Ultra-high Resolution Space-VLBI Imaging of Jets in Nearby AGN

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On behalf of the RadioAstron Nearby AGN Key Science Program team:

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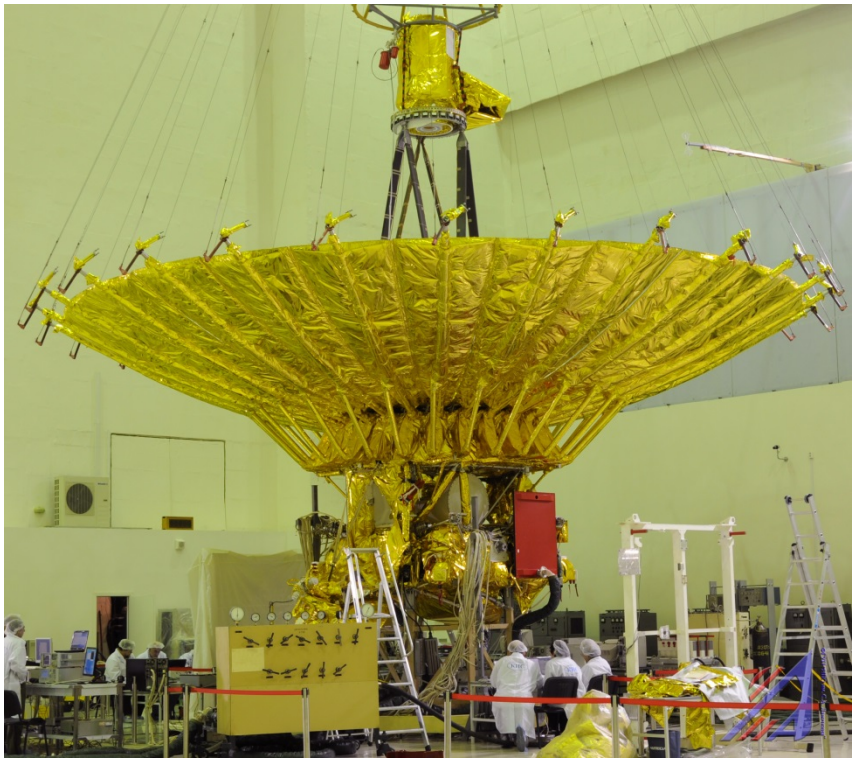
RadioAstron Space-VLBI Project



Kardashev+ 2013

- 10-m orbiting antenna
- Launched in July 2011
- Highly elliptical orbit: baselines from ~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: 7μas
- 32 MHz bandwidth, dual-pol.
- Project led by the Astro Space Center of Lebedev Physical Institute, Russia

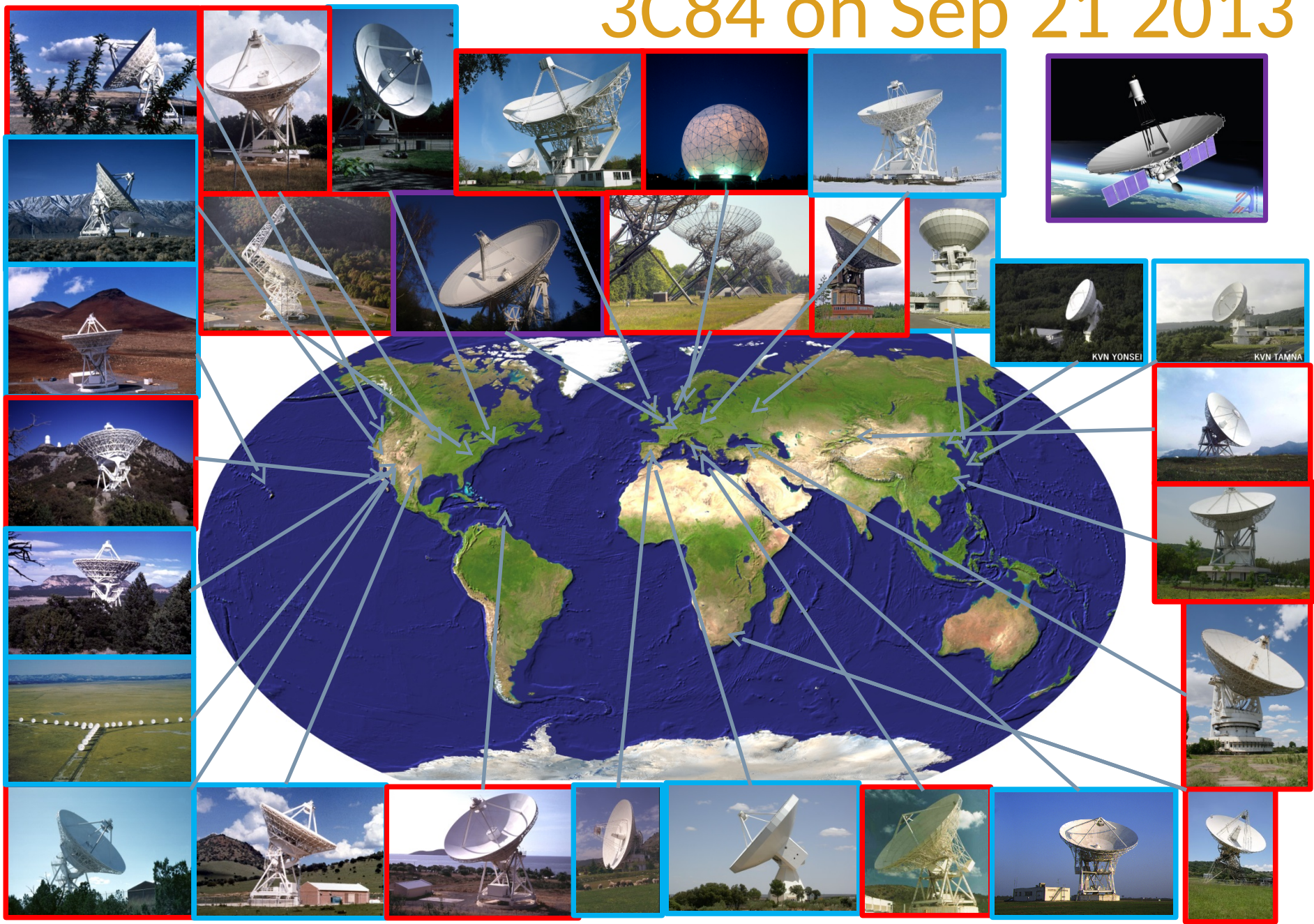
RadioAstron Nearby AGN Key Science Program

- Near-perigee imaging observations of nearby radio galaxies at 1.6, 5 and 22 GHz together with a global VLBI array (up to 33 ground radio telescopes). Target sources at distances of 4-75 Mpc → ultra-high spatial resolution (down to a few R_S) for studying the jet structure:
  - Centaurus A (D=3.8 Mpc)
    - Observed 2x in 2014 at 5 and 22 GHz
    - 1 mas = 0.018 pc = 3000 R_S ($M_{BH} = 6 \times 10^7 M_{Sol}$)
    - Max baseline ($6D_{Earth}$): 500R_S @ 5 GHz and 100R_S @ 22GHz
  - M87 (D=16 Mpc)
    - Observed 2x in 2014: 5/22 GHz and 1.6 GHz
    - 1 mas = 0.078pc ~ 140R_S ($M_{BH} = 6 \times 10^9 M_{Sol}$)
    - Max baseline (11 D_{Earth}): 12R_S @ 5GHz; 3R_S @ 22GHz
  - 3C84 (D=75 Mpc)
    - Observed 1x in 2013 at 5/22 GHz
    - 1 mas = 0.35 pc = 6000 R_S ($M_{BH} = 8 \times 10^8 M_{Sol}$)
    - Max baseline (10 D_{Earth}): 600R_S @ 5GHz; 130R_S @ 22GHz

