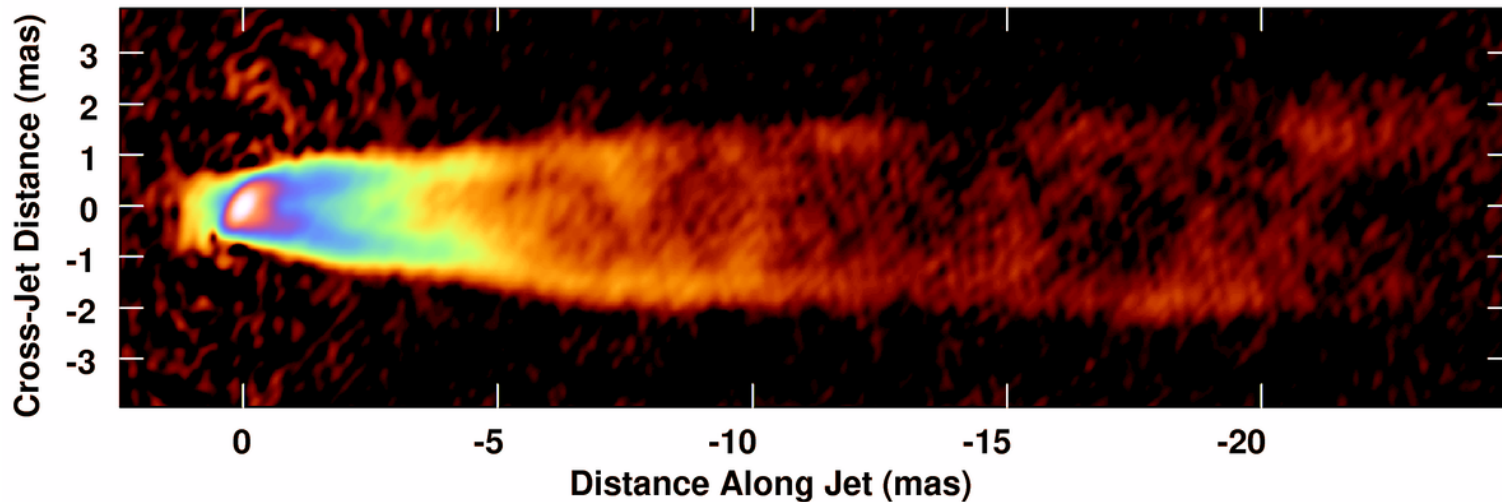


OBSERVATIONS OF THE STRUCTURE AND DYNAMICS OF THE INNER M87 JET



R. Craig Walker (NRAO)



M87 project collaborators: P. E. Hardee (U. Alabama),
C. Ly (STScI), F. Davies (MPIA), W. Junor (UC/LANL)
Motions study: F. Mertens, A. Lobanov (MIPfR)

OUTLINE



VLBA tour
this corner

- Project overview
- Morphology:
 - Edge brightening, parabolic shape
 - Counterjet
- Dynamics:
 - Movies
 - Speed measurements
- Long term changes. Annual movie.
- M84-M87 relative proper motion

M87 43 GHz PROJECT

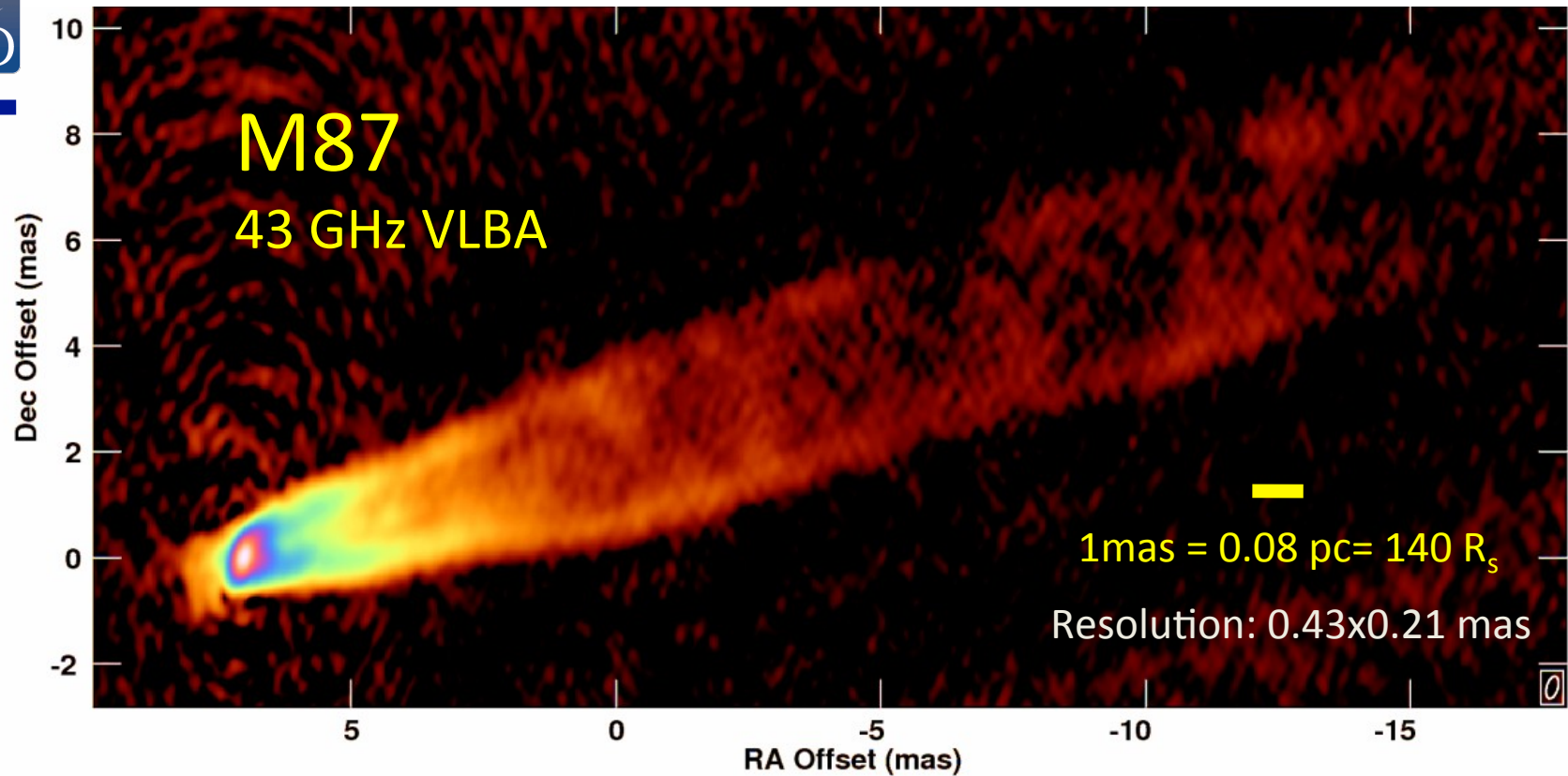


- M87 is the best source in which to study a jet base
 - 6×10^9 solar mass black hole (Some claim 3×10^9)
 - In Virgo Cluster at 16.7 Mpc.
 - VLBA 43 GHz resolution reaches $\sim 30 R_s$
- Project goal: Study jet dynamics and launch in M87
 - Movie observations in 2007 and 2008
 - Constrain jet launch models
- Secondary goal: Measure M87 – M84 relative motion
- Accidental goal: Relate radio and TeV flares
 - Side effect: Have roughly annual observations for 17 years

M84

M87

MORPHOLOGY



Edge brightened:

Emission on the surface or sheath

Wide base: Collimation region

Counterjet: In all images. Seen by others

Fades fast: Suggests beaming + acceleration

Average of 23 images

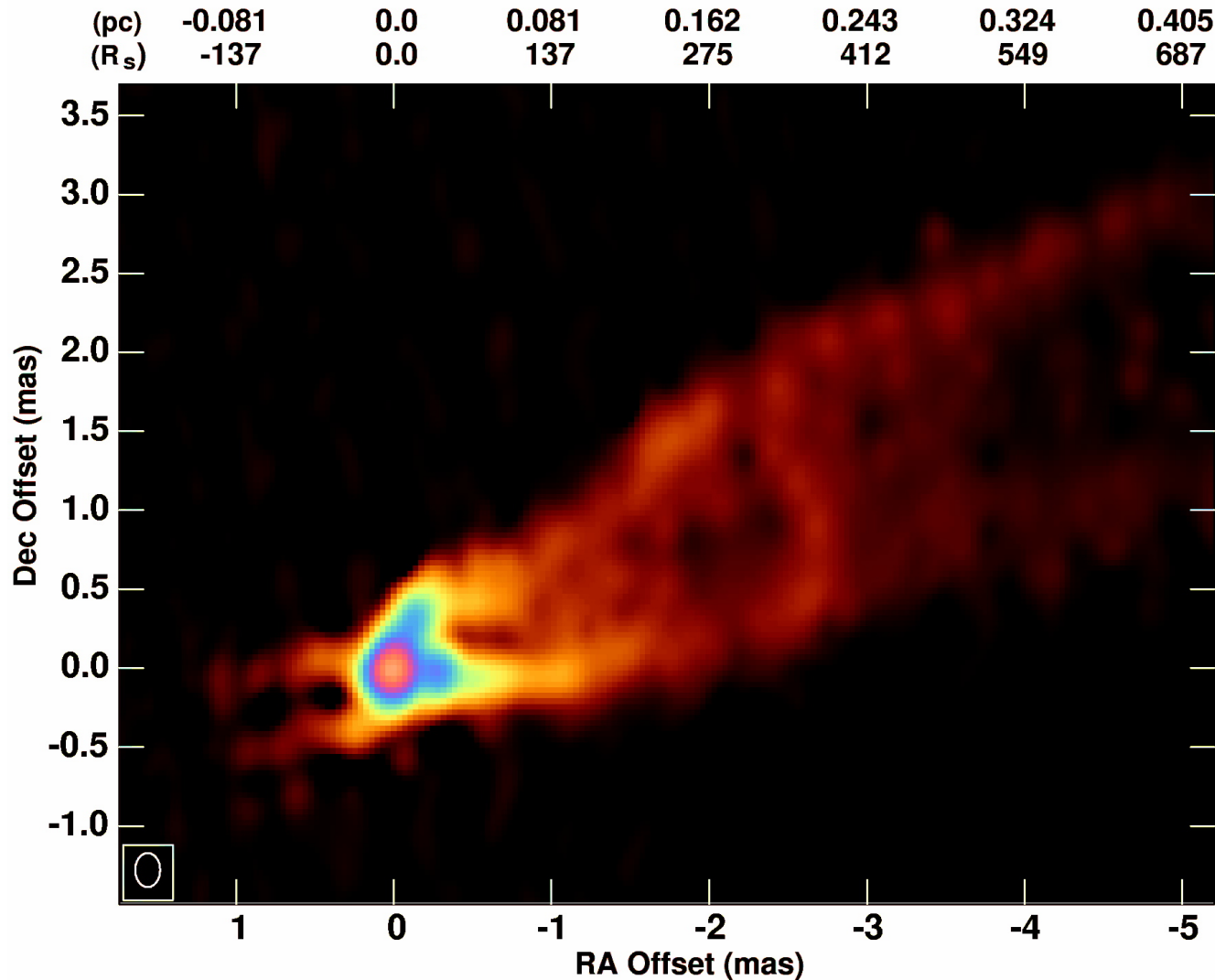
VLBA 2007, 2008, 43 GHz

Before upgrade; 256 Mbps

Average smooths changing features

Walker, Hardee, Davies, Ly, & Junor, 2016 in preparation

ZOOM IN ON CORE



VLBA 43 GHz

Jan 12, 2013

New 2 Gbps system

Beam 0.215×0.158 mas

$\approx 30 \times 22 R_s$

Uniform weight plus 30%
superresolution in N-S
direction.

Shows wide base

Details quite disturbed

Structure symmetric
between jet and
counterjet

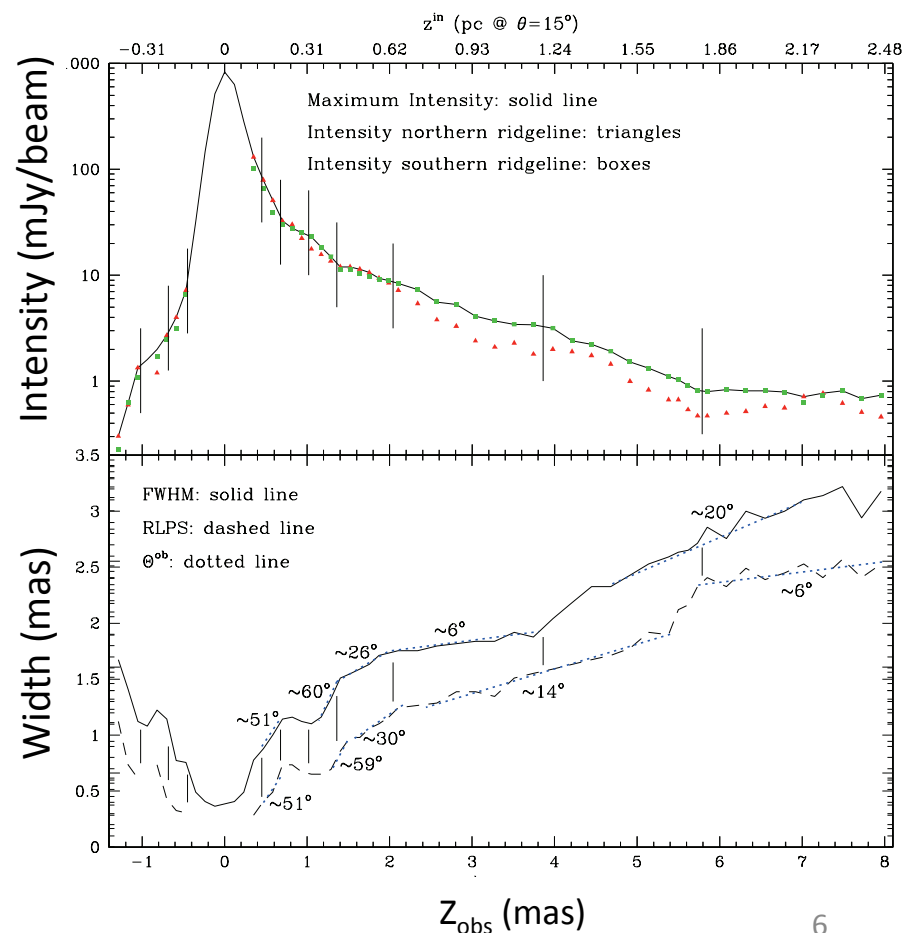
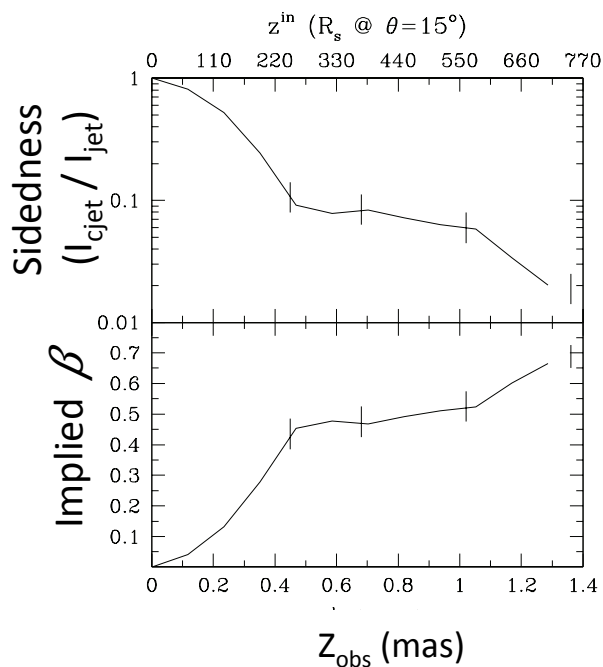
Slightly shorter on
counterjet side as
might be expected

INTENSITY, WIDTH AND SIDEDNESS

PT



- Based on average image (Shows the persistent structures)
- Shape parabolic consistent with Asada & Nakamura (2012)
- Periods of rapid expansion and recollimation
- Sidedness suggests beaming, acceleration
 - Flattens at recollimation region

