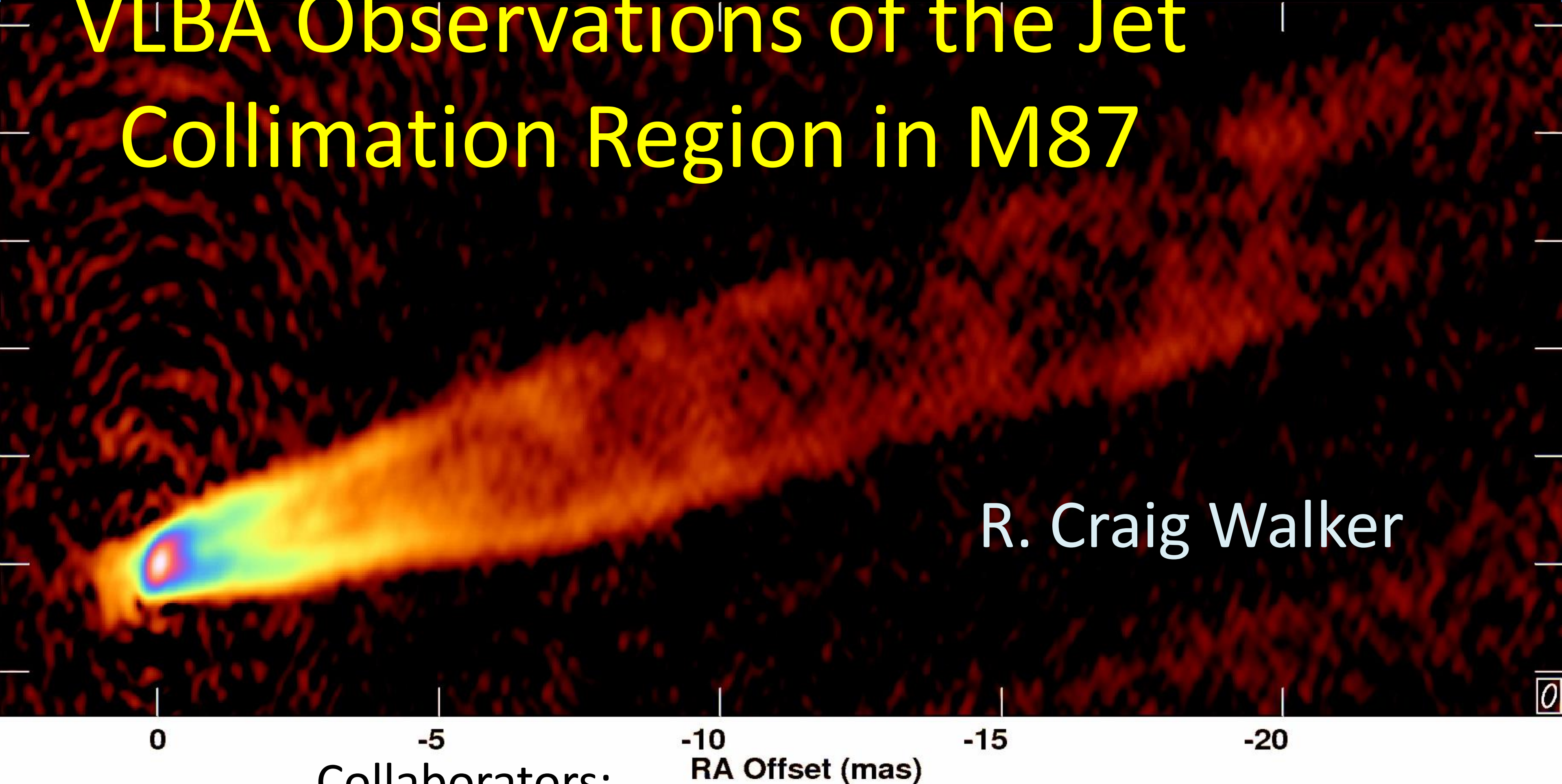
VLBA Observations of the Jet Collimation Region in M87



R. Craig Walker

Collaborators:

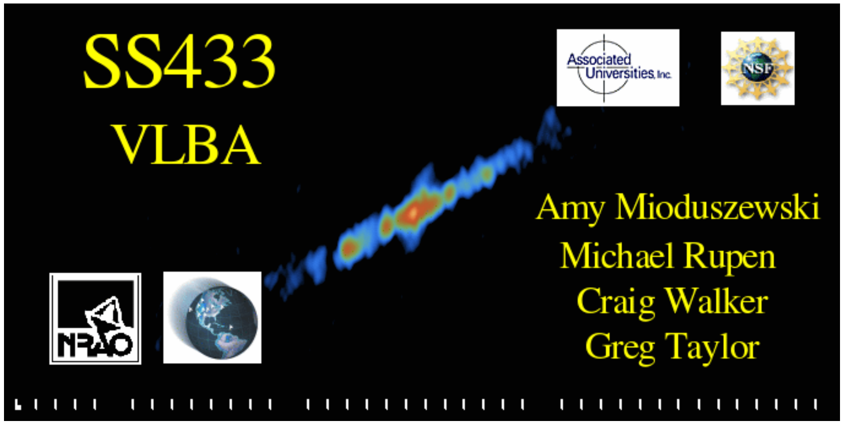
Radio: P. E. Hardee (U. Alabama), W. Junor (UC/LANL), F. Davies (UCLA), C. Ly (STScI)
TeV, γ-ray, X-ray connection: M. Beilicke (WUSTL), C. C. Cheung (NRC/NRL), D. E. Harris (DfA), H. Krawczynski (WUSTL), D. Mazin (IFAE), W. McConville (U. Maryland), M. Raue (U. Hamburg), and R. M. Wagner (MPI für Physik), The VERITAS, H.E.S.S., and MAGIC collaborations.
Velocity Measurement: Florent Mertens, Andrei Lobanov (MPIfR)

OVERVIEW

- Intent: To provide observational constraints on scales accessible to jet launch models
- Jet introduction
- Why M87?
- Morphology
- Kinematics
- Polarization (magnetic fields)
- TeV /radio connection – TeV emission location

M87 ➔

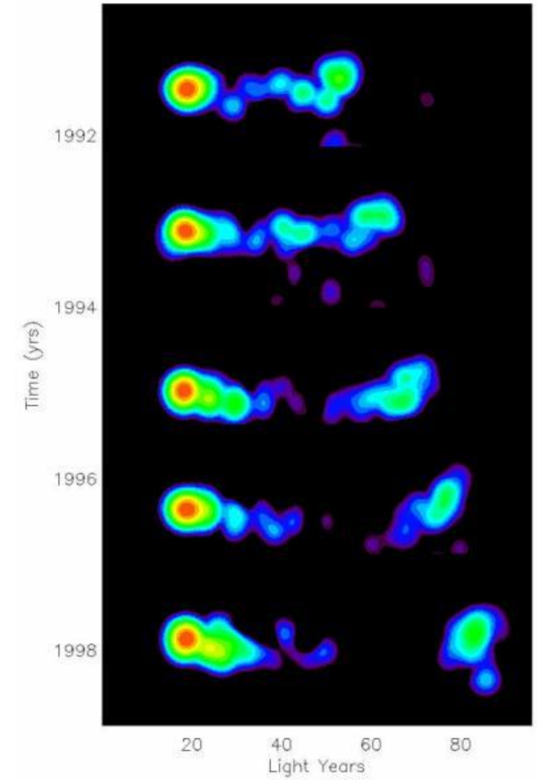
Jets are Ubiquitous
Associated with Accretion



Collapsed stars: SS433

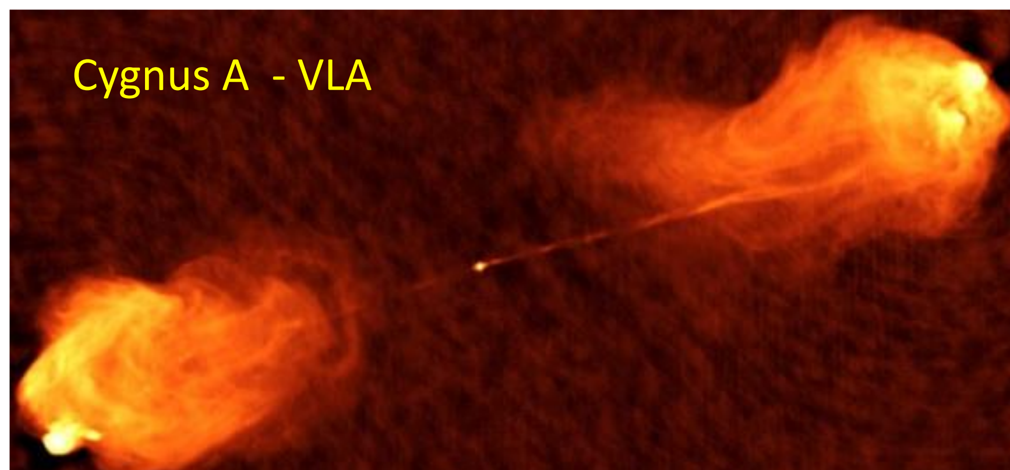
AGN

3C279 - VLBI
Superluminal
Motion



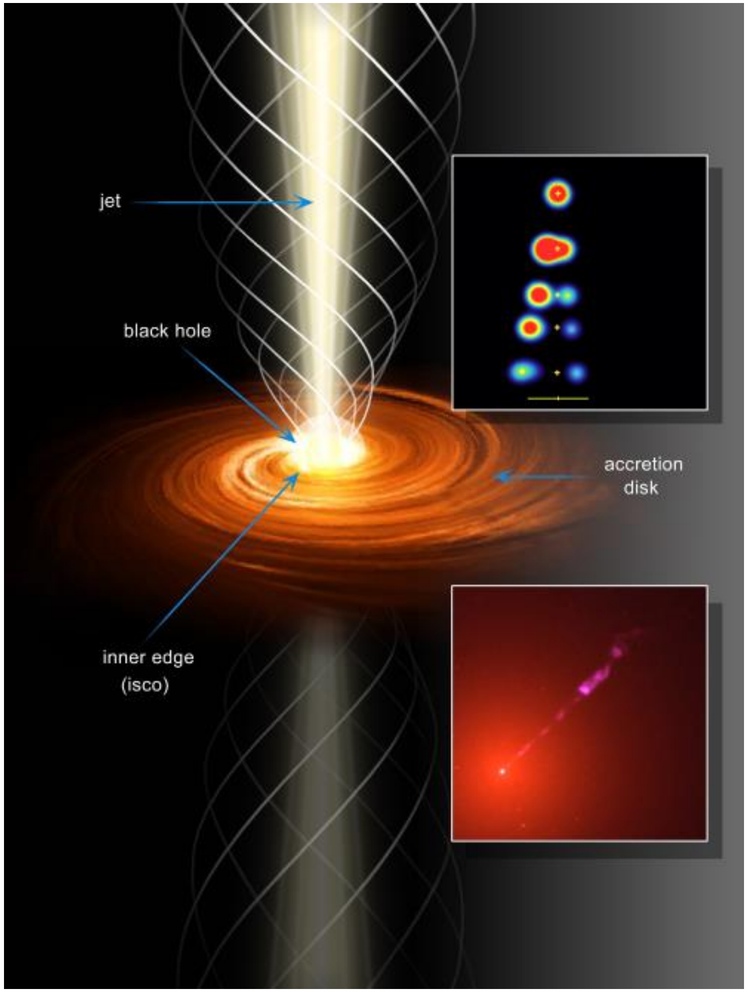
Large scale radio galaxies

Forming
stars:



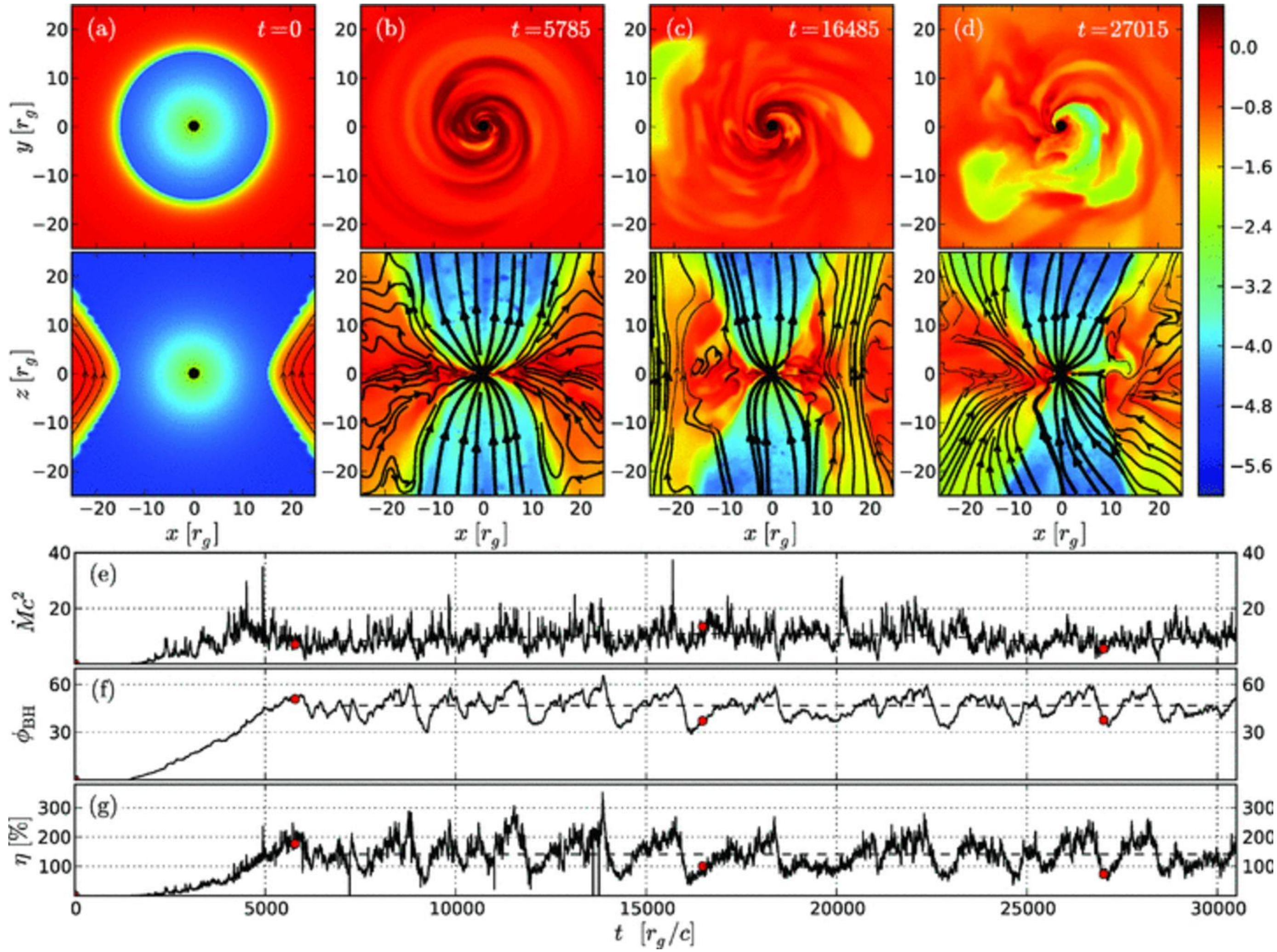
JET CREATION

- Jets are produced where there is accretion onto a compact object
  - A spinning disk is formed
  - Magnetic fields threading the disk get wound up along the polar axis
  - Outflow from the disk is accelerated and collimated by the twisted field
  - Can get Poynting flux from field carried into the central object
- Can be modeled numerically
- Our goal is to make observations to compare with simulations
  - Extreme resolution required



Credit: J.A. Biretta et al., Hubble Heritage Team (STScI /AURA), NASA

Shows results from the fiducial GRMHD simulation A0.99fc for a BH with spin parameter a = 0.99; see Supporting Information for the movie.



Tchekhovskoy A et al. MNRAS 2011;418:L79-L83

MONTHLY NOTICES of the Royal Astronomical Society LETTERS

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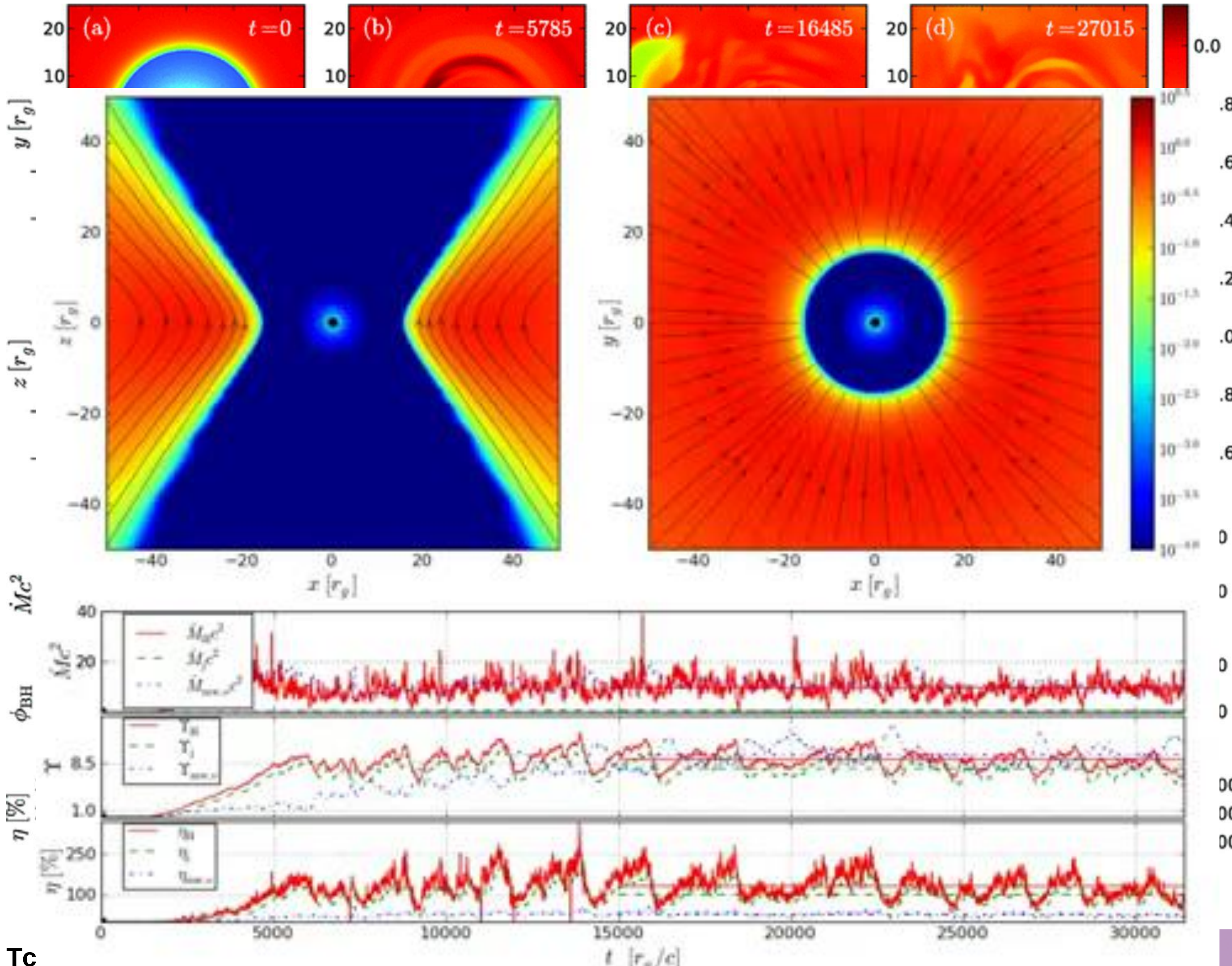


Tc

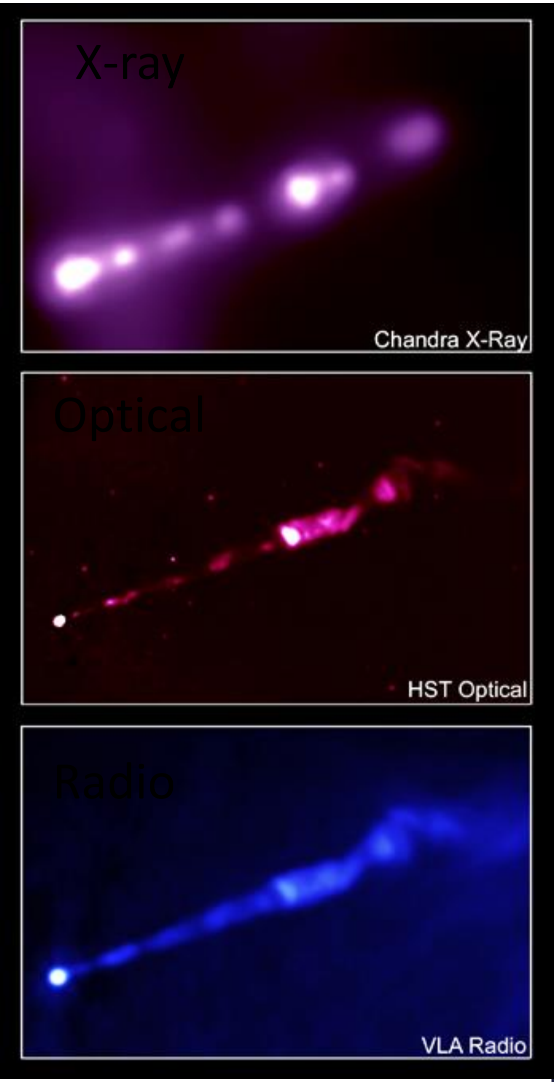
of the Royal Astronomical Society
LETTERS

WHY M87?

