

# The Nuclear Structure in Nearby AGN at 3-500 Schwarzschild Radii Resolution

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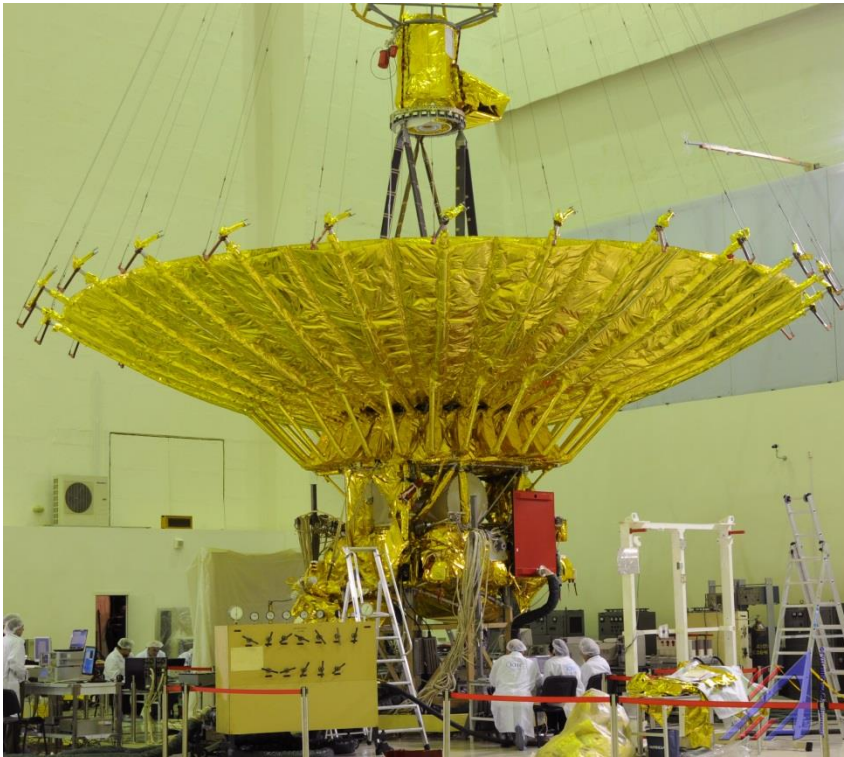
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Science Program team*



# RadioAstron Space-VLBI Project



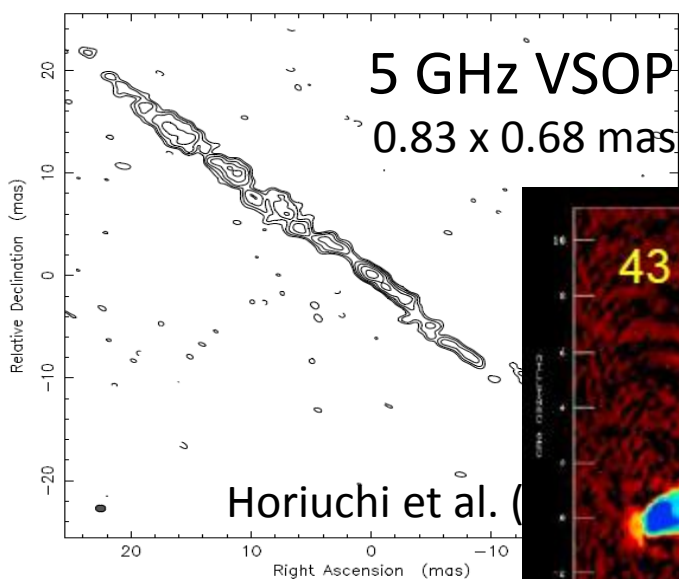
Kardashev+ 2013

- 10-m orbiting antenna (Space Radio Telescope; SRT)
- Launched in July 2011
- Highly elliptical orbit: baselines from  $\sim 1000$  km to 350000 km
- Works together with the largest ground radio telescopes to form an ultra high resolution interferometer
- Receivers onboard:
  - 0.33, 1.6, 5 and 18-25 GHz
- Max. angular resolution:  $7\mu\text{as}$
- Project led by the Astro Space Center of Lebedev Physical Institute, Russia

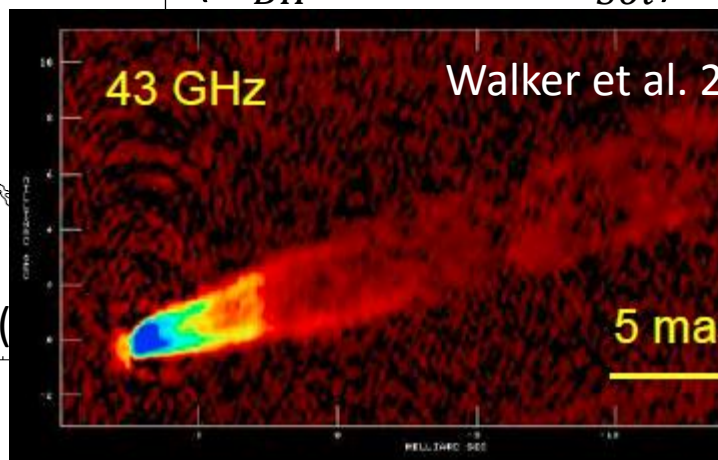
# RadioAstron Nearby AGN

## Key Science Program

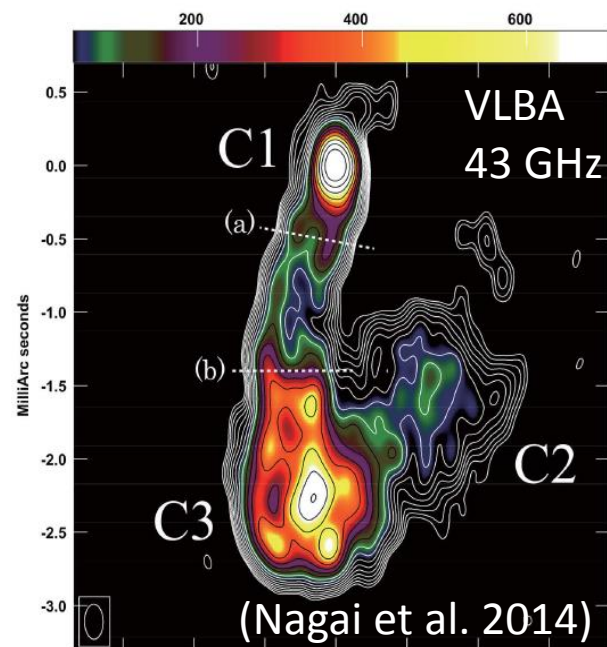
Near-perigee RadioAstron imaging observations of nearby radio galaxies. Target sources are at distances of 4-75 Mpc → **ultra-high spatial resolution (down to a few  $R_S$ )** for studying the jet acceleration and collimation zone.



**M87** (D=16 Mpc)  
1 mas = 0.078 pc = 135  $R_S$   
( $M_{BH} = 6 \times 10^9 M_{Sol}$ )

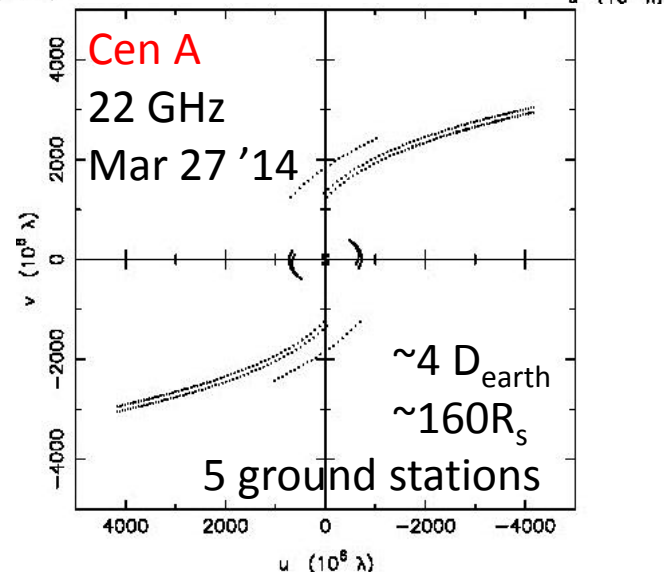
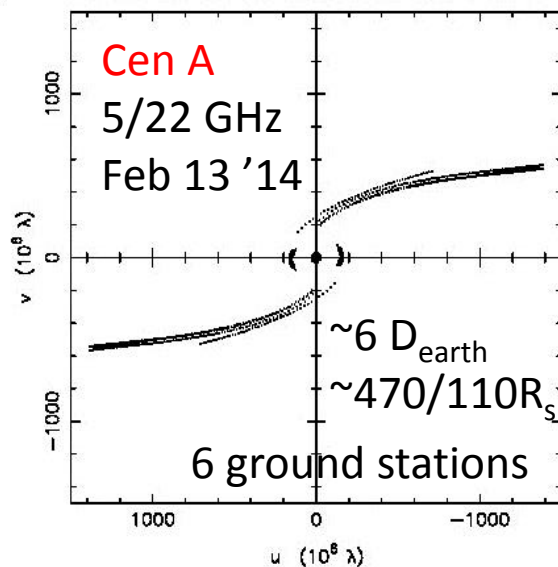
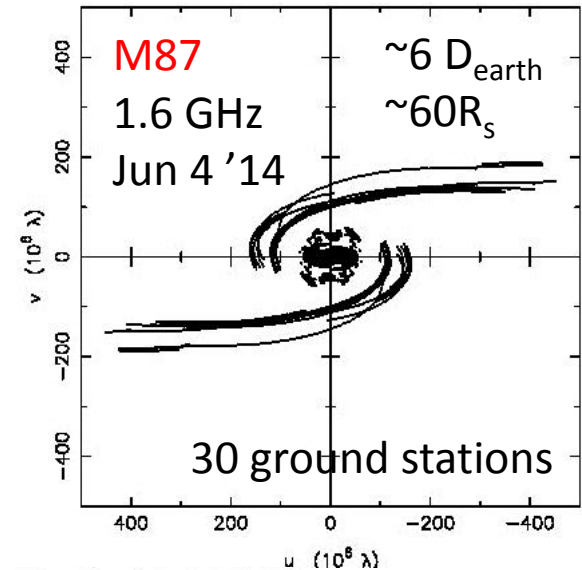
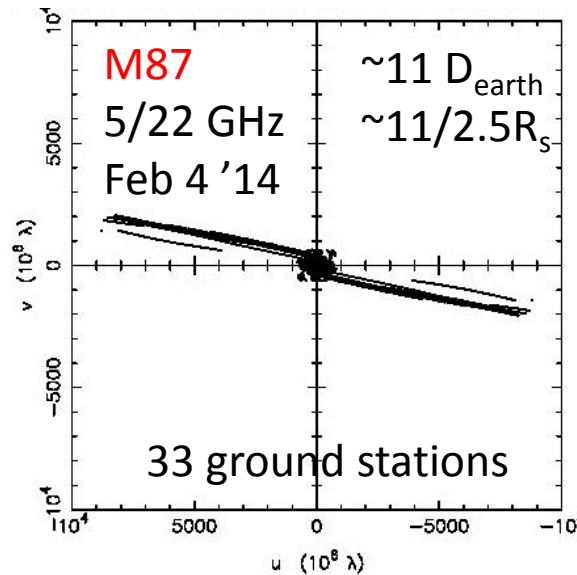
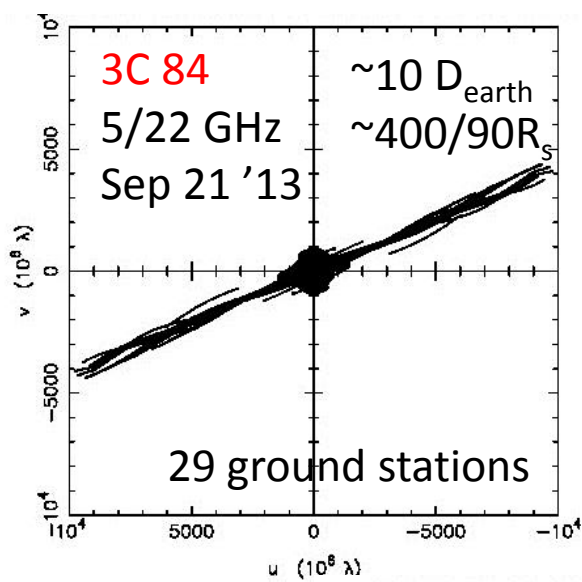


