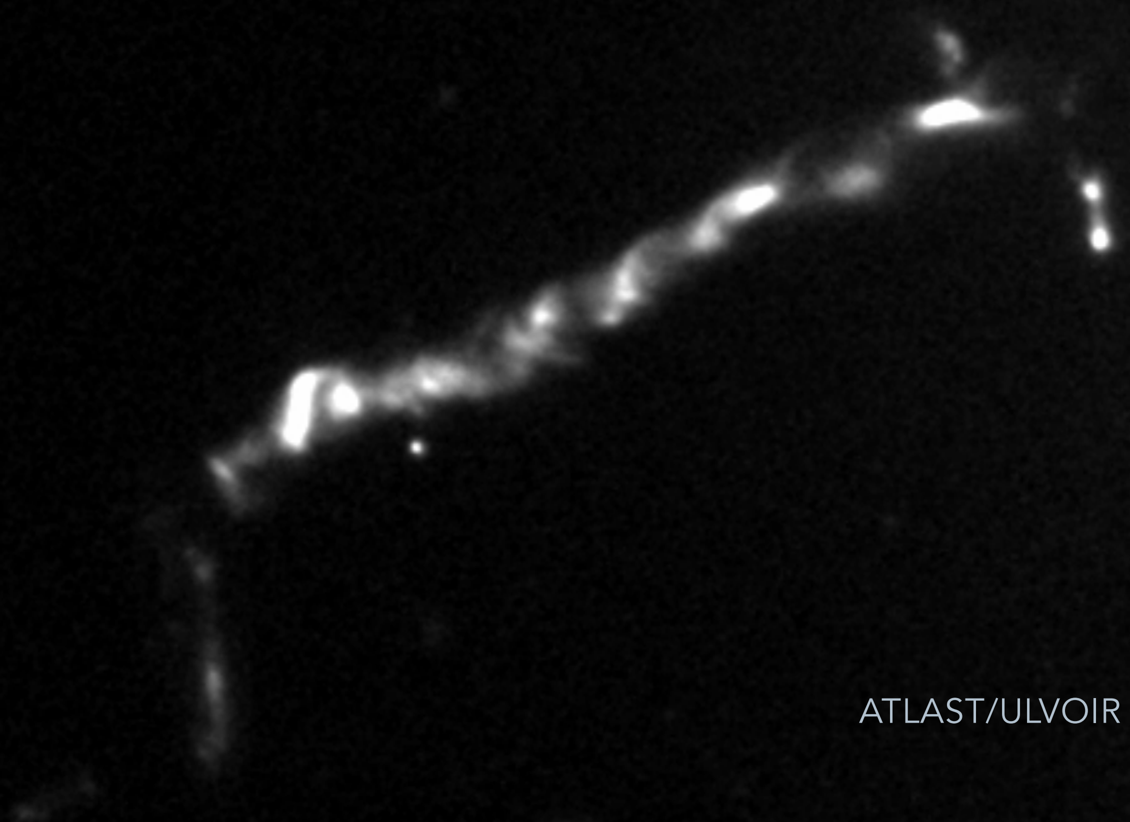
PROPER MOTIONS OF JETS FROM BLACK HOLES IN THE HST ERA AND BEYOND



Eileen Meyer

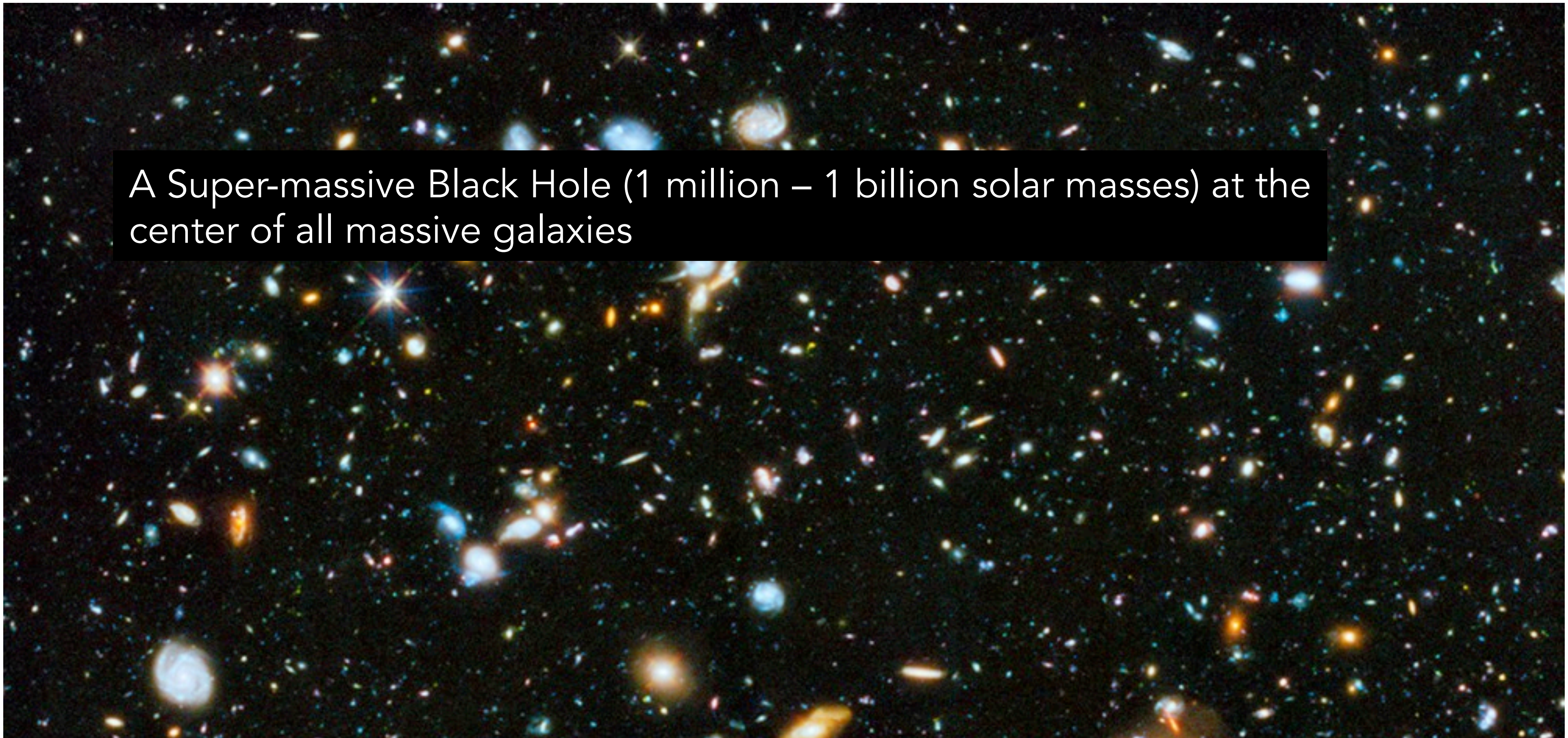
Postdoctoral Fellow

Space Telescope Science Institute

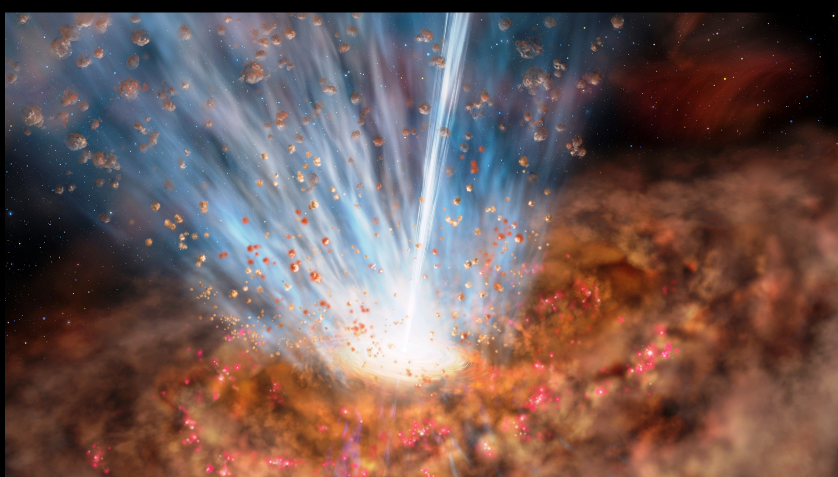
(→ UMBC this fall)

ATLAST/ULVOIR Symposium, GSFC, 12 August 2015

Bill Sparks (STScI), John Biretta (STScI), Jay Anderson (STScI), Roeland van der Marel (STScI), Tony Sohn (JHU), Marco Chiaberge (STScI), Colin Norman (JHU), Markos Georganopoulos (UMBC)



A Super-massive Black Hole (1 million – 1 billion solar masses) at the center of all massive galaxies



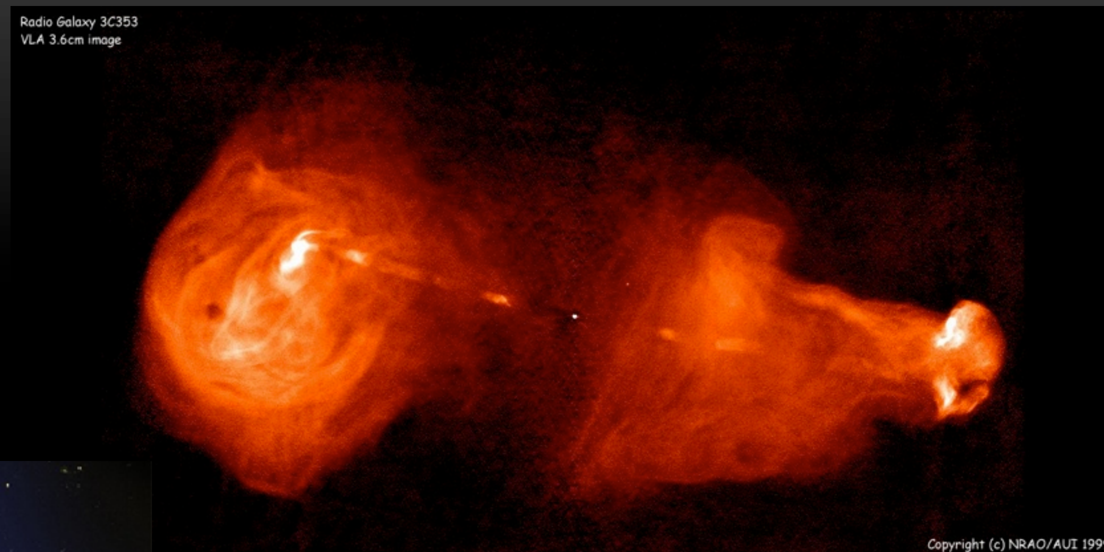
A few % of these black holes become "active" by accreting matter
→ Active Galactic Nuclei (AGN)

Luminosities up to 10^{47} erg/s

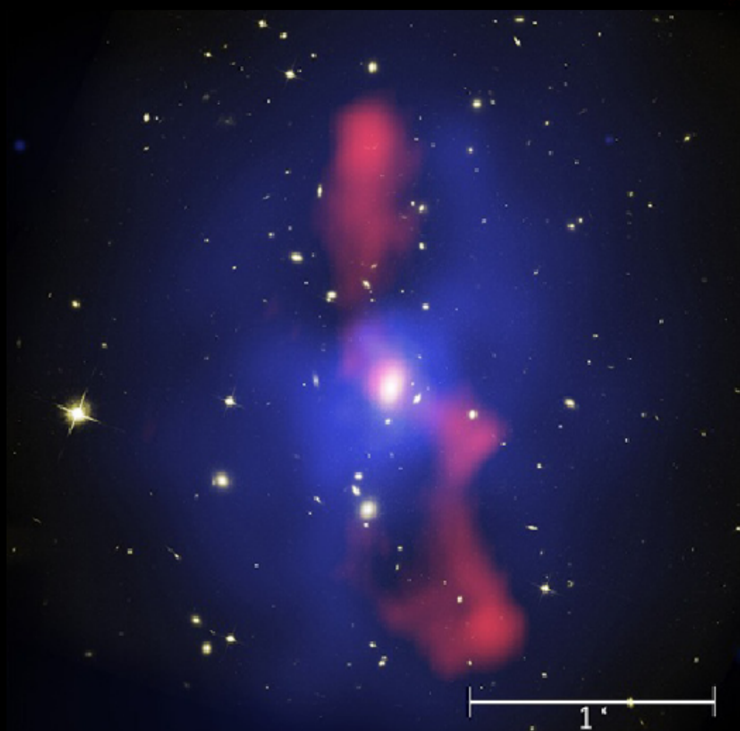
Massive Winds (3000 solar mass/year!)
Fast Winds (0.3c!)

