (z = 0.523)

Speed and Jet Power



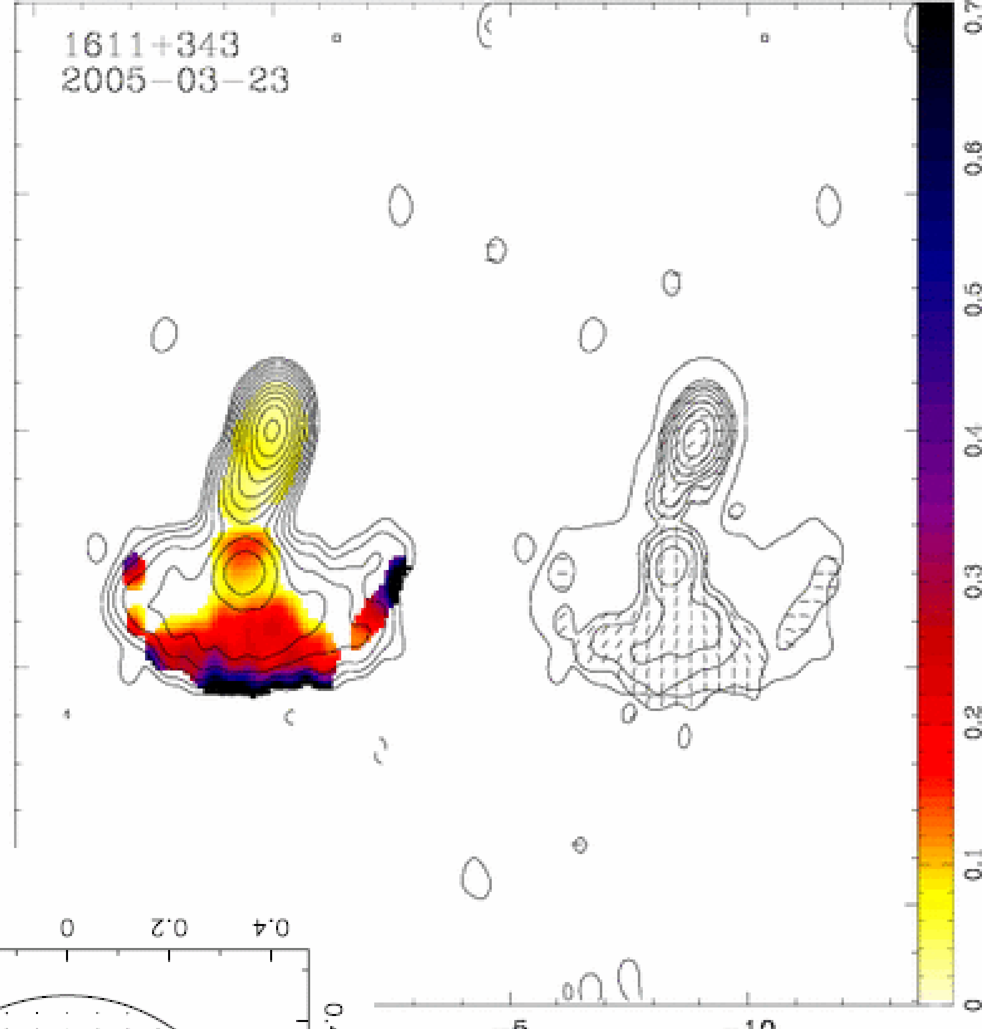
- **Faster jets have higher extended power**
  - **Parent Γ distribution and LF are both relatively steep**
  - **data for only 47 MOJAVE sources so far**
  - **must carefully account for redshift effects**

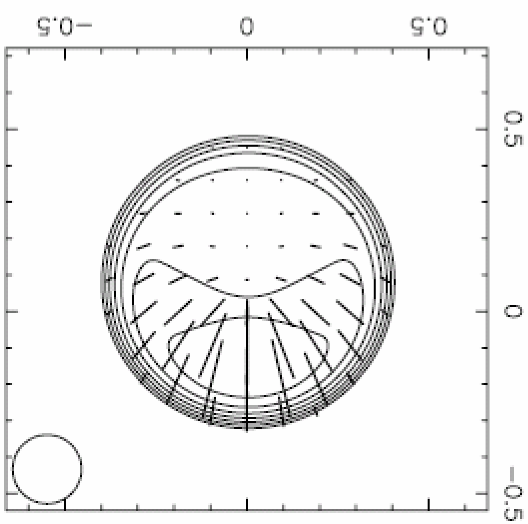
N. Cooper (PhD. Thesis, in prep.)

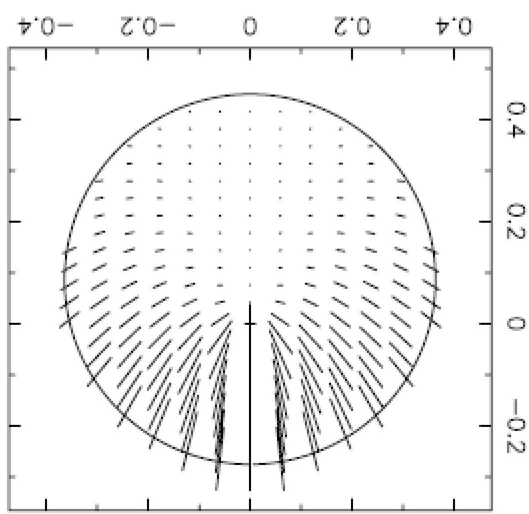
Grab-Bag Results on Individual Sources

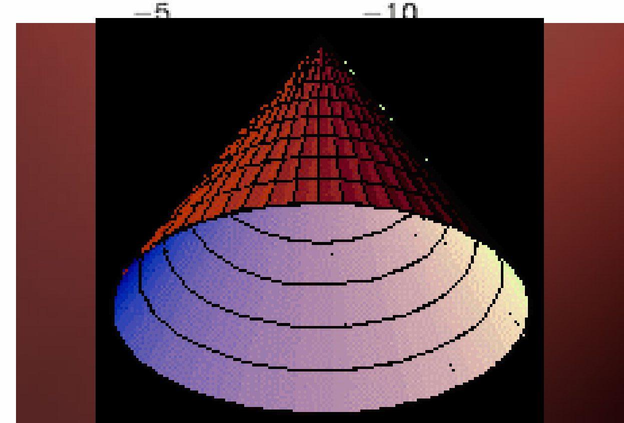
Conical shocks?

- **Splayed E-vectors in 1611+343 suspiciously similar to conical shock model predictions (Cawthorne 2006)**



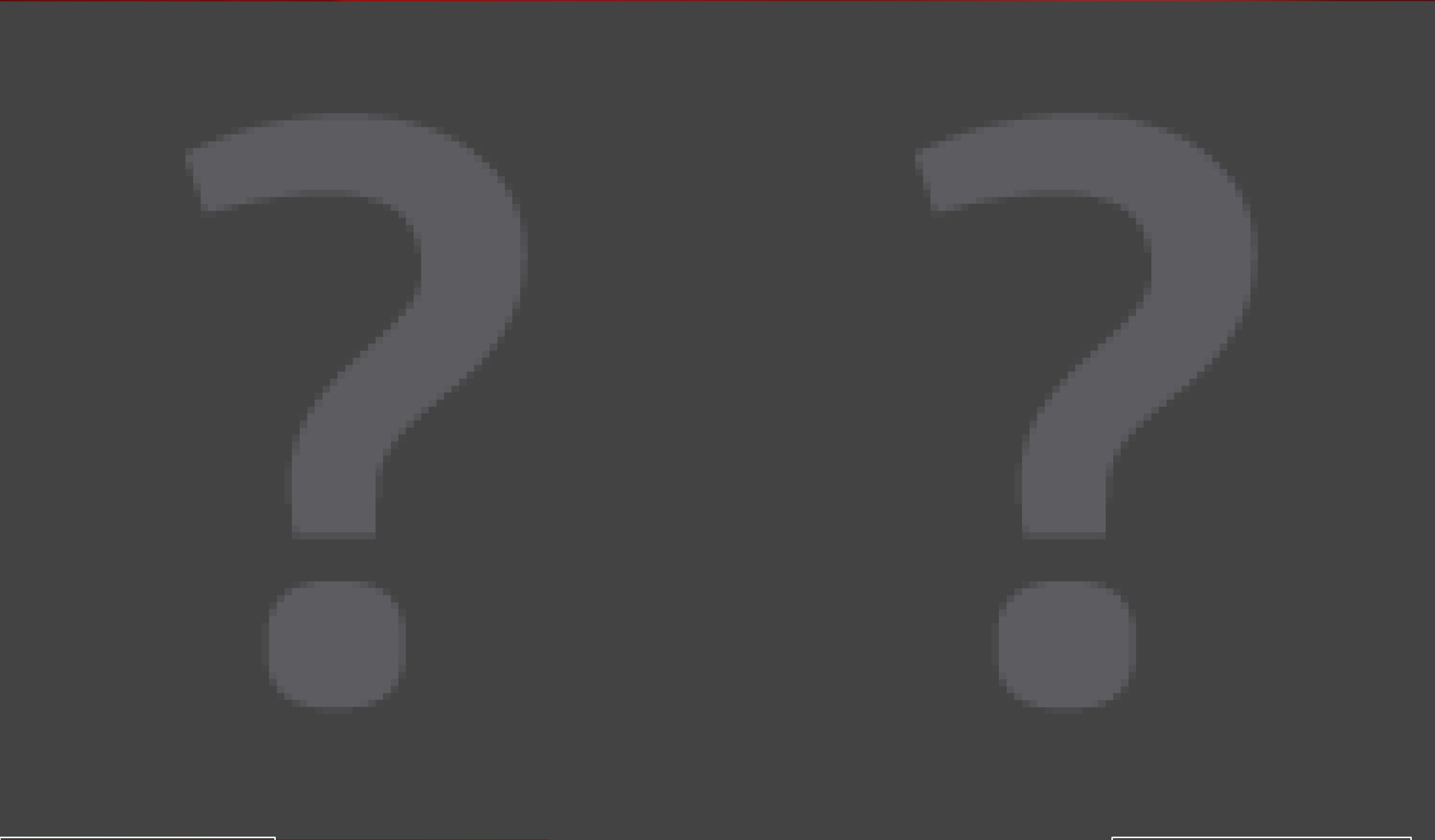






Polarization Movies

(...not all 133)



BL Lac 1308+326

*Ticks represent **electric** vector directions*

Quasar 1150+812

B fields in BL Lac jets are statistically:

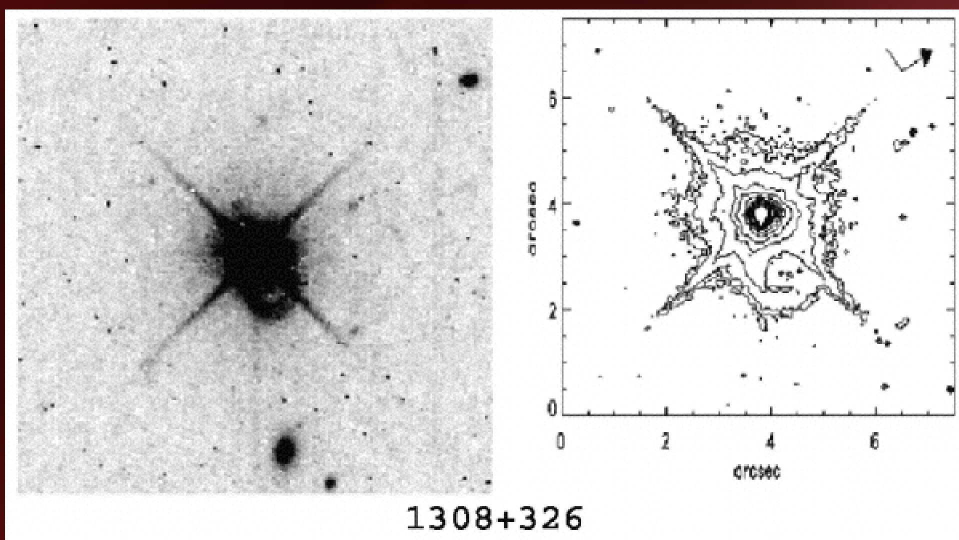
- **more highly ordered than quasars**
- **typically aligned more perpendicular to the flow**
  - **Possible explanations: shear layer, shock strength/jet power, helical fields**

