Why a cluster deep field?

Andrea BOTTEON

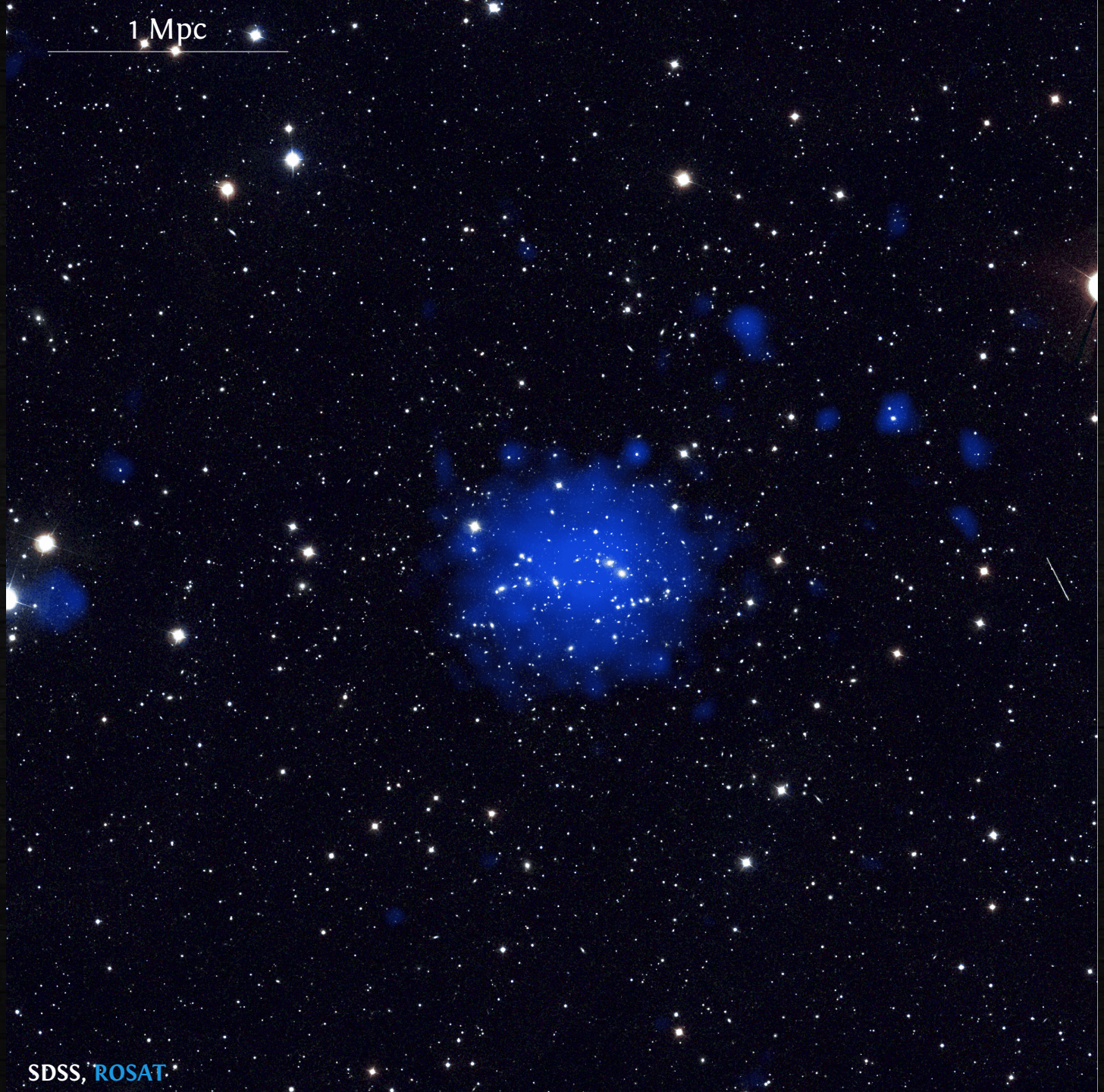
INAF – IRA

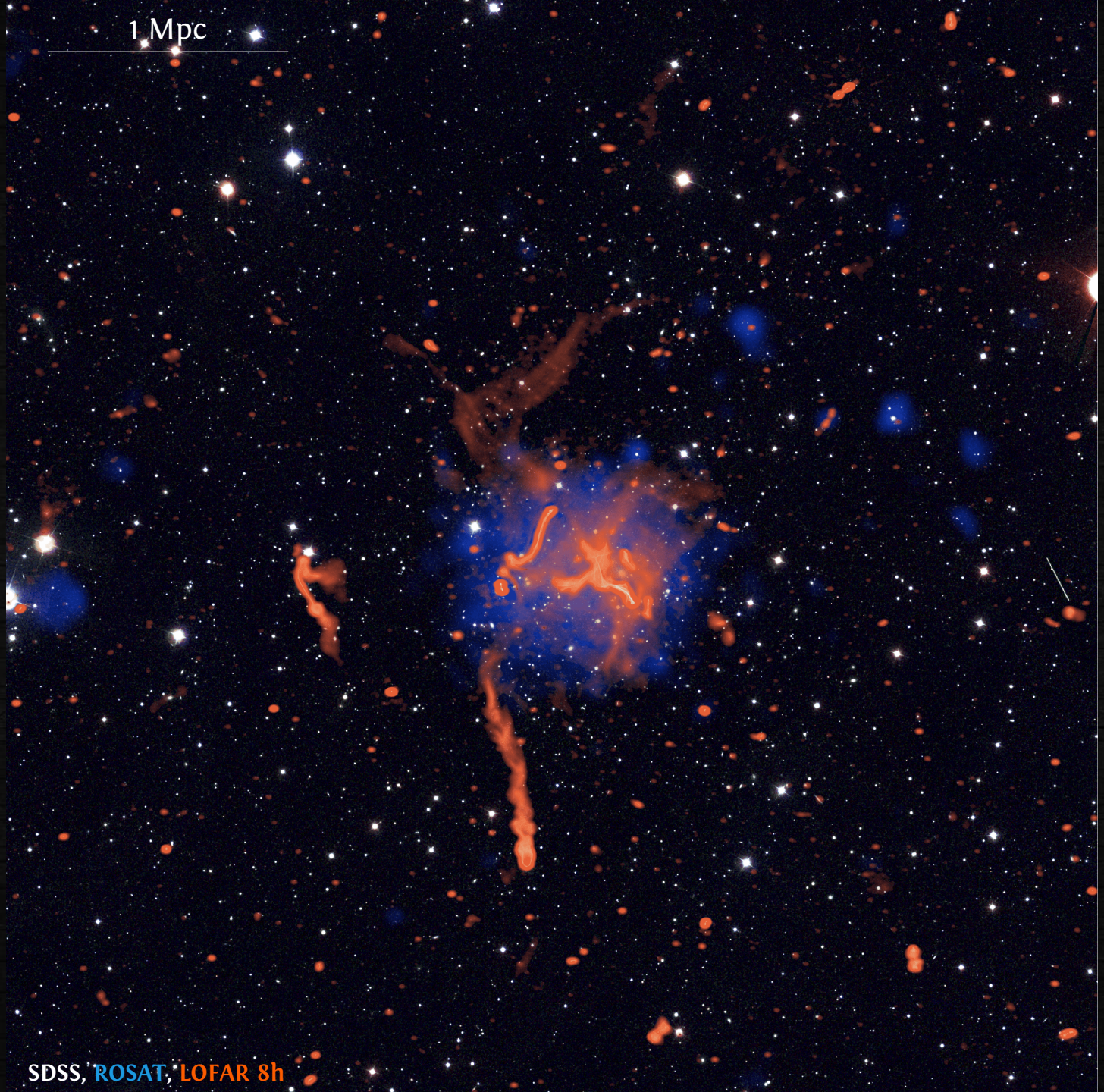
In collaboration with the LOFAR Galaxy Clusters Working Group and Surveys KSP

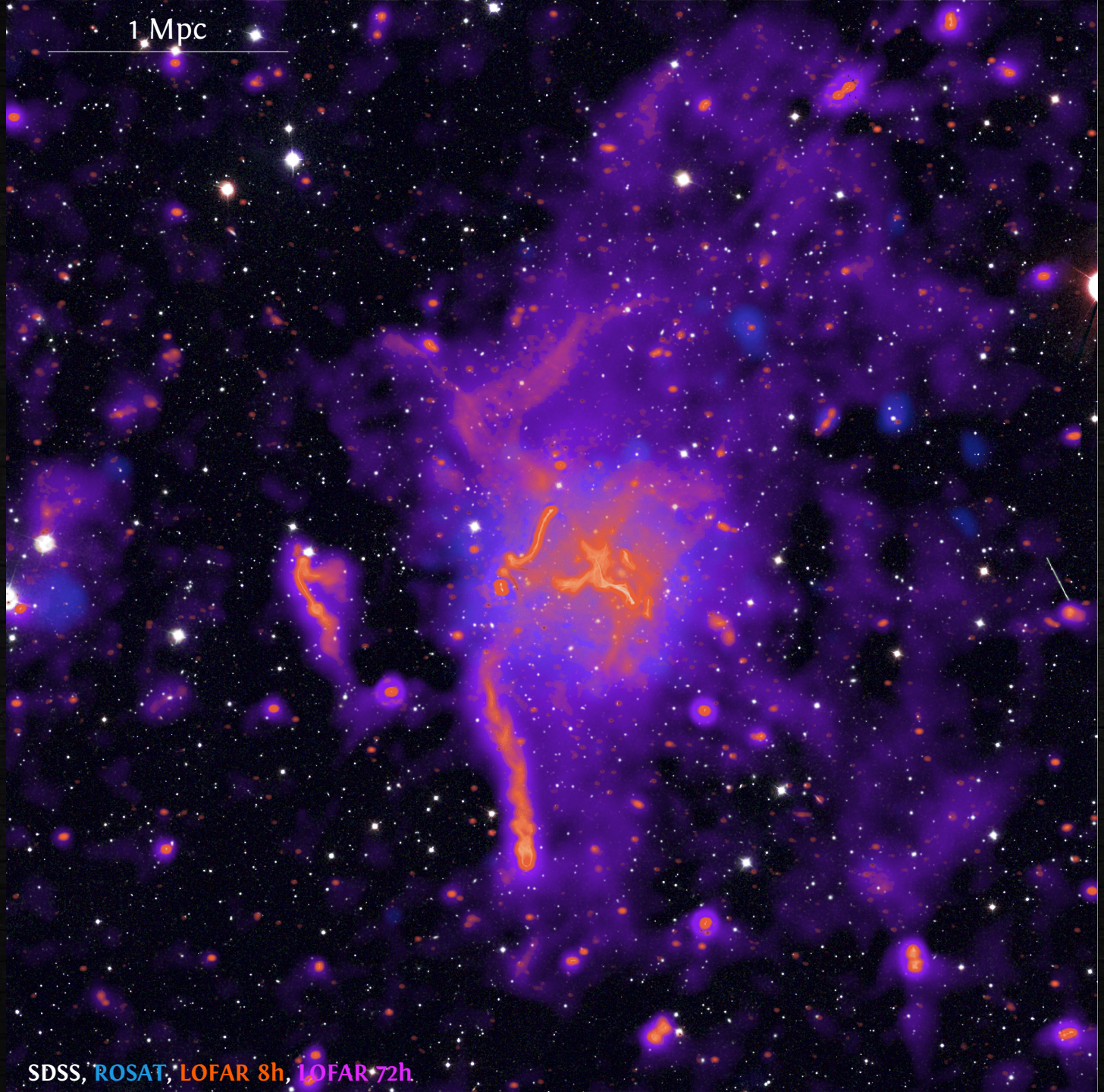
LOFAR

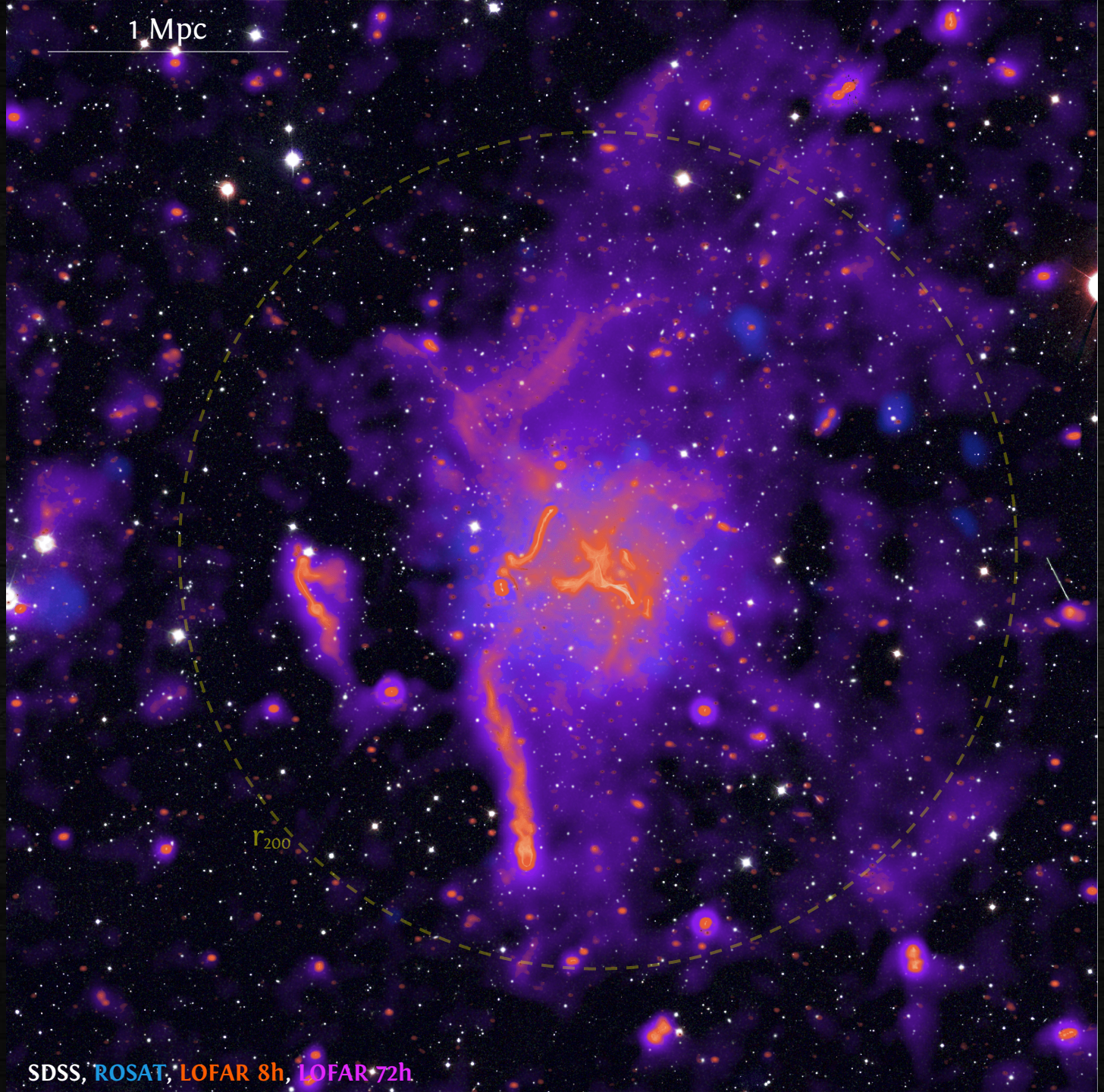
June 13, 2023 – LOFAR Family Meeting, Olsztyn


