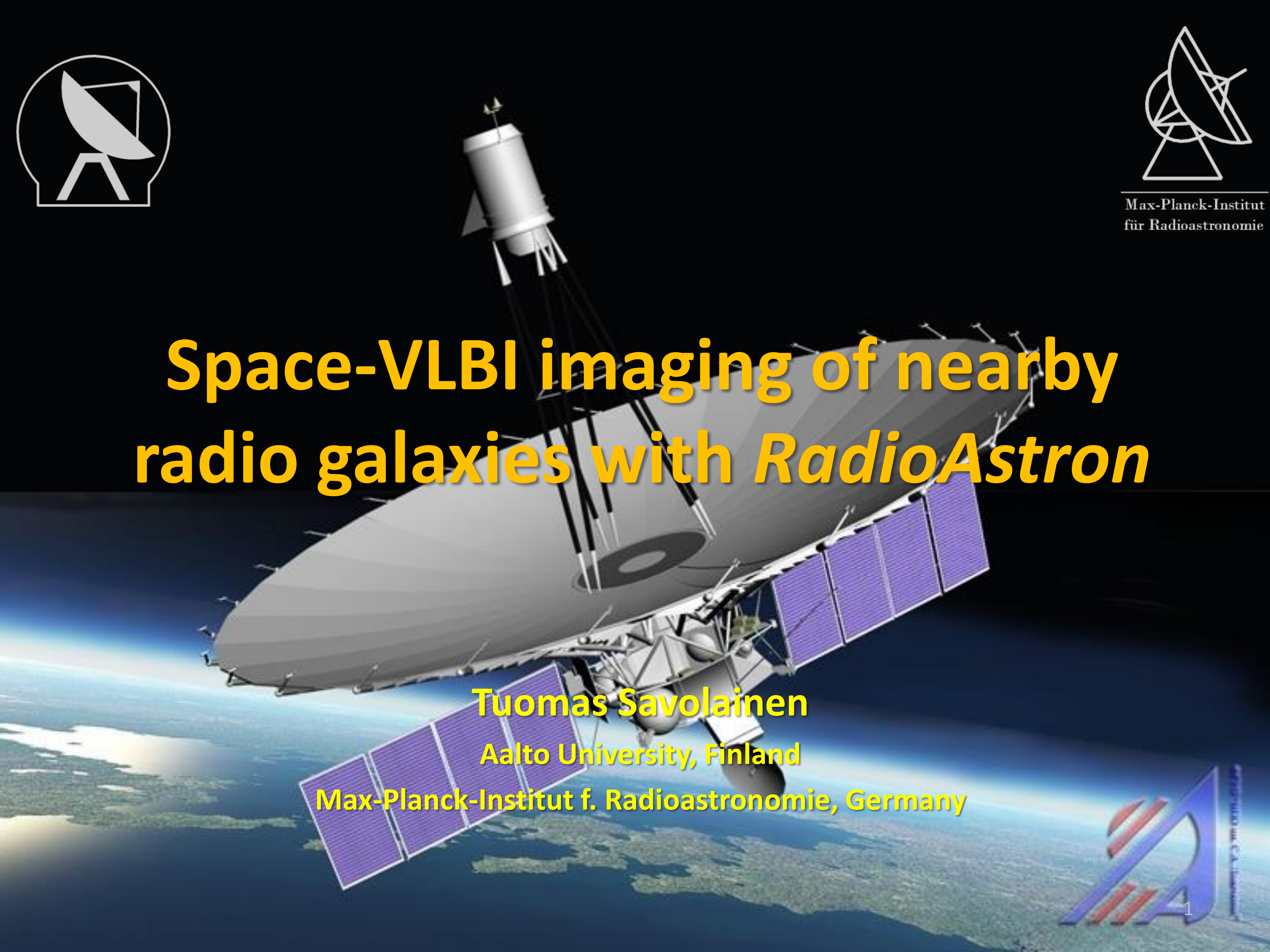


Space-VLBI imaging of nearby radio galaxies with *RadioAstron*

Tuomas Savolainen

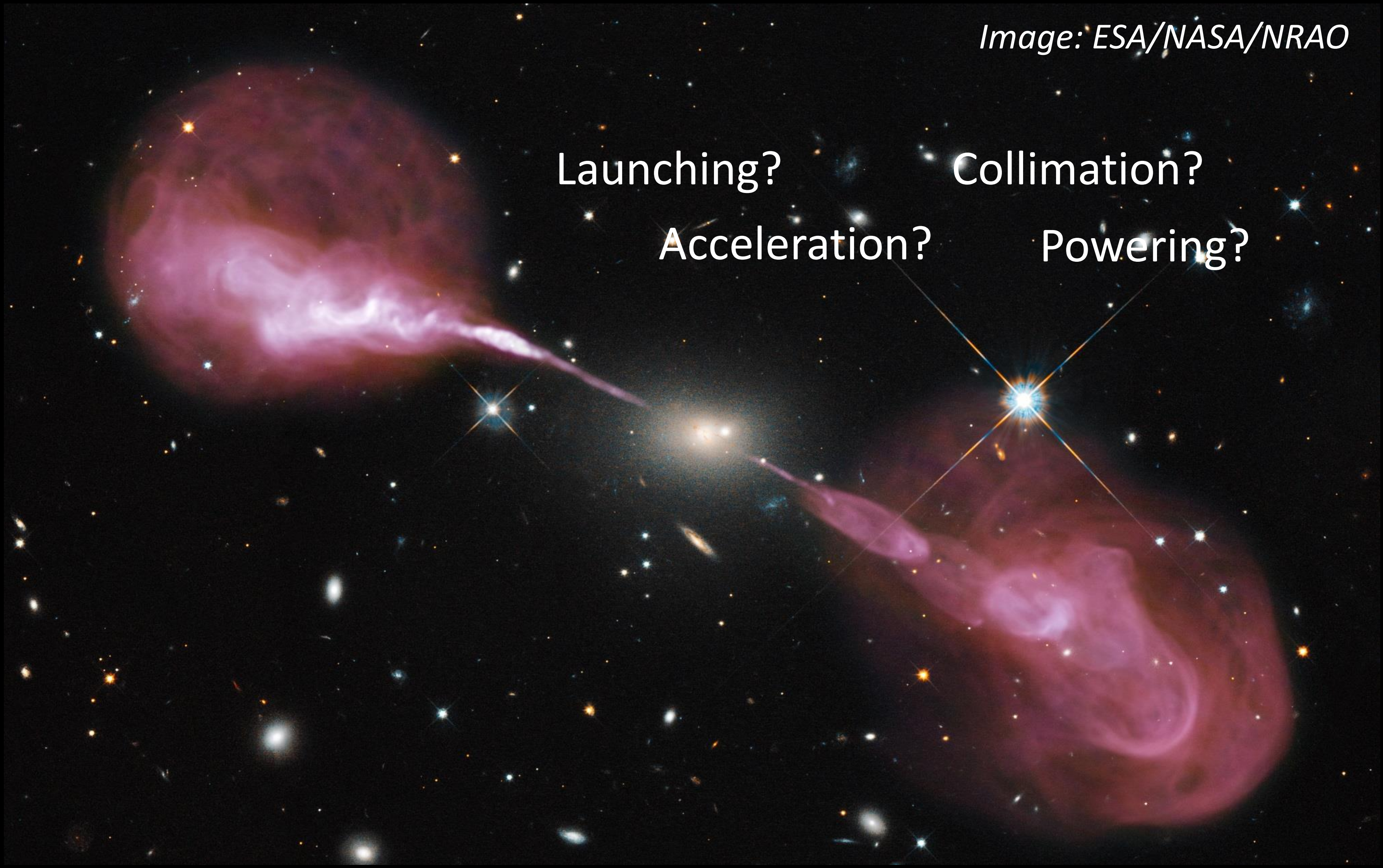
Aalto University, Finland

Max-Planck-Institut f. Radioastronomie, Germany

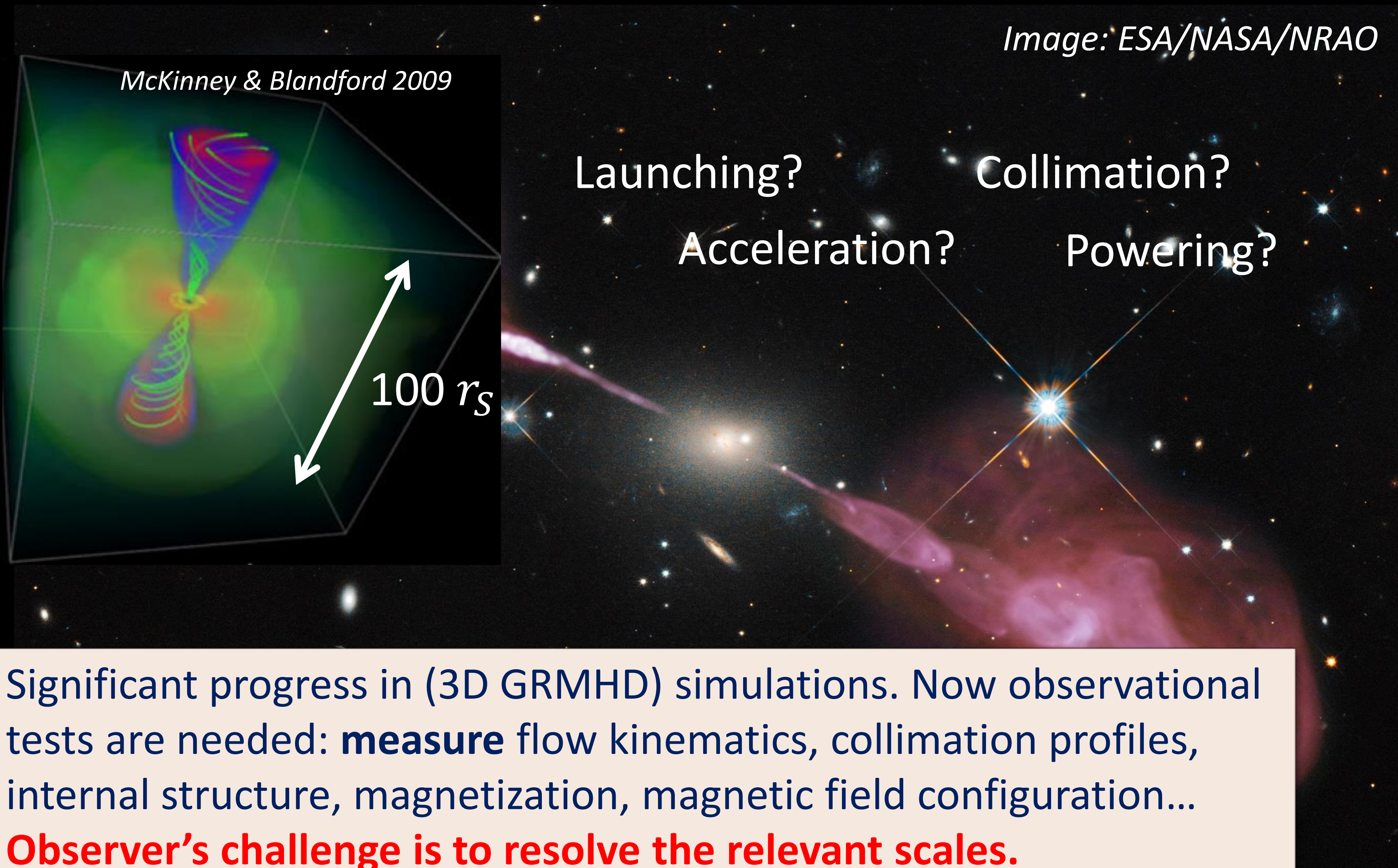
RadioAstron Nearby AGN Key Science Program team

- *PI: T.Savolainen (Aalto University, Finland)*
- *G.Giovannini, M.Giroletti , M.Orienti, F. D'Ammando, R. Lico (INAF Bologna, Italy)*
- *Y.Y.Kovalev, M.L.Lisakov, K.V.Sokolovsky, P.Voitsik (ASC Lebedev, Russia)*
- *T.Krichbaum, A.Lobanov, J.A.Zensus (MPIfR, Germany)*
- *K.Hada, M.Kino, H.Nagai, M.Honma (NAOJ, Japan)*
- *J.Hodgson, S.S.Lee, B.W.Sohn (KASI, South Korea)*
- *P.Edwards, C.Reynolds (CSIRO, Australia), S.Tingay (ICRAR, Australia)*
- *G.Bruni (INAF Rome, Italy), D.Meier (Caltech, USA), C.Fromm (Uni. Frankfurt, Germany), J. Eilek (NRAO, USA), P.Hardee (Uni. Alabama, USA)*
- *L.Petrov (AstroGeo Center, USA), J.Anderson (GFZ Potsdam, Germany)*
- *M.Nakamura (ASIAA, Taiwan)*

What do we know about jets?



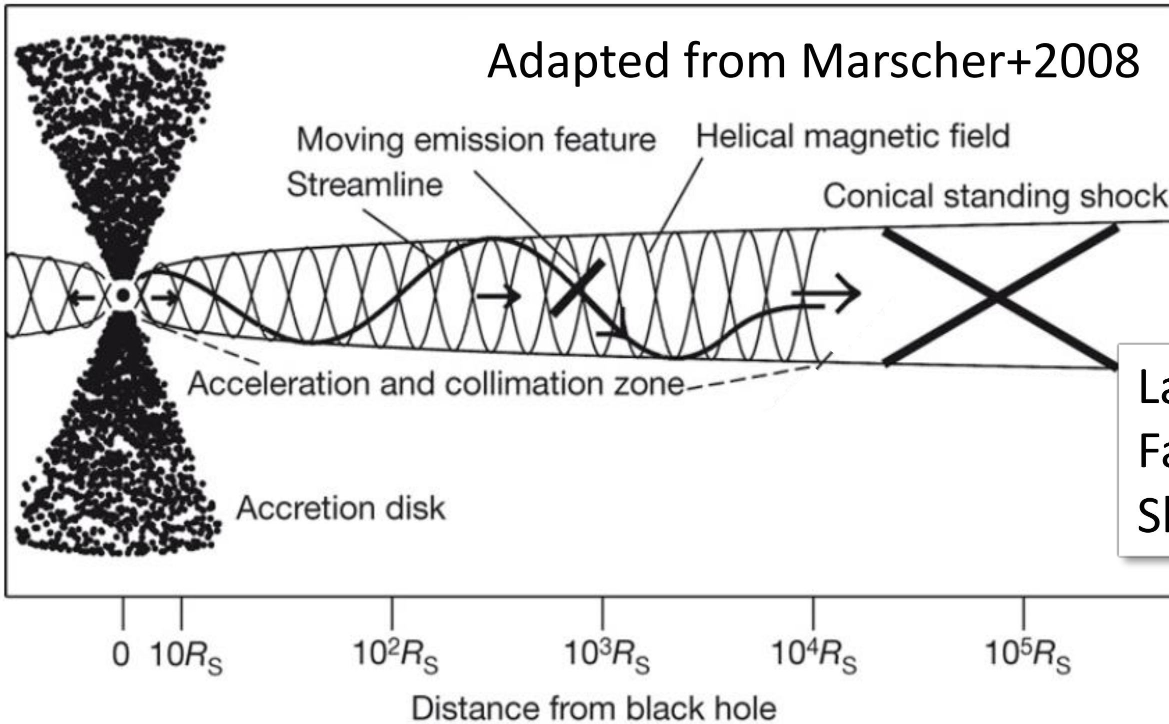
What do we know about jets?



Significant progress in (3D GRMHD) simulations. Now observational tests are needed: **measure** flow kinematics, collimation profiles, internal structure, magnetization, magnetic field configuration…

Observer's challenge is to resolve the relevant scales.