About 10% of AGN have Relativistic Jets

Synchrotron radiation from
Radio to X-rays



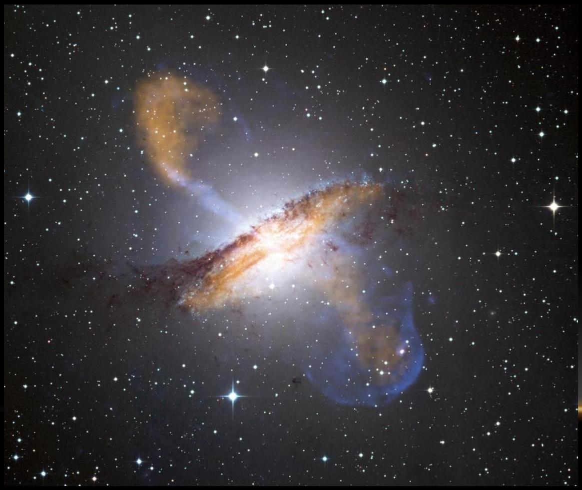
3C 353 (NRAO)



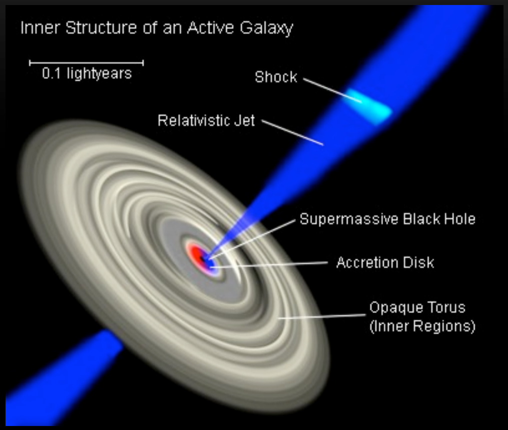
MS0735.6 (McNamara et al 2009)

Kinetic Powers up to 10^{46} erg s
Lifetimes ~ 10^{7} yr (?)
Jet lengths can reach ~1 Mpc
Heating of the galaxy-scale gas
and cluster medium

Q: How did galaxies form and evolve to produce the Universe we observe today?



JETTED AGN



AGN as systems

- Why few % of galaxies are active?
- Why 10% of AGN have jets?
- How are Jets formed/launched & connection to the black hole (mass, spin) – what is the `trigger'?
- Energy balance (what is the jet made of)?
- What are the lifetimes/duty cycles of the jet?

AGN jets and "feedback" (the "bigger picture" impact)

- Lots of energy and matter is being `recycled' on huge scales
- However, quantitatively this is not understood (see above)
- POSSIBLE impacts of jets on galaxy formation, evolution (even altering the makeup of the Universe in terms of types of galaxies produced)
- possible link to reionization

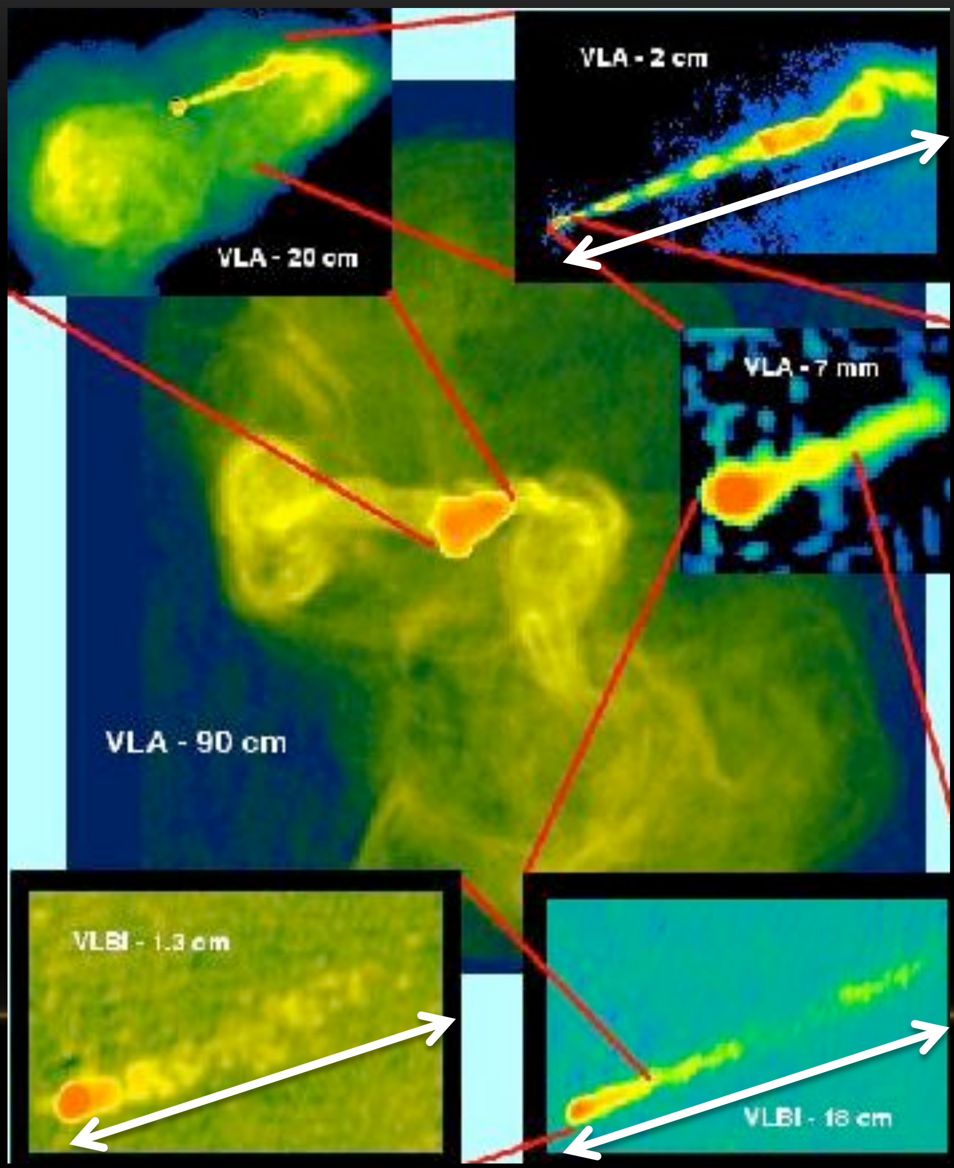
PROPER MOTIONS

PROPER MOTIONS

PROPER MOTIONS OF JETS

M87, one of the archetypical nearby jets

(Biretta & Junor 1995)

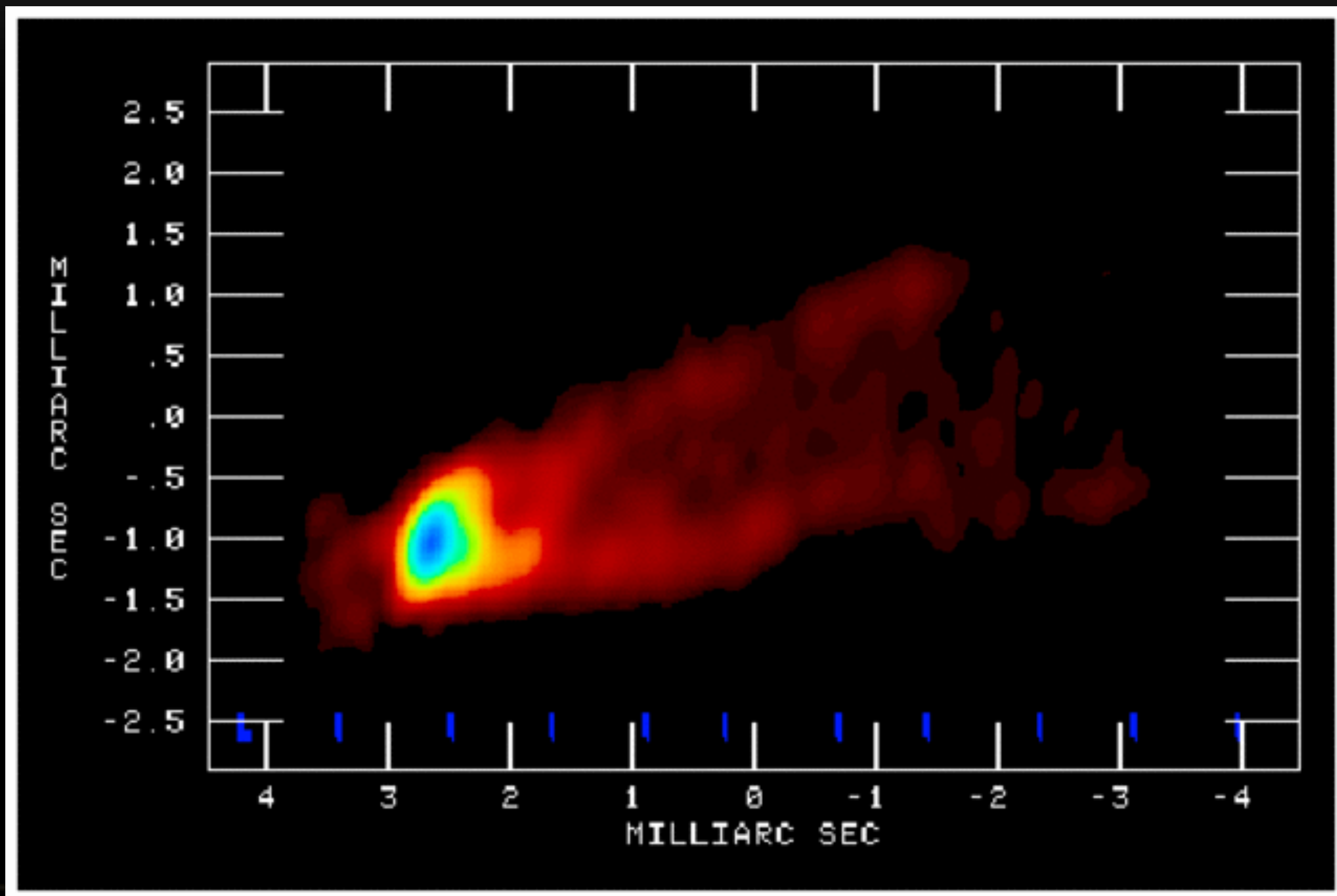


20″ (2 kpc)

24 mas (2.5 pc)

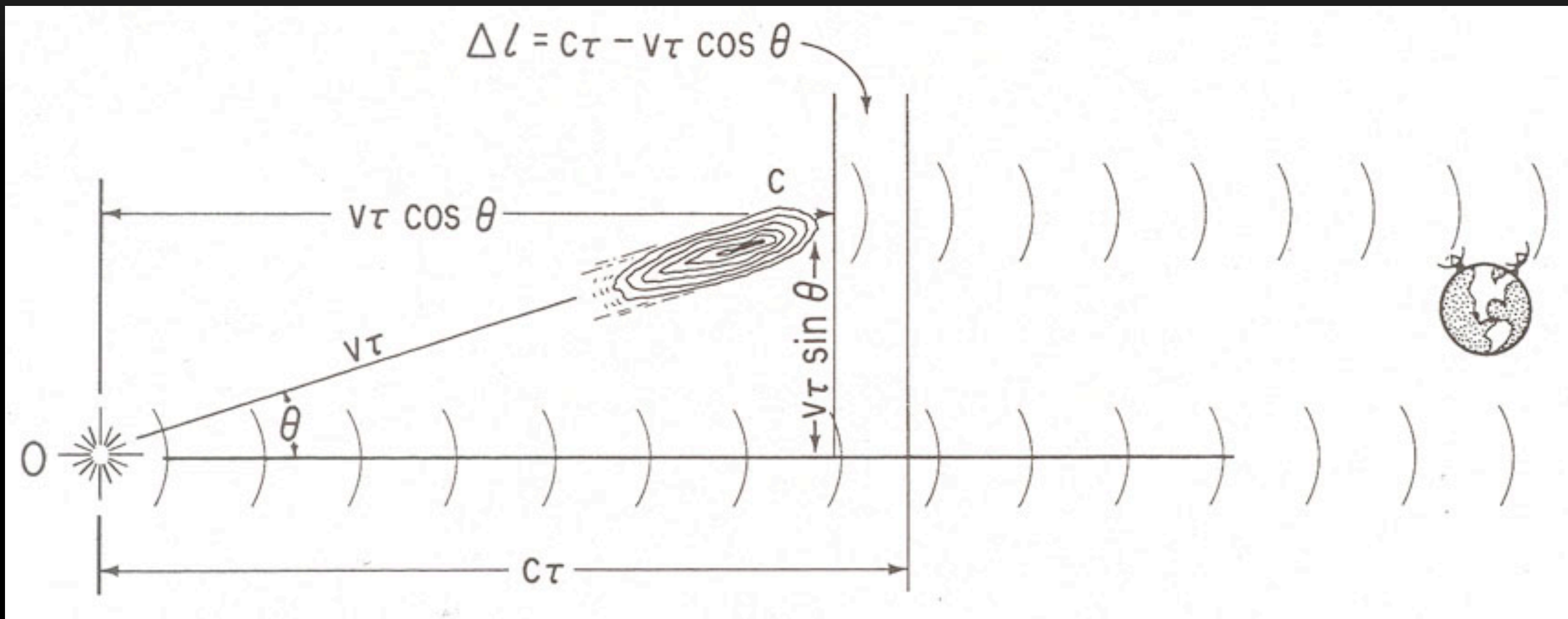
0.15″ (17 pc)