1 Mpc
SDSS

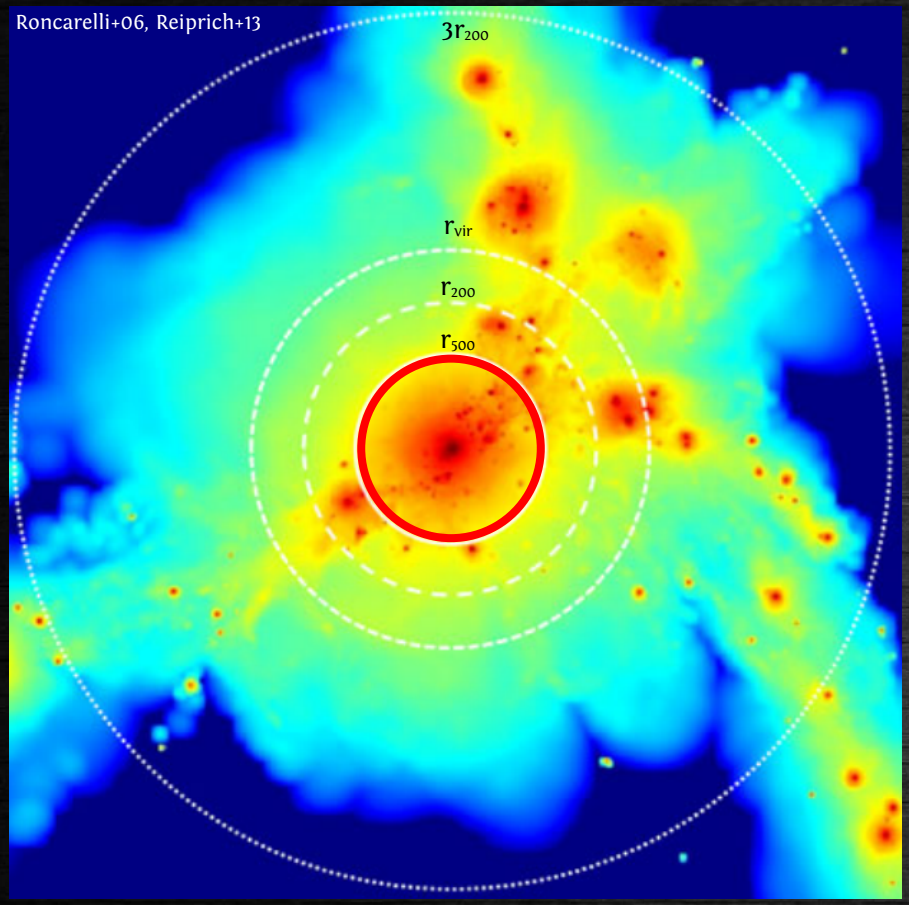

1 Mpc
SDSS, ROSAT

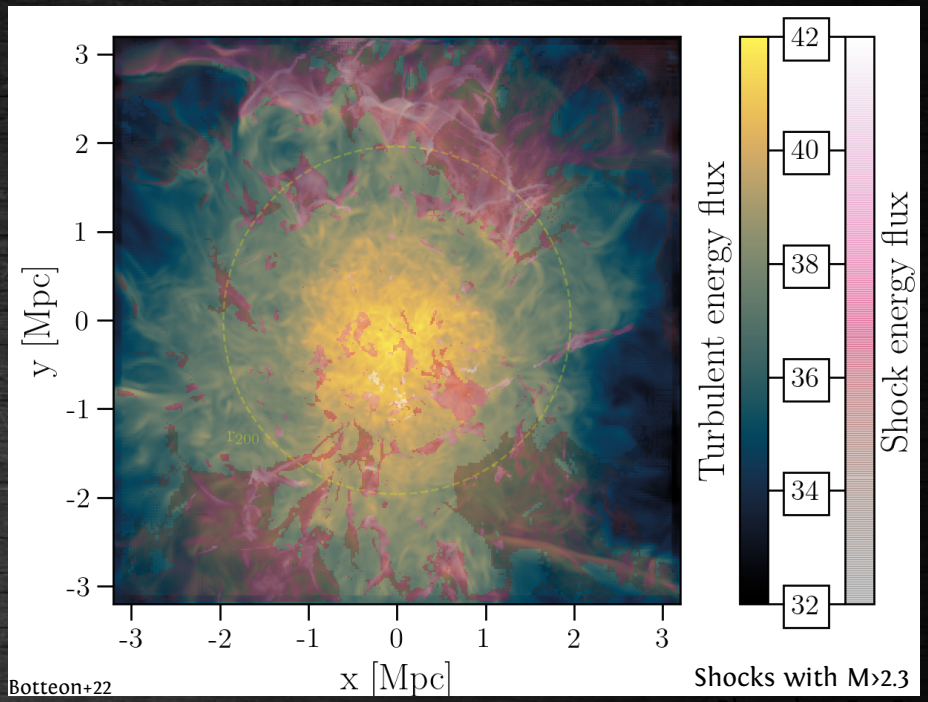

1 Mpc
SDSS, ROSAT, LOFAR 8h


1 Mpc
SDSS, ROSAT, LOFAR 8h, LOFAR 72h


1 Mpc
r_{200}
SDSS, ROSAT, LOFAR 8h, LOFAR 72h

Clusters and cluster outskirts





Inner regions ($r < r_{500}$) are well sampled in radio by *radio halos* and *radio relics*. In X-rays, they are accessible with Chandra and XMM

Deep radio observations can be used to study how *shocks* and *turbulent motions* dissipate kinetic energy into **non-thermal components** in **extreme** cluster outskirts, over the *entire* cluster volume

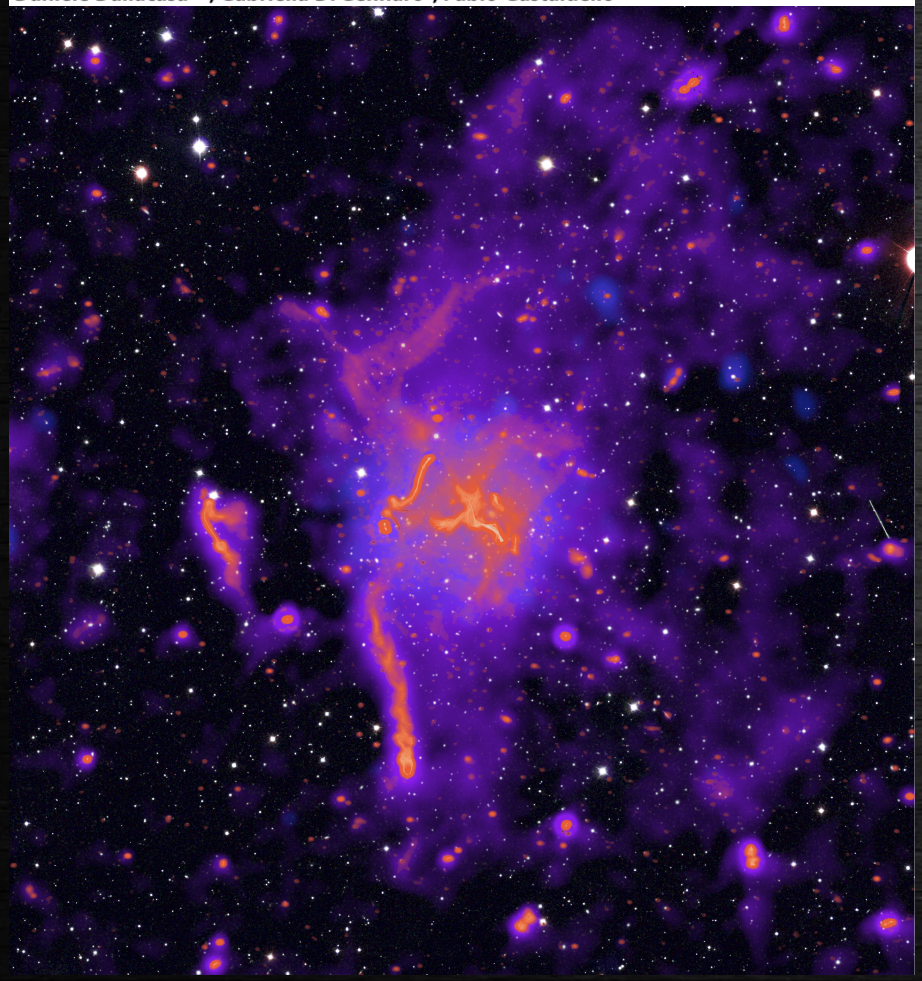
The Galaxy Cluster Deep Field

ASTRONOMY

Science Advances

Magnetic fields and relativistic electrons fill entire galaxy cluster

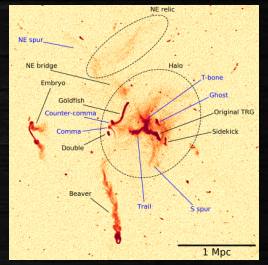
Andrea Botteon[1,2,3]*, Reinout J. van Weeren[1], Gianfranco Brunetti[3], Franco Vazza[2,3], Timothy W. Shimwell[1,4], Marcus Brüggen[5], Huub J. A. Röttgering[1], Francesco de Gasperin[3,5], Hiroki Akamatsu[6], Annalisa Bonafede[2,3], Rossella Cassano[3], Virginia Cuciti[3,5], Daniele Dallacasa[2,3], Gabriella Di Gennaro[5], Fabio Gastaldello[7]



Abell 2255

(Jaffe+Rudnick79, Feretti+97, Govoni+05,06, Pizzo+08,09,11, Botteon+20,22)

z	0.0806
Right ascension (h, m, s)	17 12 31
Declination (°, ′, ″)	+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
Scale (kpc $arcsec^{-1}$)	1.512

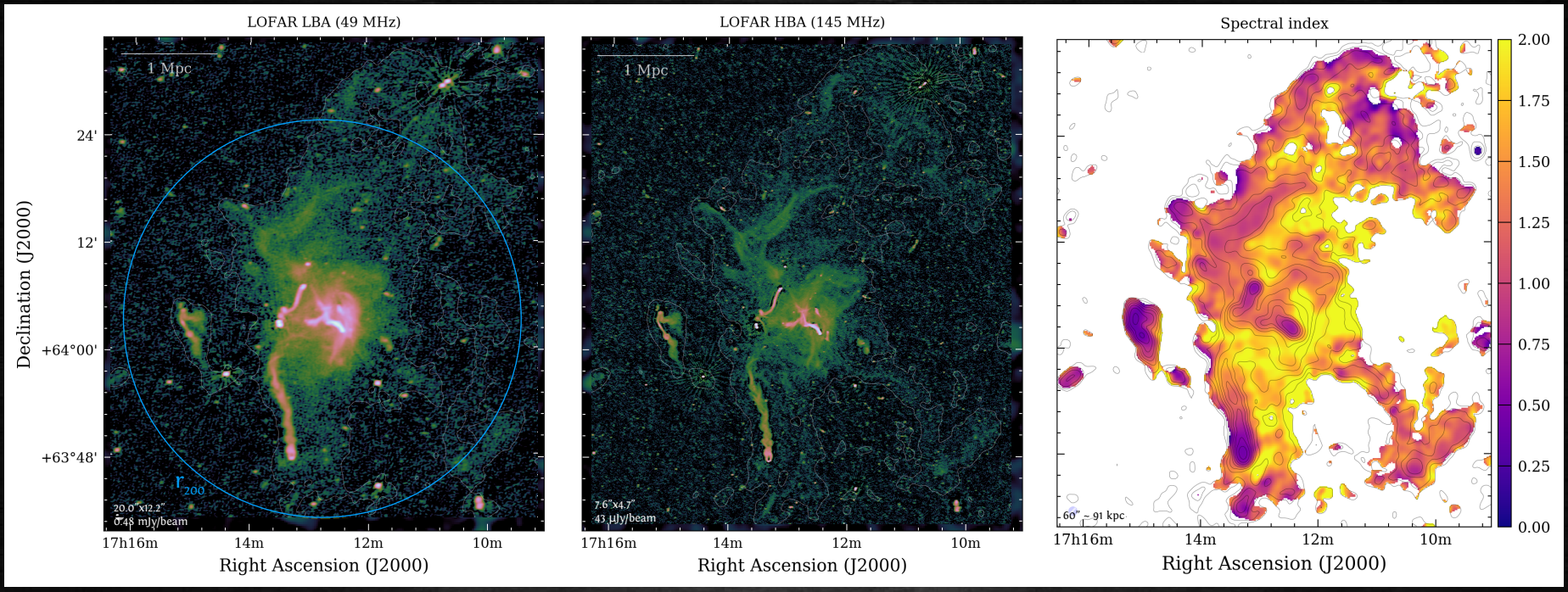


LoTSS (Botteon+2020):
8h HBA 120-168 MHz

Deep Field (Botteon+2022):
72h HBA 120-168 MHz
72h LBA 22-70 MHz

Ultra-Deep Field (202..):
336h HBA 120-168 MHz

A giant envelope of emission



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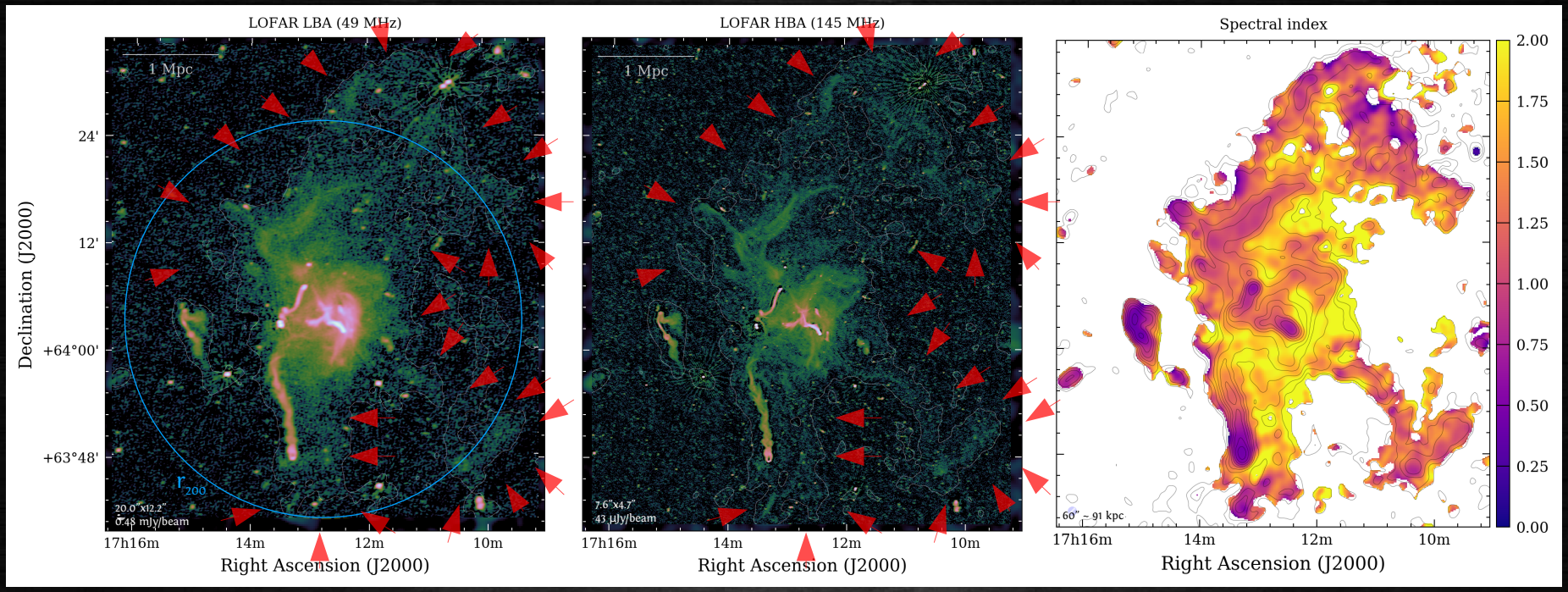

