THE RELATIVE PROPER MOTION OF THE VIRGO CLUSTER GALAXIES M87 AND M84

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M87 43 GHz Project

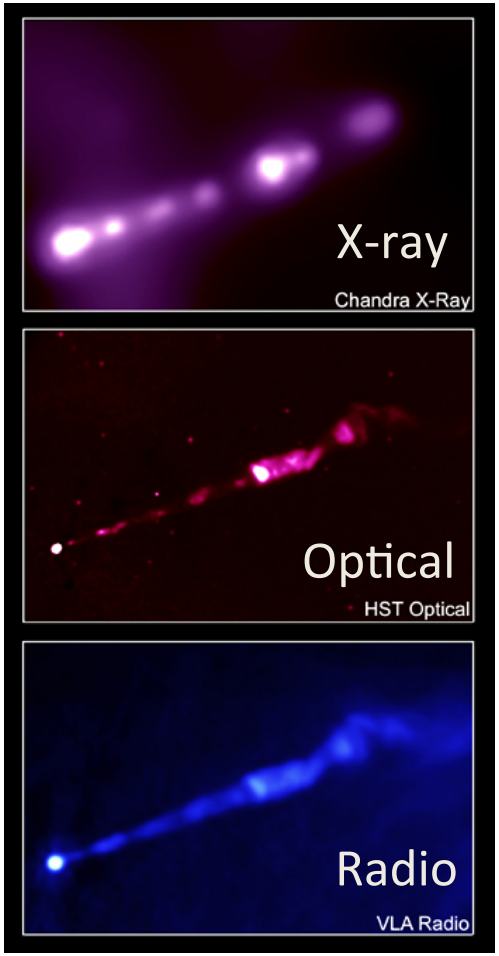
- Primary goal to study jet dynamics in M87
- M87 has a 6 X 10^9solar mass black hole
- In Virgo Cluster at 16.7 Mpc.
- VLBA 43 GHz resolution reaches ~30 R_s
- Goal: Constrain jet launch models
- Each epoch included 18-40 scans on M84 for phase referencing between it and M87 – separation 1.5 deg
- Since March 2008, geodetic segments included for atmospheric calibration

THE VLBA 43 GHz M87/M84 OBSERVATIONS

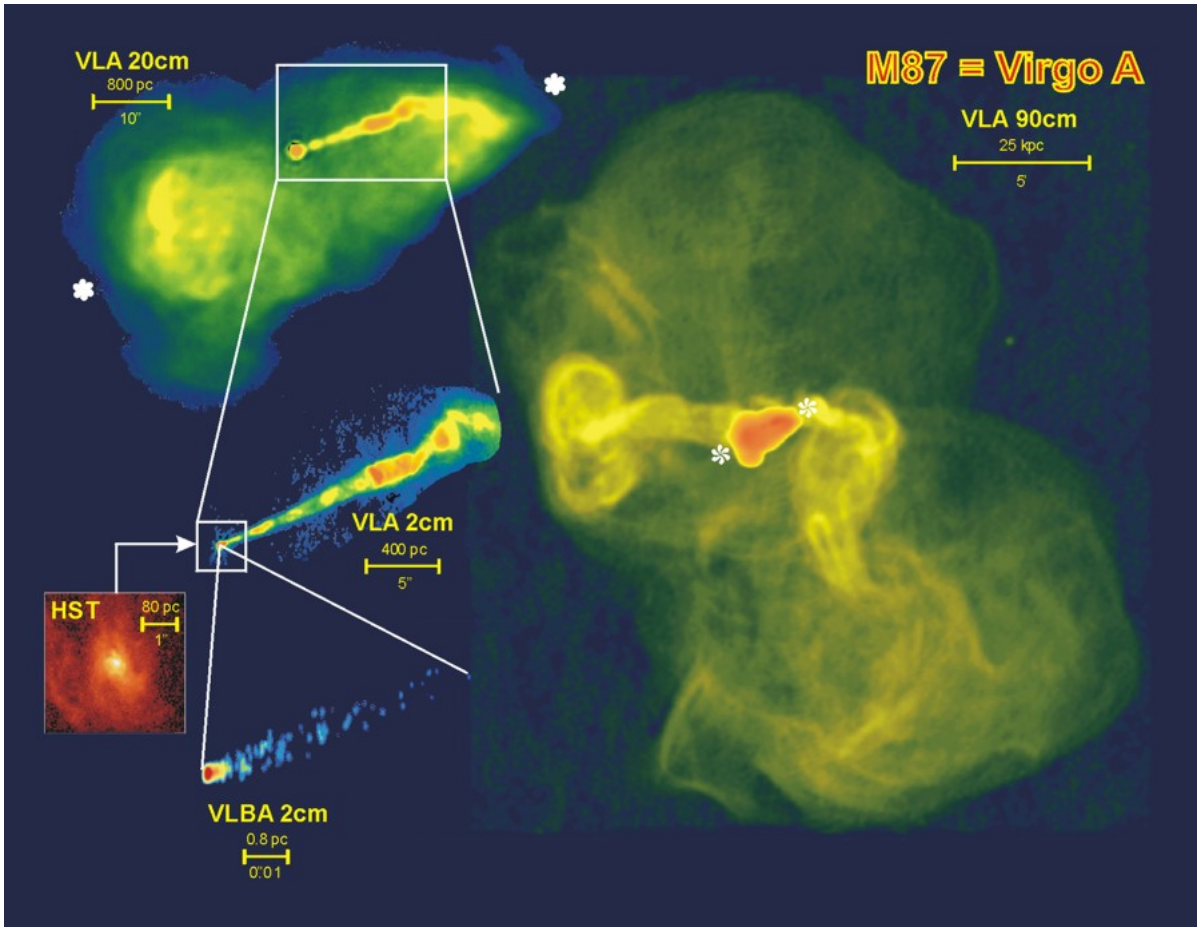
- 2001: Rapid phase referencing to image M84 (too fast).
- 2004: M84 long track imaging. Occasional M87 scan.
- 2007: 18 Observations at 3 week intervals for movie.
  - Undersampled. Not all processing finished.
- 2008: 14 Observations at 5 day intervals in early 2008
  - Major flare seen coinciding with a TeV flare.
- 2009-2015: Prepared to respond to TeV or γ-ray trigger
  - 1 or 2 background observations each year
  - Triggered 5 additional observations in 2010 but no flare
- Since 2007 there have been 15-40 M84 scans per epoch