Movies by K. O'Brien

BL Lac object 1308+326

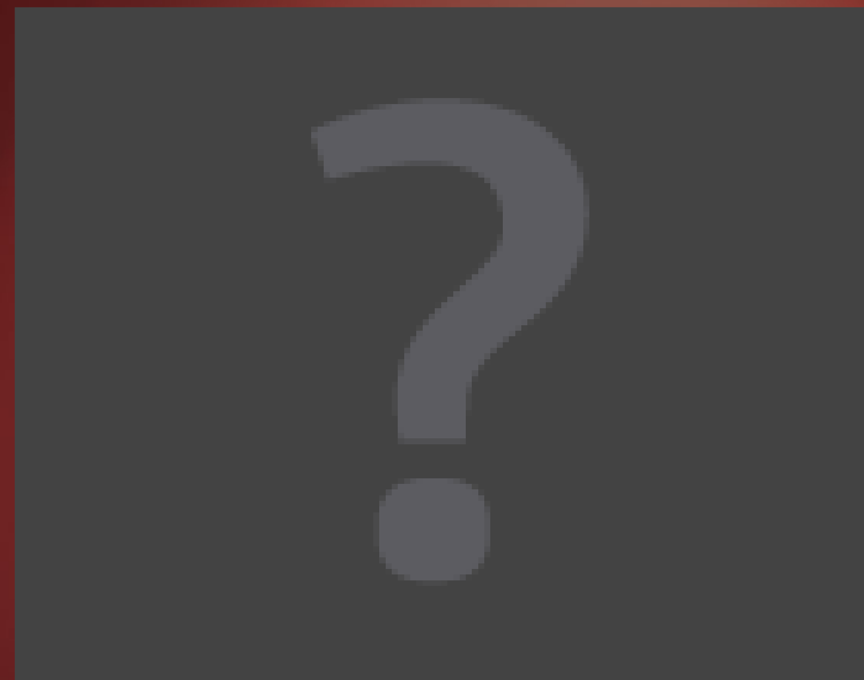
BL Lac object in rich environment at z = 1

(1 milliarcsec = 8 pc)



HST image (O’Dowd & Urry 2005)