First results:
Space-vlbi imageS of 3C84

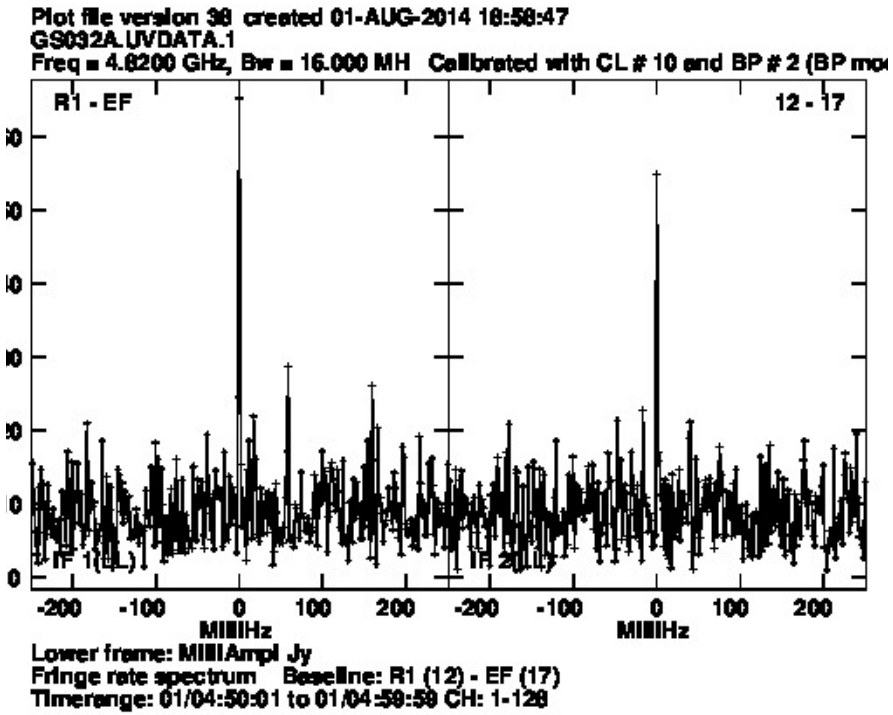
5 GHz 22 GHz 5/22 GHz

3C84 on Sep 21 2013



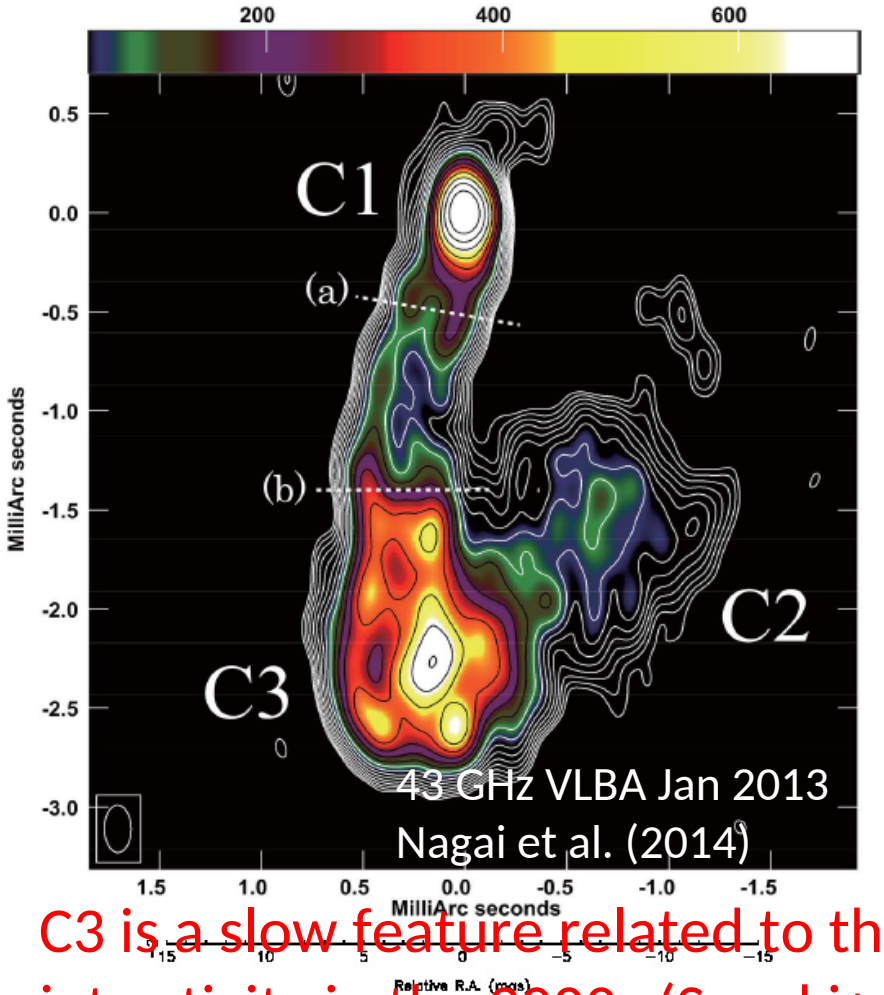
3C84 RadioAstron observations on Sep 21 2013 (5/22 GHz)

- Data correlated with a modified DiFX at the MPIfR (Bruni+ 2015)
- Fringes to RadioAstron detected:
  - 5 GHz: 0.2 - 6.9 Earth diam. (ED)
  - $V_{5GHz}(6.9ED) = 60 \pm 8$ mJy, and using Lobanov (2015):
    - $T_{b,min}(5GHz) = 1 \times 10^{12}$ K
    - $T_{b,lim}(5GHz) = 5 \times 10^{12}$ K
  - 22 GHz: 0.2 – 7.6 ED
  - $V_{22GHz}(7.6ED) = 160 \pm 50$ mJy
    - $T_{b,min}(22GHz) = 3 \times 10^{12}$ K
    - $T_{b,lim}(22GHz) = 7 \times 10^{12}$ K
  - Misaligned jet → at most only modest Doppler boosting → the RA detections may indicate T_b at the IC limit. Where does this emission come from?

