Space-VLBI observations of nearby radio galaxies with RadioAstron

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and

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Jet ~~AGN~~ astrophysical processes

Some old questions+personal opinions

What powers the jet and what sets the jet power?

Where and how is most of the energy dissipated?

How are jets accelerated?

Real progress has been made in most of them, but some are still annoyingly tough nuts to crack.

What is the internal structure of the jets?

How are jets collimated?

What is the jet composition?

How high is the jet magnetization and how it evolves along the jet?

What is the B-field configuration?

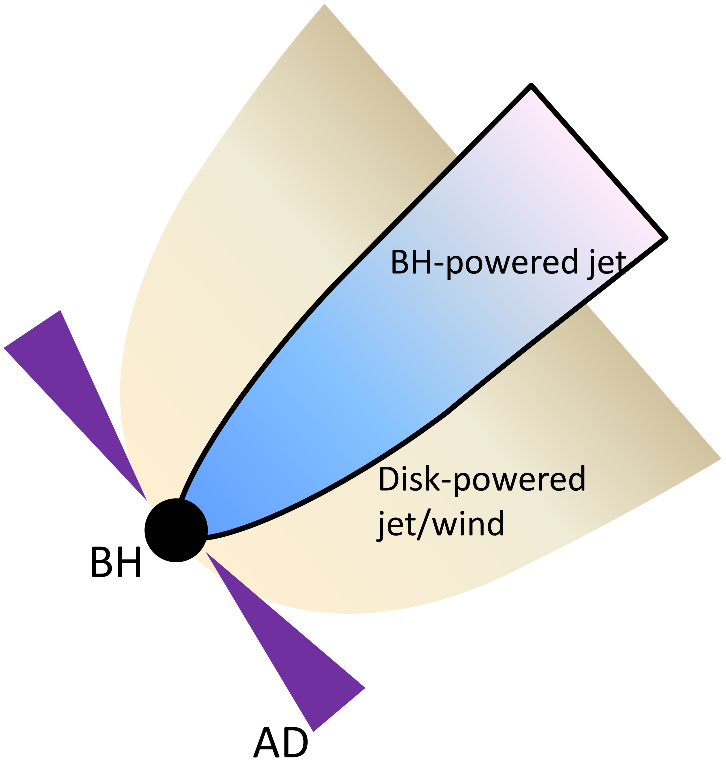
The root of it all
and the two flavours of jets

Jets powered by magnetic extraction of rotational energy of the BH (Blandford-Znajek)

- High-Γ, high efficiency jets in GRMHD simulations (McKinney+09, Tchekhovskoy+11)
- Low initial mass loading, high magnetization
- Sources with $\mathrm{P}_{\mathrm{jet}} \gtrsim \dot{m}c^2$ likely BZ-systems

Jets powered by rotating accretion disk (Blandford-Payne)

- Easily mass-loaded, but more difficult to reach high velocities
- Recent VLBI observations of initially very wide jets in radio galaxies support disk launching (Boccardi+16)

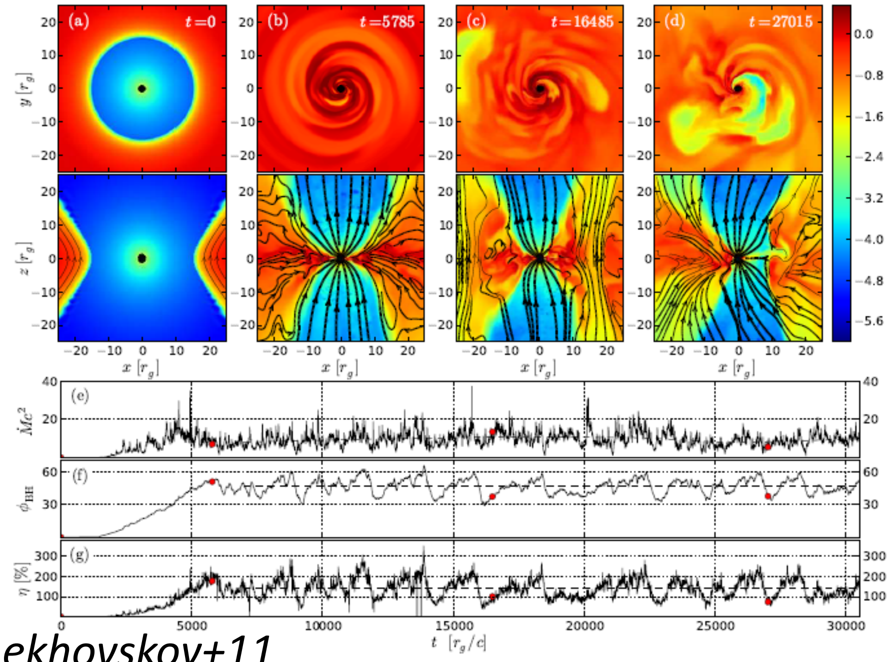


Both mechanisms co-exist producing a structured jet (one version of "spine-sheath")? Quite possibly. We should figure out, what part of the jet we actually observe in different sources!

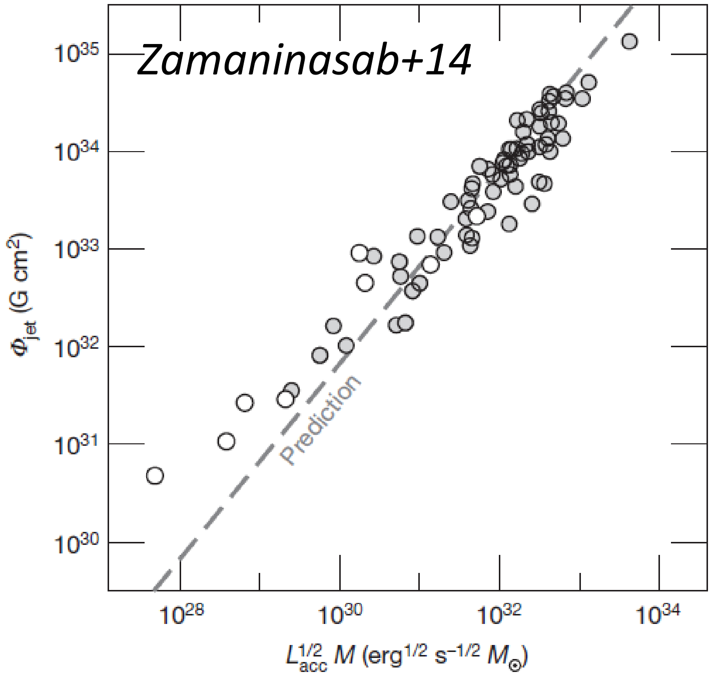
Going slightly MAD

Gravity limits BH B-field strength – accumulation only until magnetic pressure balances ram pressure of the accreting gas: $B_{max} \sim 10^4 \left(\frac{L_{acc}}{0.1 L_{Edd}}\right)^{0.5} \left(\frac{M_{BH}}{10^9 M_\odot}\right)^{-0.5}$ [G]

- When $B \gtrsim B_{max}$, "magnetically arrested disk" forms and jet power is maximized ($P_{BZ} \propto {\Phi_{BH}}^2 a^2$)
- Simulations show highly efficient (>100%) jets in MADs (Tchekhovskoy+11)



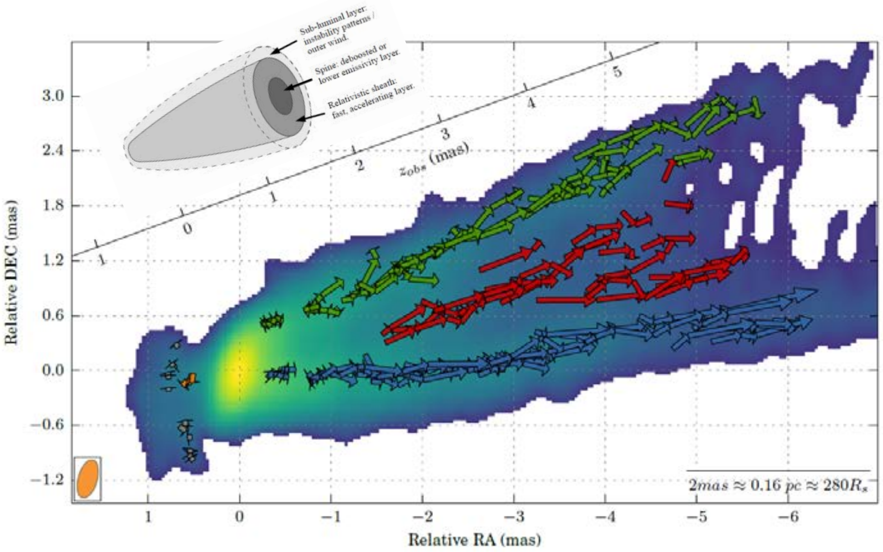
Tchekhovskoy+11

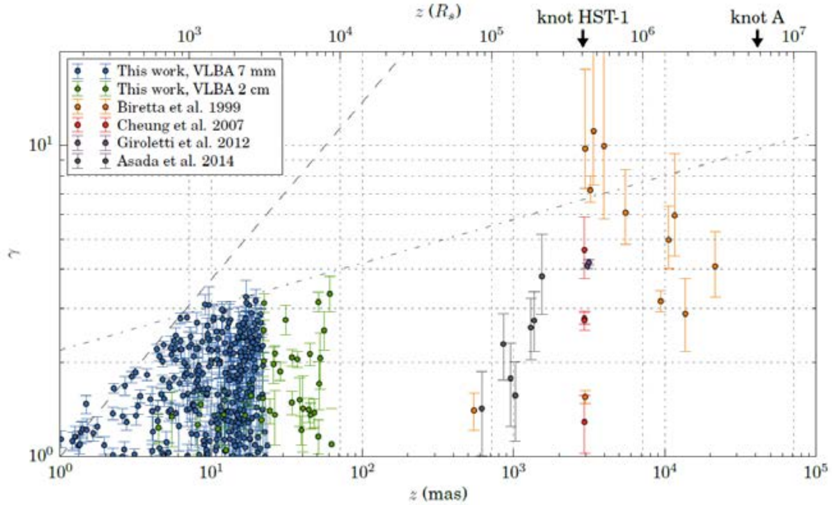


Observational evidence for MADs found in radio-loud AGN (Zamaninasab+14, Ghisellini+14, Zdziarski+15). Supports also BZ.

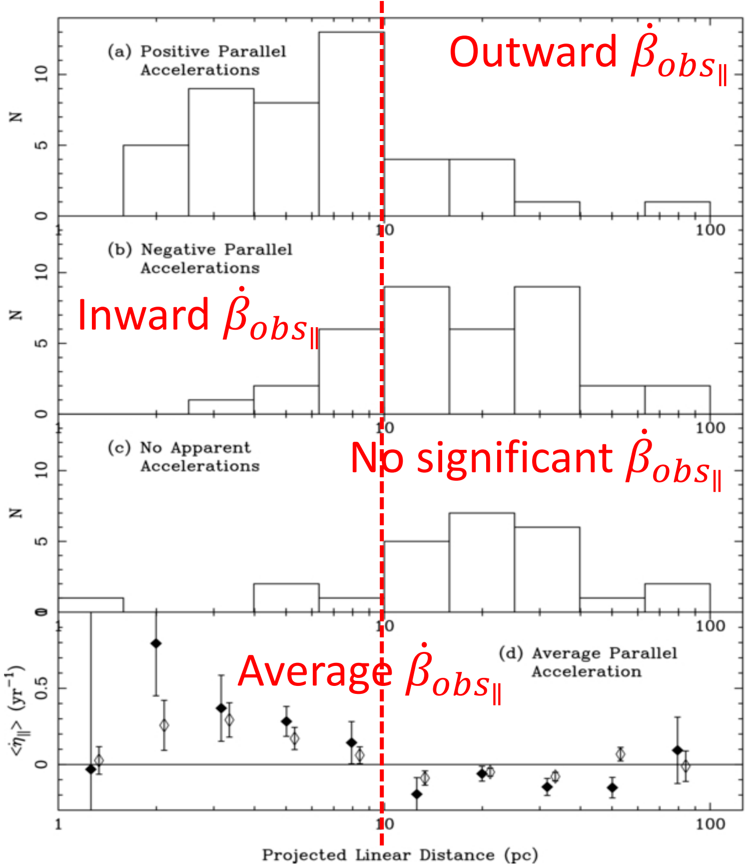
Getting up to speed

Velocity field of M87 (Mertens+16)





Statistics from the MOJAVE Survey (Homan+15)



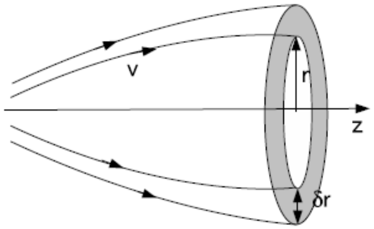
Outward $\dot{\beta}_{obs_\parallel}$

Inward $\dot{\beta}_{obs_\parallel}$

No significant $\dot{\beta}_{obs_\parallel}$

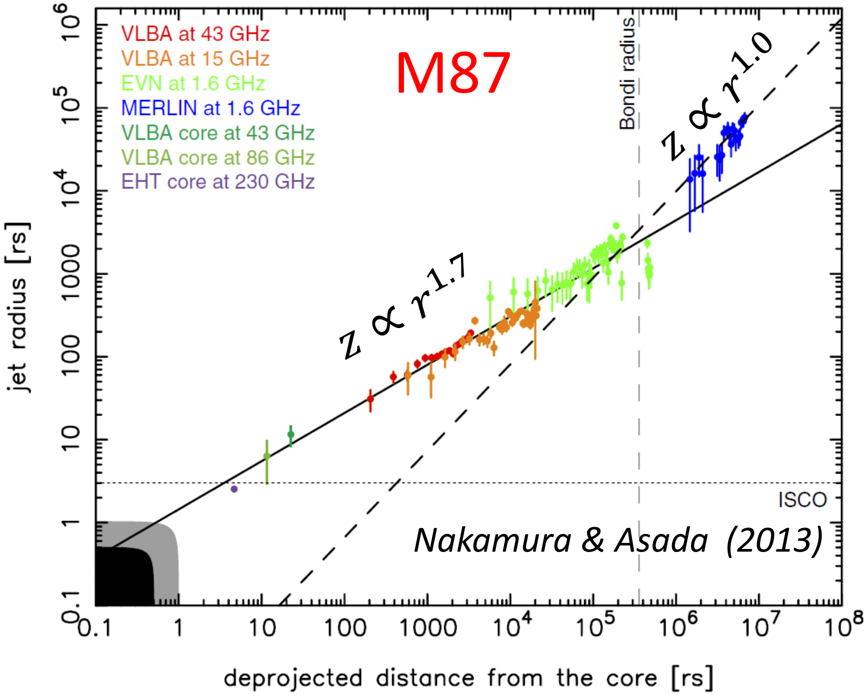
Average $\dot{\beta}_{obs_\parallel}$

Fast acceleration up to $\sim 10^3 R_g$, slower up to $\sim 10^6 R_g$

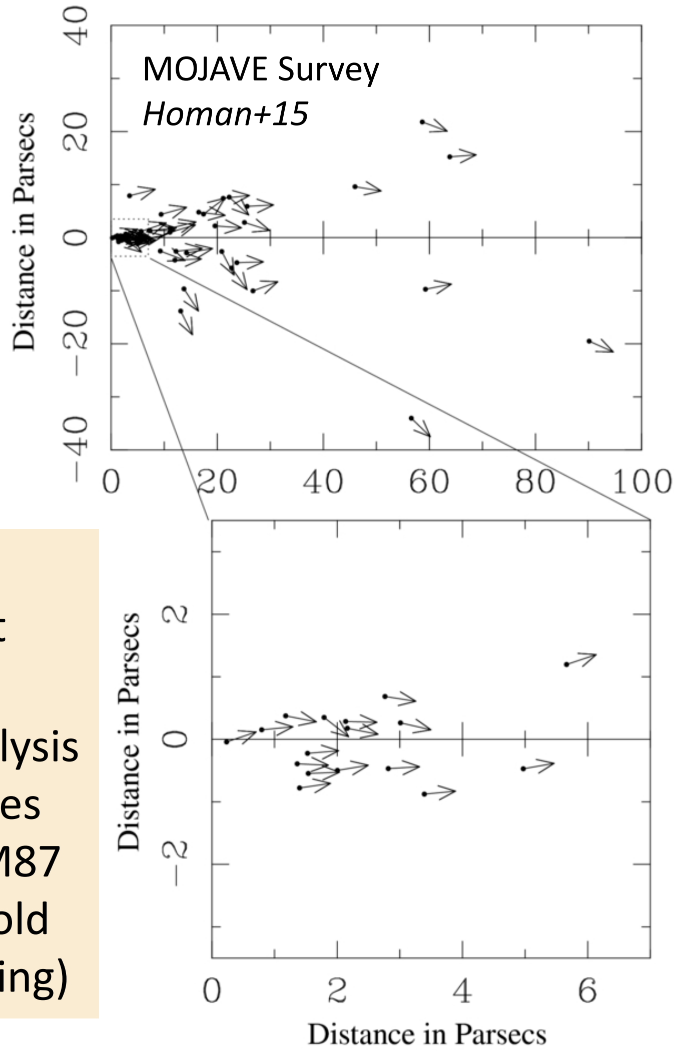


… and staying focused

- Magnetic acceleration requires differential collimation
- Self-collimation alone is not sufficient, need for confinement by external medium (giant RIAF, disk wind)
- Evidence for collimation up to $\sim 10^5 R_g$ in M87 and even further out in some MOJAVE sources



Nakamura & Asada (2013)



MOJAVE Survey
Homan+15

Needed:

- More data at $z \lesssim 100 R_g$
- Detailed analysis of also sources other than M87 (especially cold mode accreting)

Magnetic confusion

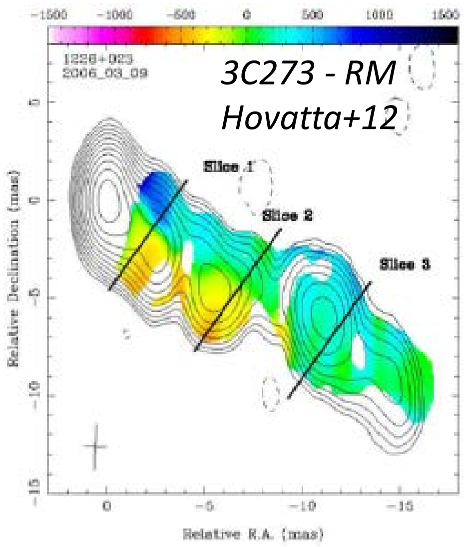
We are still uncertain about how magnetization and B-field structure evolve along the jet. The evidence can support very different scenarios.

