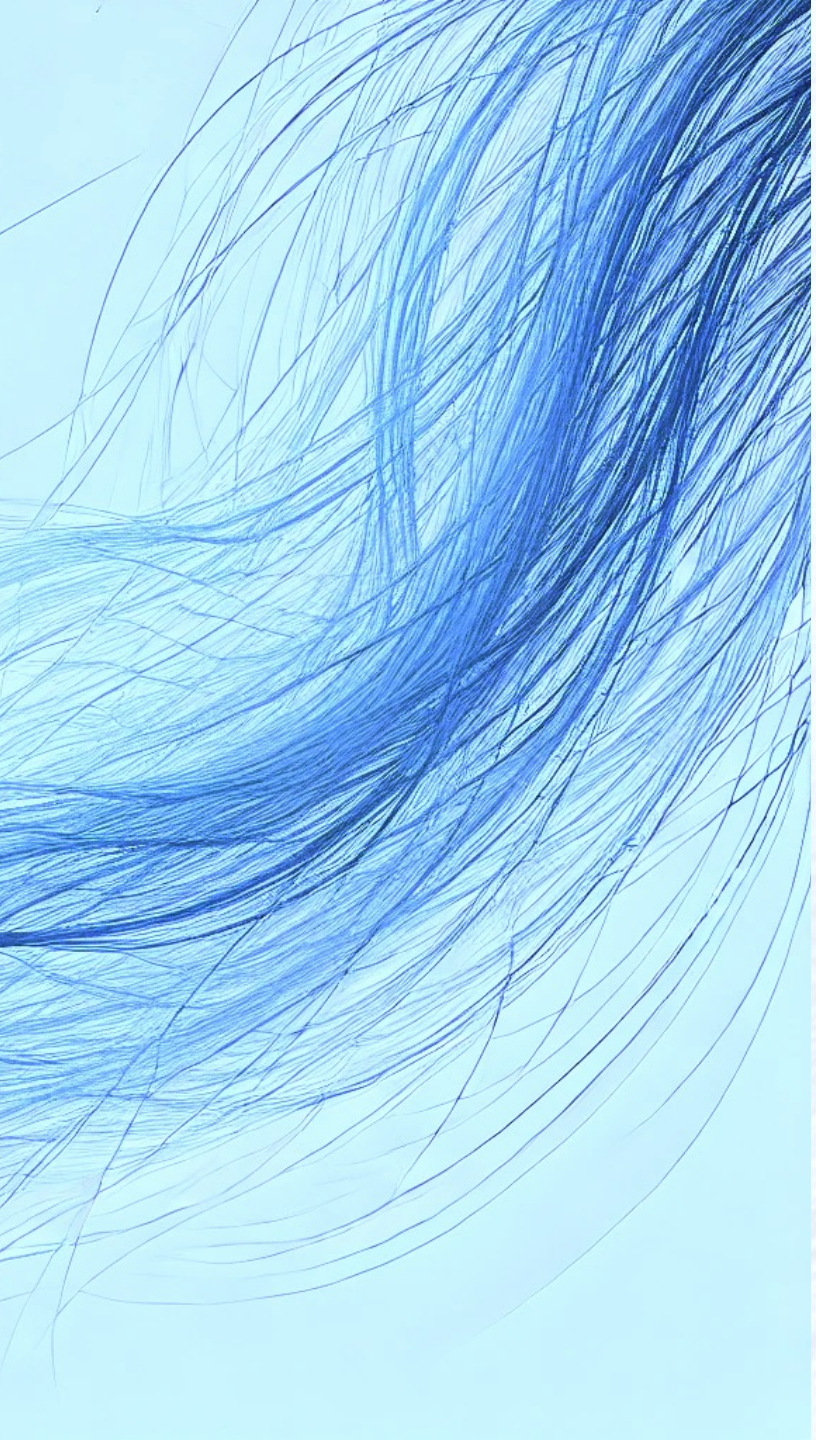


Non-thermal filaments in galaxy clusters with LOFAR-VLBI

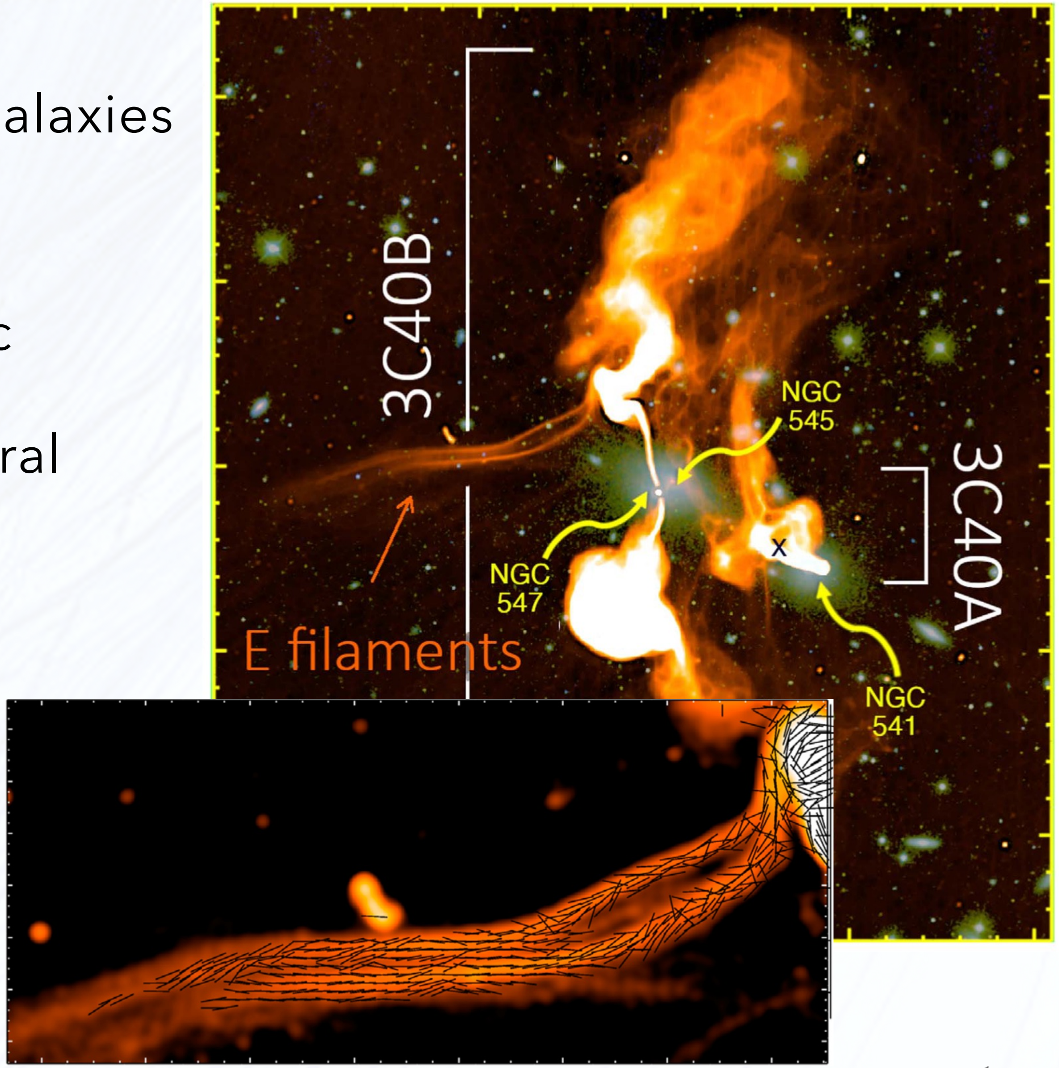
Emanuele De Rubeis, **M. Bondi**, **A. Botteon**, R. J. van Weeren, J. M. G.H. J. de Jong, **G. Brunetti**, L. Rudnick, M. Brüggen, **L. Bruno**, E. L. Escott, **C. Gheller**, L. K. Morabito, K. Rajpurohit, H. J. A. Röttgering

Hamburg Universität & INAF-IRA

Which filaments?

An increasing number of **isolated filaments** has been observed in the ICM and in the surrounding of radio galaxies

- Lengths of 10-100s kpc, widths of 100s pc - few kpc
- **Steep spectral index** ($\alpha > 1.3$), with possible spectral **steepening** along their extension
- **High fractional polarization** (up to 40-50%), with magnetic field aligned along the filament

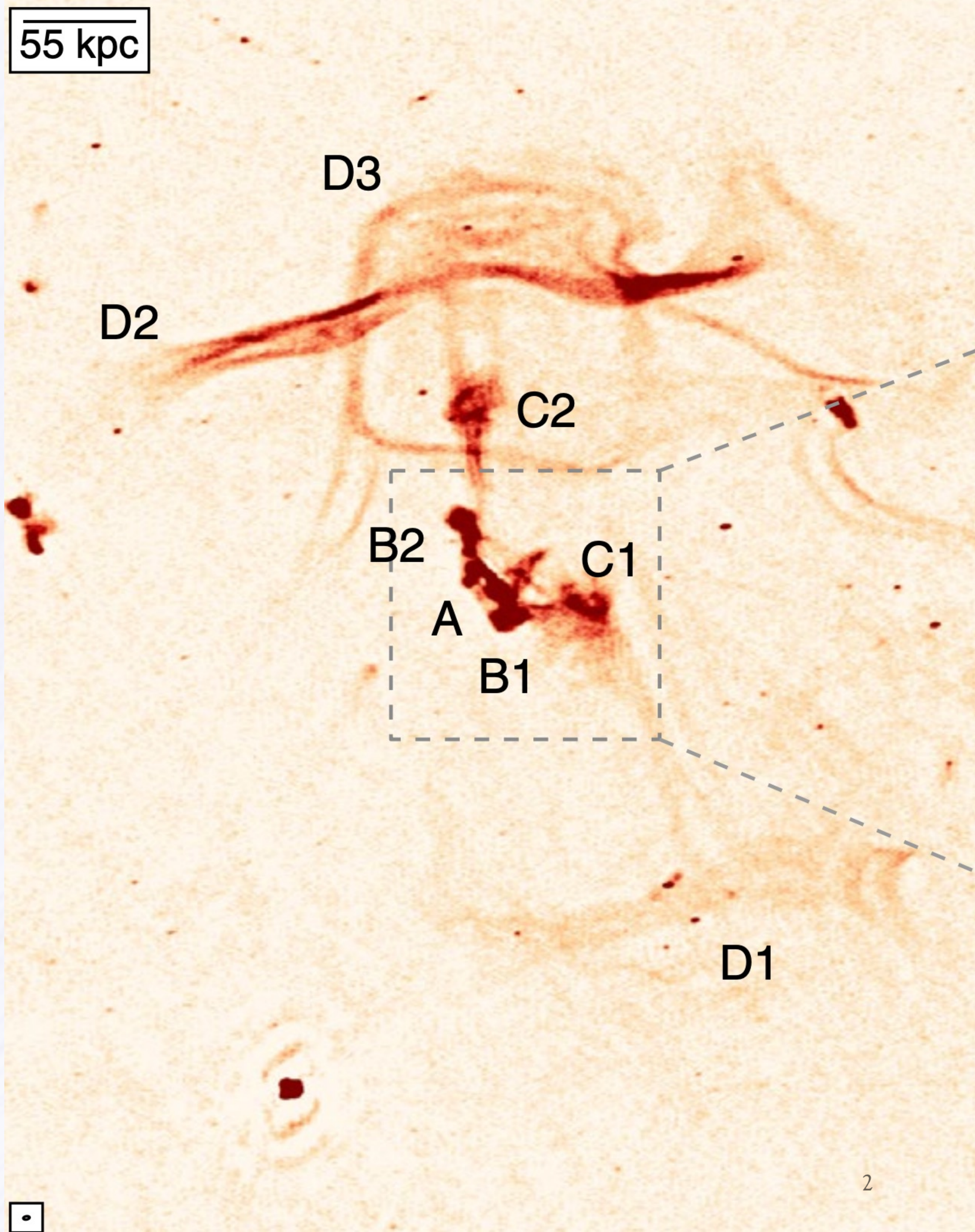


Rudnick et al. (2022)

Which filaments?

Their origin is still debated.

These structures then represent unique sites for studying the physical processes in the ICM, including their **magnetic fields** and the **evolution of cosmic rays**.



Brienza et al. (2021)

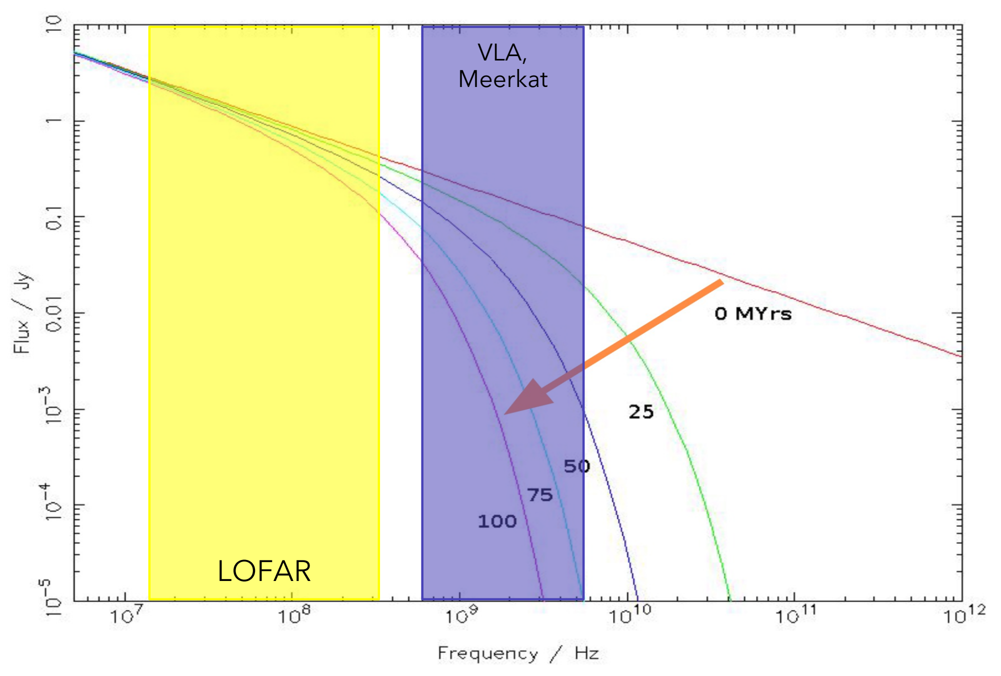
LOFAR-VLBI

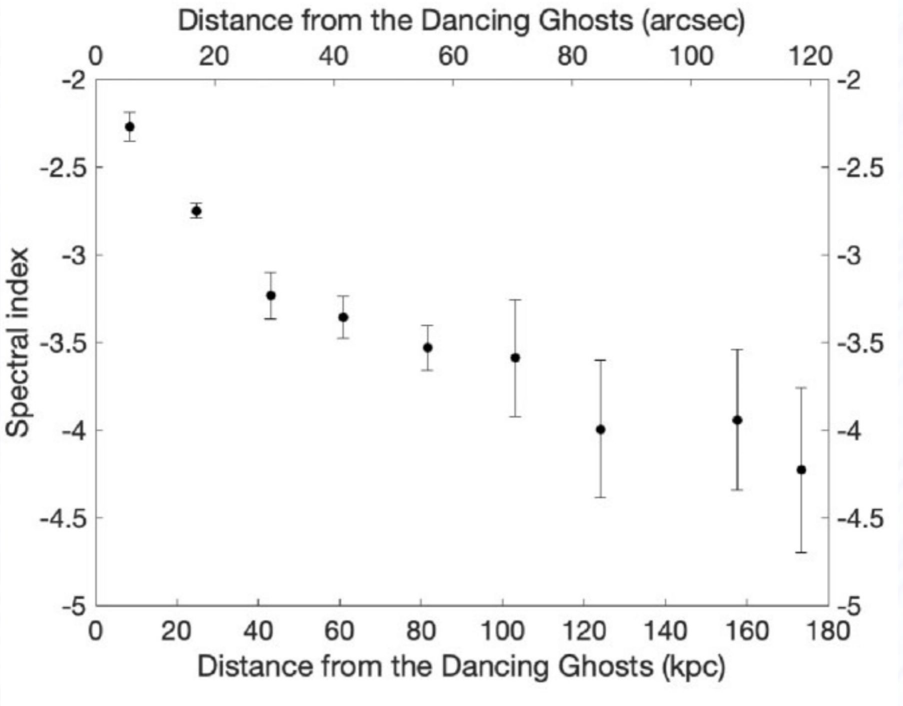
The Low Frequency ARray (**LOFAR**) is an interferometer that operates between **10-90 MHz** (LBA) and **120-240 MHz** (HBA).

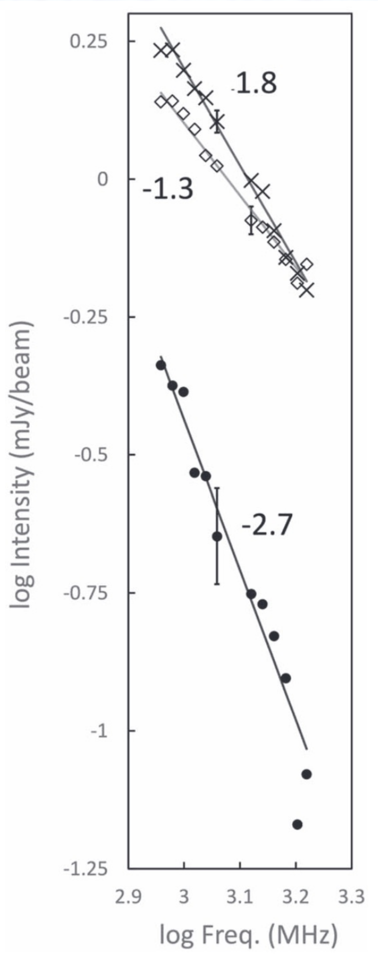
It has 38 stations in the Netherlands and 14 additional stations spread throughout Europe, called **international stations** (IS), providing a resolution of ~**0.3″ at 150 MHz**

Why LOFAR-VLBI?

LOFAR-VLBI is a unique array to study such structures, combining **high-sensitivity** and **high-resolution** at **low-frequency**







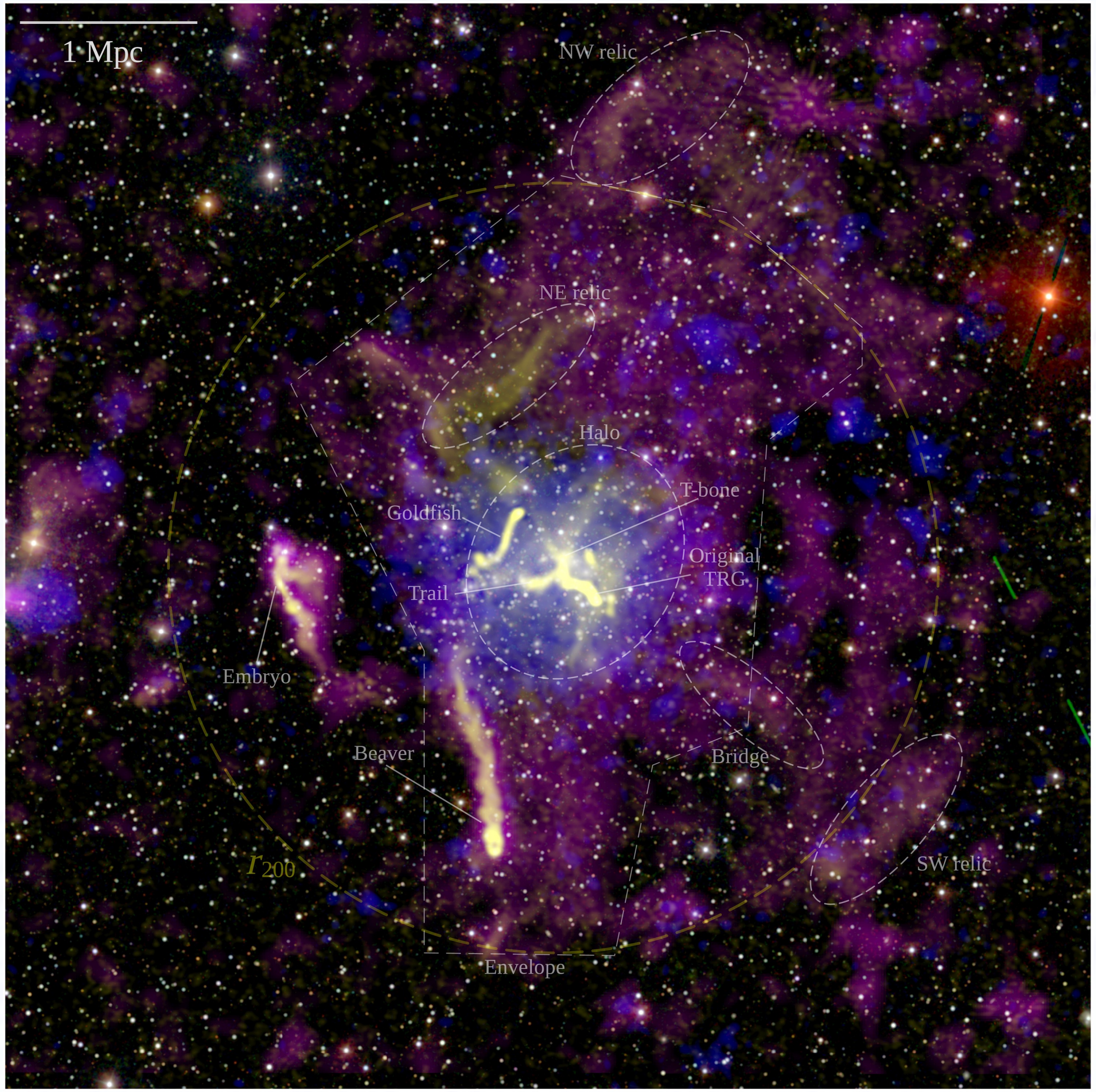
Steep spectrum and **steepening** along the filament!

Rudnick et al. (2022), Velović et al. (2023)

Why LOFAR-VLBI?

Our aim is to **study the filaments in Abell 2255** at an **unprecedented high-resolution**, to constrain their origin and their physical properties.

To do so, **deep high-resolution observations** with LOFAR-VLBI are required, given the possible broad **mixture of different spectral components** observed at lower resolution (16", Lamée 2016)



Botteon et al. (2020,2022)

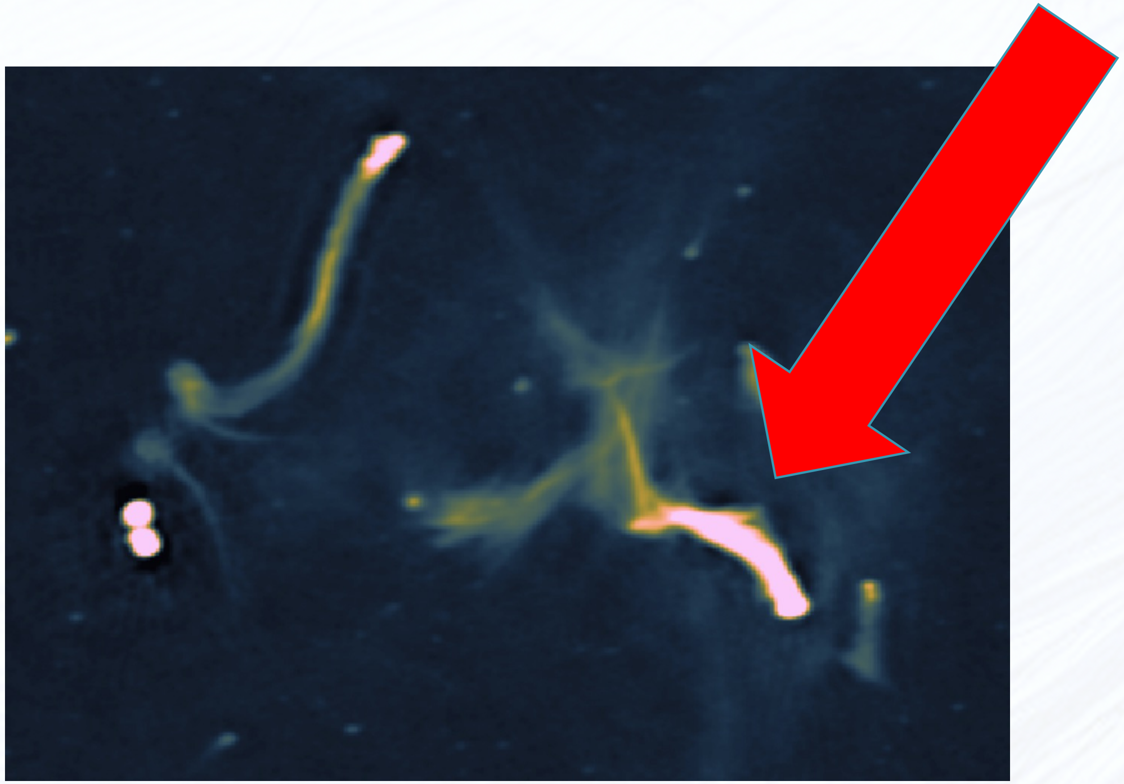
LOFAR-VLBI postage-stamp mode

We have processed **56 hours** of LOFAR HBA data (**144 MHz**) using IS (LC12_027, PI van Weeren).