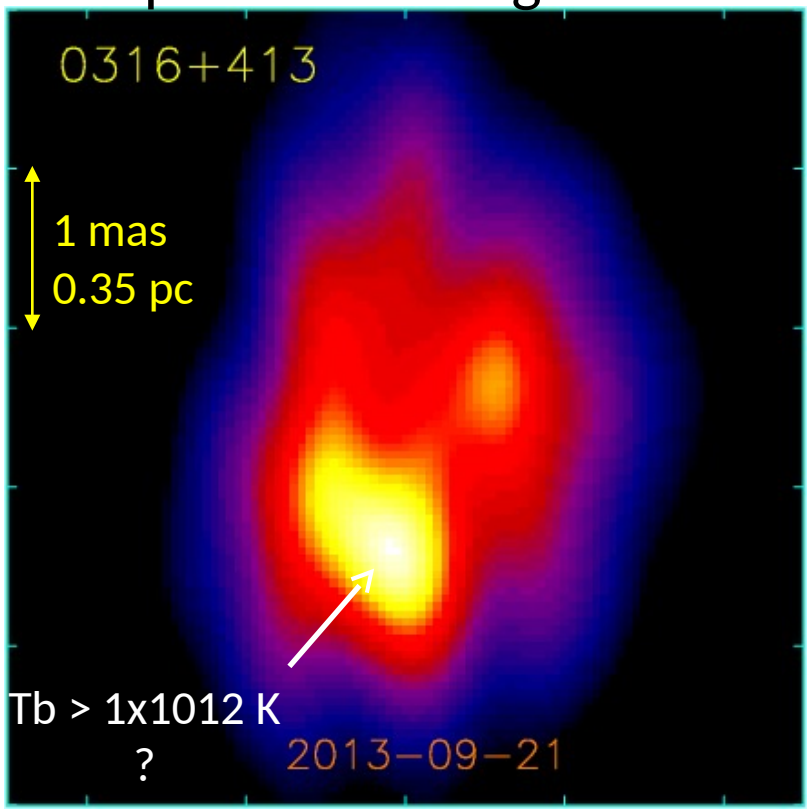


5 GHz fringe on RA-EF baseline
6.9ED (1.4Gλ) SNR = 8.6

3C84
5 GHz RadioAstron image



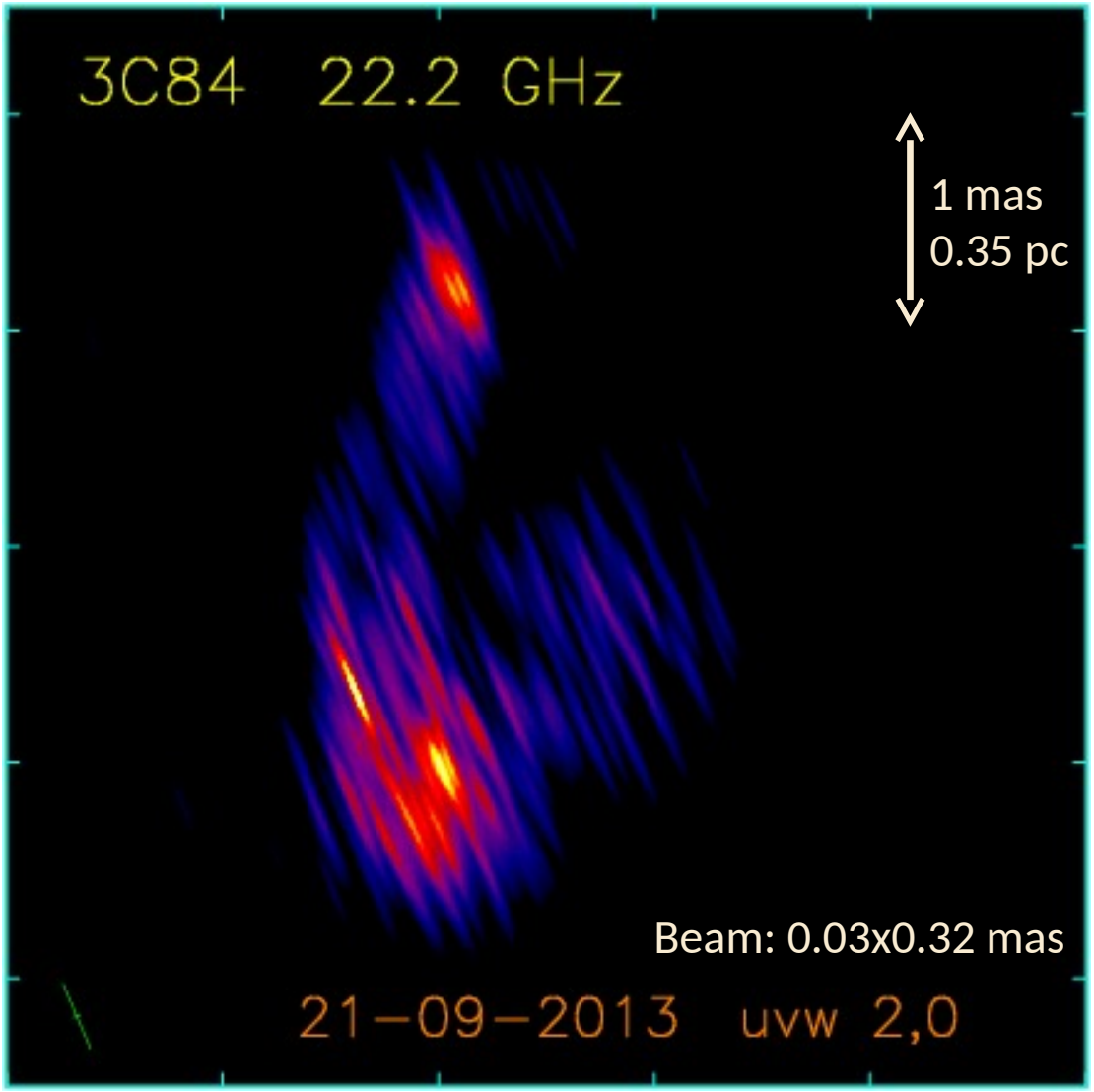
Space-VLBI image 5GHz



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

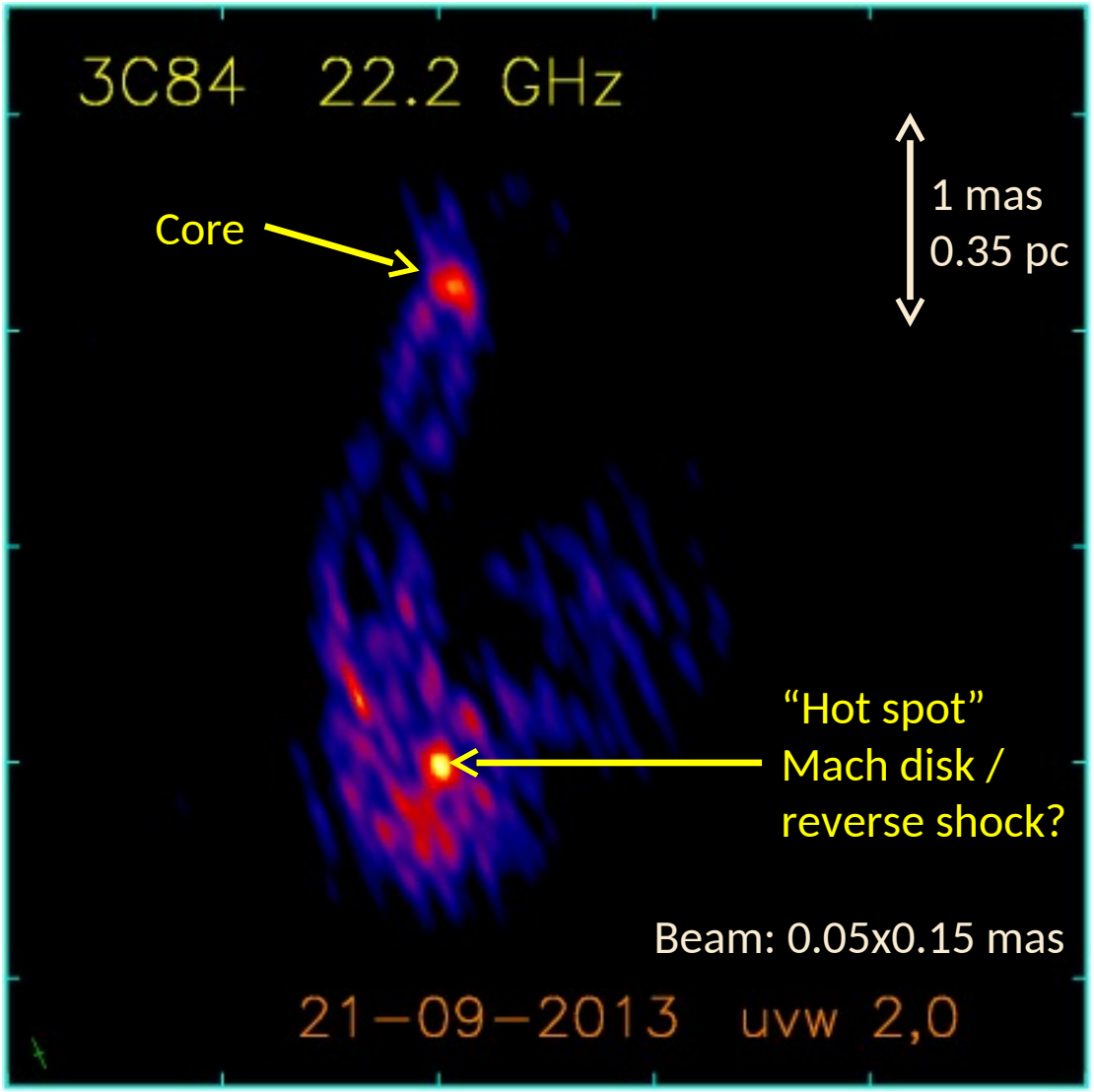
(u,v) range 0-700Mλ
Beam: 0.9x0.5mas

3C84
22 GHz RadioAstron image



Full resolution

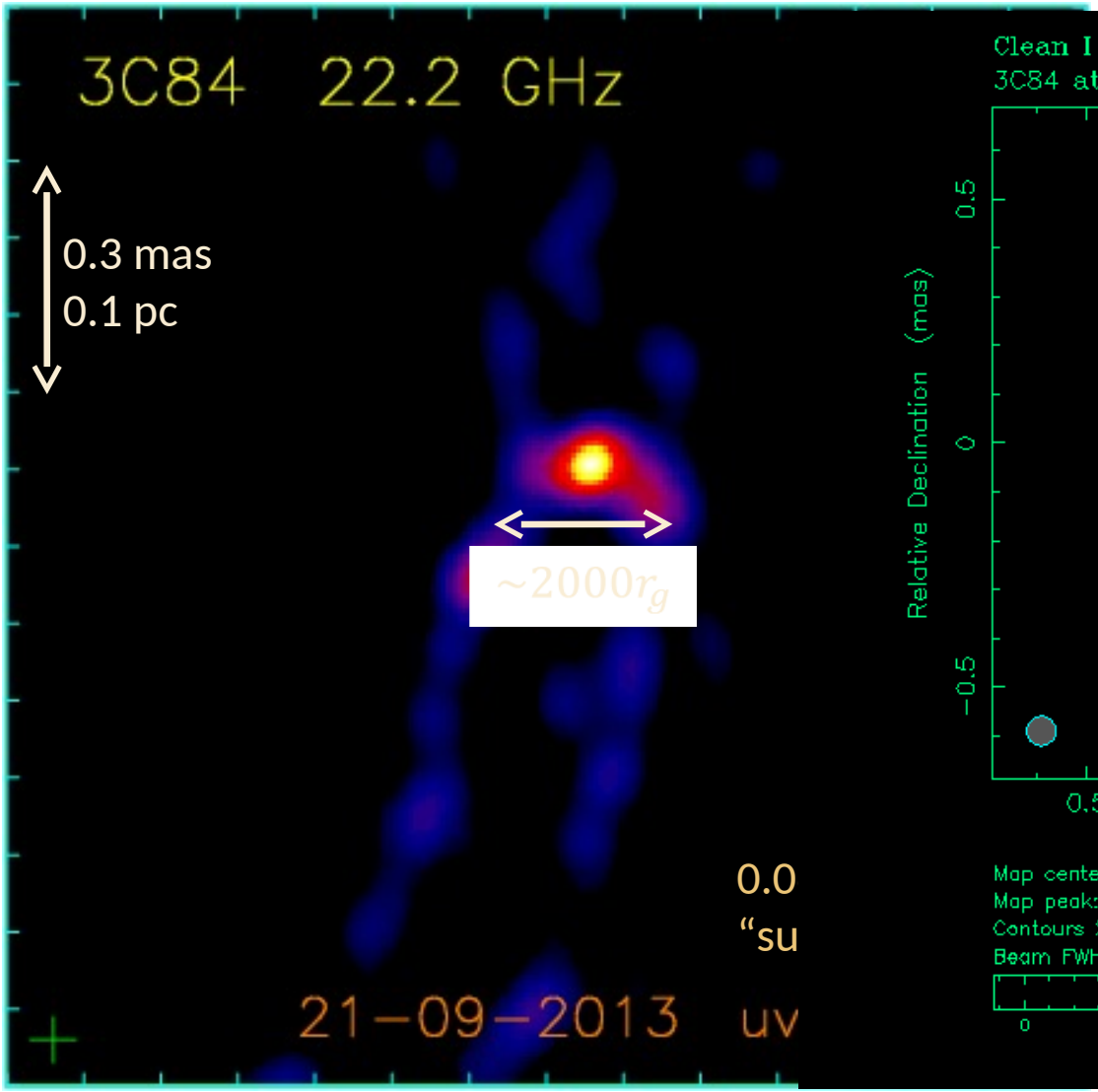
3C84
22 GHz RadioAstron image

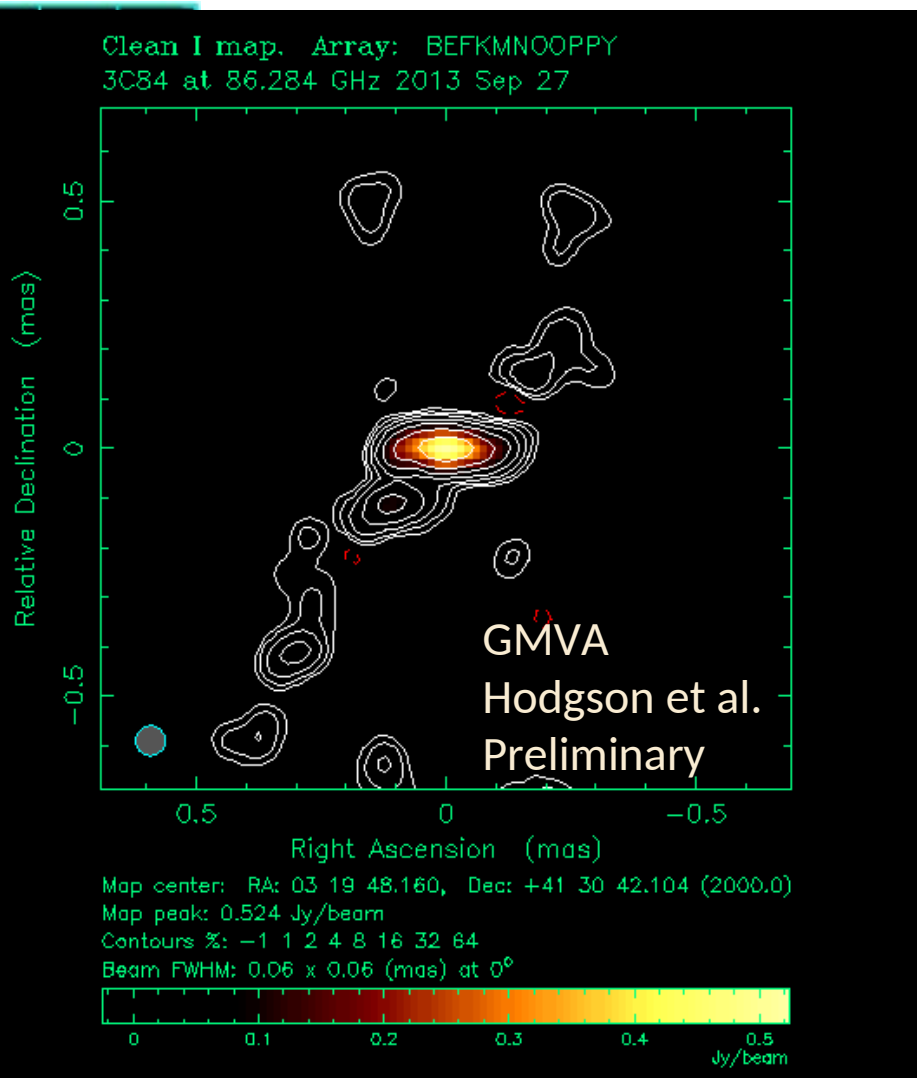


Slightly super-resolved in one direction

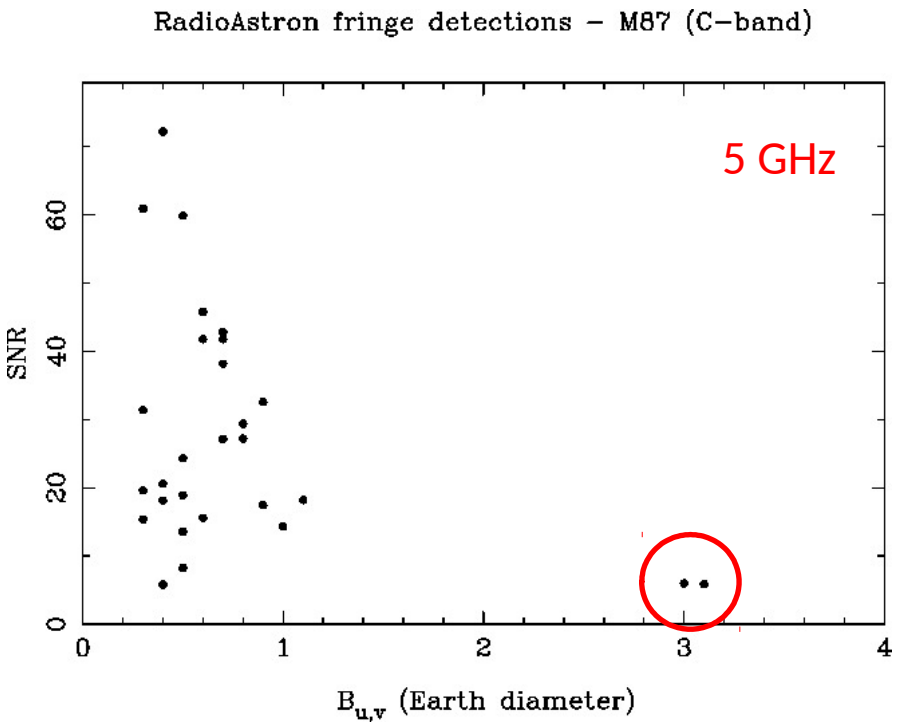
- Clearly edge-brightened jet
- Hot spot inside the moving feature C3 – the structure resembles that commonly seen in simulations of a working surface between jet and ambient medium

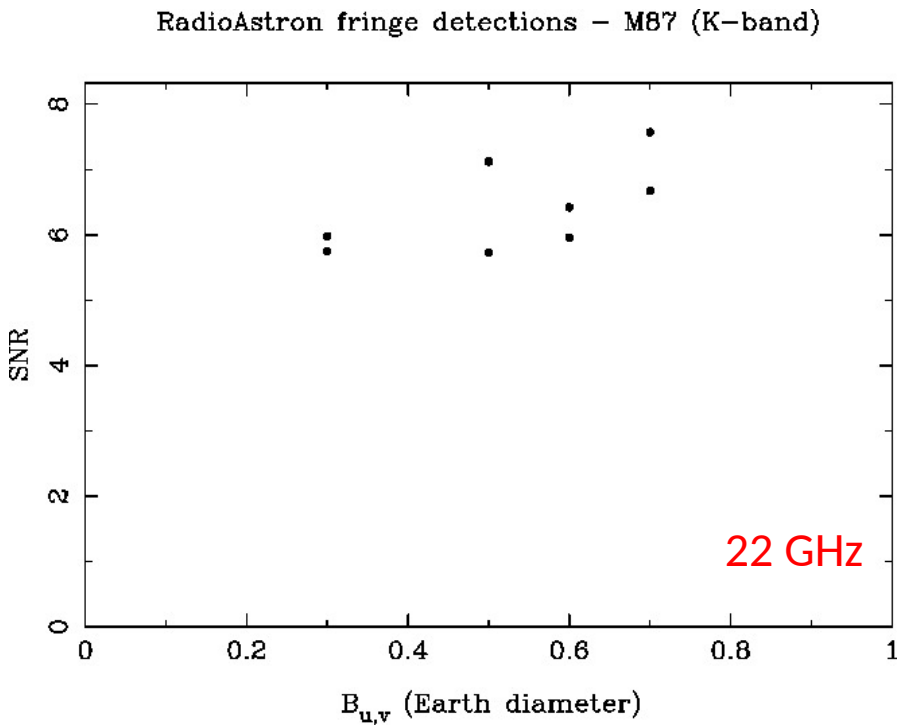
3C84 core structure





More early results: M87 space fringes detected





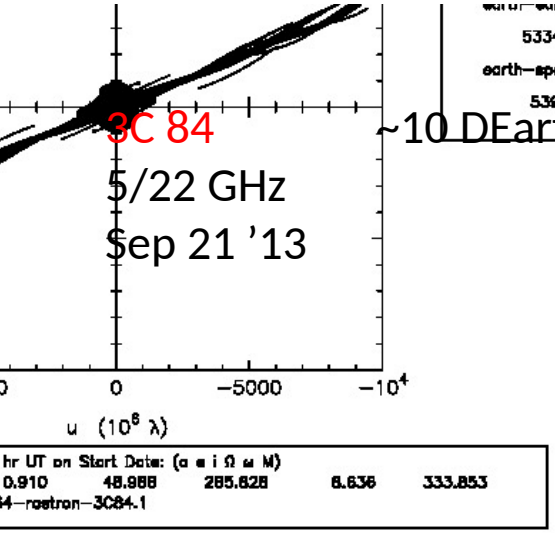
- Mostly no detections on baselines longer than Earth diameter ⇒ no ultra-compact structure brighter than RA detection limit
