A VLBA MOVIE OF THE JET LAUNCH REGION IN M87

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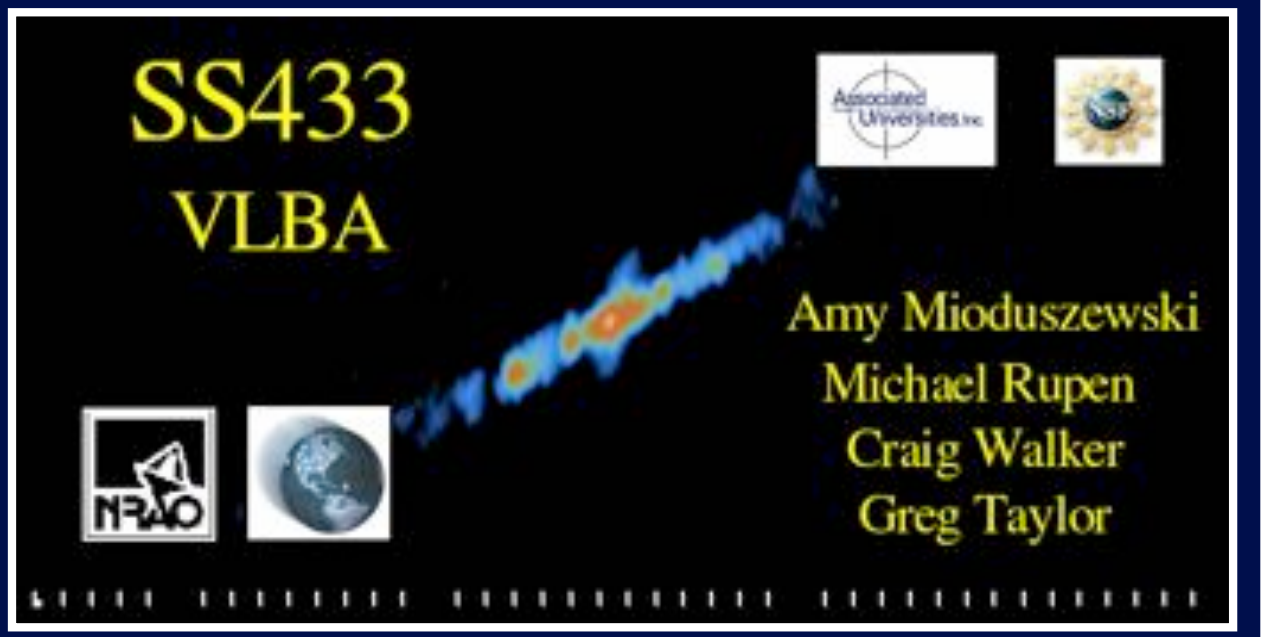
NRL Jan. 29, 2009

OUTLINE

- Introduction
  - Jets
  - The VLBA
  - M87
- The movie observations
- TeV / radio connection
- Astrometric Results
- Future prospects

JETS IN ASTROPHYSICAL OBJECTS

- A ubiquitous product of accretion disks
- Collimated outflows from protostars
- Relativistic jets from black holes in AGN and X-ray binaries



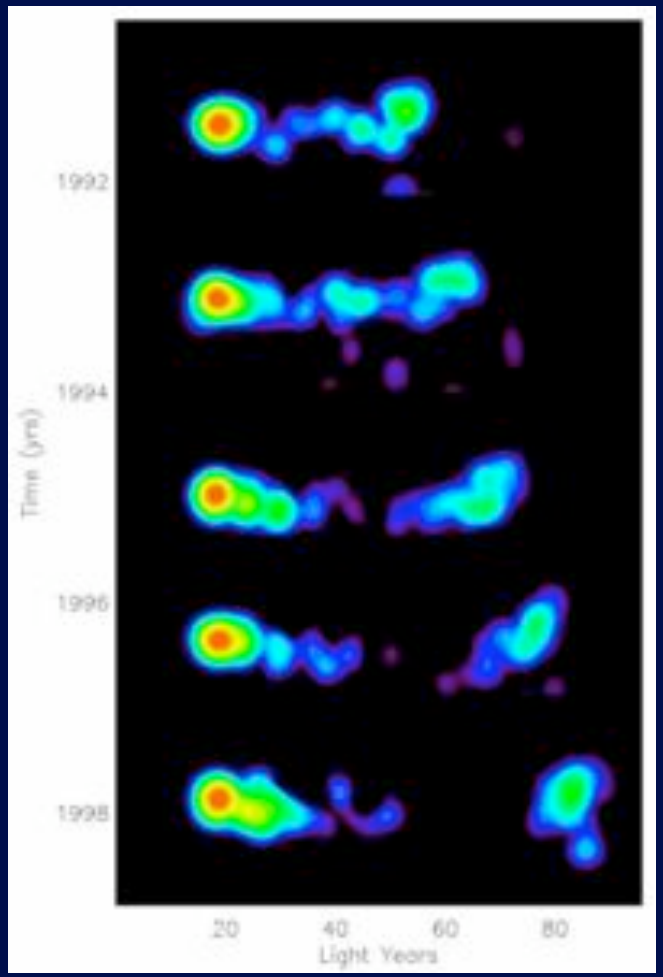
X-ray binary

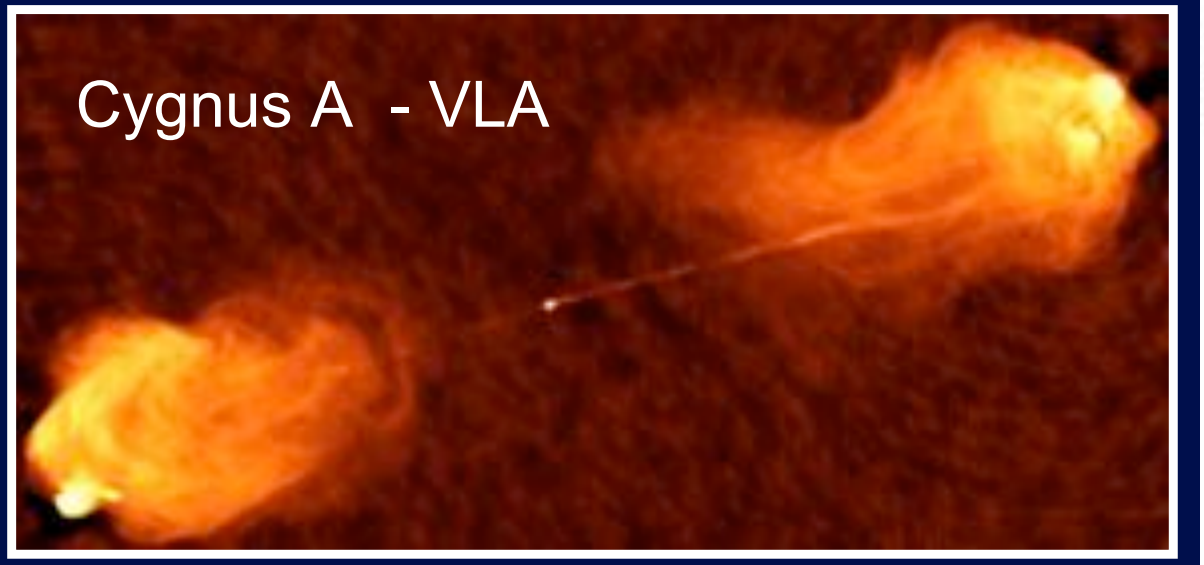
Young star

PROPERTIES OF AGN JETS

- Consequences of relativistic flow
  - Enhanced brightness if end-on from beaming
  - Appear one sided. Far side is de-boosted
  - Superluminal apparent motion possible
- Can influence the galactic and extragalactic environment
  - Feeds energy to the external medium
    - X-ray bubbles
  - Responsible for the BH/bulge mass correlation?

3C279 - VLBI
Superluminal Motion

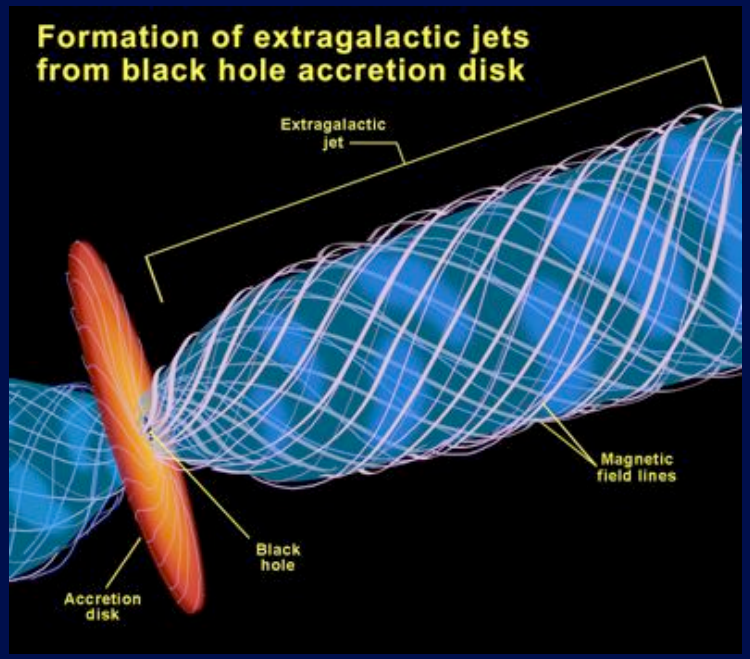




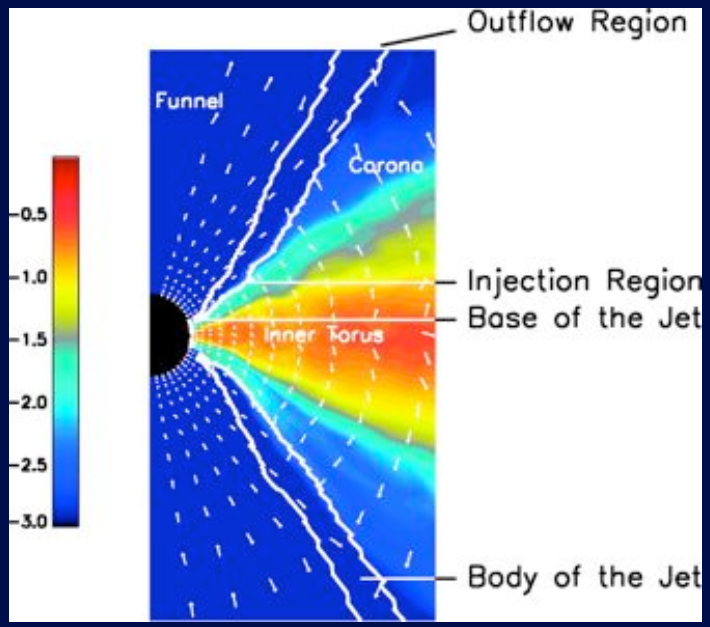
Images from www.nrao.edu

JET FORMATION

- Rapid theoretical progress lately
- Magnetic fields from accretion disk are wrapped up and forced out the poles - a natural consequence of accretion
- Forms a low mass density, high Poynting flux spine of jet
  - Can turn into a mass flow down-stream
- Highest mass flow is along a sheath anchored to disk
- Jets can be stronger from spinning black holes