Size scales involved

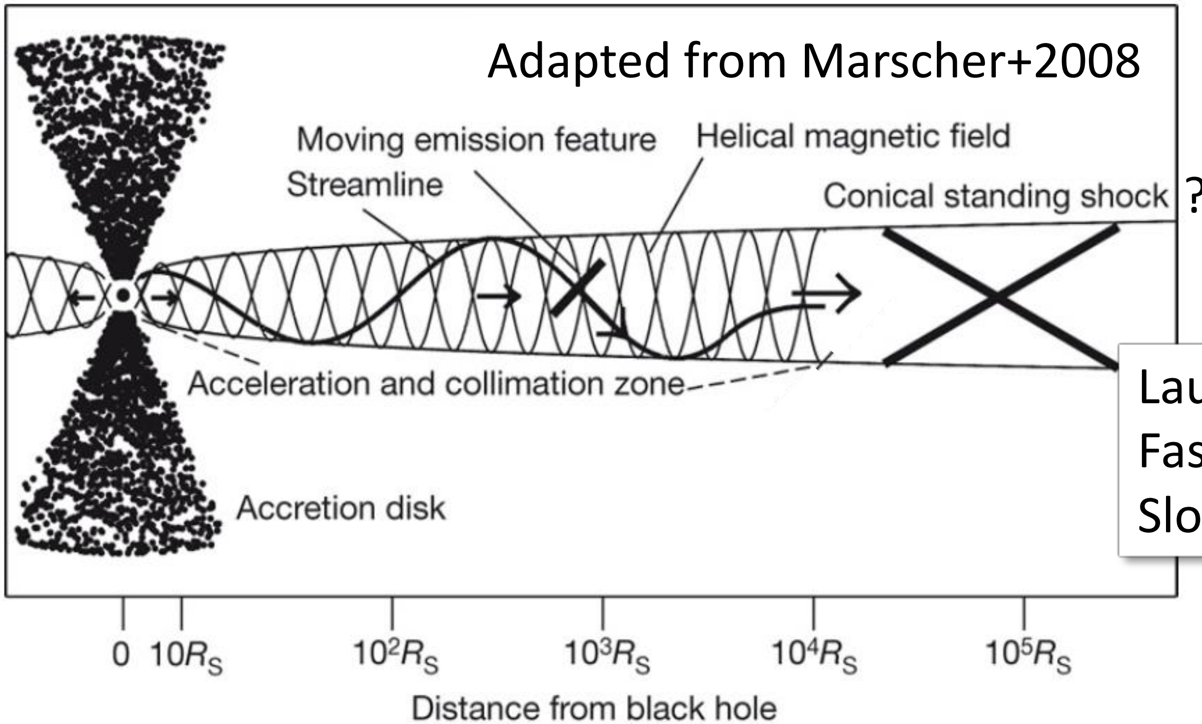


Adapted from Marscher+2008

?

Launching: $\lesssim 10 r_S$
Fast acceleration: $\lesssim 10^3\ r_S$
Slow acceleration: $\lesssim 10^{5\pm1}\ r_S$

Size scales involved



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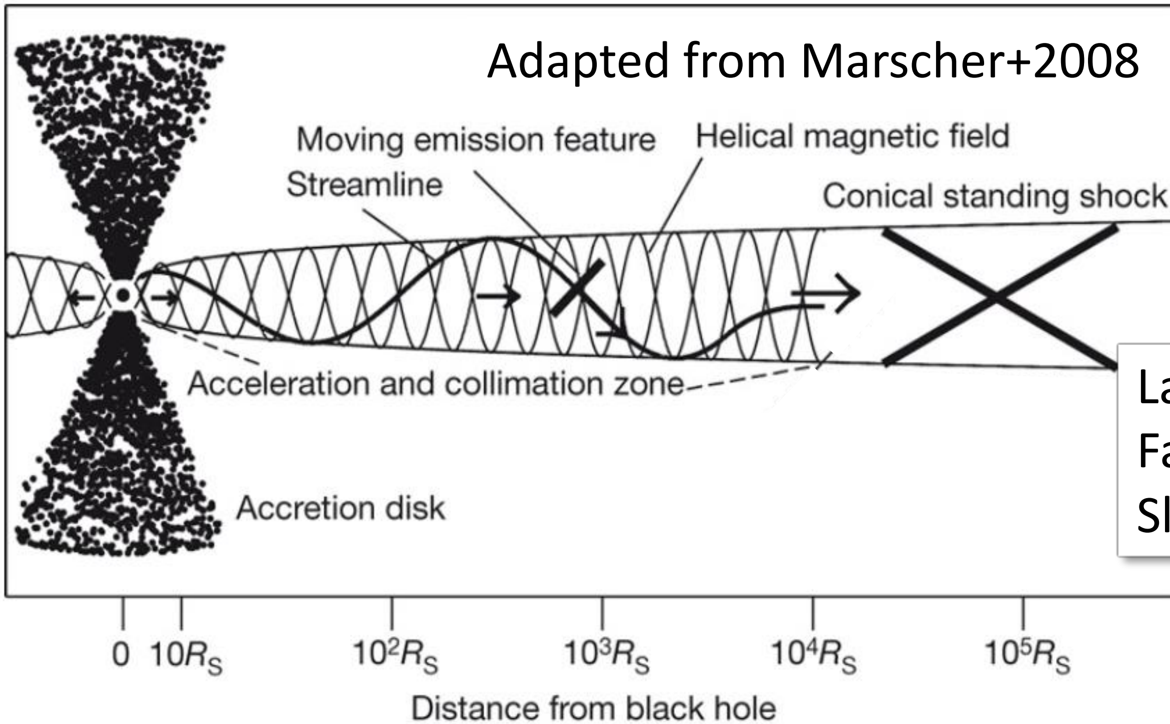
M87 (D=16Mpc; $\theta = 17°$): 21 mas

Size scales involved



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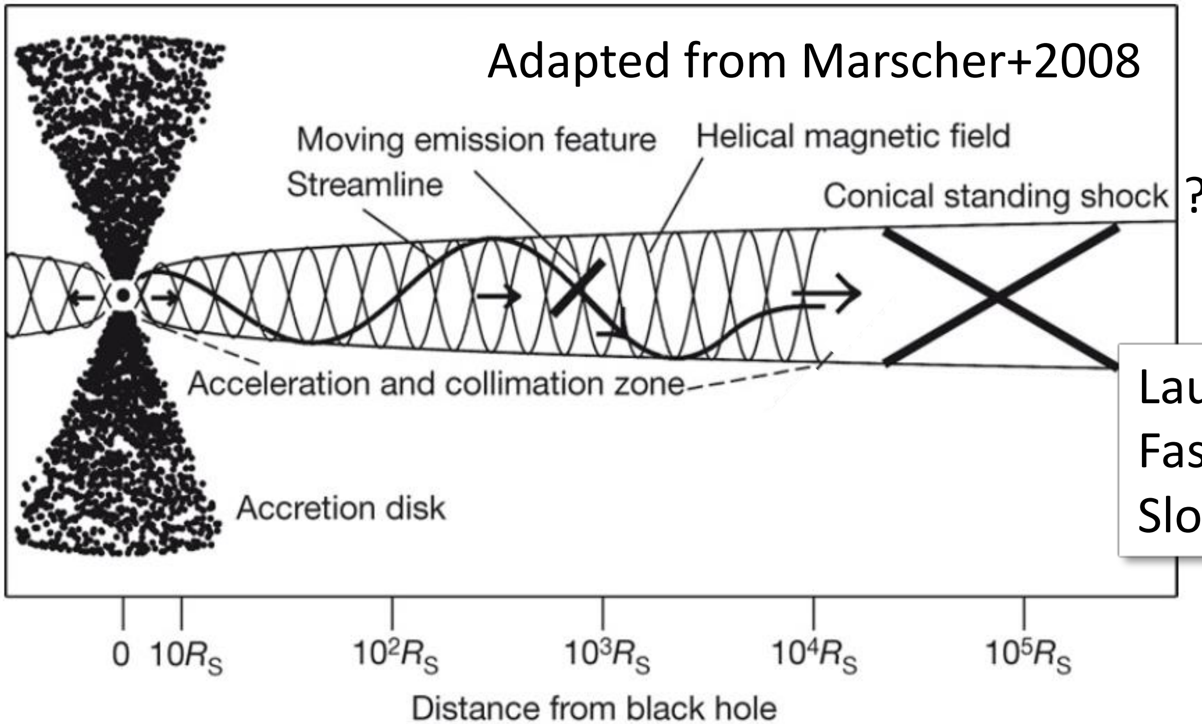
3C273 (D=734Mpc; $\theta = 10°$): 0.4 mas

Size scales involved



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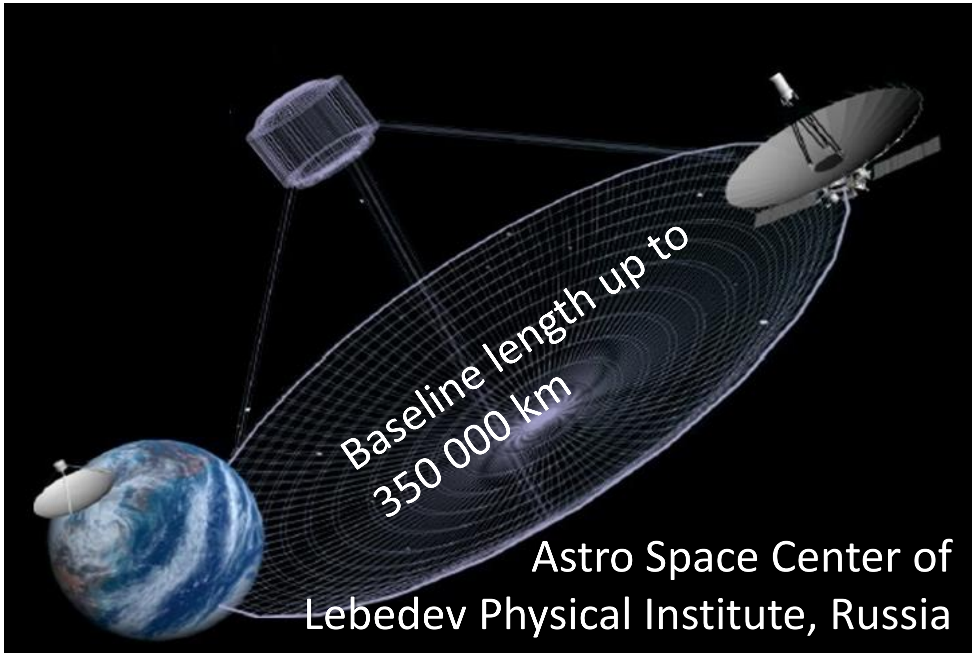
To test the MHD model, we want to resolve the jets at least down to $\mathbf{10^1 - 10^2 r_S}$. Angular resolution of a few tens of **microarcseconds** is needed even for the nearby sources.
Solutions: space-VLBI or mm-VLBI.

RadioAstron Space-VLBI mission



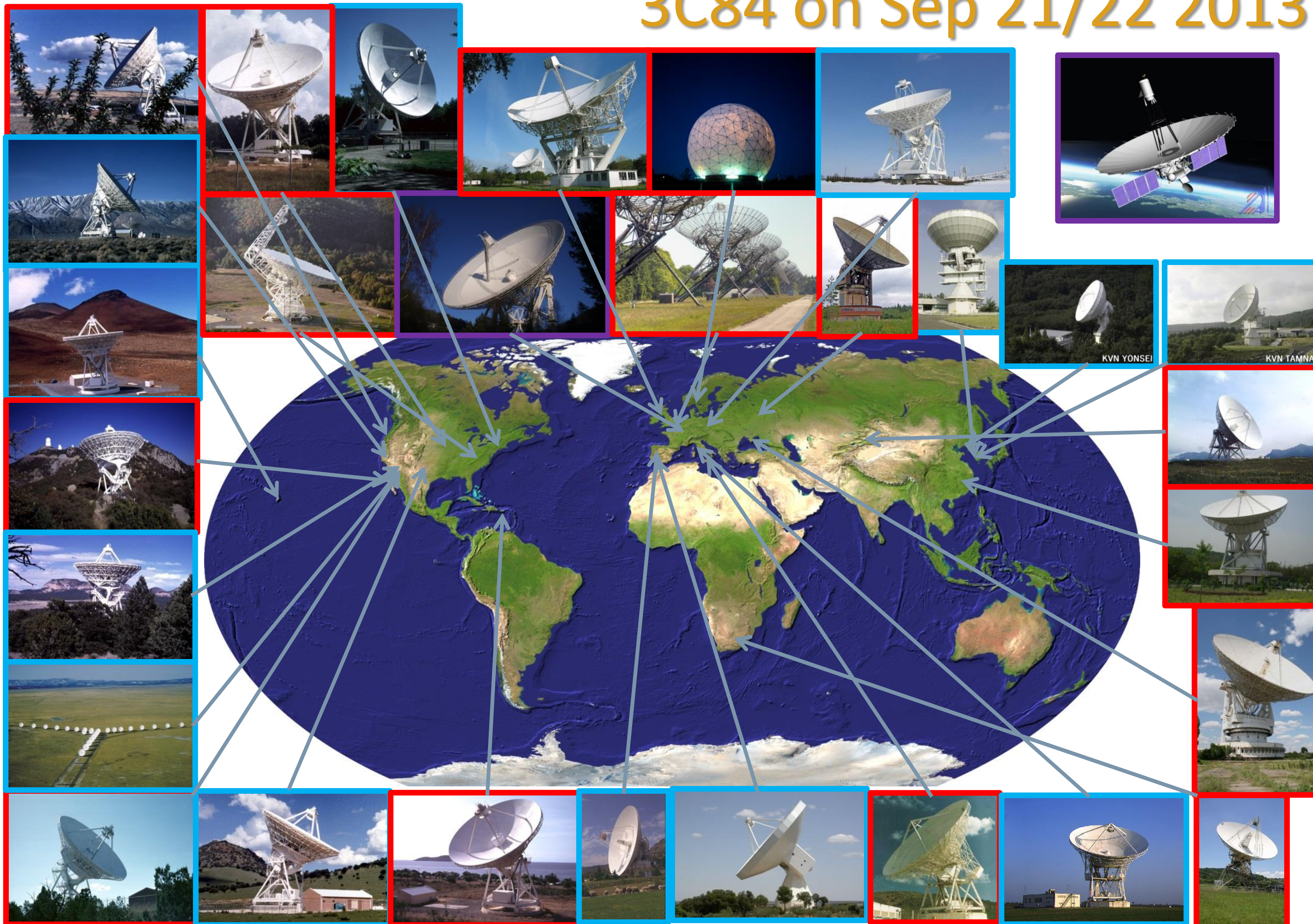
- 10-m Russian space radio telescope launched in 2011
- Apogee height: 350 000 km
- Obs. frequencies: 1.6–22 GHz
- Used together with ground radio telescopes as an interferometer
- Record angular resolutions: 8µas (H_20 megamaser in NGC4258) and 12µas (quasar 3C279; Savolainen et al. in prep.)

<u>RadioAstron Nearby AGN Key Science Program</u>

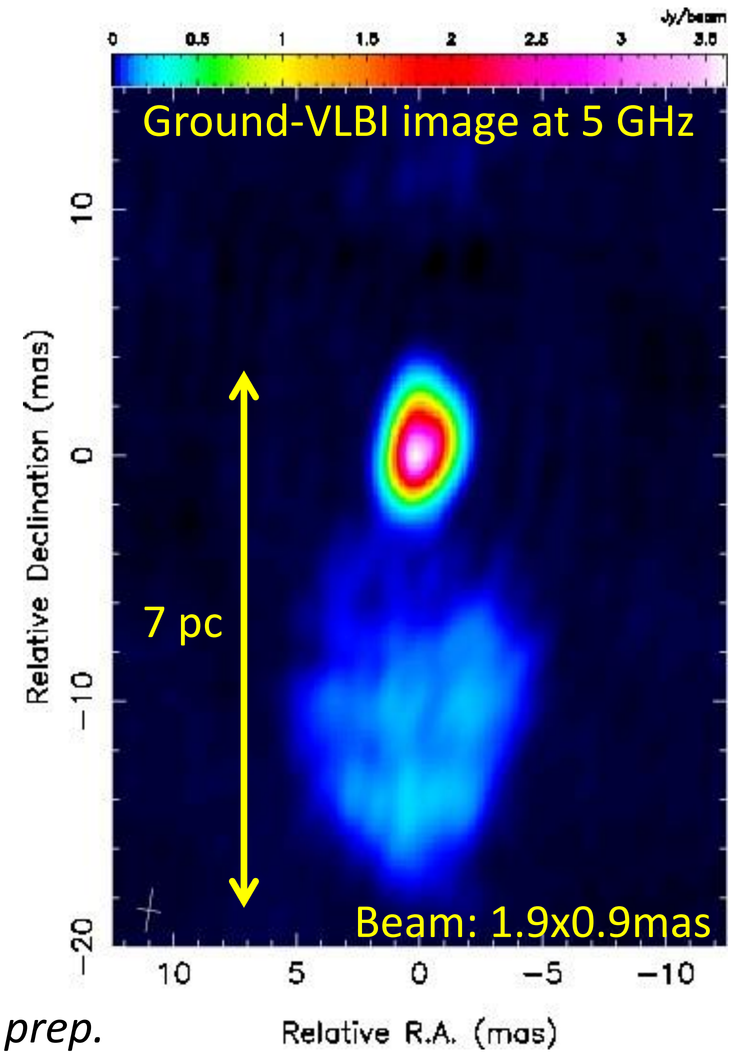
- 139 hours of near-perigee space-VLBI imaging of nearby radio galaxies
- Aims at high spatial resolution (down to a few r_S for M87) for studying the jet acceleration and collimation zone
- Targets: **Cen A** (*D=3.8Mpc, 1mas=3100*r_S), **M87** (*D=16Mpc, 1mas=140*r_S), **3C84** (*D=75Mpc, 1mas=1800*r_S)