We obtained **sub-arcsecond resolution images** of the **five, brightest cluster member radio galaxies**.

Morabito et al. (2022)

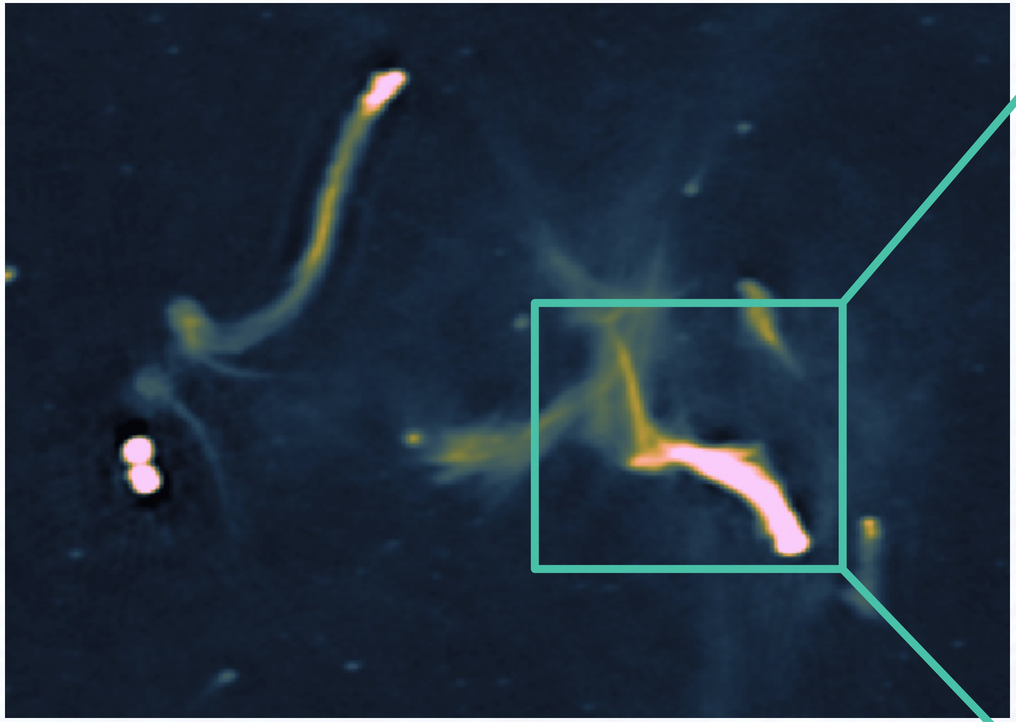
LOFAR-VLBI insights: “Original TRG”



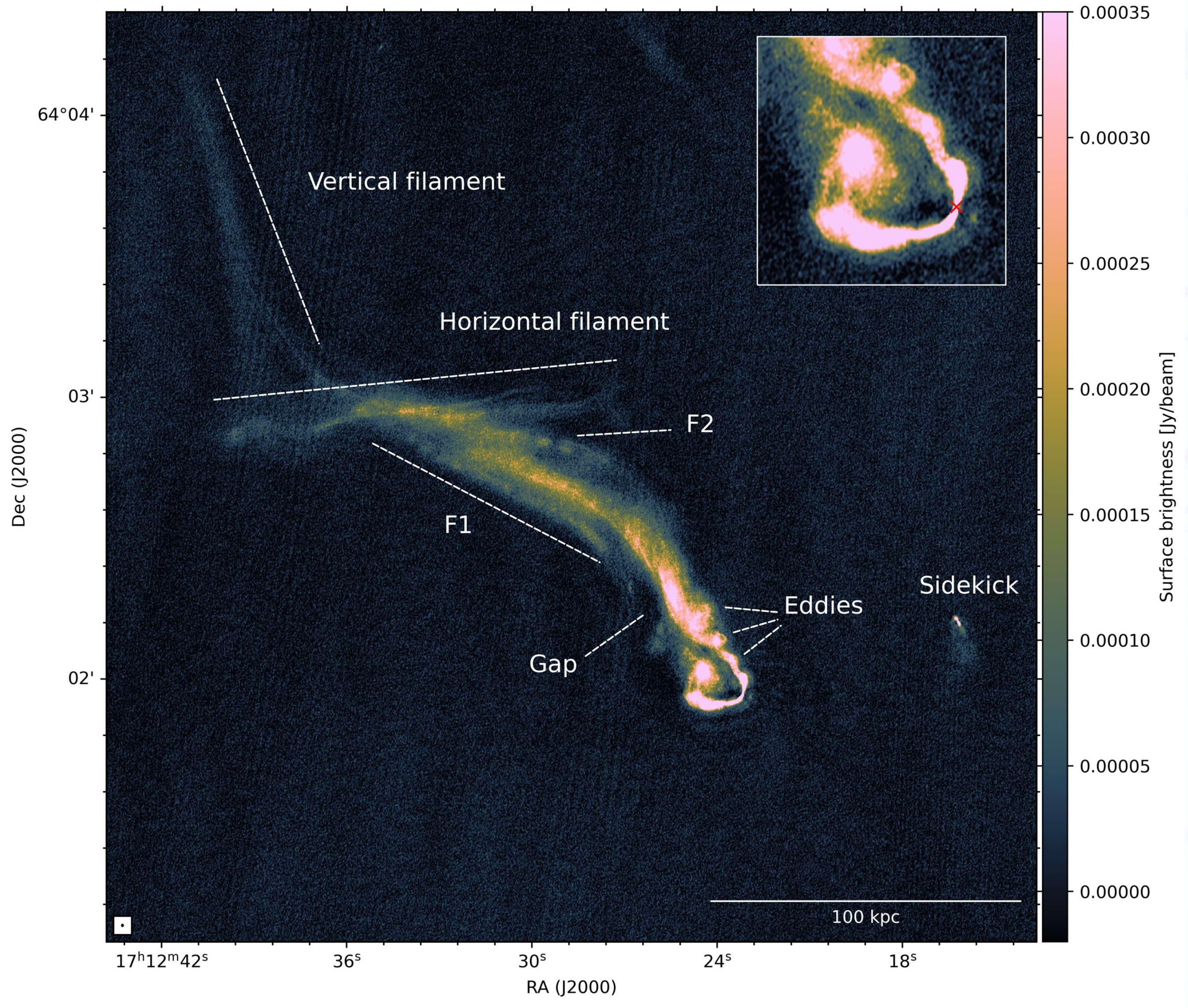
LOFAR 144 MHz image, 5″x4″, σ=55μJy/beam

De Rubeis et al. (2025)

LOFAR-VLBI insights: “Original TRG”



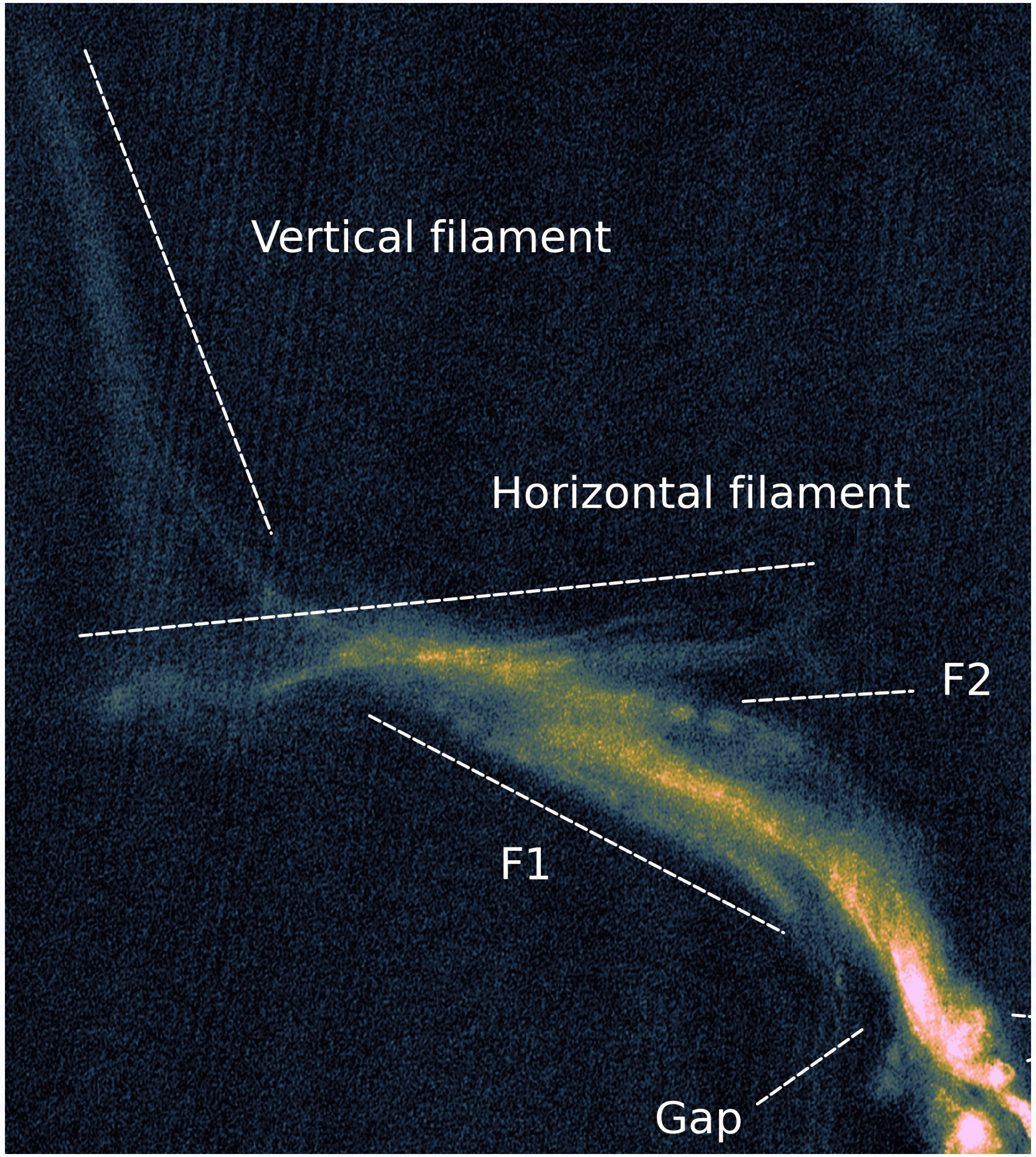
LOFAR 144 MHz image, 5”x4”, σ=55μJy/beam

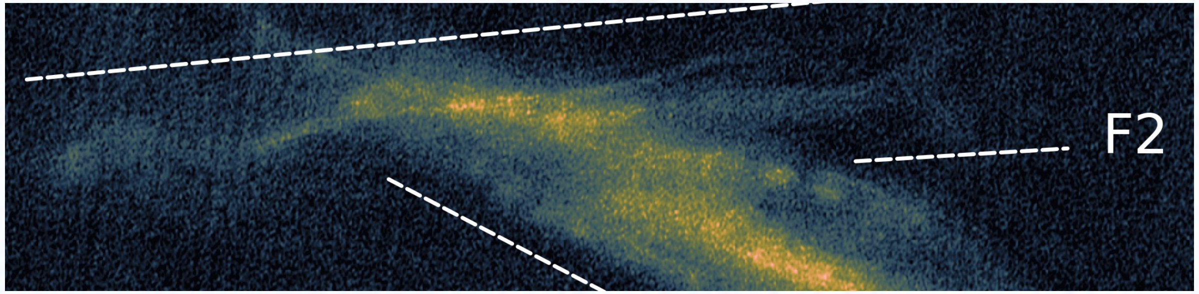


LOFAR 144 MHz image at 0.34” x 0.24”, σ = 20 μJy/beam

De Rubeis et al. (2025)

LOFAR-VLBI insights: “Original TRG”



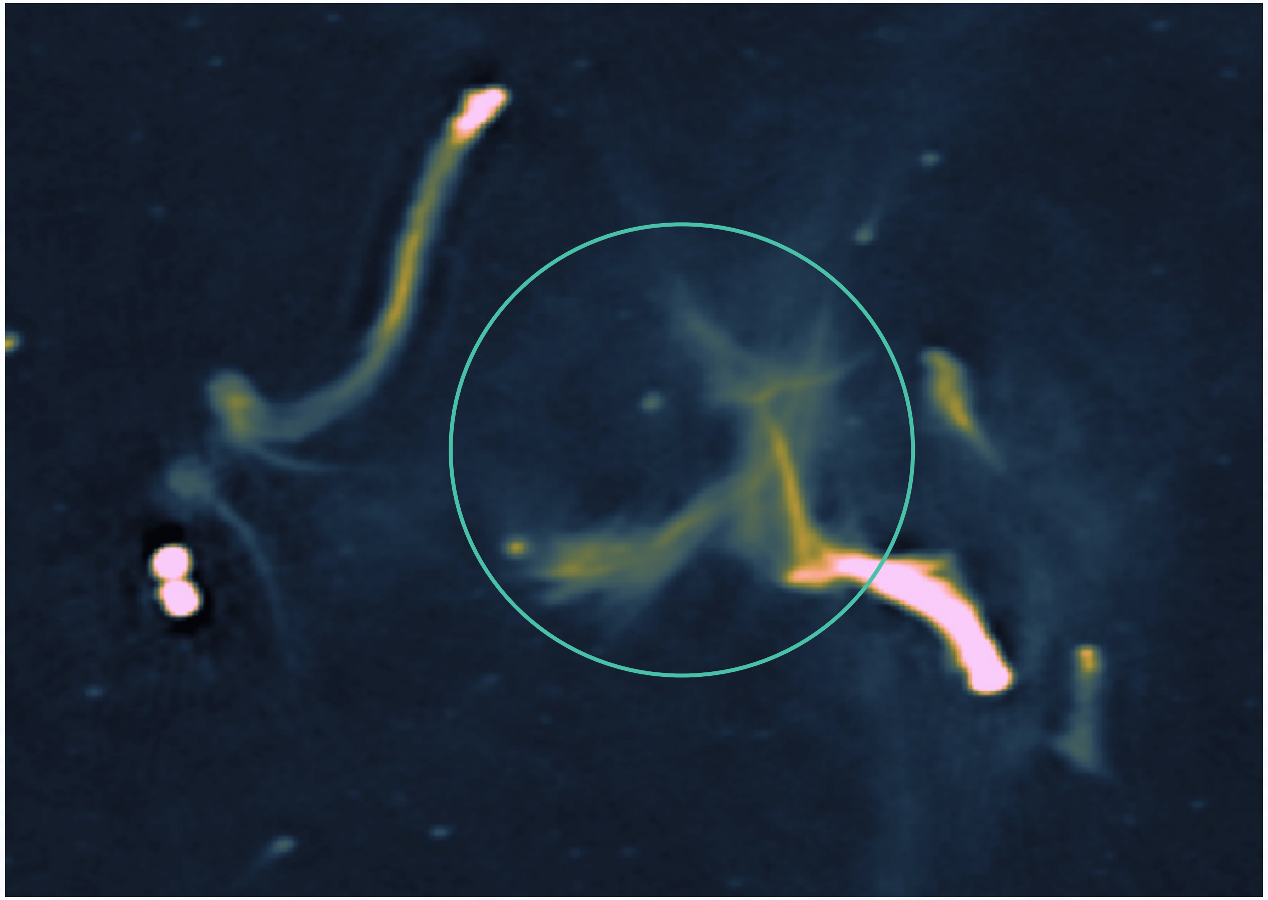


Detection of multiple filaments related to the Original TRG

- lengths between **80-110 kpc**
- widths between **3-10 kpc**

De Rubeis et al. (2025)

But we observe also “diffuse” filaments…


LOFAR 144 MHz image, 5″x4″, σ=55μJy/beam

Diffuse filaments are not directly associated to any radio galaxy: because of their length and low surface brightness they cannot be imaged individually.

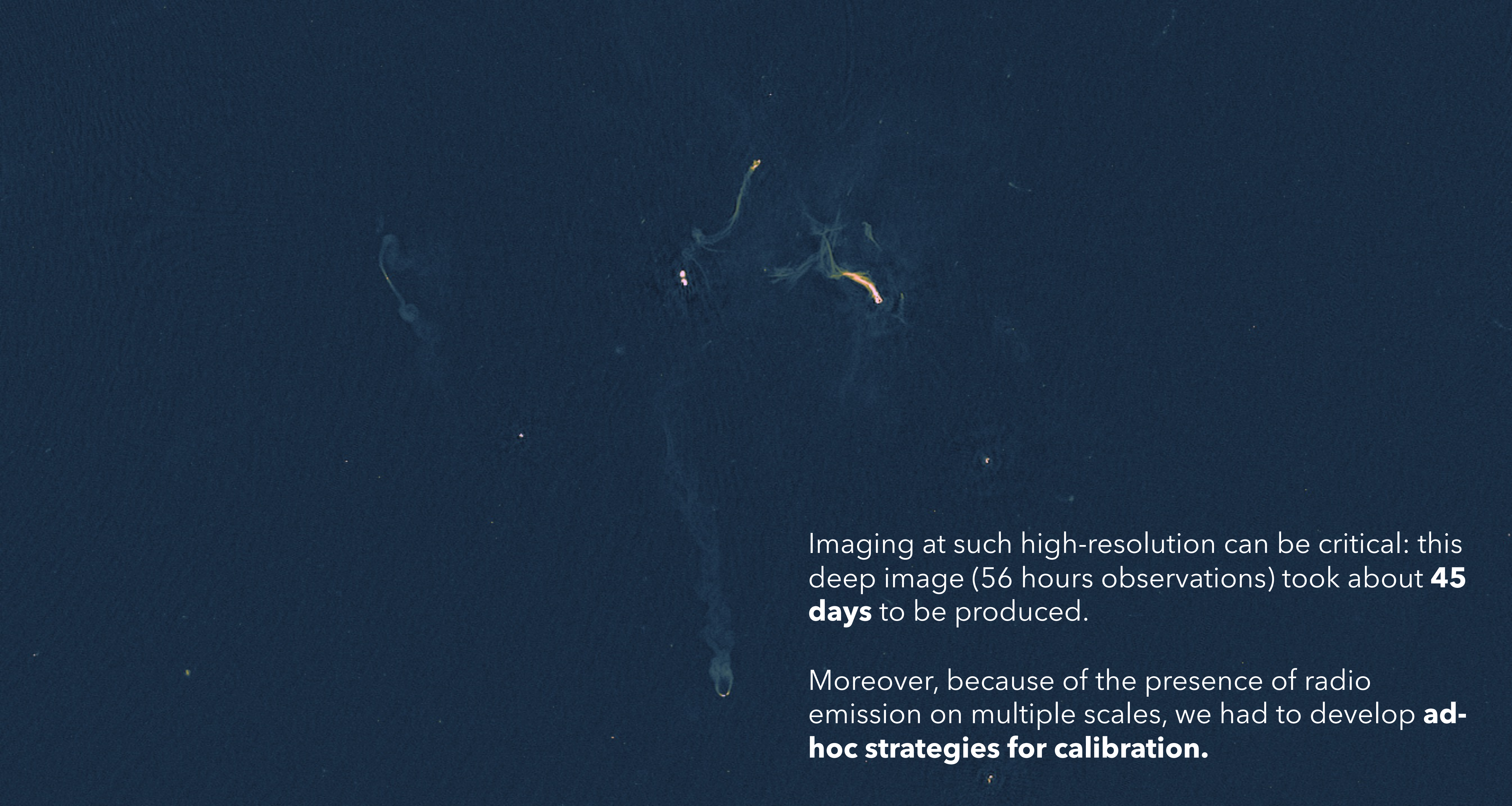
We want to use LOFAR-VLBI in the so-called **wide-field mode**, doing calibration across the whole FoV.

LOFAR-VLBI wide-field mode

We present LOFAR-VLBI image obtained with **56 hours of observations** of the galaxy cluster Abell 2255, with a **resolution of 1.5”** at **144 MHz**.

