PROPER MOTIONS OF JETS ON THE KILOPARSEC SCALE: NEW RESULTS FROM HST

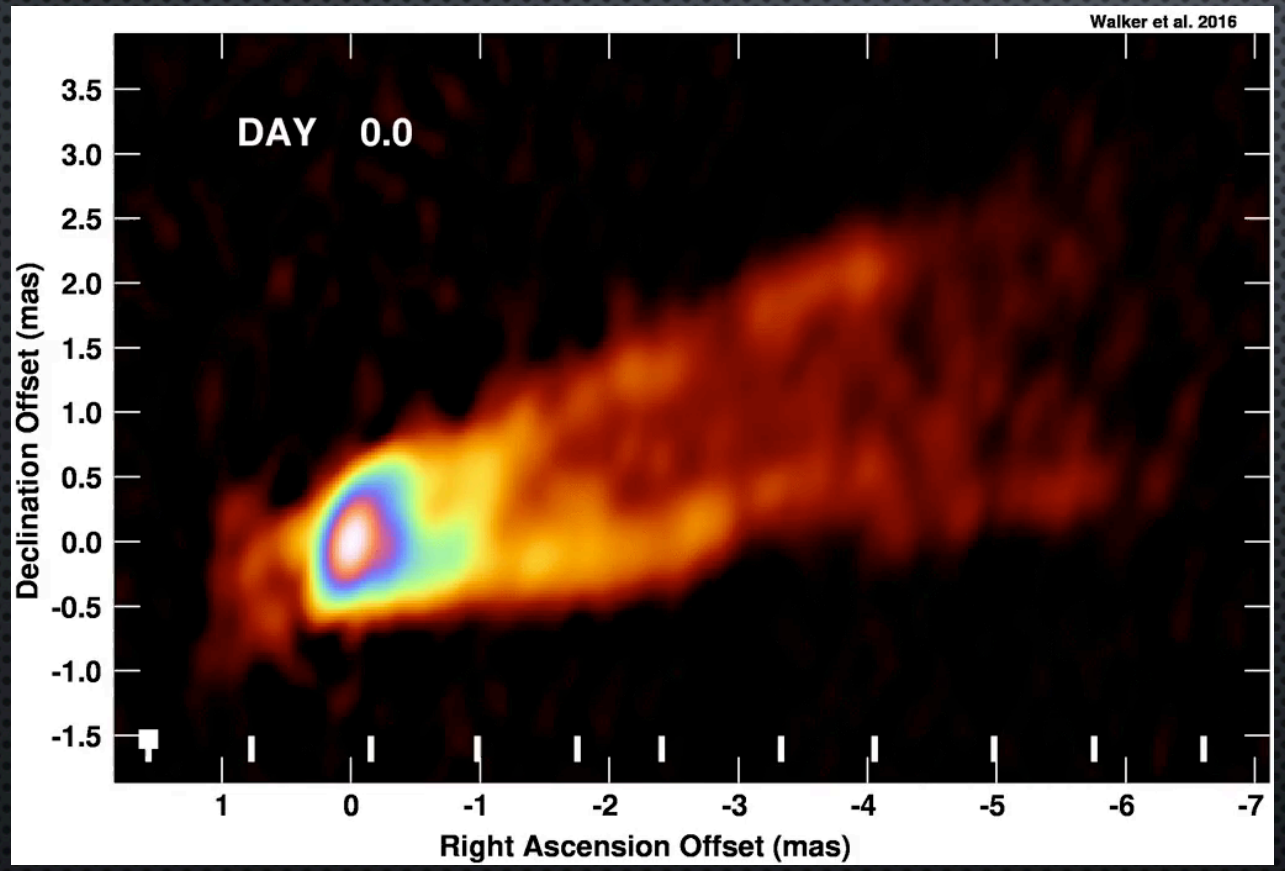
EILEEN MEYER

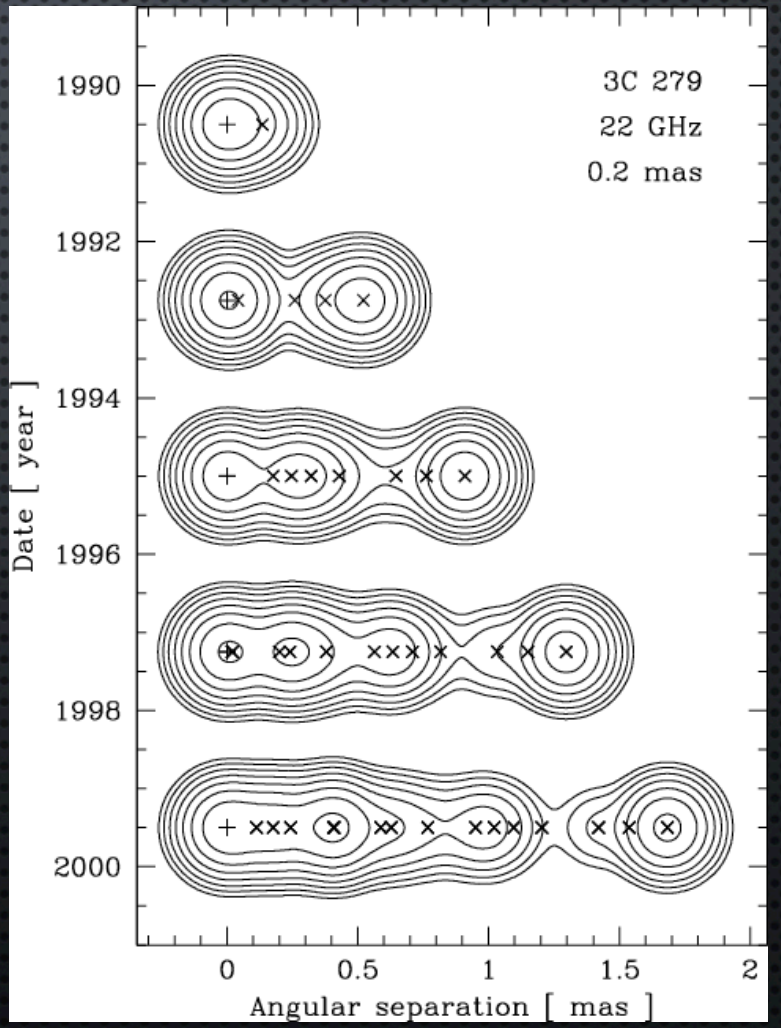
UNIVERSITY OF MARYLAND, BALTIMORE COUNTY (UMBC)

BLAZARS THROUGH SHARP MULTI-WAVELENGTH EYES

30 MAY - 3 JUNE 2016 | MÁLAGA, SPAIN

Proper Motions of Jets – A Long History with VLBI





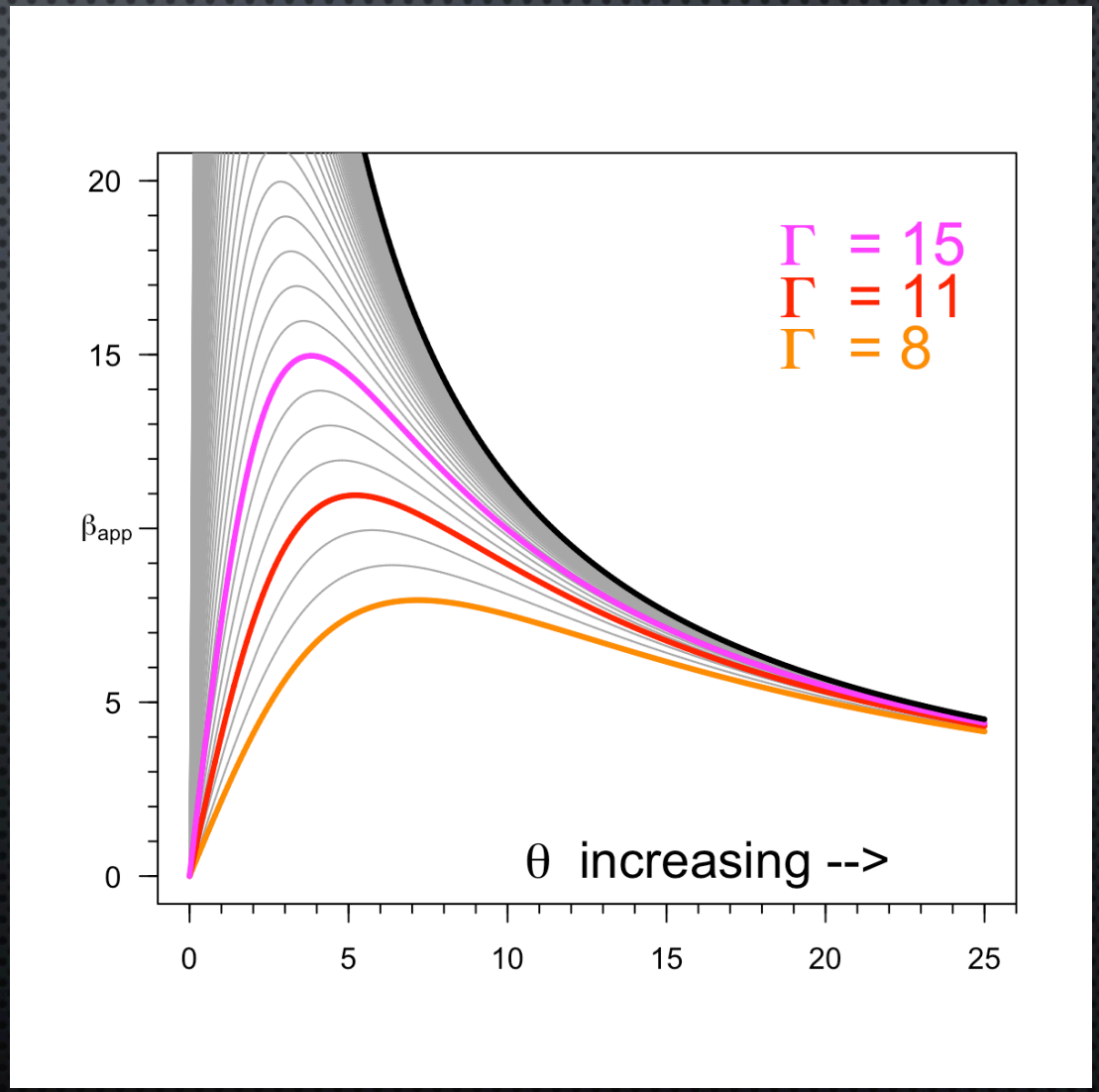
Lindfors+ 2006

Accuracies of ~ few μas/year
Probes pc to hpc scales
From stationary/subluminal (0.01c) → 50c

