Zooming in the jet formation site in AGN with *RadioAstron*

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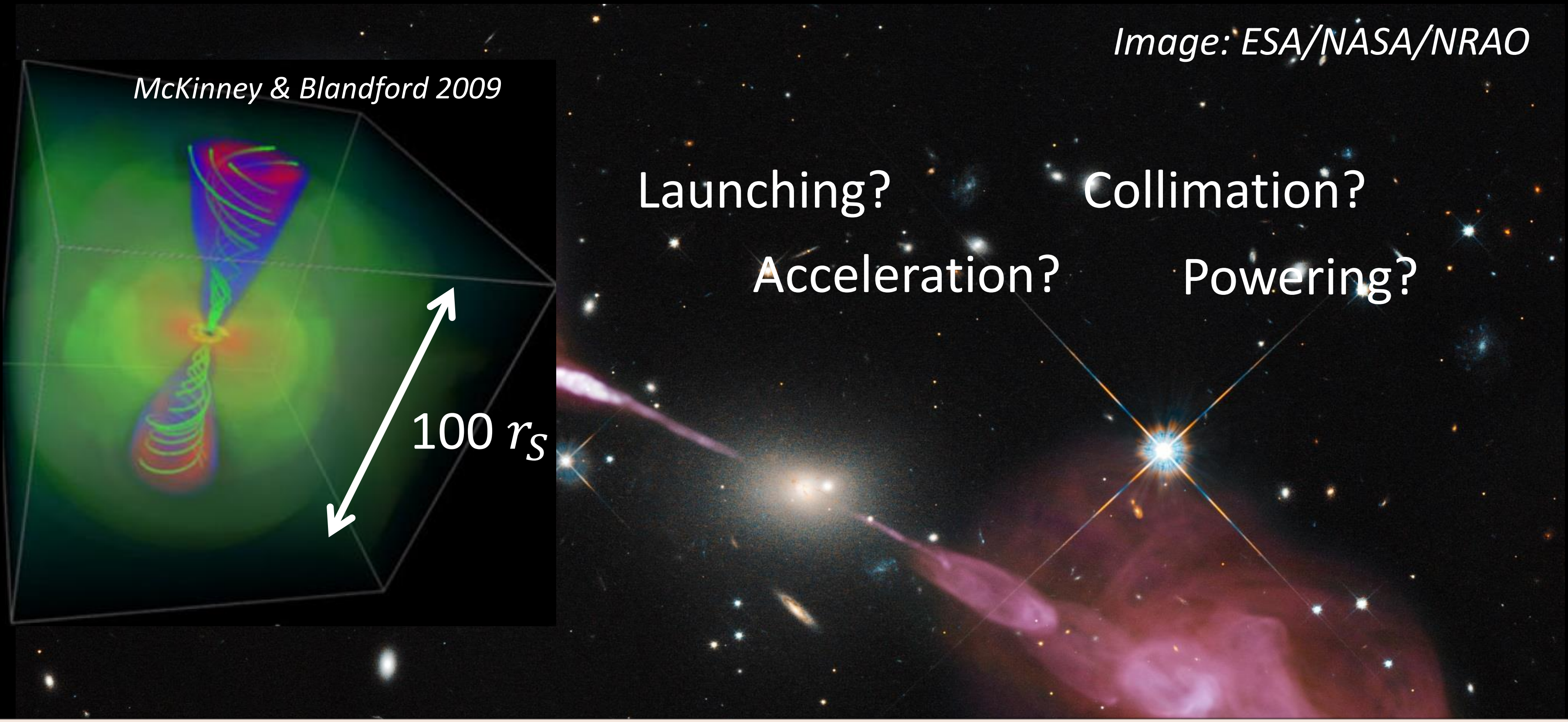
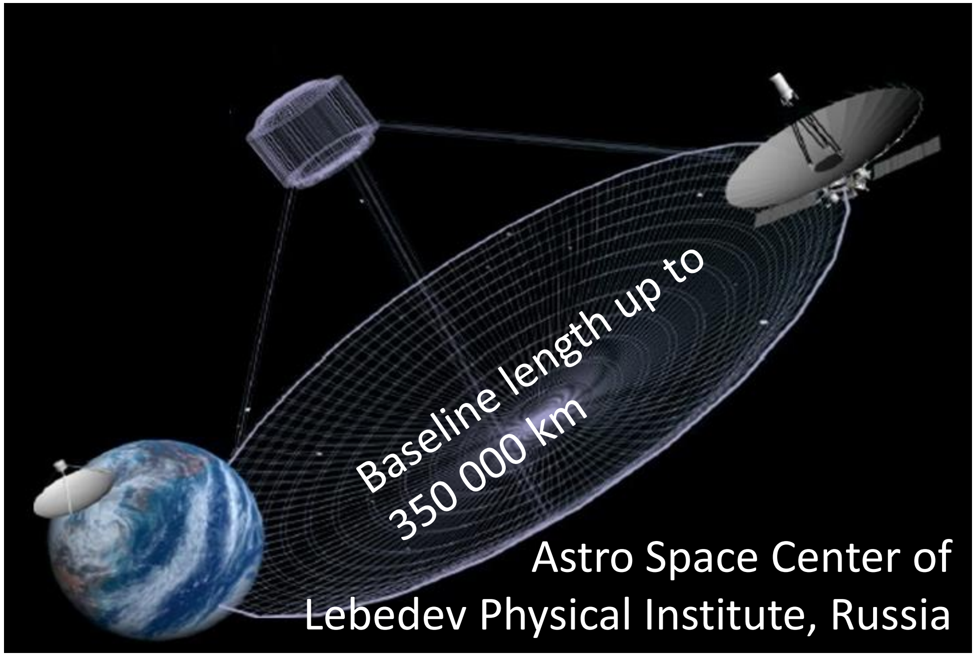
Understanding jet formation



Significant progress in (3D GRMHD) simulations. To **test** the MHD model, our observations need to resolve the jets at least down to $\mathbf{10^1 - 10^2 r_S}$. In imaging, angular resolution of a few tens of **microarcseconds** is needed even for the nearby sources. **Solutions: space-VLBI or mm-VLBI.**

RadioAstron Space-VLBI mission



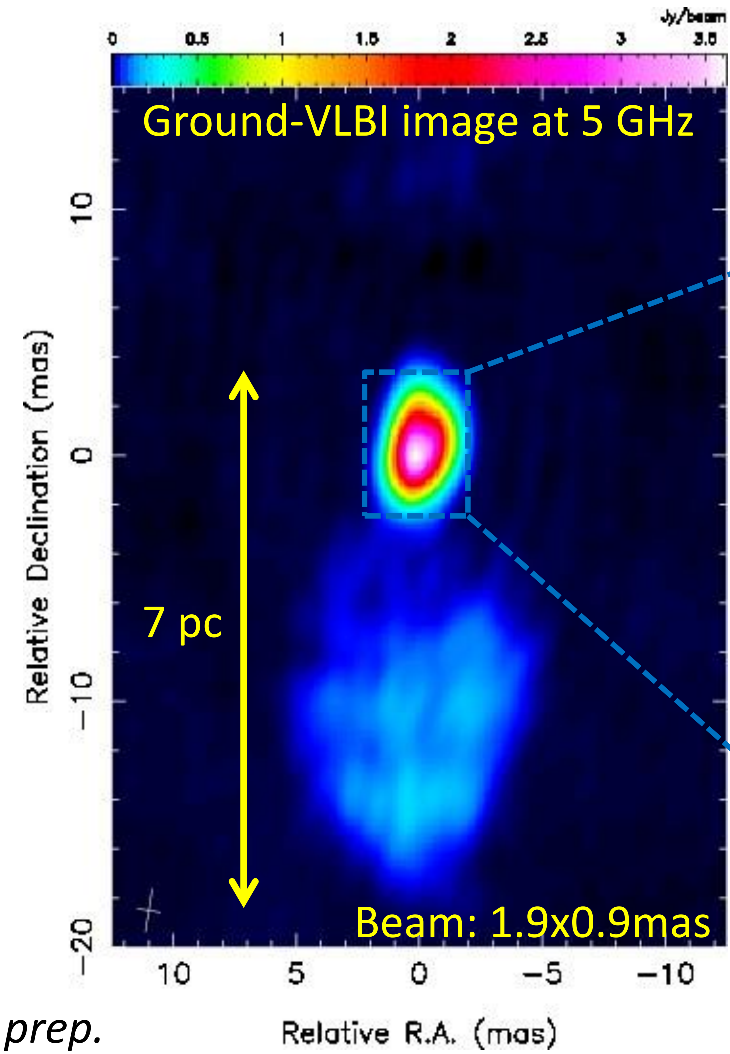
- 10-m Russian space radio telescope launched in 2011
- Apogee height: 350 000 km
- Obs. frequencies: 1.6–22 GHz
- Used together with ground radio telescopes as an interferometer
- Record angular resolutions: 8μas ($H_2$0 megamaser in NGC4258) and 12μas (quasar 3C279; *Savolainen et al. in prep.*)