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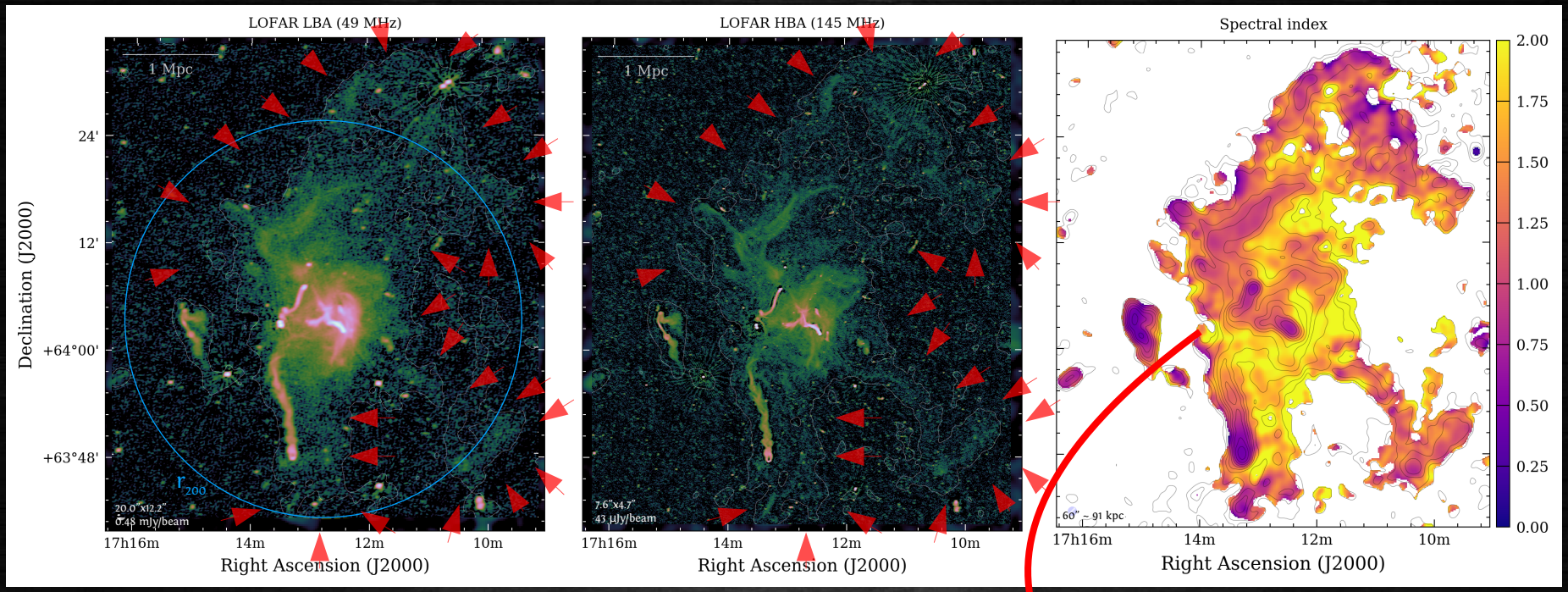
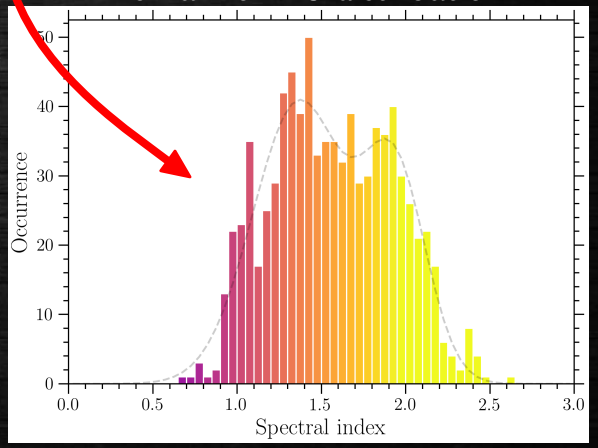


Non-uniform α distribution



From *independent* pixels excluding *discrete* sources

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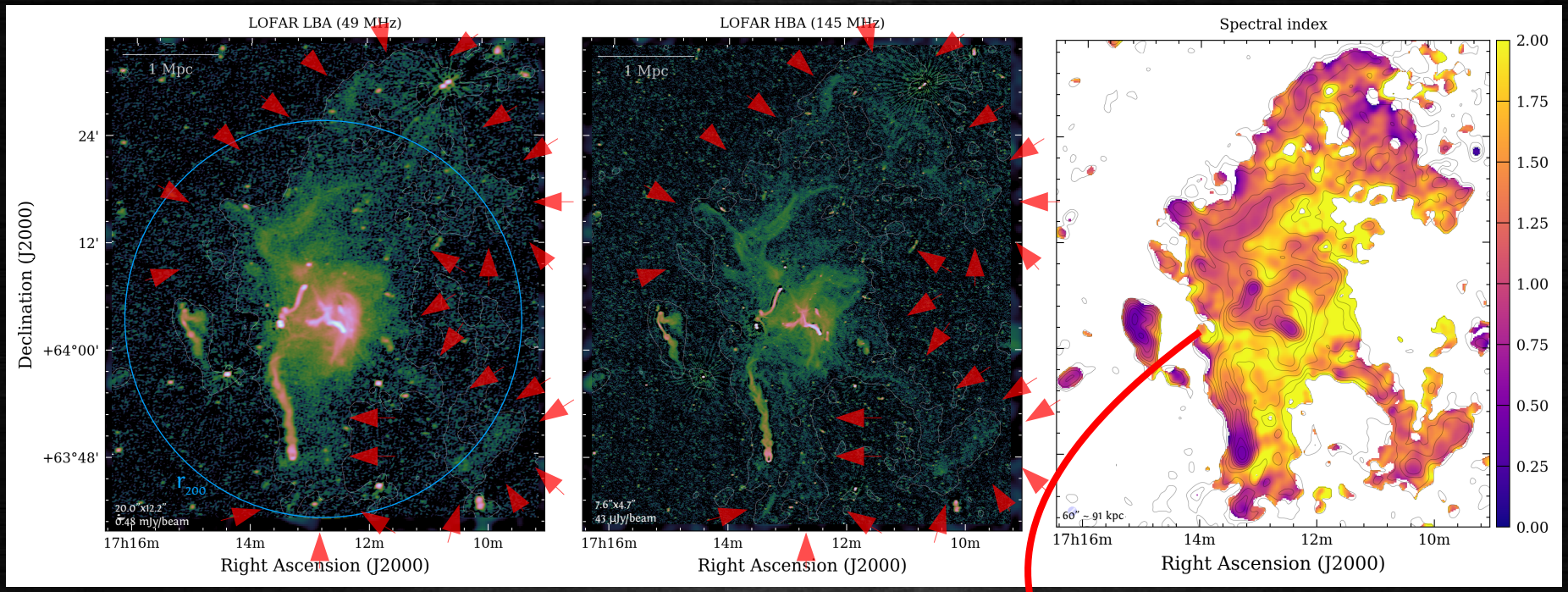

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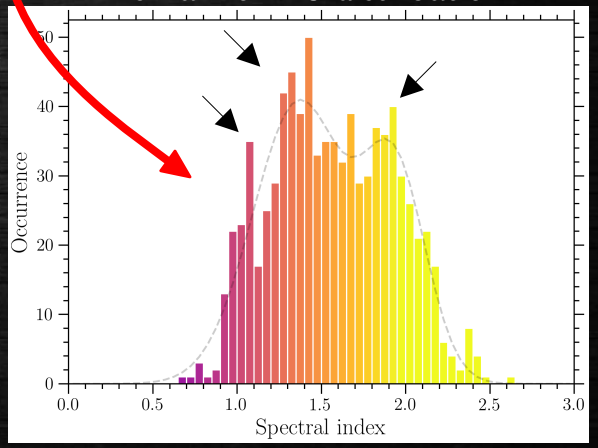

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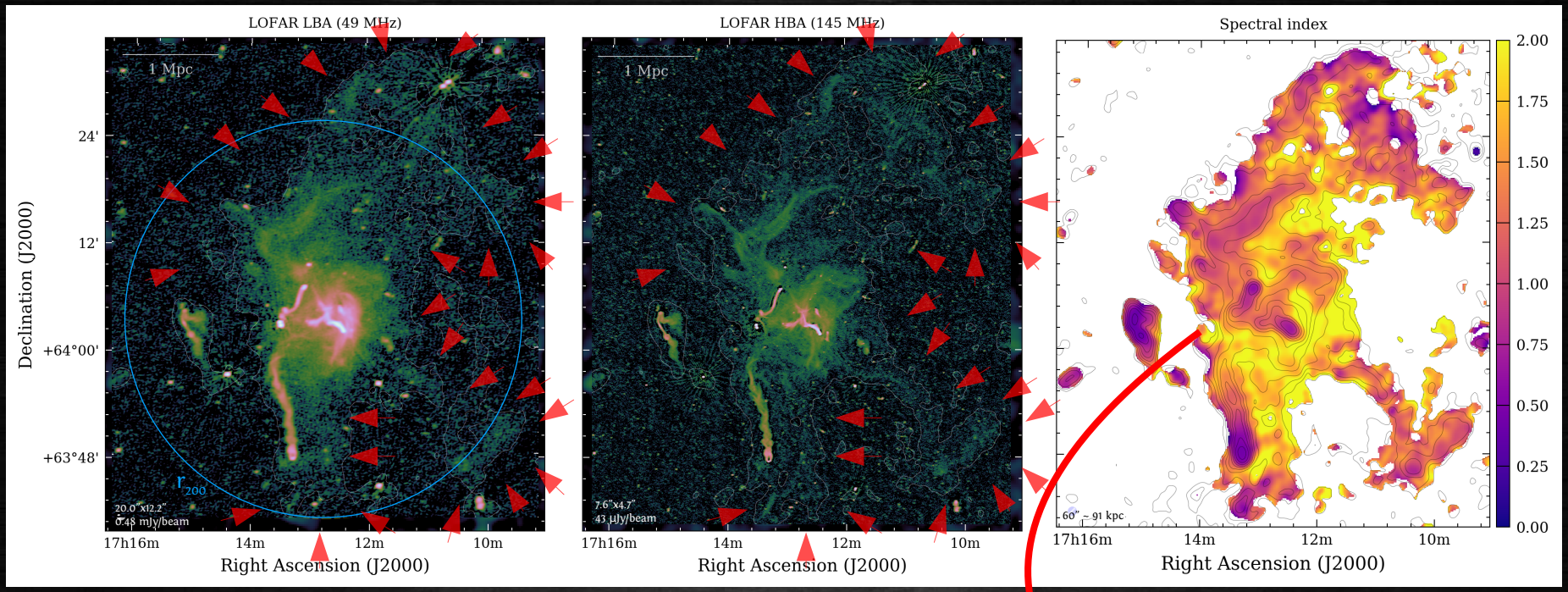

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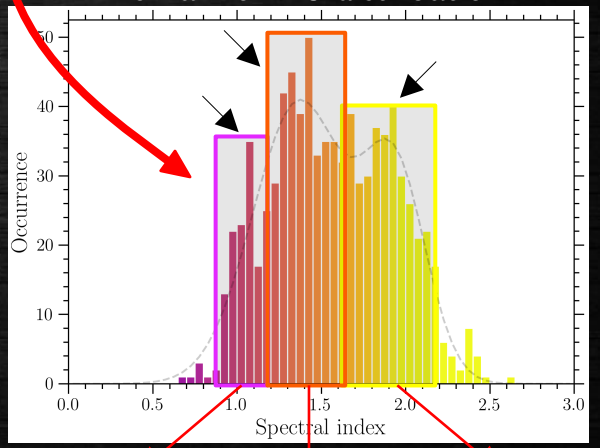


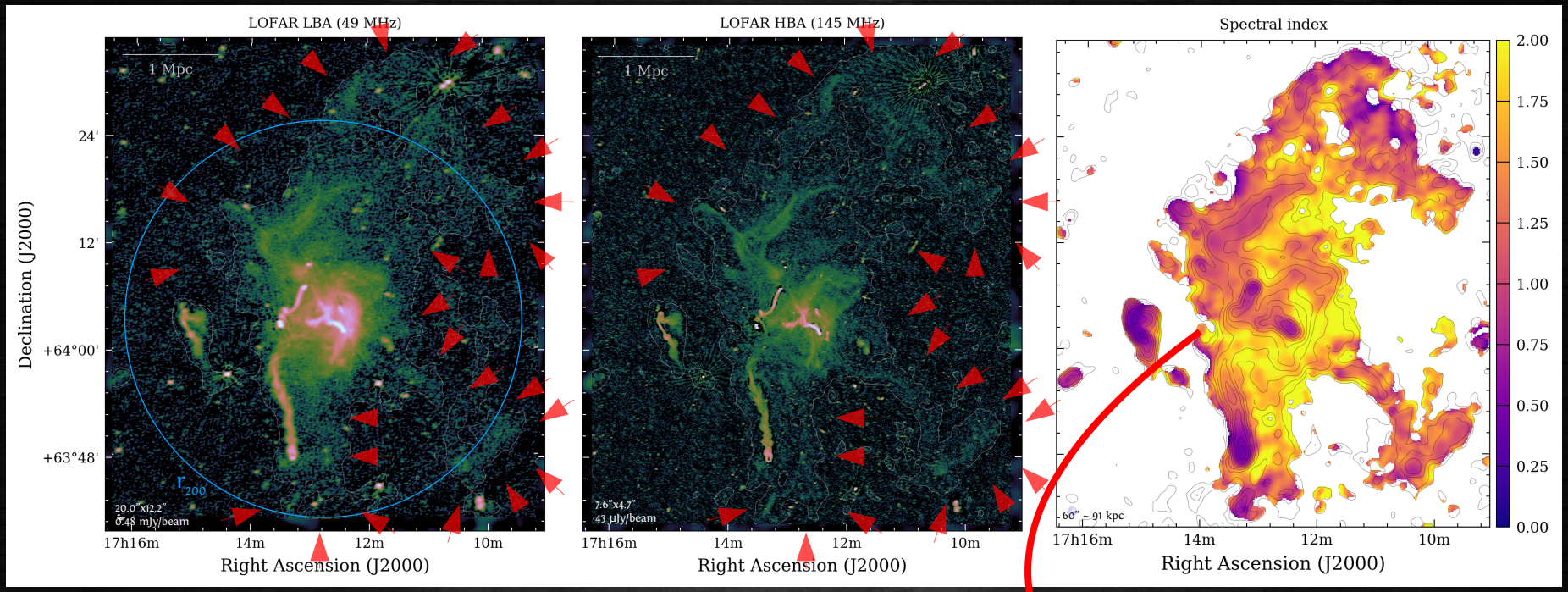
From *independent* pixels excluding *discrete* sources

Relic "fronts"

"Classic" halo + Relic "downstream"

