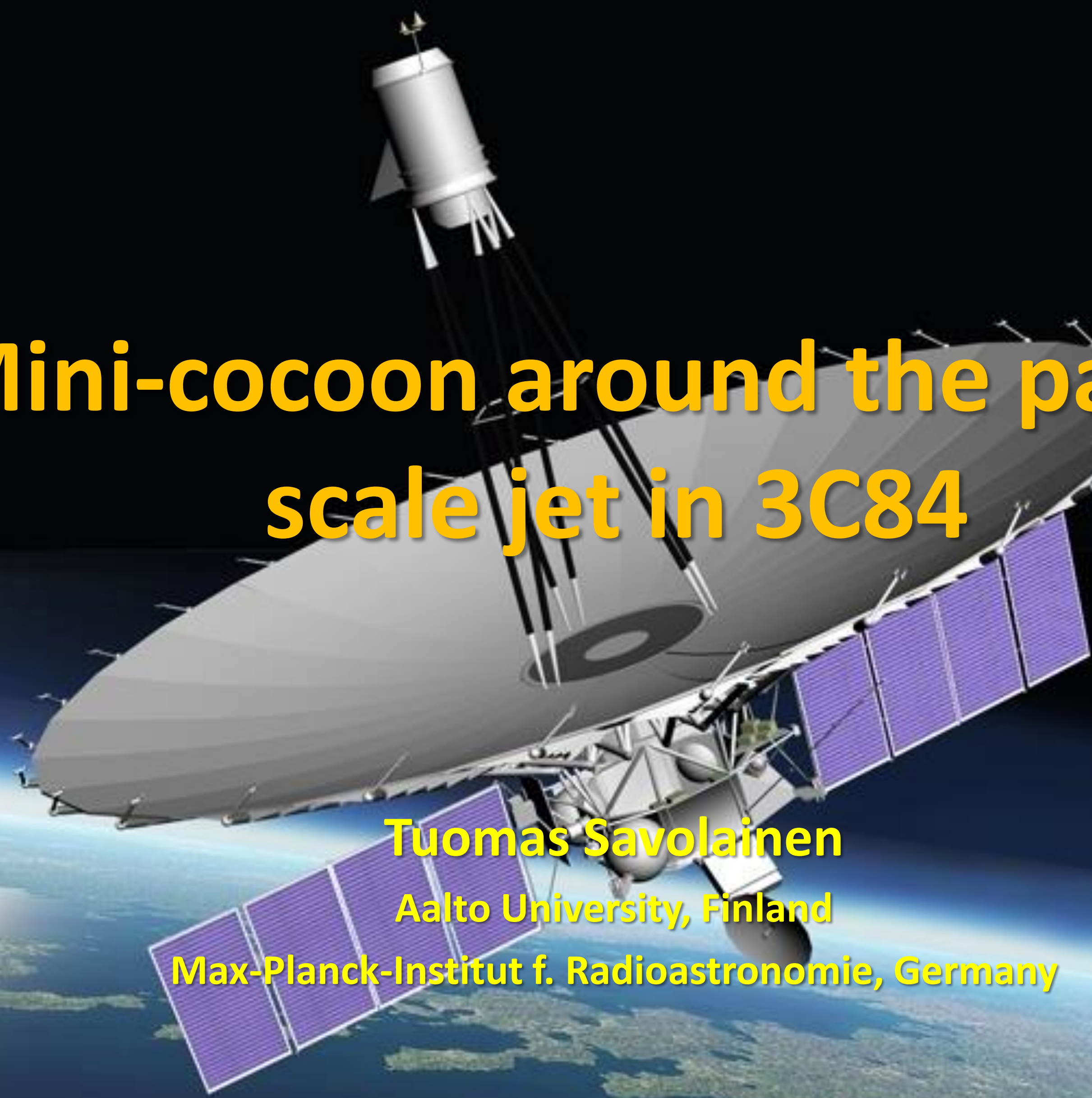

Mini-cocoon around the parsec scale jet in 3C84

Tuomas Savolainen

Aalto University, Finland

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RadioAstron Nearby AGN Key Science Program team

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- *K.Hada, M.Kino, H.Nagai, M.Honma (NAOJ, Japan)*
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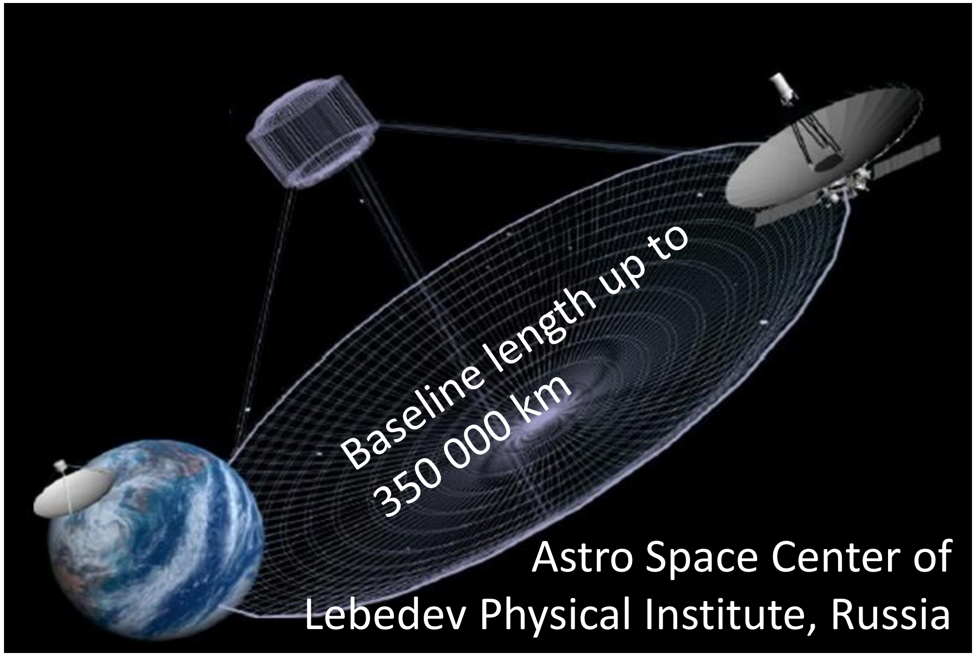
- *L.Petrov (AstroGeo Center, USA), J.Anderson (GFZ Potsdam, Germany)*
- *M.Nakamura (ASIAA, Taiwan)*

RadioAstron Space-VLBI mission



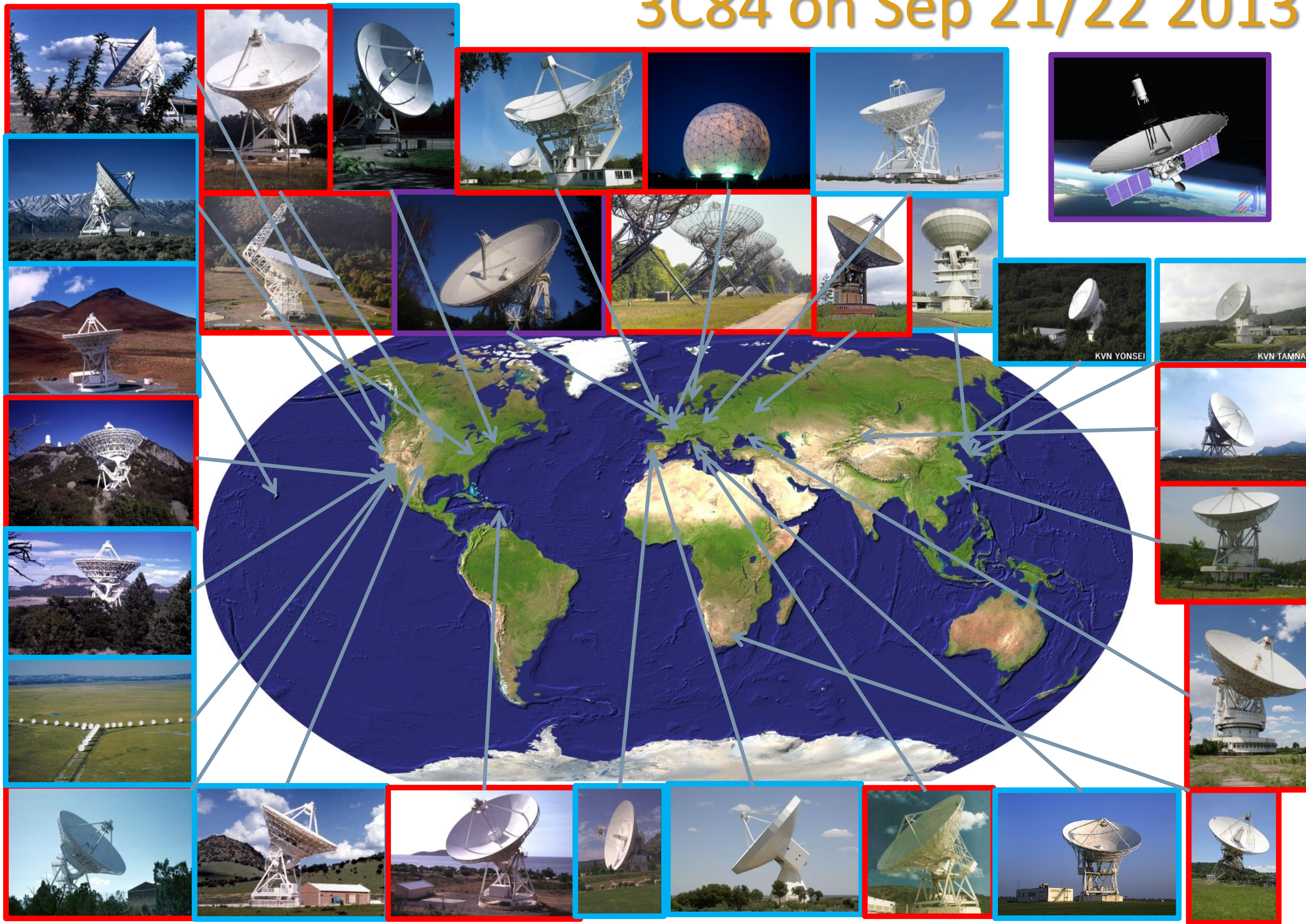
- 10-m Russian space radio telescope launched in 2011
- Apogee height: 350 000 km
- Obs. frequencies: 1.6–22 GHz
- Used together with ground radio telescopes as an interferometer
- Record angular resolutions: 8μas (H_20 megamaser in NGC4258, Maser KSP) and 12μas (quasar 3C279; TS+ in prep.)

RadioAstron Nearby AGN Key Science Program

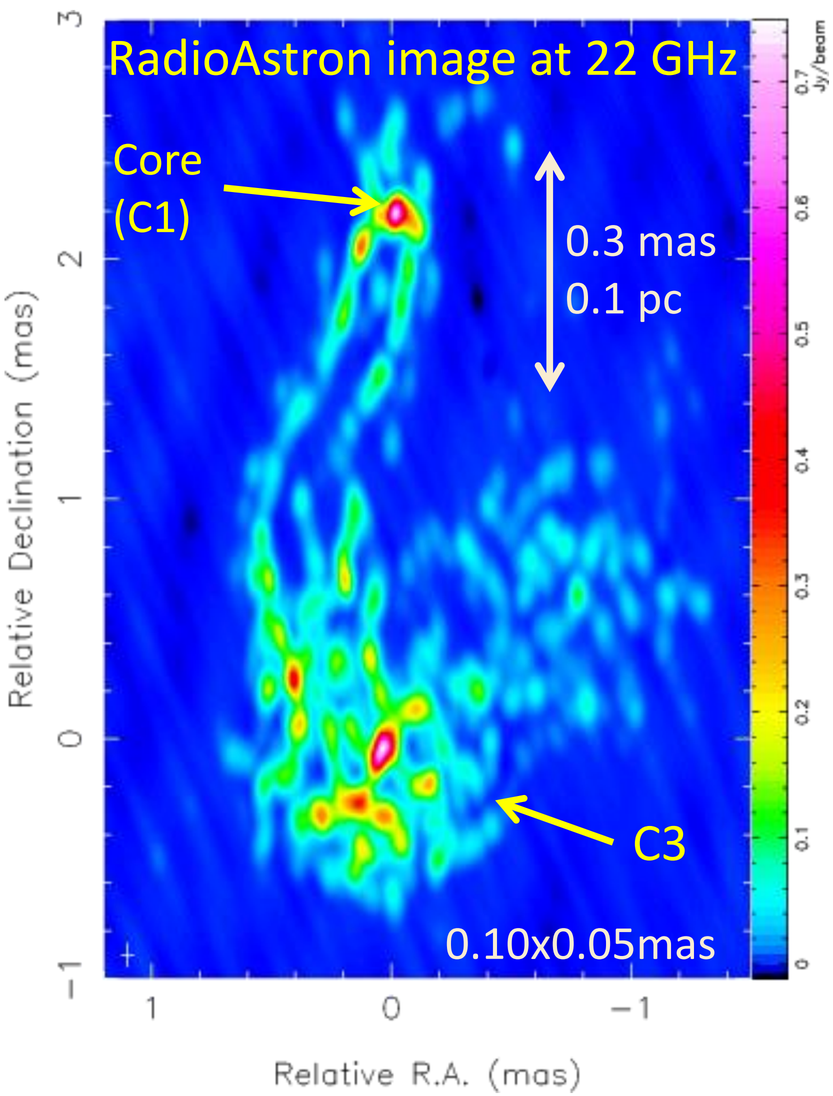
- Near-perigee space-VLBI imaging of nearby radio galaxies
- Aims at high spatial resolution (down to a few r_S) for studying the jet acceleration and collimation zone
- Targets: **Cen A** (*D=3.8Mpc, 1mas=3100*r_S), **M87** (*D=16Mpc, 1mas=140*r_S), **3C84** (*D=75Mpc, 1mas=1800*r_S)