M87 STRUCTURE OVERVIEW

1 kpc scale

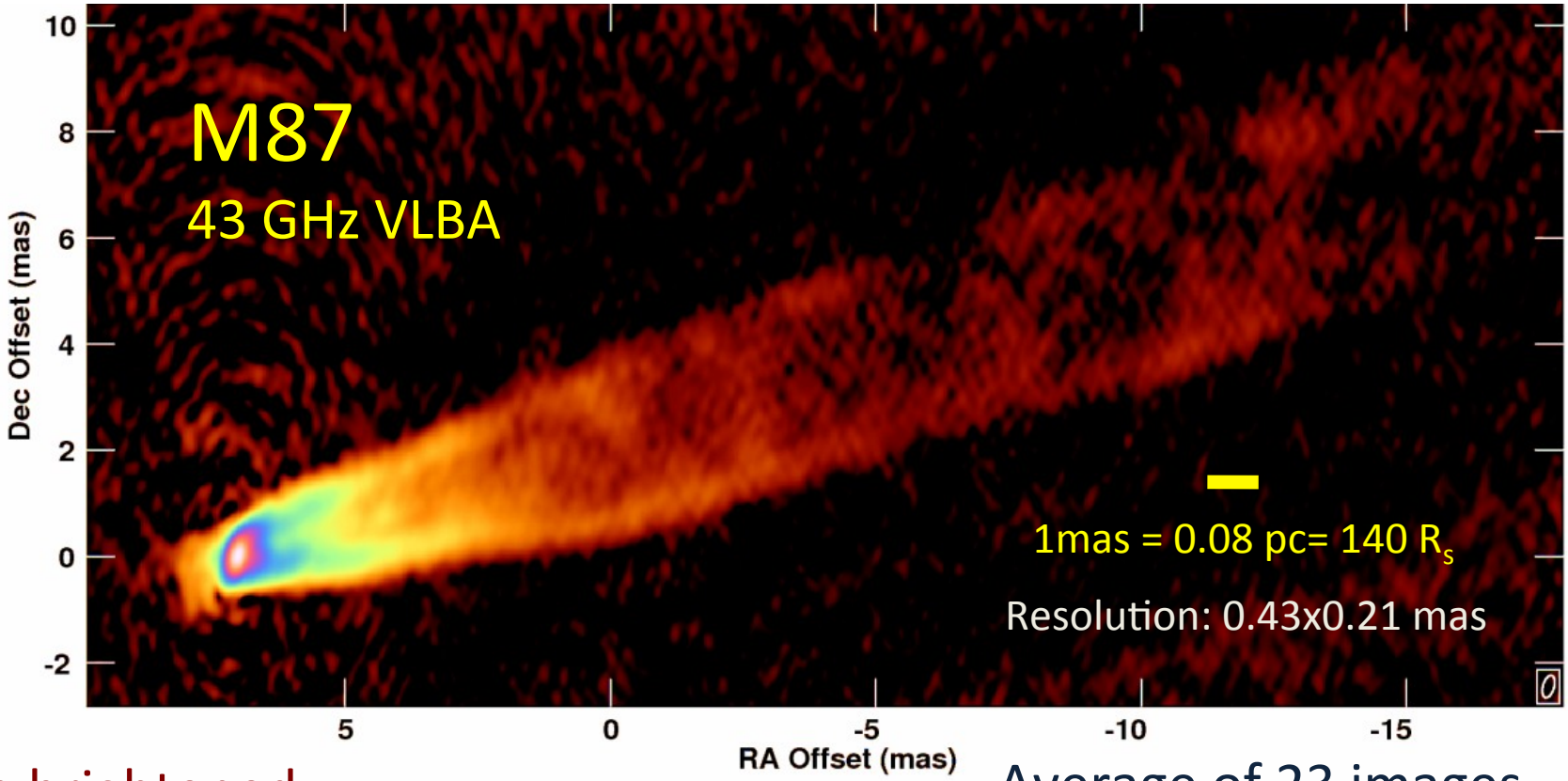


Distance: 16.7 Mpc (Mei 2007; Bird 2010)



Radio images

MORPHOLOGY



Edge brightened:

Suggests emission is from the surface or sheath

Wide base: Collimation region

Counterjet: Real – in all images. Seen by others.

Fades fast: Beaming + Acceleration?

Average of 23 images

VLBA 2007, 2008, 43 GHz

Before upgrade; 256 Mbps

Average smooths changing features – like time exposure of a waterfall

KINEMATICS: VLBA 43 GHz M87 MOVIE

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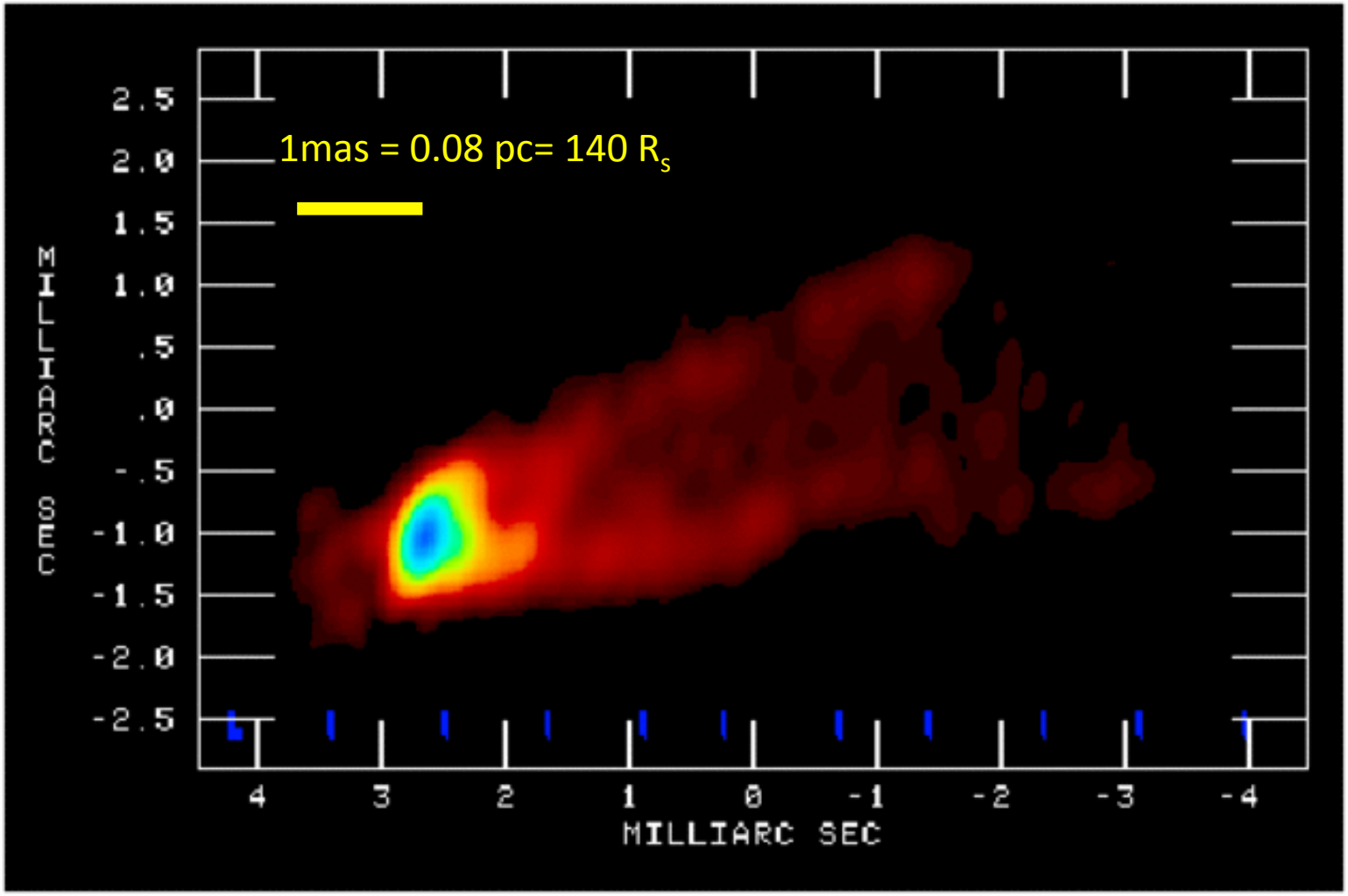
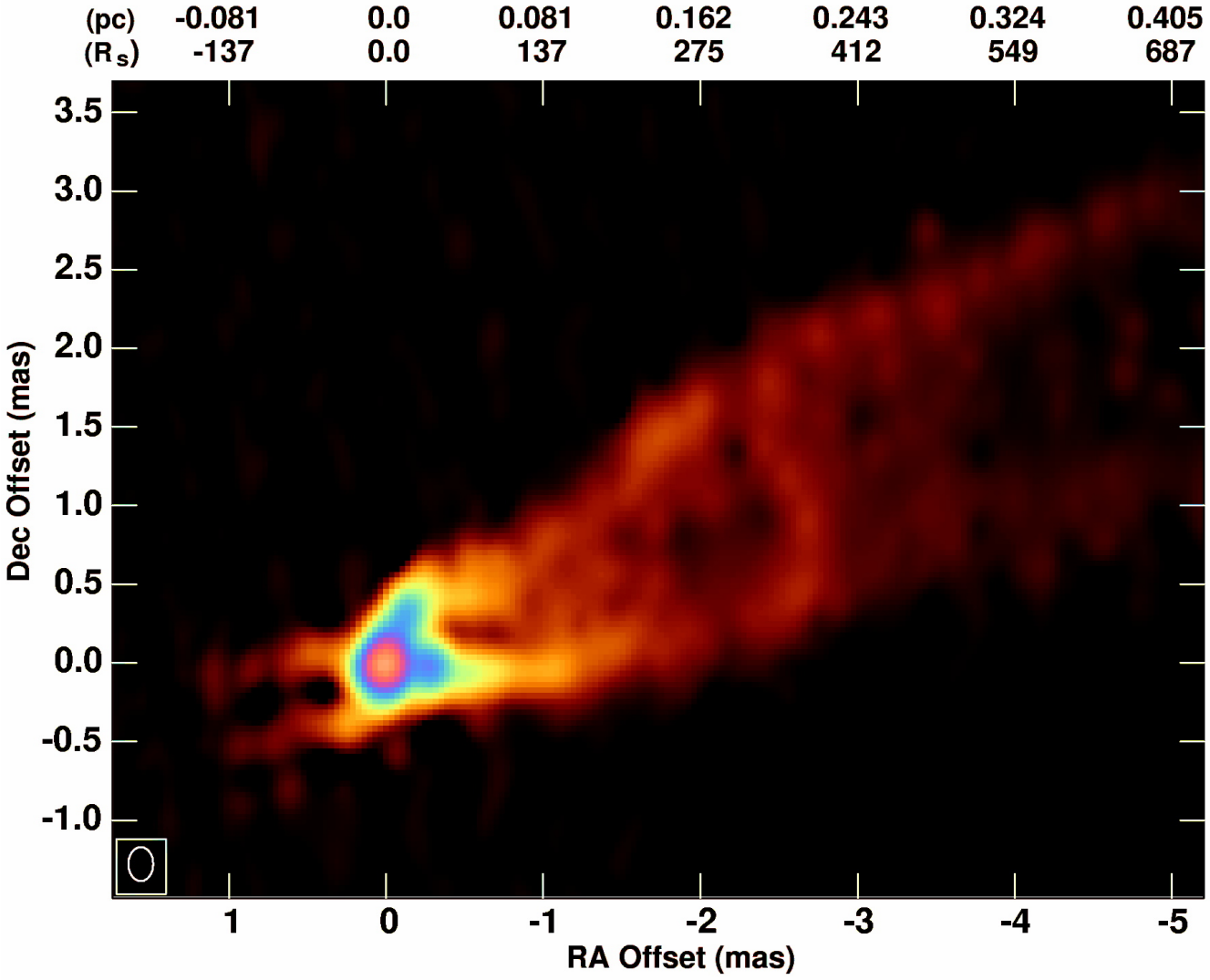


Beam
0.43x0.21 mas
0.2mas
= 0.016pc
= 28R_s
1mas/yr = 0.25c

Motions about 0.5 mas per 21 days - ~ 2c

"Smoke plume"

ZOOM IN ON CORE



VLBA 43 GHz
Jan 12, 2013
New 2 Gbps system

Beam 0.215 x 0.158 mas
- ≅ 30 x 22 R_s
- Uniform weight plus 30% superresolution in N-S direction.