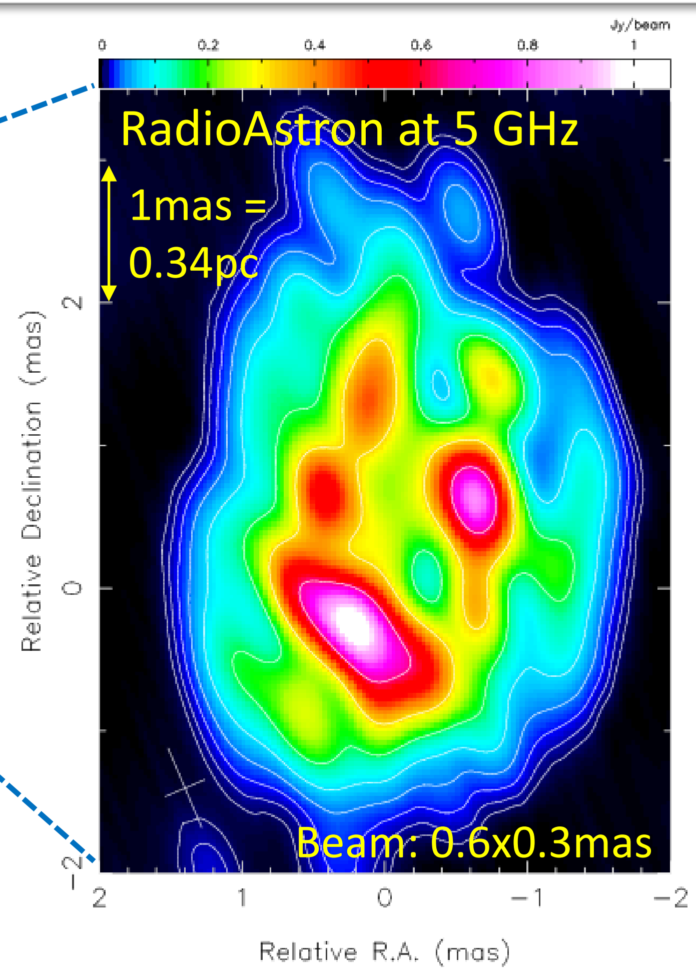
RadioAstron Nearby AGN Key Science Program

- Near-perigee space-VLBI **imaging** of nearby radio galaxies involving up to ~30 ground radio telescopes
- Aims at high spatial resolution (down to a few r_S for M87) 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** (NGC1275; *D=75Mpc, 1mas=1800*r_S)

3C84 with RadioAstron and global VLBI at 5/22 GHz

Source detected up to $8.1D_{Earth}$.
Fringe spacing of 125μas @ 5GHz.

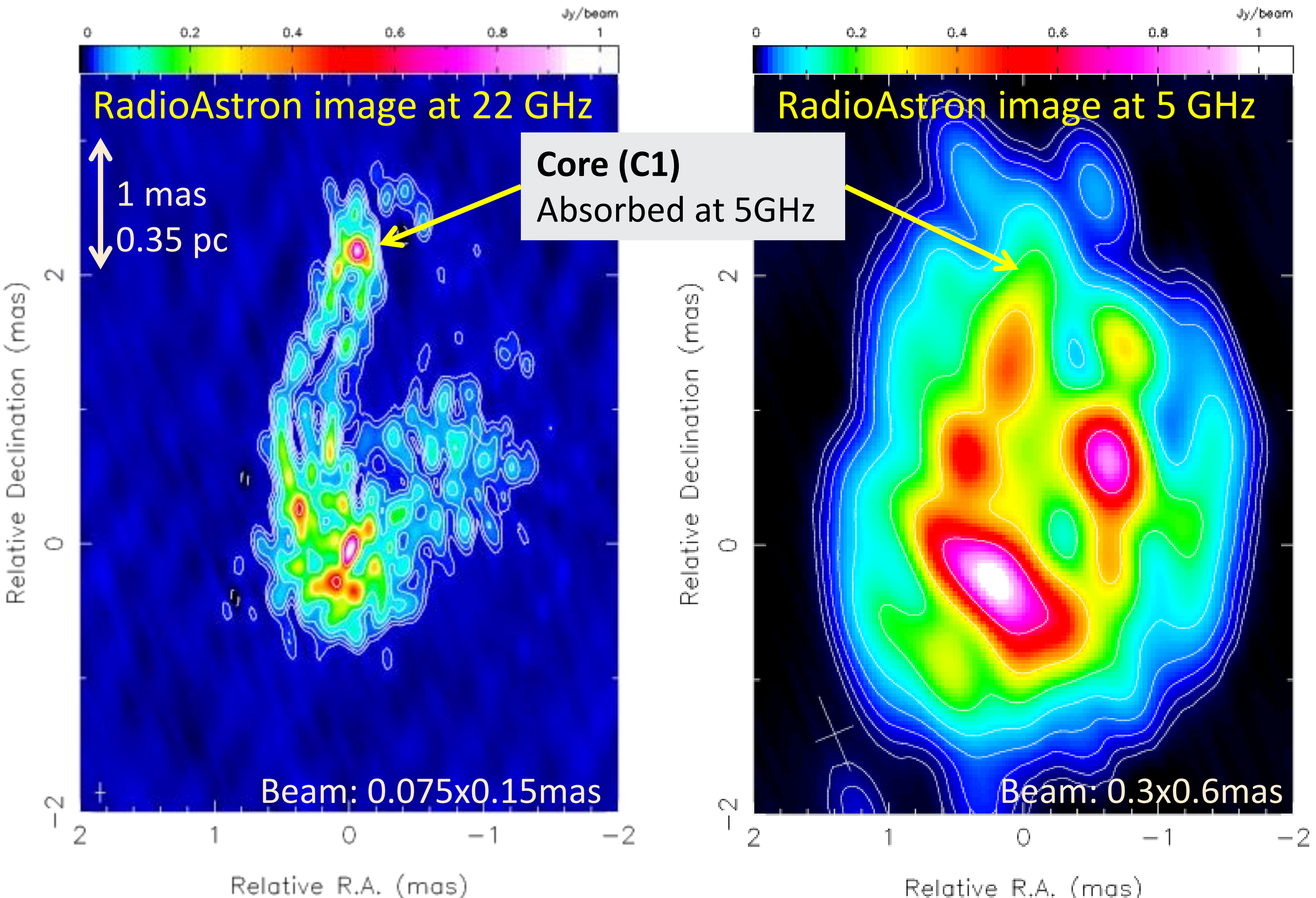




TS+ in prep.

3C84 with RadioAstron and global VLBI at 5/22 GHz

Source detected up to $8.1 D_{Earth}$. Fringe spacing of 27μas @ 22GHz.



