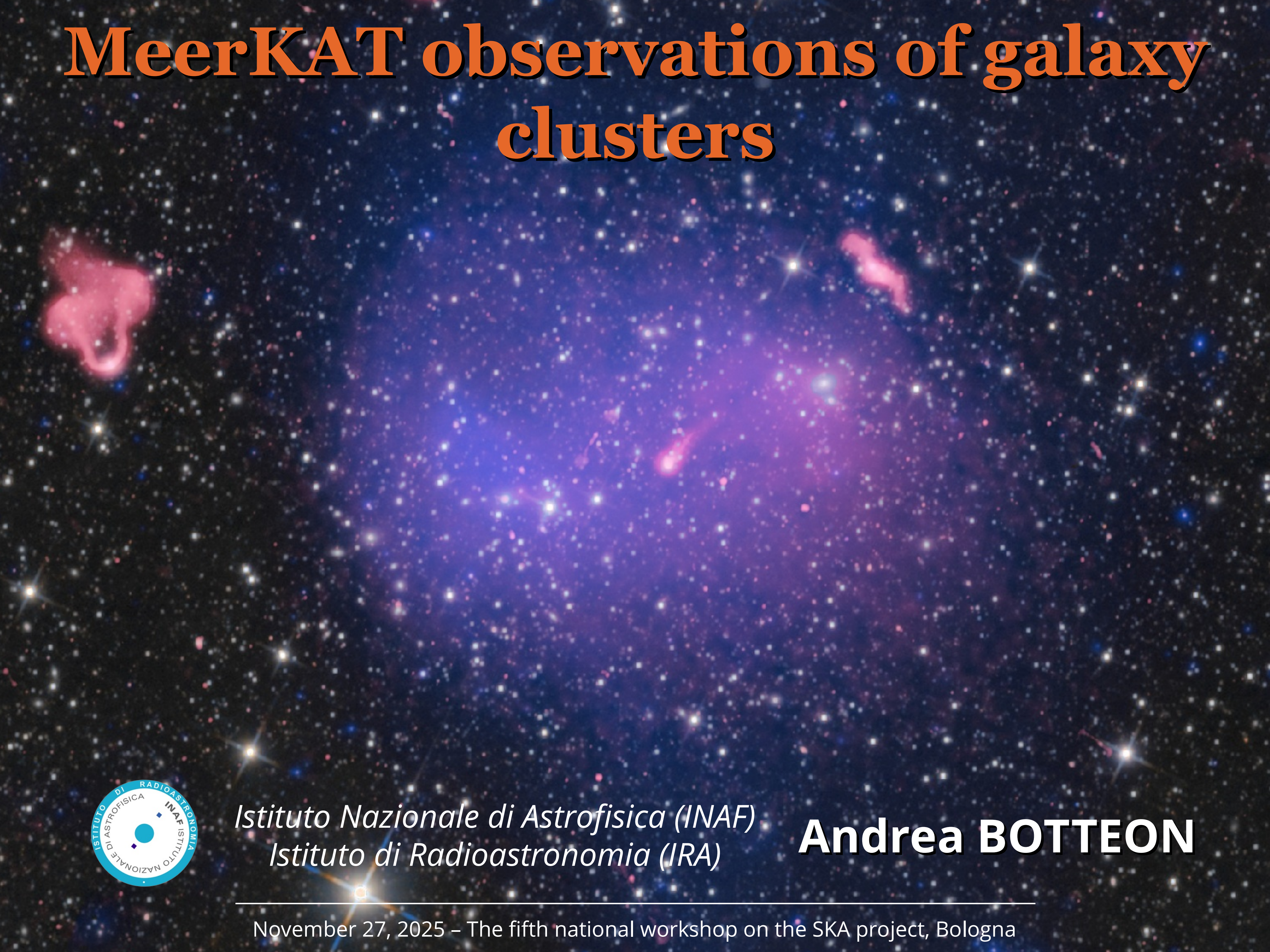
MeerKAT observations of galaxy clusters



Istituto Nazionale di Astrofisica (INAF)
Istituto di Radioastronomia (IRA)

Andrea BOTTEON

November 27, 2025 – The fifth national workshop on the SKA project, Bologna

A&A, 690, A222 (2024)

The prototypical major cluster merger Abell 754

I. Calibration of MeerKAT data and radio/X-ray spectral mapping of the cluster

A. Botteon[1,⋆], R. J. van Weeren[2], D. Eckert[3], F. Gastaldello[4], M. Markevitch[5], S. Giacintucci[6], G. Brunetti[1], R. Kale[7], and T. Venturi[1]

A&A, 698, A55 (2025)

MeerKAT *L*-band observations of the Ophiuchus galaxy cluster

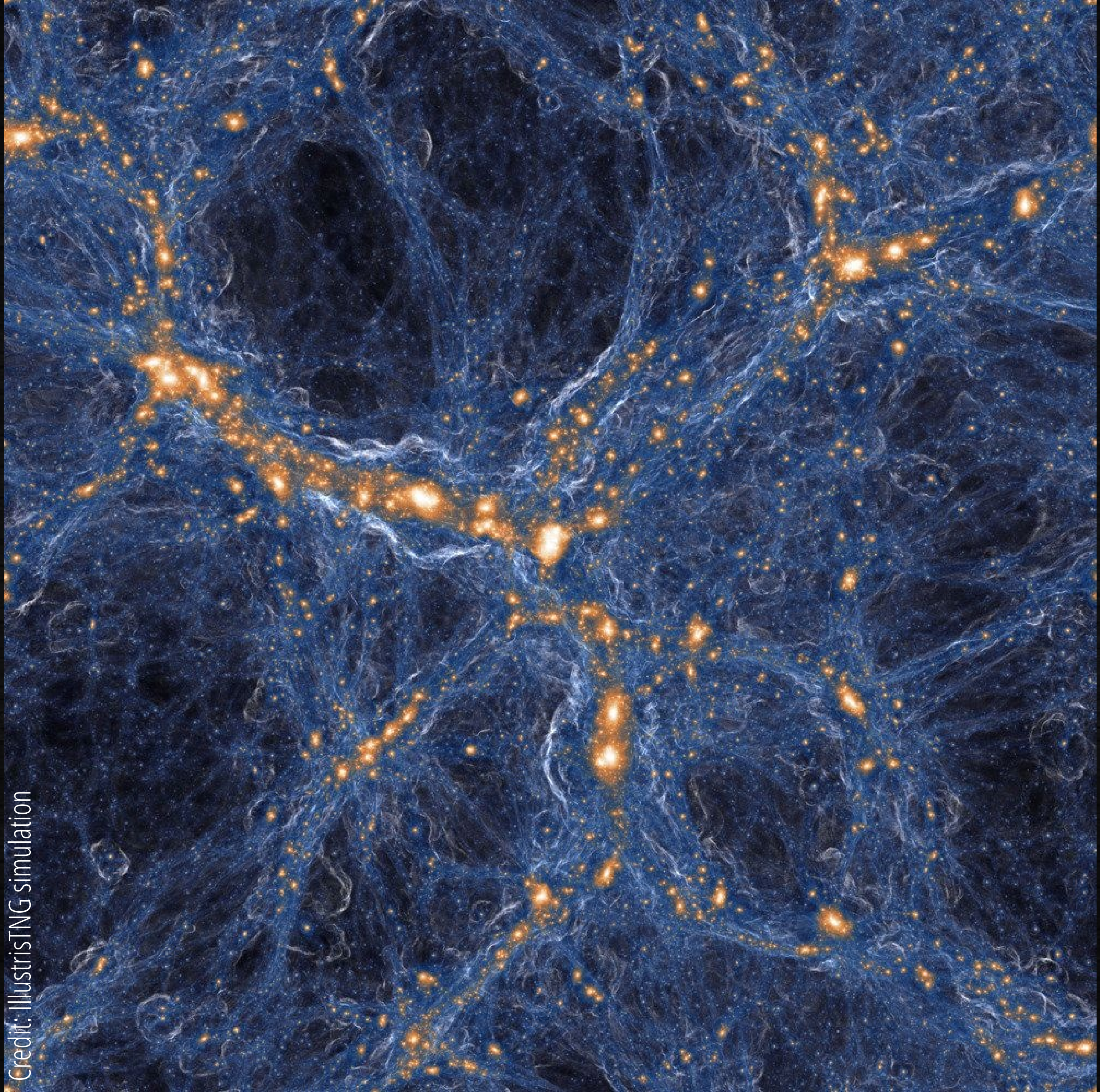
Detection of synchrotron threads and jellyfish galaxies