It represents the **deepest wide-field maps ever obtained targeting a galaxy cluster using LOFAR-VLBI.**

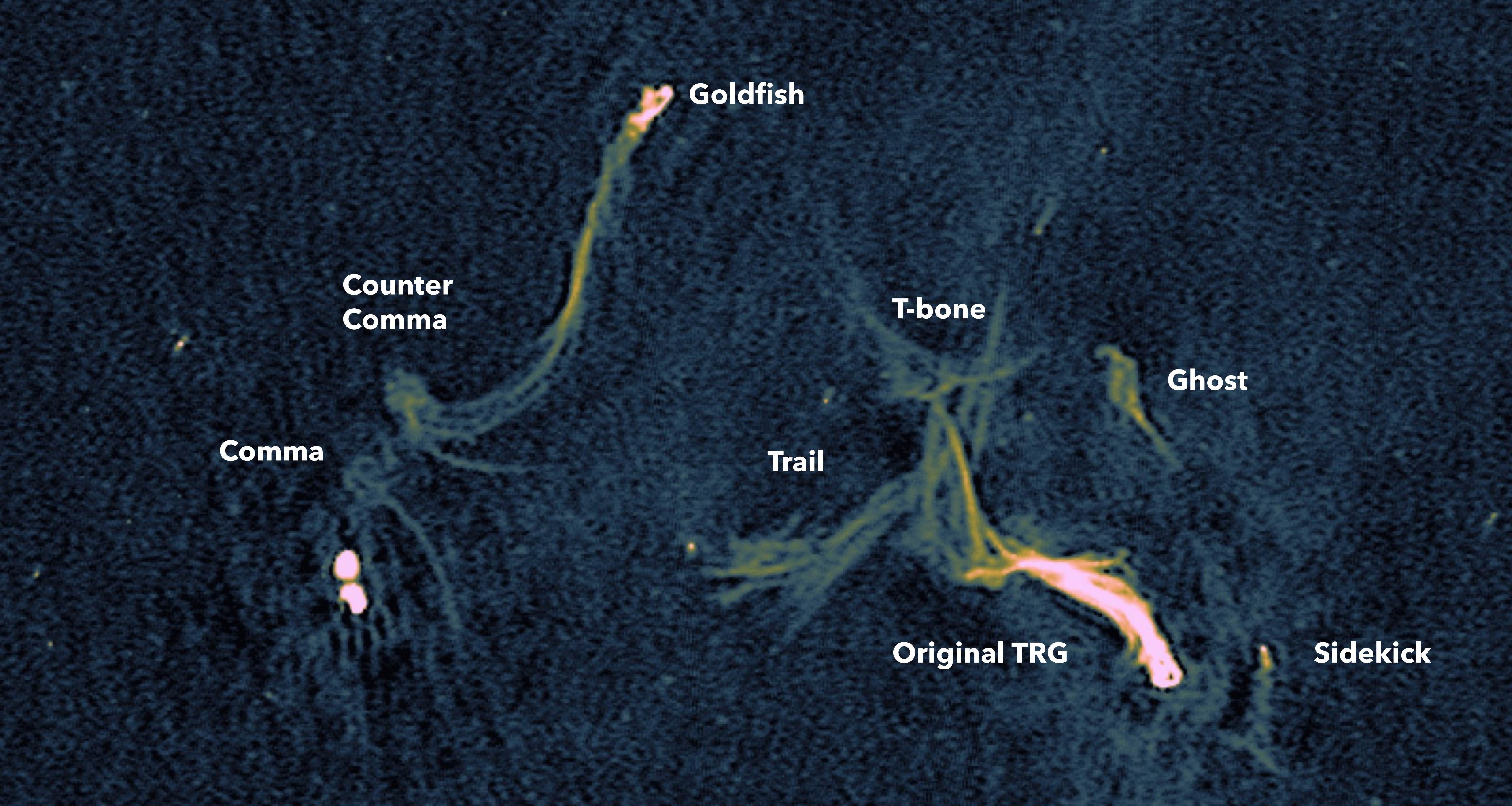
LOFAR 1.5″ image, σ=38 μJy/beam (De Rubeis et al., *submitted*)



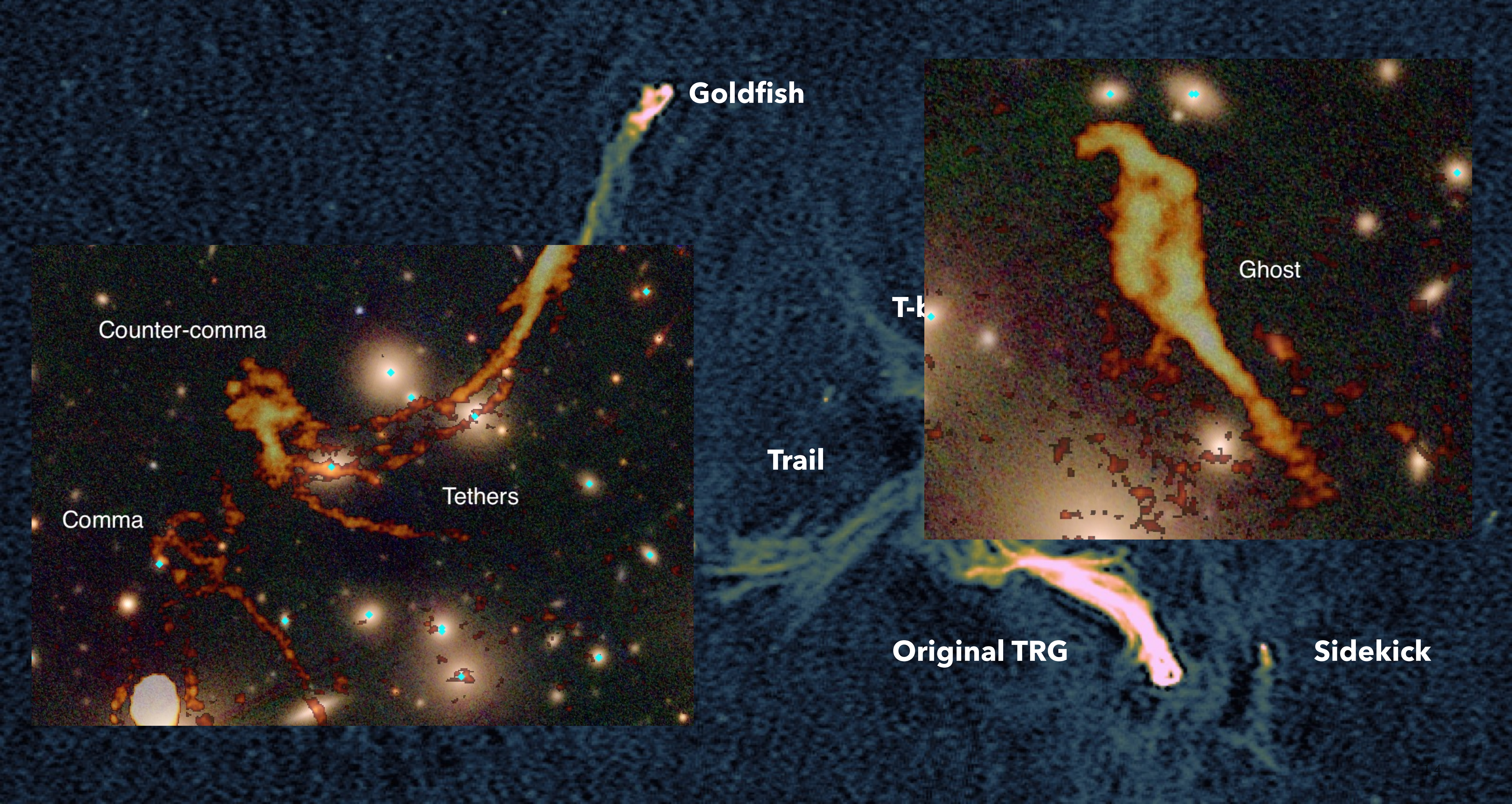
Imaging at such high-resolution can be critical: this deep image (56 hours observations) took about **45 days** to be produced.

Moreover, because of the presence of radio emission on multiple scales, we had to develop **ad-hoc strategies for calibration.**

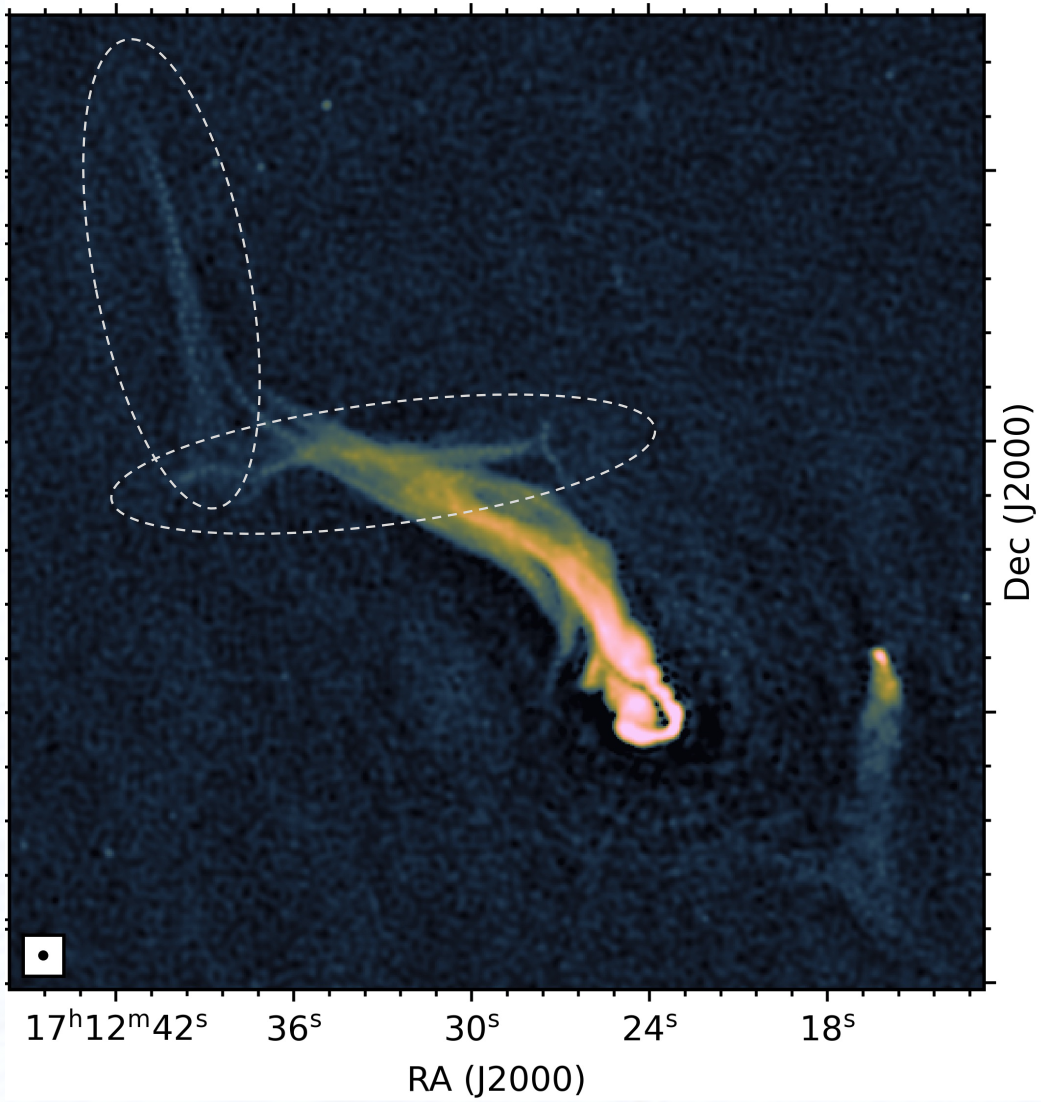
LOFAR 1.5″ image, σ=38 μJy/beam (De Rubeis et al., *submitted*)



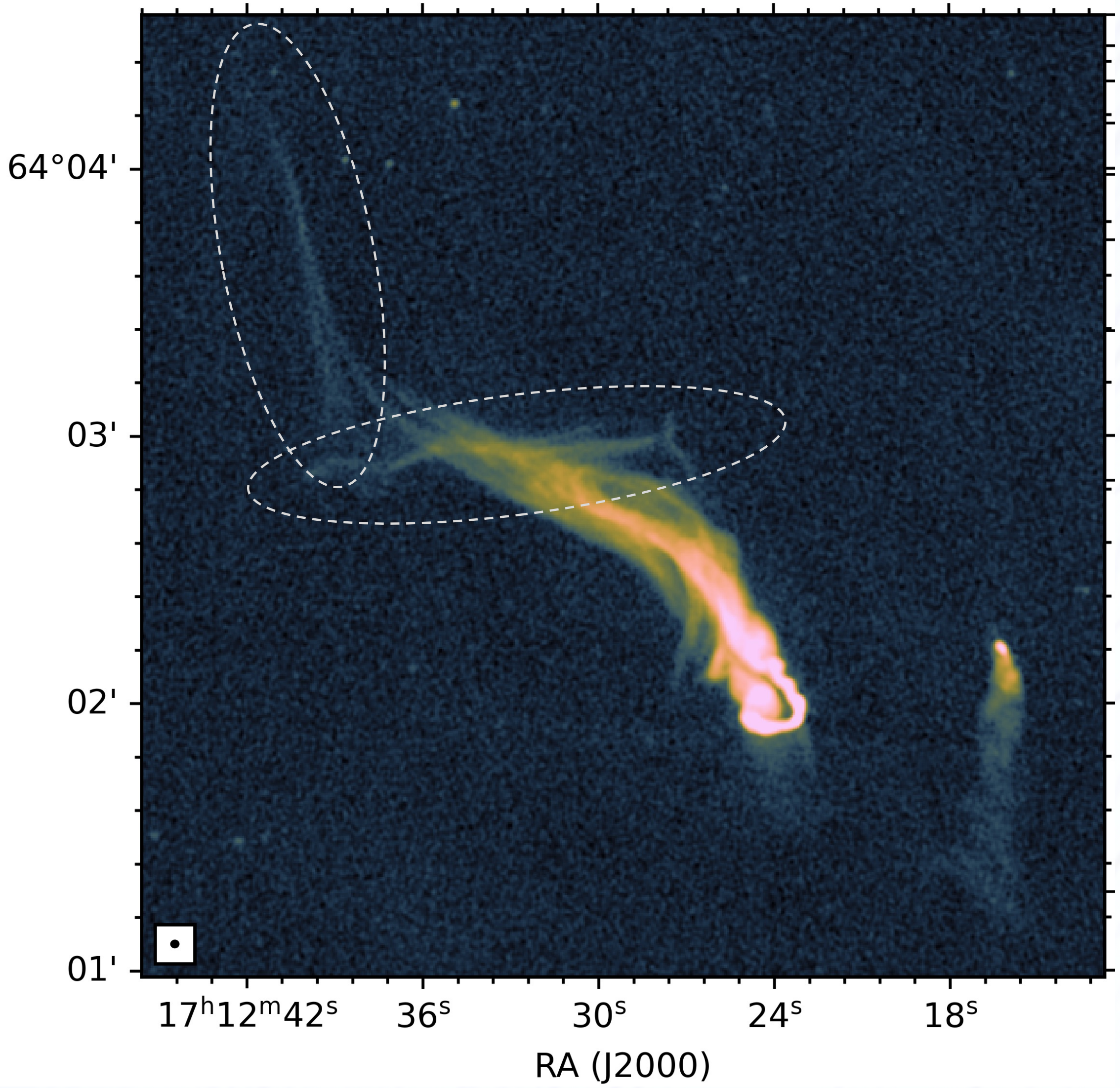
LOFAR 1.5″ image, σ=38 μJy/beam (De Rubeis et al., *submitted*)



Higher-frequency data

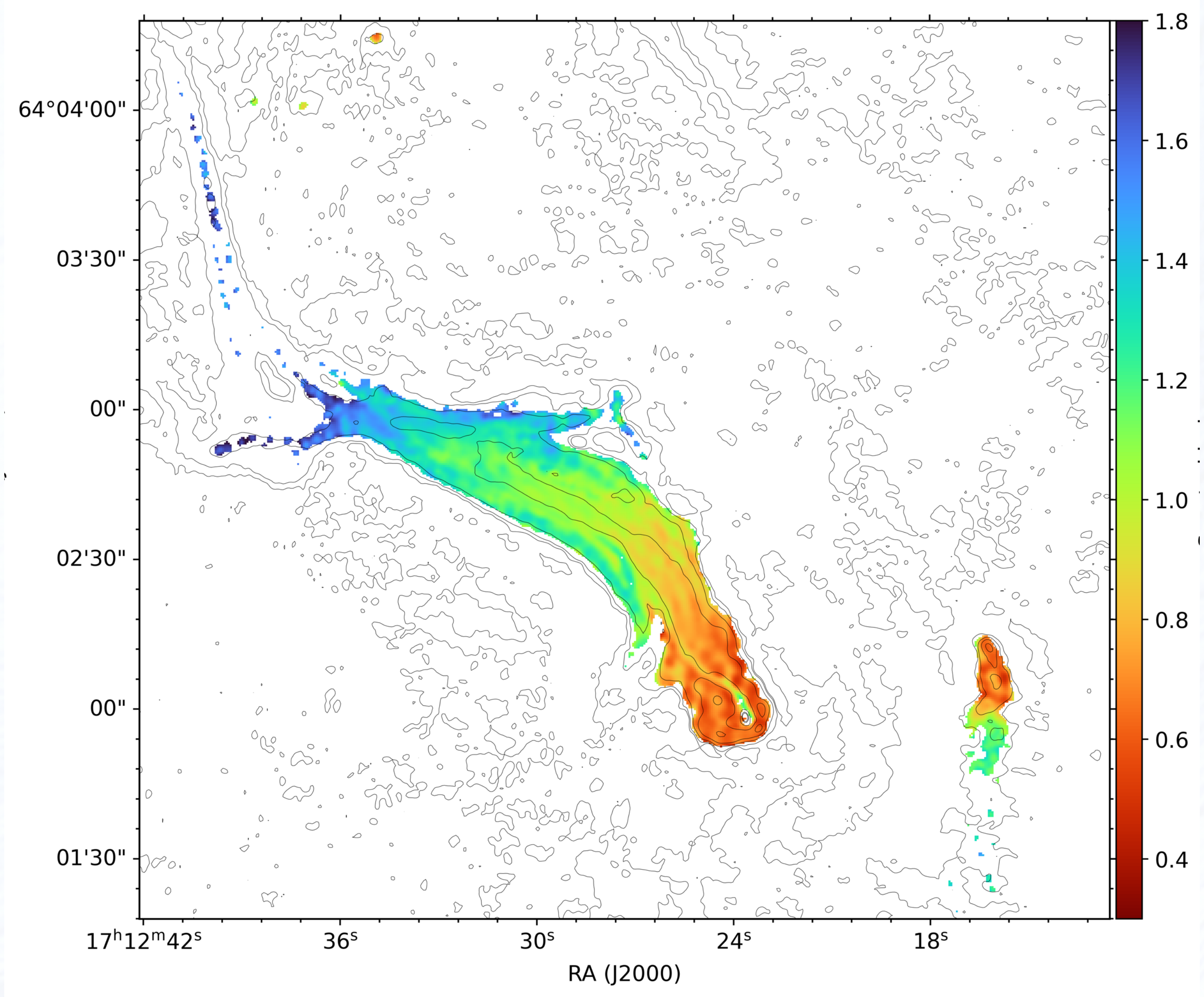


uGMRT (1260 MHz, 33 hours)



VLA (1520 MHz, 10 hours)

Spectral index map (1.5″)

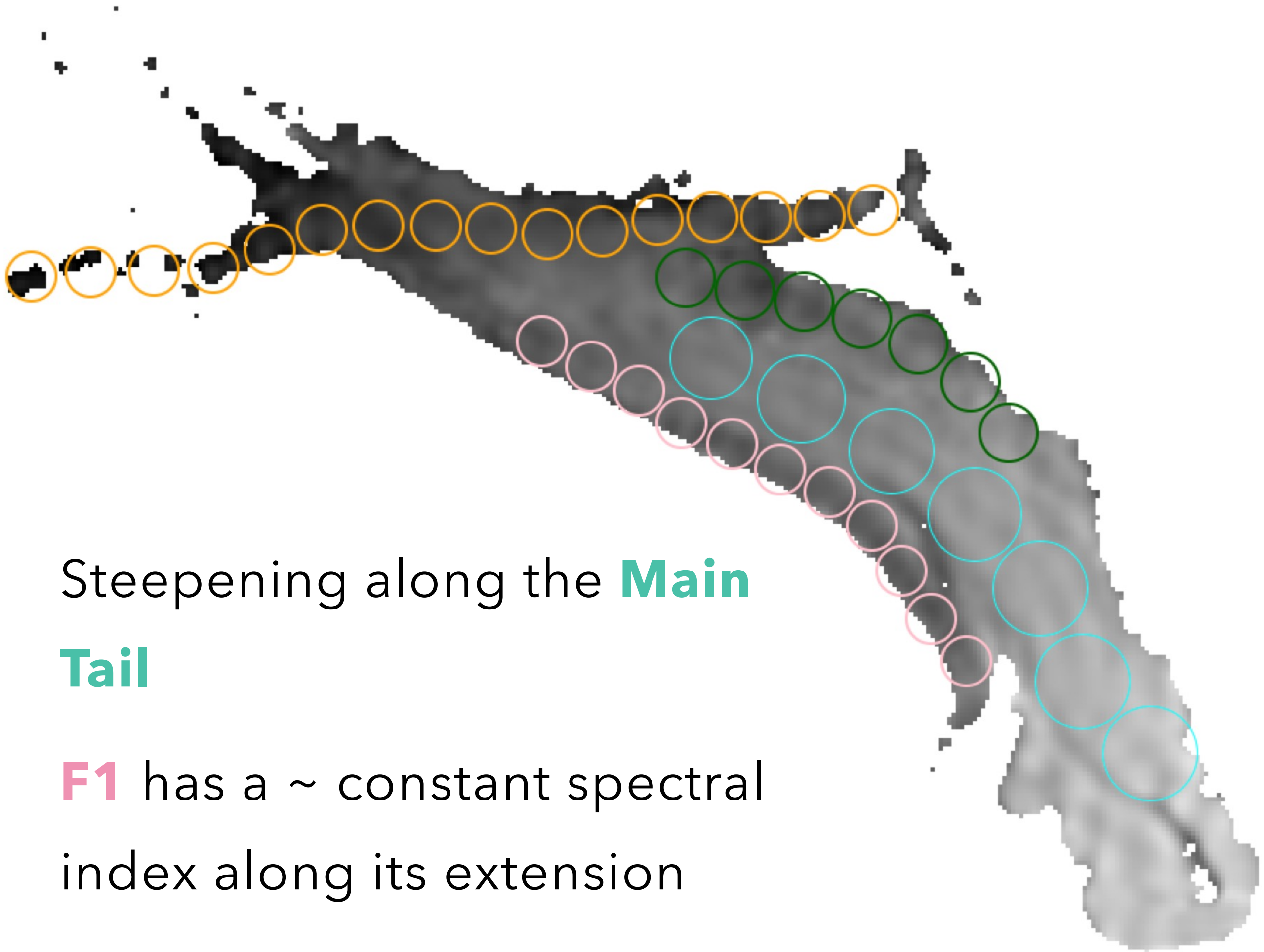


Spectral index map combining

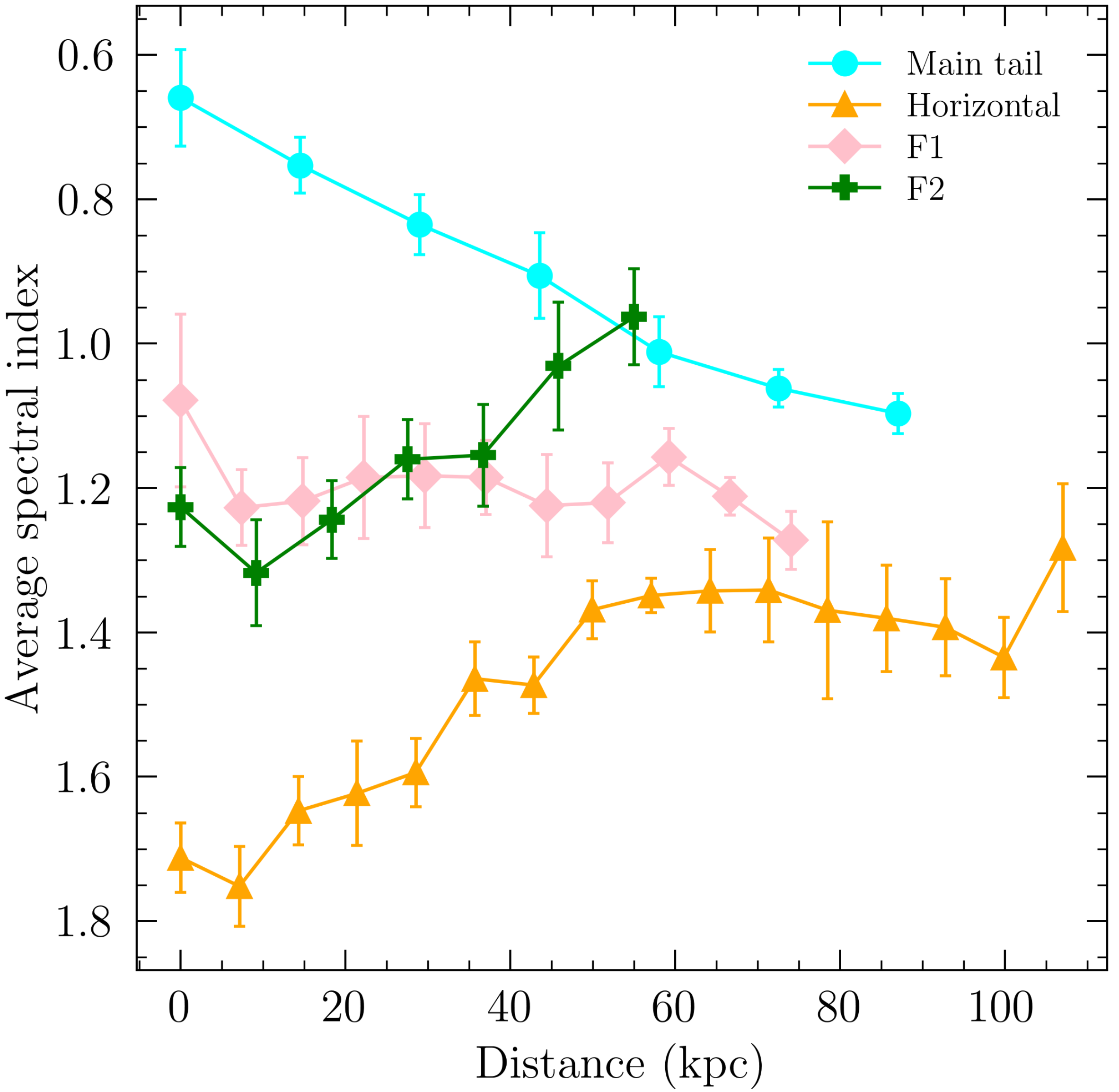
- 144 MHz (LOFAR)
- 1260 MHz (uGMRT)
- 1520 MHz (VLA)

Unprecedented high-resolution (1.5″), important to disentangle the spectral components components.