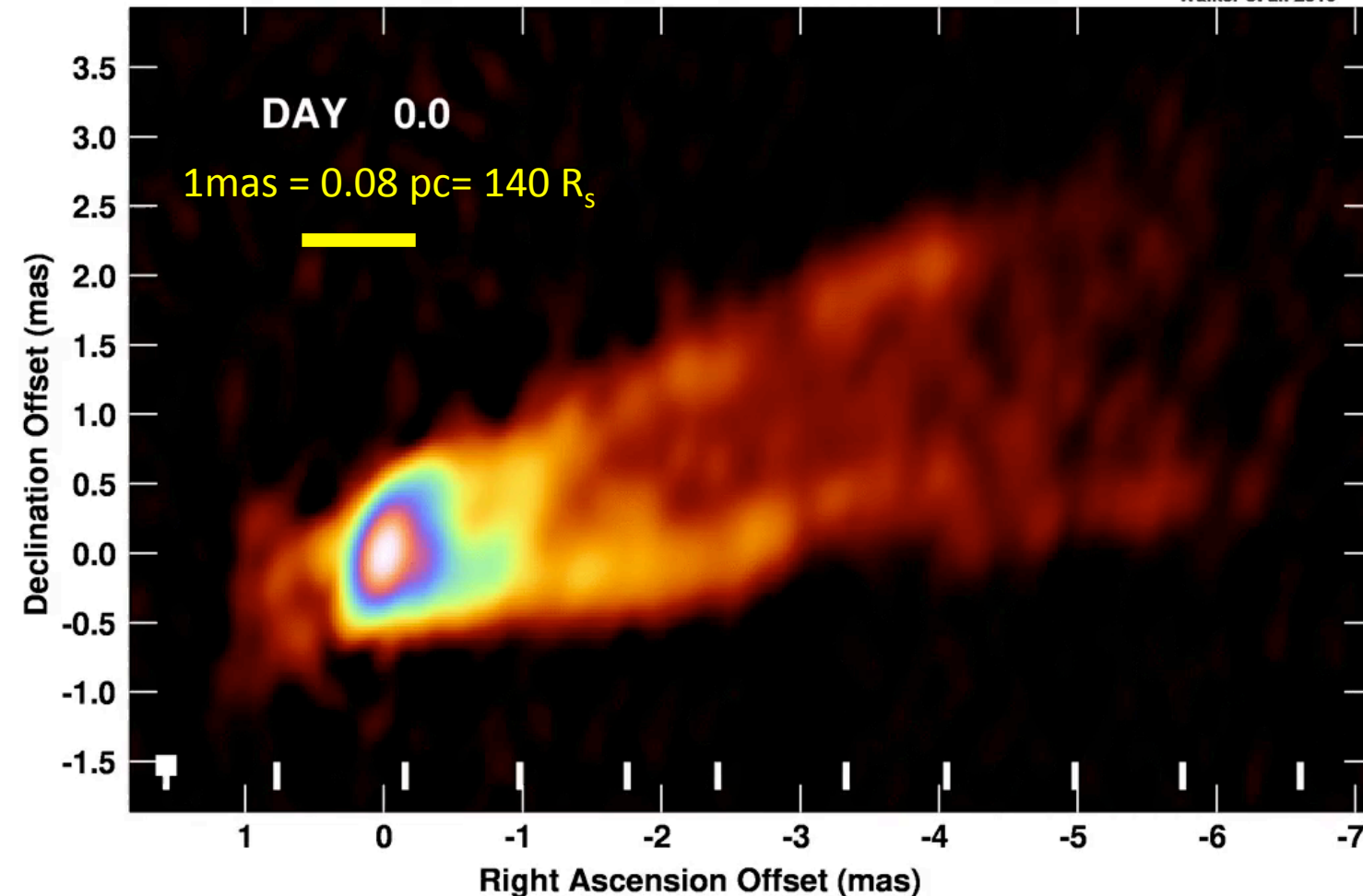




KINEMATICS: M87 2007

VLBA 43 GHz MOVIE

Walker et al. 2016



Jan-Aug 2007
3 week intervals
11 images

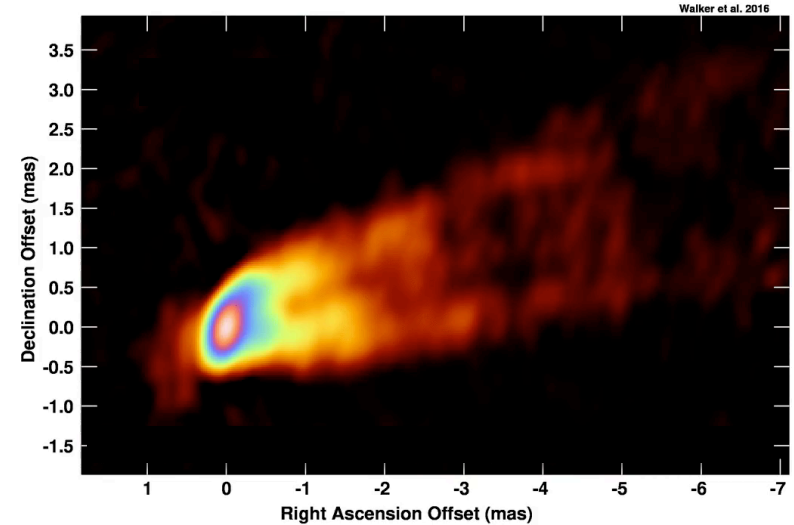
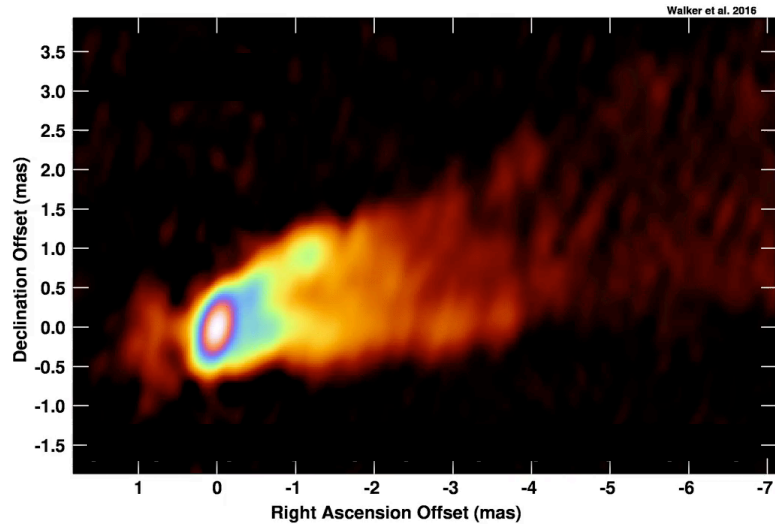
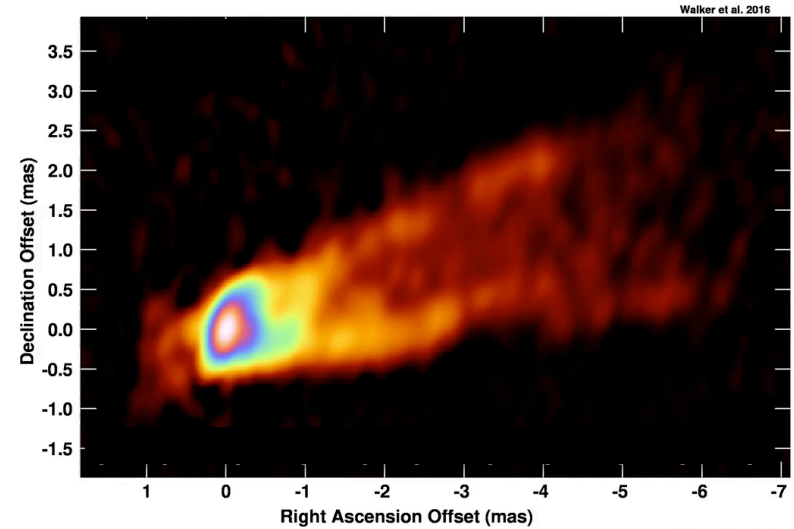
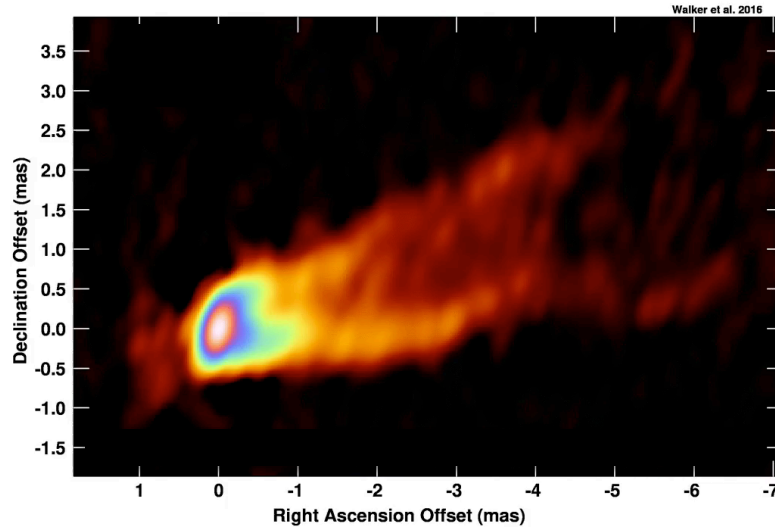
Beam
0.43x0.21 mas
1 mas/yr = 0.25c

Rapidly changing
structures

Visual impression
of Motions of
about 0.5 mas per
frame (21 days)
Approximately 2c

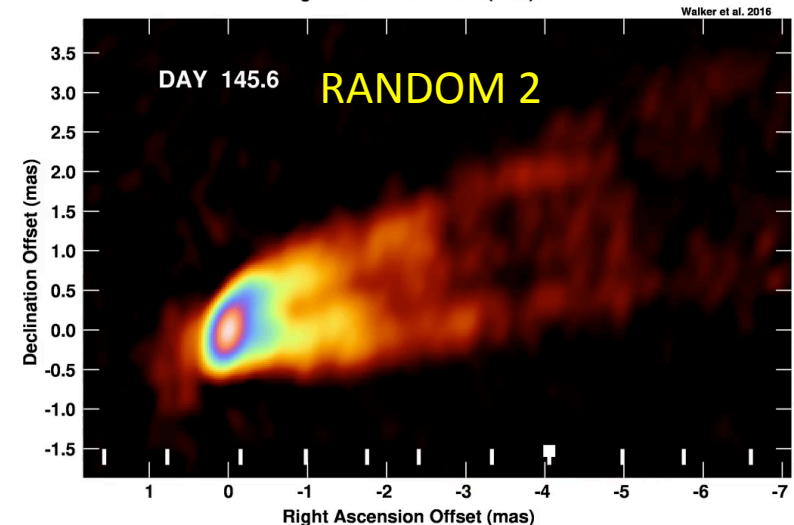
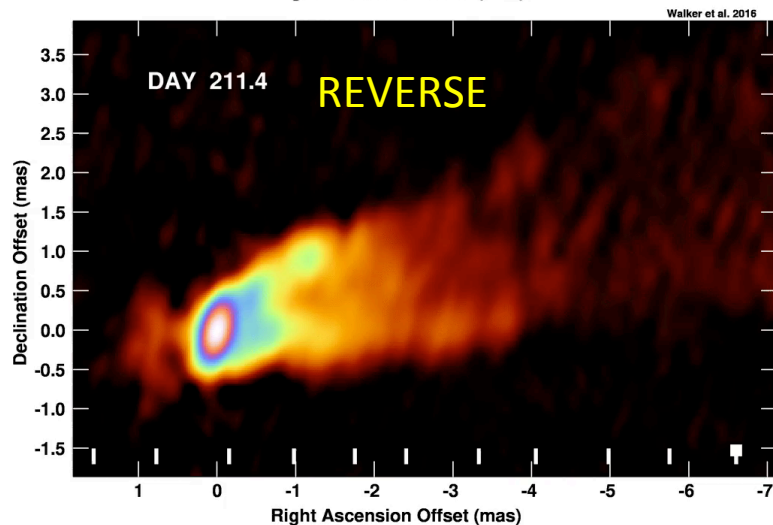
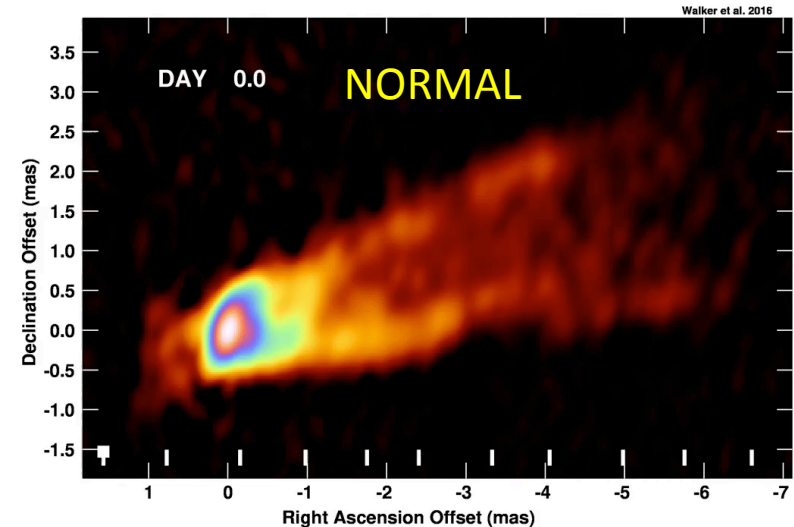
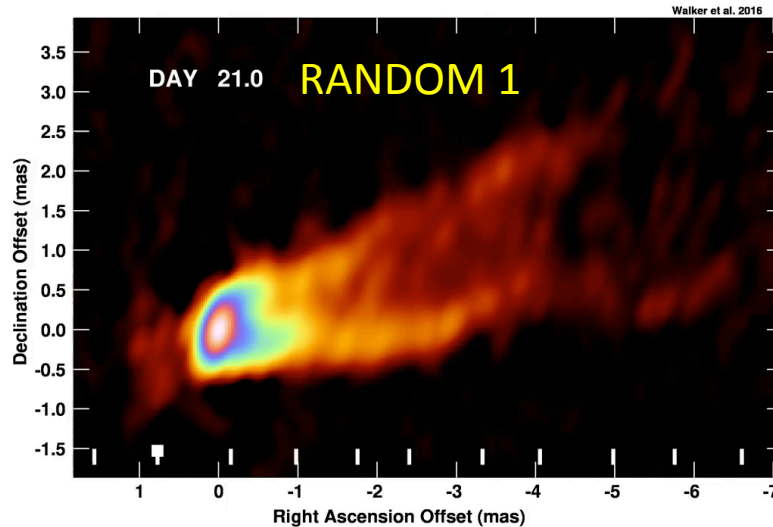
M87 MOVIE