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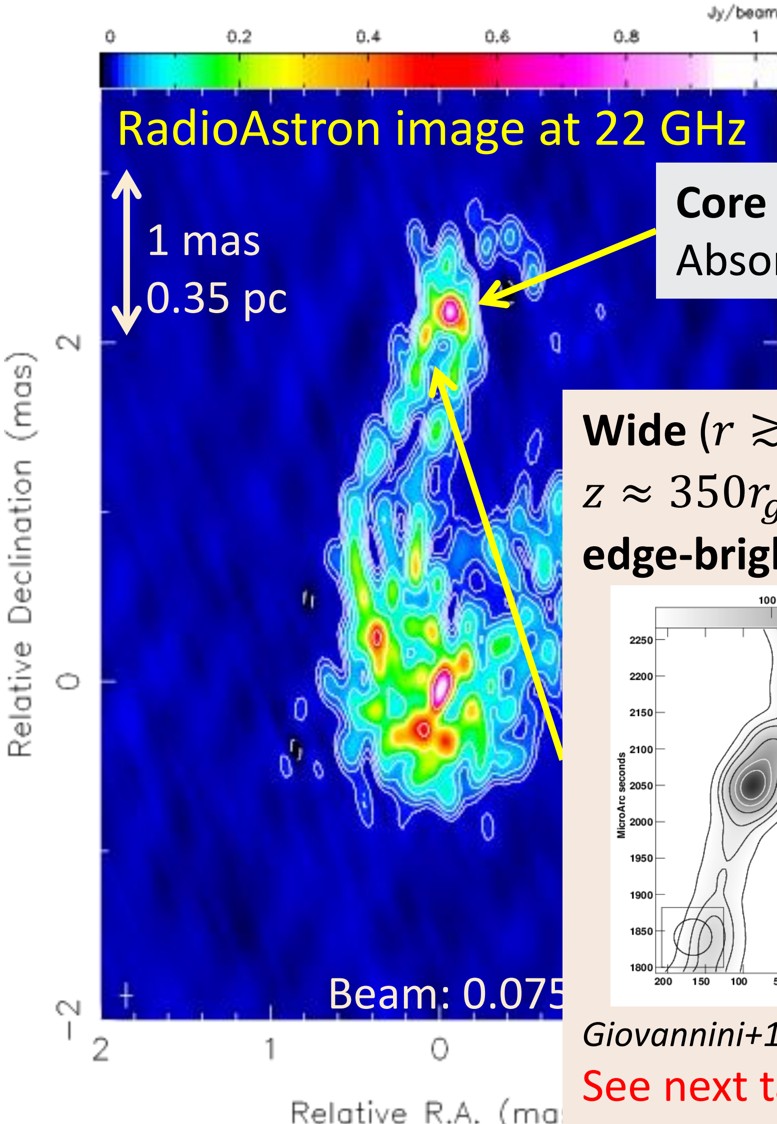
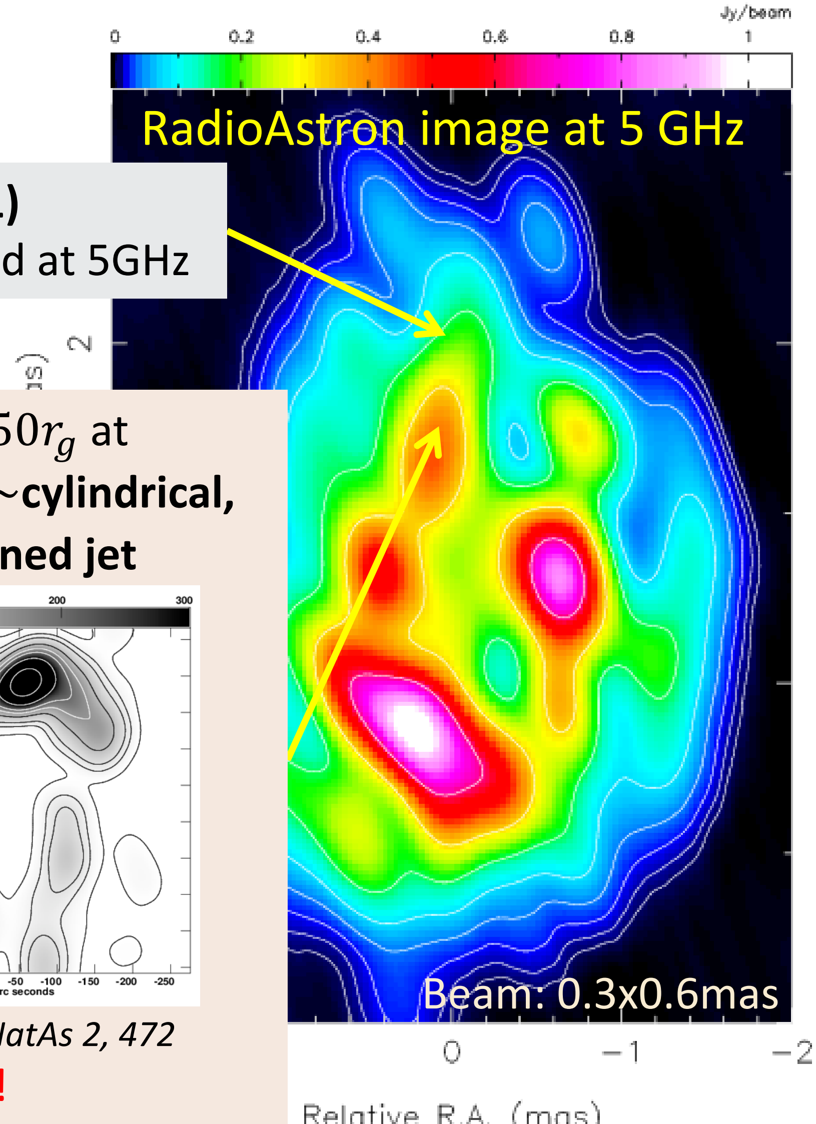
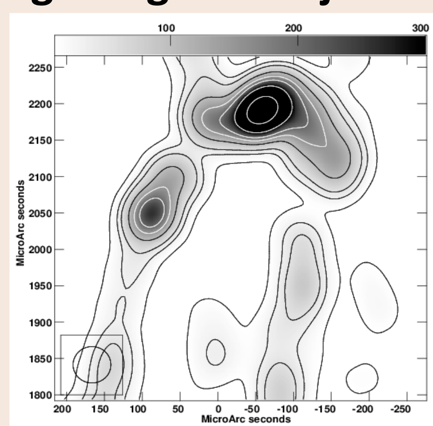




Core (C1)
Absorbed at 5GHz

Wide ($r \gtrsim 250 r_g$ at $z \approx 350 r_g$), ~**cylindrical, edge-brightened jet**



Giovannini+18, NatAs 2, 472

See next talk!

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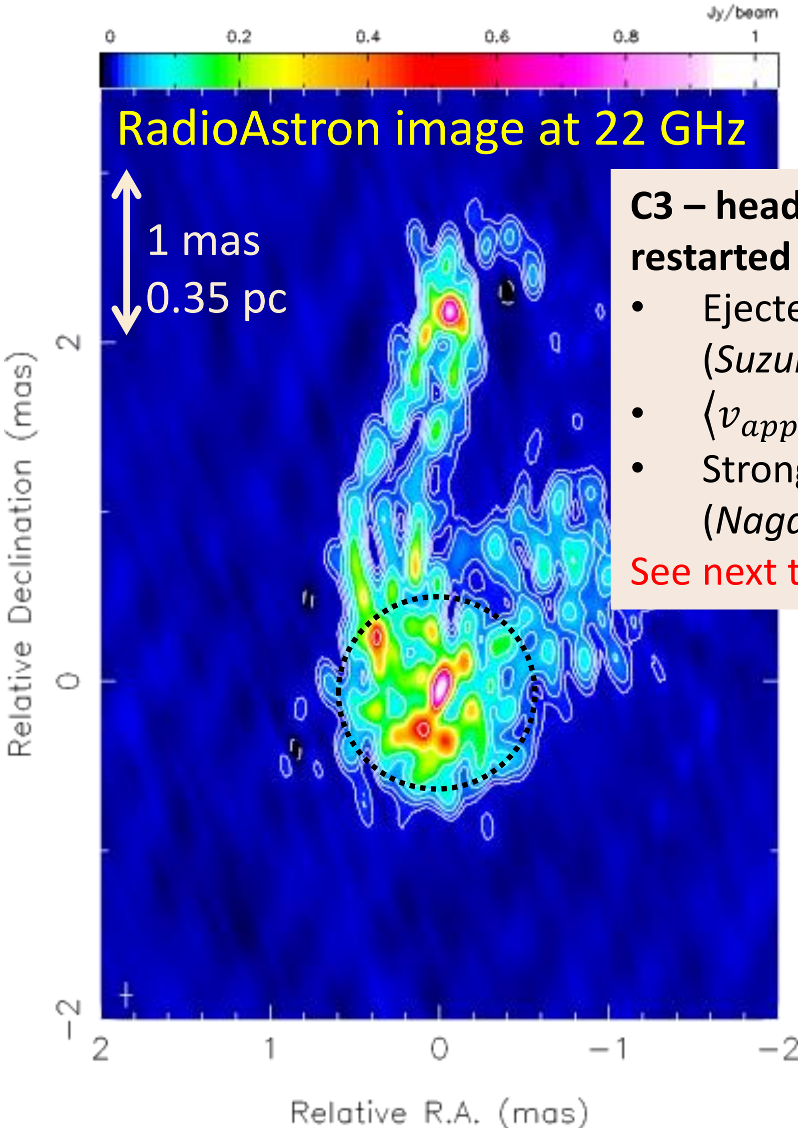
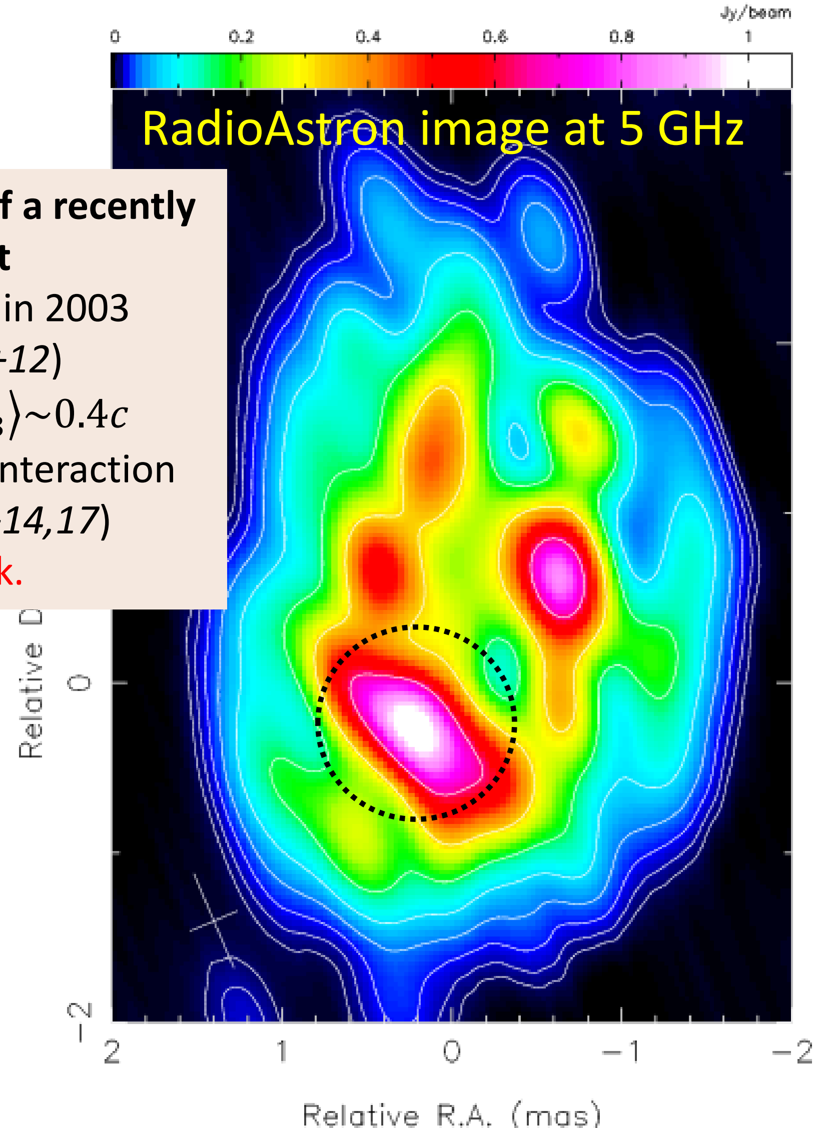