**Cen A** (D=3.8 Mpc)  
1 mas = 0.018 pc = 3100  $R_S$   
( $M_{BH} = 6 \times 10^7 M_{Sol}$ )



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

# Scheduled observations in 2013-2014



**NEARBY AGN KSP RESULTS:  
SPACE-VLBI IMAGES OF 3C84**

5 GHz

22 GHz

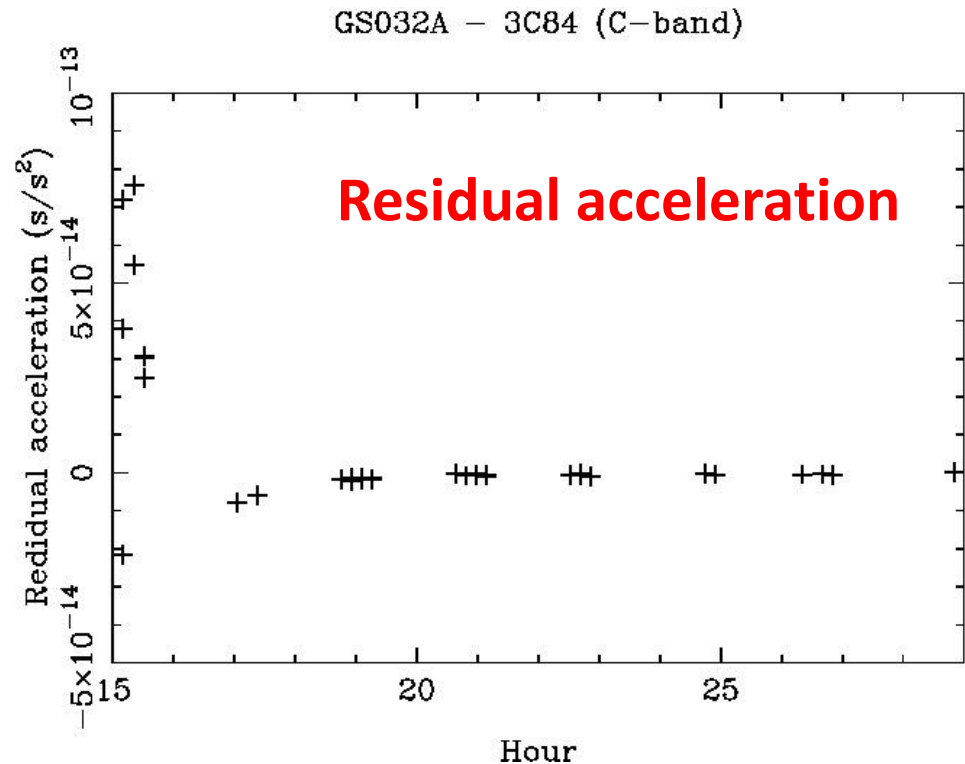
5/22 GHz

3C84 on Sep 21 2013



# 3C84 RadioAstron observations on Sep 21 2013 (5/22 GHz)

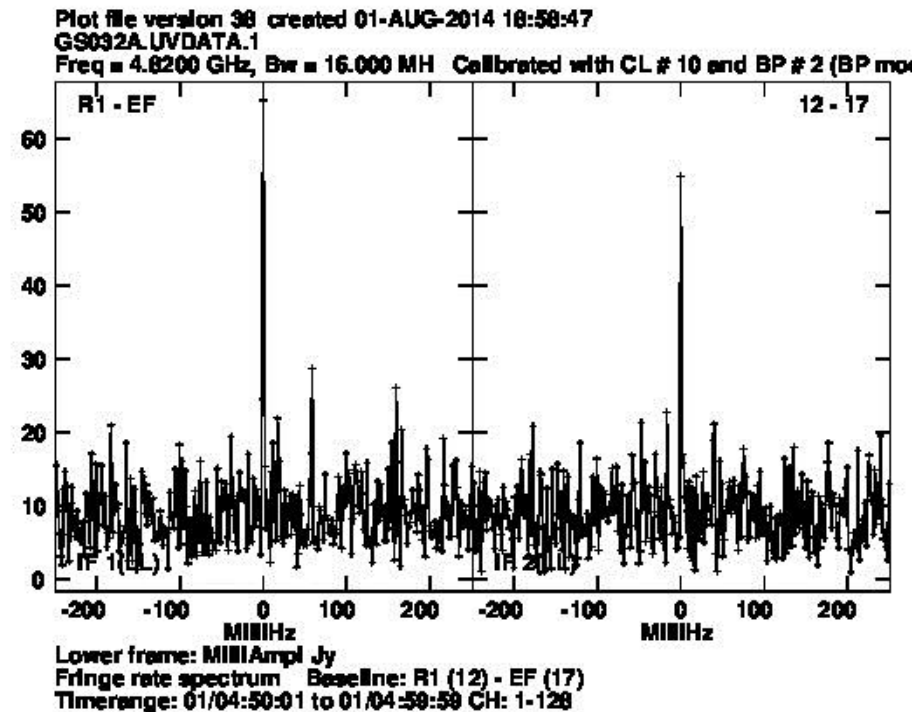
- Data correlated with a modified DiFX at the MPIfR (Bruni+ 2015)
- High residual acceleration in RadioAstron data near perigee
- Baseline-based fringe-fit of the RadioAstron data using *PIMA* (Petrov et al. 2011) and fitting for the acceleration term
- Transferred acceleration corrections to *AIPS* and carried out global fringe-fit using baseline stacking after first calibrating ground radio telescopes



# 3C84 RadioAstron observations on Sep 21 2013 (5/22 GHz)

Fringes detected on space  
baselines:

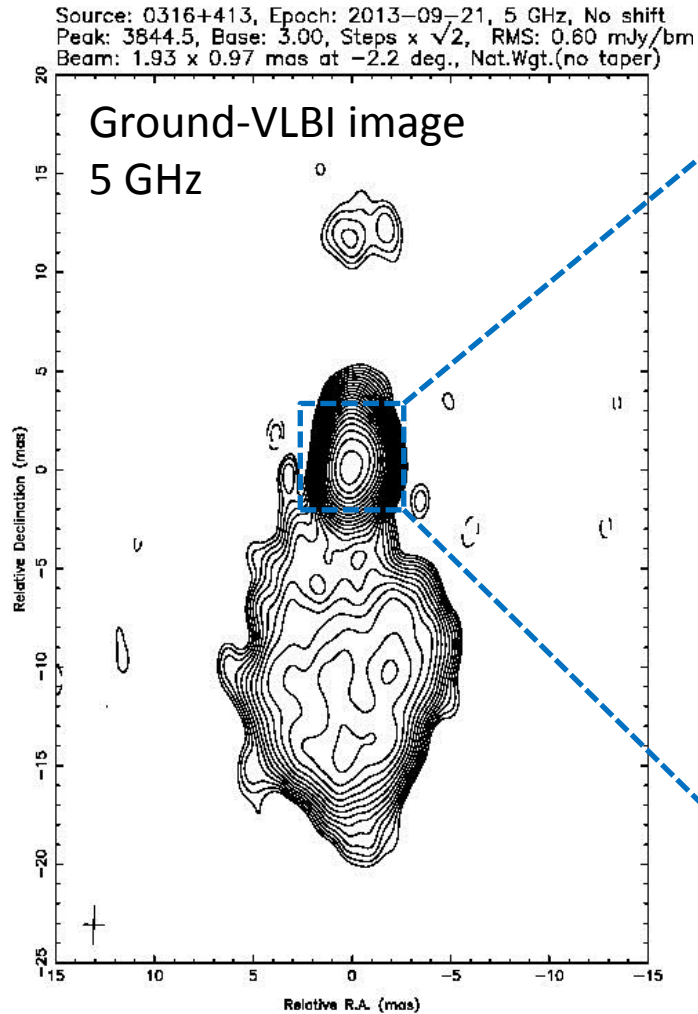
- 5 GHz:
  - PIMA: 23 scans over 0.2 - 6.9 Earth diam. (longest baseline SNR=8.6)
  - AIPS: 26 scans over 0.2 - 7.7 ED
- 22 GHz:
  - PIMA: 8 scans over 0.2 – 7.6 ED (longest baseline SNR=5.75)
  - AIPS: 12 scans over 0.2 – 7.6 ED



