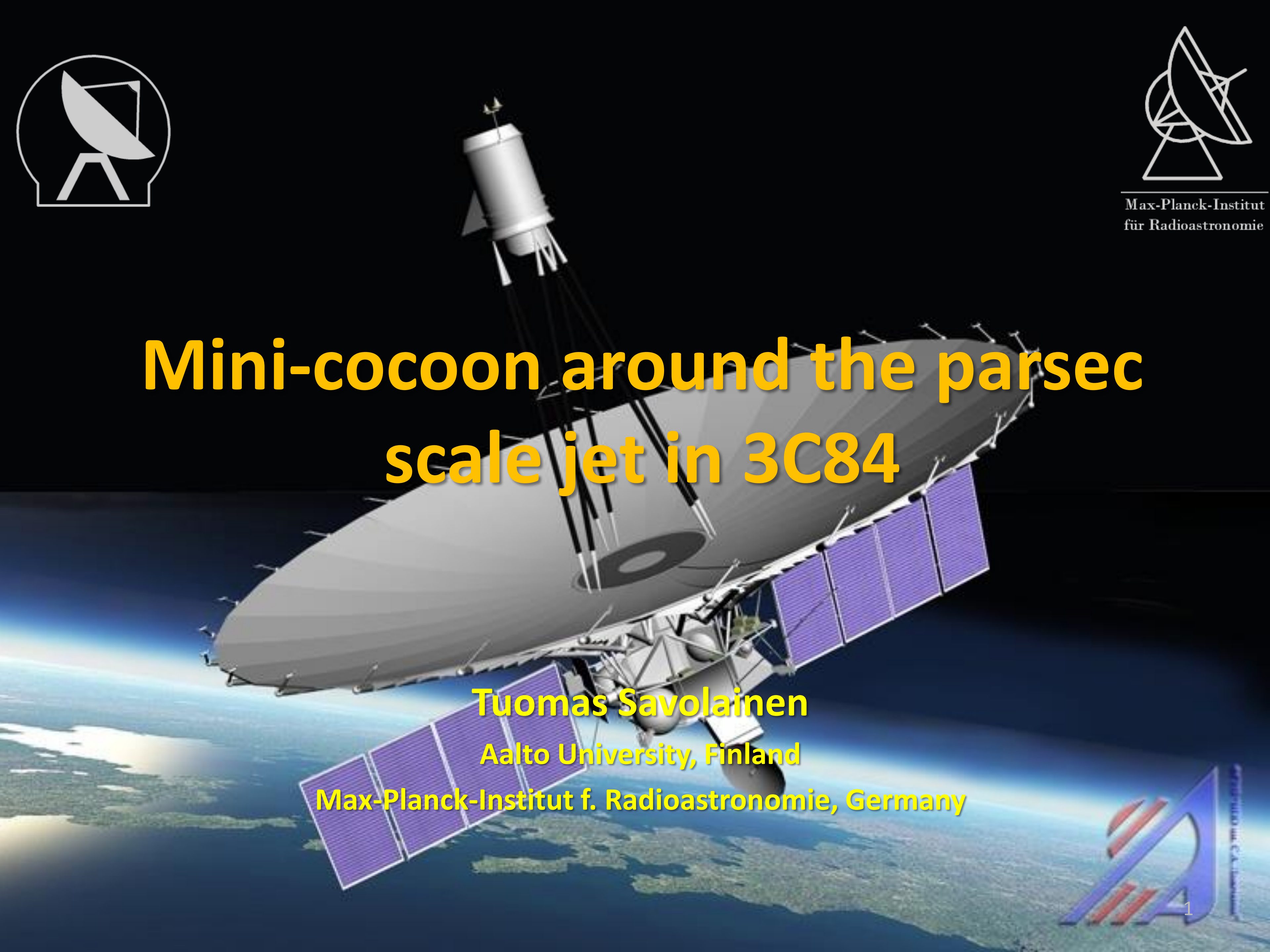

Max-Planck-Institut für Radioastronomie

Mini-cocoon around the parsec scale jet in 3C84

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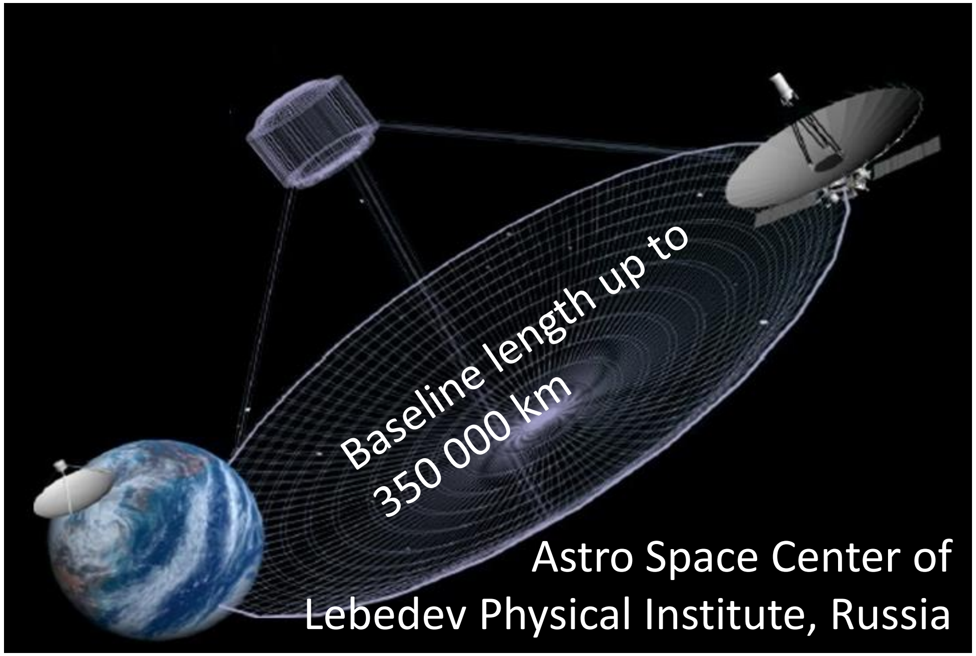
RadioAstron Space-VLBI mission



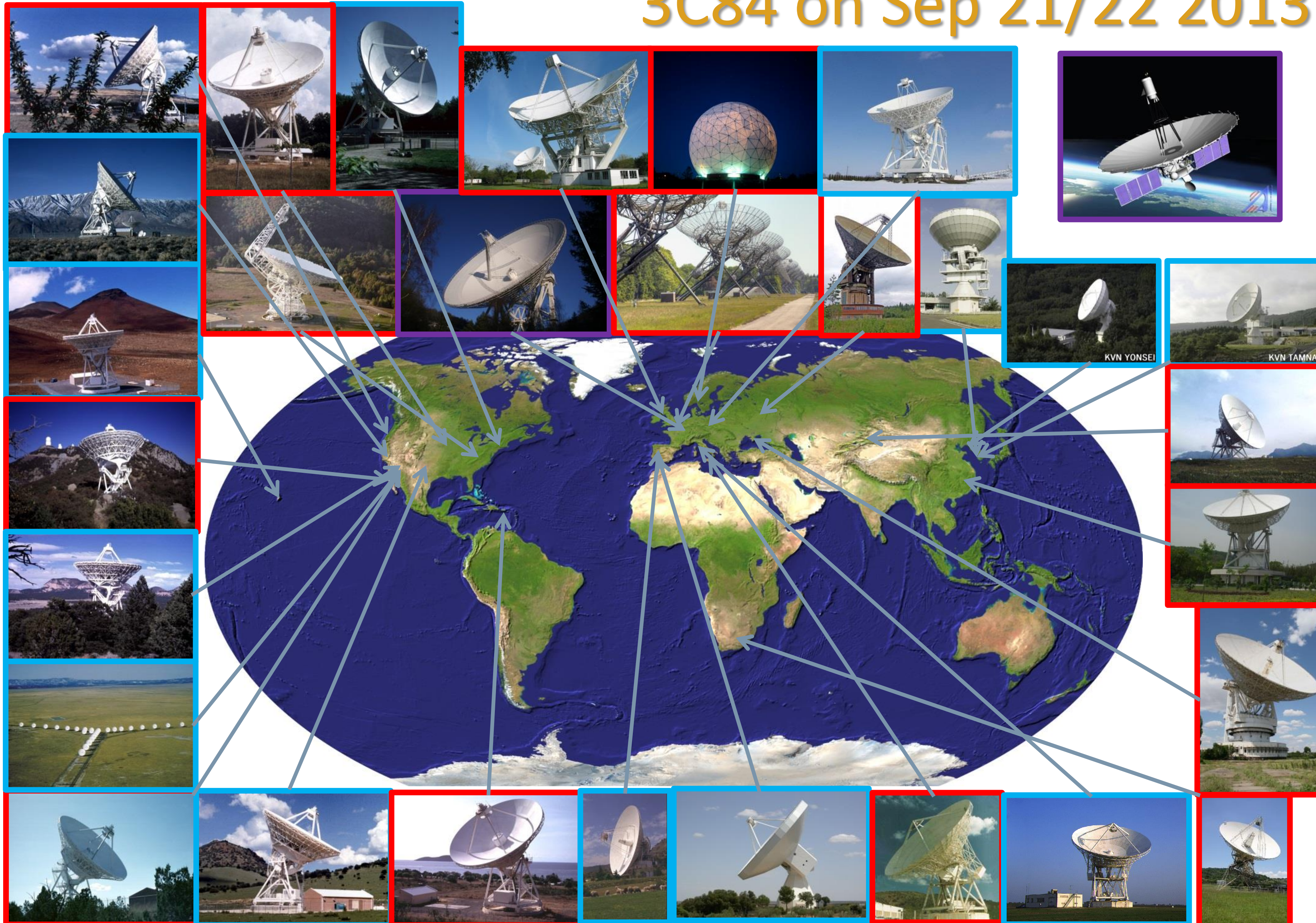
- 10-m Russian space radio telescope launched in 2011
- Apogee height: 350 000 km
- Obs. frequencies: 1.6–22 GHz
- Used together with ground radio telescopes as an interferometer
- Record angular resolutions: 8µas (H_20 megamaser in NGC4258, Maser KSP) and 12µas (quasar 3C279; TS+ in prep.)

