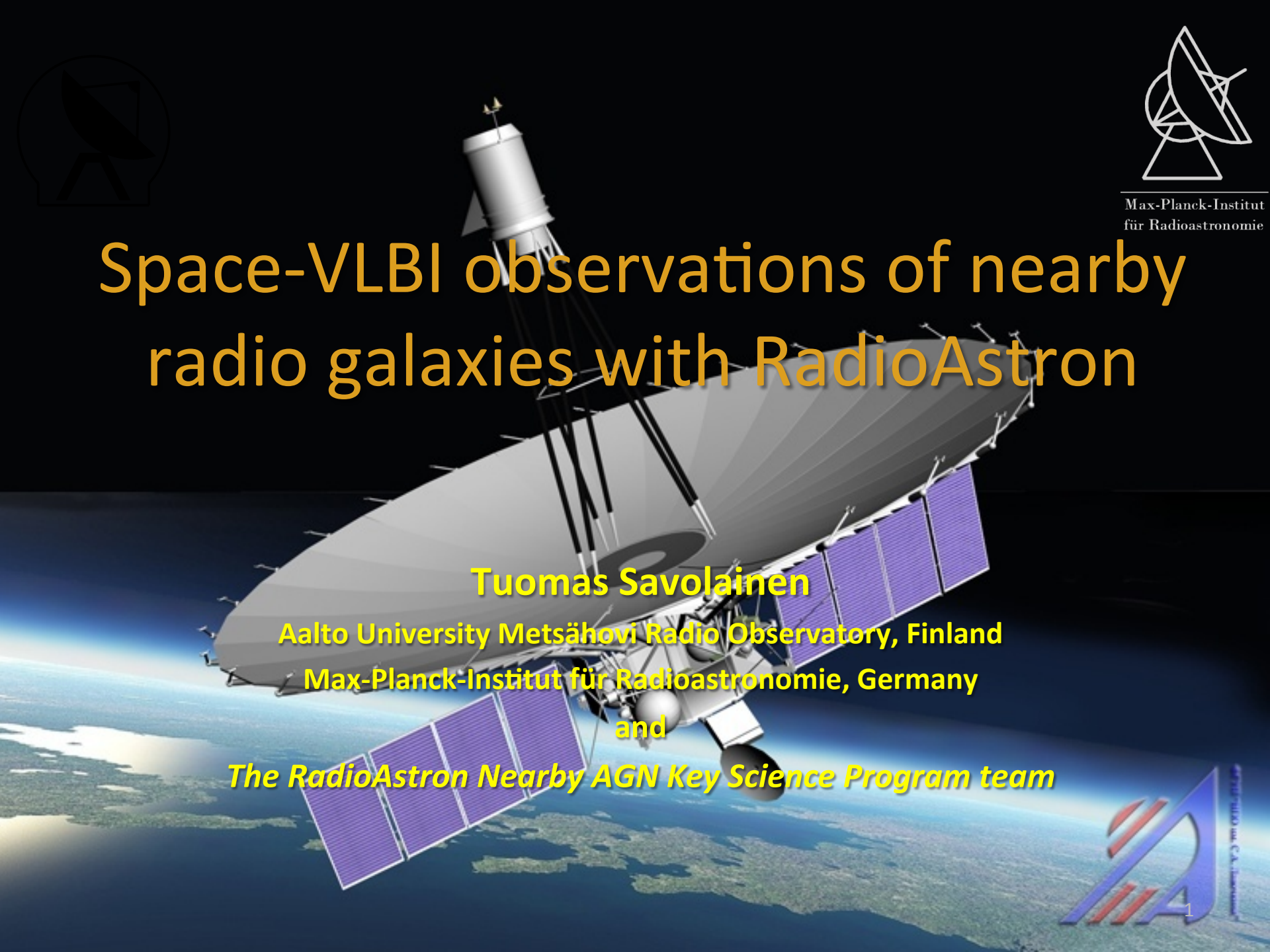

Space-VLBI observations of nearby radio galaxies with RadioAstron

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and

The RadioAstron Nearby AGN Key Science Program team

RadioAstron Nearby AGN KSP team

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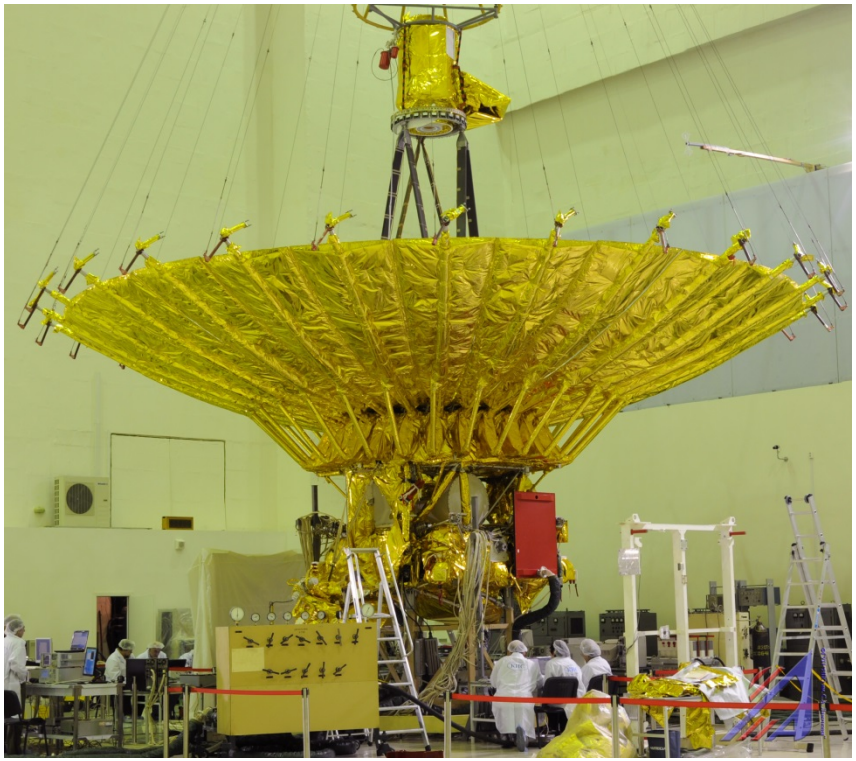
- *P.Edwards (CSIRO)*
- *P.Hardee (Uni. Alabama)*
- *C.Fromm (Uni. Frankfurt)*

RadioAstron Space-VLBI Project

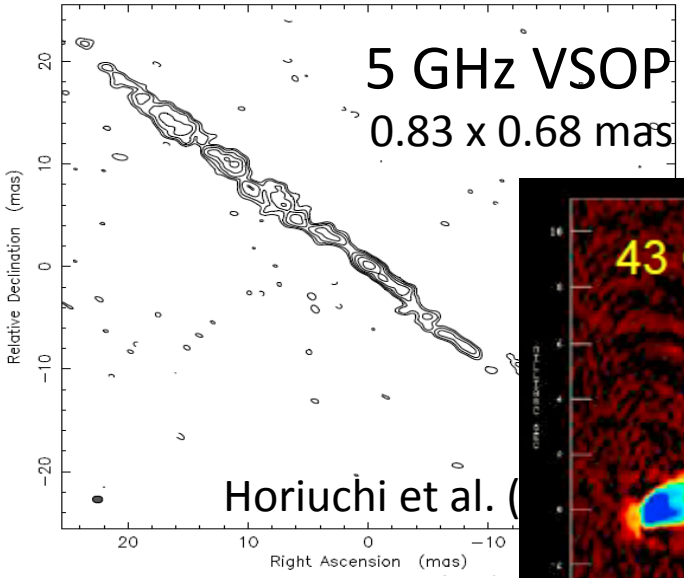


Kardashev+ 2013

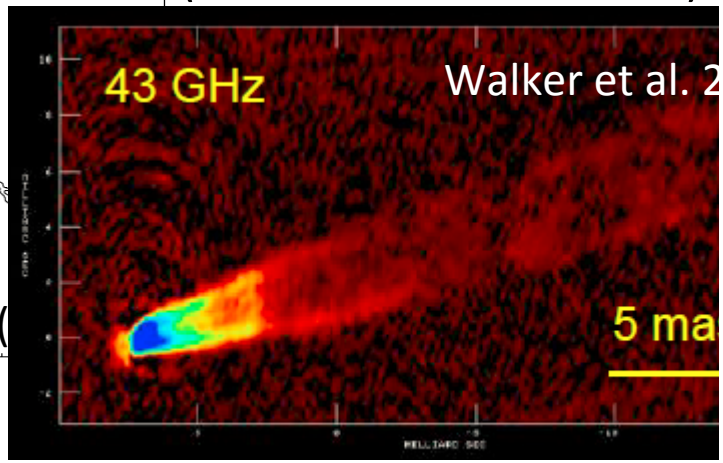
- 10-m orbiting antenna (Space Radio Telescope; SRT) launched in 2011
- Together with ground radio telescopes forms an ultra-high resolution interferometer
- Highly elliptical orbit: perigee ~10 000 km, apogee ~300 000 km. 10x max baseline length of VSOP.
- Receivers onboard:
  - 0.33, 1.6, 5 and 18-25 GHz
- Max. angular resolution: 7 μas
- Project led by the Astro Space Center of Lebedev Physical Institute, Russia