Shows wide base

Details quite disturbed

Structure symmetric between jet and counterjet
- Slightly shorter on counterjet side as might be expected

IS RADIO CORE AT THE BLACK HOLE?

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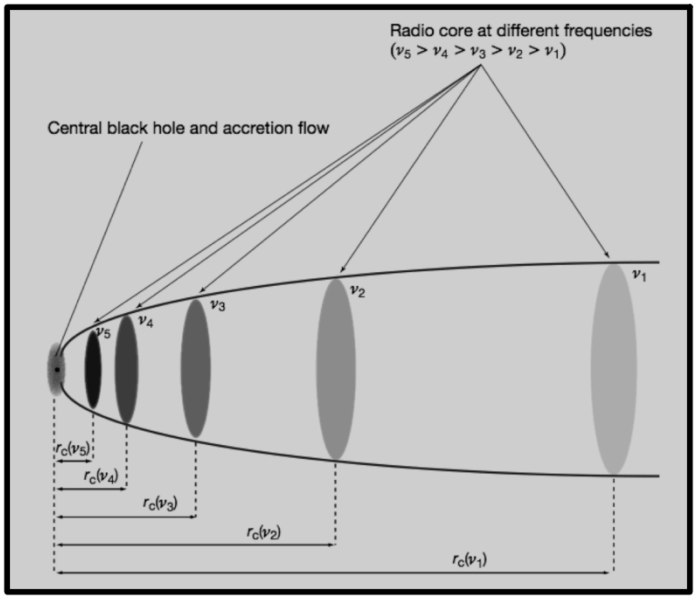
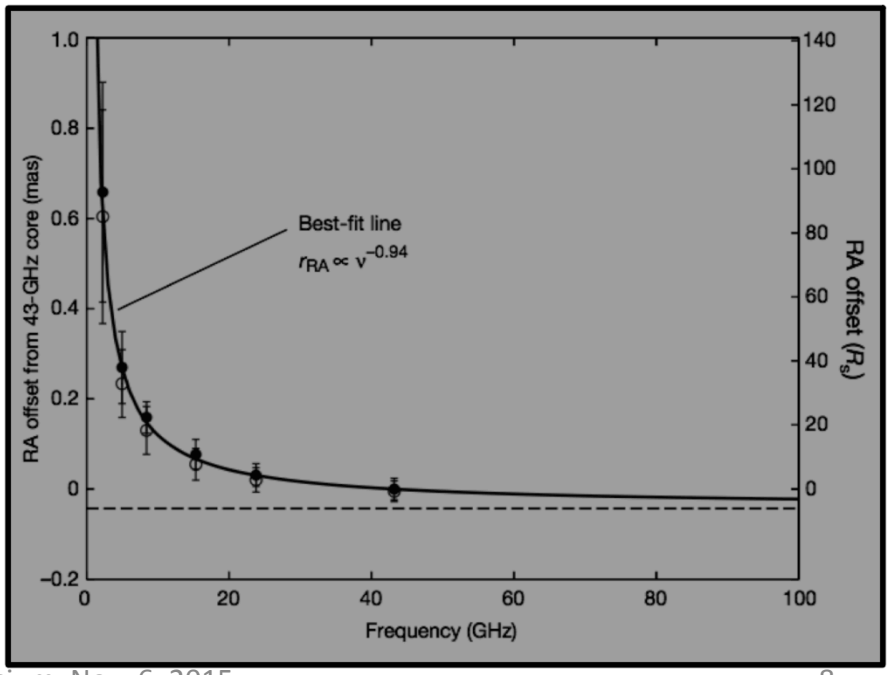
- Some blazars appear to have large offsets (~$10^5 R_s$) (cf BLLac - Marscher)
- M87 is weaker and probably at a higher angle to the line-of-sight, with less beaming
- Astrometry during a 2008 flare showed limited position change of about 50 μas or about 7 R_s (Unlikely if far down jet).
- Hada et al. (2011) showed the expected opacity effect for jet expanding from core – estimate offset 14-23 R_s