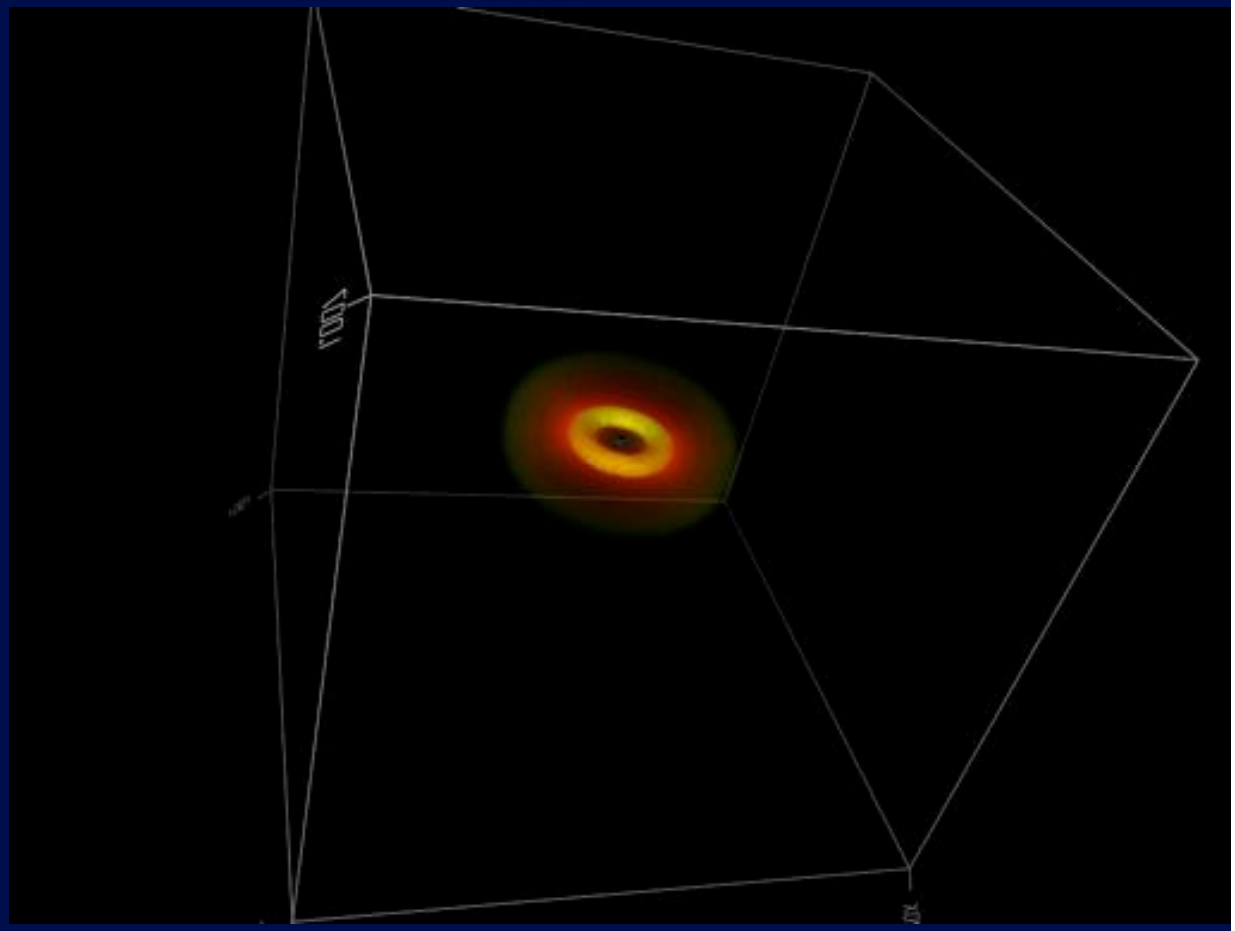
NASA



De Villiers

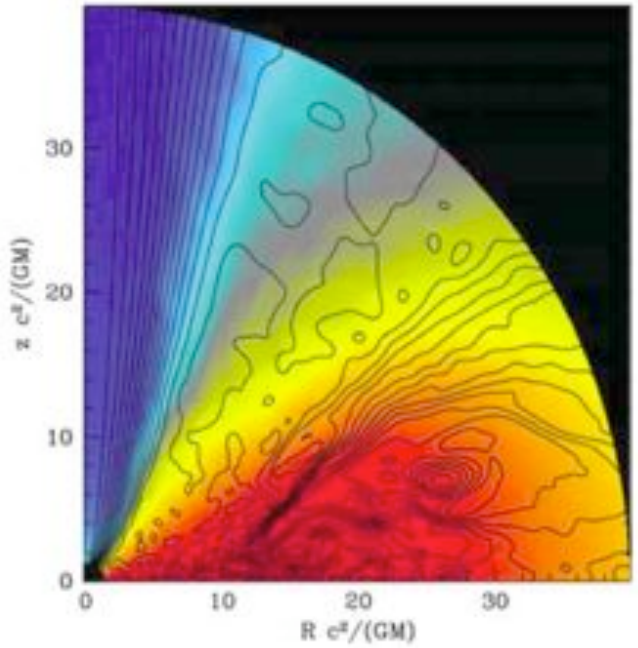
ACCRETING BLACK HOLE SIMULATION

- McKinney and Blandford 2009
- 3D general relativistic magnetohydrodynamic simulation
- Dipole field
- Quadrupolar model does not give stable jet



PROSPECTS FOR COMPARISON OF THEORY AND OBSERVATION

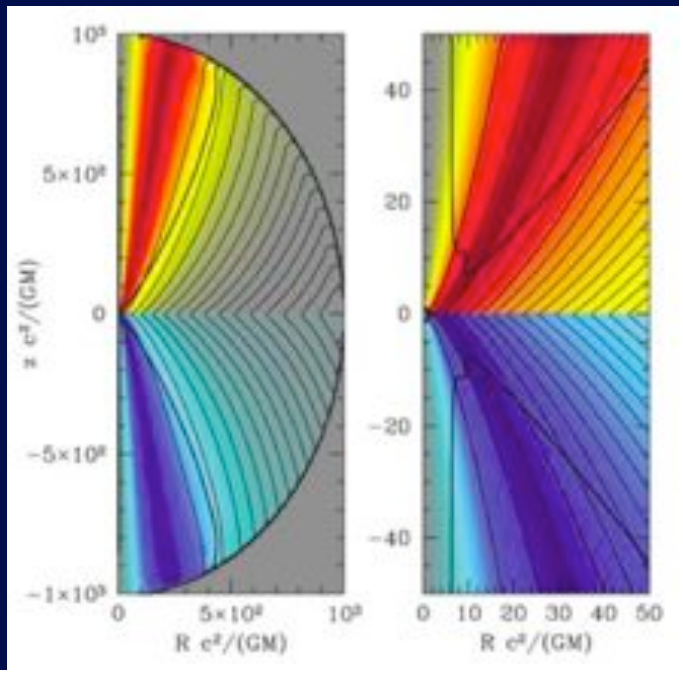
- Simulations reaching observable scales
  - Our goal is to provide a data set that constrains the theory
  - Need the best possible resolution in gravitational units
  - Effects of the launch region seen in the 10-1000 Rs region
  - VLBI just able to reach into that regime



← Max scale →

40 $c^2/(GM)$ 10^3

McKinney & Narayan 2007

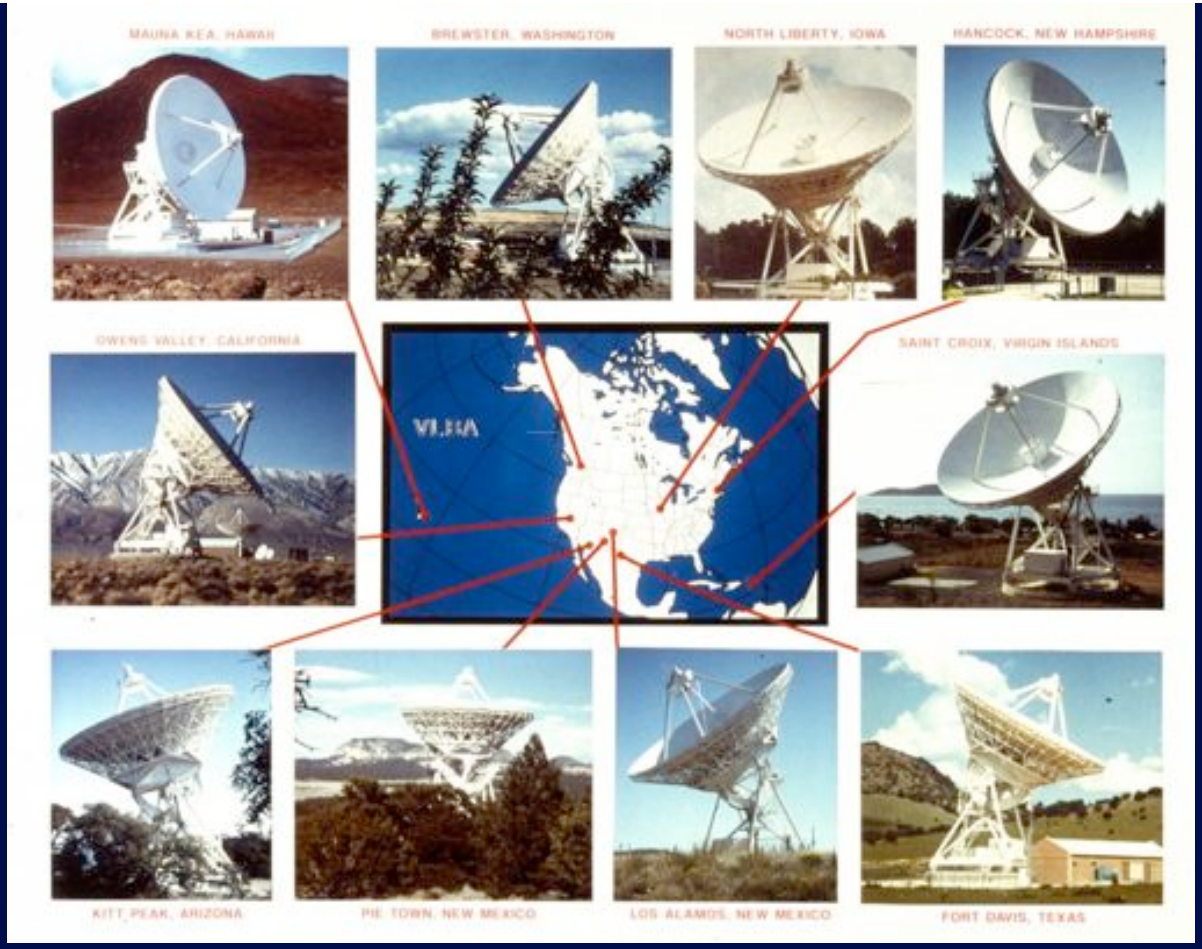


The VLBA

Ten 25m Antennas
20 Station Correlator
327 MHz - 86 GHz
Resolution 0.0002
arcsec at 43 GHz

National Radio
Astronomy Observatory

A Facility of the
National Science
Foundation

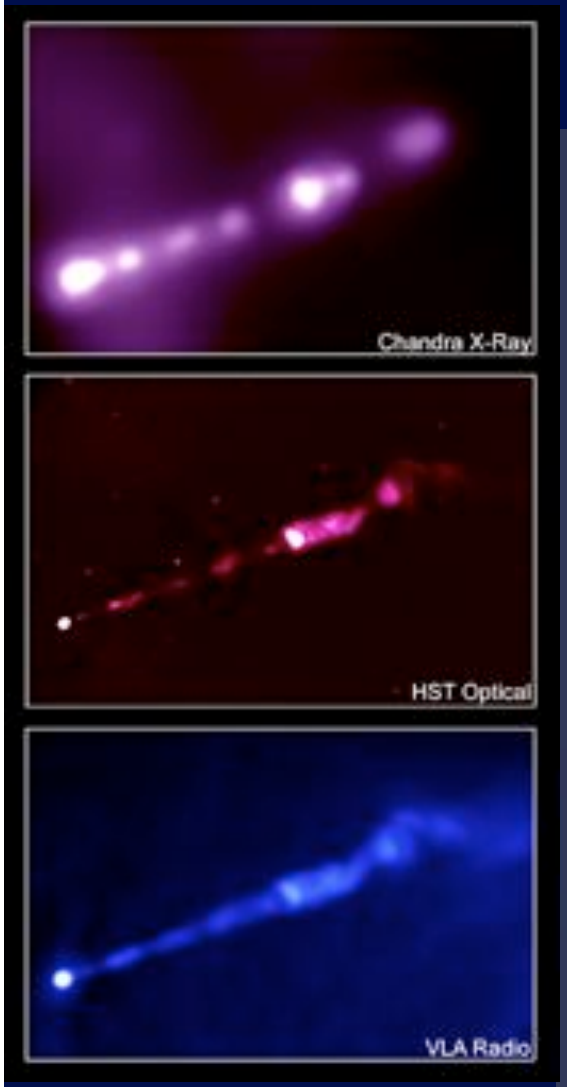


M87 - THE BEST SOURCE FOR IMAGING A JET BASE

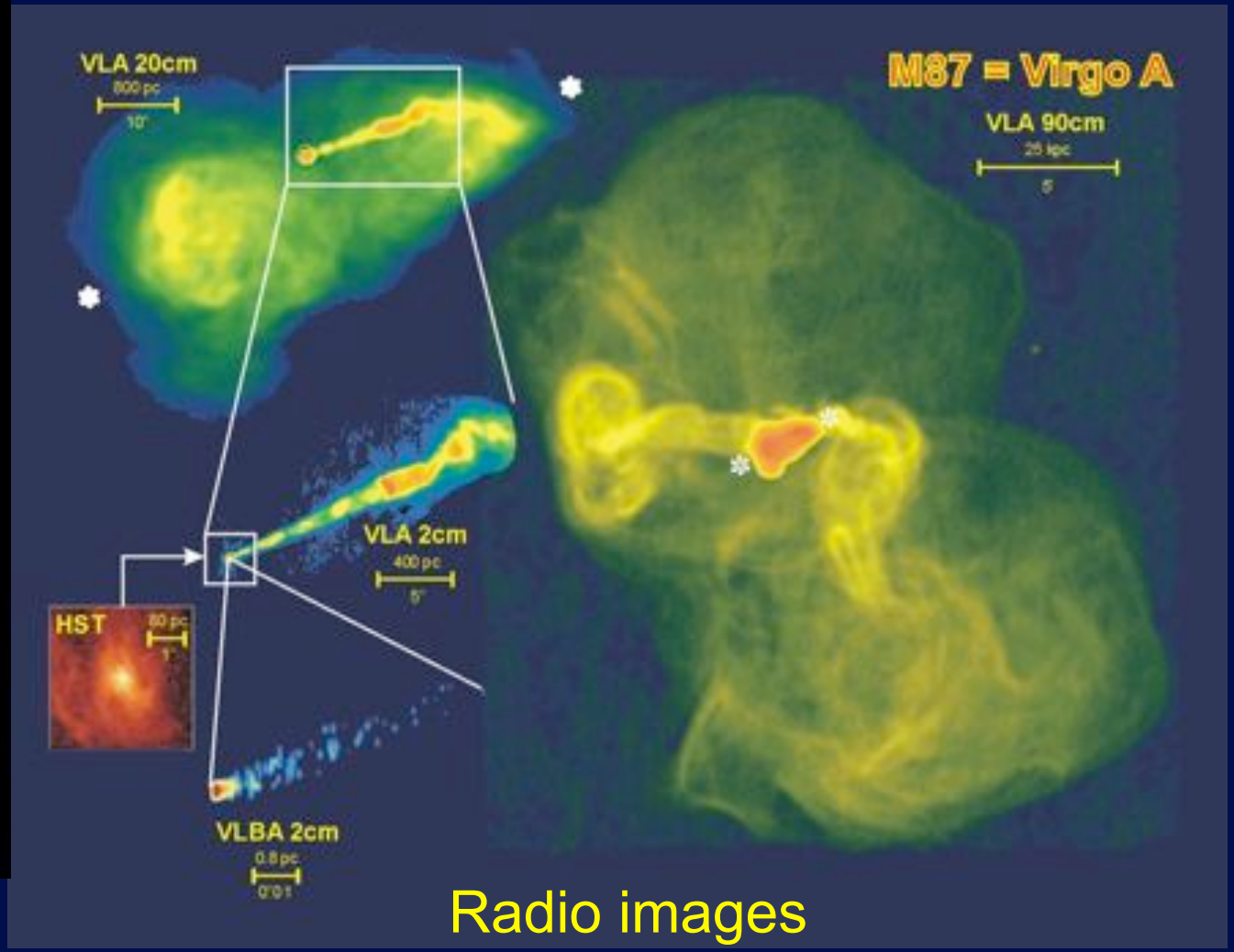
- Large angular size black hole
  - Large black hole mass: ~3X10^9 M_{sun}
  - Nearby: 16 Mpc (A central galaxy of the Virgo Cluster)
  - VLBA resolution is about 60 Schwarzschild radii at 43 GHz
  - Scale 1 mas ~ 0.078pc = 300 Rs. 1 c = 4 mas/yr
- Jet is bright enough to see significant structure
  - Core has about 0.7 Jy at 43 GHz - can self-calibrate
  - Jet well resolved transversely very near core
  - Can be seen by northern hemisphere instruments
  - Sgr A* black hole 2X higher angular size but has no jet
- Well studied at all wavelengths from radio to TEV