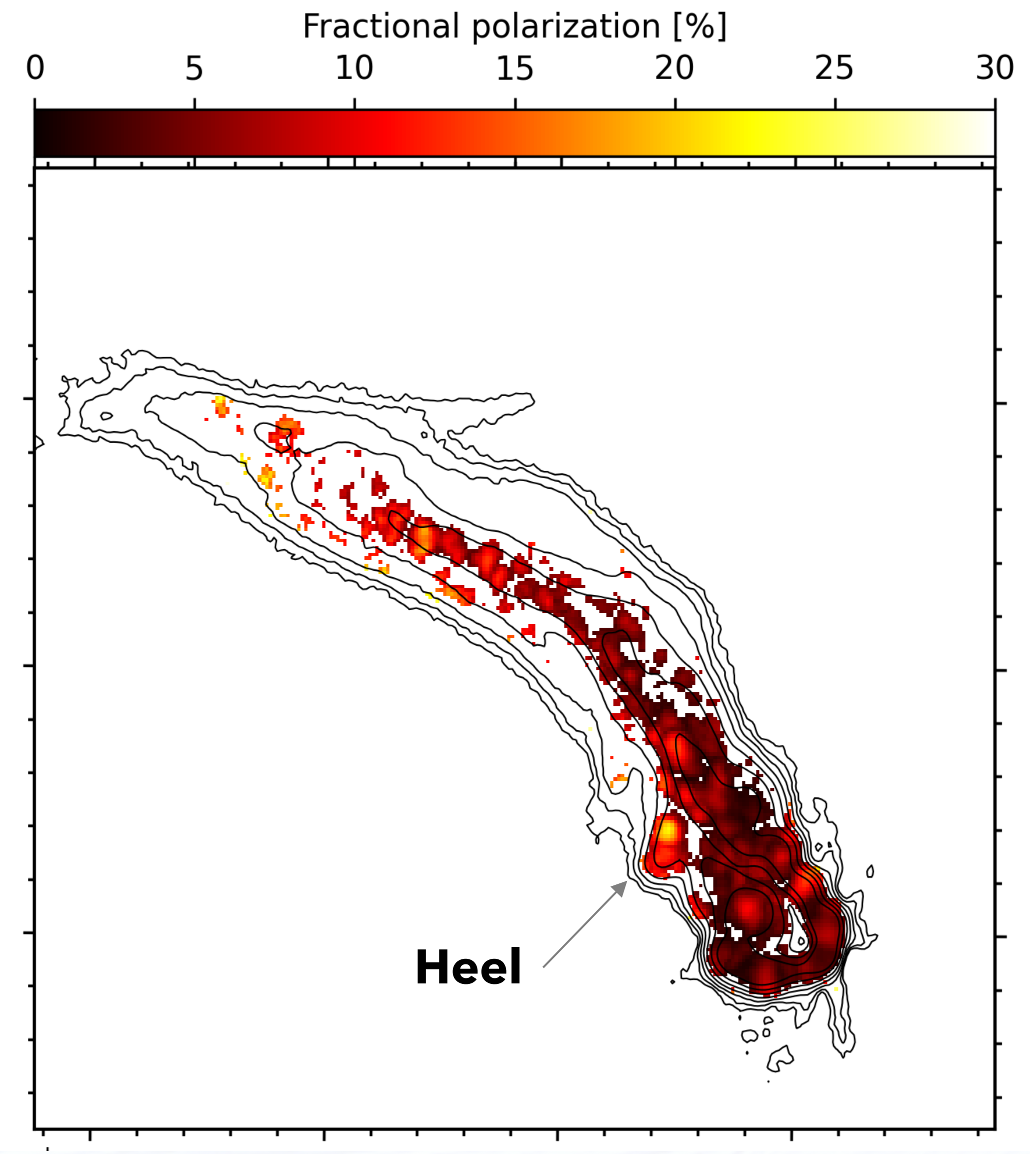
Spectral index map (1.5″)



- Steepening along the **Main Tail**
- **F1** has a ~ constant spectral index along its extension
- Bimodality for the **horizontal filament** and **F2**



Polarization properties of the Original TRG



We analyzed **polarization properties** of the Original TRG and its filaments with **VLA at 2"** resolution through **RMsynthesis**

- **4-5% at the core**, increasing **along the tail up to 18-22%**
- local flattening in the **turbulent eddies ~13%**
- **Patches in F1 with 15-22%**
- **10-22% in the Heel**

So what?

- Spectral and polarization observations both support the **presence of highly, ordered magnetized non-thermal filaments with low plasma beta** ($\beta_f \lesssim 1$)

- **High Alfvén velocity** allows electrons to **fast propagate** for such long distances without significant impact on their energy and spectrum

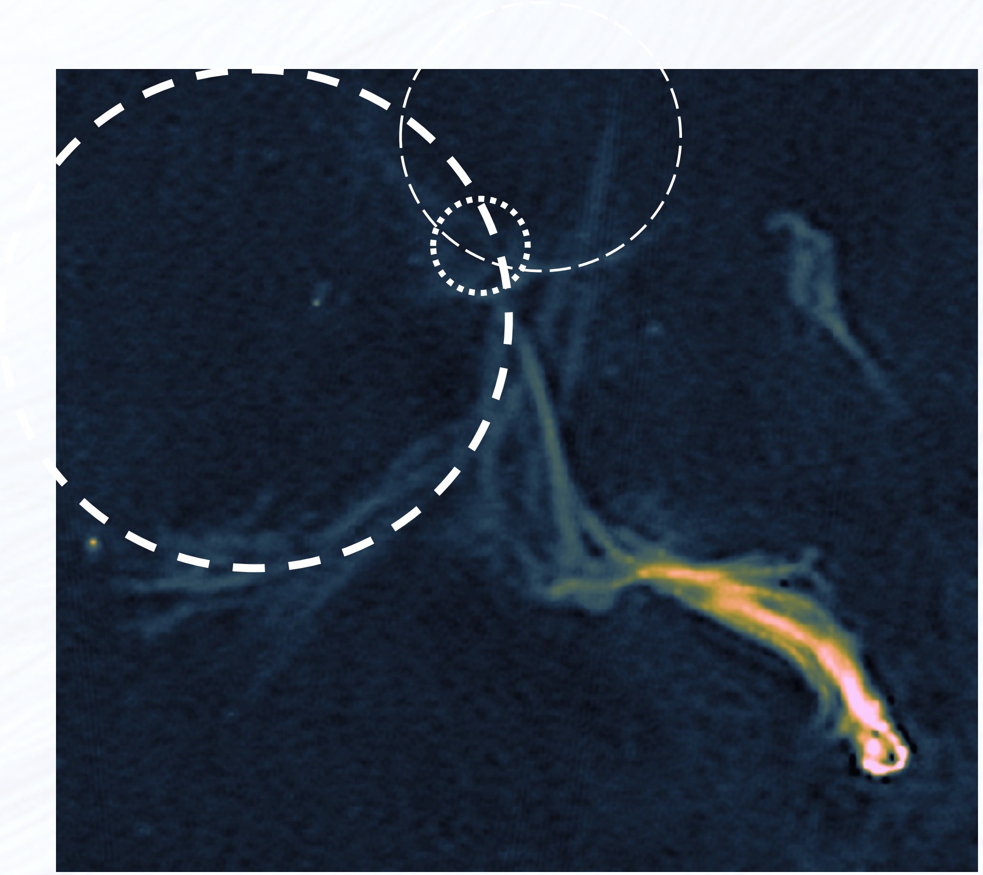
- The **radio galaxy** seems to have a crucial role in **providing electrons** to the filaments, which can "synchronize" the spectrum over the entire filament's length

$$\beta_f \ll \beta_{ICM} \Rightarrow v_{A,f} \gg v_{A,ICM}$$

Churazov et al. (2025)

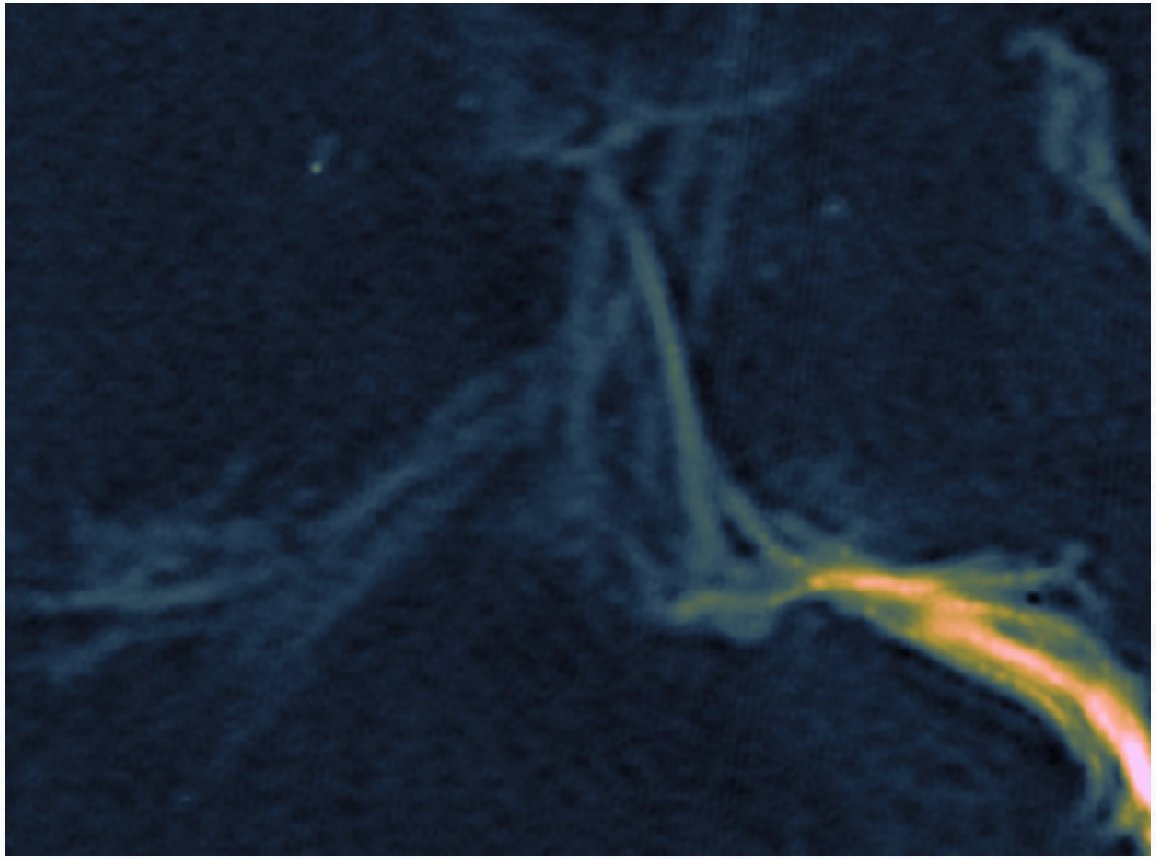
Possible scenario(s)

- Electrons can be subject to the **turbulence generated by both the merger and the RG crossing**, which subsequent magnetic field lines stretching/bending



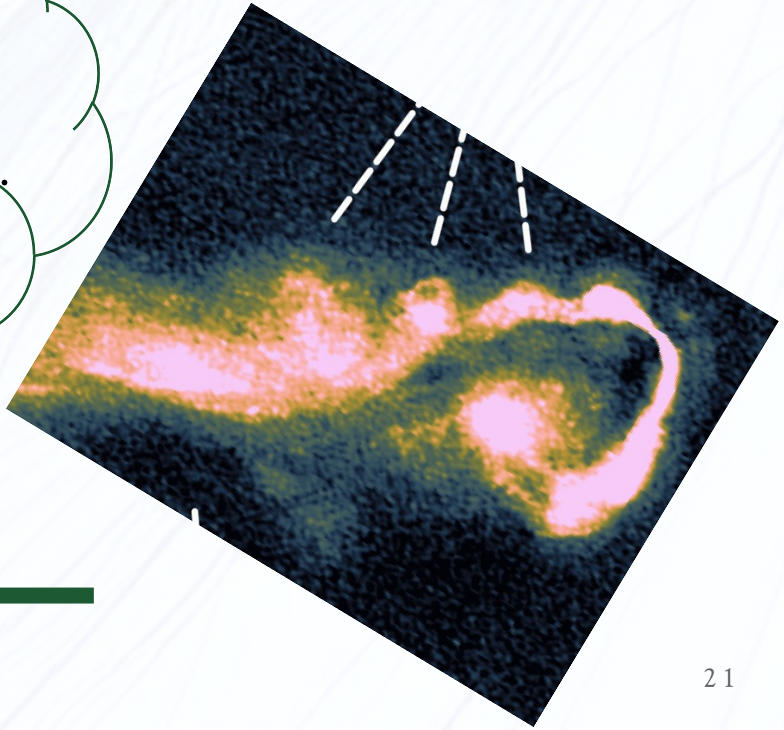
Possible scenario(s)

- Filaments arise from the **dynamical instabilities in the tail** and are then injected in the ICM



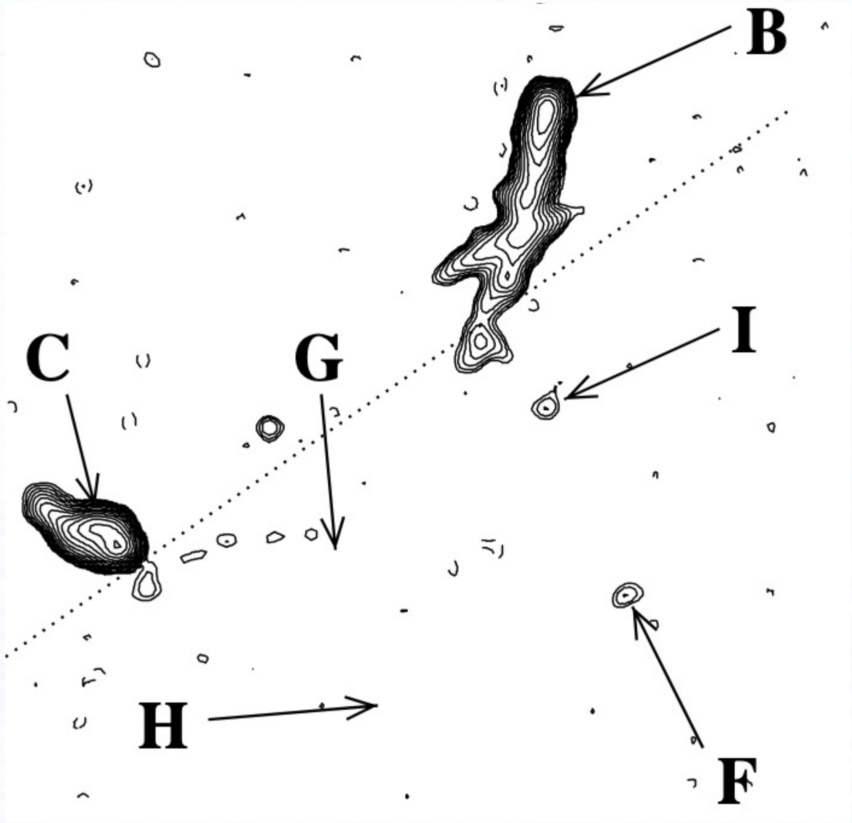
Different resolutions highlight different phases of the instabilities

Stretching et al.

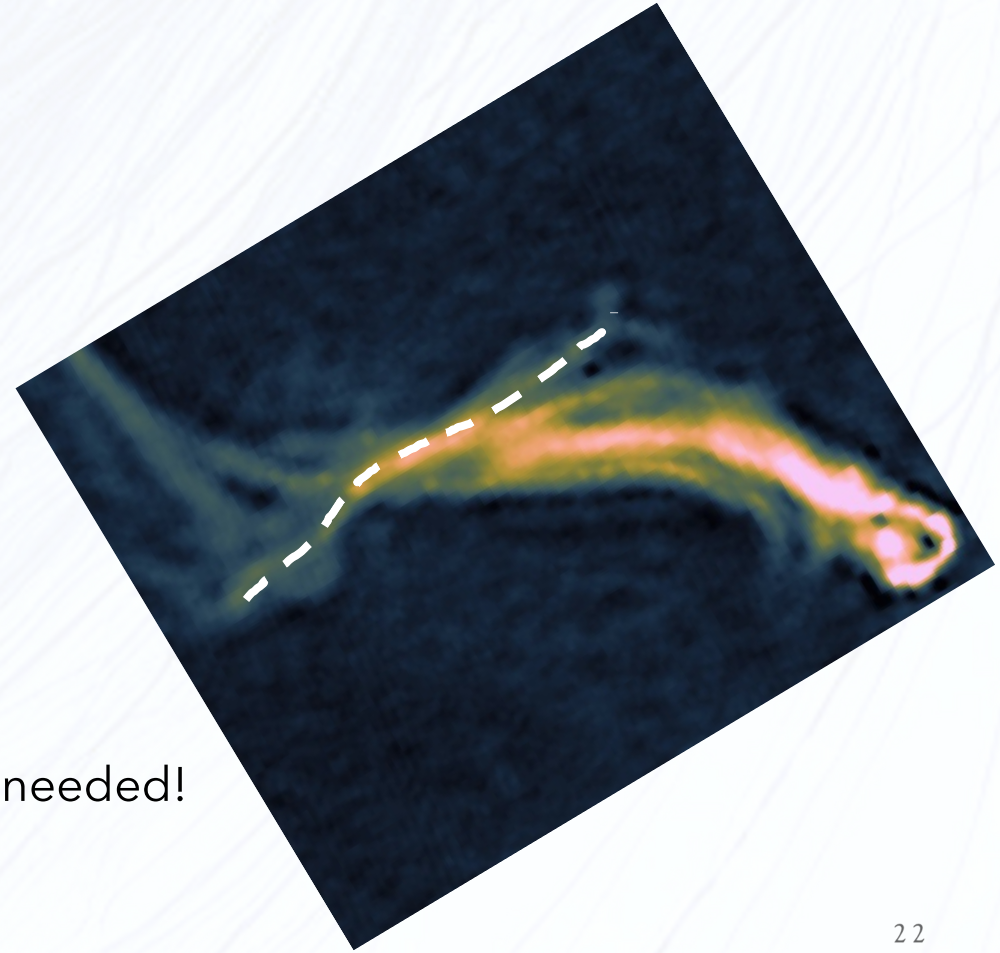


Possible scenario(s)

- **Pre-existing filaments** that are re-energized by the RG



Transversal bar in Abell 2443, similar to the horizontal filament



Reconnection needed!

Cohen & Clarke (2011)

Conclusions?

- LOFAR-VLBI is a **unique tool** to detect the **filaments and threads** present in radio galaxies/galaxy clusters
- For Abell 2255, we can study the **origin and characteristics of the filaments associated to the Original TRG**, using also **high-resolution spectral index and polarization maps** of the tail and its surroundings
- Filaments observed in A2255 are consistent with **low-β**, **highly magnetized** structures due to **shearing and stretching** of magnetic field lines caused by the turbulent ICM.

Still, discussion is open!

SKA-Low VLBI – The LAMBDA Project

The **Low-frequency Australian Megametre Baseline Demonstrator Array** (LAMBDA) is the current project to demonstrate the **feasibility** of **long baseline science** with **SKA-Low**

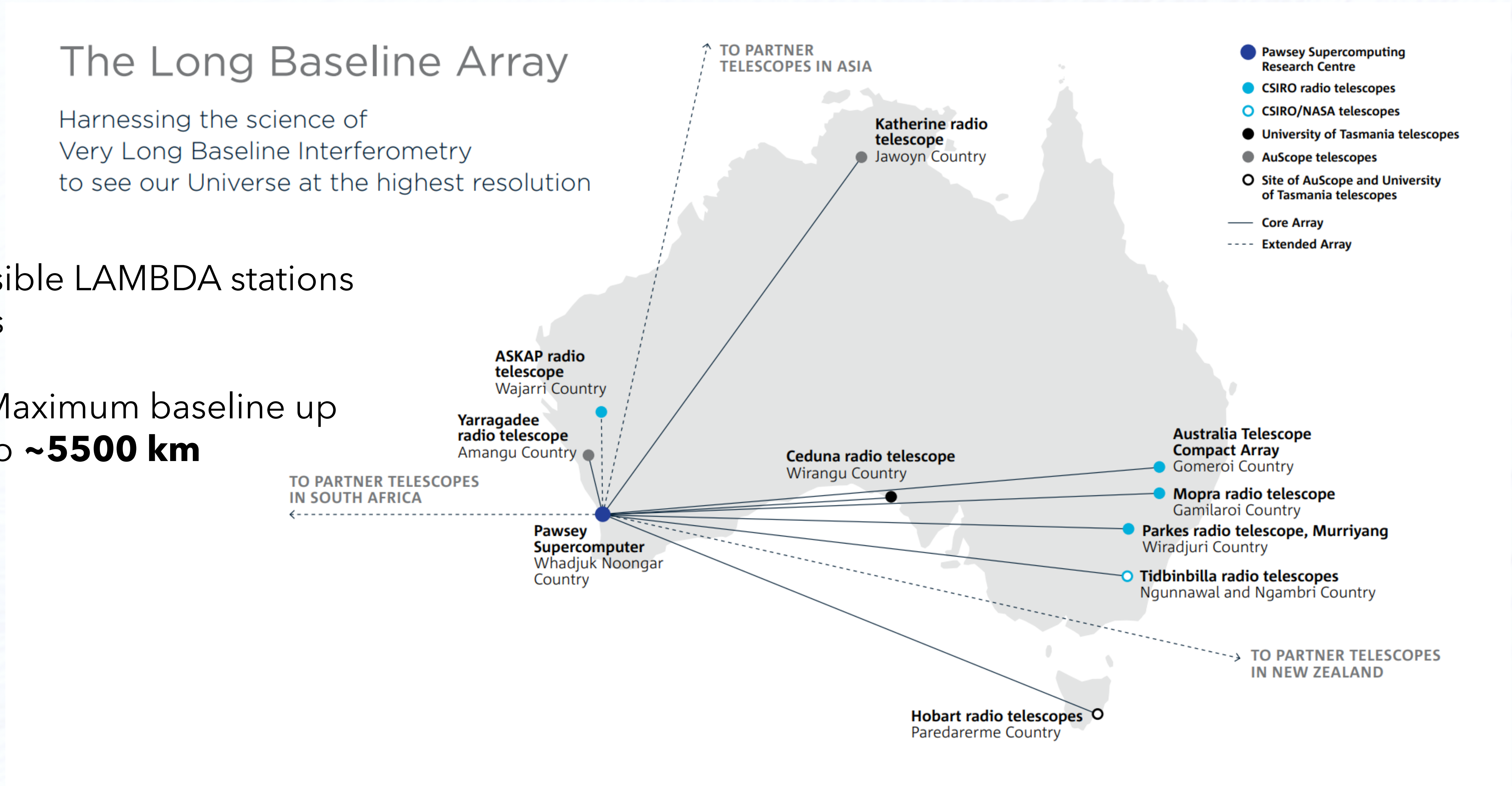
- **256** dual polarization SKA-Low **antennas**
- **50-350 MHz** frequency range
- Located at existing LBA observatories (or CSIRO sites)
- Development of **new backends** – testbed for **future SKA-Low upgrades**
- Allows for **commissioning of SKA-Low VLBI**

Credits: Tessa Vernstrom (CSIRO)