PROPER MOTIONS OF JETS



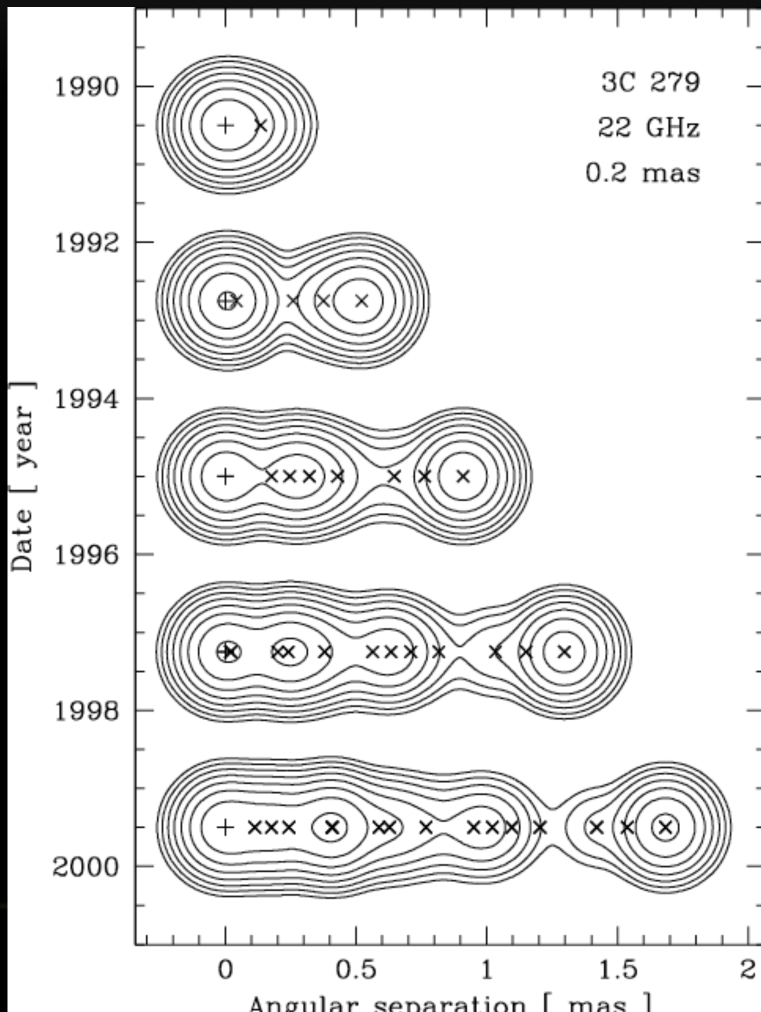
Movie Credit: Craig Walker

PROPER MOTIONS OF JETS



Superluminal motion – first predicted in the 1960s, detected soon after and confirmed the relativistic jet at the heart of radio quasars

PROPER MOTIONS OF JETS – IN THE RADIO



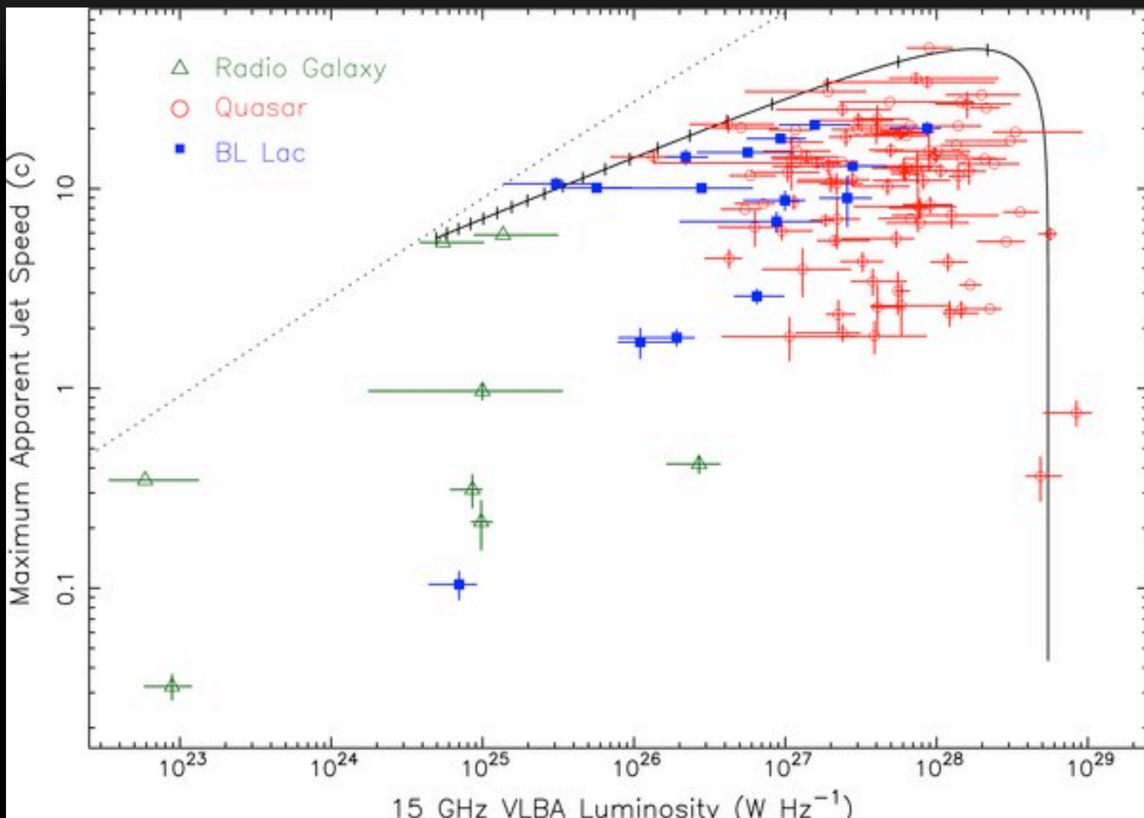
Probing scales close to the black hole (sub-pc to tens of pc)

Relies on a stable core position

Hundreds of sources with measured proper motions *(MOJAVE sample, Lister et al. 2009, also Jorstad, Marscher, Piner, many more over decades)*

Apparent velocities from sub-luminal up to 50c

PROPER MOTIONS OF JETS – IN THE RADIO

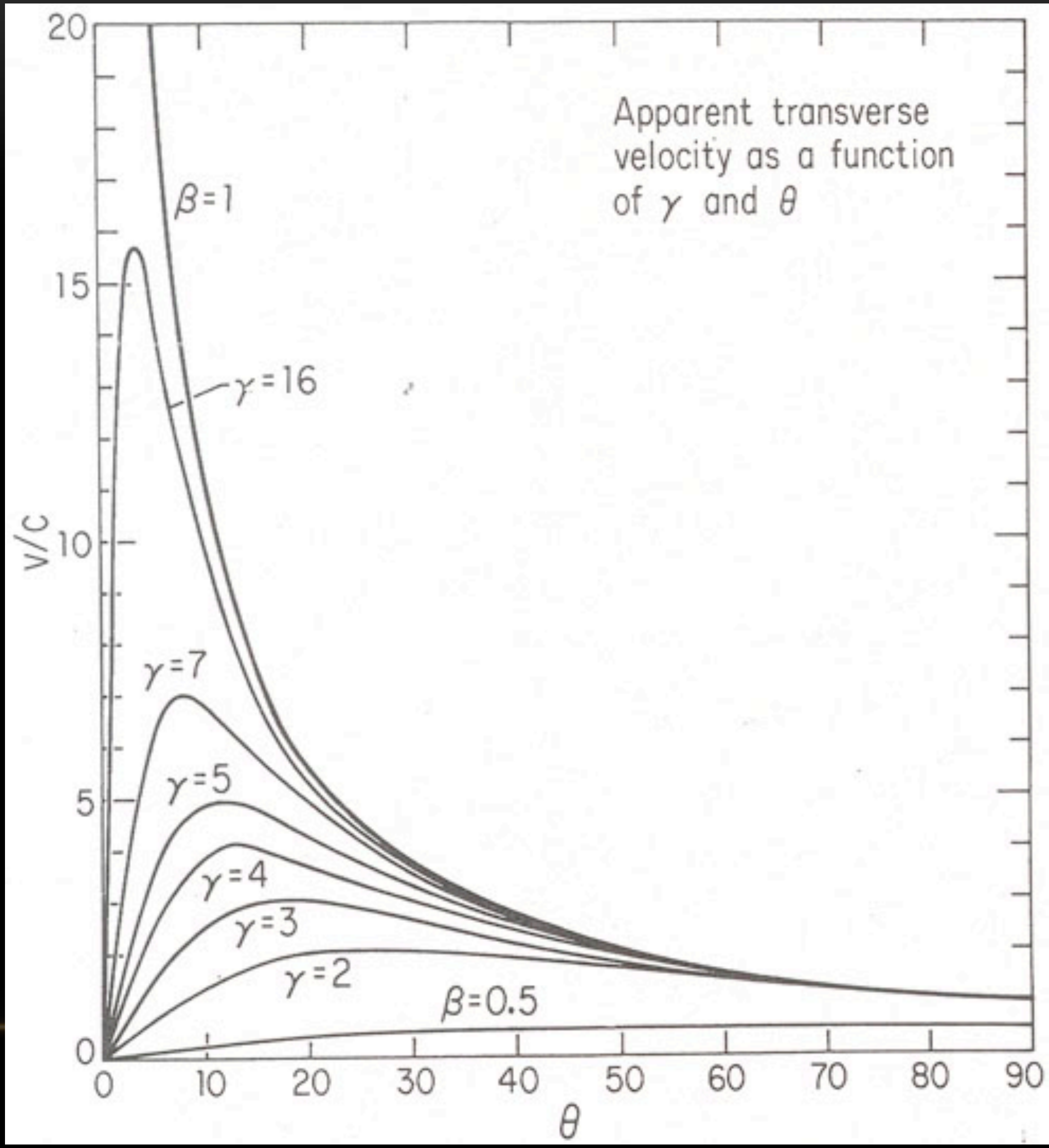


(from Lister et al. 2009)

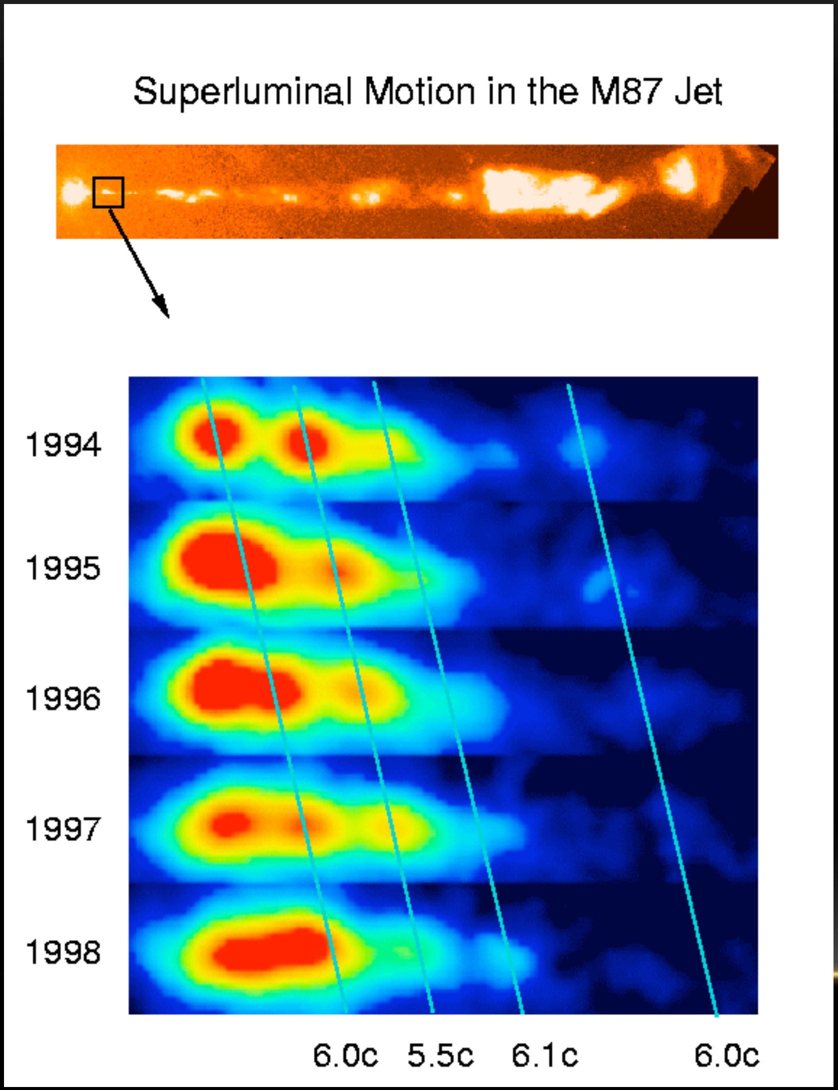
Apparent Speed versus radio power

Superluminal Speeds are Common on the parsec and sub-parsec scale near to the black hole