3C84 on Sep 21/22 2013

5GHz 22GHz 5/22GHz



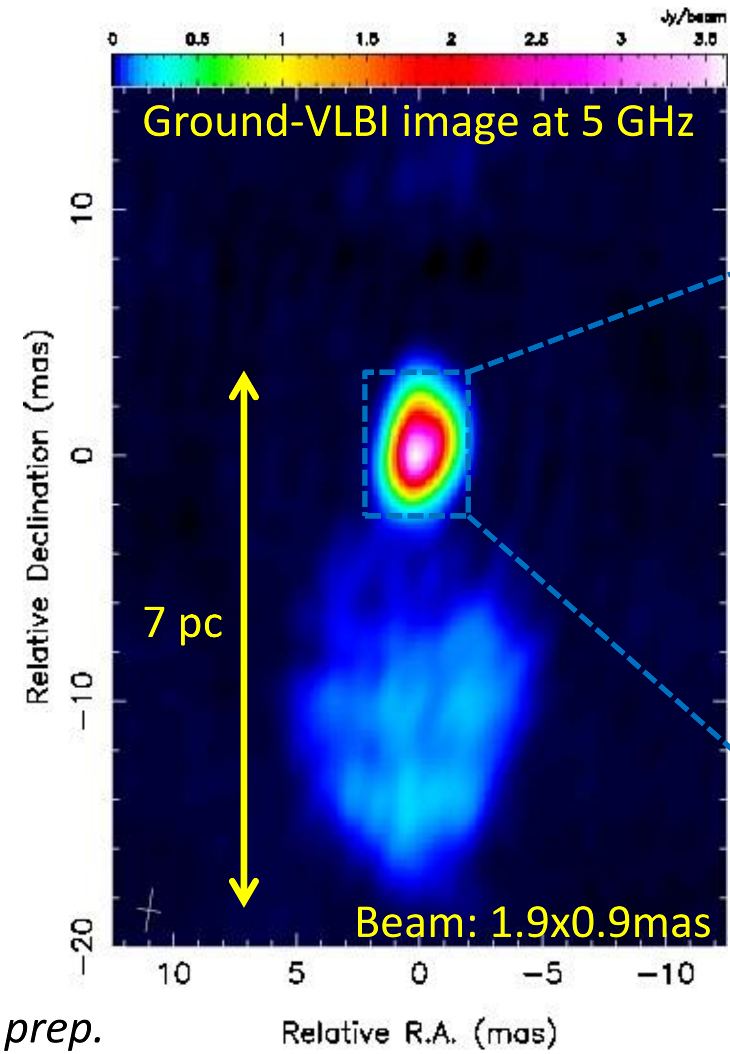
3C84 with RadioAstron at 5/22 GHz

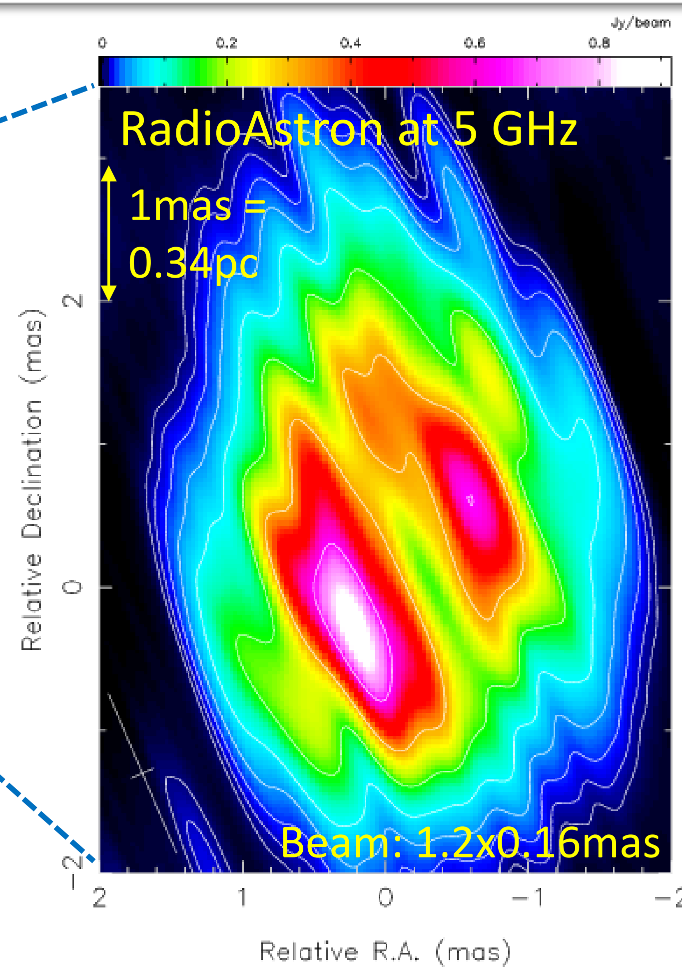


TS+ in prep.

3C84 with RadioAstron at 5/22 GHz

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





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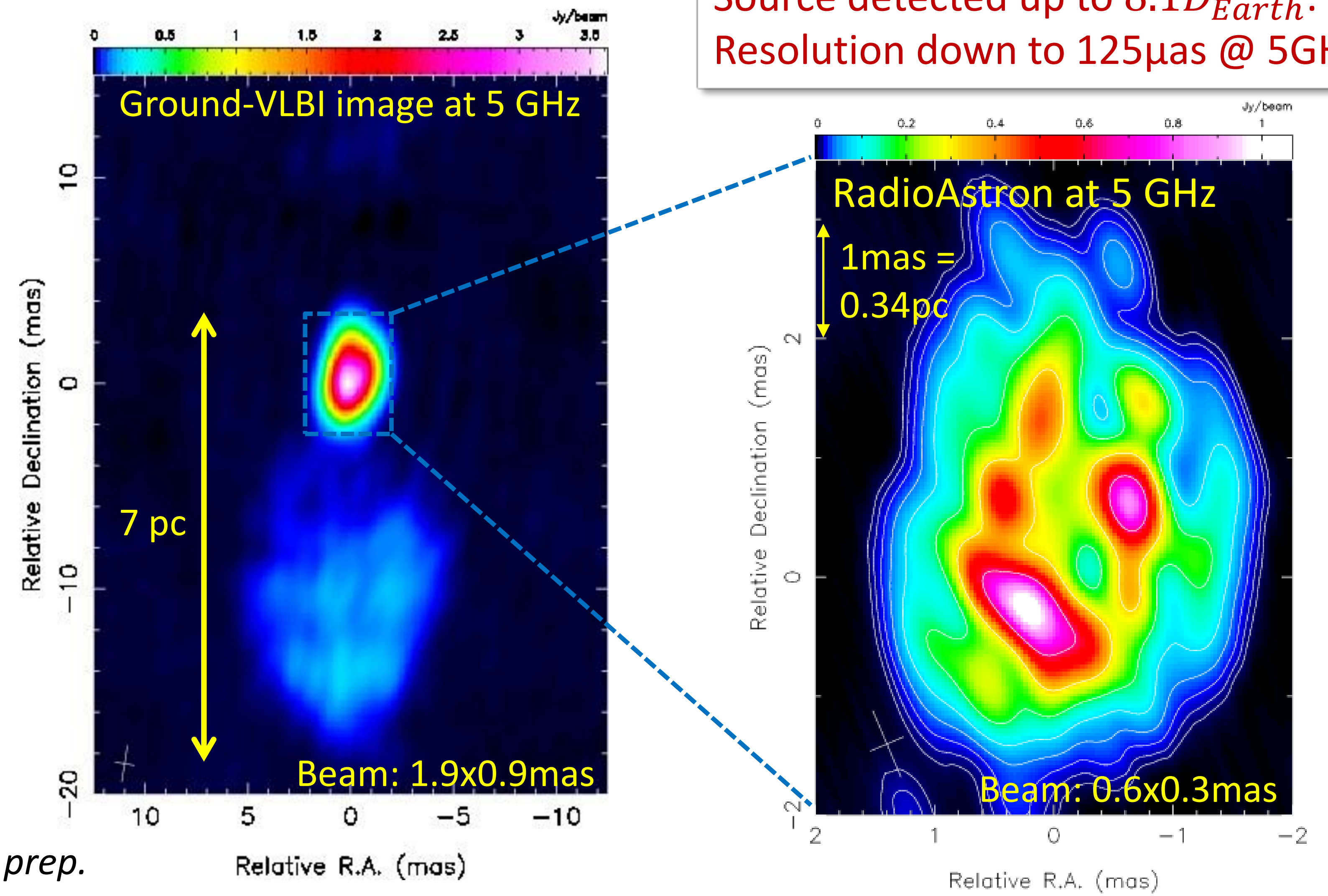
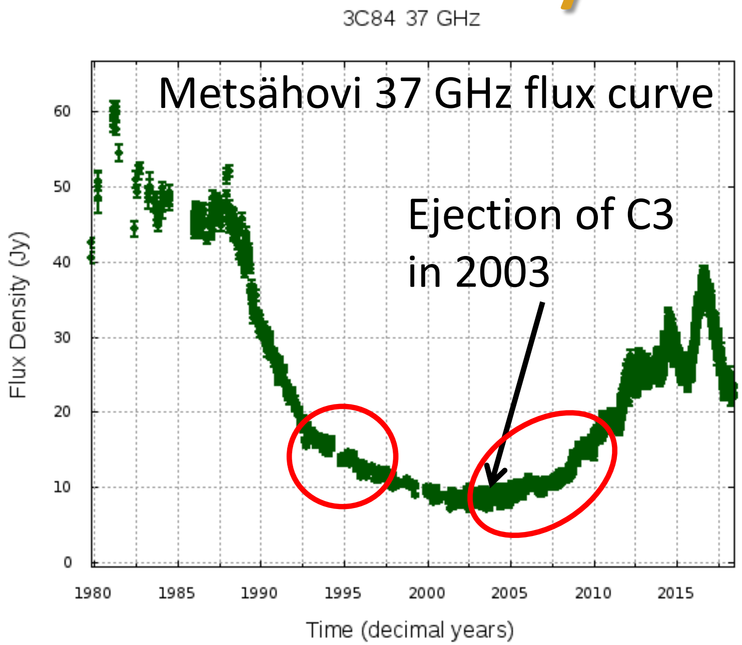
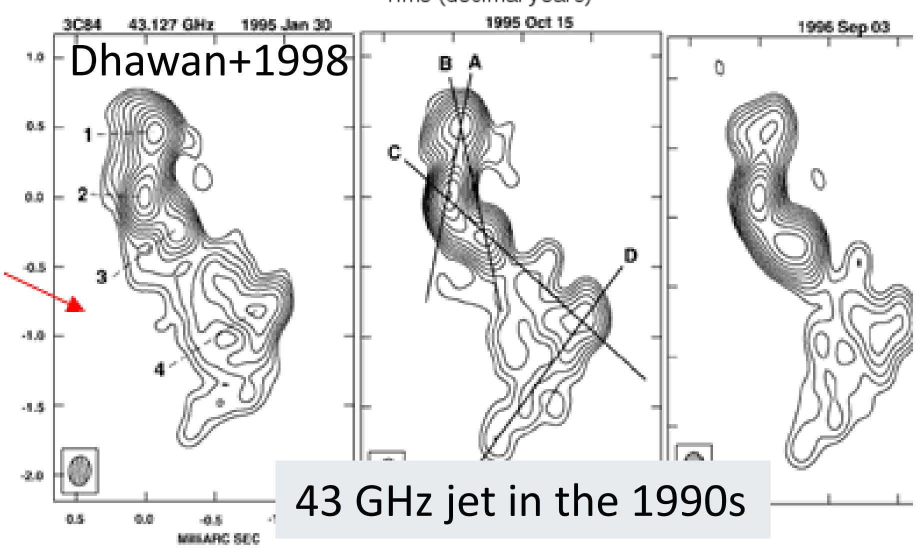
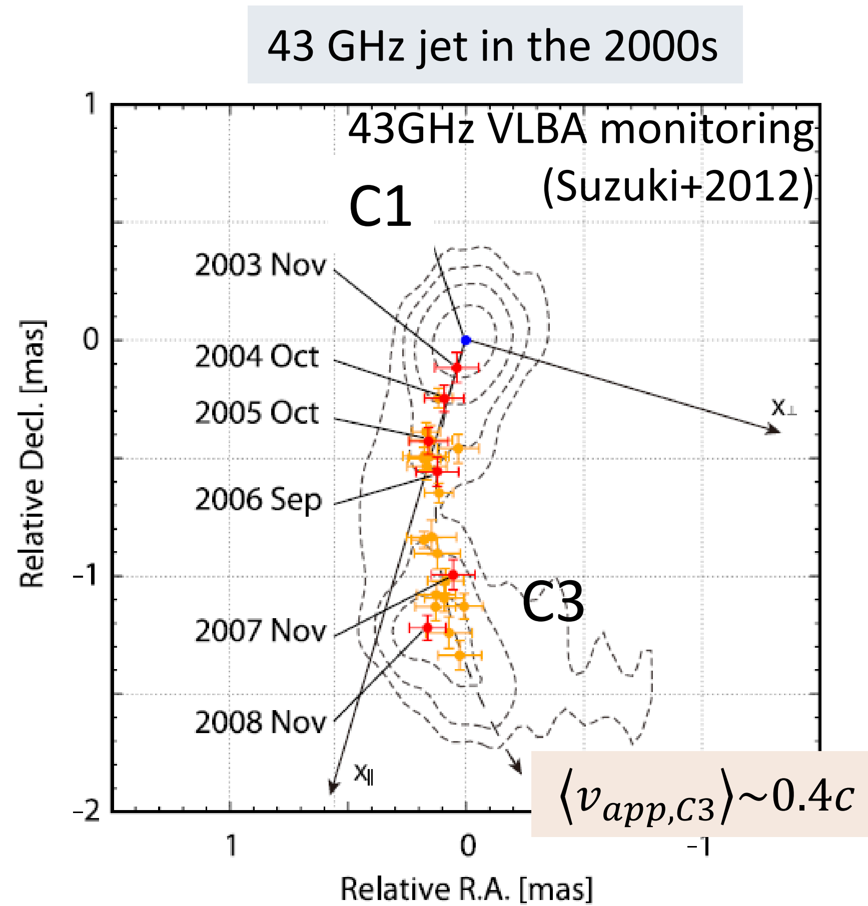


TS+ in prep.