RadioAstron Nearby AGN Key Science Program

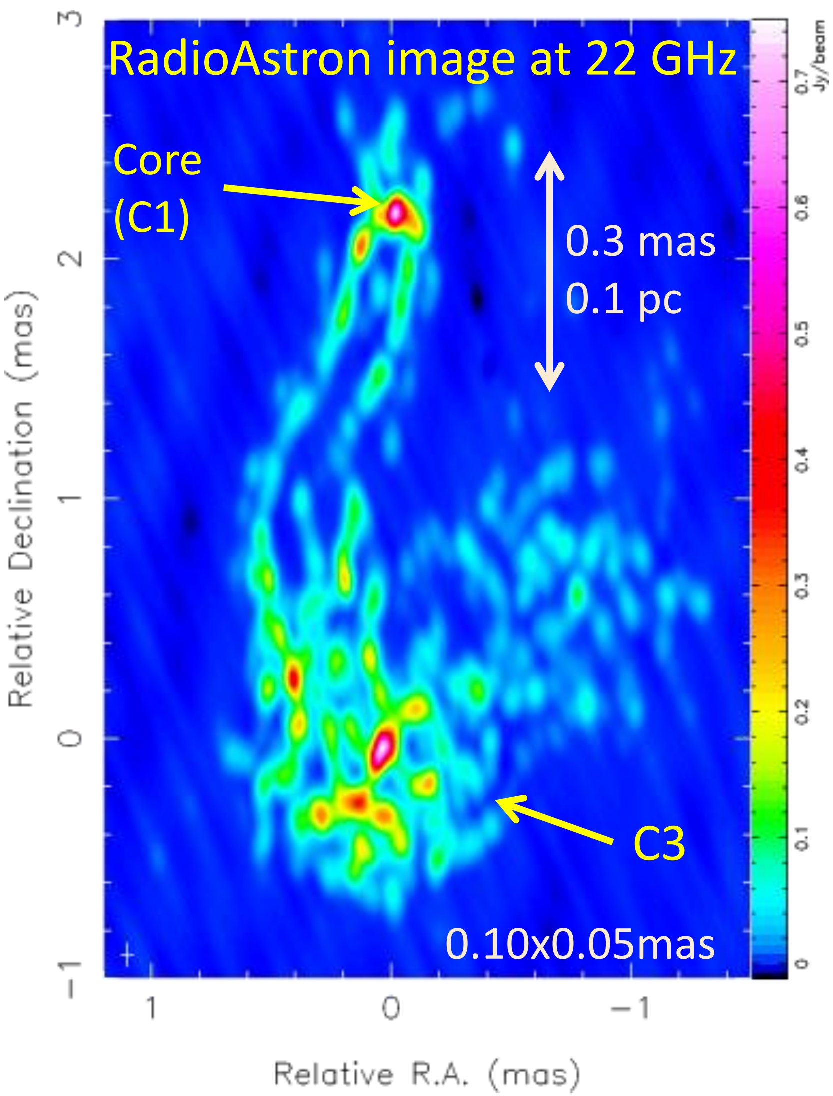
- Near-perigee space-VLBI imaging of nearby radio galaxies
- Aims at high spatial resolution (down to a few r_S) for studying the jet acceleration and collimation zone
- Targets: **Cen A** (*D=3.8Mpc, 1mas=3100*r_S), **M87** (*D=16Mpc, 1mas=140*r_S), **3C84** (*D=75Mpc, 1mas=1800*r_S)