RadioAstron Nearby AGN Key Science Program

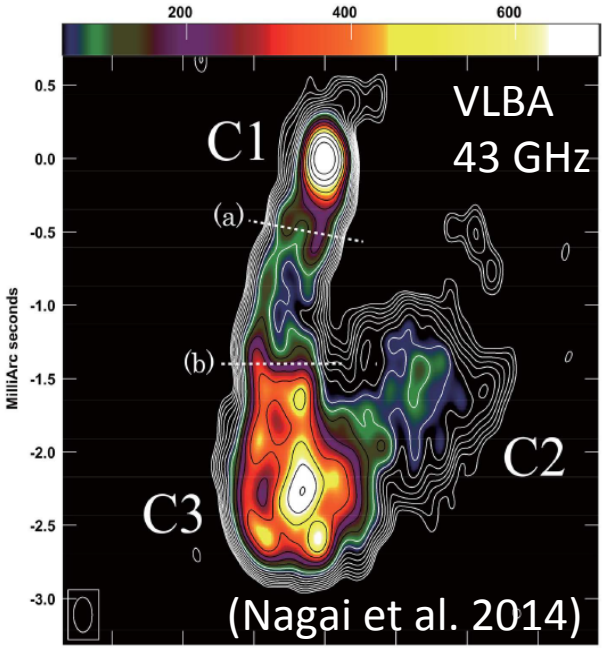
Near-perigee RadioAstron imaging observations of nearby radio galaxies. Target sources are at distances of 4-75 Mpc → aiming at high spatial resolution (down to a few R_S) for studying the jet acceleration and collimation zone.



M87 (D=16 Mpc)
1 mas = 0.08pc = 140R_S
$(M\downarrow BH = 6\times10\uparrow9\ M\downarrow Sol)$



Cen A (D=3.8 Mpc)
1 mas = 0.018 pc = 3100 R_S
$(M\downarrow BH = 6\times10\uparrow7\ M\downarrow Sol)$

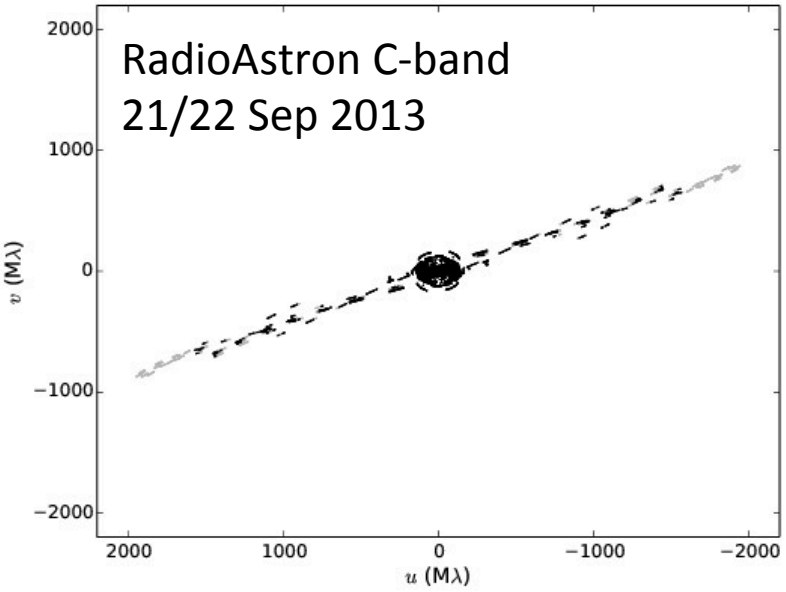


3C84 (D=75 Mpc)
1 mas = 0.34 pc = 4500R_S
$(M\downarrow BH = 8\times10\uparrow8\ M\downarrow Sol)$

3C84 RadioAstron observations

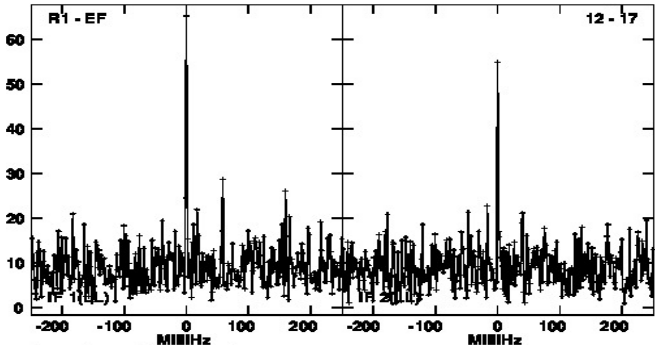
5/22 GHz in 21/22 Sep 2013

- 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



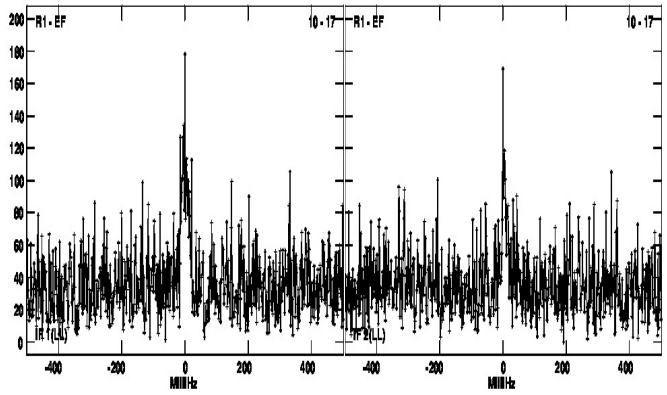
Fringes were detected on space baselines:

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



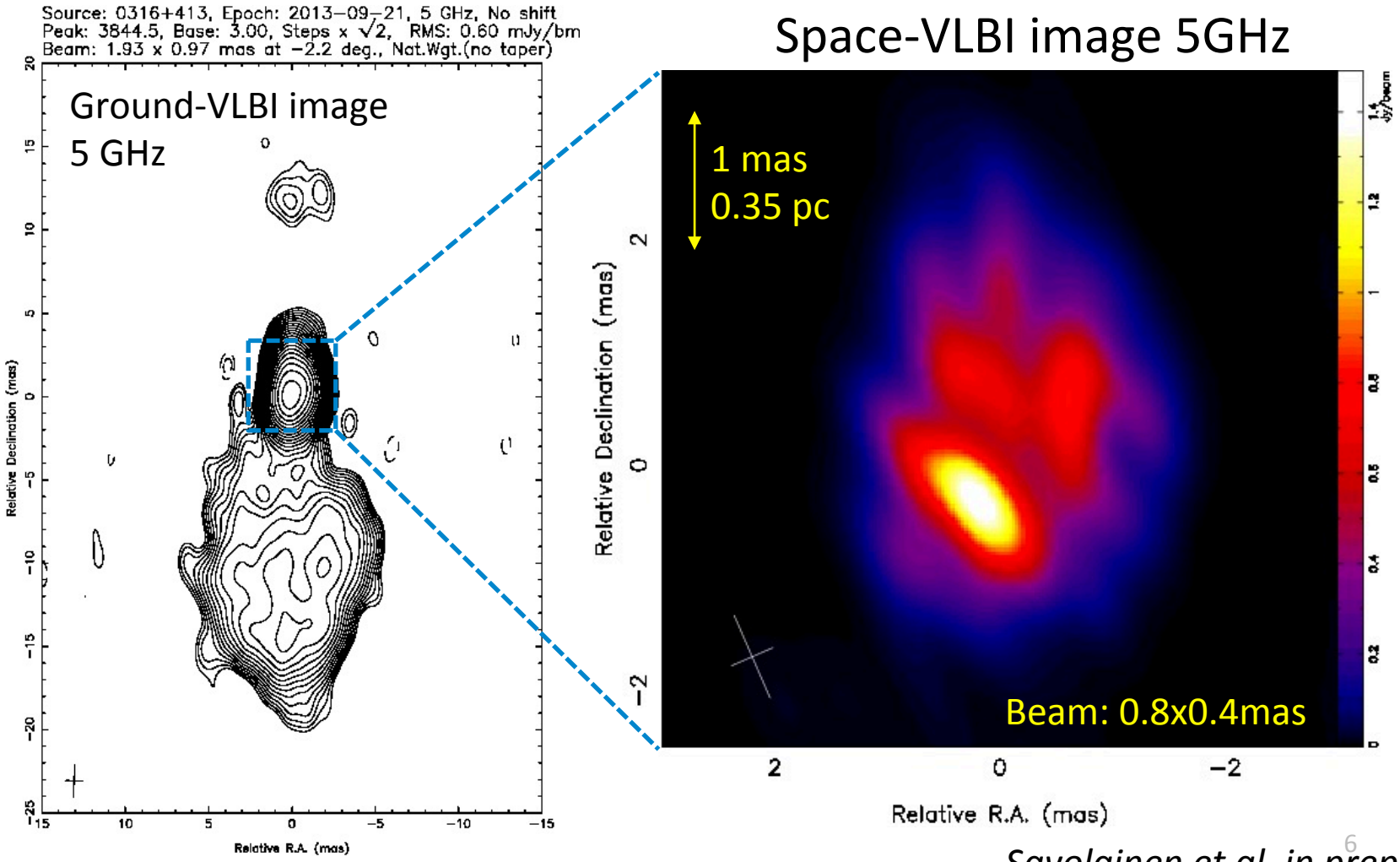
5 GHz fringe on 6.9ED (1.4Gλ) RA-EF baseline