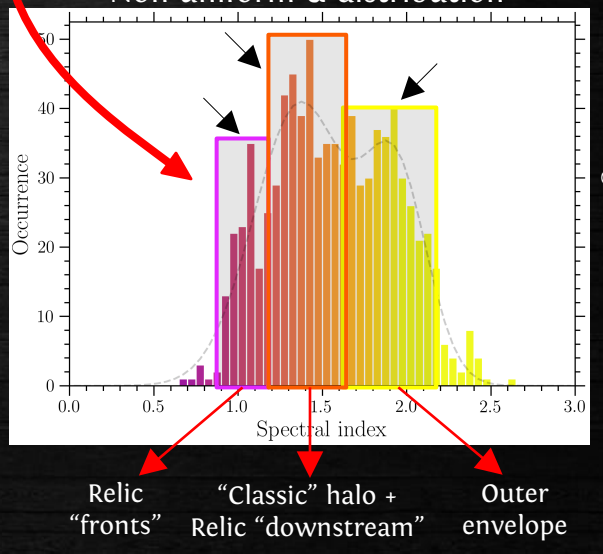
Outer envelope

A giant envelope of emission



Implications:

→ distribution of **B** and **CRe**
→ *amplification* of **B** in the outskirts
→ dissipation of *turbulence* in NT components
→ distribution of *shocks* and *turbulence* in the ICM



Magnetic field

At ~2 Mpc:

Magnetic field

At **~2 Mpc**:

- The magnetic field yielding to the **minimum energy** of the relativistic plasma is:

$$B_{min} = \left(C_\alpha \frac{L_{syn}(\nu)}{V} \nu^\alpha (1+k) \right)^{\frac{1}{3+\alpha}} \gamma_{min}^{\frac{1-2\alpha}{3+\alpha}}$$

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- Assuming *departure from equilibrium* $B = B_{min}\Delta$ the following condition must be satisfied:

$$\epsilon_{B+e} \lesssim \epsilon_{ICM} 0.05 \frac{\Delta^{-2} + \frac{2\Delta^{1+\alpha}}{1+\alpha}}{\frac{3+\alpha}{1+\alpha}}$$

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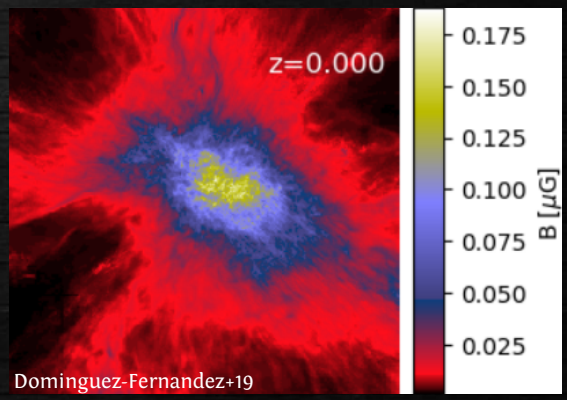
→ B ~ 0.1-1.7 μG

→ **250x** than UL on B_{cmb}

→ **10x** than strength expected from simple *compression* of B_{cmb}

Magnetic field in *cluster outskirts* must be **efficiently** amplified (role of *dynamo*)



Turbulence

Dissipation of *turbulent energy flux* into **non-thermal** components (B+e)

$$F \sim \frac{1}{2}\rho\frac{\sigma_v^3}{\Lambda}$$

ρ = density
σ = turb rms velocity
Λ = scale

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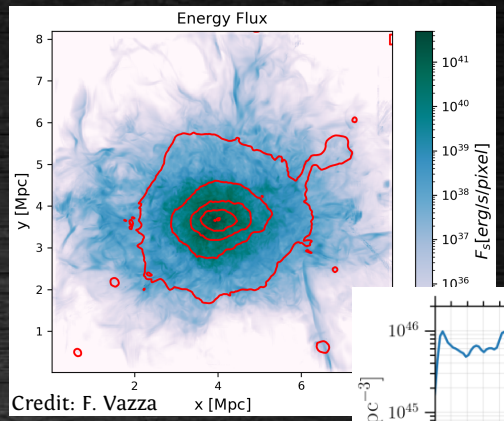
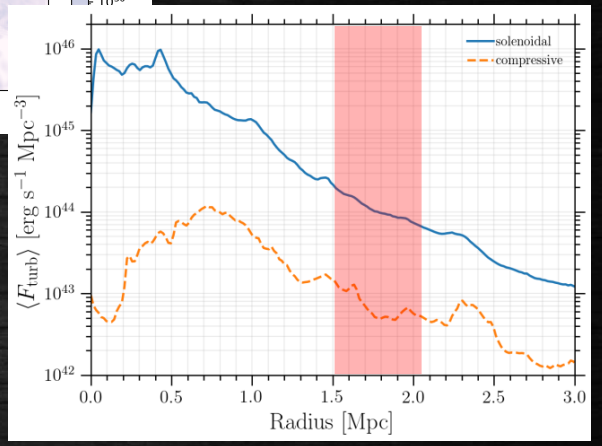


An A2255-like cluster in *simulations*



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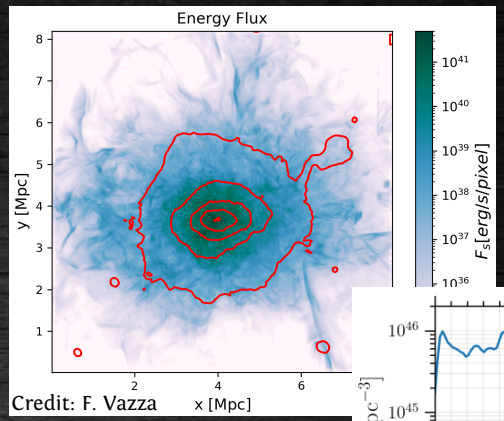
dynamo amplification

$$\frac{B^2}{8\pi} \sim \eta_B F \tau_{eddy}$$

radiation/ acceleration

$$L_{NT} \sim \eta_{acc} F V$$

$$L_{NT} = L_{syn,bol}\left(1 + \frac{B_{cmb}^2}{B^2}\right)$$



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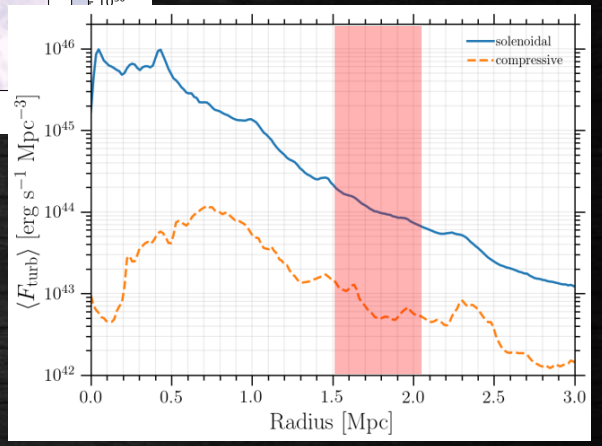

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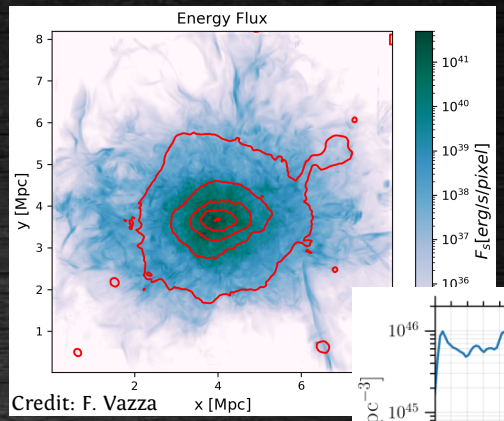

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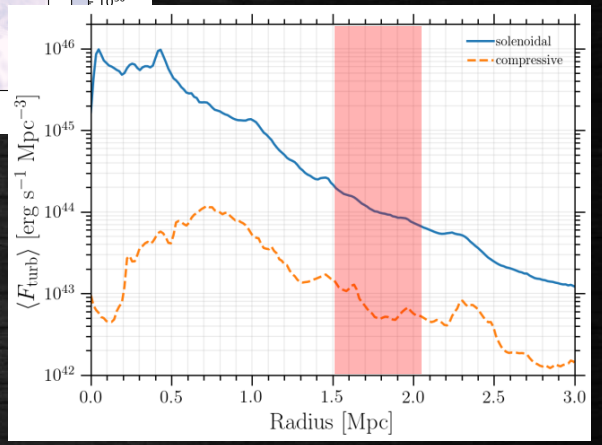

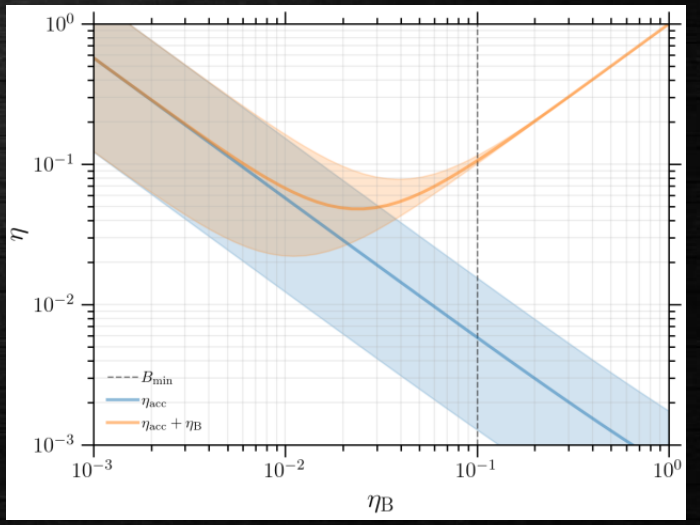

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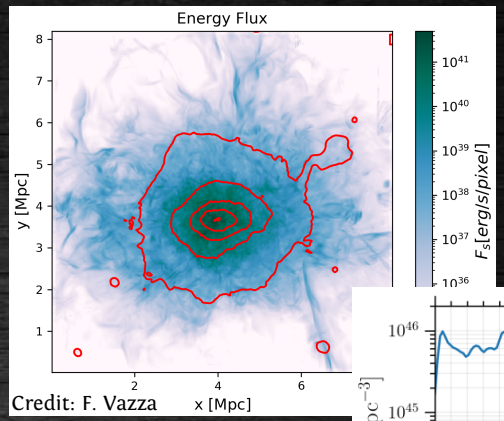

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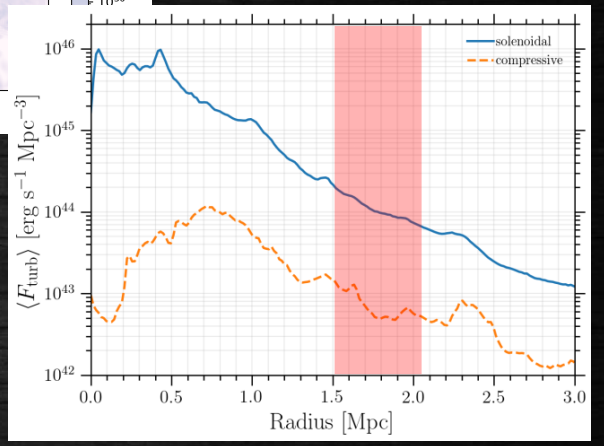
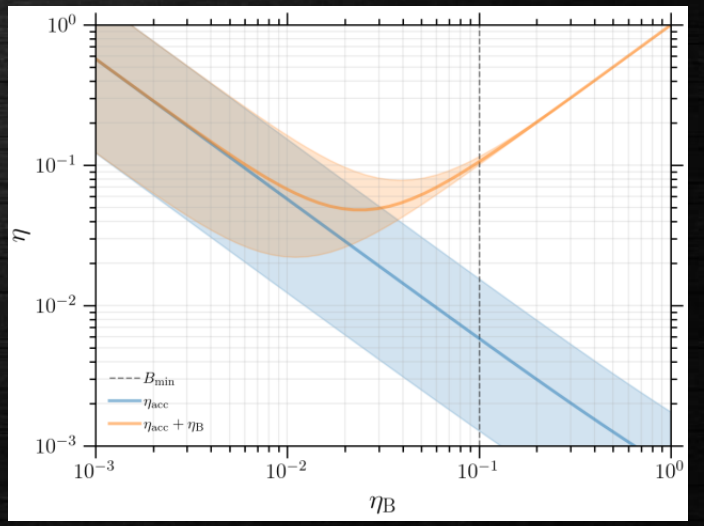
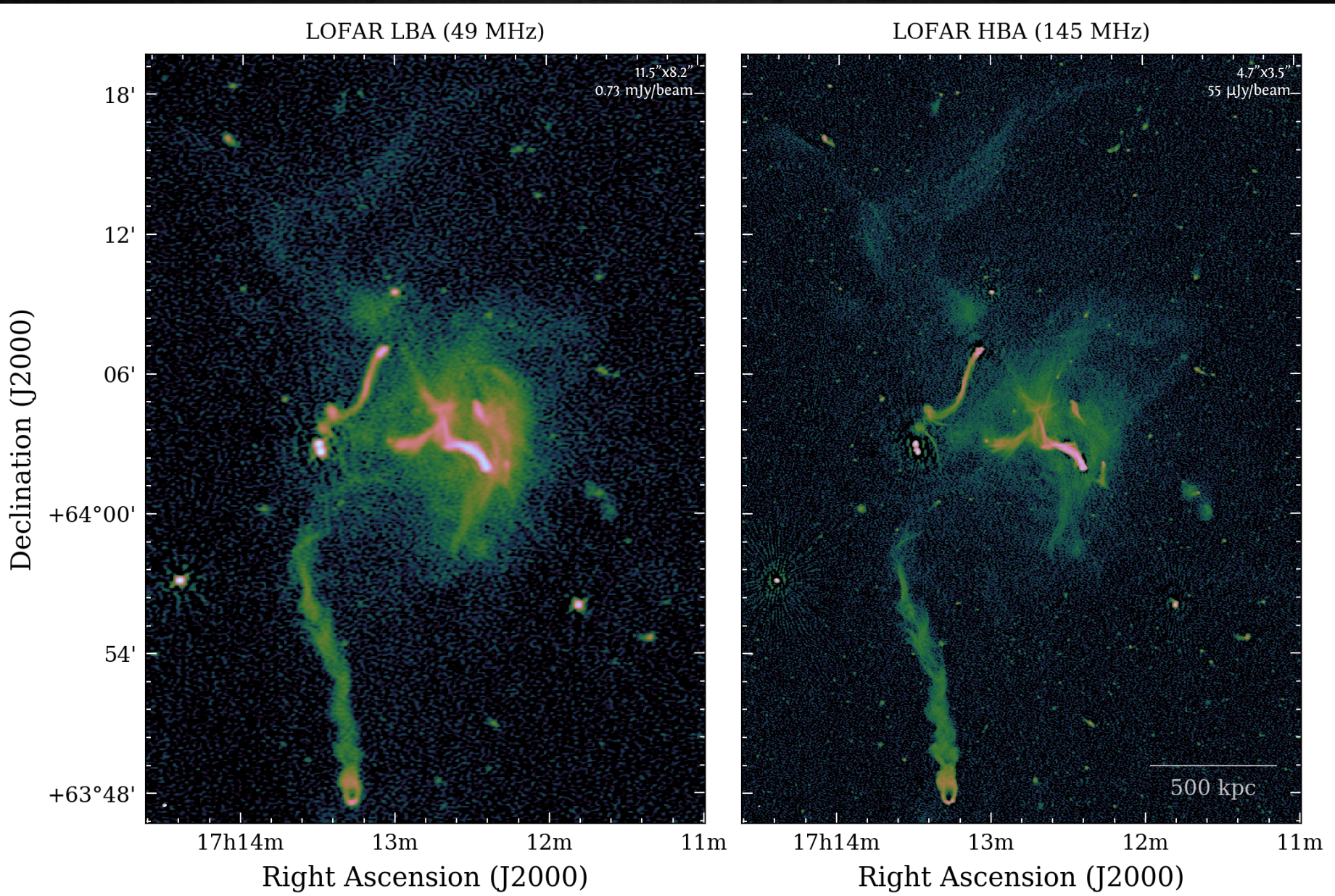