5GHz 22GHz 5/22GHz

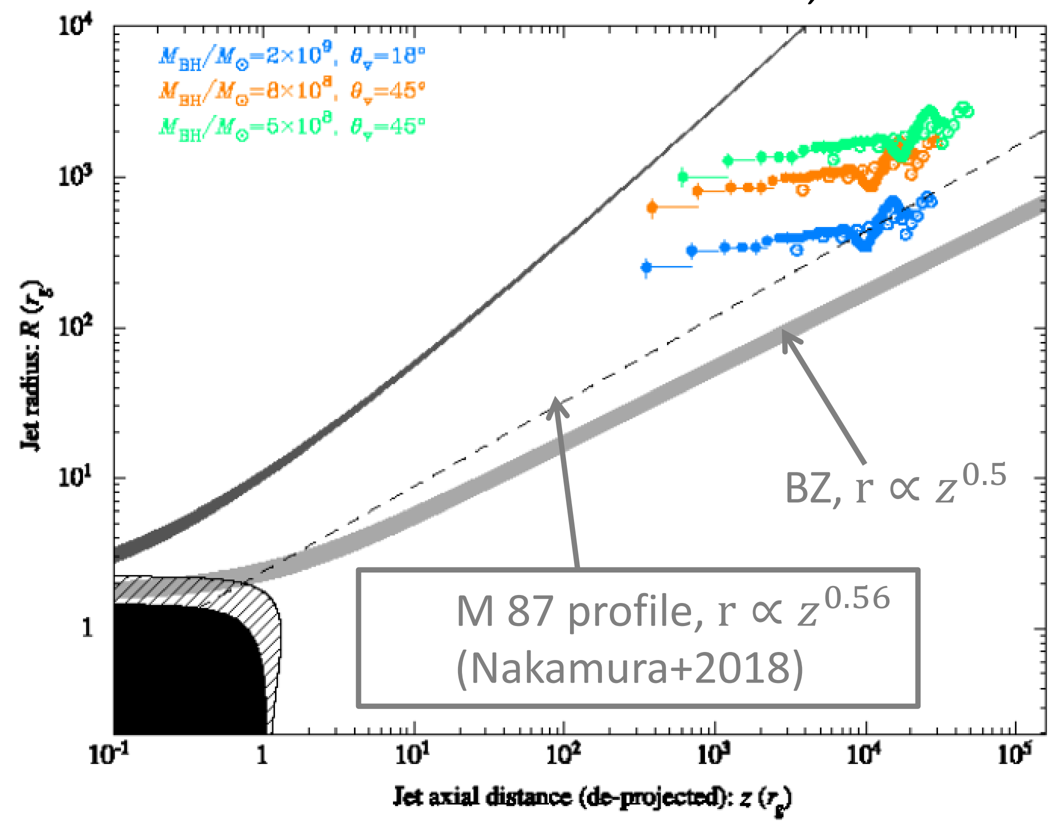
3C84 on Sep 21/22 2013



Collimation profile of the inner jet in 3C84



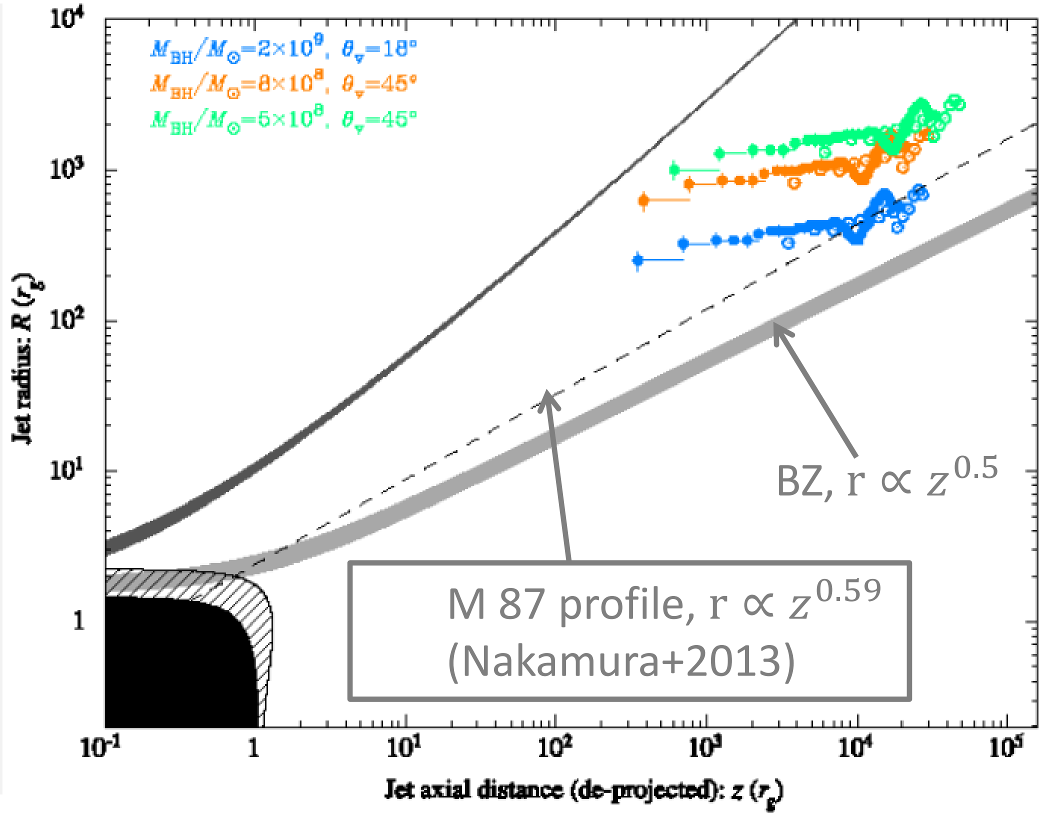
Giovannini, TS+ 2018



Collimation profile of the inner jet in 3C84

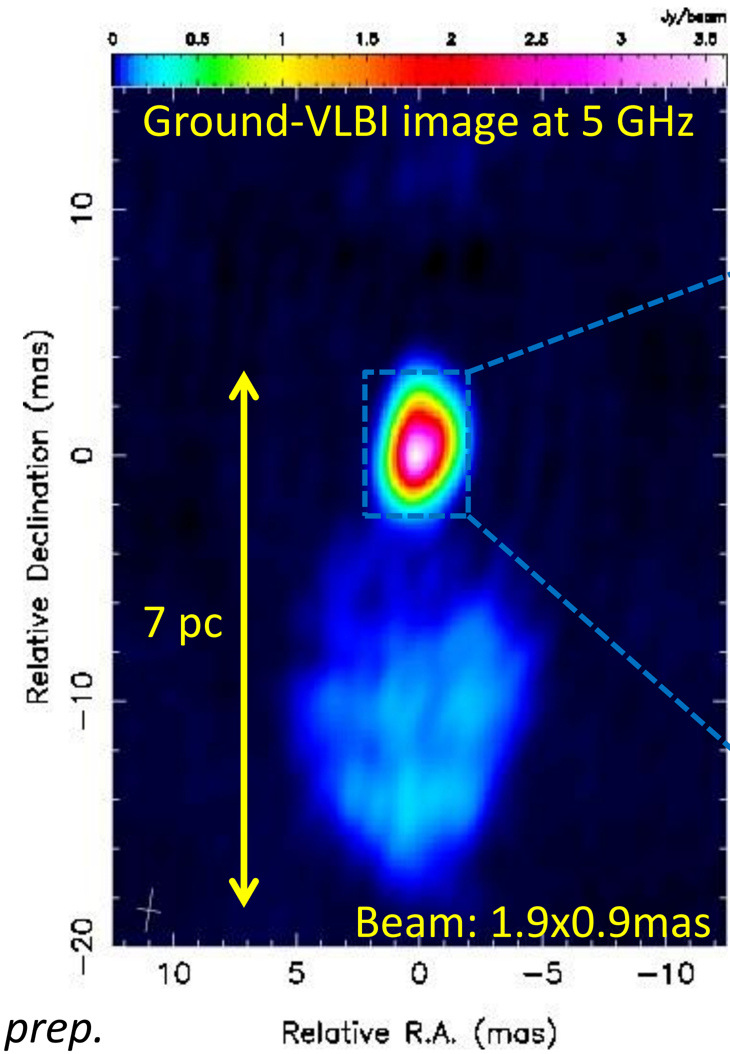
- Almost cylindrical flow with $r \propto z^{0.17}$ + oscillations of jet width. Shaped by external medium?
- If $p_{ext} \propto z^{-b}$=> $r \propto z^{b/4}$. For 3C84 $b \lesssim 1$ and $\rho \propto z^{-(b-1)} \approx z^{0}$. Flat density profile up to $\sim 10^{4} r_g \sim 0.8$ pc.
- What kind of 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)