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



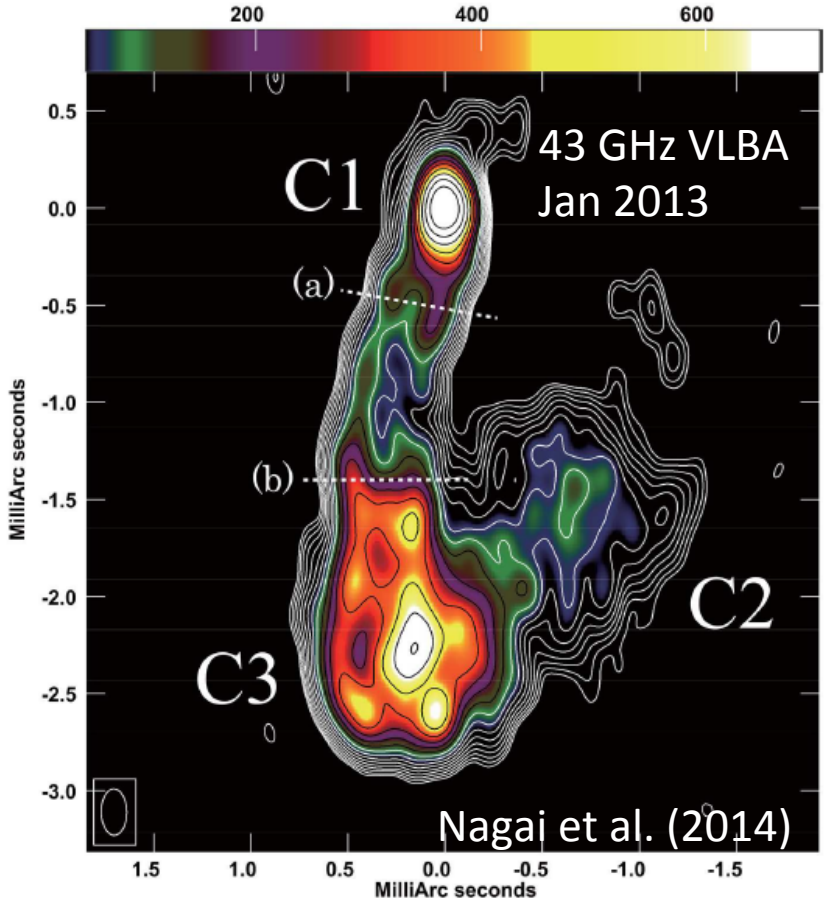
22 GHz fringe on 6.7ED (6.3Gλ) RA-EF baseline

3C84
5 GHz RadioAstron image

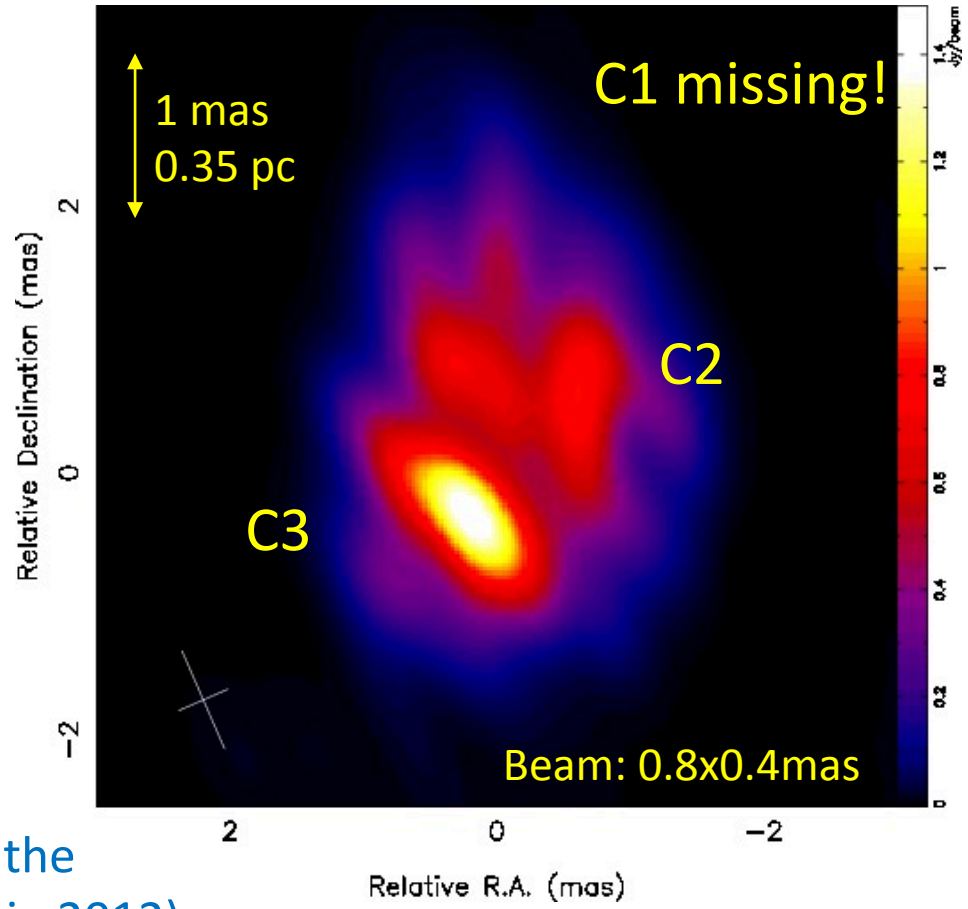


Savolainen et al. in prep.

3C84
5 GHz RadioAstron image



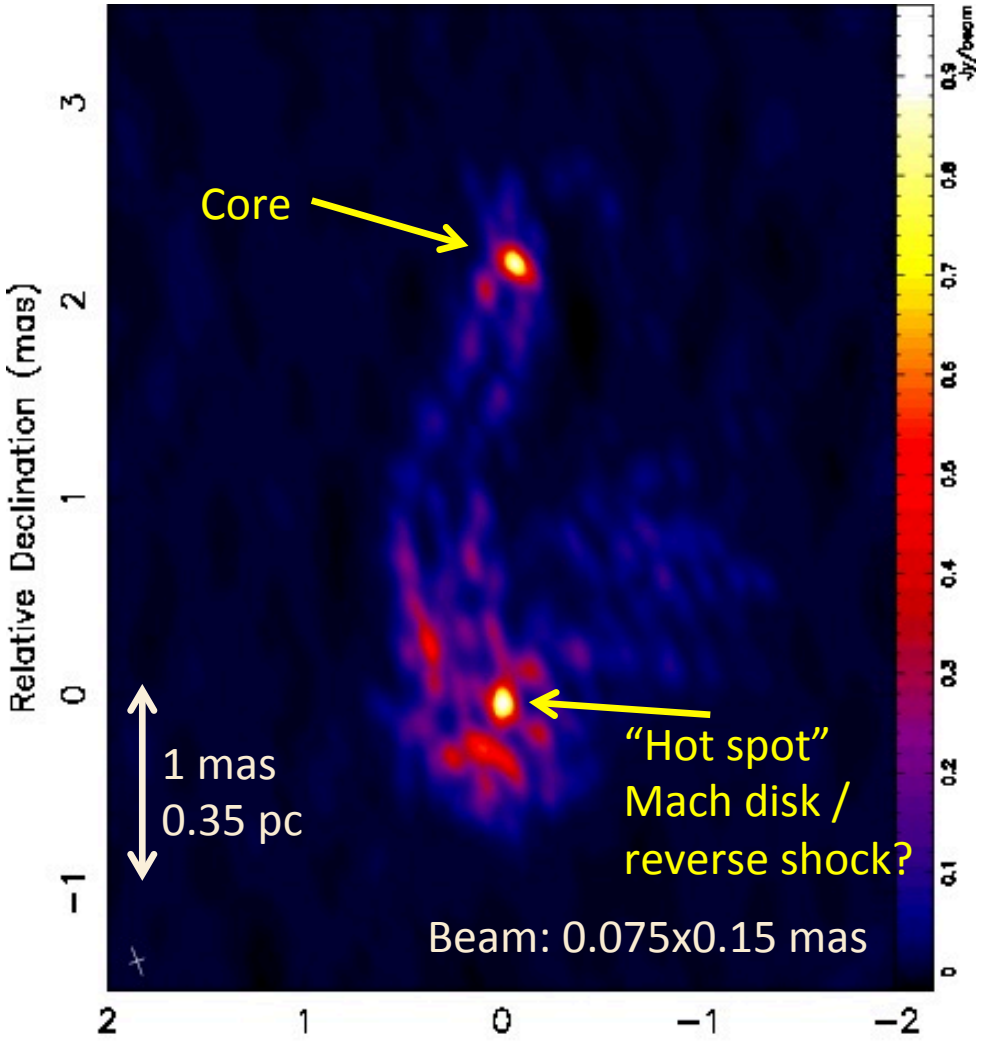
Space-VLBI image 5GHz



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

Savolainen et al. in prep.