FOUR FRAME ORDERS



M87 MOVIE

FOUR FRAME ORDERS

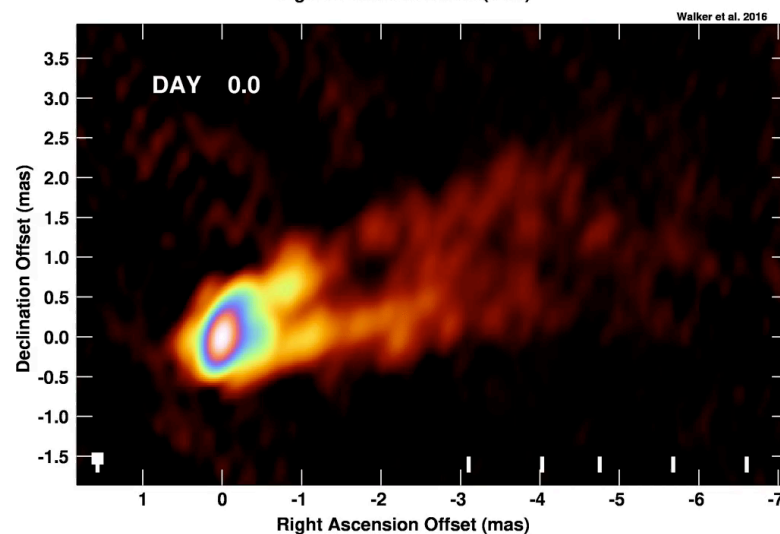
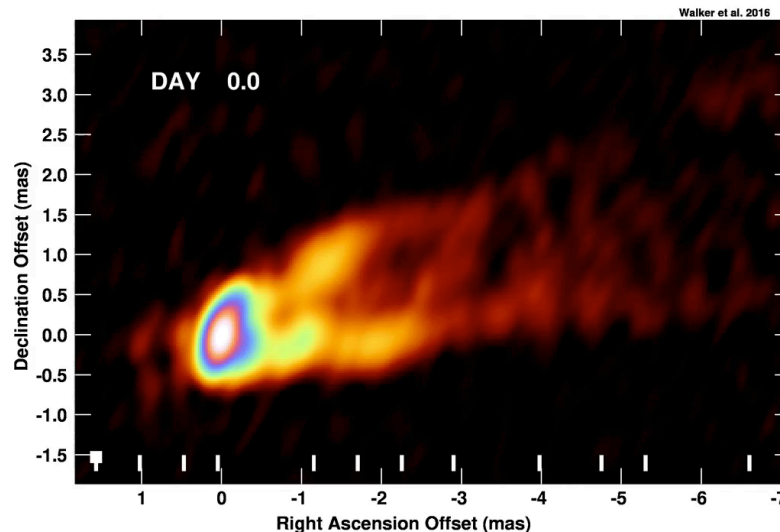


2008 & 2010 MOVIES



- 12 sessions in **2008**
- 5 day interval
- Hard for dynamic scheduling
 - Many poor images
- Flare seen.
 - Start near TeV flare

- **2010** observations triggered by TeV flare
- Early background run plus 5 triggered sessions
- 2 week intervals
- No flare





NEW FEATURE AT CORE

During a significant radio flare
Core brightened
New features appear
TeV flare (Acciari et al 2009)

A: Average of 2007 images

B: April 5 2008 image

C-F: 2008 difference images

The 2007 average subtracted

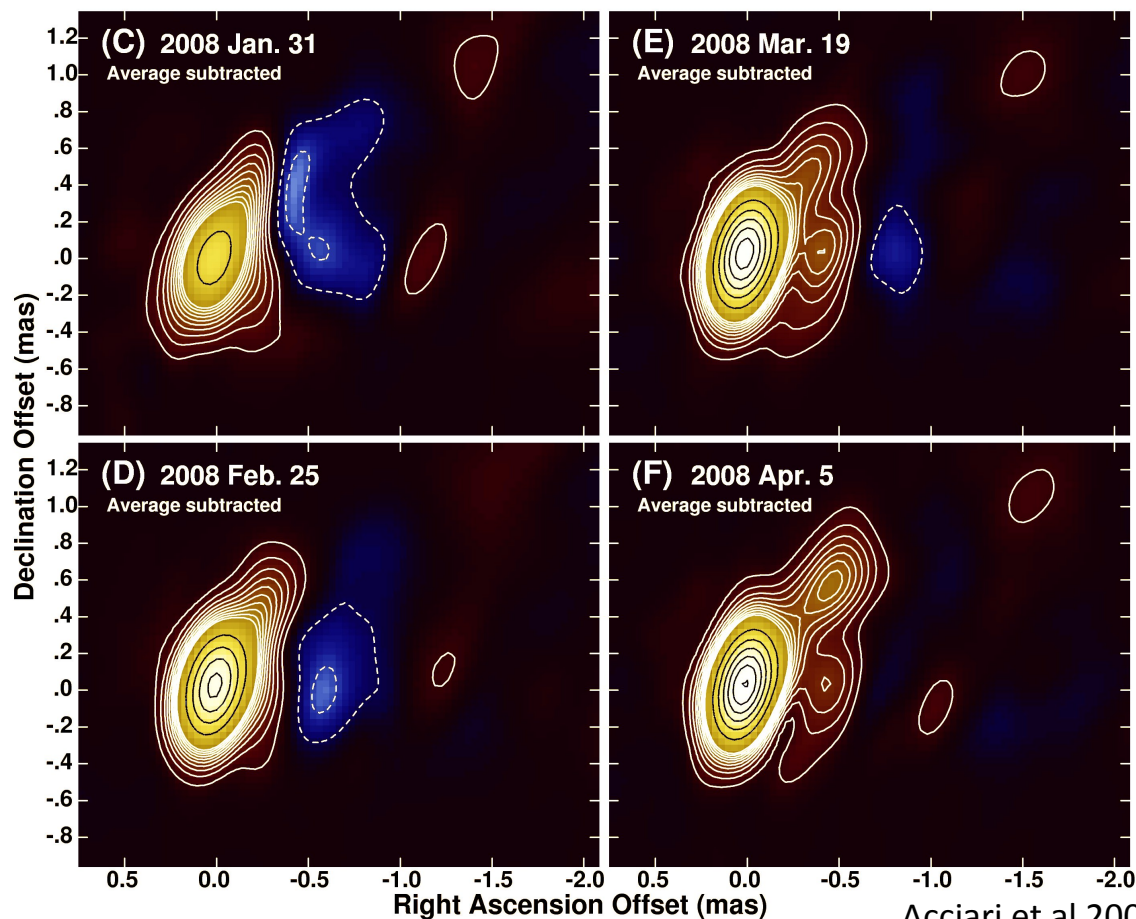
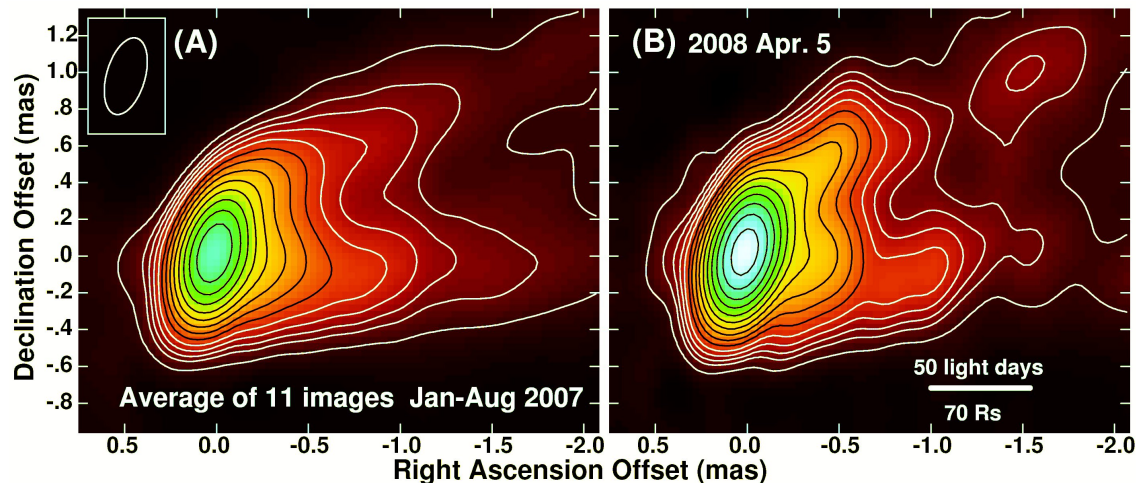
New feature speed $\sim 0.4 c$