3C84 on Sep 21/22 2013

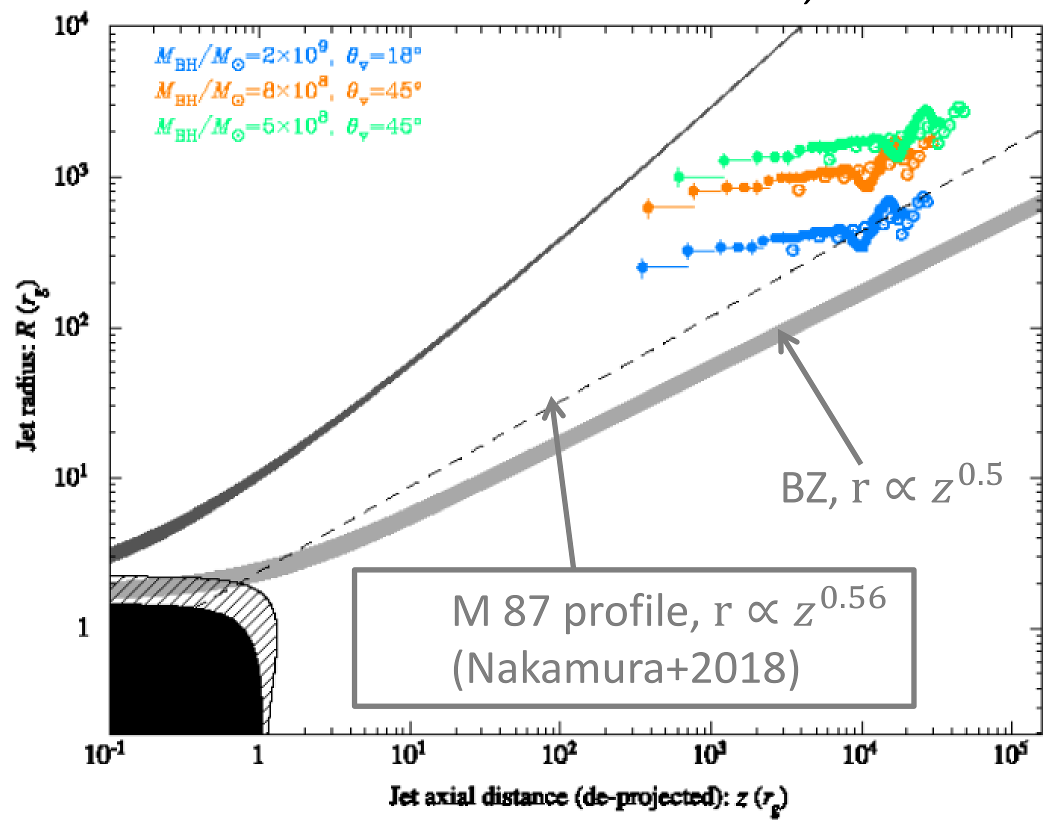
5GHz 22GHz 5/22GHz



Collimation profile of the inner jet in 3C84



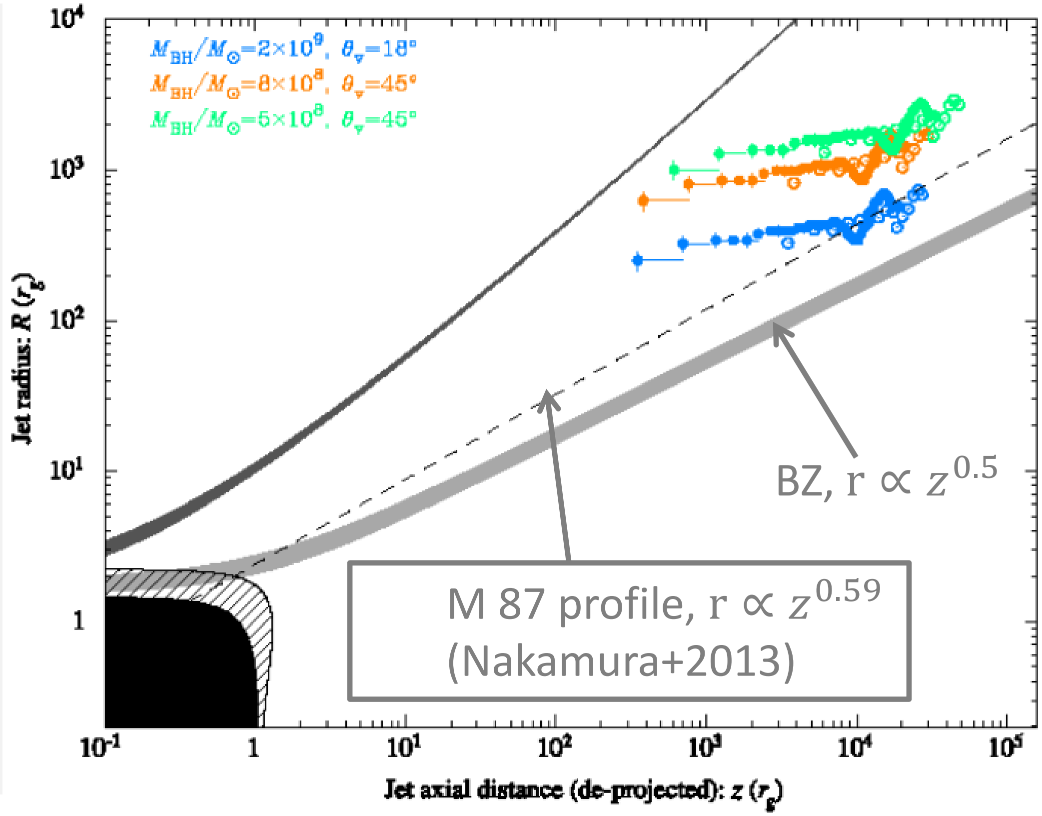
Giovannini, TS+ 2018



Collimation profile of the inner jet in 3C84

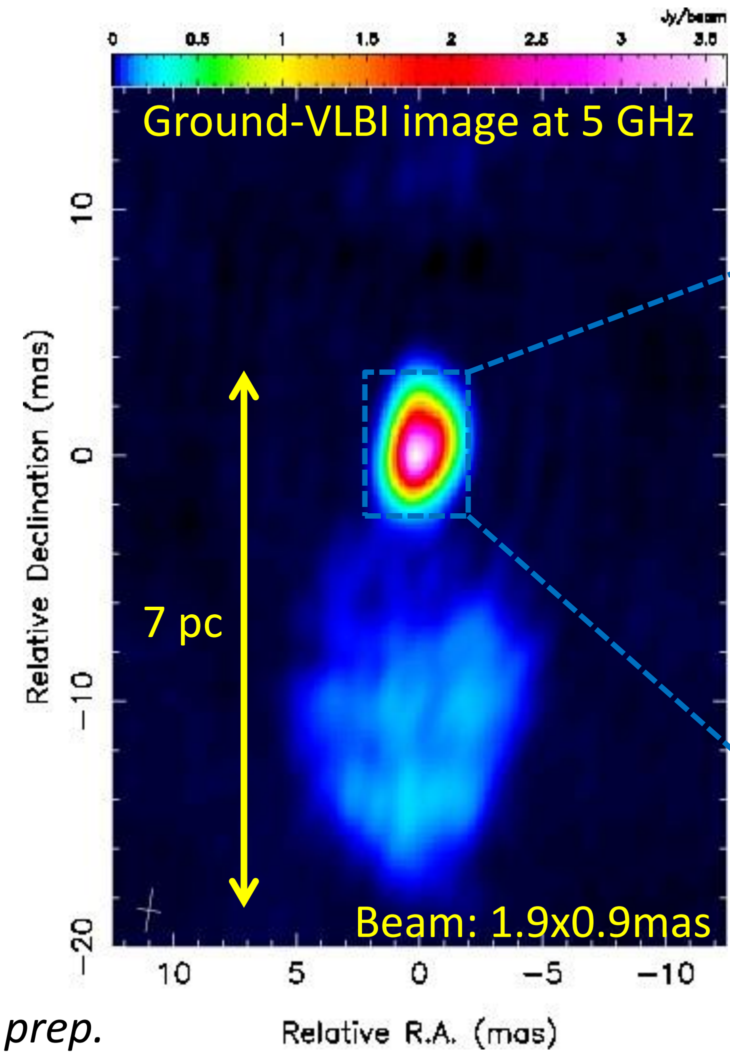
- Almost cylindrical flow with $r \propto z^{0.17}$ + oscillations of jet width. Shaped by external medium?
- If $p_{ext} \propto z^{-b}$=> $r \propto z^{b/4}$. For 3C84 $b \lesssim 1$ and $\rho \propto z^{-(b-1)} \approx z^0$. Flat density profile up to $\sim 10^4 r_g \sim 0.8$ pc.
- What kind of medium?
  - Gas in nearly free fall (e.g., Bondi) has $\rho \propto z^{-3/2}$. Excluded.
  - Inner edge of a thick disk or torus? Unlikely.
  - Hot cocoon of shocked gas? (Nagai+17, Giovannini+18)

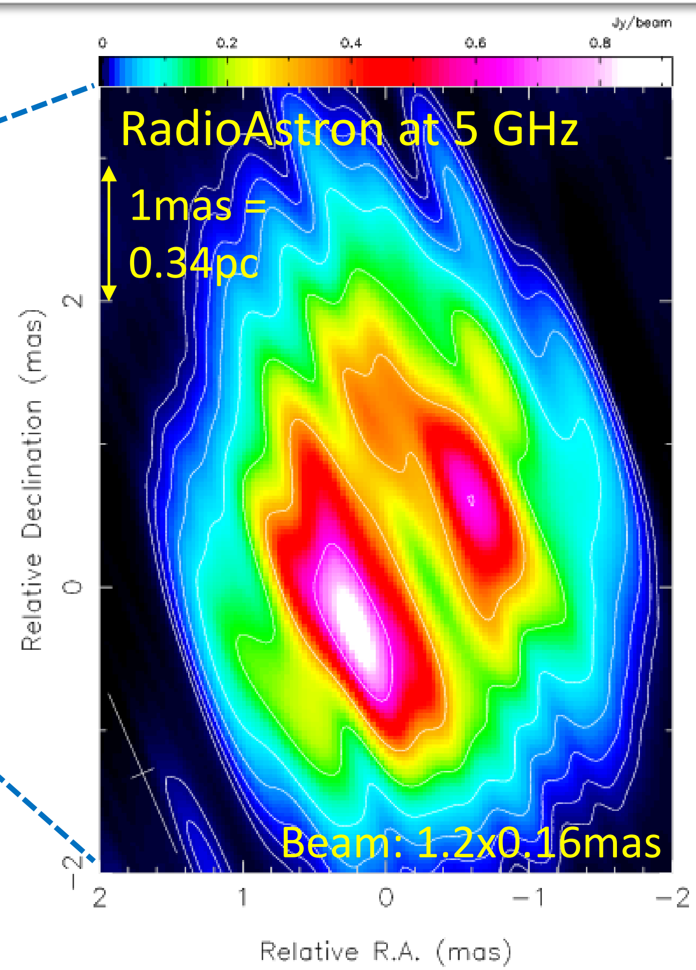
Giovannini, TS+ 2018



3C84 with RadioAstron at 5 GHz

Source detected up to $8.1 D_{Earth}$.
Resolution down to 125μas @ 5GHz.





TS+ in prep.