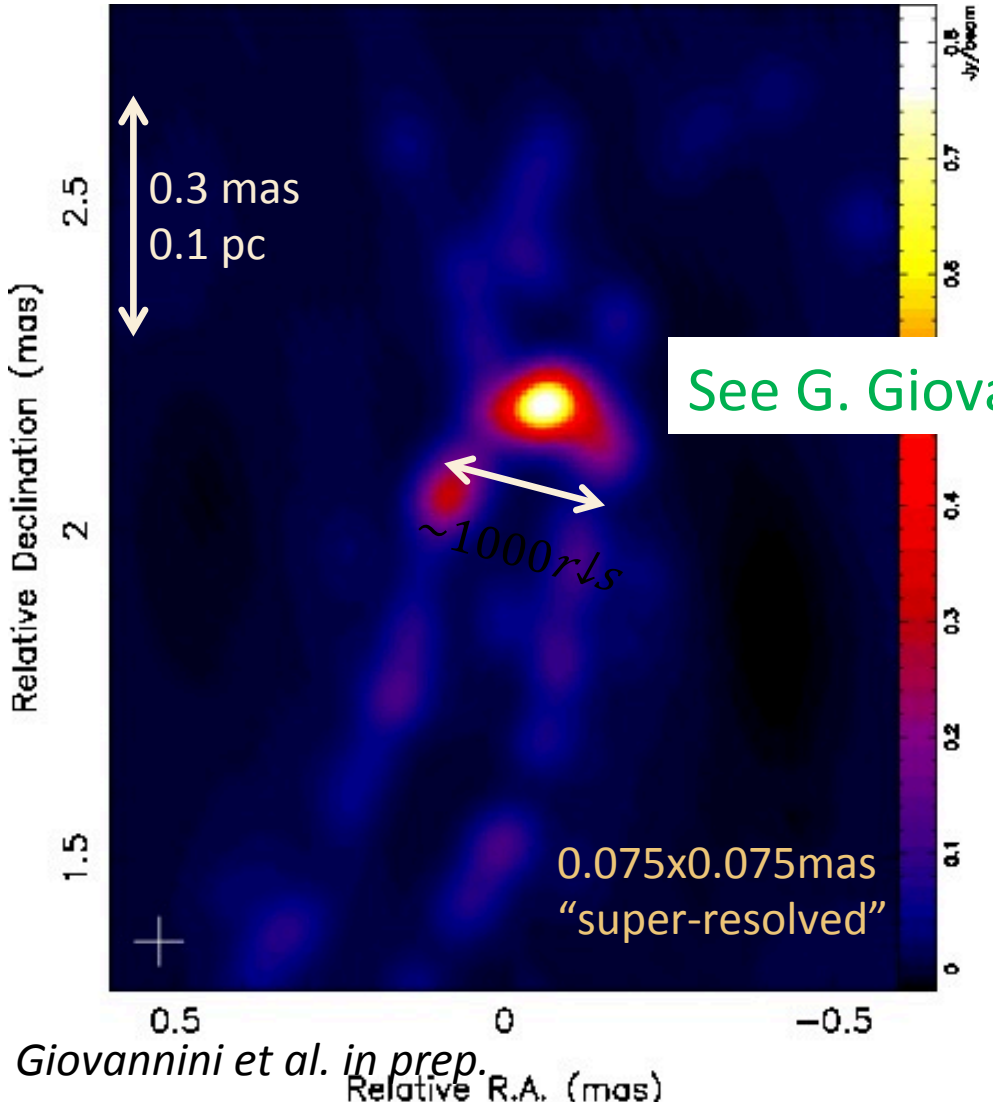
3C84
22 GHz RadioAstron image



- Weights: super-uni. / $\sigma\uparrow -1$
- Factor of 2 super-resolution in N-S direction
- Clear edge-brightening
- Emission on the counter-jet side
- "Hot spot" inside the moving feature C3 – the structure resembles that commonly seen in simulations of a working surface between jet and ambient medium (already suggested by Nagai et al. 2014).

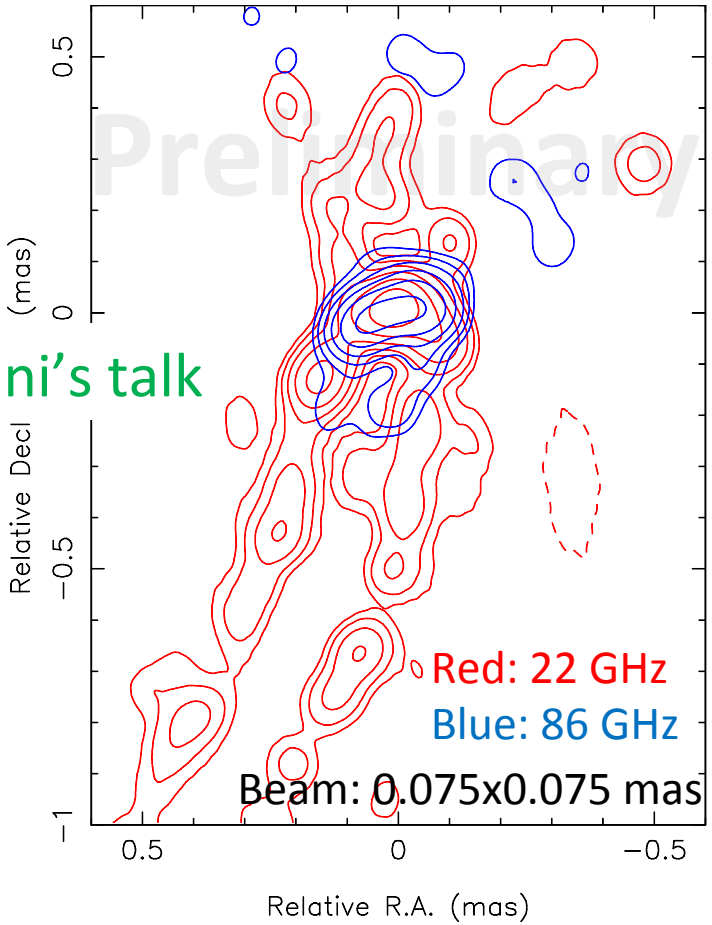
Savolainen et al. in prep.

3C84
Core structure at 22 GHz



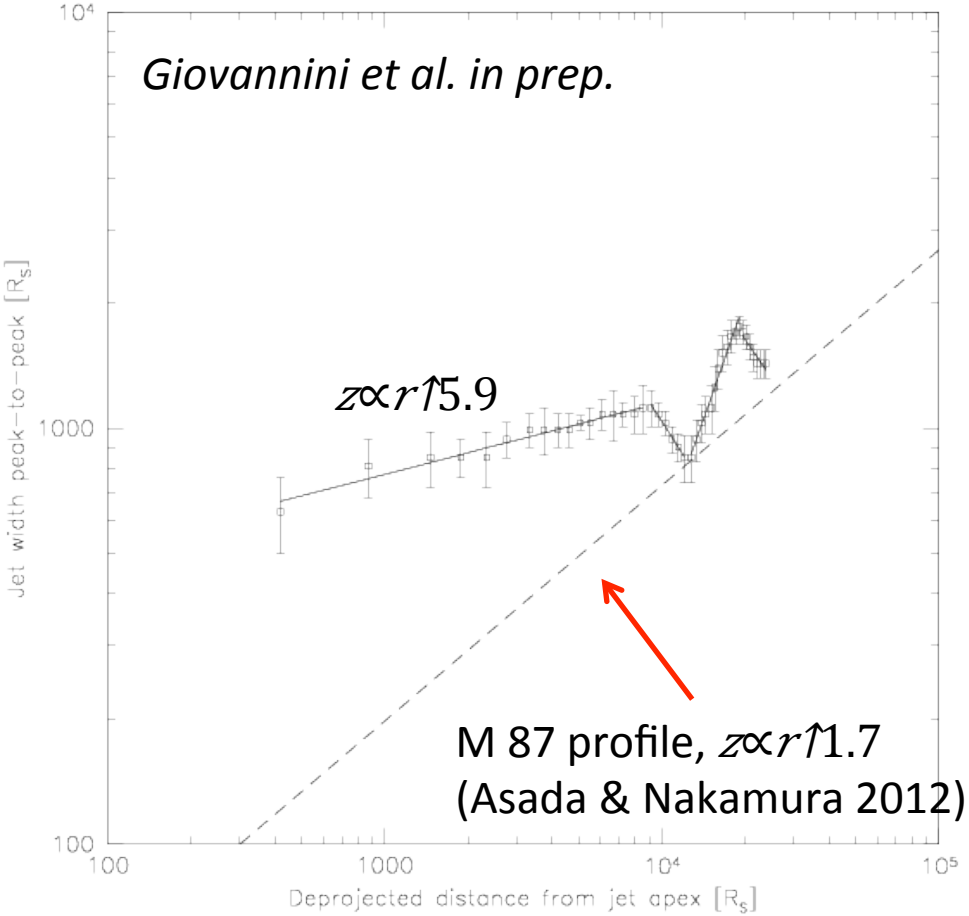
Giovannini et al. in prep.