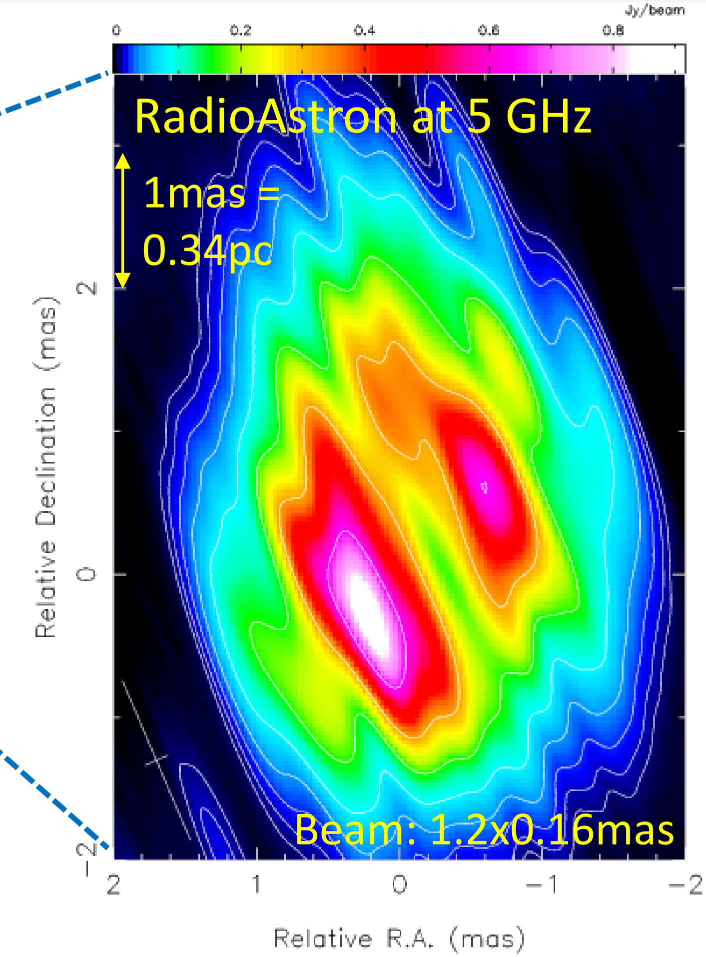
Giovannini, TS+ 2018



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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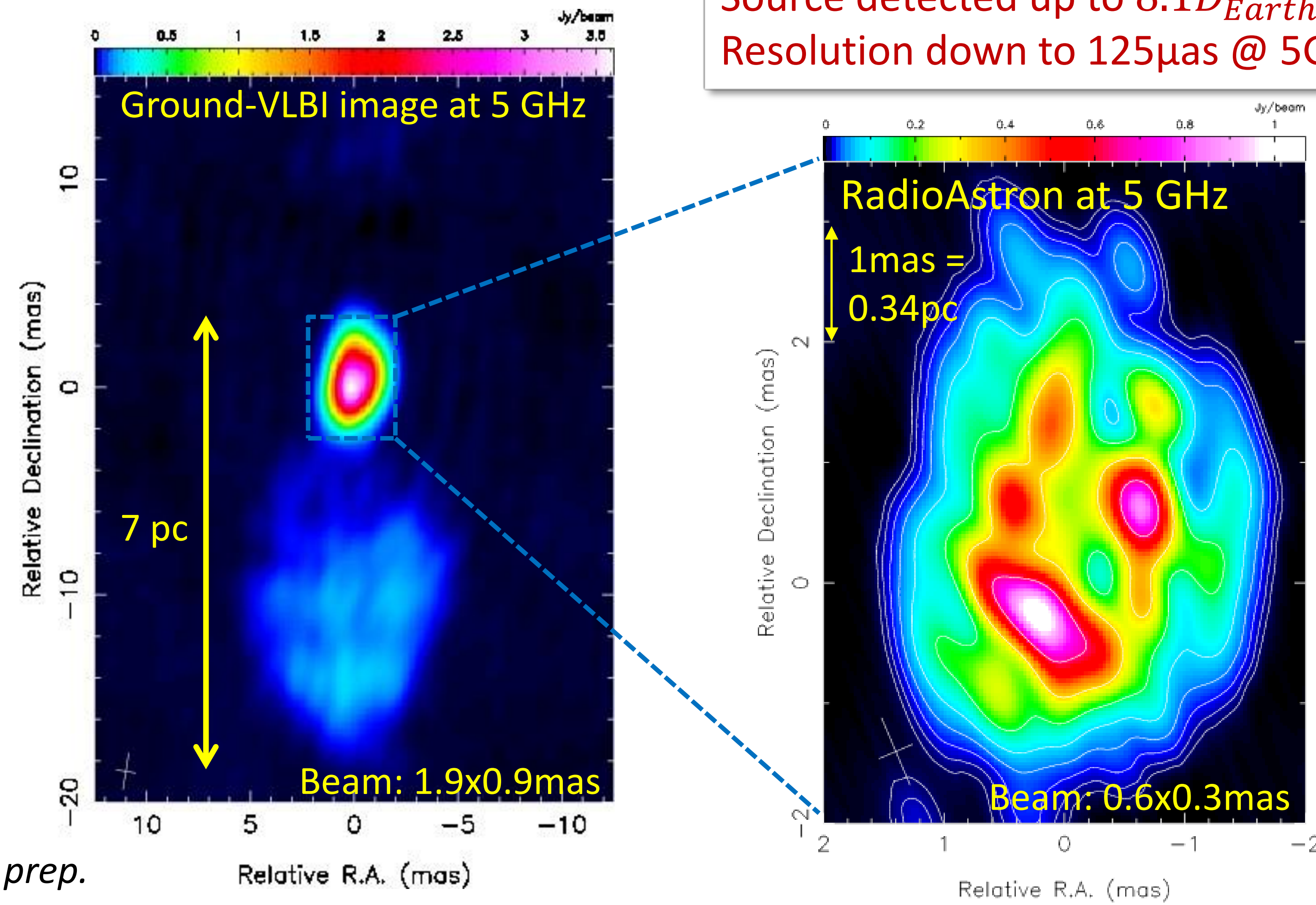
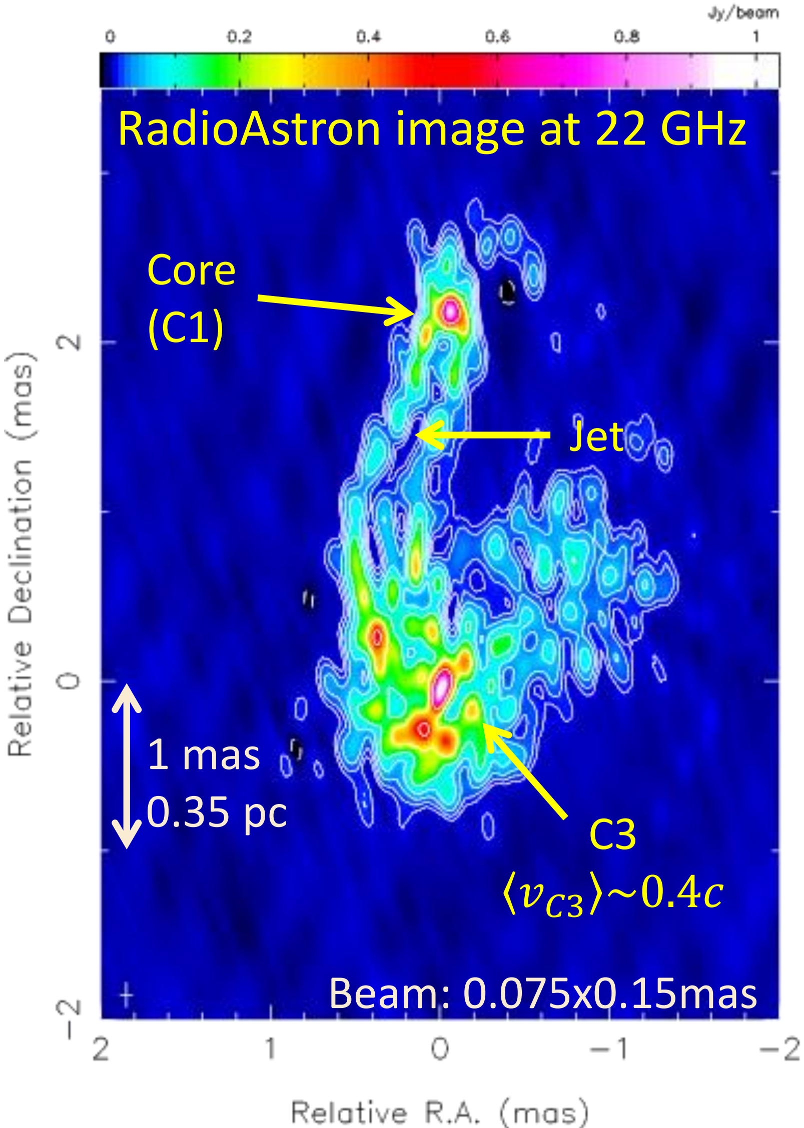
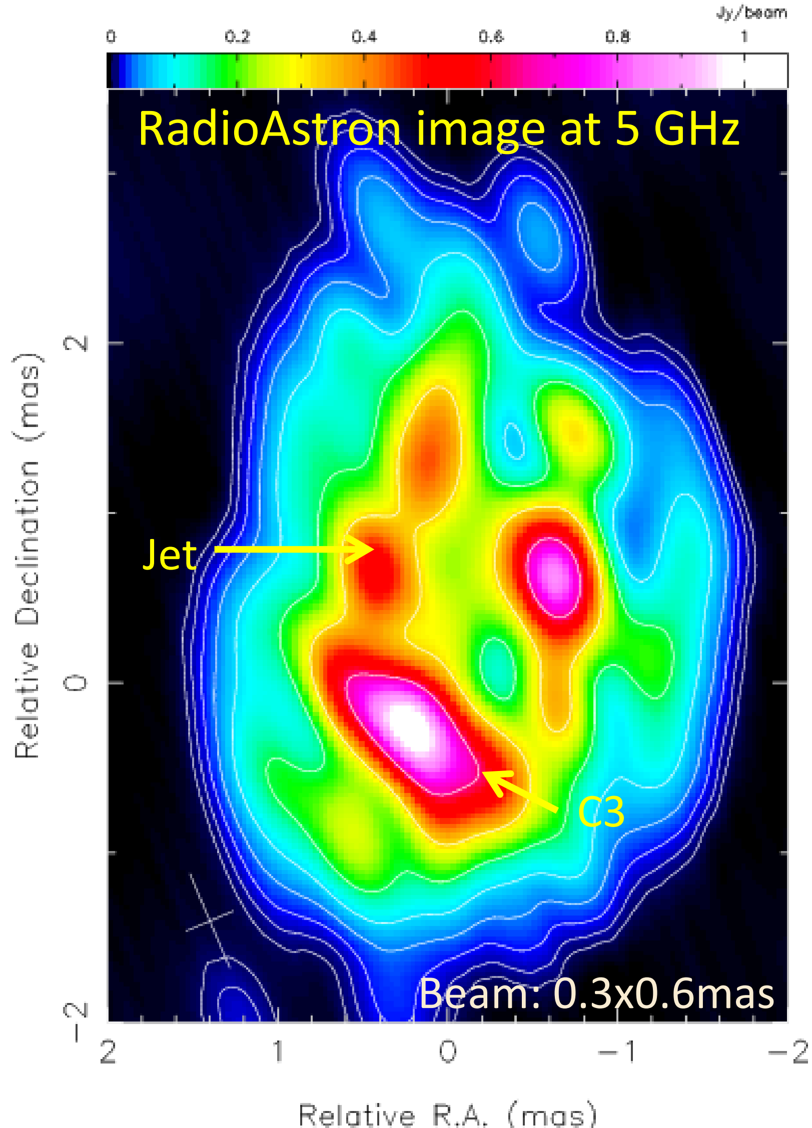