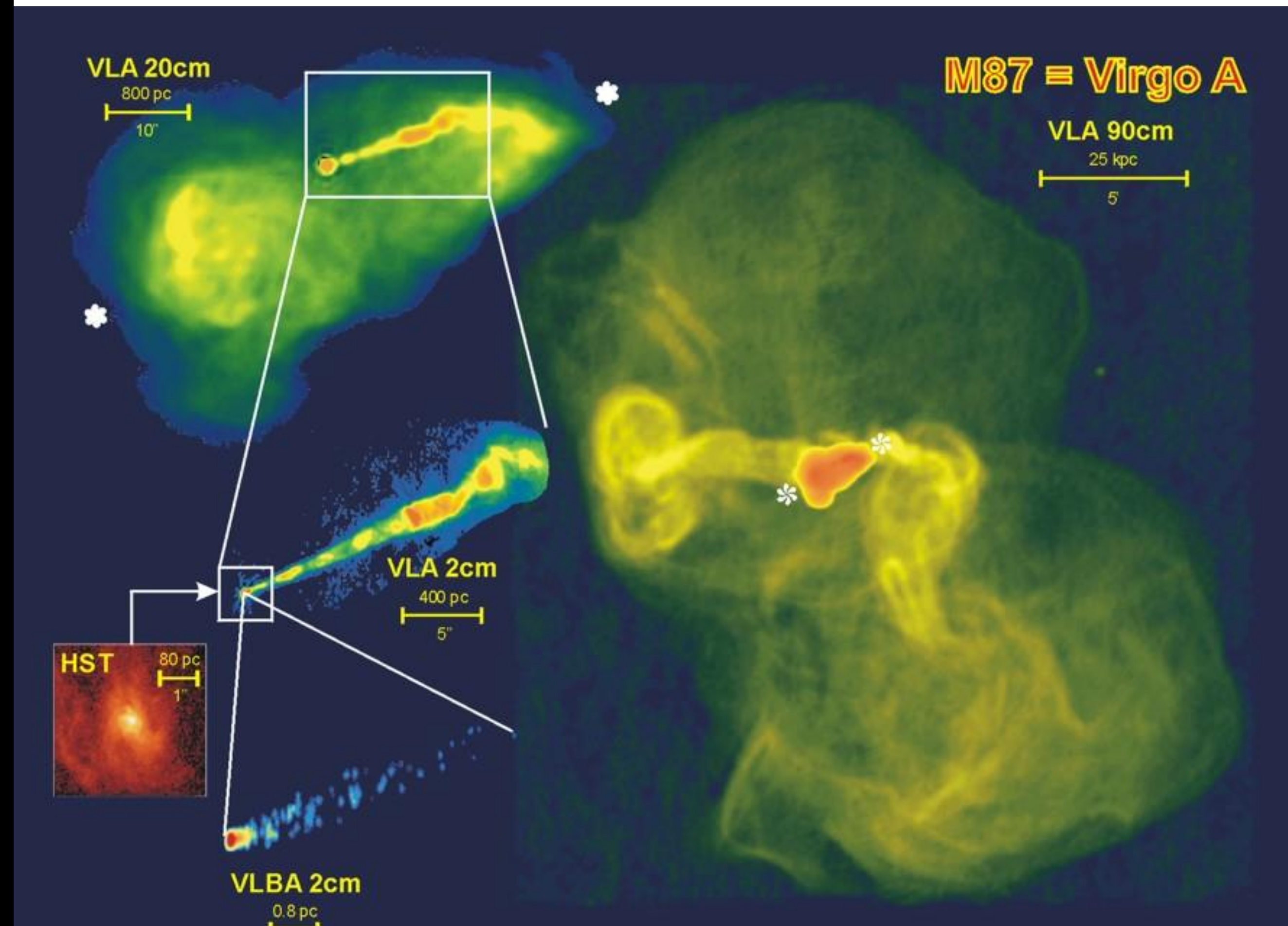
- THE BEST SOURCE FOR IMAGING A JET BASE
- Large angular size black hole
  - **Nearby**: 16.7 Mpc (Virgo Cluster: Mei 2007; Bird 2010)
    - 1mas = 0.081 pc = 16700 au; 1 c = 3.8 mas/yr
  - **Massive**: $6.2 \times 10^9 M_\odot$ (Gebhardt et all. 2011 scaled for distance)
    - Caution – the mass is controversial
  - Scale: $R_s = 7.2\ \mu as = 120$ 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 STRUCTURE OVERVIEW

1 kpc scale

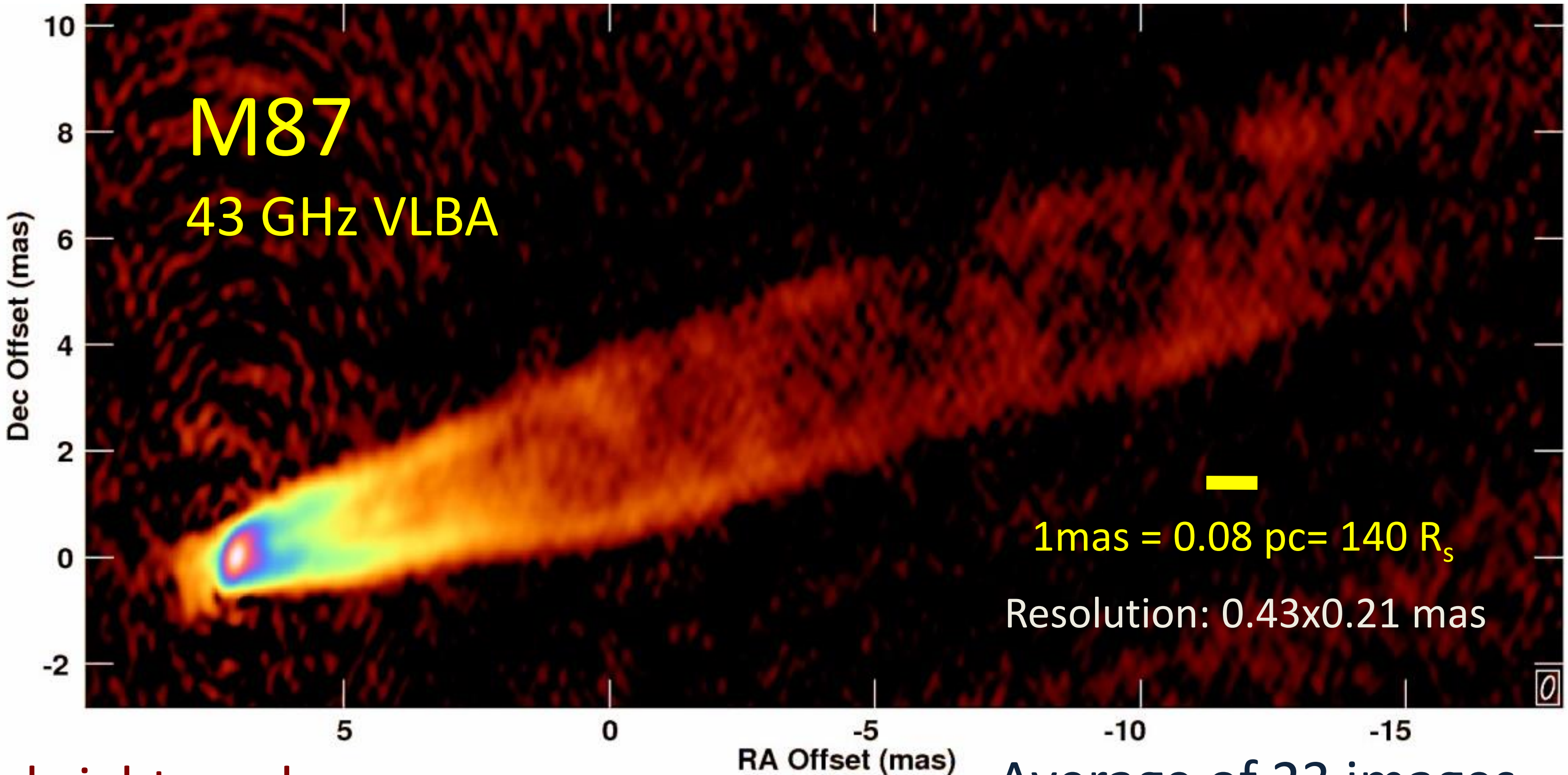


Chandra



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

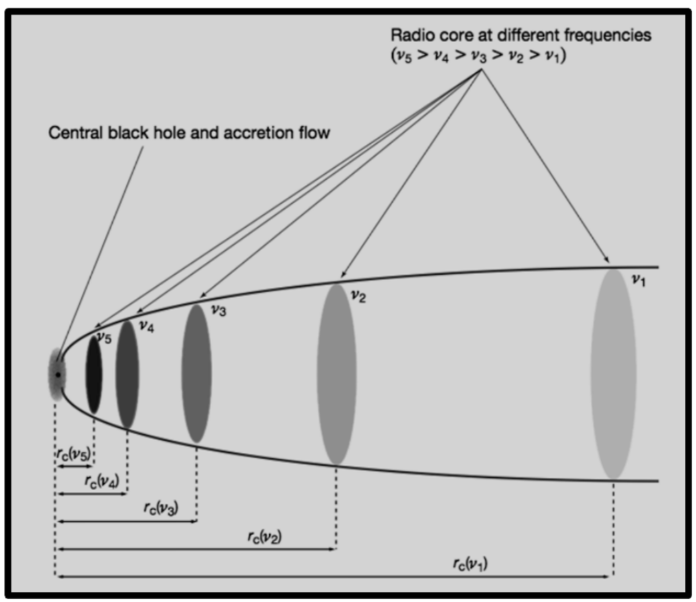
Before upgrade; 256 Mbps

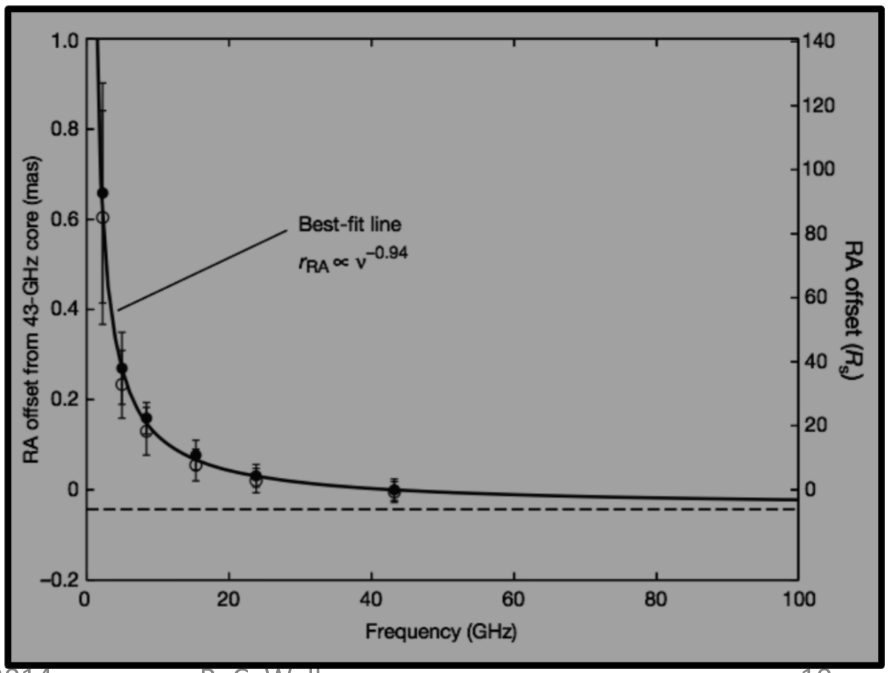
Average smooths changing features – like time exposure of a waterfall