- Baseline stacking could yield a few more detections, though
- Imaging in progress

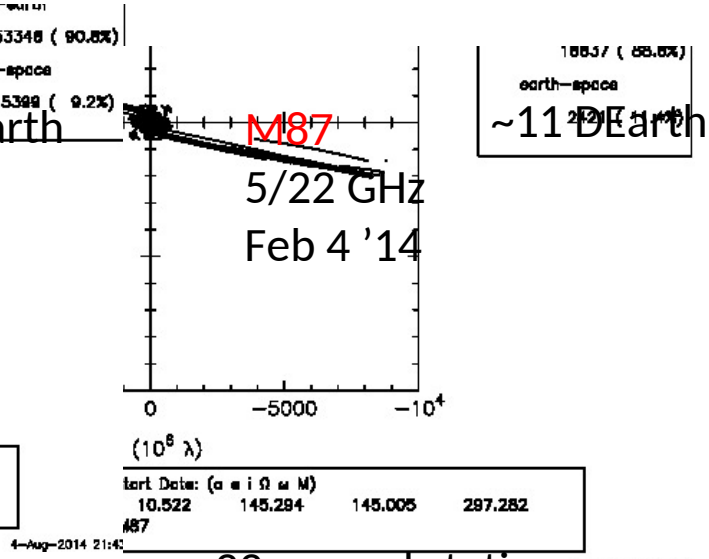
Summary

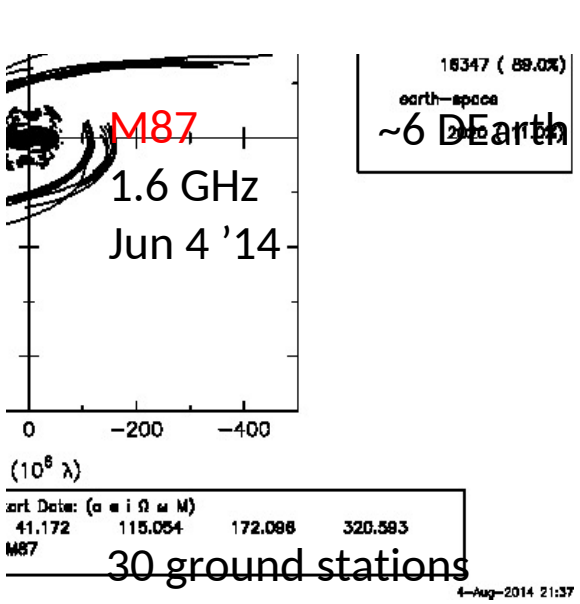
- 3C84, M87 and Cen A were observed within the RadioAstron Nearby AGN KSP at 1.6 (M87), 5 and 22GHz
- Fringes on space baselines have been detected so far on M87 (up to 3 ED baseline lengths) and 3C84 (up to 7.6 ED)
- 3C84 fringe detections suggest $10^{12} < T_b < 7 \times 10^{12}$K → since little Doppler boosting is expected for 3C84, this may indicate emission at the IC limit from the most compact part of the source
- Space-VLBI images of 3C84 reveal a rich structure inside 1pc:
  - Edge-brightened jet between the core and the moving feature C3
  - Hot spot in C3 behind the leading edge of the feature
  - Core is resolved transverse to the flow direction at 22 GHz
  - Edge-brightened emission seen upstream of the core
  - What is the core? A re-collimation shock? The jet base?