M87 STRUCTURE OVERVIEW

1 kpc scale



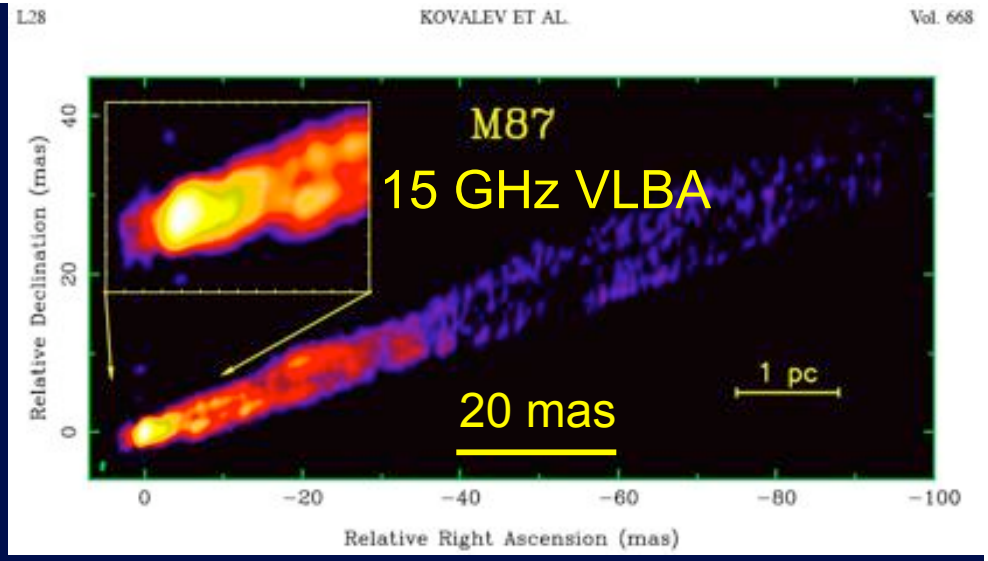
Chandra



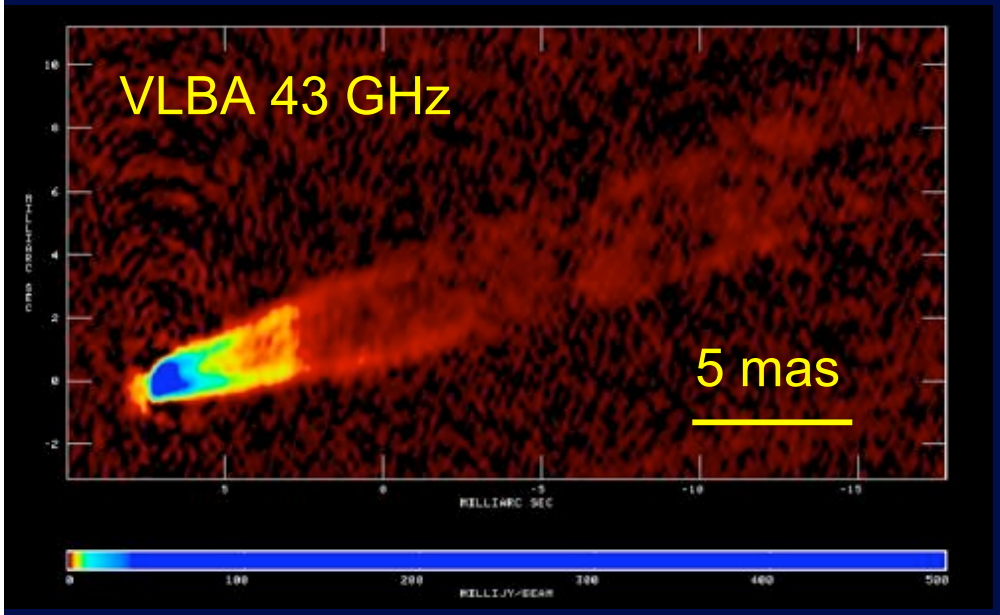
Radio images

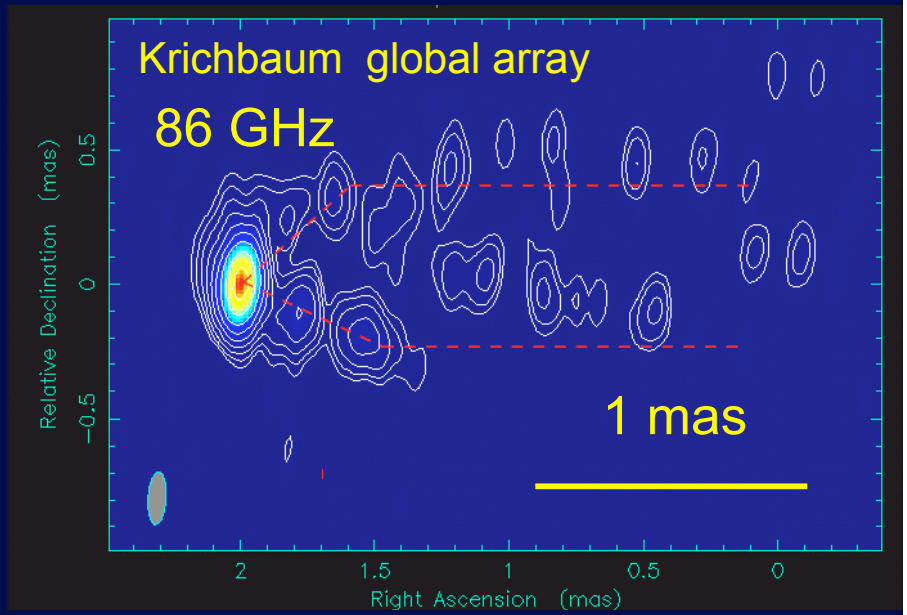
HIGH RESOLUTION STRUCTURE

- 15, 43, and 86 GHz images
- Edge brightened
- Wide opening angle base
- Counter feature



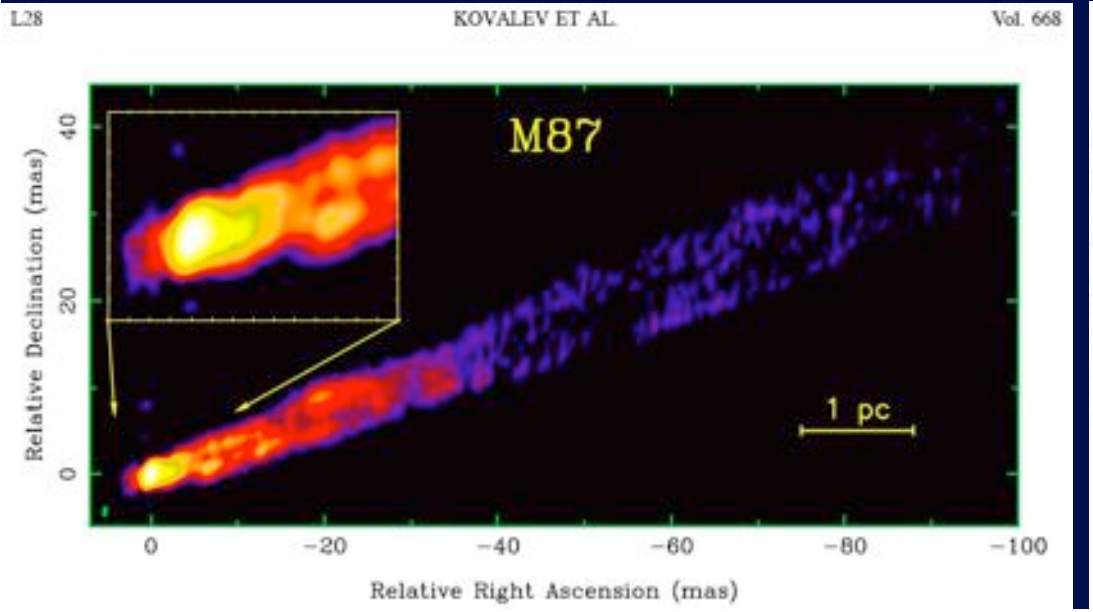
1 mas = 0.08 pc = 300 Rs

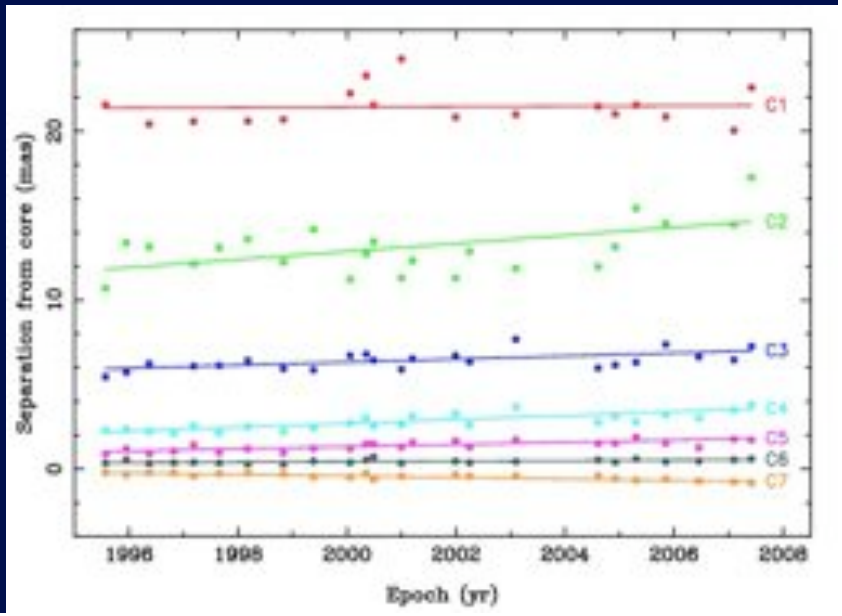




VLBI SUBLUMINAL MOTION MEASUREMENTS

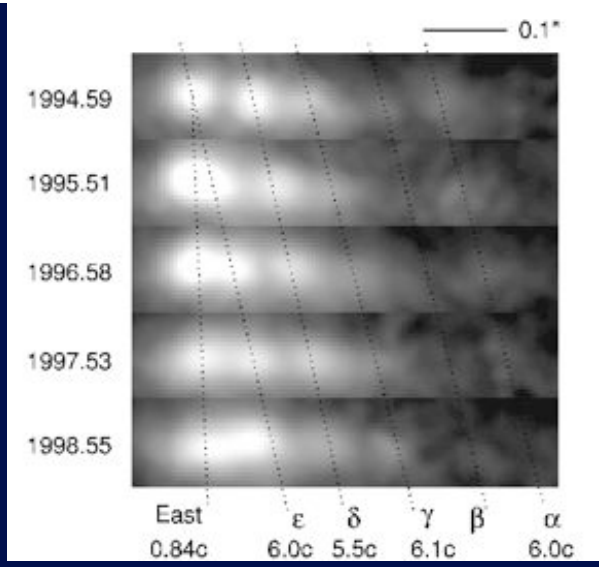
- Many VLBI observations show slow motions
  - VLBA < 0.1c (Biretta & Junor 1995; Junor & Biretta 1995)
  - VSOP No motions (Dodson et al 2006)
  - VLBI 1.6 GHz 0.28c (Reid et al 1989)
  - VLBA 43 GHz 0.25-0.40c (Ly et al 2007)
- Perhaps best case is 15 GHz monitoring (Kovalev et al. 2007)
  - A few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