To reproduce the *envelope* of radio emission in A2255 it is required that **5-10%** of F_{turb} is channeled into *NT components*

A2255 at high resolution



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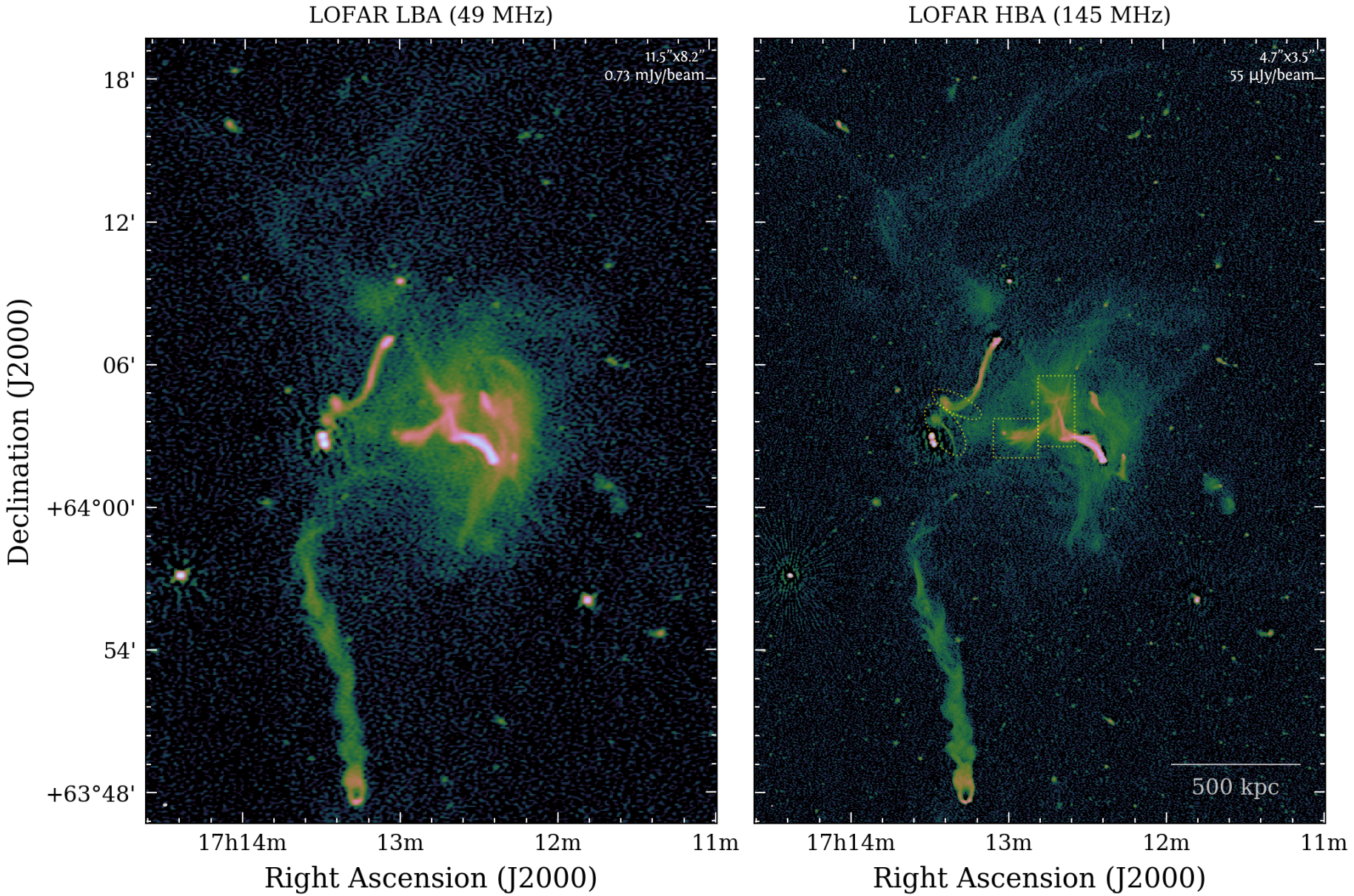

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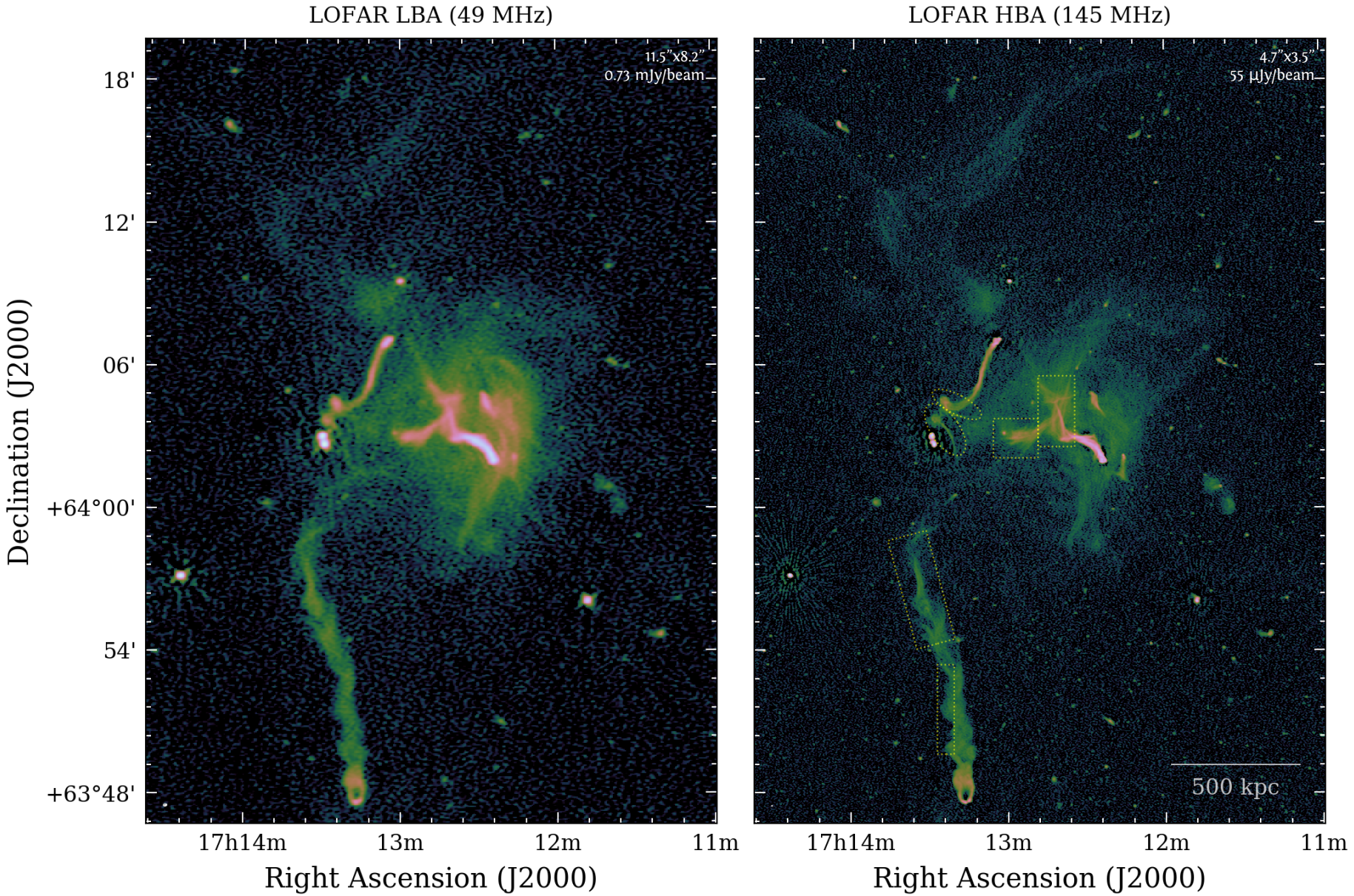

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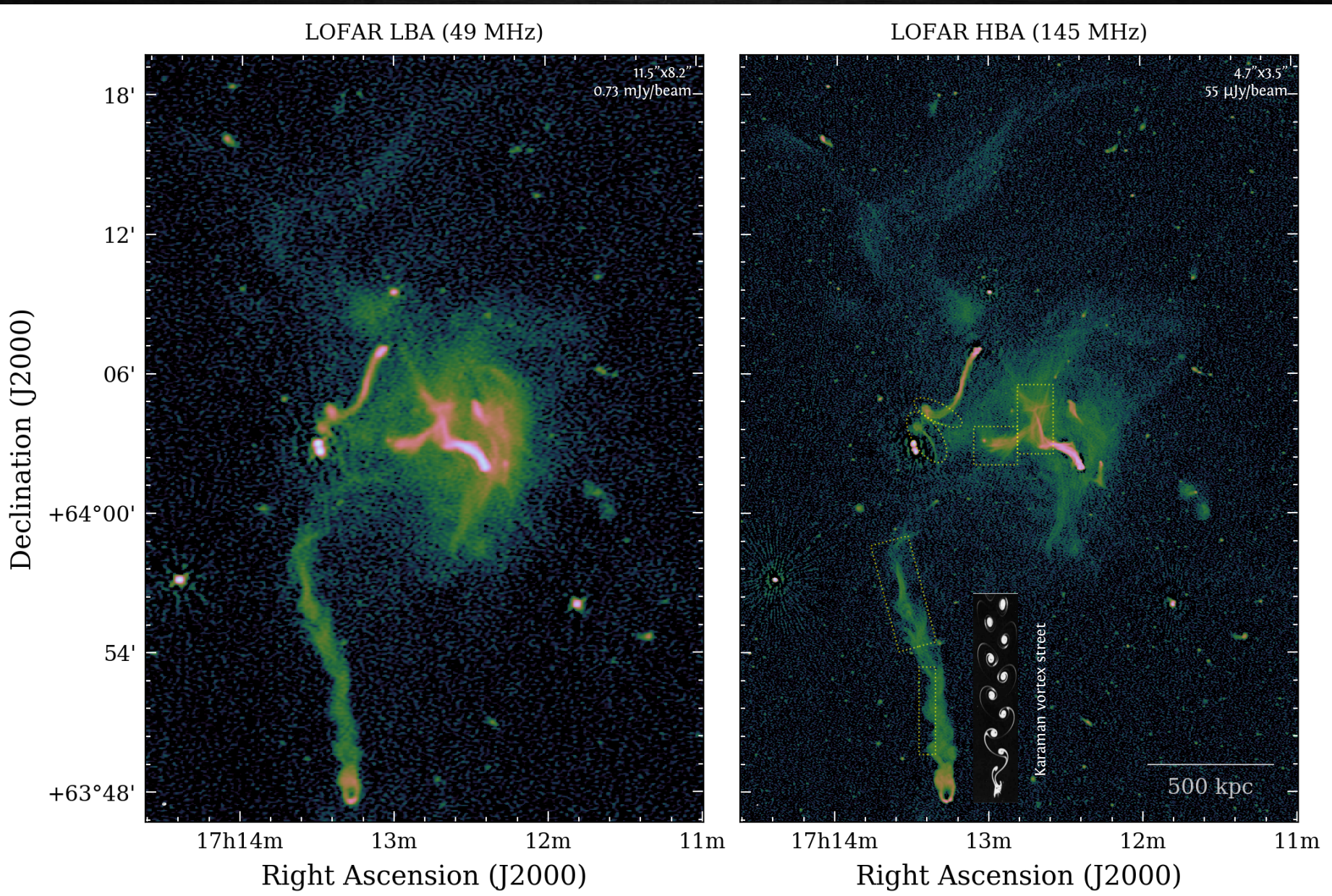

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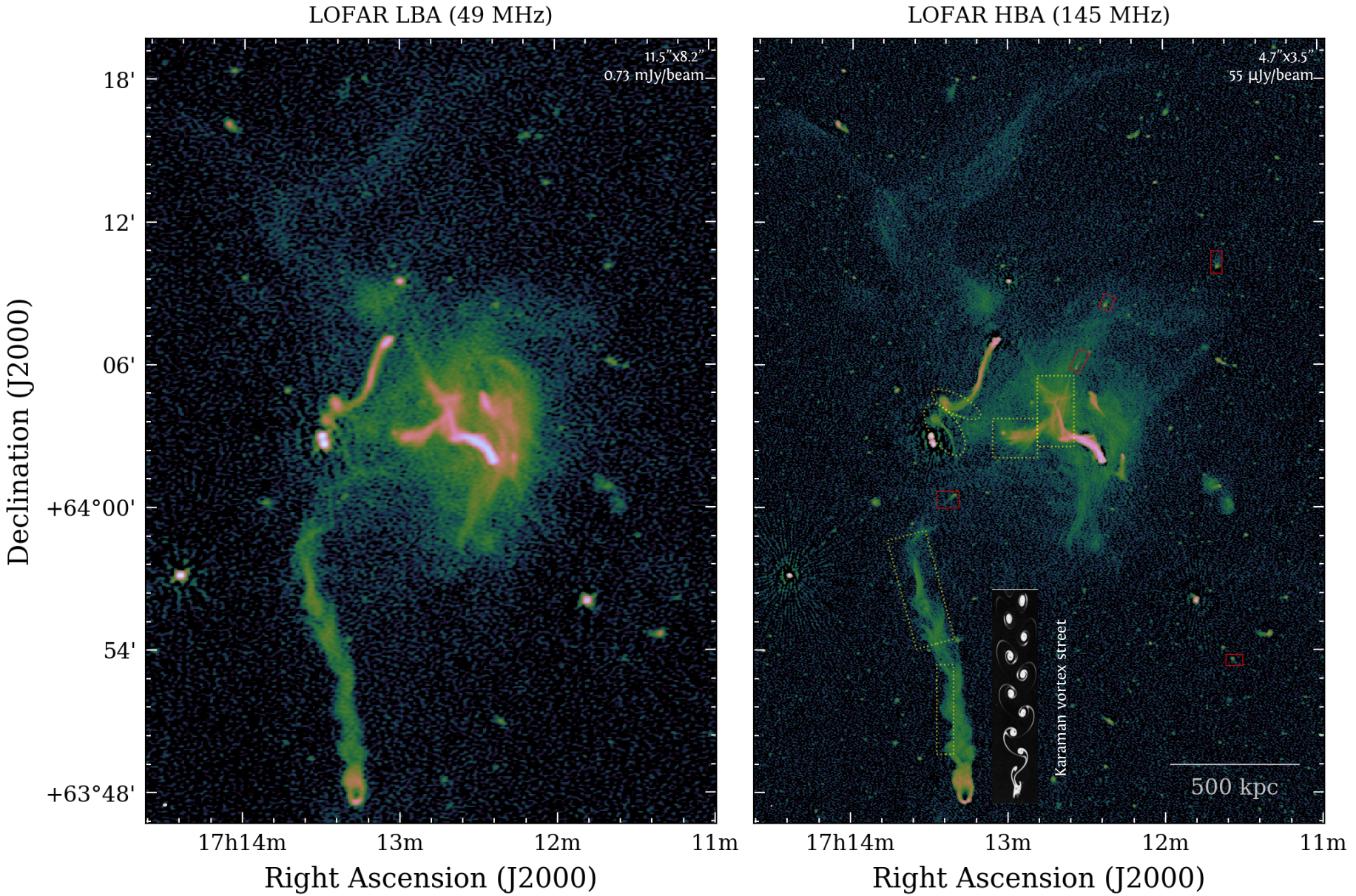