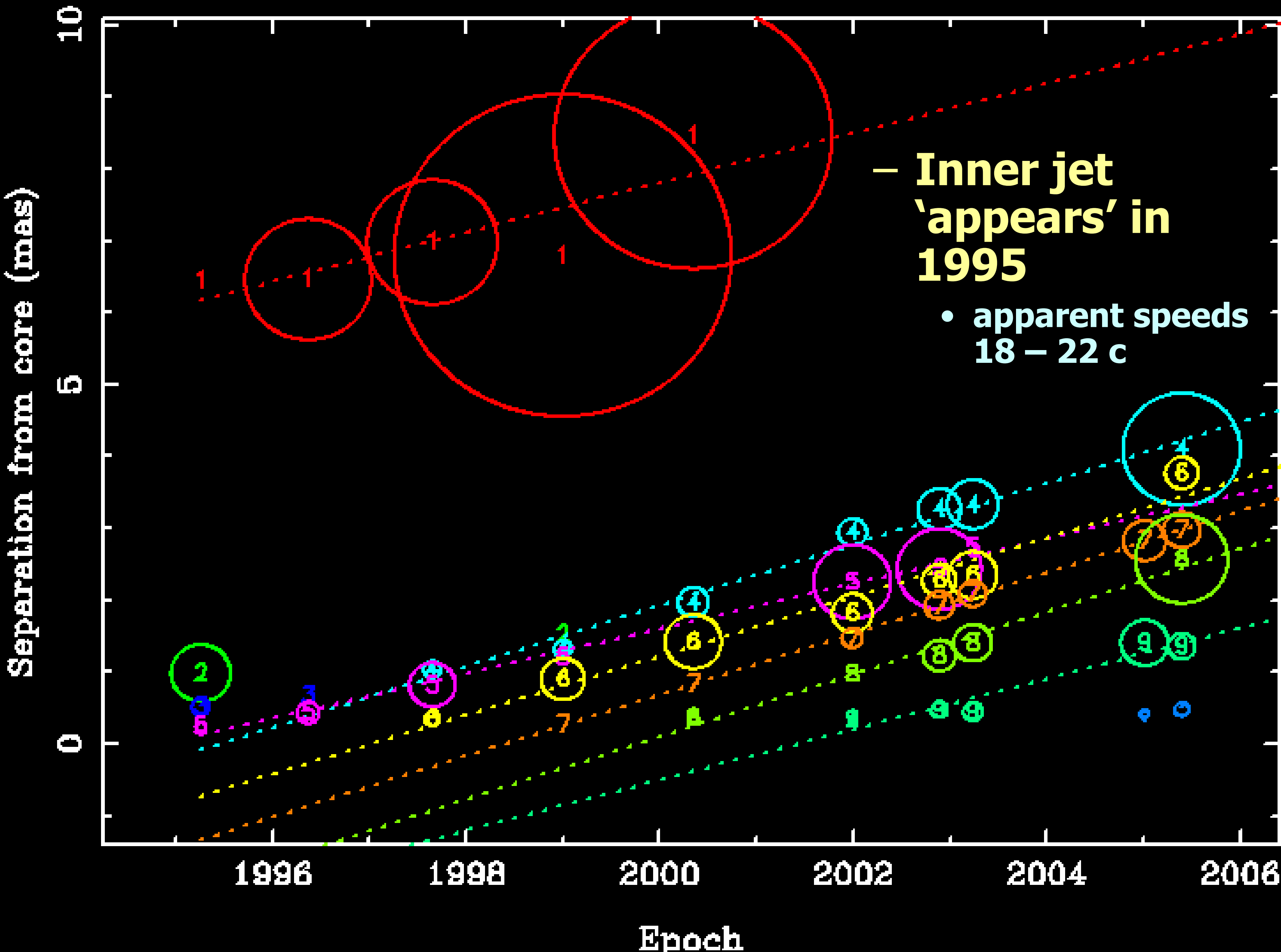
30 pc



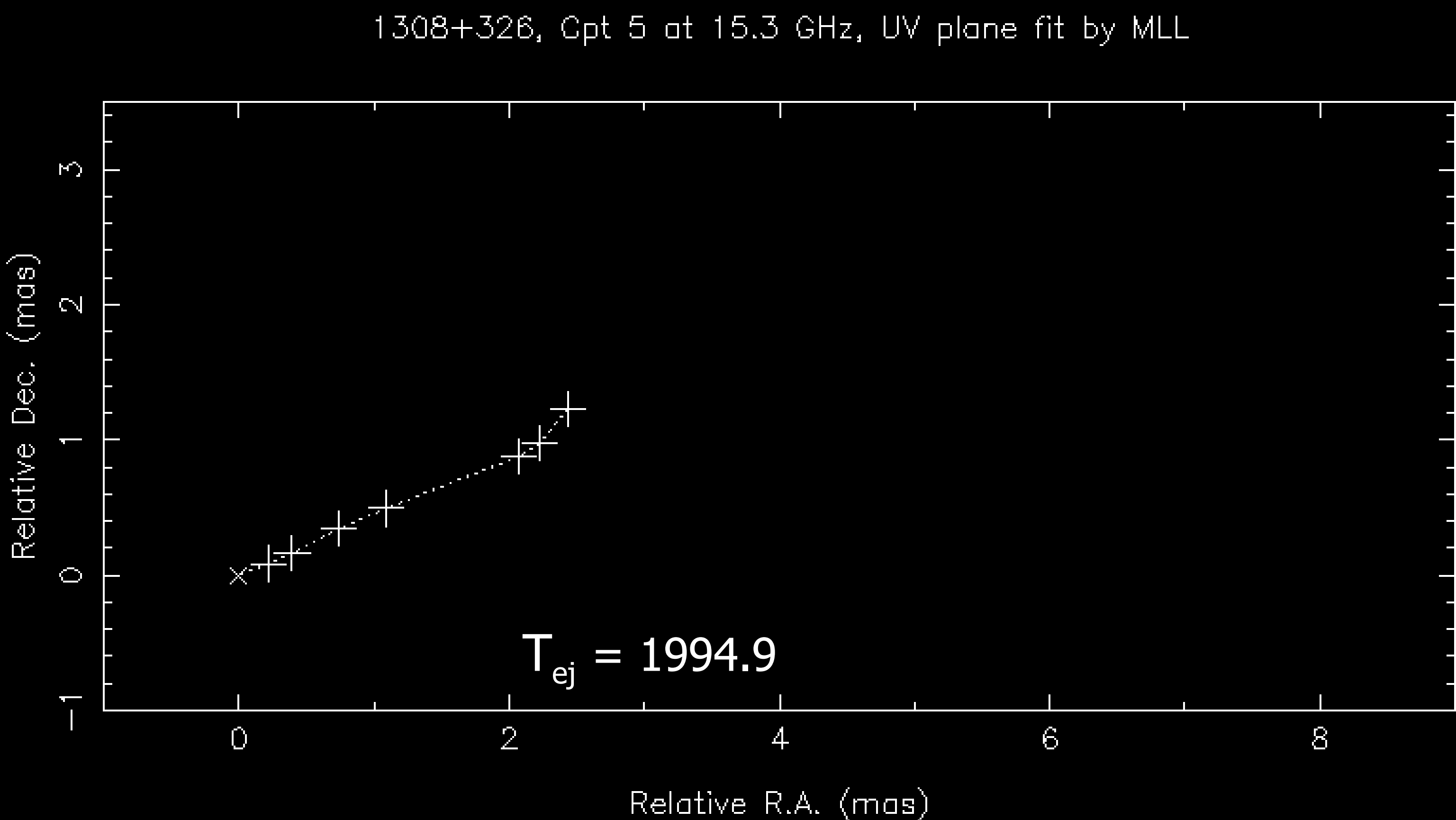
VLBA Movie of 1308+326 by K. O’Brien

No sign of extended jet prior to 1995

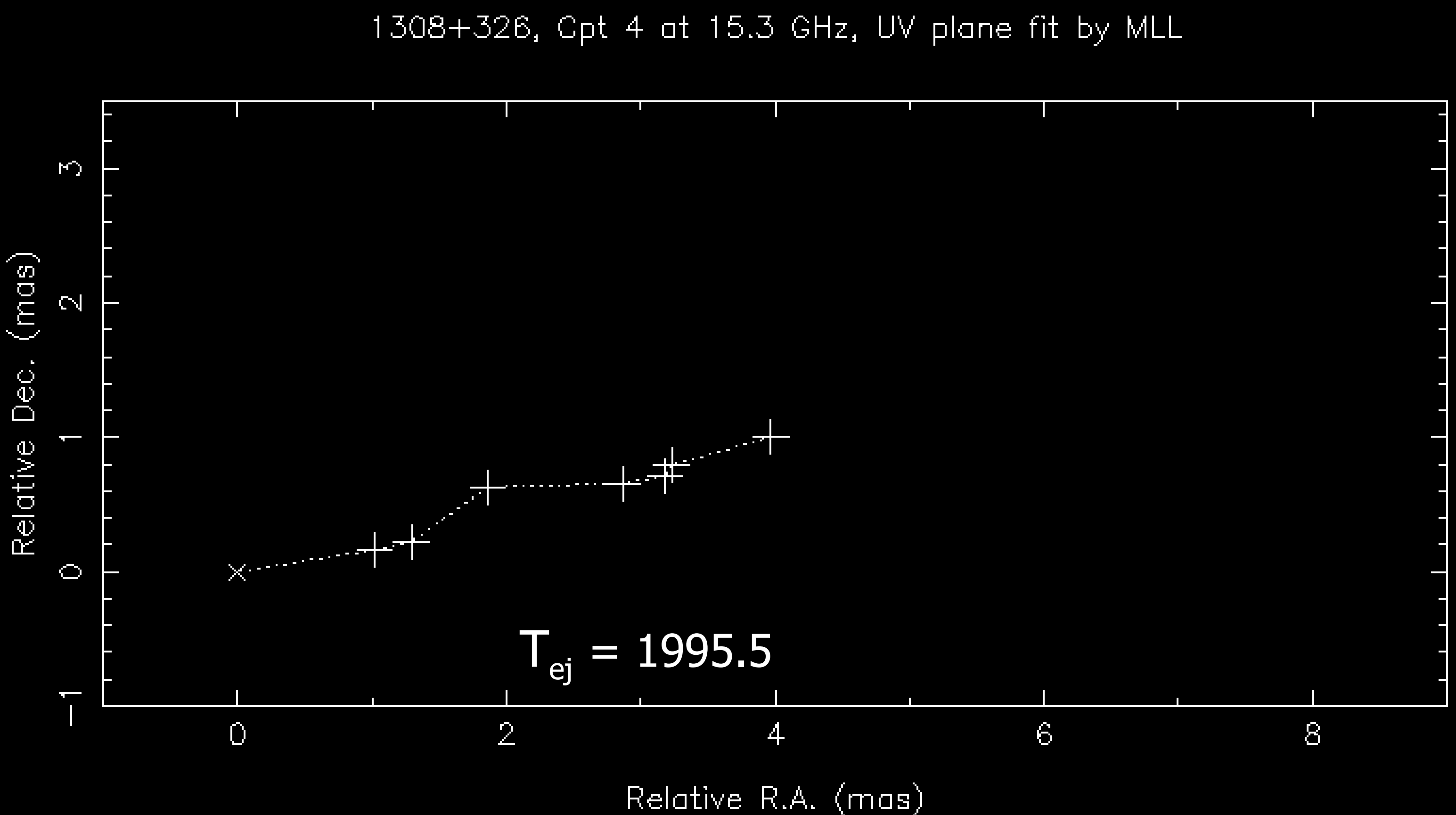
– only a single partially resolved blob (‘core’)



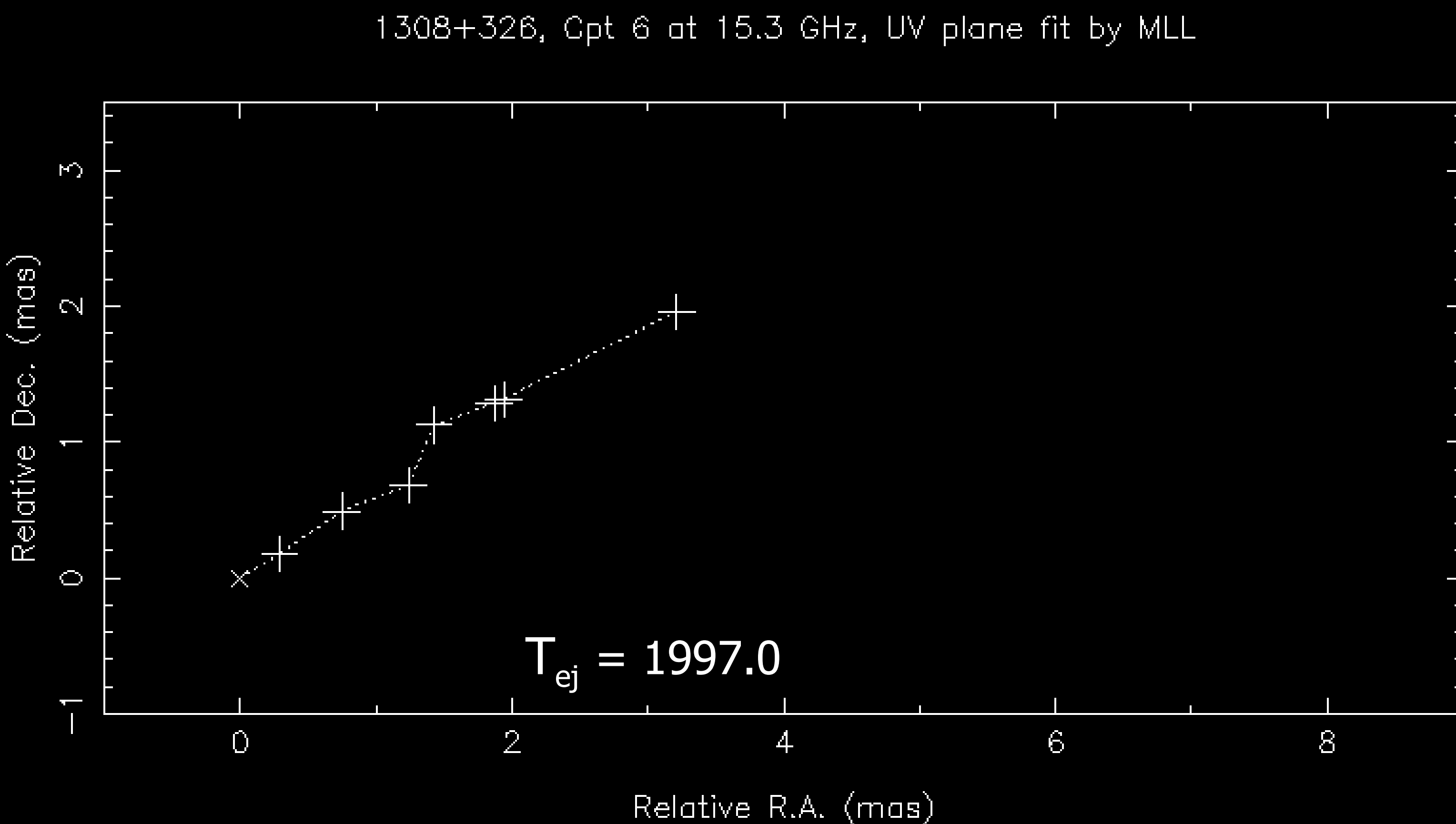
- Inner jet ‘appears’ in 1995
  - apparent speeds 18 – 22 c