C3 – head of a recently restarted jet

- Ejected in 2003 (*Suzuki+12*)
- $\langle v_{app,C3} \rangle \sim 0.4c$
- Strong interaction (*Nagai+14,17*)

See next talk.



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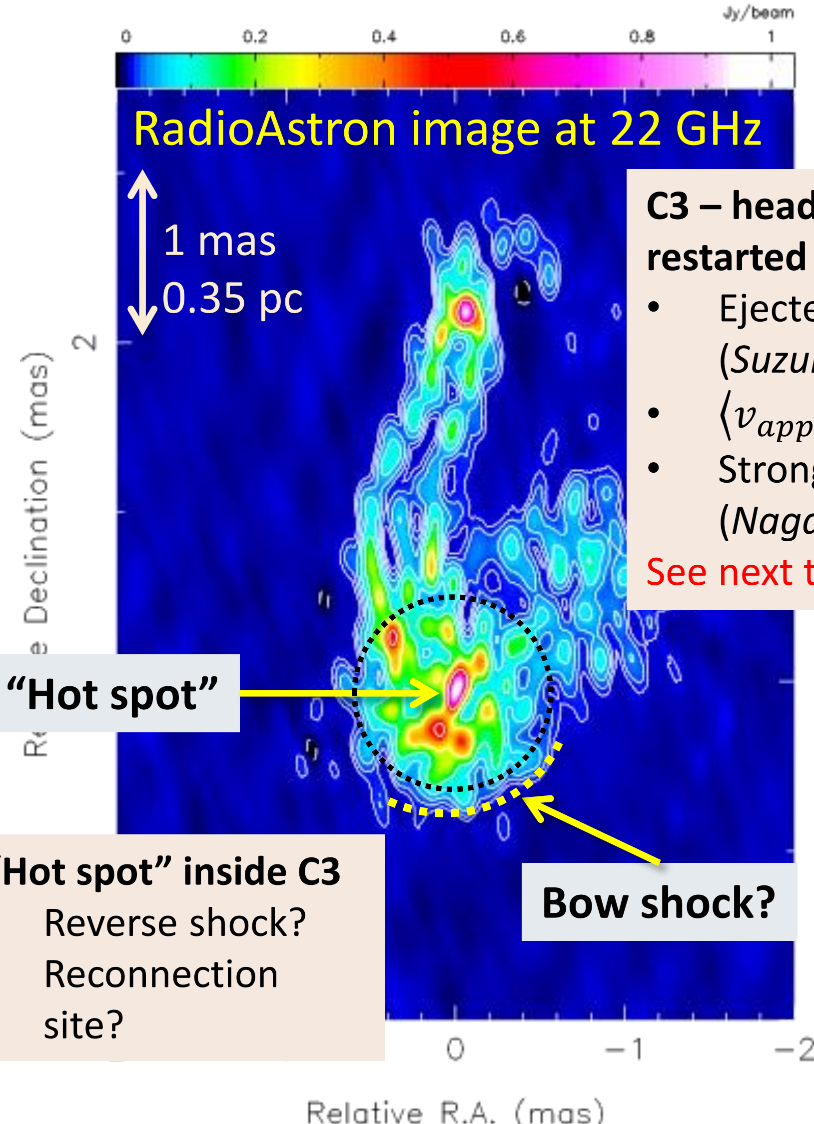

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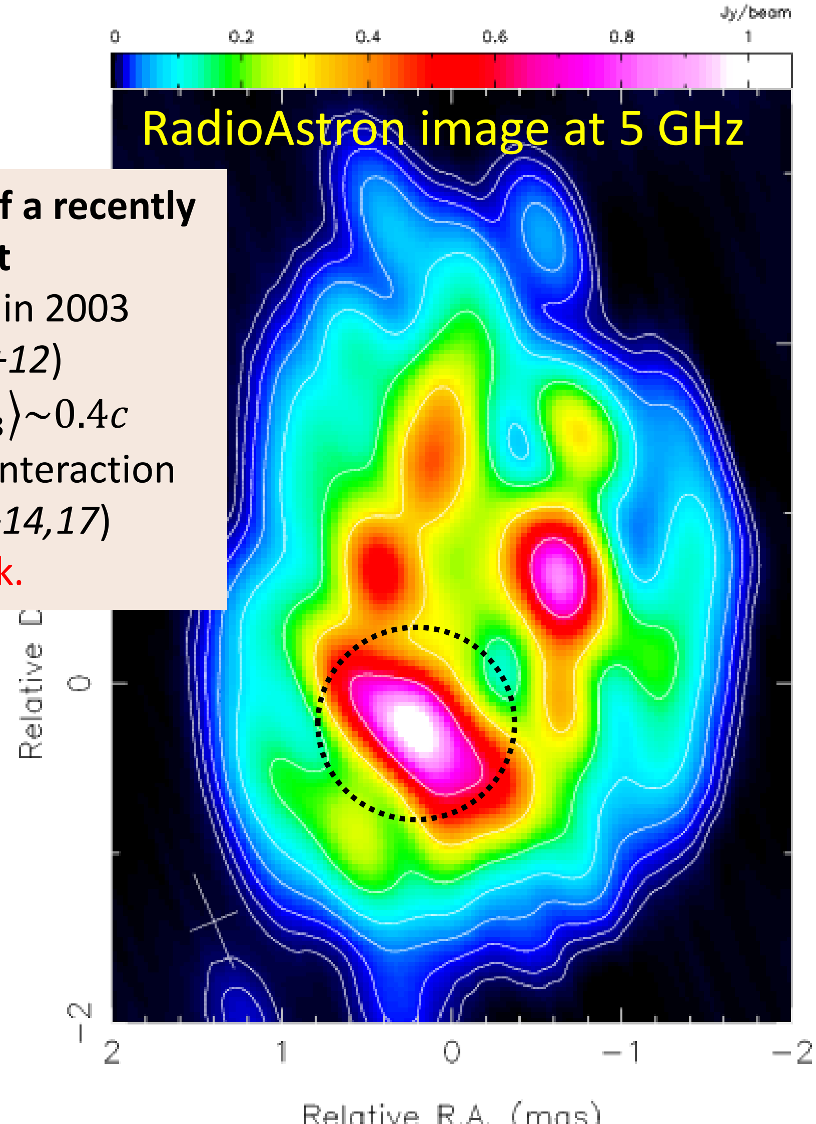
"Hot spot" inside C3
- Reverse shock? Reconnection site?