Ordered helical B-field:

- Explains transverse RM gradients (e.g., Asada+02; Gabuzda+13; Hovatta+12)
- Explains long (>180deg) and smooth optical EVPA rotations (Marscher+10; Kiehlmann+16)
- Explains correlated transverse asymmetries in *I*, *m* and RM in some sources (Zamaninasab+13; Gomez+16)

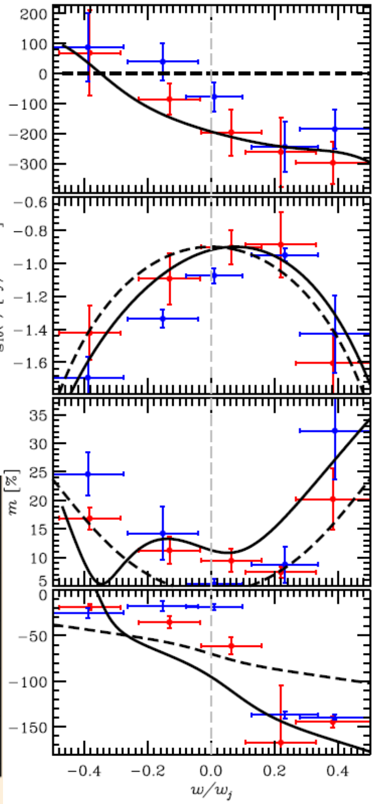
Disordered B-field:

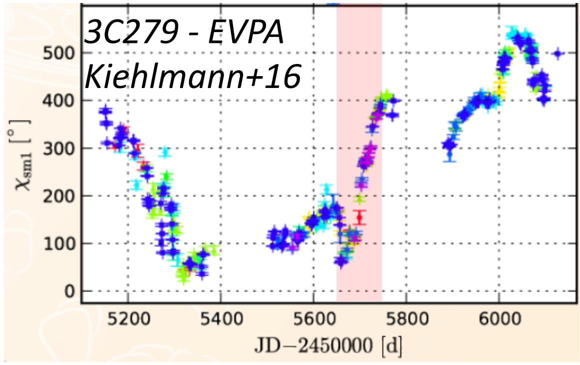
- Expected from CDI when σ approaches unity
- Explains low and variable polarization degree, variable EVPA (Marscher14)
- Shock compression explains polarization behaviour during flares



3C273 - RM
Hovatta+12

3C454.3 - ⊥-profiles
Zamaninasab+13





3C279 - EVPA
Kiehlmann+16

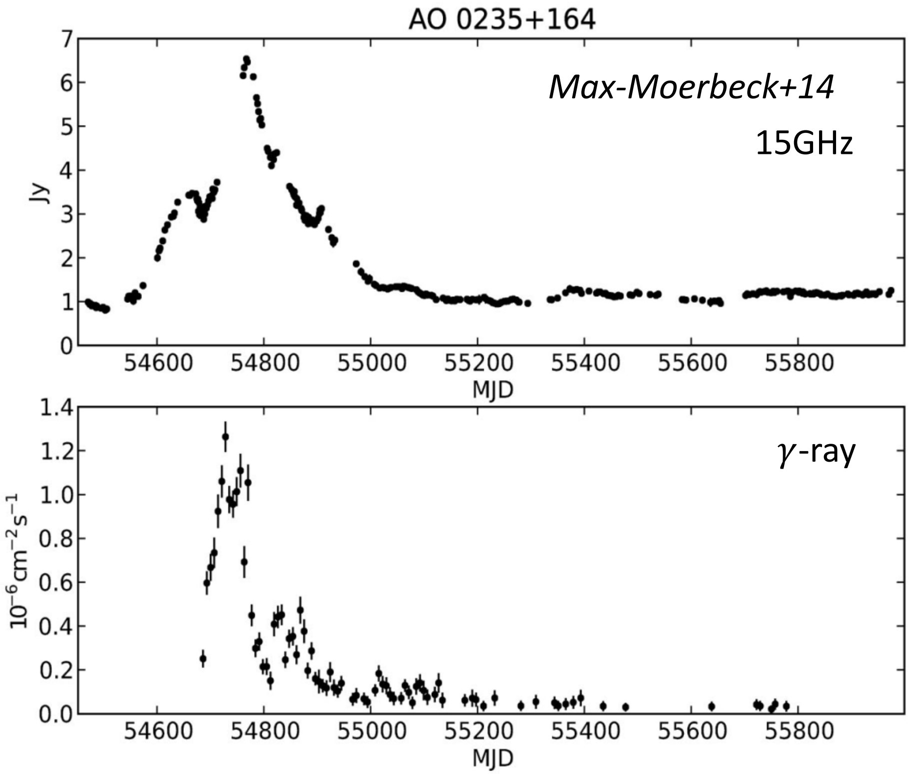
Lose that energy

Dissipation by shocks

- In kinetic flux dominated jets
- Bright “knots” in 10s of pc scale likely moving shocks; also standing shocks in over-pressured jets
- Increased emissivity due to compression → dissipation
- But! Recent PIC simulations: efficient particle acceleration does not produce high γ electrons in shocks and vice versa (Sironi+15)

Dissipation by magnetic reconnection

- Requires $\sigma \gtrsim 1$ to take place, results in rough energy equipartition downstream
- Very efficient mechanism
- Need testable predictions



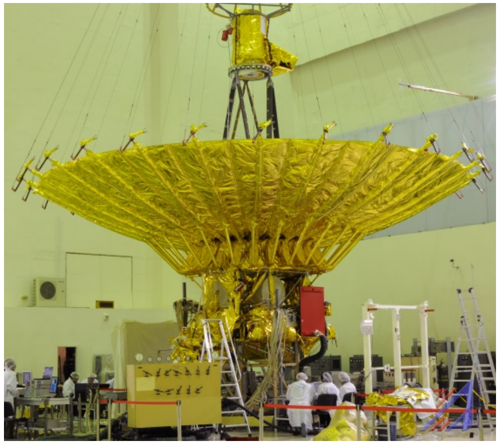
AO 0235+164

Max-Moerbeck+14

… and there is an embarrassing problem with the gamma-rays. We are still not sure where they originate: from close to the BH, within the BLR or from the mm-VLBI core.

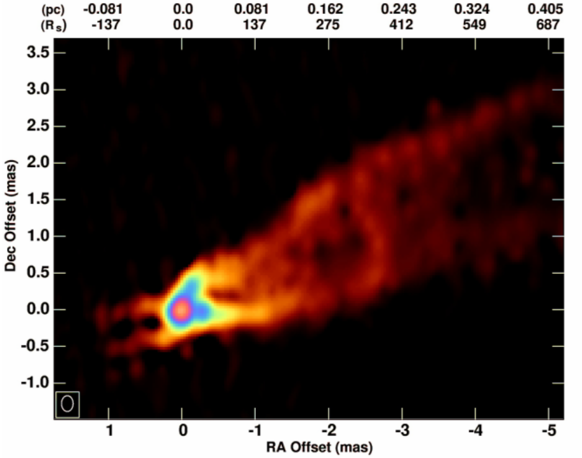
Making progress by increasing (spatial) resolution

Space-VLBI



mm-VLBI

Nearby sources

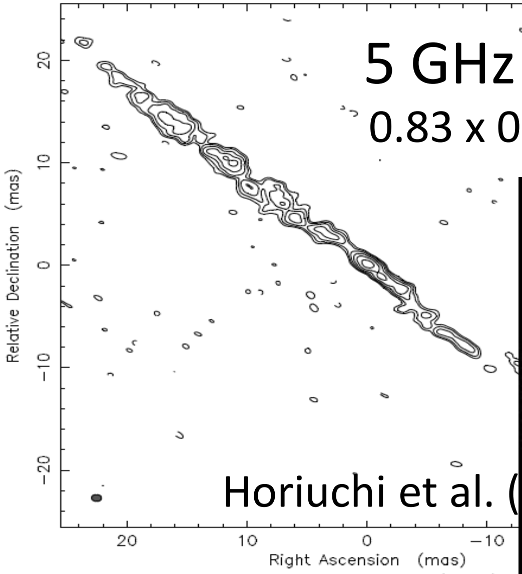


In this session we will hear exciting results of high angular resolution studies of nearby sources (Britzen, Baczko, Boccardi, Kim, Lu, Schulz, Koyama, Matveyenko, Savolainen) as well as mm-VLBI (Karamanavis, Lisakov) and space-VLBI (Vega García) observations of blazars.

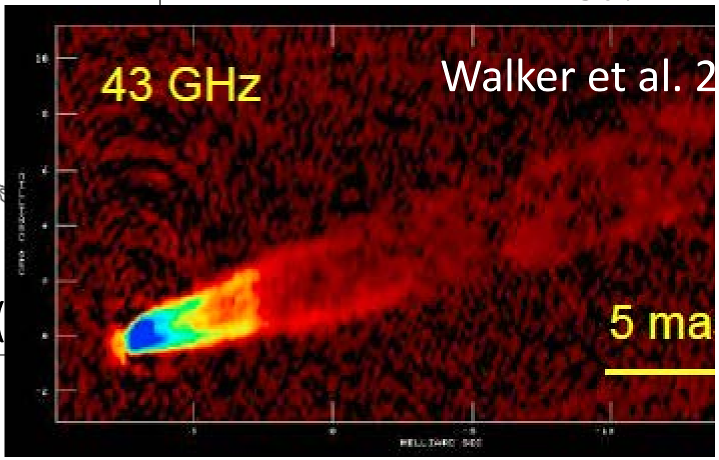
On the other hand, with increasing resolution and fidelity of our images, it becomes more and more evident that AGN jets are highly complex systems.

RadioAstron Nearby AGN Key Science Program

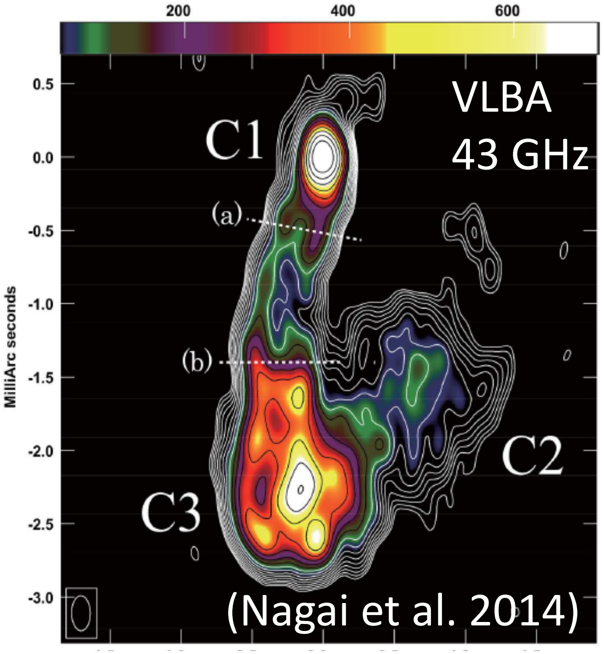
Near-perigee RadioAstron imaging observations of nearby radio galaxies. Target sources are at distances of 4-75 Mpc → aiming at high spatial resolution (down to a few R_S) for studying the jet acceleration and collimation zone.



M87 (D=16 Mpc)
1 mas = 0.08pc = 140R_S
$(M_{BH} = 6 \times 10^9 M_{Sol})$



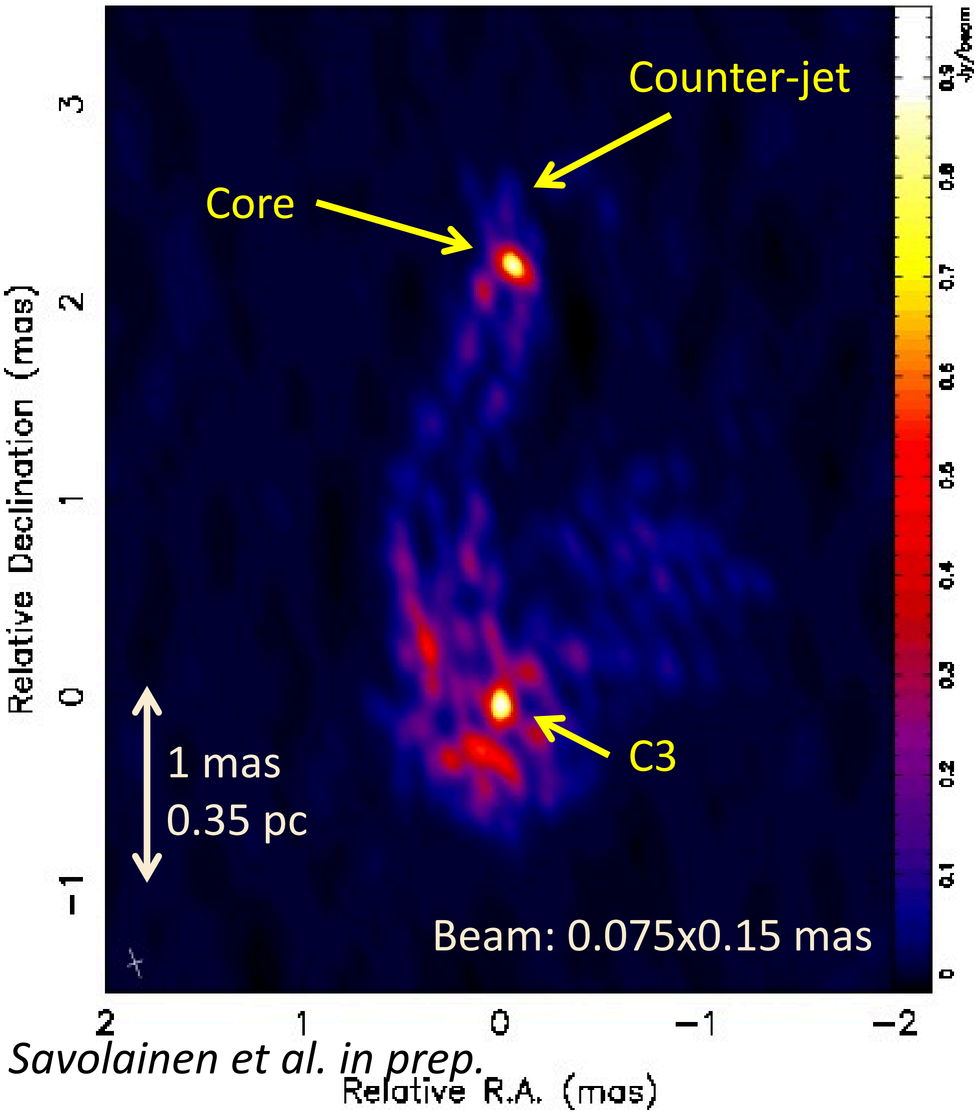
Cen A (D=3.8 Mpc)
1 mas = 0.018 pc = 3100 R_S
$(M_{BH} = 6 \times 10^7 M_{Sol})$



(Nagai et al. 2014)

3C84 (D=75 Mpc)
1 mas = 0.34 pc = 4500R_S
$(M_{BH} = 8 \times 10^8 M_{Sol})$

3C84
22 GHz RadioAstron image



Savolainen et al. in prep.