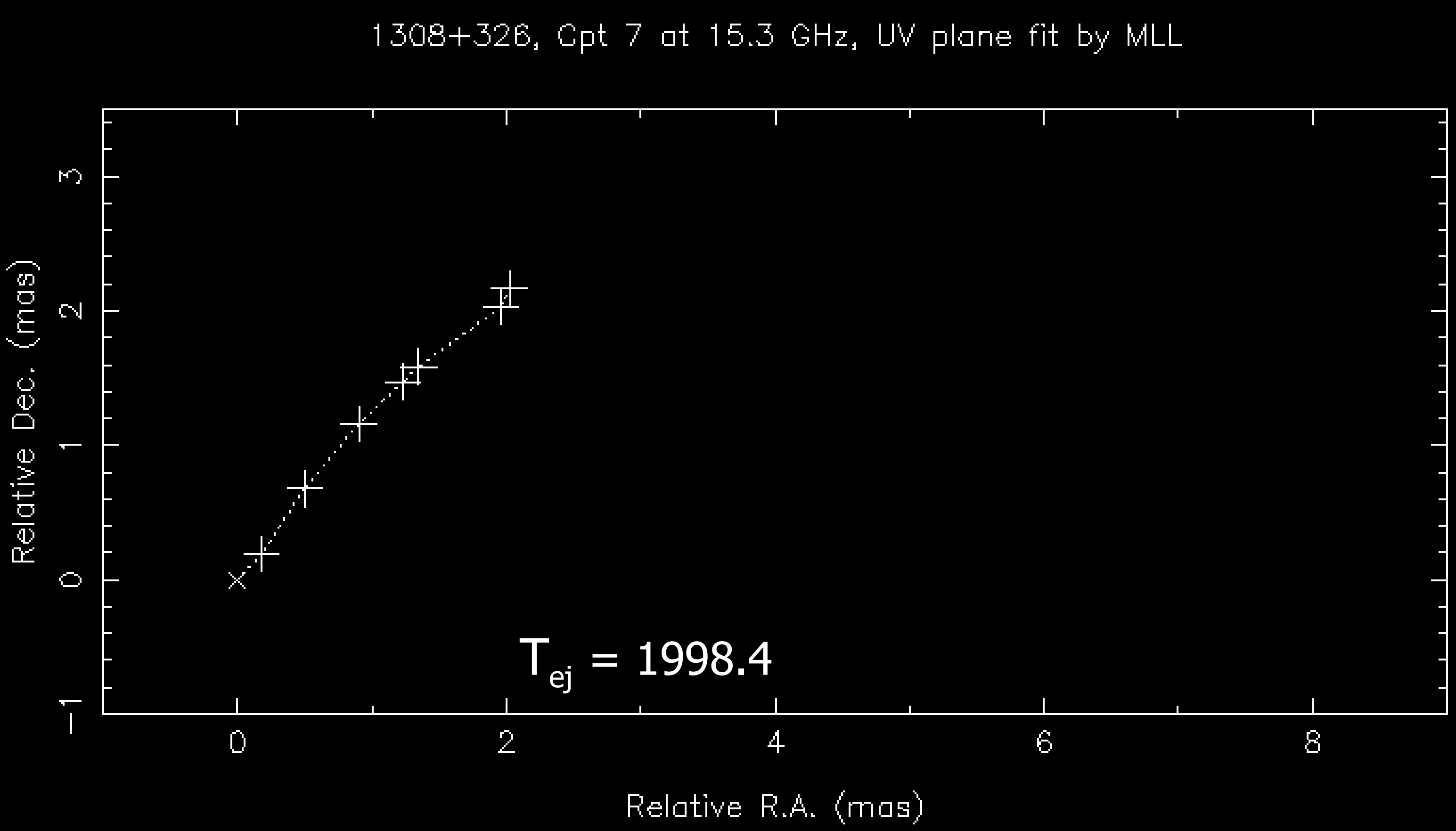


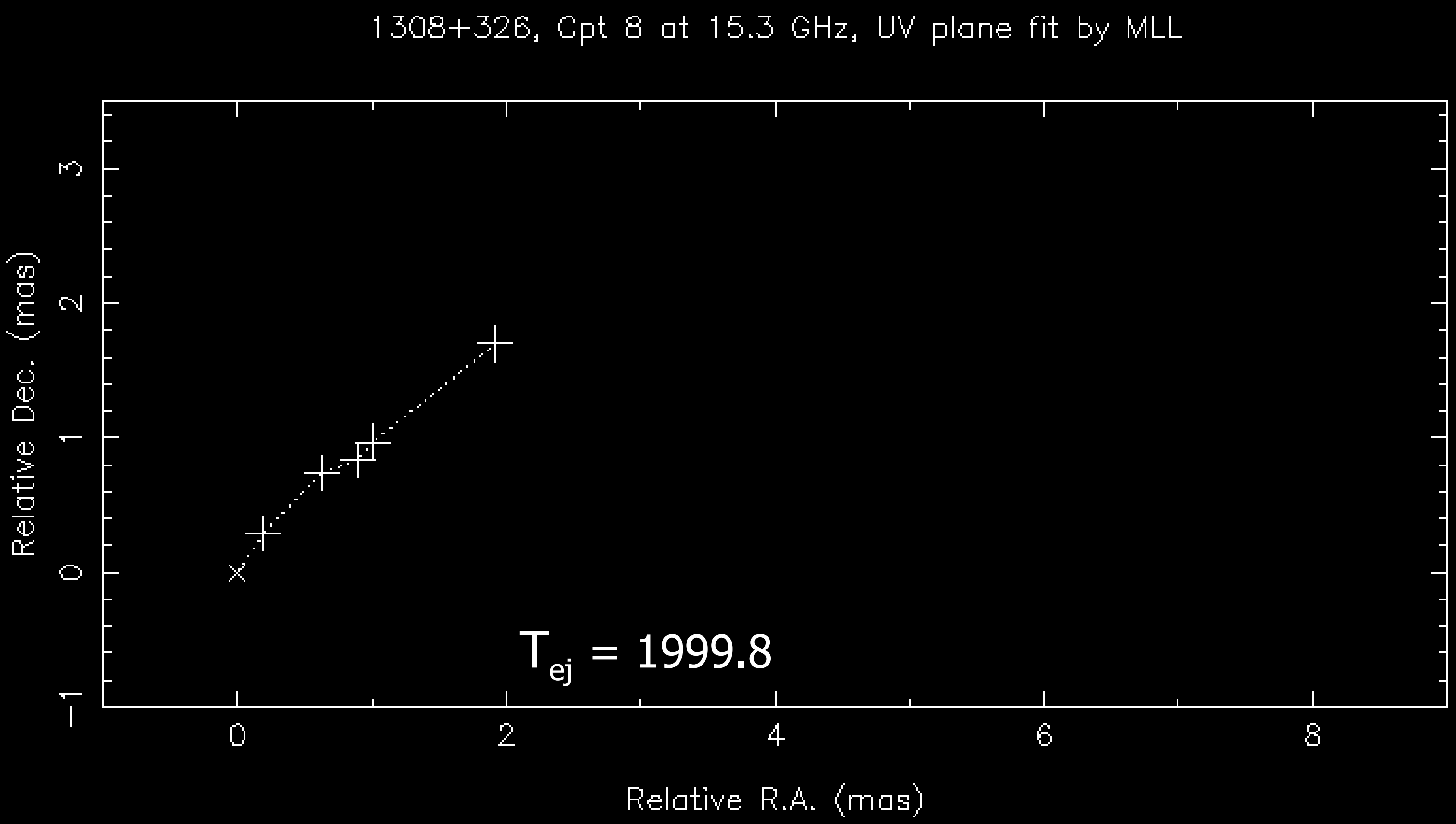
1308+326, Cpt 5 at 15.3 GHz, UV plane fit by MLL
Relative Dec. (mas)
Relative R.A. (mas)
3
2
1
0
−1
0
2
4
6
8
T_{ej} = 1994.9



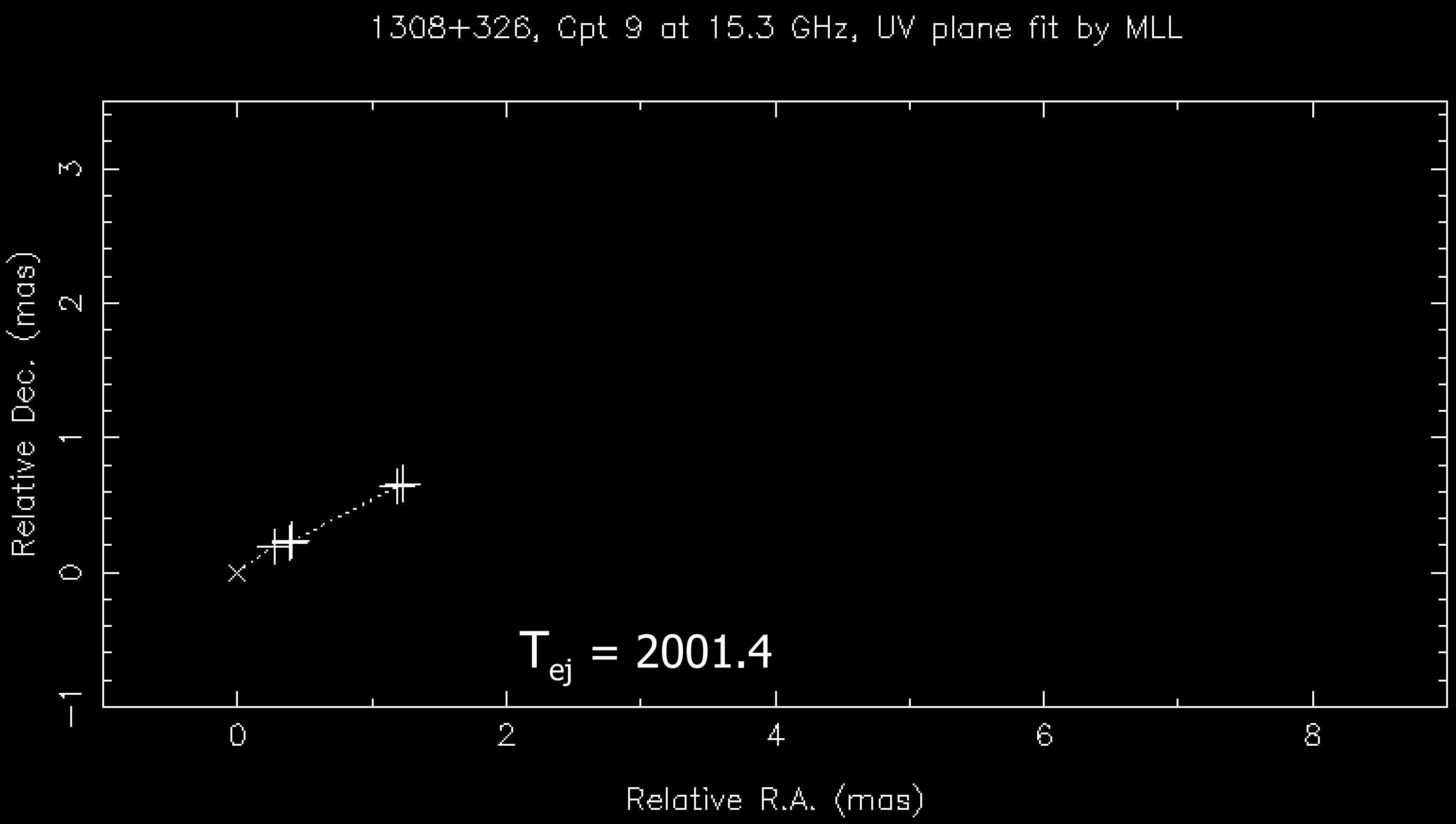
1308+326, Cpt 4 at 15.3 GHz, UV plane fit by MLL
Relative Dec. (mas)
Relative R.A. (mas)
-1
0
1
2
3
0
2
4
6
8
T_ej = 1995.5


1308+326, Cpt 6 at 15.3 GHz, UV plane fit by MLL
Relative Dec. (mas)
Relative R.A. (mas)
T_ej = 1997.0
3
2
1
0
−1
0
2
4
6
8

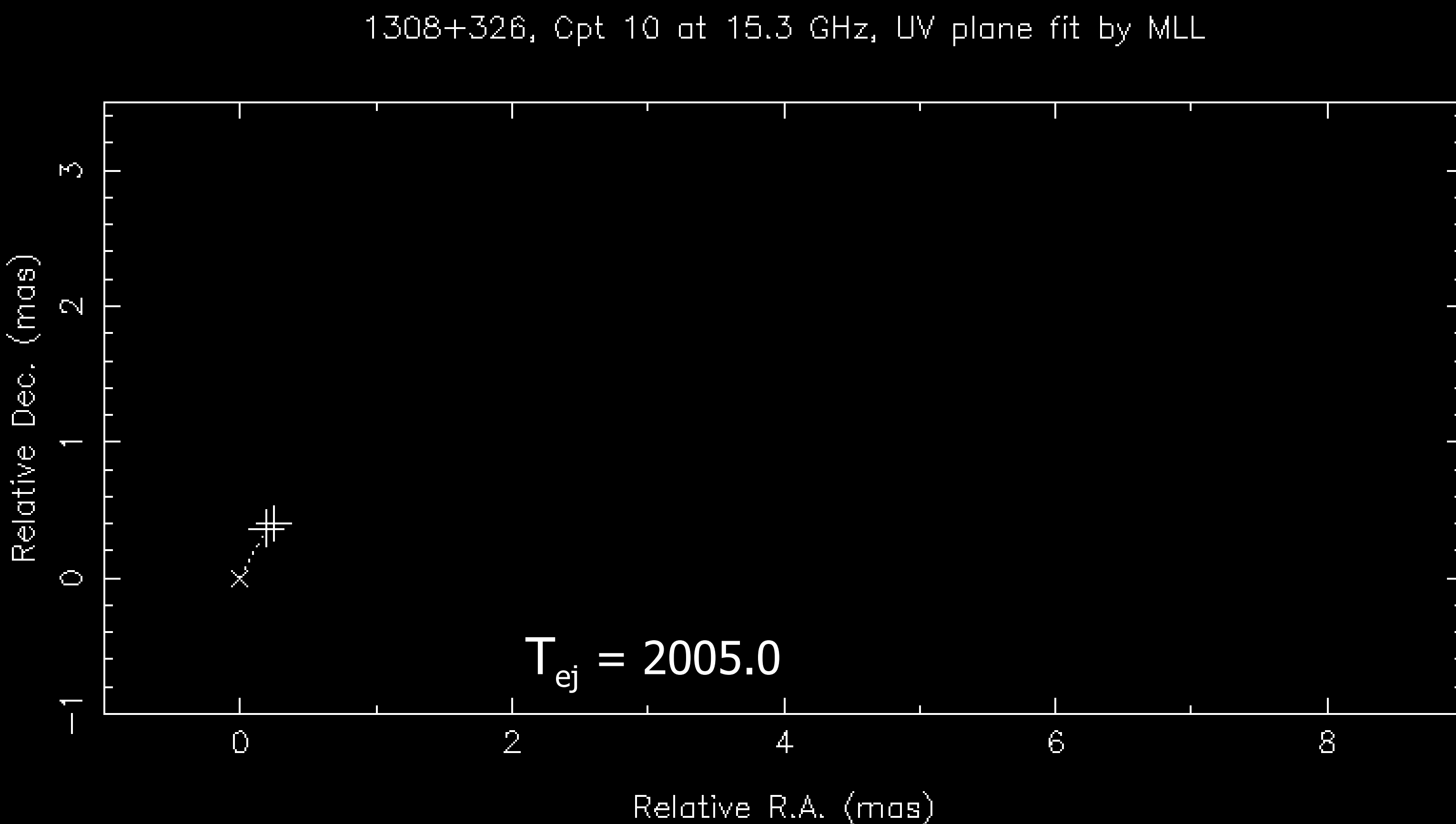

1308+326, Cpt 7 at 15.3 GHz, UV plane fit by MLL
Relative Dec. (mas)
Relative R.A. (mas)
T_ej = 1998.4



1308+326, Cpt 8 at 15.3 GHz, UV plane fit by MLL
Relative Dec. (mas)
Relative R.A. (mas)
-1
0
1
2
3
0
2
4
6
8
T_ej = 1999.8