FD

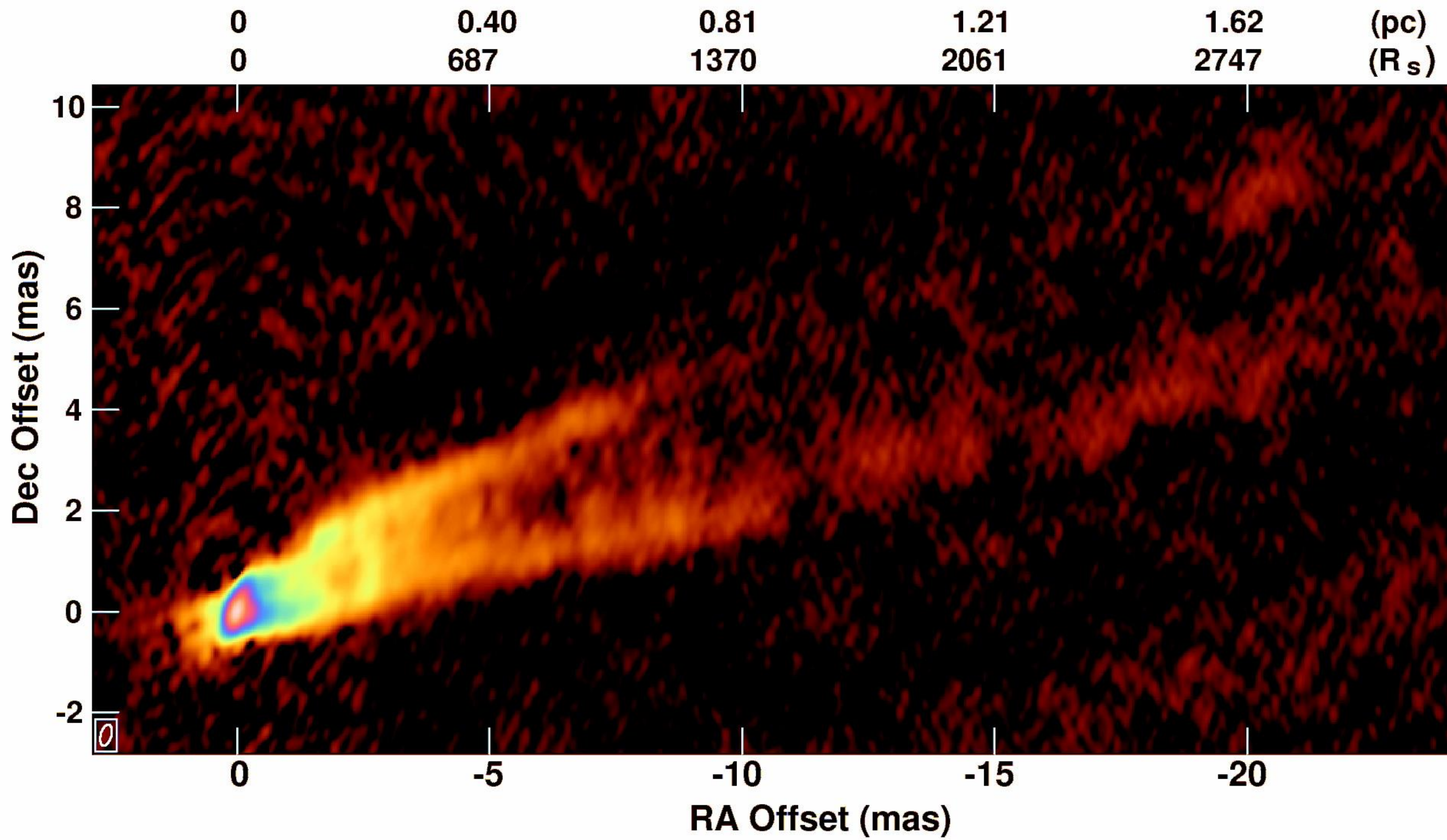
IS RADIO CORE AT THE BLACK HOLE?

- 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 no position change to 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