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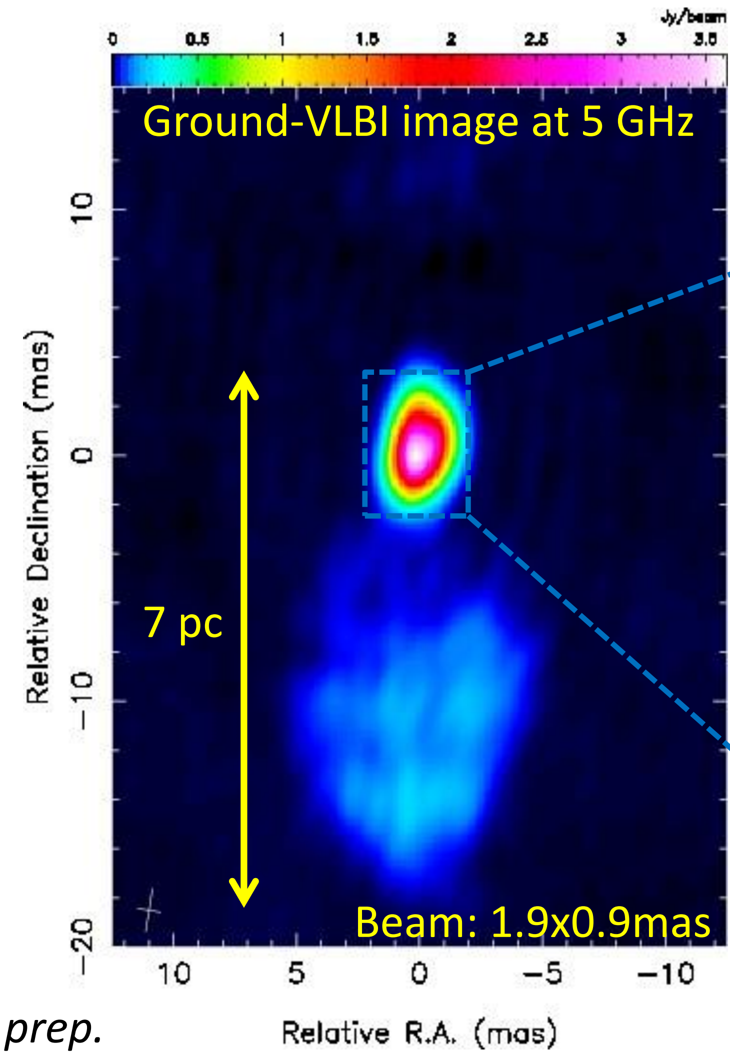
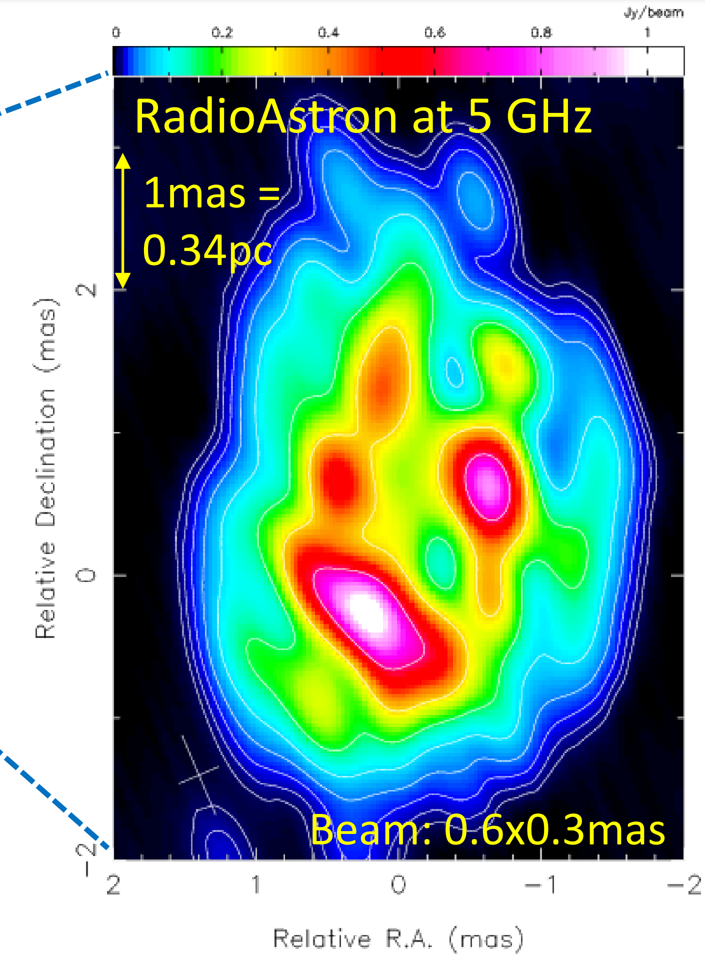
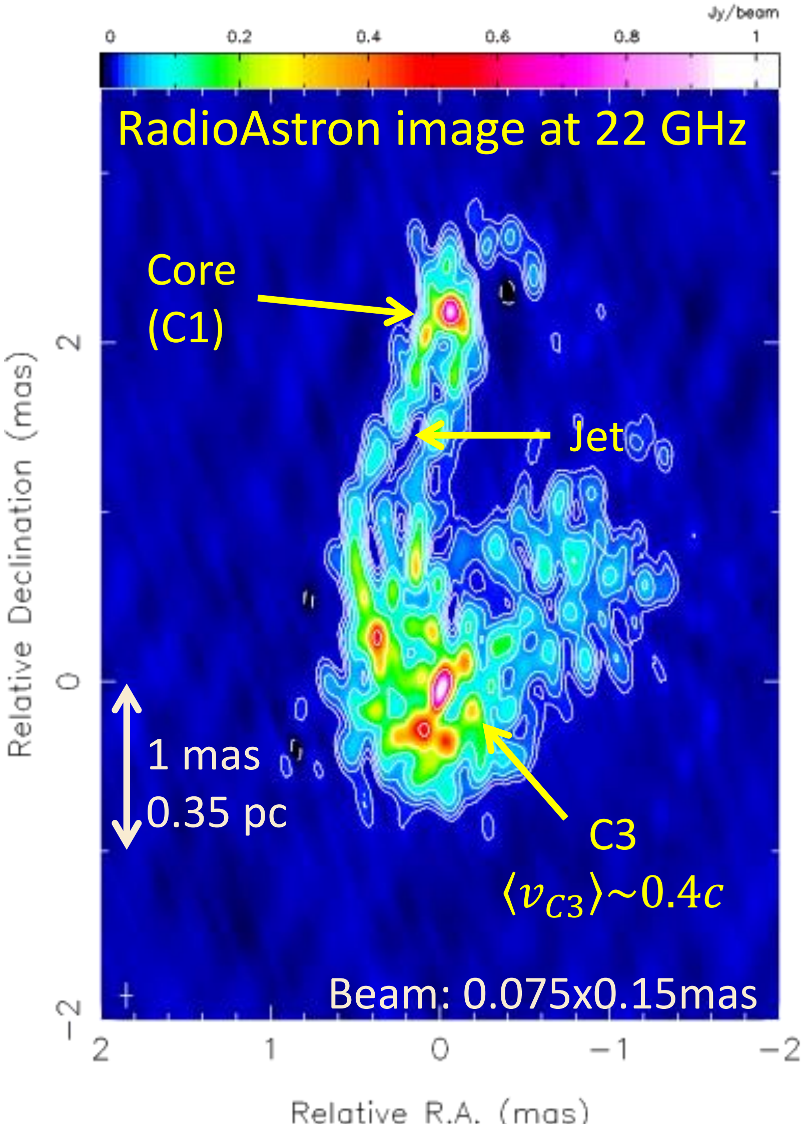
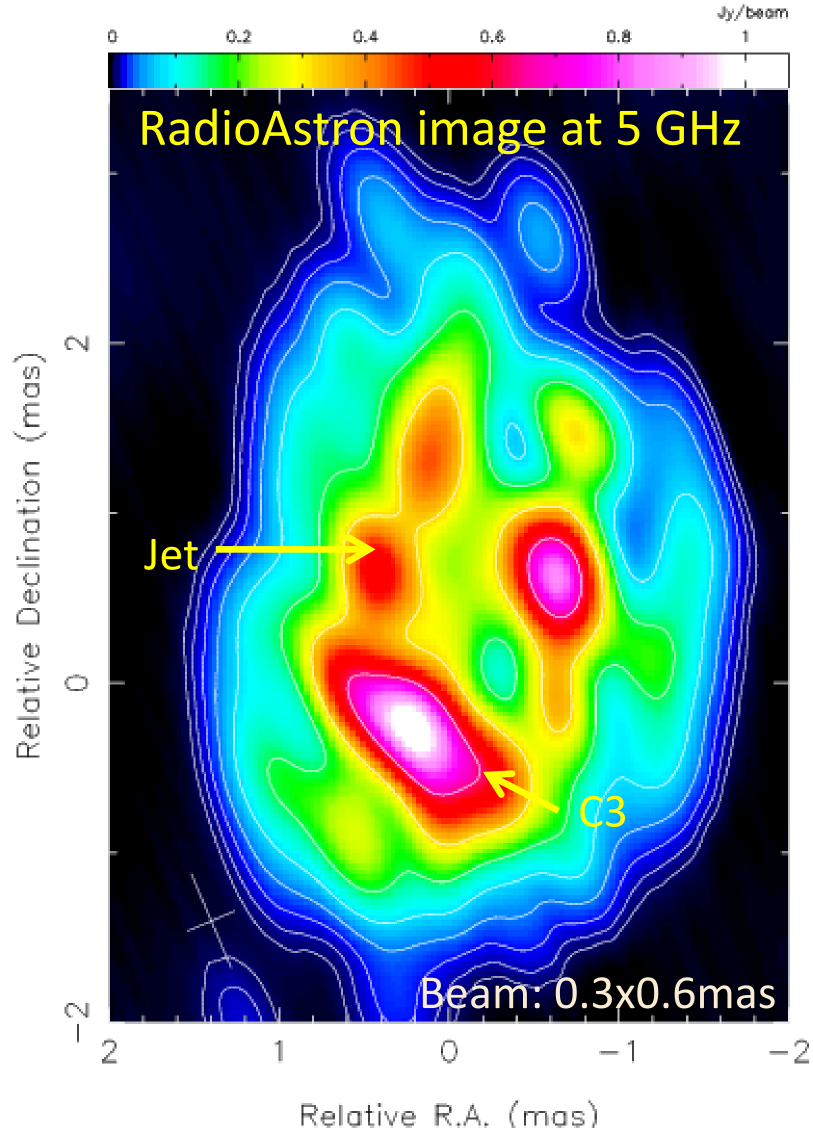




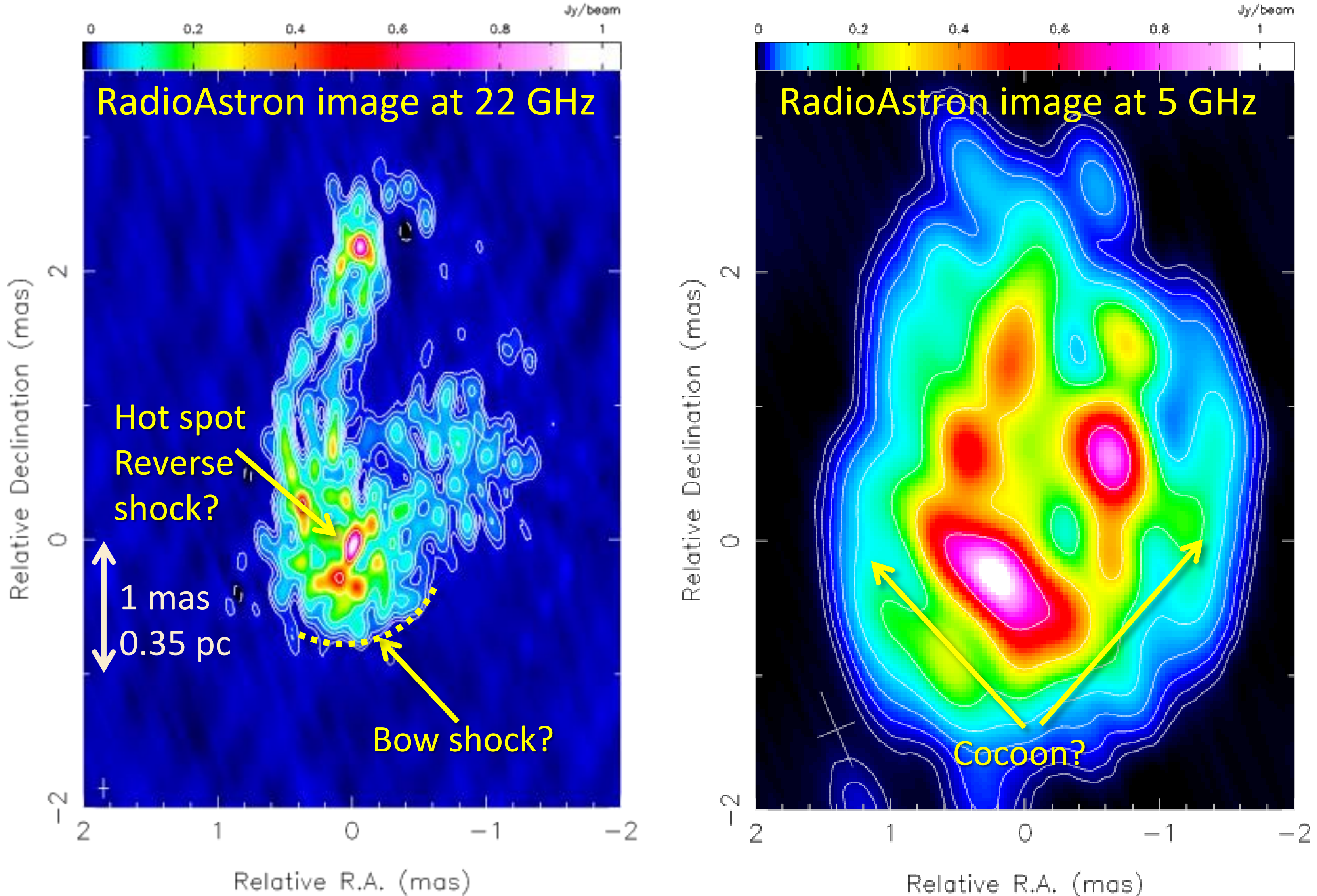
TS+ in prep.