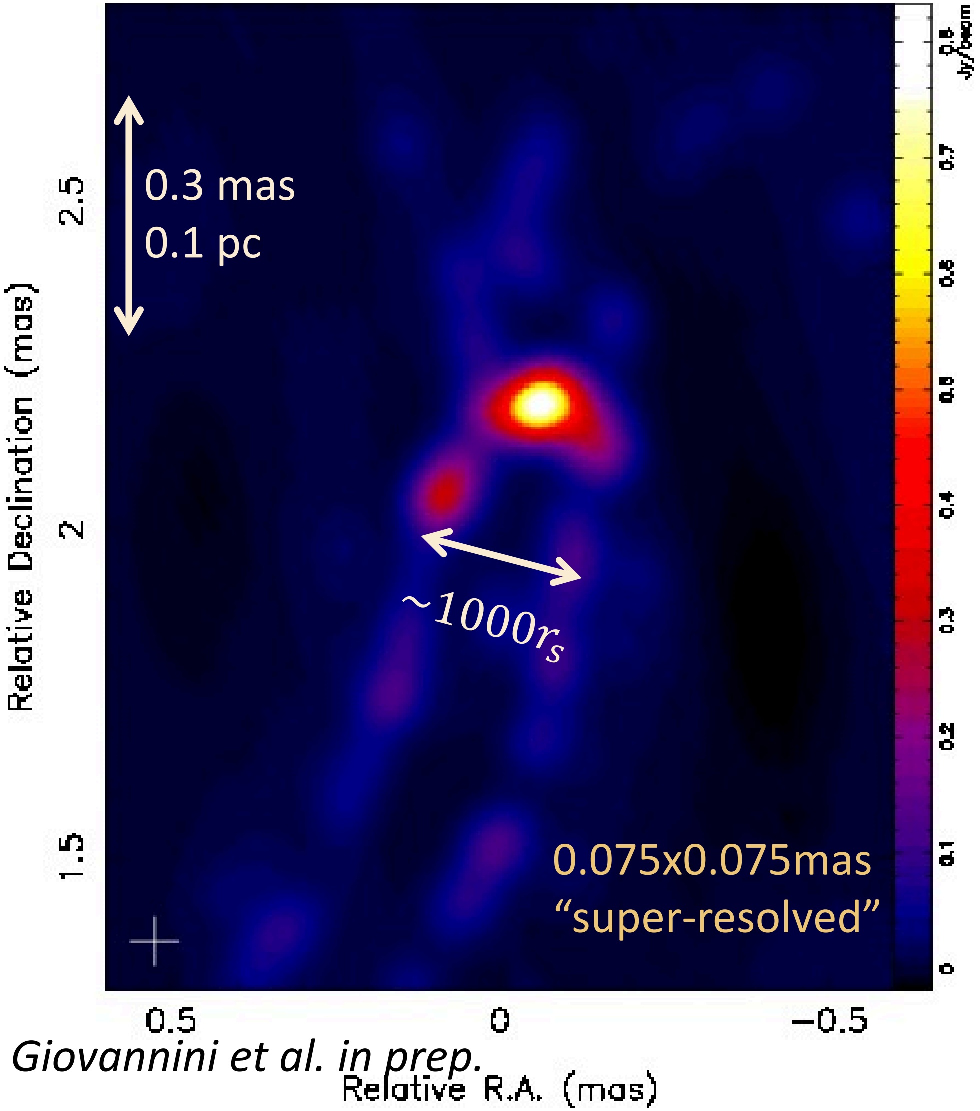
- Maximum fringe spacing corresponds to 27 µas, i.e., ~120 R_s
- Slightly symmetrized beam: 30x300 -> 75x150 µas

Strong edge-brightening with a factor of 20 intensity contrast (edges/center)

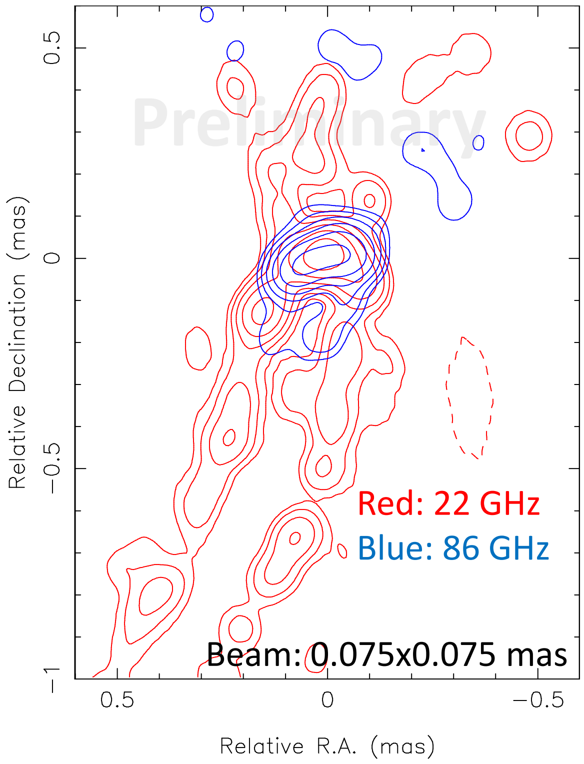
- Velocity structure across the jet? If θ=18deg is assumed, Γ=20 spine + Γ=3 sheath works.
- Low emissivity in the central part?
- ”Spine” becomes visible before C3?

“Hot spot” (reverse shock / Mach disk?) inside the moving feature C3 – the structure resembles simulations of a working surface between jet and ambient medium (see also Nagai+14). Sign of strong jet-ISM interaction.

3C84
Core structure at 22 GHz



Giovannini et al. in prep.

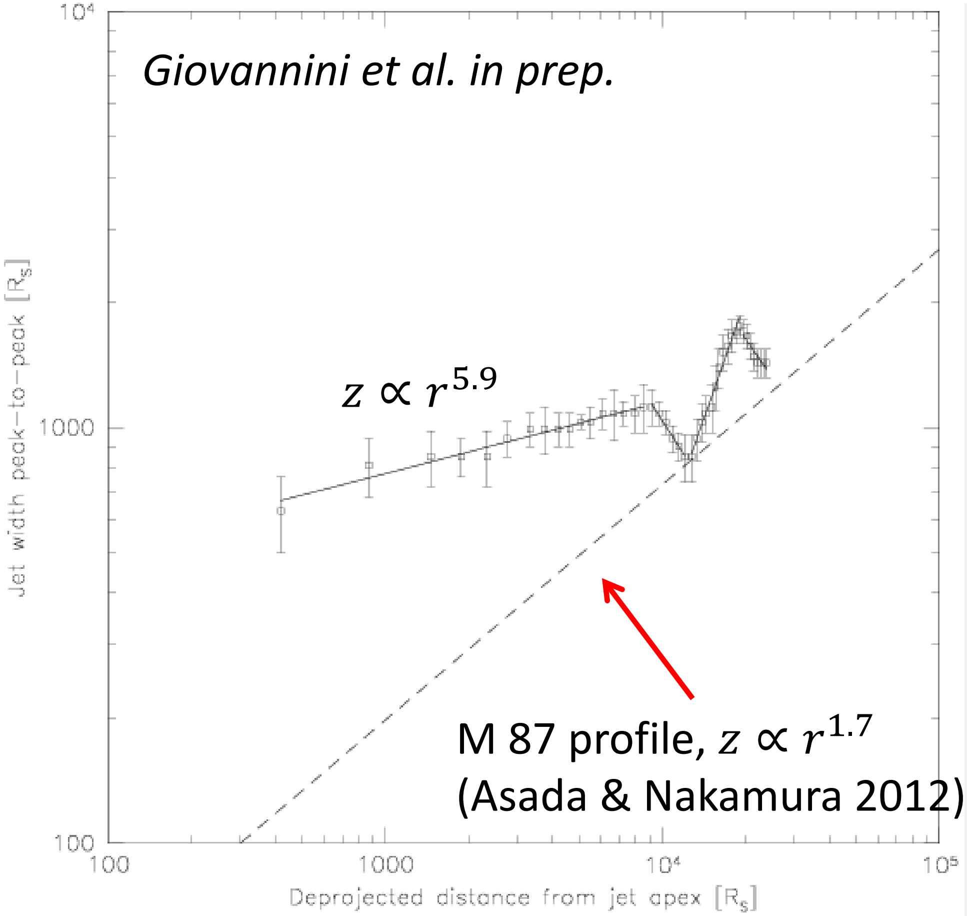


GMVA data
from J.Hodgson

Jet has a <u>very</u> large initial opening angle of 134° and it experiences a rapid collimation to almost cylindrical flow.

3C84

Jet collimation profile at 22 GHz



Giovannini et al. in prep.

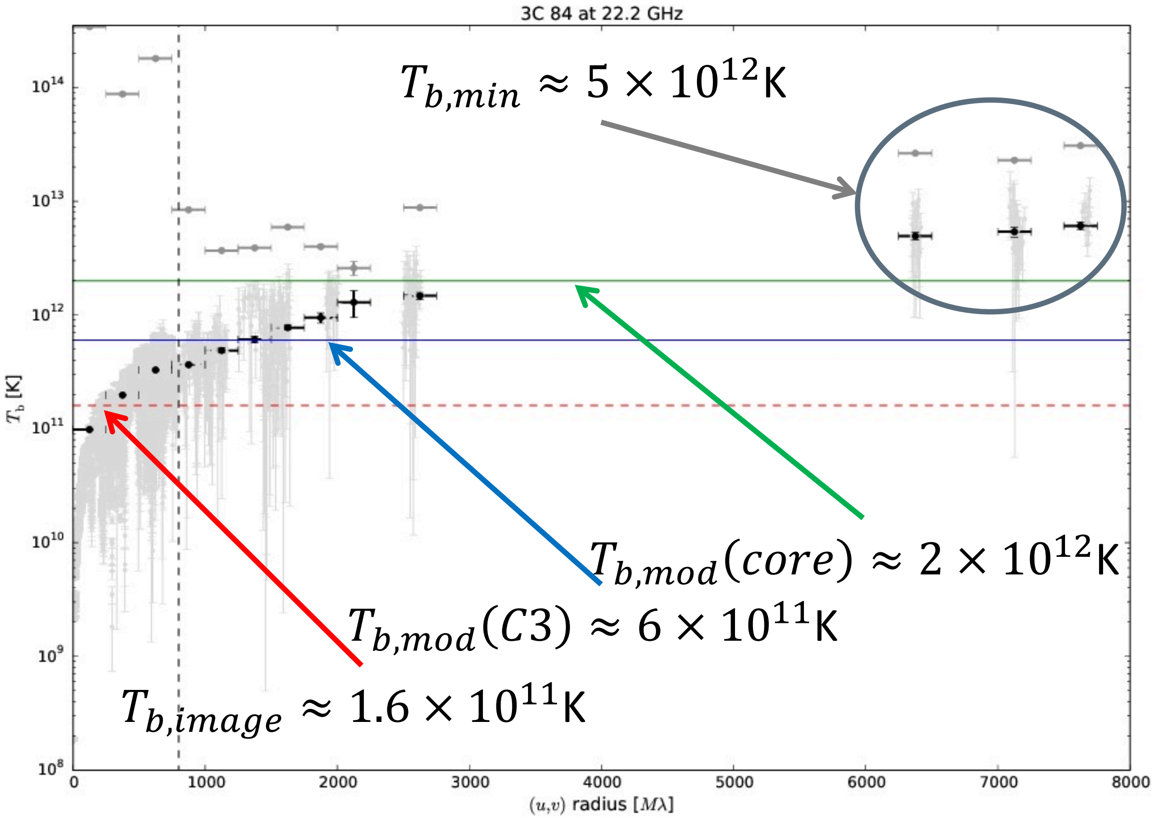
$z \propto r^{5.9}$

M 87 profile, $z \propto r^{1.7}$
(Asada & Nakamura 2012)

Viewing angle of 18 deg assumed
(Tavecchio & Ghisellini 2014)

- Collimation profile beyond $400R_s$: $z \propto r^{5.9}$. Requires a quite shallow ISM profile ($p_{ext} \propto z^{-0.7}$).
- Rapid collimation by external medium – but no recollimation shock visible. Why?
- Jet is wide: $\sim 600\ R_s$ peak-to-peak at $400R_s$ from the 22 GHz core. Parabolic extrapolation would lead to $\sim 30\ R_s$ jet width at $\mathrm{z} = 1\ R_s$ (assuming no core shift).
- Is the edge-brightened part of the jet launched from the disk? (Note that there can still be a BZ jet inside.)

3C84
Brightness temperature at 22 GHz

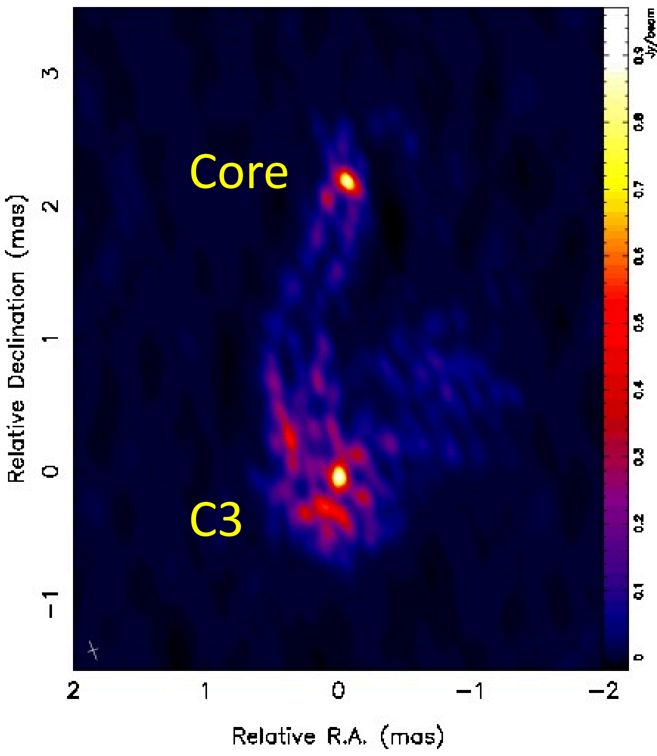


$T_{b,min} \approx 5 \times 10^{12}$K

$T_{b,mod}(core) \approx 2 \times 10^{12}$K

$T_{b,mod}(C3) \approx 6 \times 10^{11}$K

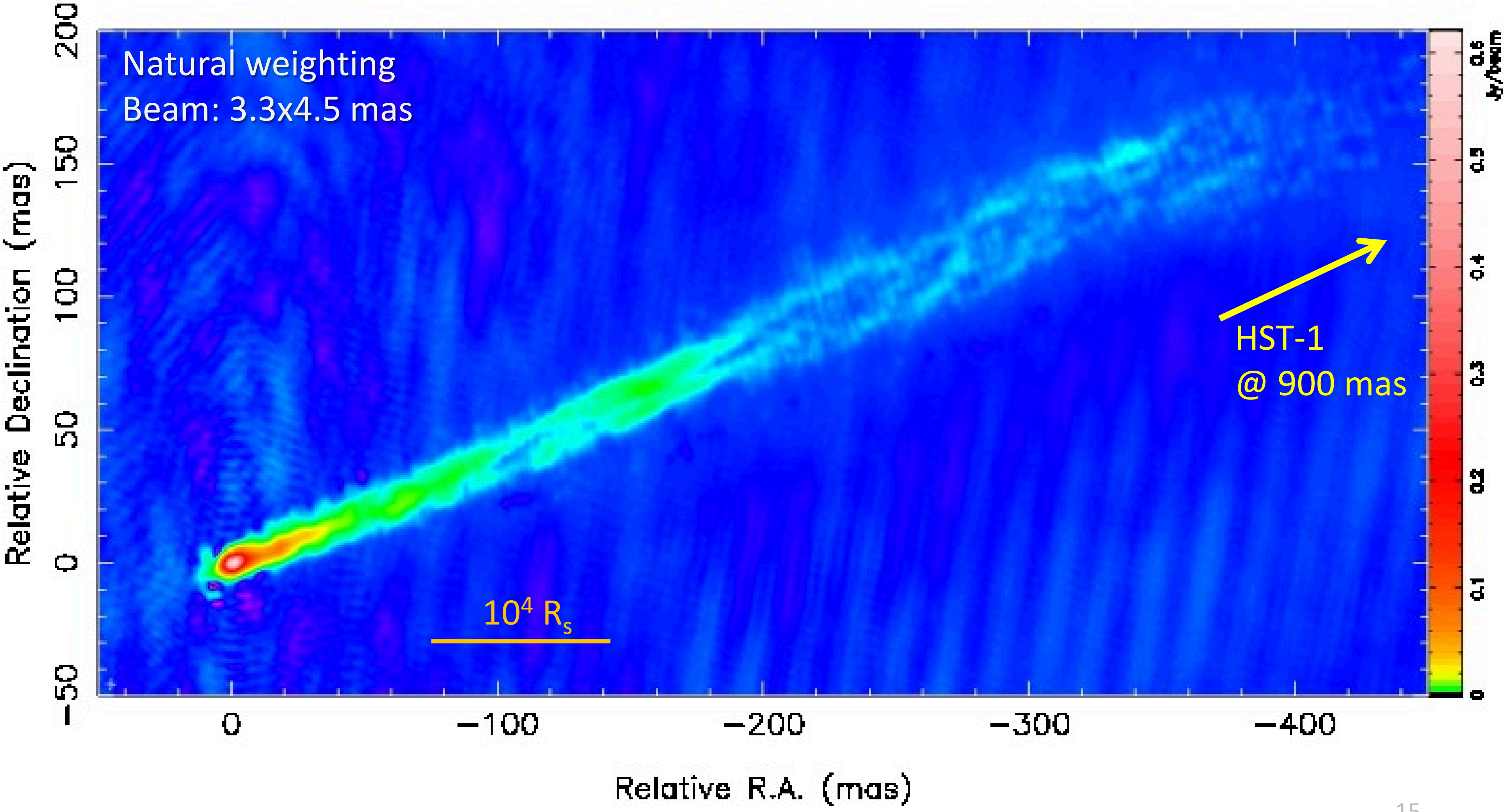
$T_{b,image} \approx 1.6 \times 10^{11}$K



$T_{b,min}$ and $T_{b,lim}$ calculated as in Lobanov (2015)