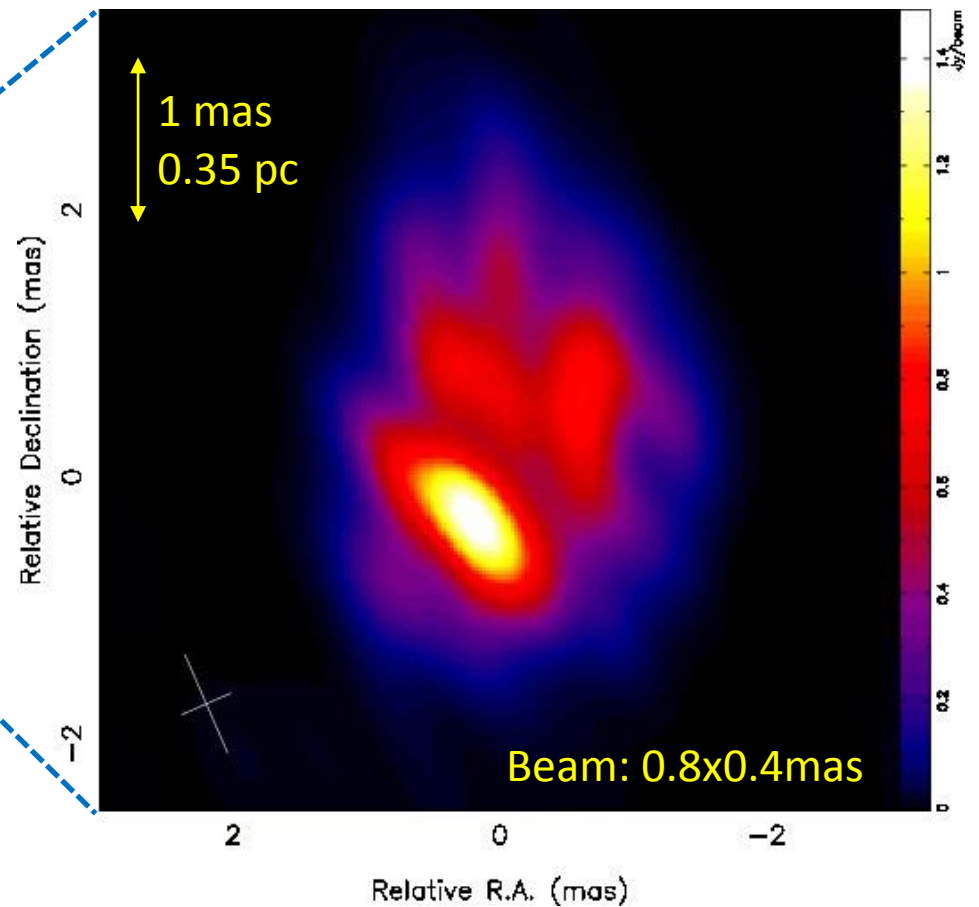
5 GHz fringe on RA-EF baseline  
6.9ED ( $1.4G\lambda$ ),  $60 \pm 8$  mJy

# 3C84

## 5 GHz RadioAstron image



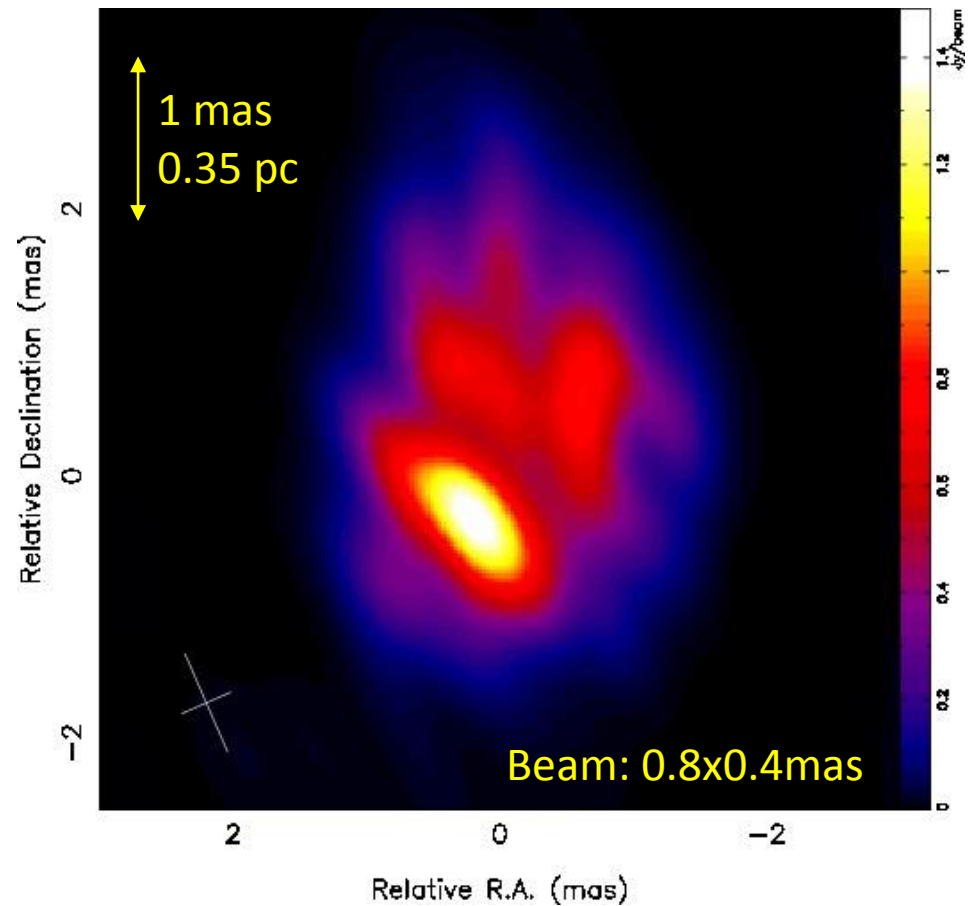
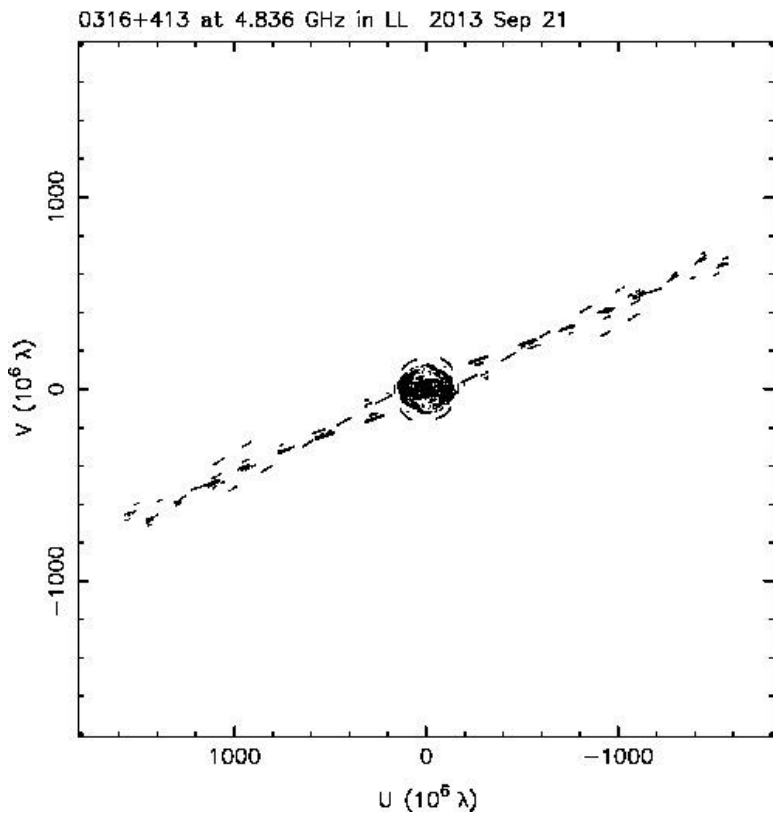
### Space-VLBI image 5GHz