Jet-ISM interaction within 1 pc

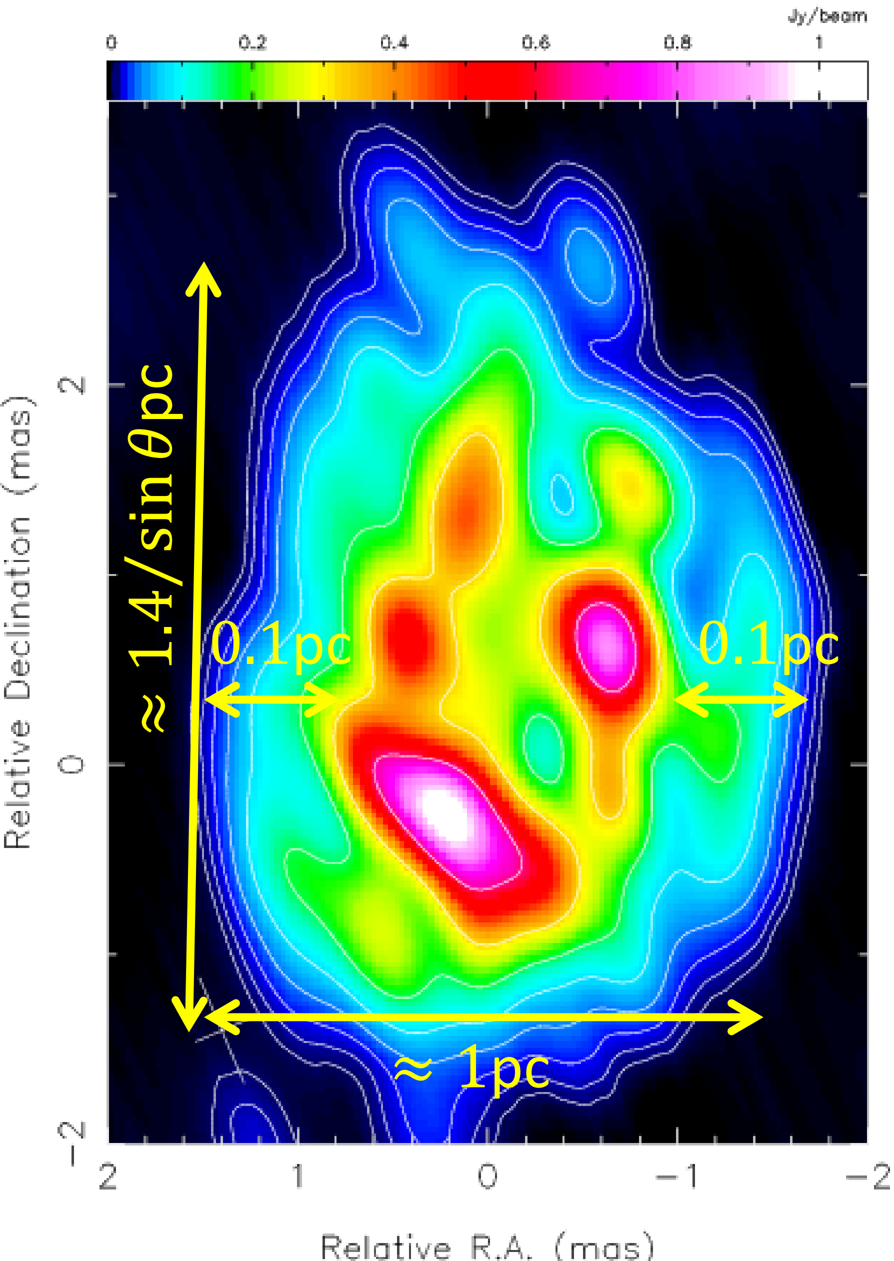




Jet-ISM interaction within 1 pc



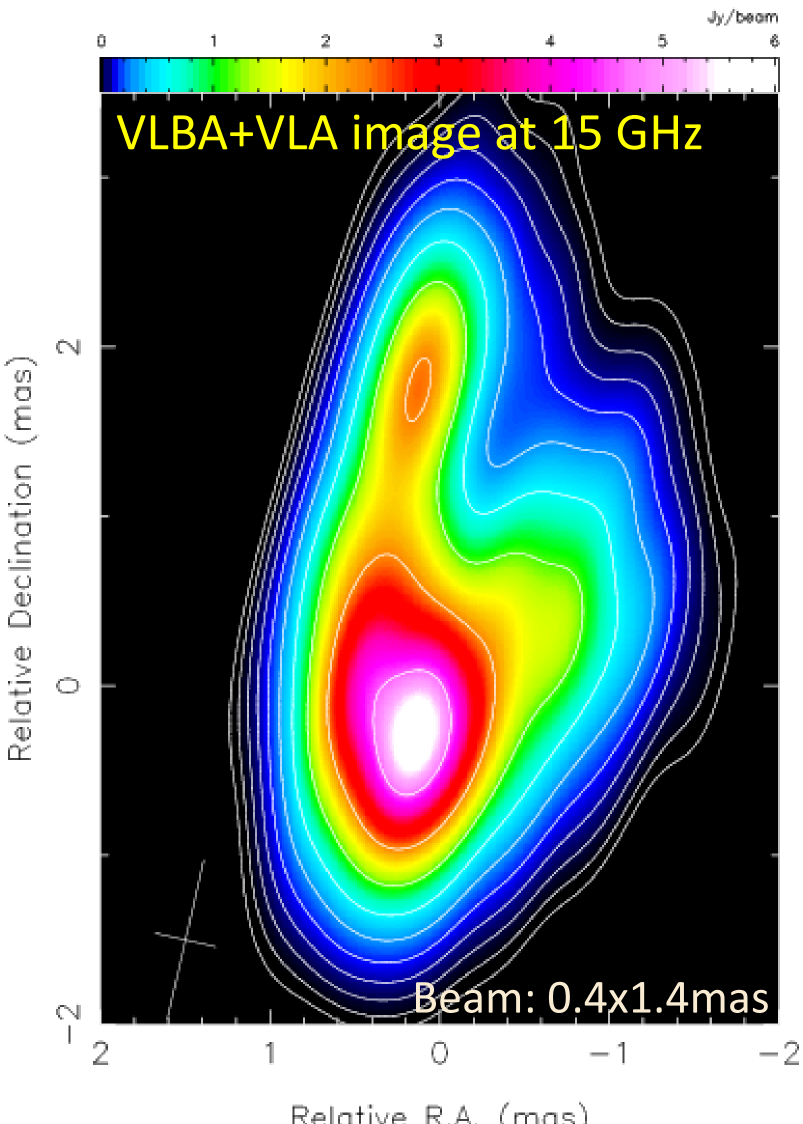
Mini-cocoon

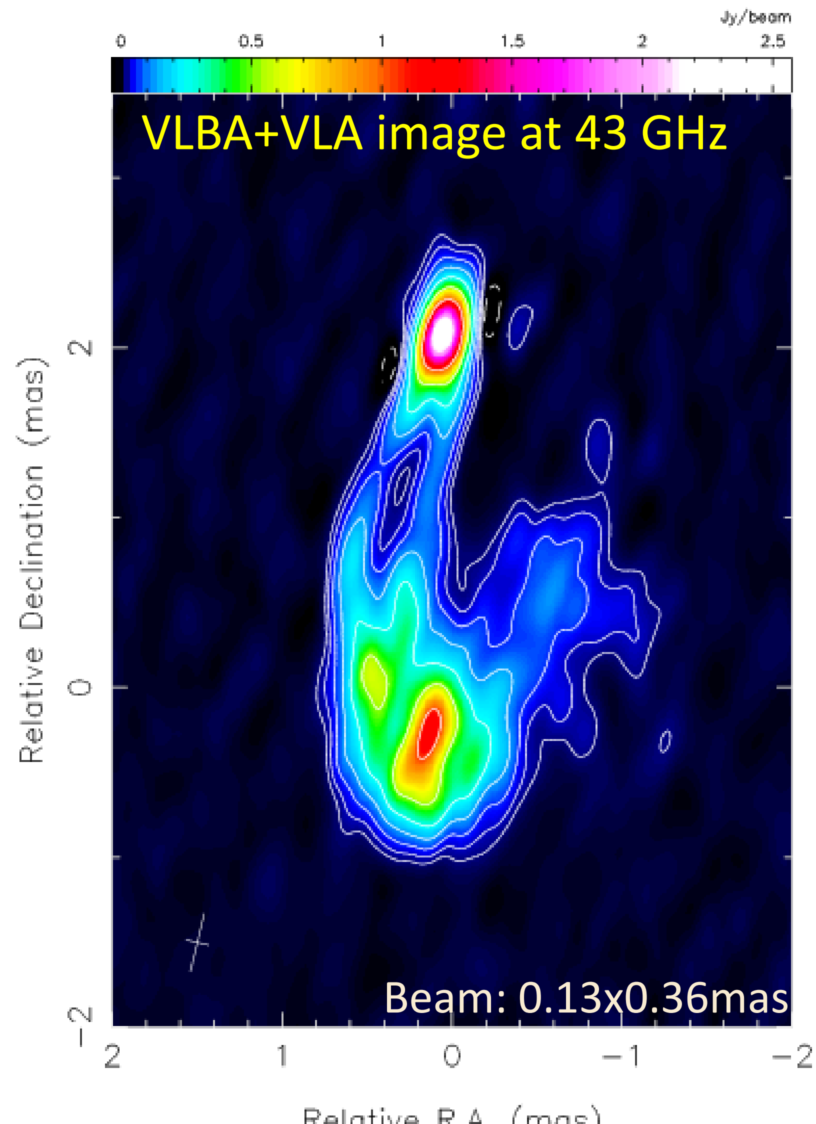


Measured properties

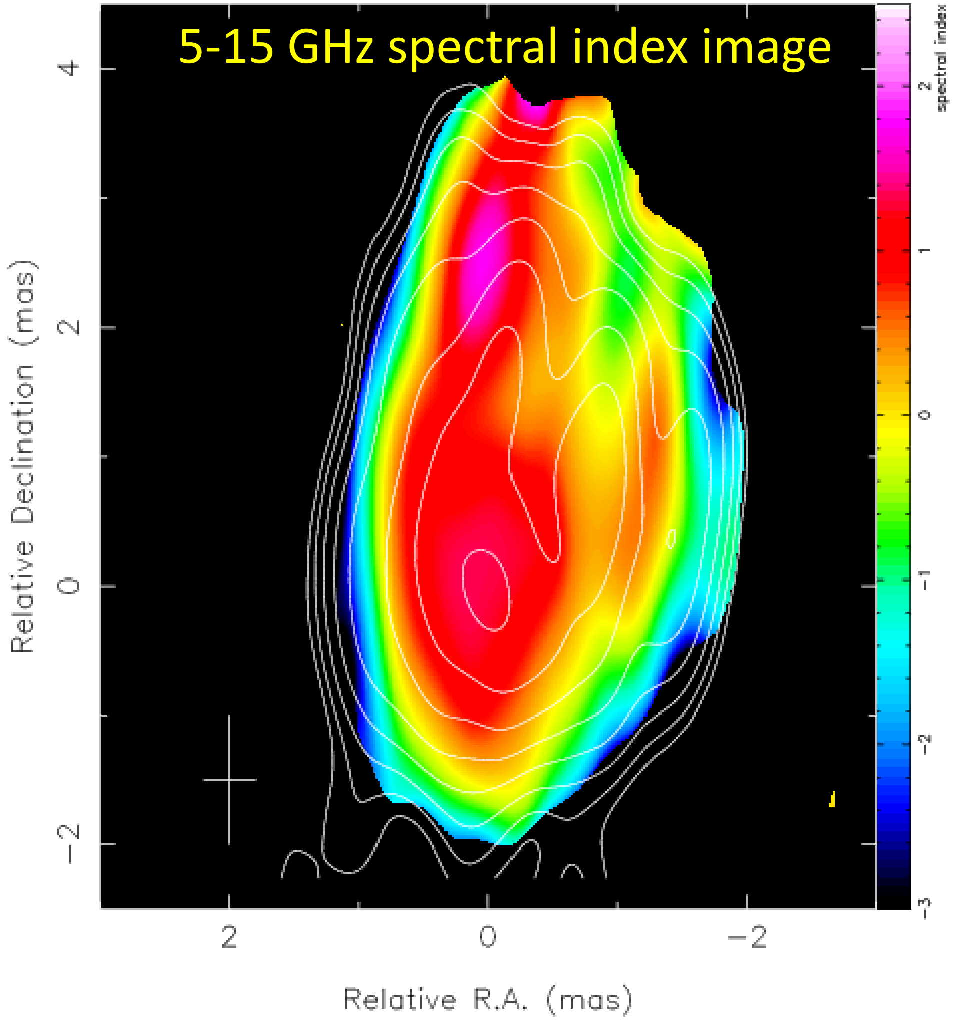
- $V_{c,tot} = 1.1/\sin\theta$ pc^3
- Shell of 0.1 pc thickness: $V_{c,shell} = 0.6/\sin\theta$ pc^3
- $T_{b,c} \sim 3 \times 10^{10}$K