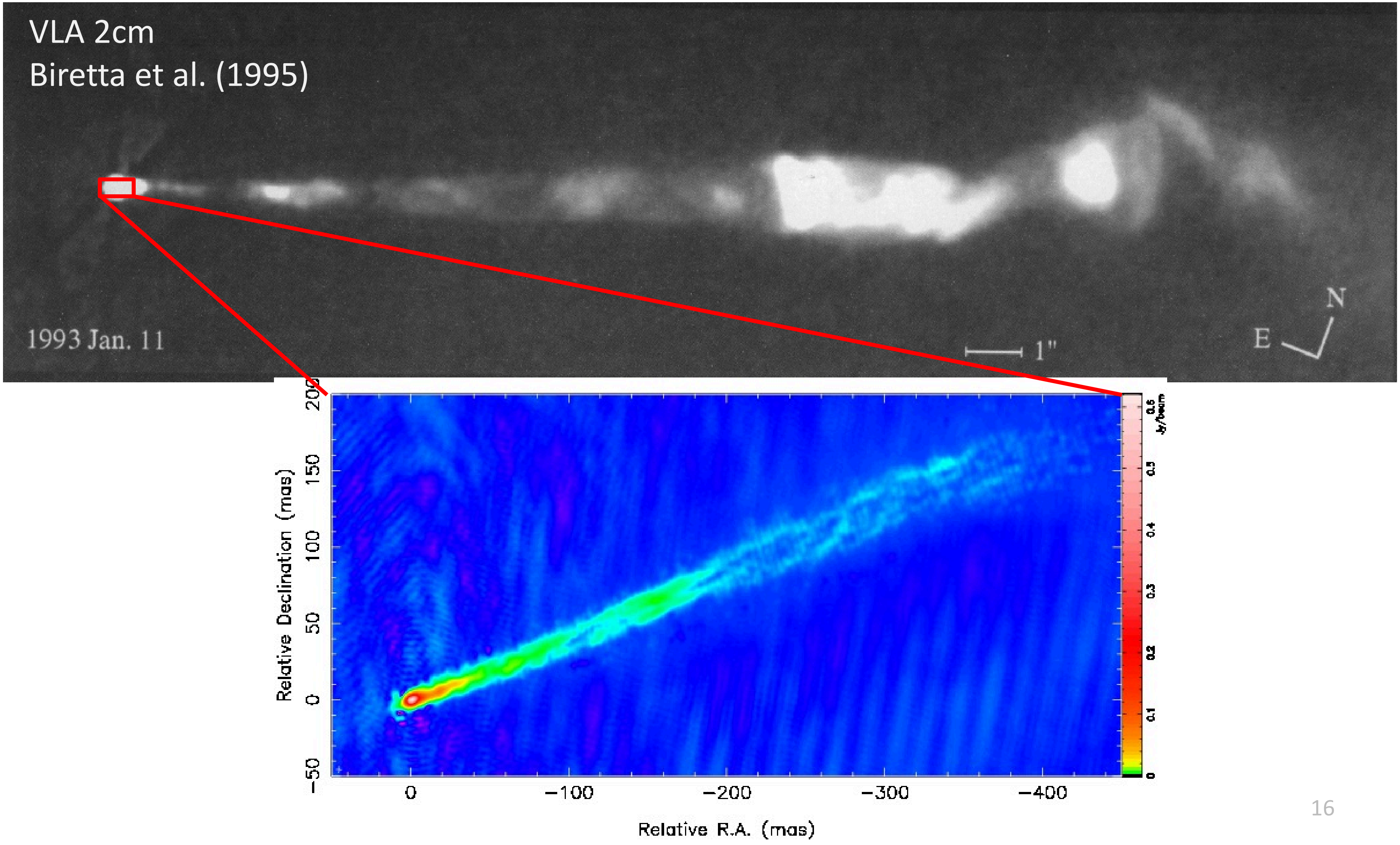
Savolainen et al. in prep.

M87 with RadioAstron at 18cm – 26 ground radio telescopes



Savolainen et al. in prep.

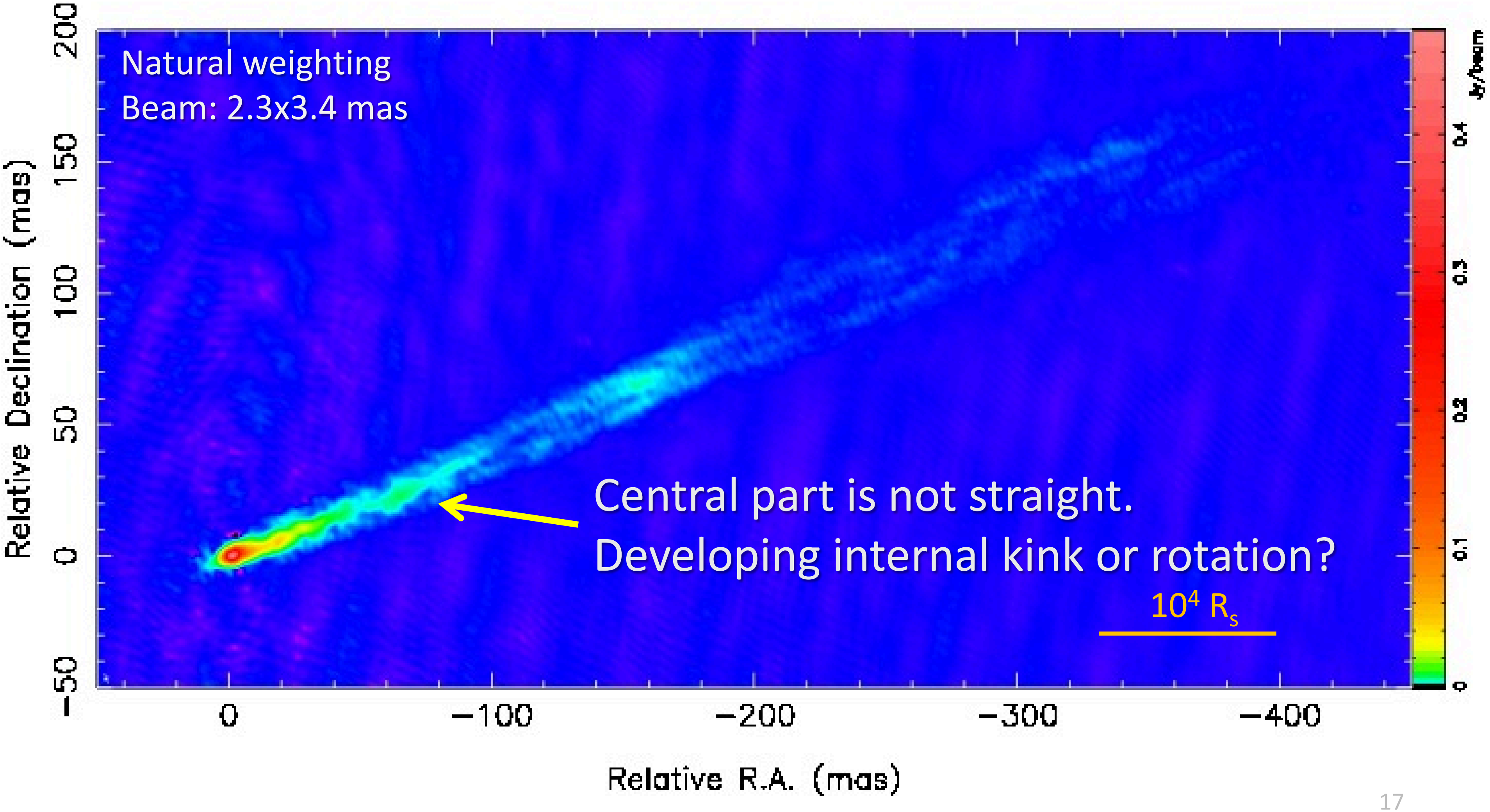
Helical filaments in arcsec and milliarcsec scales



VLA 2cm

Biretta et al. (1995)

M87 at 18cm – including RadioAstron

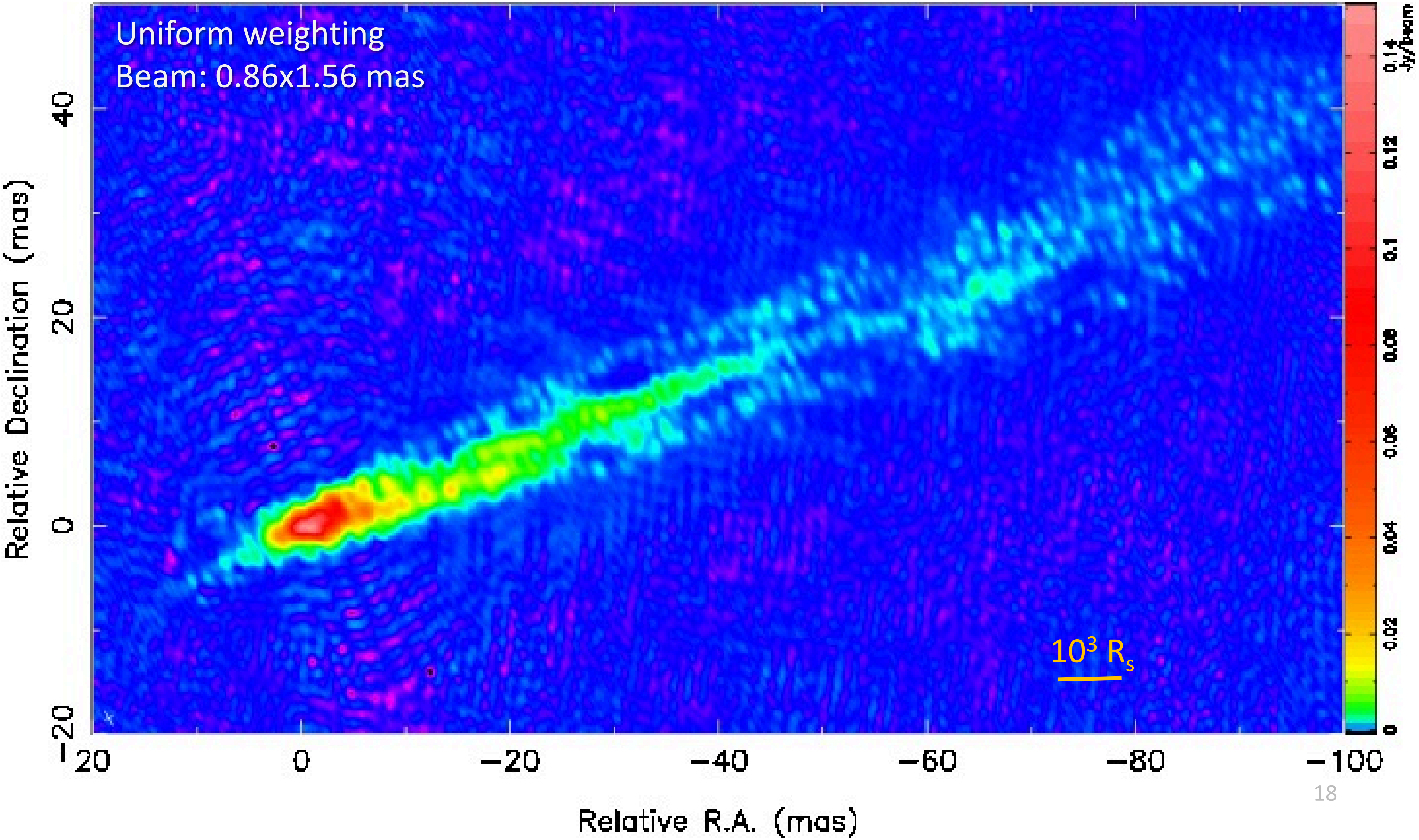


Natural weighting
Beam: 2.3x3.4 mas

Central part is not straight.
Developing internal kink or rotation?

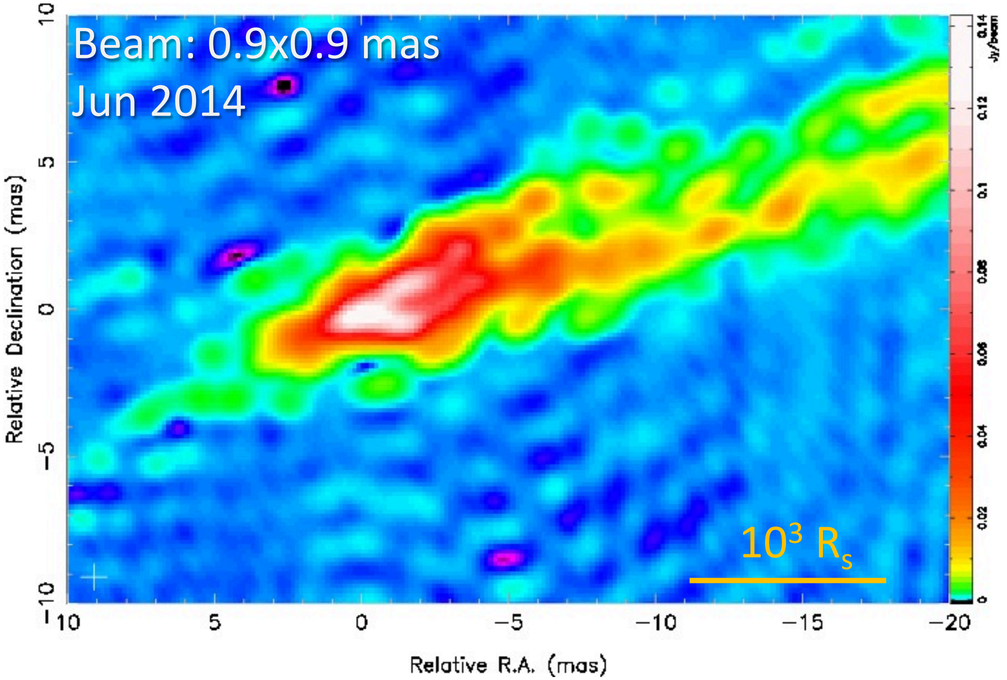
10^4 R_s

M87 at 18cm – inner 100 mas



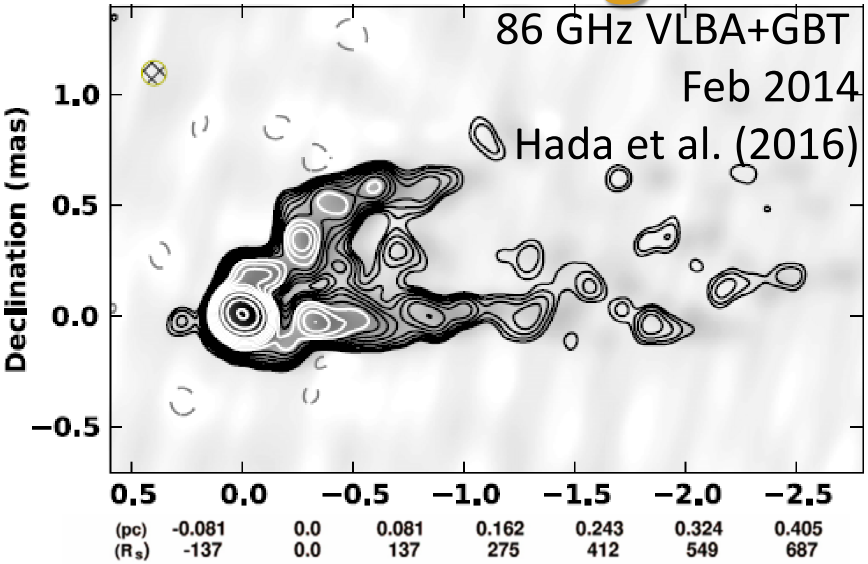
Uniform weighting
Beam: 0.86x1.56 mas

M87 at 18cm – core region



Beam: 0.9x0.9 mas

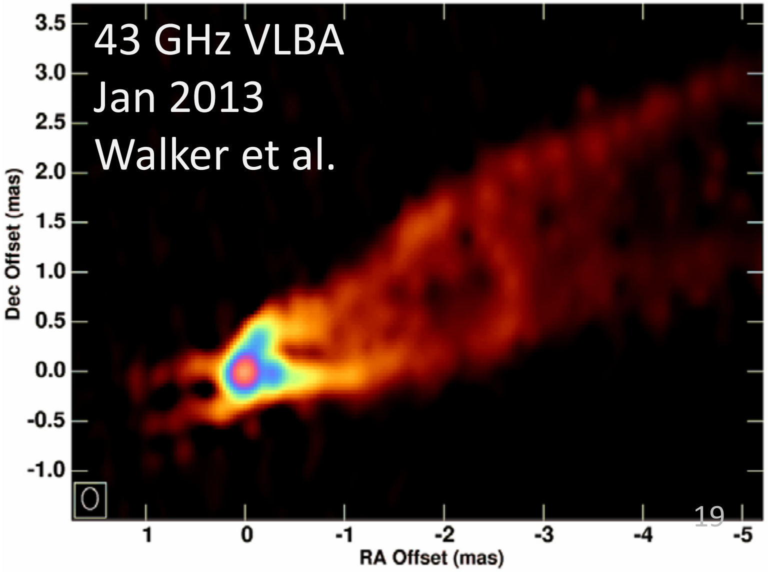
Jun 2014



86 GHz VLBA+GBT

Feb 2014

Hada et al. (2016)



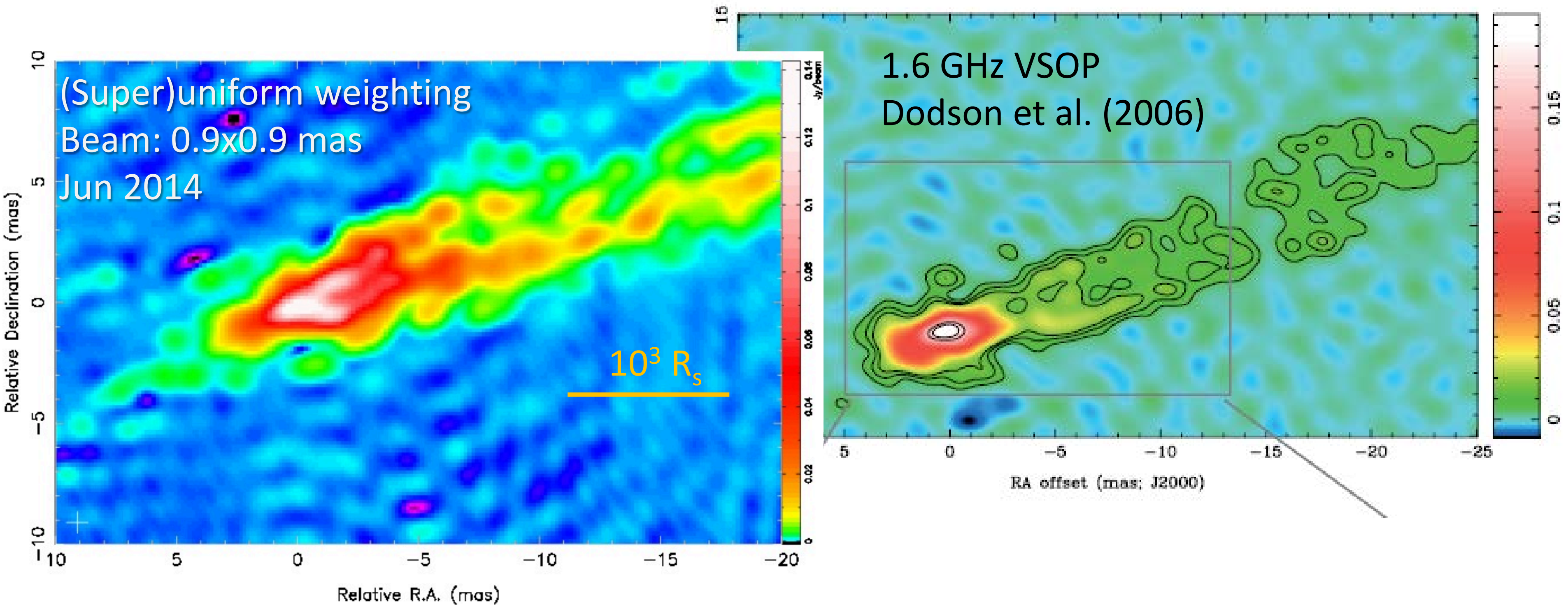
43 GHz VLBA

Jan 2013

Walker et al.