See G. Giovannini's talk



GMVA data from J. Hodgson

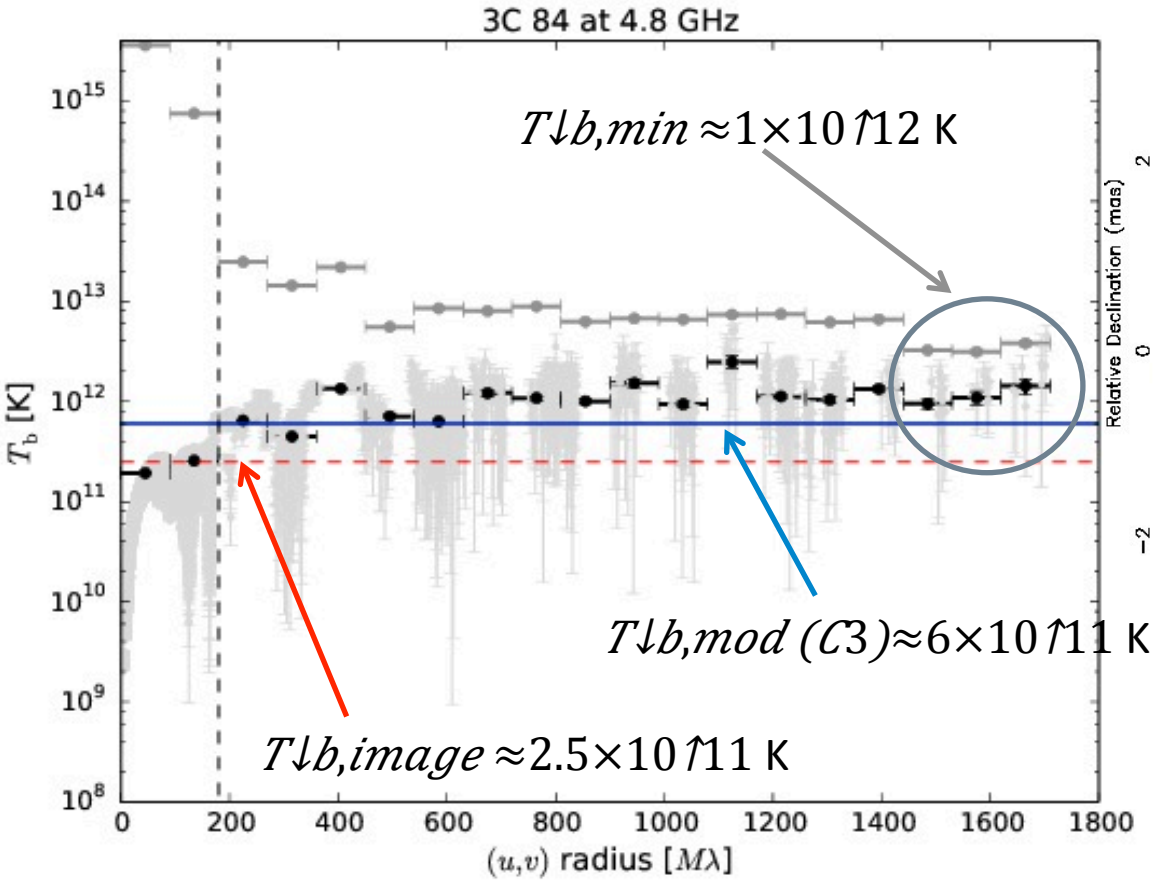
3C84
Jet collimation profile at 22 GHz

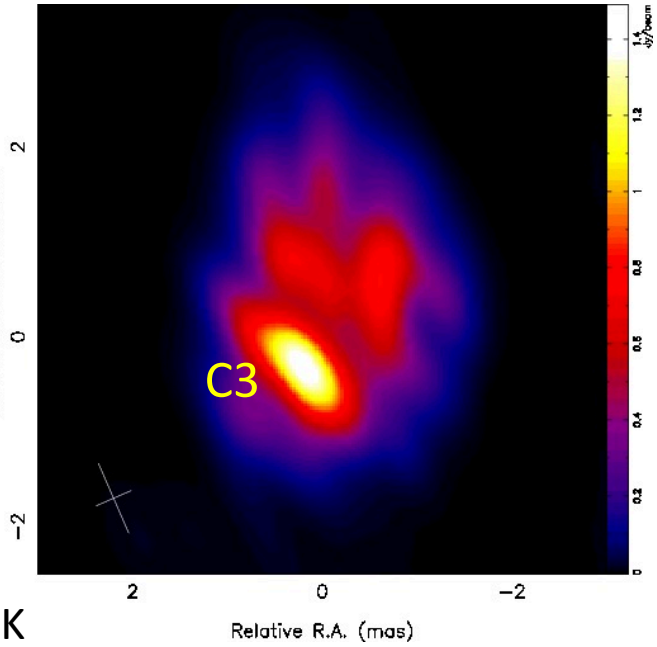


Viewing angle of 18 deg assumed
(Tavecchio & Ghisellini 2014)

- Very shallow collimation profile beyond $400 R_s$: $z \propto r^{5.9}$. Differs from M87. Caveat: 3C84 measured over much smaller *z* range.
- Jet is wide: $\sim 600\ R_s$ peak-to-peak at $400 R_s$ from the 22 GHz core
- 22GHz core size $\sim 50 \mu as \sim 210 R_s$; similar core size at 86 GHz
- The visible counter-jet limits the possible core-shift
- Is edge-brightened part of the jet launched from the disk? (Note that there can still be a BZ jet inside.)

3C84
Brightness temperature at 5 GHz





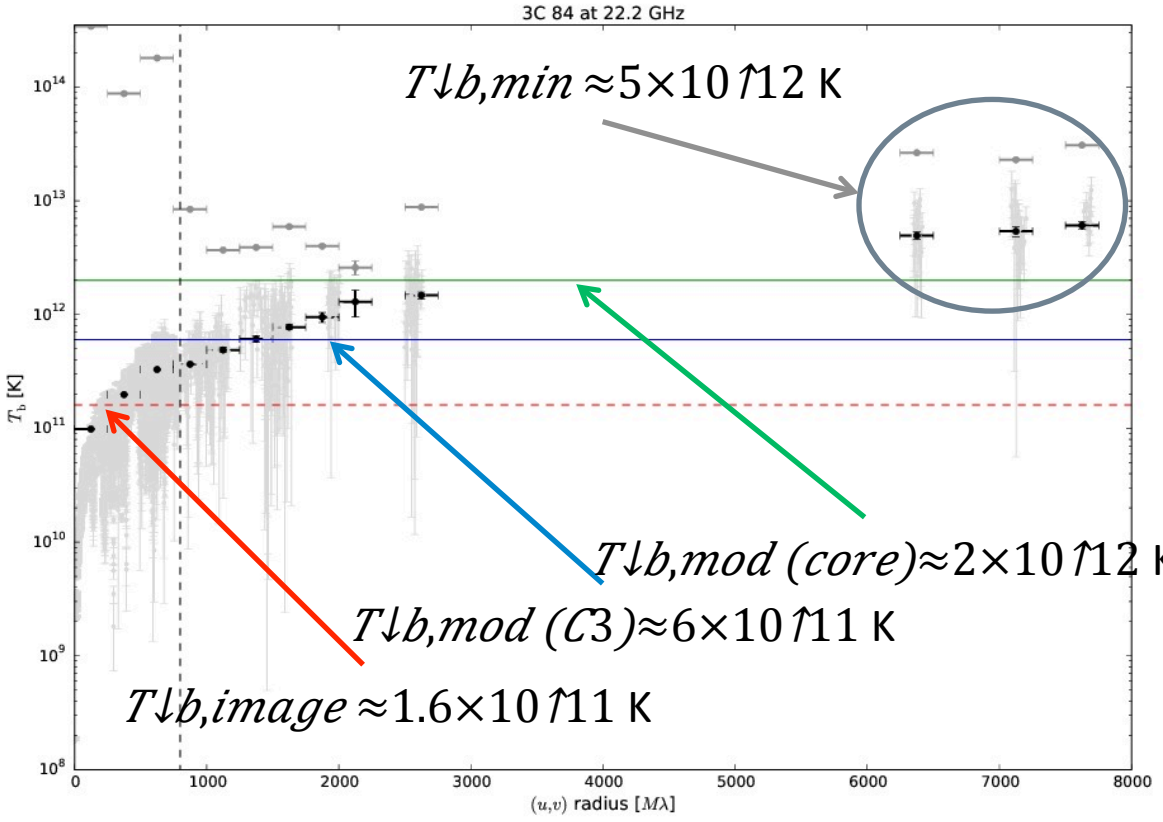
$T_{b,min}$ higher than $T_{b,mod}$:

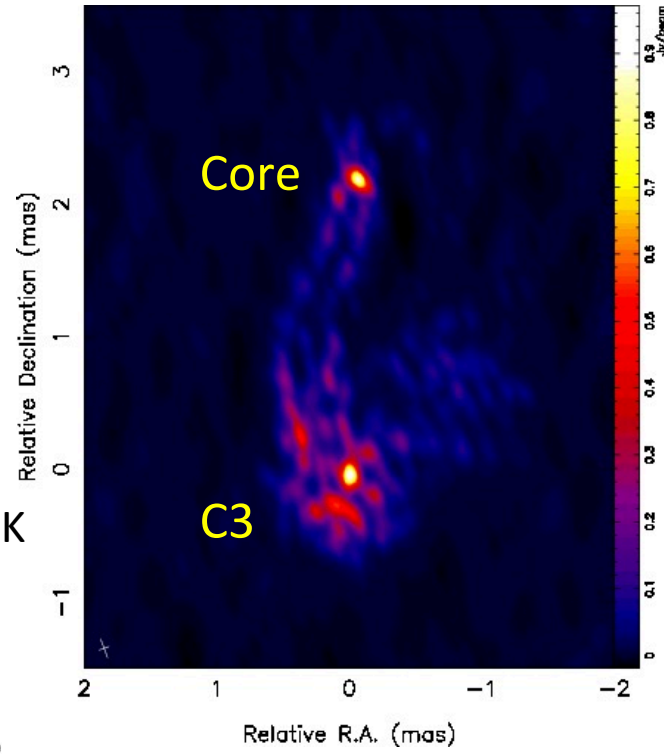
- Geometry of C3?
- Substructure of C3?