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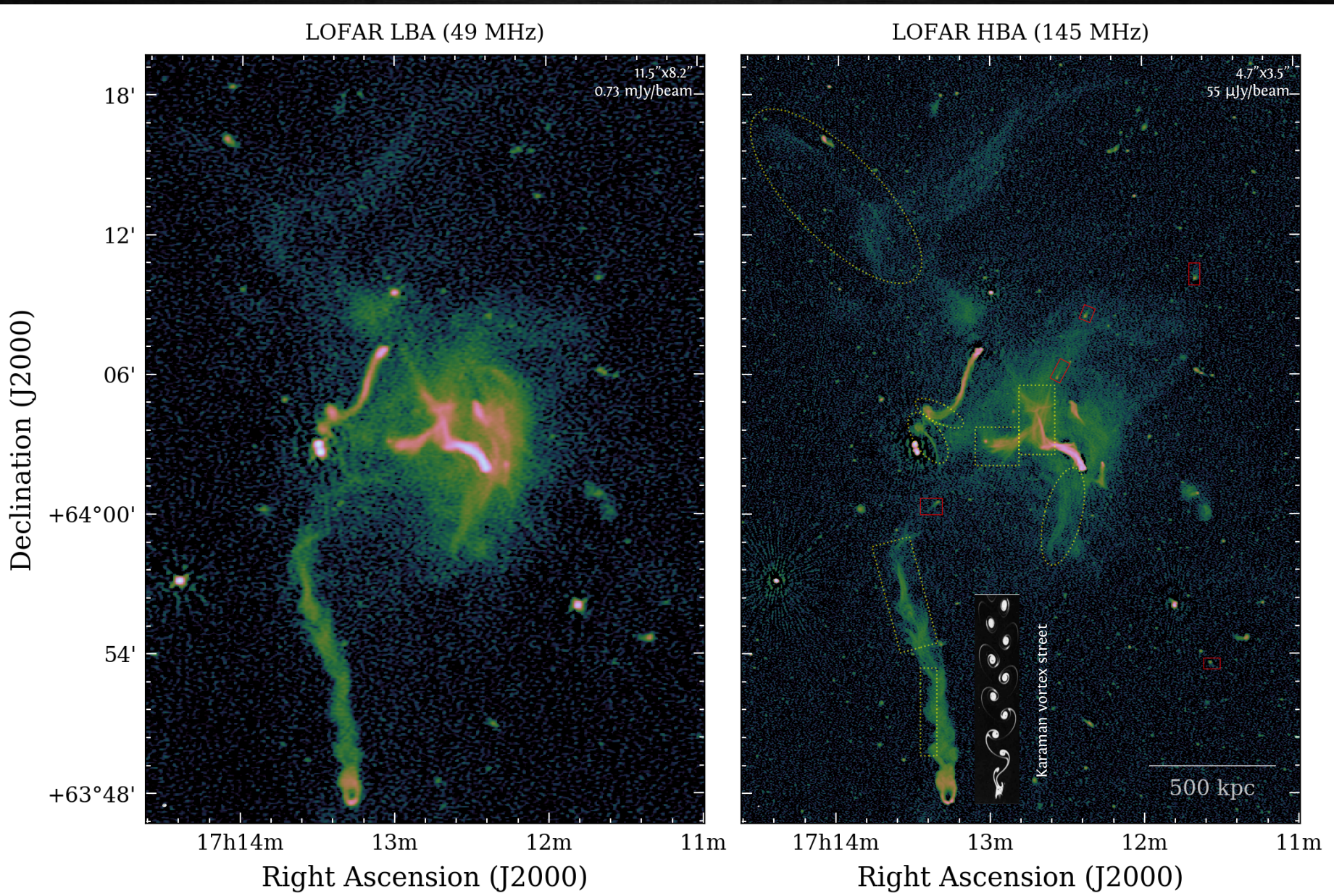

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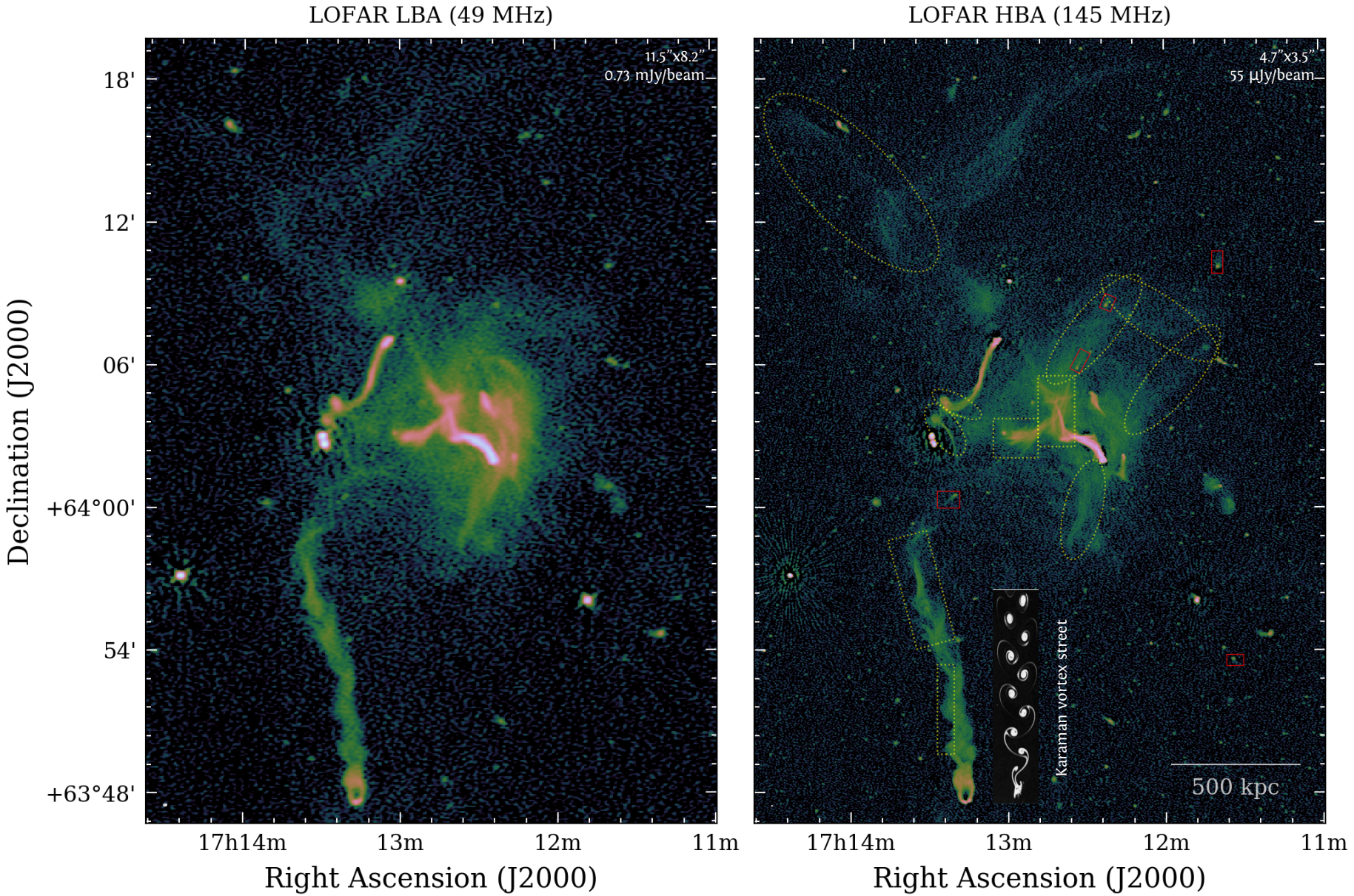

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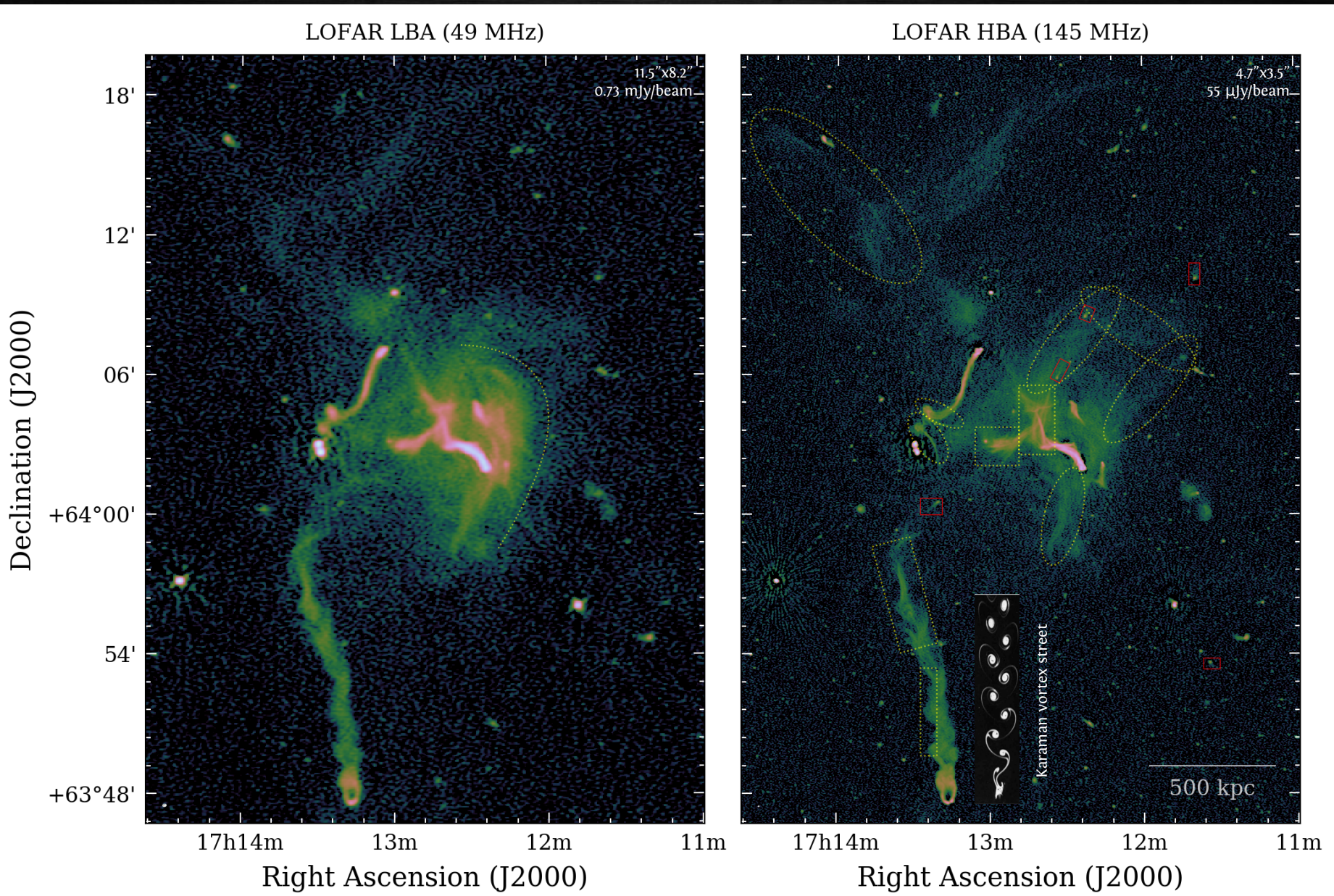
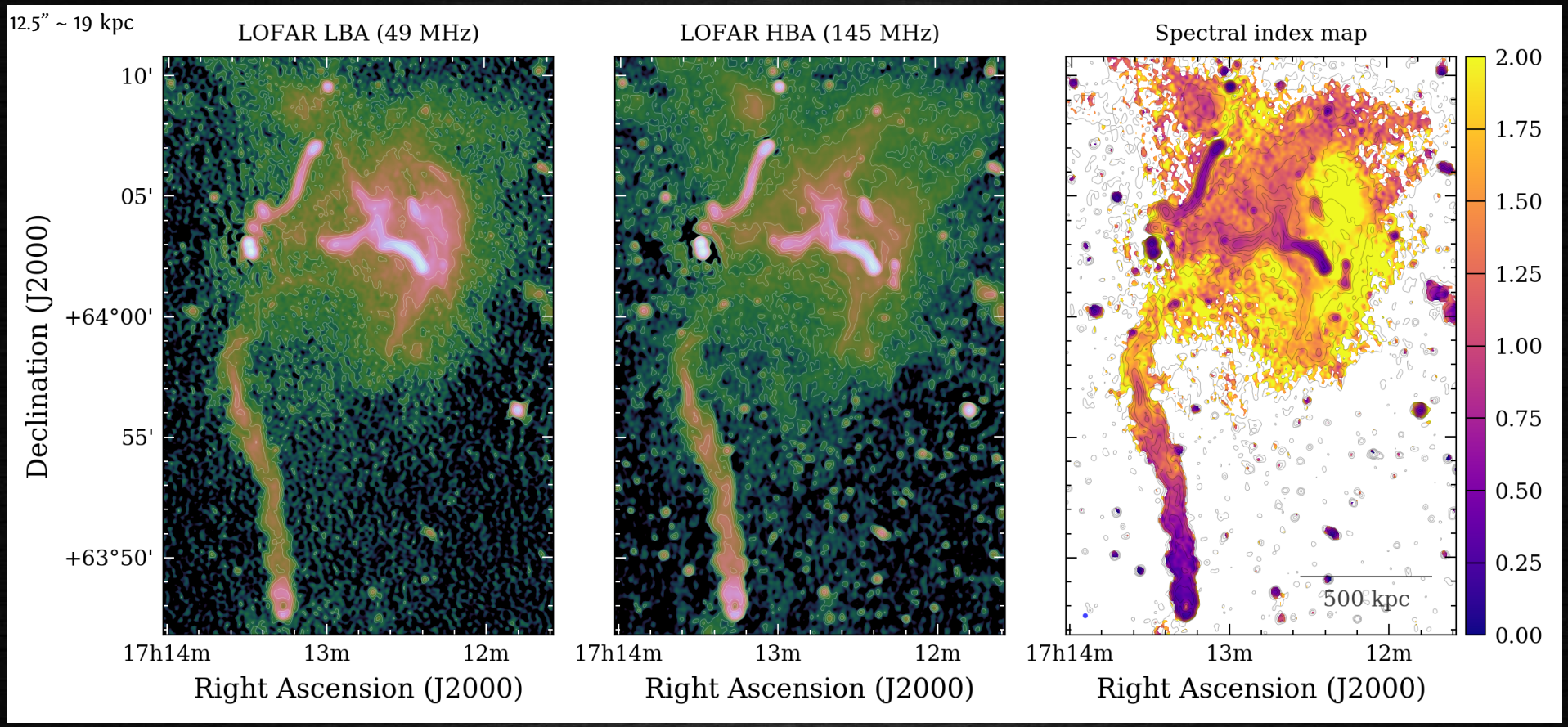
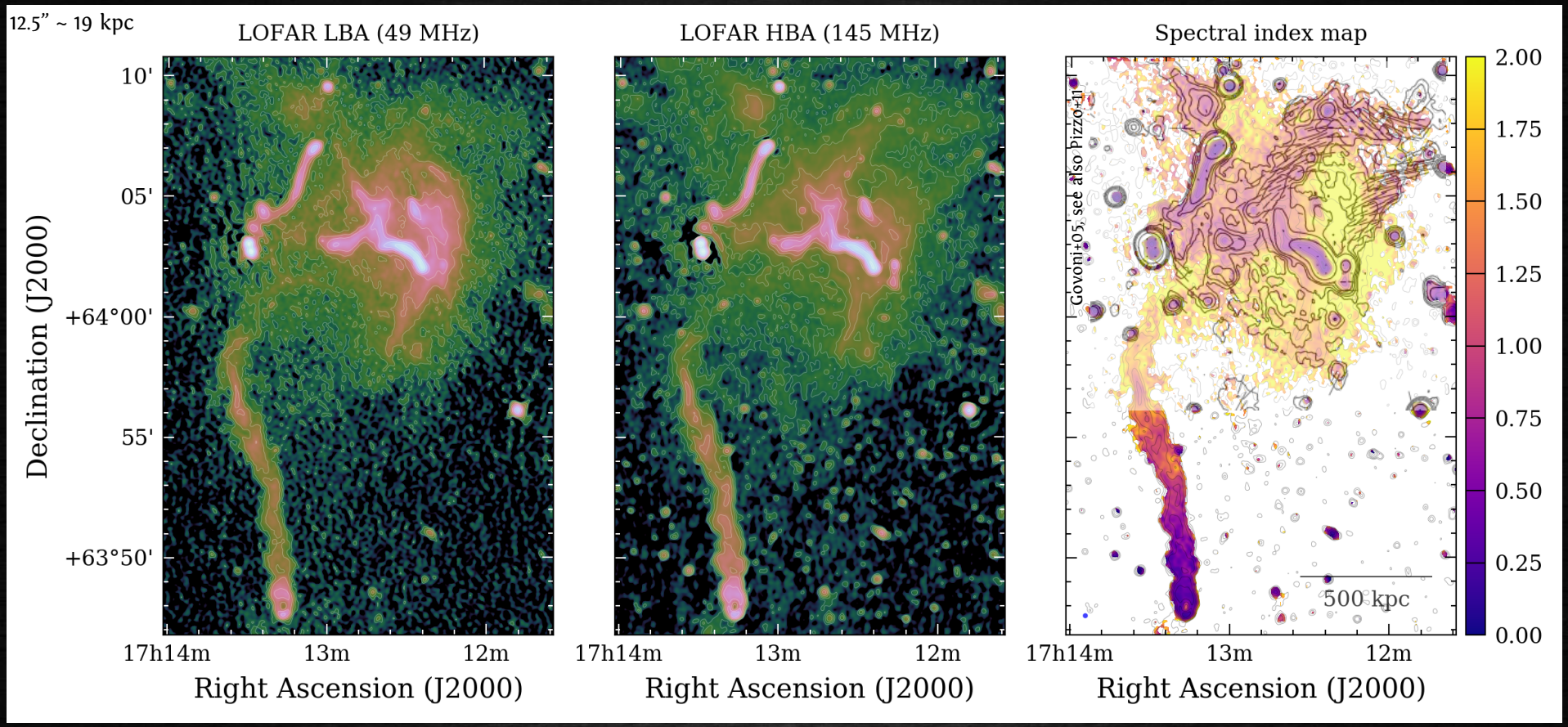