Apparent Superluminal Motion → Physical Constraints

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

$$\beta_{app} = \beta \sin\theta / (1 - \beta \cos\theta)$$

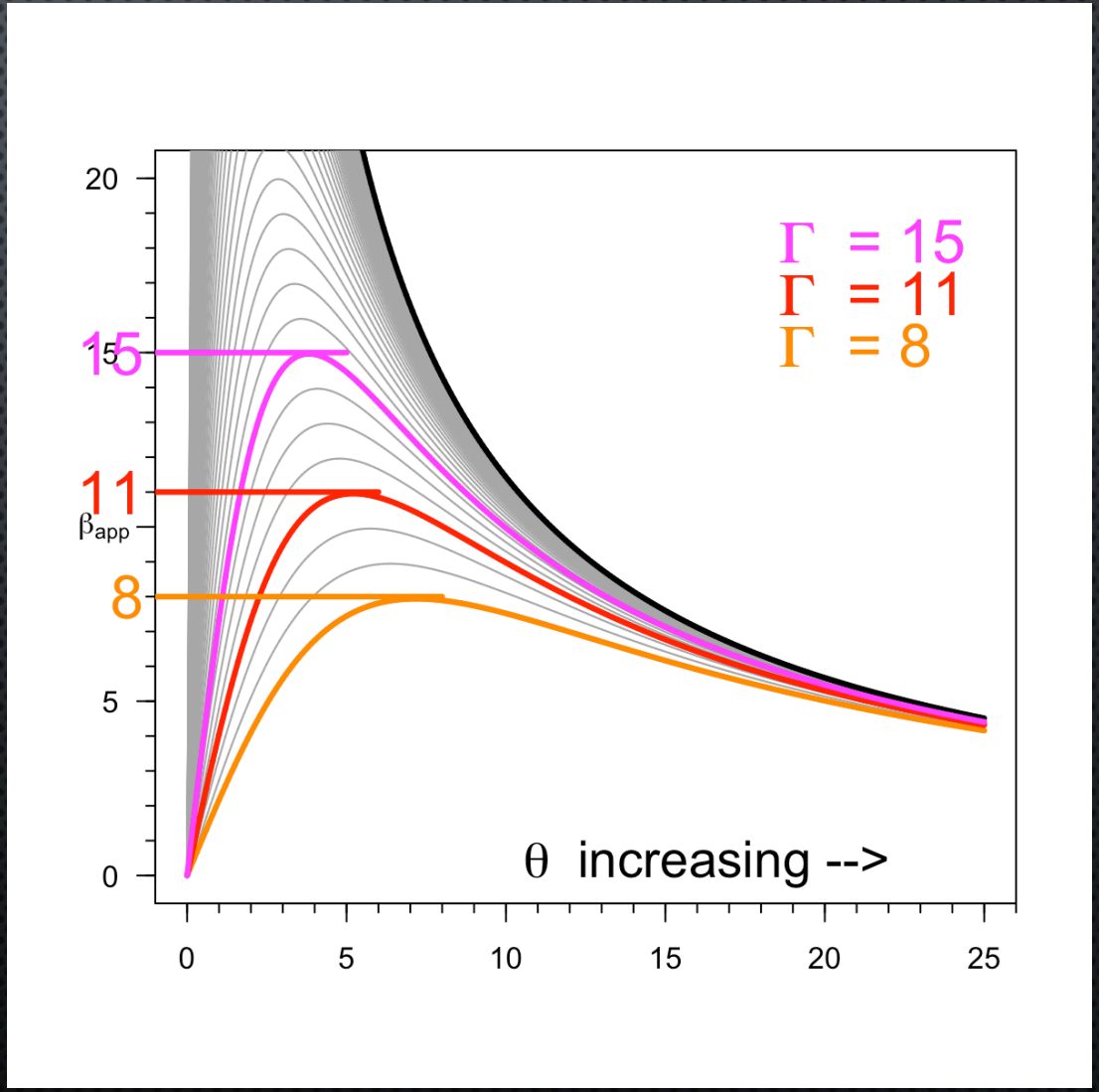


Apparent Superluminal Motion → Physical Constraints

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

$\beta_{app} = \beta \sin\theta / (1 - \beta \cos\theta)$

The maximum value of β_{app} is equal to Γ

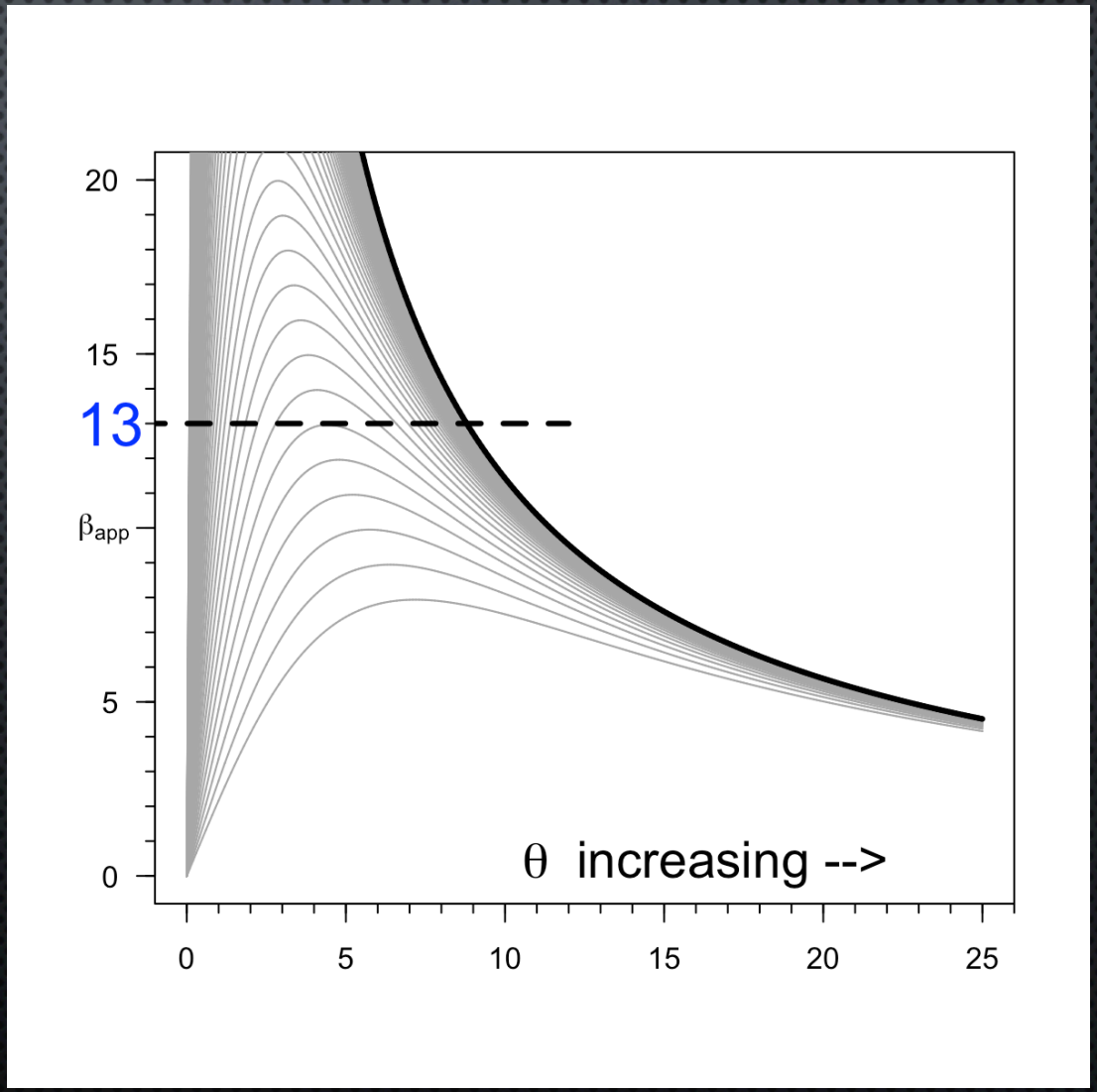


Apparent Superluminal Motion → Physical Constraints

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

$\beta_{app} = \beta \sin\theta / (1 - \beta \cos\theta)$

A measurement of β_{app}:



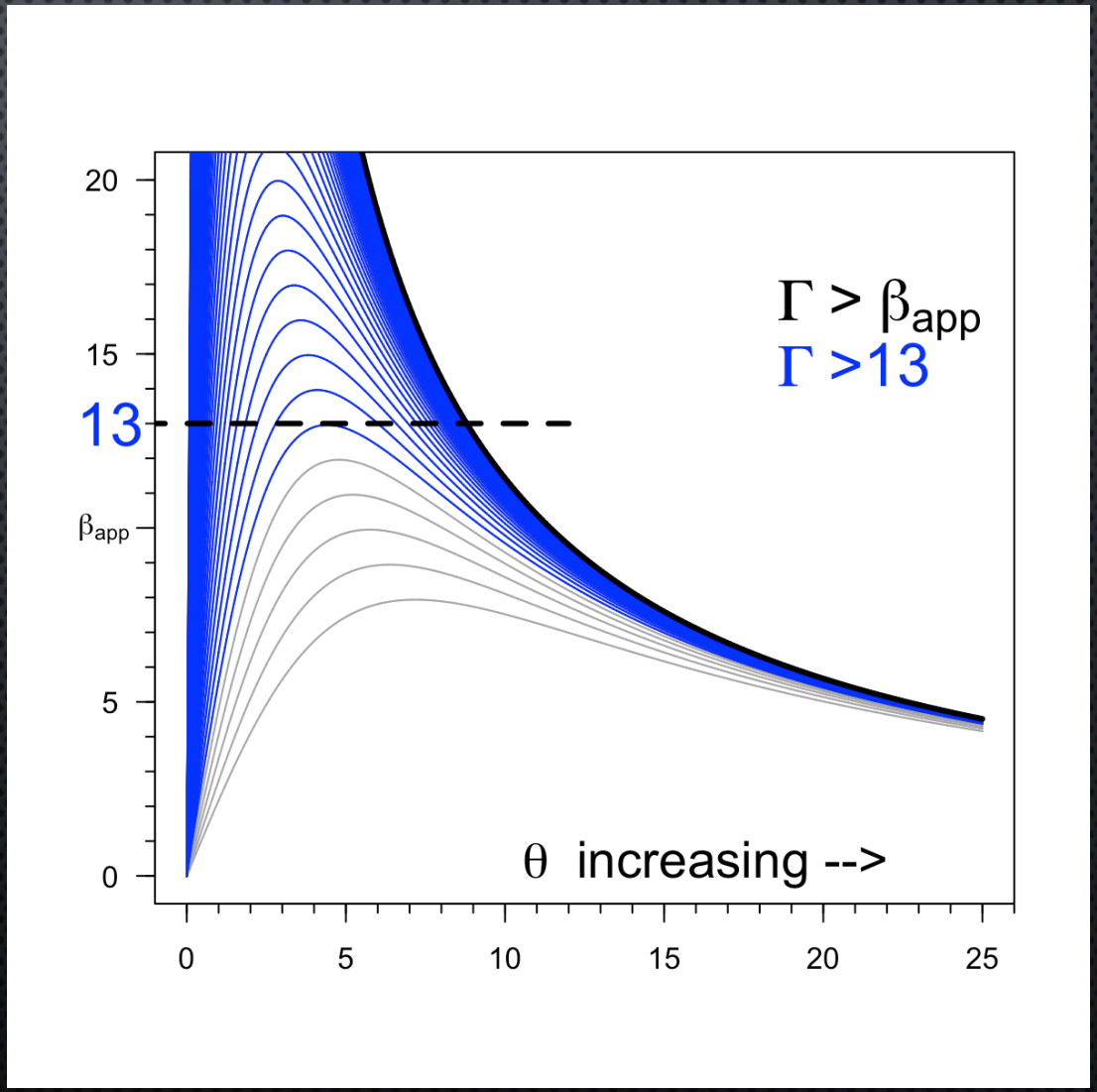
Apparent Superluminal Motion → Physical Constraints