- Edge-brightened core structure visible at both 1.6 GHz RadioAstron and 86 GHz VLBA+GBT images
- Counter-jet visible
- Kink at 2-3 mas from the core at 1.6 GHz?

M87 at 18cm – core region



(Super)uniform weighting
Beam: 0.9x0.9 mas
Jun 2014

10^3 R_s

1.6 GHz VSOP
Dodson et al. (2006)

- VSOP (Dodson et al. 2006): “haze” around the core in the 18cm
- RadioAstron: low-intensity emission around the conical core and edge-brightened jet – sub-luminal layer / wind? Width ~ 5mas ~ 700 R_S

Summary

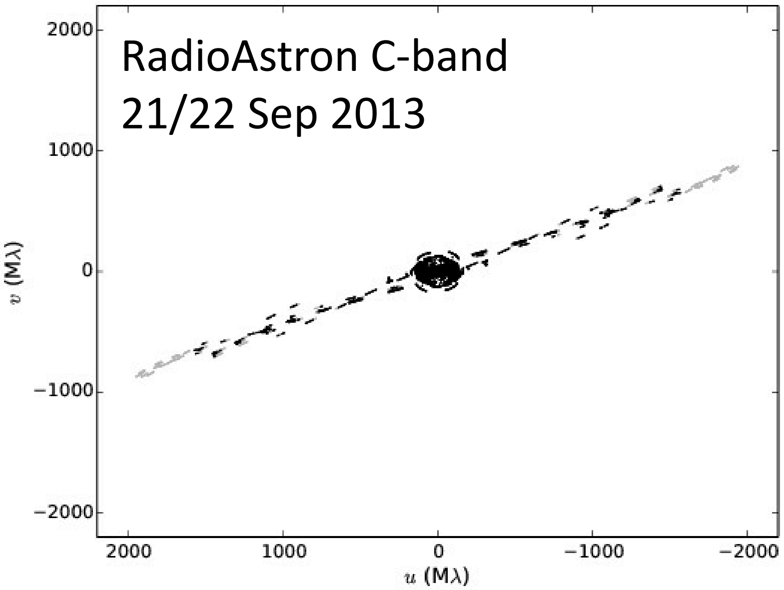
- RadioAstron images of nearby radio galaxies 3C84 and M87 were presented.
- Key results for 3C84:
  - Strongly edge-brightened jet
    - Velocity structure (“spine-sheath”)?
    - Low-emissivity inner jet?
  - Very compact emission feature inside C3, well behind the leading edge of C3 – a pc-scale version of a kpc-scale termination shock?
  - 22 GHz image shows a wide initial opening angle together with rapid collimation to an almost cylindrical jet. Appears to differ from M87.
  - $T_b \sim$ IC limit. High for a misaligned AGN.
- Key results for M87:
  - Helical filaments embedded in the mas-scale jet
  - The helical structure continues down to the core. A kinked spine?
  - The core in 1.6 GHz space-VLBI image resembles that of 86 GHz image
  - There is low-intensity emission around the core at 1.6 GHz

BACKUP SLIDES

3C84 RadioAstron observations

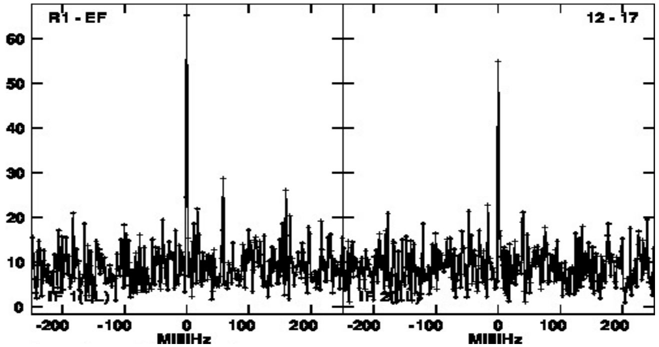
5/22 GHz in 21/22 Sep 2013

- 25 ground telescopes divided in two arrays (EVN+VLBA+KVN+Gb+VLA+Kl)
- Data correlated with modified DiFX correlator in Bonn (Bruni et al. 2015).
- High residual acceleration term near perigee needed to be corrected in post-processing


RadioAstron C-band
21/22 Sep 2013

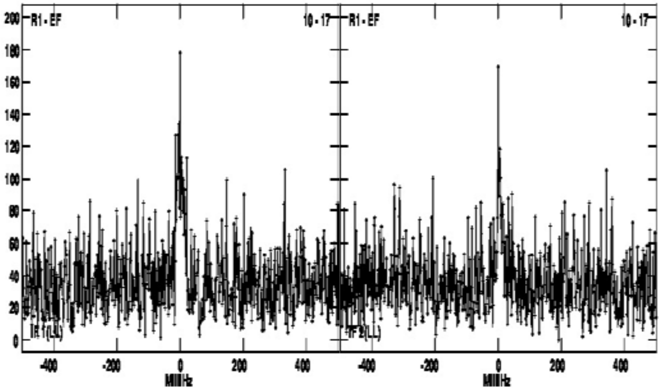
Fringes were detected on space baselines:

- 5 GHz PIMA: 23 scans over 0.2 - 6.9 Earth diam.
- 5 GHz AIPS: 26 scans over 0.2 - 7.7 ED



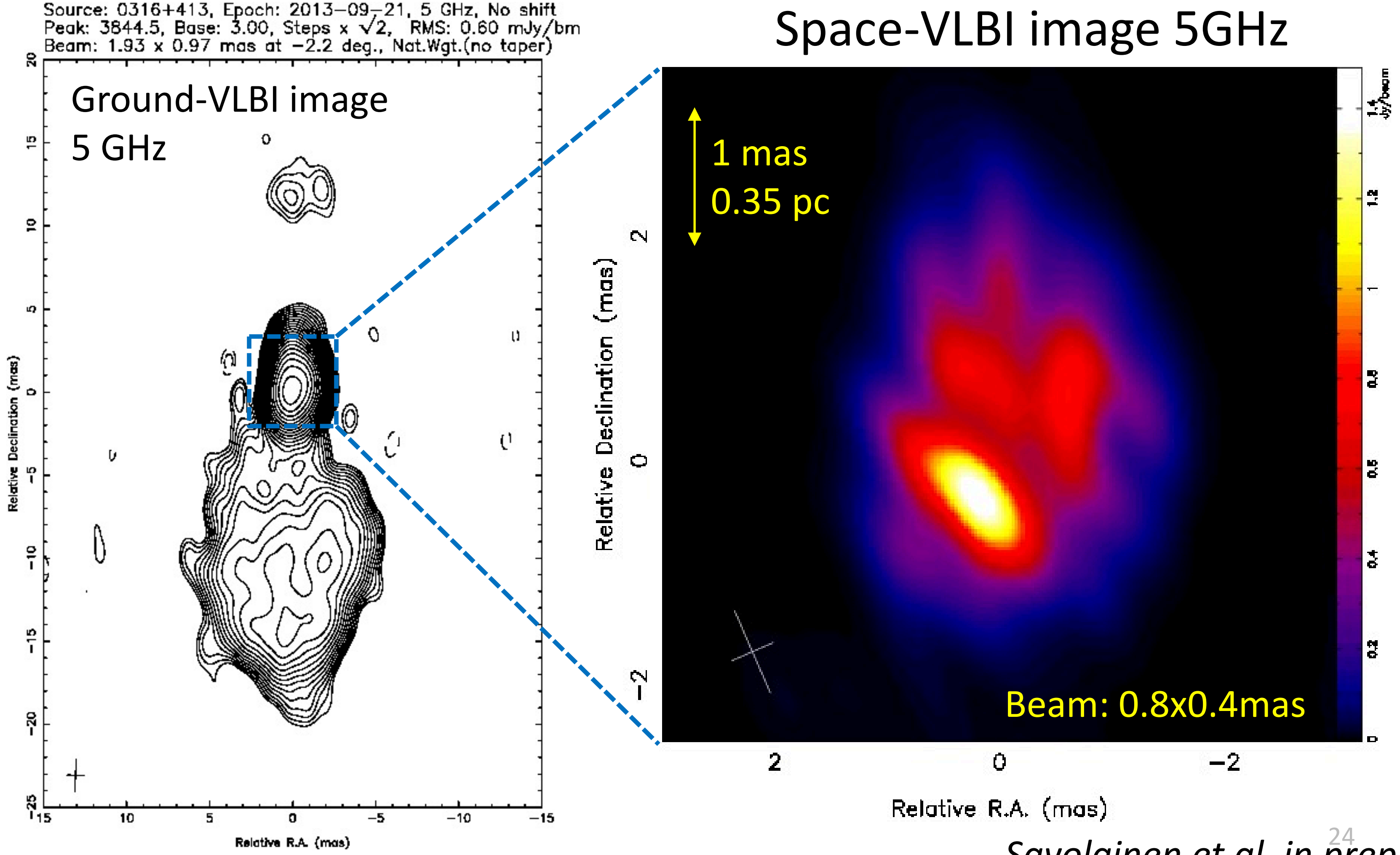
5 GHz fringe on 6.9ED (1.4Gλ) RA-EF baseline

- 22 GHz PIMA: 8 scans over 0.2 – 7.6 ED
- 22 GHz AIPS: 12 scans over 0.2 – 7.6 ED



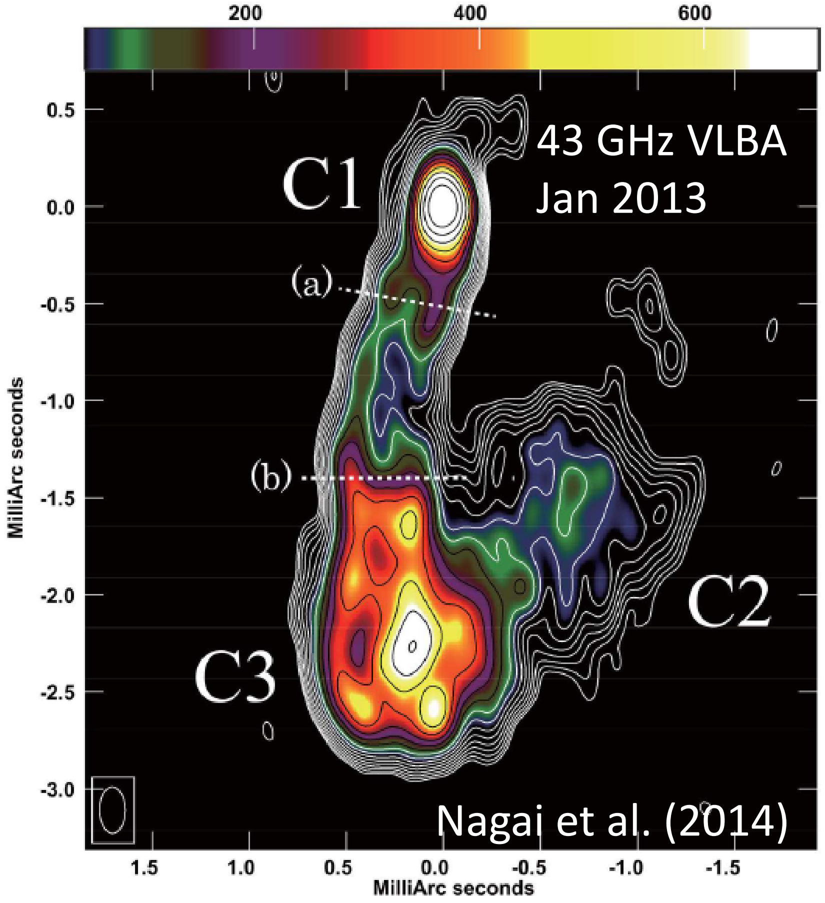
22 GHz fringe on 6.7ED (6.3Gλ) RA-EF baseline

3C84
5 GHz RadioAstron image



Savolainen et al. in prep.

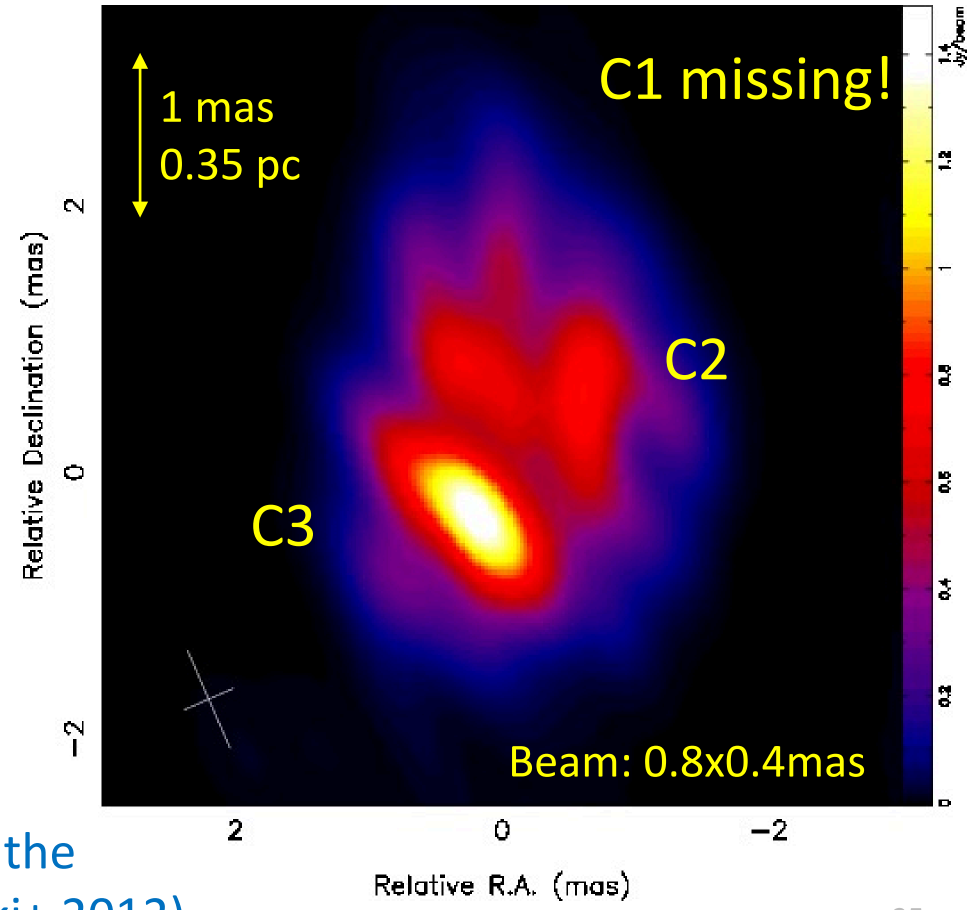
3C84
5 GHz RadioAstron image



43 GHz VLBA
Jan 2013

Nagai et al. (2014)

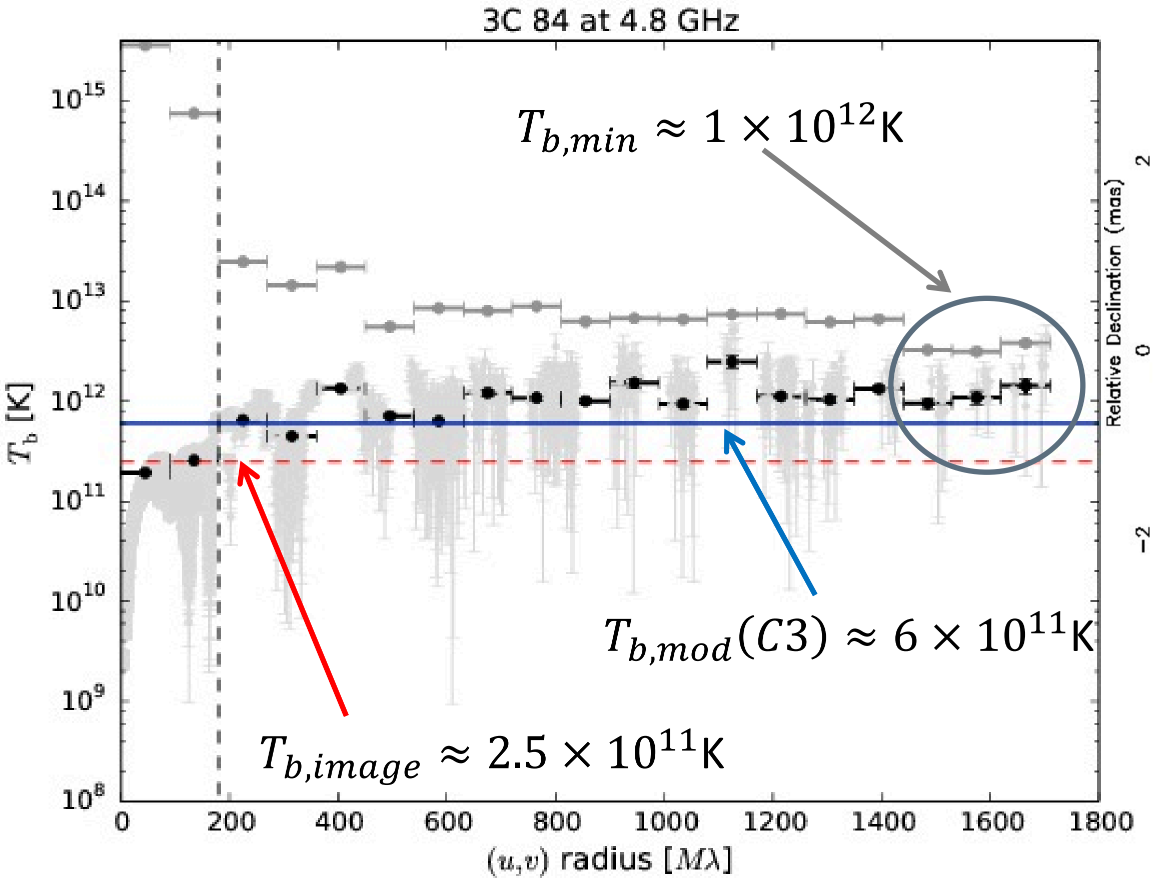
Space-VLBI image 5GHz



Savolainen et al. in prep.