Recently "restarted" jet in 3C84

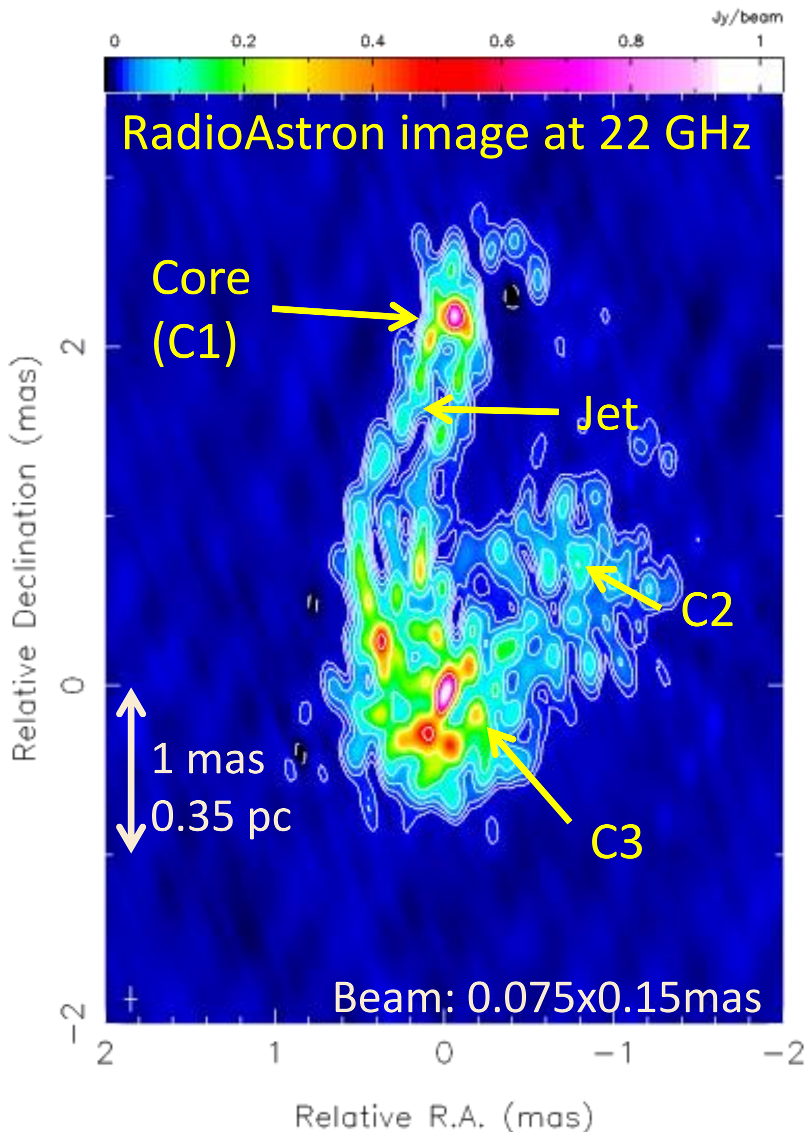


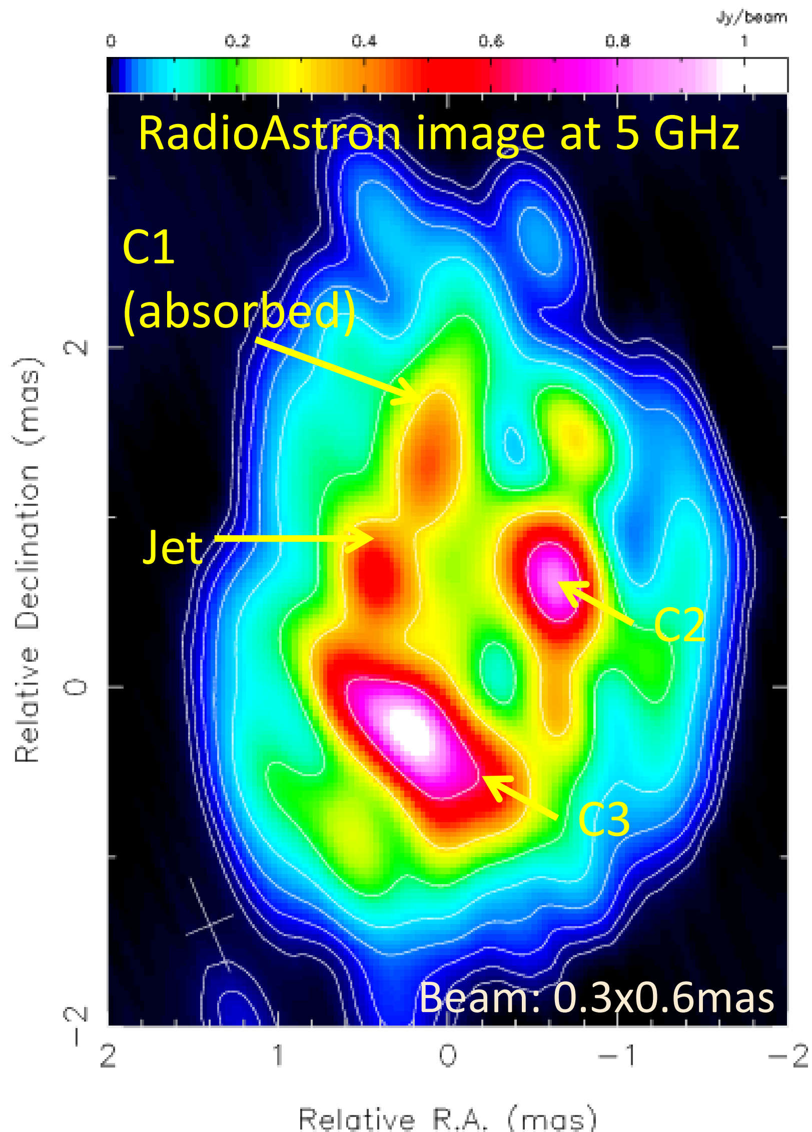




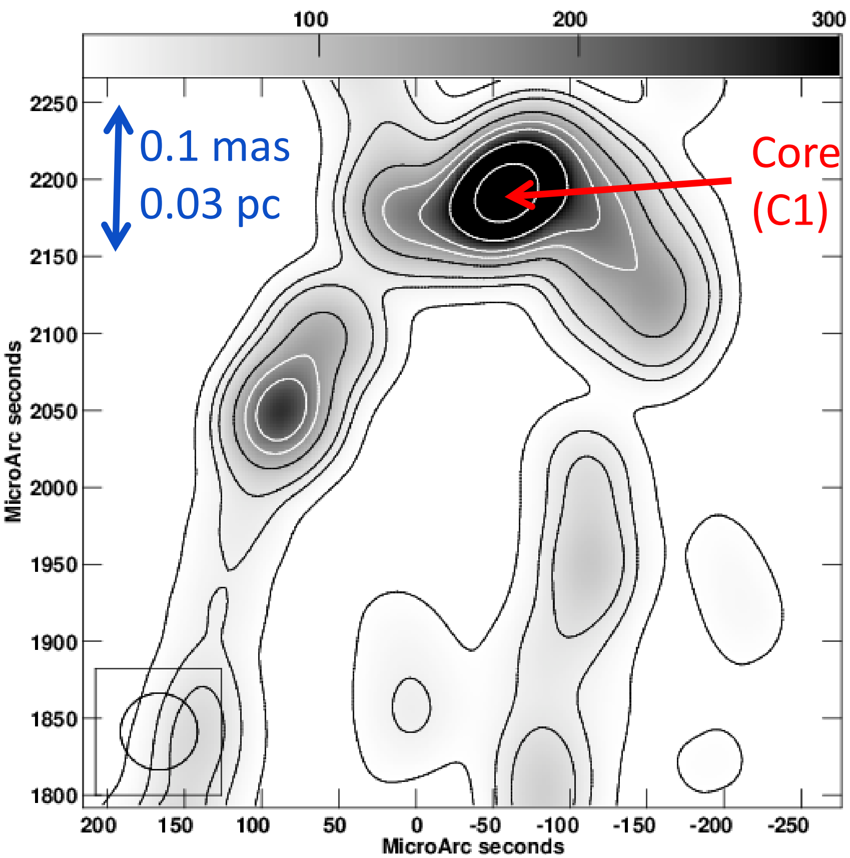
Source detected up to $8.1 D_{Earth}$.
Resolution down to: 27μas @ 22GHz.

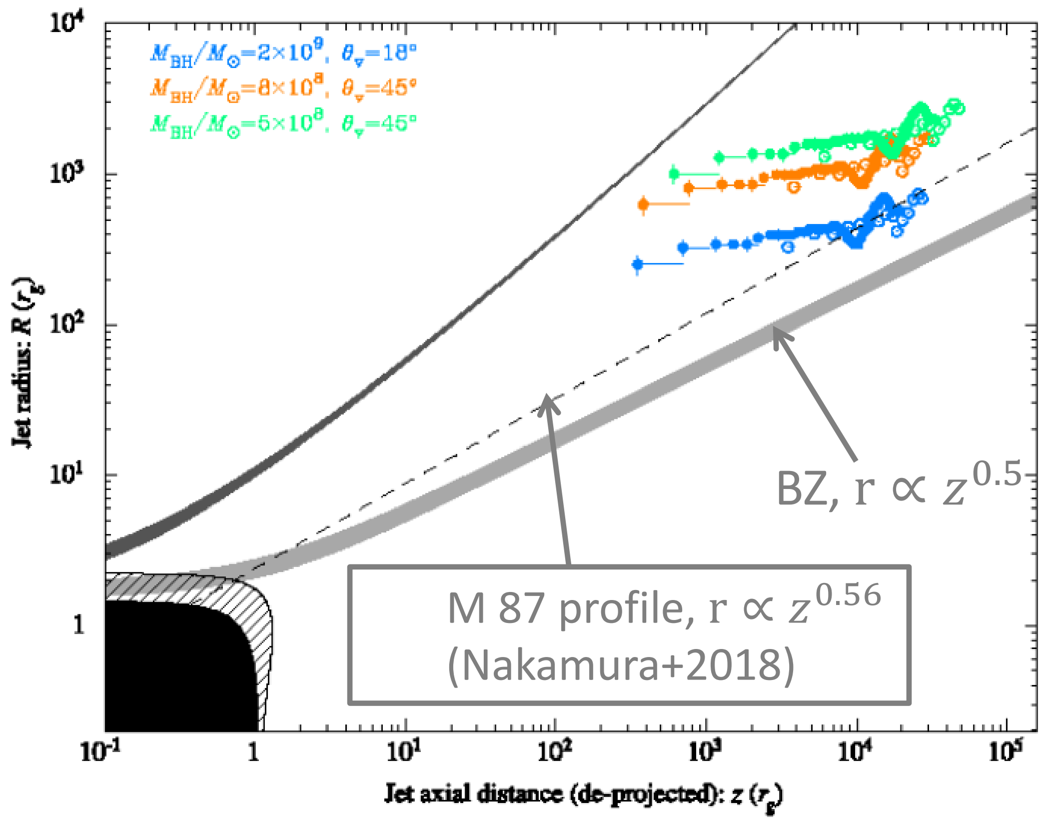
3C84 with RadioAstron at 5/22 GHz





Broad jet close to the central engine

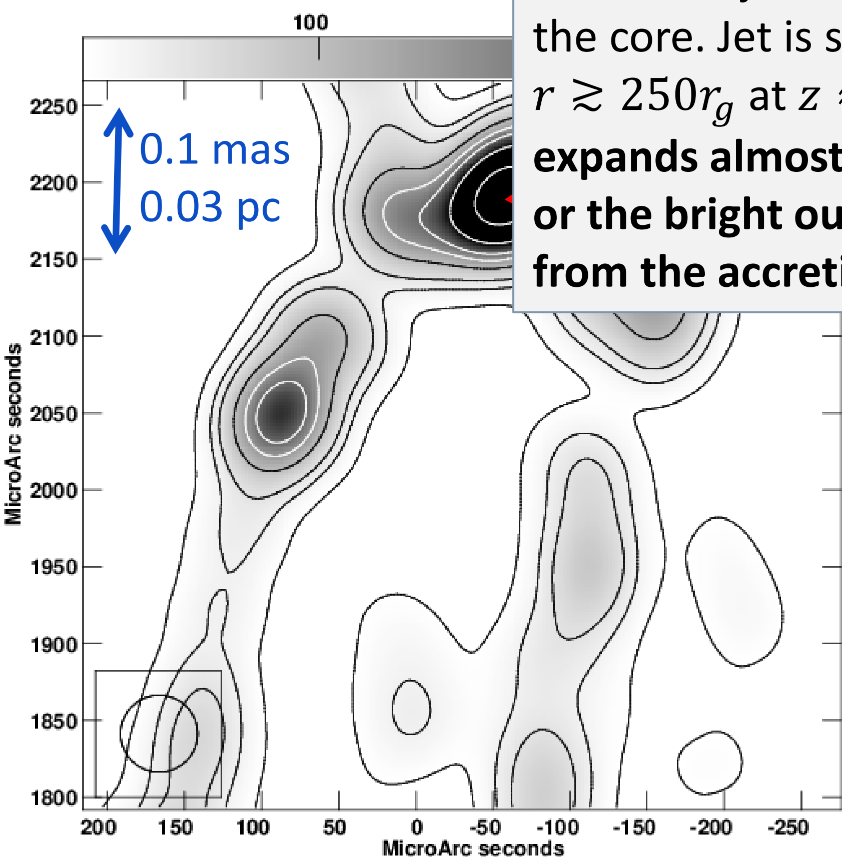


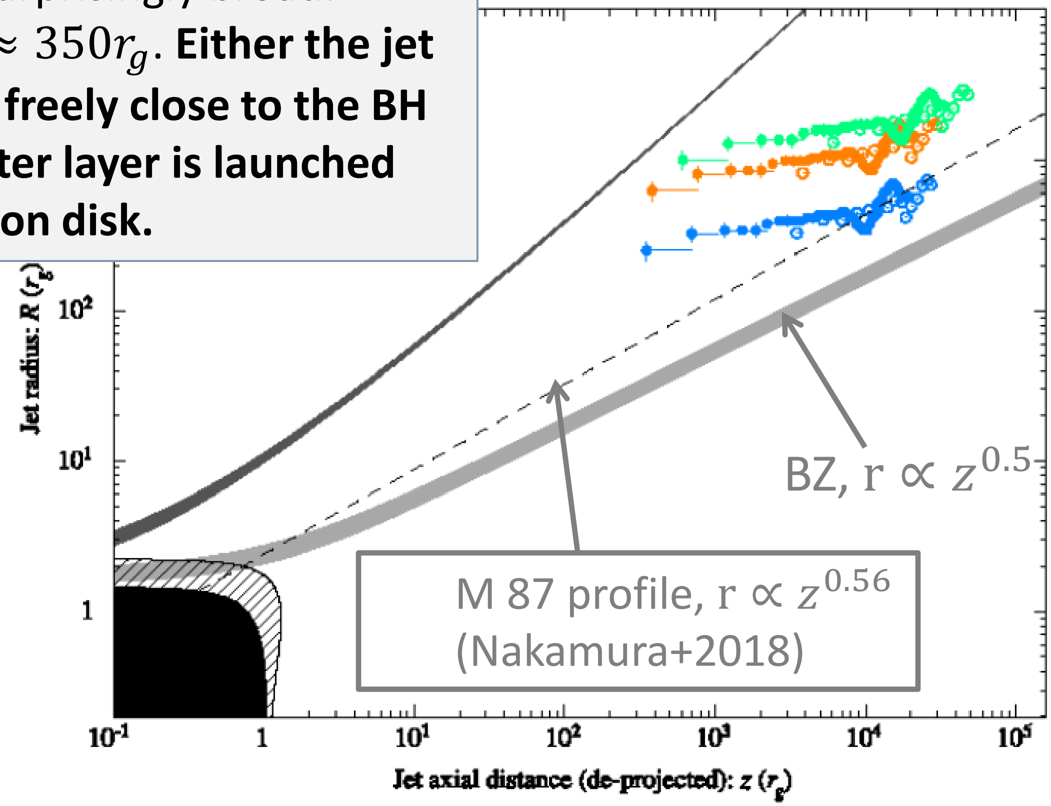


Giovannini, TS+ 2018,
Nature Astronomy

Broad jet close to the central engine

Measured jet width just 30 μas from the core. Jet is surprisingly broad: $r \gtrsim 250 r_g$ at $z \approx 350 r_g$. **Either the jet expands almost freely close to the BH or the bright outer layer is launched from the accretion disk.**

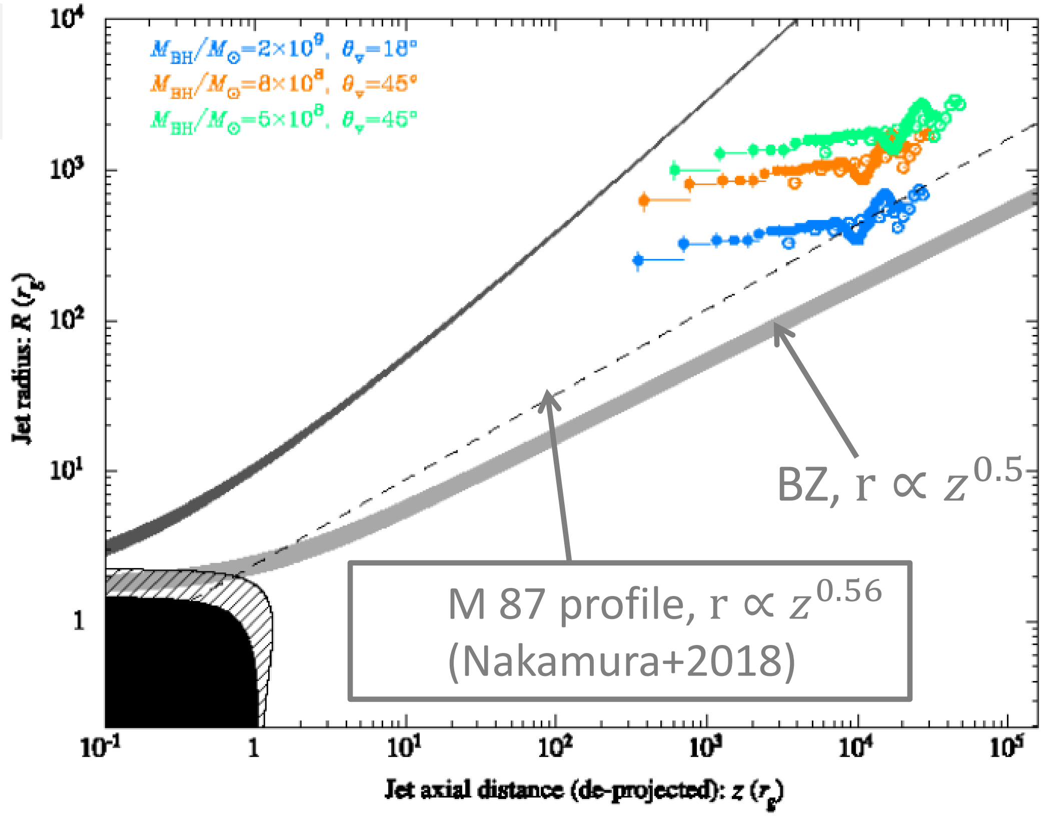




Giovannini, TS+ 2018, Nature Astronomy

Collimation profile

- Almost cylindrical flow with $r \propto z^{0.17}$. Different from M87.