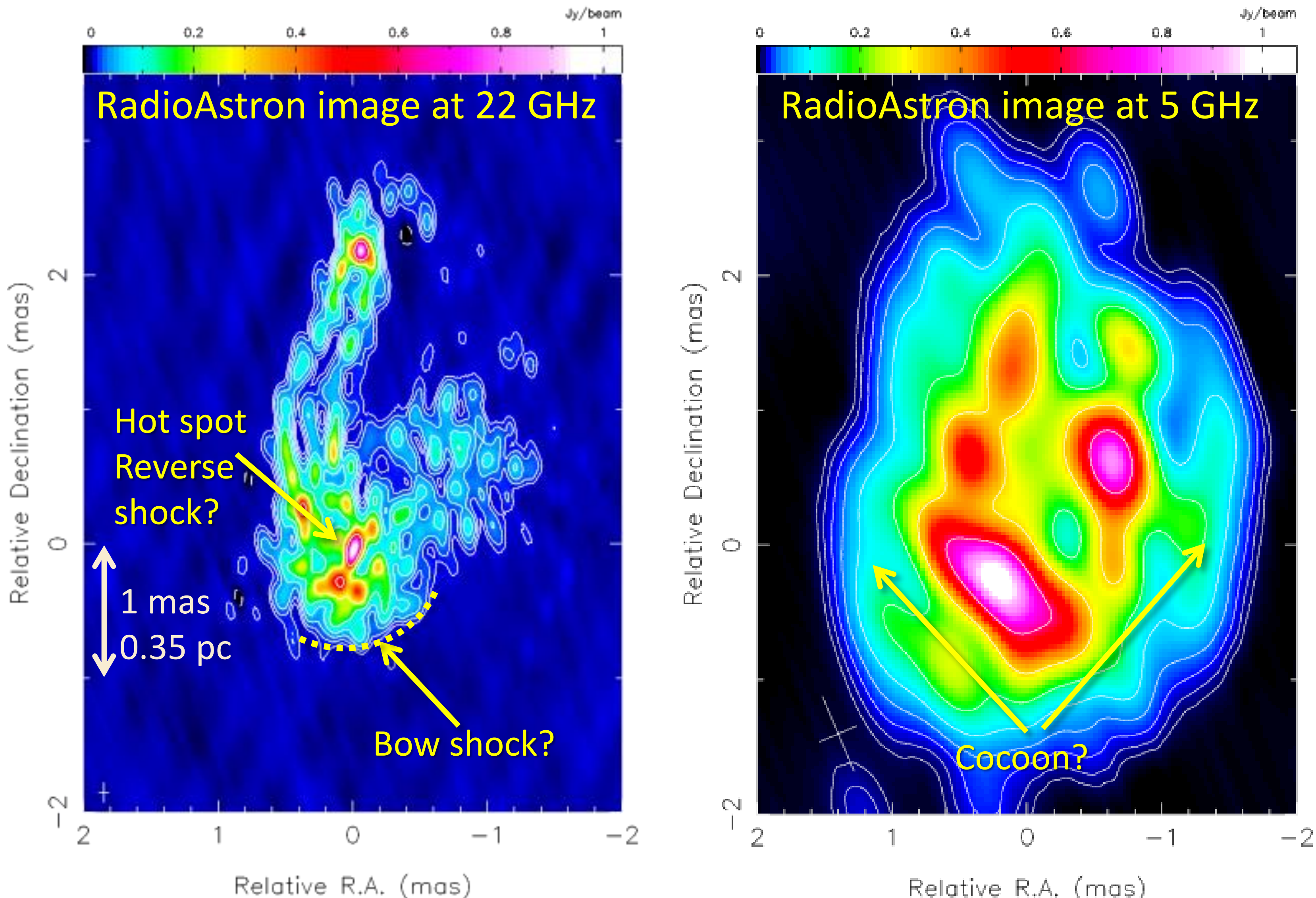
TS+ in prep.