Simultaneous VLBA+VLA observations at 15 and 43 GHz





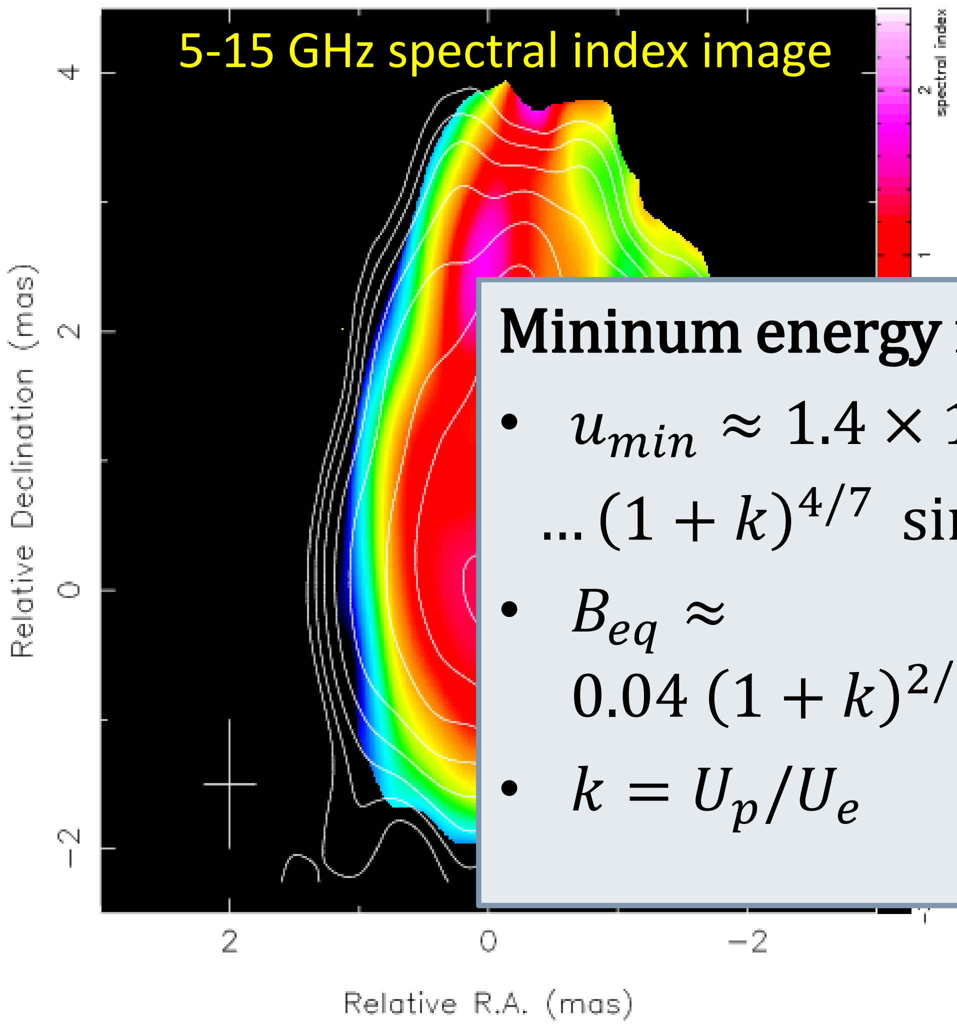
Mini-cocoon



Measured properties

- $V_{c,tot} = 1.1/\sin\theta\ \mathrm{pc}^3$
- Shell of 0.1 pc thickness: $V_{c,shell} = 0.6/\sin\theta\ \mathrm{pc}^3$
- $T_{b,c} \sim 3 \times 10^{10}\mathrm{K}$
- $\alpha_c(East) < -1.0$
- $\alpha_c(West) \sim -1.0$

Mini-cocoon



Measured properties

- $V_{c,tot} = 1.1/\sin\theta$ pc³
- Shell of 0.1 pc thickness:
  $.6/\sin\theta$ pc³
- 0^{10}K
- < -1.0
- ~ -1.0

Mininum energy in the cocoon

- $u_{min} \approx 1.4 \times 10^{-4}$ …
  … $(1+k)^{4/7}\ \sin^{4/7}\theta$ erg/cm³
- $B_{eq} \approx$
  $0.04\ (1+k)^{2/7} \sin^{2/7}\theta$ G
- $k = U_p/U_e$

Is the "mini-cocoon" formed by the recent activity?

- At the time of RA obs., $\Delta t_{C3} \sim 10\text{yr}$
- Power requirements. Assuming minimum energy in the cocoon shell and $\theta = 18°$, the power needed to feed the cocoon in 10 yrs: $1.3 \times 10^{43}(1+k)^{4/7}\text{erg/s}$
  - $k = 1$: $P_{cocoon} \sim 2 \times 10^{43}\text{erg/s}$
  - $k = 100$: $P_{cocoon} \sim 2 \times 10^{44}\text{erg/s}$
  - Long term average from X-ray cavities: $P_{cav} \sim 1.5 \times 10^{44}\text{erg/s}$ (Rafferty+06).
  - $\mathrm{L_{bol}} \sim 10^{44}\text{erg/s}$ (Abdo+09)

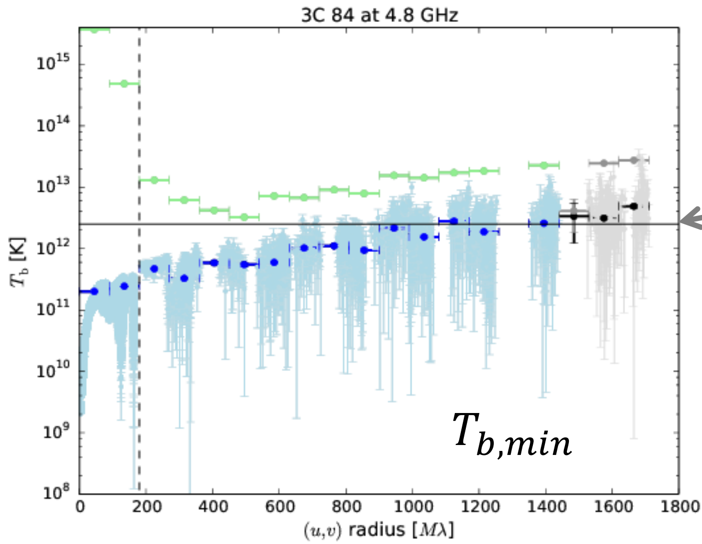
The typical jet power of 3C84 is enough to inflate the mini-cocoon in 10 years

Is the "mini-cocoon" formed by the recent activity?

- Synchrotron life time assuming $\theta = 18°$ and $B_{eq} \approx 28\,(1+k)^{2/7}$ mG:
  - $k = 1$: $t_{1/2} \approx 75$ yr $> \Delta t_{C3}$
  - $k = 100$: $t_{1/2} \approx 14$ yr $> \Delta t_{C3}$
- Expansion speed:
  - $\langle v_{h,app} \rangle \approx 0.4$c => $\langle v_h \rangle \approx 0.6$c if $\theta = 18°$
  - $\langle v_{cocoon} \rangle = r_c / \Delta t_{C3} \approx 0.16$c
  - $\langle v_h \rangle > \langle v_{cocoon} \rangle$
- Implication to the ambient density assuming $p_c = \rho_a v_c^2$ and minimum energy in the cocoon:
  - $\rho_a \gtrsim 8 \times 10^{-25} (1+k)^{4/7}$g/cm3
  - $k = 1$: $n_p \gtrsim 0.7$ cm^{-3}
  - $k = 100$: $n_p \gtrsim 7$ cm^{-3}

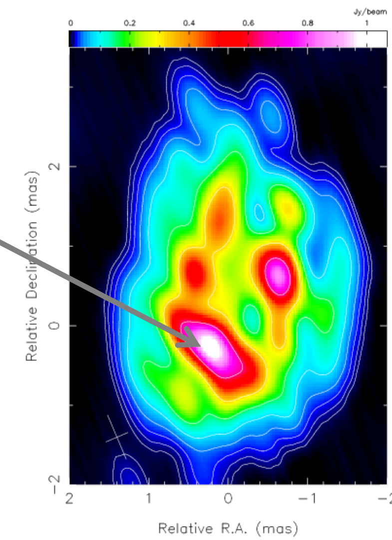
A FEW WORDS ABOUT PHYSICAL CONDITIONS IN C3 HOT SPOT

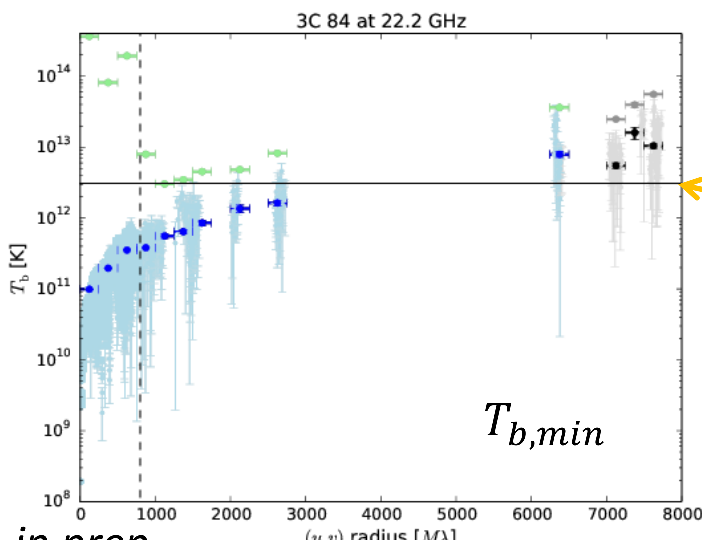
High brightness temperature in C3



5 GHz

$T_{b,mod}(C3) =$
$2.5 \pm 1 \times 10^{12}$K

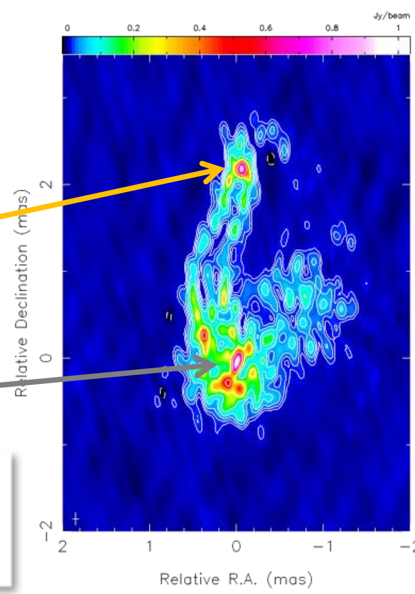




22 GHz

$T_{b,mod}(C1) =$
$3 \pm 2 \times 10^{12}$K

$T_{b,mod}(C3) =$
$8 \pm 2 \times 10^{11}$K

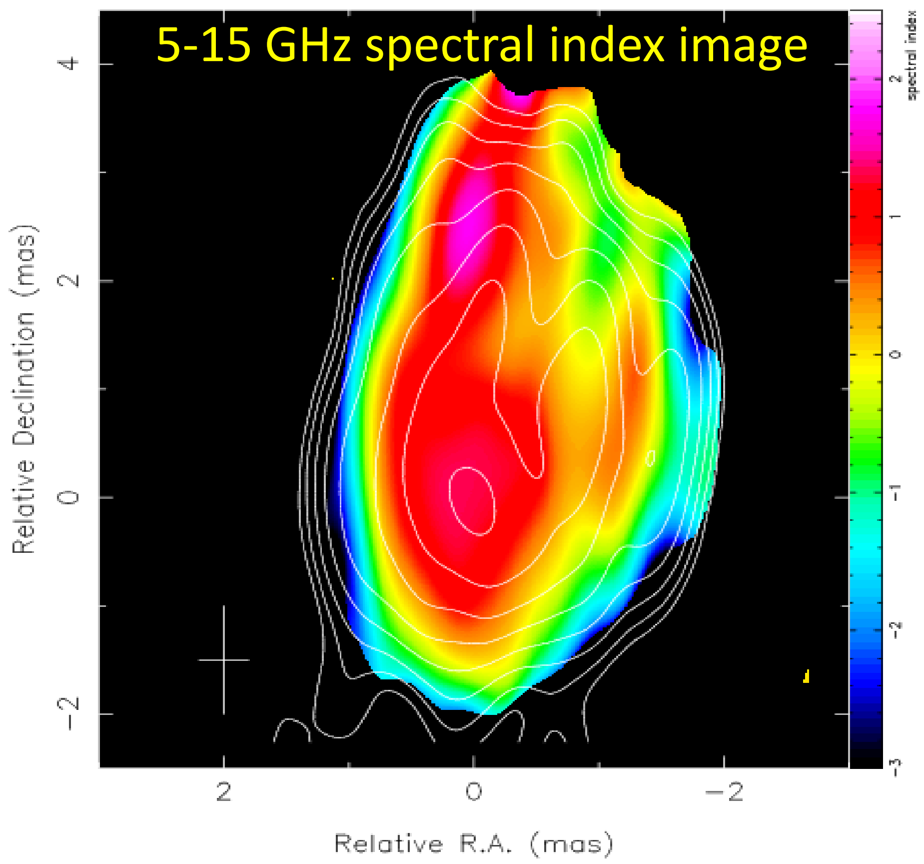


Inverse Compton limit:
$T_{b,obs} \lesssim 10^{12} \cdot \delta$ K

TS+ in prep.