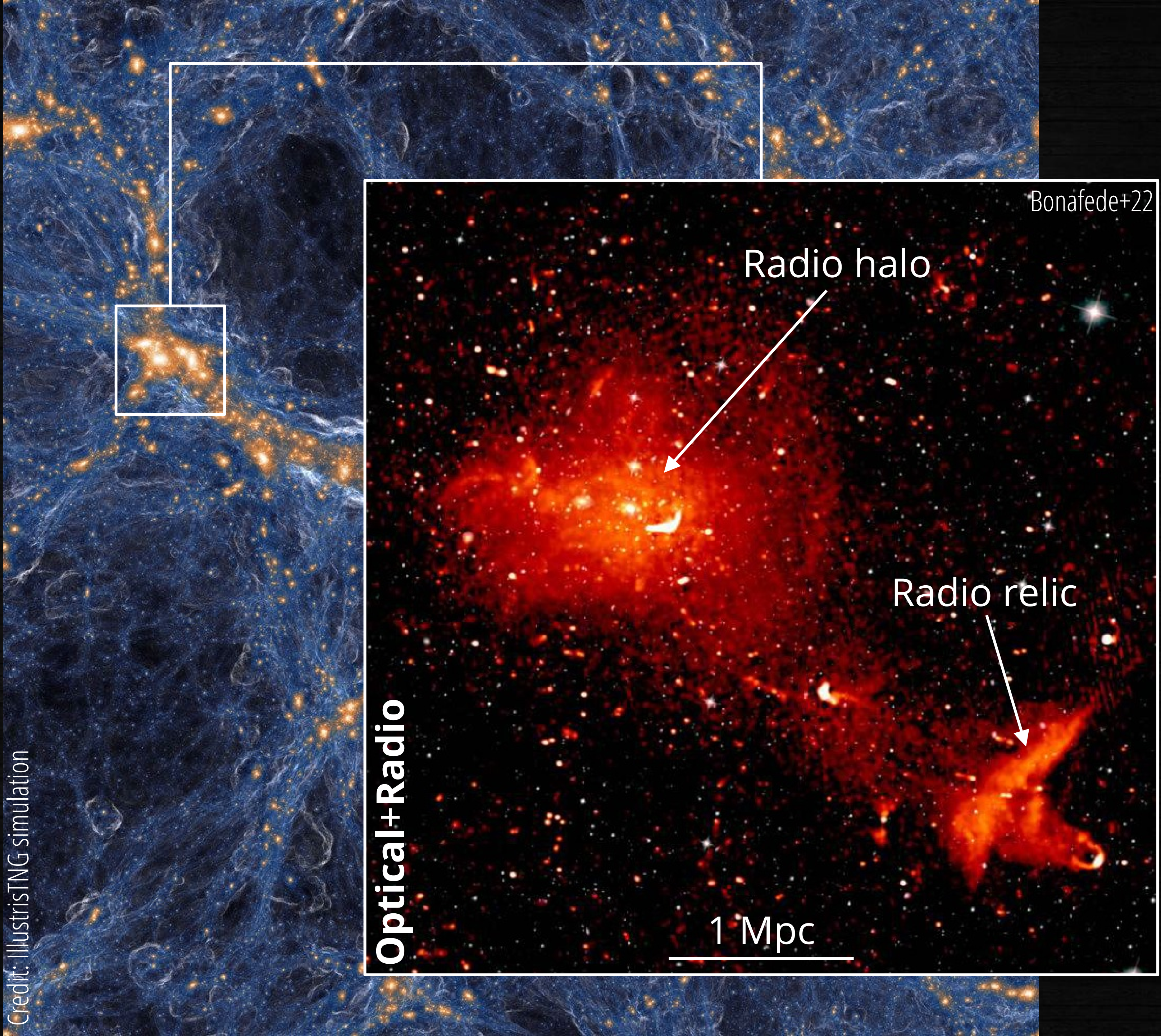
Andrea Botteon[1,⋆], Marco Balboni[2,3], Iacopo Bartalucci[3], Fabio Gastaldello[3], and Reinout J. van Weeren[4]

A&A, submitted

Enhanced radio emission between a galaxy cluster pair

Andrea Botteon[1], Turgay Caglar[2,3], Sibel Döner[4,2], Reinout J. van Weeren[3], and Krista Lynne Smith[2]


Credit: IllustrisTNG simulation

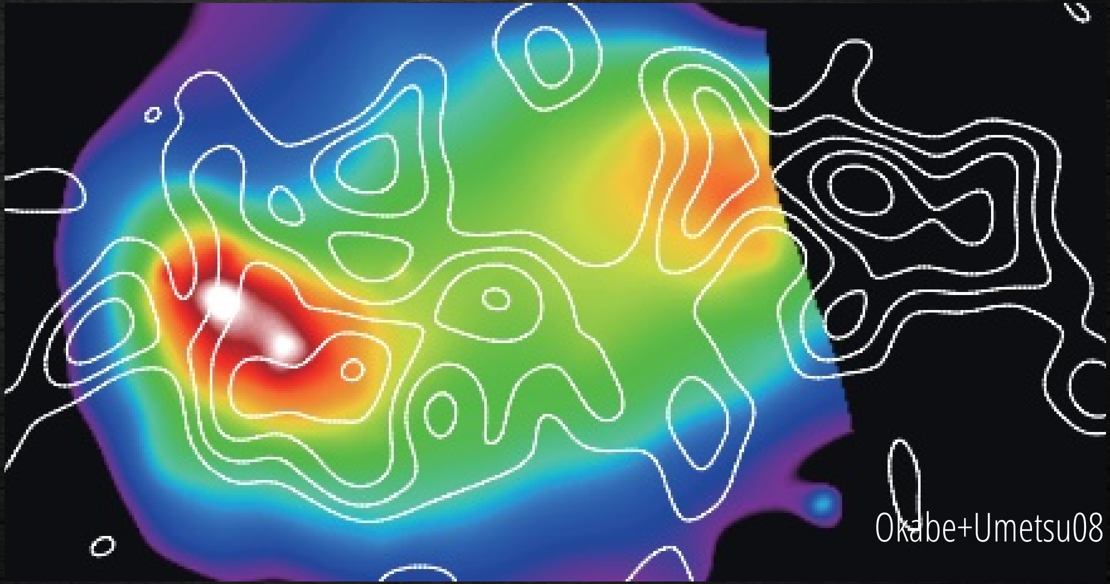

Bonafede+22
Radio halo
Radio relic
Optical+Radio
1 Mpc
Credit: IllustrisTNG simulation

Abell 754: a merging cluster

z	0.0543
Right ascension (h, m, s)	09 09 08
Declination (°, ′, ″)	−09 39 58
M_{500} (10^{14} $M_{\odot}$)	$6.85^{+0.12}_{-0.13}$
Y_{500} (10^{-3} arcmin^2)	40.2 ± 2.7
r_{500} (kpc)	1322 ± 8
L_X (10^{44} erg s^{-1})	5.56 ± 0.15
K_0 (keV cm^2)	270 ± 70
$kT_{\rm vir}$ (keV)	11.1 ± 0.4
$\sigma_v^{\rm turb}$ (km s^{-1})	676 ± 46
$\sigma_v^{\rm gal}$ (km s^{-1})	953 ± 40

Massive, low-z, cluster with a radio halo + relic(?) + shock detected in X-rays

(Wielebinski+77, Millis+78, Harris+80, Kassim+01, Bacchi+03, Kale+Dwarakanath09, Macario+11)



Okabe+Umetsu08

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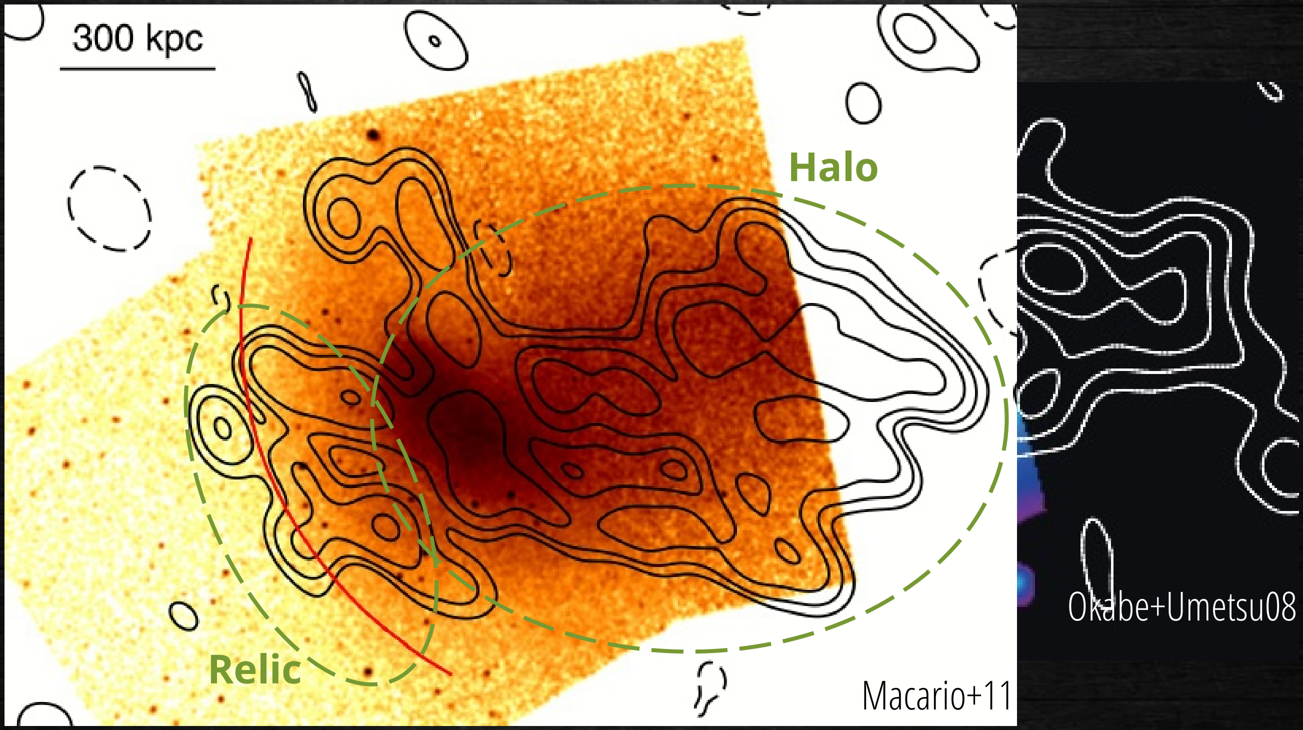