CONSTRAINTS FROM PROPER MOTIONS



PROPER MOTIONS OF JETS – *WITH HST*



M87: Very nearby, very well-studied jet (19 Mpc)

Biretta et al., 1999

4 years of time-elapsed FOC imaging

First optical proper motions measured in extragalactic jets

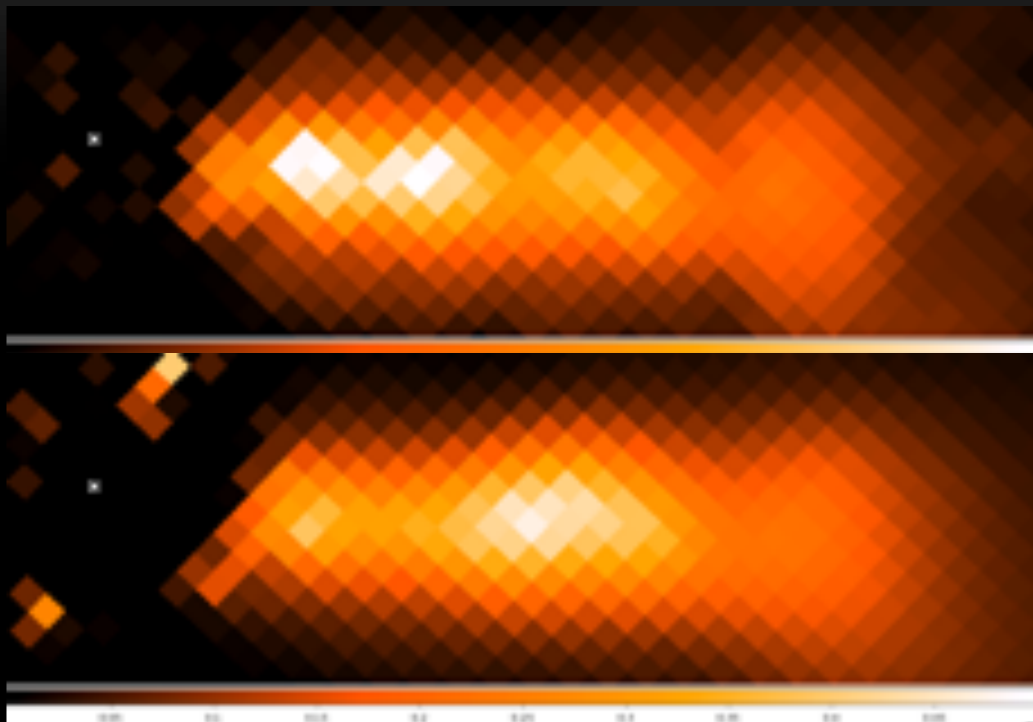
Superluminal speeds ~ 6c

This remained the only measurement of proper motions on kpc scales

VLBI gives low speeds (less constraining)

The Present

HST observed the first jets with WFPC2 in the early to mid-1990s



3C 264, 1994

3C 264, 2014

Today: 20+ year baselines

Bill Sparks & John Biretta

The Present

State-of-the-art Astrometry

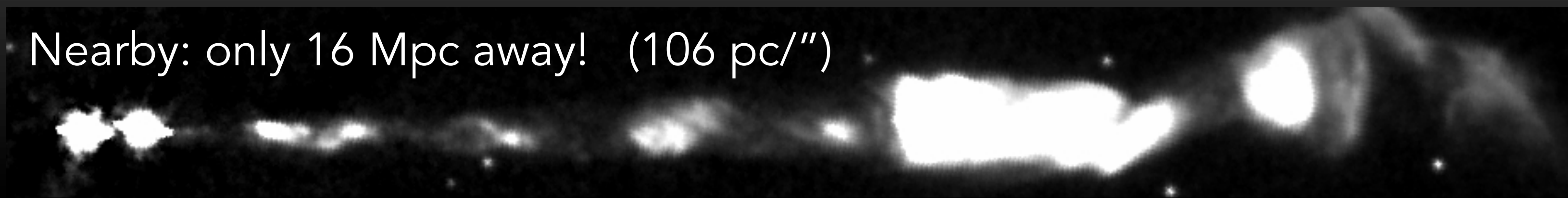
- Easily register images to 5 mas using globular clusters and background galaxies (0.17 mas in M87 study)
- In extragalactic jets, we are dominated by the error in measuring the jet components, not the systematics

Tony Sohn (Johns Hopkins)

Jay Anderson (STScI)

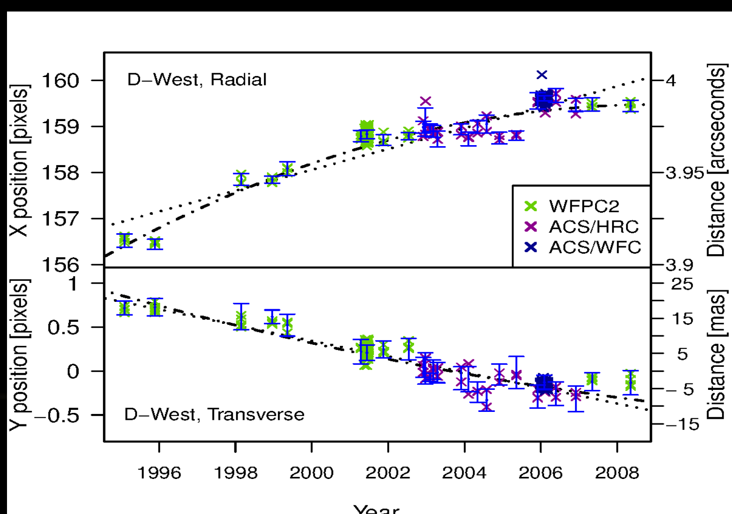
Roeland Van der Marel (STScI)

First Test: Back to M87

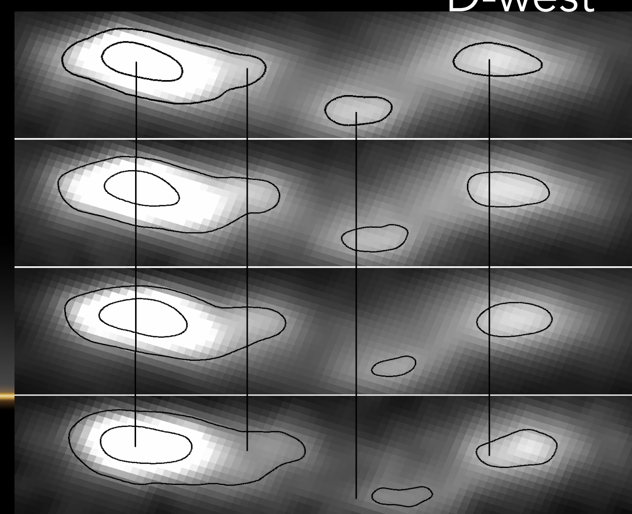


<u>Meyer et al., 2013 (ApJ, 744 ,L21) Key Results:</u>

- Unprecedented accuracy of < 0.1c
- Measured deceleration and transverse motions for the first time
- Helical pattern in outer knots
- Superluminal speeds in the outer knots



D-west

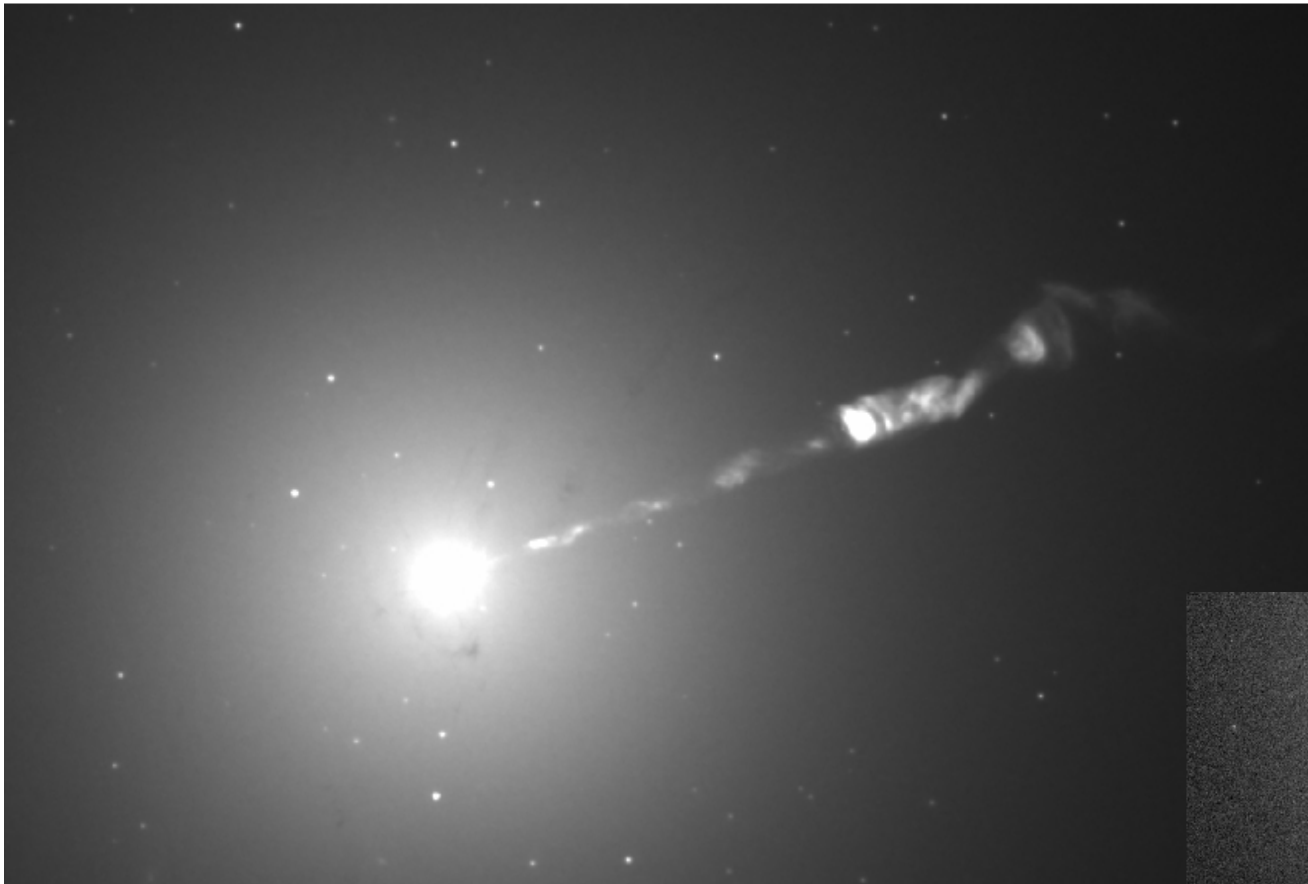


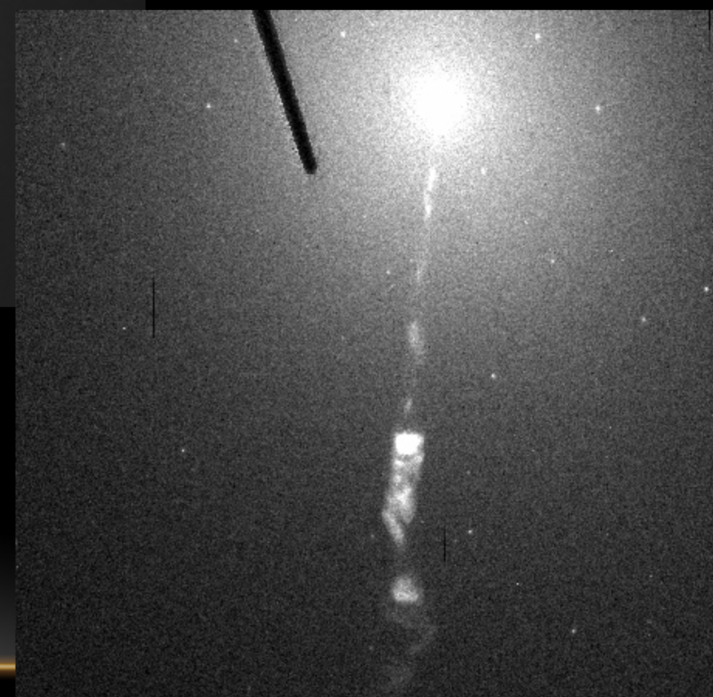
1995

1998

2001

2008





First Test: Back to M87

More M87 movies available at http://www.stsci.edu/~meyer/M87.html

M87 knot D (wide V band)