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

$\beta_{app} = \beta \sin\theta / (1 - \beta \cos\theta)$

A measurement of β_{app}:

- implies a lower limit on Γ



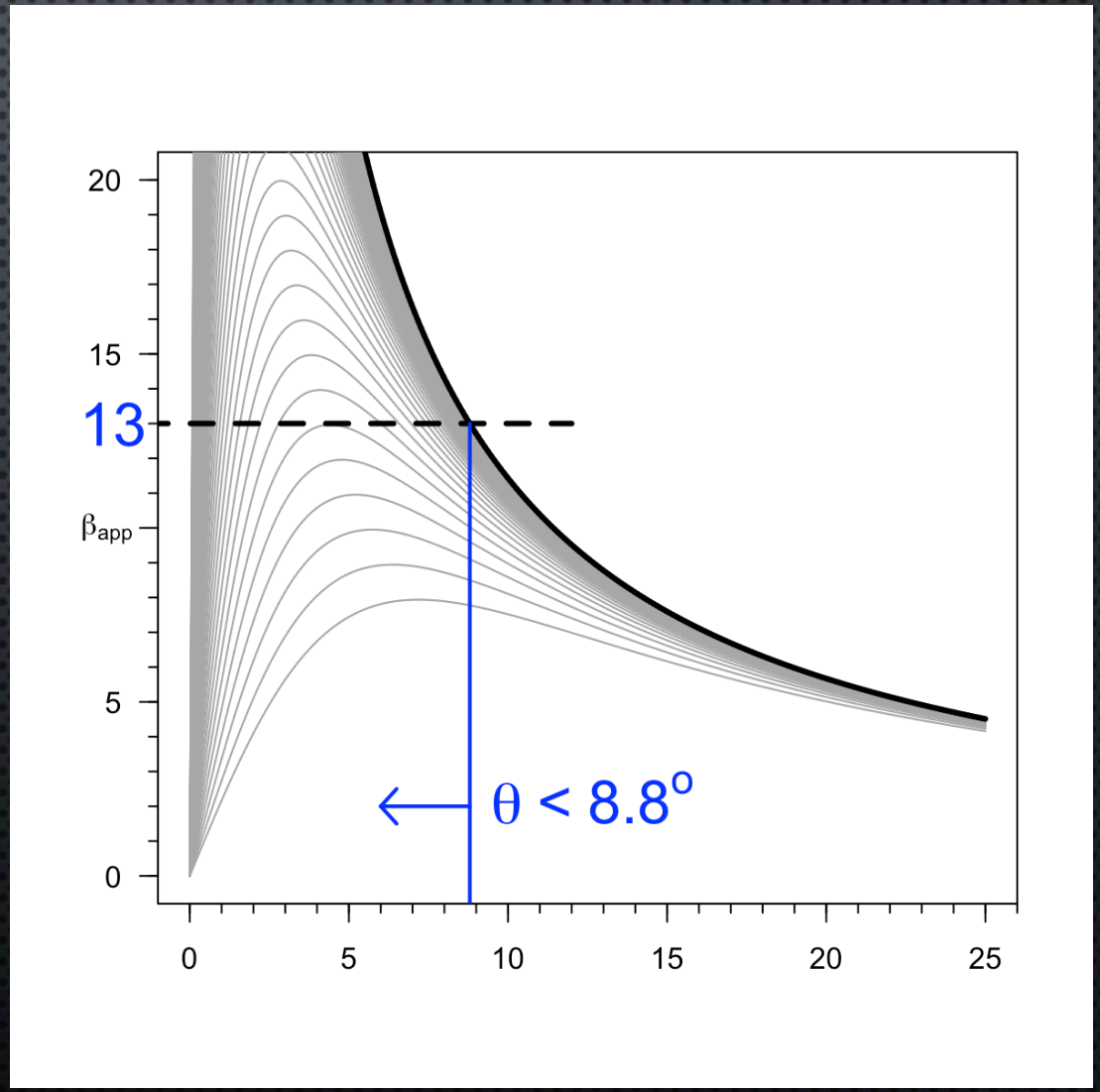
Apparent Superluminal Motion → Physical Constraints

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

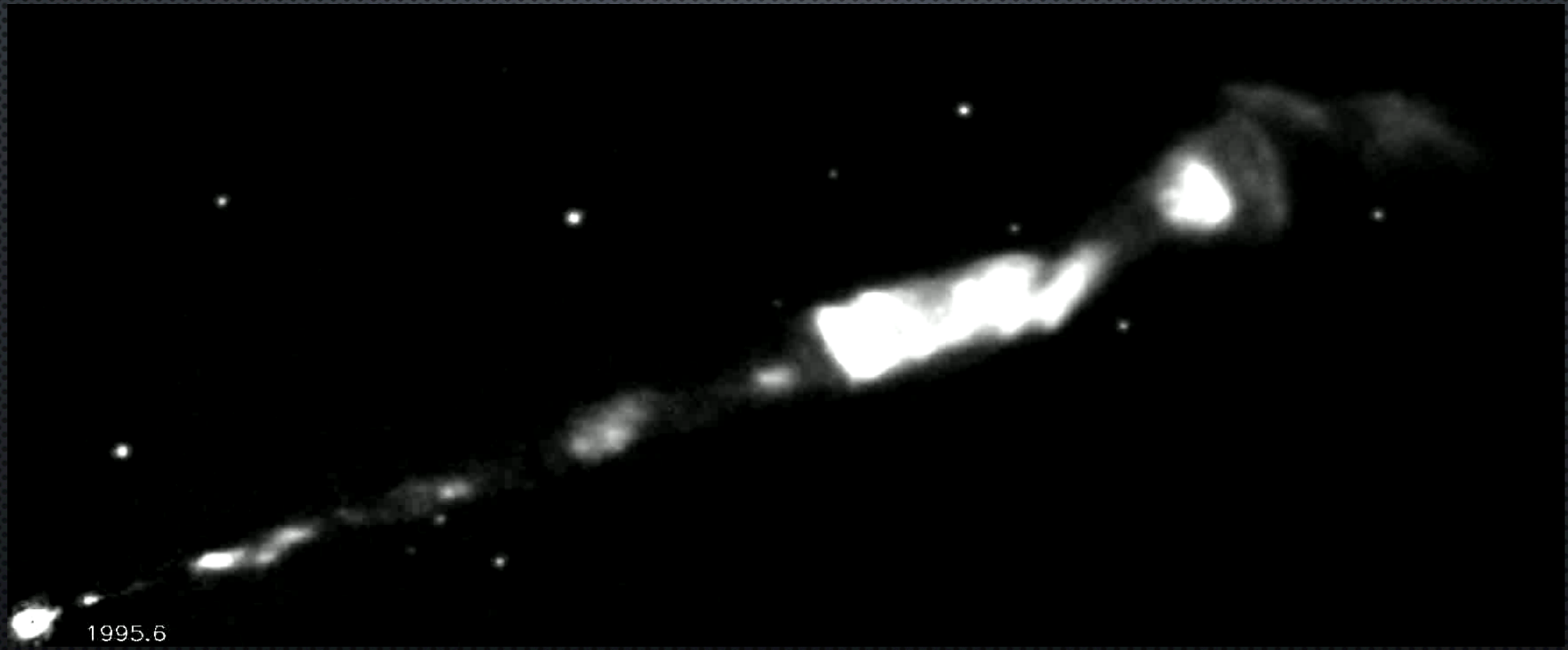
$\beta_{app} = \beta \sin\theta / (1 - \beta \cos\theta)$

A measurement of β_{app}:

- implies a lower limit on Γ
- implies a range on θ



HST Proper Motions: M87

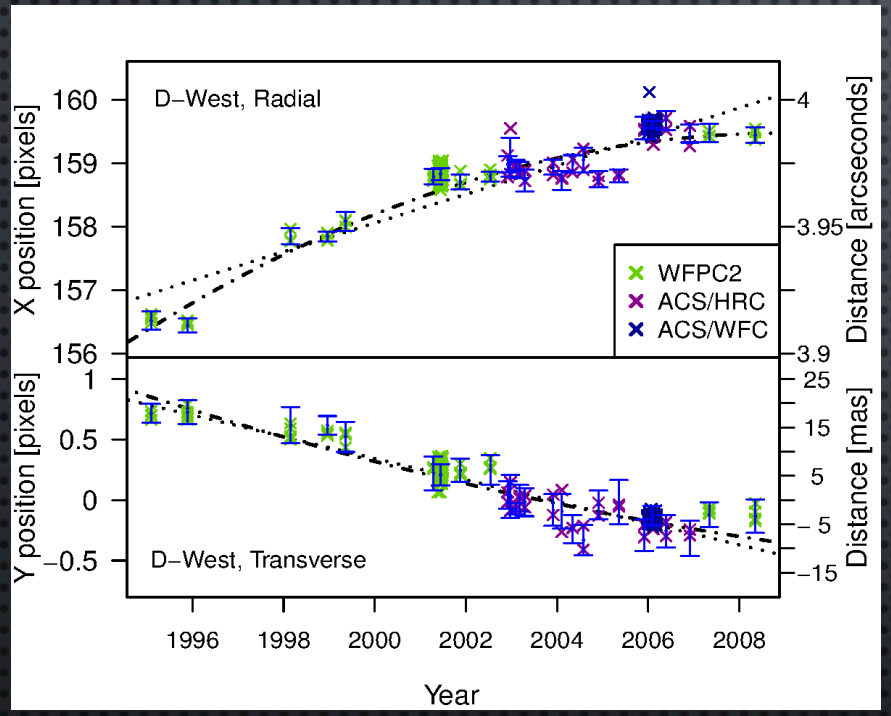


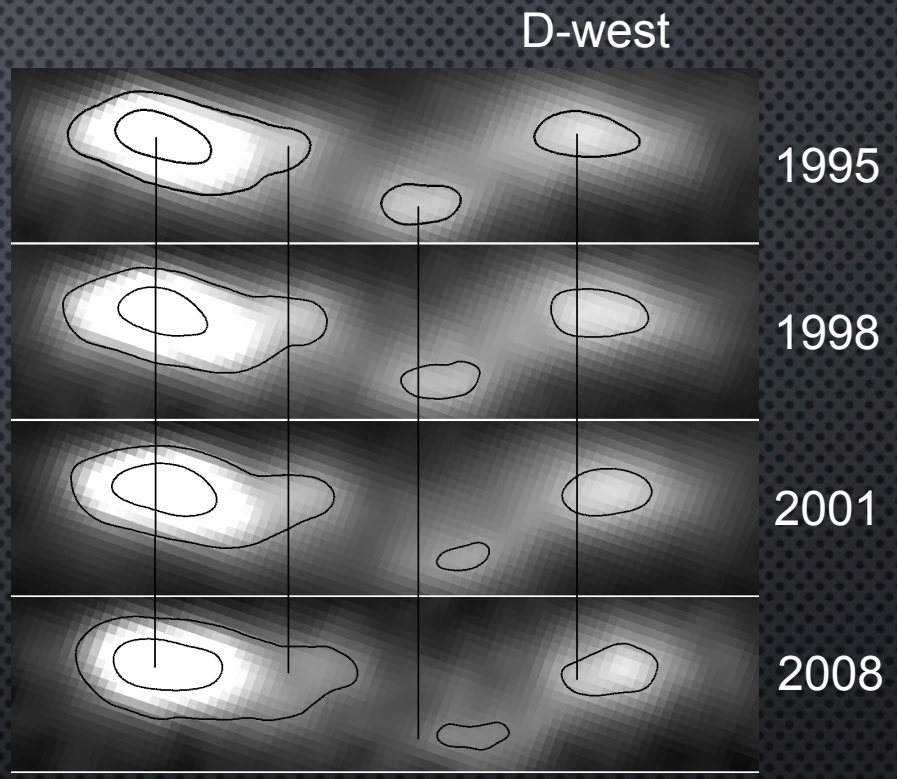
(1995 – 2008) Meyer et al., 2013 ApJ 744, L21

HST Proper Motions: M87

HST Proper Motions: M87

HST Proper Motions: M87





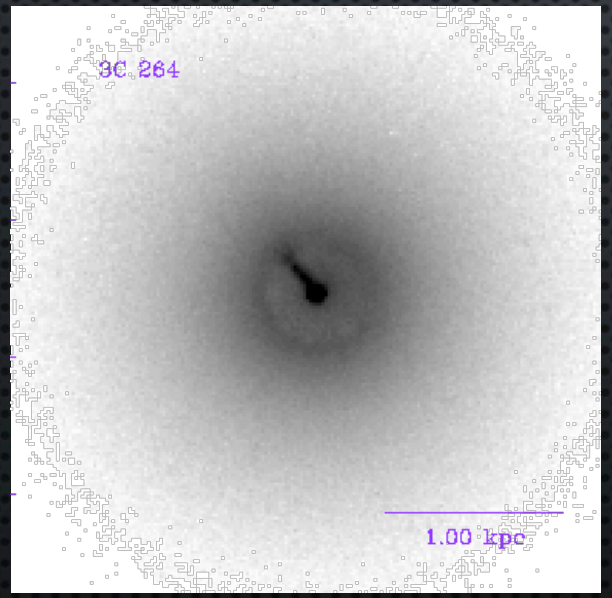
- Unprecedented accuracy of < 0.1c
- Measured deceleration and transverse motions for the first time
- Helical pattern in outer knots
- Superluminal speeds in the outer knots

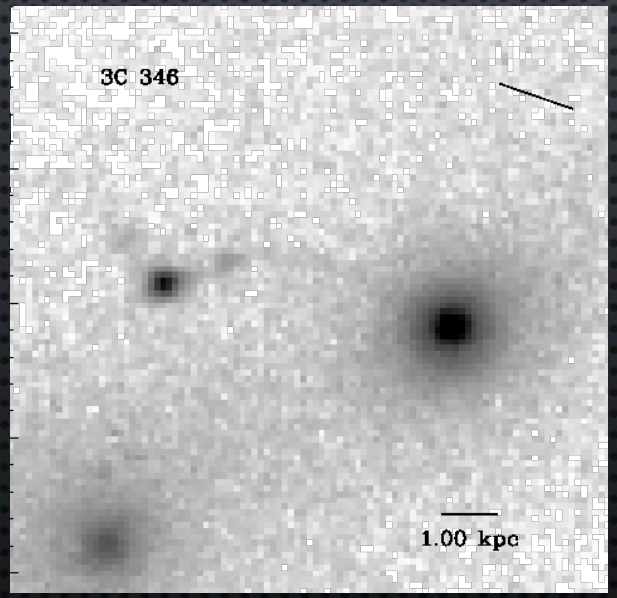
HST Proper Motions Requirements

1. Long Time Baselines (Observations in the 1990s)
2. State-of-the-Art Astrometry

HST Proper Motions Requirements

1. Long Time Baselines (Observations in the 1990s) + Nearby (these trade off)
2. State-of-the-Art Astrometry



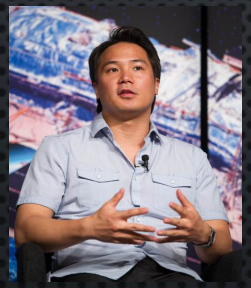


Bill Sparks & John Biretta

HST Proper Motions Requirements

1. Long Time Baselines (Observations in the 1990s)
2. State-of-the-Art Astrometry

HST Proper Motions Group



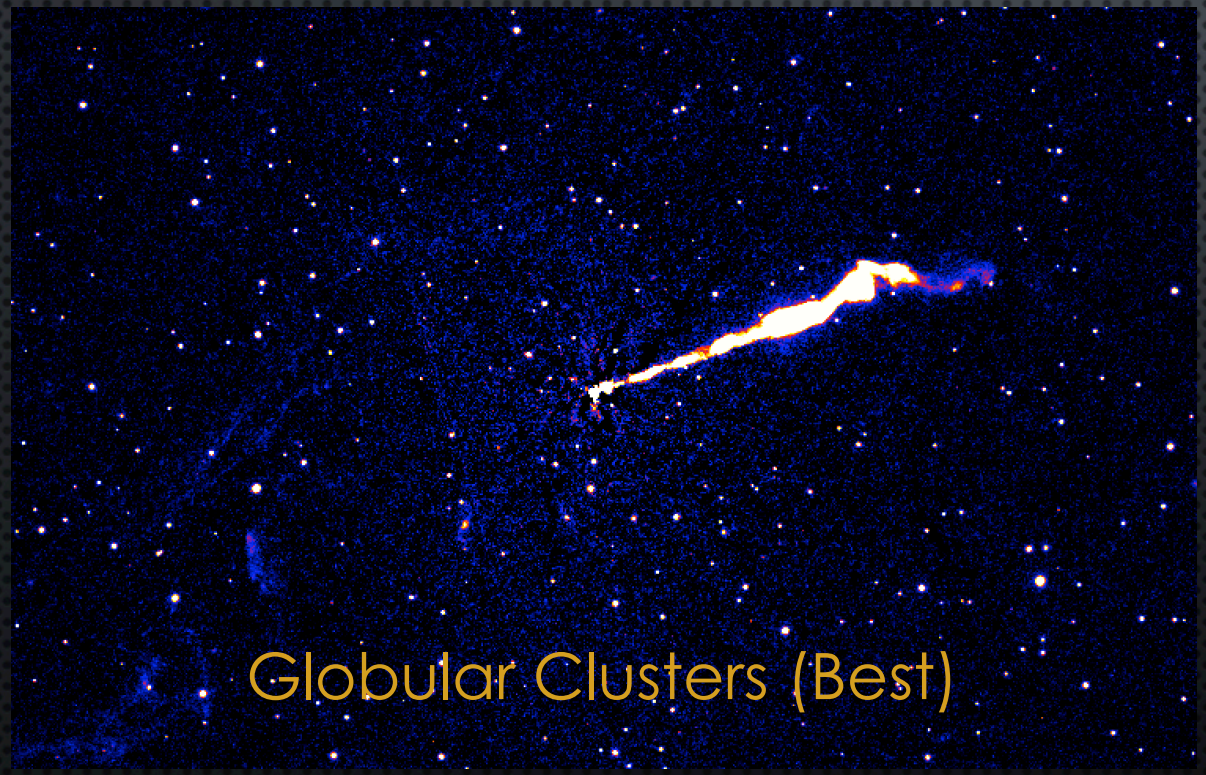
Tony Sohn (Johns Hopkins)

Jay Anderson (STScI)

Roeland Van der Marel (STScI)