Significantly slower than

The jet further out

Suggests the jet is still
accelerating at 100 Rs

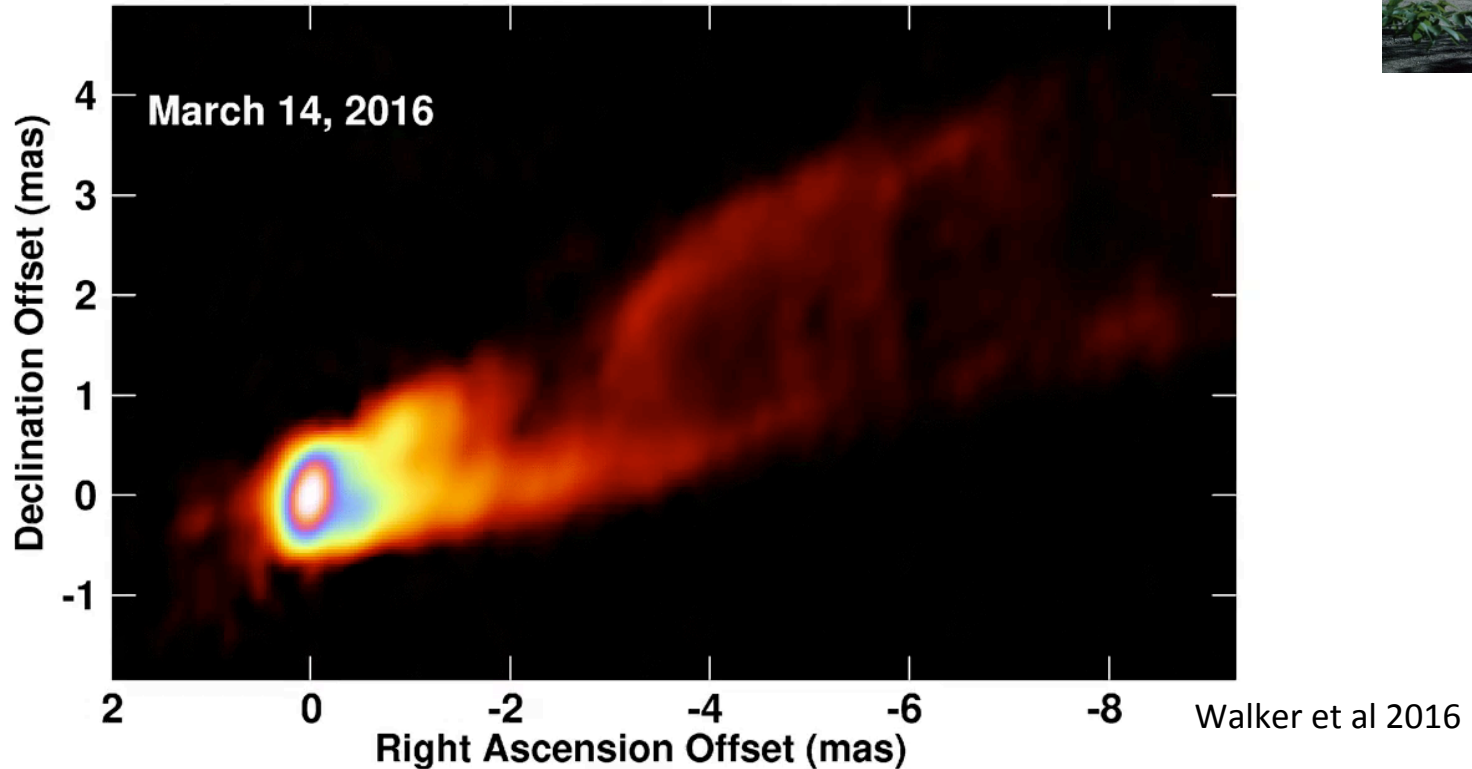
Walker et al.



Acciari et al 2009

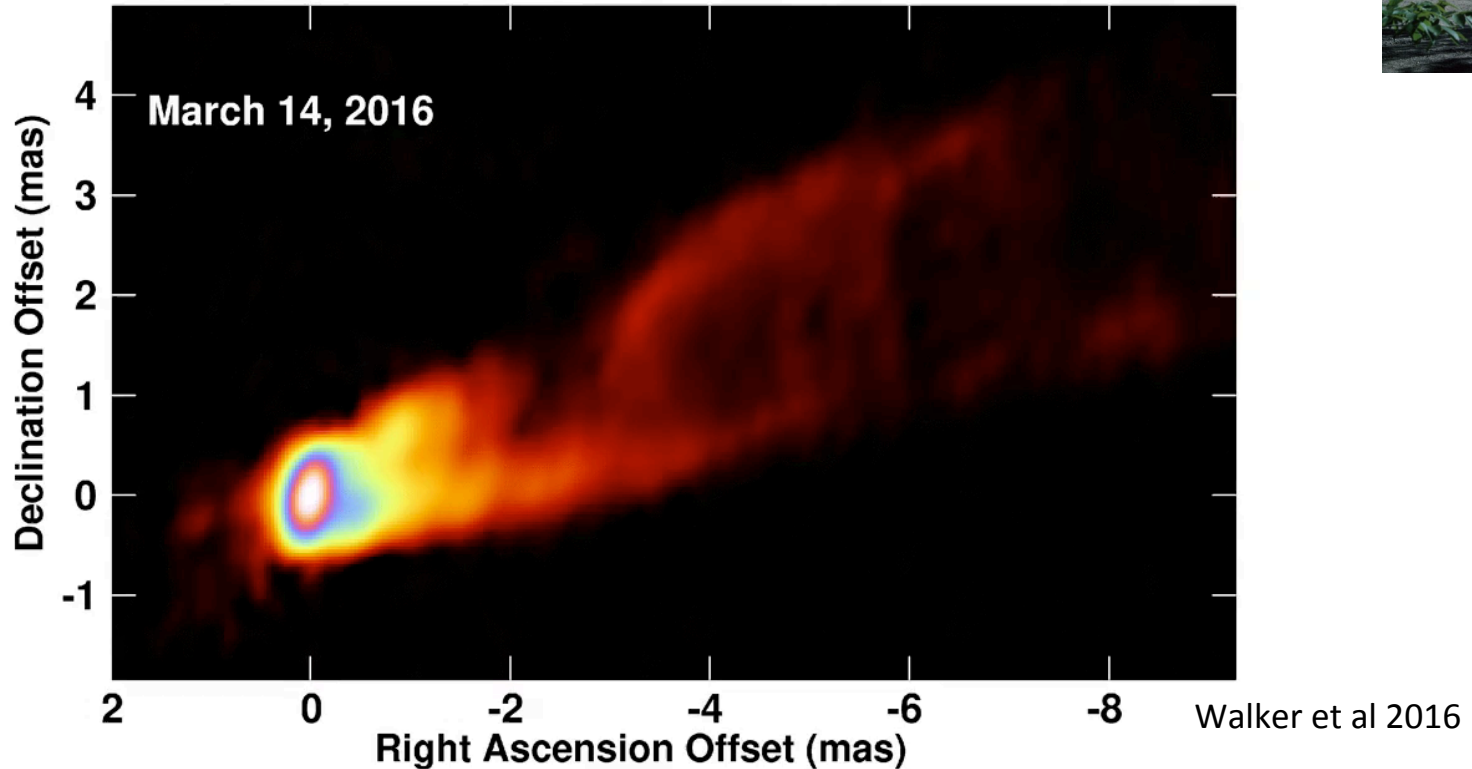


2016



- Got TeV trigger – barely. No clear radio flare
- Clear motions near core, change farther out
- Pronounced gap in northern side

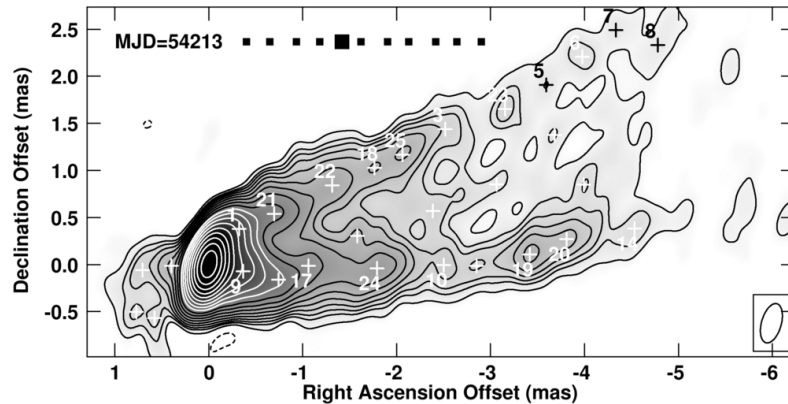
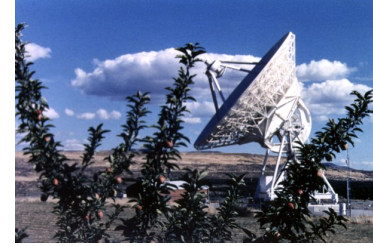
2016



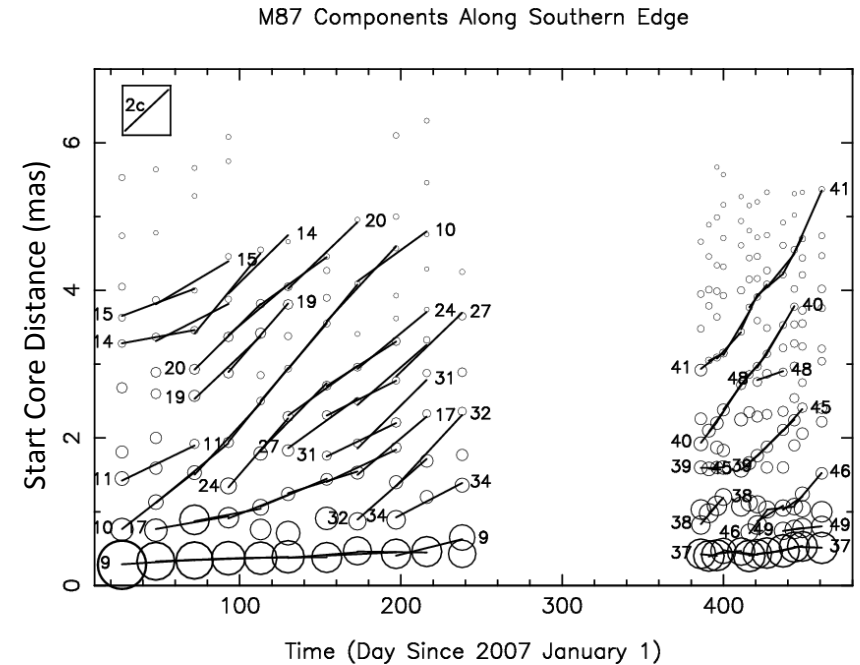
- Got TeV trigger – barely. No clear radio flare
- Clear motions near core, change farther out
- Pronounced gap in northern side