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

Savolainen et al. in prep.

3C84
Brightness temperature at 22 GHz





$T_{b,min}$ overestimated because of geometry?

Savolainen et al. in prep.

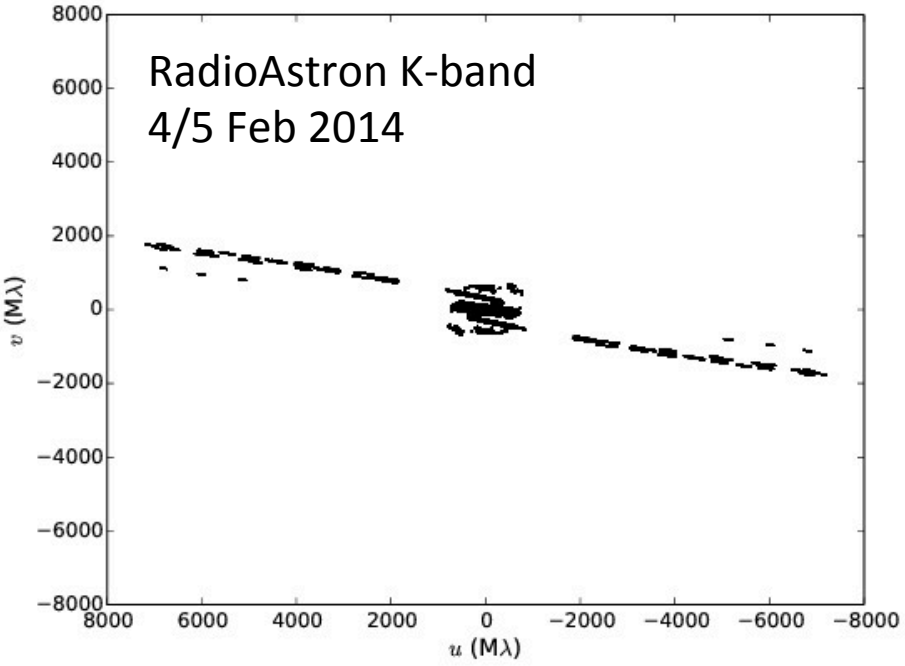
M87 RadioAstron observations

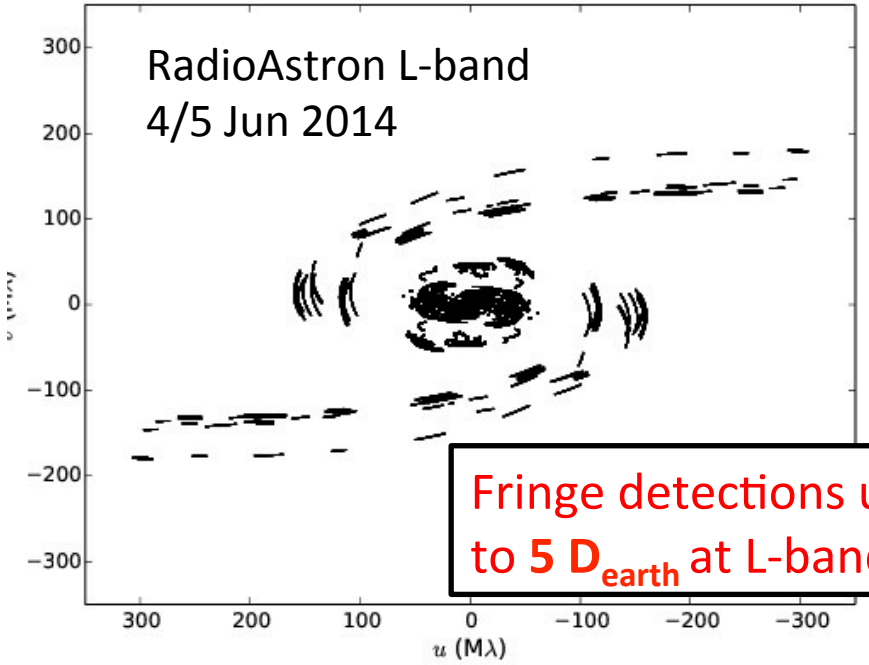
5/22 GHz in 4/5 Feb 2014

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

1.6 GHz in 4/5 Jun 2014

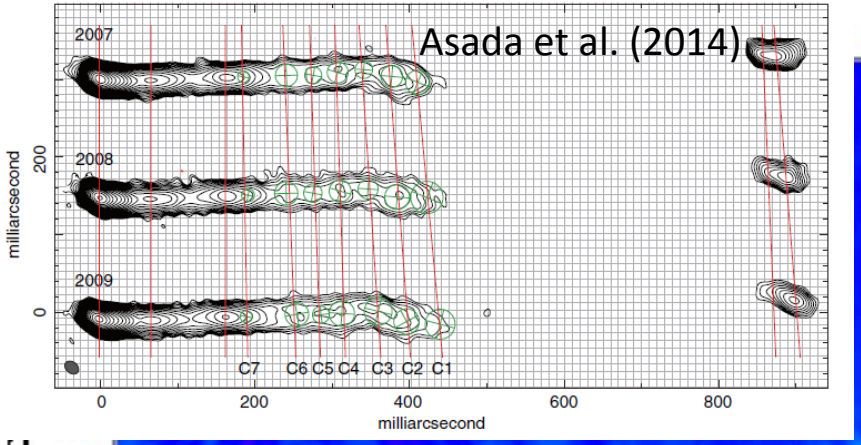
- 26 ground radio telescopes in a single array
- EVN+VLBA+LBA+Ar+Kl





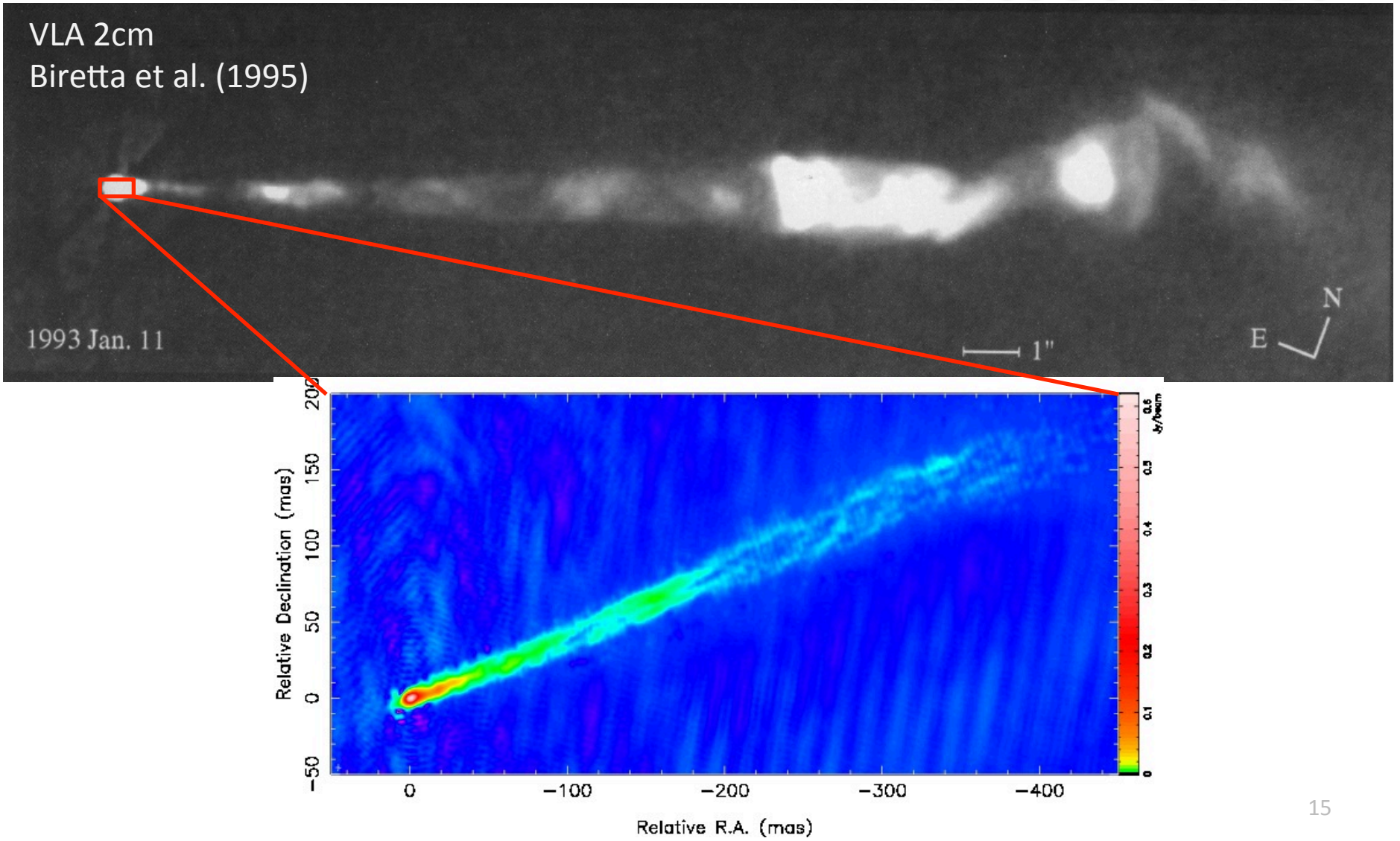
Data correlated with modified DiFX correlator in Bonn (Bruni et al. 2015).