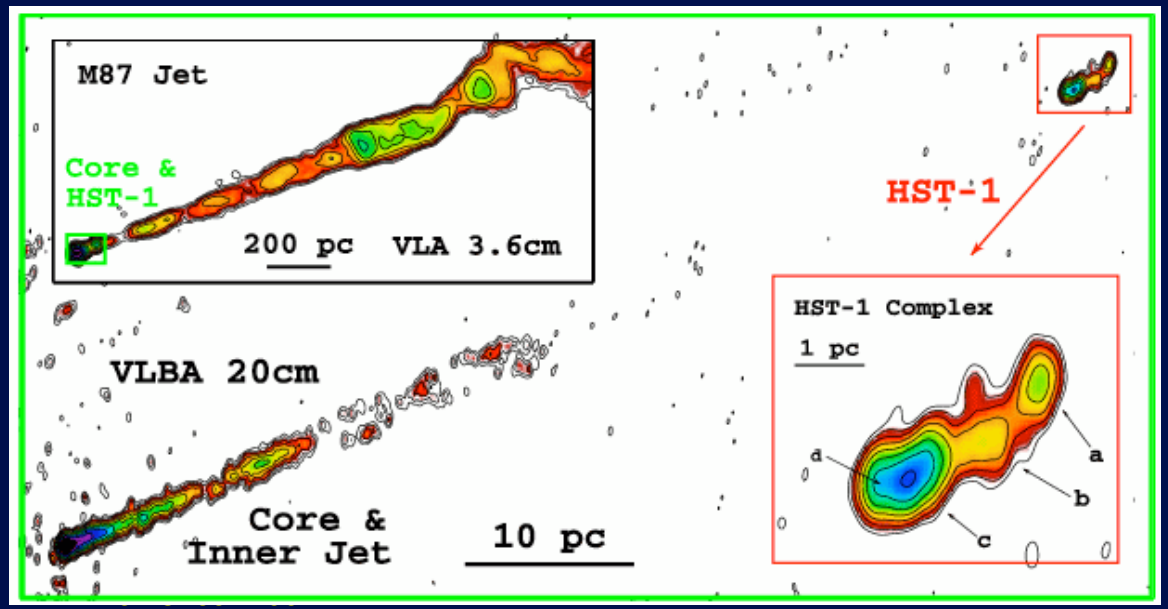


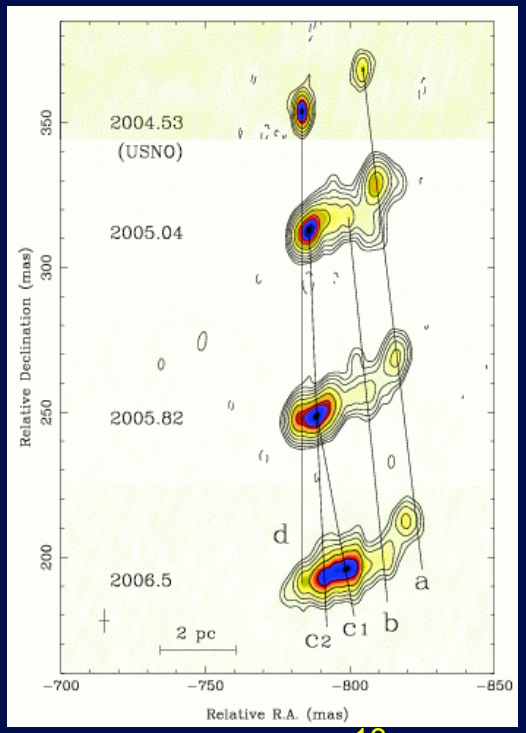


SUPERLUMINAL MOTIONS

- 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)
  - Speeds 2.5 - 4.5 c.
  - Feature near core slow
  - HST-1 Plausible site for TEV emission



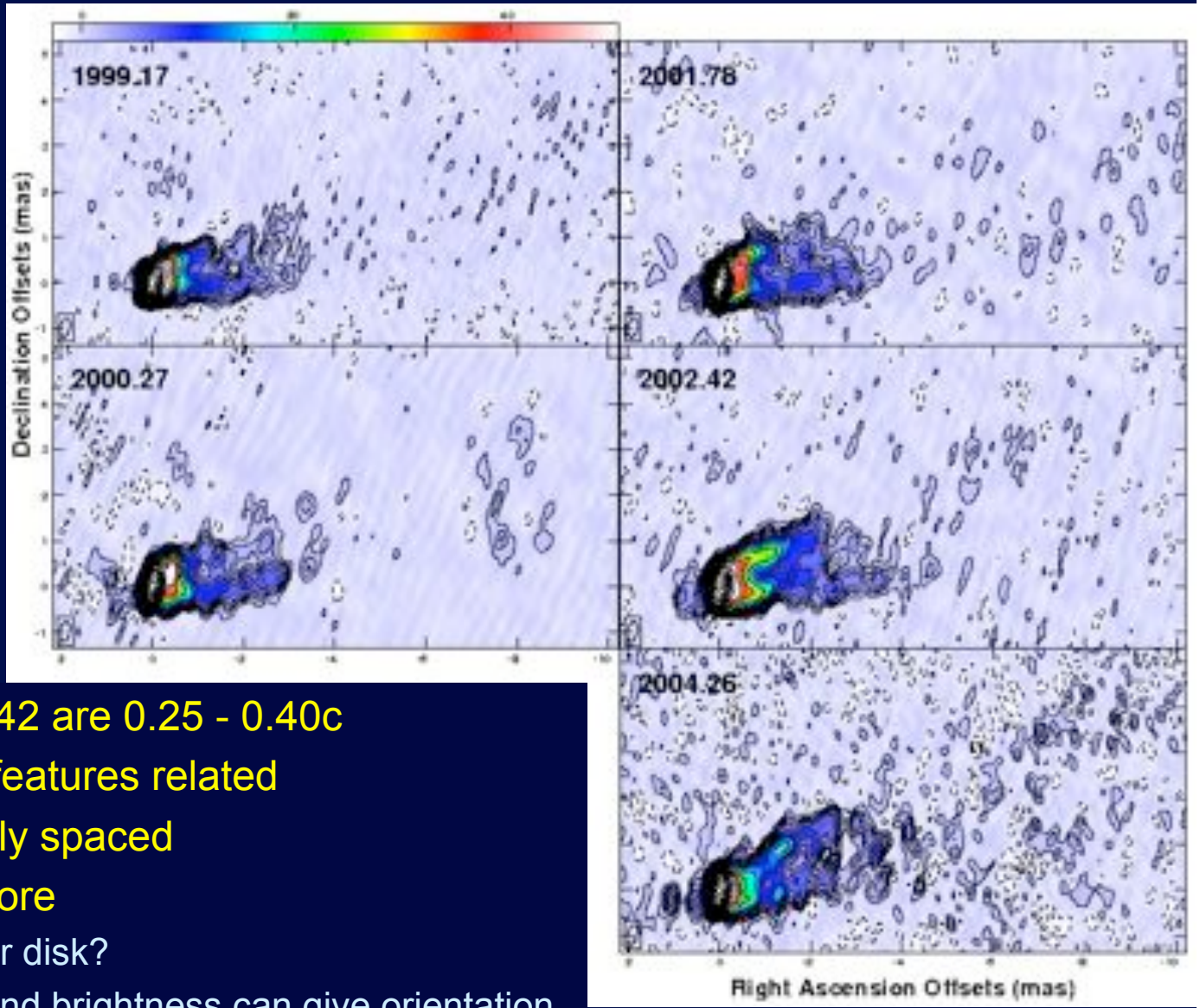




M87 43 GHZ IMAGES AT ~1 YR INTERVALS

Our old observations and archive data. Mostly from use of M87 as phase reference source.
(Ly, Walker, & Junor, 2007, Ap. J. 660, 200.)

- Basic edge brightened structure maintained
- Dominant edge shifts from south to north



- Rates 2001.78 - 2002.42 are 0.25 - 0.40c
  - 1.0 to 1.7 mas/yr if features related
- Other epochs too widely spaced
- Feature seen east of core
  - Counterjet, inner jet, or disk?
  - If counterjet, speeds and brightness can give orientation

ARE THE VLBI OBSERVATIONS UNDERSAMPLED?

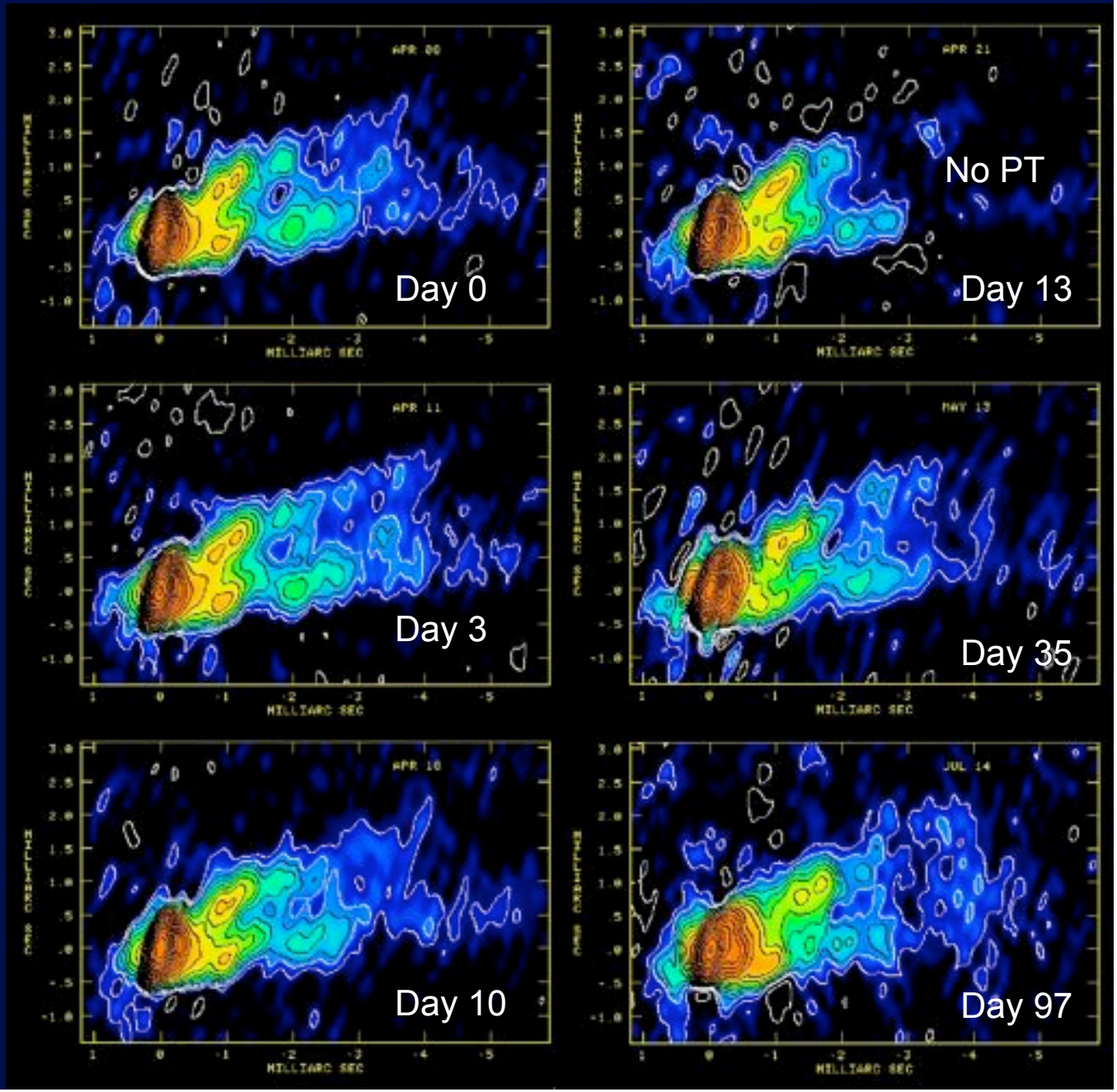
- Previous VLBI observations had sampling intervals of months to years
- Is this too slow?
  - 43 GHz beam is 0.2 mas
  - 1 c is 4 mas/yr or 1 beamwidth in 18 days
  - 6 c is 24 mas/yr or 1 beamwidth in 3 days
  - Observations every few months too slow
  - But clearly some features are slow - patterns?
- VLBA 43 GHz movie project - fast sampling at high resolution

PILOT PROJECT

- To determine movie frame rate:
  - –VLBA 43 GHz 2006
  - –10hr observations, 128 Mbps, full polarization
- Good consistency between close epochs
- Motions near 2.2 mas/yr (0.6c) at 1.5 mas from core
- About 1.5 mas/yr near core
- Superluminal motions not seen
- Feature east of core still seen