Magnetic and particle energy densities in C3 hot spot

- C3 is optically thick at 5GHz ($\alpha_{C3}^{5-15} = +1.3$)
- Hence, $T_{b,5GHz} \sim T_e$ and we can estimate magnetic field: $B \approx 1.4 \times 10^{21} \upsilon_{GHz} T_b^{-2} \ldots$ $\ldots \delta(1+z)^{-1} \approx 1 \cdot \delta$ mG



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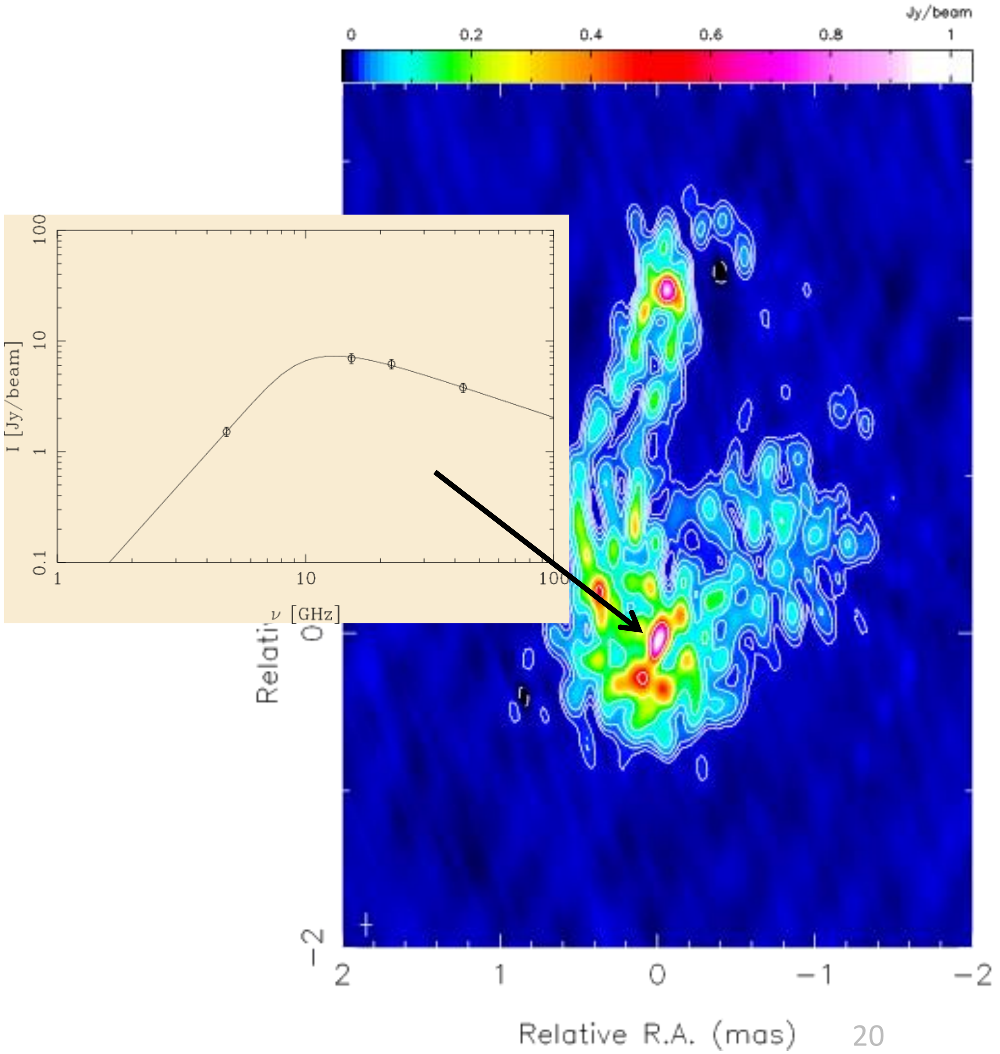
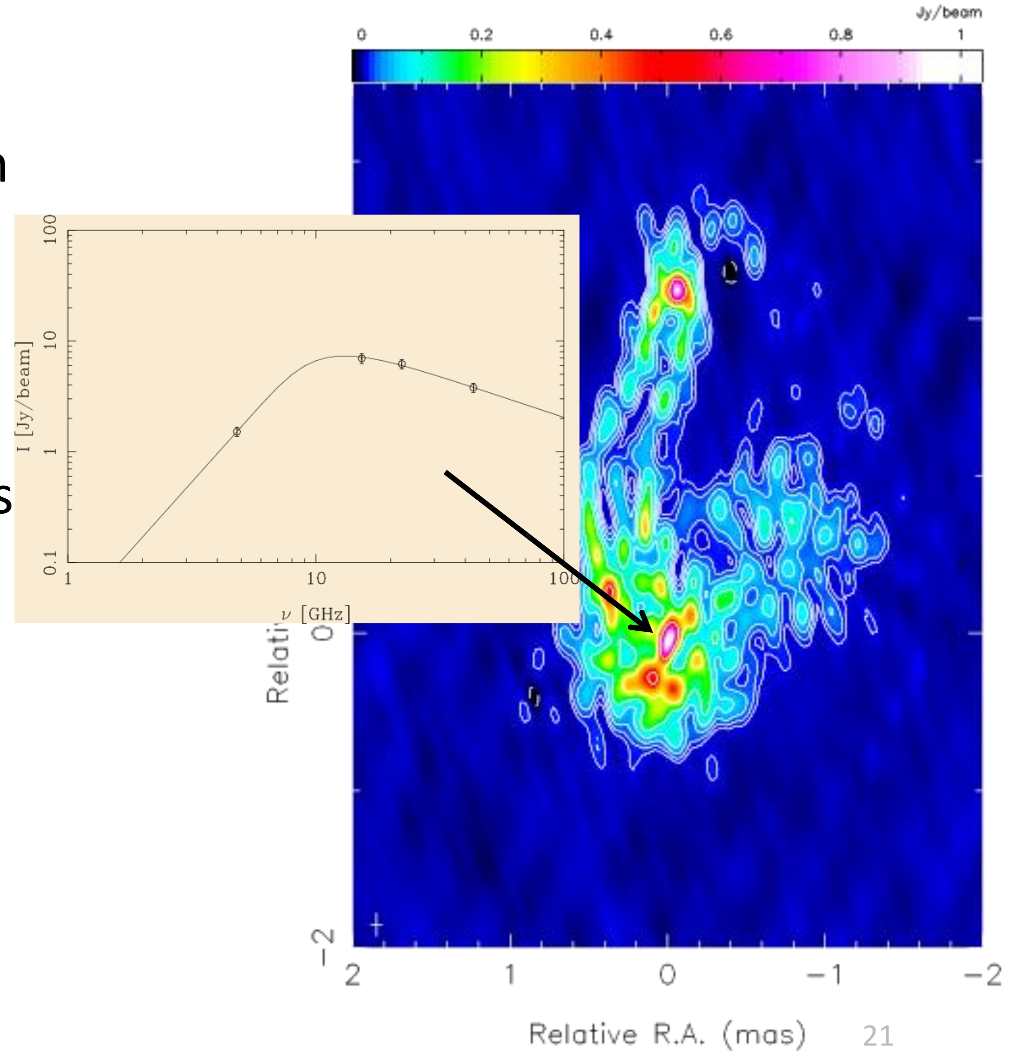
- Hence, $T_{b,5GHz} \sim T_e$ and we can estimate magnetic field:
  $B \approx 1.4 \times 10^{21} \upsilon_{GHz} T_b^{-2}$ …
  … $\delta (1+z)^{-1} \approx 1 \cdot \delta$ mG
- Other way: measure intensity of a resolved emission region at the synchrotron turnover frequency:
  $B_{SSA} \approx 10^{-3 \pm 0.5} \delta$ G



Magnetic and particle energy densities in C3 hot spot

- The high brightness temperature implies strong deviation from equipartition in C3 hot spot. From SSA: $U_{re}/U_B \sim 10^{10\pm2}\delta^{-7}$
- Equipartition would require $\delta \sim 27$, but if C3 hot spot is a reverse shock, the emitting gas should be moving at $v \sim v_h \approx 0.6c$!
- Need extra Doppler boosting? Jet-in-a-jet from magnetic reconnection (Giannios+09)?



Summary

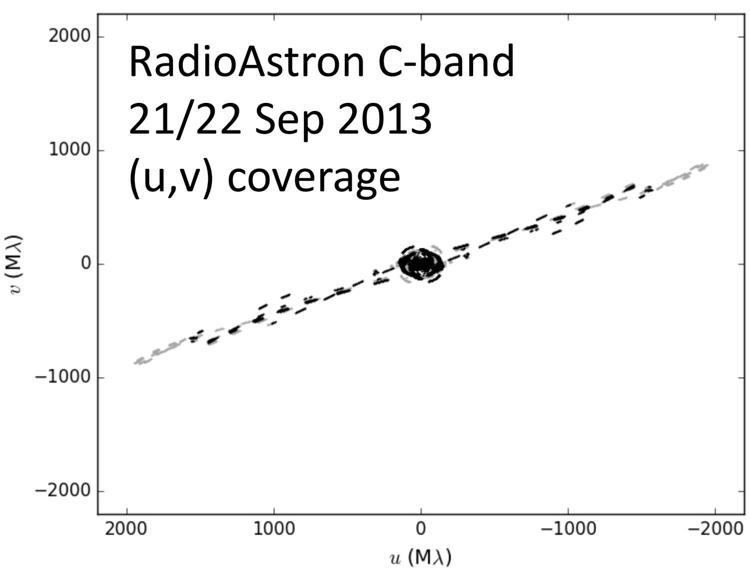
- 5 GHz RadioAstron image reveals cocoon-like emission around the innermost 1pc long jet.
  - Pressure from a hot cocoon can explain the almost cylindrical shape of the jet
  - The mini-cocoon could have been formed by the increased jet activity since 2003 (energetics, synchrotron life-time, expansion speed, ambient density are all sensible in this scenario)
- High brightness temperature in hot spot of C3 implies strong deviation from equipartition, if the speed of the emission region corresponds to that of the jet head.