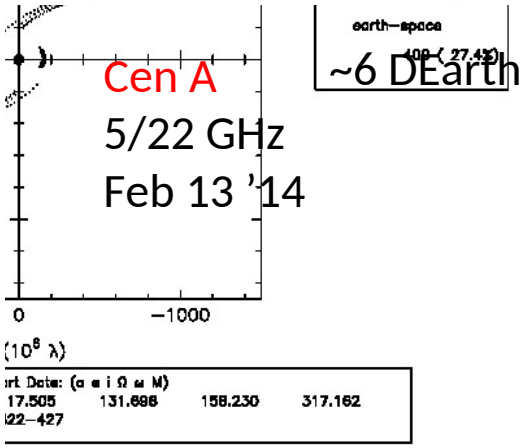
Backup slides

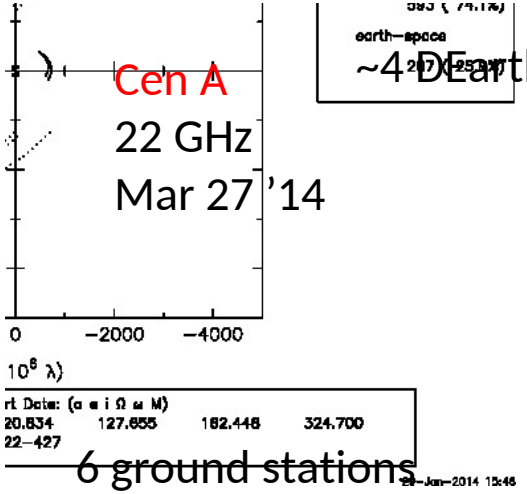
Nearby AGN KSP observations in AO-1



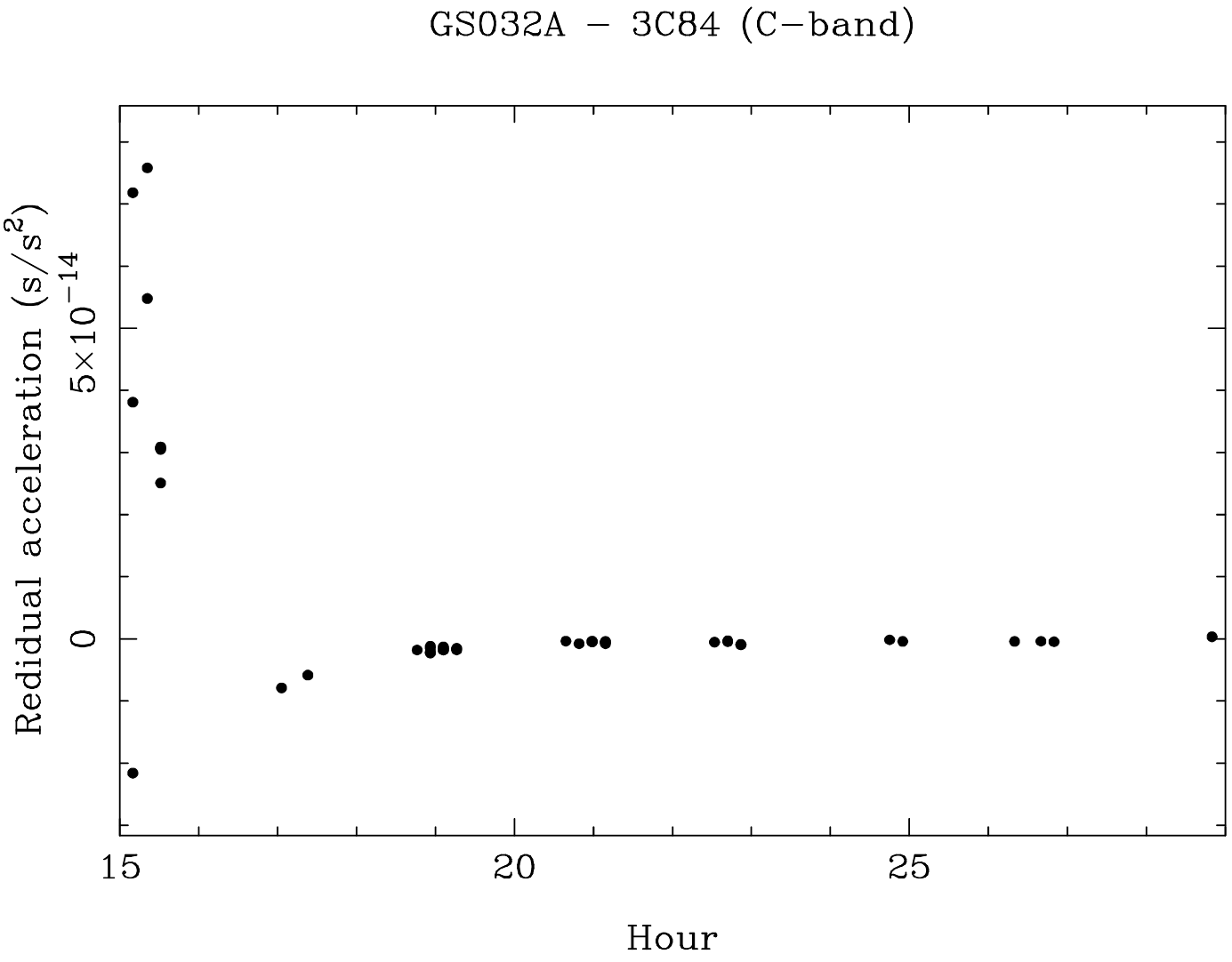




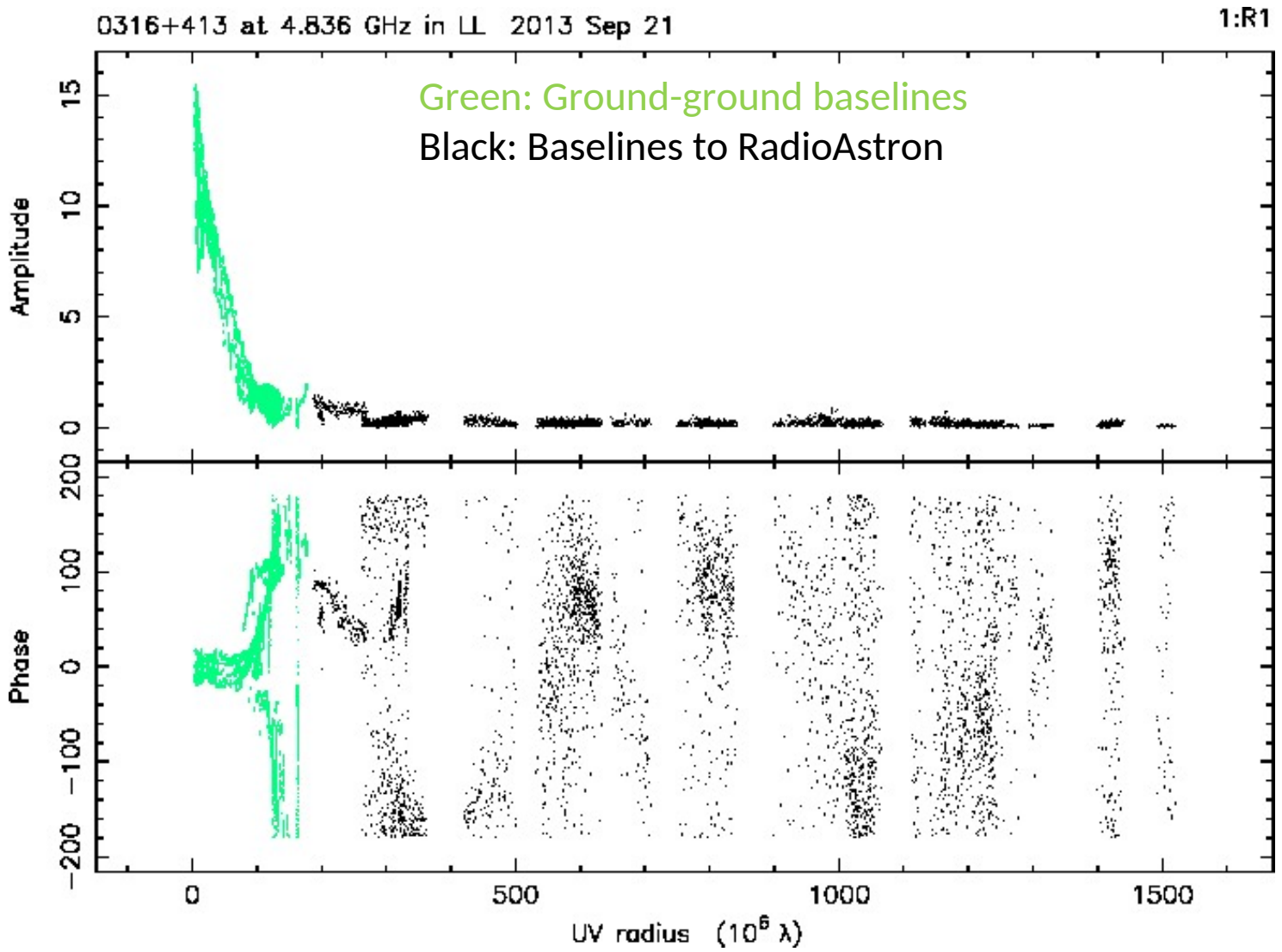