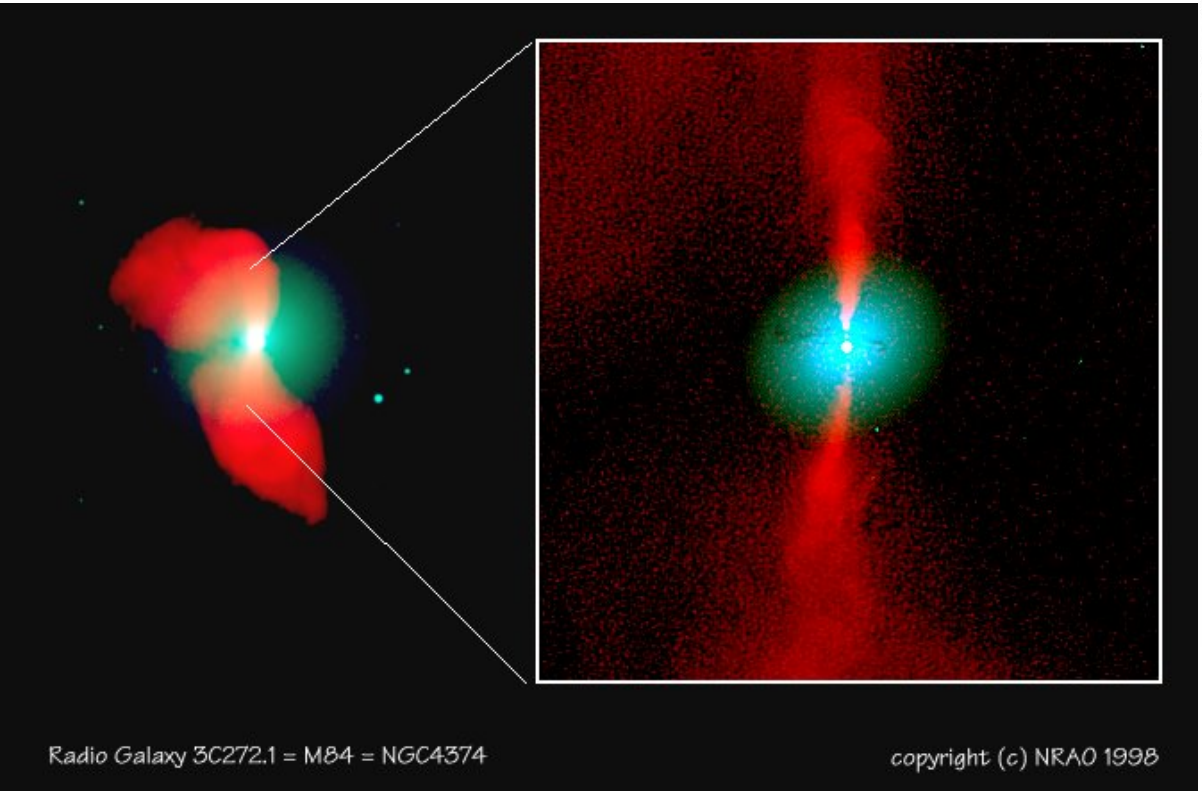
M84=NGC4374=3C272.1

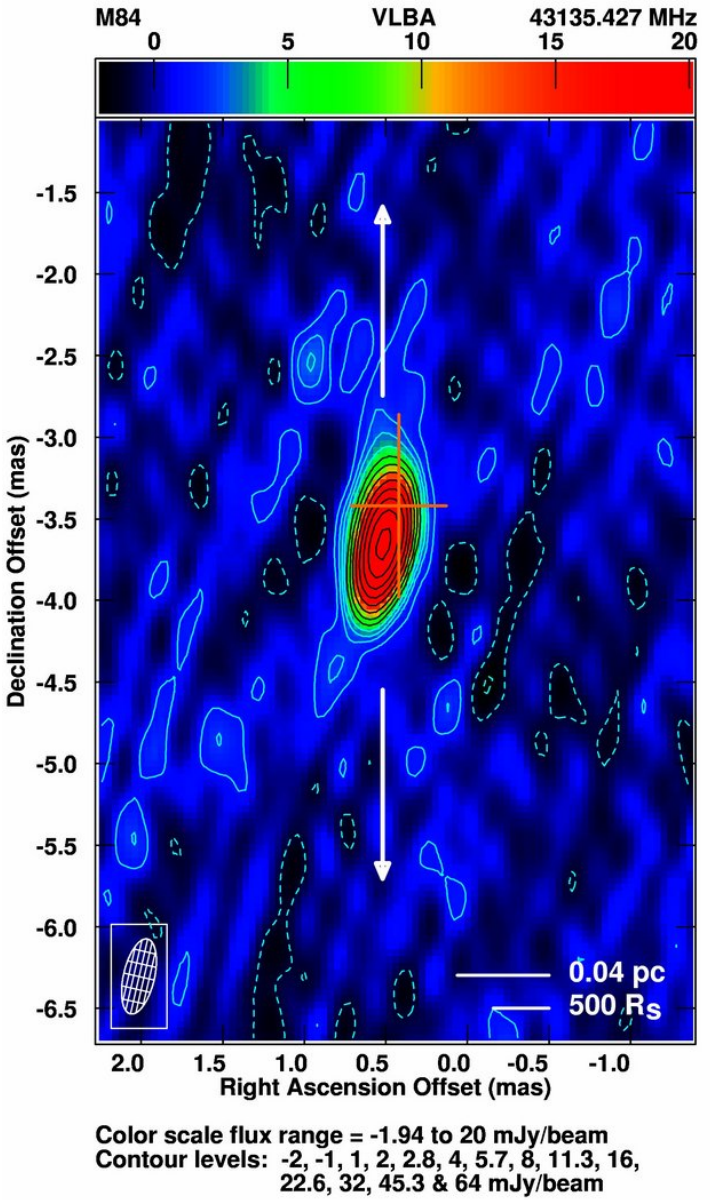
Classical FR I – Distance 18.5 Mpc

Blakeslee et al 2009 Ap. J. 694.

Compact core about 50 mJy at 43 GHz

Jets nearly perpendicular to M87 jet 1.49° from M87.





Color scale flux range = -1.94 to 20 mJy/beam
Contour levels: -2, -1, 1, 2, 2.8, 4, 5.7, 8, 11.3, 16, 22.6, 32, 45.3 & 64 mJy/beam

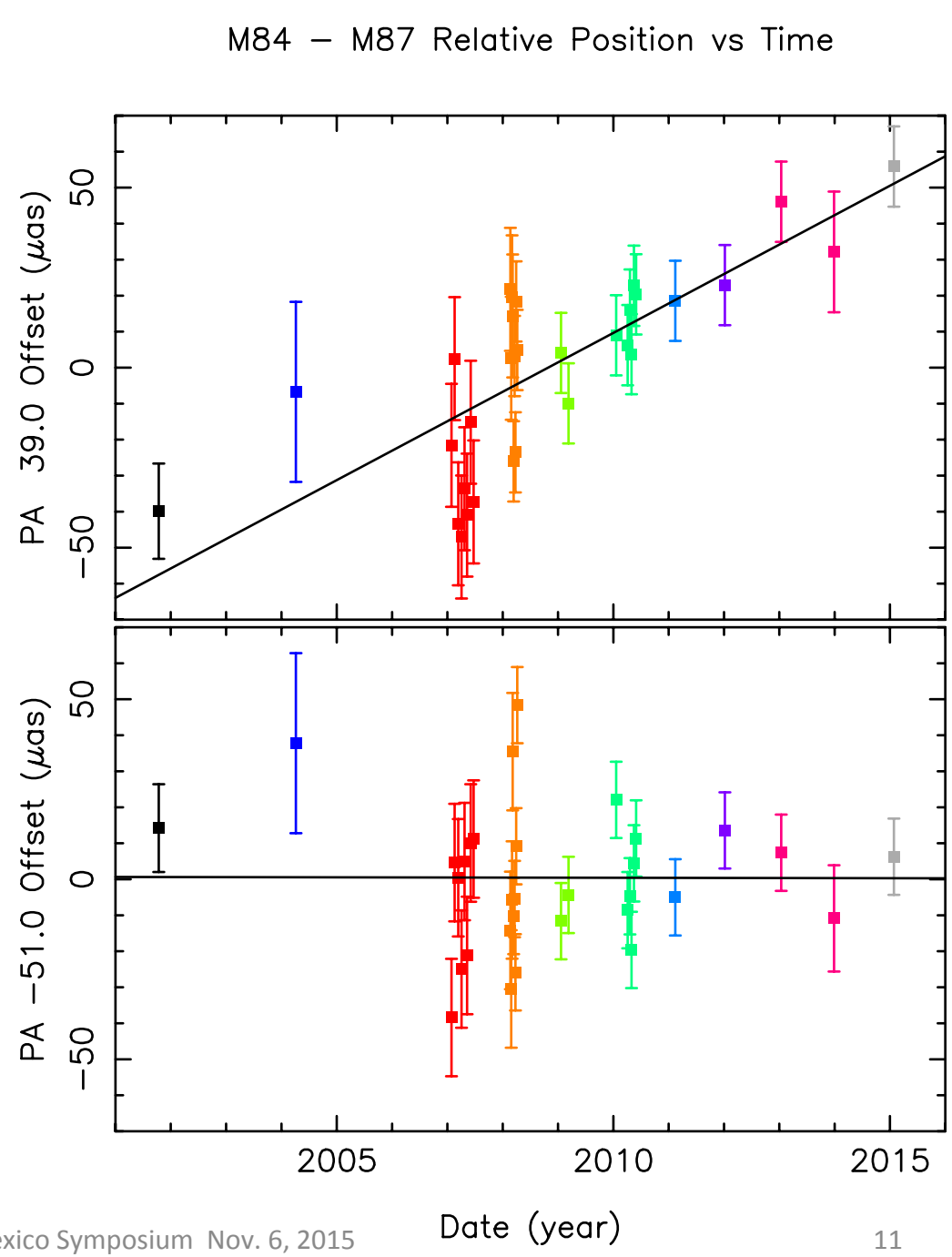
43 GHz VLBA
Ly, Walker, & Wrobel 2004

ASTROMETRIC CALIBRATION

- Ionsophere corrections with global GPS models (TECOR)
- UT and pole position corrections with updated EOP file.
- Atmospheric delay corrections based on fringe rate until March 2008 ("rate DELZN").
- Atmospheric delay and clock corrections based geodetic segments after March 2008 (based on delay DELZN).
- M87 position: Gaussian fit to peak (JMFIT)
- M84 position: Fit to phase referenced UV data (UVFIT)
- Offsets from average position for obtained for each epoch for each source
- Final offset is the M84 offset minus the M87 offset.
- Errors estimated from scatter of 2007 (rate DELZN) and 2010 (delay DELZN) data

M84 – M87 Relative Positions vs Time

- Top along PA 39° Bottom along PA -51°
- Fit result:
- **8.18 ± 0.94 μas/yr** =
- 717 ± 82 km/s at M84
- 648 ± 74 km/s at M87
- First 6 points in 2008 (flare) not included in fit or plot