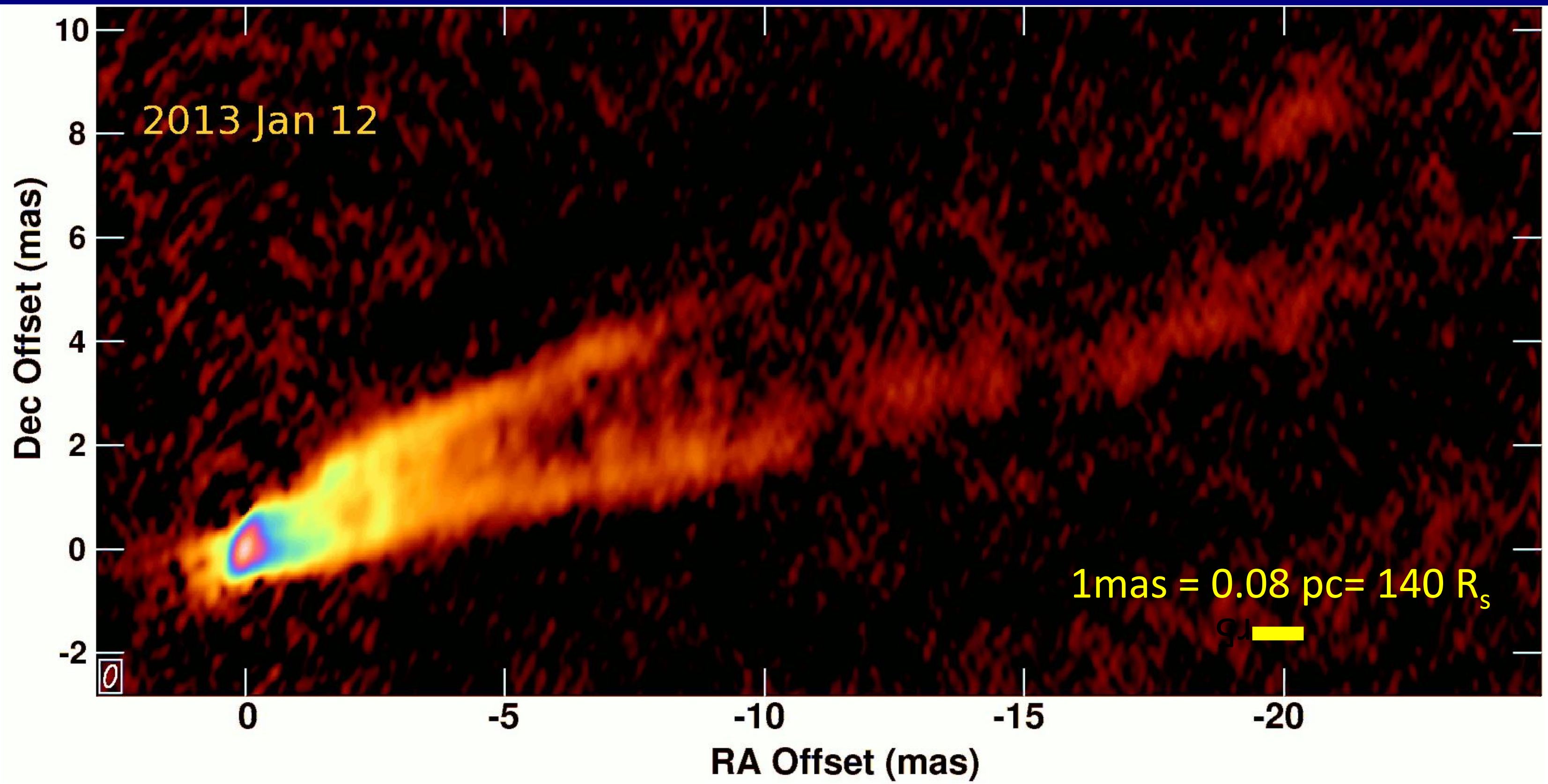
M87 in Jan. 2013



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

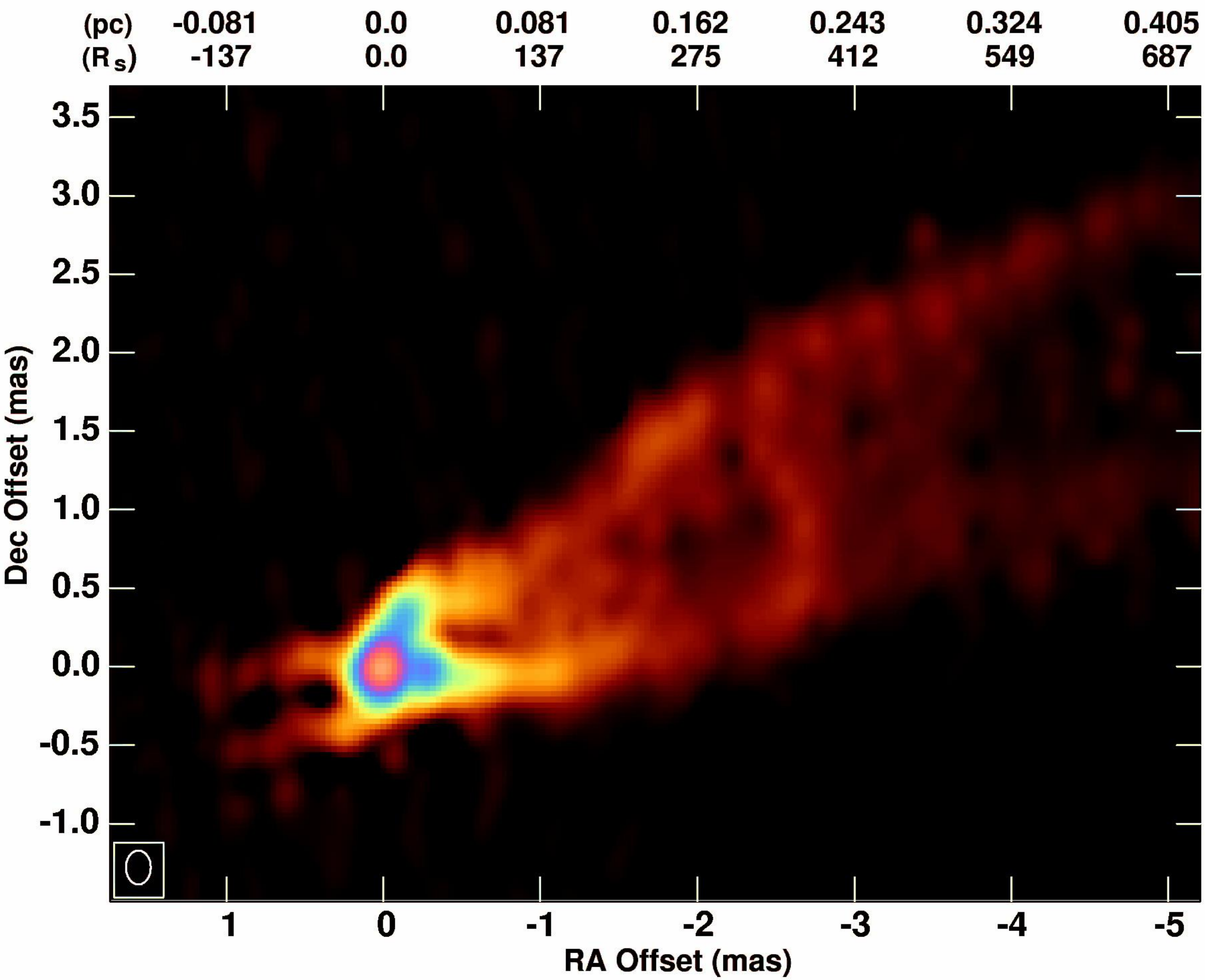
CHANGE IN JET ENVELOPE

KP



- 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

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

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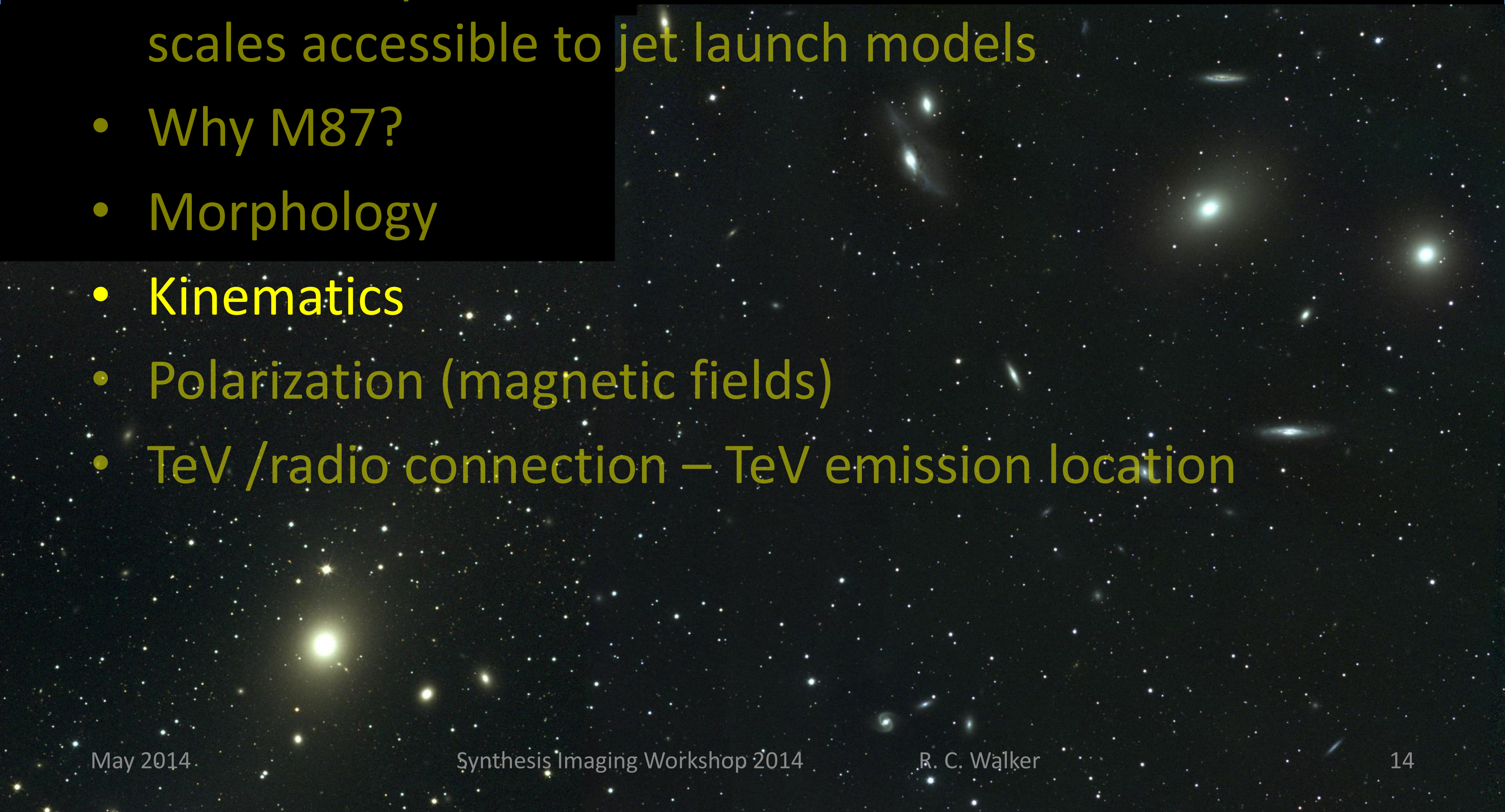

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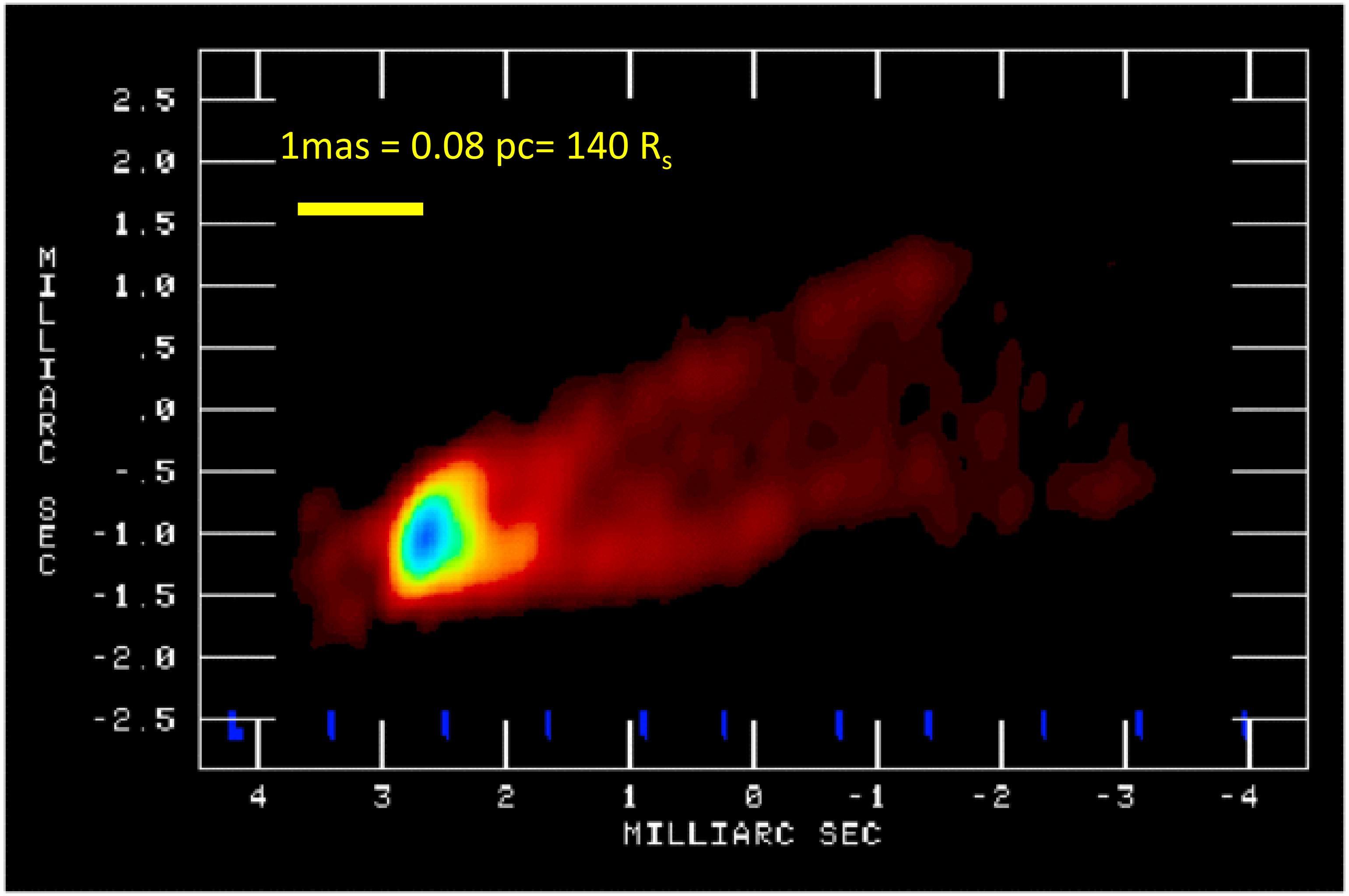
KINEMATICS: VLBA 43 GHz M87 MOVIE



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”

BR

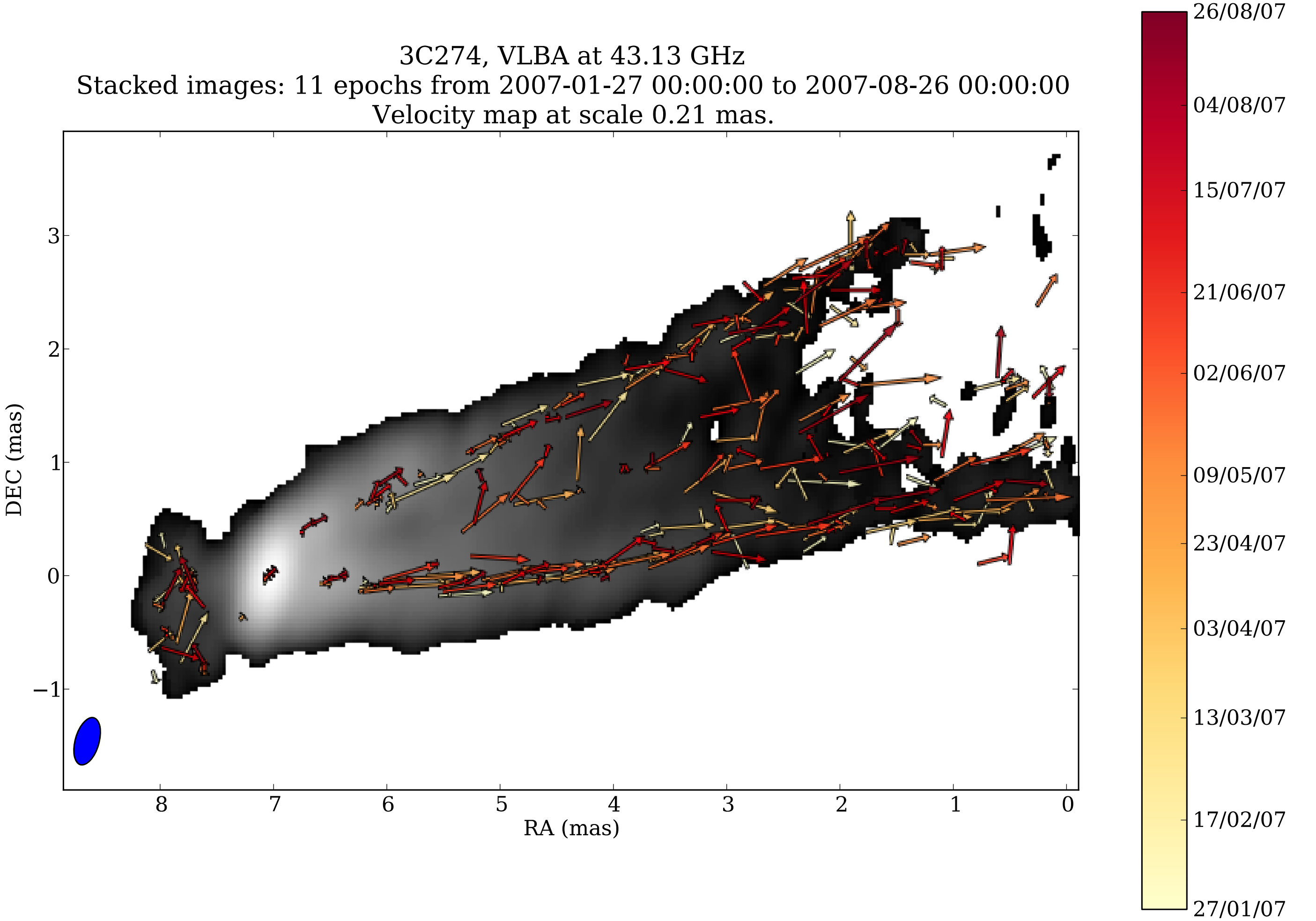
JET SPEED

Few persistent features

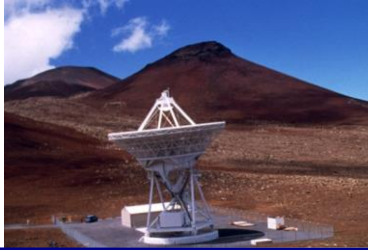
By eye comparison of features in adjacent epochs suggests ~2c