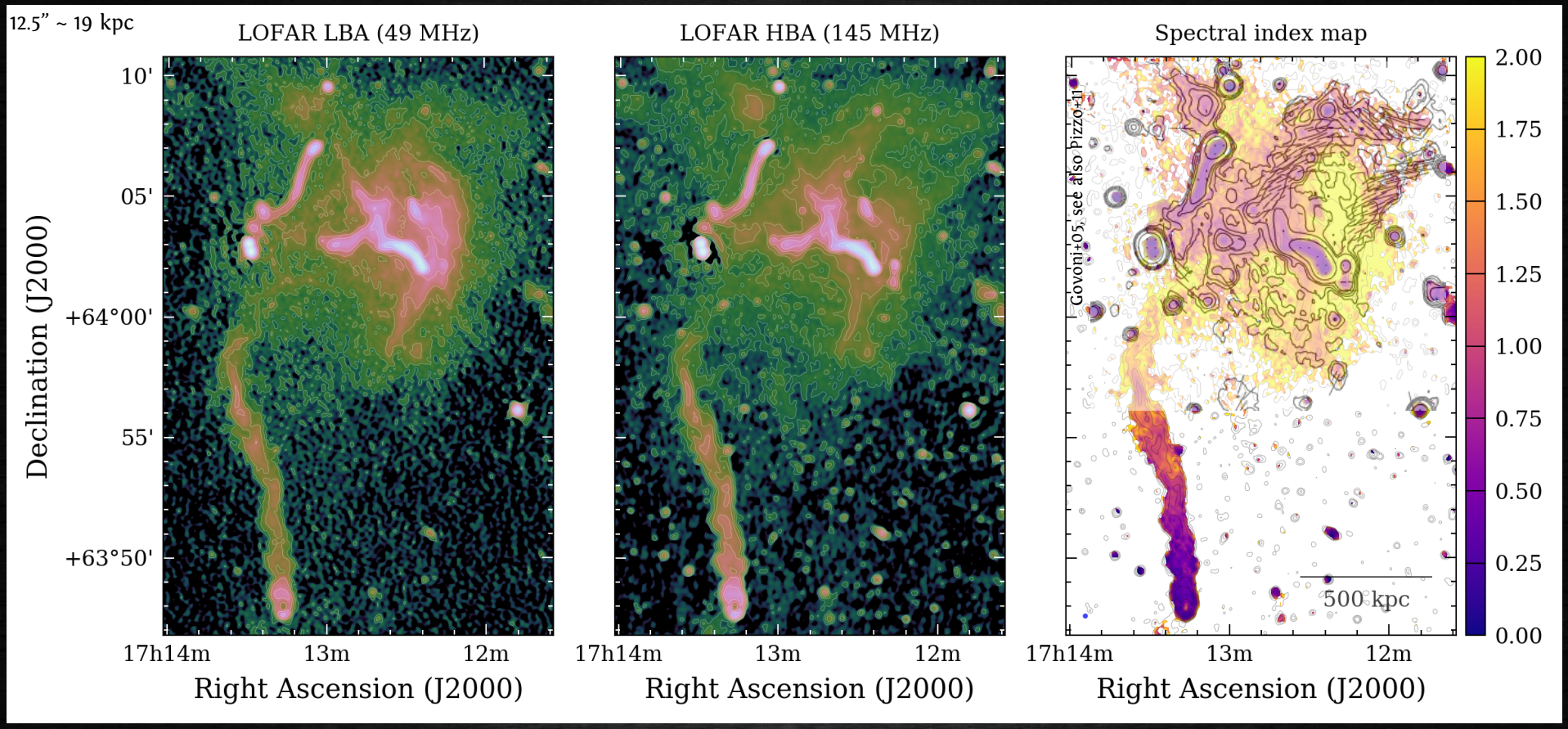
Overlapping structures



Overlapping structures



Overlapping structures



The structures with *filamentary* morphology have *flatter* spectra and are polarized at **1.4 GHz**

Consistent with the fact that we are observing **relic-like** emission *projected* onto the cluster center

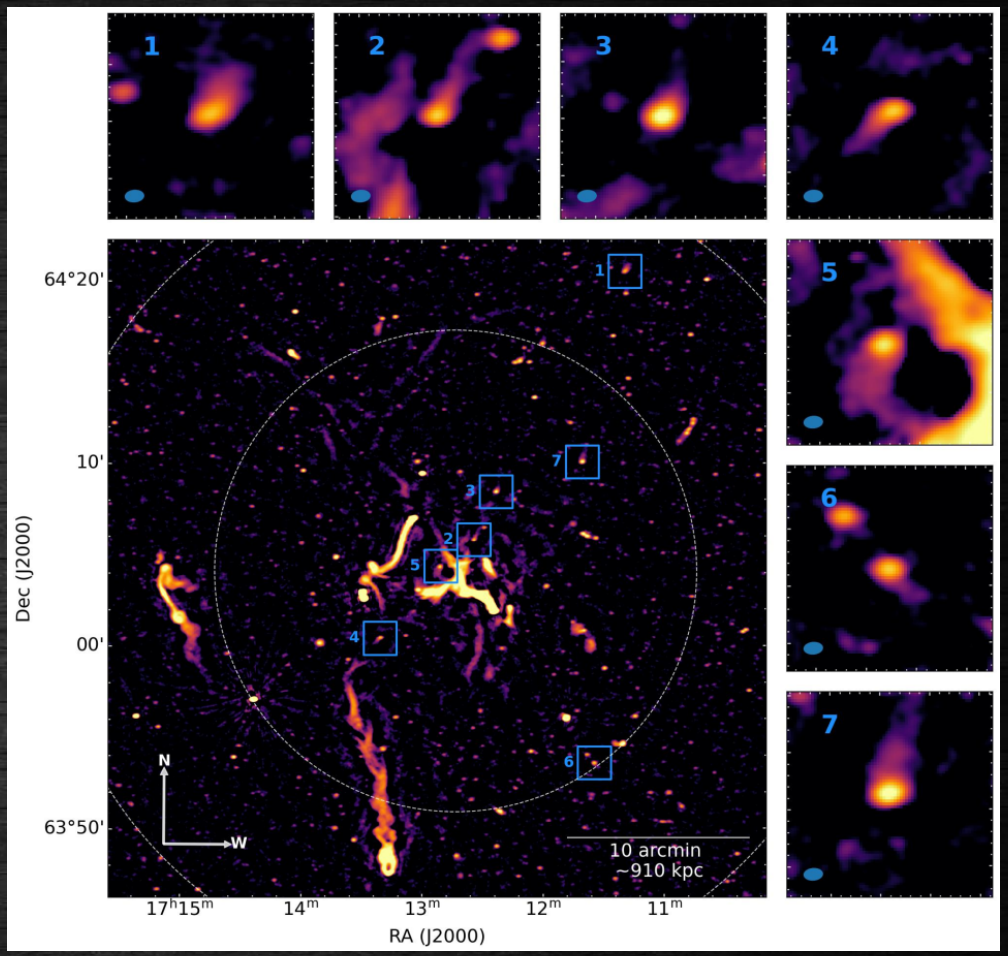
Follow-up studies

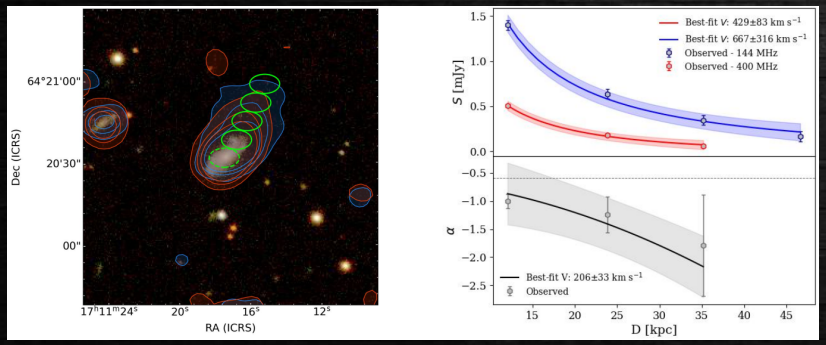
Ram pressure stripping

Ignesti+23

7 radio selected *RPS galaxies*
(6 within r_{500} + 1 close to r_{200})

Deep LOFAR HBA+uGMRT band 3 data
→ flux density and spectral index *profiles along the tails*



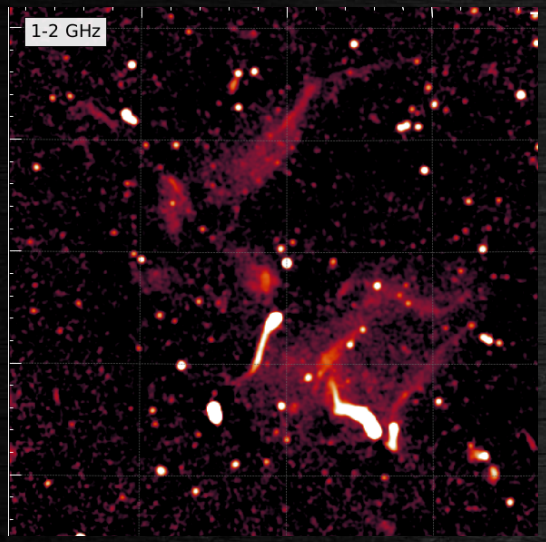


Constraints on the projected *radio plasma velocity* along the tails (100-500 km/s)

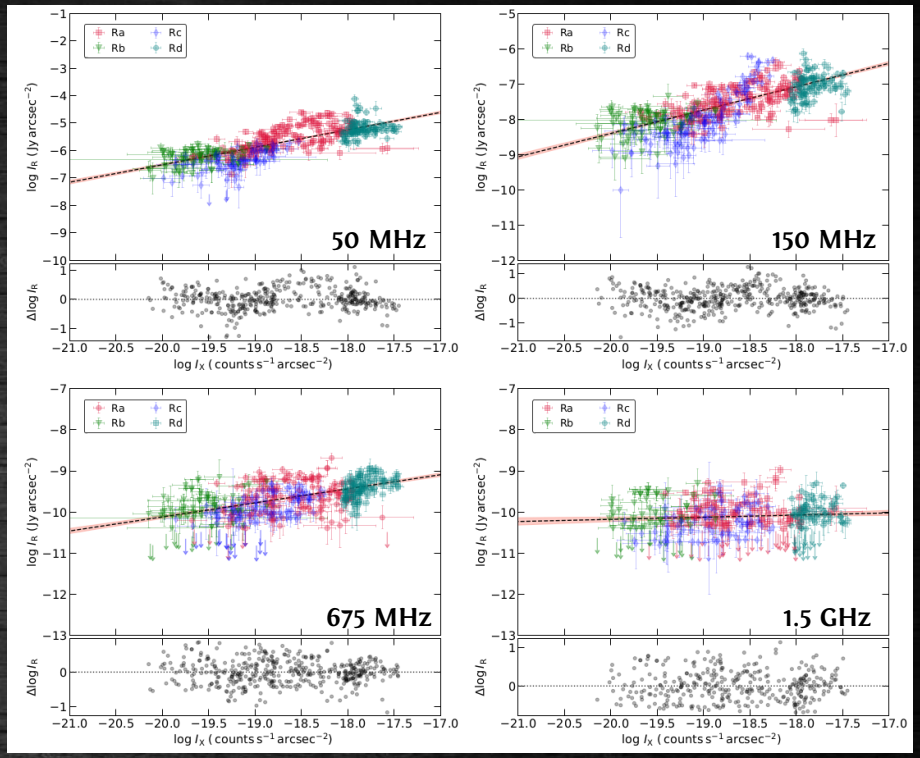
Broad band spectral index analysis

Rajpurohit+ in prep.