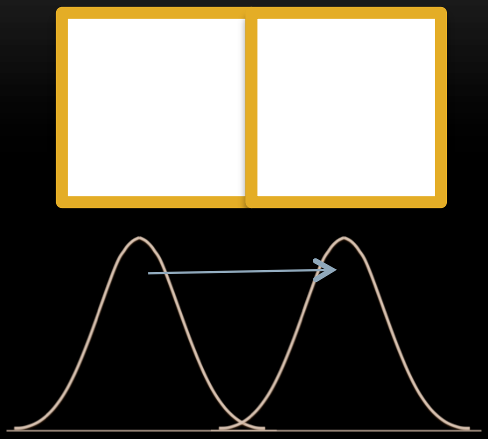
More M87 movies available at http://www.stsci.edu/~meyer/M87.html

First Test: Back to M87

More M87 movies available at http://www.stsci.edu/~meyer/M87.html

Proper Motions in the HST Era

detection depends on resolution – entering a new era
more distant the target, the faster the velocity for same angular shift



A shift of 1 ACS pixel (50 mas)
over 10 years becomes
superluminal (faster-than-light)
beyond a distance ~ 120 Mpc

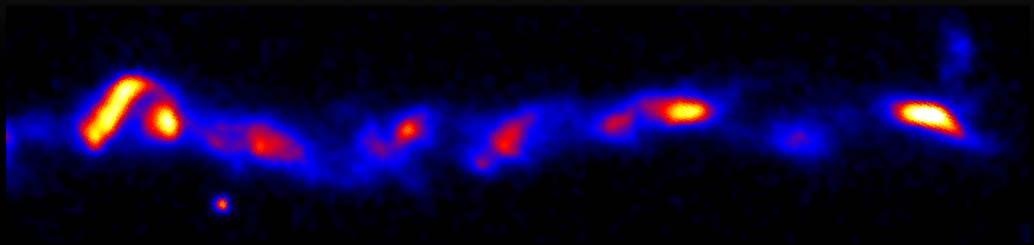
LIMITING FACTORS:

- resolution (HST ~< 0.1″)
- sensitivity (WFPC2 is noisy, faint background sources washed out)
- field of view (lesser extent, but important in PC & HRC)

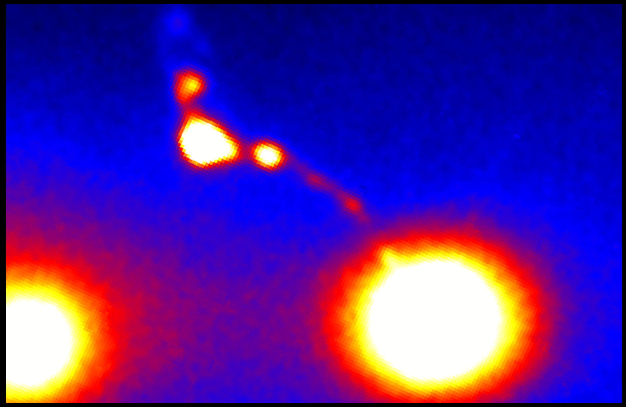
  ACS = 202″ x 202″

The Present: A New Campaign

20 year baseline + 2 mas accuracy = 1c → 500 Mpc 'horizon'

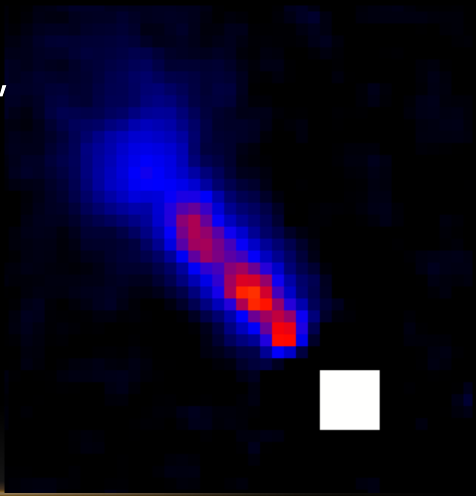


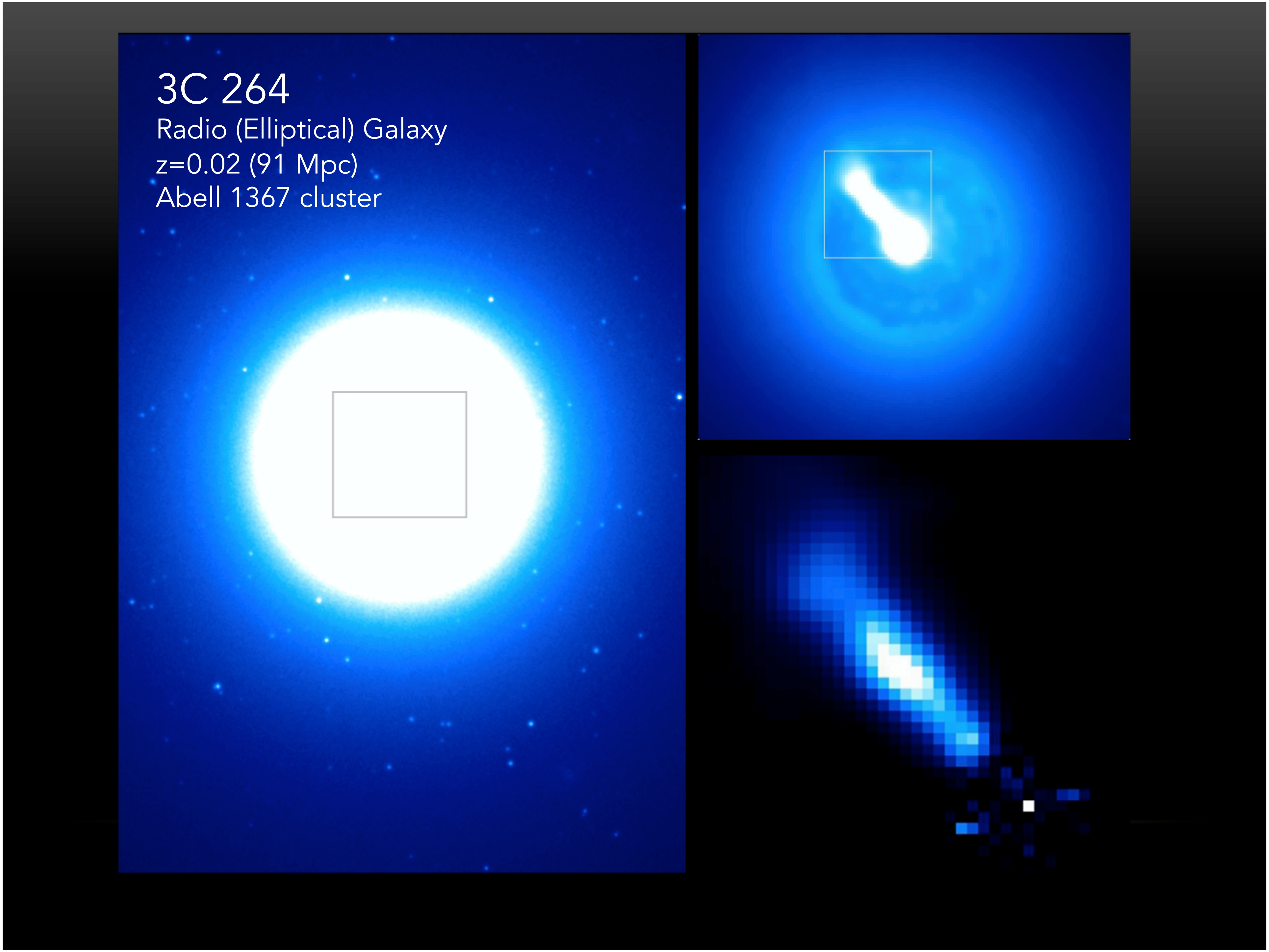
3C 273 – powerful quasar jet at 546 Mpc



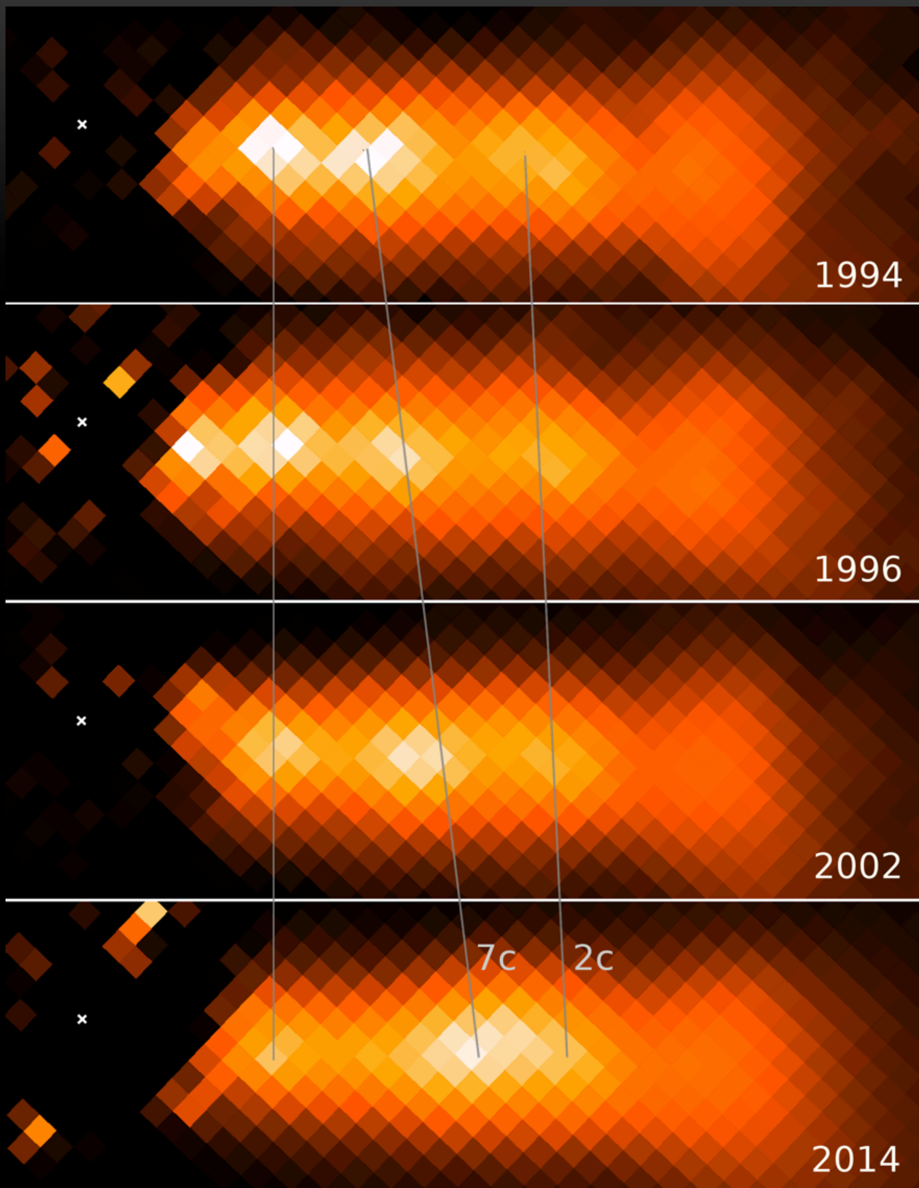
3C 346 – unusual 'bent' jet in merger system – an FR I/II moderate-power jet at 553 Mpc

3C 264, an "M87 analog" at 91 Mpc




3C 264
Radio (Elliptical) Galaxy
z=0.02 (91 Mpc)
Abell 1367 cluster

3C 264:First-ever direct evidence for the internal shock model?