Beam: 0.42x0.18 mas
0.2mas = 0.016pc = 60R_s
1mas/yr = 0.25c

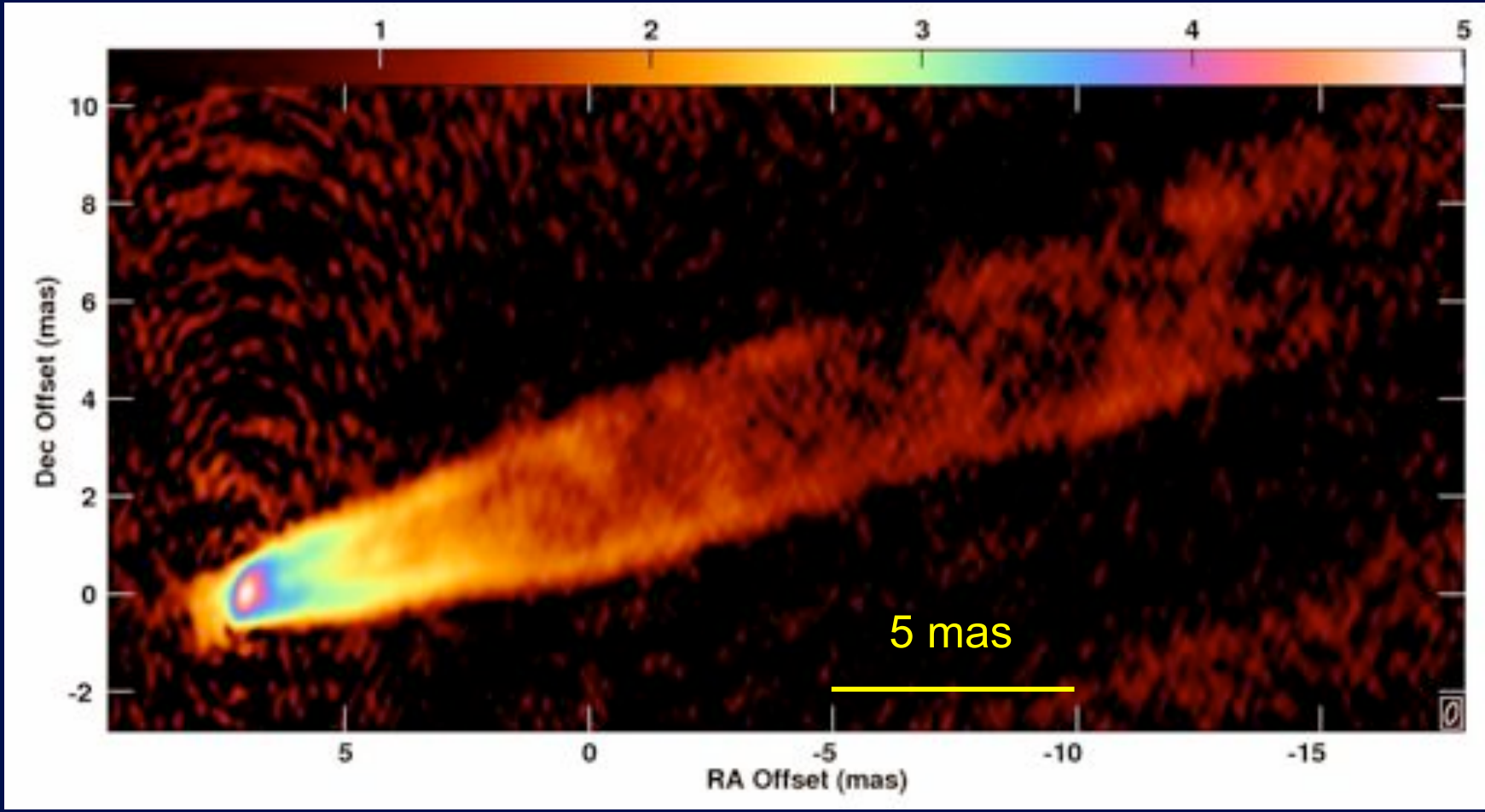
Walker Jan. 09



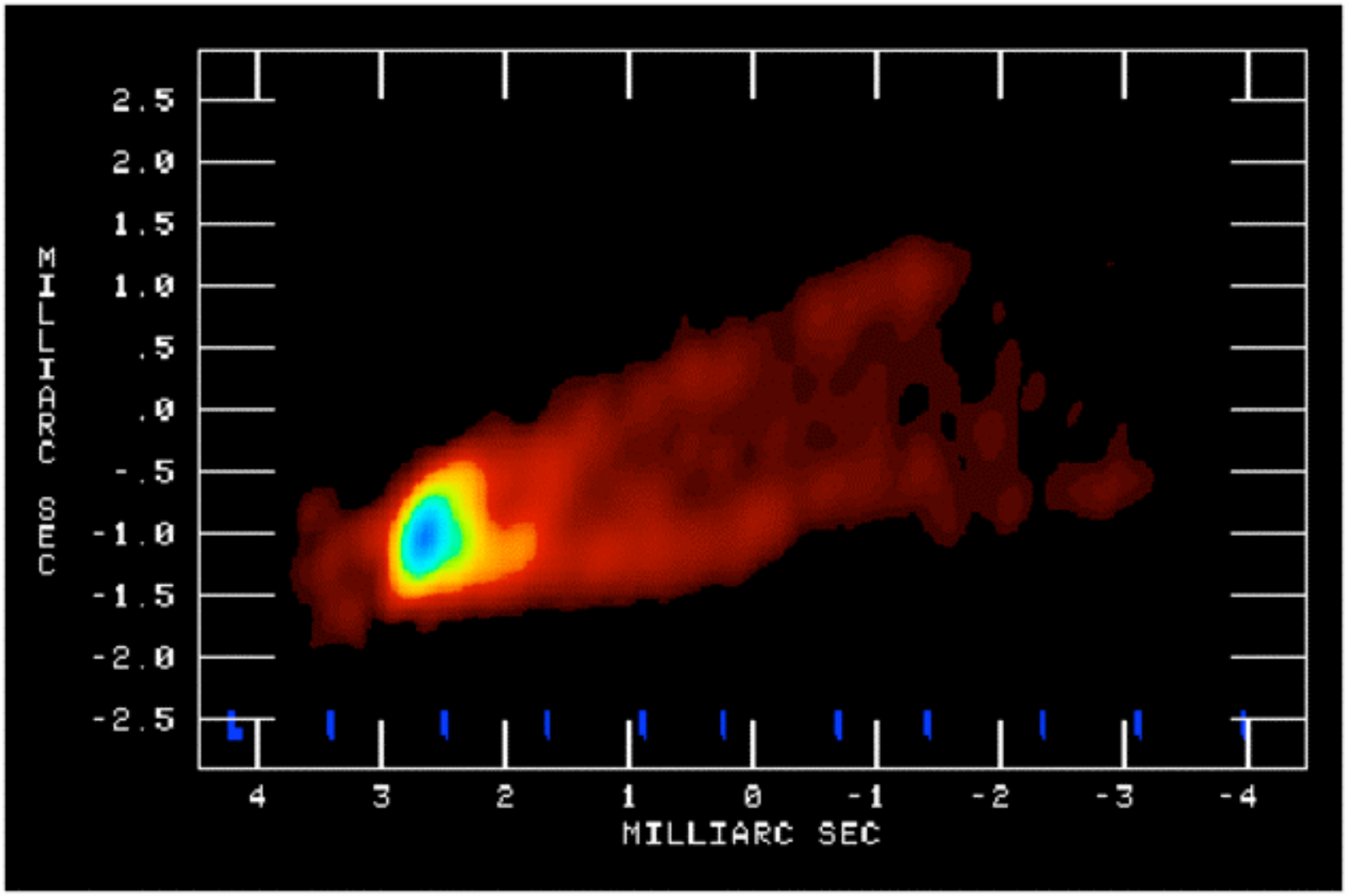
THE VLBA 43 GHz M87 MOVIE

- Observed 18 frames at 3 week intervals
  - Interval based on Pilot Project results
  - Dynamic scheduling within windows of ±5 days
  - Observations from Jan. 27, 2007 to Jan. 21, 2008
- Fast sampling project - 5 day intervals
  - Three week intervals under sampled the motions
  - Jan. 26 to April 5, 2008 (14 frames)
- Observational parameters
  - 10 hr at 256 Mbps (Twice the bandwidth of pilot)
  - Full stokes
  - Primary calibrators 3C279 and OJ287
  - Five bursts of 4 phase referencing scans to M84

THE VLBA 43 GHz M87 MOVIE
23 OBSERVATIONS STACKED



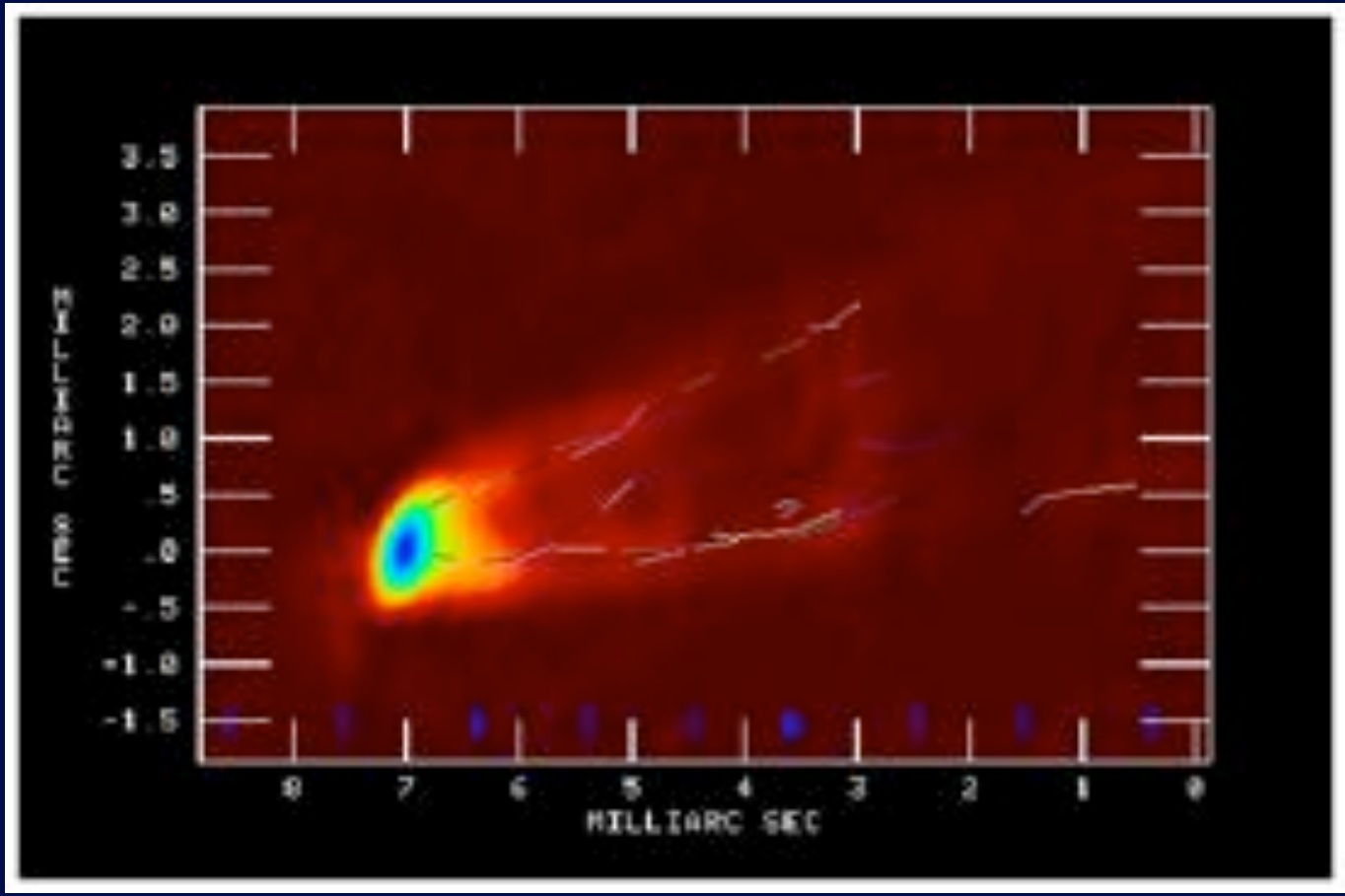
Beam: 0.43x0.21 mas 0.2mas = 0.016pc = $60R_s$ 1mas/yr = 0.25c



Beam: 0.43x0.21 mas 0.2mas = 0.016pc = $60R_s$ 1mas/yr = 0.25c

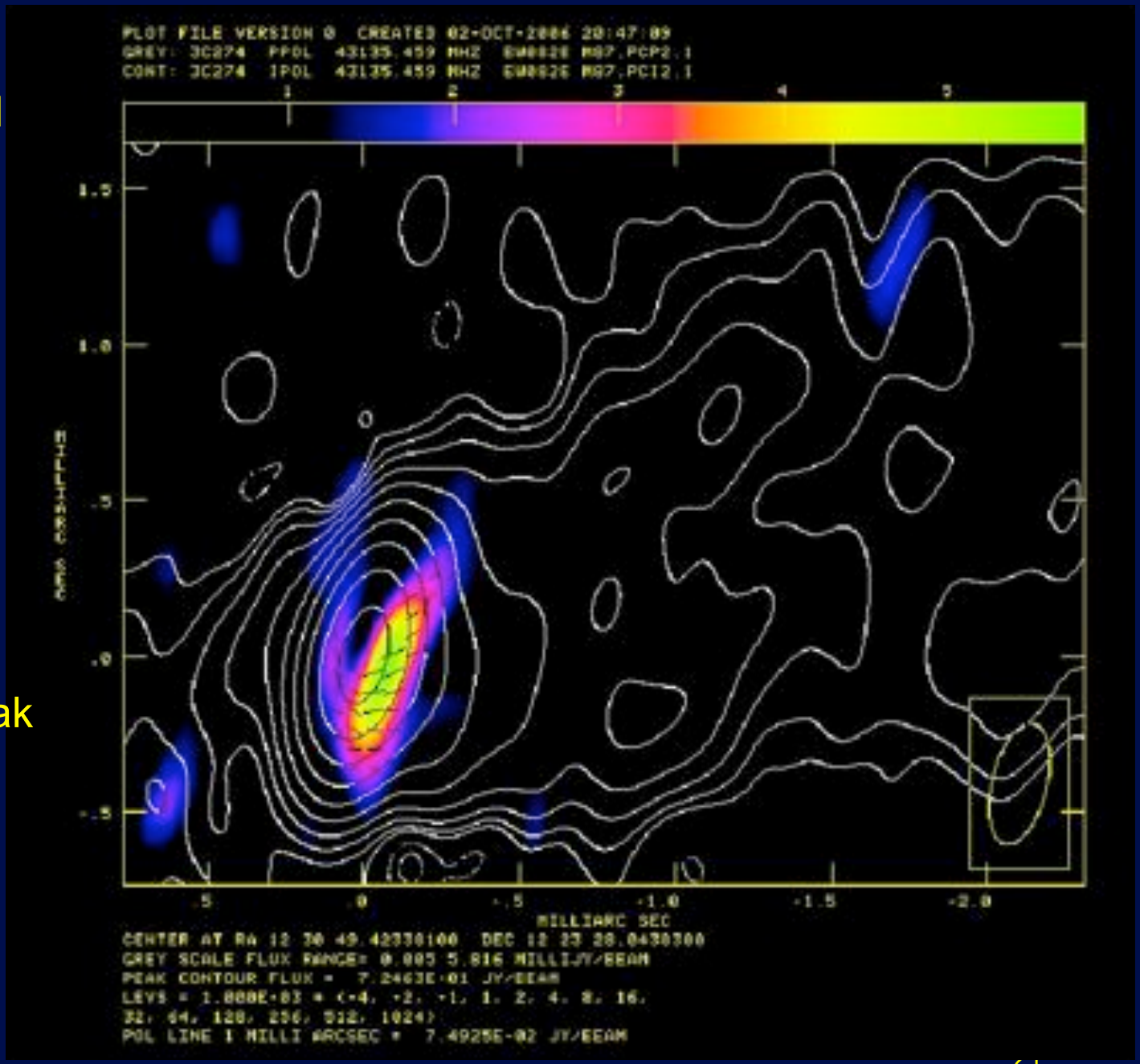
VELOCITY FIELD

- Lines connect related features in adjacent epochs.
- Most lines about 0.5 mas long. Intervals about 3 weeks.
- Speed: 2c



POLARIZATION STRUCTURE

- 0.8% on peak
- Polarized peak offset from total intensity
- Position angle rotates
- Polarization not detected off peak