# 3C84

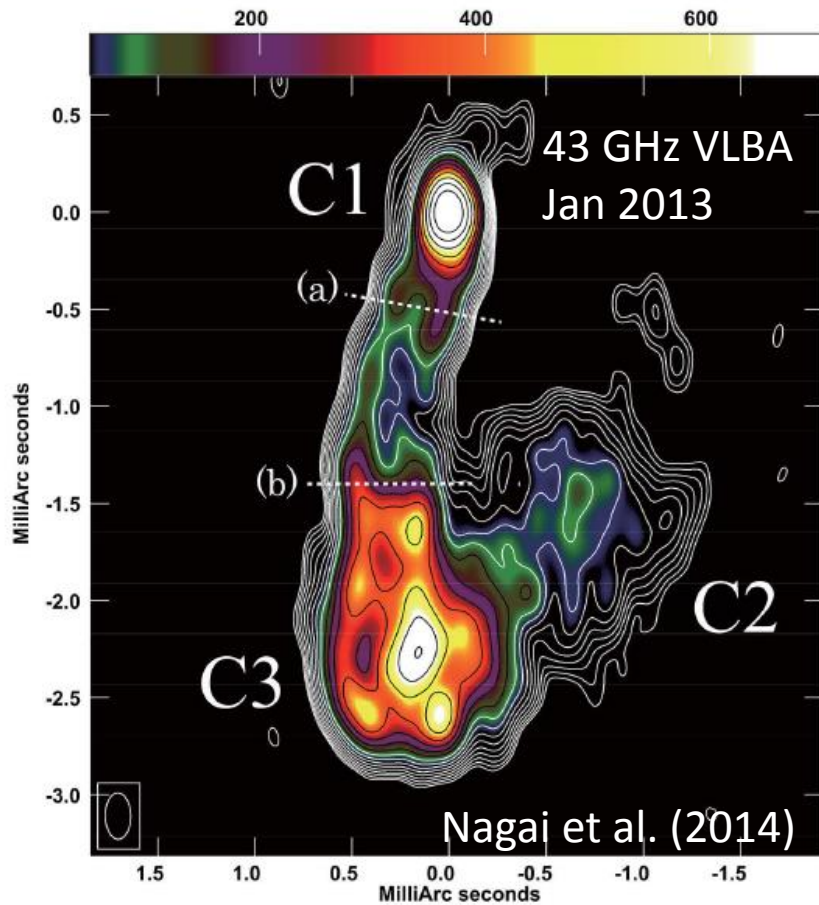
## 5 GHz RadioAstron image

### Space-VLBI image 5GHz

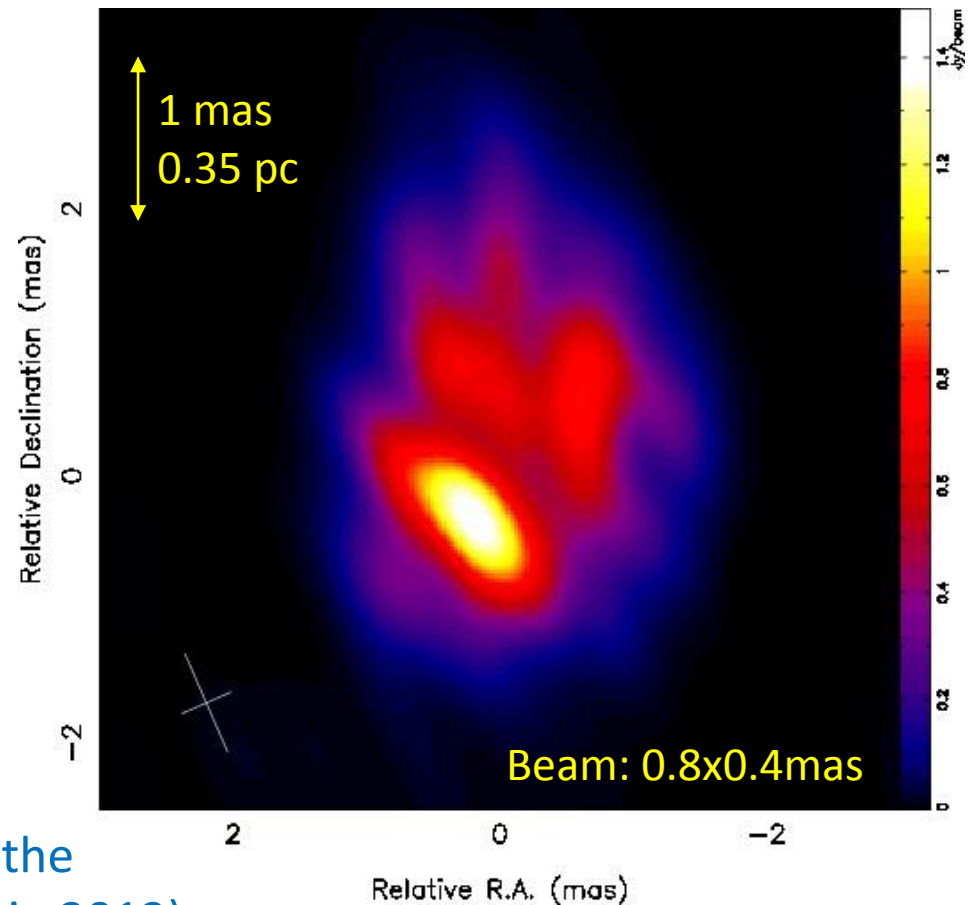


# 3C84

## 5 GHz RadioAstron image



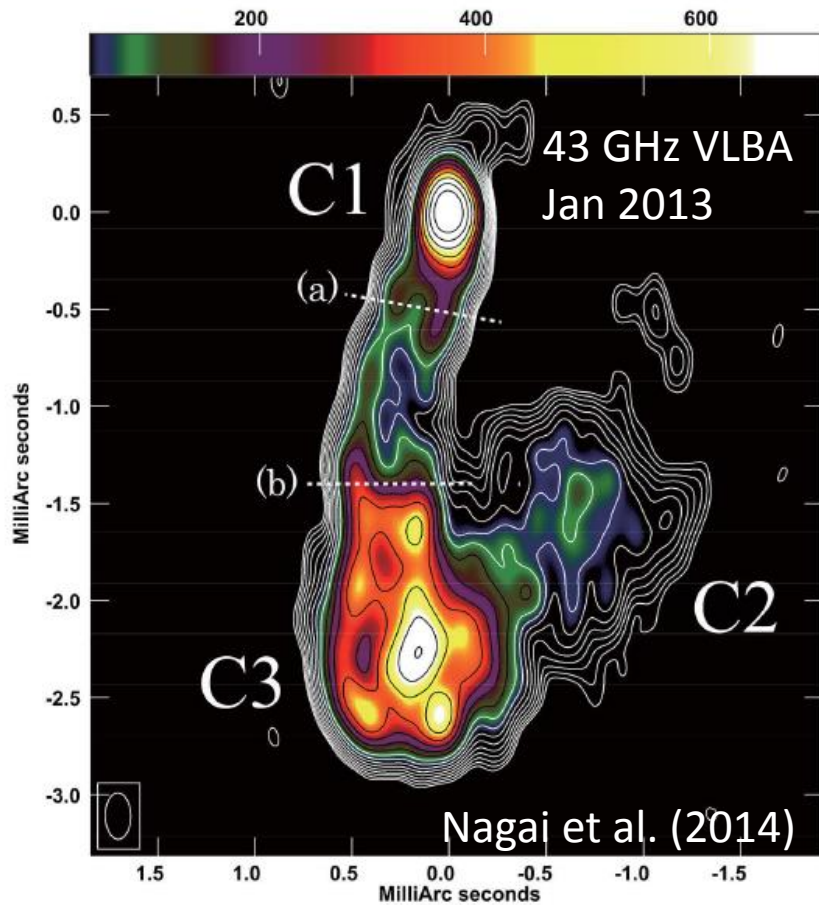
### Space-VLBI image 5GHz



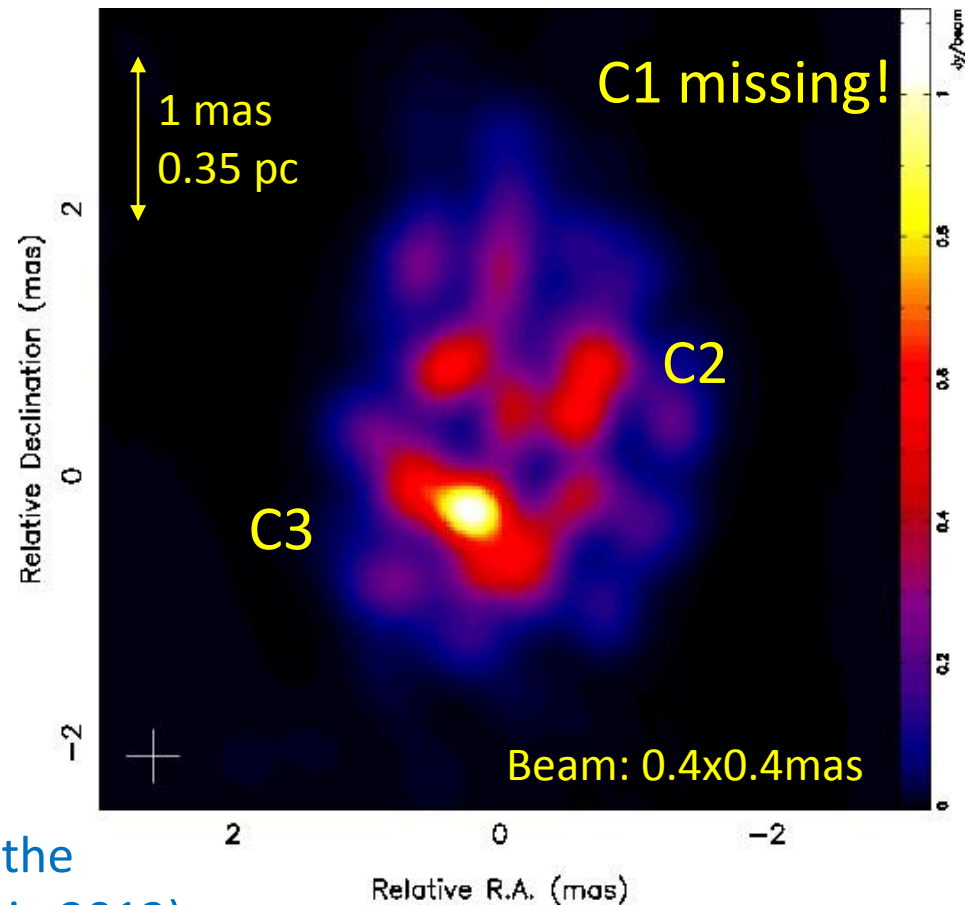
C3 is a slowly moving feature related to the restarted jet activity in the 2000s (Suzuki+ 2012)