Wavelet analysis by Mertens and Lobanov gives similar answer. Analysis still in progress

Speed seems lower close to core



The VLBA 43 GHz M87 Fast Sample Movie



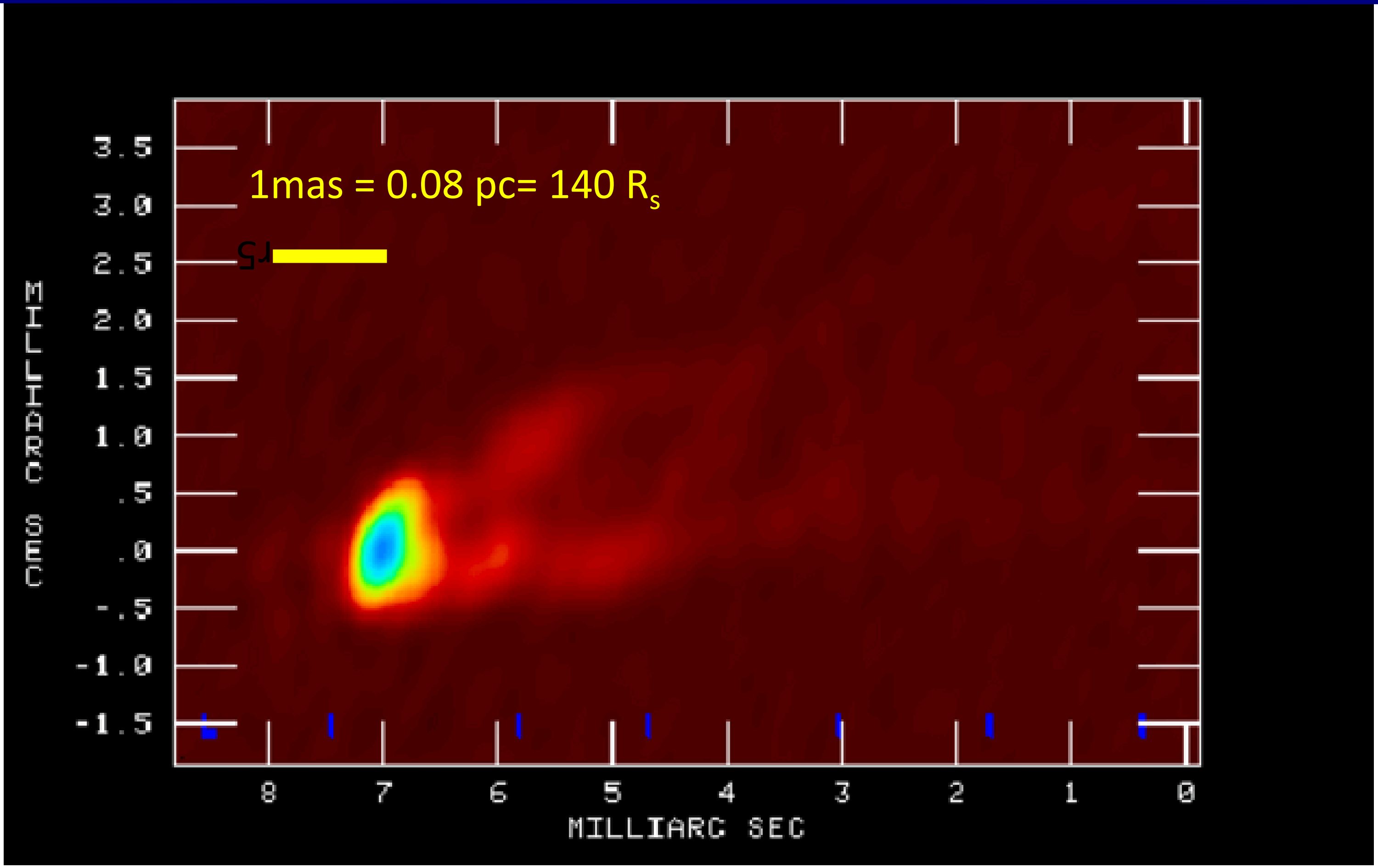
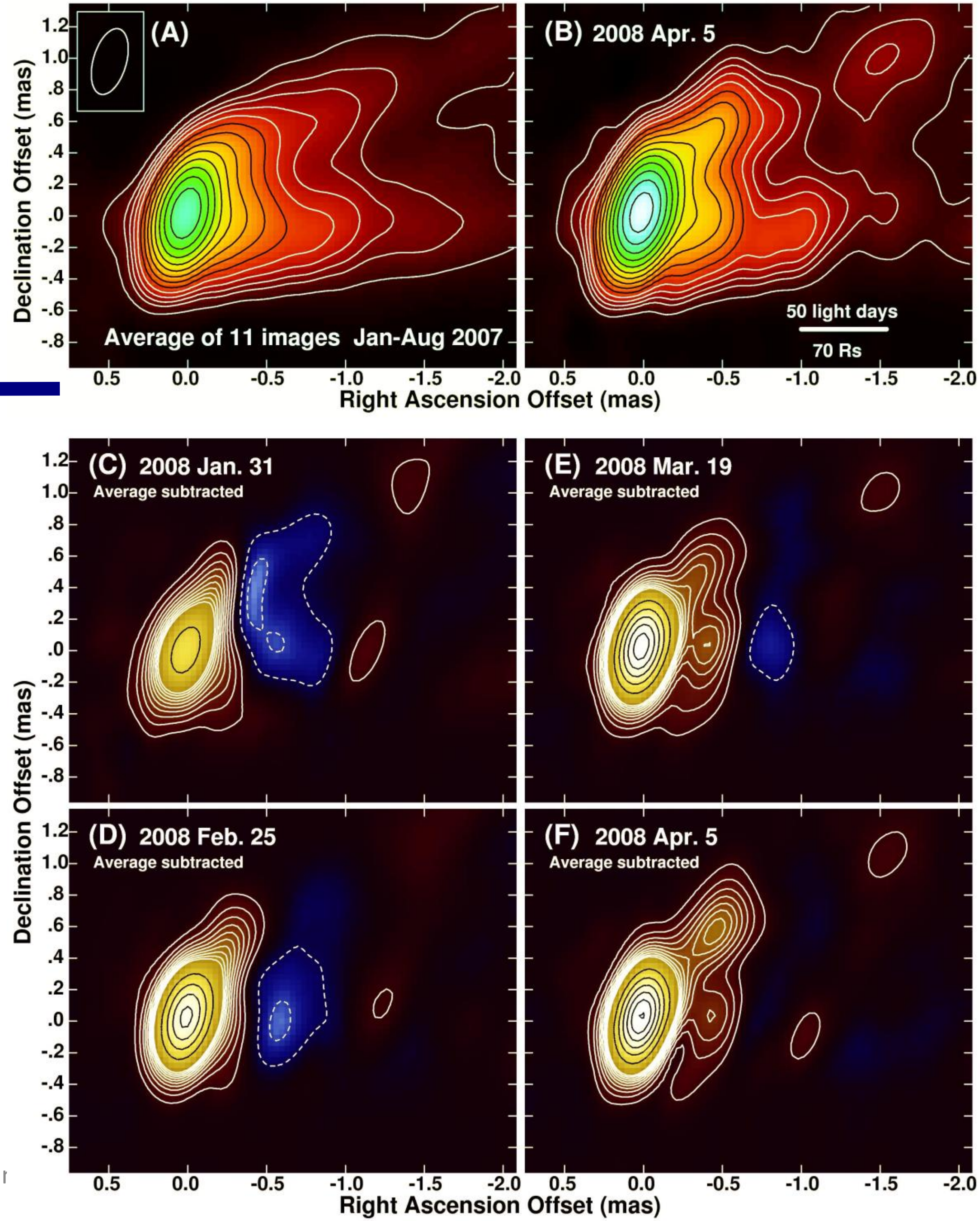


Image every 5 days. Flare on core. New features

– Flare coincides with TeV flare

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

M87 BRIGHTNESS PROFILE ALONG JET

N
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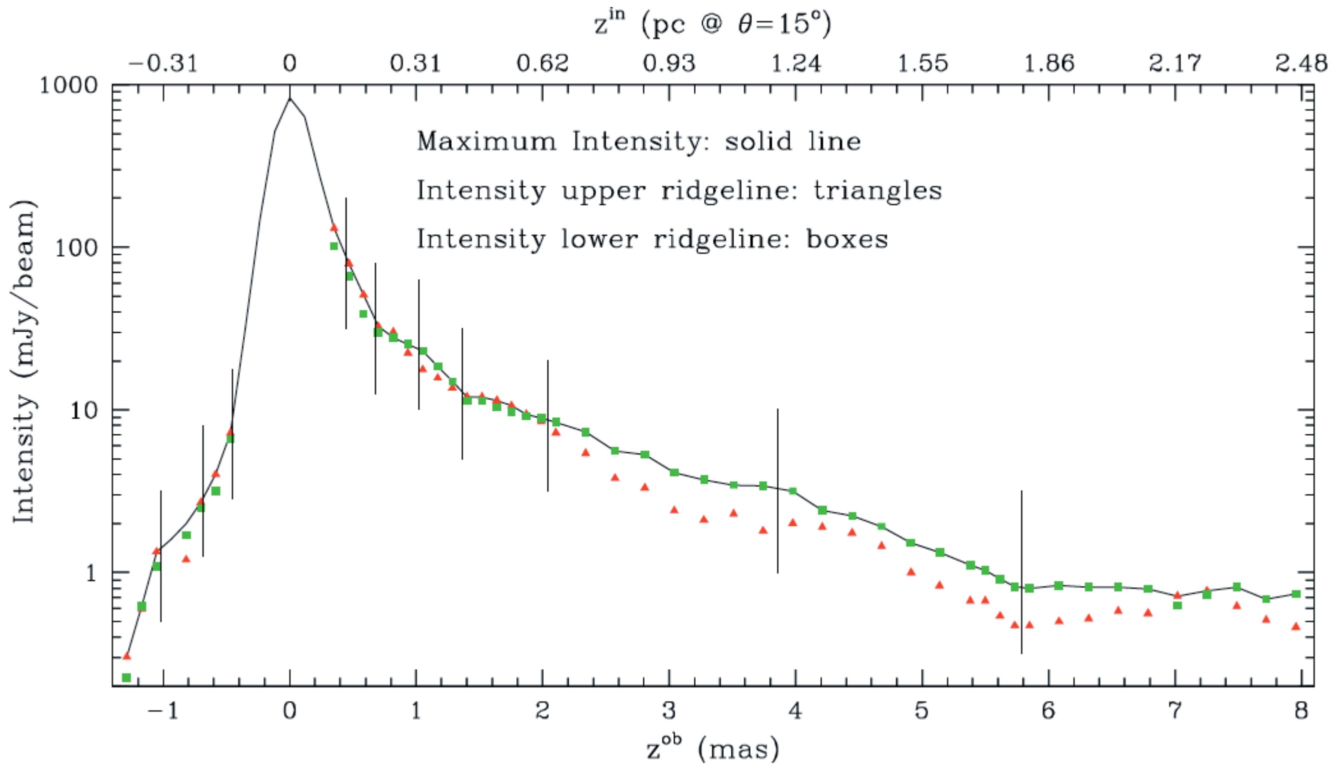