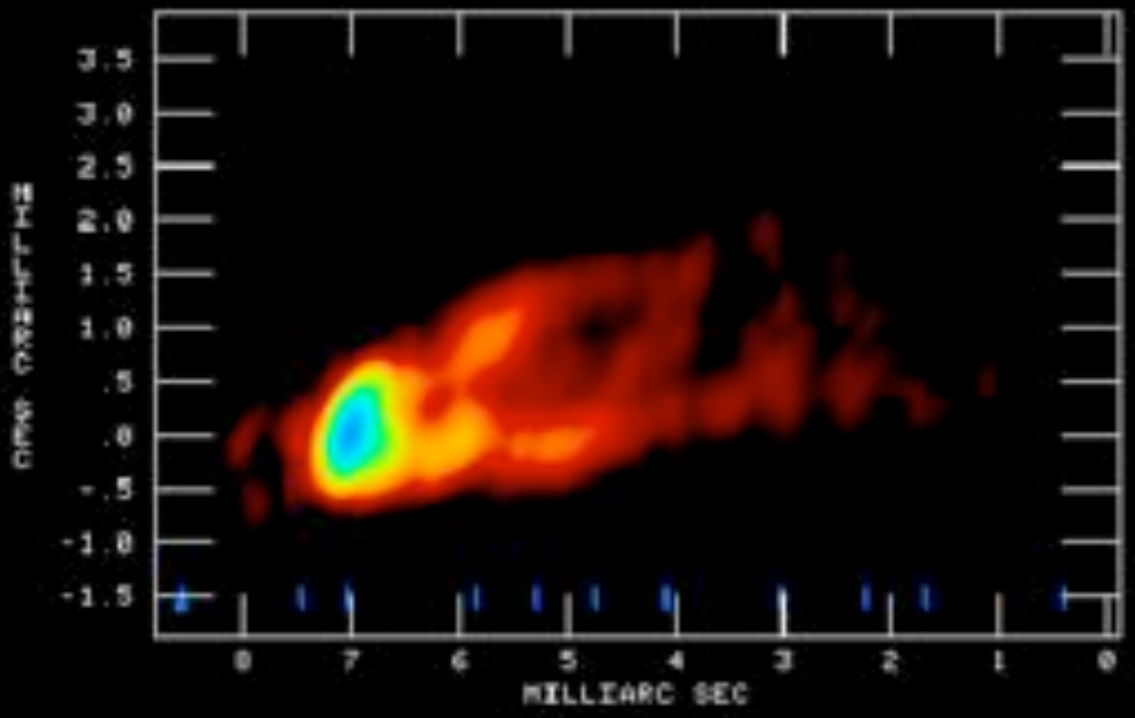


PRELIMINARY RESULTS

- Superluminal speeds
  - Visible portion is relativistic. Not a slow sheath
    - But could be slower than unseen jet center
  - Hints of a spine seen
- Fast changing structure
  - Not clear “components”
  - Reminiscent of a smoke plume
    - Could be a disturbed sheath
- The counter feature
  - Always there --- Real
  - Nature of dynamics not yet clear at all
  - Inner jet, counter jet, something else --- not clear
- Still much data reduction to do.

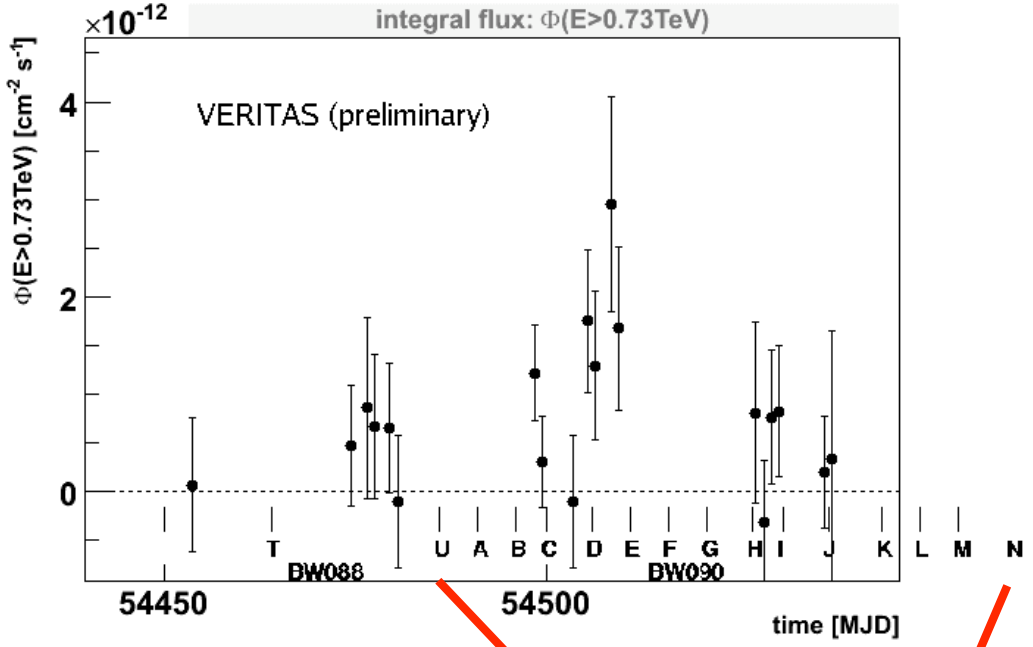
PRELIMINARY FAST SAMPLING MOVIE

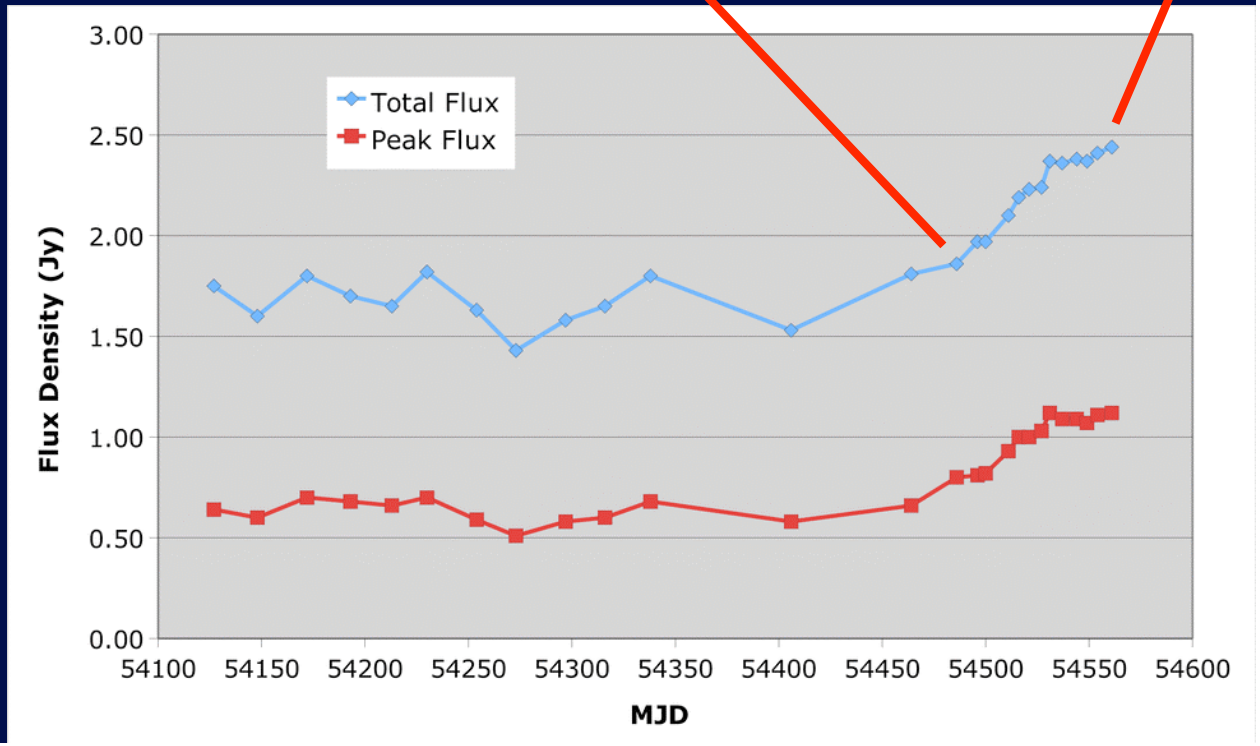
- 11 Epochs. Some relatively poor images omitted
- Sampled at 5 day intervals Jan. - Apr. 2008
- Some of the images need improvement

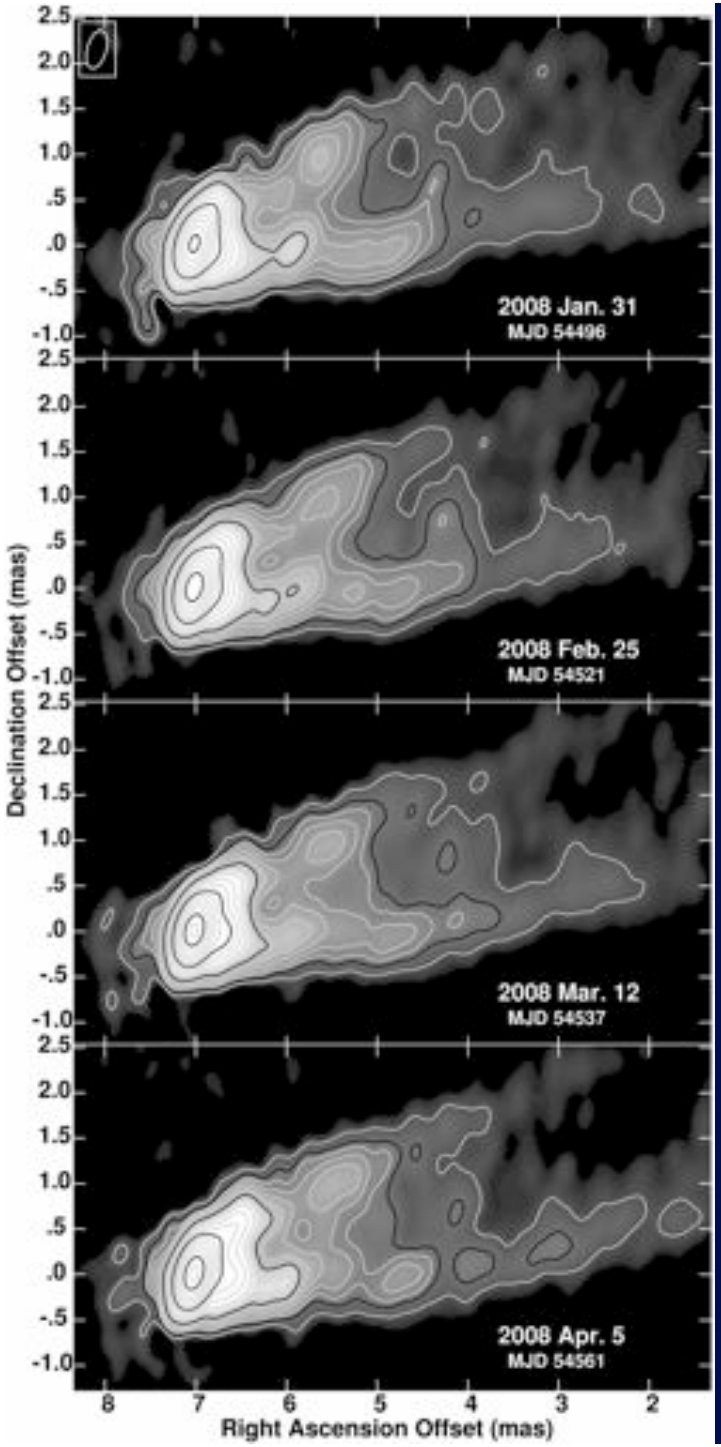


TeV FLARE

- Observed by VERITAS, MAGIC and H.E.S.S
- During the Fast Sampling project
- Plots are total and peak flux densities in the M87 images
- Locates TeV emission site in core --- previously not clear

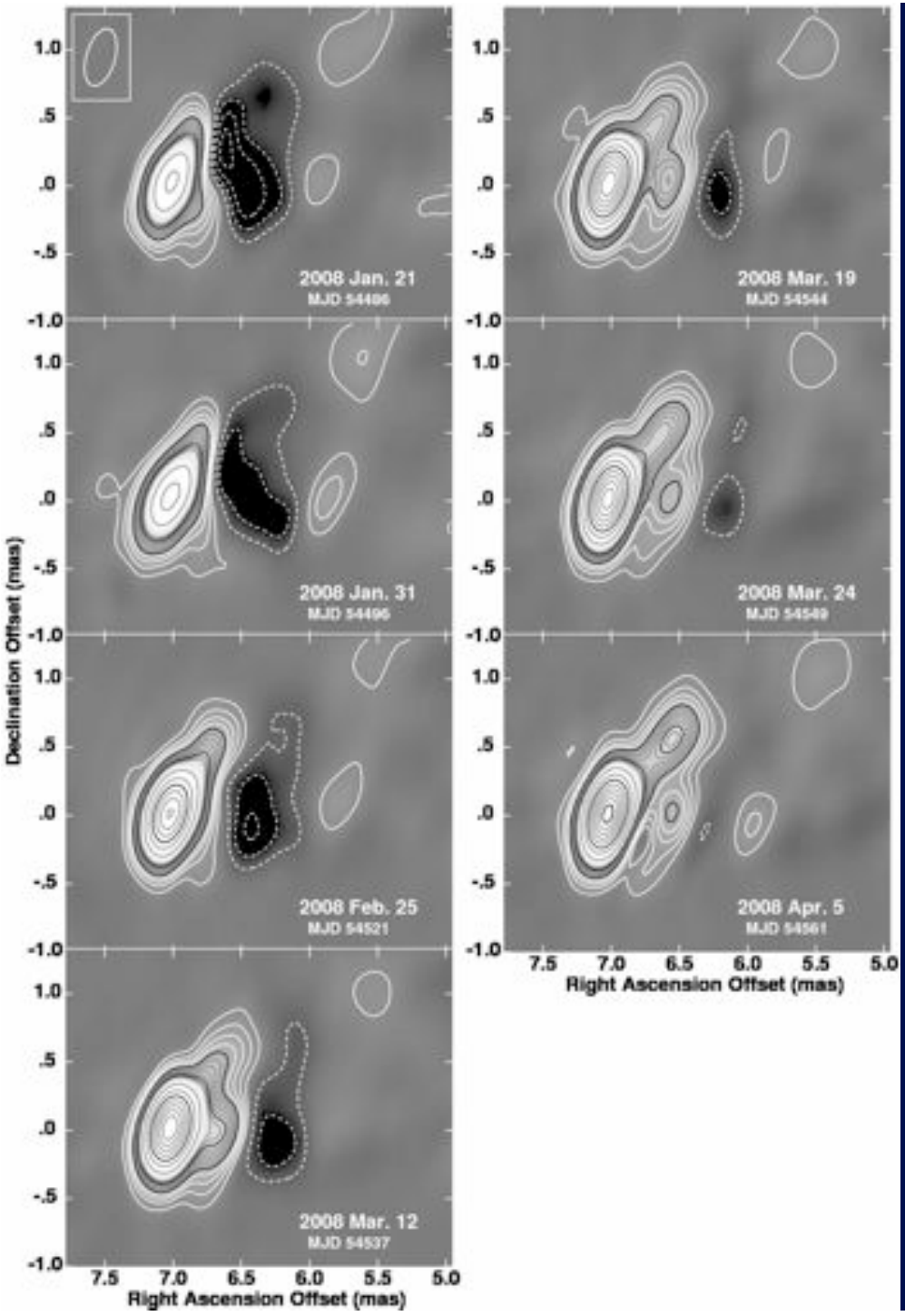






Radio Flare Structure

- Selected images during the flare.
  - Logarithmic contours
- Core brightens
- Inner features brighten
- Implies initial activity is in the unresolved core
  - <60 Rs