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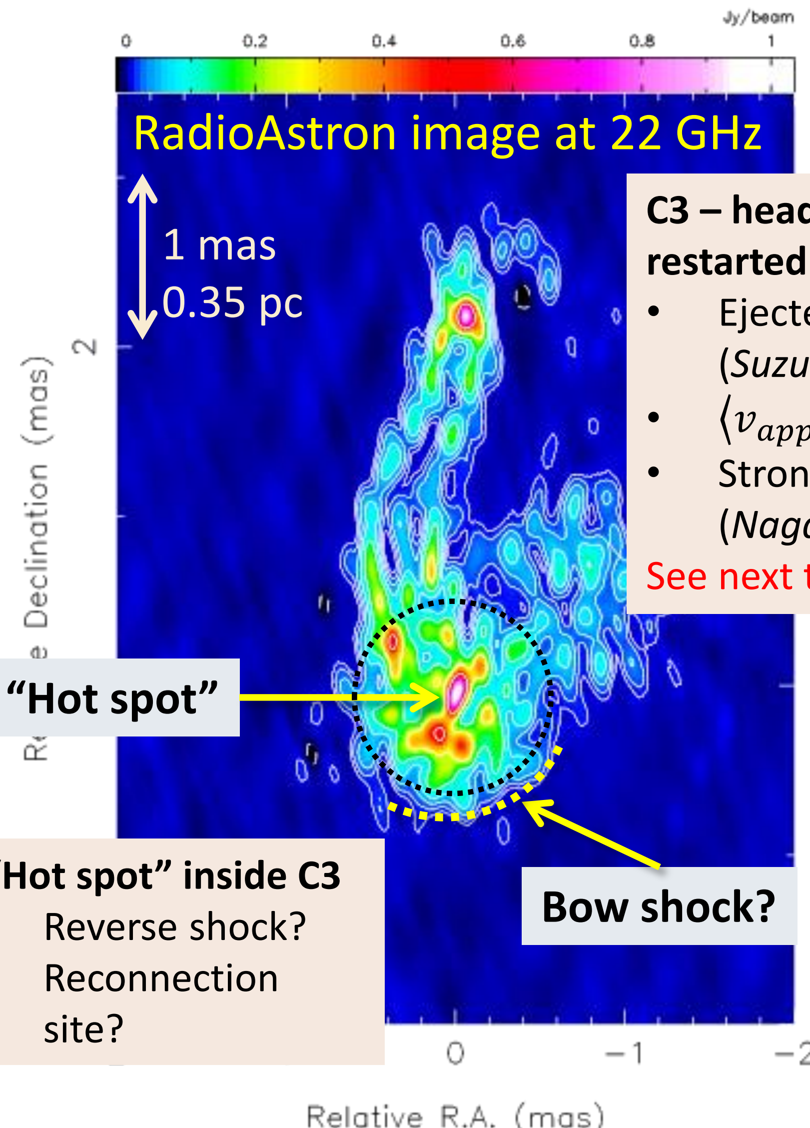

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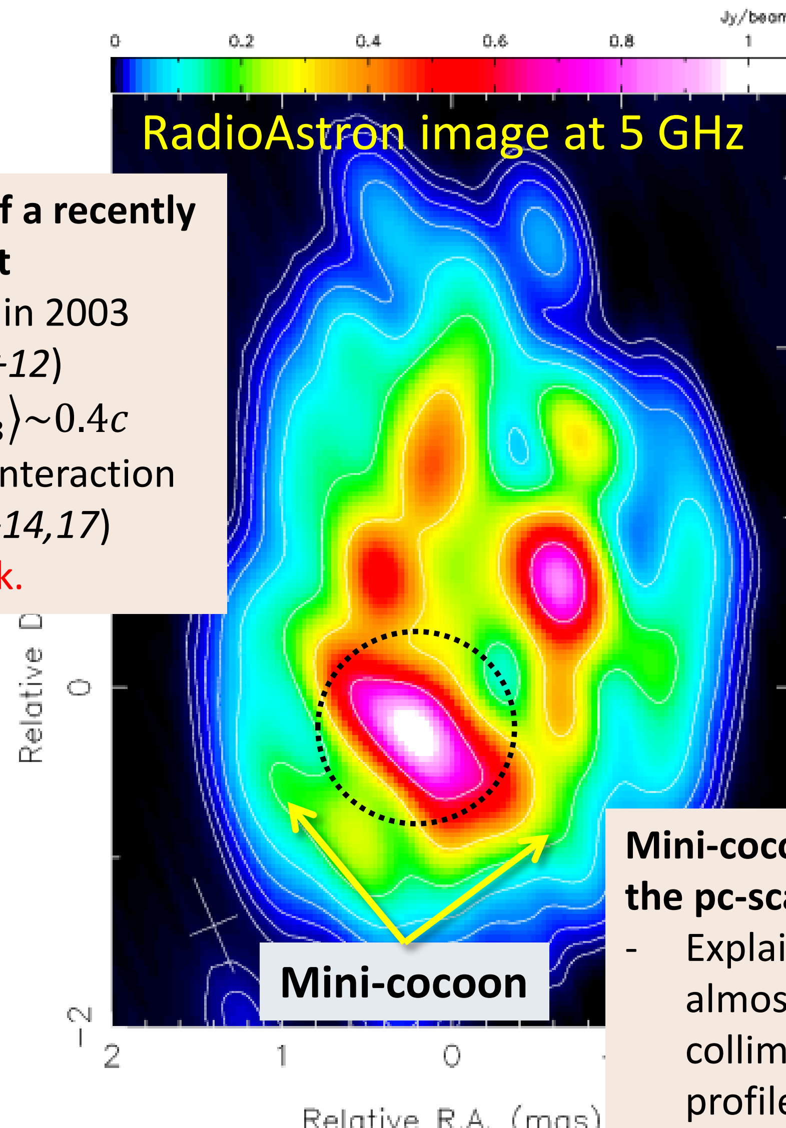
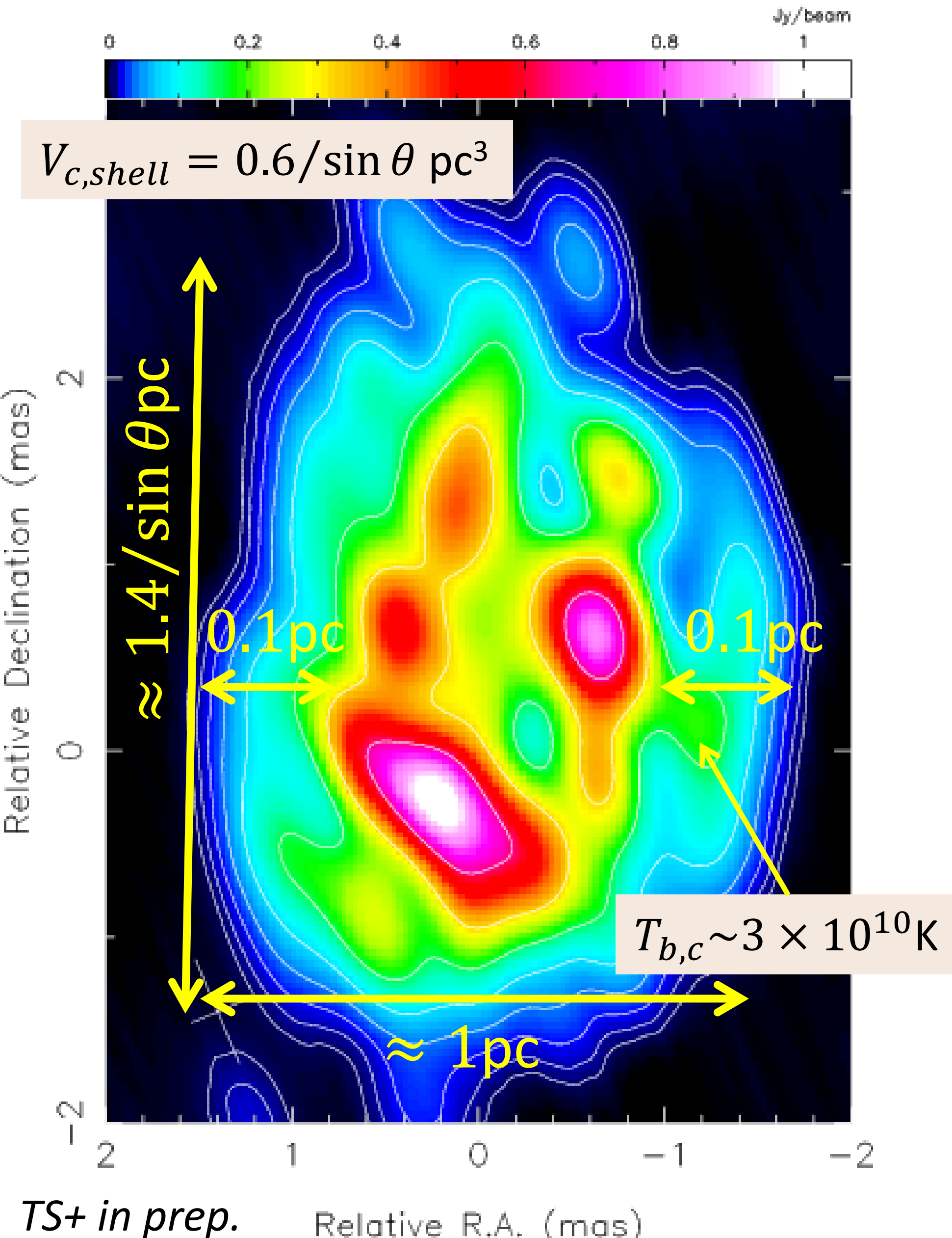