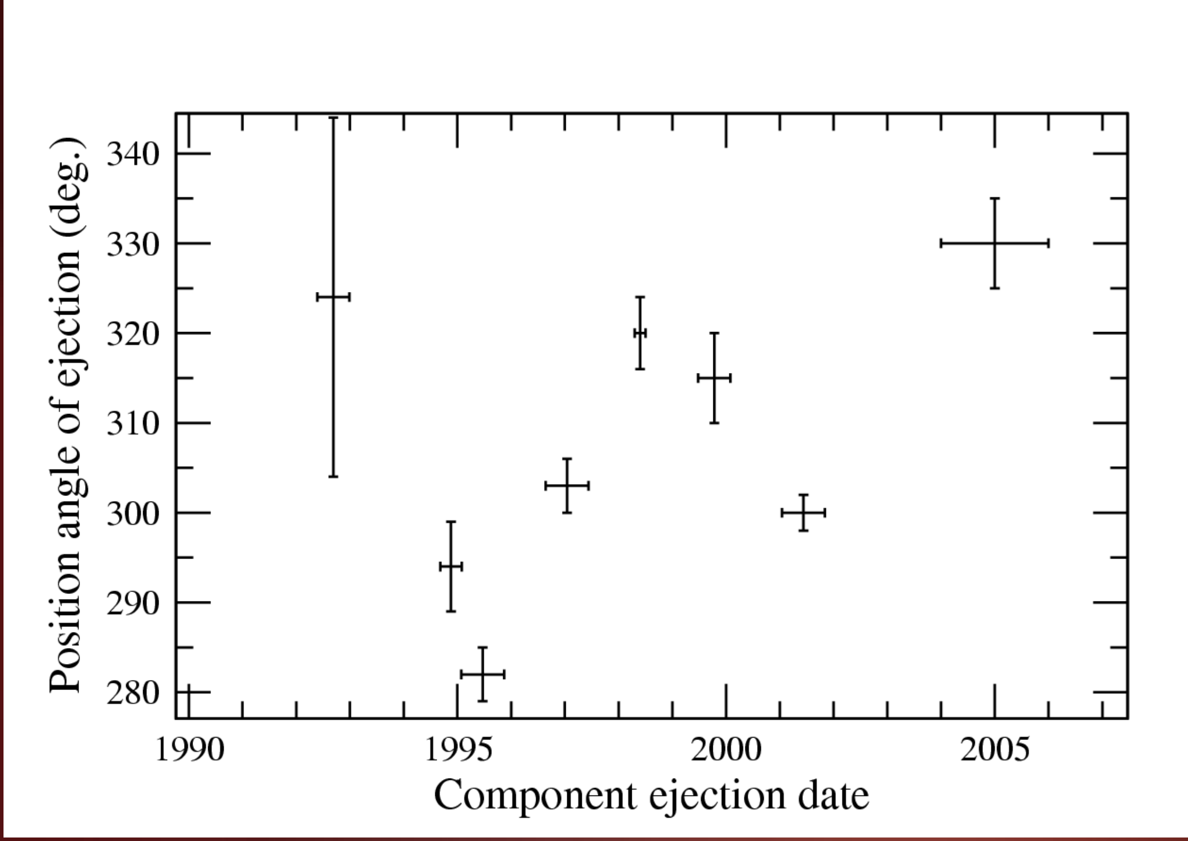
1308+326, Cpt 9 at 15.3 GHz, UV plane fit by MLL
Relative Dec. (mas)
Relative R.A. (mas)
-1
0
1
2
3
0
2
4
6
8
T_ej = 2001.4


1308+326, Cpt 10 at 15.3 GHz, UV plane fit by MLL
Relative Dec. (mas)
Relative R.A. (mas)
3
2
1
0
−1
0
2
4
6
8
T_ej = 2005.0

Nozzle Precession

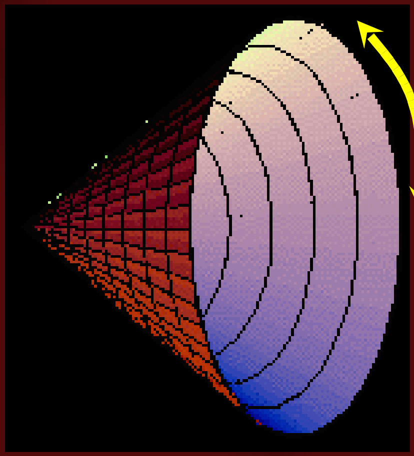
- Dramatic changes in ejection direction

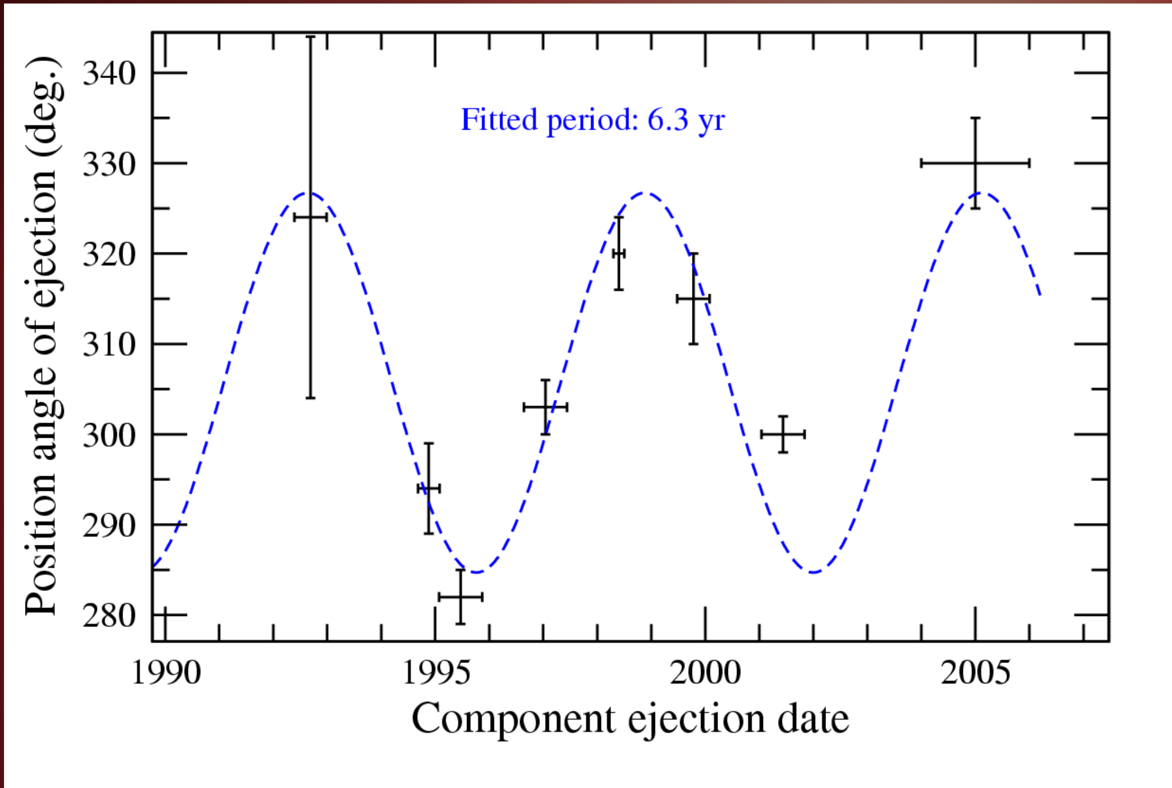
- Also seen in other AGN:
  - 3C 279 (> 12 yr)
  - BL Lacertae (2 yr)
  - OJ 287 (12 yr)
  - NRAO 150 (> 6 yr)
  - 0716+714 (7 yr)
  - 3C 273 (> 10 yr)
  - 3C 120 (?)