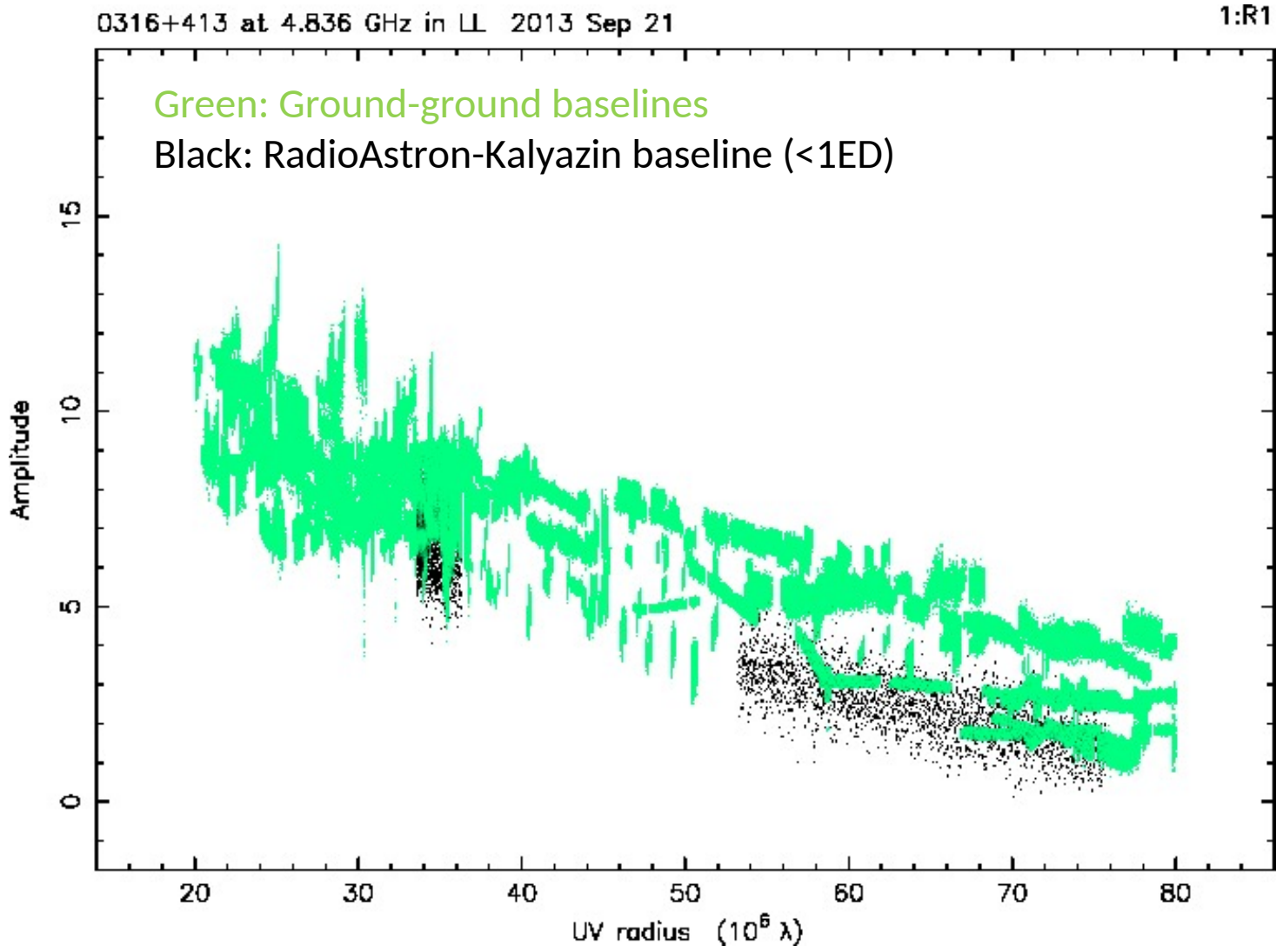
Residual acceleration of the RadioAstron



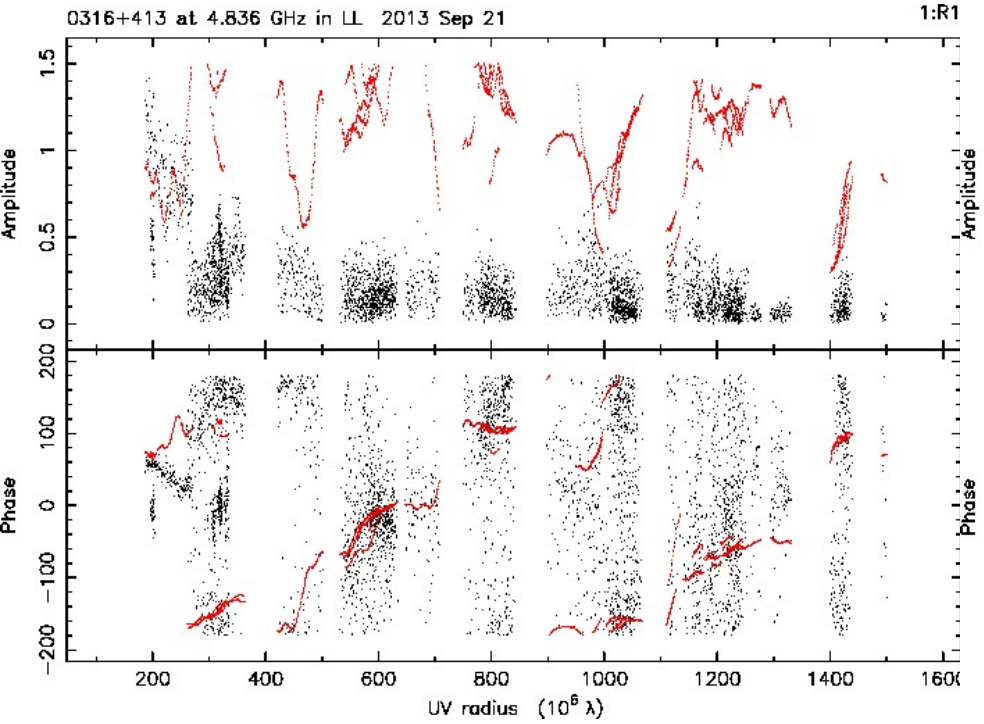
3C84 at 5GHz
RadioAstron visibilities



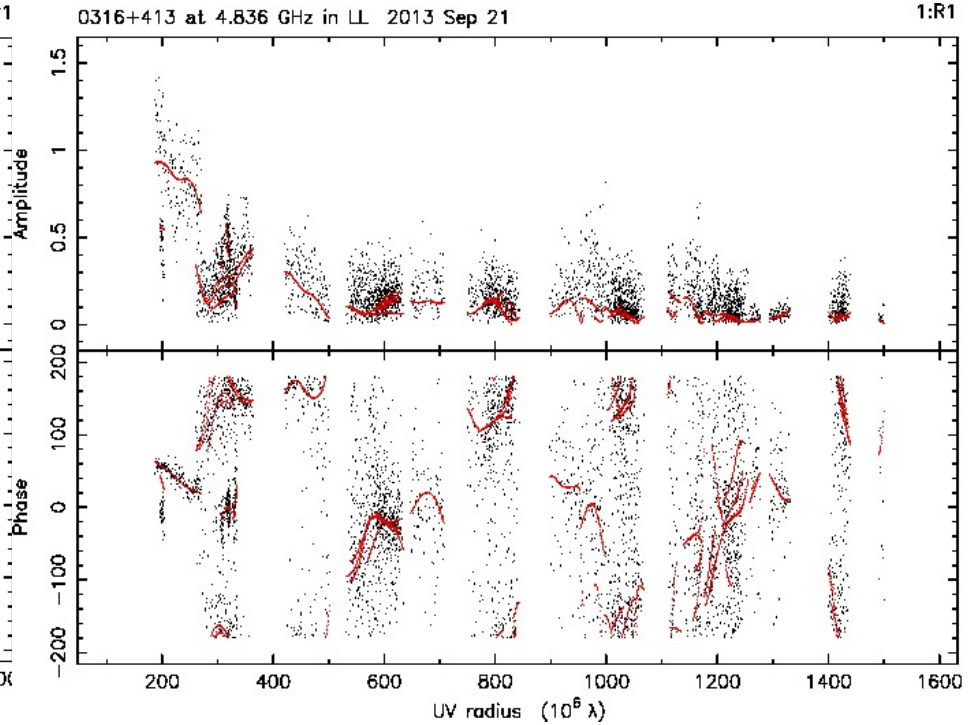
3C84 at 5GHz
- calibration accuracy of the SRT