HST Proper Motions Requirements

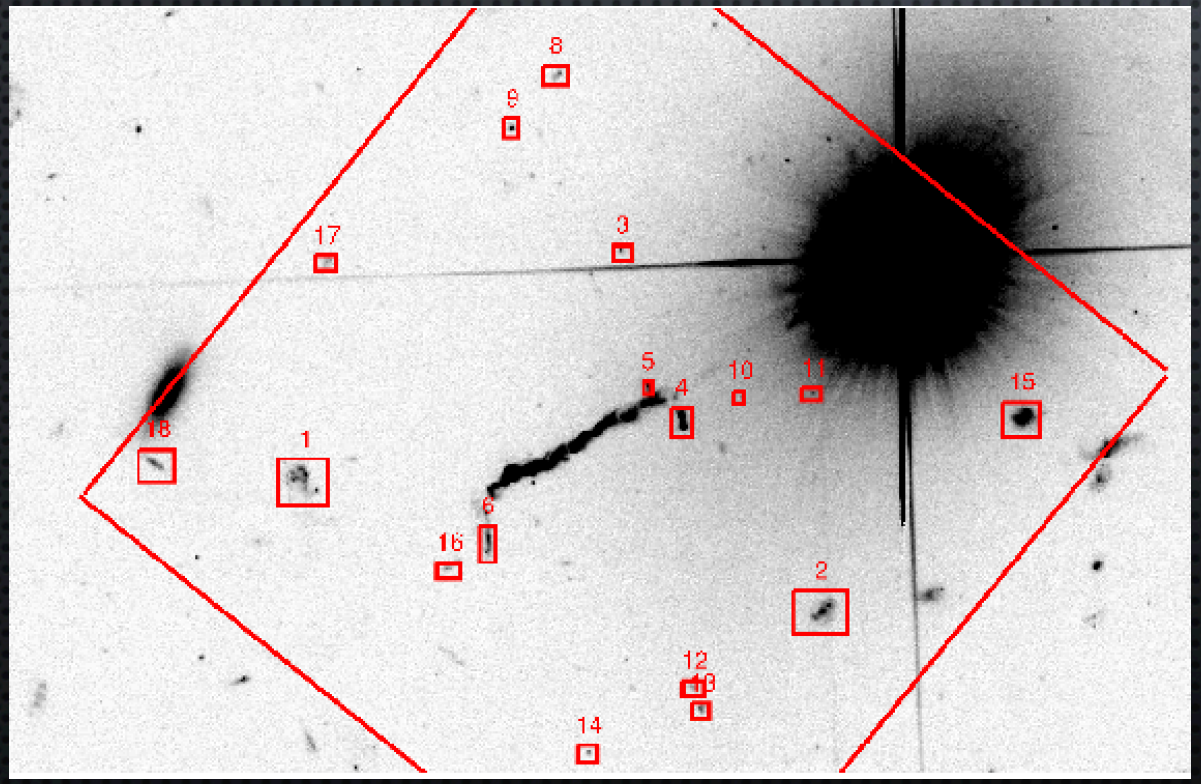
1. Long Time Baselines (Observations in the 1990s)
2. State-of-the-Art Astrometry



- Easily register images to 0.17 mas (M87 Study)
- Equivalent to 10s of μ as/year
- In the most nearby jets (with visible globulars) we are dominated by the error in measuring the jet components, not the systematics

HST Proper Motions Requirements

1. Long Time Baselines (Observations in the 1990s)
2. State-of-the-Art Astrometry

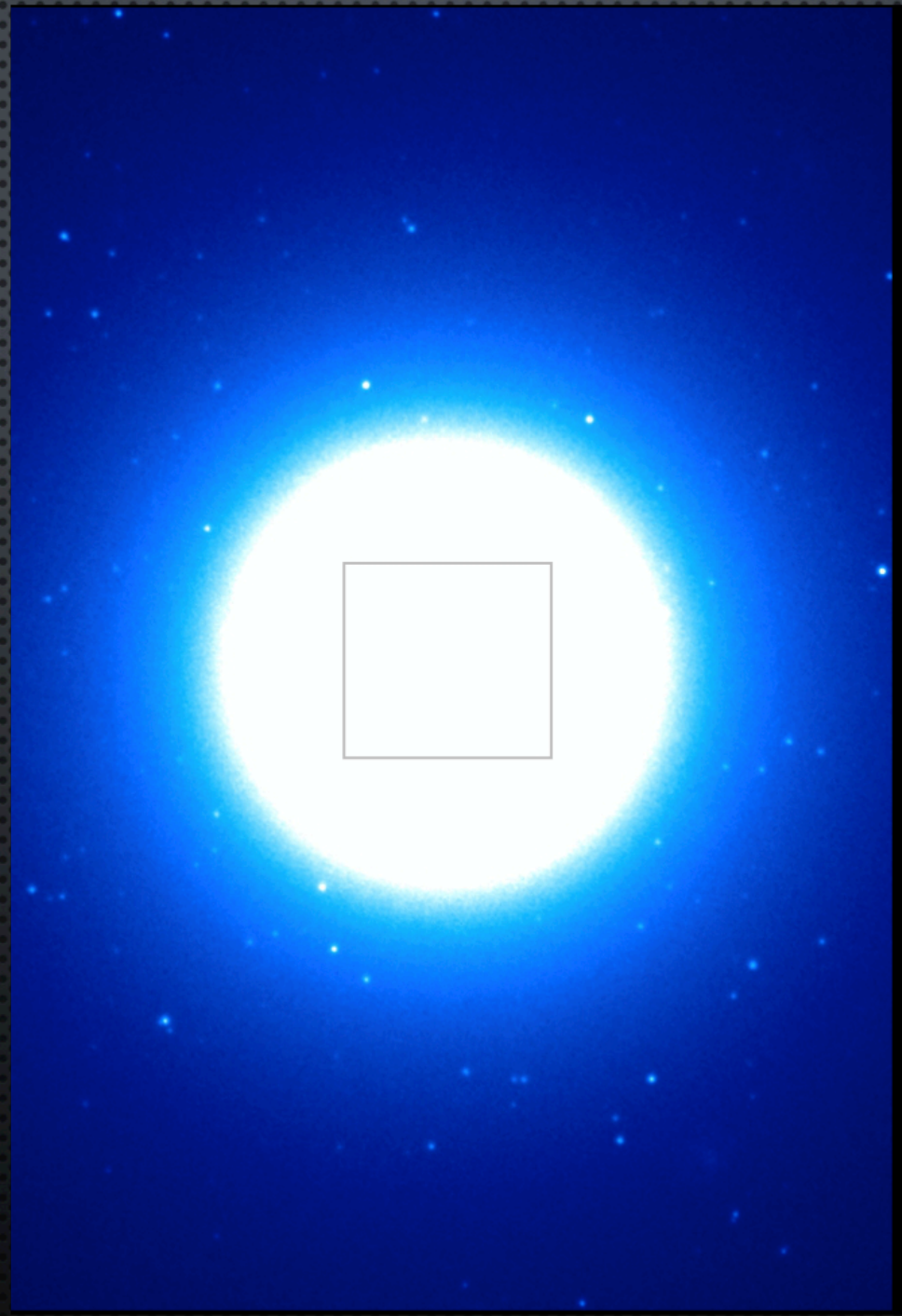


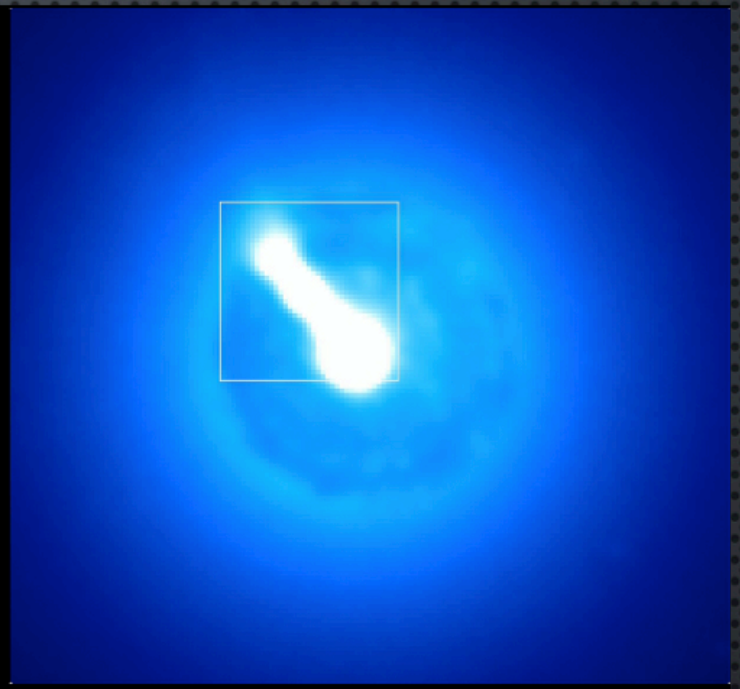
Background Galaxies

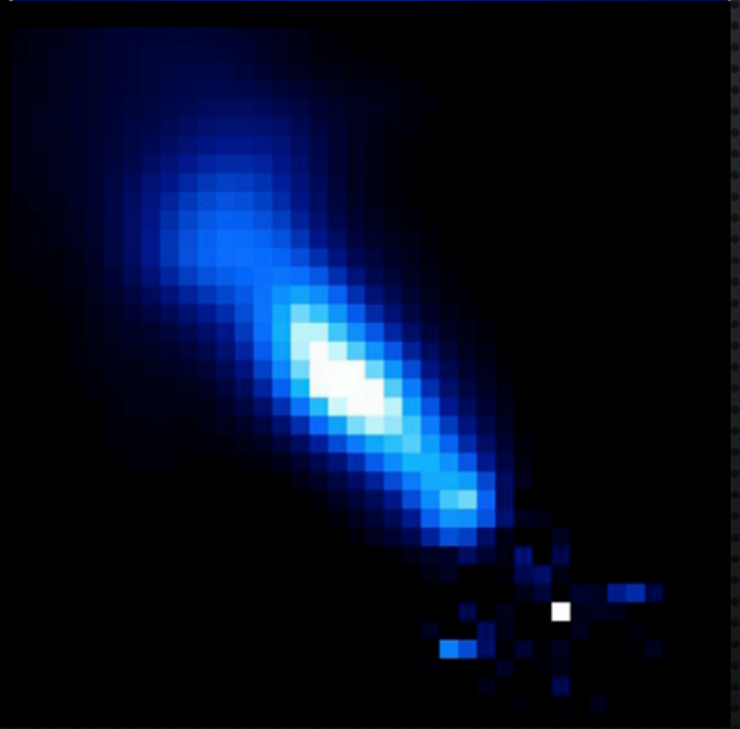
- **Difficult,** but reach d = 100-700 Mpc
- Registration errors on the order of 5 mas in 3C 273 study (comparable to uncertainties in defining components)
- Hope to Improve this!! (stay tuned)