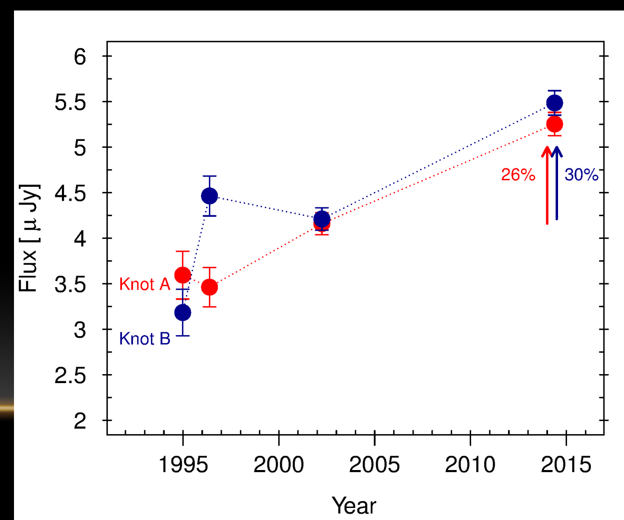
3C 264 – 91 Mpc (5x M87 distance)

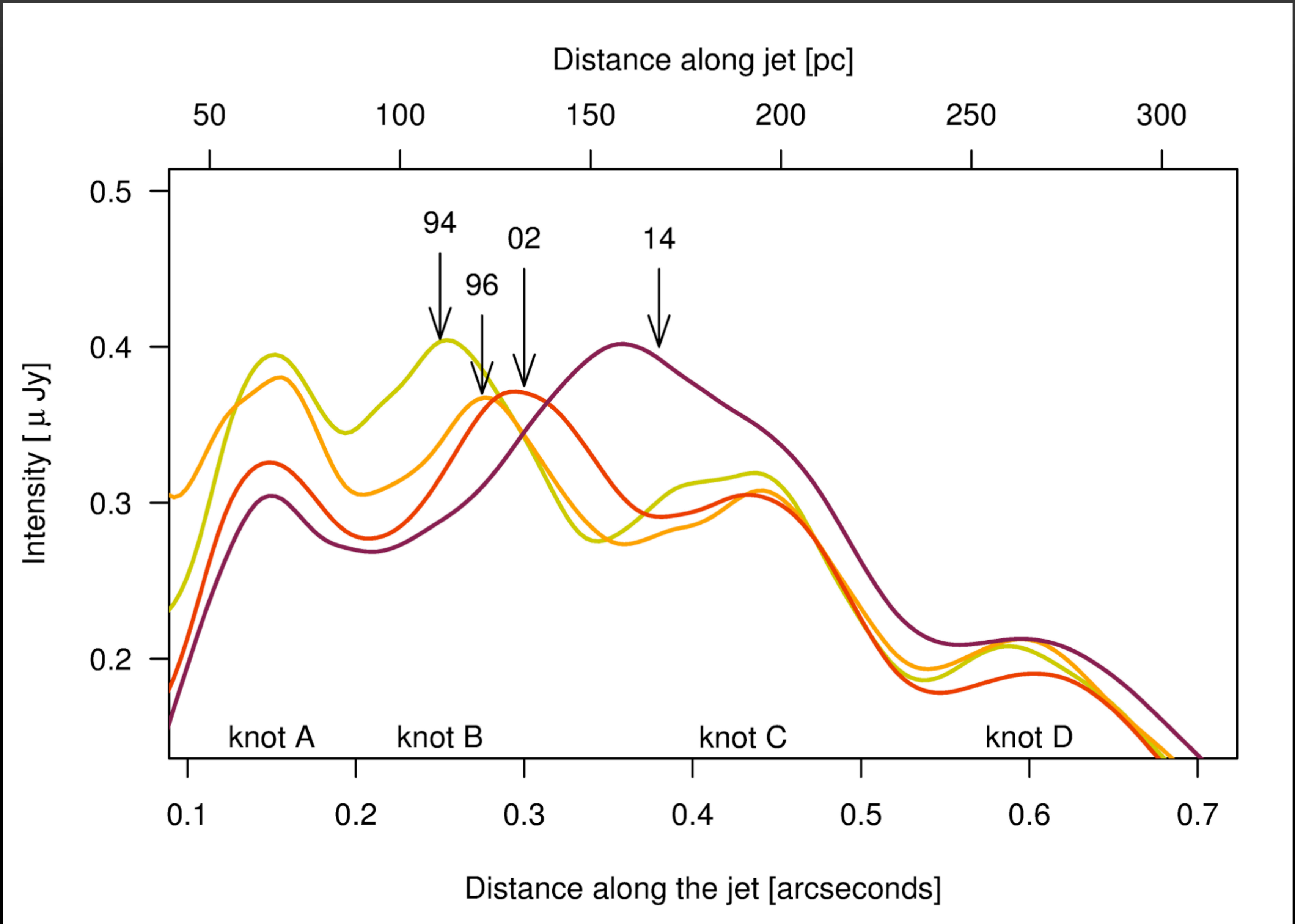
Jet is 0.4 kpc in length

Knot B has apparent speed of 7+/-0.8 c *(highest ever measured at these distances)*

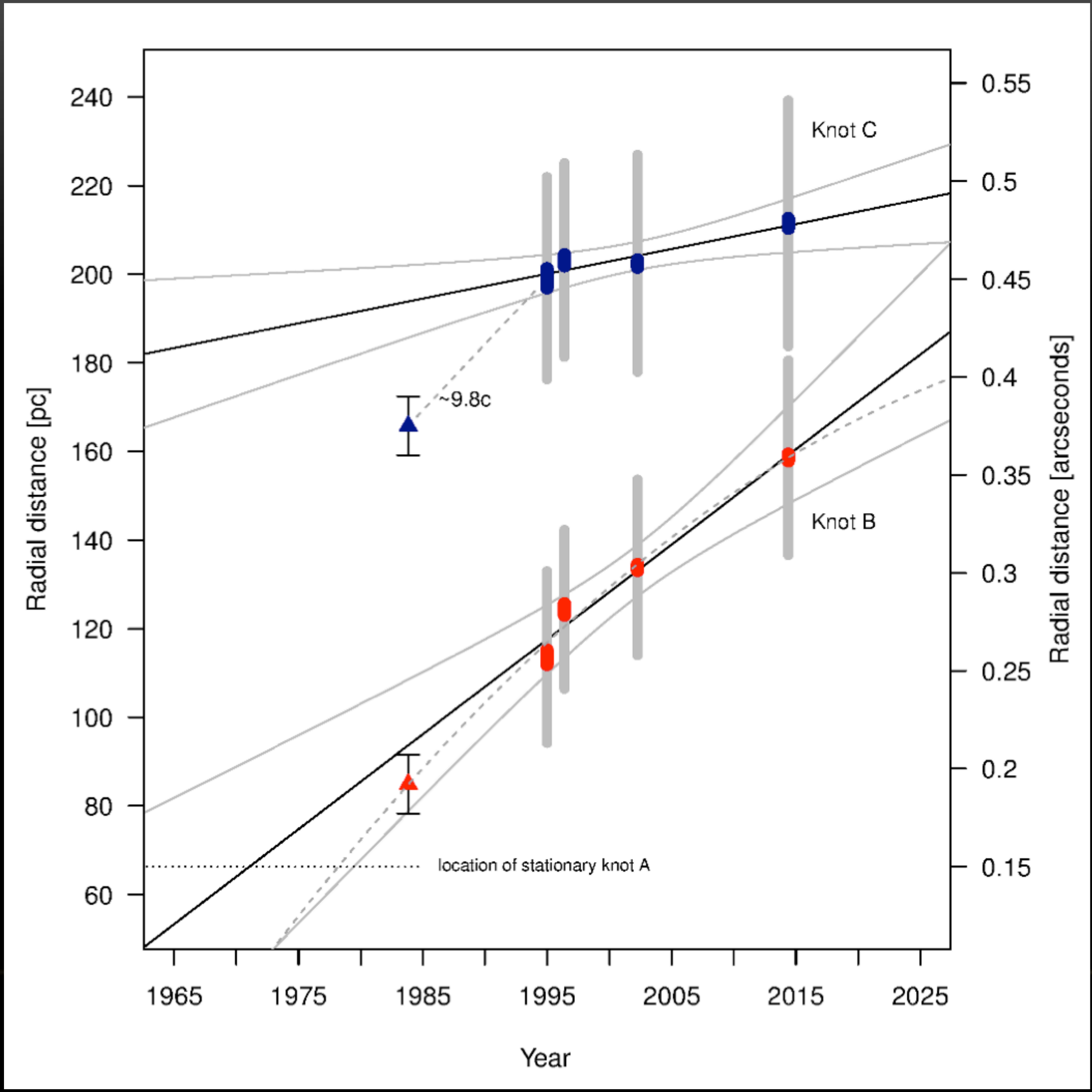
Colliding with Knot C in final epoch

Significant Brightening Observed





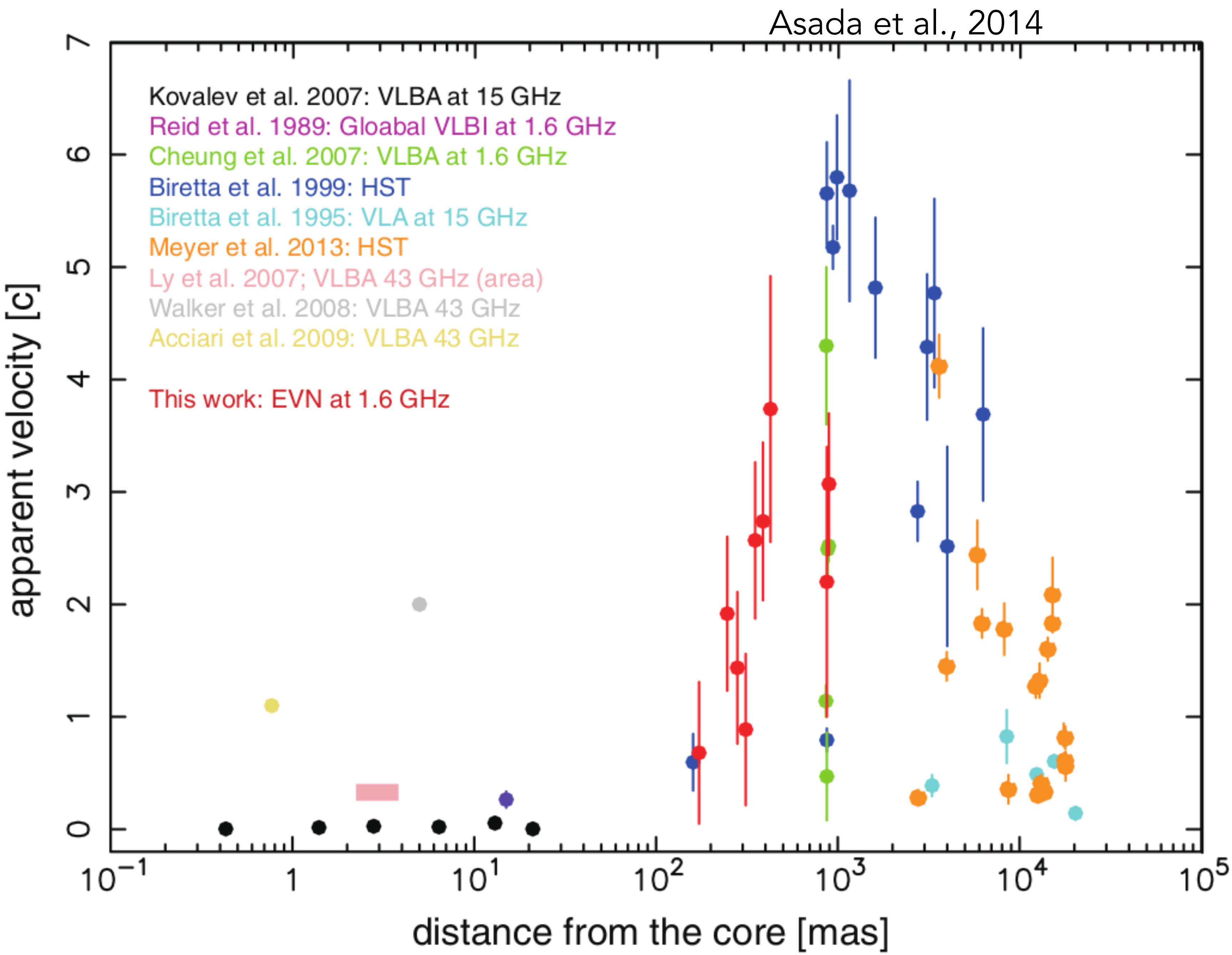
Distance along jet [pc]
50
100
150
200
250
300
0.5
0.4
0.3
0.2
Intensity [μ Jy]
94
96
02
14
knot A
knot B
knot C
knot D
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Distance along the jet [arcseconds]



Radial distance [pc]
240
220
200
180
160
140
120
100
80
60
Radial distance [arcseconds]
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
Knot C
~9.8c
Knot B
location of stationary knot A
1965
1975
1985
1995
2005
2015
2025
Year

3C 264

(Probable collision timescale ~ 30 years. Ongoing HST monitoring approved!)