M84 – M87 Relative Positions

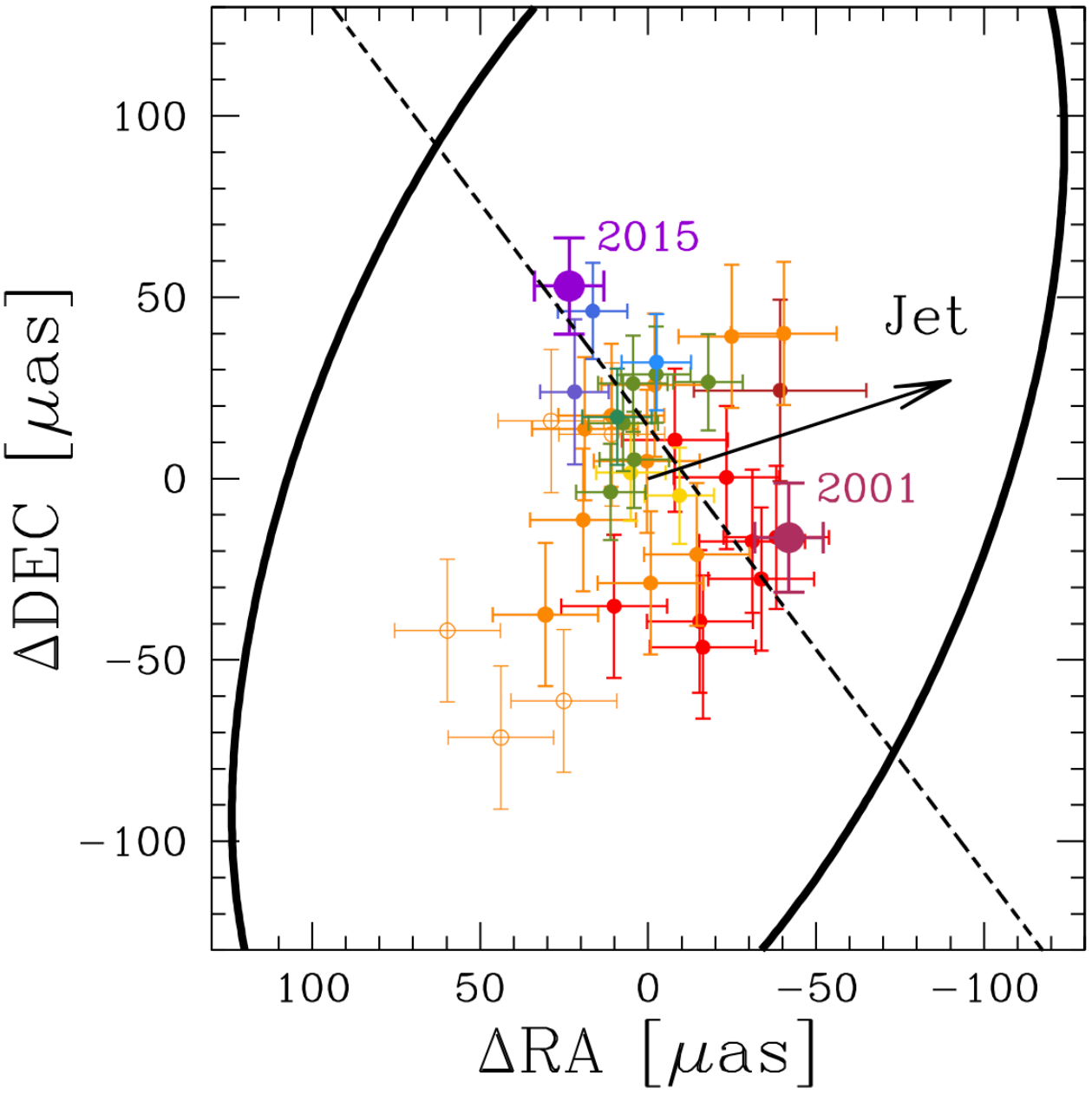
All points shown

- Deviant southeast points are during flare.
- Not used in fit.

Ellipse is beam.

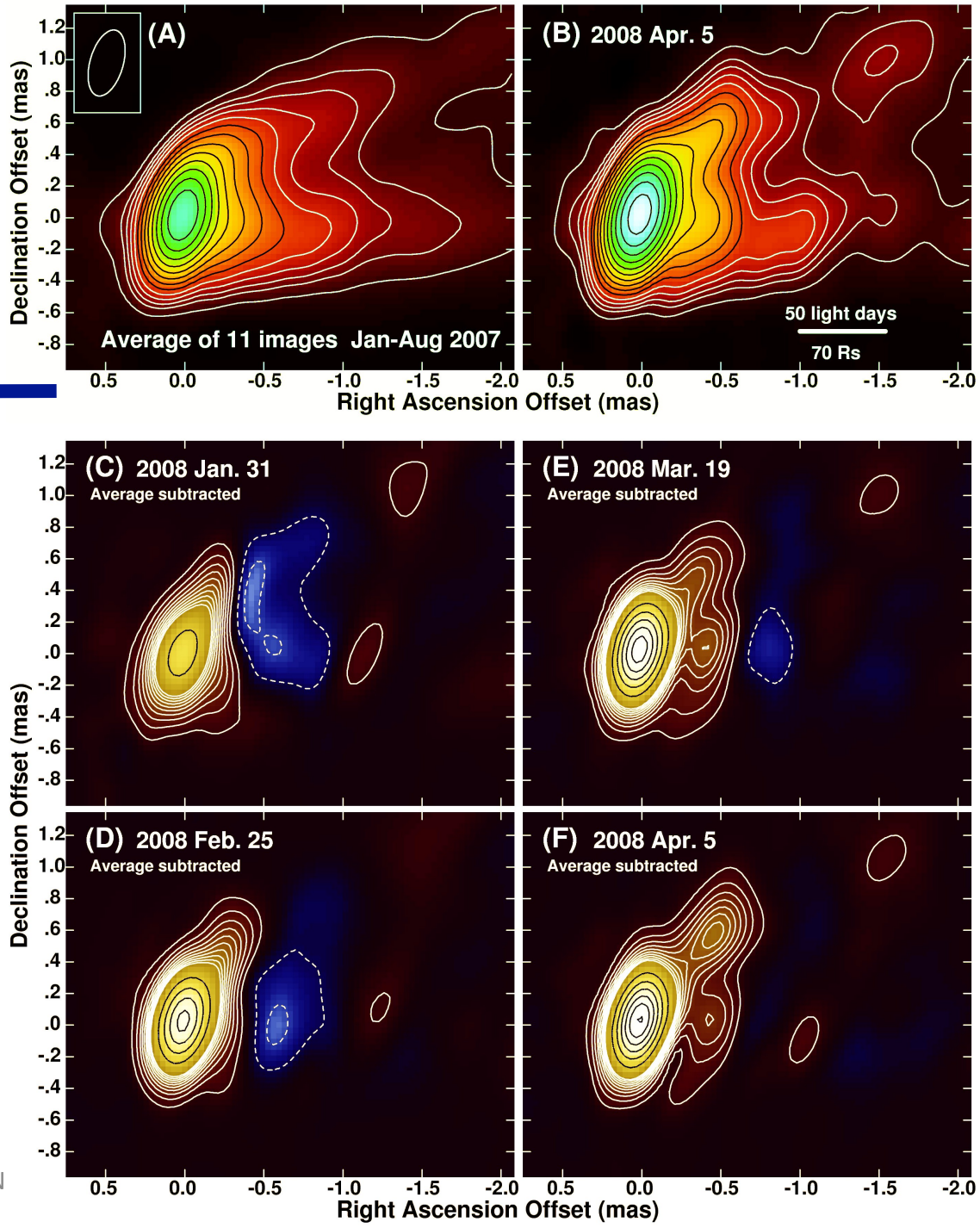
Dashed line is fitted motion.

Scale is 100 μas = 0.0081 pc = 1670 au



Davies and Walker

NEW FEATURE AT CORE



A: Average of 2007 images
B: April 5 2008 image
C-F: 2008 difference images
The 2007 average subtracted

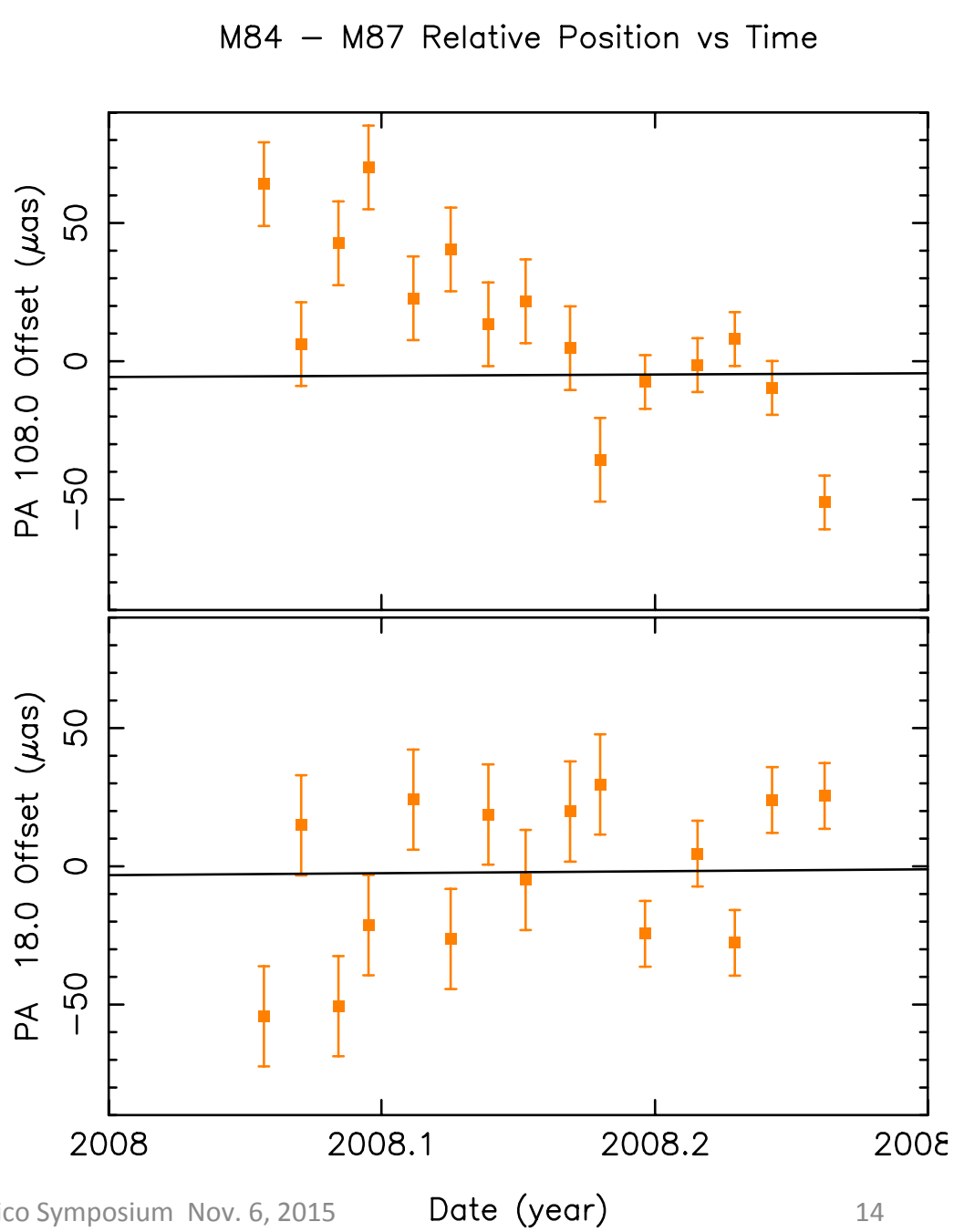
During a significant flare
Core brightened
New feature
TeV flare (at end of talk)