# 3C84

## 5 GHz RadioAstron image



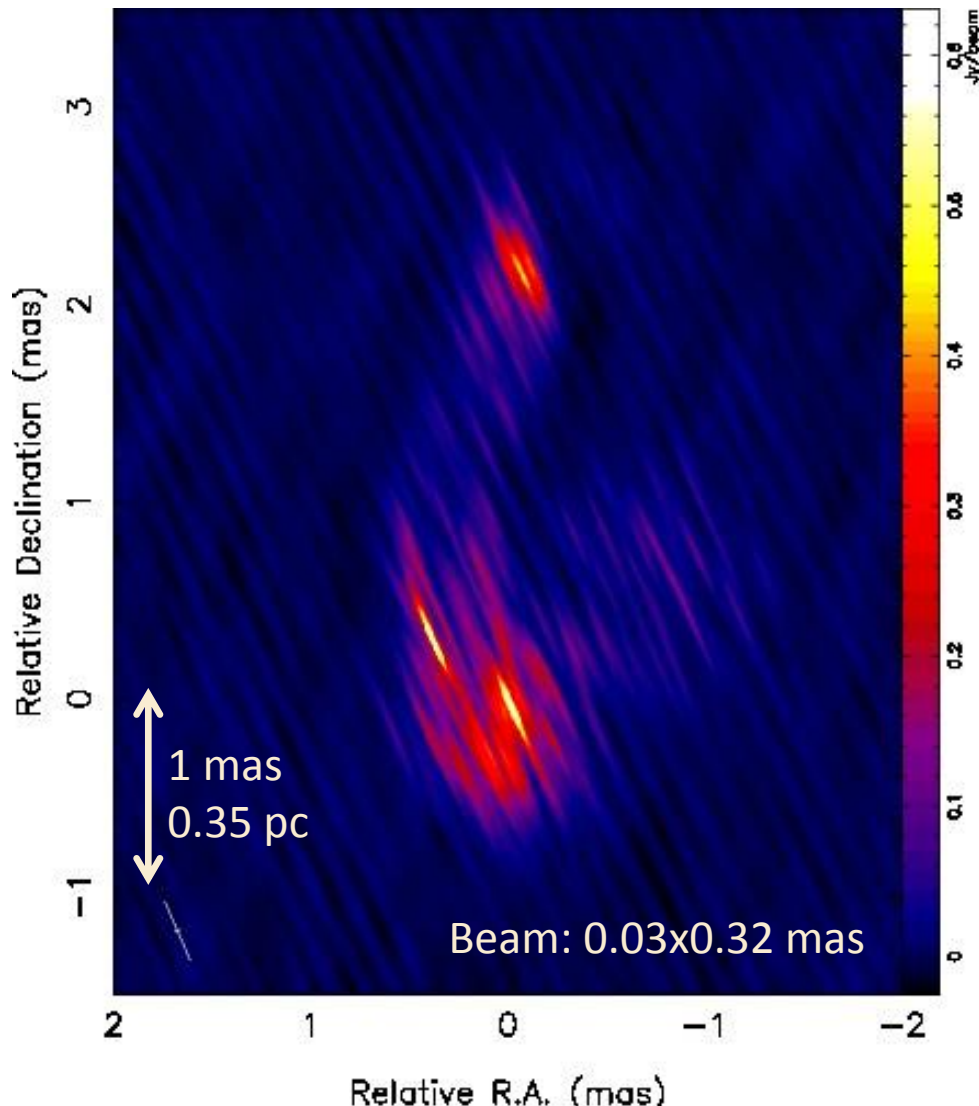
### Space-VLBI image 5GHz



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

# 3C84

## 22 GHz RadioAstron image

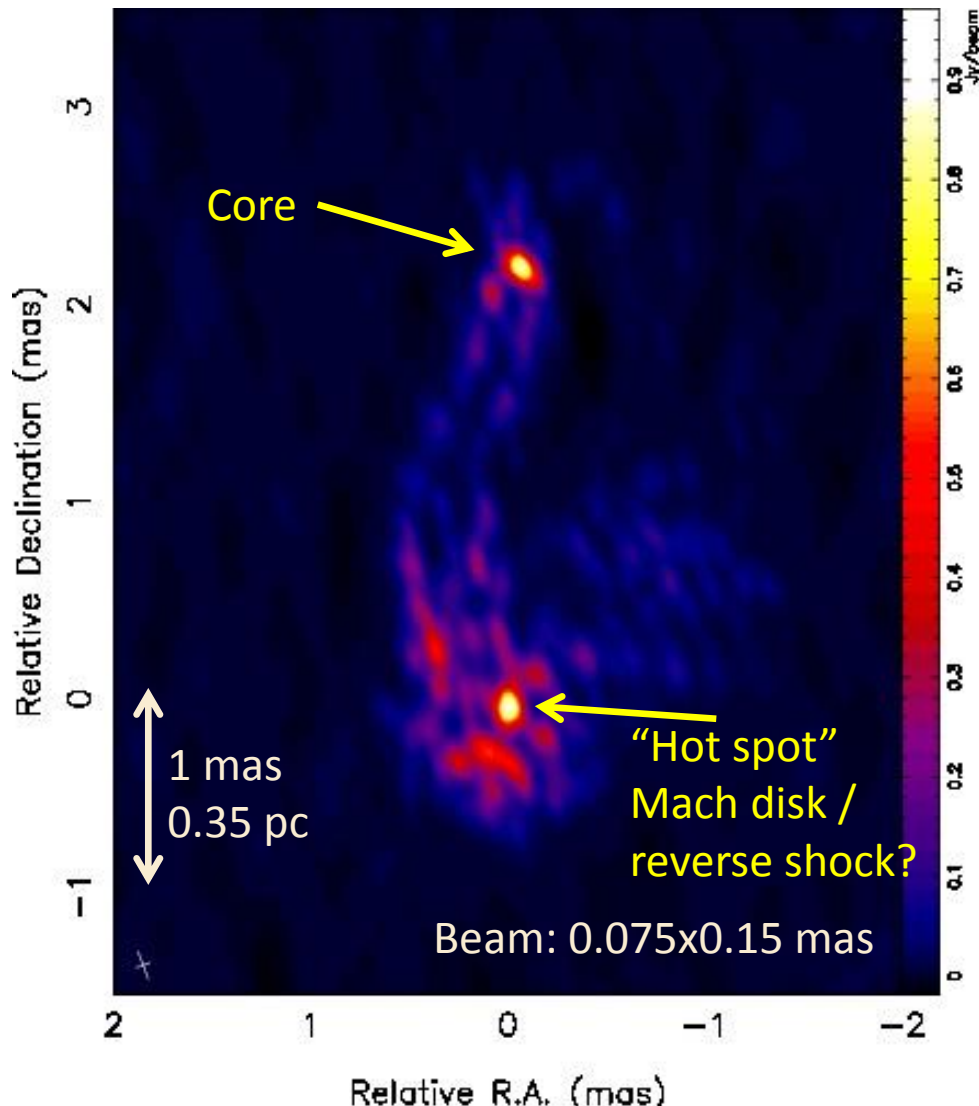


### Full resolution

- Maximum fringe spacing corresponds to  $27 \mu\text{as}$ , i.e.,  $\sim 120 R_s$
- Maximum resolution image made with superuniform (u,v) weighting and no error weights
- 1:10 beam ratio makes it difficult to interpret the image

# 3C84

## 22 GHz RadioAstron image

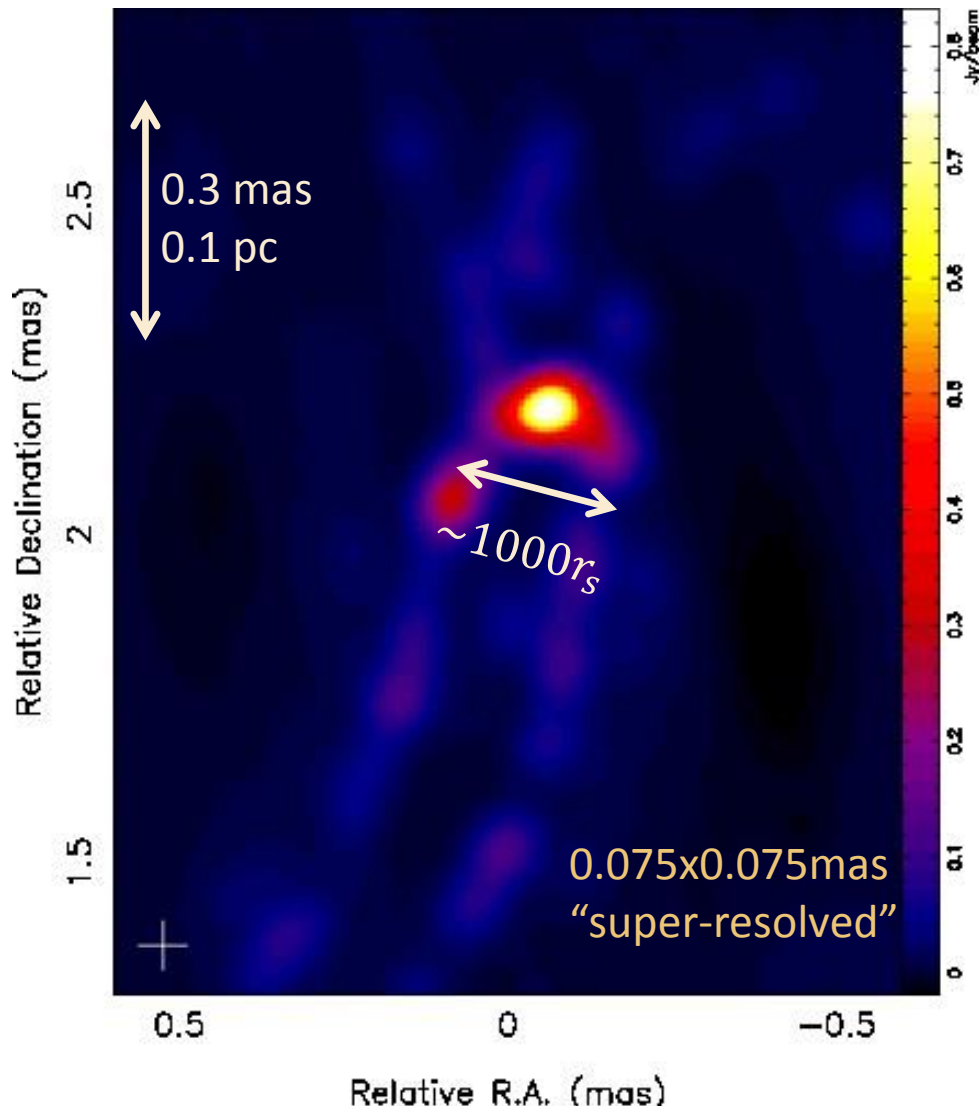


Slightly super-resolved in one direction

- Weights: superuni. /  $\sigma^{-1}$
- Counter-jet visible
- Clearly edge-brightened jet
- “Hot spot” inside the moving feature C3 – the structure resembles that commonly seen in simulations of a working surface between jet and ambient medium, as already suggested by Nagai et al. (2014).