The relic emission blends with the radio halo at low frequency/resolution

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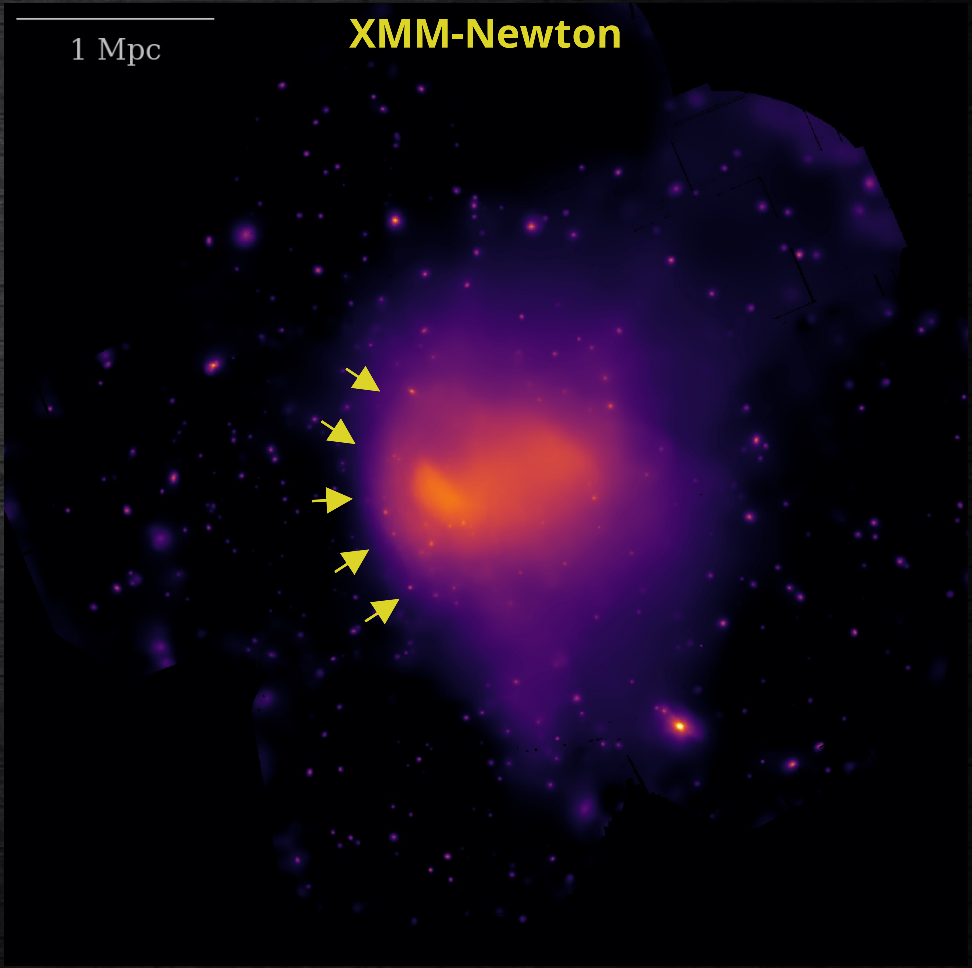
- **MeerKAT** L (**10 h**, 1.28 GHz)
- **XMM-Newton** 13 ObsIDs (**350+ ks**)



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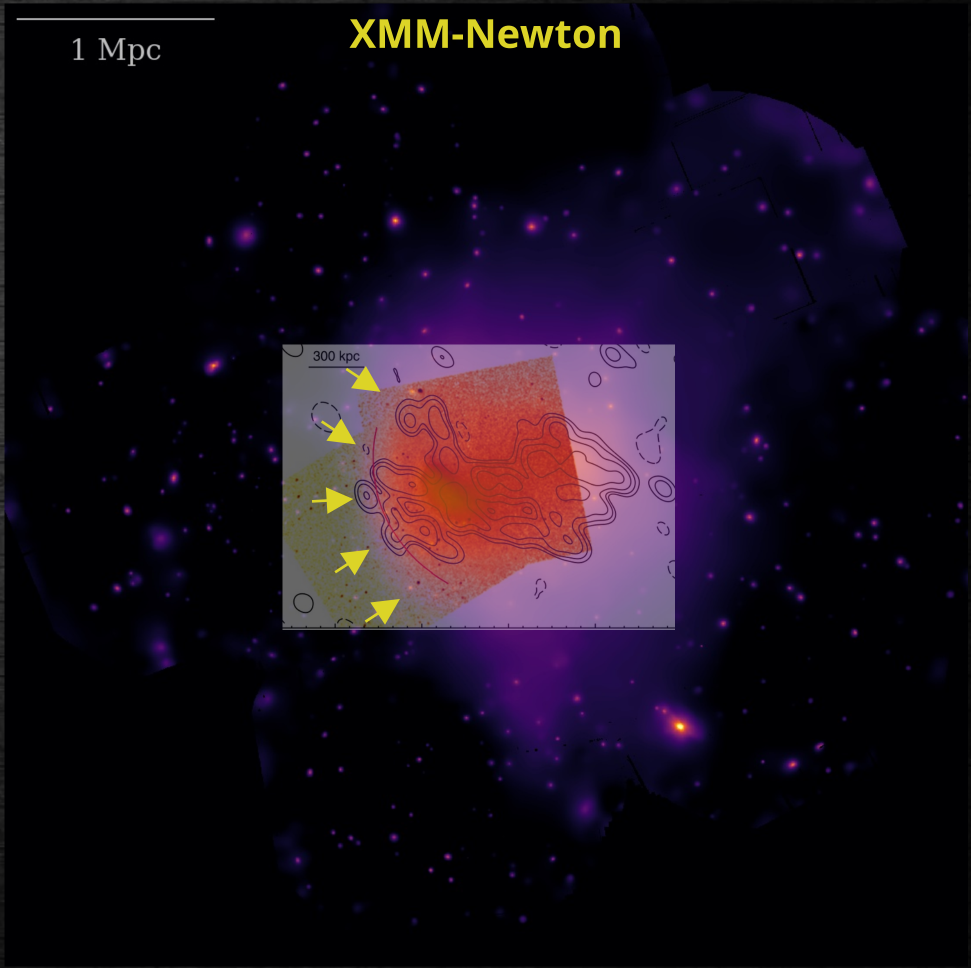