C3 is a slowly moving feature related to the restarted jet activity in the 2000s (Suzuki+ 2012)

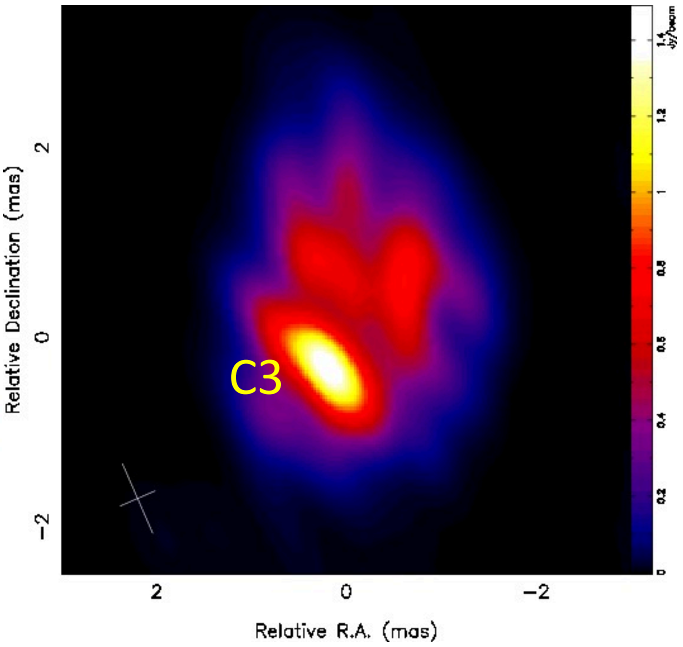
3C84
Brightness temperature at 5 GHz



$T_{b,min} \approx 1 \times 10^{12}$K

$T_{b,mod}(C3) \approx 6 \times 10^{11}$K

$T_{b,image} \approx 2.5 \times 10^{11}$K



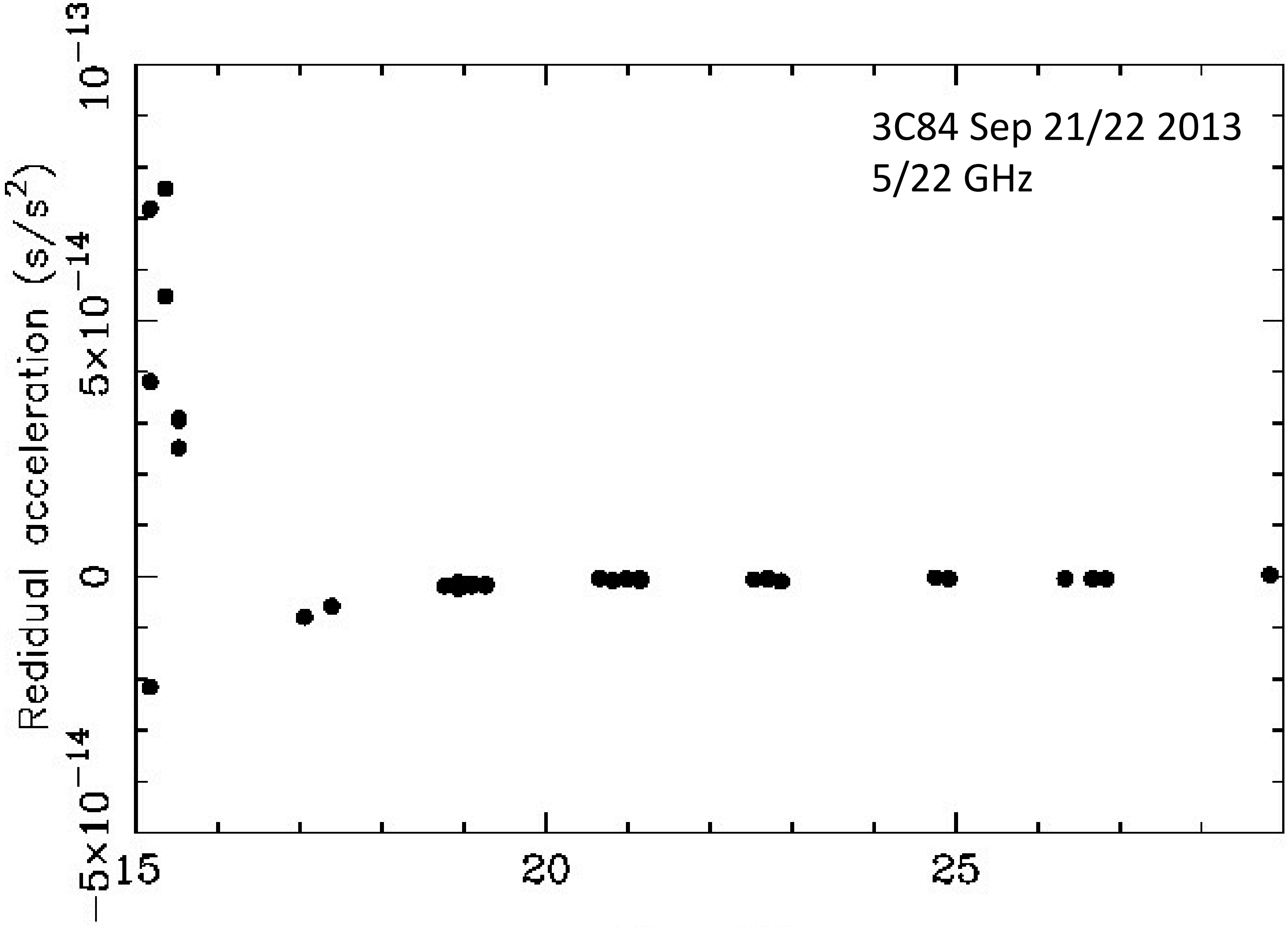
$T_{b,min}$ higher than $T_{b,mod}$:

- Geometry of C3?
- Substructure of C3?

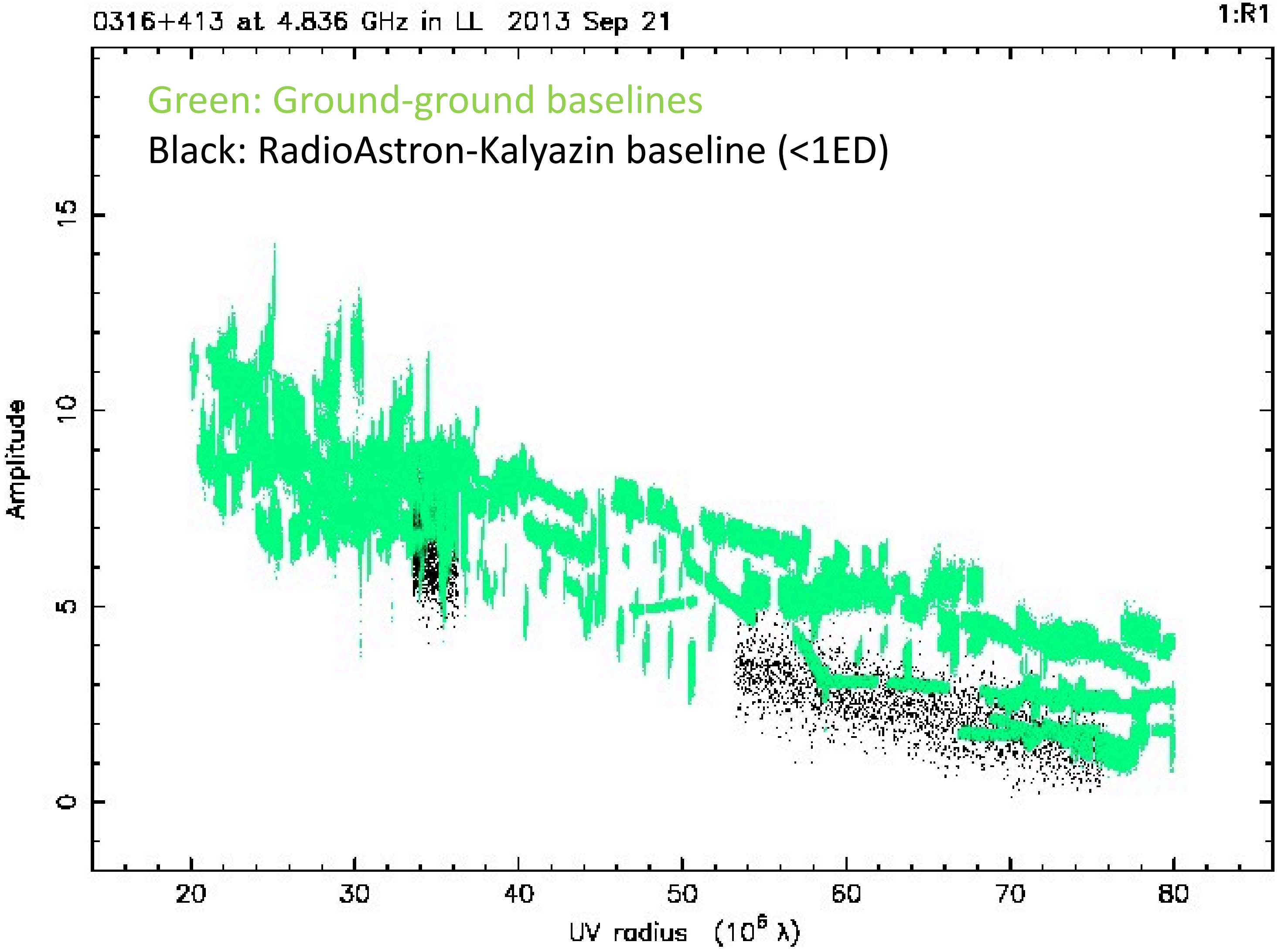
$T_{b,min}$ and $T_{b,lim}$ calculated as in Lobanov (2015)

Savolainen et al. in prep.

RadioAstron residual acceleration near perigee



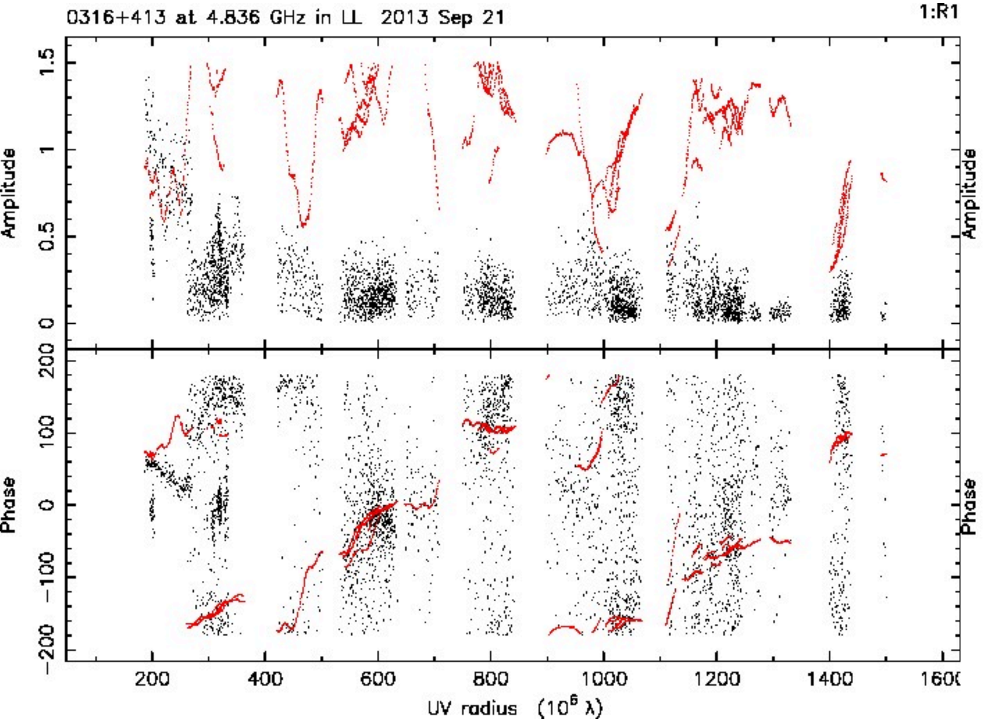
3C84 at 5GHz - calibration accuracy of the SRT



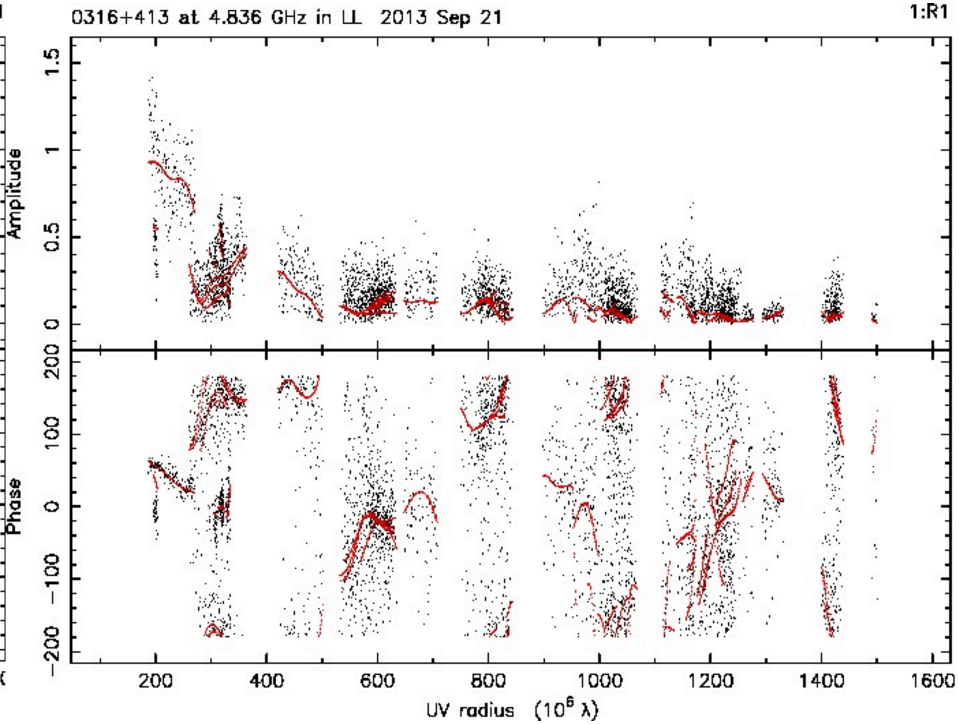
Green: Ground-ground baselines

Black: RadioAstron-Kalyazin baseline (<1ED)

3C84 at 5GHz
with space baselines



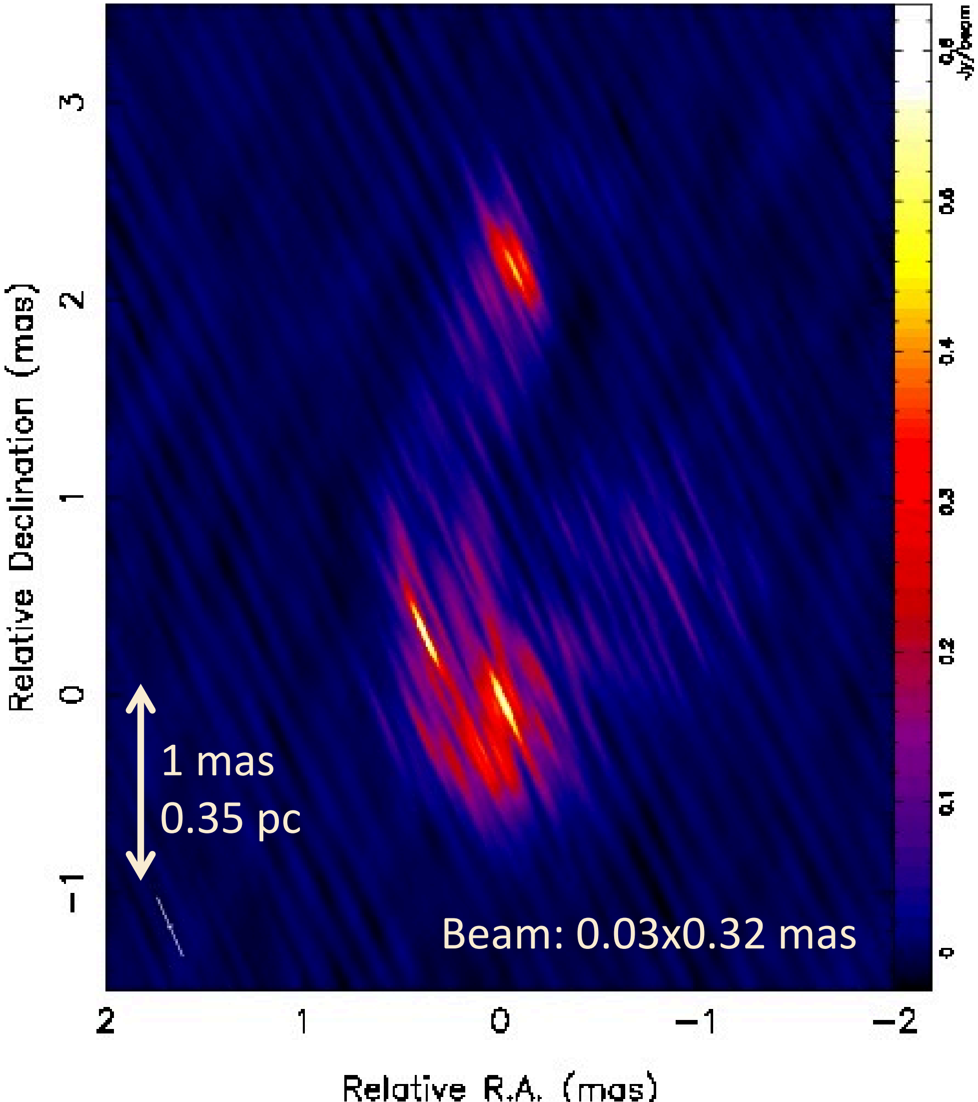
RA data and ground-only model



RA data and ground+space model

Savolainen et al. in prep.