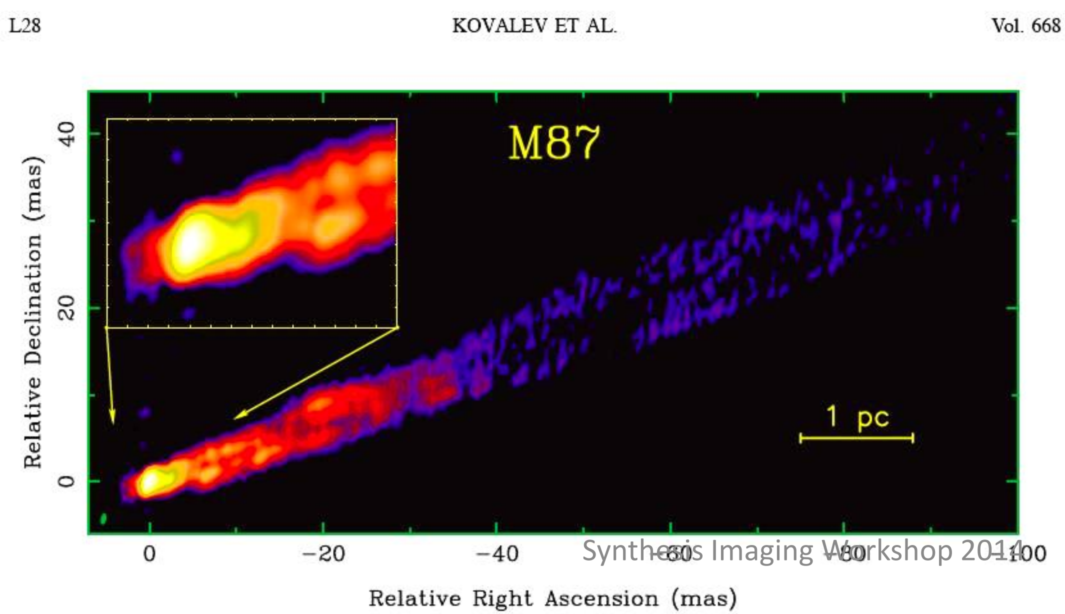
Rapidly increasing jet/counterjet sidedness ratio

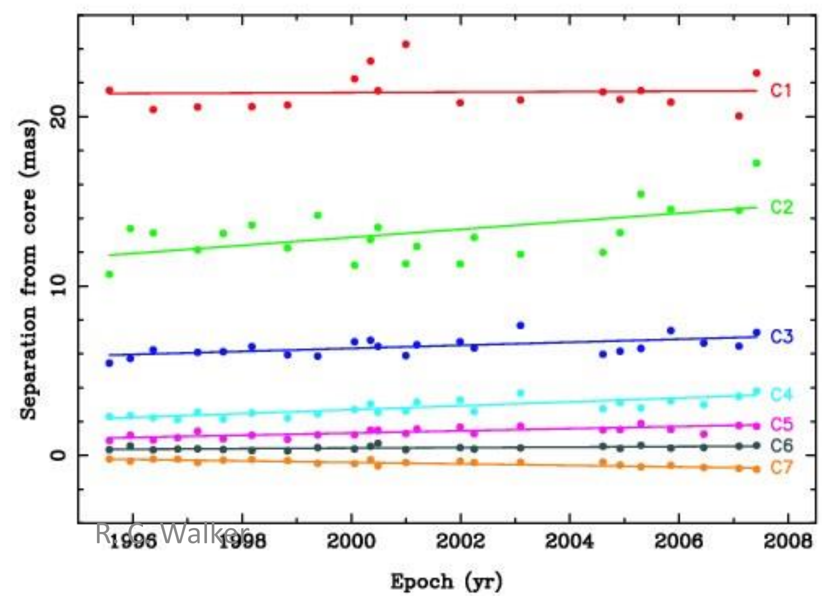
Suggests beaming with acceleration over at least 1 mas

Analysis of this and transverse structure data in progress (Hardee)

KINEMATICS: VLBI SUBLUMINAL MOTION MEASUREMENTS

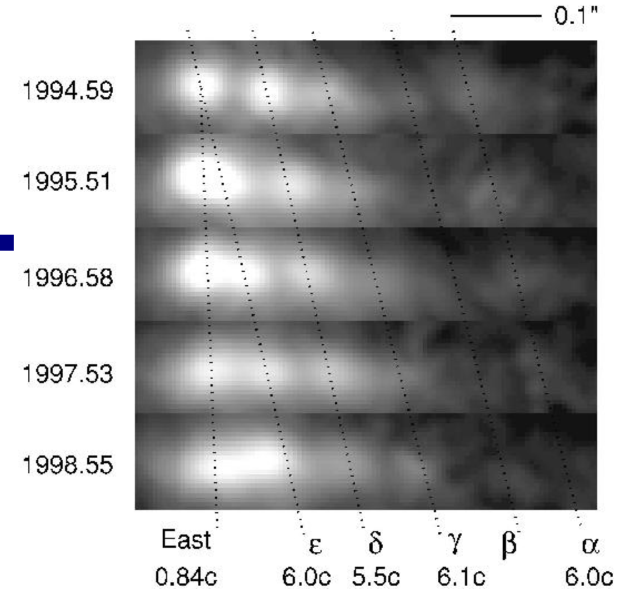
- Many VLBI observations show slow motions
  - VLBA < 0.1c (Biretta & Junor 1995; Junor & Biretta 1995)
  - VSOP No motions (Dodson et al 2006)
  - VLBI 1.6 GHz 0.28c (Reid et al 1989)
  - VLBA 43 GHz 0.25-0.40c (Ly et al 2007)
- Perhaps best case is 15 GHz monitoring (Kovalev et al. 2007)
  - A few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