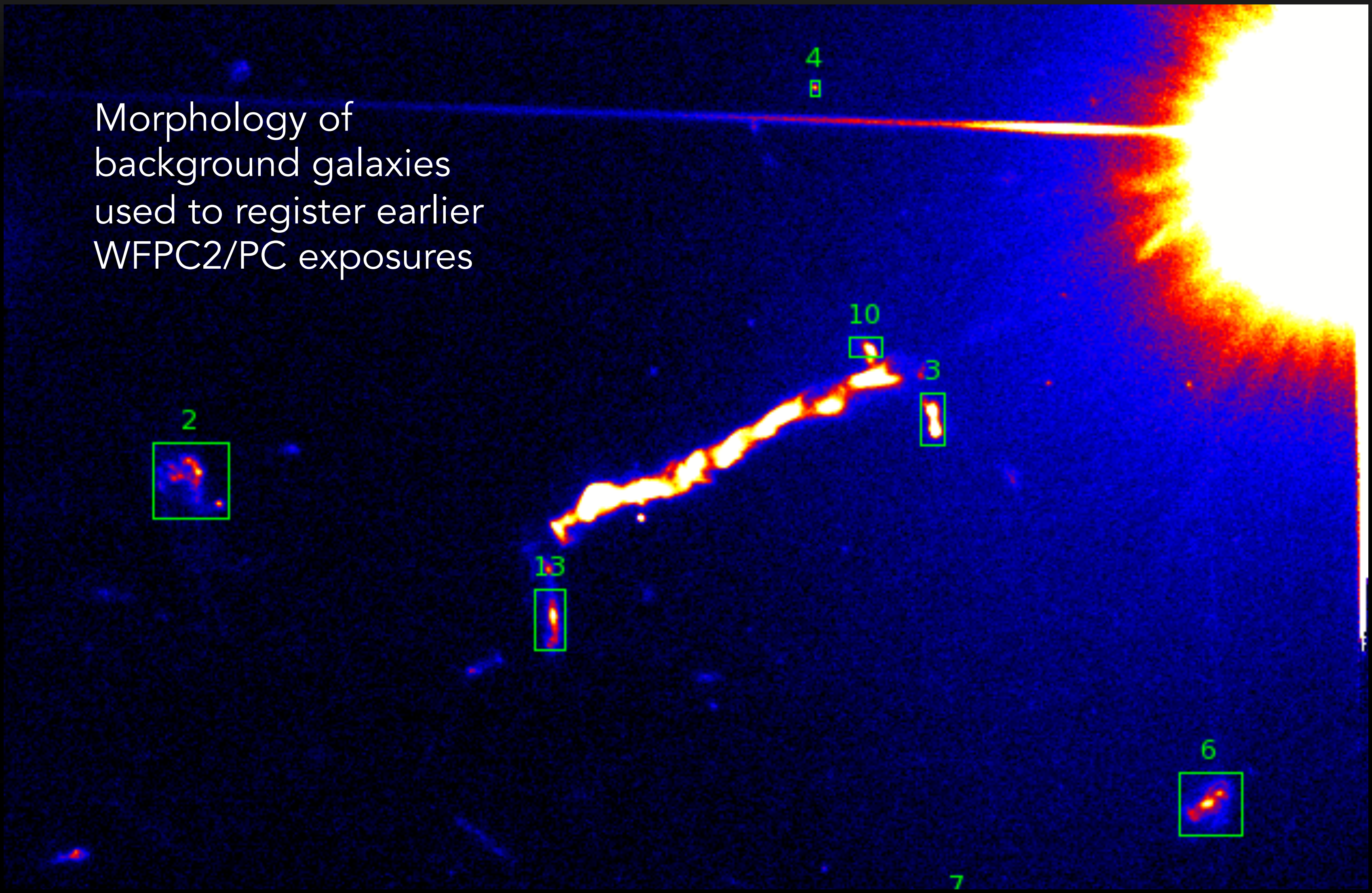


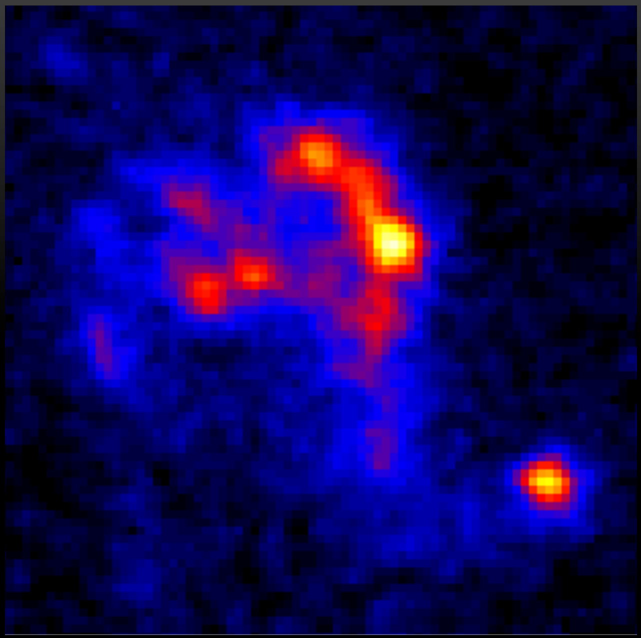
Asada et al., 2014
Kovalev et al. 2007: VLBA at 15 GHz
Reid et al. 1989: Gloabal VLBI at 1.6 GHz
Cheung et al. 2007: VLBA at 1.6 GHz
Biretta et al. 1999: HST
Biretta et al. 1995: VLA at 15 GHz
Meyer et al. 2013: HST
Ly et al. 2007; VLBA 43 GHz (area)
Walker et al. 2008: VLBA 43 GHz
Acciari et al. 2009: VLBA 43 GHz
This work: EVN at 1.6 GHz
apparent velocity [c]
distance from the core [mas]
0
1
2
3
4
5
6
7
10^{-1}
1
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}

3C 264 CONCLUSIONS

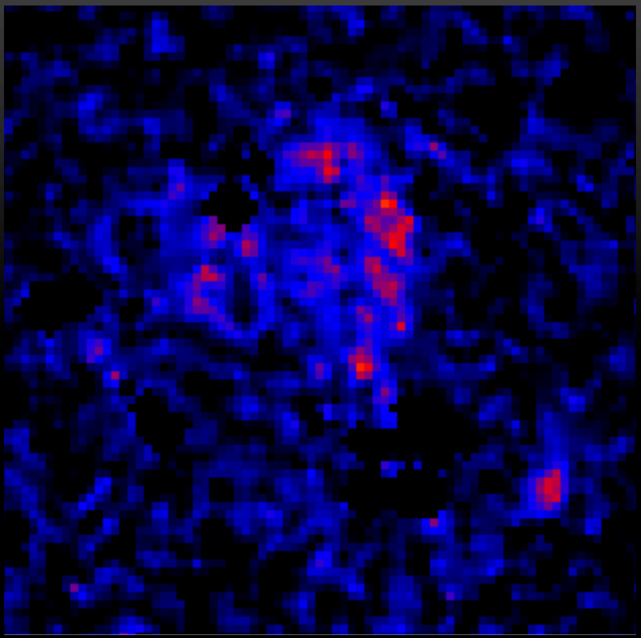
- Internal shocks observed in real time
- Mass of the knots is only ~ 5% M_{sol}
- Timescale is about 30 years to finish colliding
- Plan to monitor with HST and VLA
- 3C 264 looks remarkably like M87, including the presence of a stationary knot ~ 100 pc from the core (aka HST-1 analog)

3C 273


Morphology of
background galaxies
used to register earlier
WFPC2/PC exposures
4
10
3
2
13
6
7

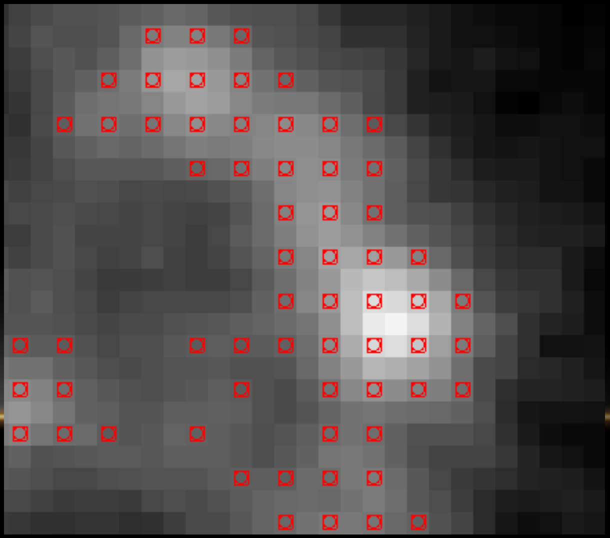


2014 ACS/WFC
(deep reference image stack)



Same galaxy,
Single WFPC2
exposure from
1995

Galaxy positions are determined by finding the optimal overlap over the extent of the galaxy.

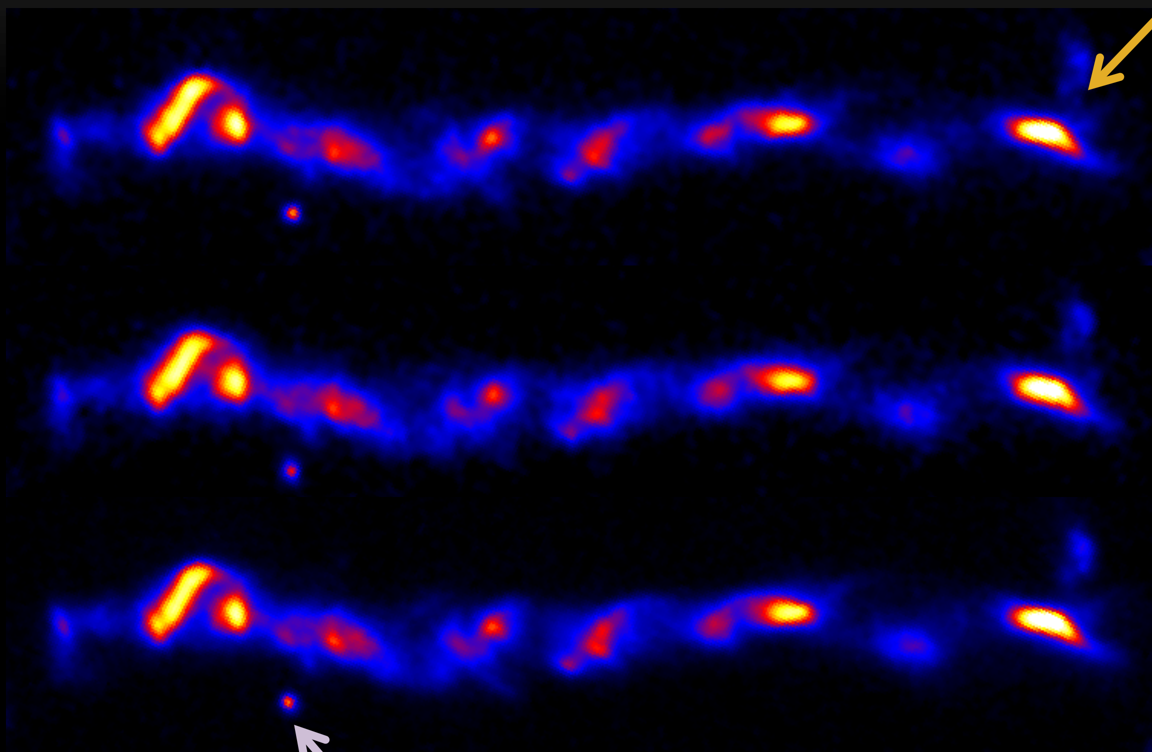


Close-up of 'reference' pixels as noted by red points

(submitted to ApJ)

3C 273

Knot A



The Jet in 1995

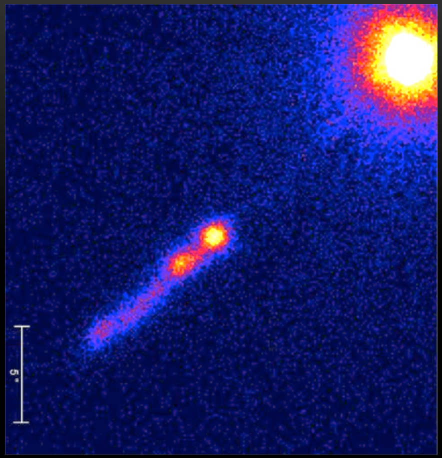
The Jet in 2003

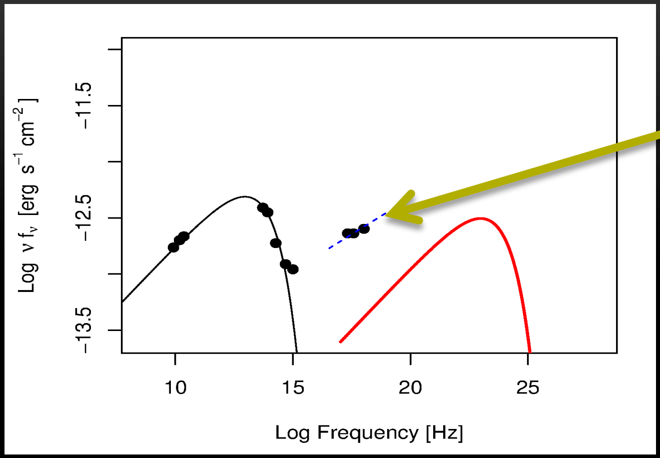
The Jet in 2014

The only thing moving is this foreground object!

Results: no apparent proper motions in any knots.
no flux changes (compare to Pictor A, M87, …)
Knot A speed limit of < 2c → RULES OUT IC/CMB X-ray model

The kpc-scale jet of 3C 273 is very bright in X-rays





X-rays from a second component: inverse Compton or synchrotron?

The popular explanation is that the jet is still *highly relativistic* (Γ =10) on kpc scales, so that Doppler-boosted inverse Compton emission from CMB photons can explain the X-rays.