JET SPEED: TRADITIONAL MEASUREMENT

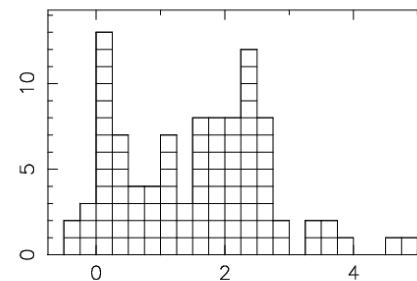
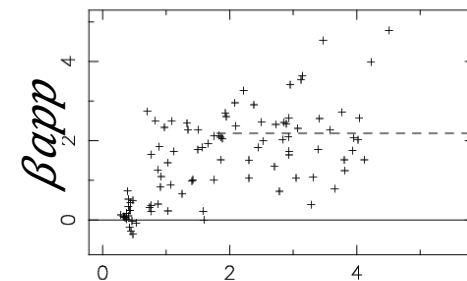
BR



- Sample image, 1 of 23
- Positions of local peaks measured
- Identify related peaks from epoch to epoch (Visually)
- Get speeds for groups of 3 points
- Significant range of speeds seen
- Some slow, especially near core
- Some near $\beta_{app} = 2.5$
- Acceleration near core



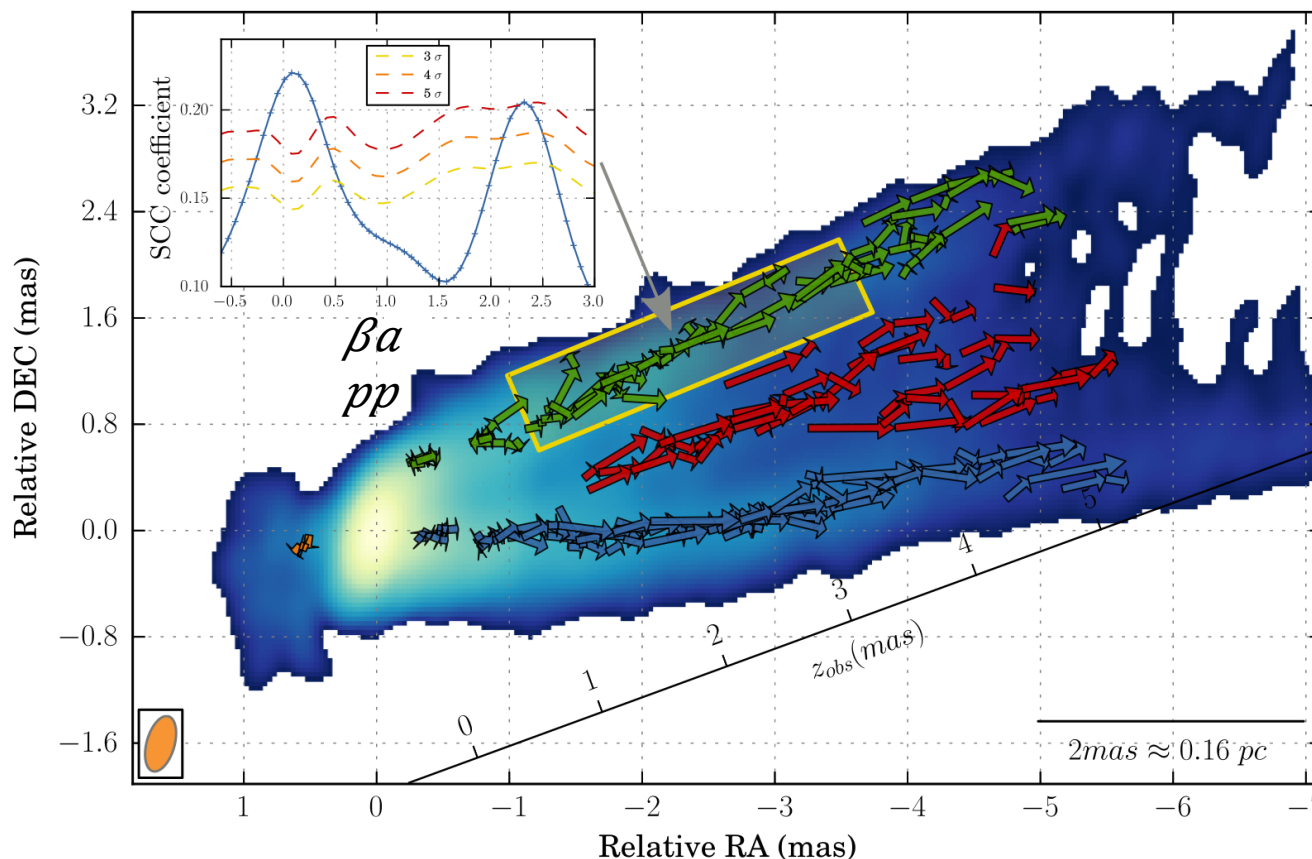
Count of 3 Point Lines


 β_{app}


Start Core Distance (mas)

JET SPEED: WISE METHOD

MK



WISE - Wavelet-based Image
Segmentation and Evaluation

Mertens and Lobanov 2015

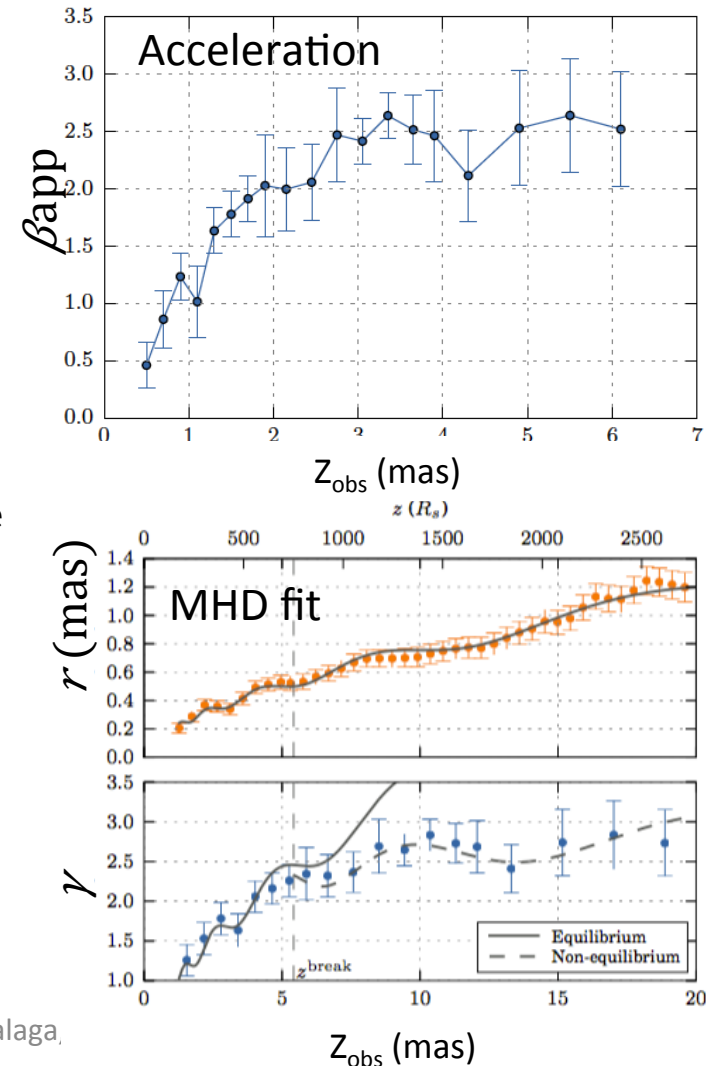
Finds overlapping fast ($\beta_{app} \sim 2.5$) and
slow components

M87 results in Mertens, Lobanov, Walker,
and Hardee (2016) submitted

WISE RESULTS

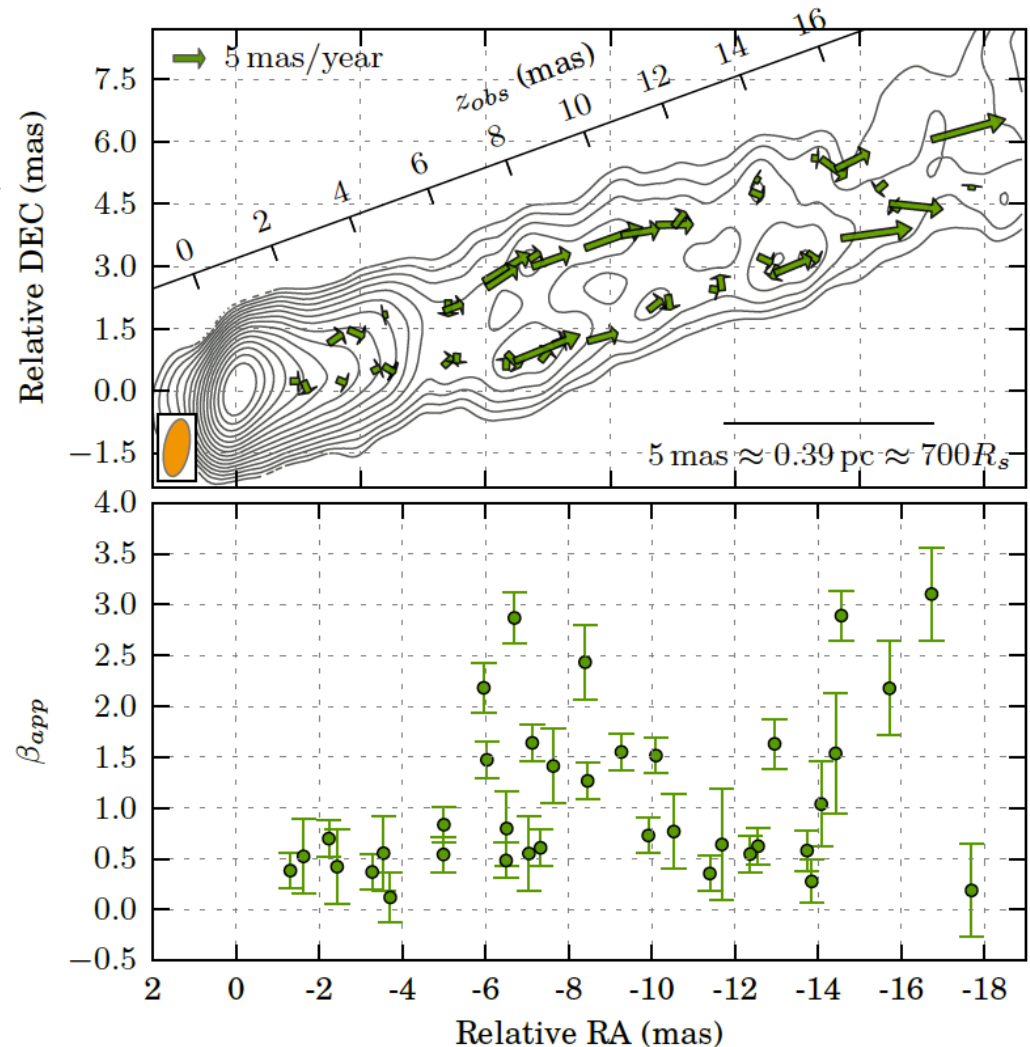


- Overlapped velocity systems
 - Stratification or patterns
 - No clear spine detection
- Acceleration in the inner 2 mas
- $\gamma \propto r \propto z^{0.58}$
 - Shape agrees with Asada & Nakamura (2012) and Hada et al (2013, 2016) .
- N-S velocity diff suggests rotation
 - $\Omega \sim 10^{-6} \text{ s}^{-1}$ Suggests launch at $r_0 \sim 5 R_s$
- MHD modeling of acceleration and collimation
 - Plot shows Poynting flux dominated approximation case
 - Poynting/kinetic equipartition at about 3000 R_s
- Angle to line of sight $\sim 18^\circ$ from 3 methods:
 - Sidedness and Counter jet speed
 - Rotation
 - MHD fits modeling
- Please see Mertens, Lobanov, Walker, and Hardee, (2016, submitted) for details