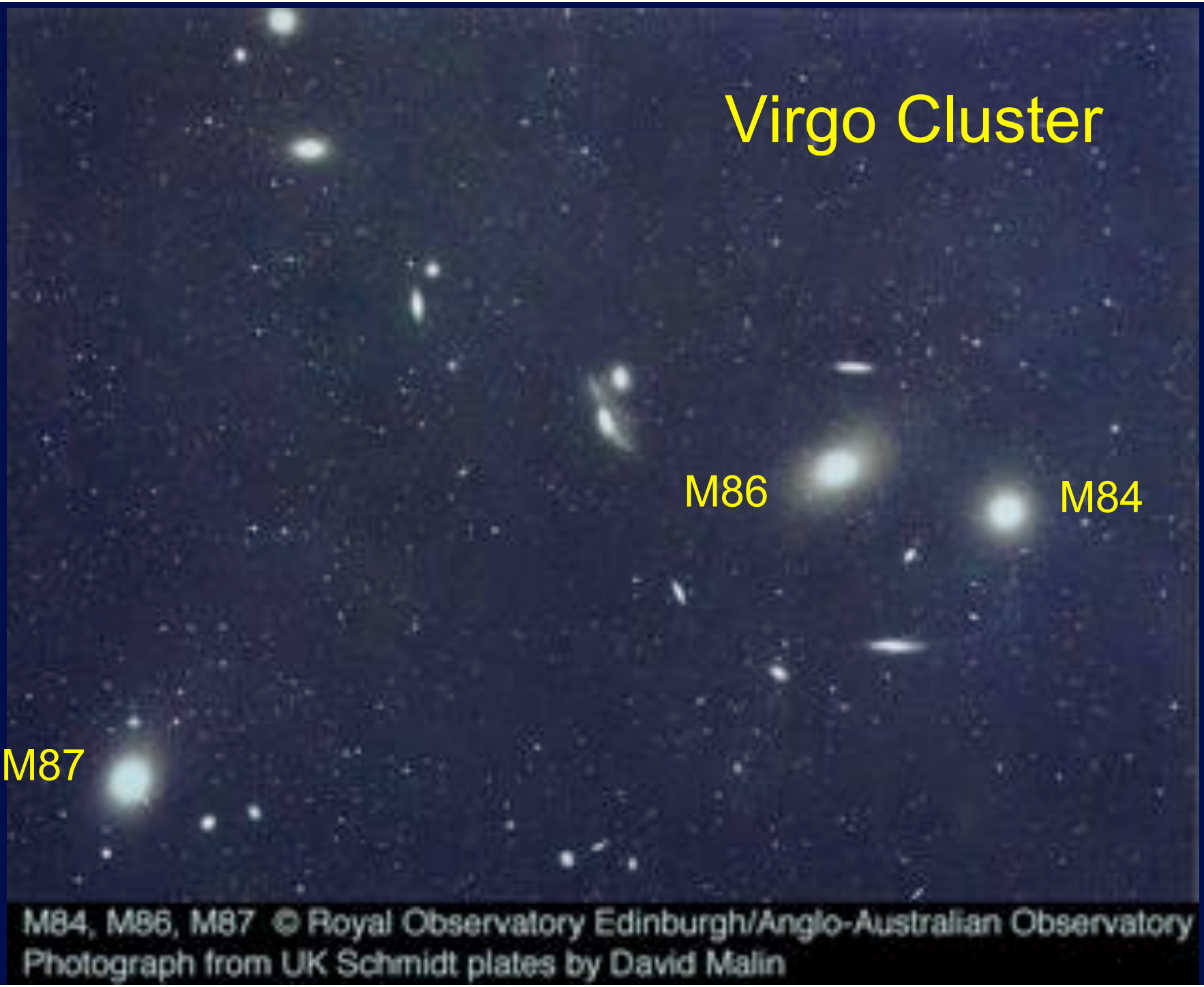


Difference Images

- Images from time of the 2008 flare with average of first 9 images of 2007 subtracted.
- Linear contours
- Core was already above average at start
- Inner jet was weak
- Core brightens and jet components appear
- Analysis proceeding

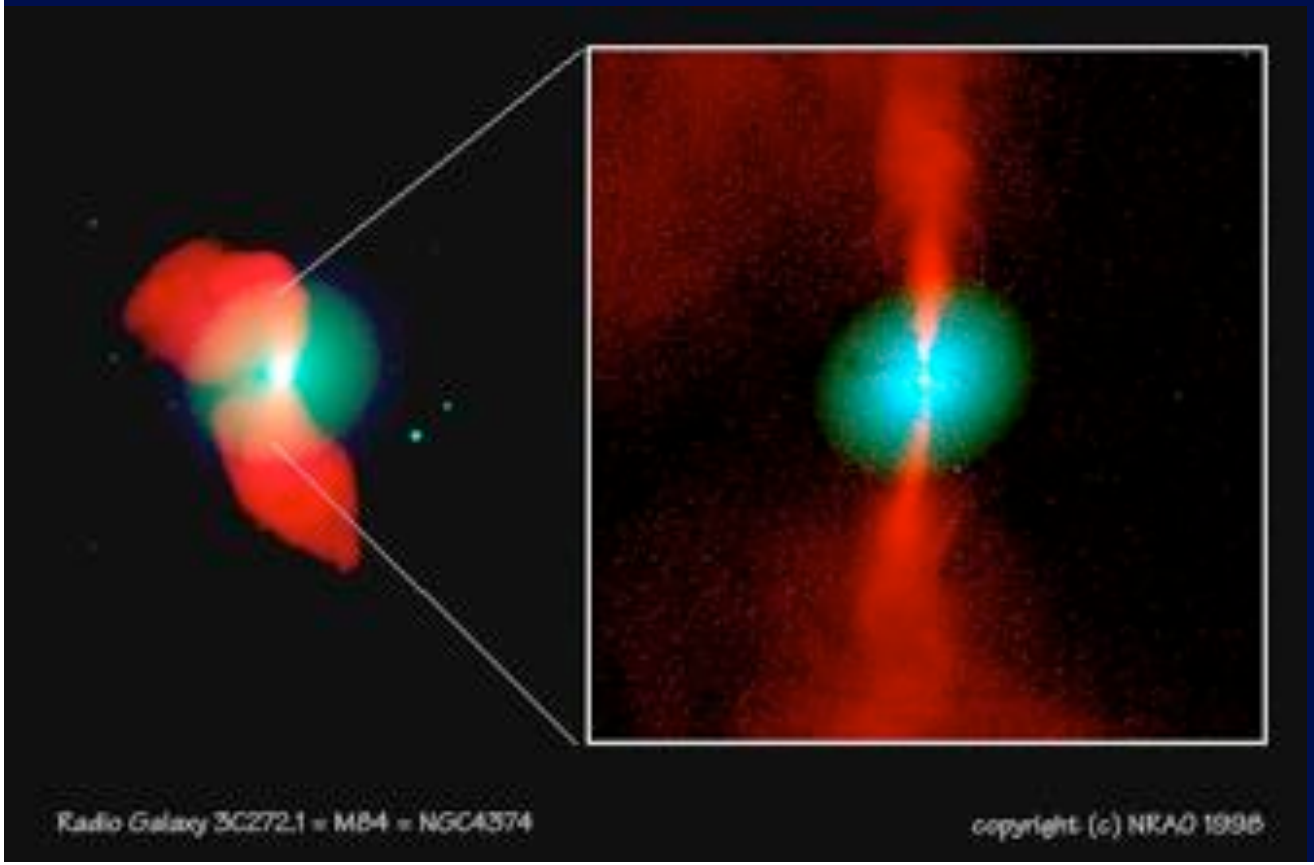
M87-M84 RELATIVE MOTION

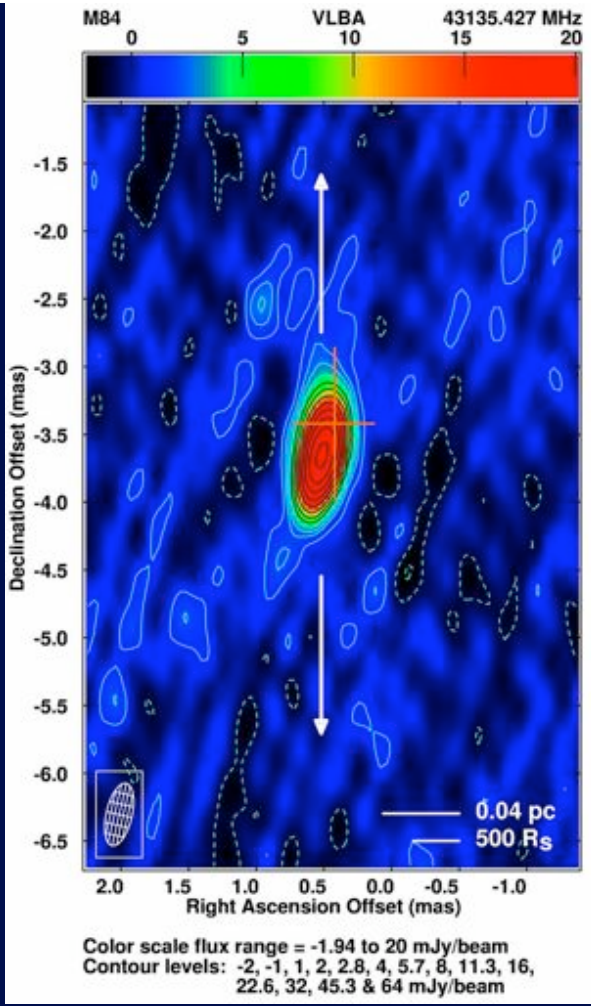
- Summer student project for 2008 - Fred Davies
- All movie observations included 5 sets of 4 nods between M87 and M84 - separation 1.44 deg.
  - Final 5 epochs included geodesy type segments to measure atmosphere (DELZN)
- Scatter in 2007 and 2008 indicates the stability of the “core”
- Archival 2001 observations used to attempt relative proper motion measurement
  - From Ly, Walker, and Wrobel 2004
  - Reprocessed in manner similar to recent data


Virgo Cluster
M86
M84
M87
M84, M86, M87 © Royal Observatory Edinburgh/Anglo-Australian Observatory
Photograph from UK Schmidt plates by David Malin

M84=NGC4374=3C272.1

- Classical FR I
- Compact core with about 50 mJy at 43 GHz
- Jets nearly perpendicular to M87 jet