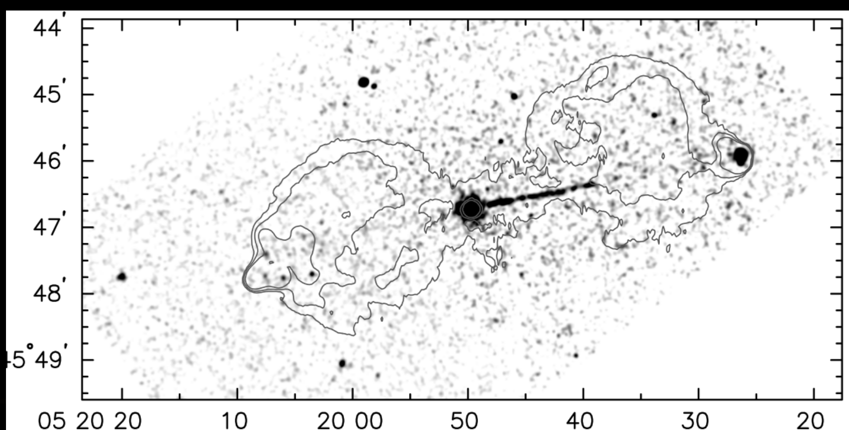
This model explicitly requires that the knots are *moving features.*

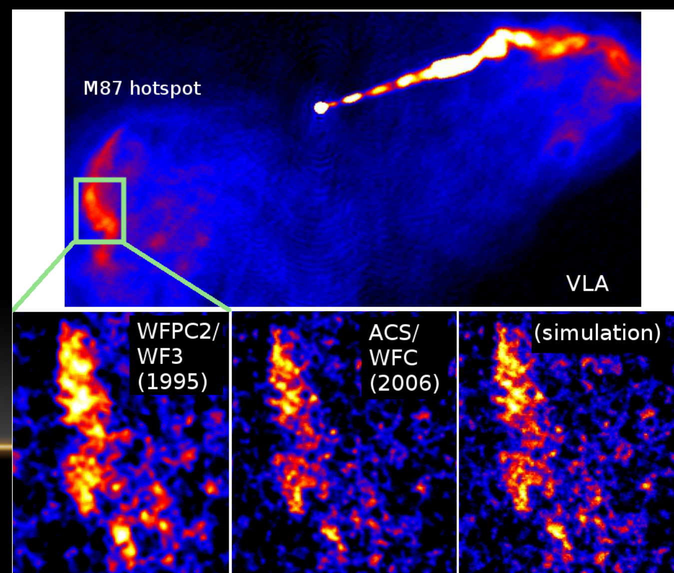
We have thus (independently!) ruled out the IC/CMB model for the X-ray emission in 3C 273.

The Future

Analysis of the lensing cluster + jet in 3C 346 ongoing.

“Hotspot” proper motions! → Approved program to measure the advance speed of hotspots in Pictor A and M87

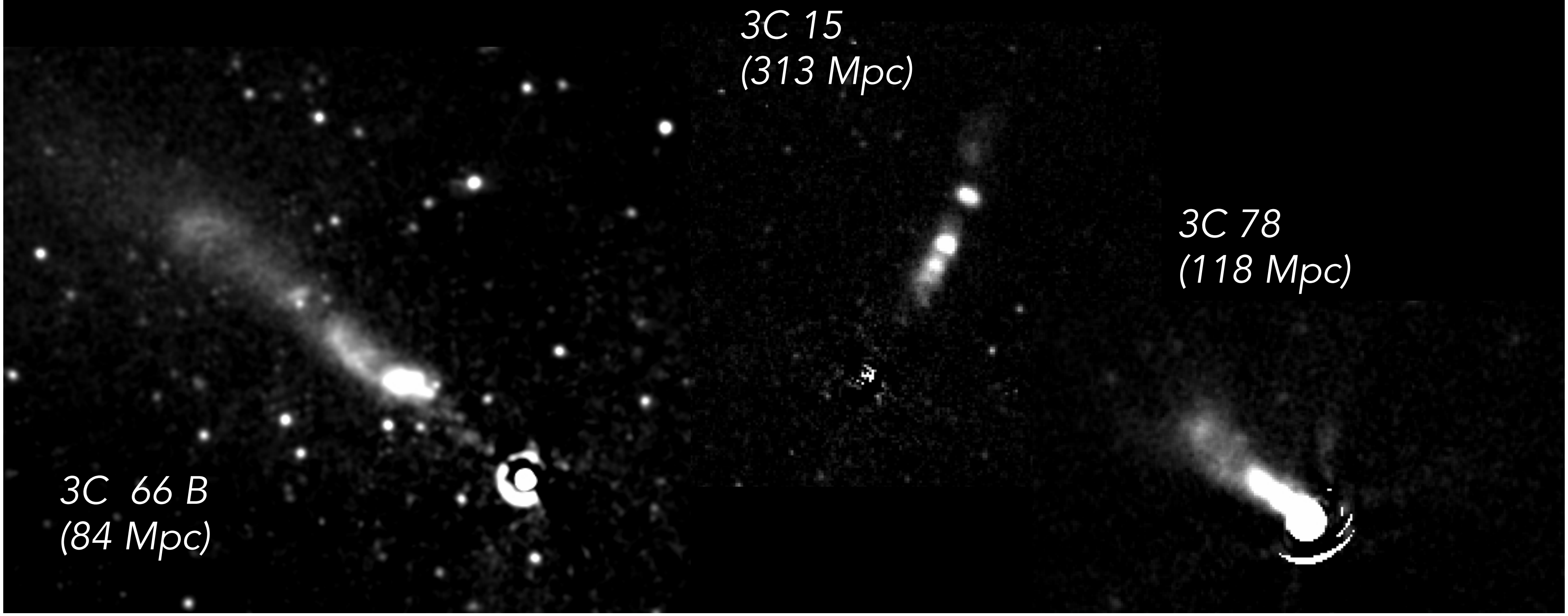




The Future

The remaining 7 jets in the "proper motions sphere" of ~ 500 Mpc – recently approved!

- We require a detection of the optical jet ~ 15 – 20 years ago: usually relies on very short WFPC2 imaging from the 3C snapshot survey
- While 2 baselines is the technical minimum, 3 or more is far better



The Future

Current & Future Space Observatories

Current list of viable targets:

- Observed by HST < ~ 2000
- Within a z< 0.15

Extending Time Baselines (2 mas over 30 years = 1.8 kpc/" aka z = 0.3

HST – cannot be topped for sensitivity & resolution

JWST
WFIRST
} Both can take over -- synchrotron emission doesn't change much from V-band to R or IR

The Future

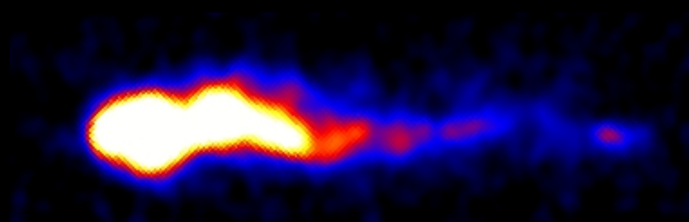
From the Ground:

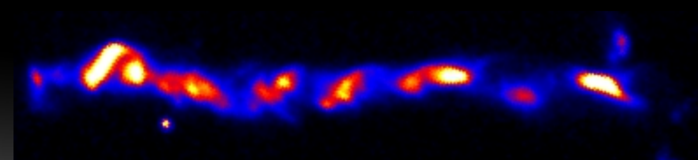
Adaptive Optics? – yes for resolution, ~ for sensitivity

ALMA – changing spectral window to millimeter-wavelengths
Advantage: High Resolution, better compactness of features than VLA, similar long lifetime of instrument (decades)

VLA & ALMA also have issues with needing multiple observations in different configurations to map all scales

However: new techniques (wavelet analysis) may improve the velocity mapping using existing observations





The Future

A New Mission

10-20 times better resolution:

A study that previously took 10-20 years will take 1

No longer reliant on early HST observations!

(prospective, designed studies of individual objects)

Better sensitivity:

There are hundreds of radio jets in the nearby ($z<0.1$) and nearby-ish ($z<0.3$) Universe

Many of these have *not* been detected in the optical, because HST time is expensive, but almost certainly will be (synchrotron emission peaks in the optical)

Combined with better resolution, you could complete a massive survey of jets within $z<0.3$ very quickly

Plus: Jets and the stationary objects are usually bright (relatively short exposures, equiv. ½ an orbit with HST)

Bigger Field of View:

More background sources for registration = beat down systematic errors (but modulo geometric corrections)

A New Mission would allow us to completely map the velocity structure of hundreds of jets from sub-parsec scale near the black hole out to the final deceleration terminus

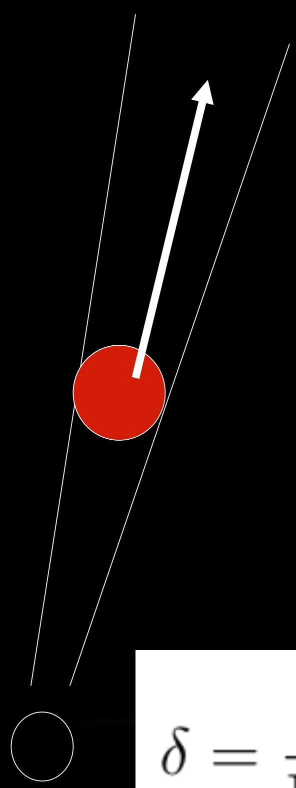
Very important step towards understanding the actual energetic content of these jets and their structure (note: we still do not know generally what the "knots" in the jets represent)

Critical constraints on the acceleration properties that cannot be probed in any other way.

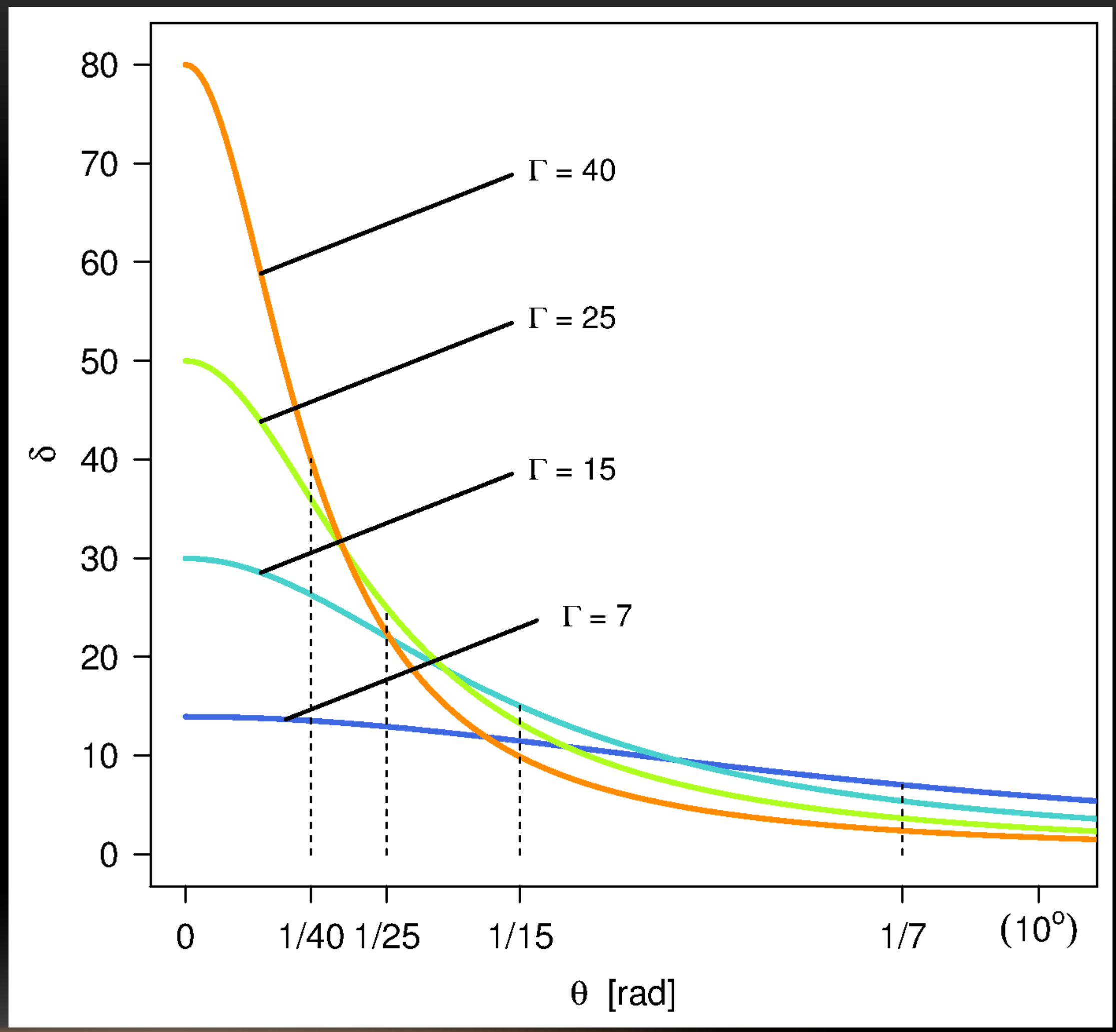
CONSTRAINTS FROM PROPER MOTIONS

$$\Gamma = (1-\beta^2)^{-1/2}$$

$$\Gamma = 2\text{—}50$$



$$\delta = \frac{1}{\Gamma\,(1 - \beta\cos\theta)}$$



➢ Doppler Boosting of the Apparent Luminosity and Peak Frequency

$$F_\nu = \delta^{3+\alpha} F'_\nu$$

$$\nu = \delta \nu'$$