Giovannini, TS+ 2018, Nature Astronomy

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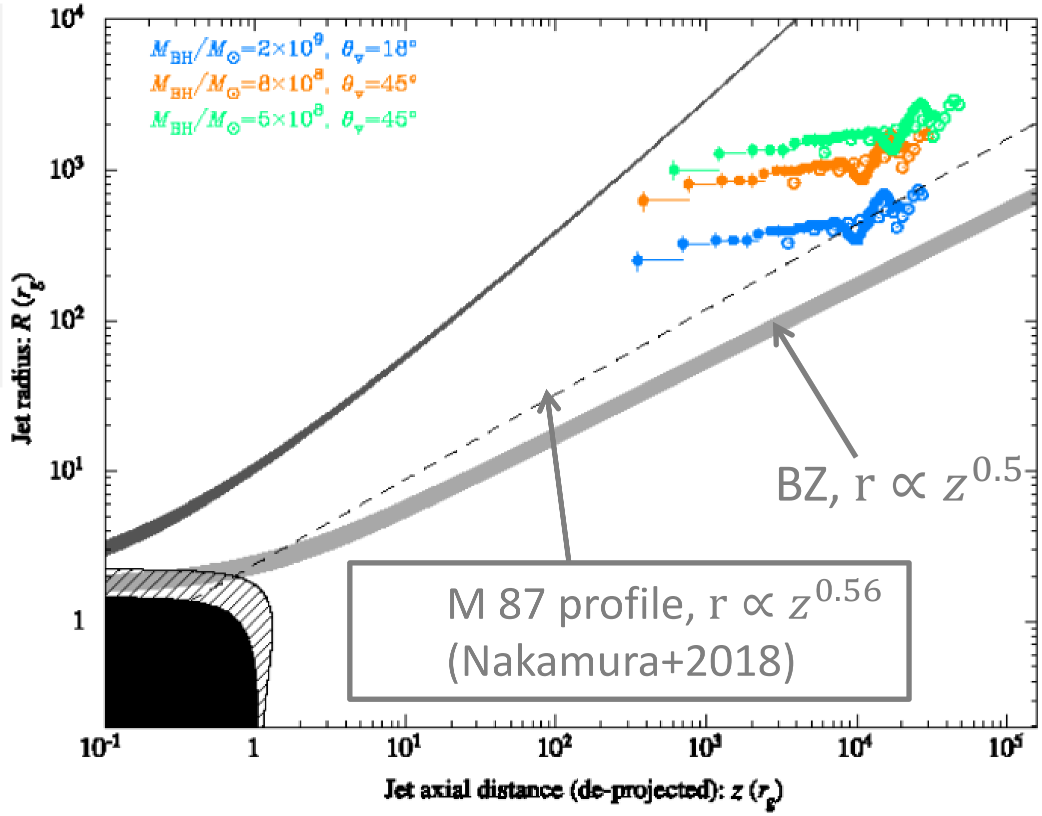
- Almost cylindrical flow with $r \propto z^{0.17}$. Different from M87.
- If $p_{ext} \propto z^{-b}$=> $r \propto z^{b/4}$. For 3C84, $b \lesssim 1$ and $\rho \propto z^{-(b-1)} \approx z^0$. **Flat density profile for the external medium up to $\sim\mathbf{10^4 r_g \sim 0.8}$ pc.**



Giovannini, TS+ 2018, Nature Astronomy

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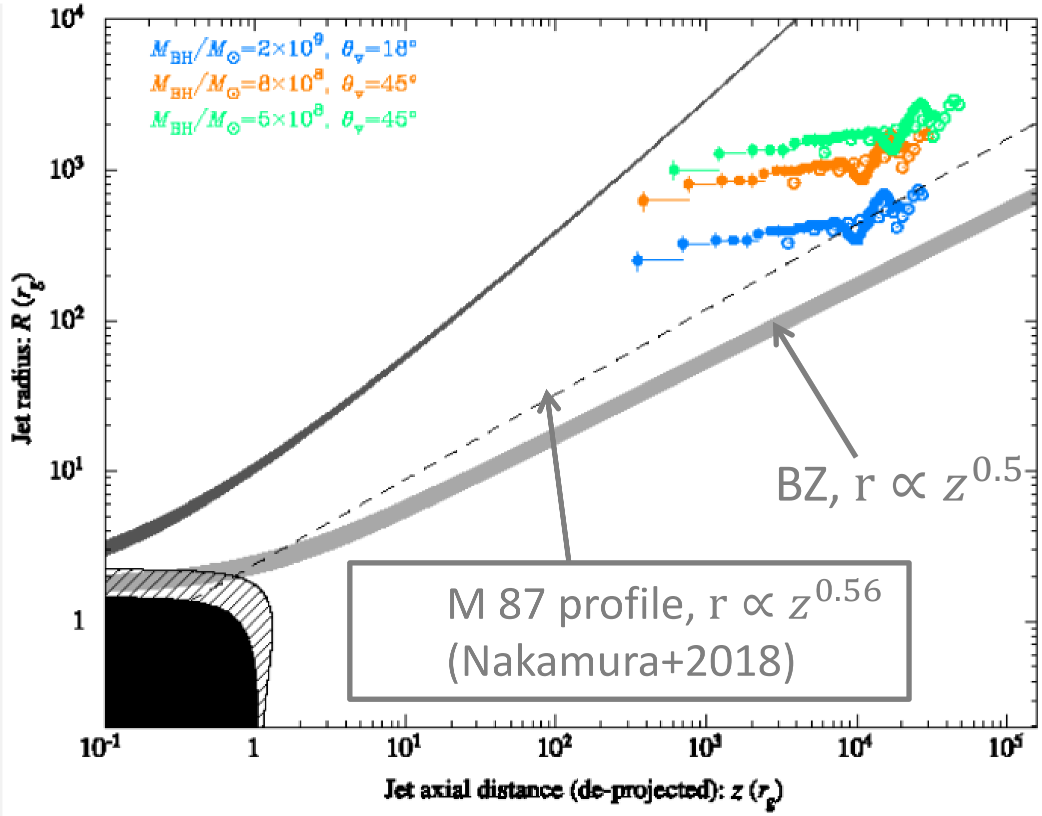
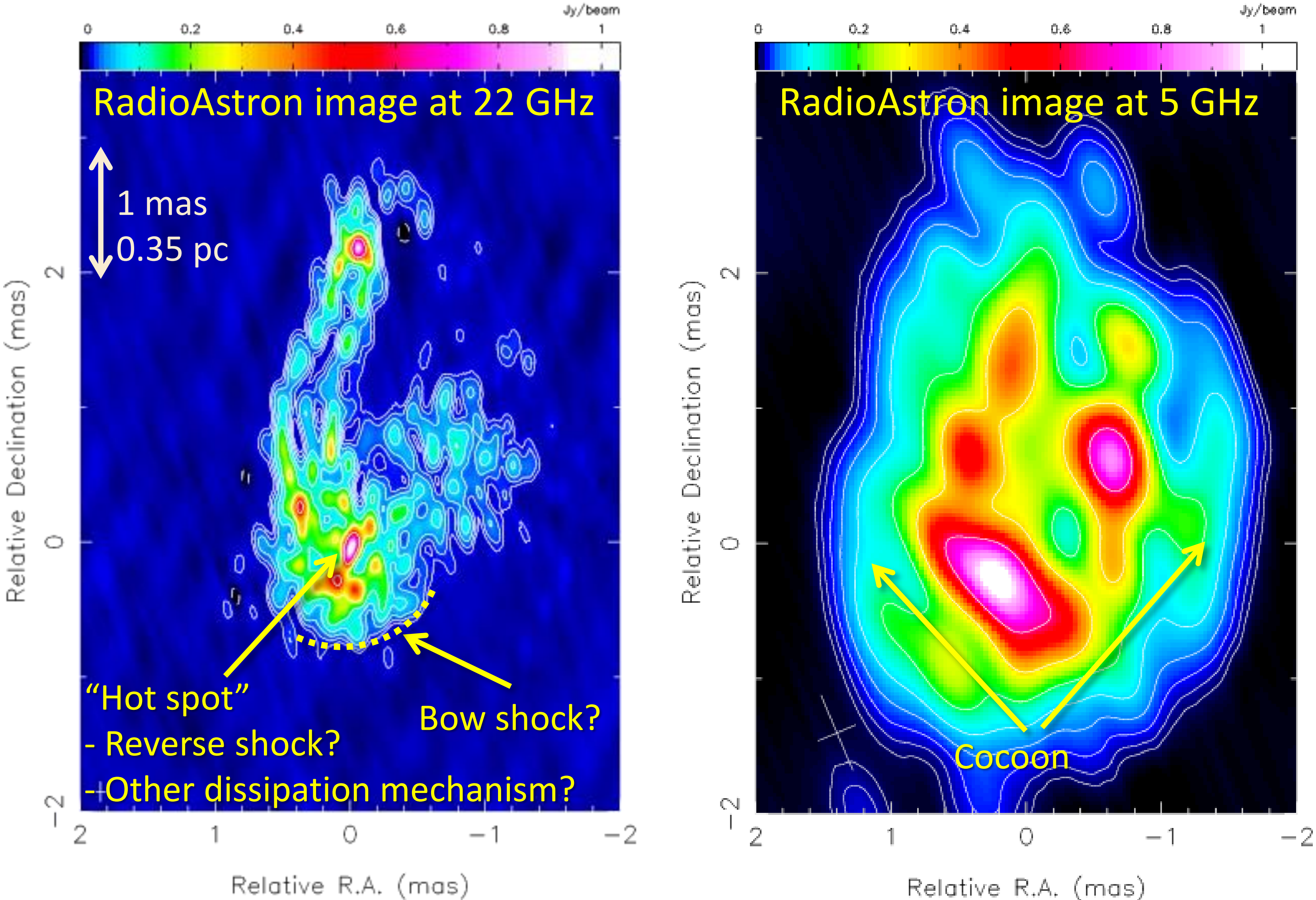
- What kind of medium?
  - Gas in nearly free fall (e.g., Bondi accretion and original ADAF model) has $\rho \propto z^{-3/2}$. Excluded.
  - Inner edge of a thick disk or torus? Unlikely.
  - **Hot cocoon of shocked gas. Quite possibly.**



Giovannini, TS+ 2018, Nature Astronomy

Jet-ISM interaction within 1 pc



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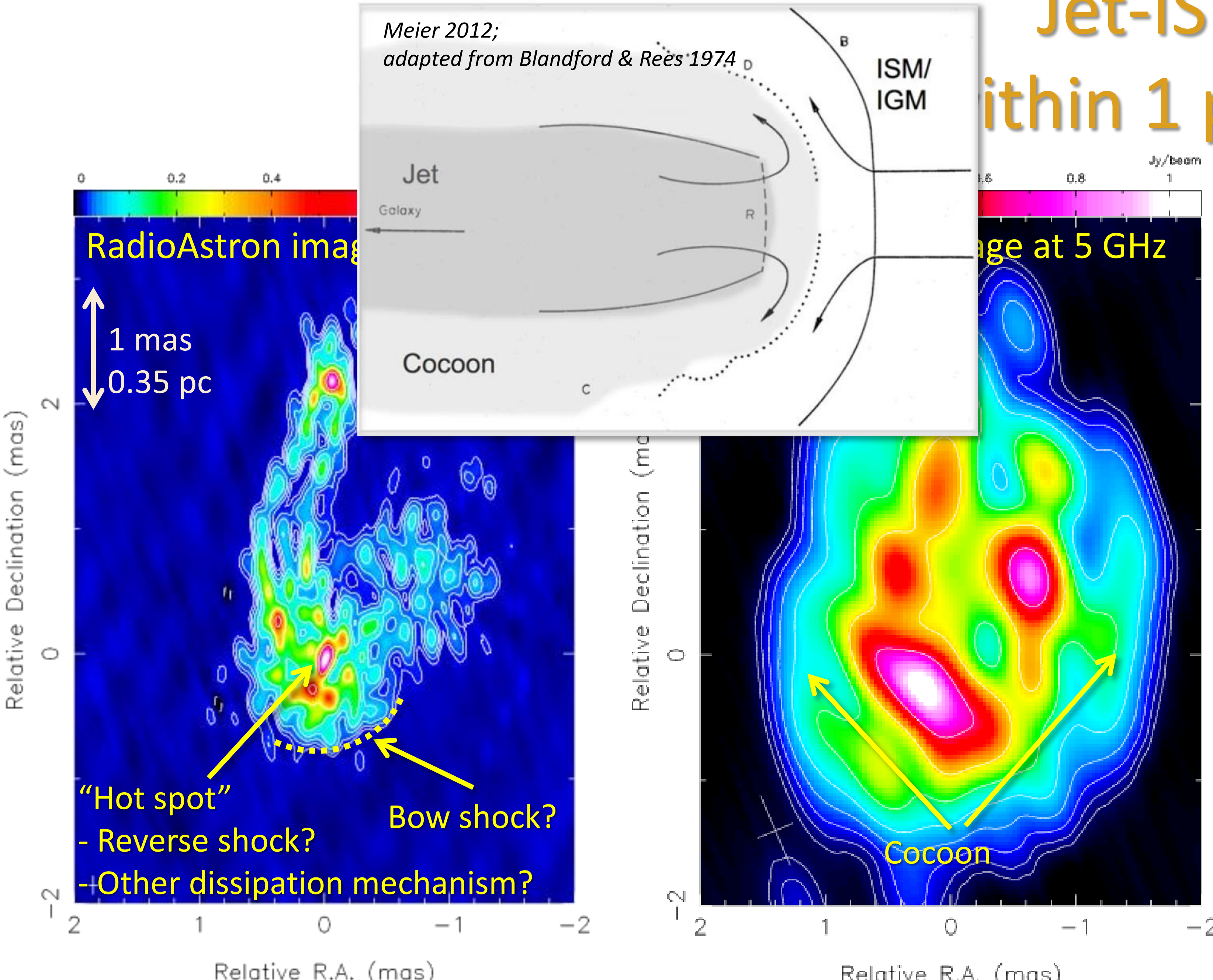