BACKUP SLIDES

3C84 RadioAstron observations

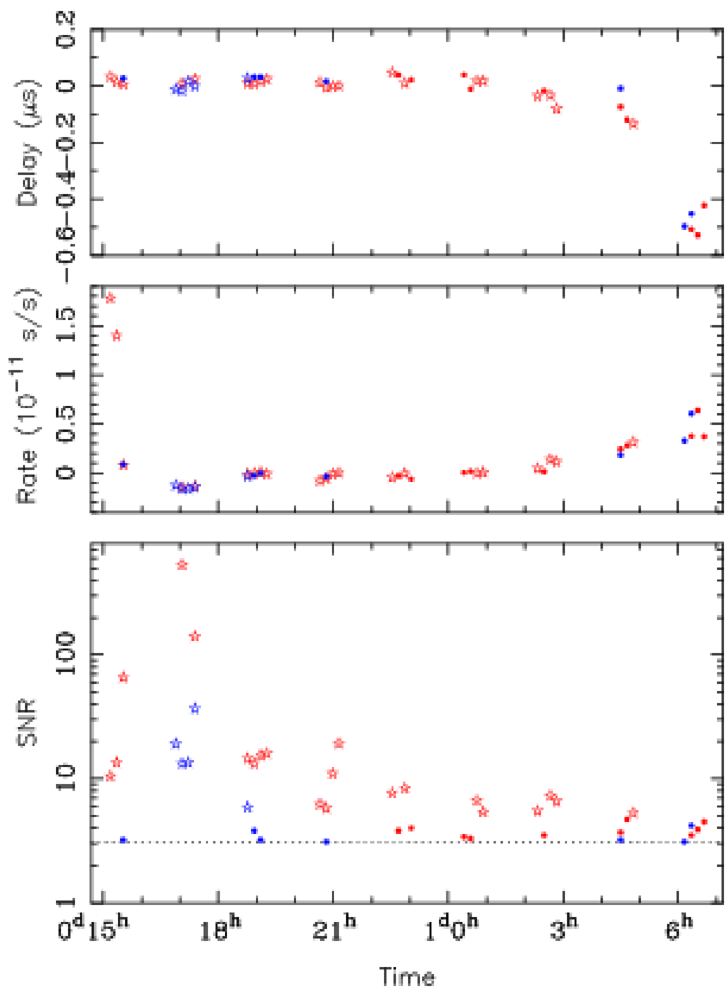
5/22 GHz in 21/22 Sep 2013

- 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 (up to 7×10^{-13} s/s^2) near perigee needed to be corrected in post-processing
- Fringe-fitting with PIMA and AIPS



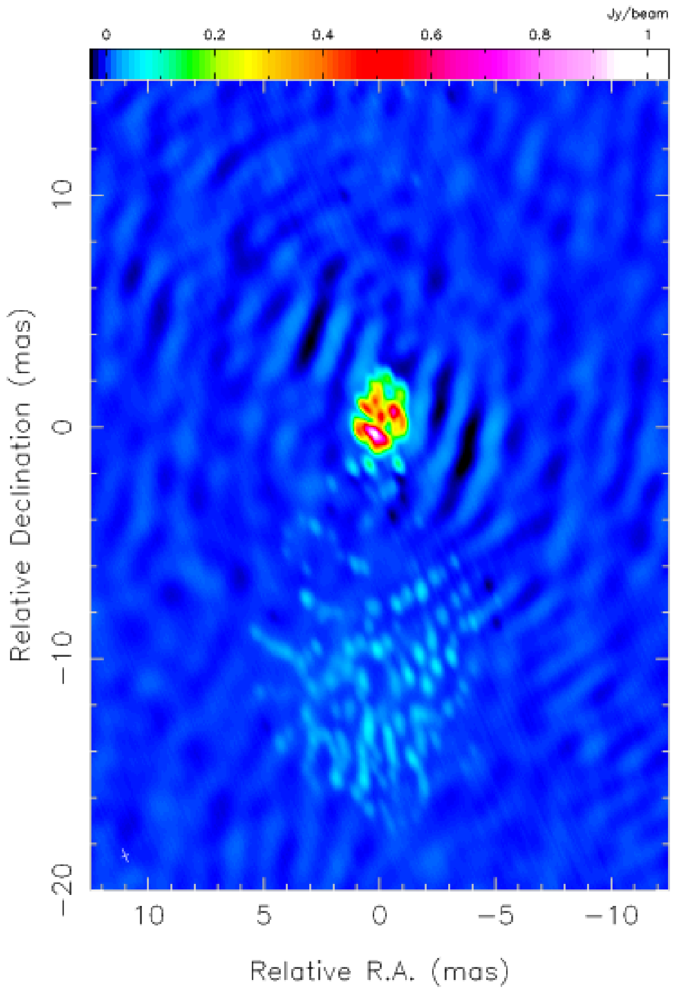
Fringes were detected on space baselines:

- 5 GHz AIPS global fringe fitting: 33 scans over 0.2 - 8.1 ED
- 22 GHz AIPS global fringe fitting: 12 scans over 0.2 – 8.1 ED