3C 264:
‘M87 Analog’ at 91 Mpc

Observed in:
1994
1996
2002
2014

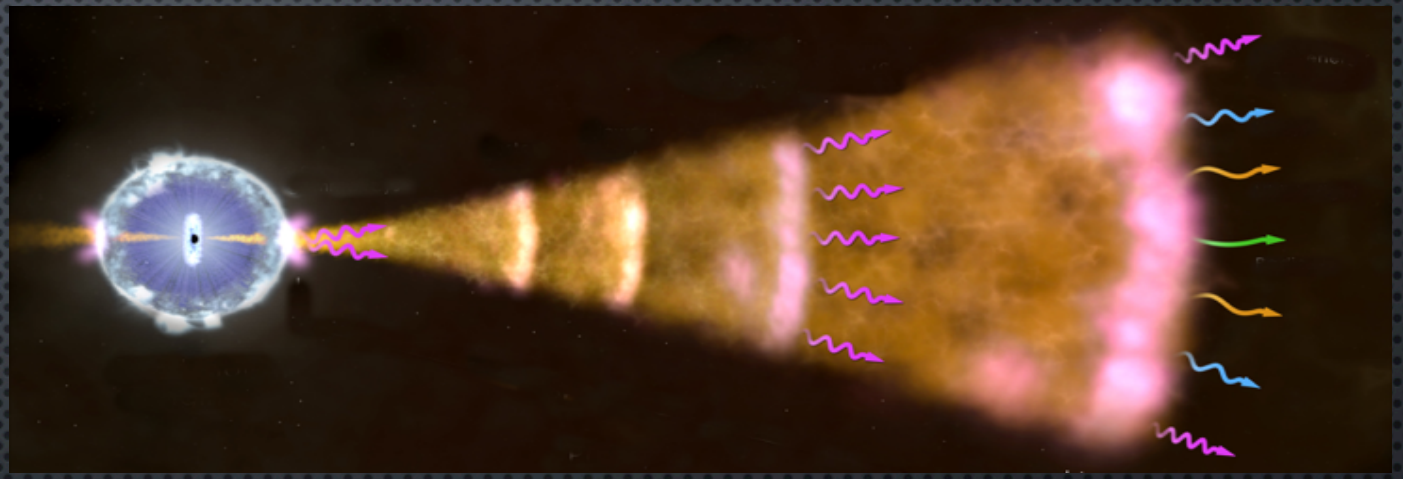






The Internal Shock Model (Rees 1978)

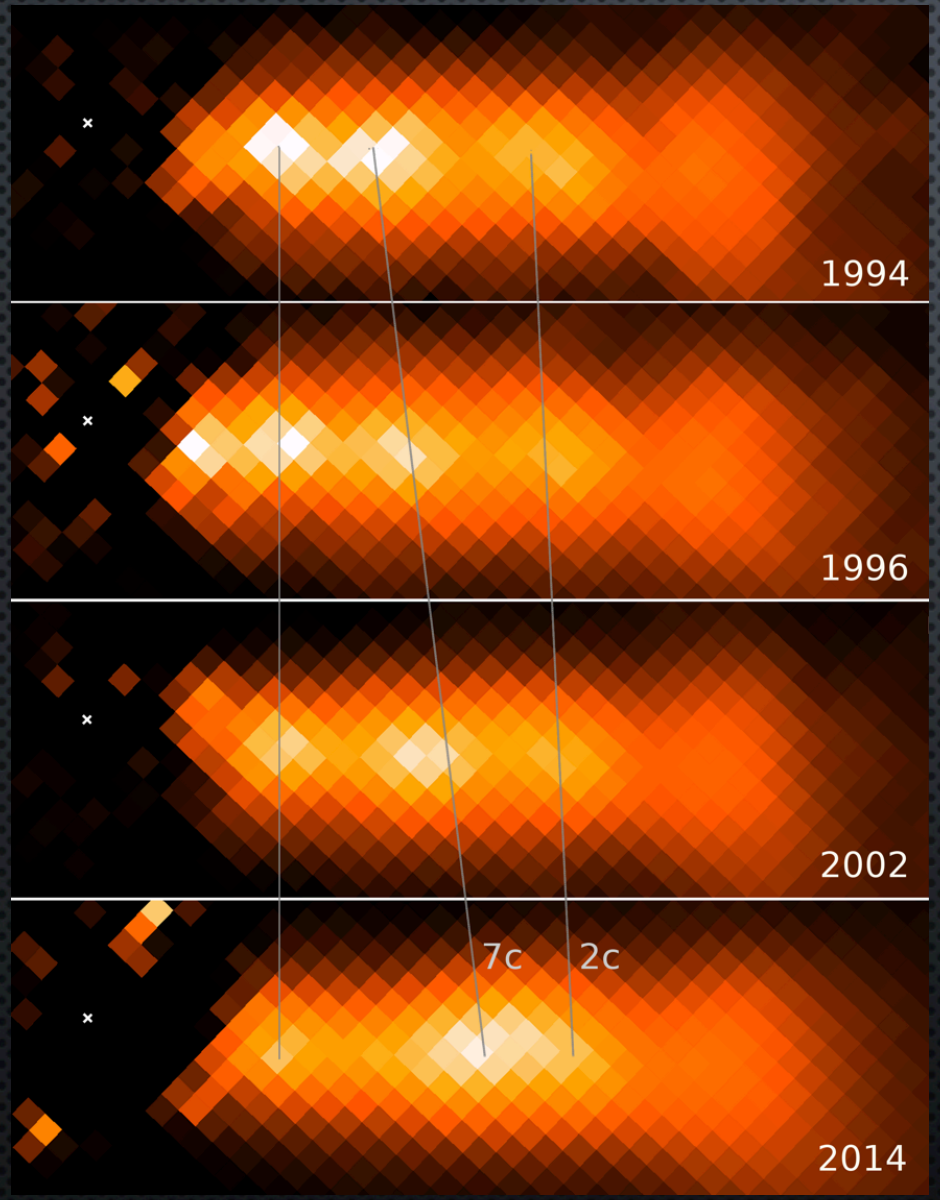
Variable, High-E Radiation
→ Energetic Particles
→ Shocks
→ Unsteady Flow
in the Jet



Gamma-ray bursts

X-ray Binaries

Jetted AGN



3C 264

Jet is 0.4 kpc in length

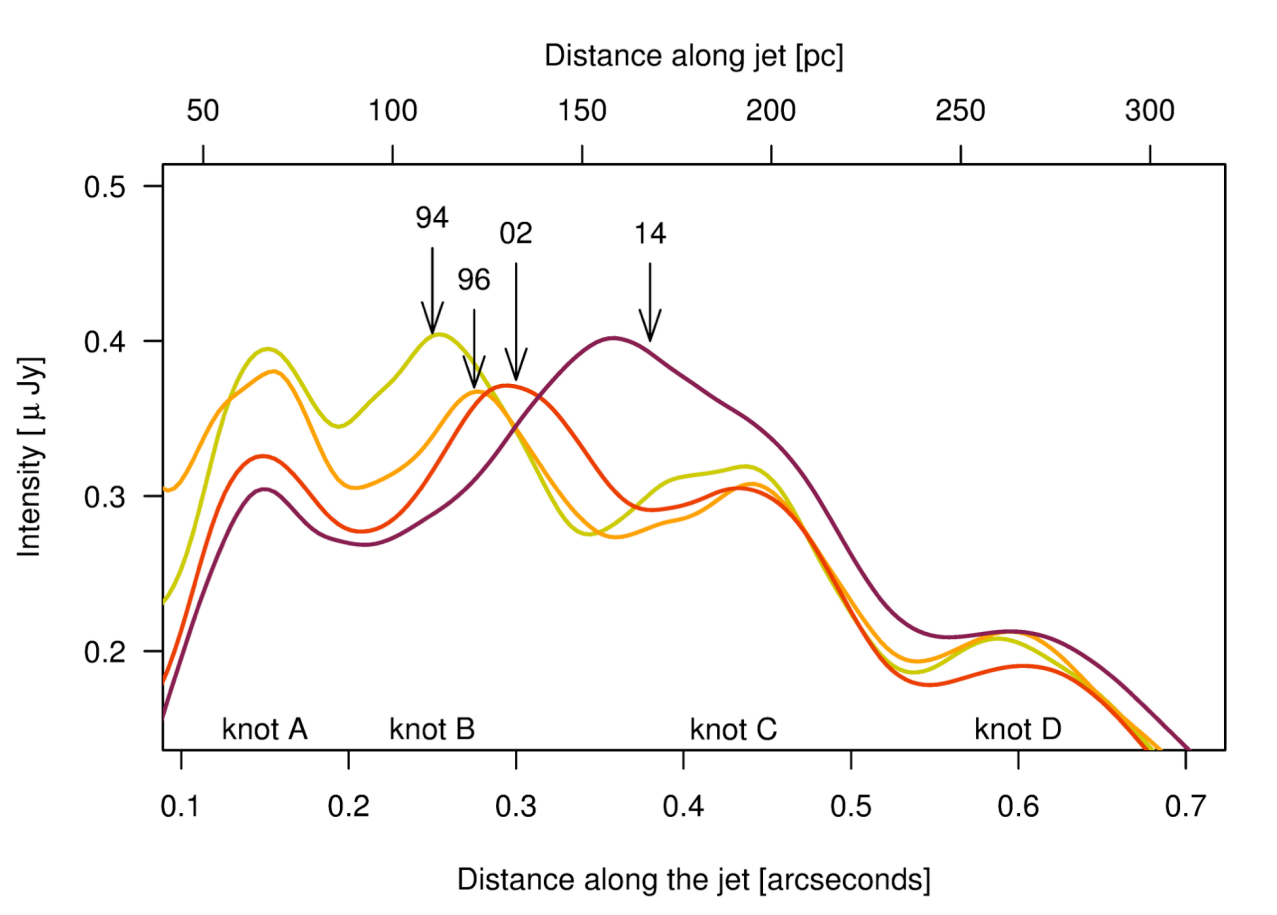
Knot B has apparent speed of 7+/-0.8 c
(highest ever measured at these distances)