New feature speed ~0.4 c
Significantly slower than
The jet further out

Suggests the jet is still accelerating at 100 Rs

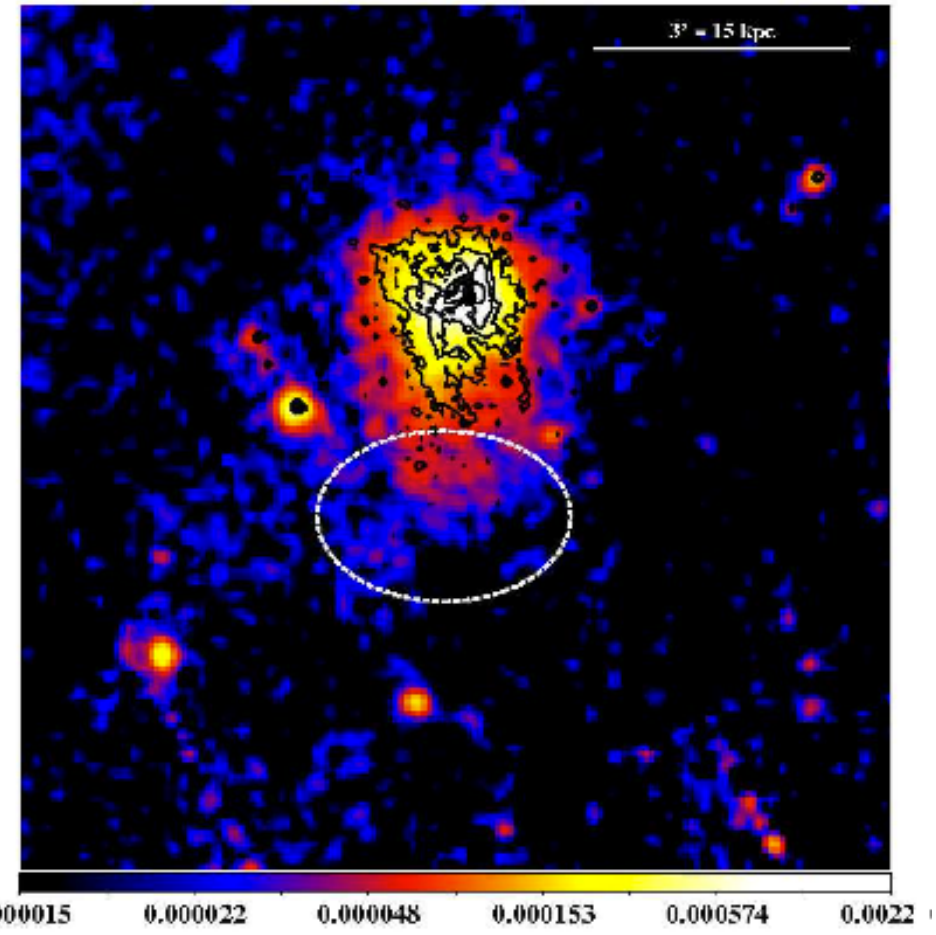
M84 – M87 Relative Position During 2008 Flare

- Top PA 108°
  - If motion is in M87, shows along jet.
- Indicates centroid of core displaced along jet at start of flare.
- Centroid returns to normal position (fit line) as component separates.



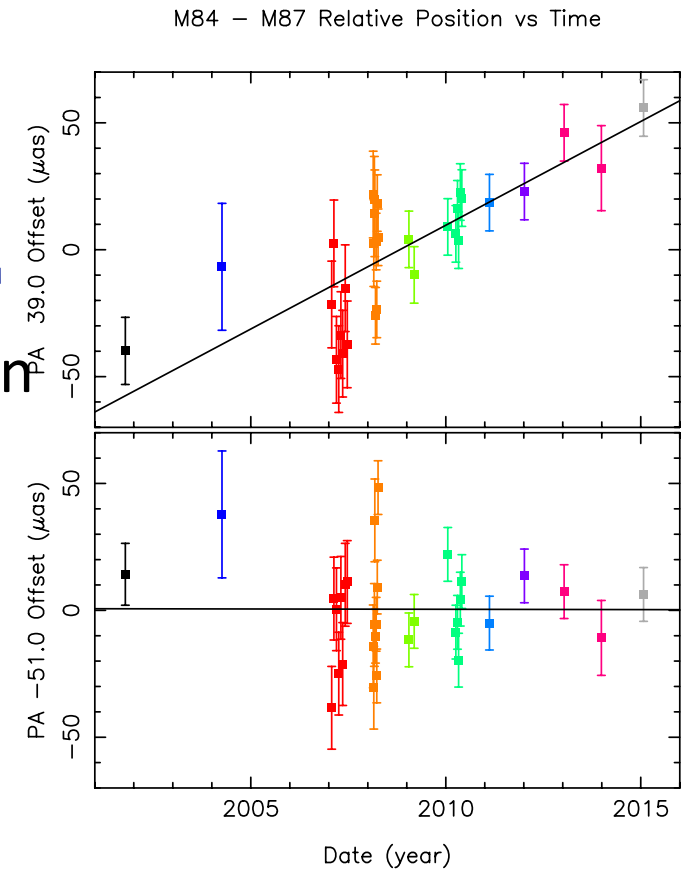
Other Information on M84 motion

- Ehlert et al. MNRAS 2012.
  - XMM_Newton data with others
  - Stripping plume to south – roughly consistent with our data.
- Literature search still needed.



SUMMARY

- Relative proper motion detected between M84 and M87
  - **8.18 ± 0.94 μas/yr**
  - 717 ± 82 km/s at M84
  - Position angle 39°
- Sky separation 1.49° = 0.434Mpc at M87
- Radial distance separation based on surface brightness fluctuation method: 18.5-16.7 = 1.8 Mpc
- Systemic velocities M87: 1284 km/s
  M84: 1017 km/s Diff: 267 km/s (NED)
- Virgo Cluster radial velocity dispersion: 699 km/s.