# 3C84

## Core structure at 22 GHz

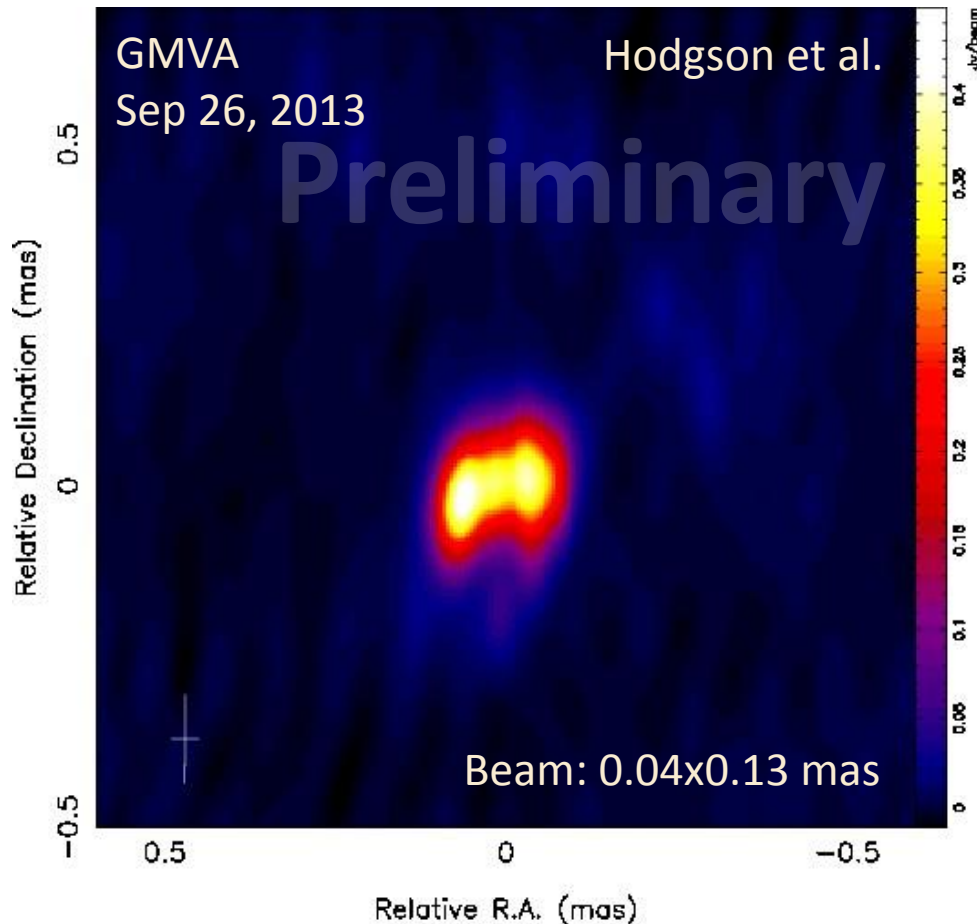


Strongly super-resolved in one direction

- Core resolved in direction transverse to the jet – the brightest feature in the middle of the flow
- Very wide opening angle at first, then rapid collimation to almost cylindrical jet (see [Monica Orienti's talk](#))
- Edge-brightened emission upstream of the core

3C84

# Core in the 86 GHz GMVA image



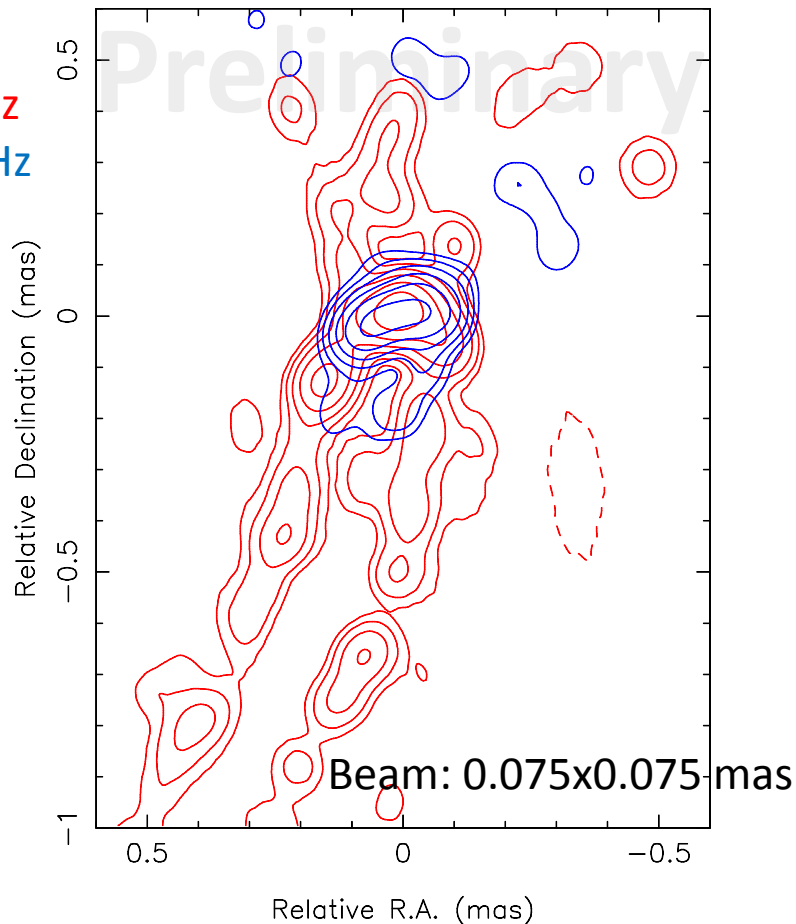
Confirms the features seen in the RadioAstron image

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

# 3C84

## Core in the 86 GHz GMVA image

Red: 22 GHz  
Blue: 86 GHz

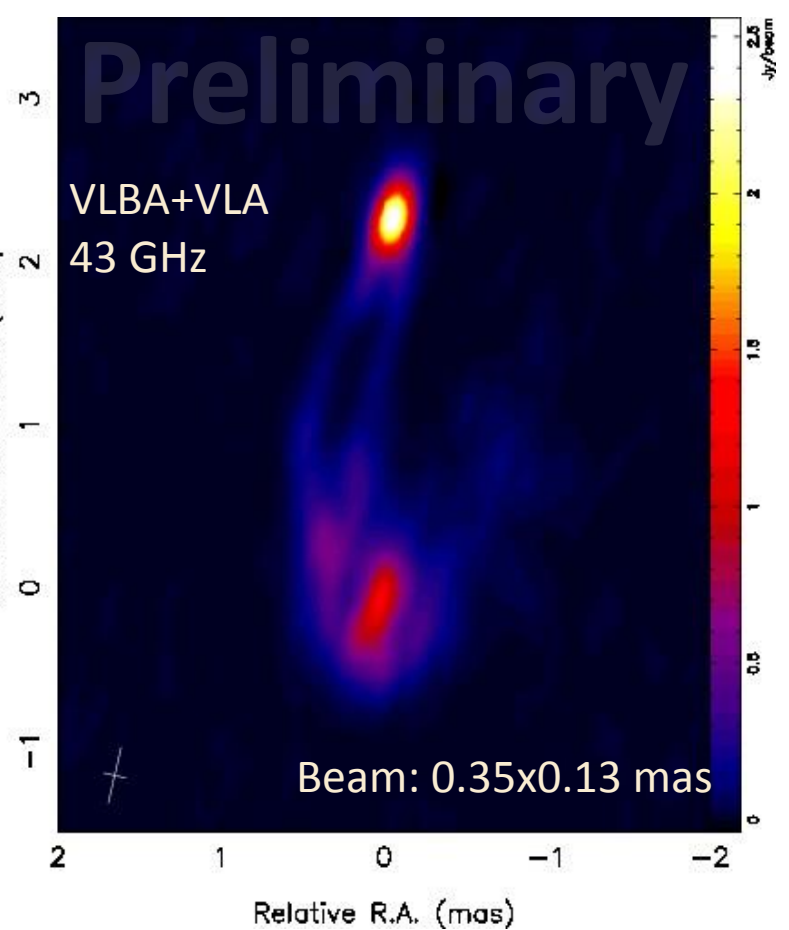
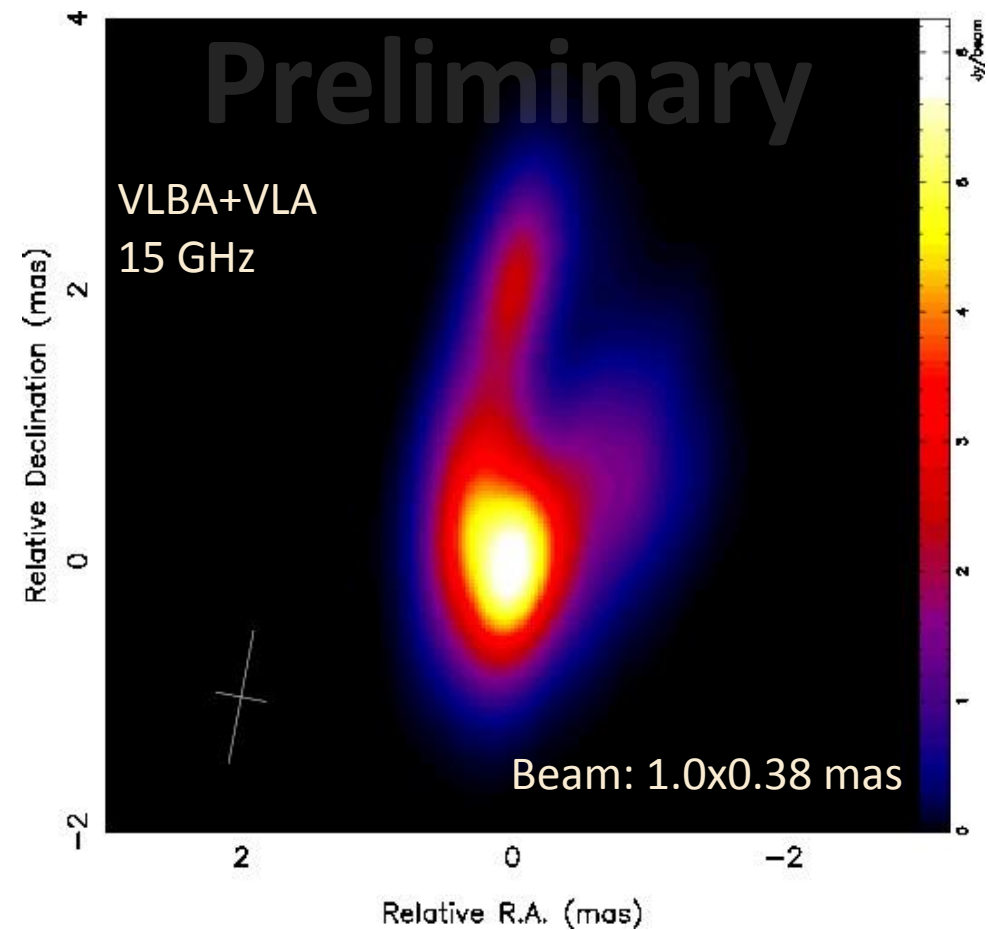