3C84
22 GHz RadioAstron image



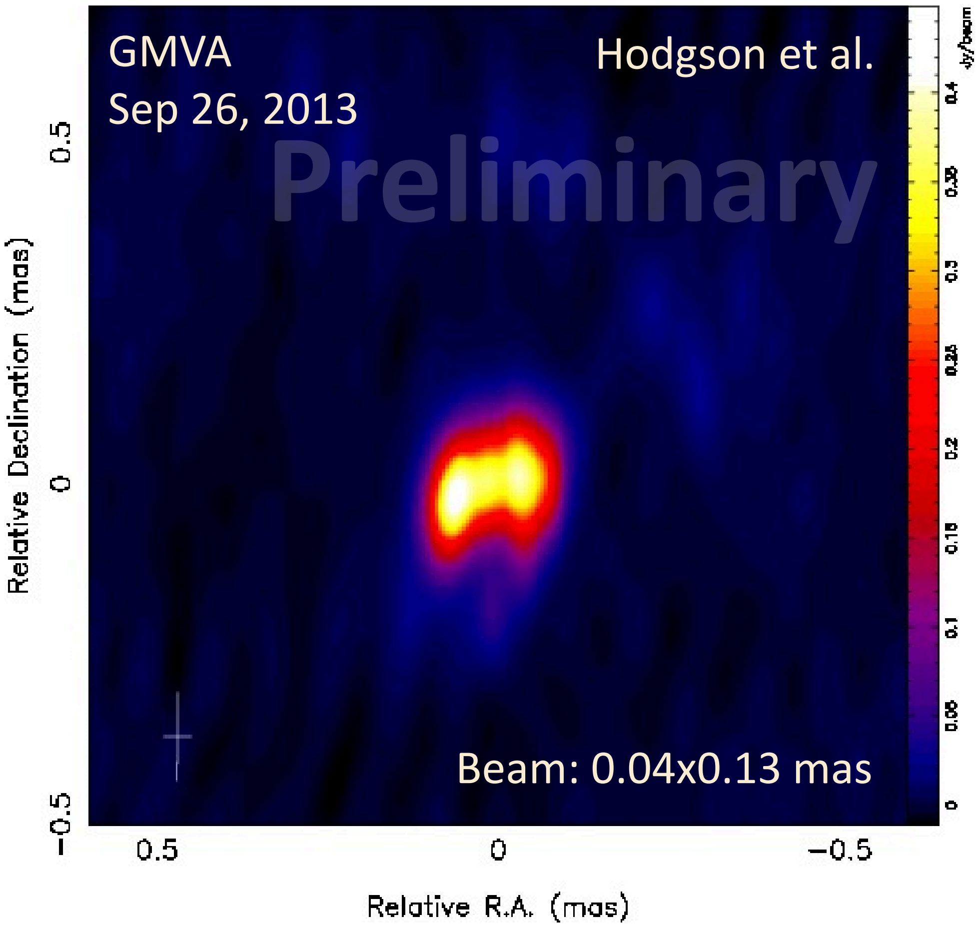
1 mas
0.35 pc

Beam: 0.03x0.32 mas

Full resolution (1:10 rest. beam ratio)

- Maximum fringe spacing corresponds to 27 μas, i.e., ~120 R_s
- Maximum resolution image made with super-uniform (u,v) weighting and no error weights

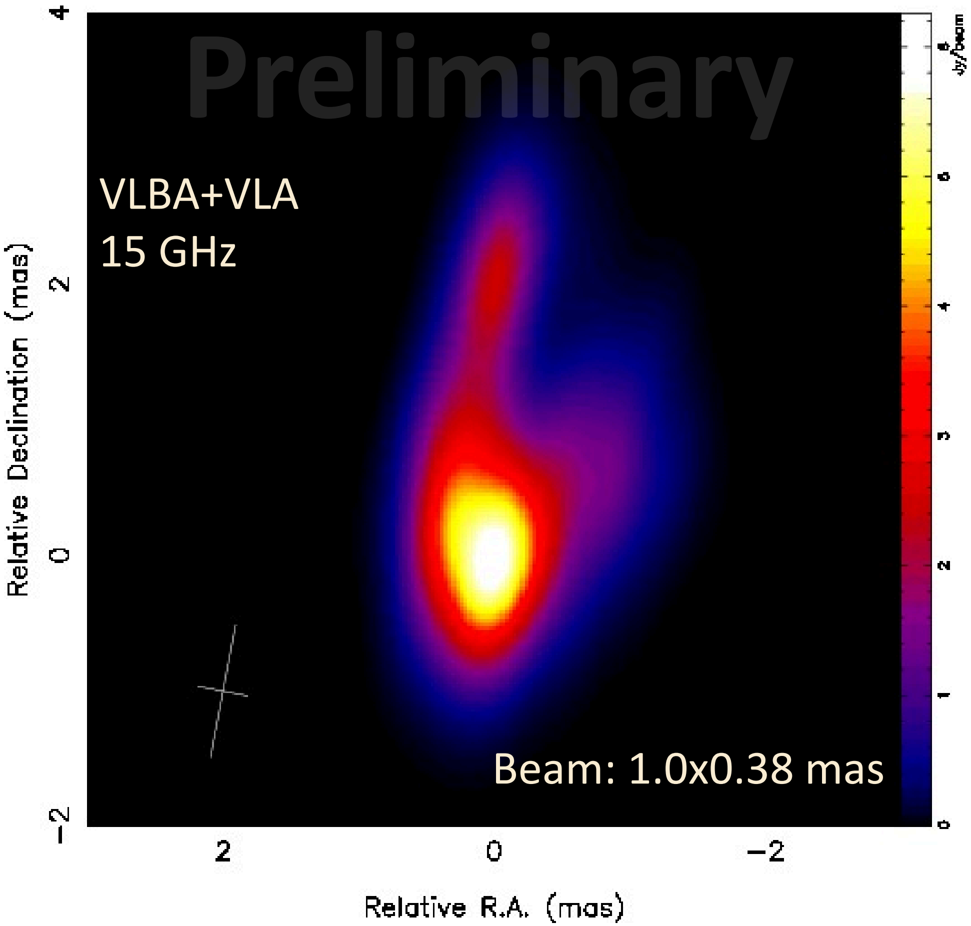
3C84
Core in the 86 GHz GMVA image



Confirms the features seen in the RadioAstron image

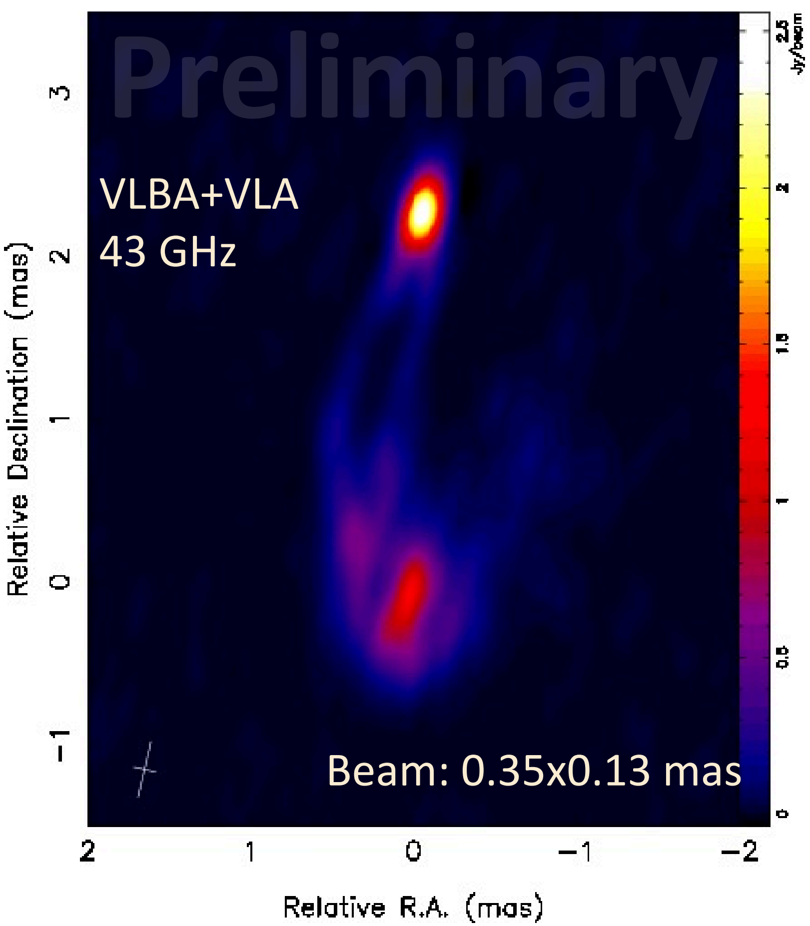
- Core clearly elongated in E-W direction
- Edge-brightened jet
- Emission on the counter-jet side