Mini-cocoon

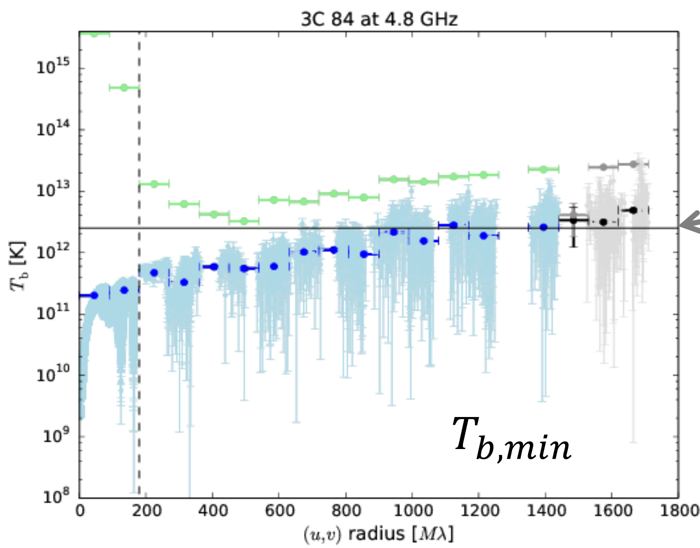


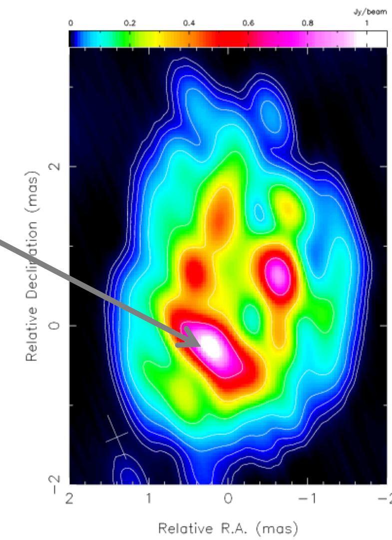
TS+ in prep.

Could the recent jet activity be responsible for the observed "mini-cocoon"?

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

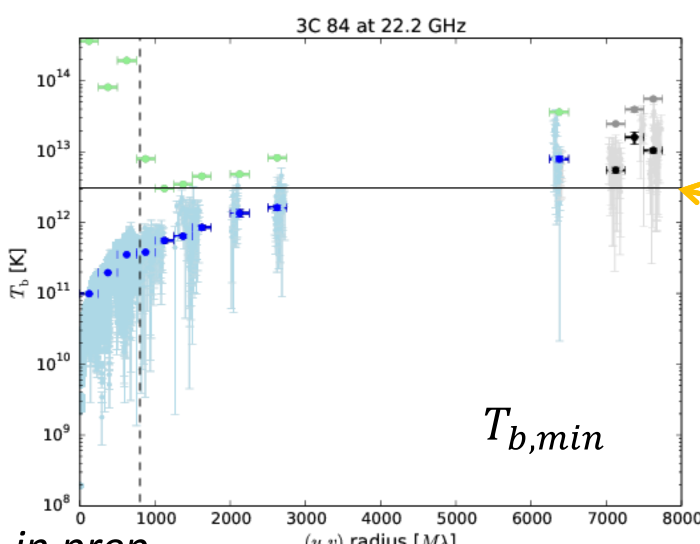
High brightness temperature in C3 hot spot

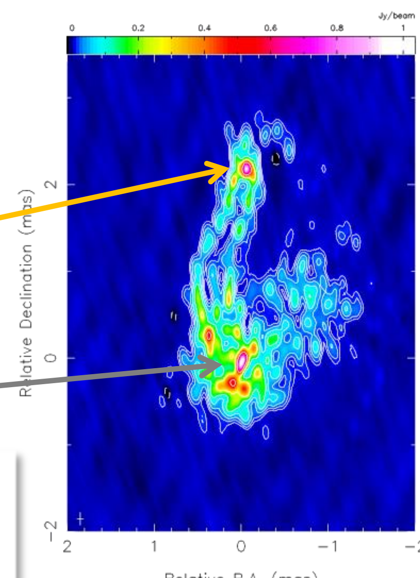




5 GHz

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





22 GHz

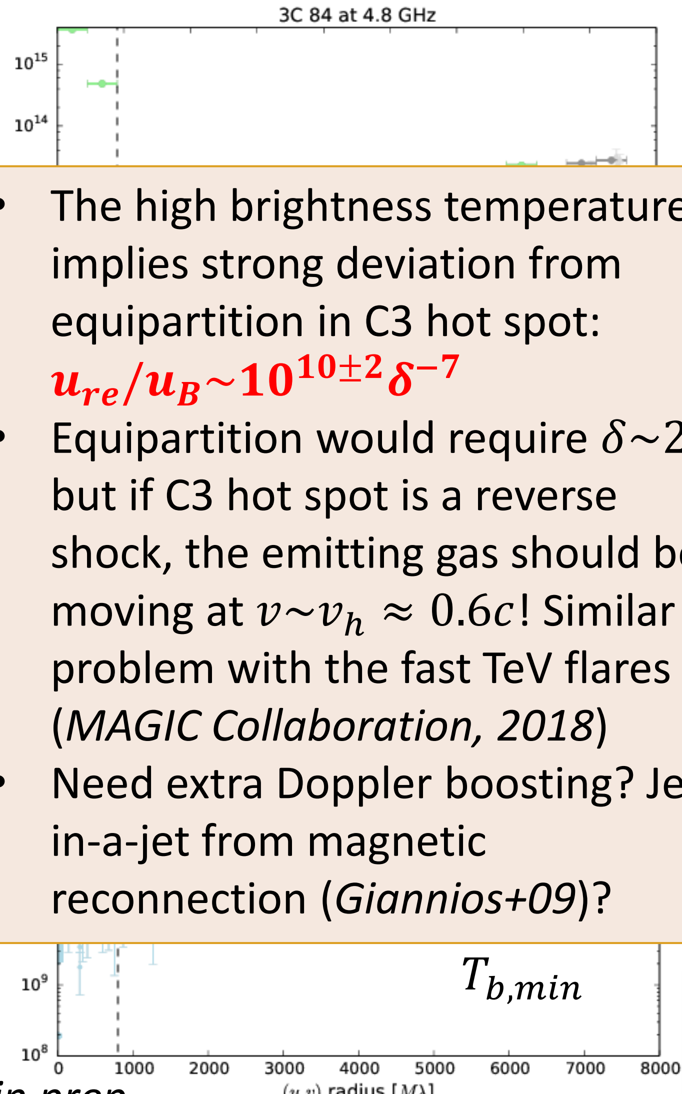
$T_{b,mod}(C1) =$
$3 \pm 2 \times 10^{12}$K

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

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

TS+ in prep.

High brightness temperature in C3 hot spot

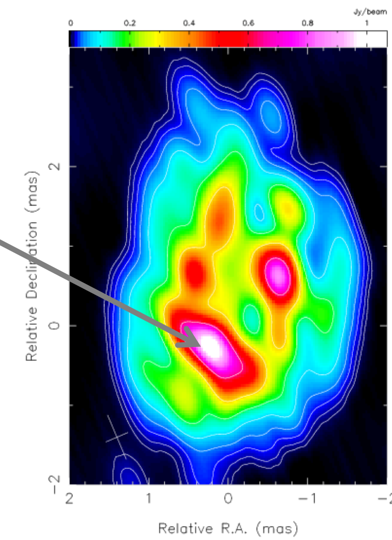


- The high brightness temperature implies strong deviation from equipartition in C3 hot spot: $\boldsymbol{u_{re}/u_B \sim 10^{10\pm2}\delta^{-7}}$
- Equipartition would require $\delta\sim27$, but if C3 hot spot is a reverse shock, the emitting gas should be moving at $v\sim v_h \approx 0.6c$! Similar problem with the fast TeV flares (*MAGIC Collaboration, 2018*)
- Need extra Doppler boosting? Jet-in-a-jet from magnetic reconnection (*Giannios+09*)?

TS+ in prep.