WISE ANALYSIS OF 15 GHz DATA

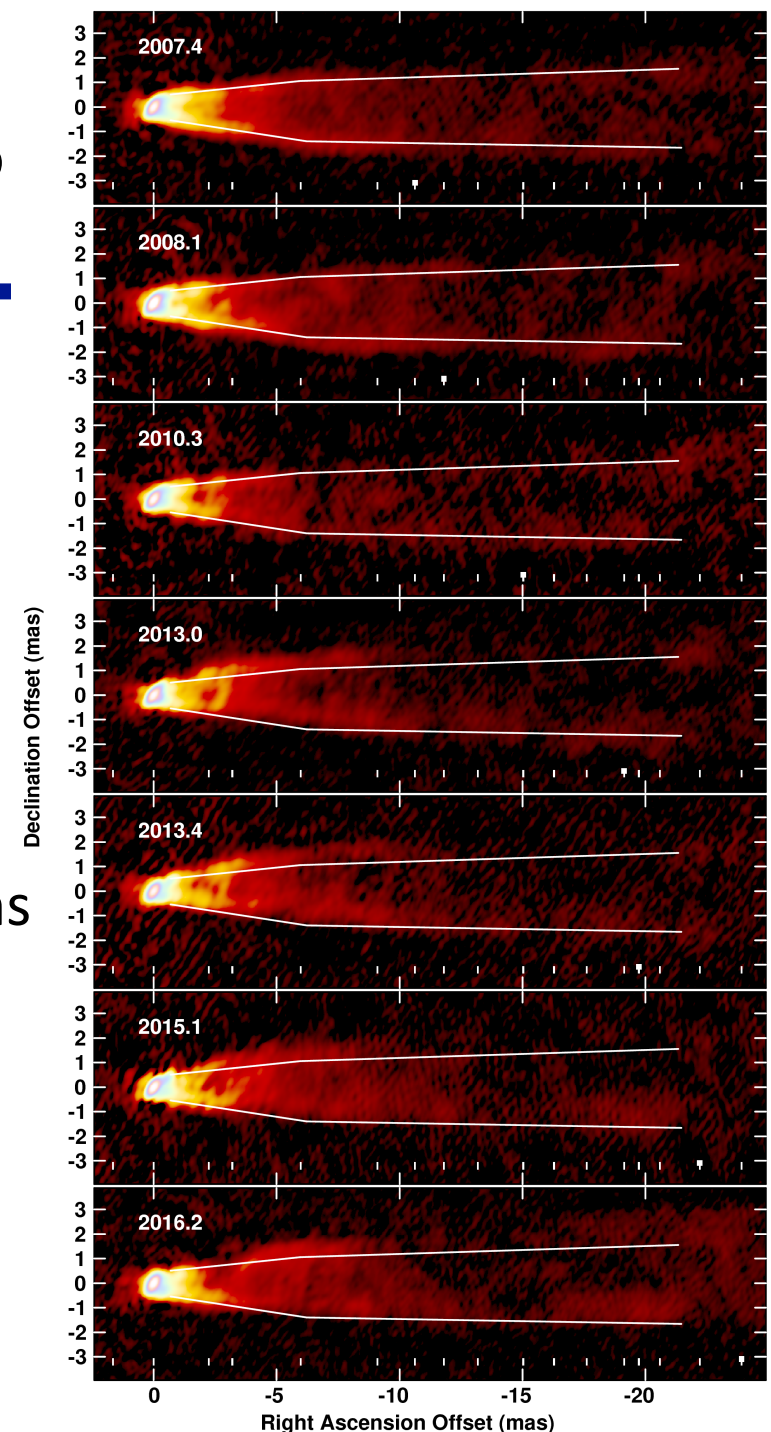
- Kovalev 2007 reports only slow ($<0.05c$) motions (30 images)
 - Cadence slow for detection of fast speeds
- MOJAVE:
 - 2000/04/07
 - 2000/06/27
- Long tracks: Kovalev et al. 2007
 - 2000/01/22
 - 2000/05/08
- WISE sees fast and slow speeds
- Too few components to define the velocity field
- For future: could do the job with full tracks at 2 month intervals
- In Mertens+ 2016



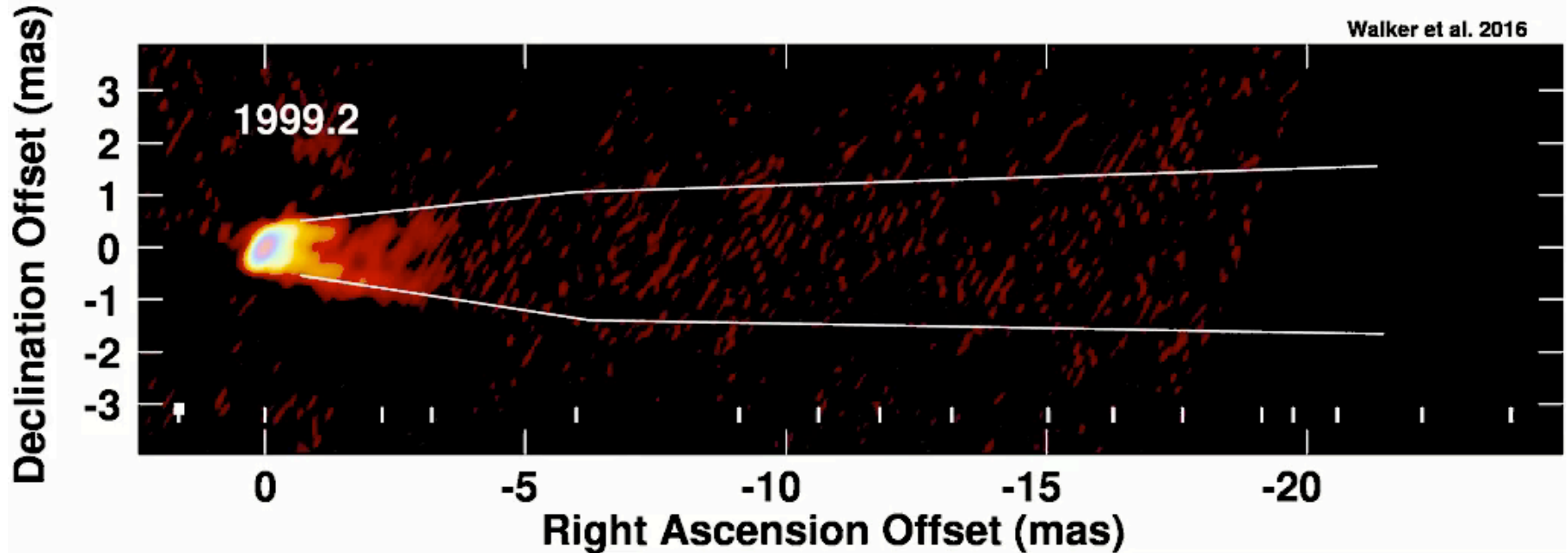


ANNUAL IMAGES

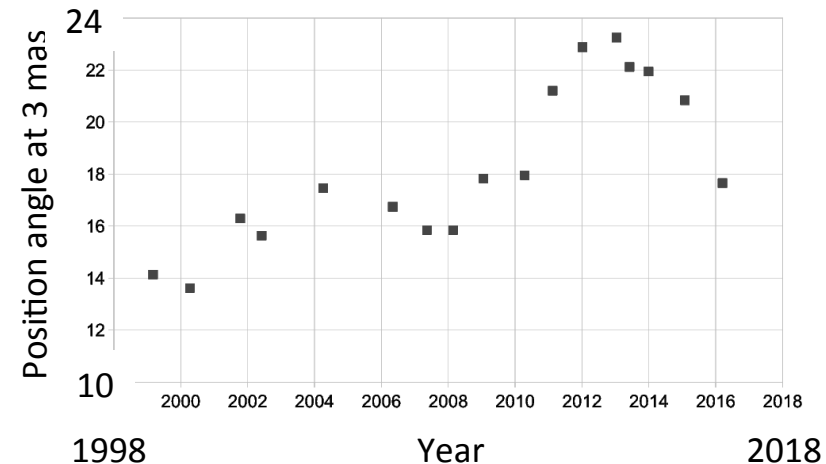
- Roughly annual images 1999-2016
 - The 7 best of 17 in plot
- 2006, 2007, 2008, and 2010 are stacks
- 2013 and later use new wide bandwidth system
 - Image quality from single sessions comparable to older stacks
- Lines mark 2007 edges
- Shows side-to-side motions
- To be in Walker+ 2016



ANNUAL IMAGE MOVIE



- Movie made from the annual images
- Watch for sideways shifts of envelope
 - Probably instabilities
- Note: fast motions would be undersampled ($2c=7.6$ mas/yr)