M87 at 18cm – 26 ground radio telescopes

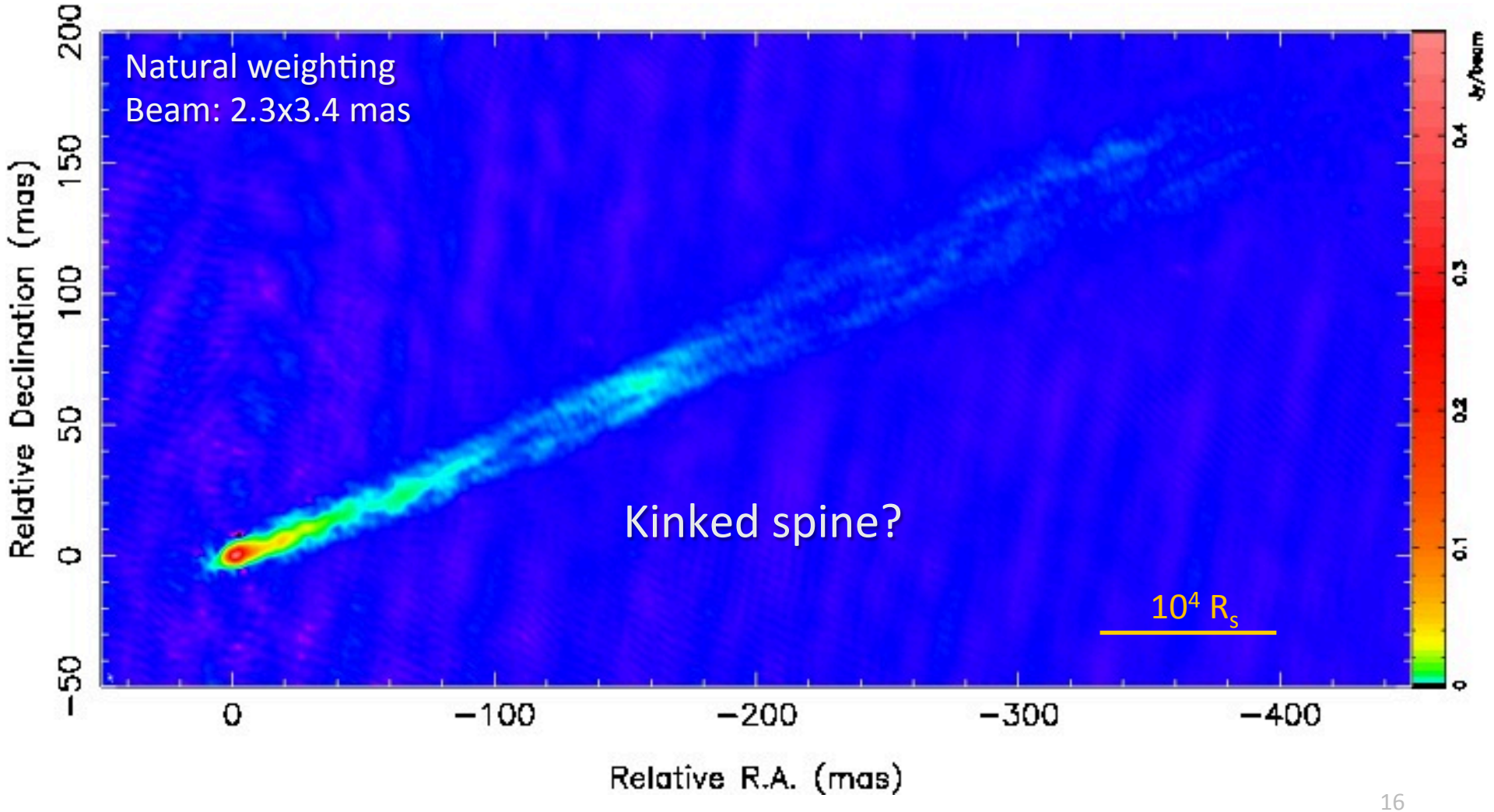


Savolainen et al. in prep.

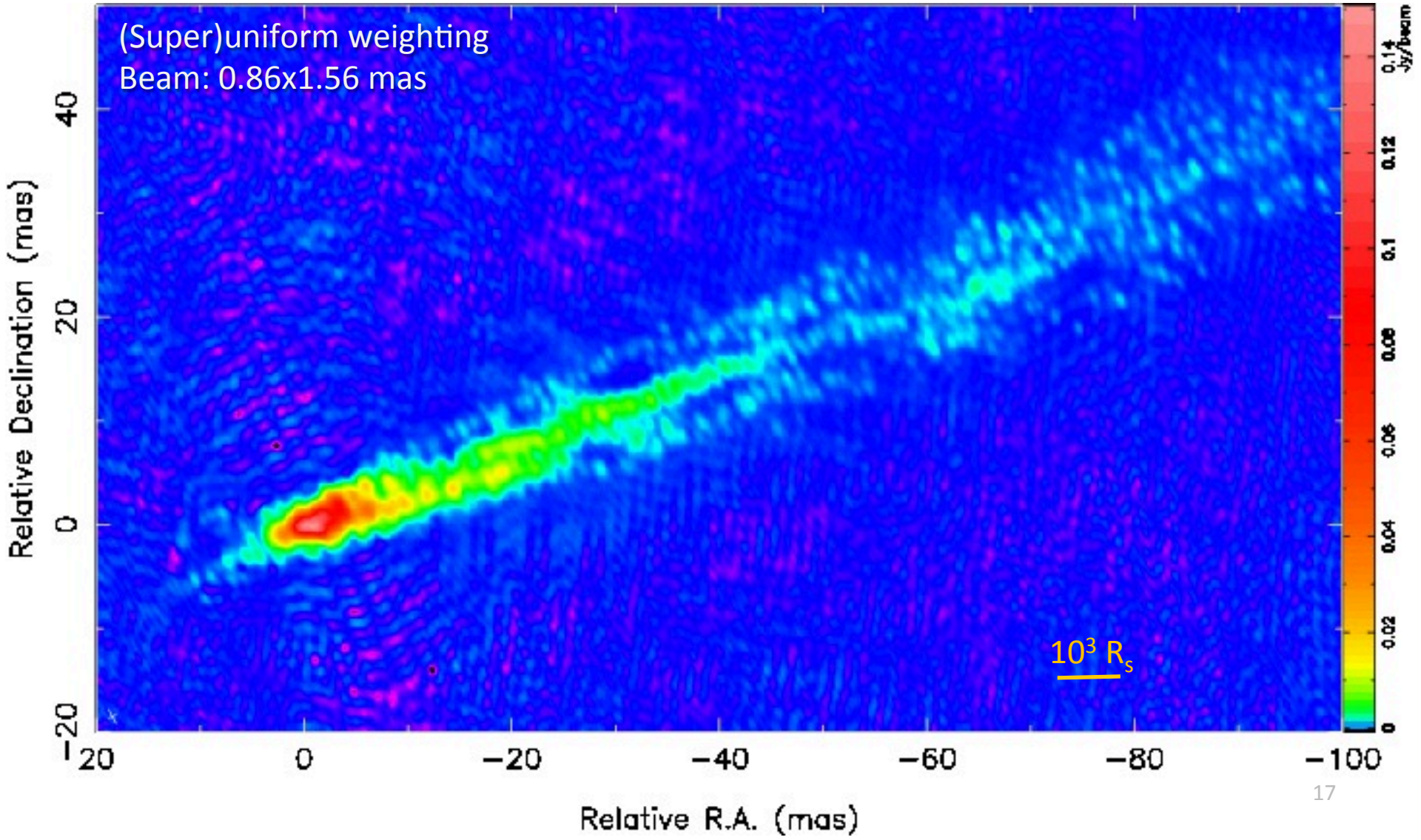
Helical filaments in arcsec and milliarcsec scales