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

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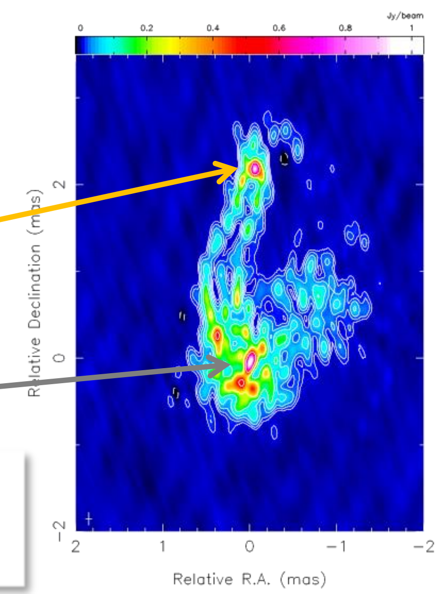
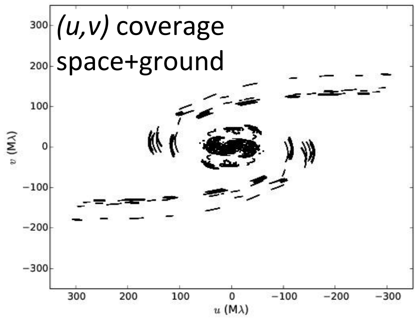
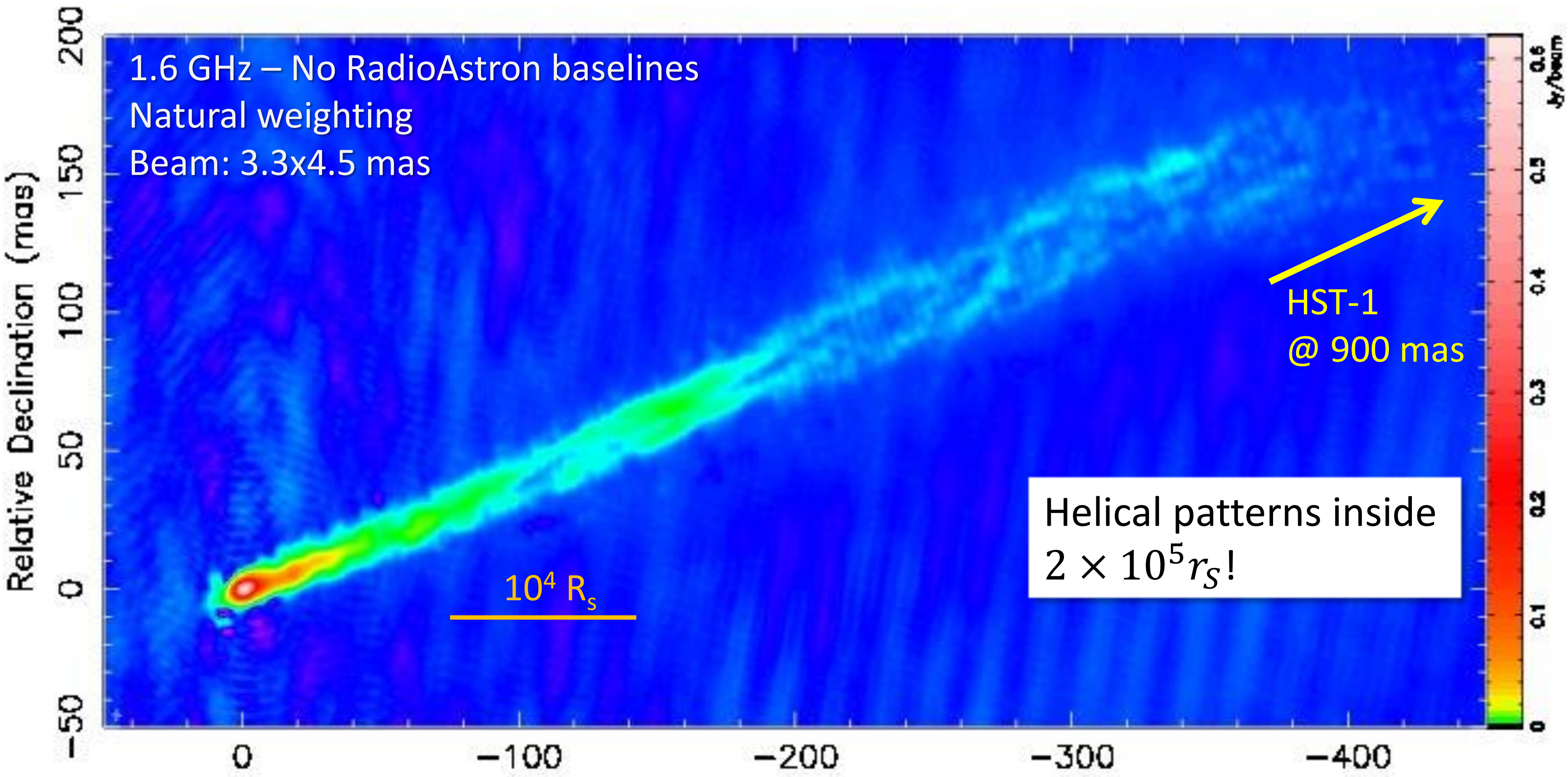


Inverse Compton limit: $T_{b,obs} \lesssim 10^{12} \cdot \delta$ K

Unprecedented antenna coverage on the ground: **26** radio telescopes in a single array spanning the whole Earth



M87 RadioAstron imaging at 1.6 GHz



TS+ in prep.

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Fringe spacing of 0.5 mas @ 1.6GHz.

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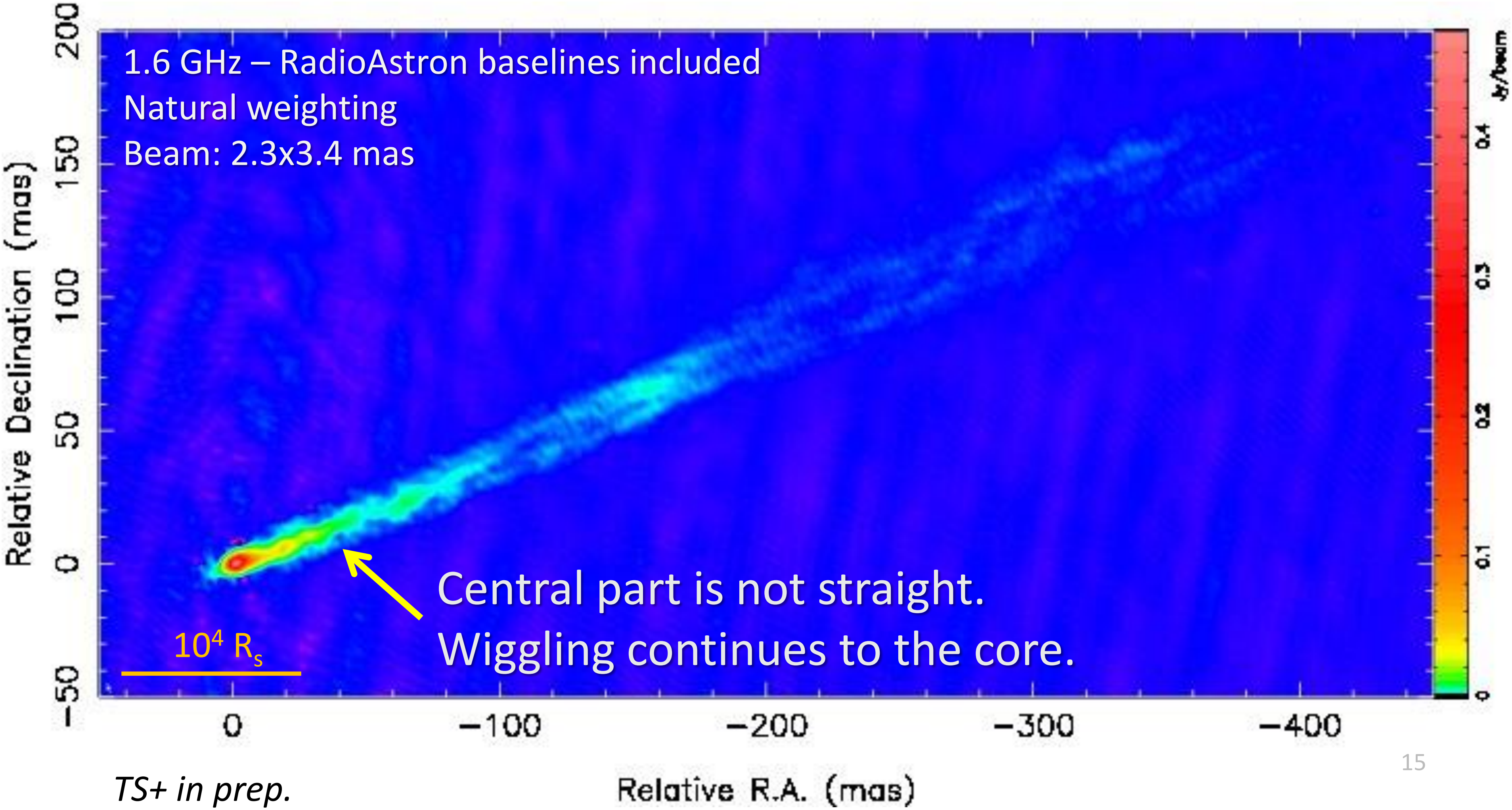


TS+ in prep.