Confirms the features seen in the RadioAstron image

- Core clearly elongated in E-W direction
- Edge-brightened jet
- Emission on the counter-jet side
- Edge-brightened jet narrower at 86 GHz?
- Note that alignment is uncertain

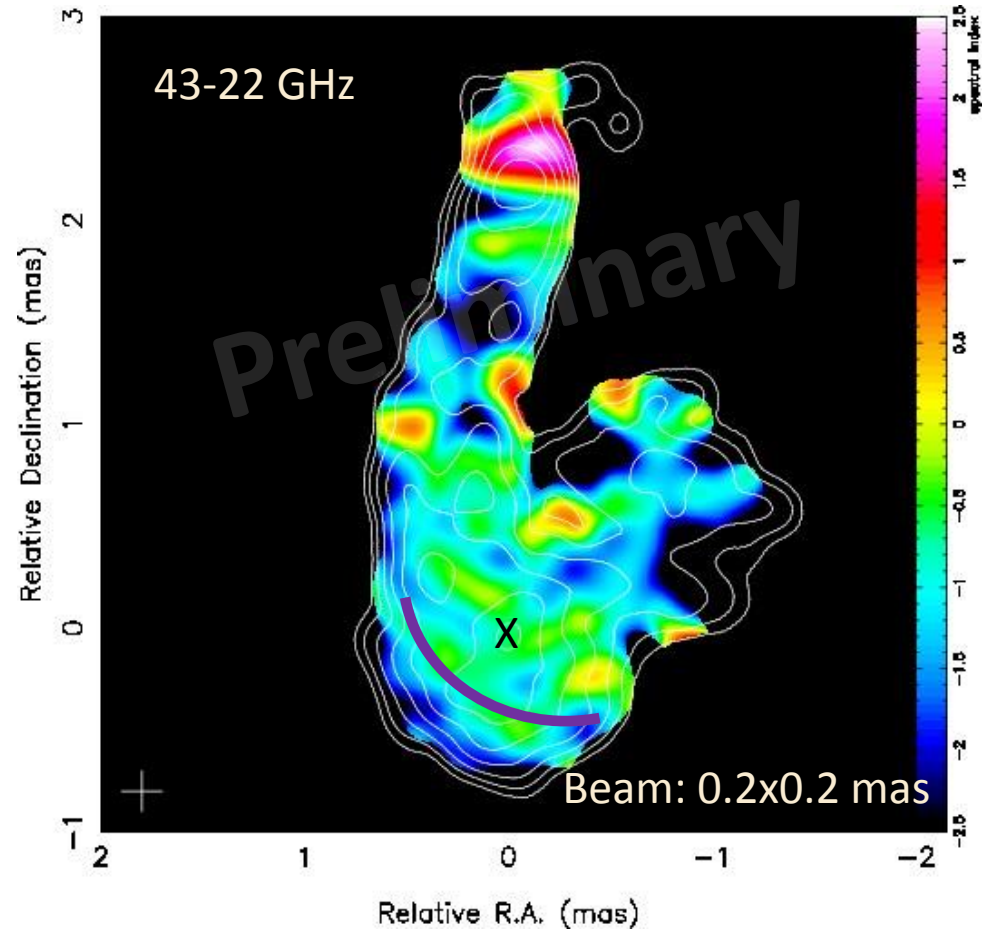
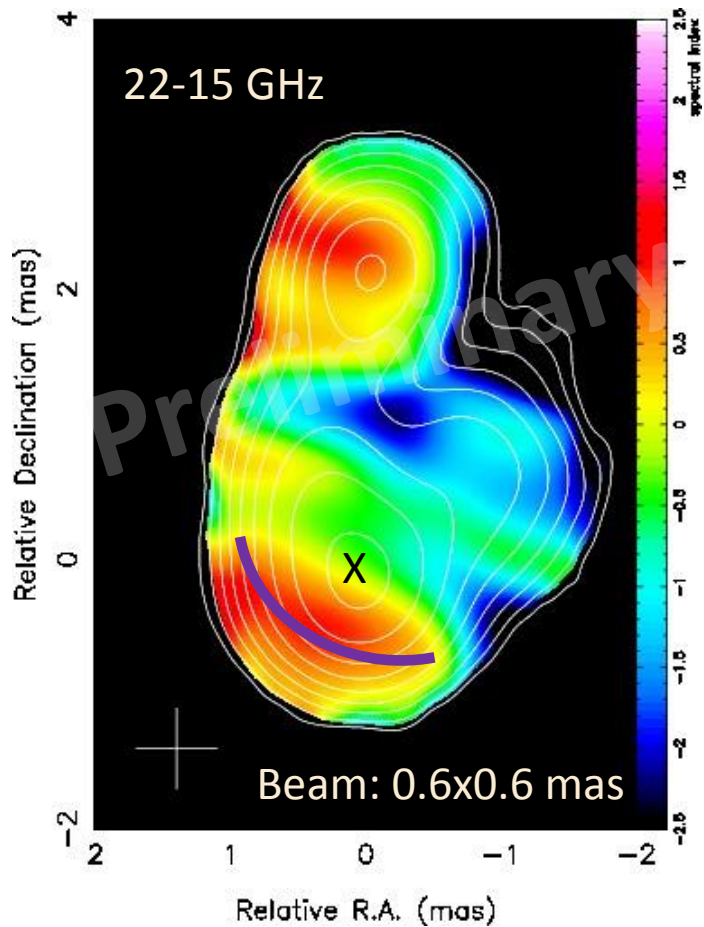
3C84

# Simultaneous 15 and 43 GHz images



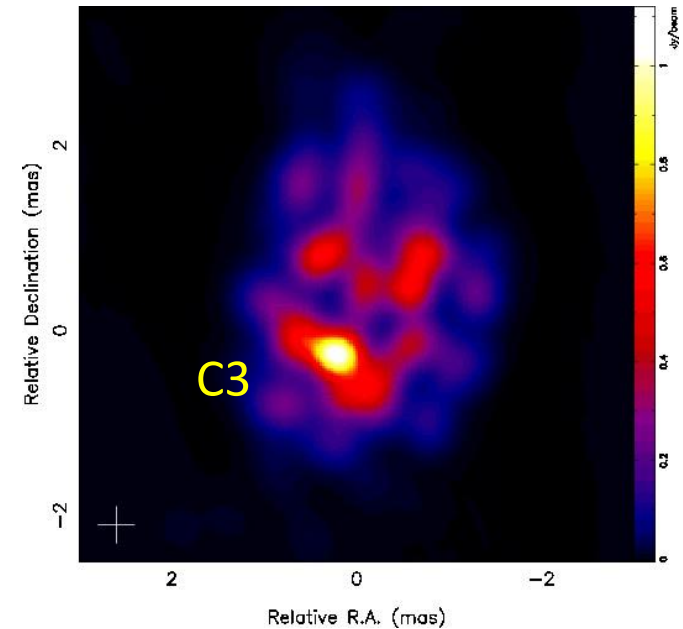
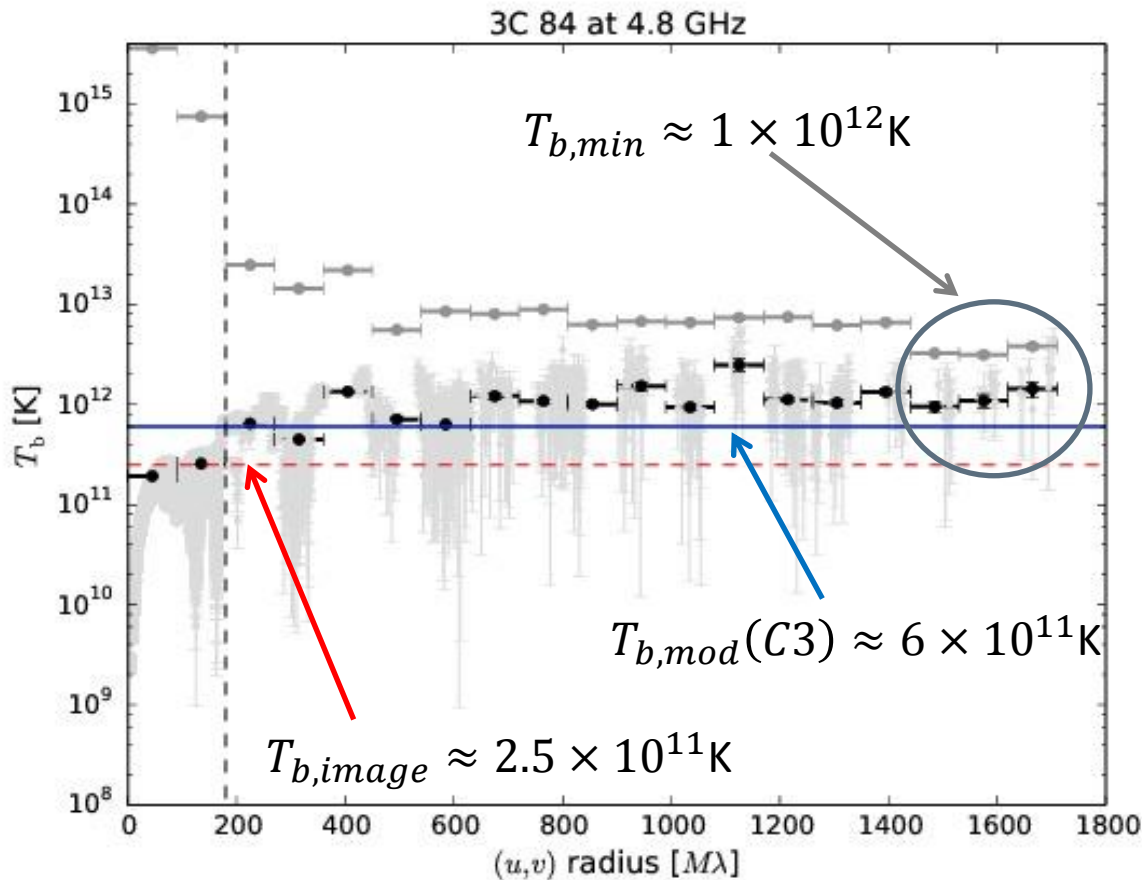
# 3C84