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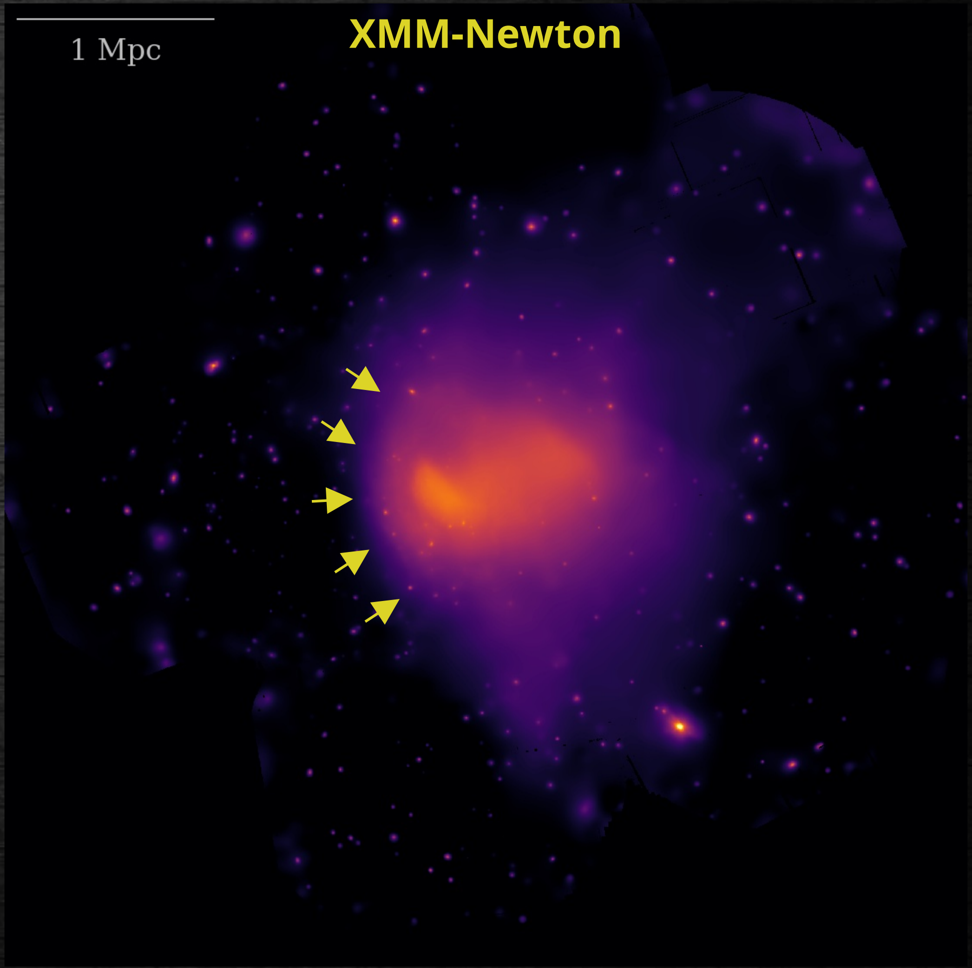

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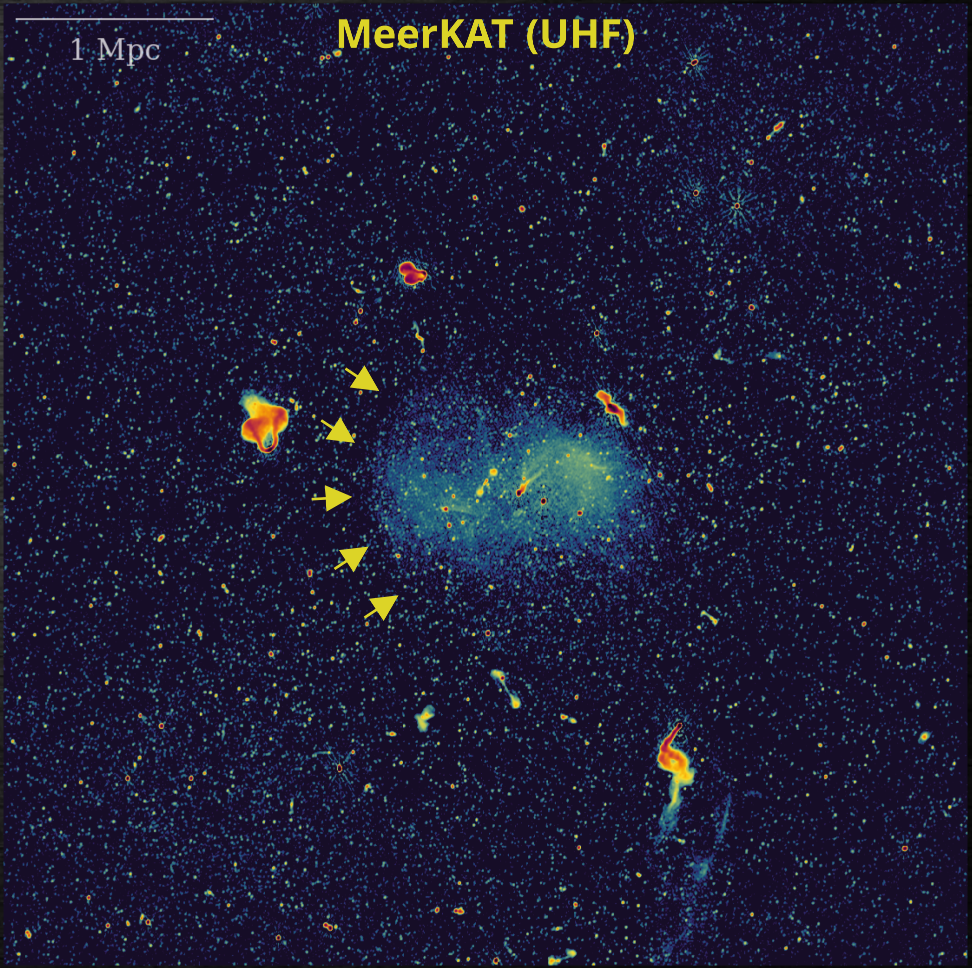

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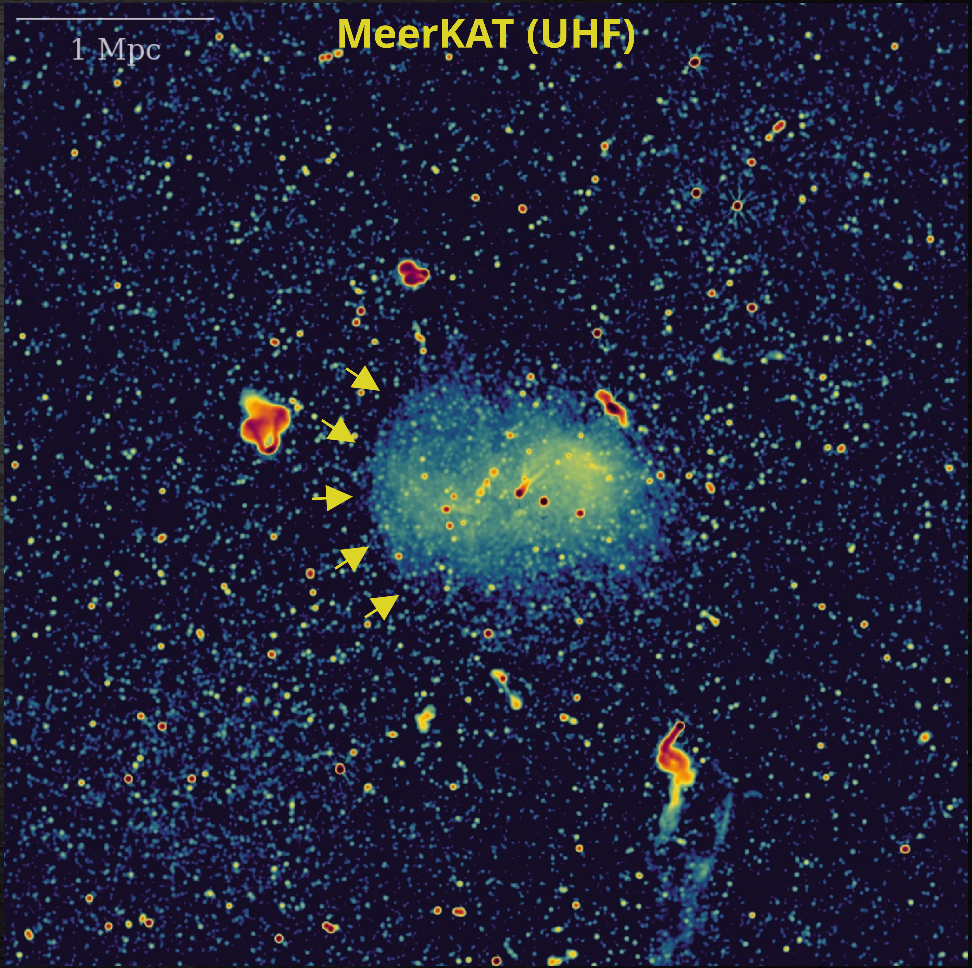
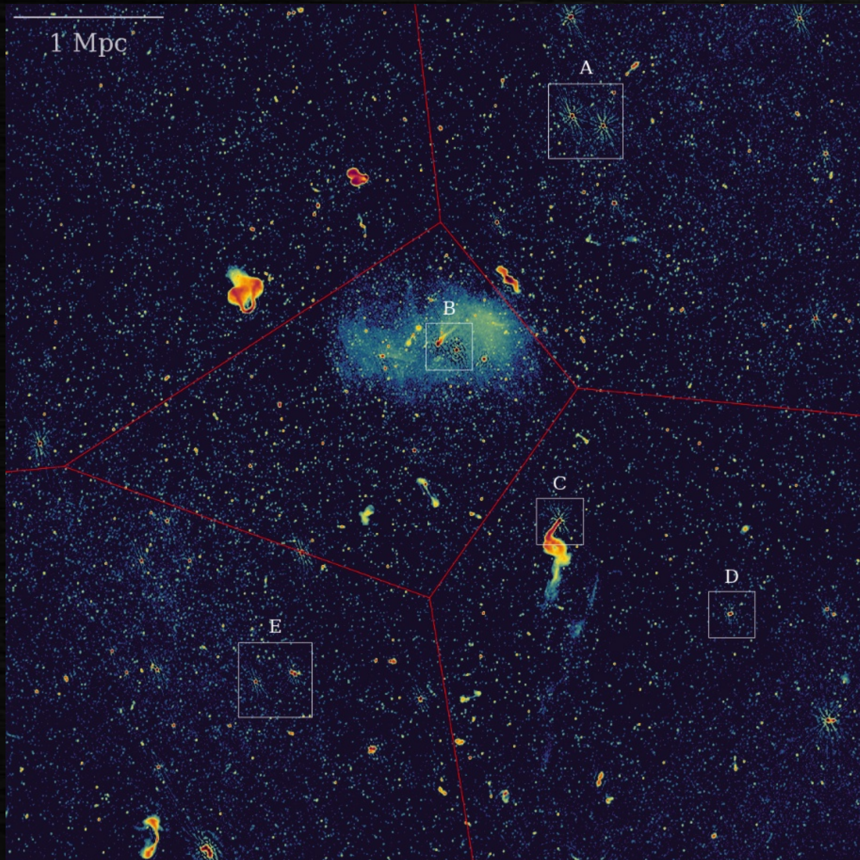
A case of **halo-shock connection**
(as A520, Bullet, Coma, Toothbrush...)