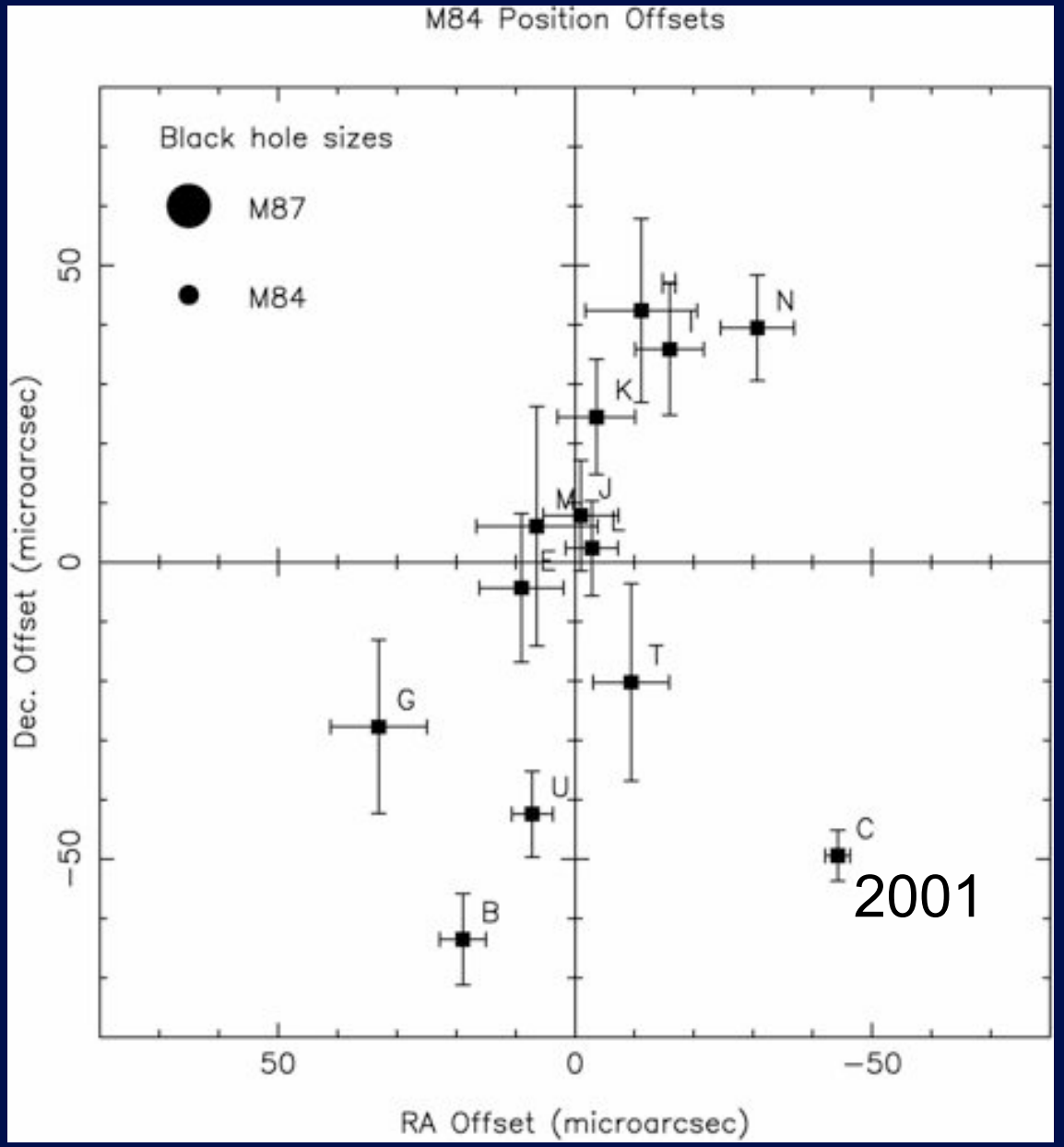




43 GHz VLBA
Ly, Walker, & Wrobel 2004

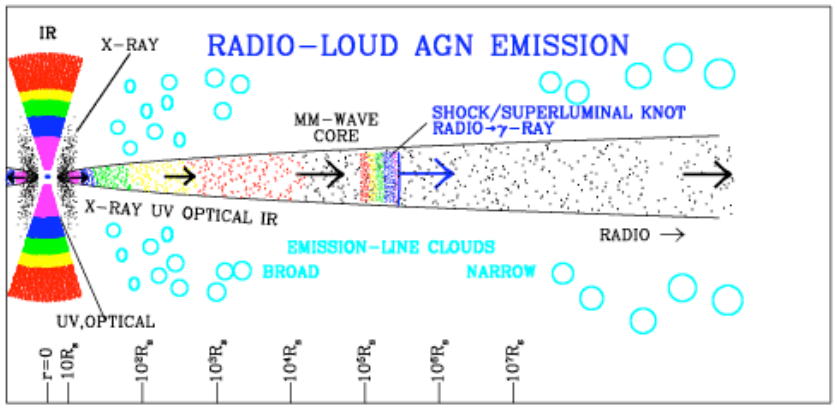
POSITIONS OF M84 RELATIVE TO M87

- Positions shown relative to mean of 2008 results
- “C” is the 2001 position
- Error bars shown are formal JMFIT errors
- Systematic errors still under study



PRELIMINARY ASTROMETRY RESULTS

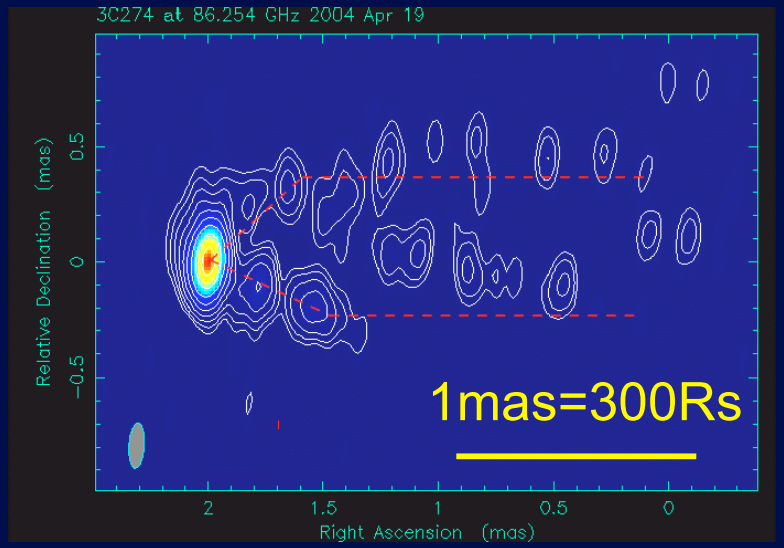
- Proper motion: about 66 μas position change since 2001
  - Needs careful study of long term systematic errors
  - About 5X the scatter in recent data
  - Would correspond to relative velocity of about 800 km/s
  - This is about the mean transverse Virgo cluster velocity deduced from radial velocities
- Core wander: Scatter in recent positions ~ 11 X 34 μas
  - Those are scatters in the beam major and minor axis directions
  - About 3 X 10 Rs
  - That constraint applied during the flare
  - Intuitively not consistent with a large (10^5 Rs = 0.3 arcsec!) core offset



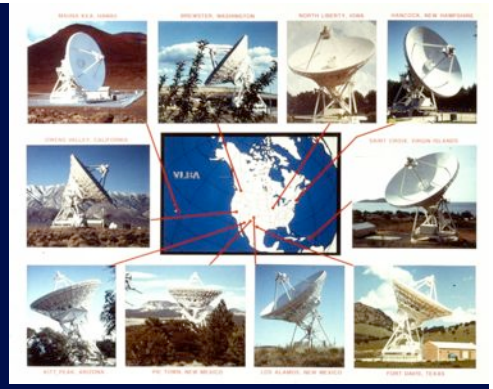
Marscher, Jorstad

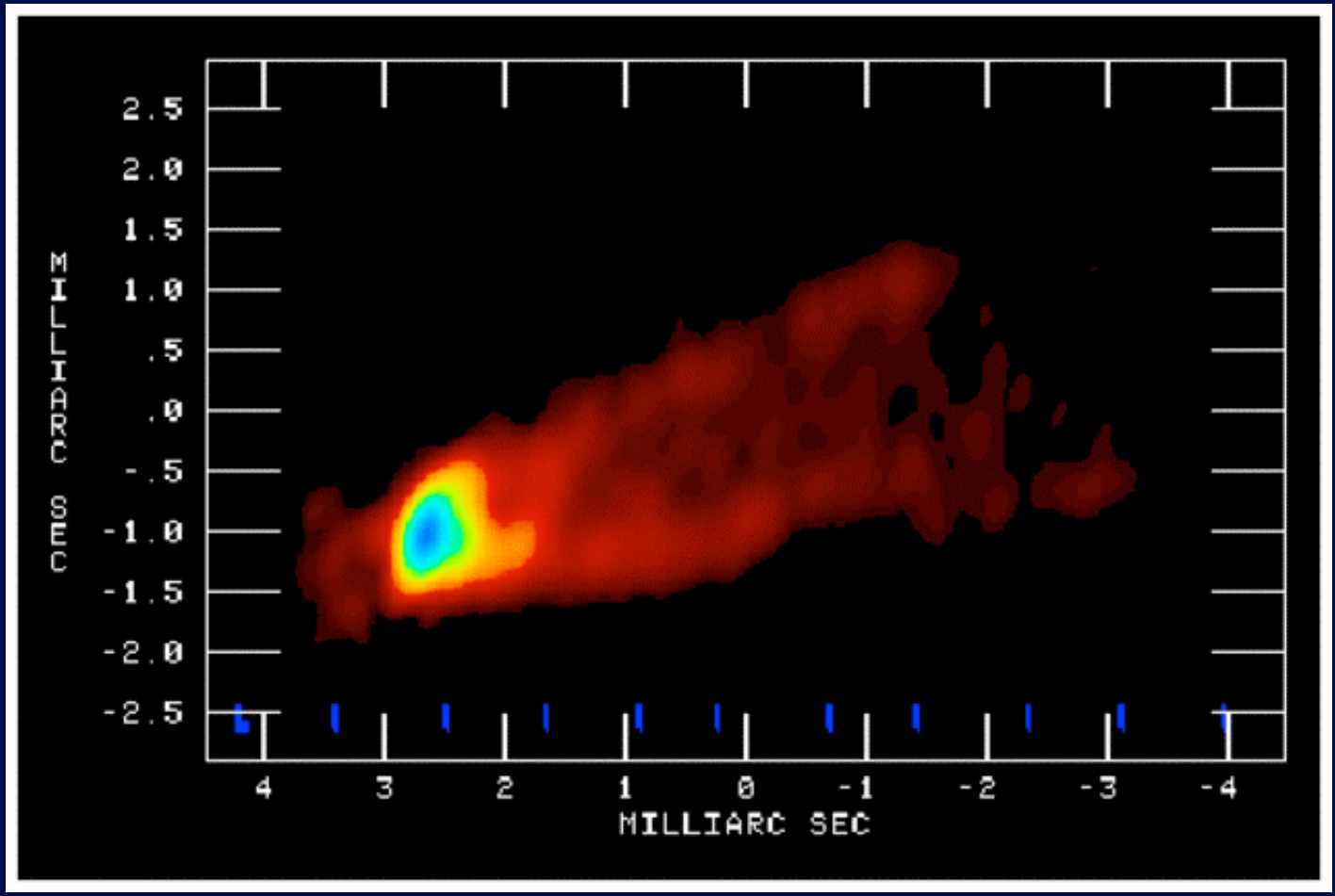
Prospects for Higher Resolution

- Global VLBI at 86 GHz
  - Krichbaum et al 2007
  - Starting to resolve high opening angle region
  - Data from Apr 2004
  - Beam 0.20 x 0.066 mas
  - Peak 0.38 Jy
  - Lowest contour 1.1 mJy
- VSOP2 at 43 GHz
  - Japanese space VLBI project
  - Approved 2012 launch
- Movie frame rate of 1 or 2 days.



THE END




2.5
2.0
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-2.0
-2.5
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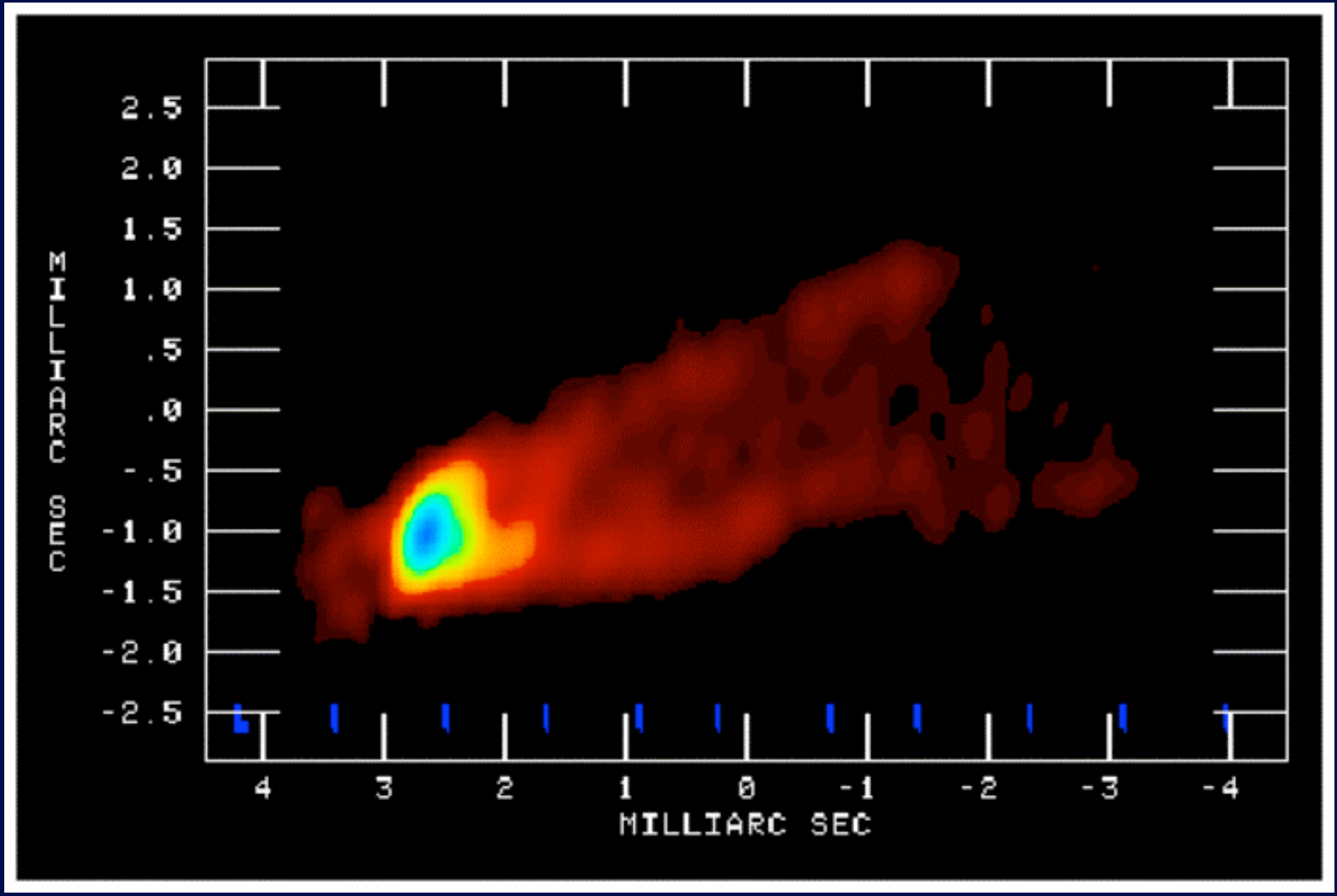
MILLIARC SEC

SLOW VERSION OF MOVIE



The VLBA 43 GHz M87 Movie
First Frame Jan 27, 2007