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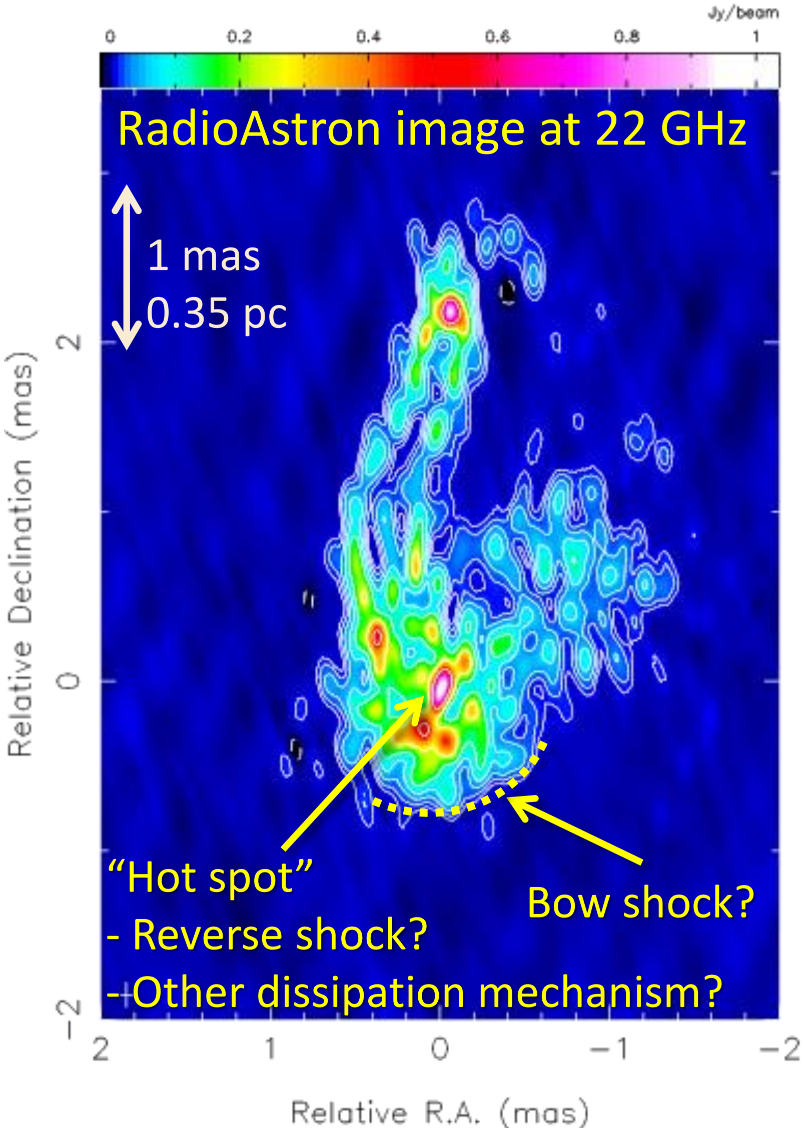
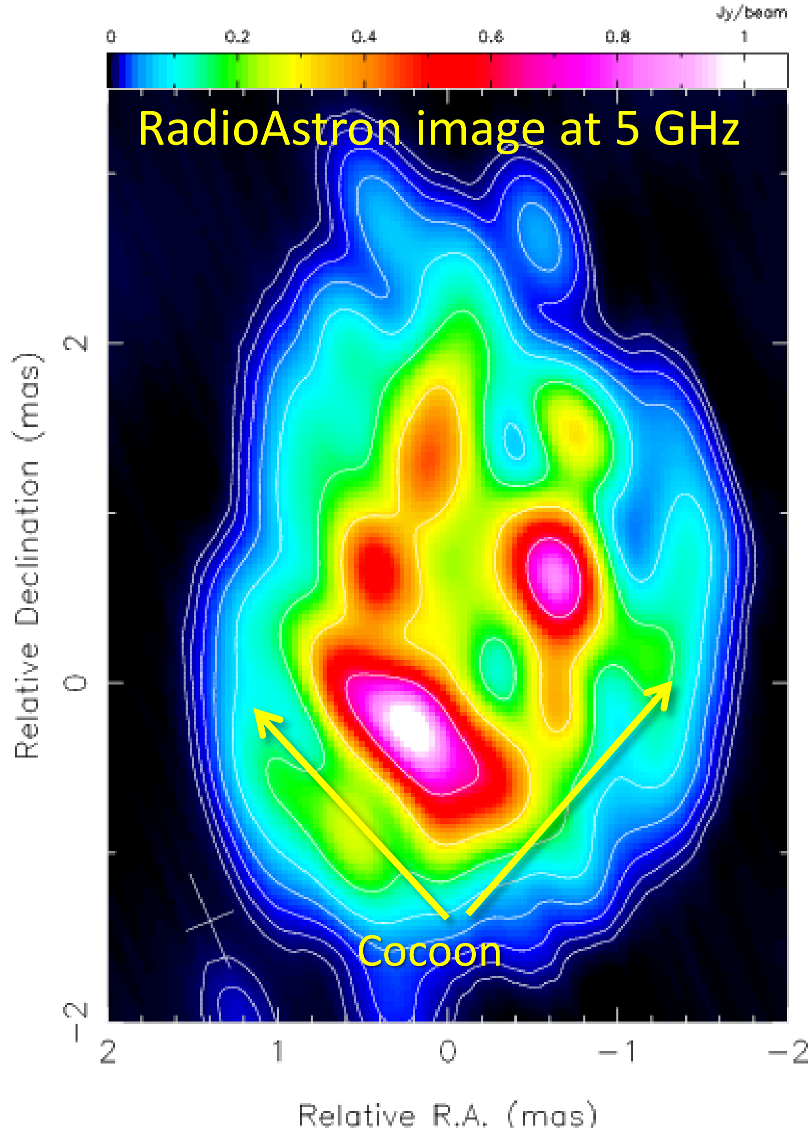
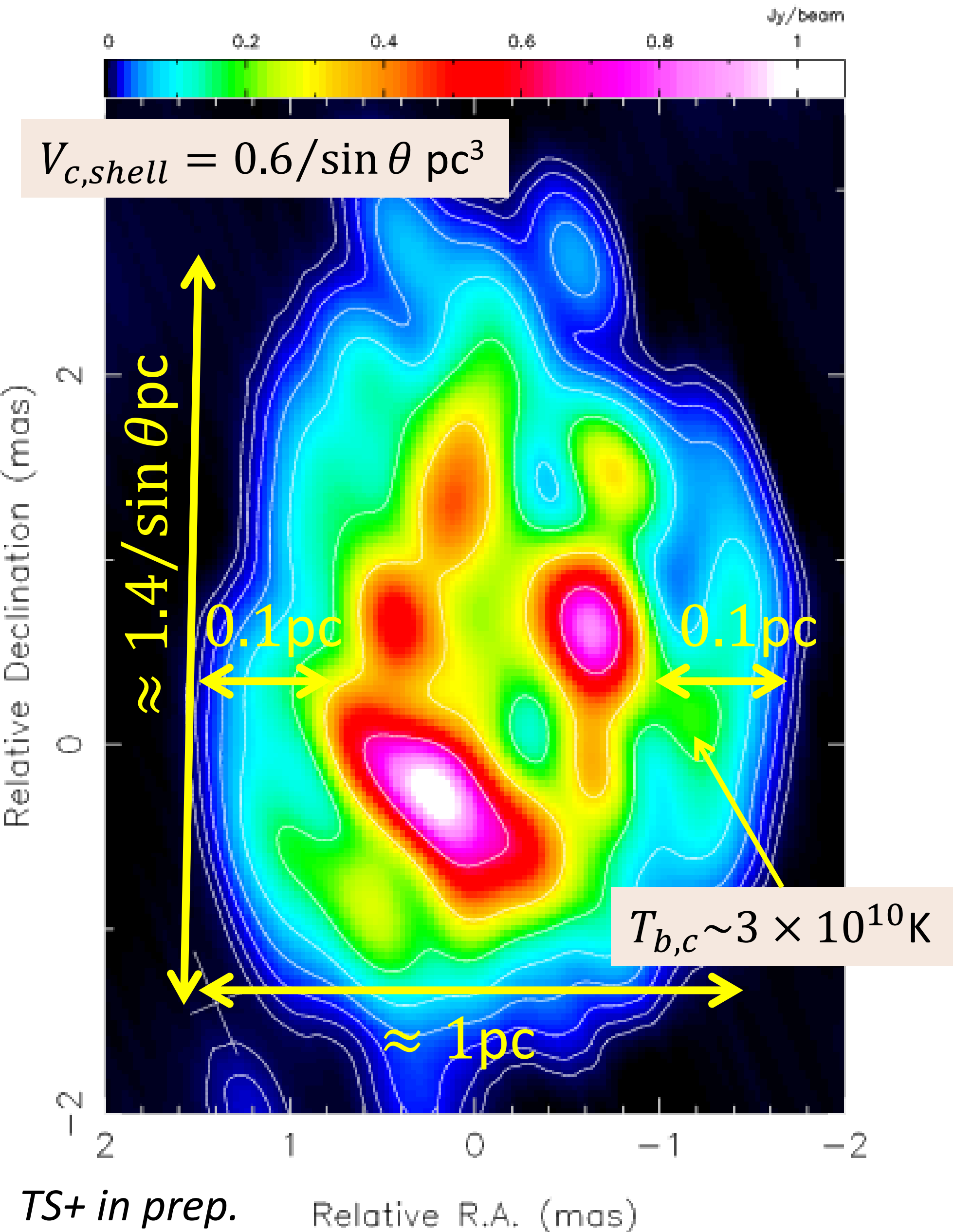




Mini-cocoon



TS+ in prep.

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

- At the time of RA obs., $\Delta t_{C3} \sim 10$yr

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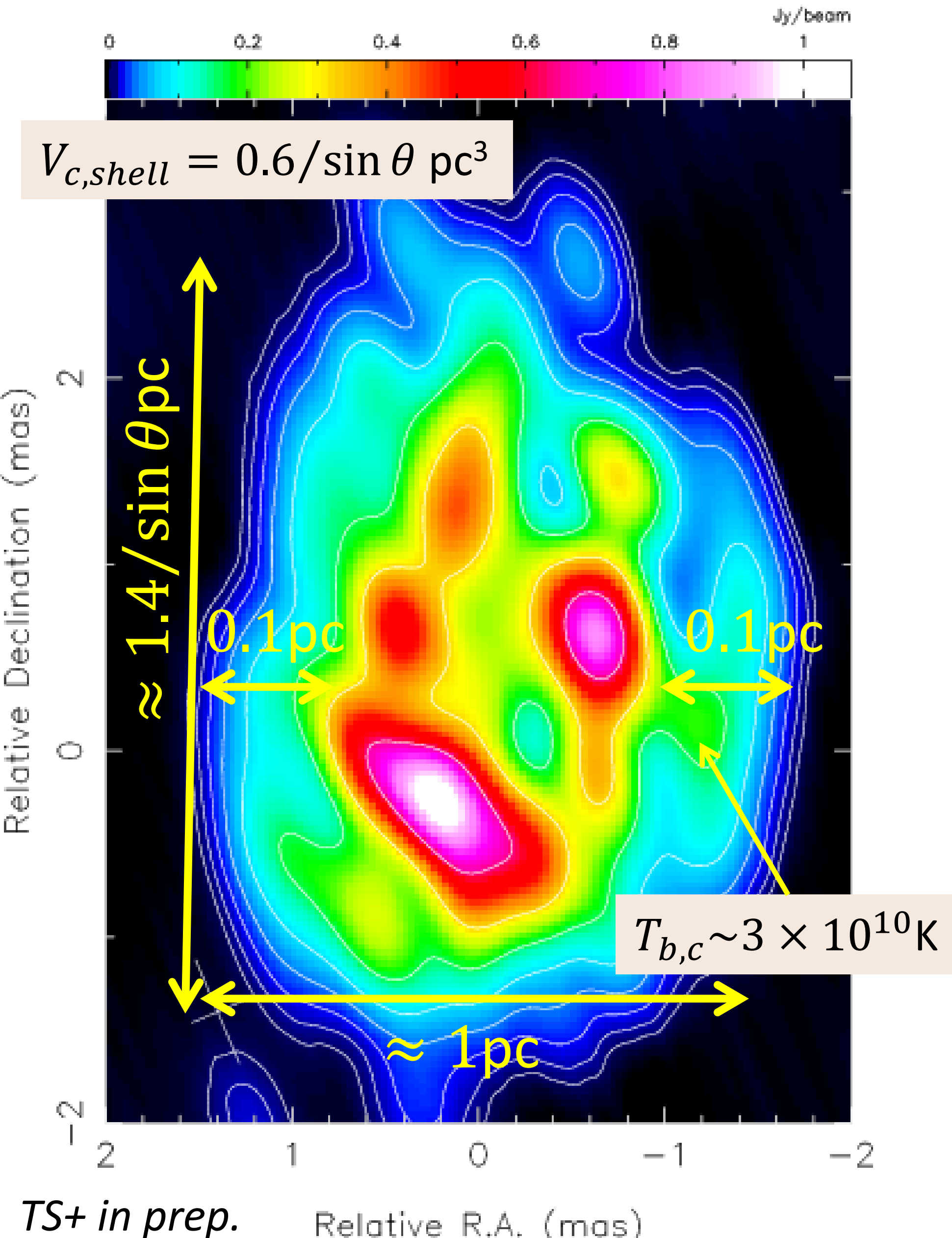

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  - $P_{cocoon} \sim 2 \times 10^{44}$erg/s ($k$=100)
  - Long term average from X-ray cavities (Rafferty+06): $P_{cav} \sim 1.5 \times 10^{44}$erg/s

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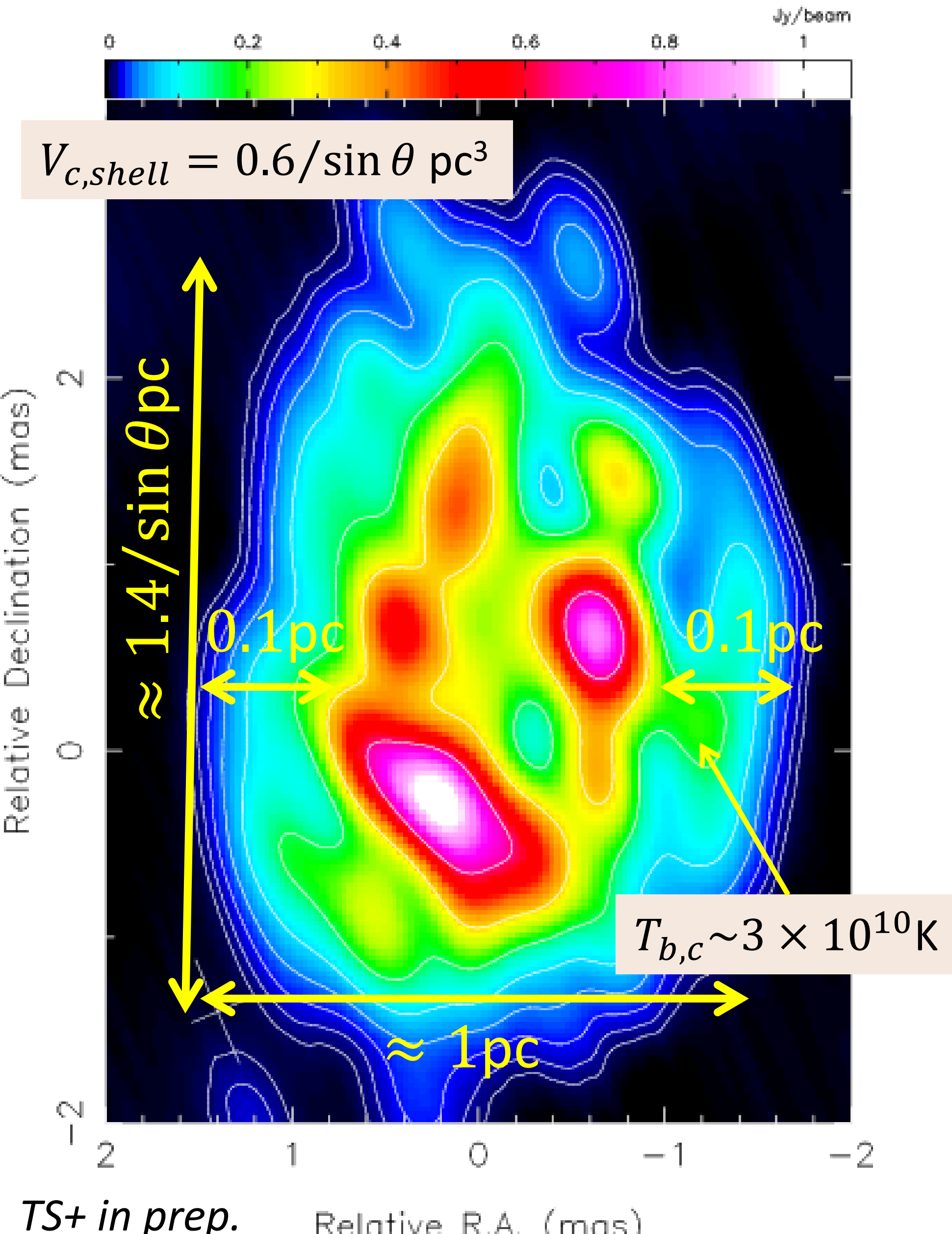

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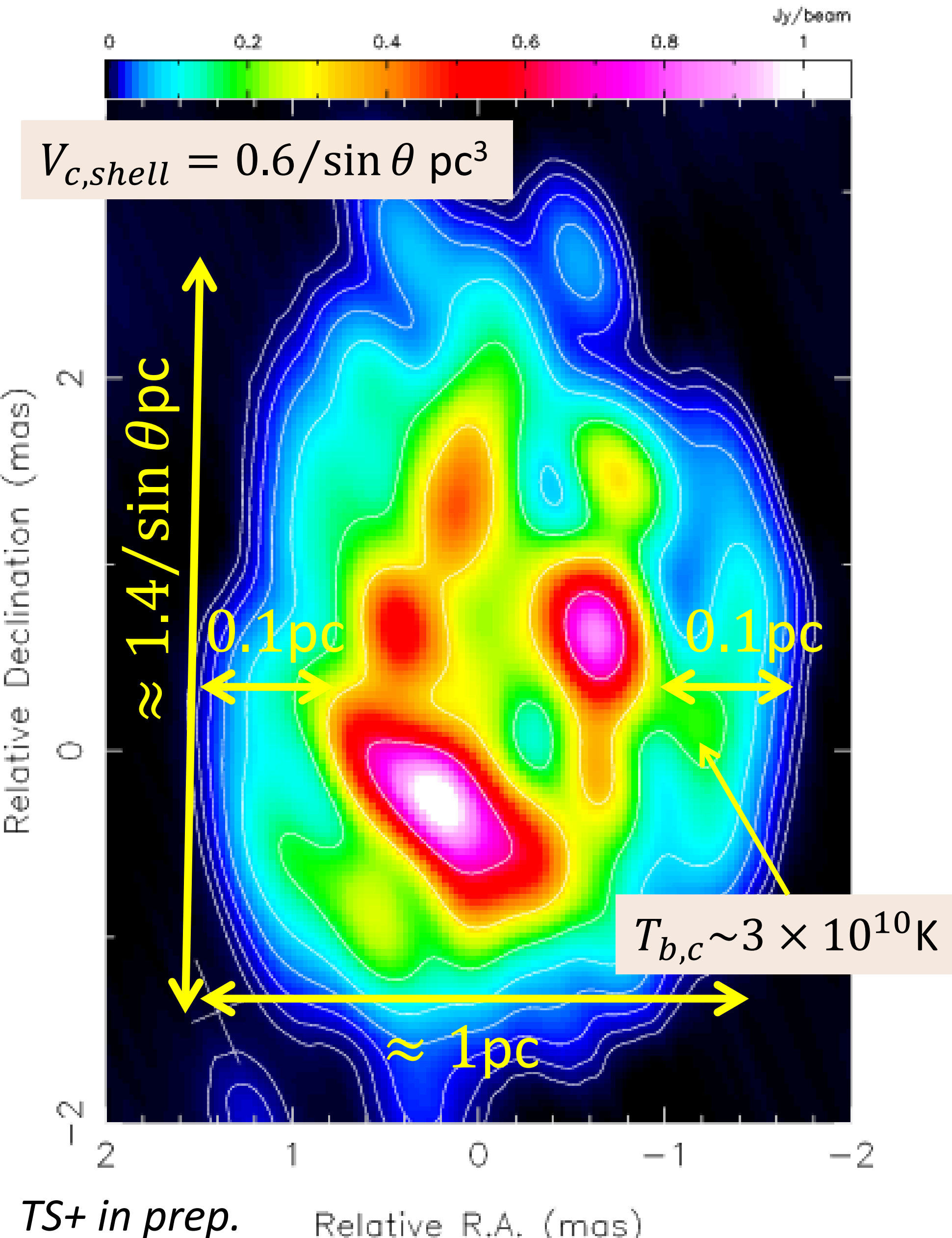