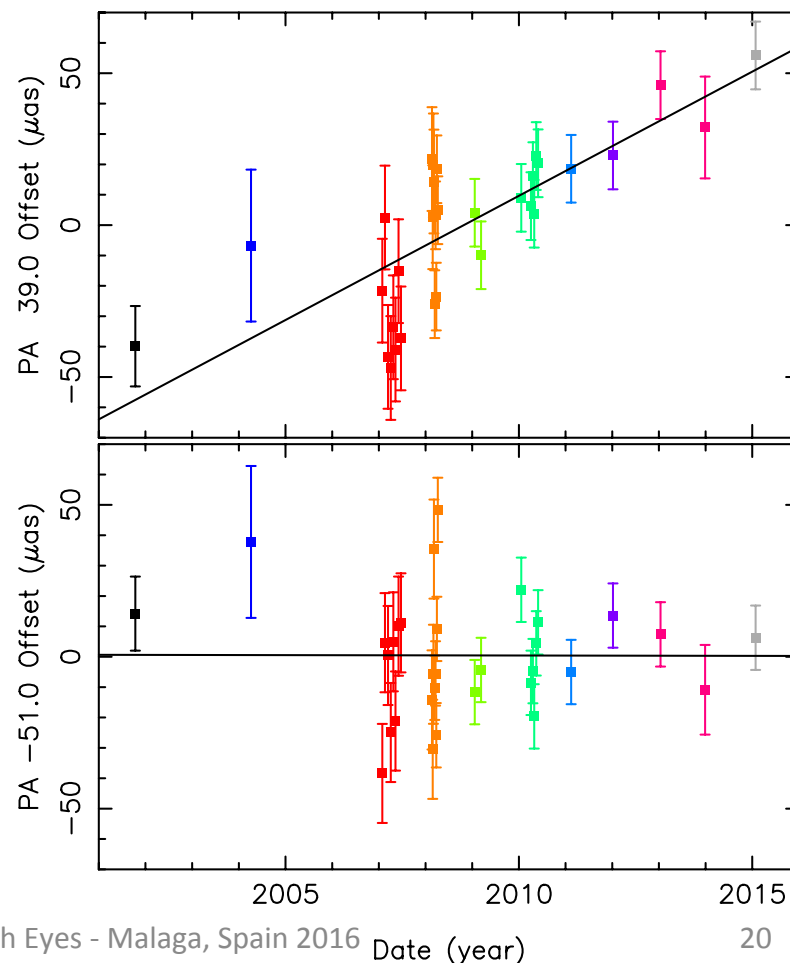


M84 – M87 RELATIVE PROPER MOTION



- Both Virgo Cluster elliptical galaxies
- Observations:
 - 2001, 2004 phase referencing
 - Astrometric segments in all 43 GHz sessions 2007-2015
- Plots after subtracting nominal offsets
 - Top along PA 39°
 - Bottom along PA -51°
- Data corrected for EOP, ionosphere, troposphere (DELZN, rate or delay)
- Fit result:
- **$8.18 \pm 0.94 \mu\text{as/yr}$**
 - $717 \pm 82 \text{ km/s}$ at M84
 - $648 \pm 74 \text{ km/s}$ at M87
- First 6 points in 2008 (flare) not included in fit or plot
- Within range of Virgo Cluster velocities
- Will be in Davies et al, in preparation

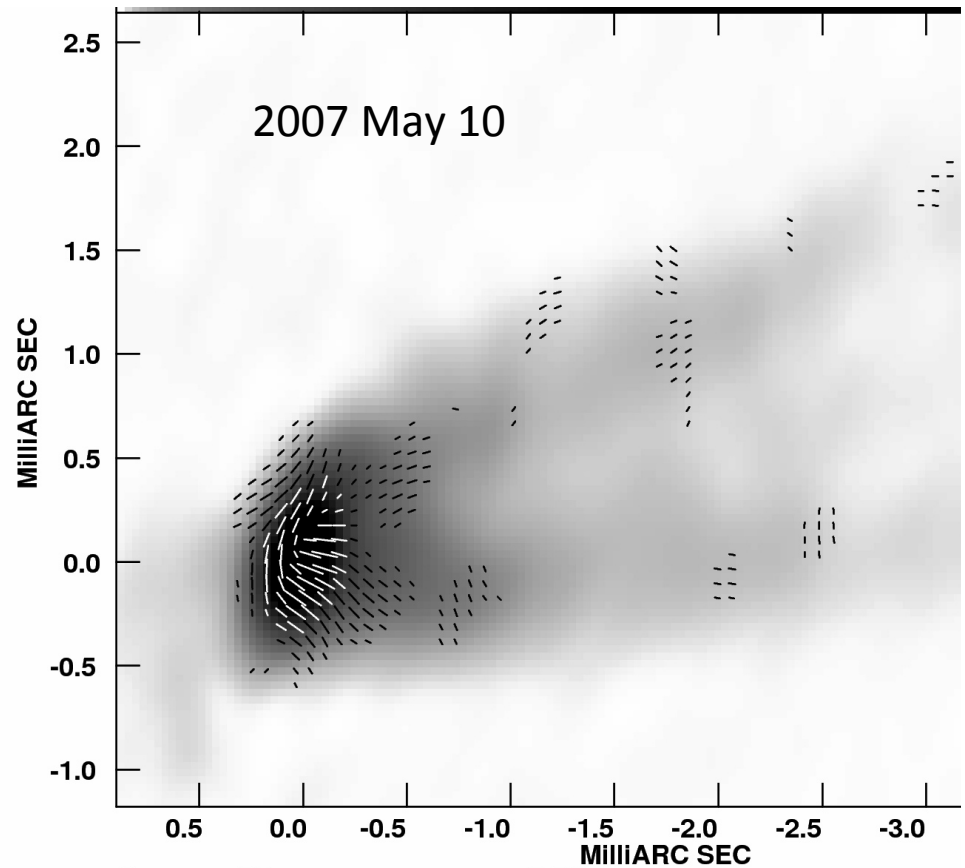
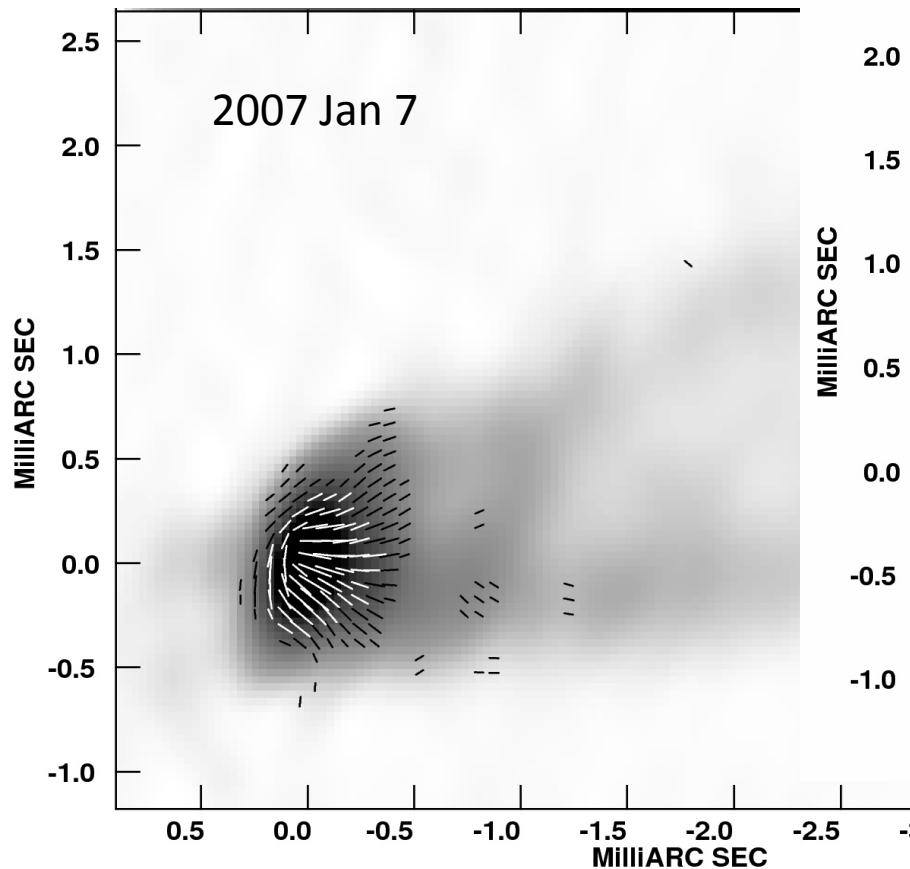
M84 – M87 Relative Position vs Time



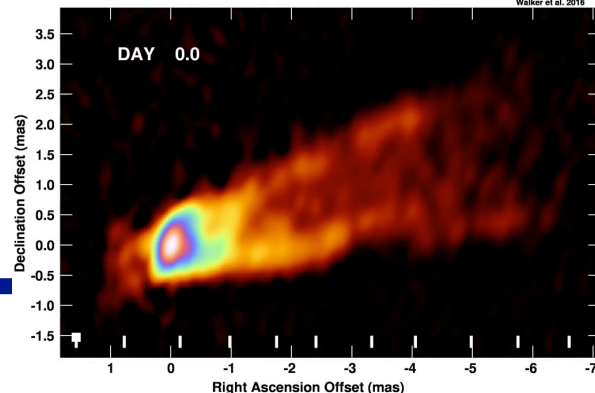
M87 POLARIZATION TEASER

Grey – Total intensity
Electric vectors shown

1mas = 0.08 pc = 140 R_s



CONCLUSIONS



- Jet edge brightened, with wide opening angle base, parabolic shape
- Rapidly changing jet structures
 - Both slow ($\beta_{app} \sim 0.5$) and fast ($\beta_{app} \sim 2.5$) motions seen.
 - Slow system could be patterns or stratification
 - Acceleration seen in the inner 2 mas
- Counterjet structure like main jet but dims rapidly
 - Beaming from accelerating, relativistic jet
- Angle to the line-of-sight about 18°
 - From counterjet, rotation analysis, and MHD modeling of WISE results
- Transverse motions of whole jet seen
 - Possible cycling over ~ 9 yr.
- M87 – M84 relative proper motion detected
- Movies, images at www.aoc.nrao.edu/~cwalker/M87/index.html
- Data and initial discussion: Walker, Hardee, Davies, Ly & Junor (2016) in preparation
- WISE analysis: Mertens, Lobanov, Walker, & Hardee (2016) submitted