Using LOFAR pipelines on MeerKAT

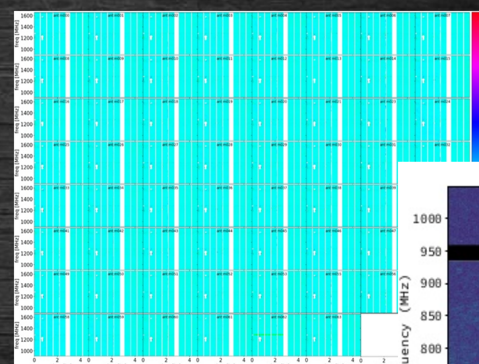


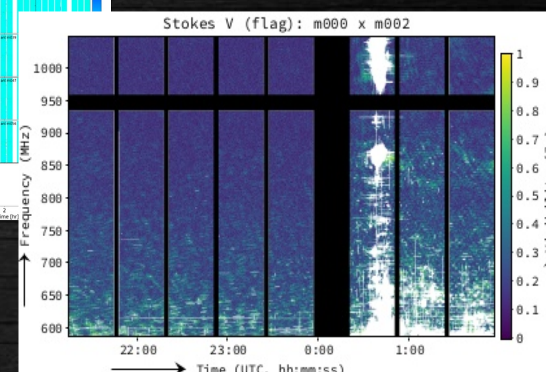
Calibration done with **facetselfcal.py**

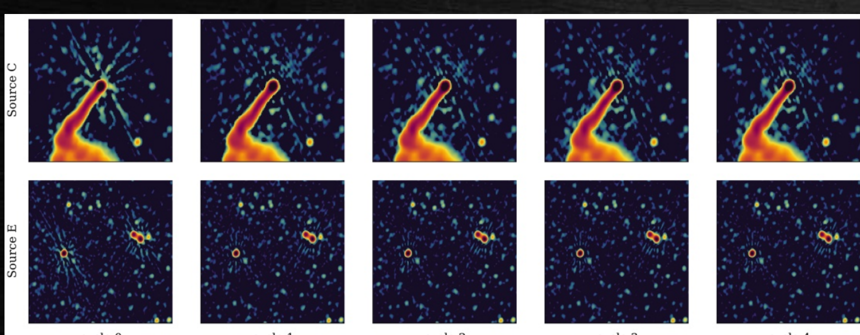
https://github.com/rvweeren/lofar_facet_selfcal

(vanWeeren+21)

Mainly relies on: WSClean, DP3, losoto, python-casacore (AOFlagger, LSMTool, pyBDSF, DDF)







→ What's new?

Direction-dependent calibration

The halo and the (new) relic

The halo and the (new) relic

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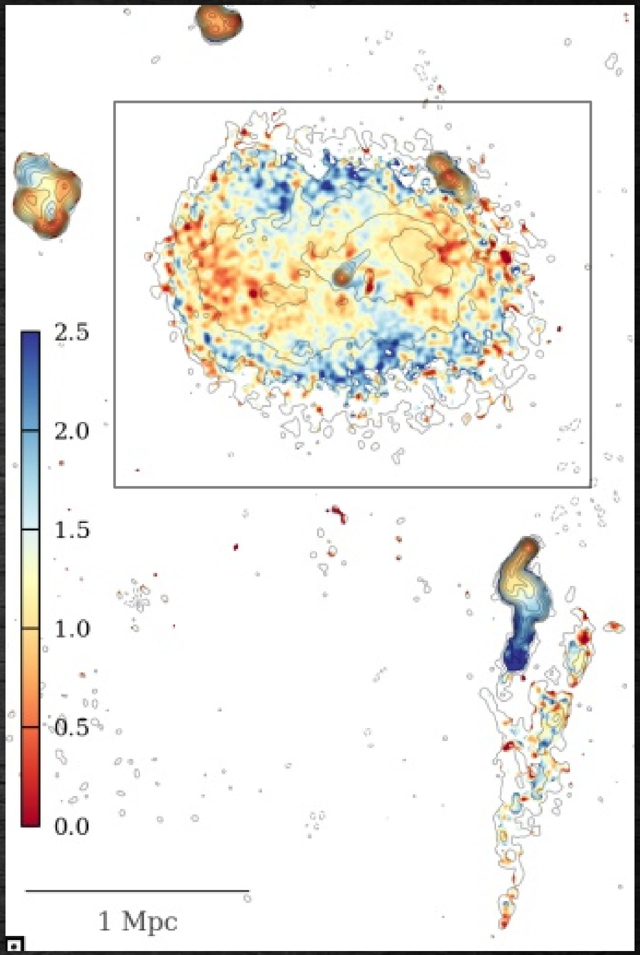
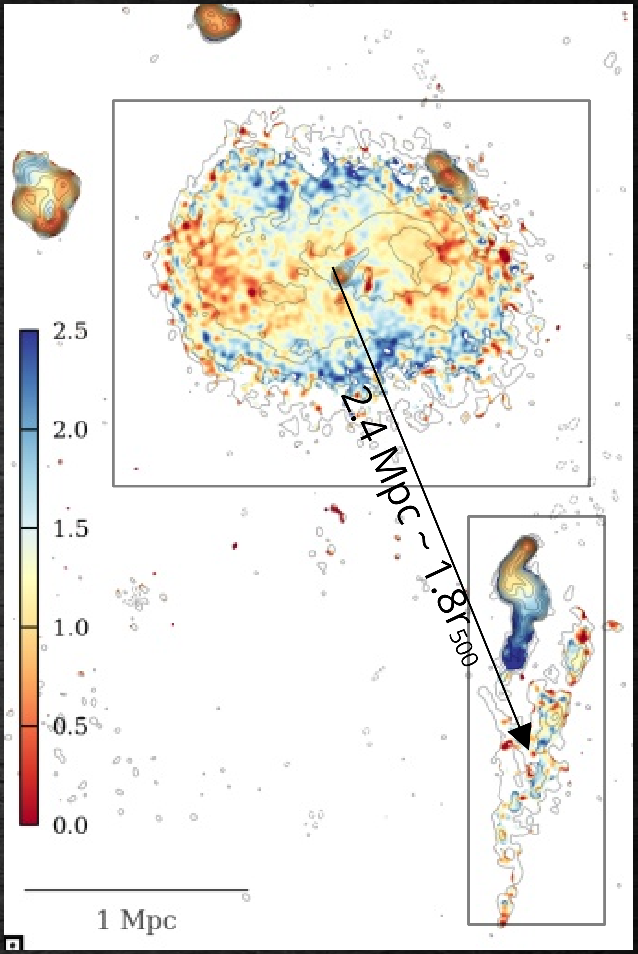


<u>Halo:</u> different particle acceleration efficiencies ∥ and ⊥ to the main cluster merger axis?