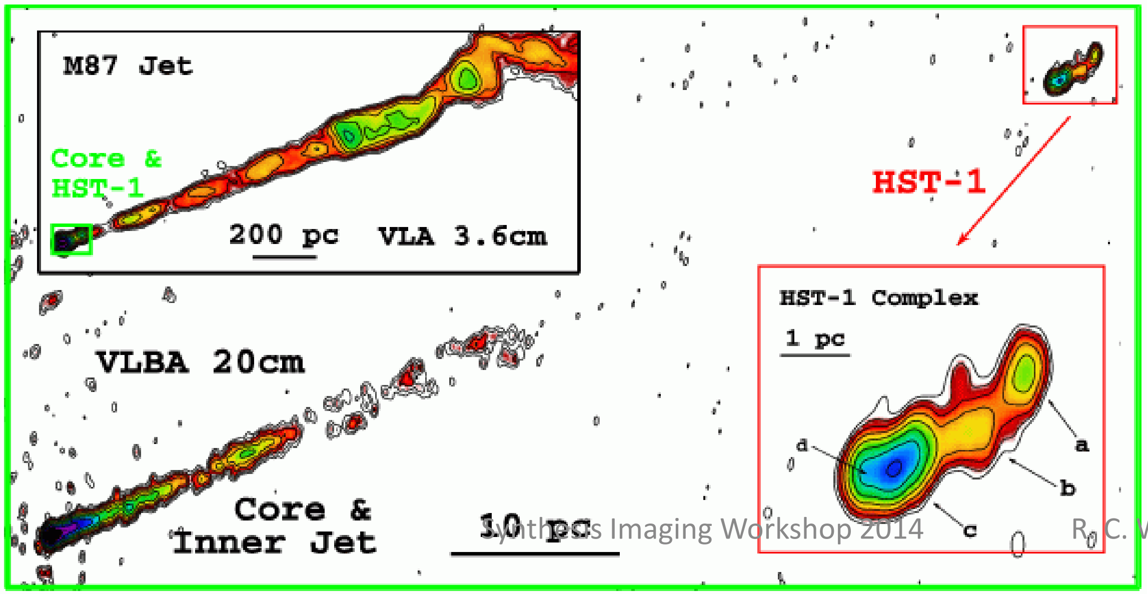


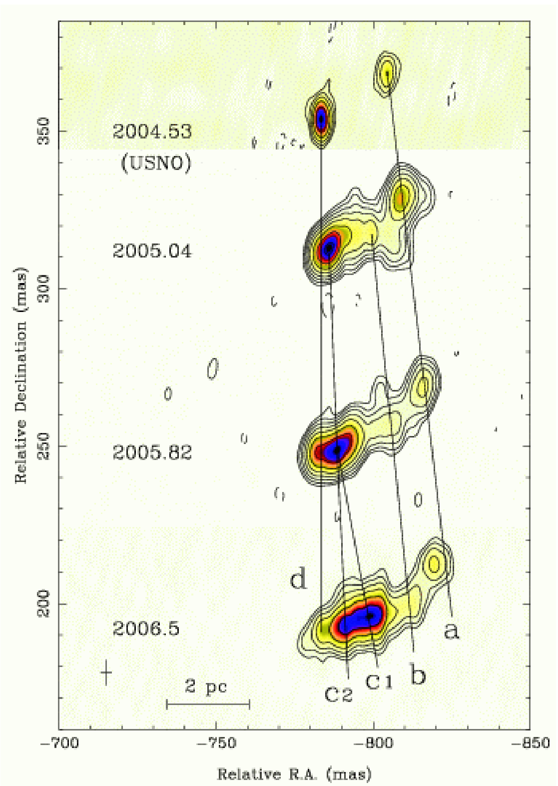


KINEMATICS: SUPERLUMINAL MOTIONS

- 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







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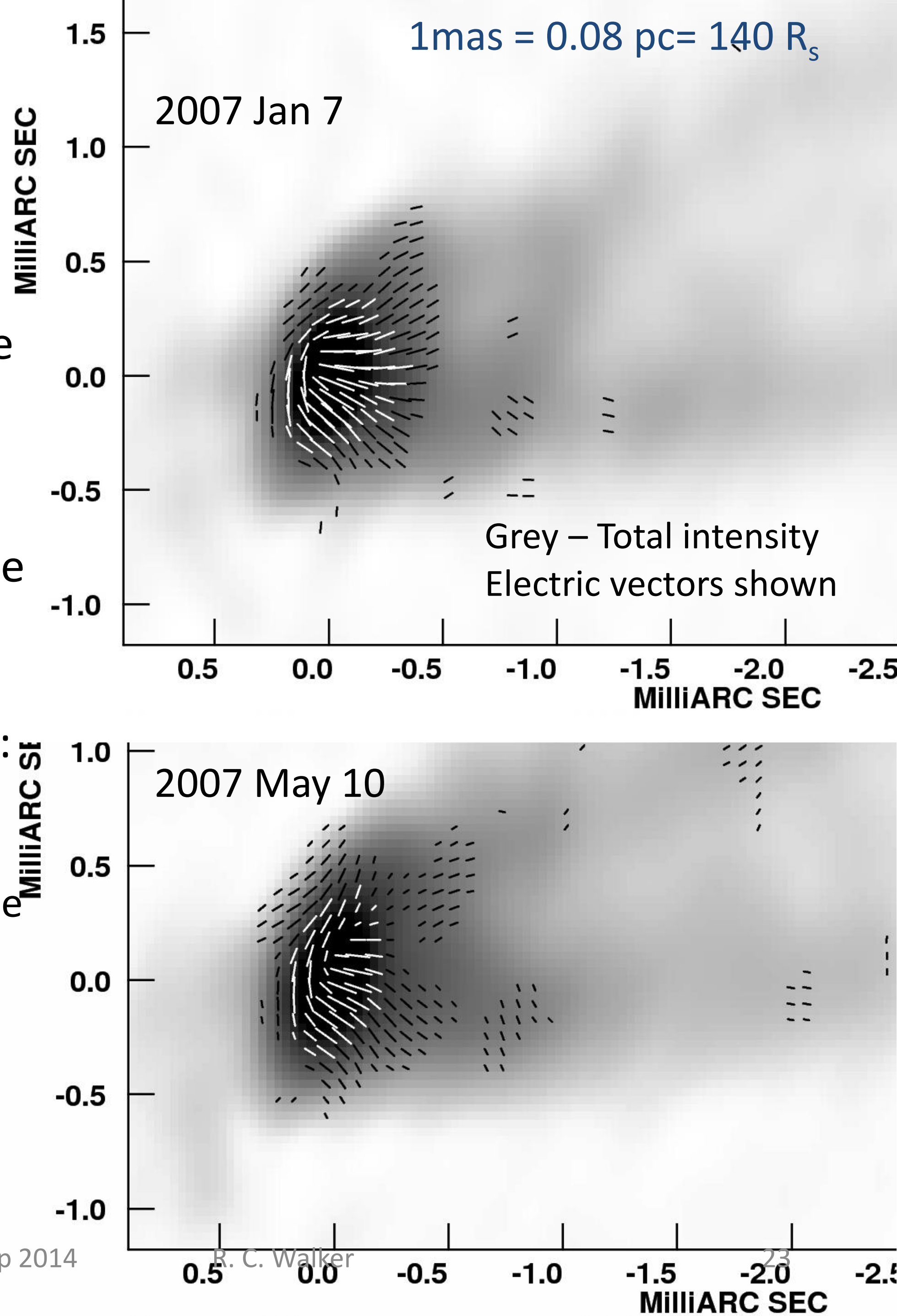
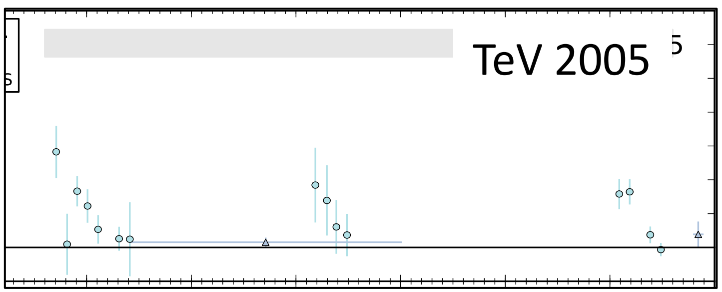
POLARIZATION

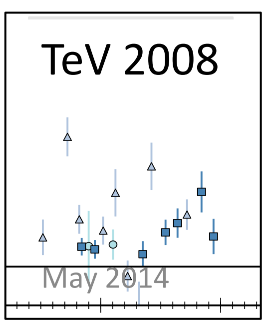
- Jet side of core: E vectors are along the jet direction suggesting transverse field
  - Vectors show the wide opening angle base
- Counterjet side: E vectors are across the jet, or wrapped around core
- Probable azimuthal field geometry, but modeling is needed taking into account:
  - Close angle to line of sight
  - Wide opening angle base
  - Rapid brightness decrease with distance
  - Opacity
  - Counterjet
  - Possible acceleration, beaming, optical depth and faraday rotation effects
- Much data awaits processing

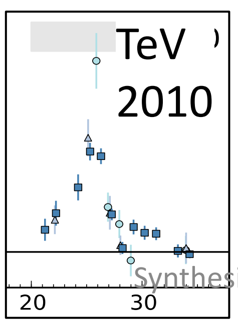


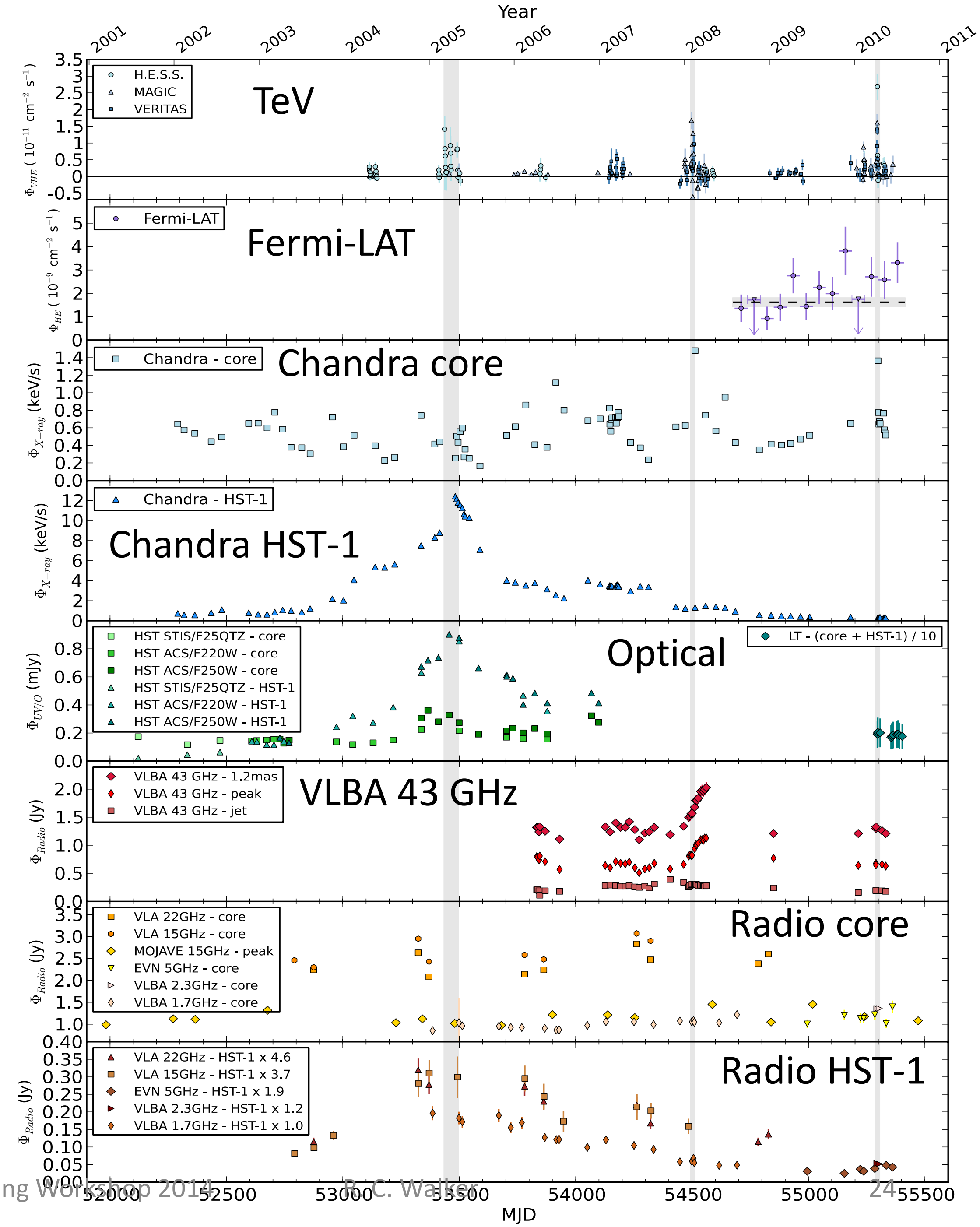
TeV FLARES

- 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

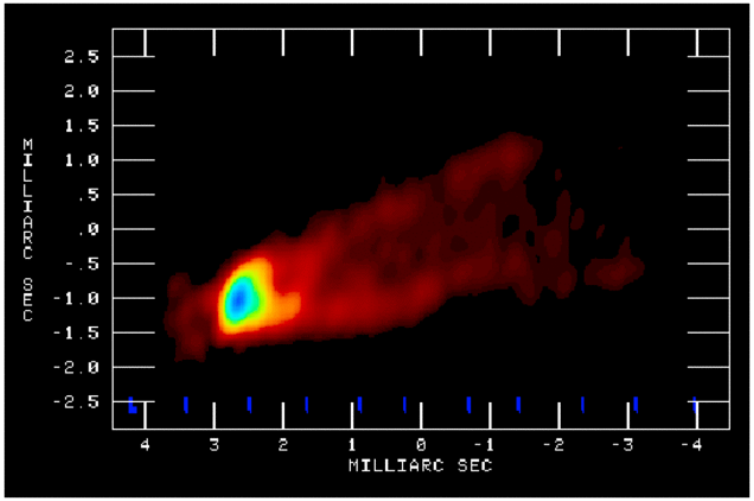








SUMMARY



- M87 is the best source for imaging a jet launch region
  - Nearby, Massive Black Hole, Bright Jet
- Implications of multi-epoch VLBA observations of M87
  - Edge brightening: We see the surface or sheath in this region
  - One sidedness and motions of 2c in inner jet: Relativistic
  - Counterjet and flare components: Jet accelerating to at least 150 Rs in projection
  - Motions of 4c at HST1: Suggest a fast central jet not seen near the core
  - Measured slow motions before HST1 are likely patterns
  - Magnetic field appears to be azimuthal
  - TeV/VLBI flare in 2008 suggests TeV from very near BH
    - 2010 results confuse the issue
- Request: Carry the models to at least 1000 Rg for comparison with data
- Question: What sets the transverse size when collimation complete?
  - Is there a possible way to measure the BH mass based on that size?