- **LOFAR** 50 MHz + 150 MHz
- **uGMRT** 400 Mz + 675 MHz
- **JVLA** 1-2 GHz



+ connection with X-ray emitting *thermal gas*



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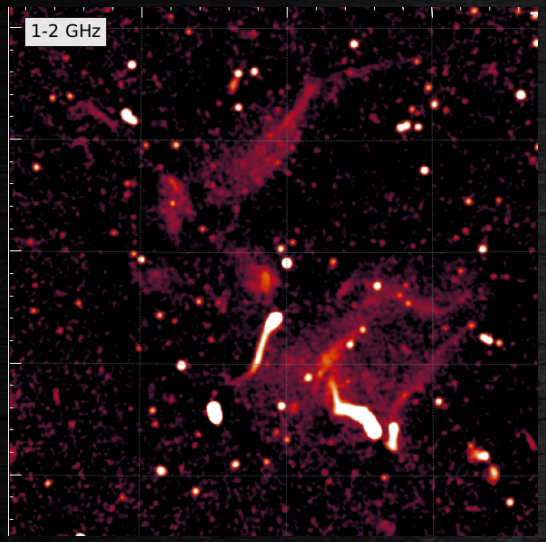

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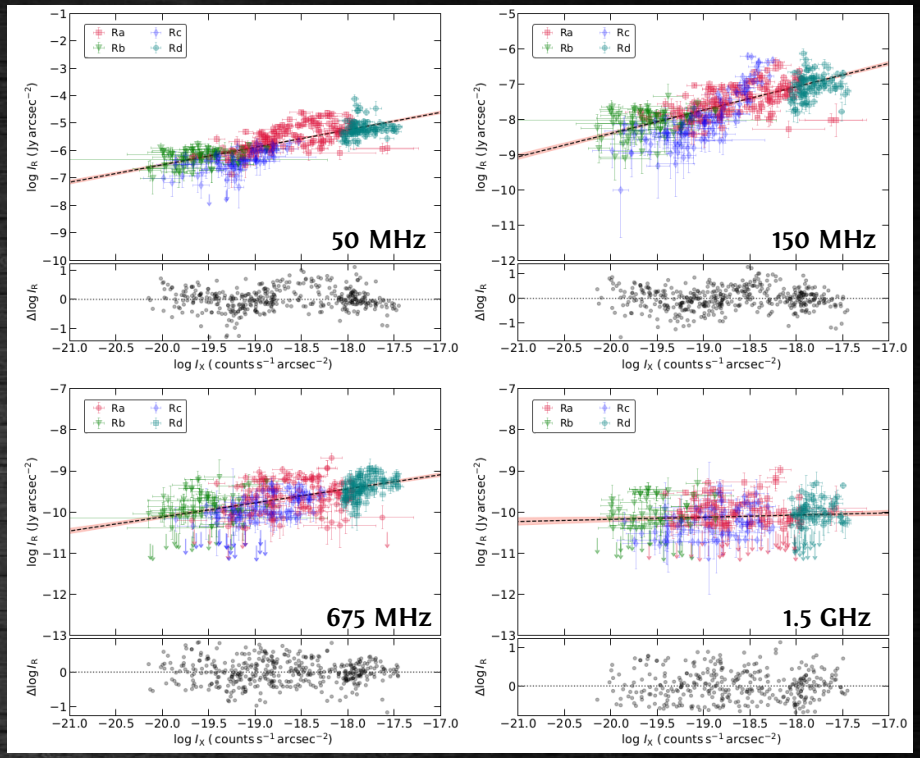
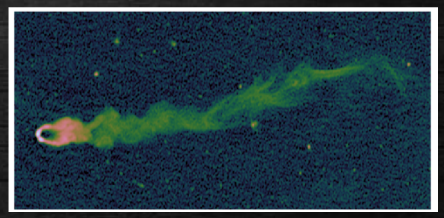
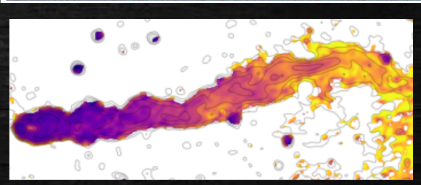
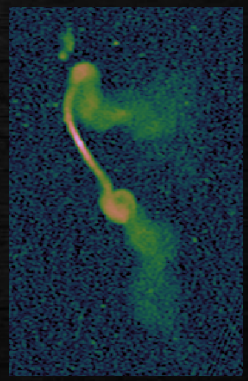


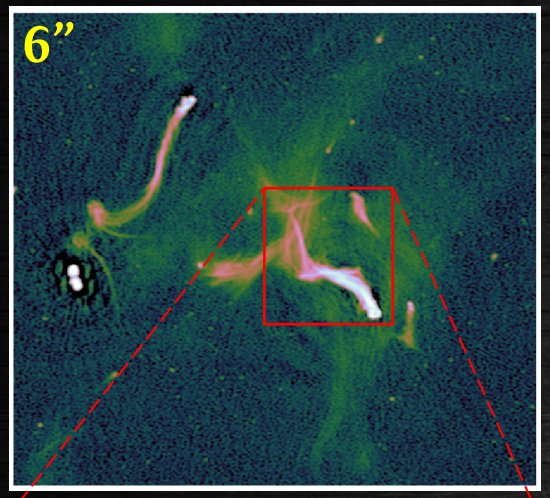
Spectral index study of the *extended radio galaxies* in the cluster
→ **re-acceleration** processes in the tails?







Long baseline imaging



De Rubeis+ in prep.

Bright and *extended* AGN can be imaged with LOFAR *long baselines*

What is the origin of the **filaments** in the radio emission and what do they tell us about *AGN/ICM physics*?

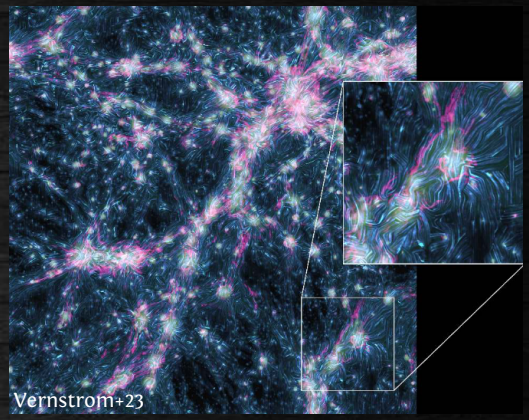
Other possible projects:

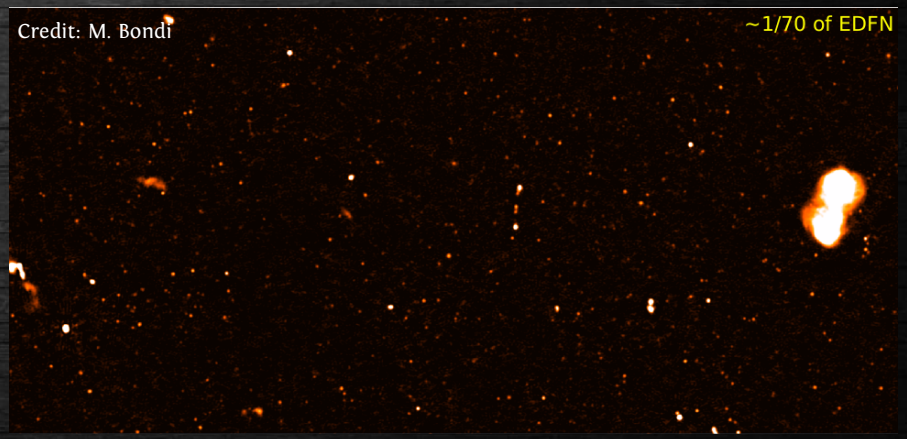
- Imaging LBA data **<30 MHz** (see Groeneveld talk)
- **RM synthesis**
- ...

Ultra-deep field & LOFAR2.0

LOFAR **336h** HBA observations completed in *May 2023*

- Does the envelope show *boundaries*?
- Can we detect the synchrotron *cosmic web*?
- *Wide field* imaging with *long baselines*





LOFAR2.0:

- EoI submitted
- Synergy with **LUDO** (see P. Best talk)
- Observations with **LLoCuSS** (130 μJy/beam @ 40 MHz)

Conclusions

- **Abell 2255** is the **LOFAR Cluster Deep Field**
- **Giant envelope** of emission embedding the known emission
- A number of *filamentary* structures are detected
- Implications on *acceleration mechanisms* on very large scales

- The large dataset triggered *different* follow-ups

- The processing of the **336h** LOFAR1.0 (HBA) is *ongoing*
- Looking forward to **LOFAR2.0**

Conclusions

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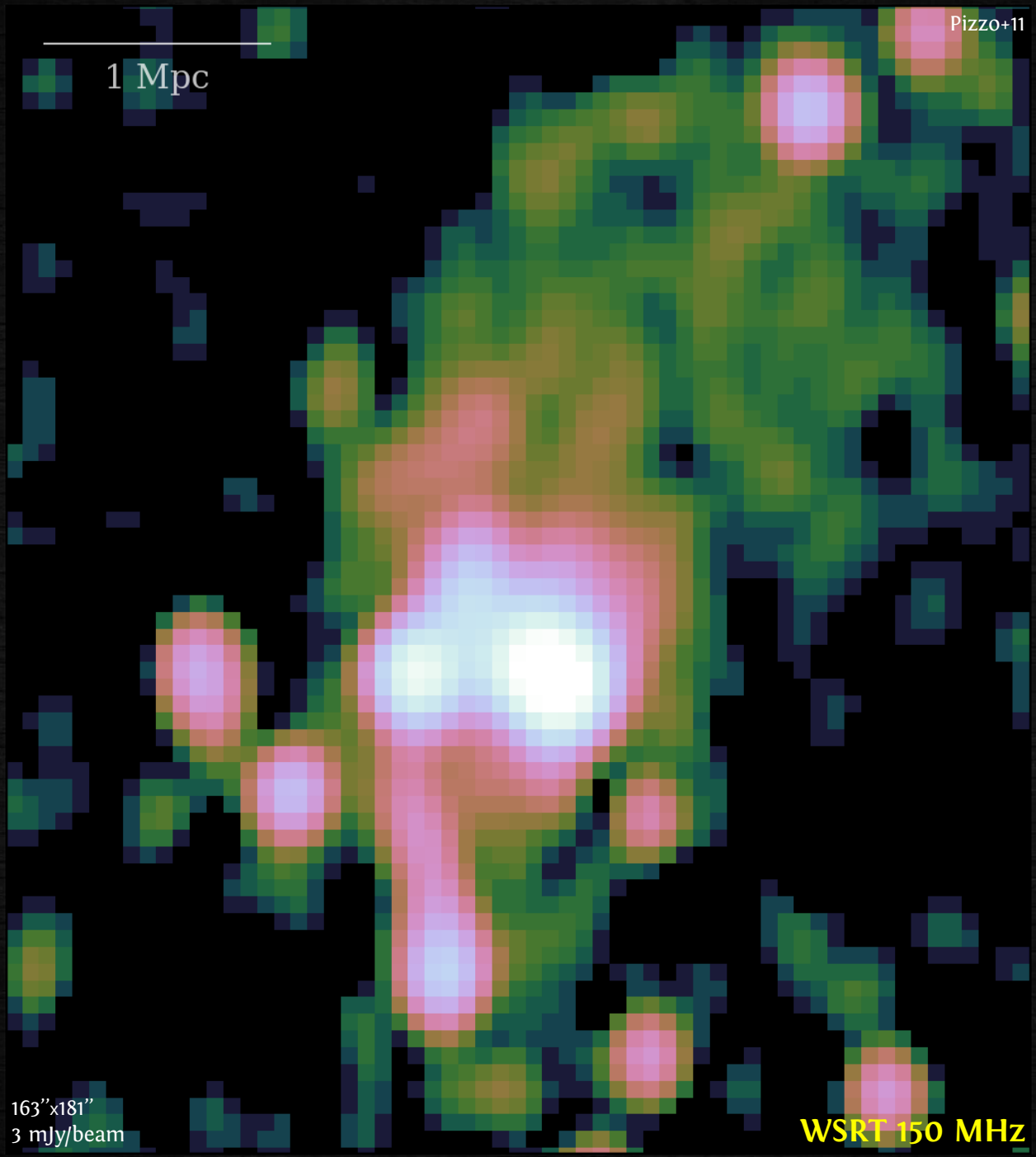
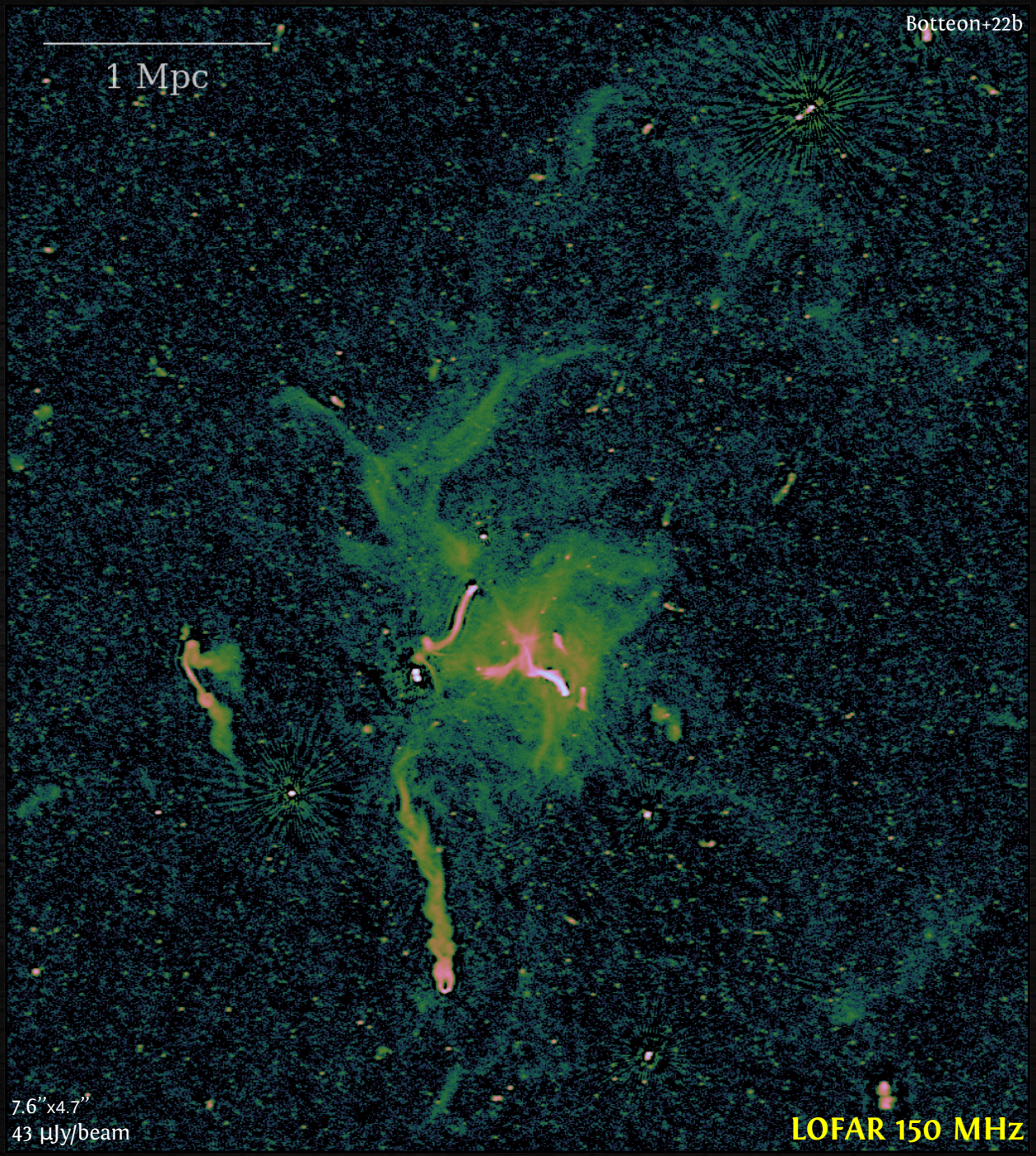
Thank you

Extra slides


1 Mpc
Pizzo+11
163''x181''
3 mJy/beam
WSRT 150 MHz


Botteon+22b
1 Mpc
7.6”x4.7”
43 μJy/beam
LOFAR 150 MHz