Jet-ISM interaction within 1 pc

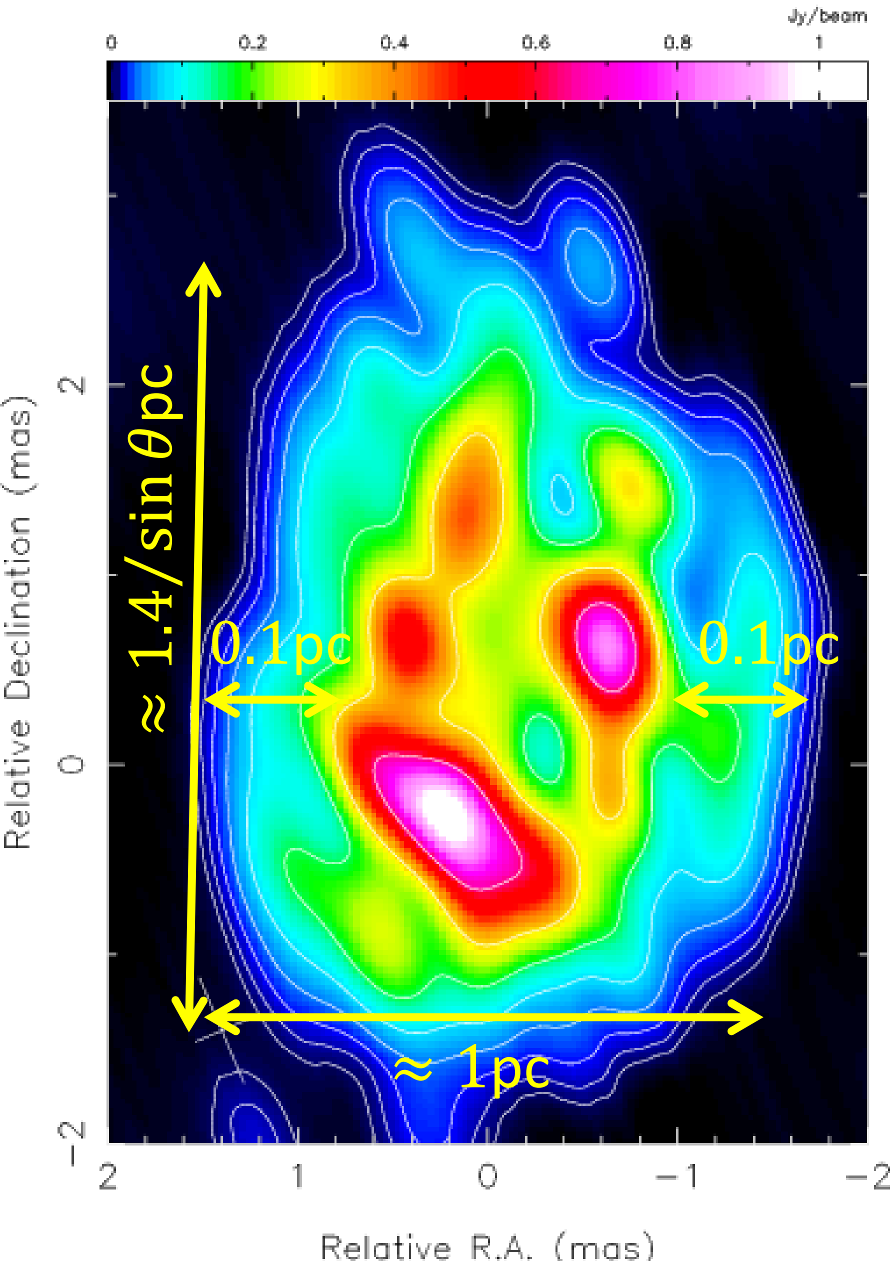




Jet-ISM interaction within 1 pc



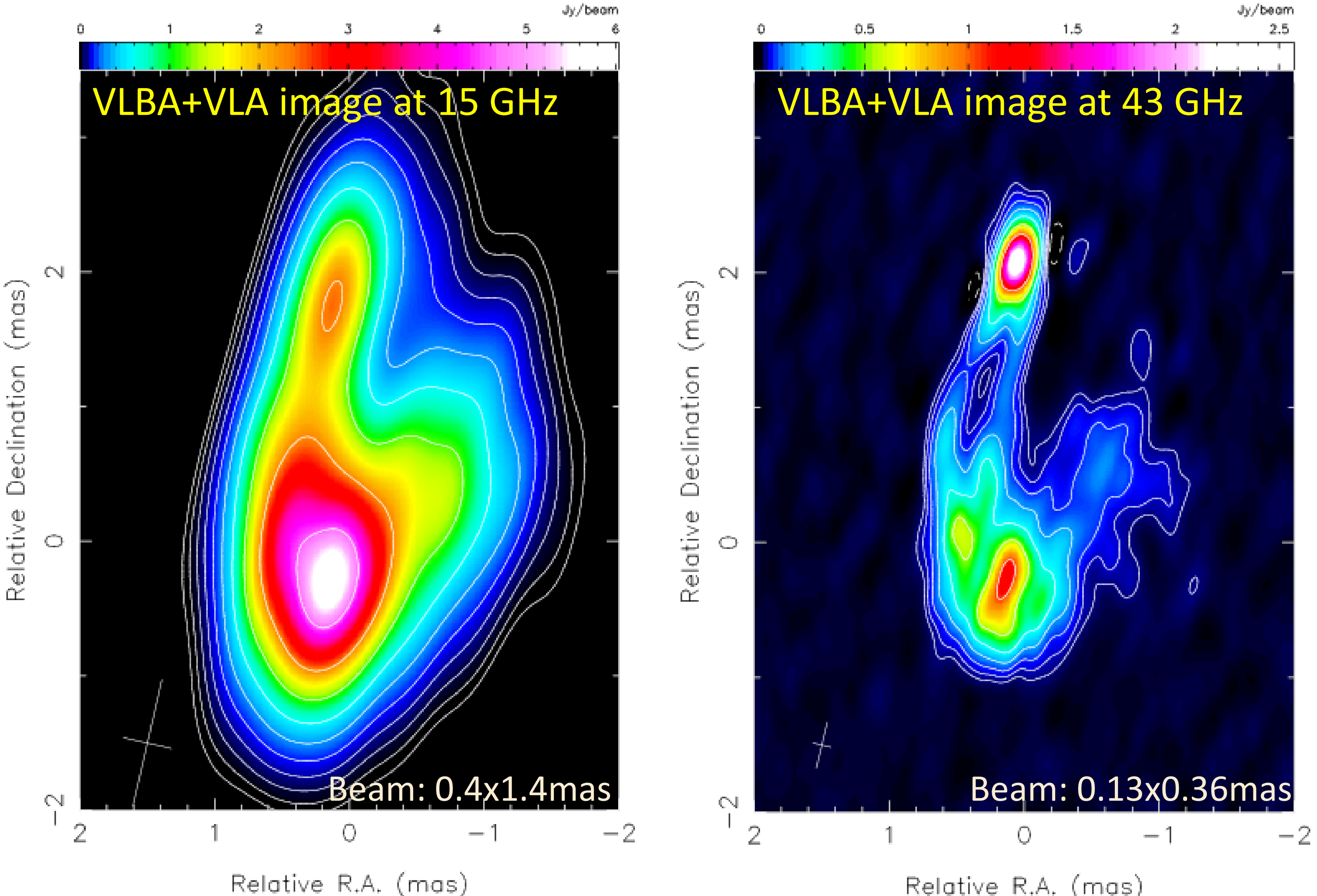
Mini-cocoon



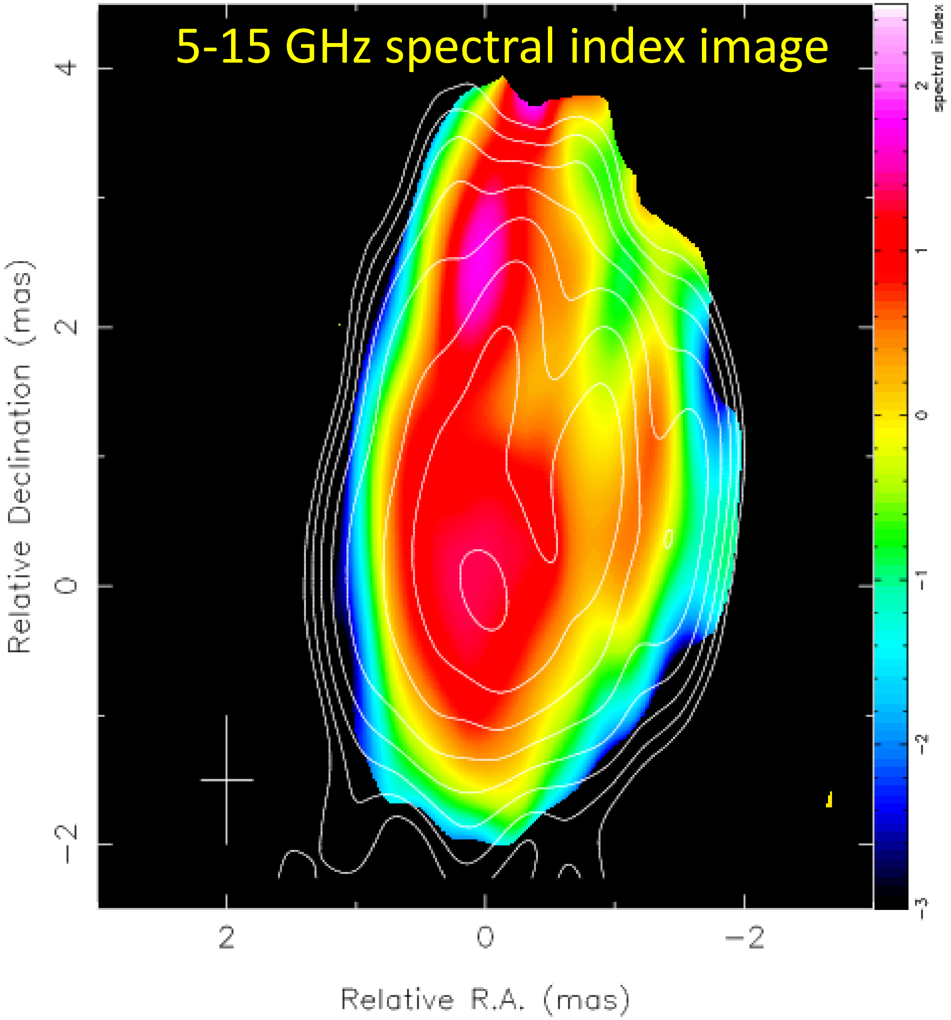
Measured properties

- $V_{c,tot} = 1.1/\sin\theta$ 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