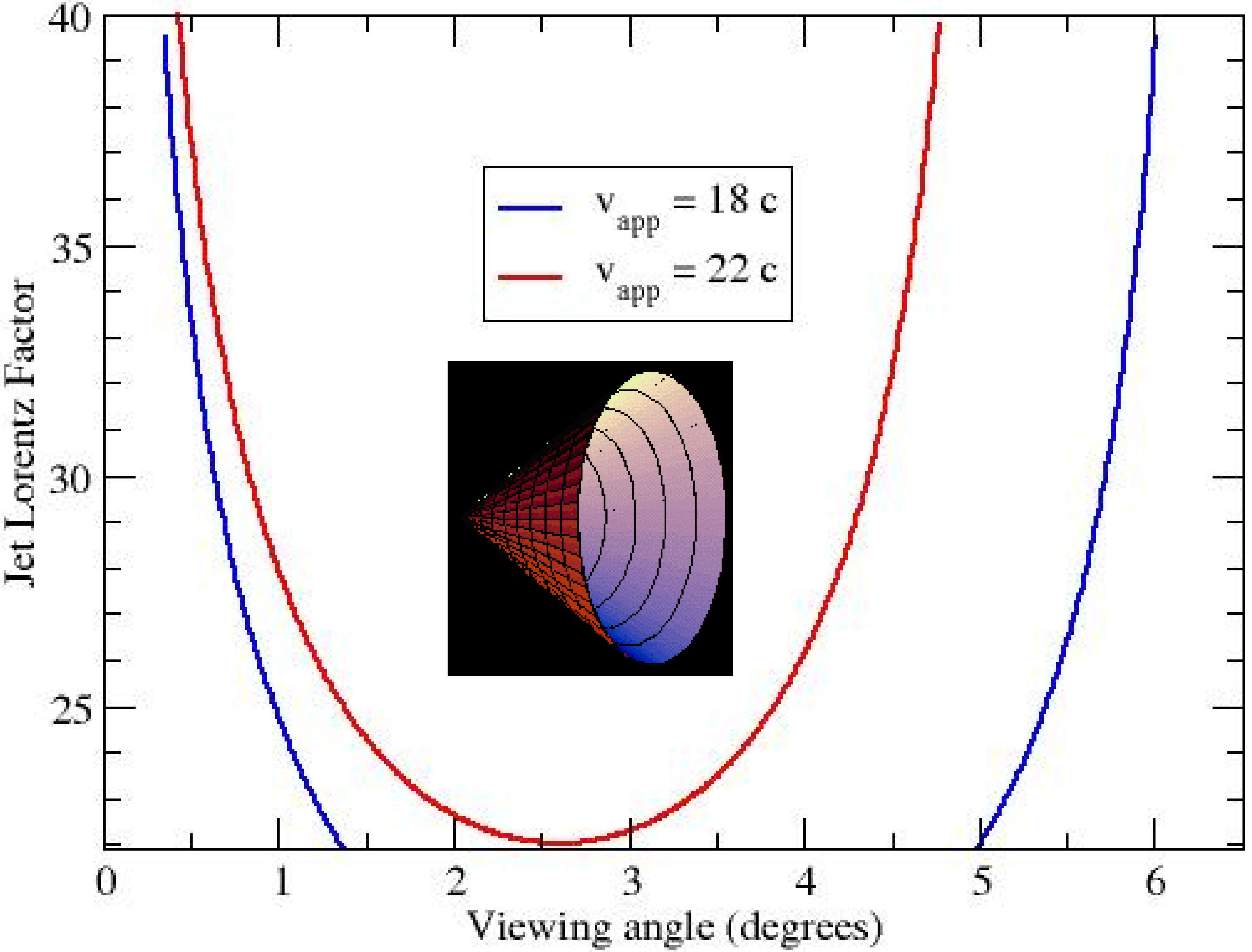


Nozzle precession in 1308+326

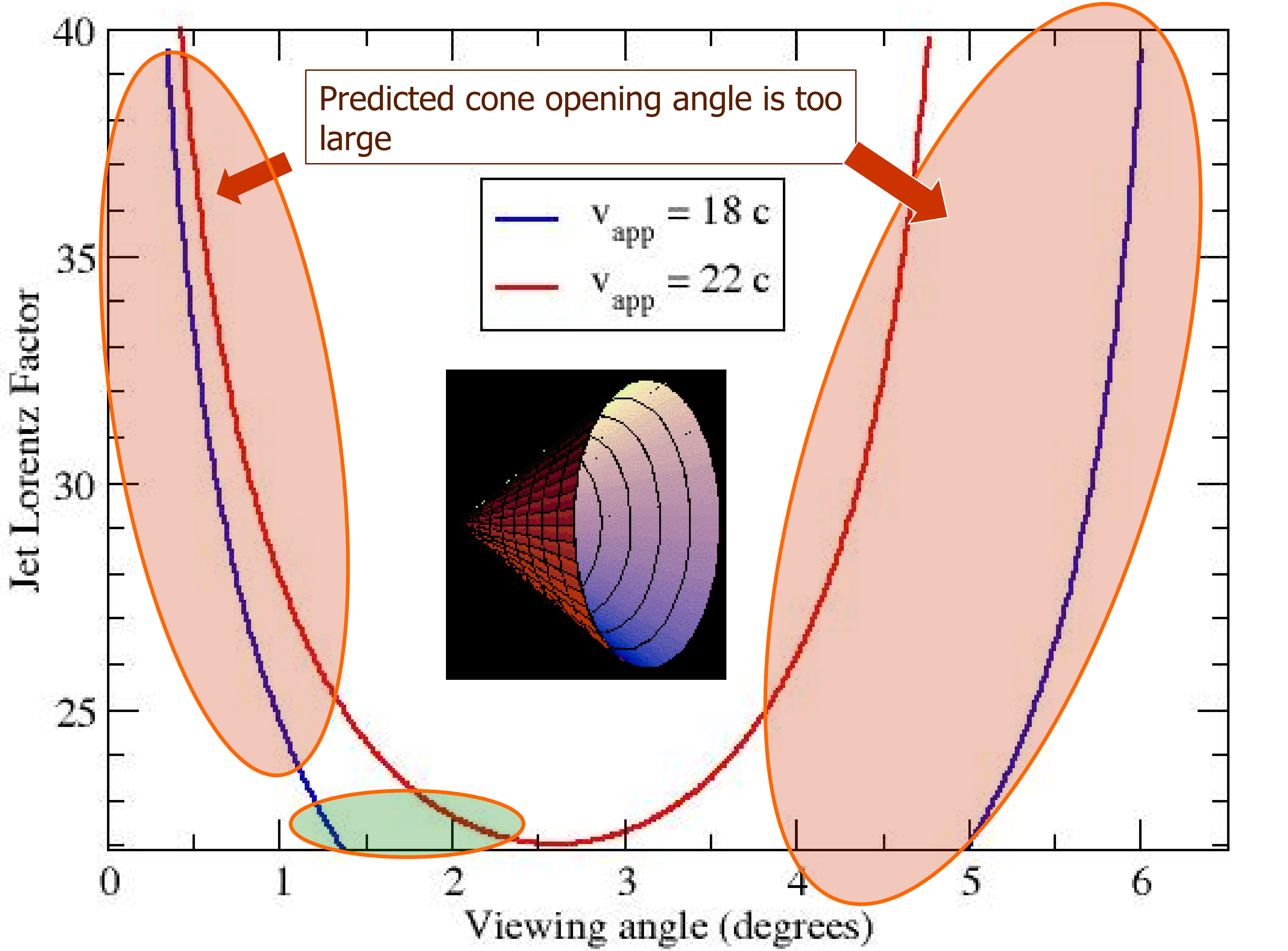
- Speeds imply viewing angles < 5°
- Periodic? (6.3 yr)
- Precession cone ½ angle < 1.7°







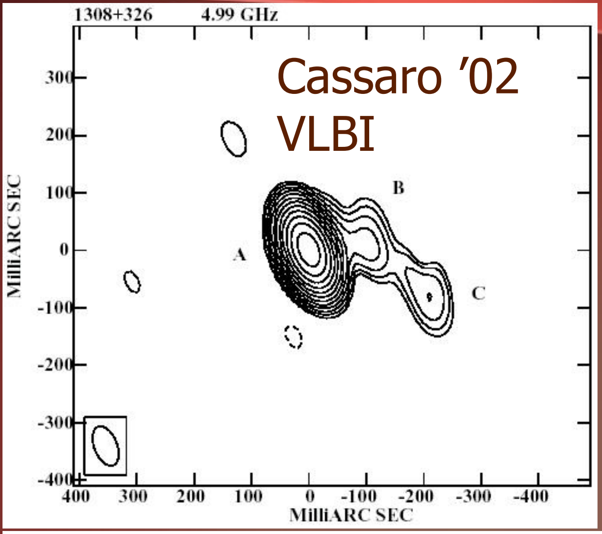
40
35
30
25
0
1
2
3
4
5
6
Jet Lorentz Factor
Viewing angle (degrees)
v app = 18 c
v app = 22 c



Predicted cone opening angle is too large
v_{app} = 18 c
v_{app} = 22 c
Jet Lorentz Factor
Viewing angle (degrees)
40
35
30
25
0
1
2
3
4
5
6

1308+326

- **Problems with simple ballistic model:**
  - curved trajectory of C7
  - extended radio structure
- **Are we seeing density enhancements moving within a broader, much fainter outflow?**
  - apparent opening angles exaggerated by csc θ
  - need very high-sensitivity or space VLBI at lower frequencies



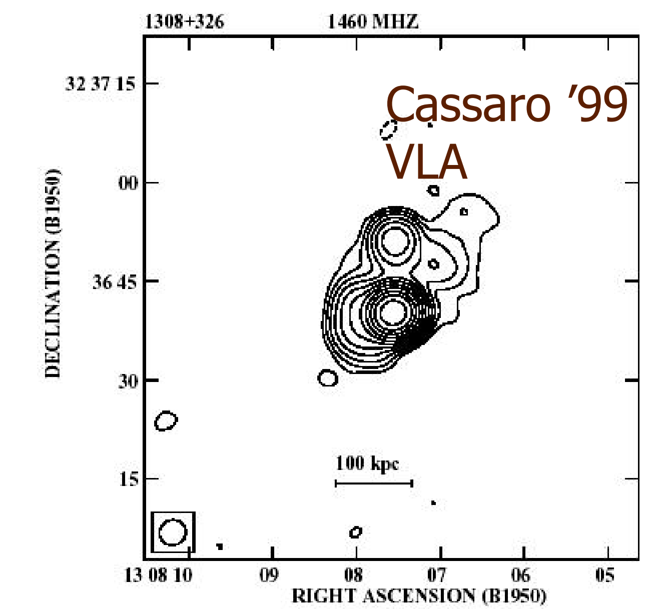
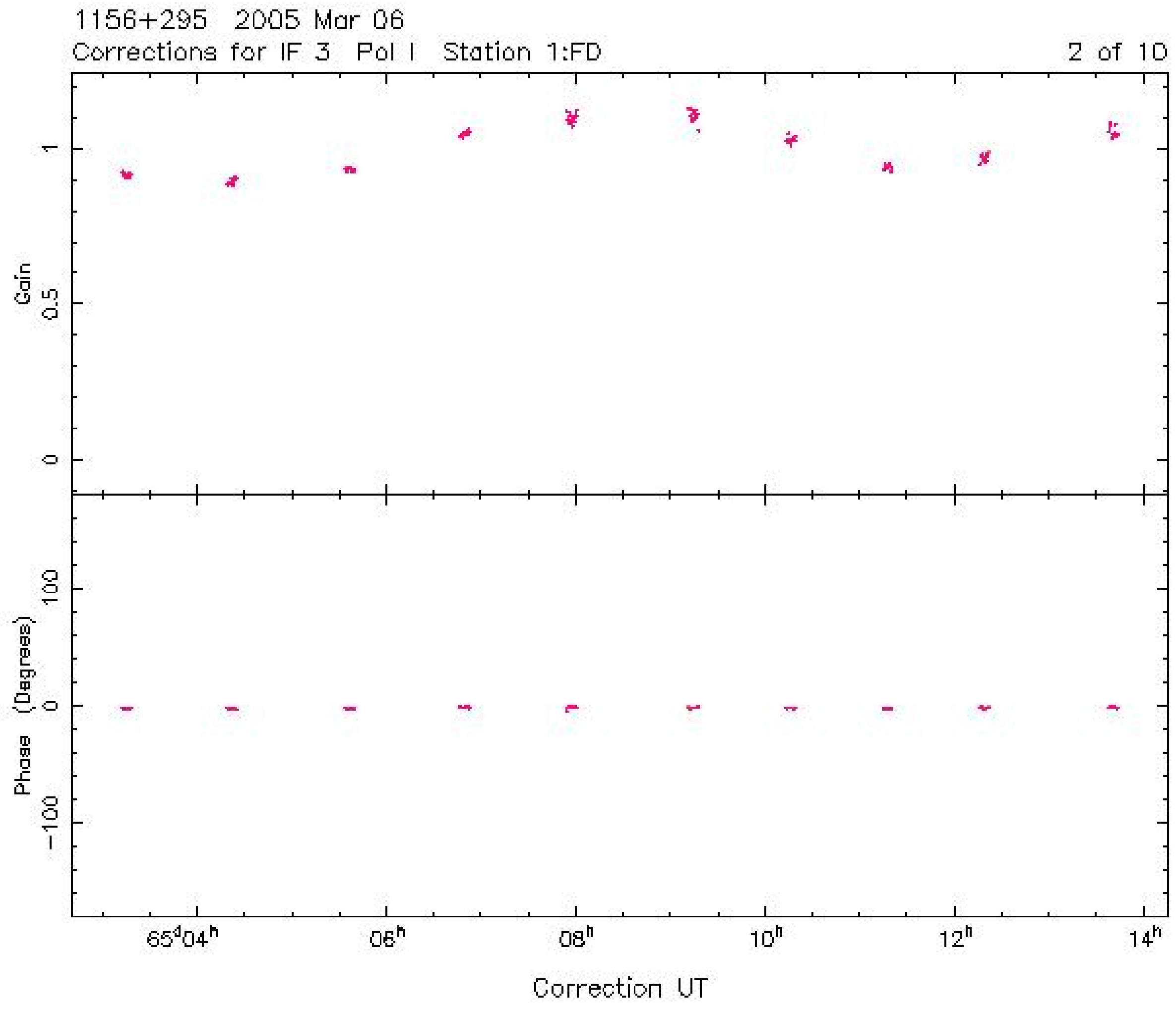


Fig. 17. 1308+326, VLA B configuration, 1.46 GHz. The restoring beam is 4.3 × 4.3 arcsec. The peak flux density is 859 mJy/beam and the rms noise on the image is 0.15 mJy/beam

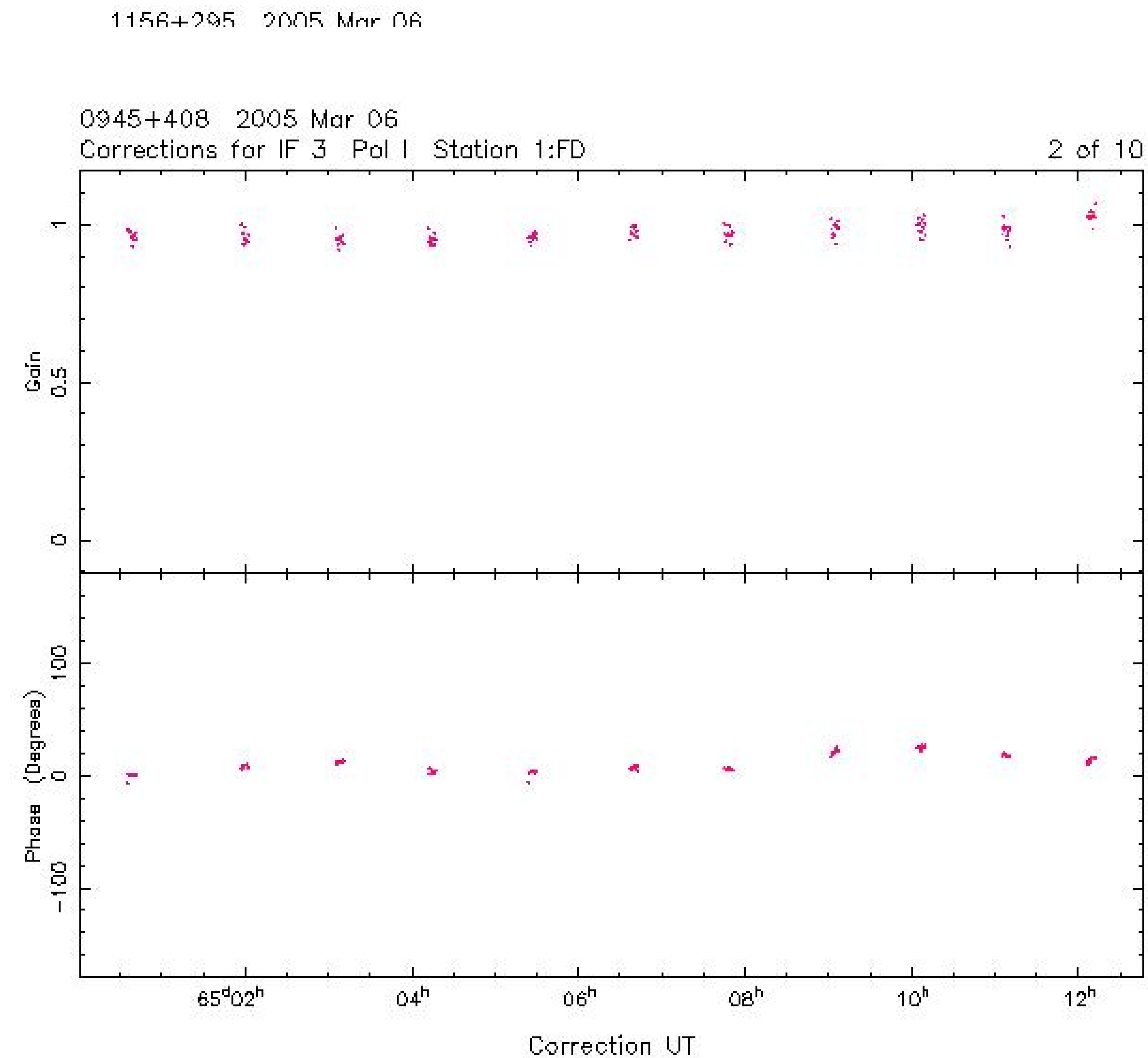
Probing IDV with MOJAVE

- **Each VLBA run:**
  - **18 sources observed over 24 hours**
- **Hour-scale flux variations of 15% in EGRET blazar 1156+295**
- **Systematic check on other sources is underway**