SKA-Low VLBI – The LAMBDA Project

Possible LAMBDA stations sites

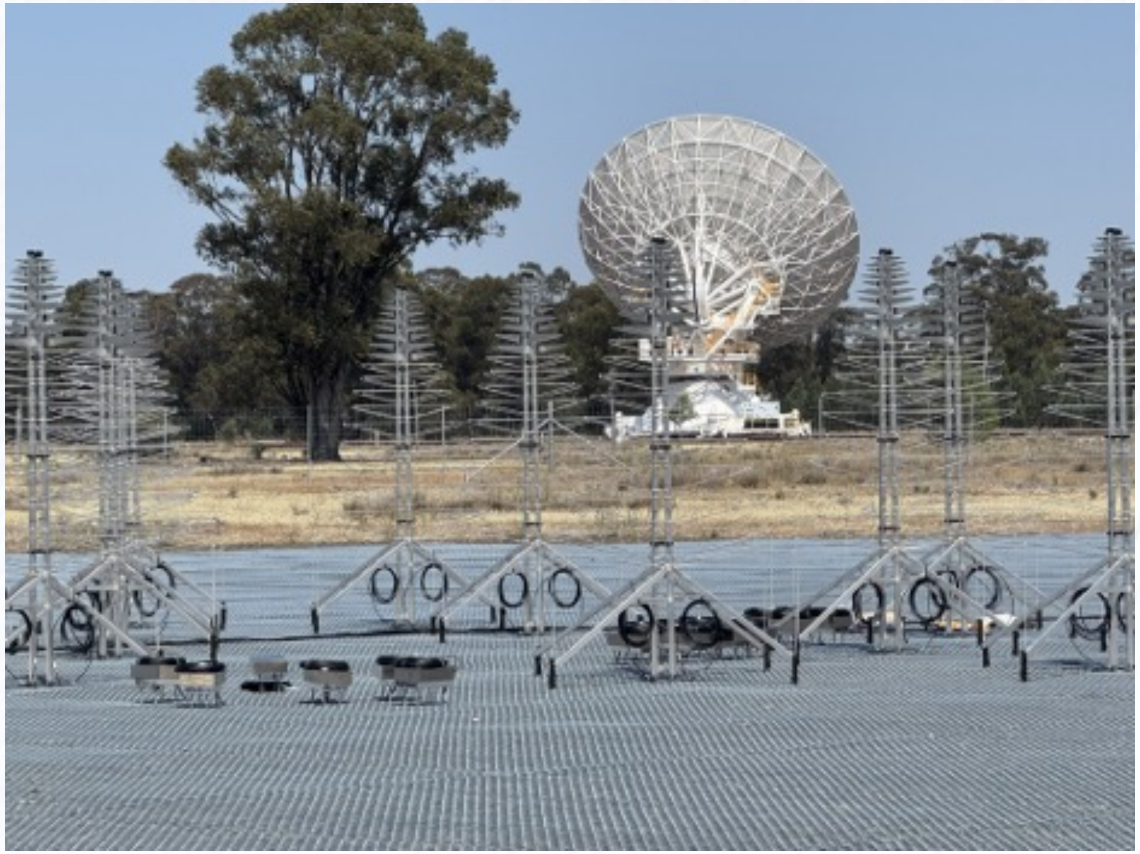
- Maximum baseline up to **~5500 km**



Credits: Tessa Vernstrom (CSIRO)

SKA-Low VLBI – The LAMBDA Project

- **36 antennas are currently being deployed** at Narrabiri site
- **Test signal chain** before deploying full station



Credits: Tessa Vernstrom (CSIRO)

SKA-Low VLBI – The LAMBDA Project

- Technosignature Searches (SETI)
- Ionosphere and Space Weather
- Transient / sky-monitoring

Single station

- Pulsar astrometry(?)
- AGN core identification

Single baseline

- Pulsar distances, proper motions, scintillometry (minimum 3 baselines)
- FRB follow-up and host imaging with optical resolution (minimum 3-4 baselines)
- Long period transient localisation (minimum 3-4 baselines)
- High resolution (sub-kiloparsec scale at all redshifts) mapping of AGN
- Young stellar objects and Supernova Remnants in our Galaxy
- Redshifted HI

More baselines

- Resolving stellar/planetary systems, distinguishing planet from host star
  - e.g., Sun-Jupiter system to D ~ 50 parsecs – would require international baselines
- Unknown → high resolution ultra-low frequency one of the least explored parameter spaces in all of astronomy, leaves the door open for new and exciting science

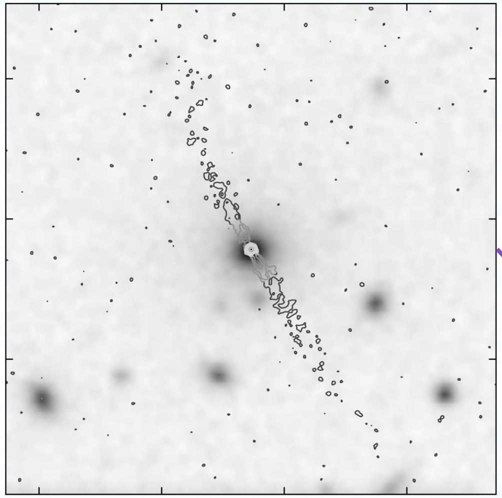
International baselines

Credits: Tessa Vernstrom (CSIRO)

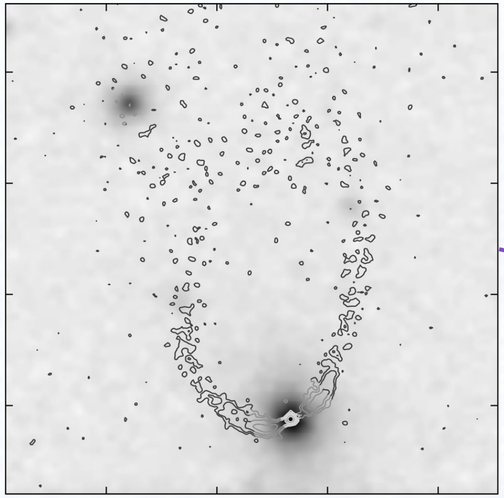
Thank you!

Extra slides

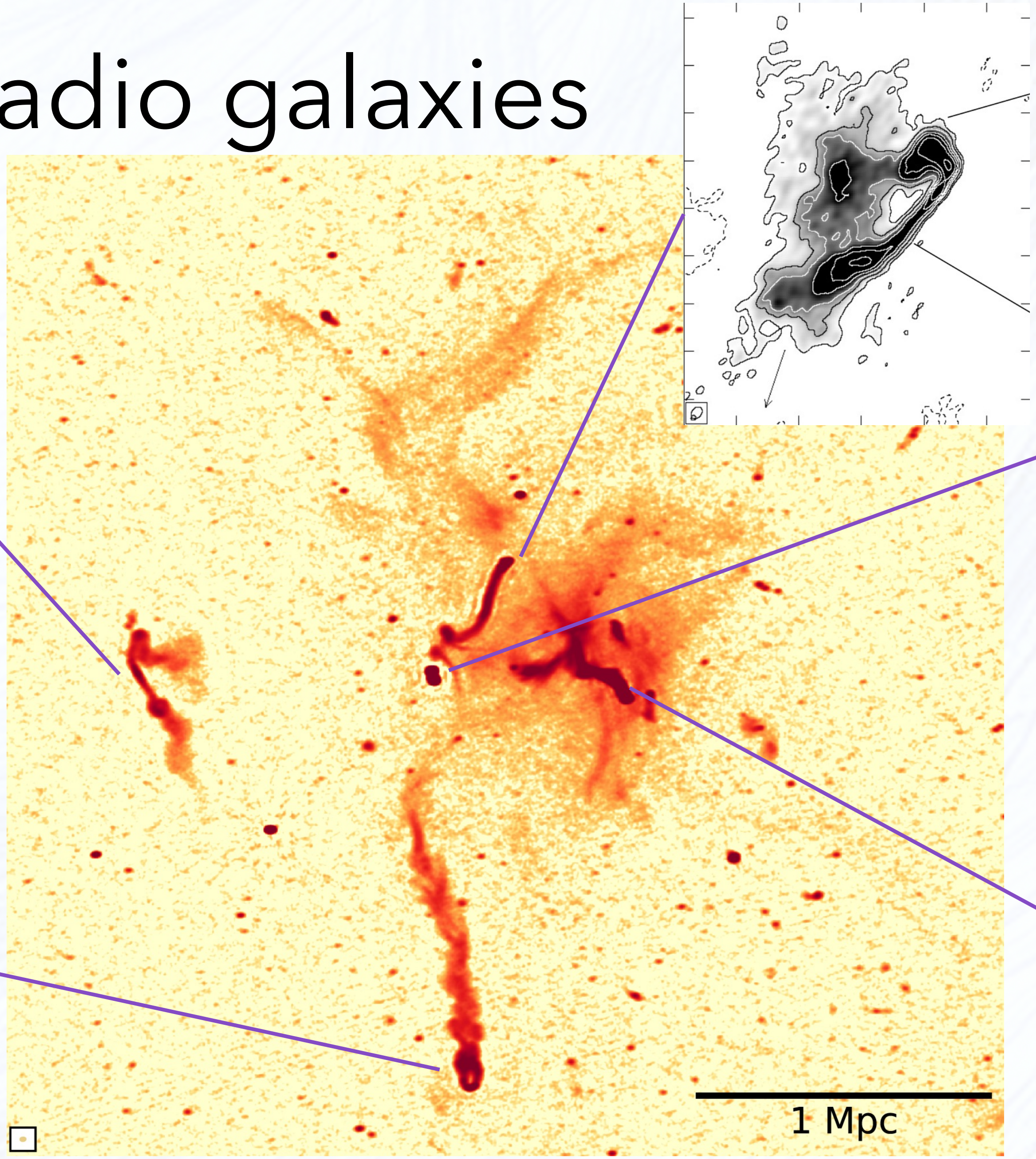
Abell 2255 – radio galaxies



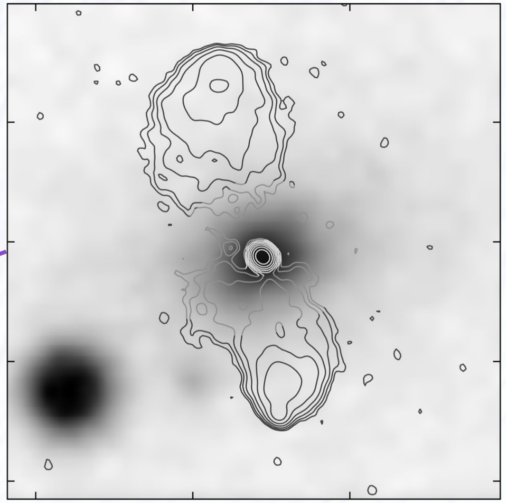
Embryo



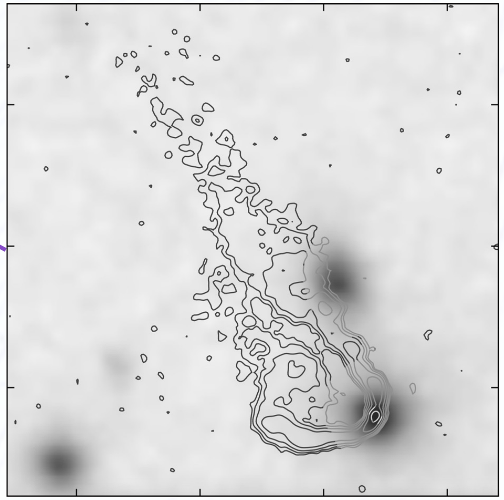
Beaver



Goldfish



Double



Original TRG

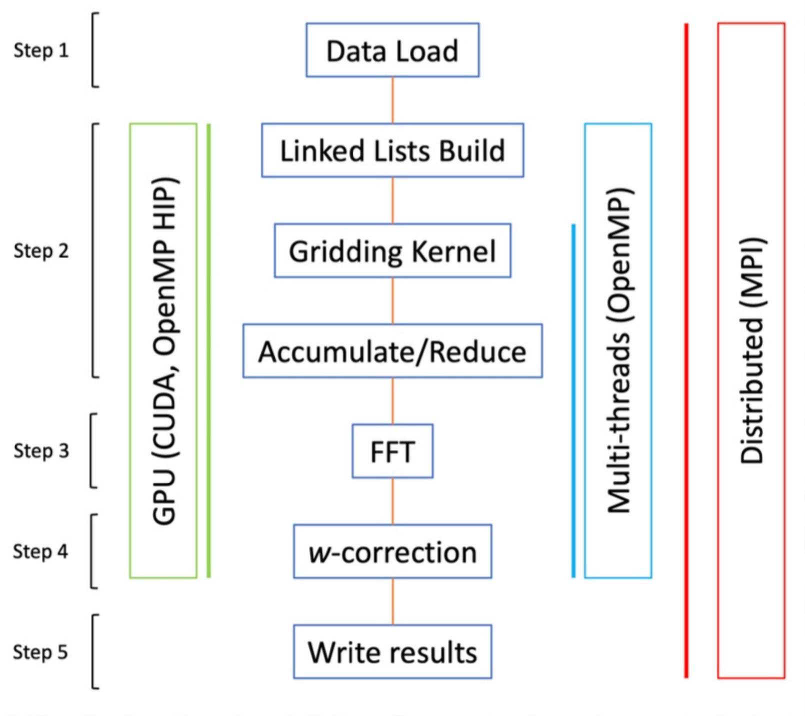
Govoni et al. (2006); Terni de Gregory et al. (2017); Botteon et al. (2020)

Accelerating radio astronomy with RICK

- Library called RICK (Radio Imaging Code Kernels)
- Perform the most computationally demanding steps of *w*-stacking algorithm using parallelism (both MPI and OpenMP) and multiple GPU off-loading (using CUDA and HIP)
- Time for inversion a 137 billion pixels image

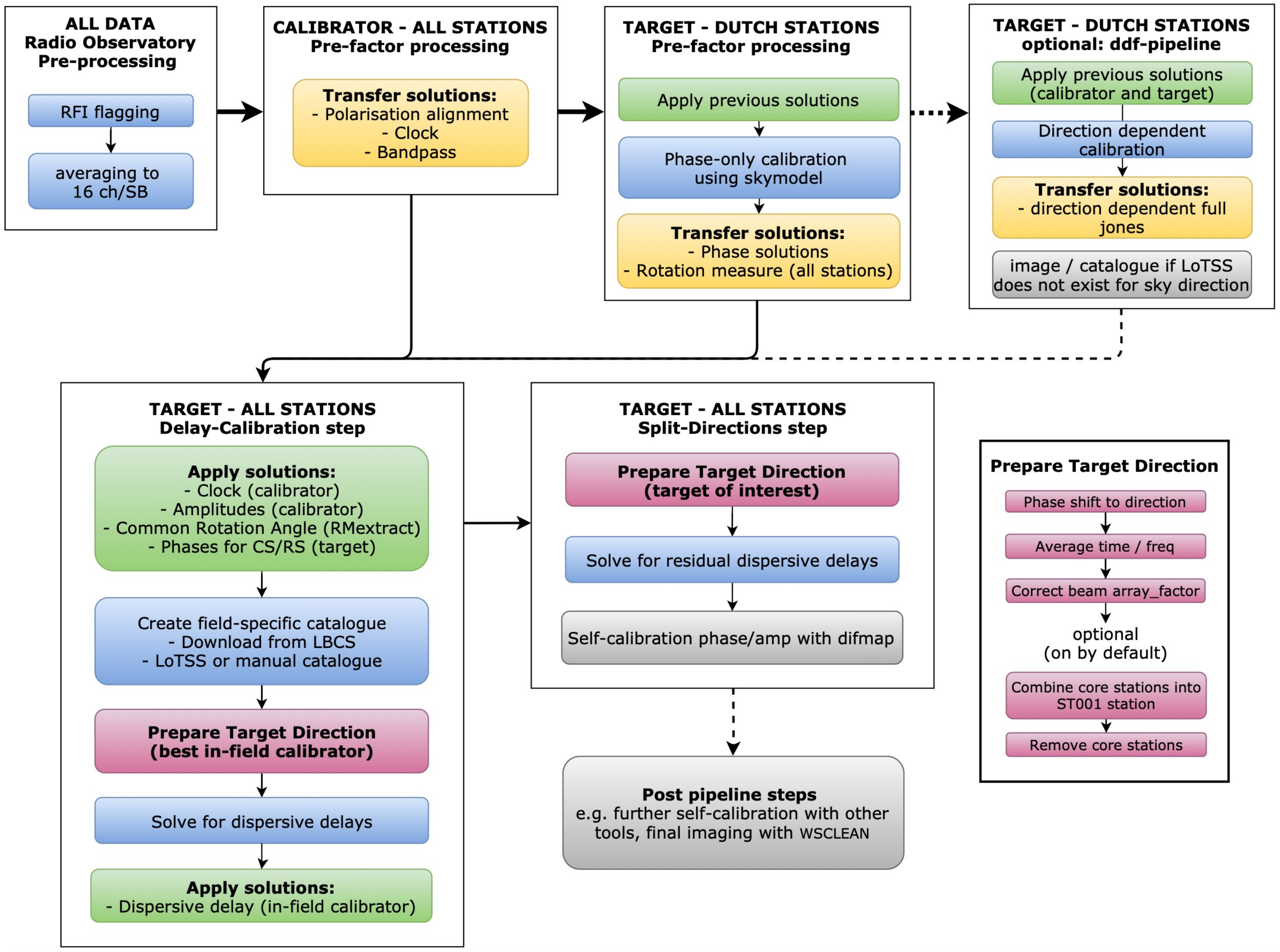
  ~2 hours for the CPU code

  ~70 sec for the GPU code



De Rubeis et al. (2025)

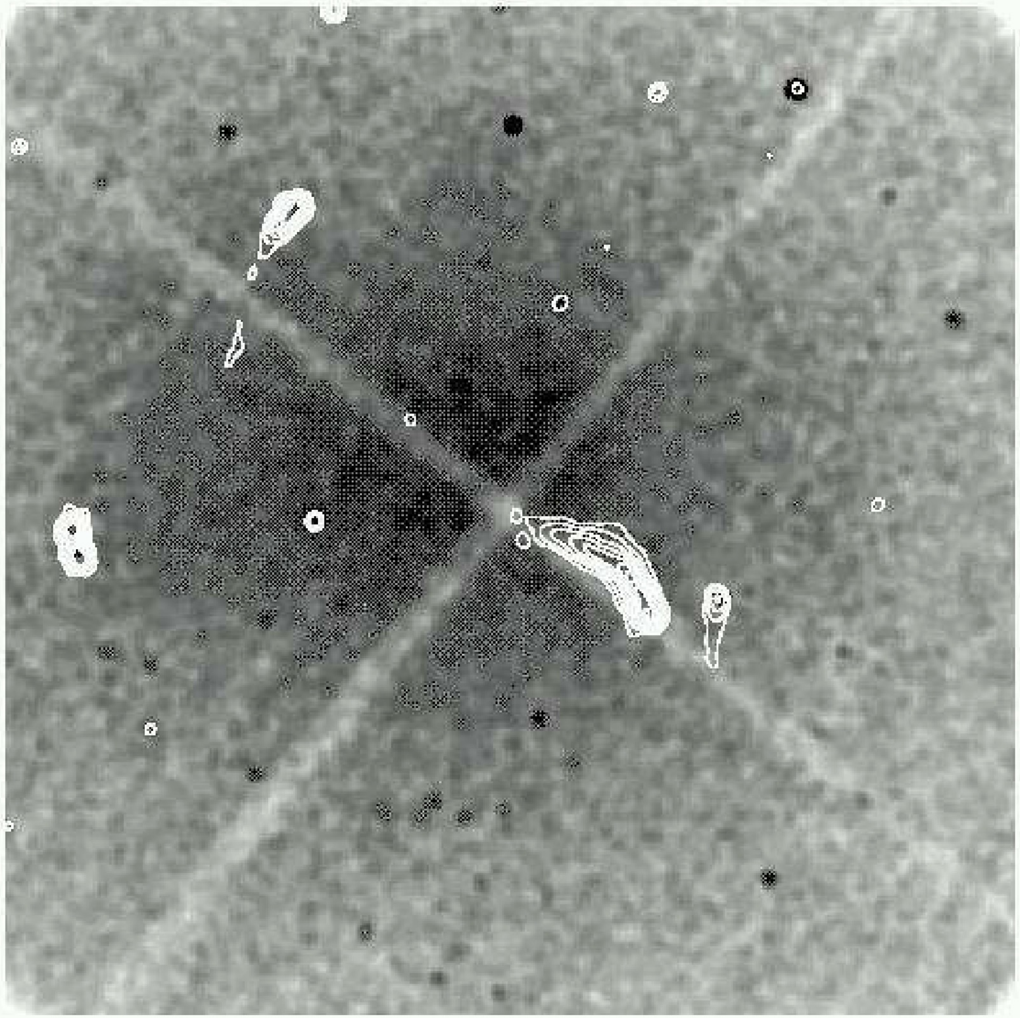
LOFAR-VLBI pipeline



Morabito et al. (2022)

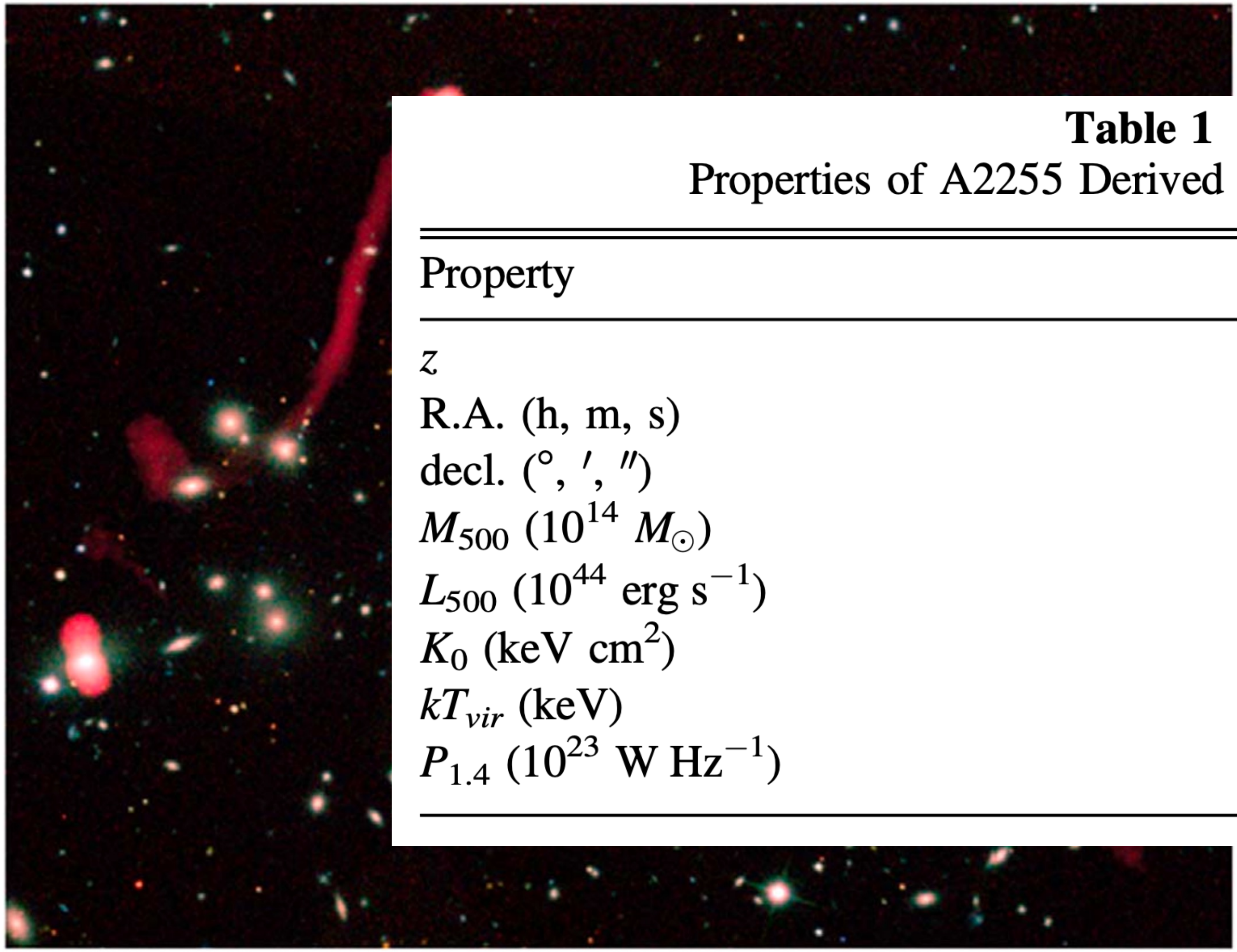
Multi-wavelength view of the cluster

Botteon et al. (2022)



Davis et al. (2003)