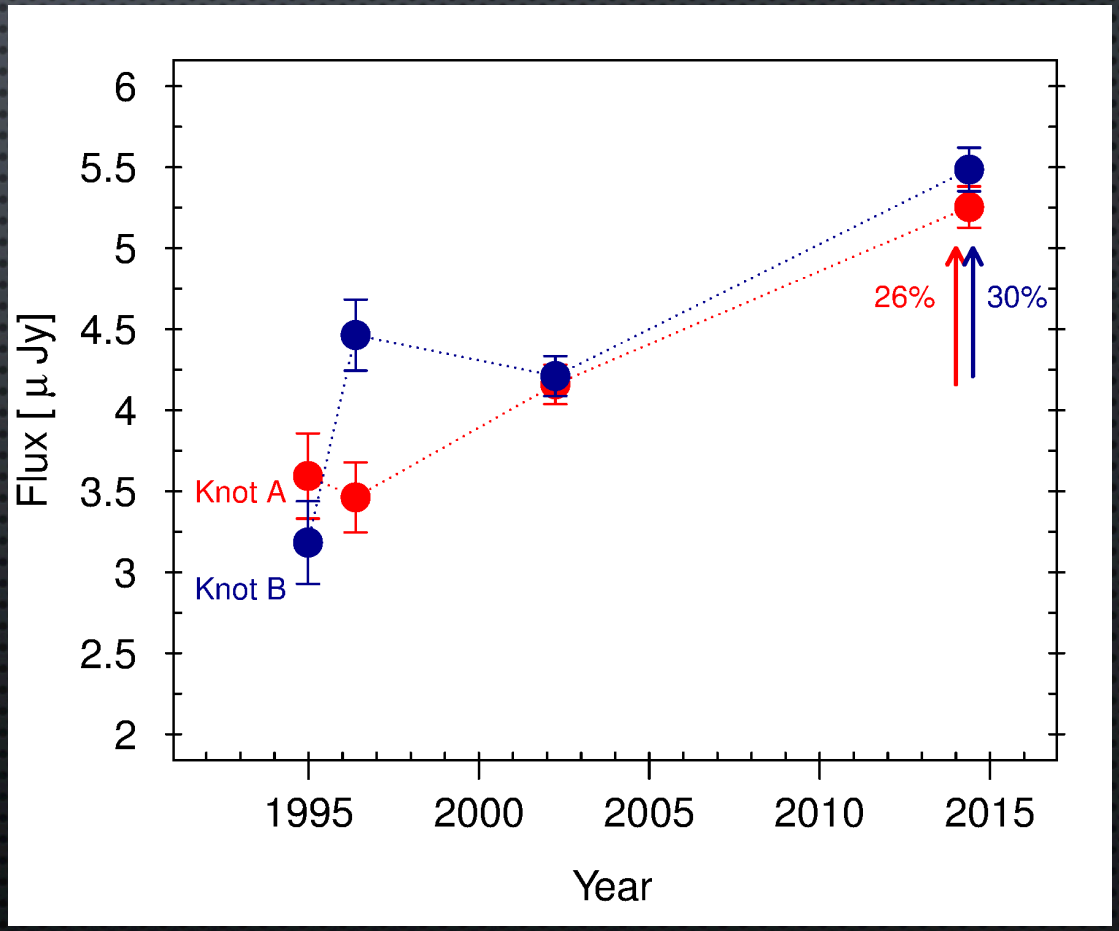
Knot C has apparent speed of 1.8+/-0.5c

Collision of Knots B and C
Significant Brightening Observed

(Meyer et al., 2015, Nature)

Internal Shock in 3C 264



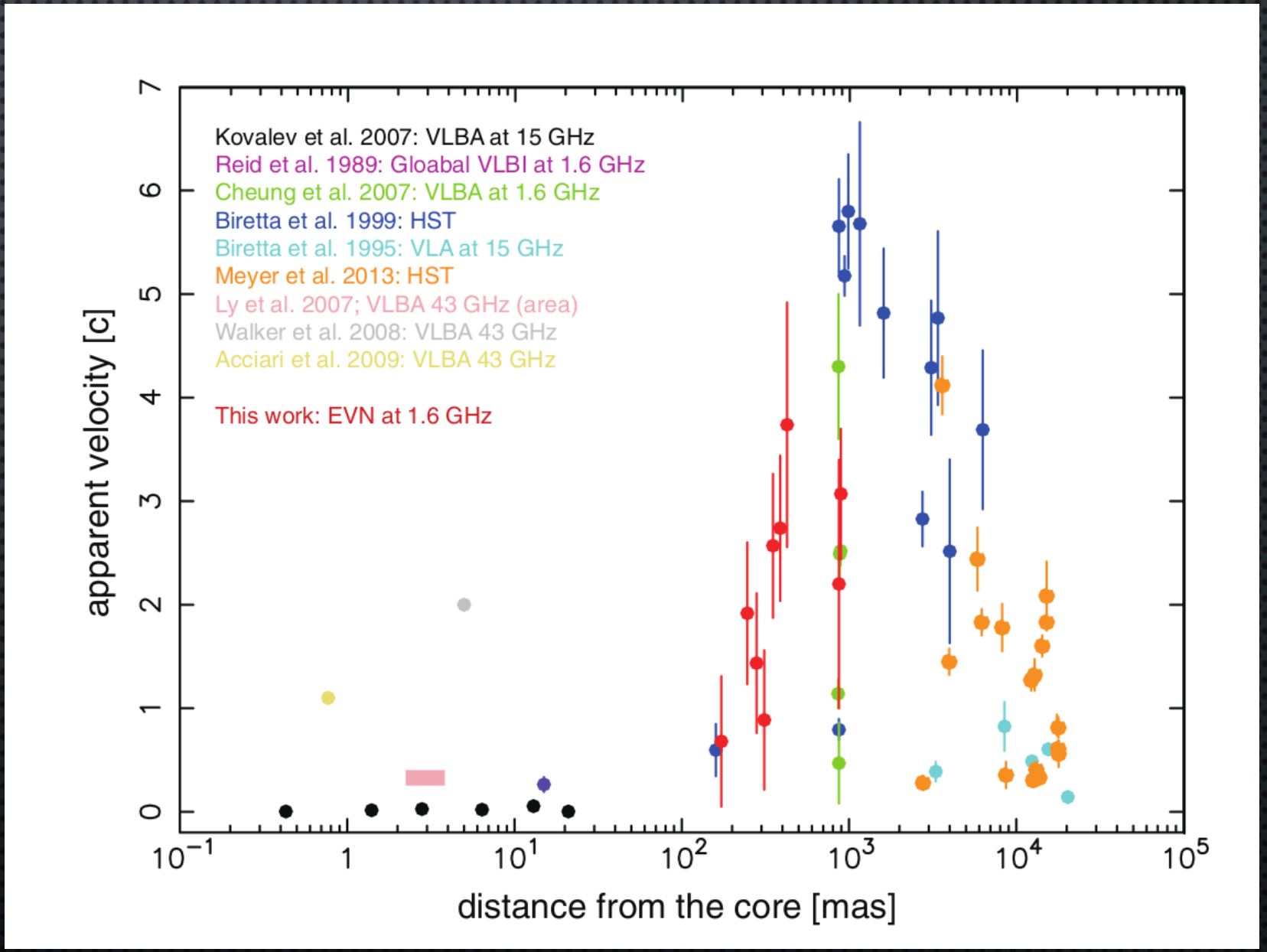


This is M87, but matches 3C 264 pattern exactly.

Very sub-luminal up to HST-1 (100 pc from the core)

Sudden acceleration (?) to 6c at 100 pc

Slow ‘envelope’ of deceleration over ~ 2 kpc



Efficiency of the Internal Shock in 3C 264

We estimate ~30 years for the collision to go to completion

Pessimistically, assume flux steady at 2014 level

Taking minimum Lorentz factors Γ_B=7.1, Γ_C = 2.8 (angle of 8.1°)
→ produces Γ_m = 3.7 for the combined knot post-collision

Assume cooling time << collision time (radiates 30 years)

$E_{diss}=2.6\times10^{51}$ erg → $\eta = 10^{-3}$ *minimum*

3C 264 Summary

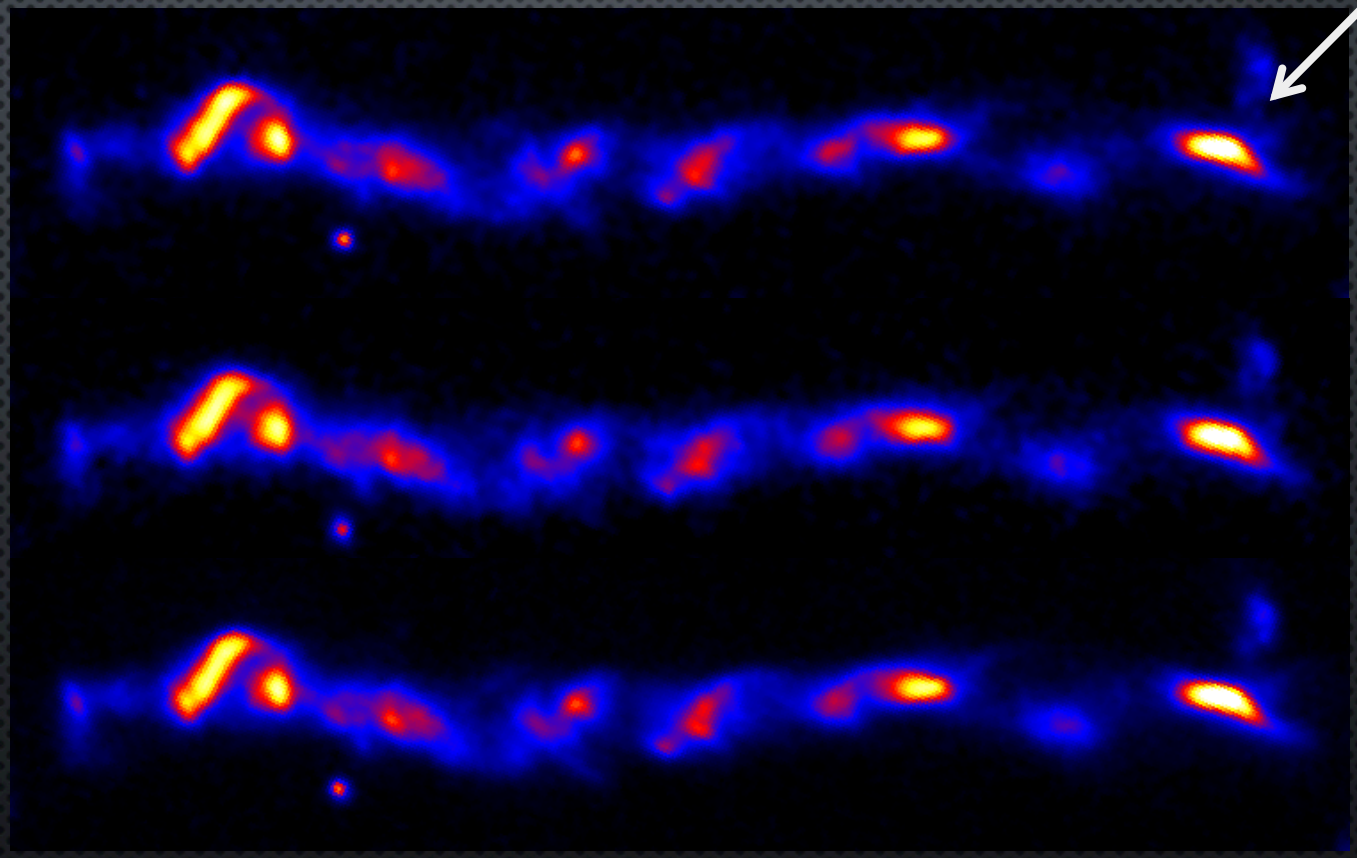
- Knots of 3C 264 show variable speeds
- Two knots appear to be converging in the final epoch
- 30 year timescale for completion
- Combined Flux is increasing → particle acceleration?
- So far, increased flux is linear with time