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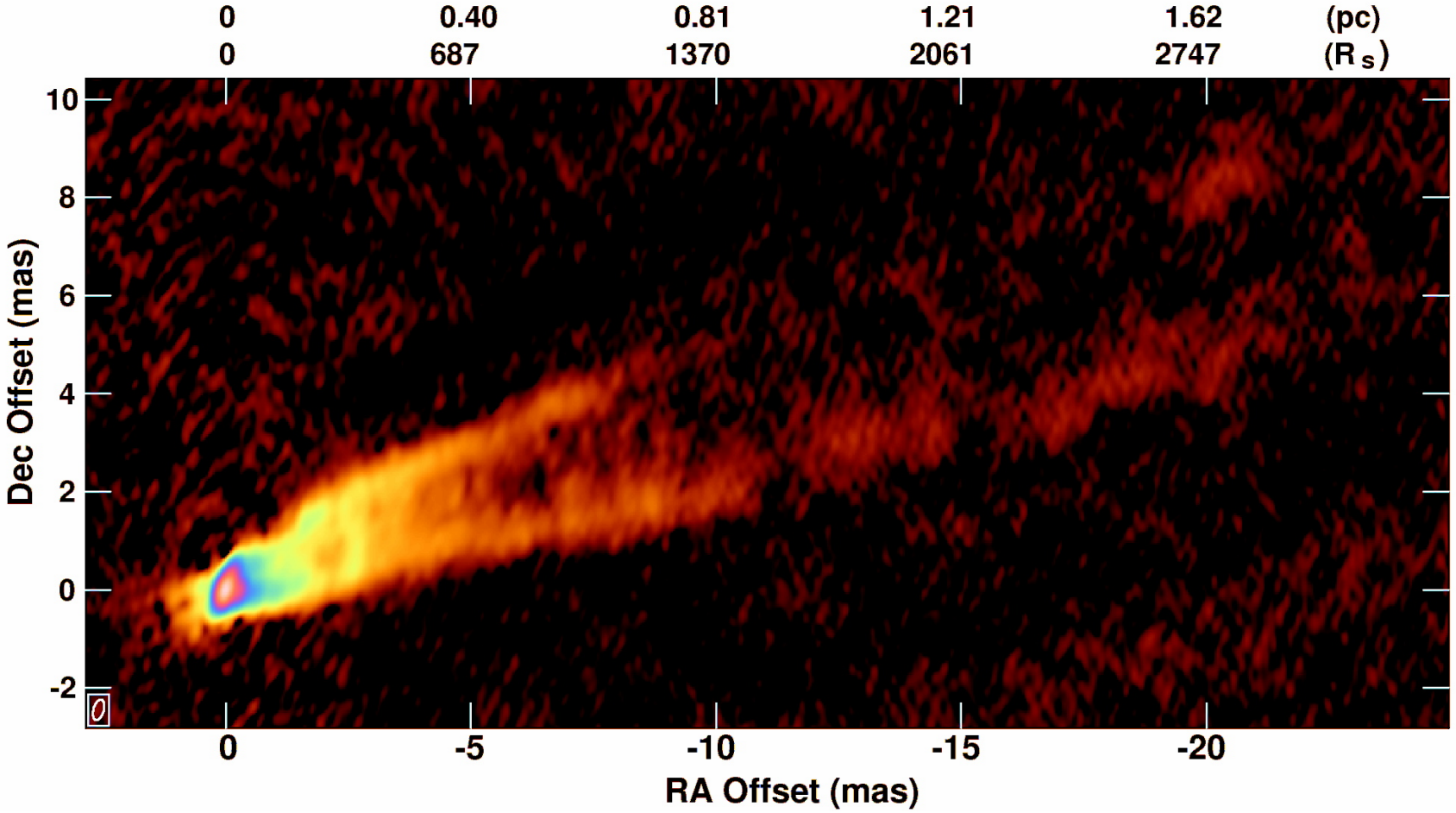
WHY M87?

- THE BEST SOURCE FOR IMAGING A JET BASE
- Large angular size black hole
  - **Nearby**: 16.7 Mpc (Virgo Cluster: Mei 2007; Bird 2010)
    - 1mas = 0.081 pc = 16700 au; 1 c = 3.8 mas/yr
  - **Massive**: 6.2 X 10^9 $M_\odot$ (Gebhardt et all. 2011 scaled for distance)
    - Caution – the mass is controversial
  - Scale: R_s = 7.2 μas = 120 au ($R_s = 2GM/c^2 = 2R_g$)
    - VLBA 43 GHz resolution; 210 X 430 μas ≅ 30 X 60 R_s
- **Bright jet** with complex observable structure
  - 43 GHz Peak ~0.7 Jy – can self-calibrate VLBI data
  - Resolved transversely very near core – uncommon for VLBI jets
  - Easy to observe with northern hemisphere instruments
- Well studied at all wavelengths from radio to TeV
- Other candidates have no jet (SgrA*) or smaller black hole (CenA)

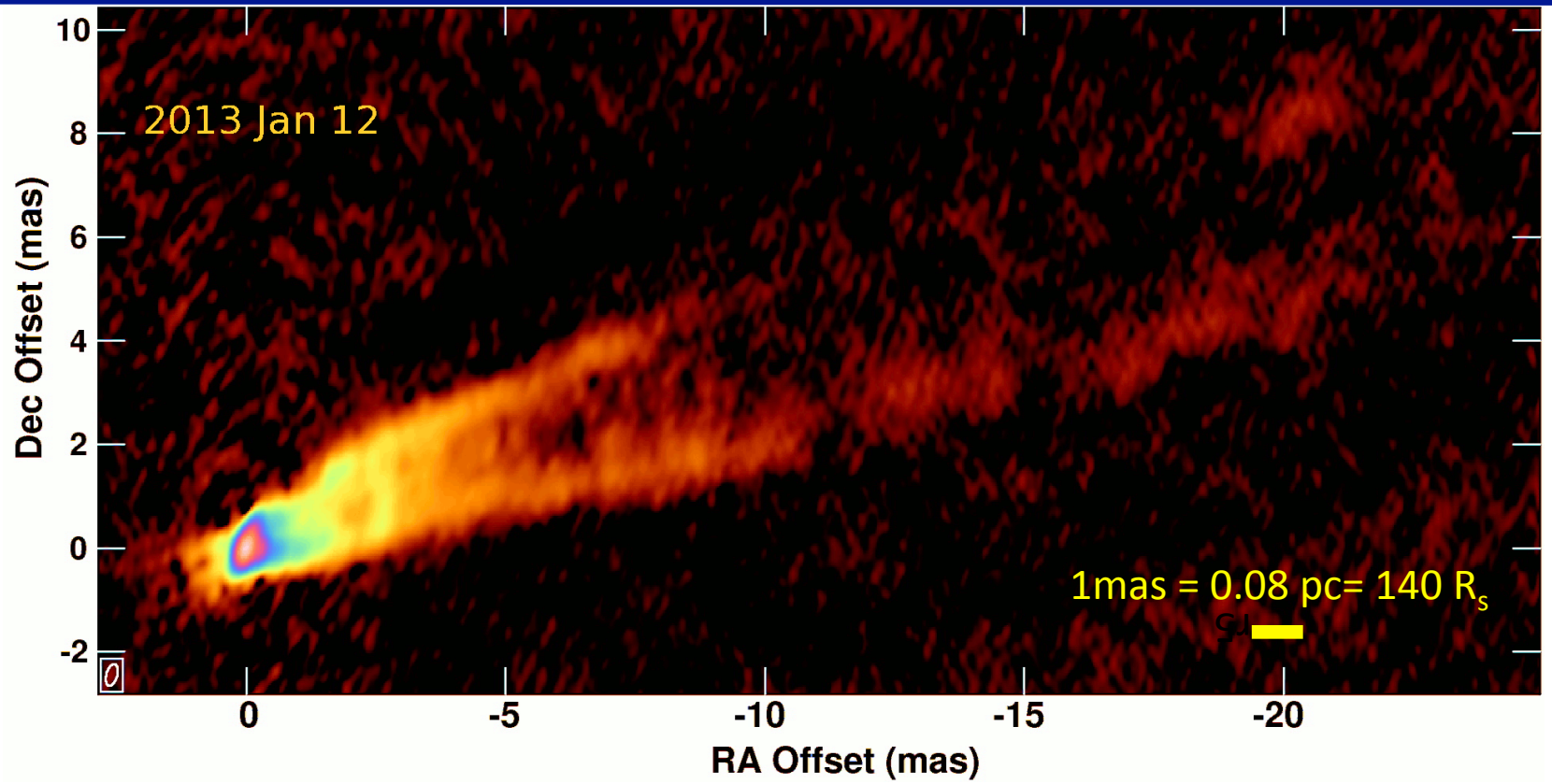
M87 in Jan. 2013



Jan 12, 2013. Upgraded system at 2 Gbps. RMS similar to 23 image average
Single image – no smoothing effect. Note double counterjet and pinch in main jet