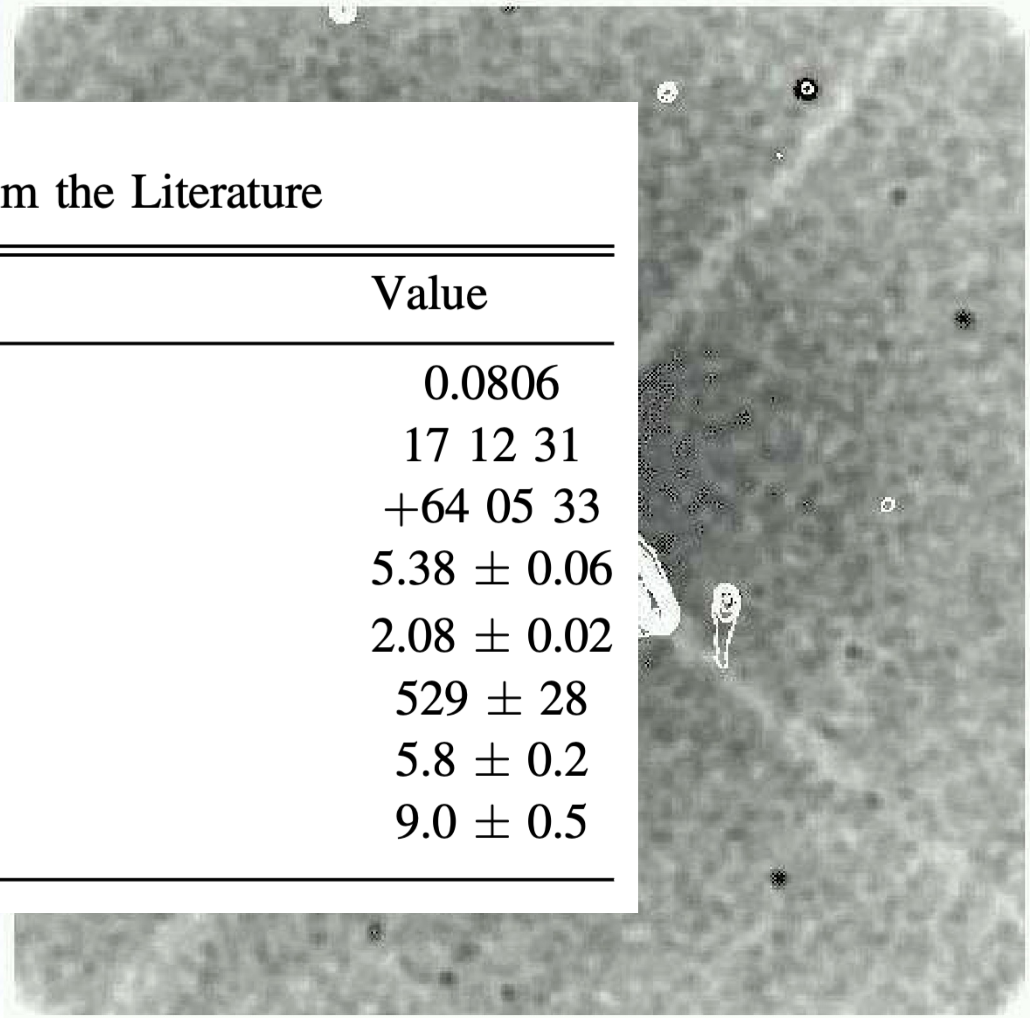
Multi-wavelength view of the cluster



Botteon et al. (2022)

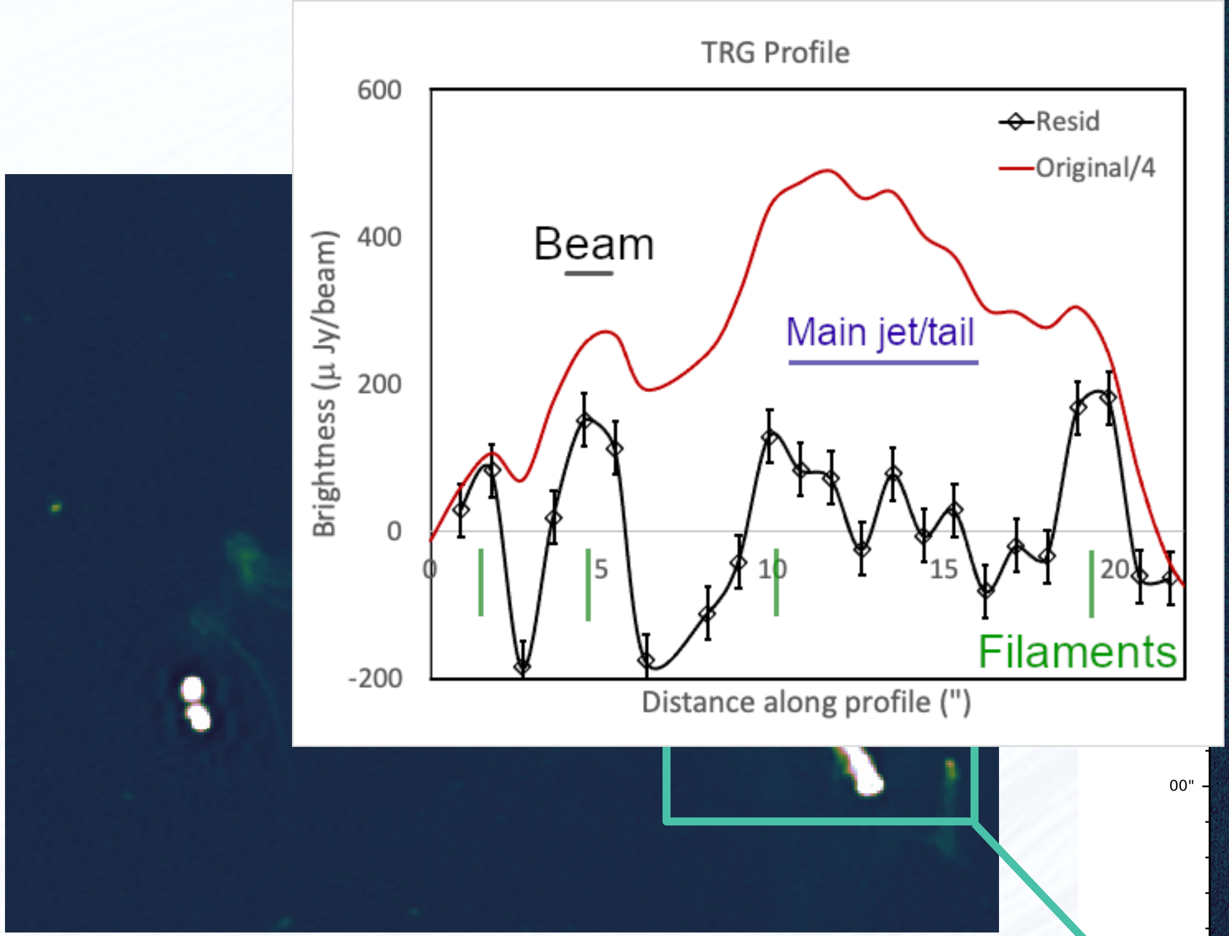
Table 1
Properties of A2255 Derived from the Literature

Property	Value
z	0.0806
R.A. (h, m, s)	17 12 31
decl. (°, ′, ″)	+64 05 33
M_{500} (10^{14} $M_\odot$)	5.38 ± 0.06
L_{500} (10^{44} erg s^{-1})	2.08 ± 0.02
K_0 (keV cm^2)	529 ± 28
kT_{vir} (keV)	5.8 ± 0.2
$P_{1.4}$ (10^{23} W Hz^{-1})	9.0 ± 0.5

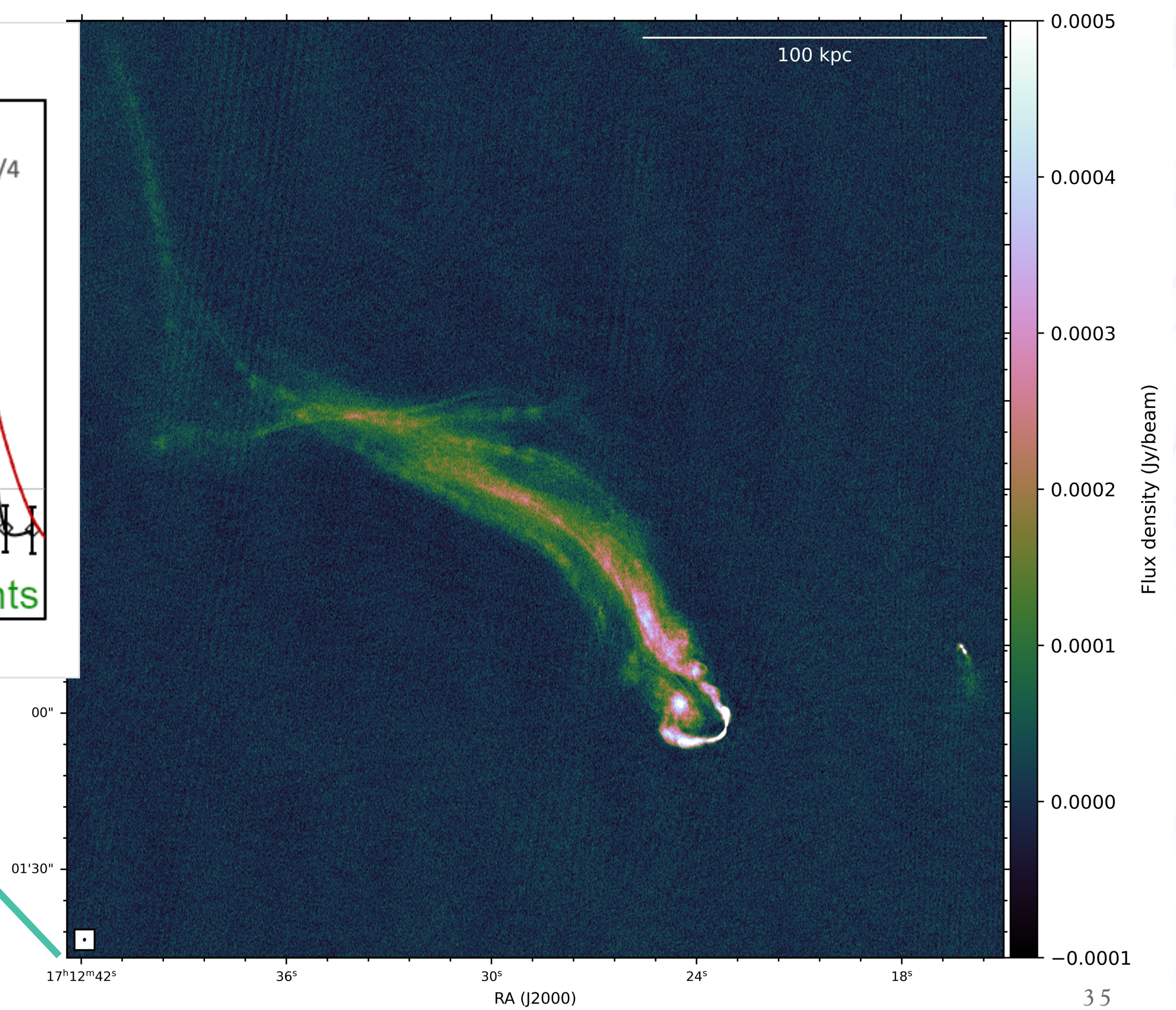


Davis et al. (2003)

Original TRG and its filamentary tail

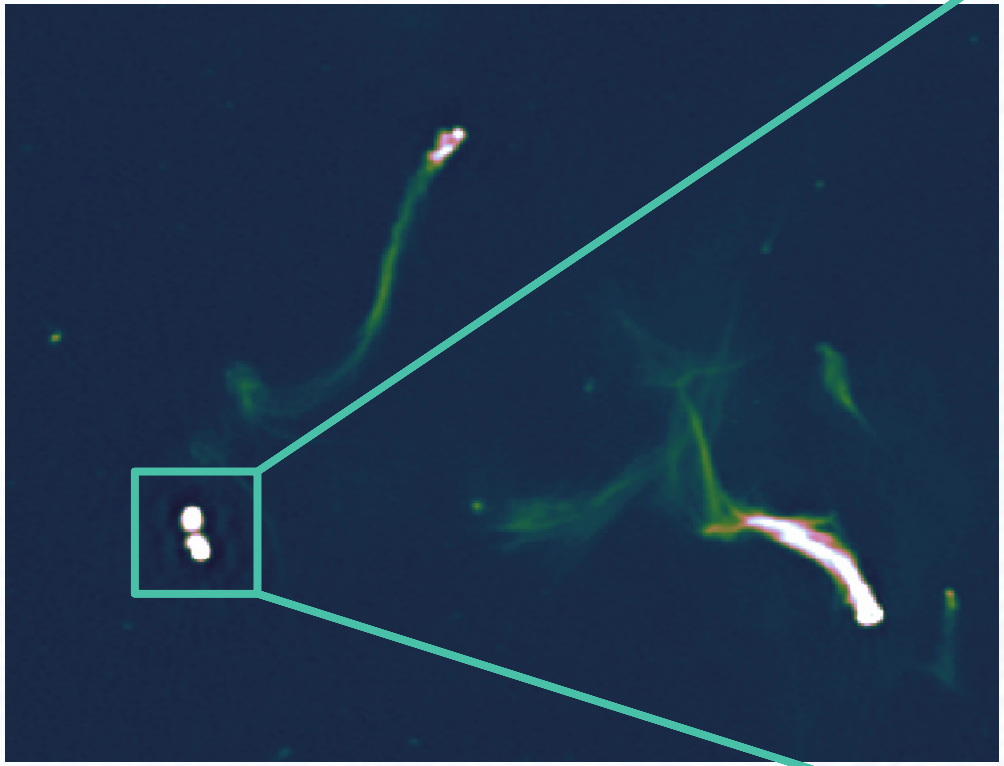


LOFAR 144 MHz image, 5″x4″, σ=55μJy/beam

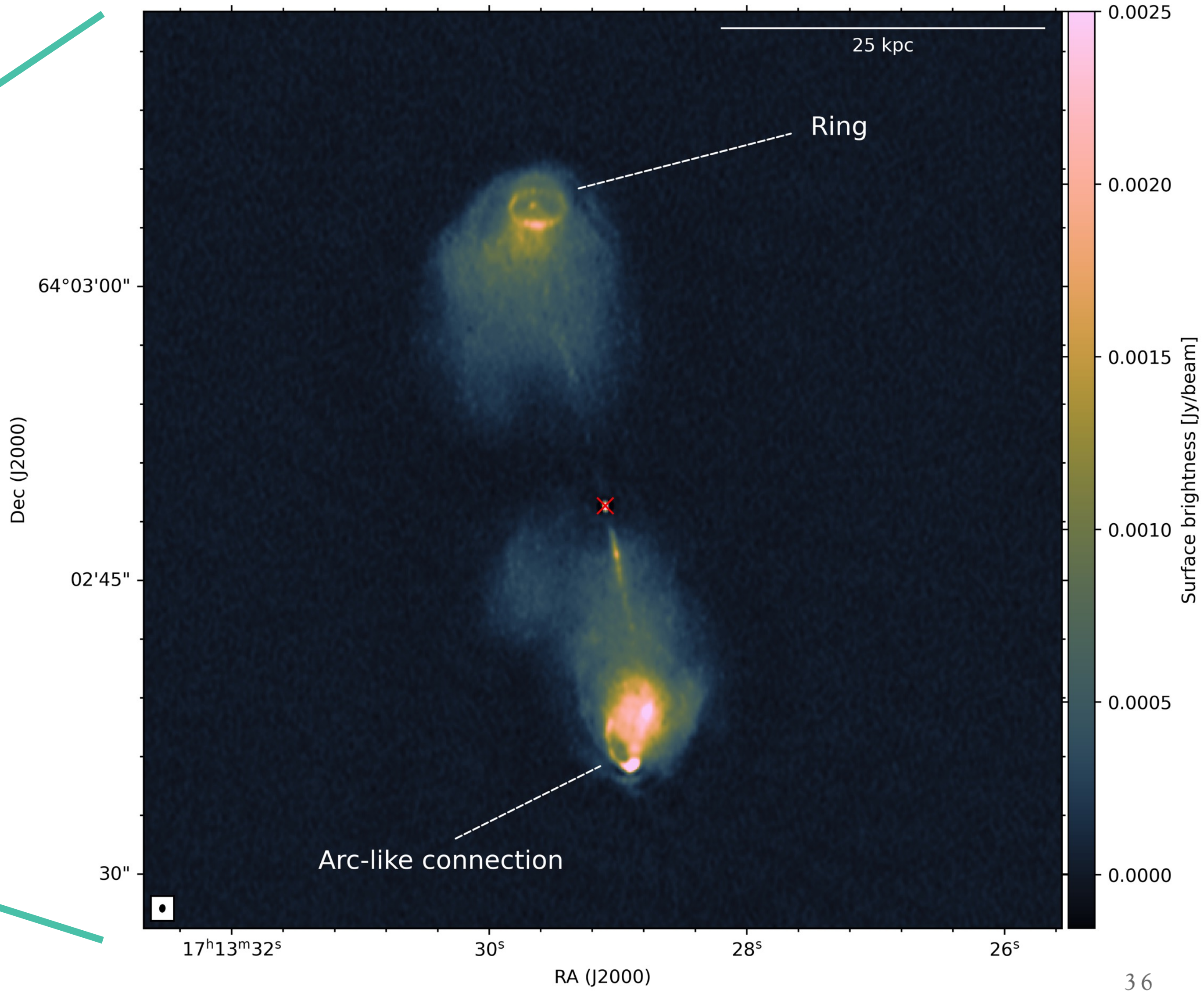


LOFAR 144 MHz image at 0.34″ x 0.24″, σ = 20 μJy/beam

LOFAR-VLBI insights: “Double”



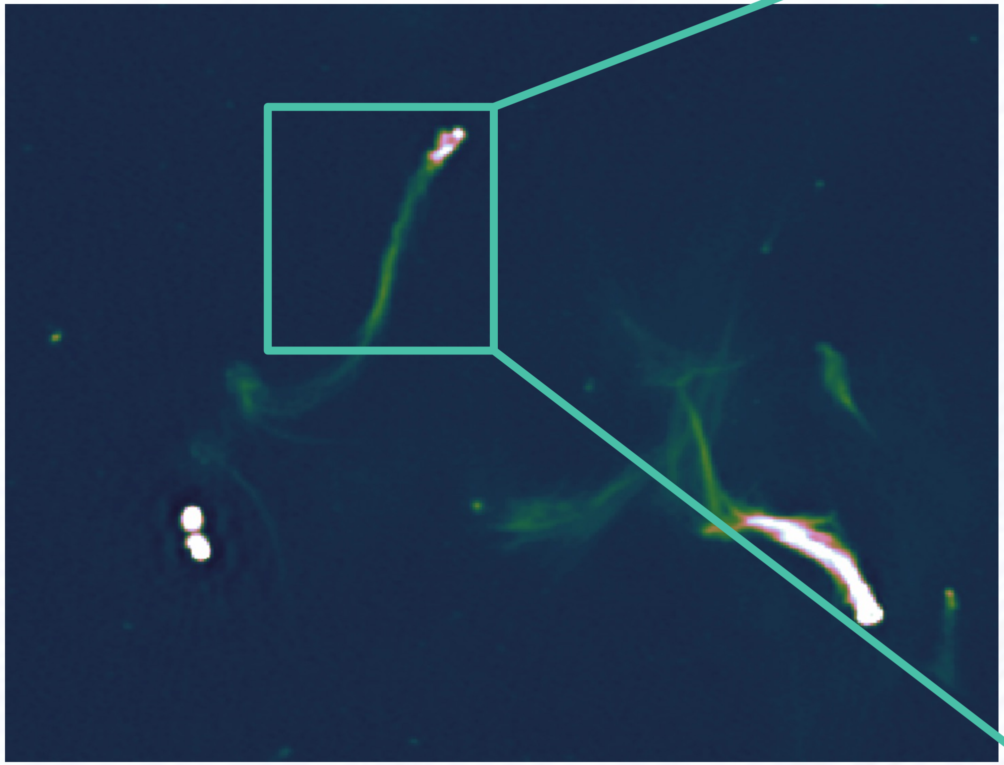
LOFAR 144 MHz image, 5”x4”, σ=55μJy/beam



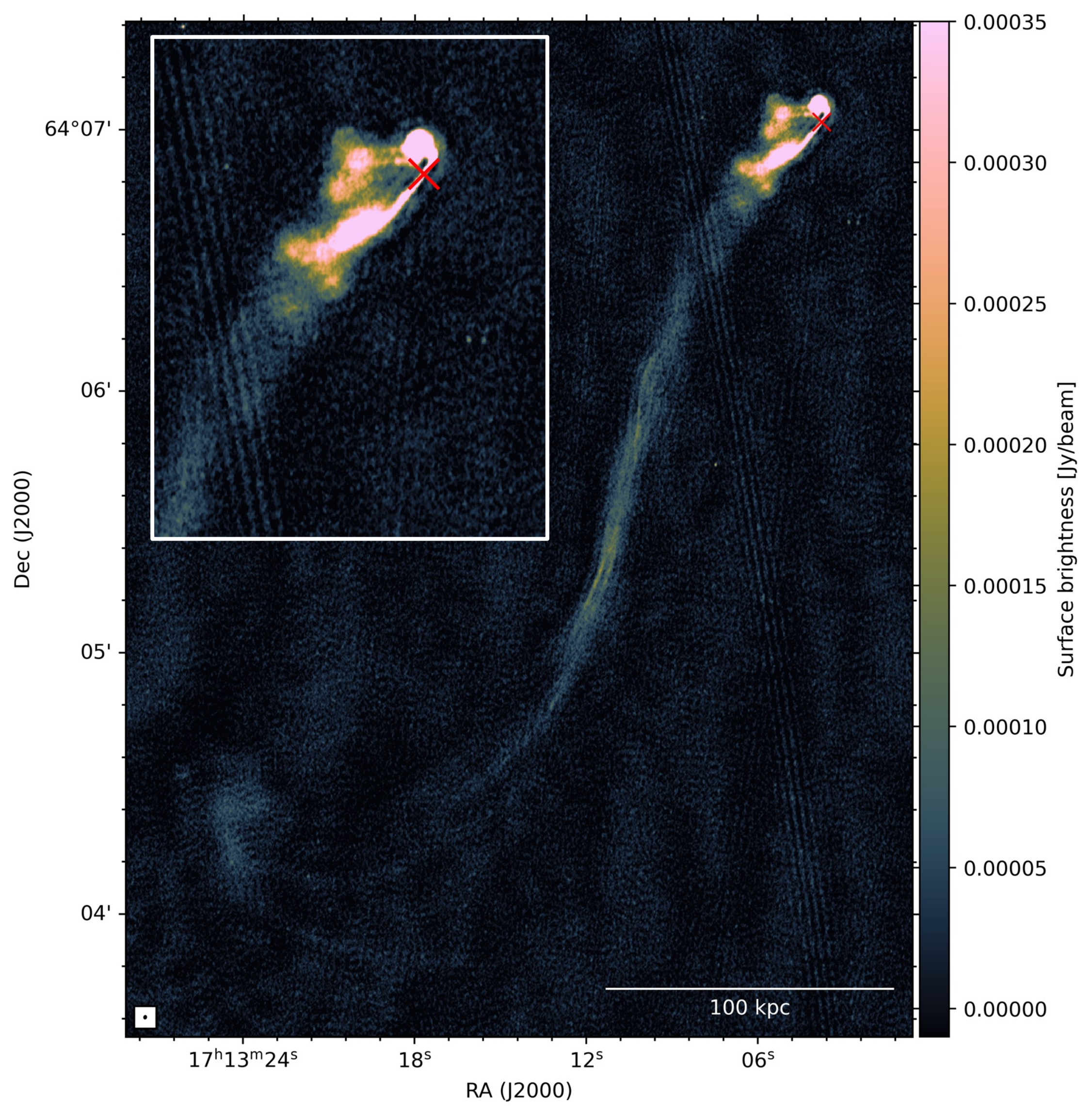
LOFAR 144 MHz image at 0.3” x 0.24”, σ = 18 μJy/beam

De Rubeis et al. (2025)

LOFAR-VLBI insights: “Goldfish”