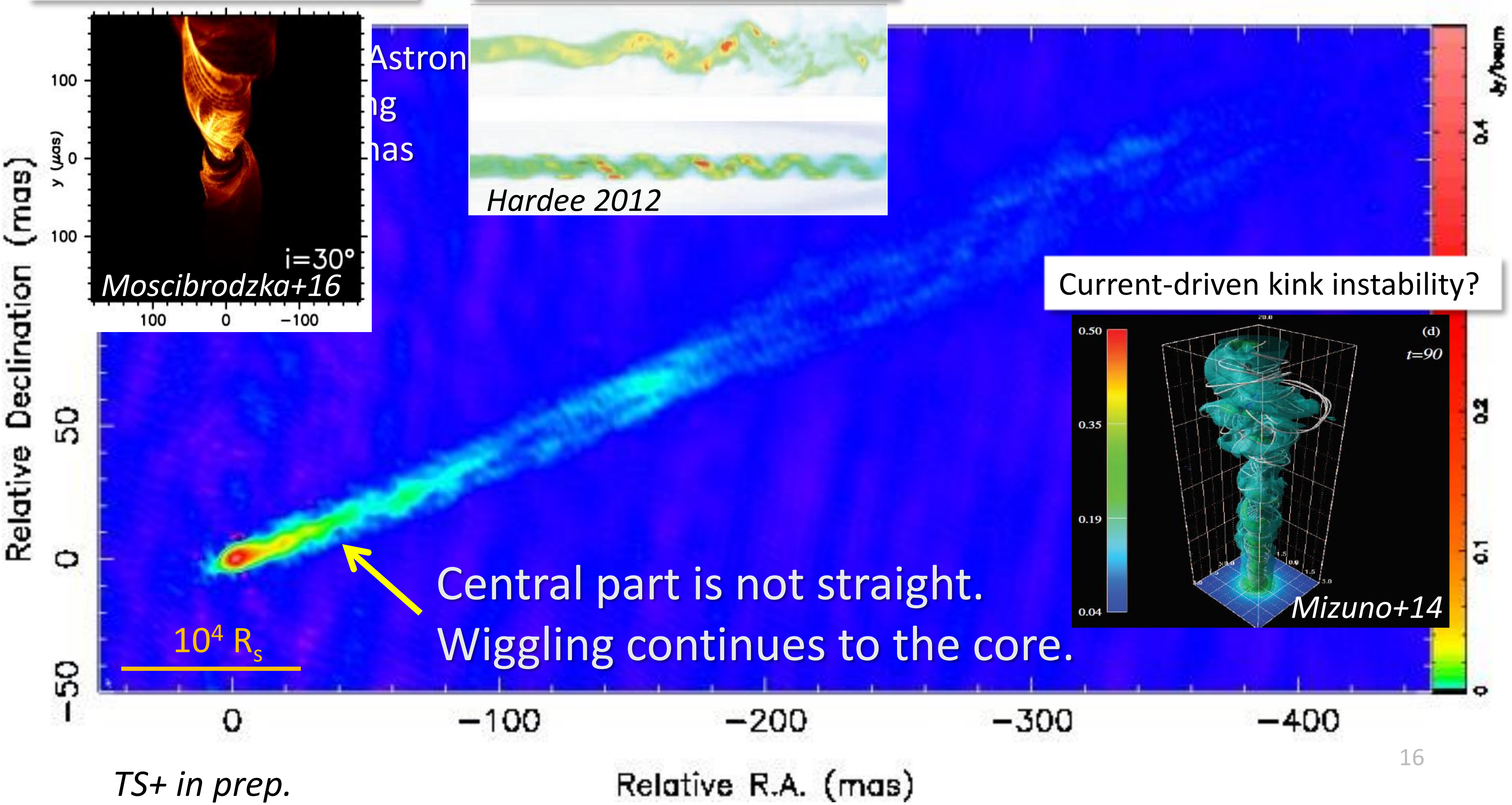
M87 RadioAstron imaging at 1.6 GHz

Source detected up to **5 D$_{earth}$** .
Fringe spacing of 0.5 mas @ 1.6GHz.

Rotating plasma following helical B-field lines?

Kelvin-Helmholtz instability?

Current-driven kink instability?



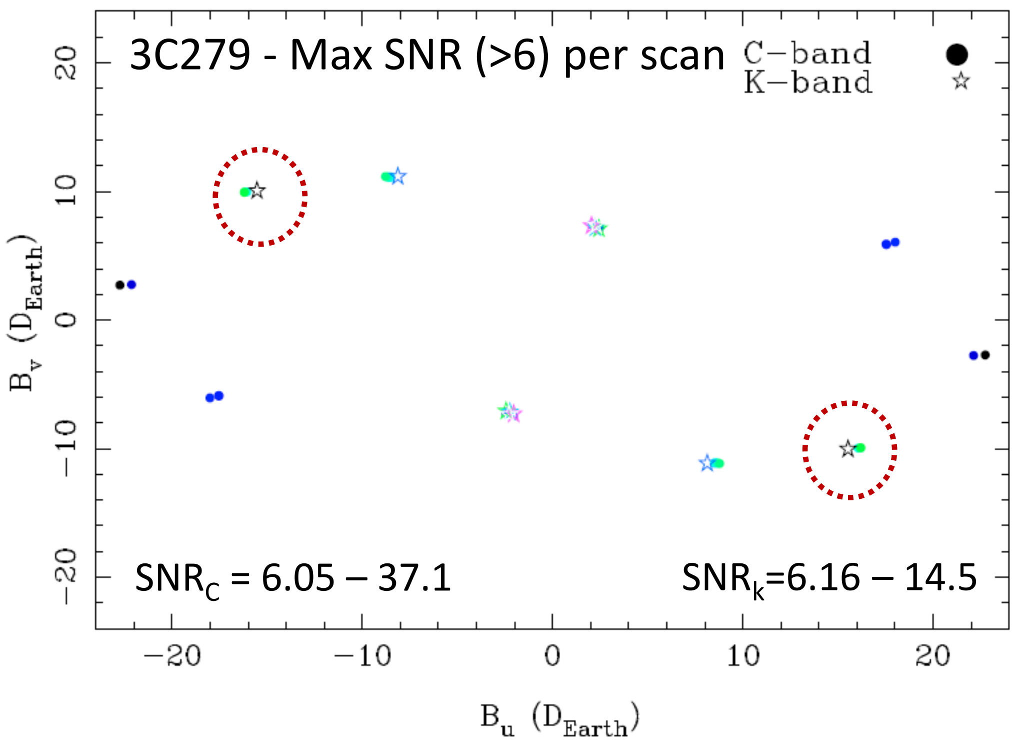
TS+ in prep.

Sneak peek: Full orbit observation of quasars 3C273 and 3C279

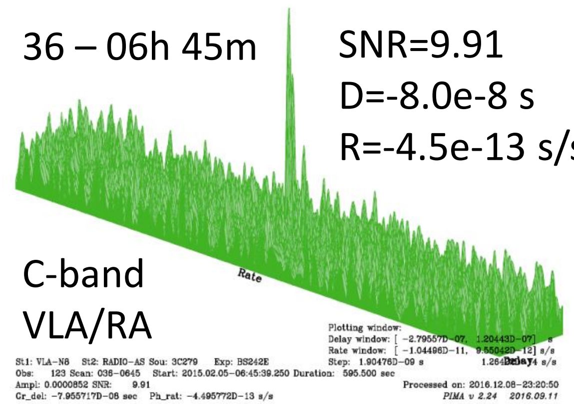
Aim: Core geometry/sub-structure at tens of µas

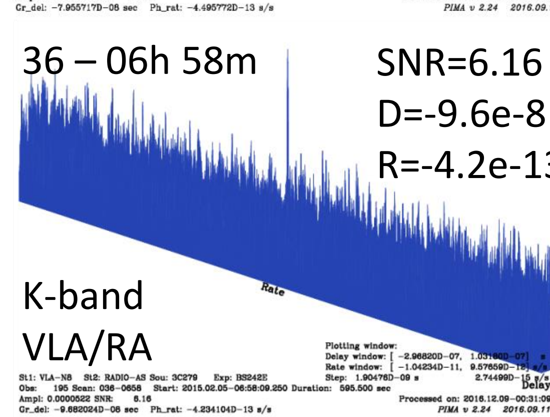
Obs. conf: Almost full-orbit; 2.5 hr/day on 7 consecutive days; C / wide K-band

Array: RadioAstron, VLA, GBT, Effelsberg, VLBA



RadioAstron Newsletter 31; TS+ in prep.





3C279 fringe detection on 18.5 ED (235000km) baseline at 22 GHz: 12µas **fringe spacing**!

Conclusions

- Space-VLBI imaging of nearby AGN reveals previously unresolved internal jet structures that could be compared to GRMHD simulations in the future.
- 3C84 has an initially broad jet just a few hundred r_g from the BH. More in the next talk.
- A newly "restarted" jet seems to inflate a "mini-cocoon" already in parsec-scale. Shocked material in the cocoon can explain the almost cylindrical collimation profile of the 3C84 jet.
- There is a very high brightness temperature "hot spot" inside the jet head in 3C84, which is problematic given the low velocity of the emission region.
- RadioAstron image of M87 shows a complex internal structure of the jet in the acceleration/collimation zone with helical filaments.
- More data processing on-going:
  - Full orbit observations of 3C273/3C279.
  - Imaging of M87 at 5 and 22 GHz – including a polarimetric 22 GHz observation close-in-time to the 2018 Event Horizon Telescope campaign.