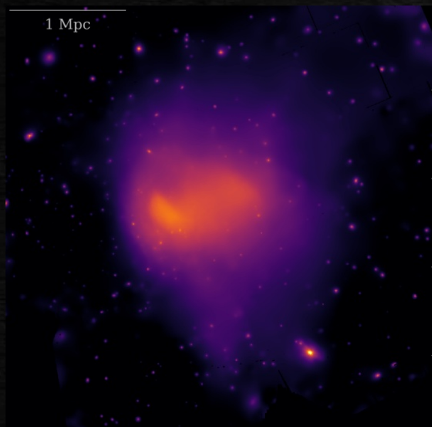
The halo and the (new) relic

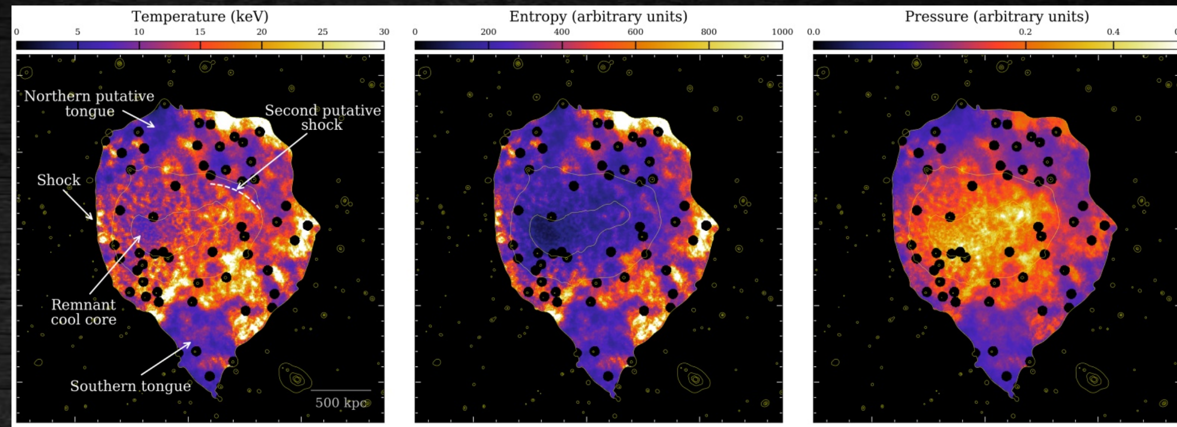


Halo: different particle acceleration efficiencies ∥ and ⊥ to the main cluster merger axis?

Relic: a weak radio relic powered by direct acceleration of thermal pool electrons?

Merger scenario





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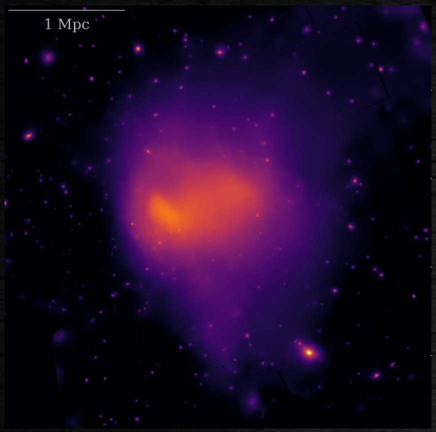

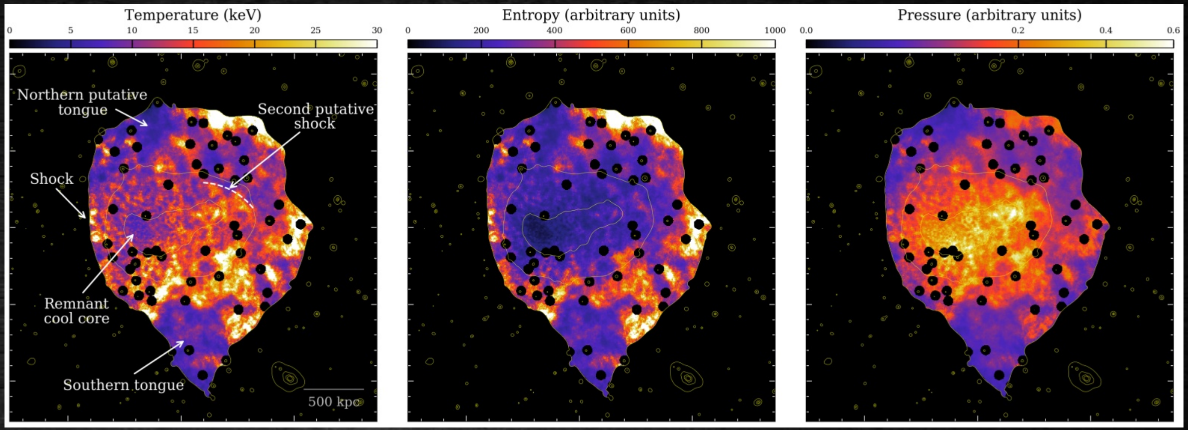

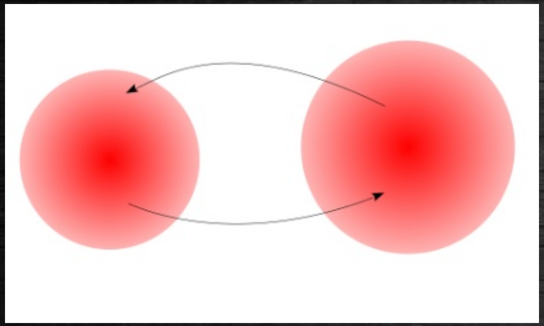

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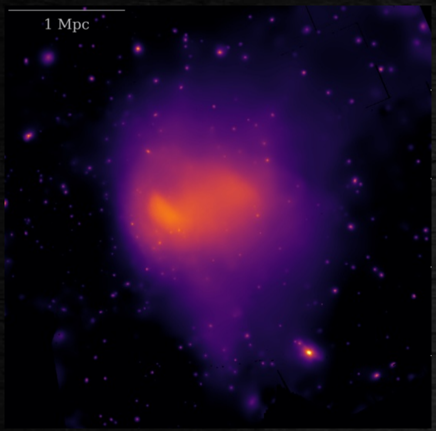

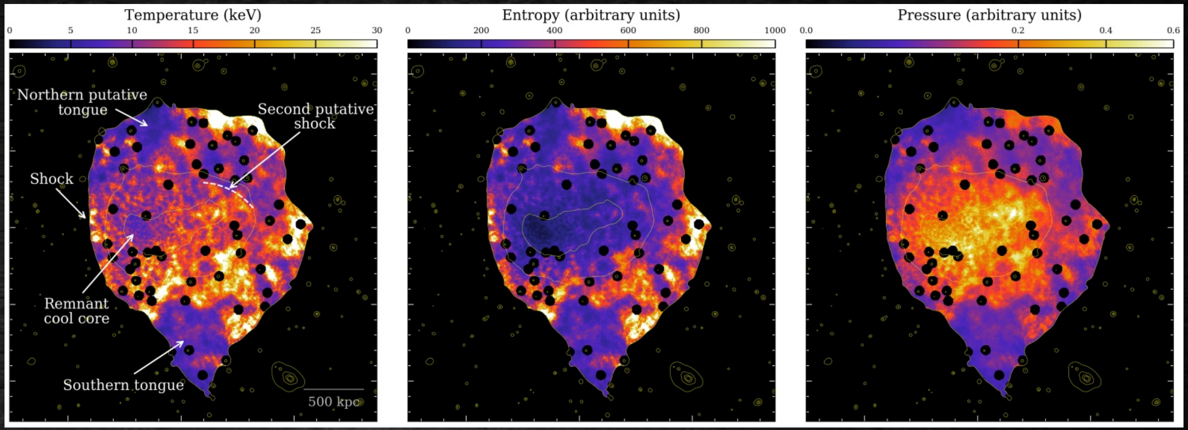

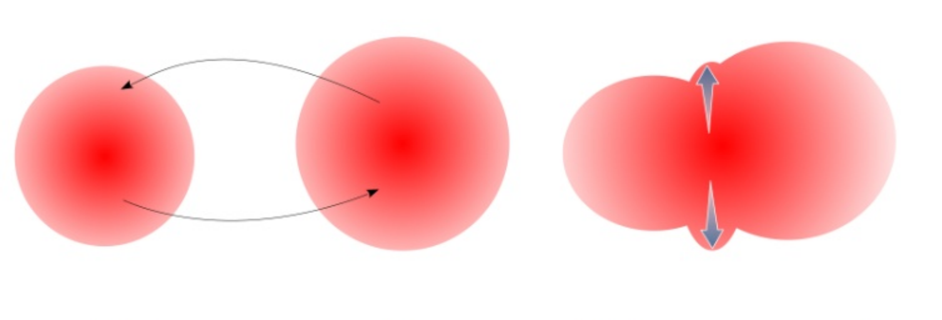

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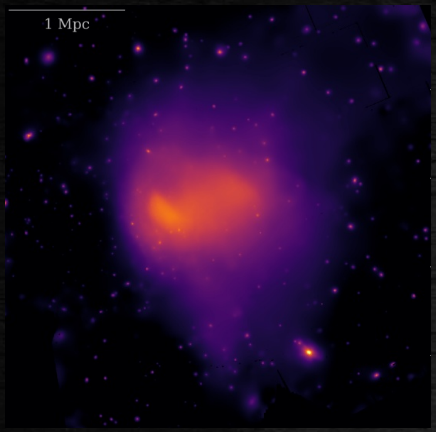