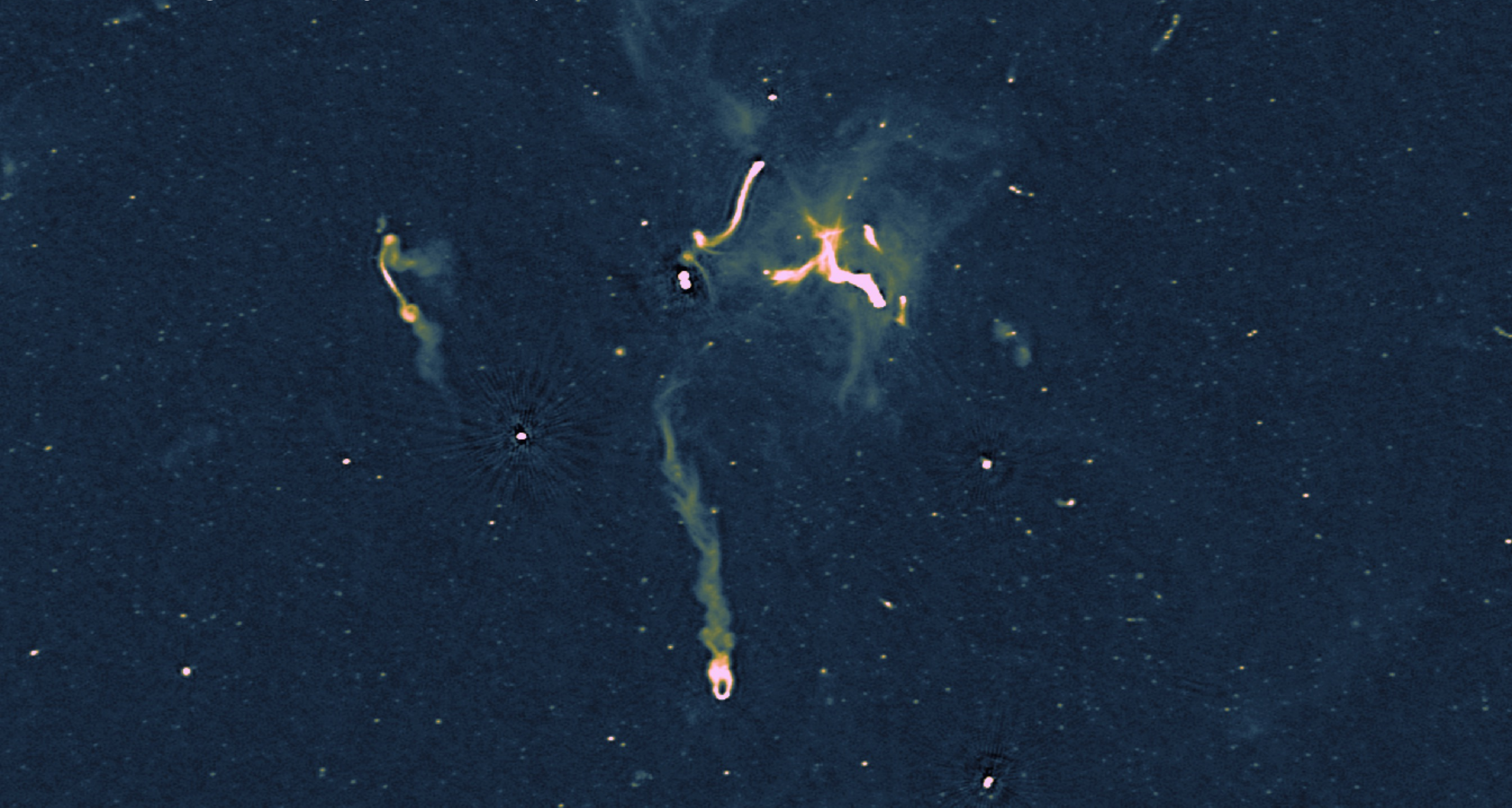
LOFAR 144 MHz image, 5”x4”, σ=55μJy/beam



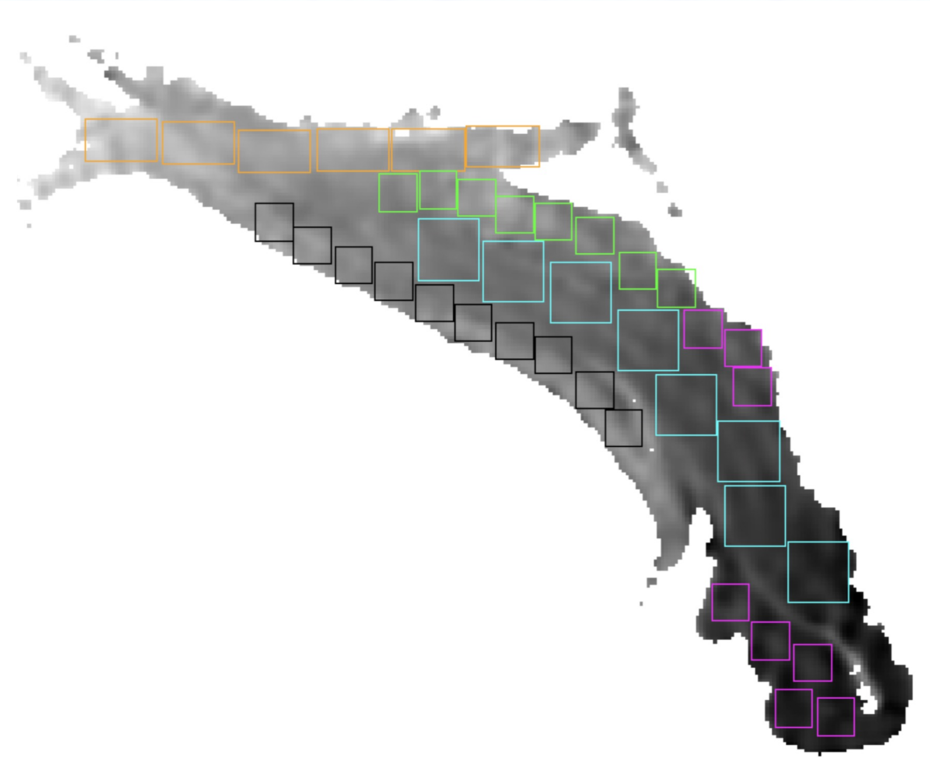
LOFAR 144 MHz image at 0.9” x 0.7”, σ = 32 μJy/beam

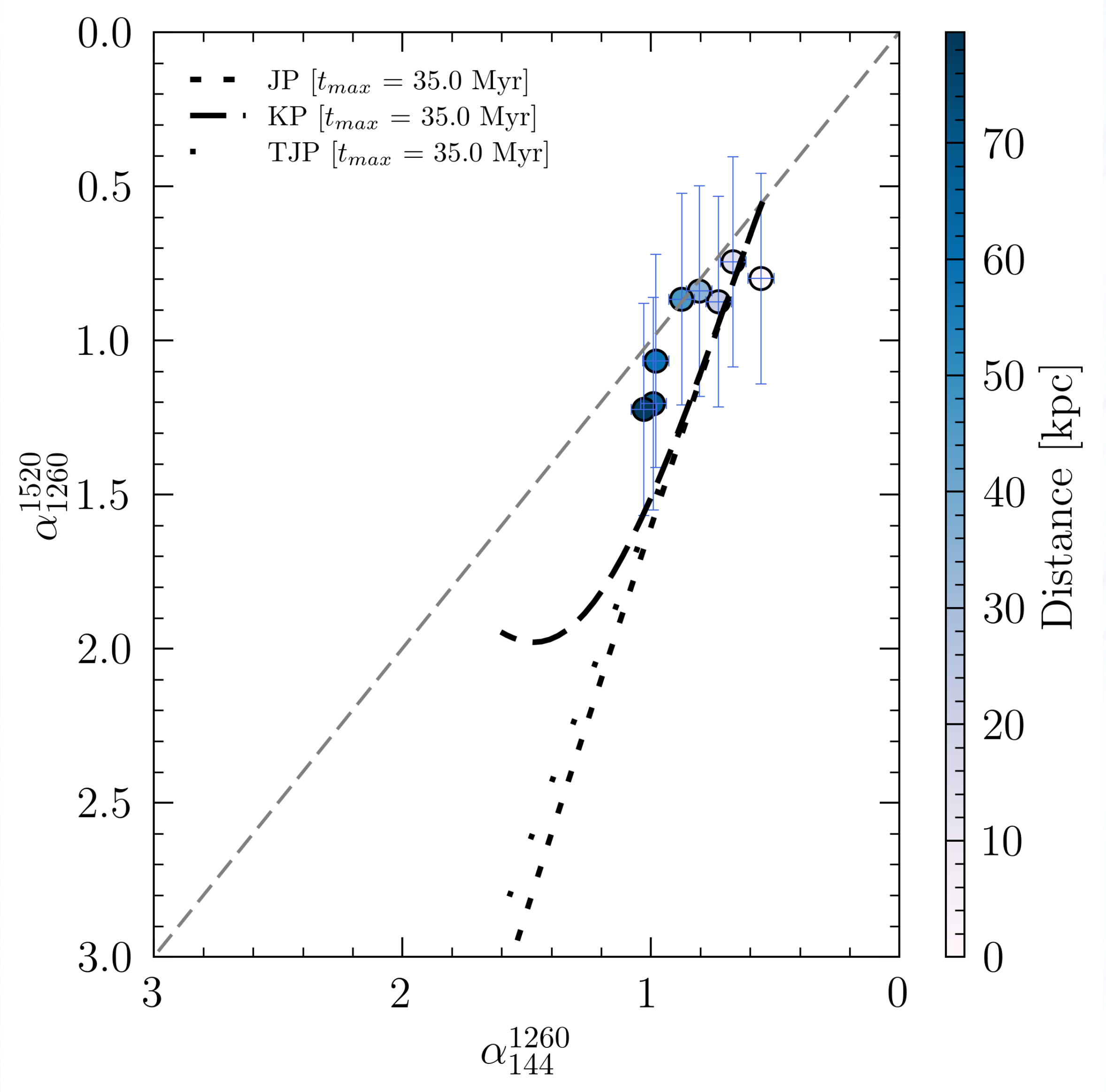
De Rubeis et al. (2025)

LOFAR 6″ image, σ=55 μJy/beam (adapted from Botteon et al. 2022)

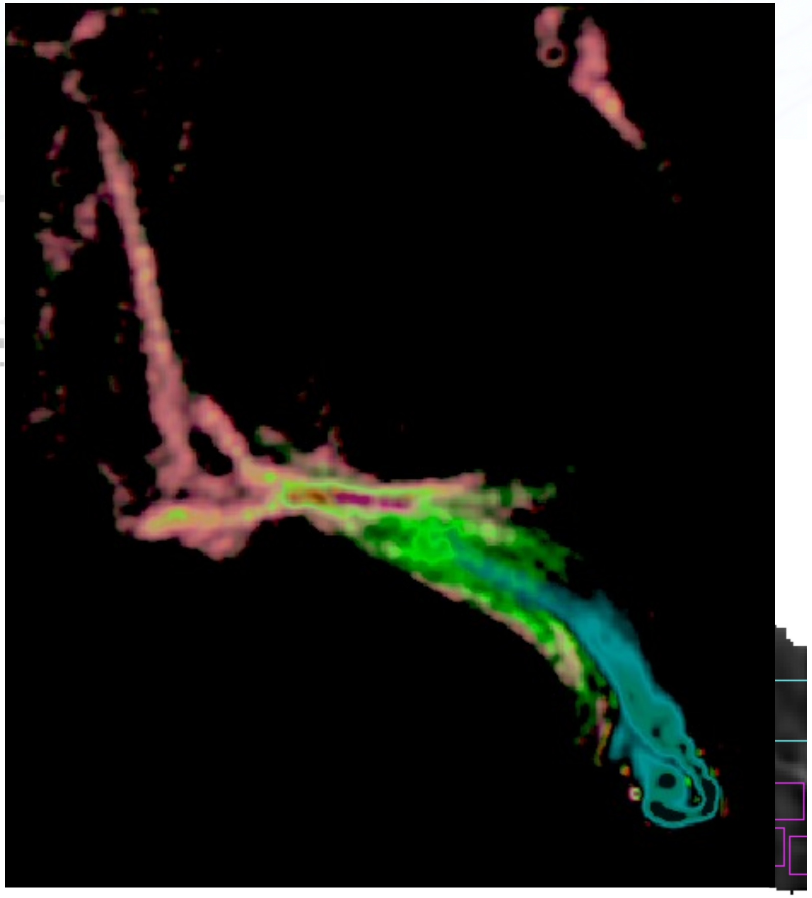


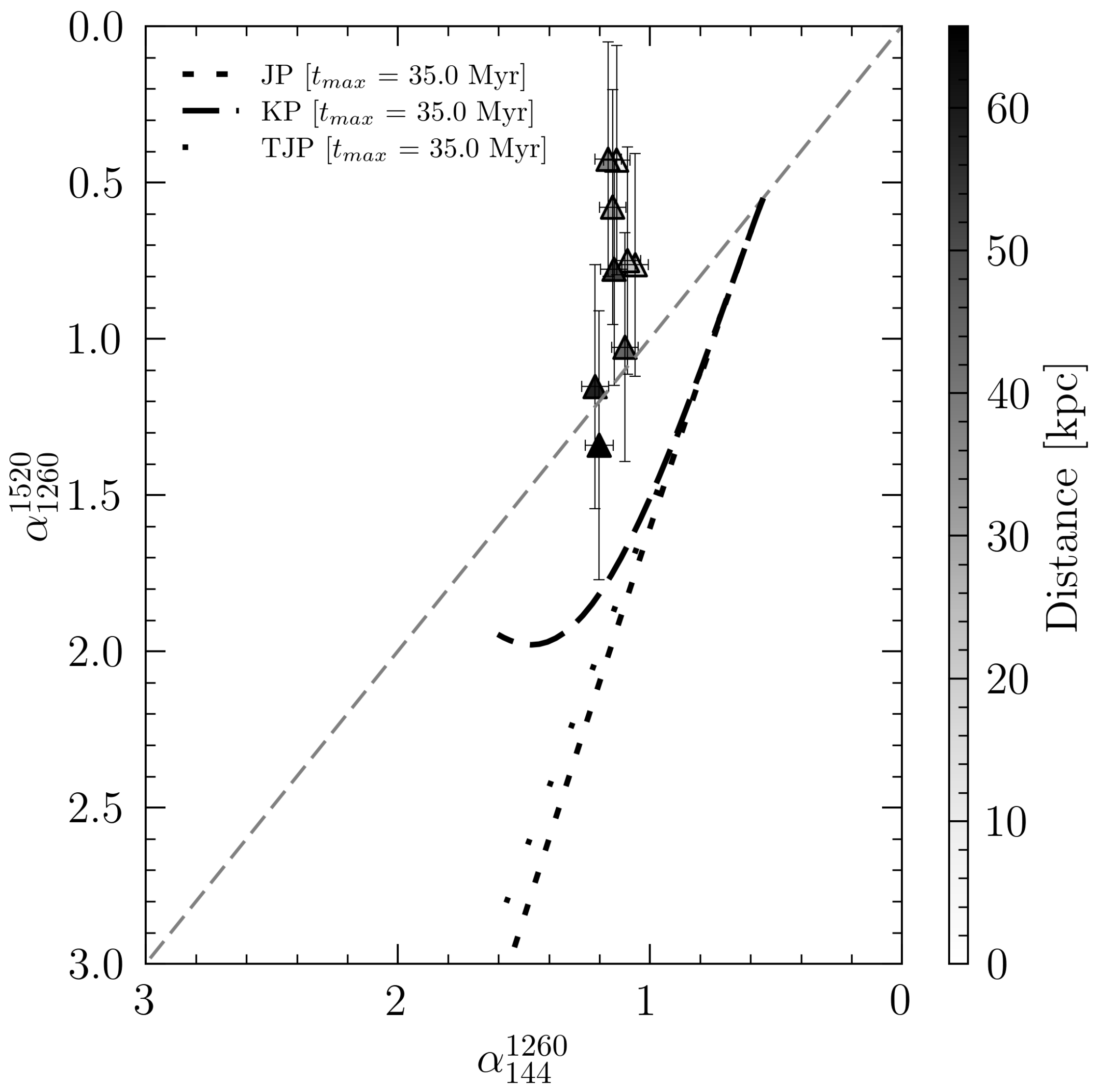
Color-color plots (1.5″)

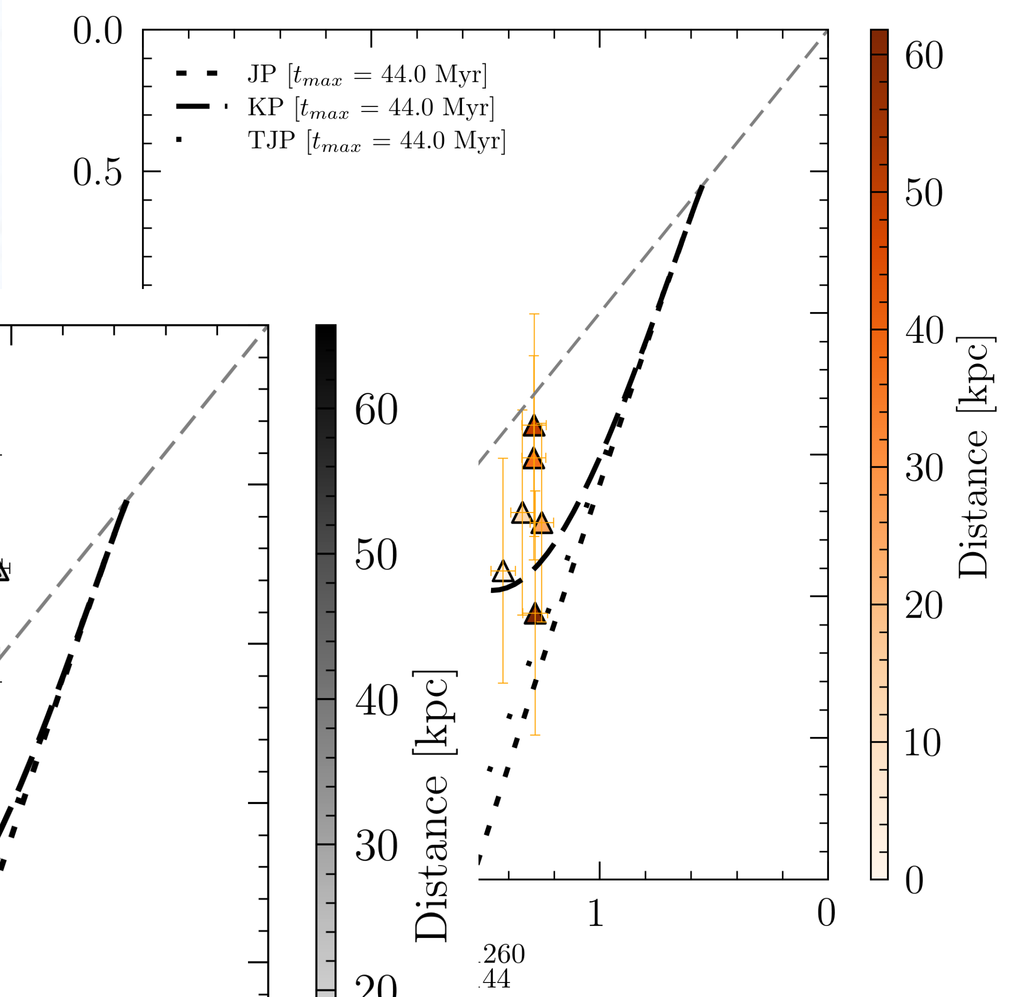




Color-color plots (1.5″)

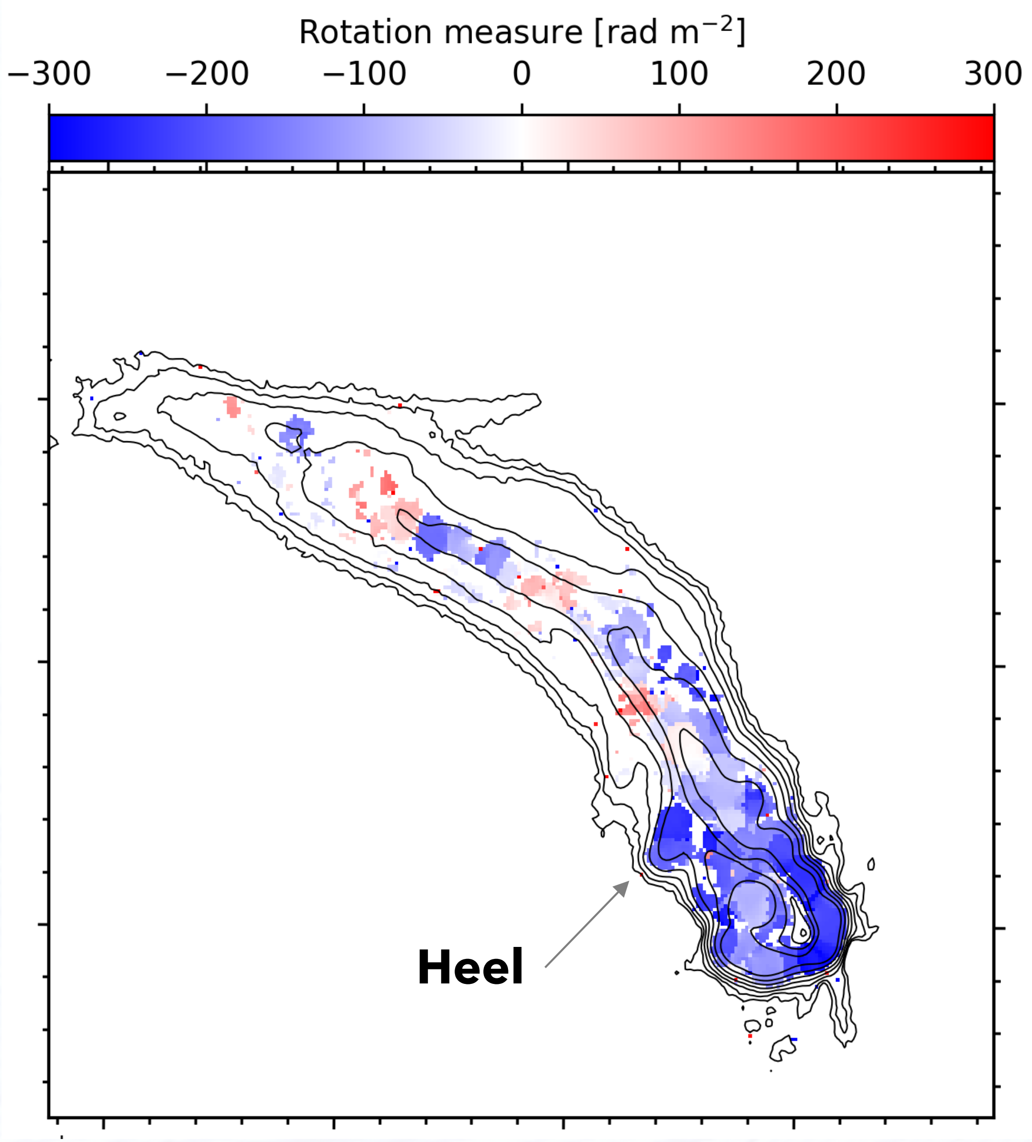






Variety of magnetic fields?
spectral components?