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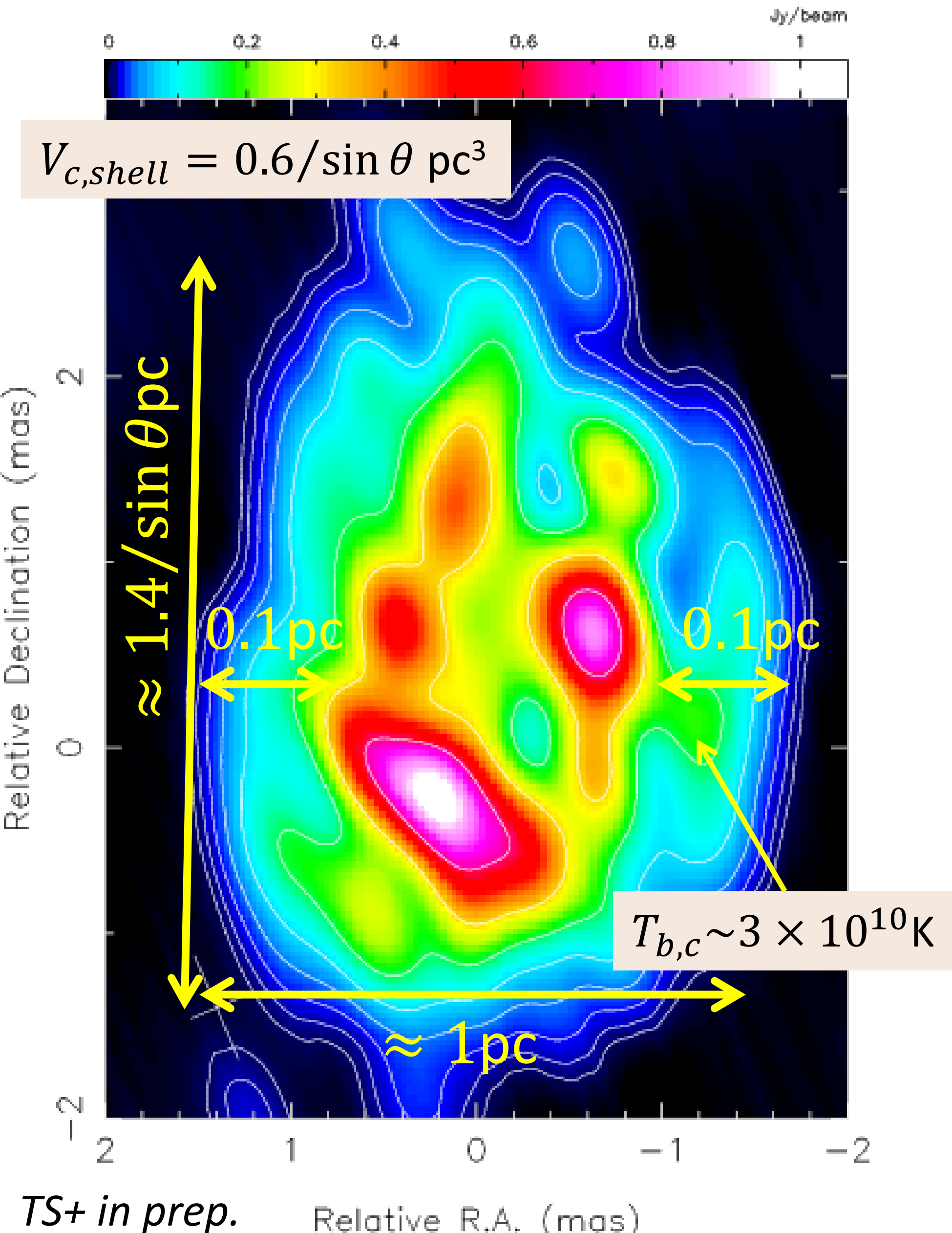

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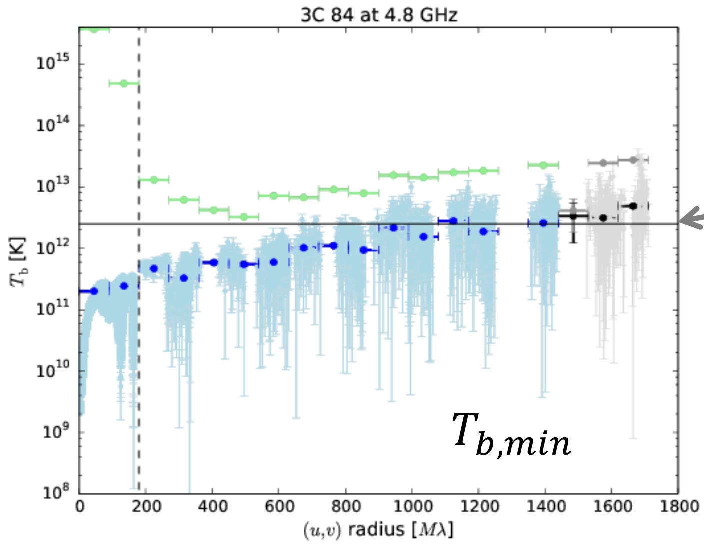
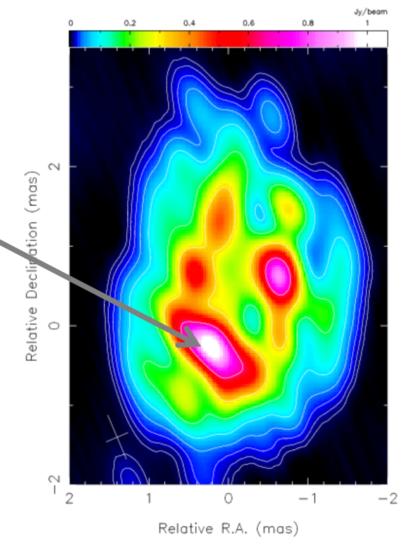
- Expansion speed: $\langle v_{cocoon} \rangle \approx$ 0.16c
- Implication to the ambient density: assuming $p_c = \rho_a v_c^2$ and minimum energy in the cocoon , $n_p \gtrsim 7$ cm^{-3}

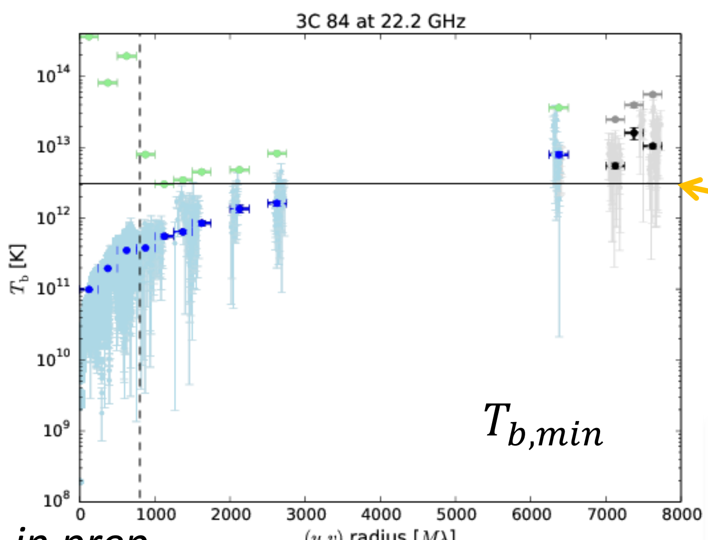
High brightness temperature in C3 hot spot



5 GHz

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

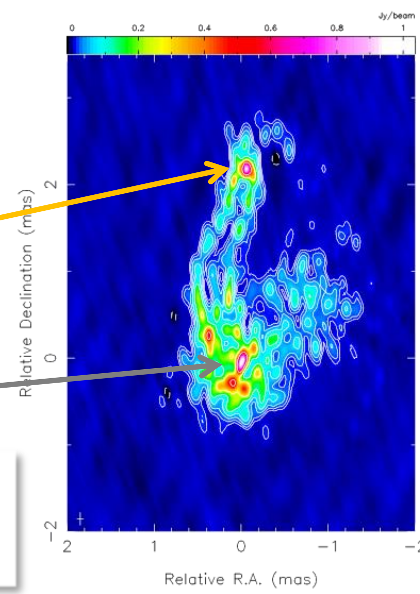




22 GHz

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

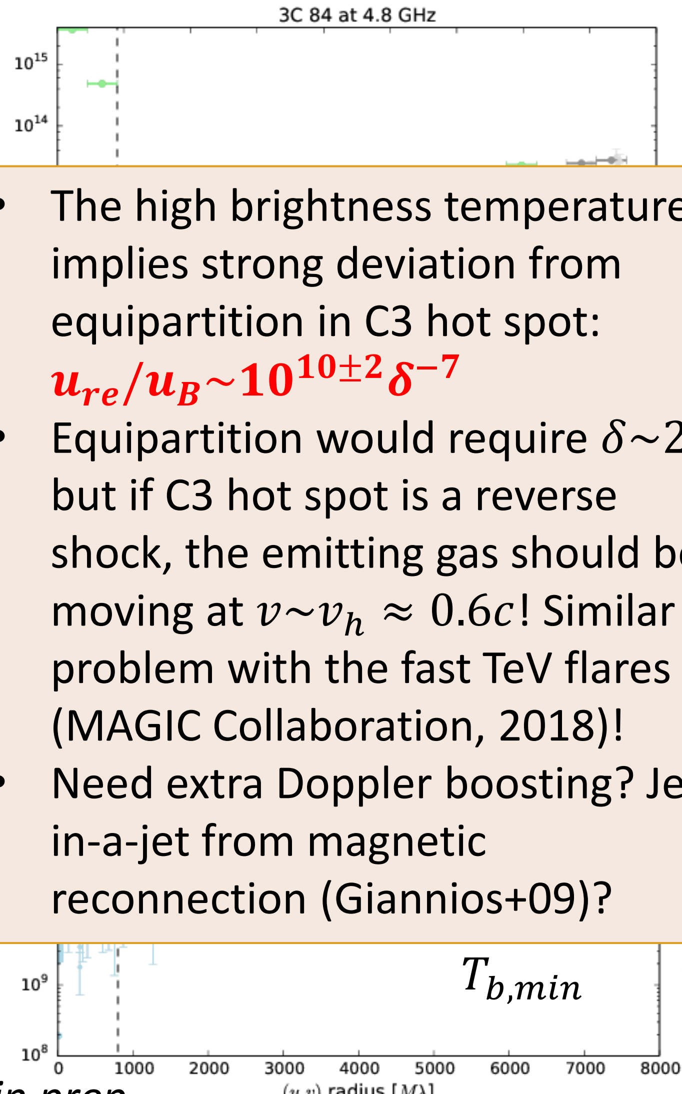
$T_{b,mod}(C3) = 8 \pm 2 \times 10^{11}$K



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

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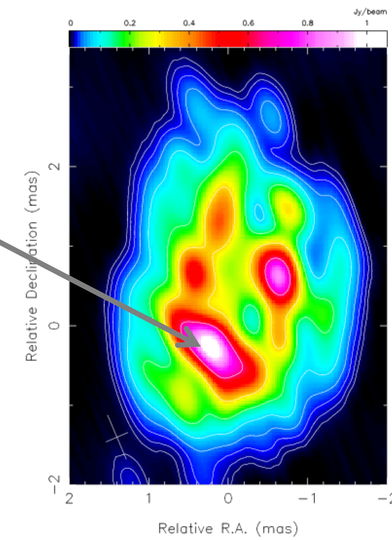

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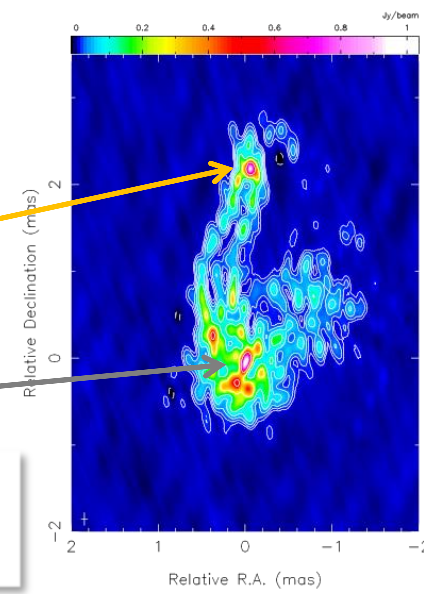

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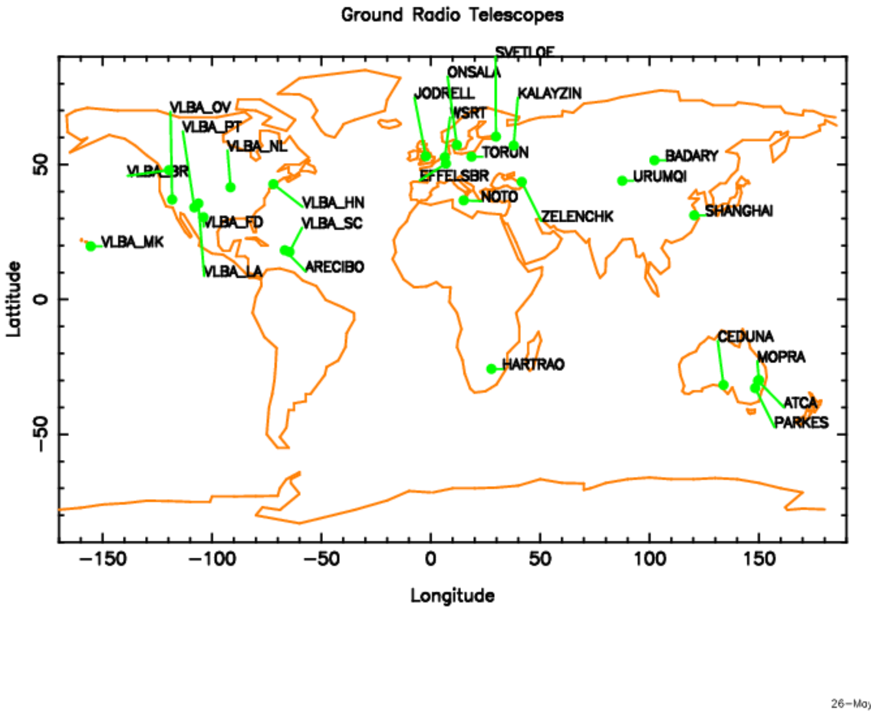
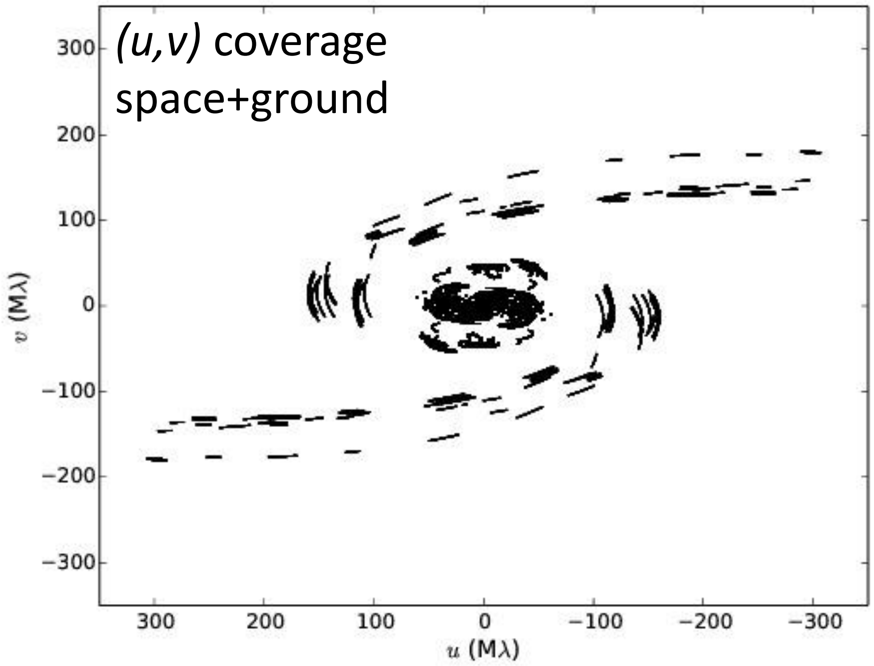
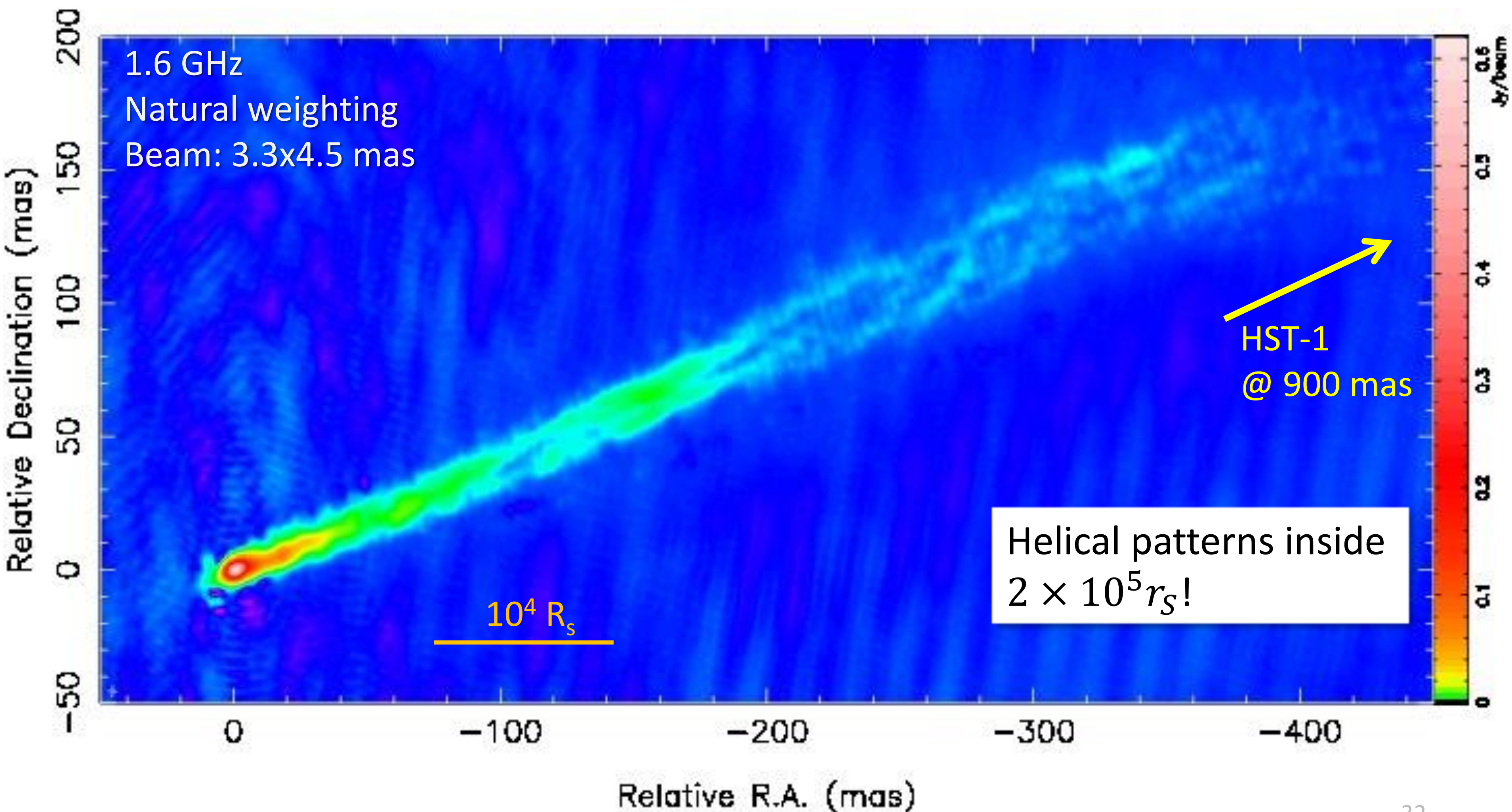
M87 RadioAstron imaging in June 2014 at 1.6 GHz