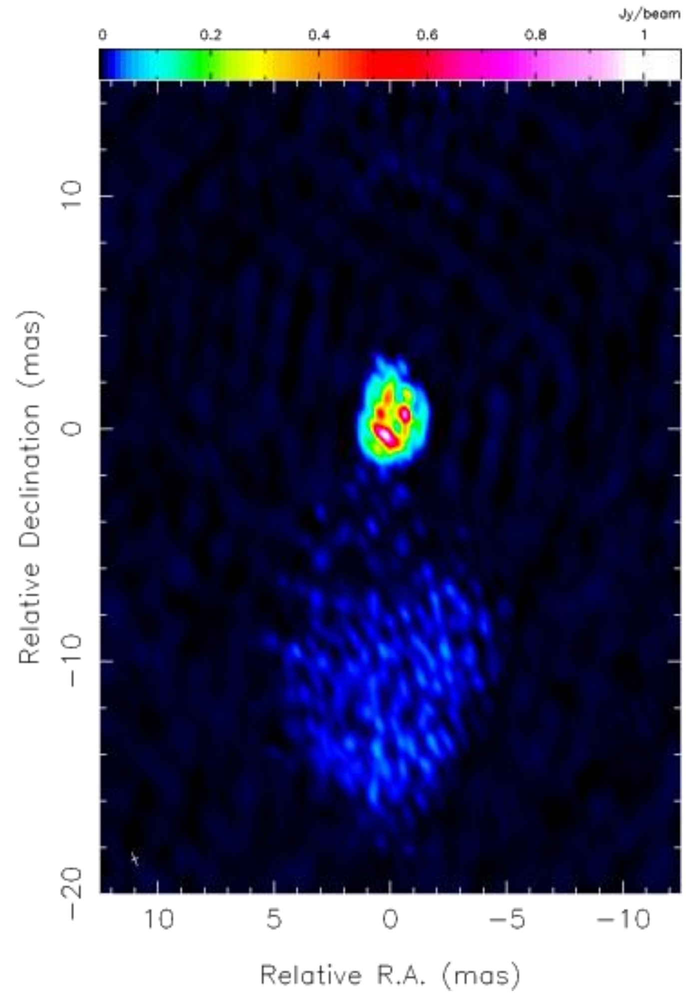


Test: imaging with and without cocoon

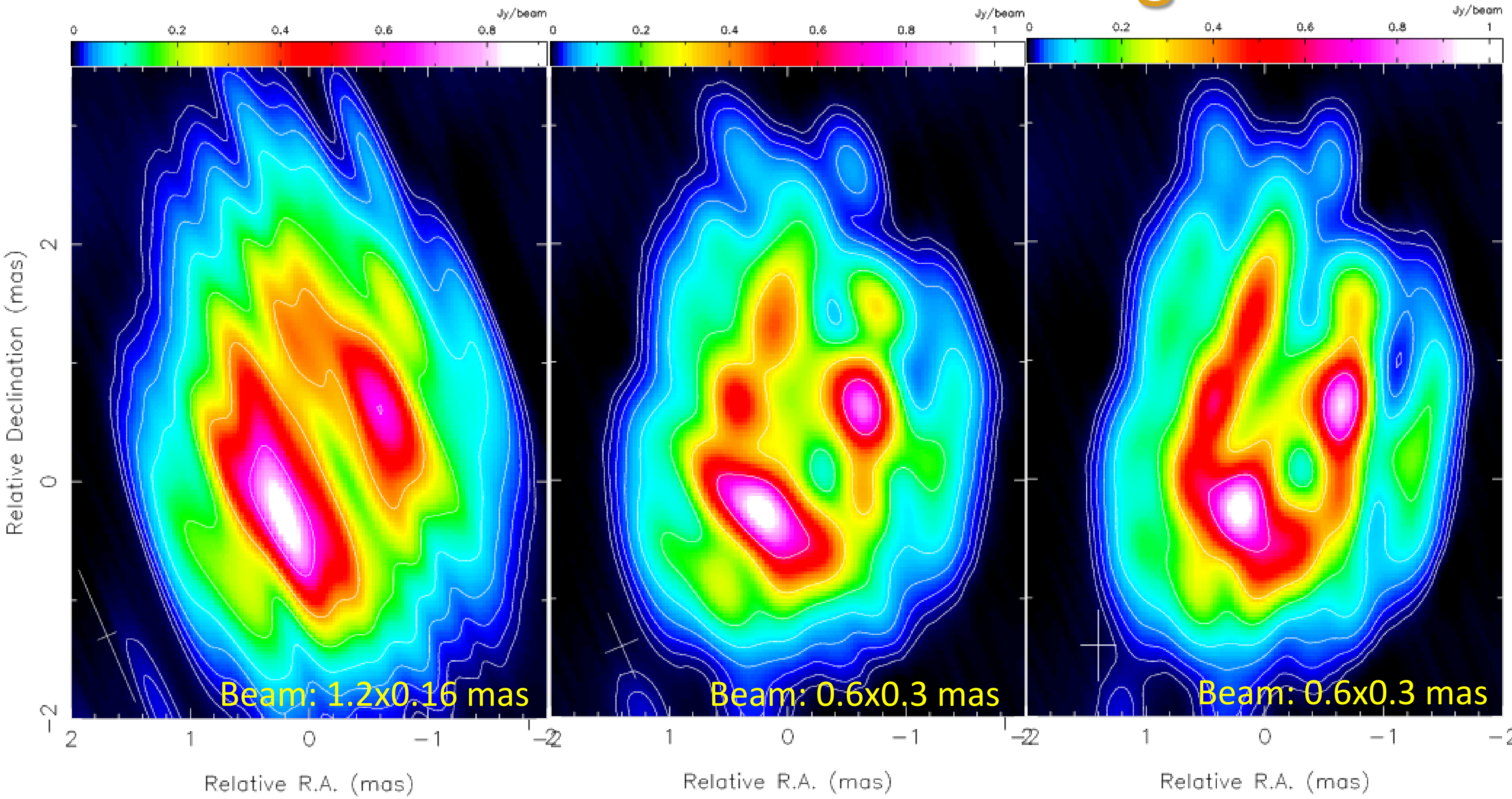
No CLEAN boxes in cocoon area



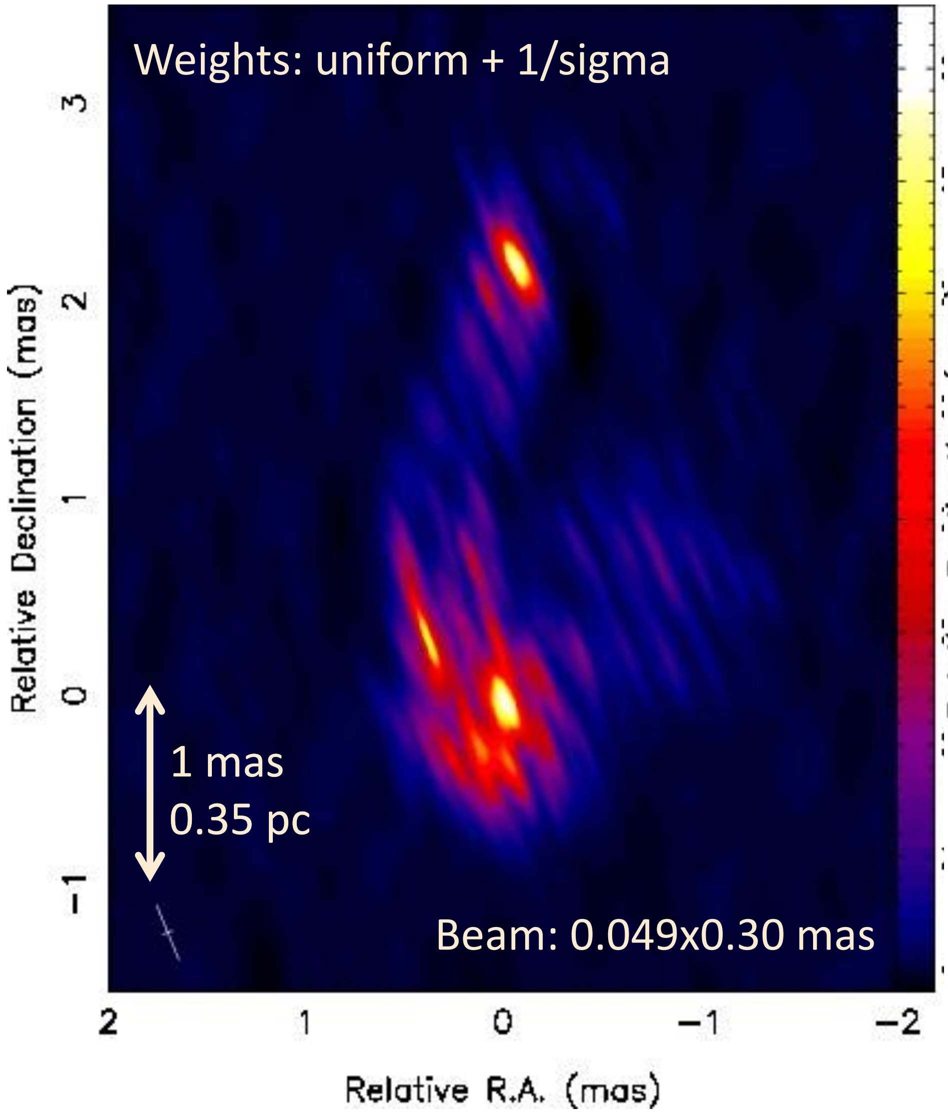
CLEAN boxes allowed in the cocoon area

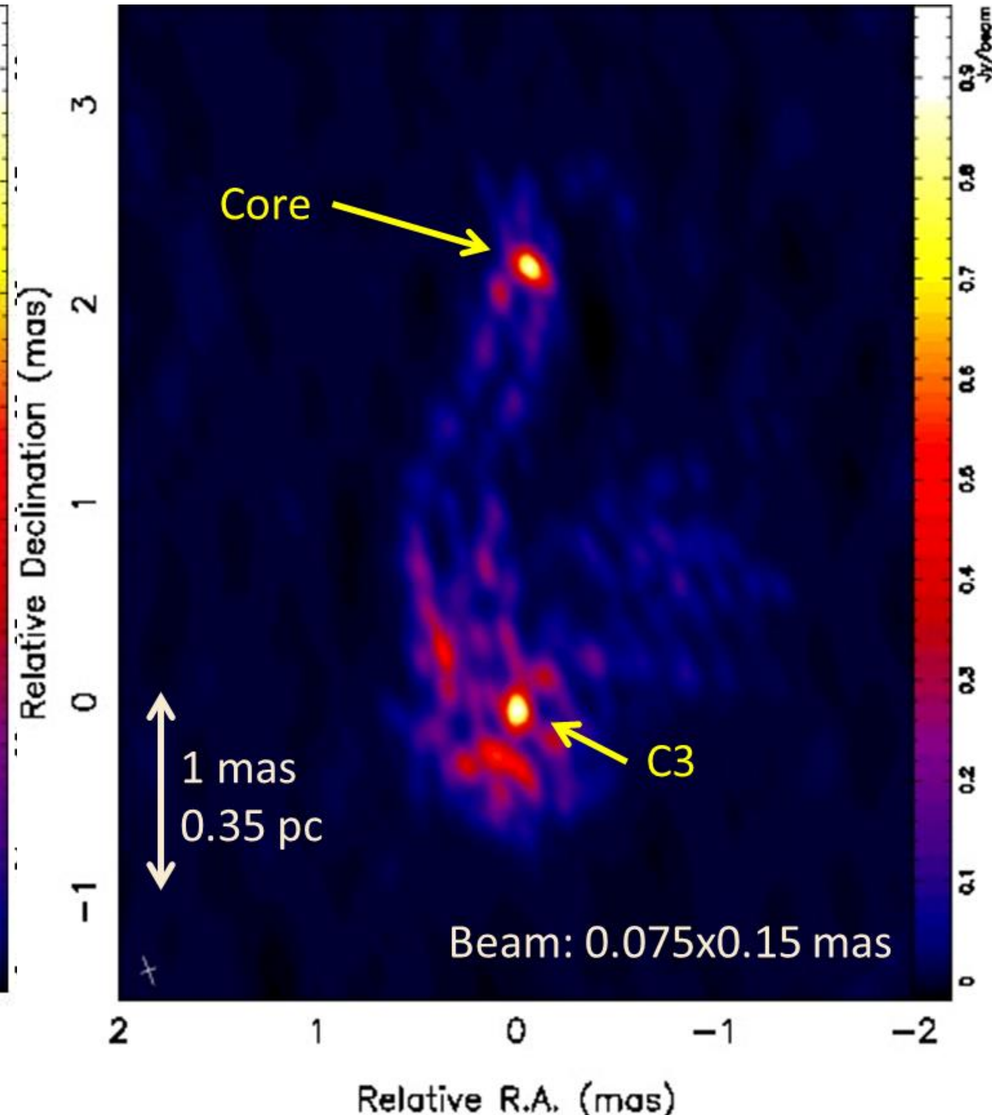


3C84 - 5 GHz RadioAstron images with different restoring beams



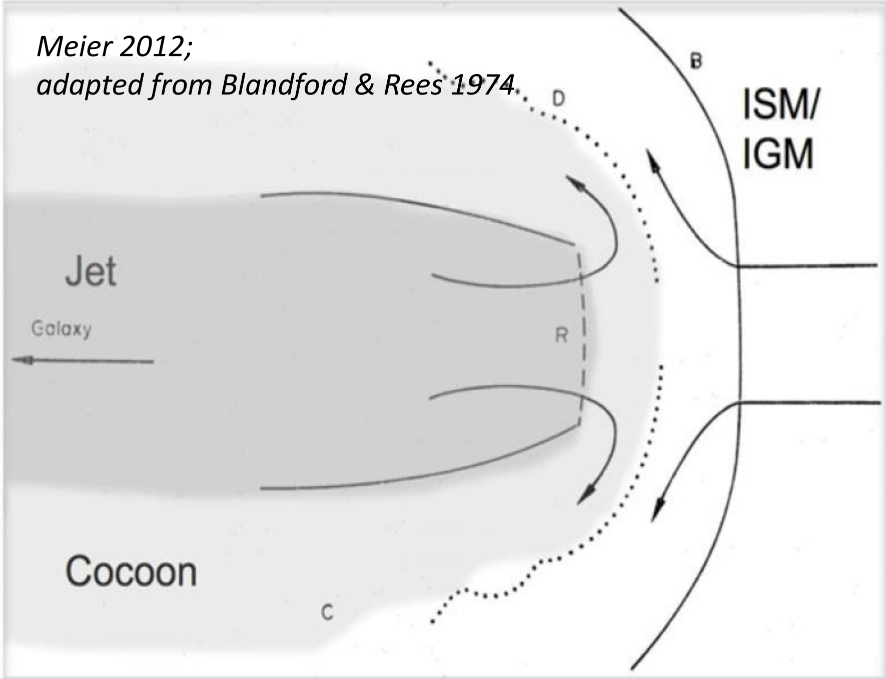
3C84 - 22 GHz RadioAstron images with different beams



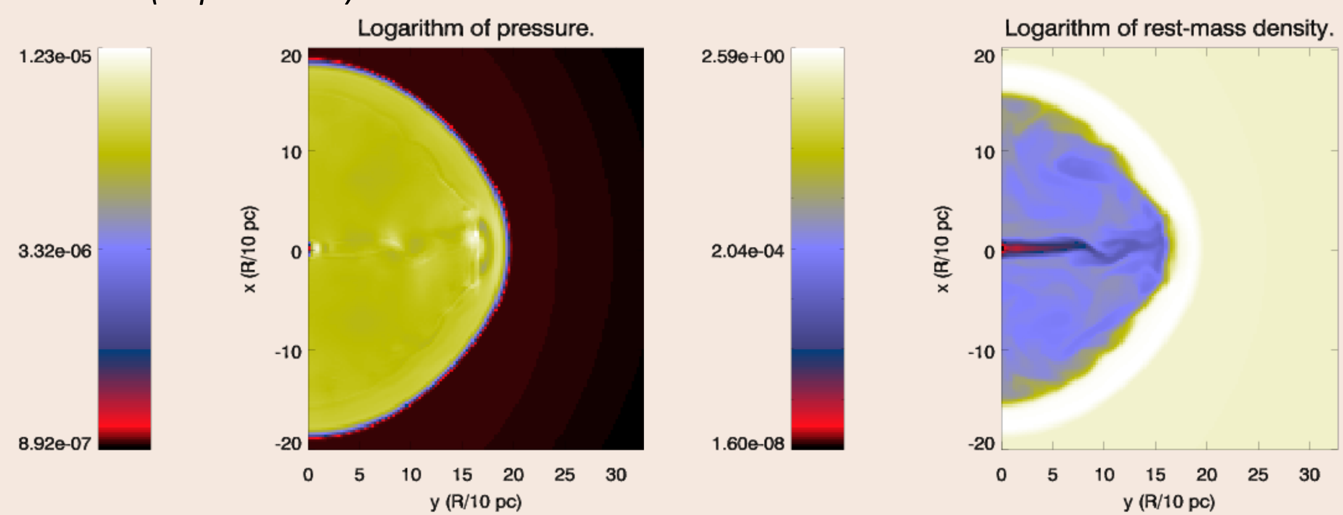


Jet termination

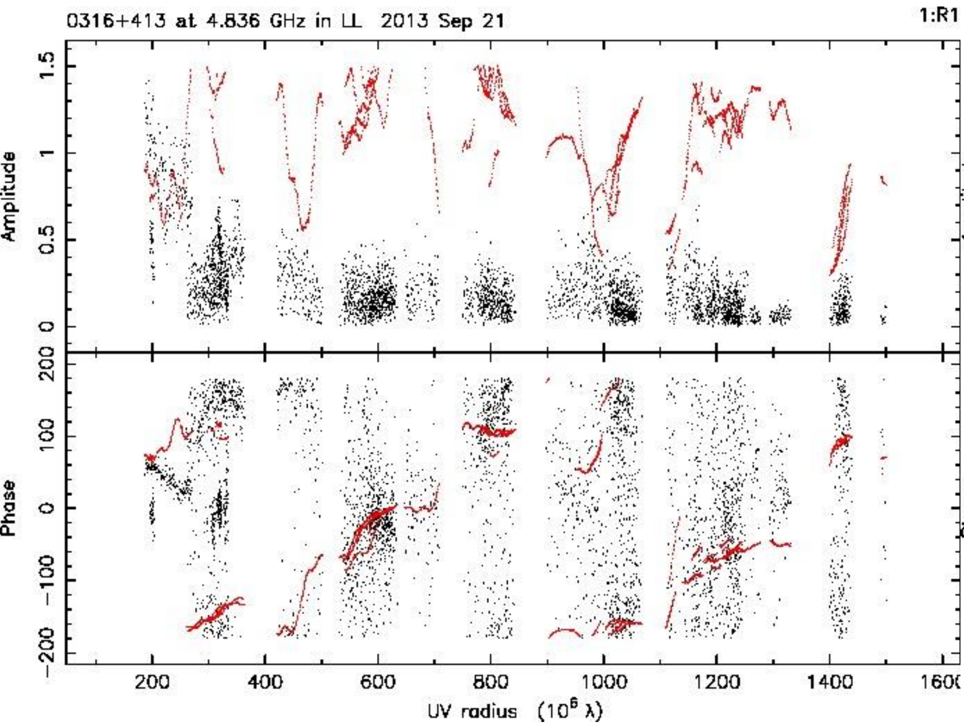
Meier 2012; adapted from Blandford & Rees 1974



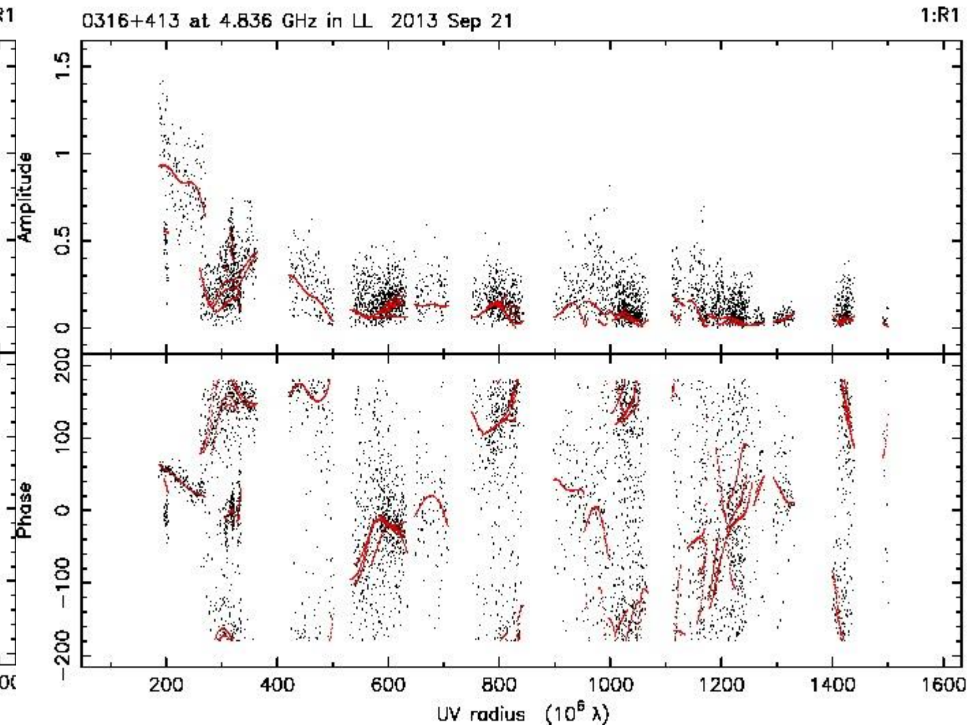
M. Perucho (unpublished)



3C84 at 5GHz with space baselines



RA data and ground-only model



RA data and ground+space model

Savolainen et al. in prep.

3C84 at 5GHz
- calibration accuracy of the SRT