3C84
Simultaneous 15 and 43 GHz images



VLBA+VLA
15 GHz

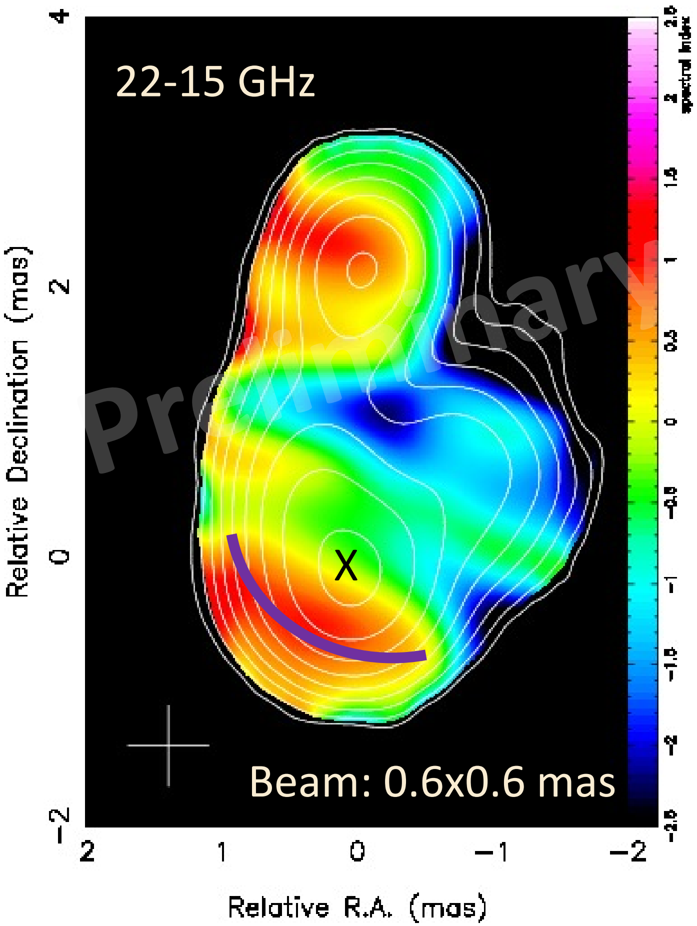
Beam: 1.0x0.38 mas

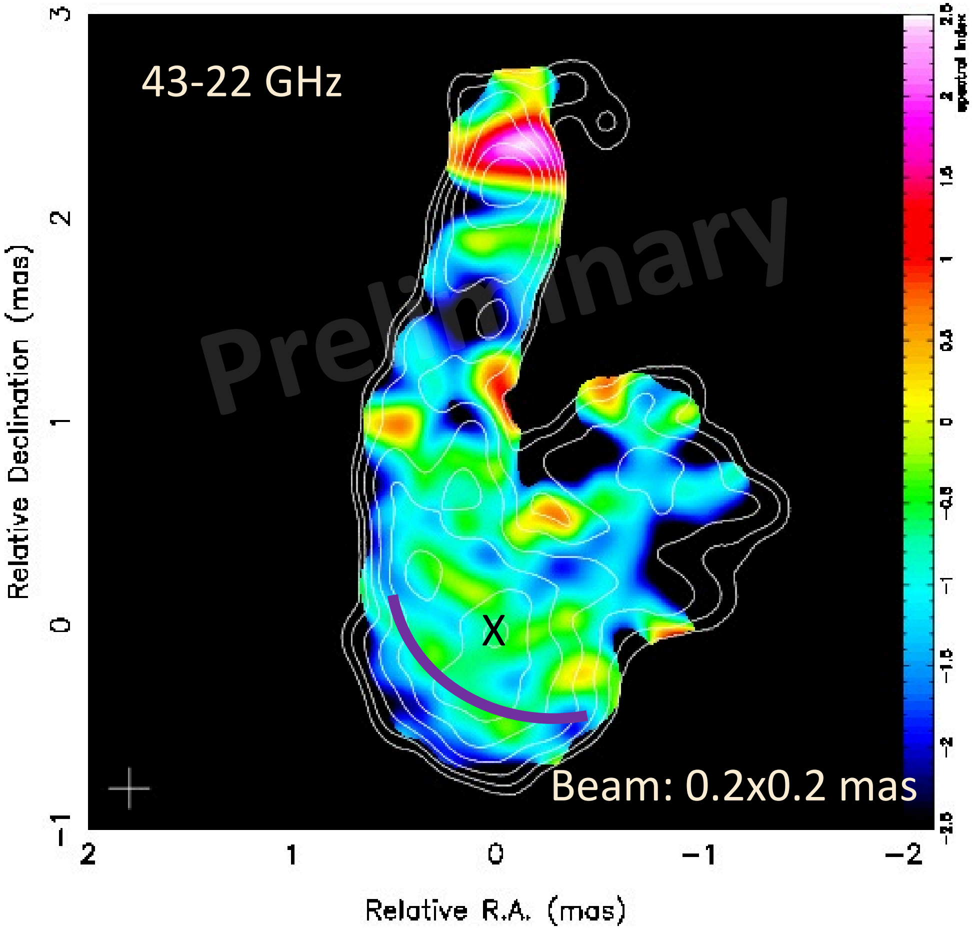


VLBA+VLA
43 GHz

Beam: 0.35x0.13 mas

3C84
Spectral index maps





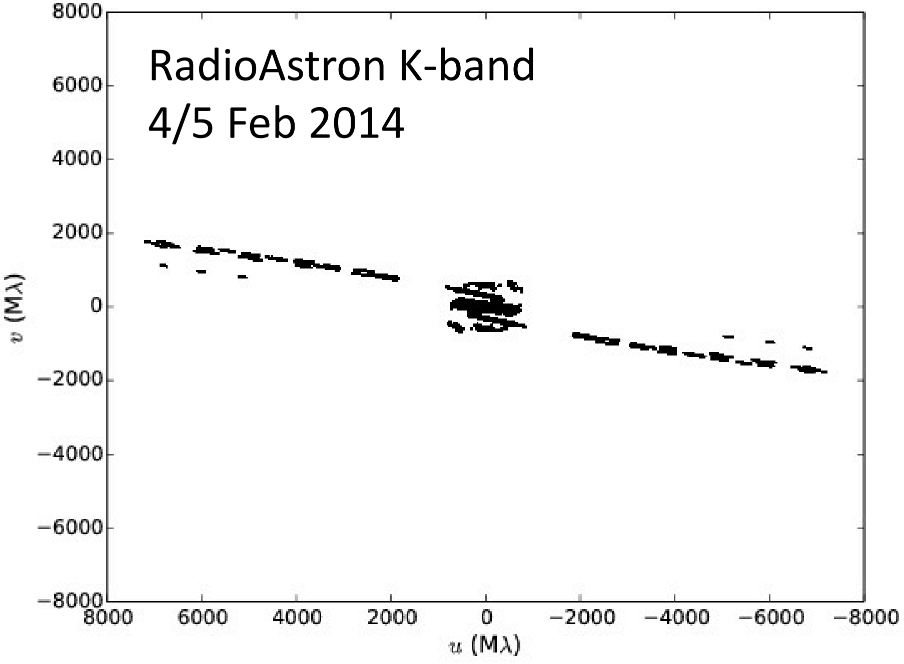
M87 RadioAstron observations

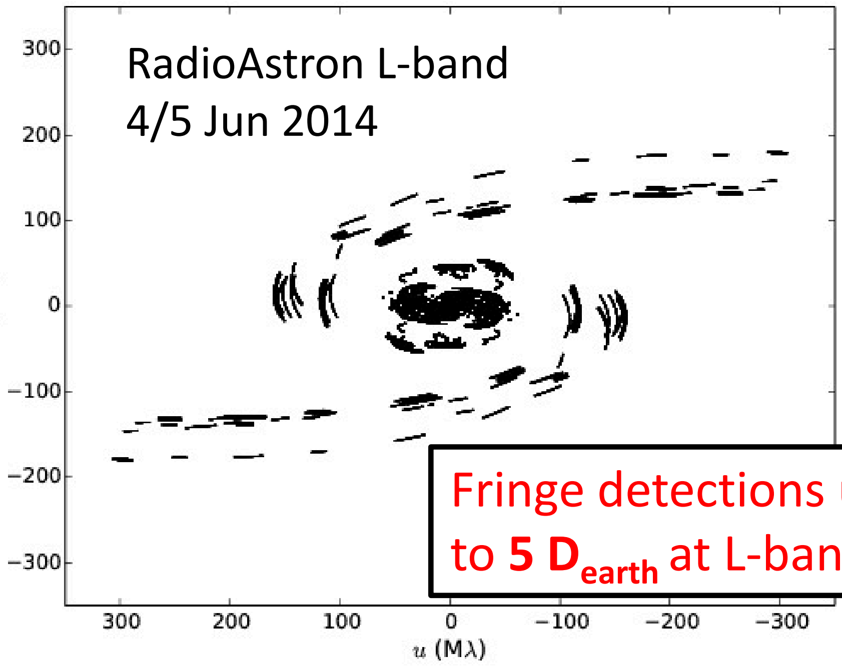
5/22 GHz in 4/5 Feb 2014

- 29 ground radio telescopes divided in two arrays
- EVN+VLBA+LBA+KVN+Gb+Kl

1.6 GHz in 4/5 Jun 2014

- 26 ground radio telescopes in a single array
- EVN+VLBA+LBA+Ar+Kl

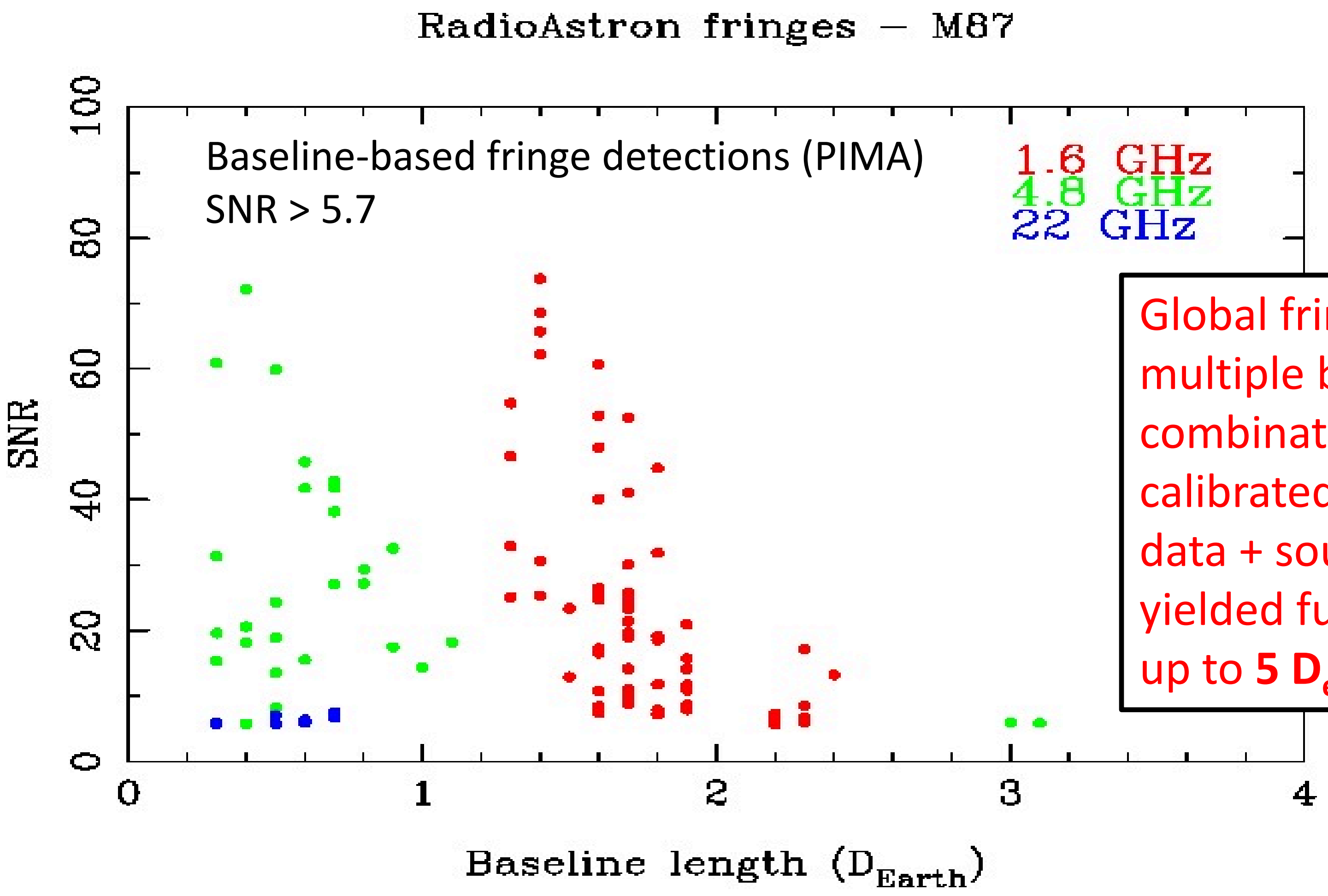




Fringe detections up to **5 D_{earth}** at L-band.

Data correlated with modified DiFX correlator in Bonn (Bruni et al. 2015).

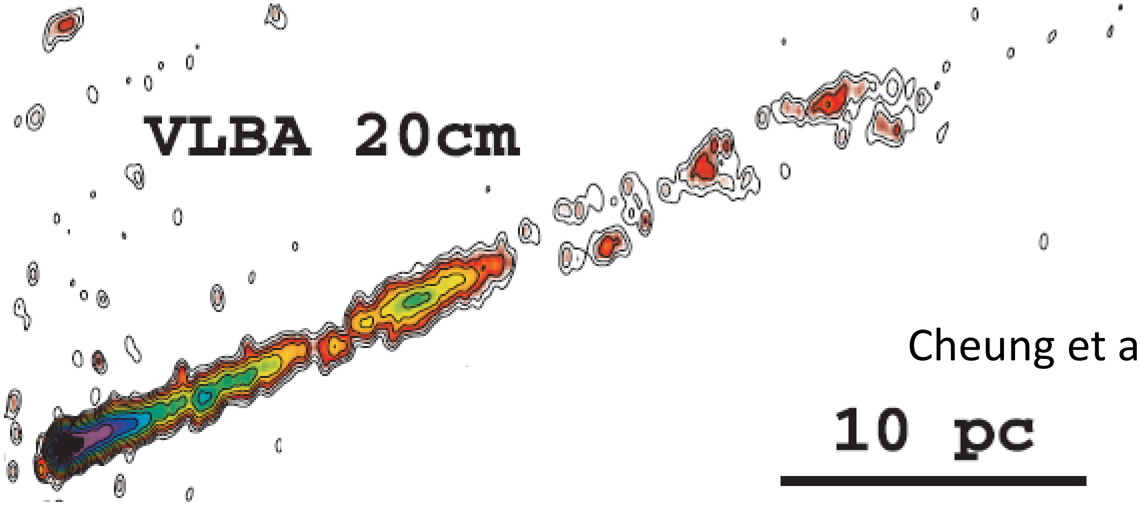
M87 - space fringes detected



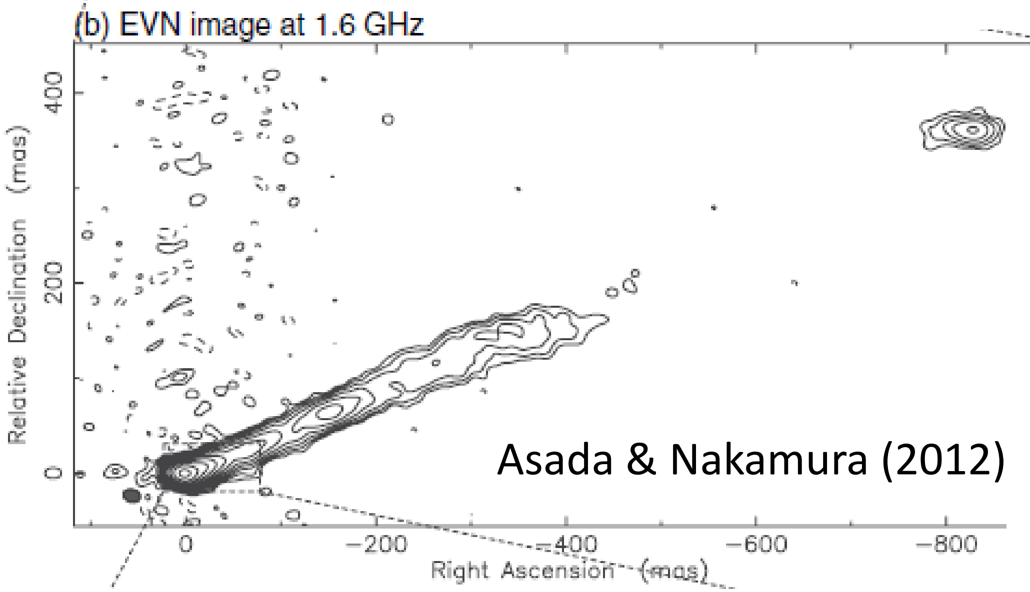
Baseline-based fringe detections (PIMA)
SNR > 5.7

Global fringe fitting using multiple baseline combinations and fully calibrated ground array data + source model yielded further detections up to **5 D_{earth}** at L-band.

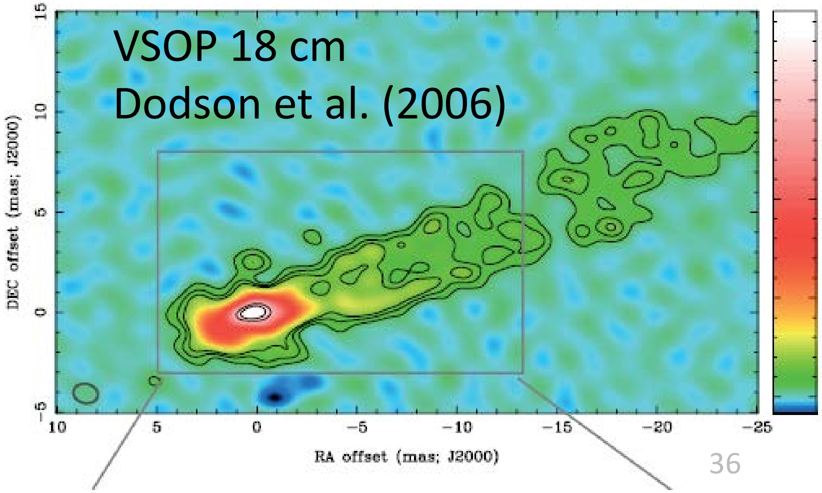
Previous M87 L-band VLBI observations



Cheung et al. (2006)

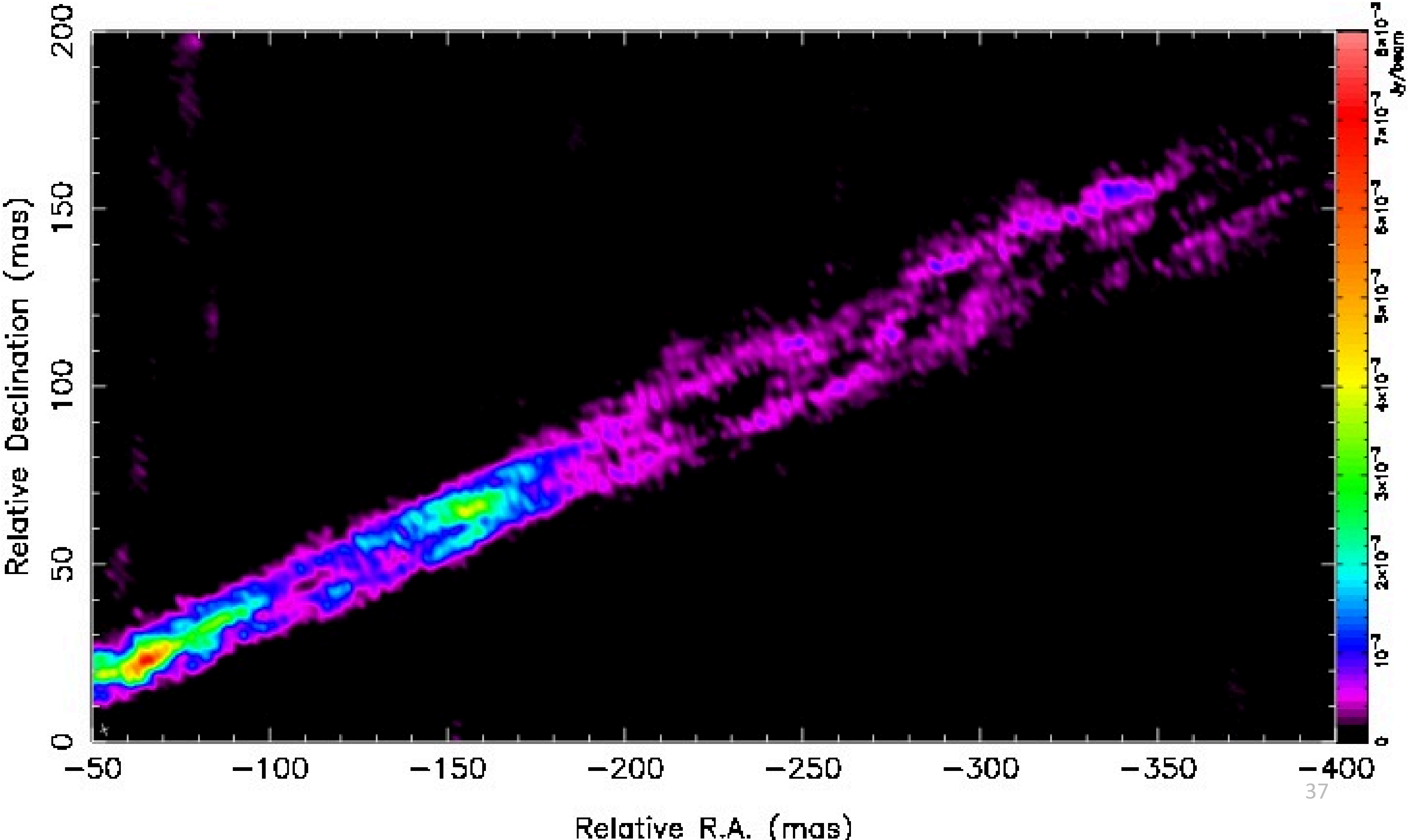


Asada & Nakamura (2012)



VSOP 18 cm
Dodson et al. (2006)

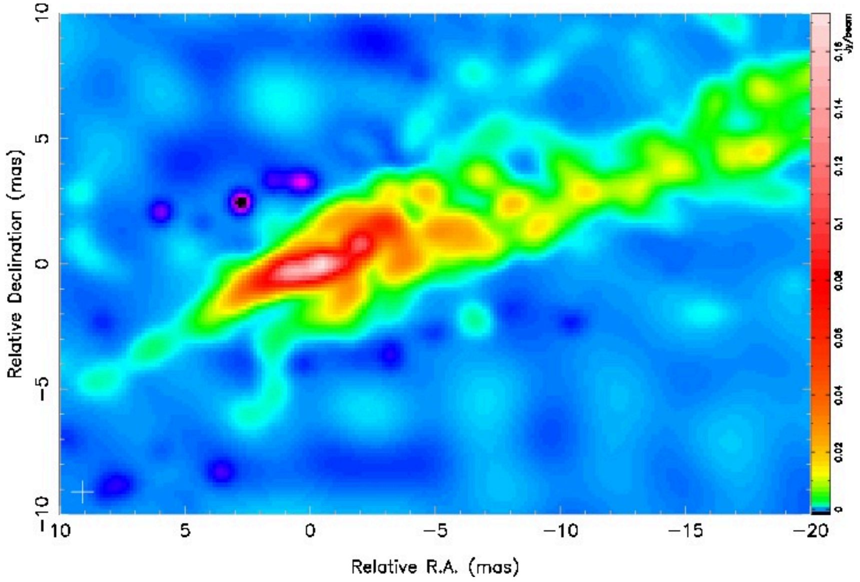
M87 at 18cm – outer 50-400 mas



M87: space baselines do matter

No space baselines

Super-resolved by factor of 4-5



Space baselines included

Super-resolved by factor of 1-1.7