3C84 at 5GHz with space baselines

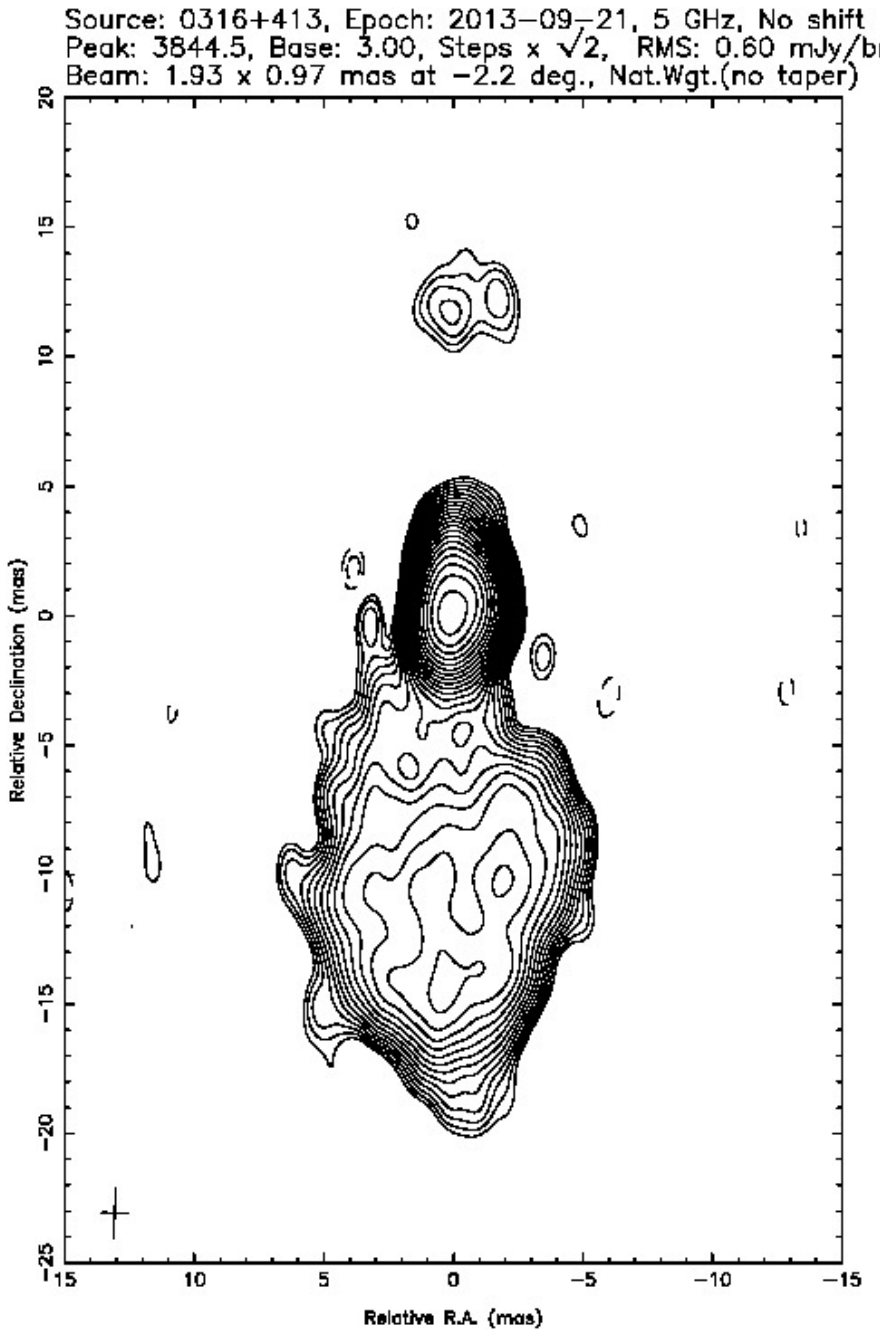


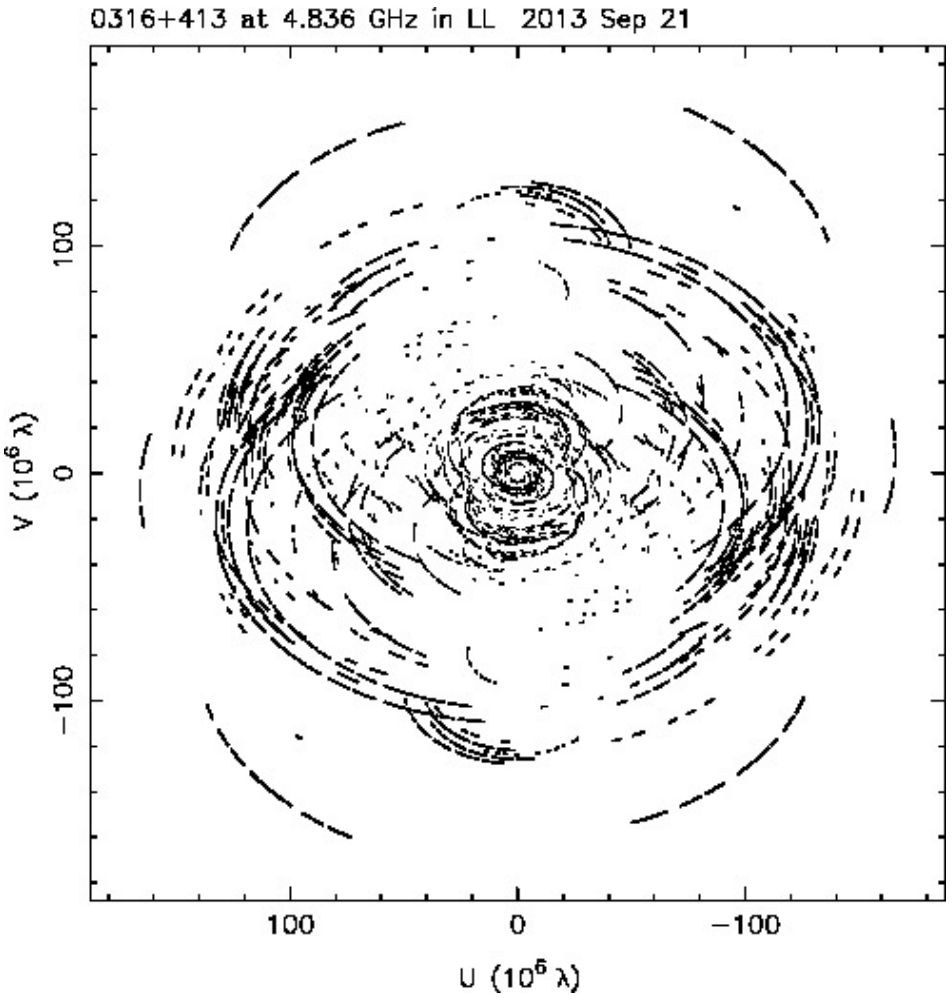
RA data and ground-only model



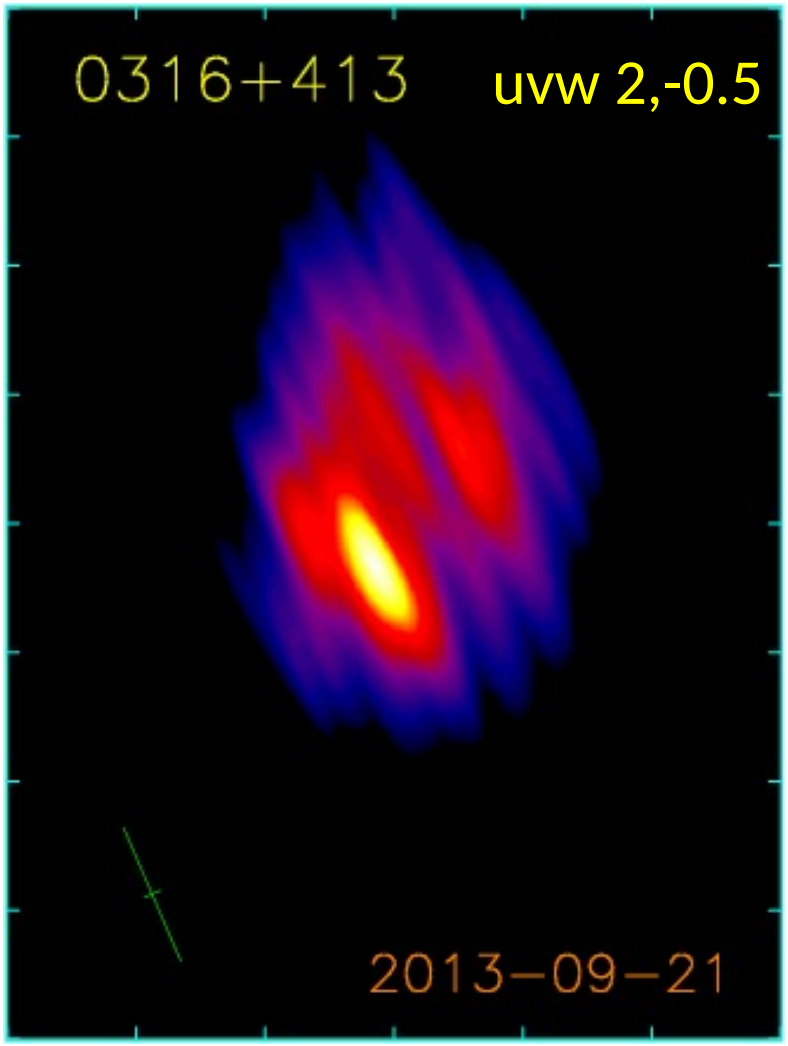
RA data and ground+space model

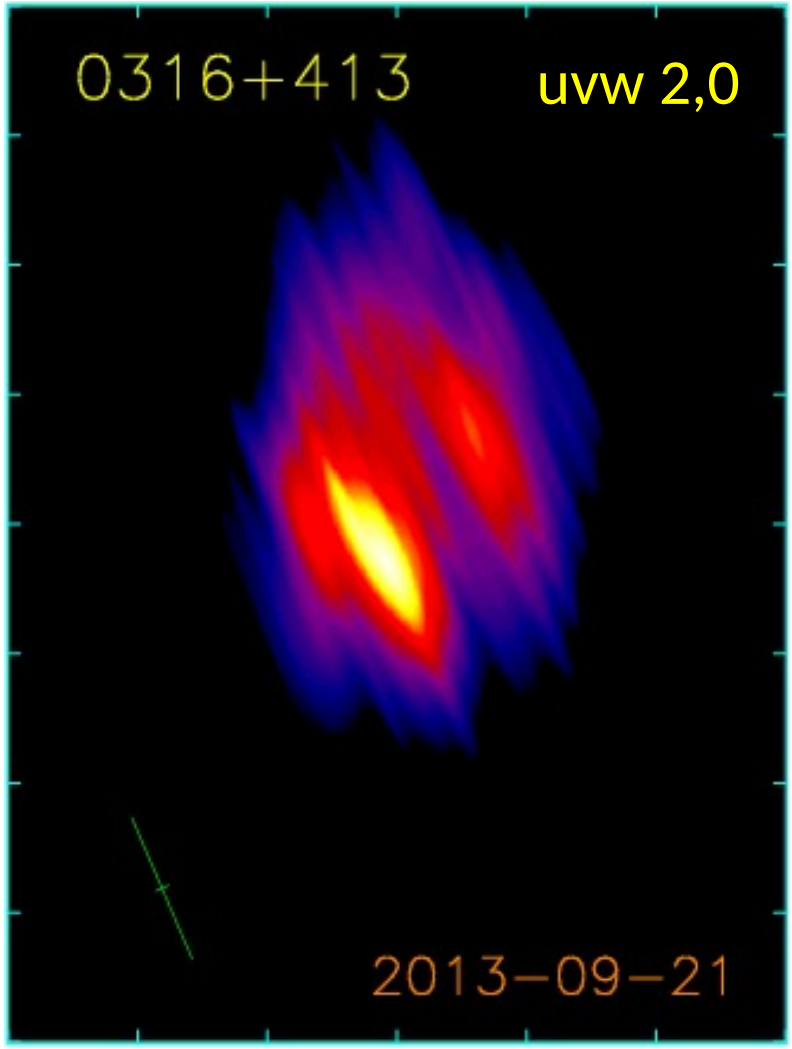
3C84 at 5GHz ground-only image



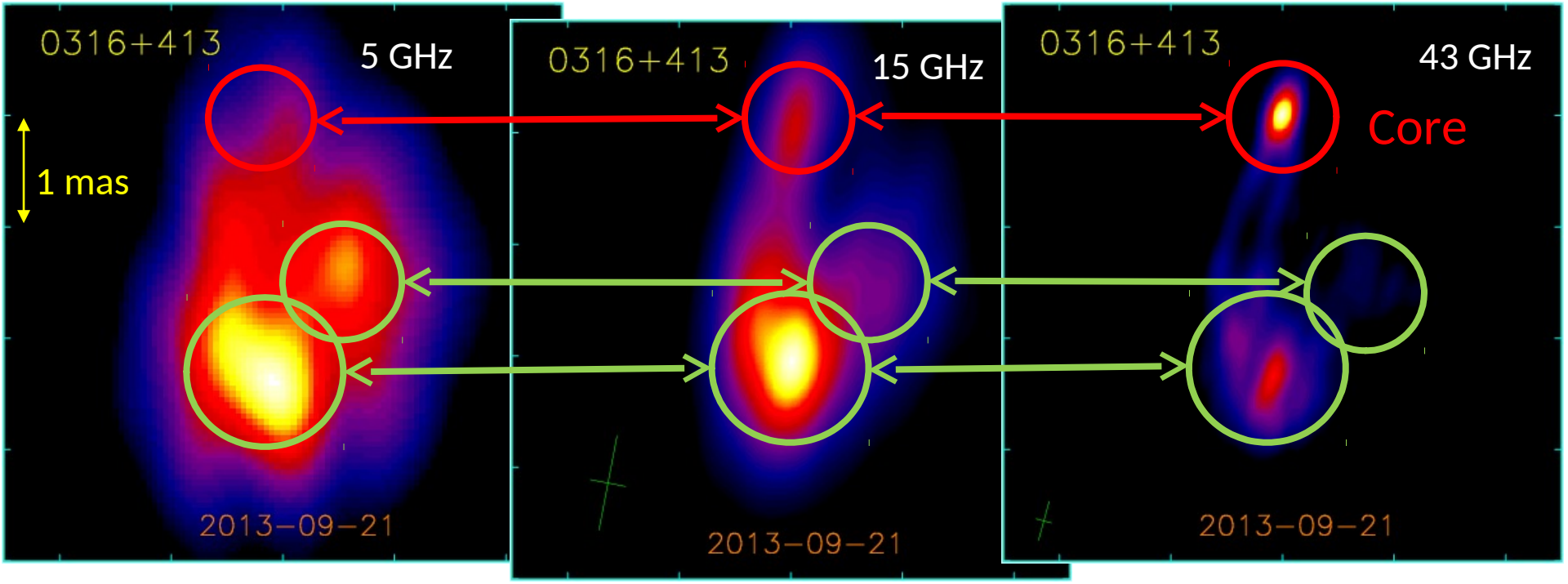