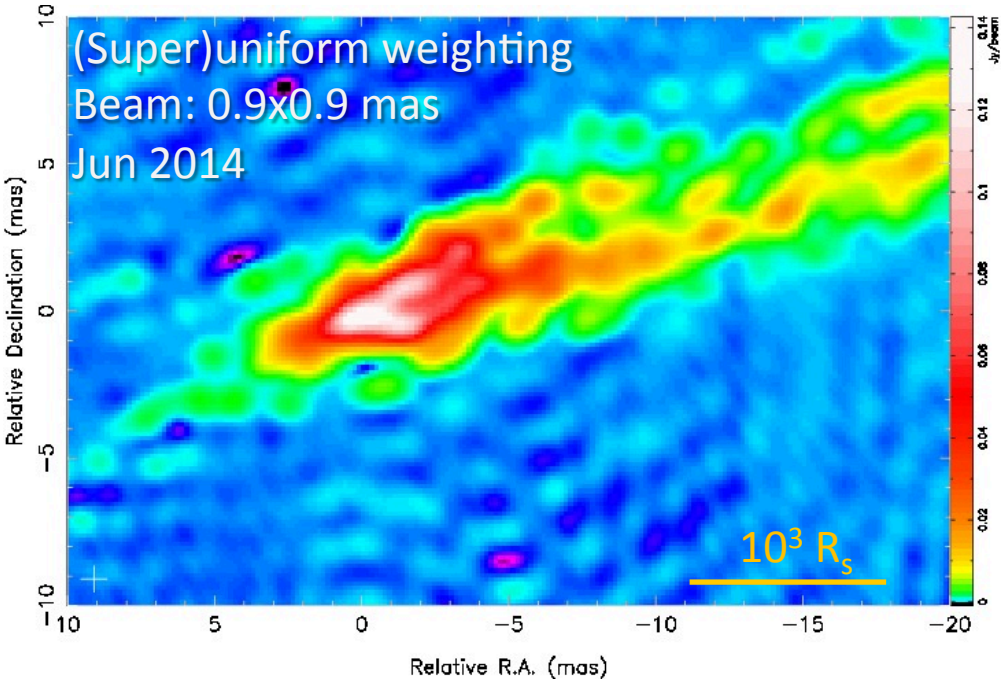
M87 at 18cm – including RadioAstron

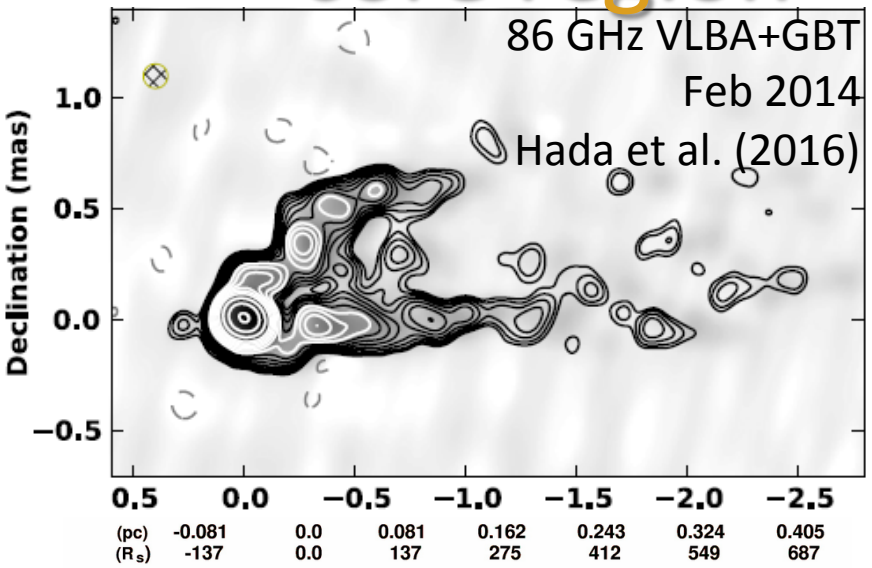


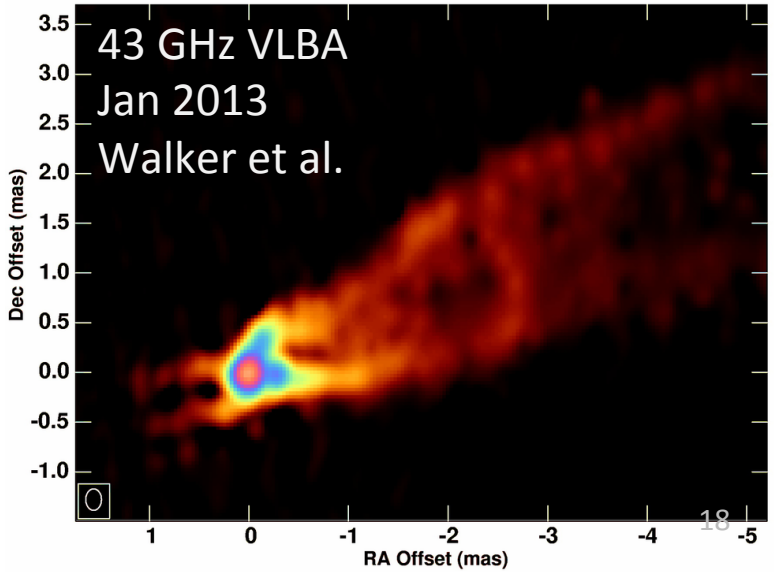
M87 at 18cm – inner 100 mas



M87 at 18cm – core region

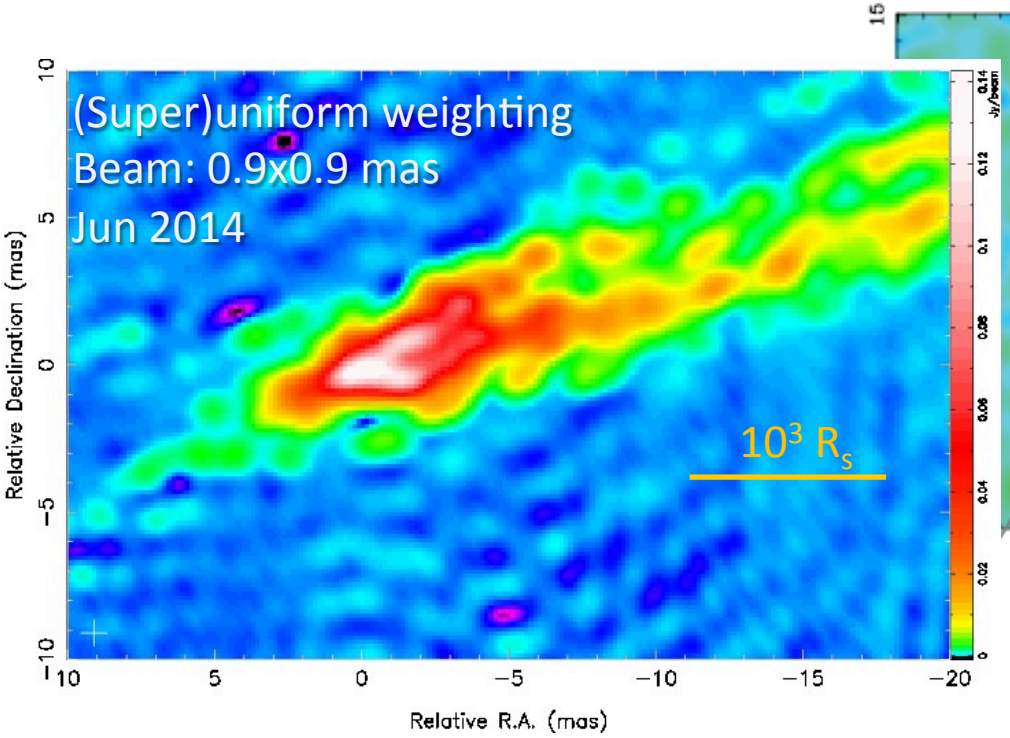


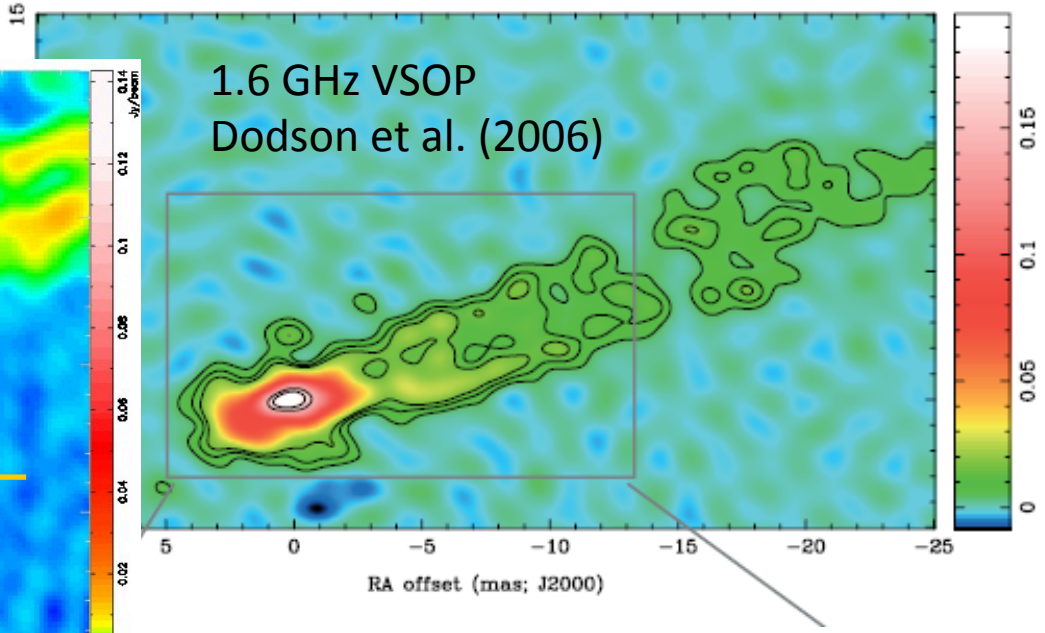




- Edge-brightened core structure visible at both 1.6 GHz RadioAstron and 86 GHz VLBA +GBT images
- Counter-jet visible
- Kink at 2-3 mas from the core at 1.6 GHz?

M87 at 18cm – core region





- VSOP (Dodson et al. 2006): “haze” around the core in the 18cm
- RadioAstron: low-intensity emission around the conical core – sheath? Width ~ 5mas ~ 700 R_S

Summary

- Nearby radio galaxies 3C84, M87 and Cen A were observed with the RadioAstron at 1.6, 5 and 22GHz. Fringes on space baselines have been detected so far for M87 (up to 5 ED baseline lengths) and 3C84 (up to 7.7 ED). No space fringes detected for Cen A.
- RadioAstron can produce great space-VLBI images
- Key results for 3C84:
  - Strongly edge-brightened jet between the core and the moving feature C3
  - Very compact hot spot inside C3, well behind the leading edge of the feature
  - 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, but with changing pitch angle and amplitude. 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