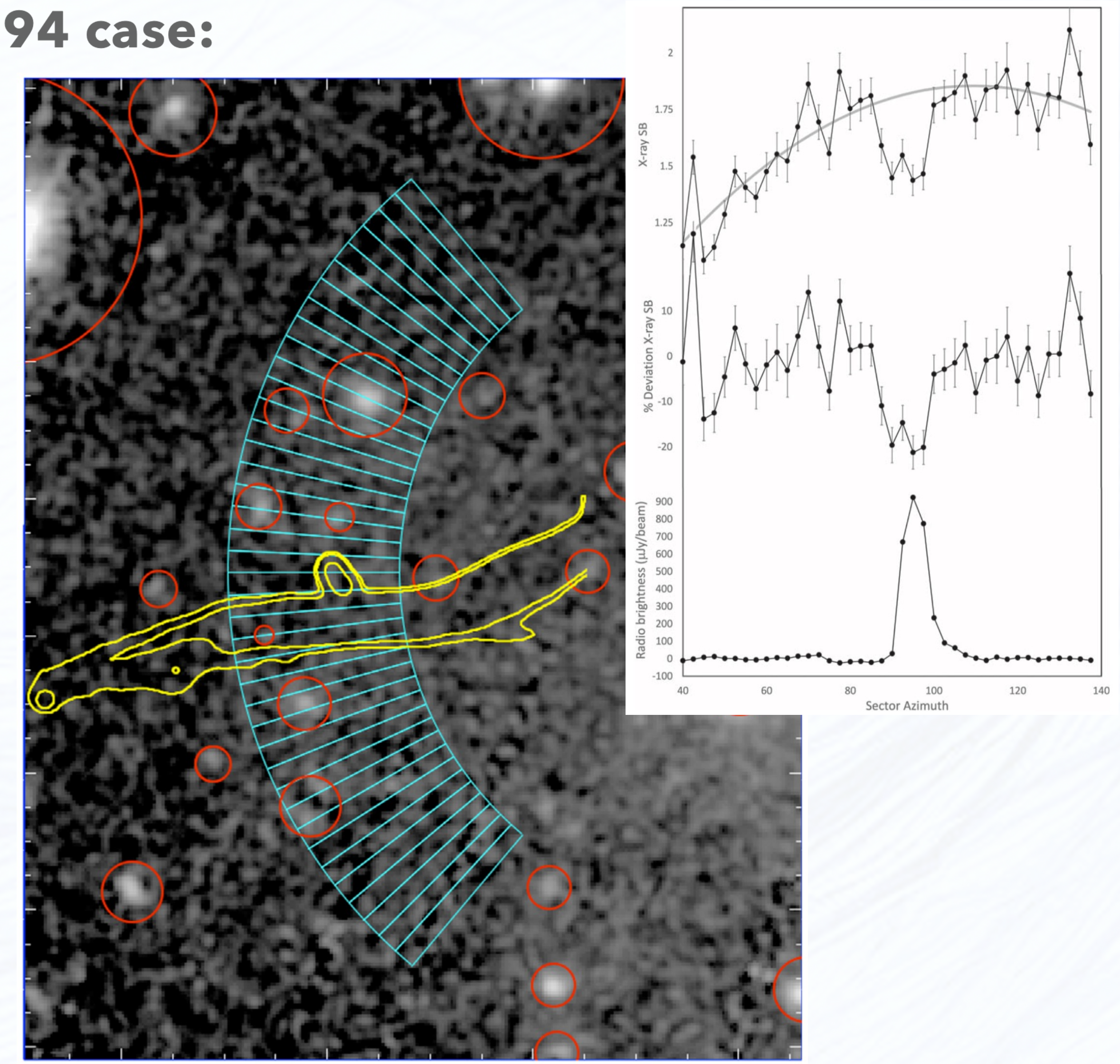
Polarization properties of the Original TRG



- Large RM values, **source deeply embedded in the ICM**
- RM variation along the tail, **B** variation in direction

X-ray dips

A194 case:



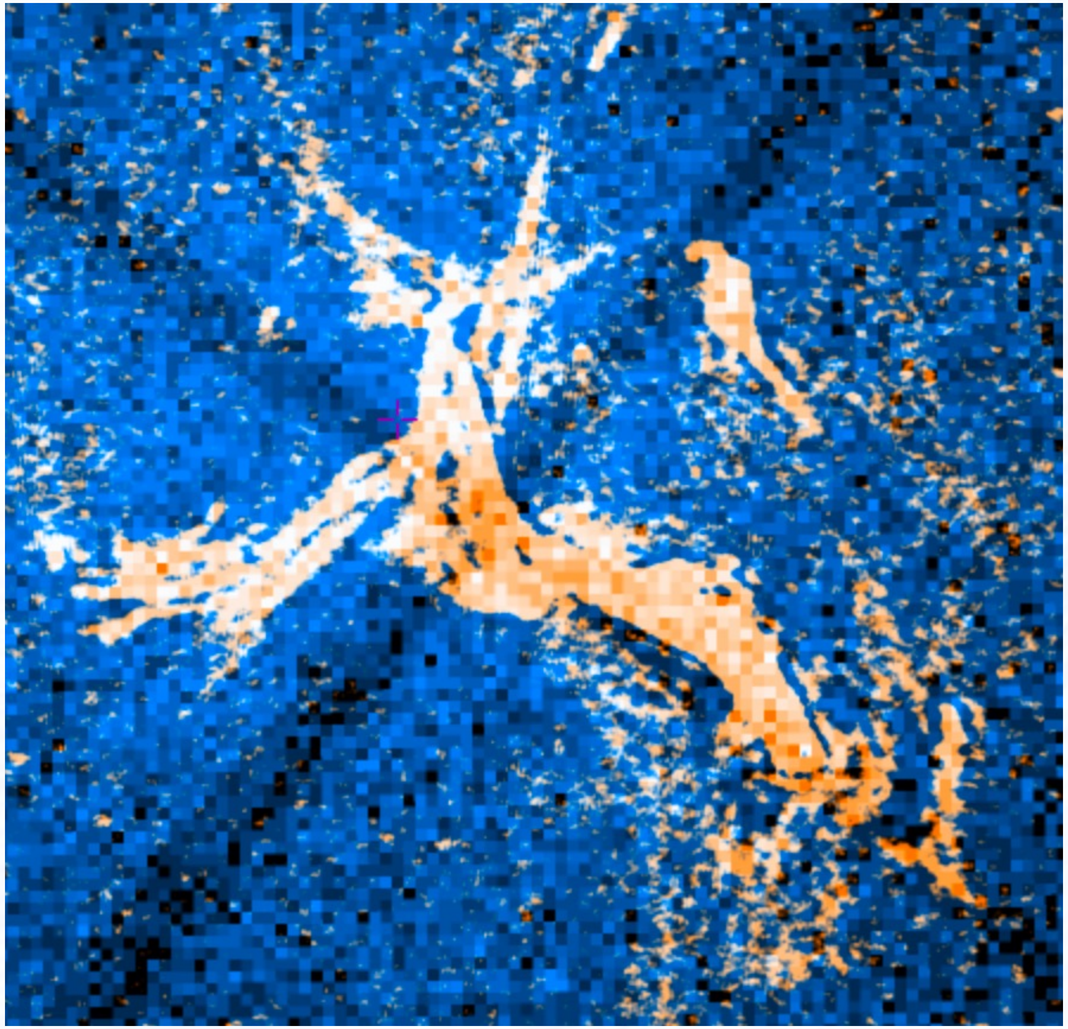
Rudnick et al. (2022)

Dip of ~20% at the location of the *E-fils*, corresponding with a 35 kpc radius cylinder.

Magnetic pressures in filaments can reach **significant fractions of the ambient thermal pressures**, and together with accompanying cosmic rays, can plausibly **expel the local thermal plasma**.

X-ray cavities?

What for Abell 2255?

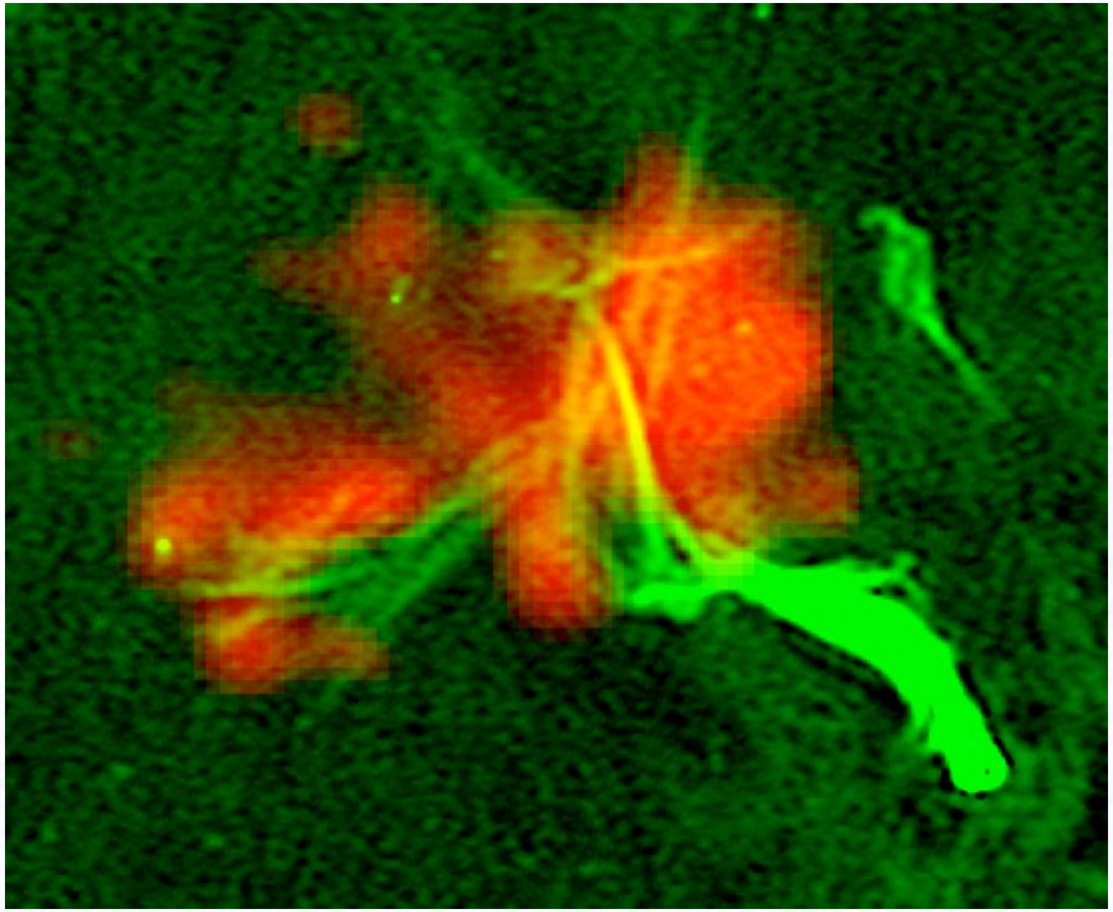


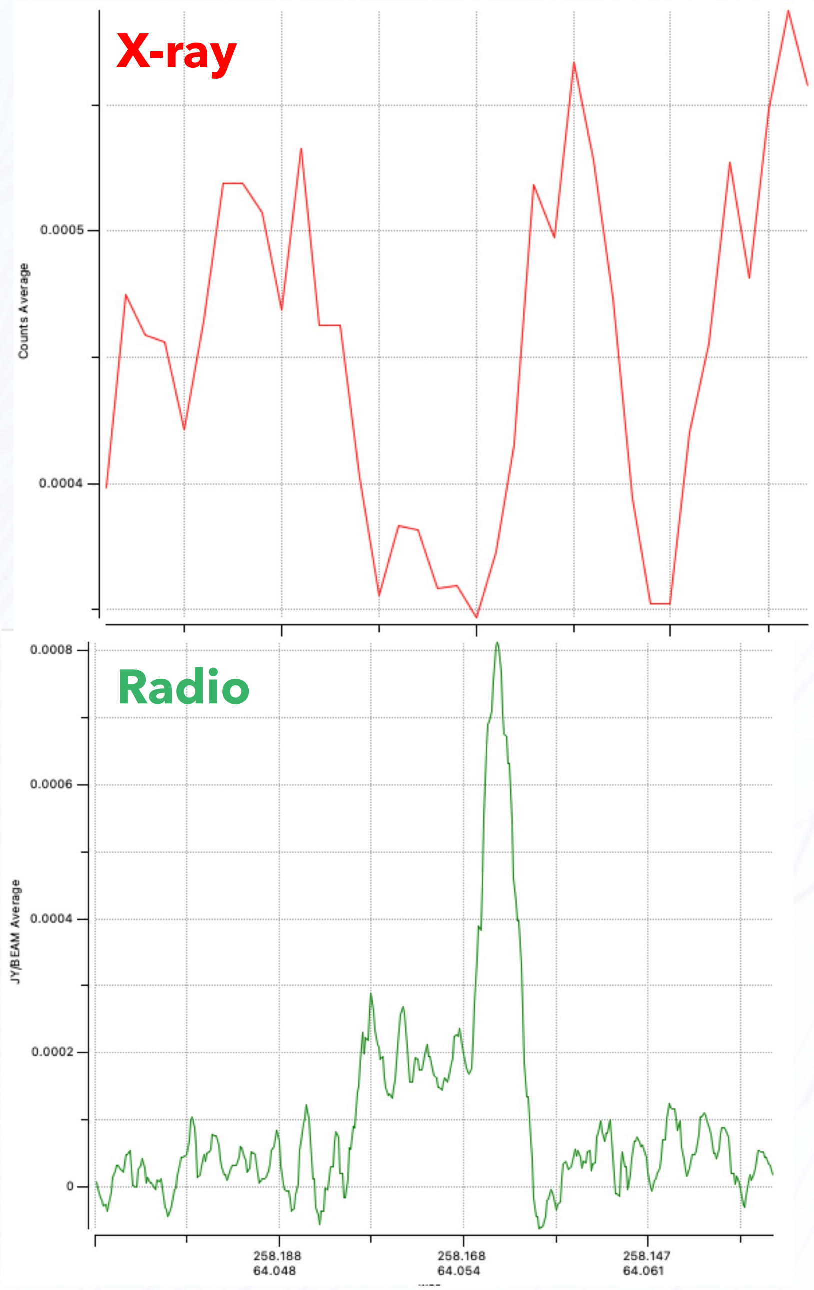
Unlucky archival observations with Chandra (40 ks, ObsID 894) ☹

Large proposal accepted for Chandra (P.I. Rajpurohit, 460 ks).

X-ray cavities?

What for Abell 2255?

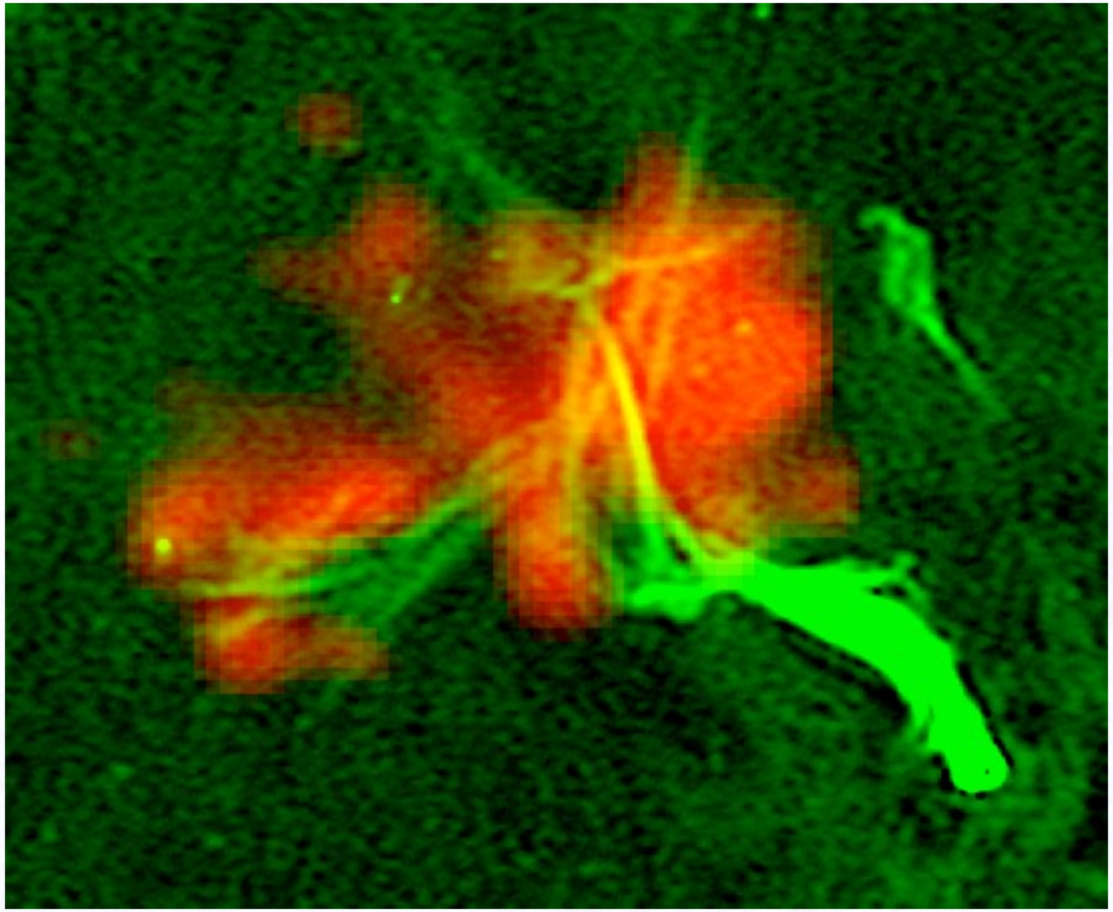




Many thanks to Larry!

X-ray cavities?

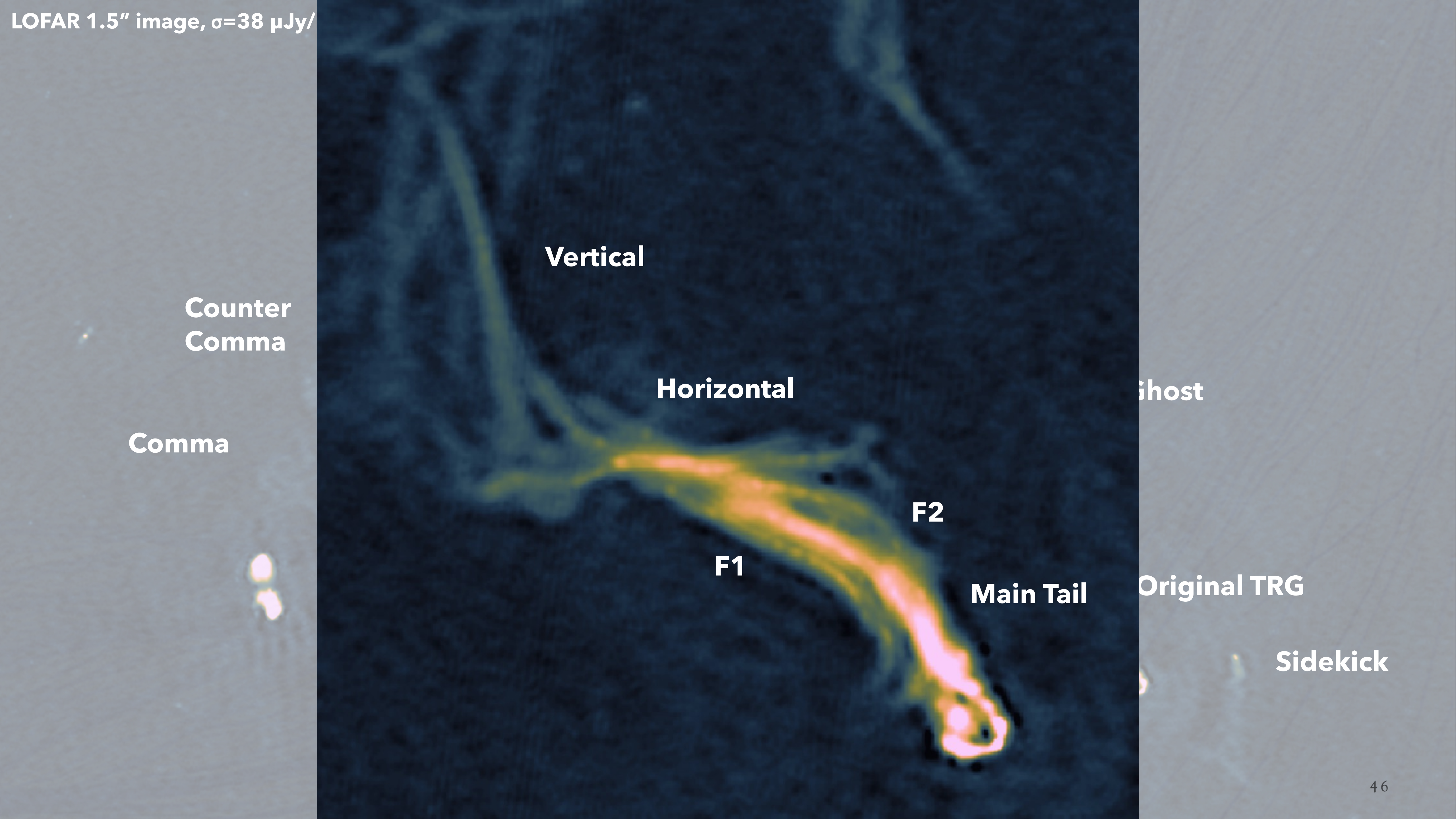
What for Abell 2255?

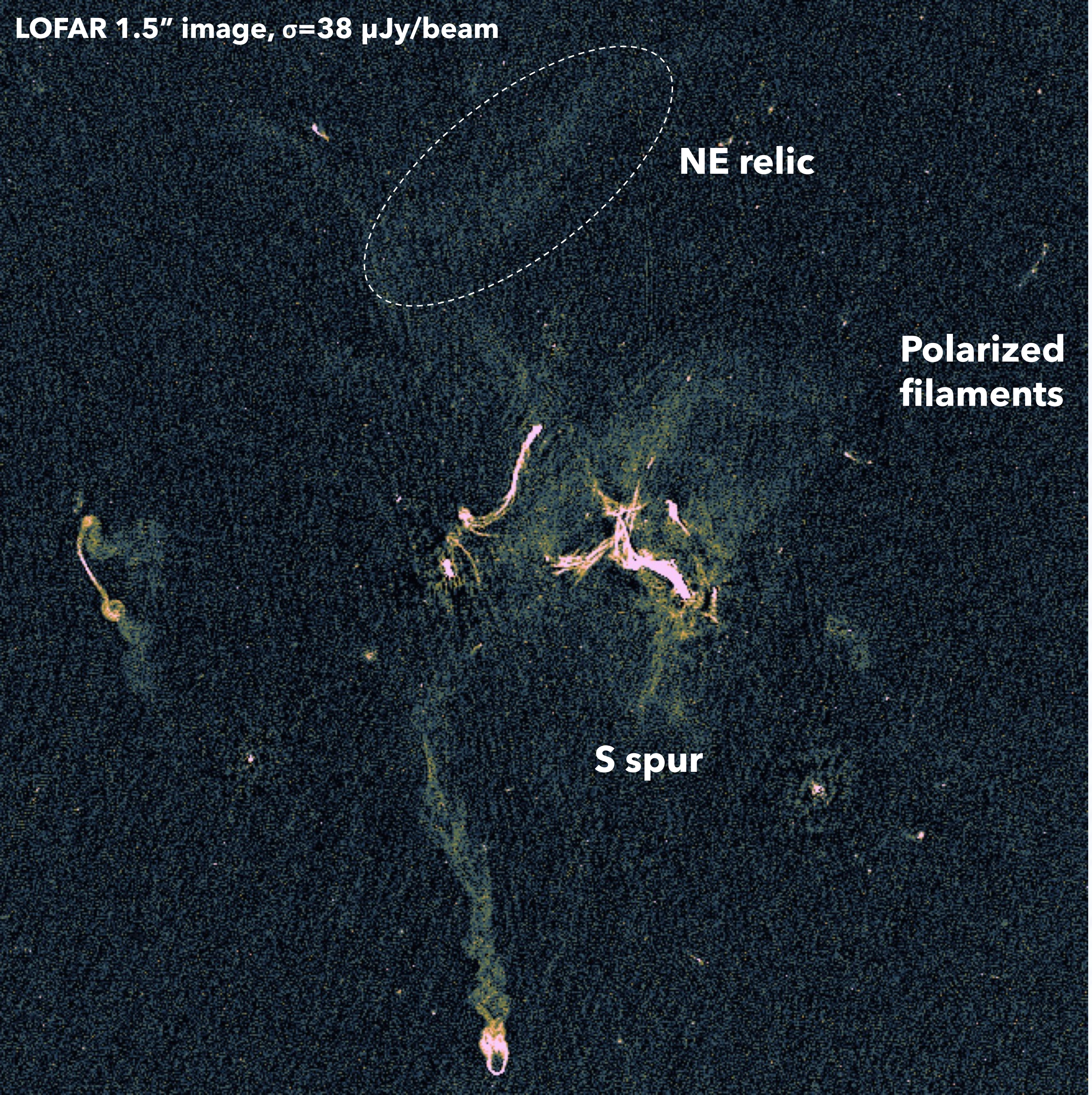


From archival XMM-Newton data, there seems to be **spatial correspondence between X-ray lowering and the vertical filament**.

- (super)sonic motions
- low-β filaments – high magnetic field pressure regions

Many thanks to Larry!


LOFAR 1.5″ image, σ=38 μJy/
Vertical
Counter
Comma
Horizontal
Ghost
Comma
F2
F1
Main Tail
Original TRG
Sidekick



Still, with high-resolution, we can recover also the **more diffuse emission thanks** to **LOFAR high-sensitivity**.