KP

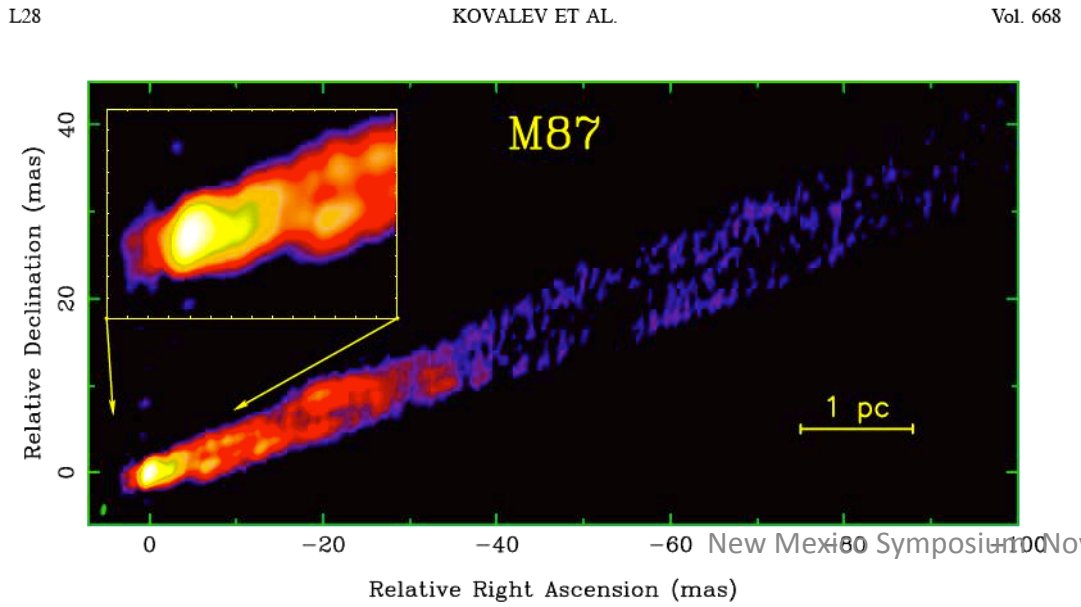
CHANGE IN JET ENVELOPE

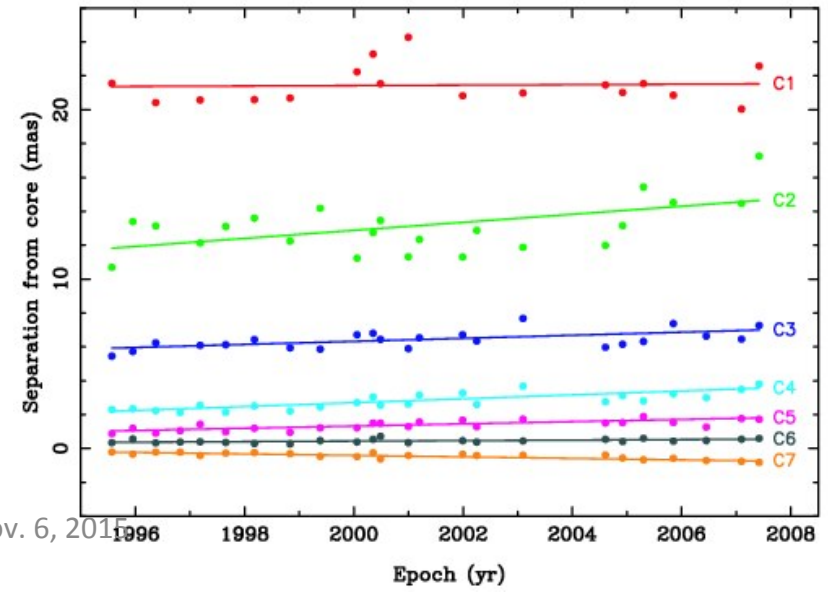


- Blink comparison of 2007/8 average and 2013
- Significant changes in overall jet structure and position
  - Hardee looking at implications for stability
  - We will investigate further with nearly annual observations since 1999

KINEMATICS: VLBI SUBLUMINAL MOTION MEASUREMENTS

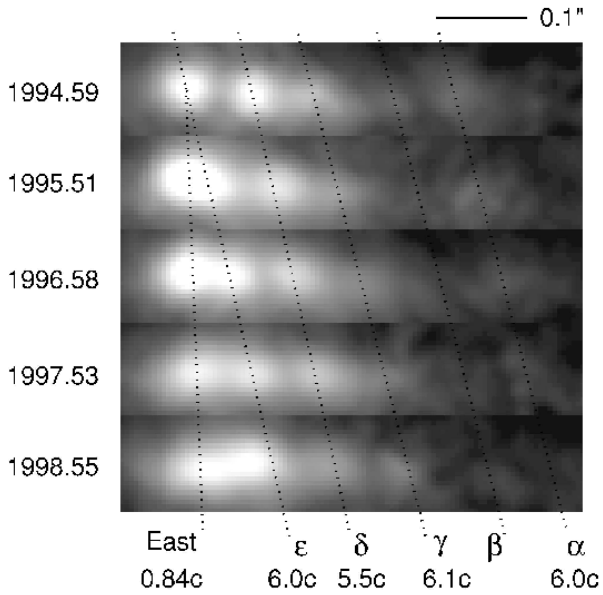
- Many VLBI observations show slow motions
  - VLBA < 0.1c (Biretta & Junor 1995; Junor & Biretta 1995)
  - VSOP No motions (Dodson et al 2006)
  - VLBI 1.6 GHz 0.28c (Reid et al 1989)
  - VLBA 43 GHz 0.25-0.40c (Ly et al 2007)
- Perhaps best case is 15 GHz monitoring (Kovalev et al. 2007)
  - A few percent of the speed of light
  - Sampling interval 5±3 months
- Slow material or is it patterns, perhaps from instabilities?

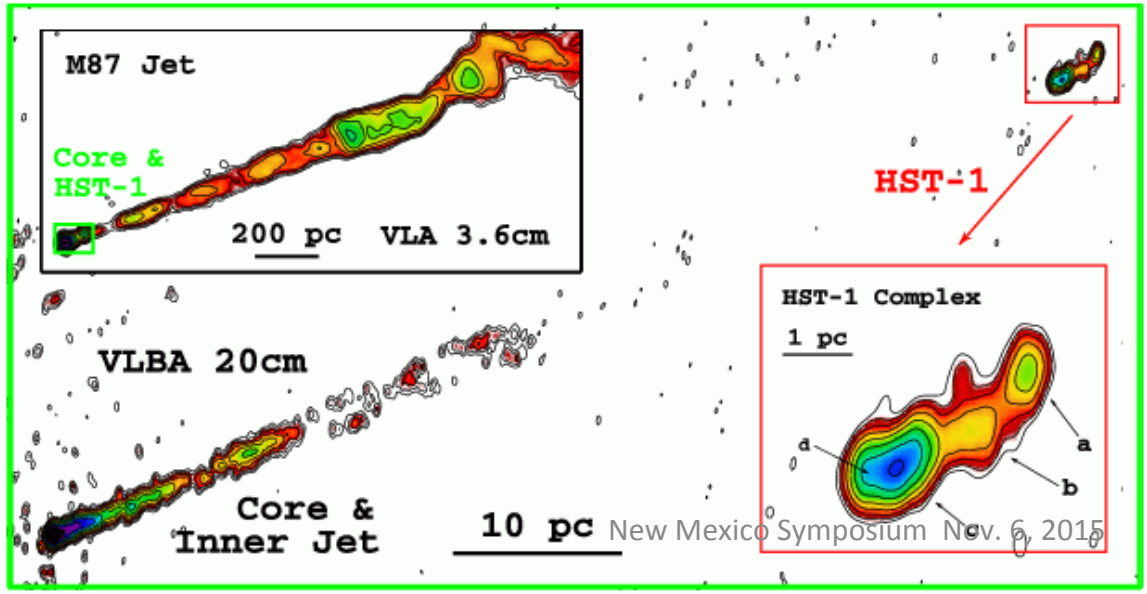


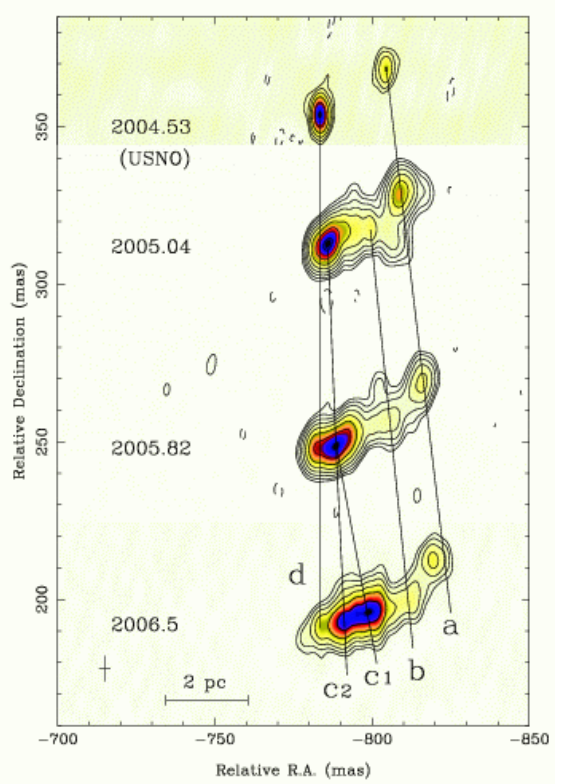


KINEMATICS: SUPERLUMINAL MOTIONS

- VLA Typical 0.5 c, but up to 2.5c (Biretta et al 1995)
- HST-1 Optical with HST (Biretta et al 1999)
  - Knot at 0.9" (70pc projected) Speeds ~5-6 c
- HST-1 VLBA 20cm (Cheung et al 2007; Giroletti et. al. 2012)
  - Downstream component speeds 2.5 - 4.5 c.
  - Feature near core slow
  - HST-1 Plausible site for TEV emission
- EVN Possible acceleration from 160 mas to HST1 (Asada et al)
- HST1 superluminal motions suggest a fast core







TeV FLARES

- Location of TeV emission not known
- TeV and 43 GHz VLBI flares at same time in 2008 - suggests TeV in core
  - Acciari et al. 2009, *Science*, 325, 444.
- But no 43 GHz with 2010 TeV flare
  - Abramowski et al, 2012, Ap. J. 746, 151.
  - Possible activity at HST1
  - Giroletti et al 2012 A&A
  - Weak core flare? Hada et al 2012