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





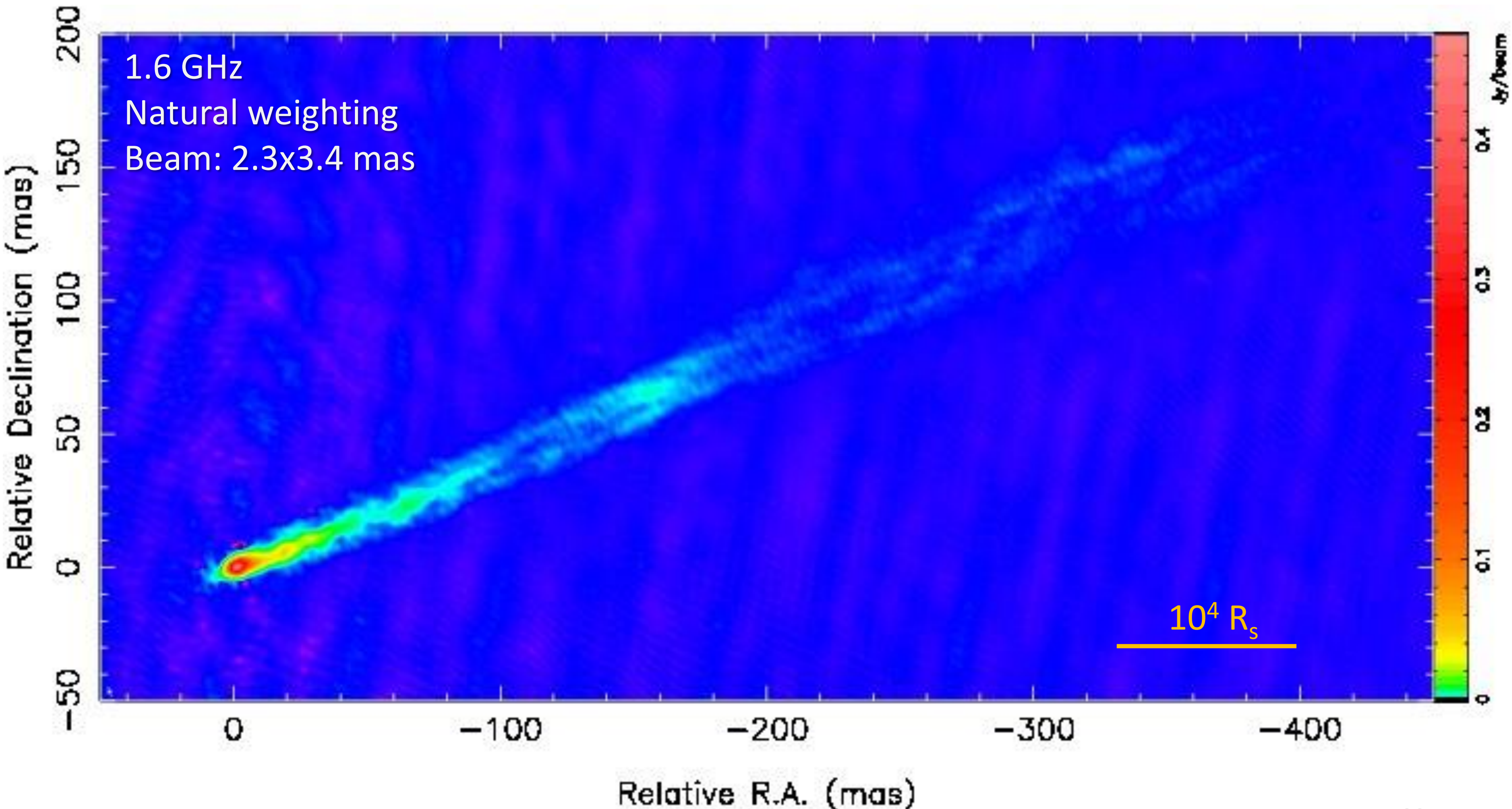
M87 in June 2014 with 26 ground radio telescopes



TS+ in prep.

Source detected up to **5 D_{earth}** .
Resolution down to 0.5 mas @ 1.6GHz.

M87 in June 2014 including RadioAstron baselines



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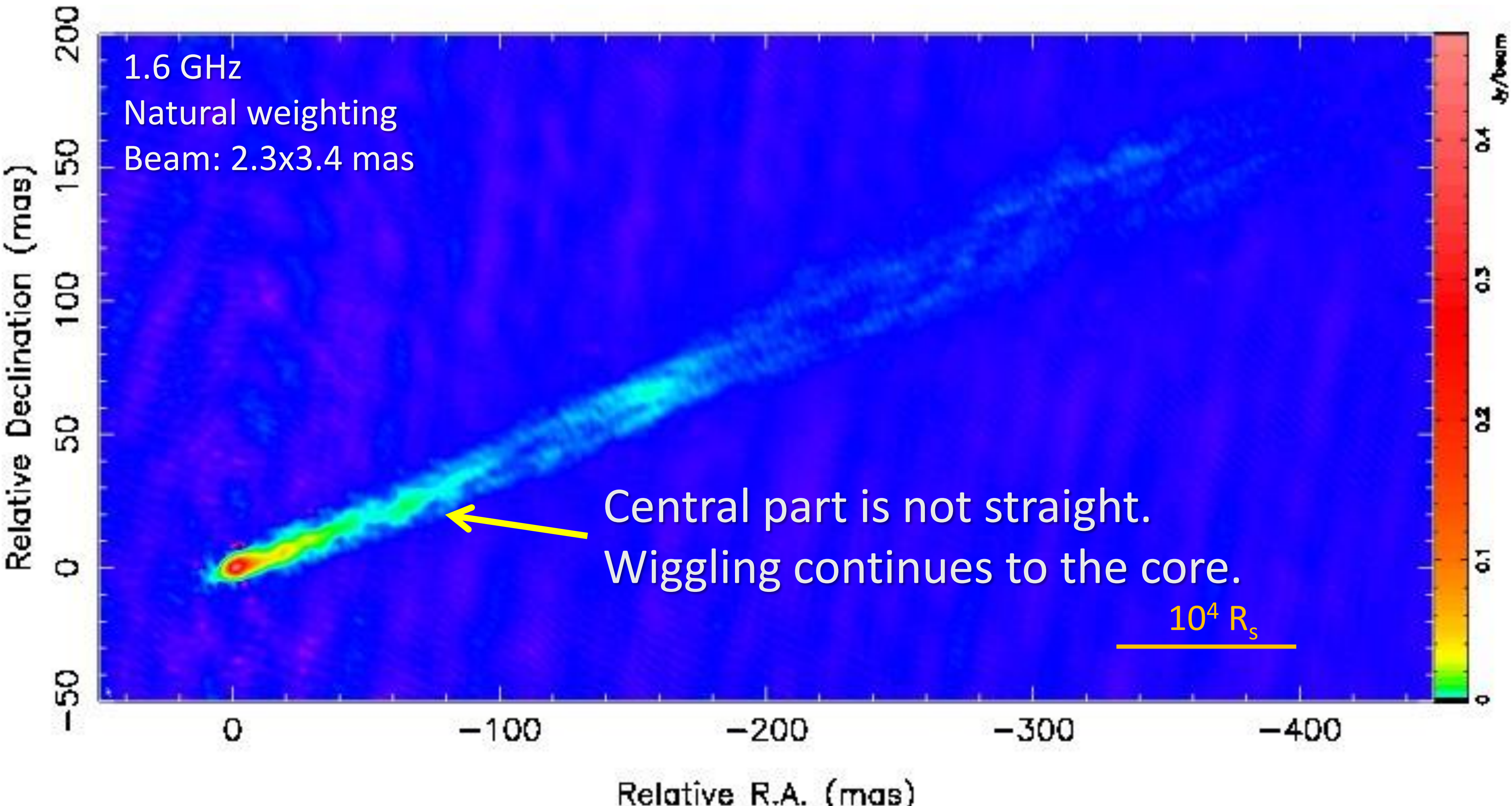
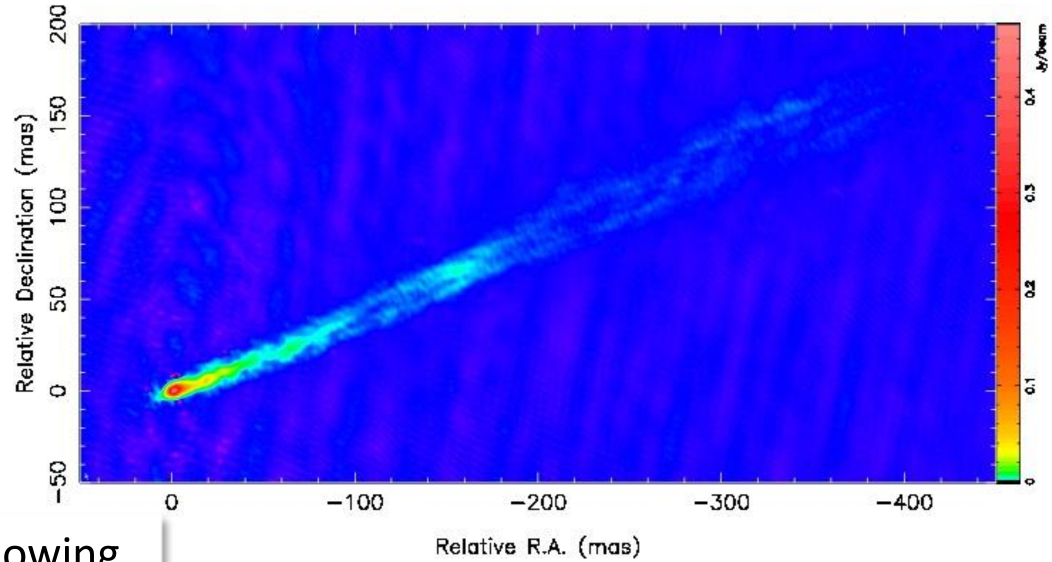


TS in prep.

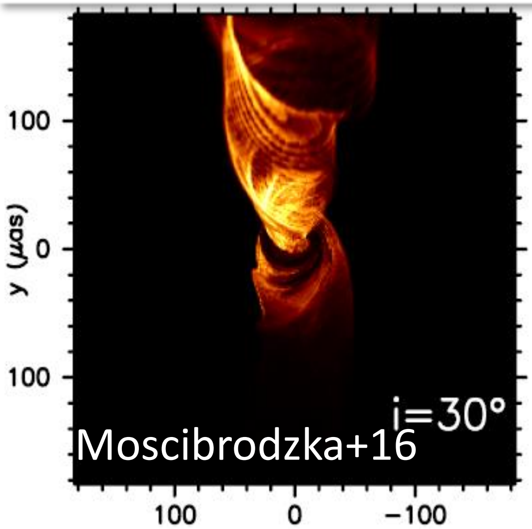
Origin of the patterns?



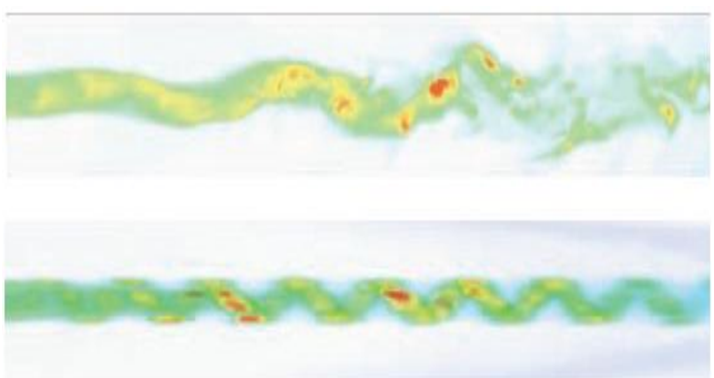
Rotating plasma following helical B-field lines?

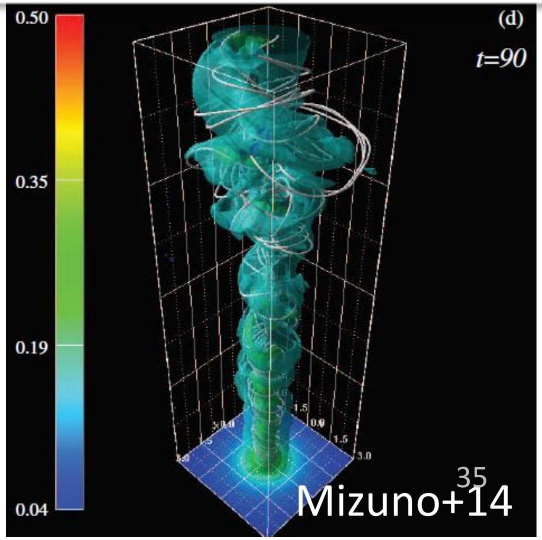
Kelvin-Helmholtz instability?

Current-driven kink instability?



Moscibrodzka+16


Hardee 2012



Mizuno+14

Conclusions

- Space-VLBI imaging of nearby AGN reveals previously unresolved internal jet structures that could be compared to GRMHD simulations
- M87 and 3C84 have quite a different jet structure. This may be related to differences in accretion mode and/or the environment.
- 3C84 has an initially broad jet just a few hundred r_g from the BH. Can ergosphere-driven jets expand almost freely at $z < 100r_g$ or is the outer jet layer launched from the accretion disk?
- 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. Perhaps this is related to the fast TeV flares?
- RadioAstron image of M87 shows a complex internal structure of the jet in the acceleration/collimation zone with helical filaments.
- More to come! *RadioAstron* imaging observations of M87 at 5 and 22 GHz have been made – including a polarimetric 22 GHz observation close-in-time to the 2018 EHT campaign.