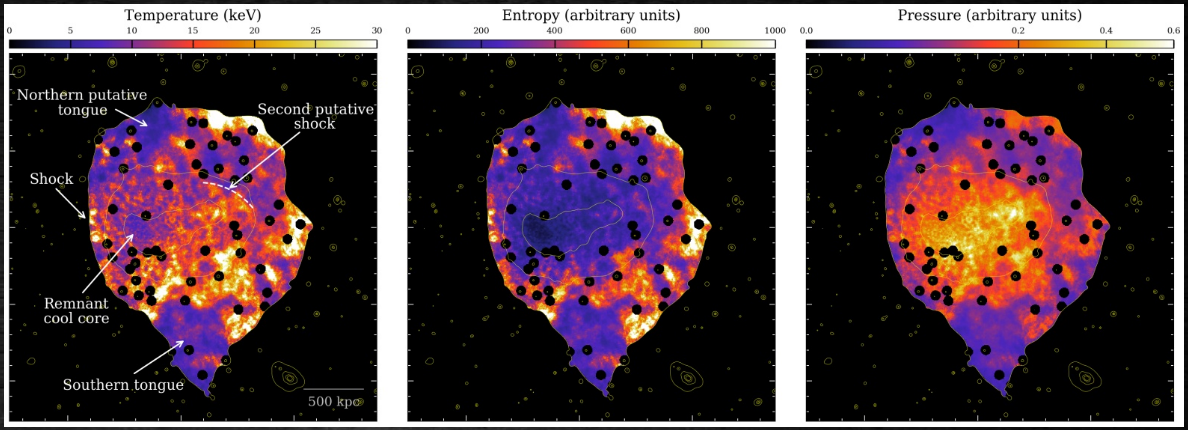

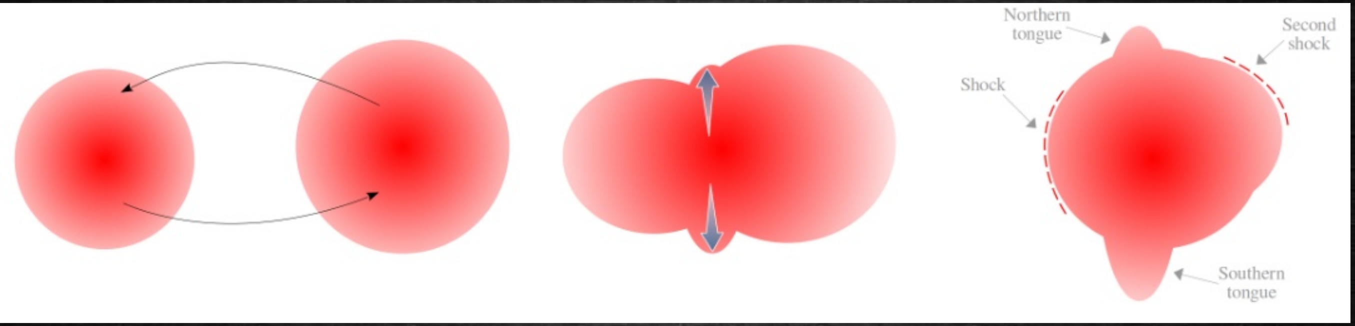

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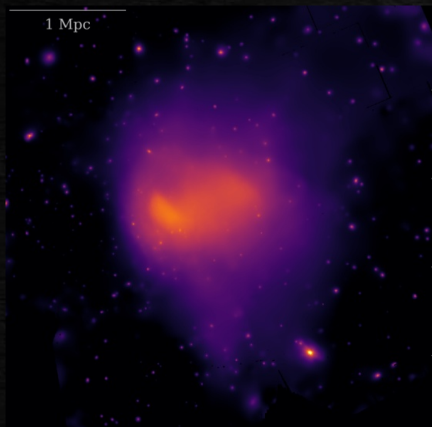

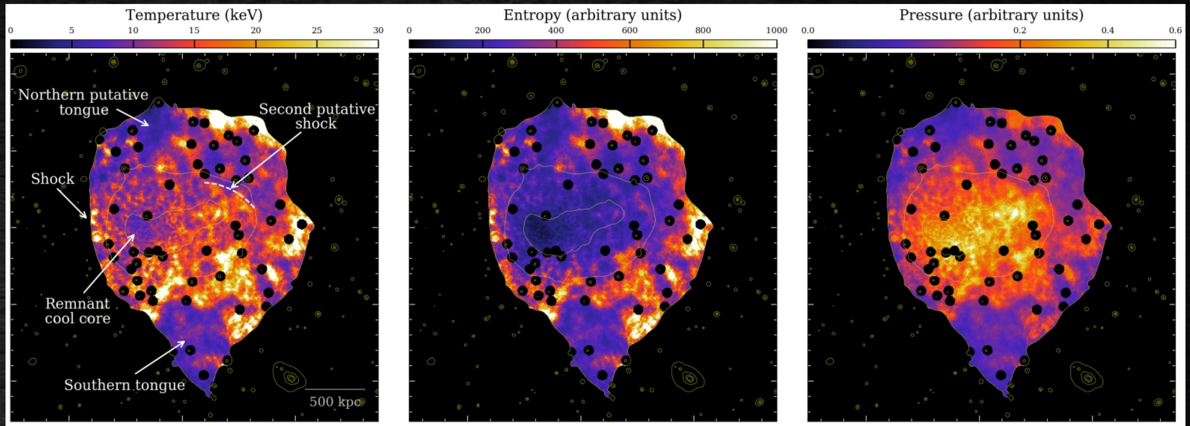

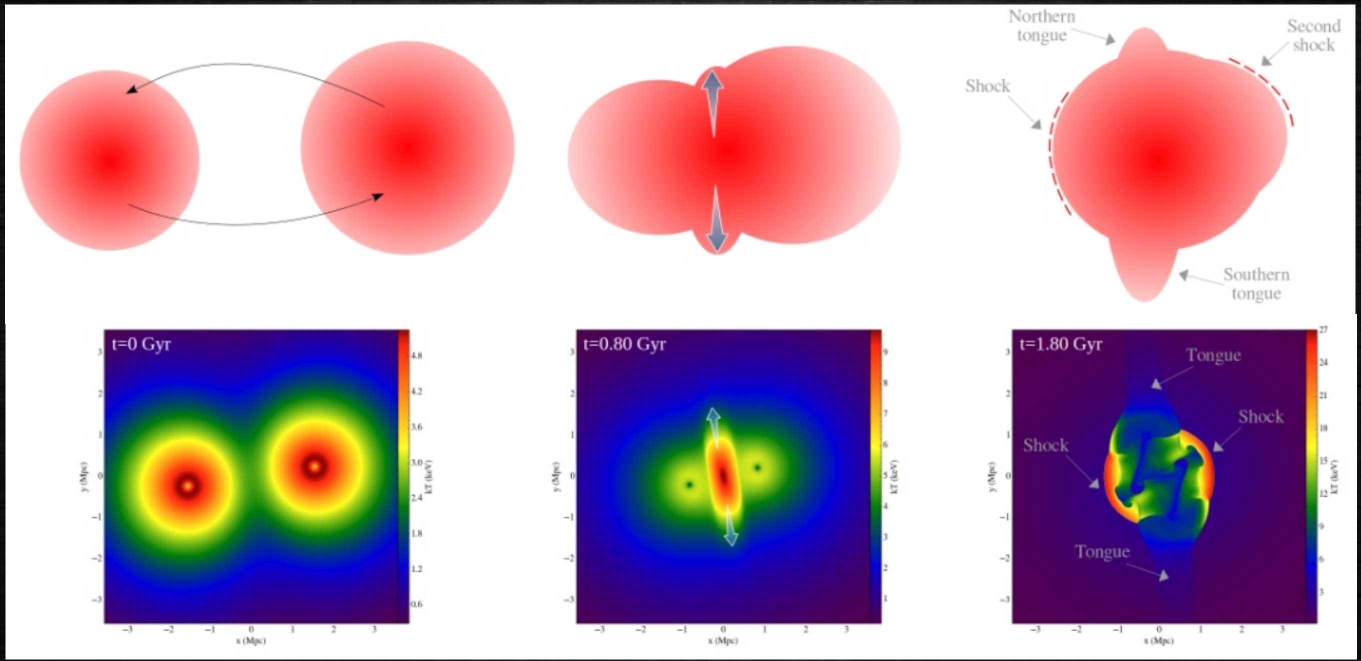

Comparison with a
M1:M2 = 1:1
b = 500 kpc
simulation by
ZuHone+18

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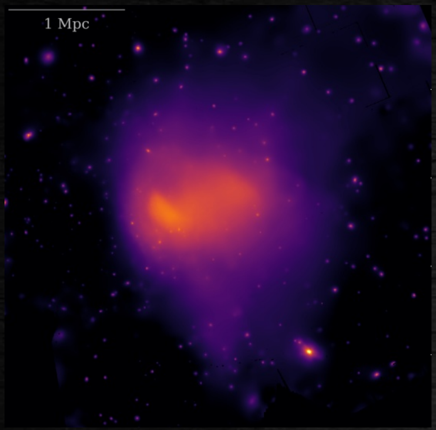