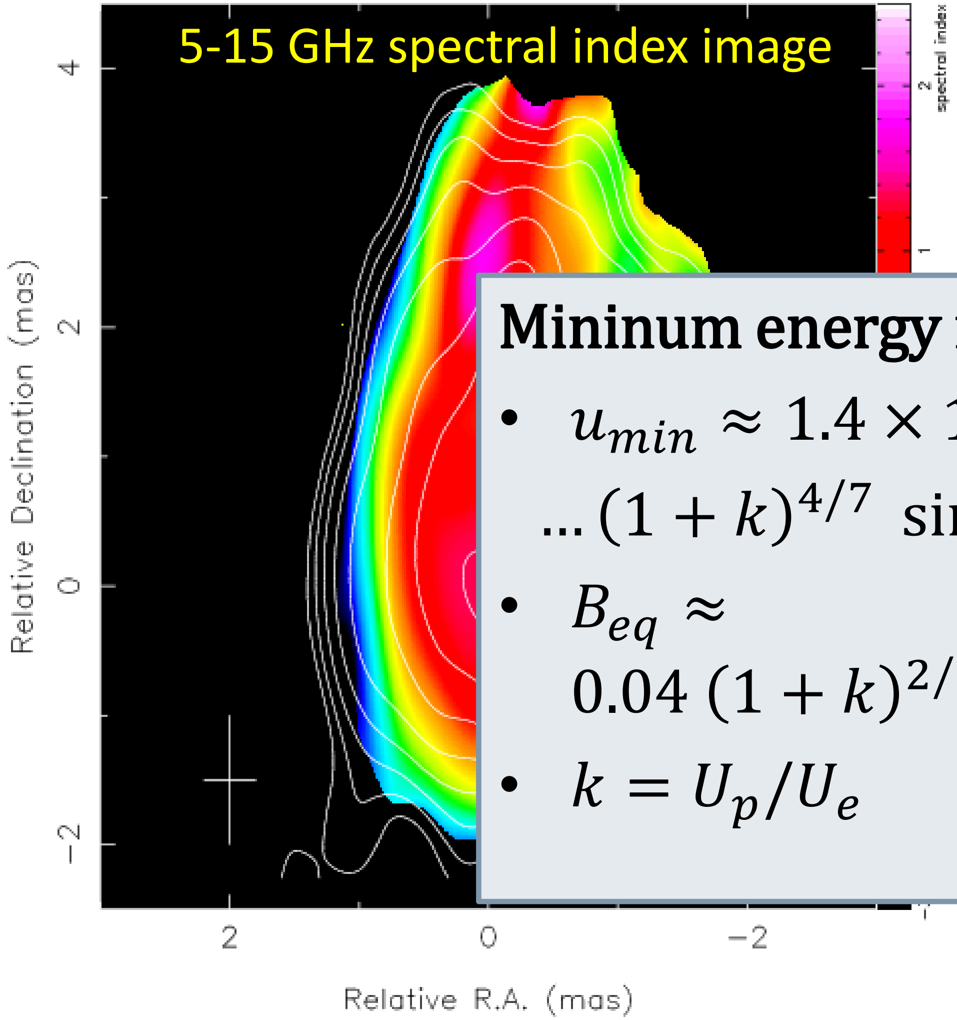
Mini-cocoon



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

- $V_{c,tot} = 1.1/\sin\theta$ pc^3
- Shell of 0.1 pc thickness:

$.6/\sin\theta$ pc^3

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/cm^3
- $B_{eq} \approx$
  $0.04\ (1+k)^{2/7} \sin^{2/7}\theta$ G
- $k = U_p/U_e$

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

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

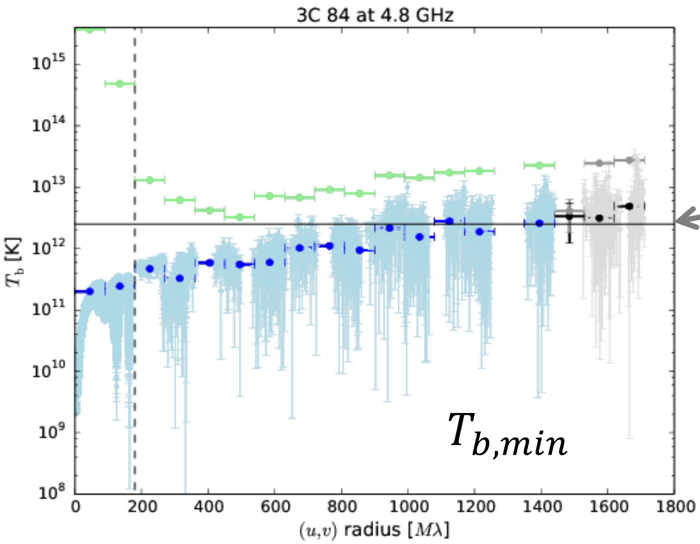
The typical jet power of 3C84 is enough to inflate the mini-cocoon in 10 years

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}

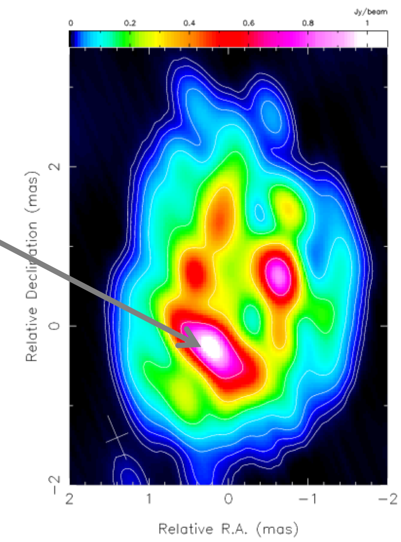
A FEW WORDS ABOUT PHYSICAL CONDITIONS IN C3 HOT SPOT

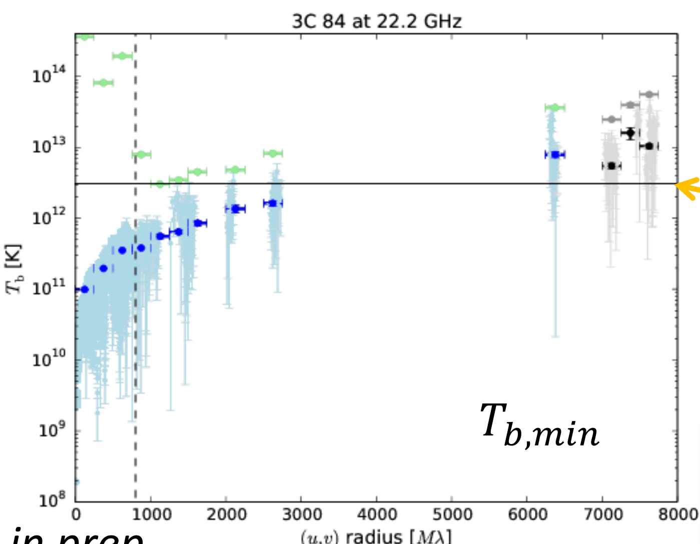
High brightness temperature in C3



5 GHz

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

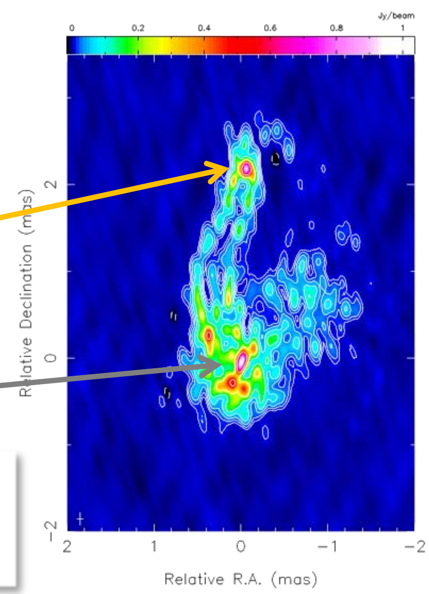




22 GHz

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

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

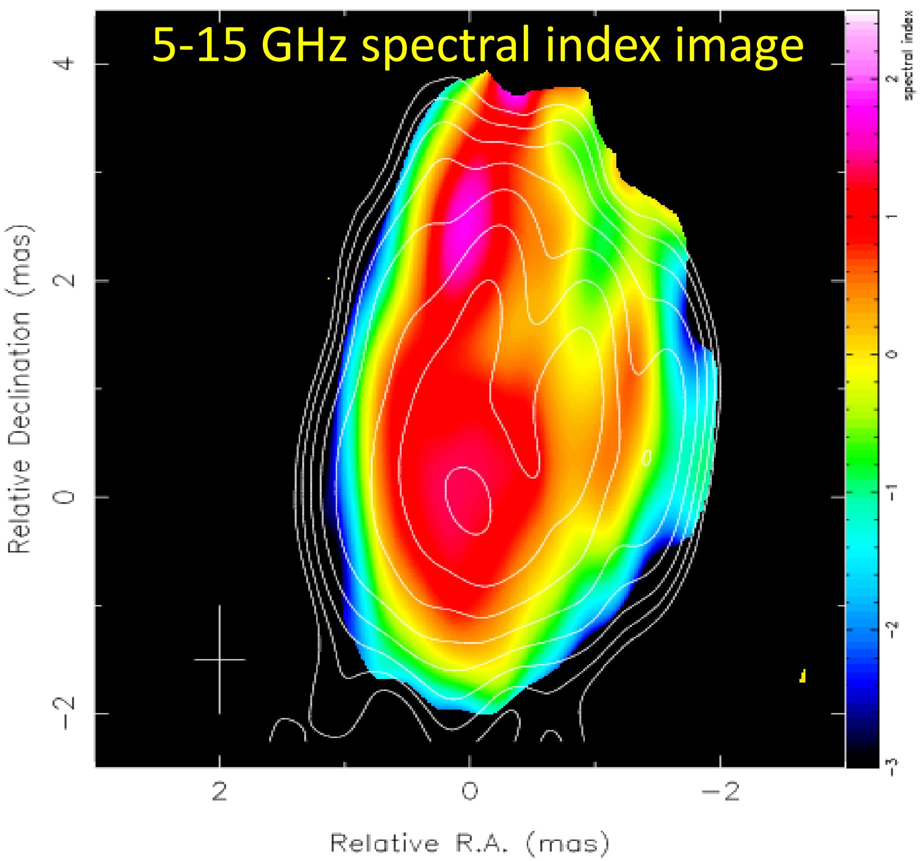


Inverse Compton limit:
$T_{b,obs} \lesssim 10^{12} \cdot \delta$ K

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: $B \approx 1.4 \times 10^{21} \upsilon_{GHz} T_b^{-2}$ … … $\delta (1+z)^{-1} \approx 1 \cdot \delta$ mG