3C 84 at 5GHz – Full resolution





3C84 - Other frequencies

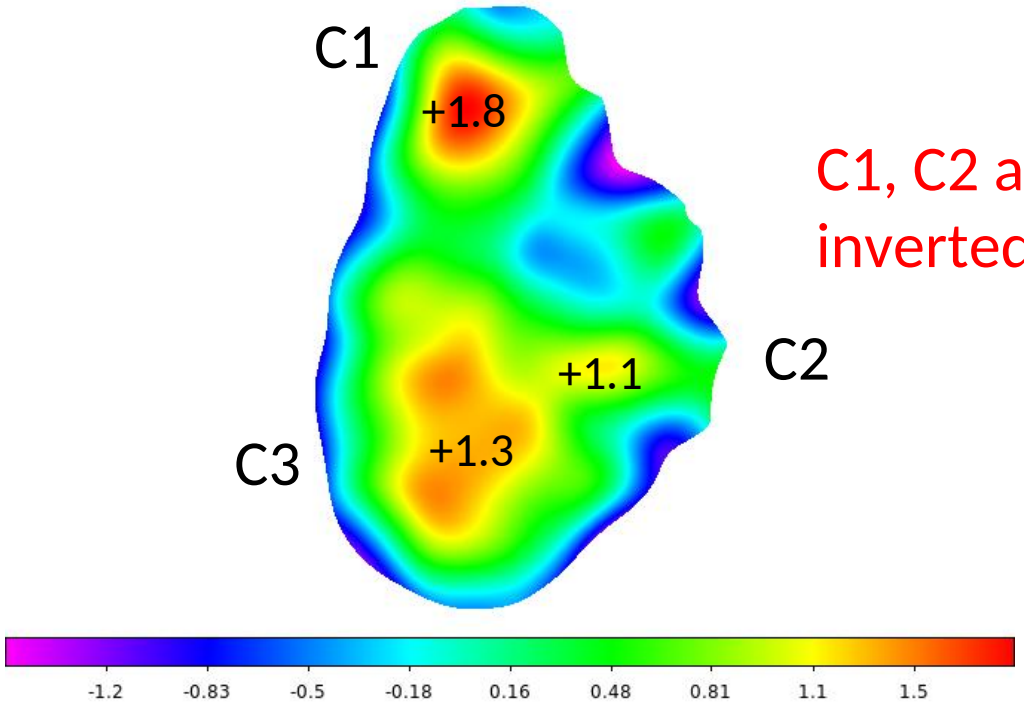


Peak: 1.5 Jy/beam
beam 0.9x0.5mas

Peak: 5.3 Jy/beam
beam 0.8x0.3mas

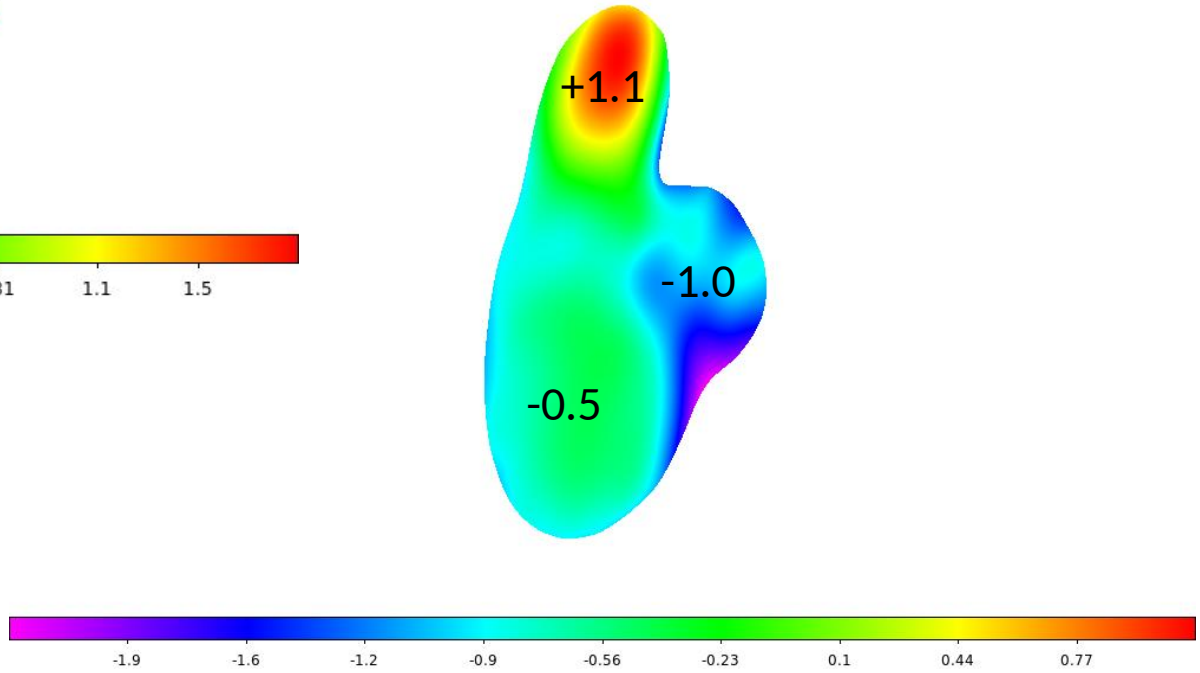
Peak: 2.5 Jy/beam
beam 0.4x0.15mas

3C84 - Spectra



5-15 GHz spectral index

C1, C2 and C3 ALL have inverted spectrum at 5GHz



15-43 GHz spectral index