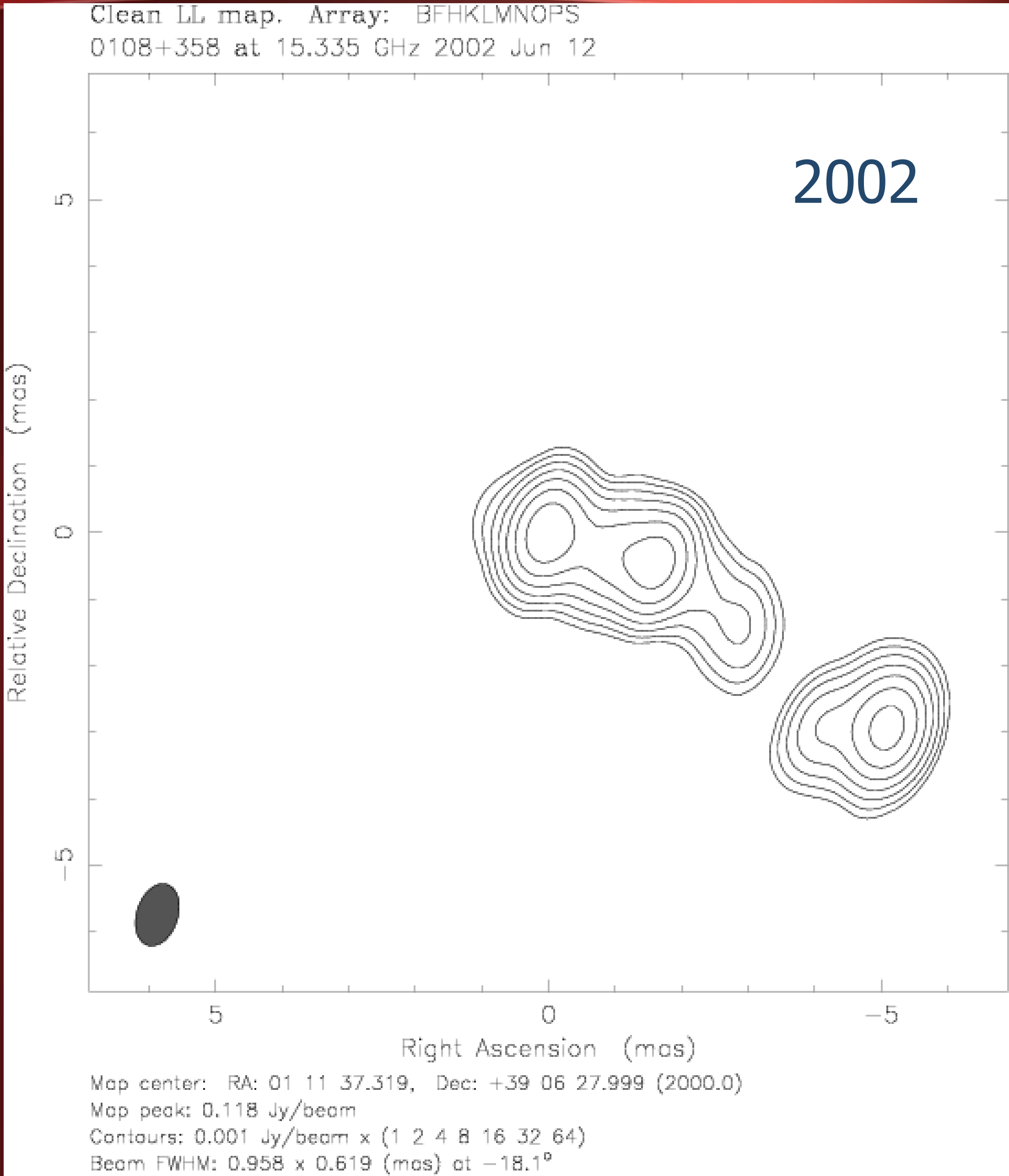


Probing IDV with MOJAVE

- **Each VLBA run:**
  - **18 sources observed ove 24 hours**
- **Hour-scale flux variations of 15% in EGRET blazar 1156+295**
- **Systematic check on other sources is underway**



GPS Source 0108+388



Still to come...

- Improved statistics on precession and speeds of blazar jets

- Pc-scale circular pol. (poster by D. Homan)
  - common feature of all blazars?
  - 17% detected in 1st epoch: (Homan & Lister 2006 AJ 131,1262)
  - what is the prime generation mechanism?
  - stability of CP sign over time? → helical magnetic fields?

- Linear polarization
  - comparisons with kinematics

MOJAVE-II

- Began in Feb. 2006
- Adds 59 AGN, so as to contain:
  - 18 GPS sources
  - 34 low-z (low-L) radio galaxies
  - all 44 blazars in EGRET 3rd catalog
  - highly curved jets
- 4-frequency VLBA (8 – 15 GHz)
  - Faraday rotation/depol./gradients on a complete sample
  - CP spectrum
  - track steep-spectrum features to larger distances

Summary

MOJAVE so far:

- VLBA is a powerful tool for understanding jet evolution:
  - how common are precession and bending?
  - are VLBI jets part of broader outflows?
  - can we detect a jet acceleration/deceleration region?

- Intrinsic jet properties of blazar parent population
  - fastest jets have to be intrinsically the most powerful in population
  - Jet Lorentz factors > 30 in AGN (e.g. 3C 279) are exceedingly rare

Still to come:

- **Determination of useful jet parameters for all 'famous' blazars and others likely to be detected by GLAST**

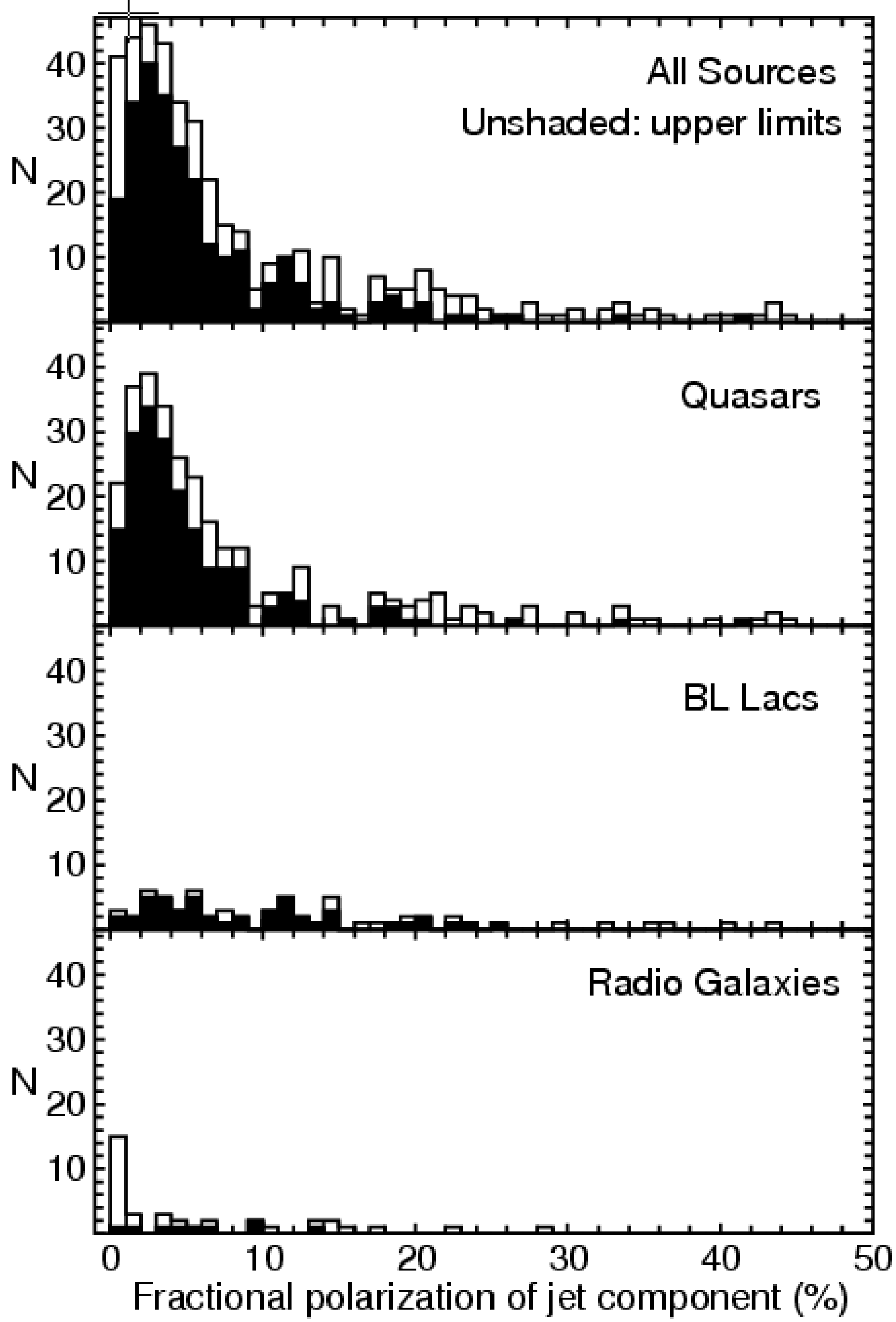
- **Better understanding of linear and circular polarization mechanisms, and their connection with jet kinematics**