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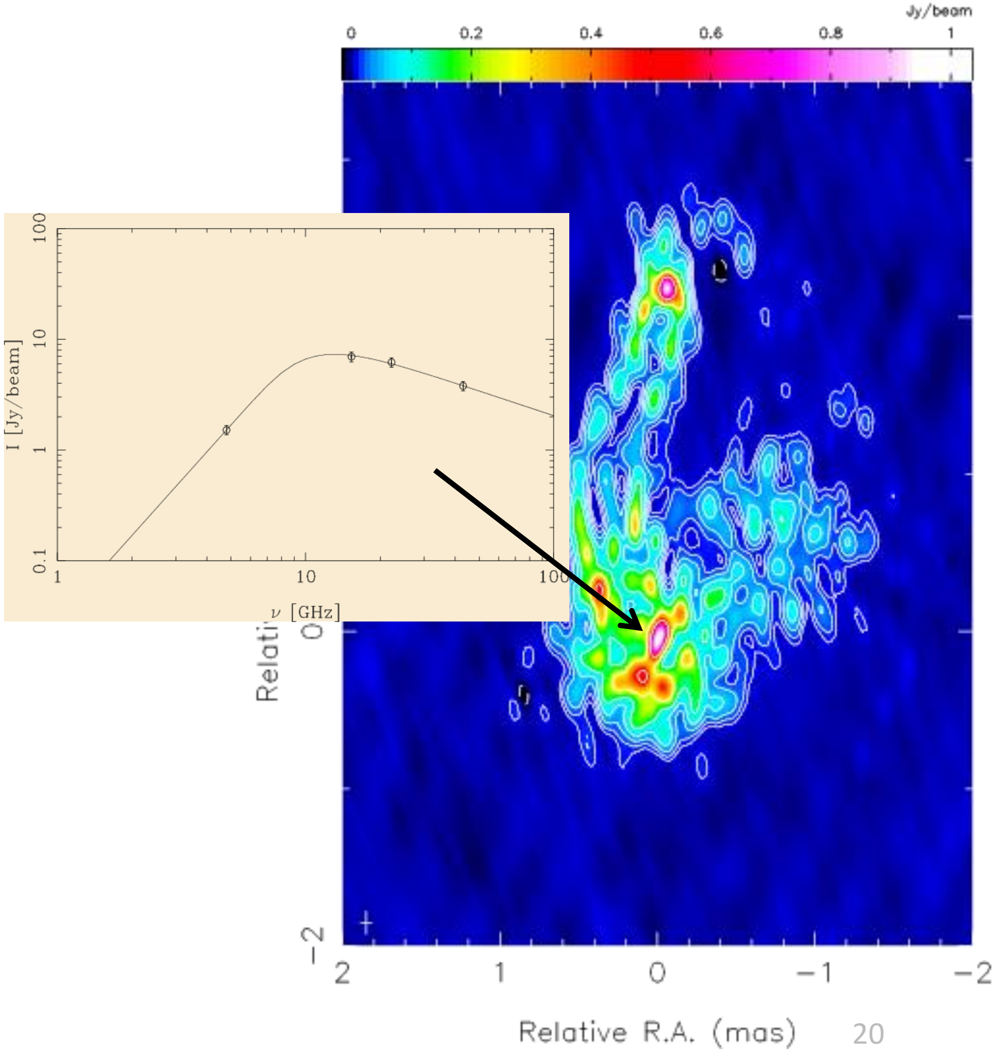
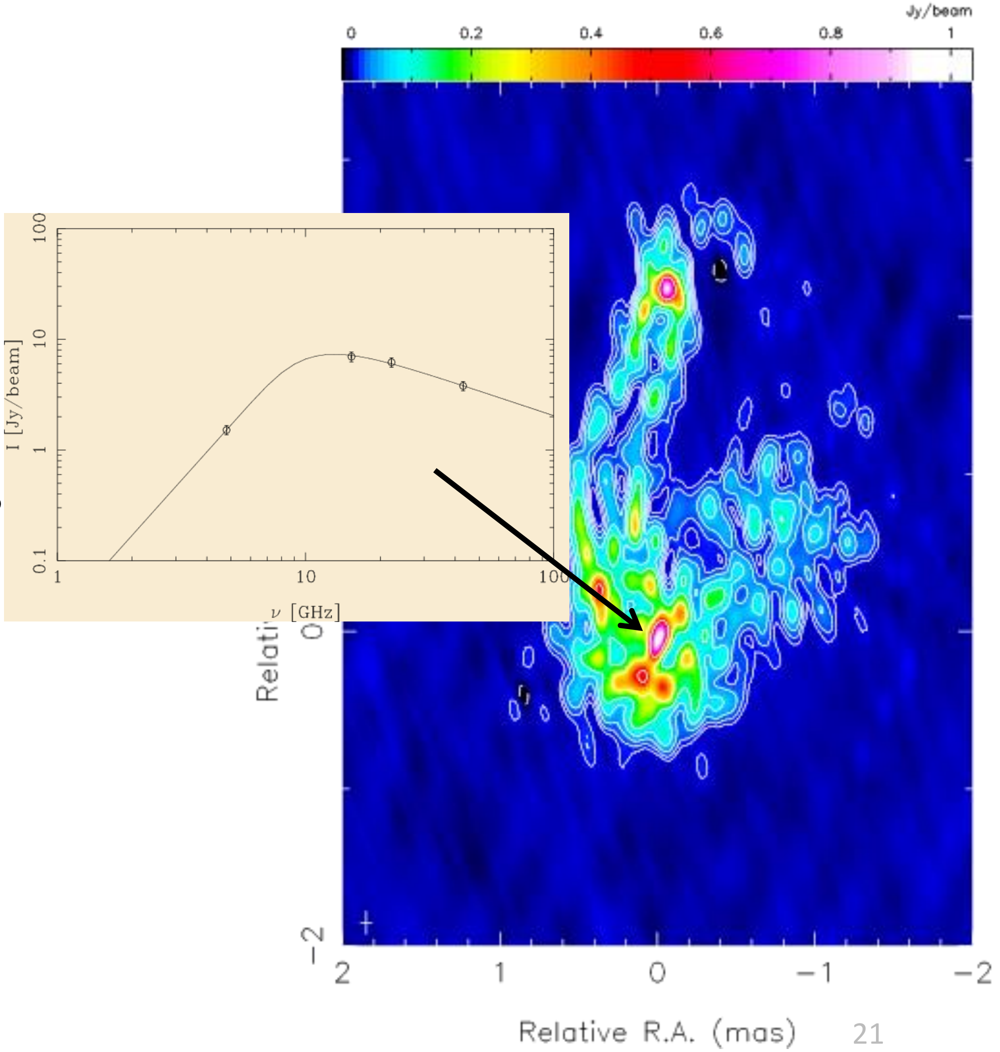
- Hence, $T_{b,5GHz} \sim T_e$ and we can estimate magnetic field:
  $B \approx 1.4 \times 10^{21} \upsilon_{GHz} T_b^{-2}$ …
  … $\delta (1+z)^{-1} \approx 1 \cdot \delta$ mG
- Other way: measure intensity of a resolved emission region at the synchrotron turnover frequency:
  $B_{SSA} \approx 10^{-3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