3C 273

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

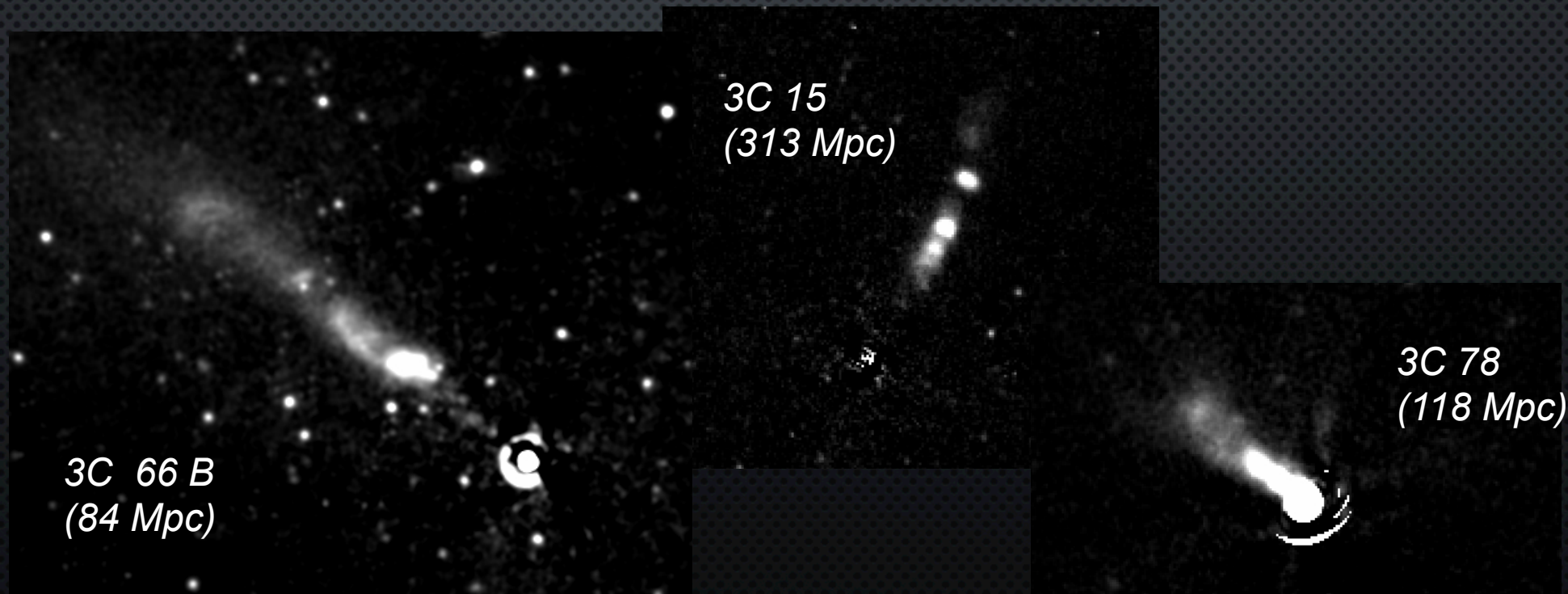


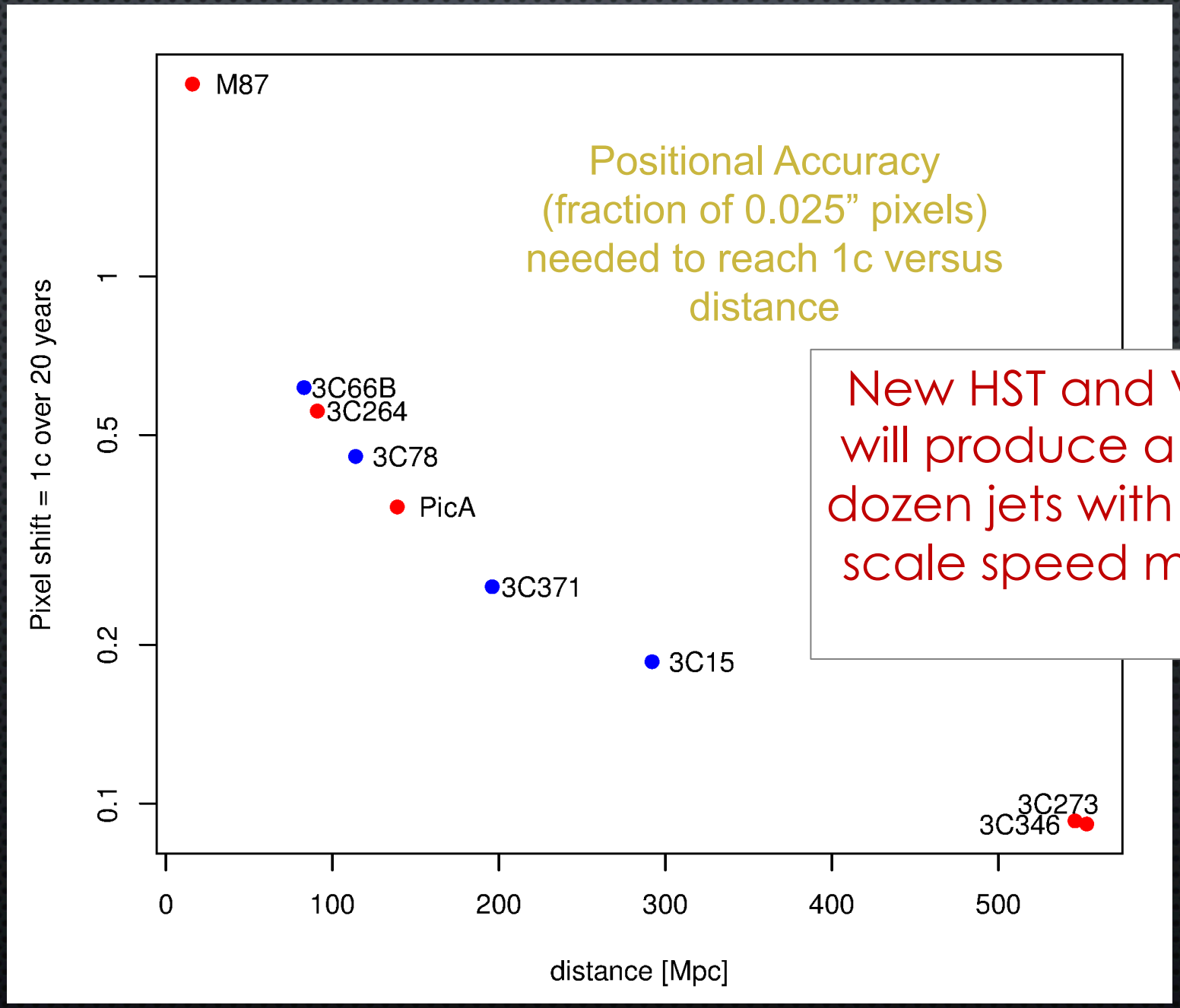
The only thing moving is this foreground object!

The Future

The remaining jets in the “proper motions sphere” of ~ 500 Mpc

- 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





New HST and VLBI Proposals will produce a sample of ~ 1 dozen jets with parsec-to-kpc scale speed measurements.

The Future

From Space:

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

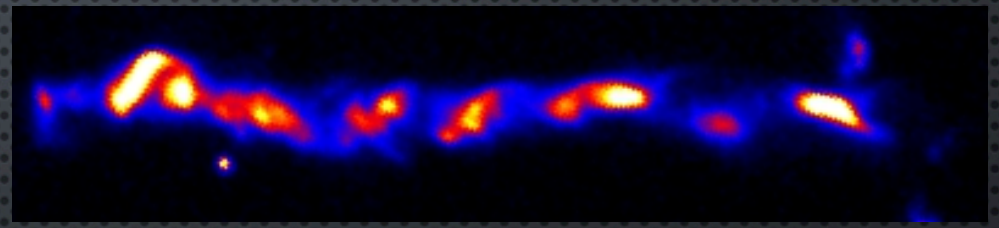
The Future

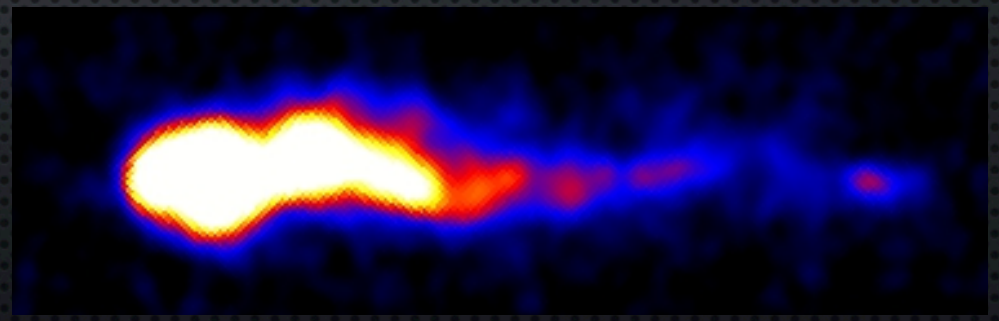
From the Ground:

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)





University of Maryland, Baltimore County

Collaborators:

Markos Georganopoulos (UMBC)
Bill Sparks, John Biretta (STScI)
Jay Anderson, Roeland van der Marel, Tony Sohn (STScI & JHU, Proper Motions Group)
Eric Perlman (FIT)
Marco Chiaberge (STScI), Colin Norman(JHU)

Summary

- M87: Transverse motions & Helical Alignment
- 3C 264: Evidence for Internal Shocks
- 3C 273: Independent Evidence for a Slow Jet (or Standing Shocks)
- FR Is have long acceleration zones?
- More to Come: Sample of about 1 Dozen will come out in the next few years, VLBI + HST