## Spectral index maps



# 3C84

## Brightness temperature at 5 GHz



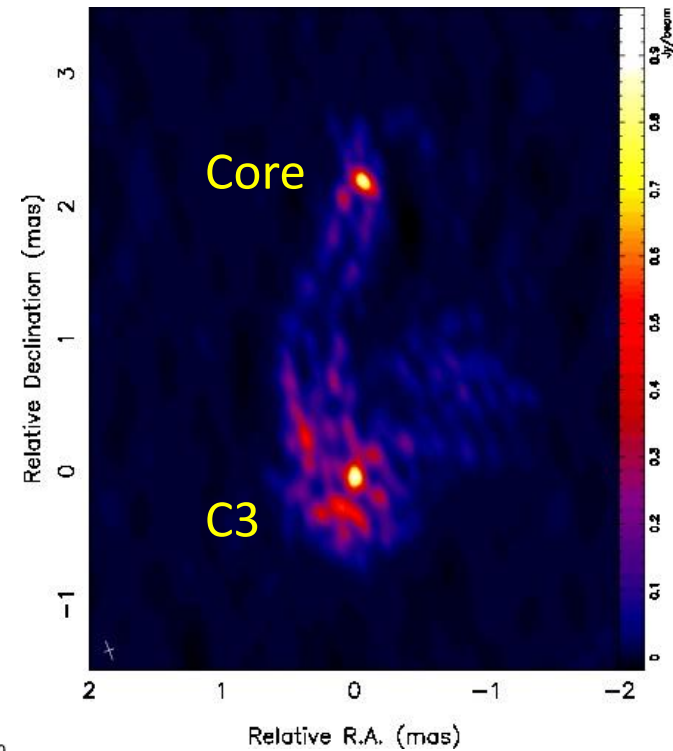
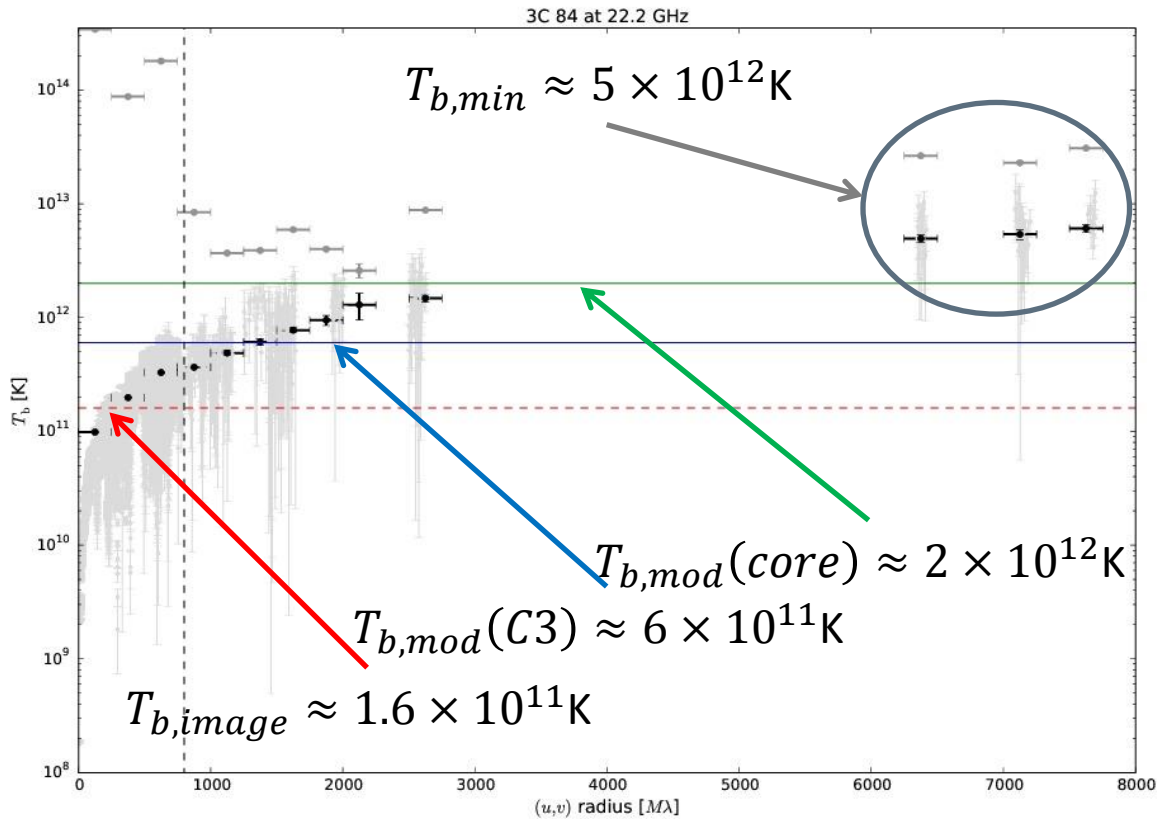
$T_{b,min}$  higher than  $T_{b,mod}$ :

- Geometry of C3?
- Substructure of C3?
- Highest  $T_b$  feature not C3?

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

# 3C84

## Brightness temperature at 22 GHz



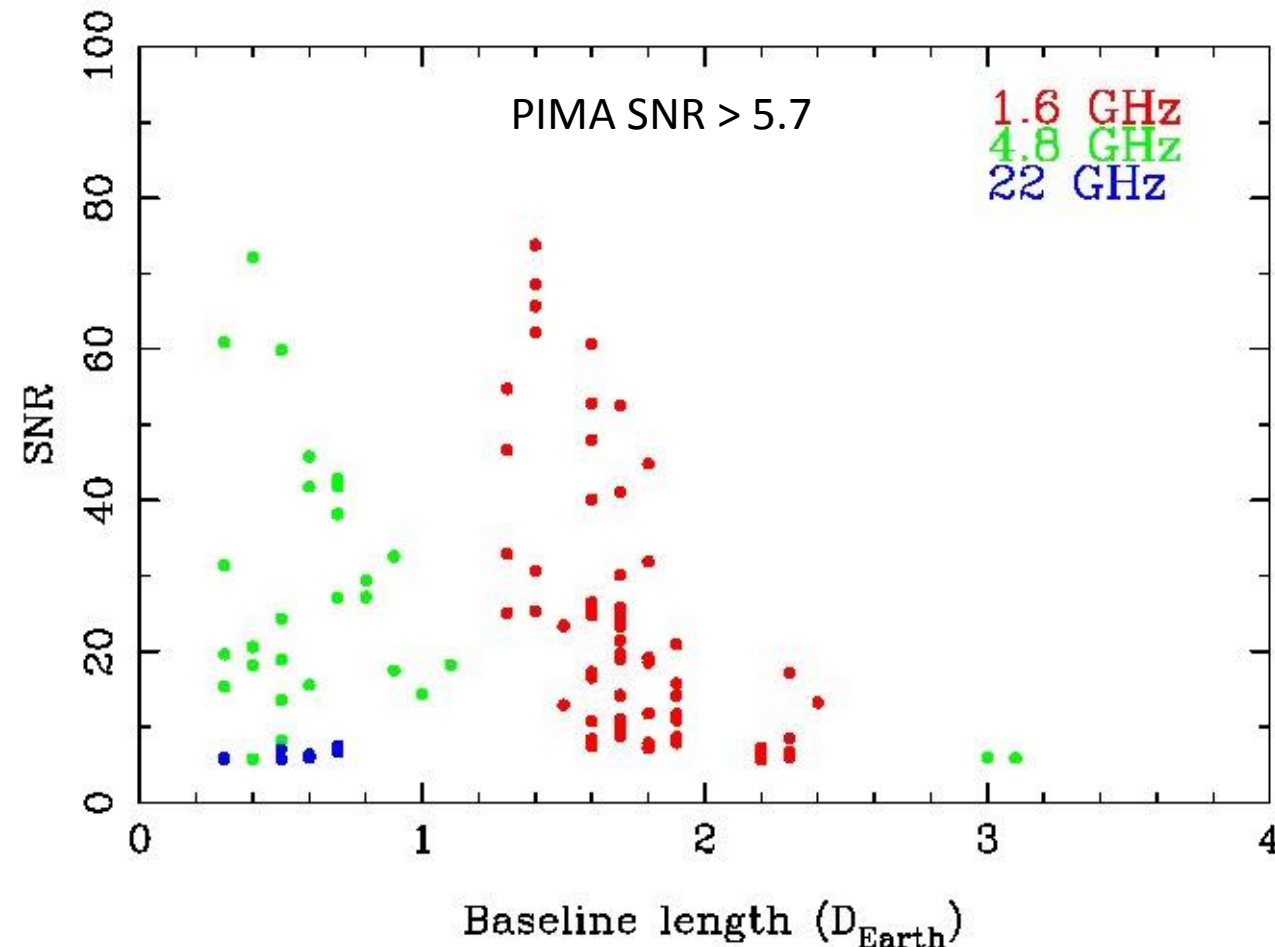
$T_{b,min}$  overestimated because of geometry?

**NEARBY AGN KSP RESULTS:  
M87 SPACE FRINGES DETECTED**

# M87

## Space fringes detected

RadioAstron fringes – M87



- Fringe detections up to **3.1 Earth diameter** baselines at 5 GHz with PIMA, corresponding to  $\sim 40R_s$  spatial scales
- Baseline stacking may yield more detections
- Imaging in progress
- Correlation of L-band data done with two phase centers: core and HST-1

# Summary

- 3C84, M87 and Cen A were observed within the RadioAstron Nearby AGN KSP at 1.6 (M87), 5 and 22GHz
- Fringes on space baselines have been detected so far for M87 (up to 3.1 ED baseline lengths) and 3C84 (up to 7.7 ED). No space fringes detected for Cen A.
- Space-VLBI images of 3C84 reveal a rich structure inside 1pc:
  - Edge-brightened jet between the core and the slowly moving feature C3
  - Hot spot in C3 behind the leading edge of the feature. The leading edge has a local increase in spectral index.
  - Core is resolved transverse to the flow direction at 22 GHz and exhibits very wide opening angle together with rapid collimation.
  - Edge-brightened emission seen upstream of the core
- Brightness temperatures close to IC limit measured for 3C84. This is surprising for a misaligned AGN.