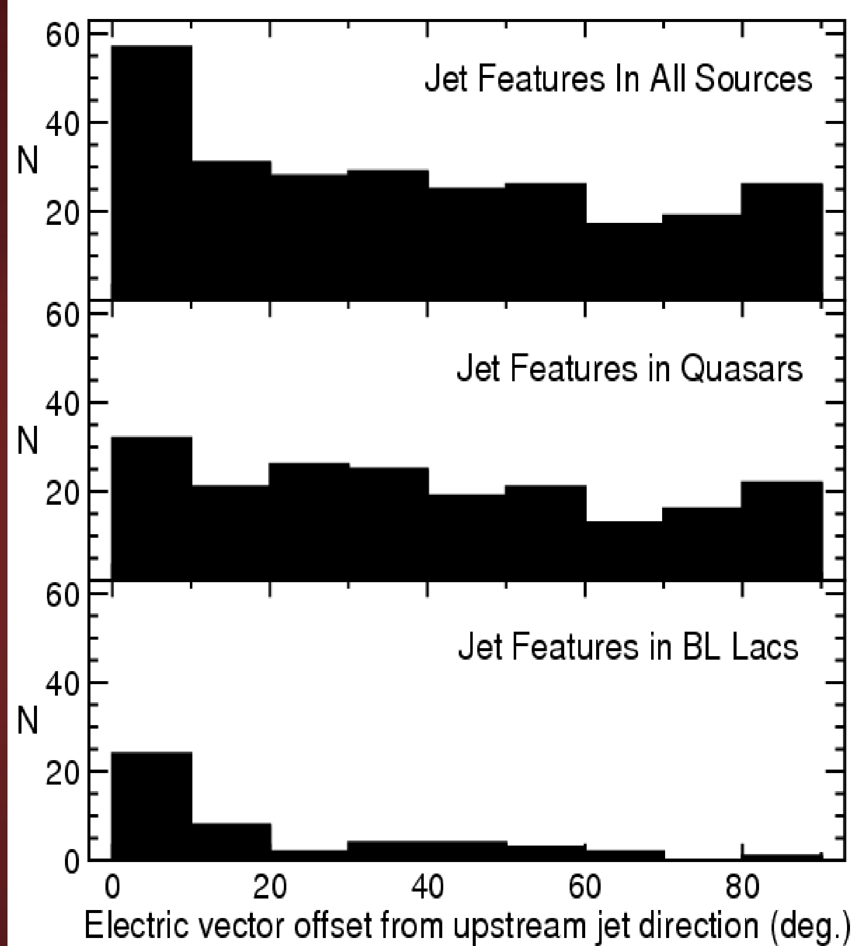
Shameless Advertising Section:

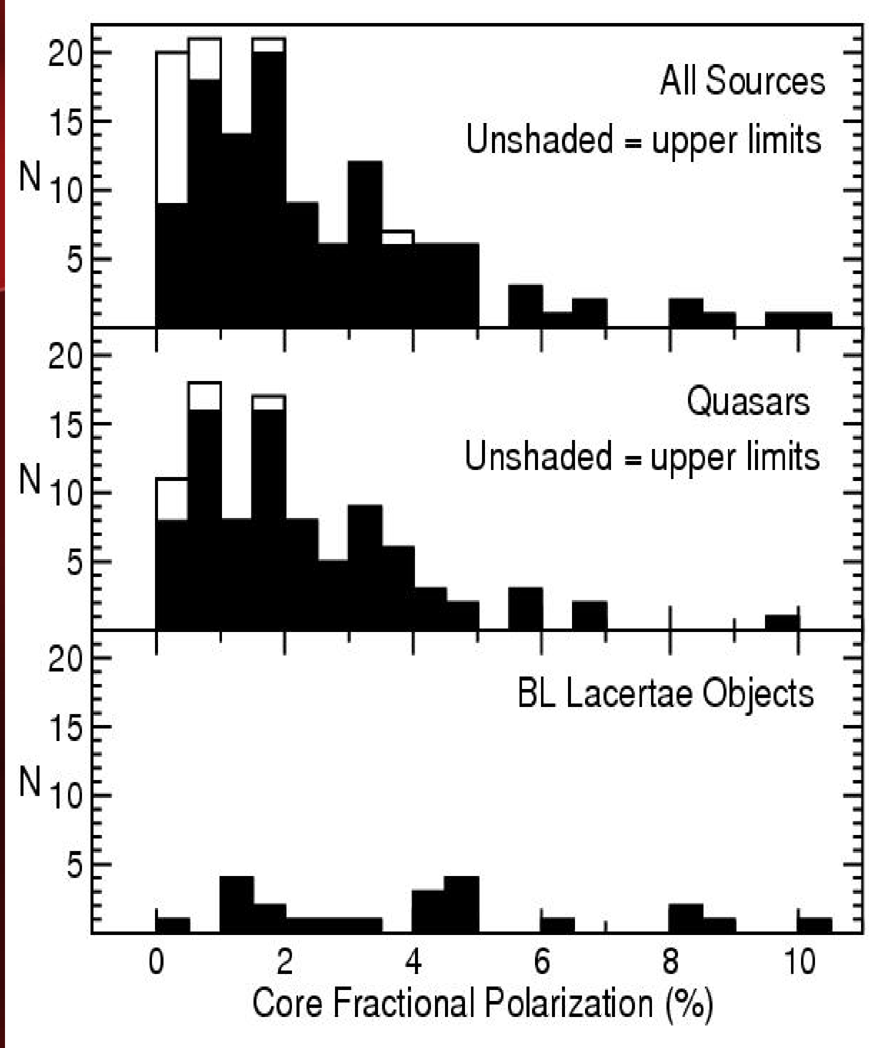
I) www.physics.purdue.edu/astro/MOJAVE

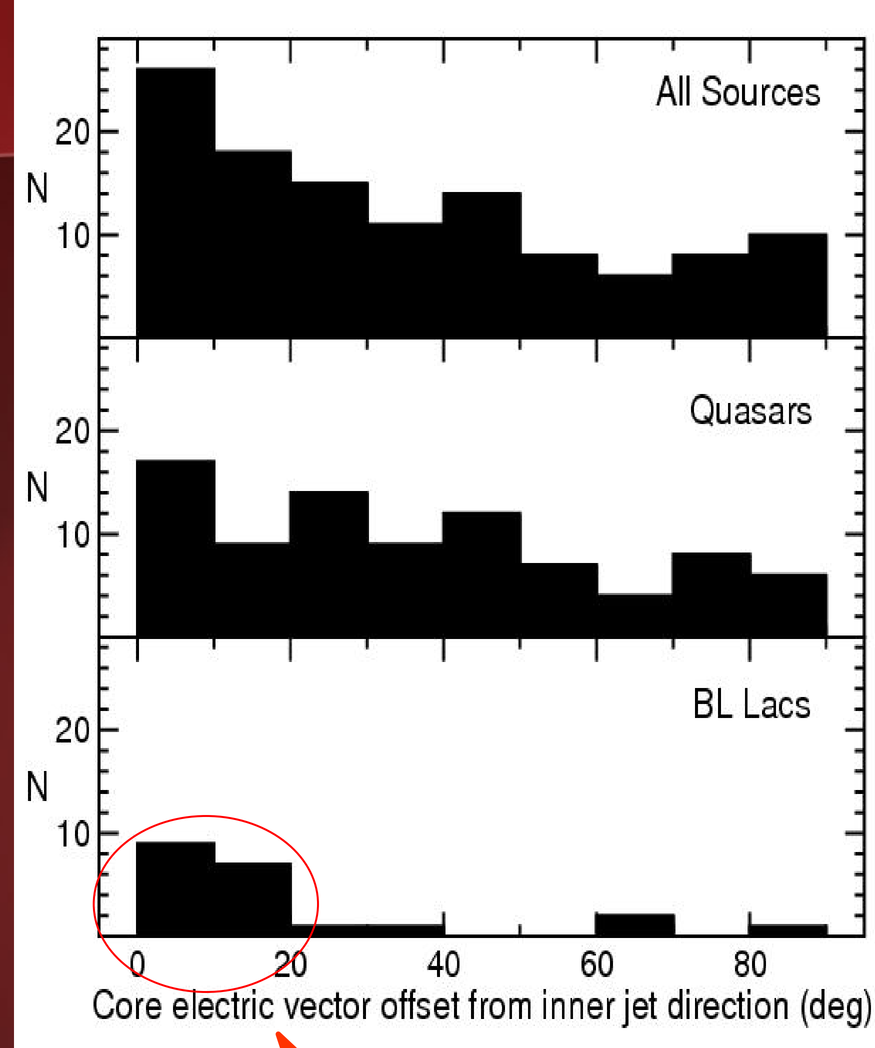
II) I'm currently looking to hire a postdoc

- Same holds true for jet regions downstream





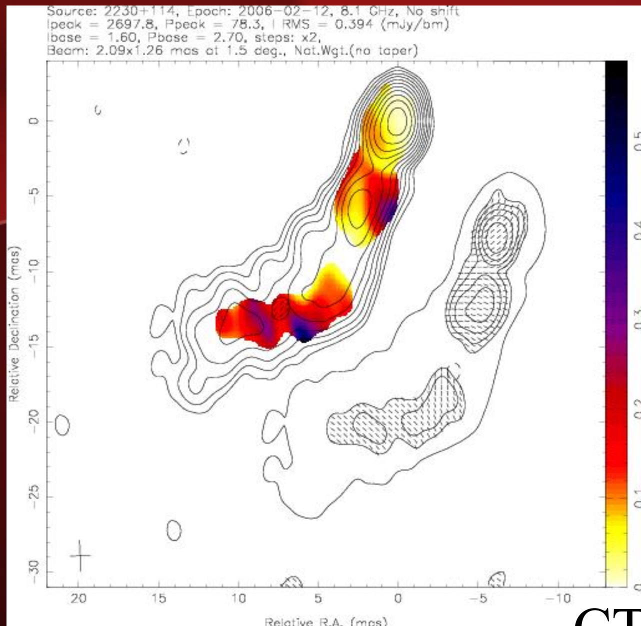




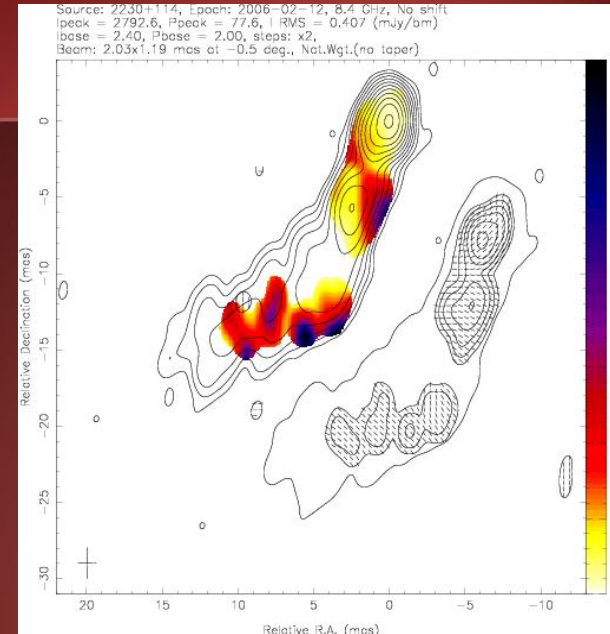
- B fields in BL Lac cores appear more highly ordered than quasars and better aligned with jet.

CTA 102: Feb 2006

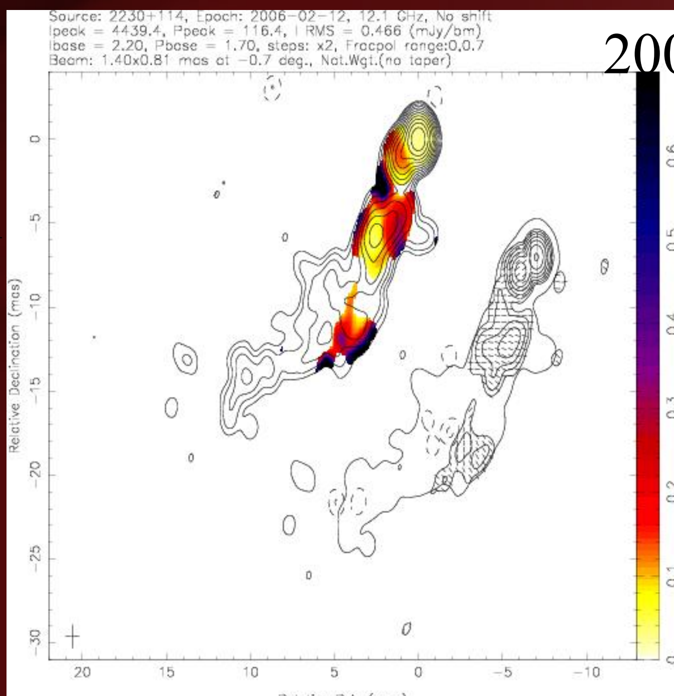
8.1



8.4



12.1



15.3