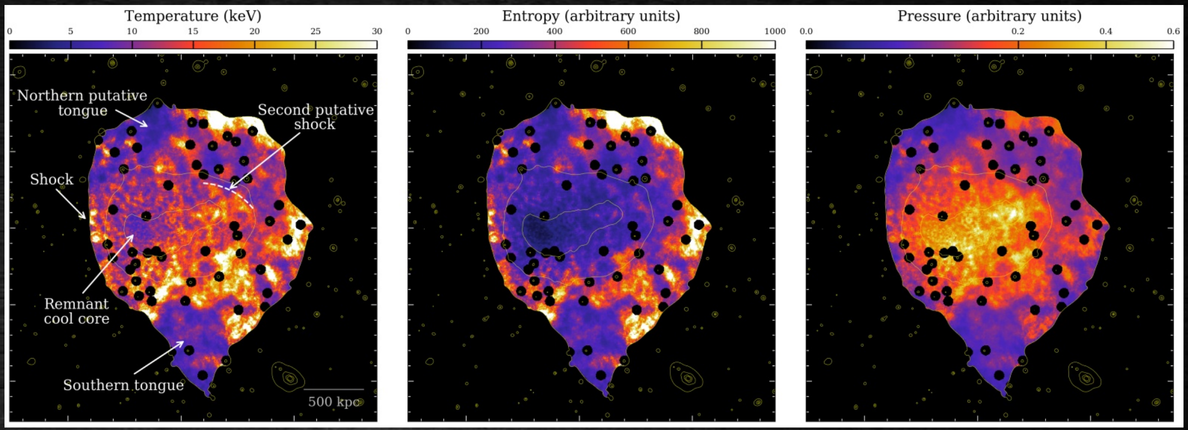

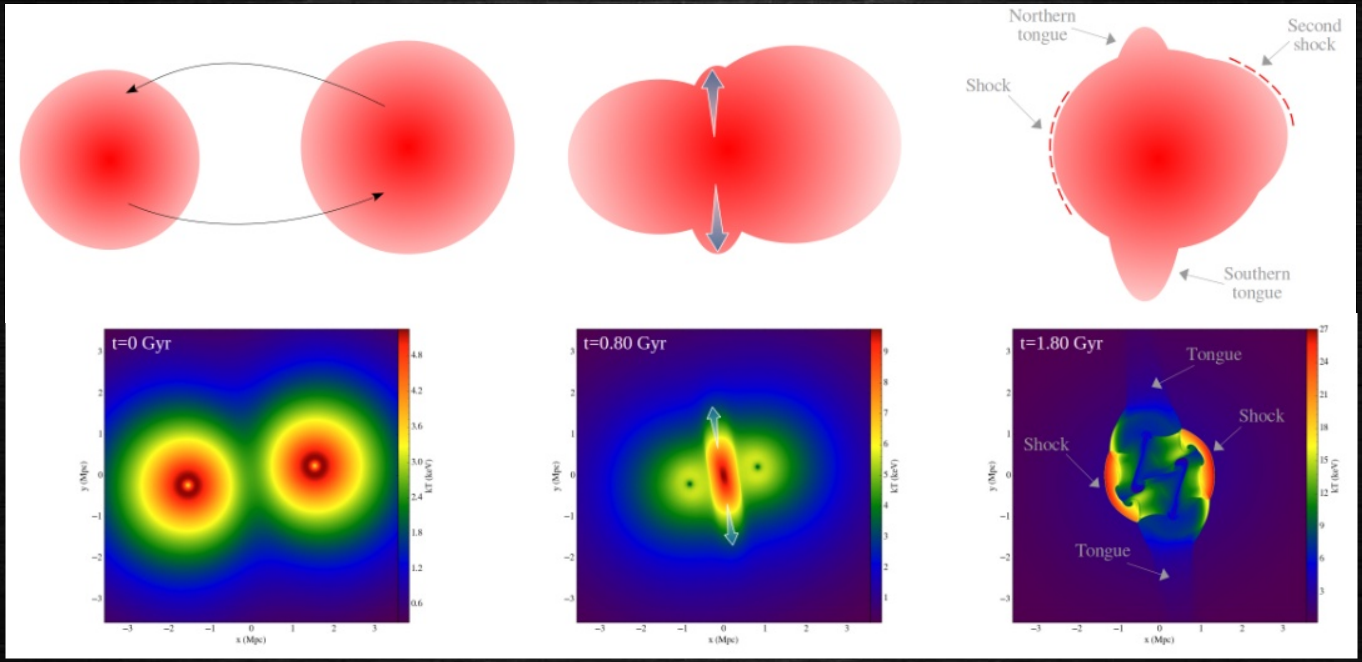

Comparison with a
M1:M2 = 1:1
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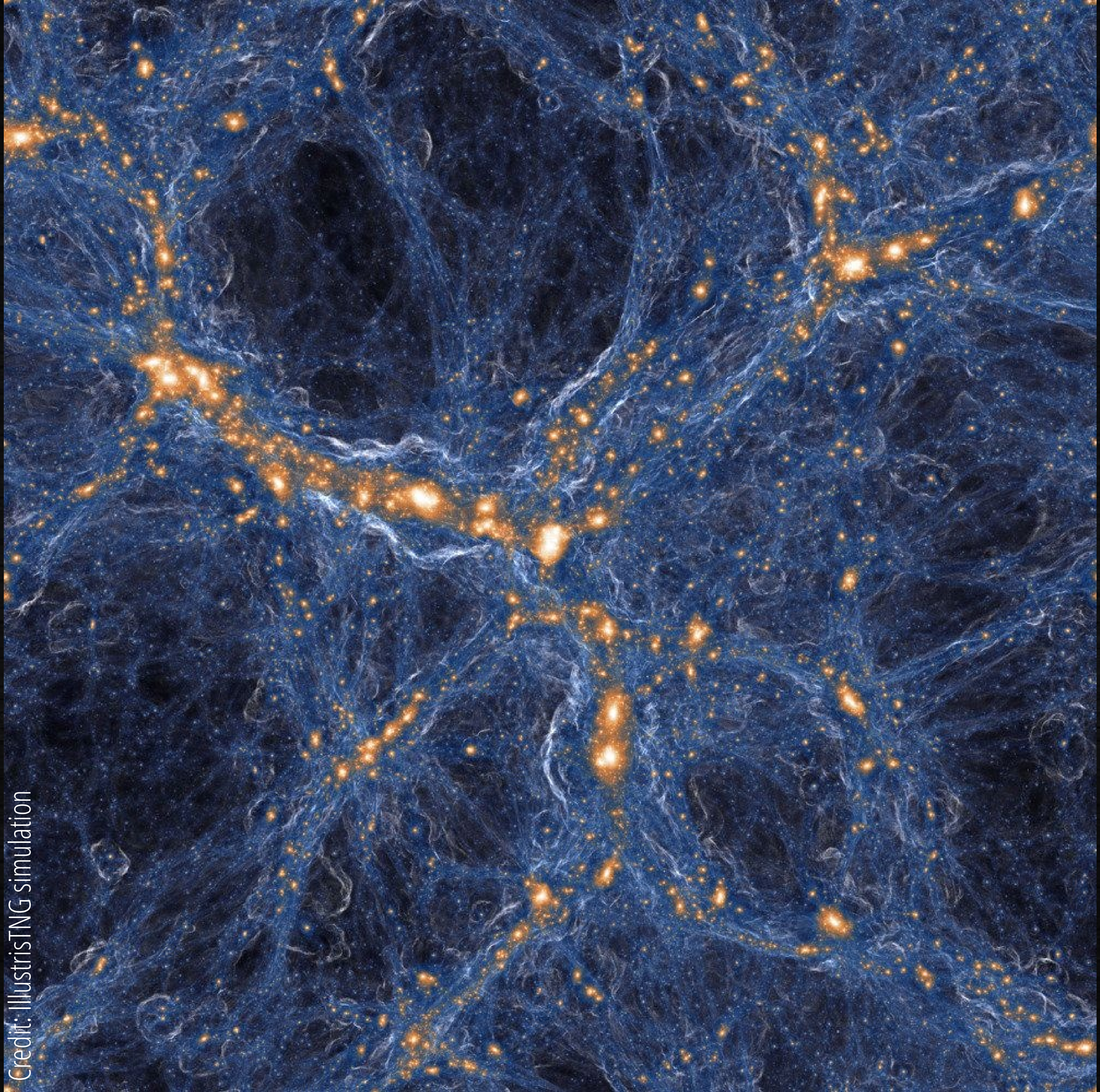
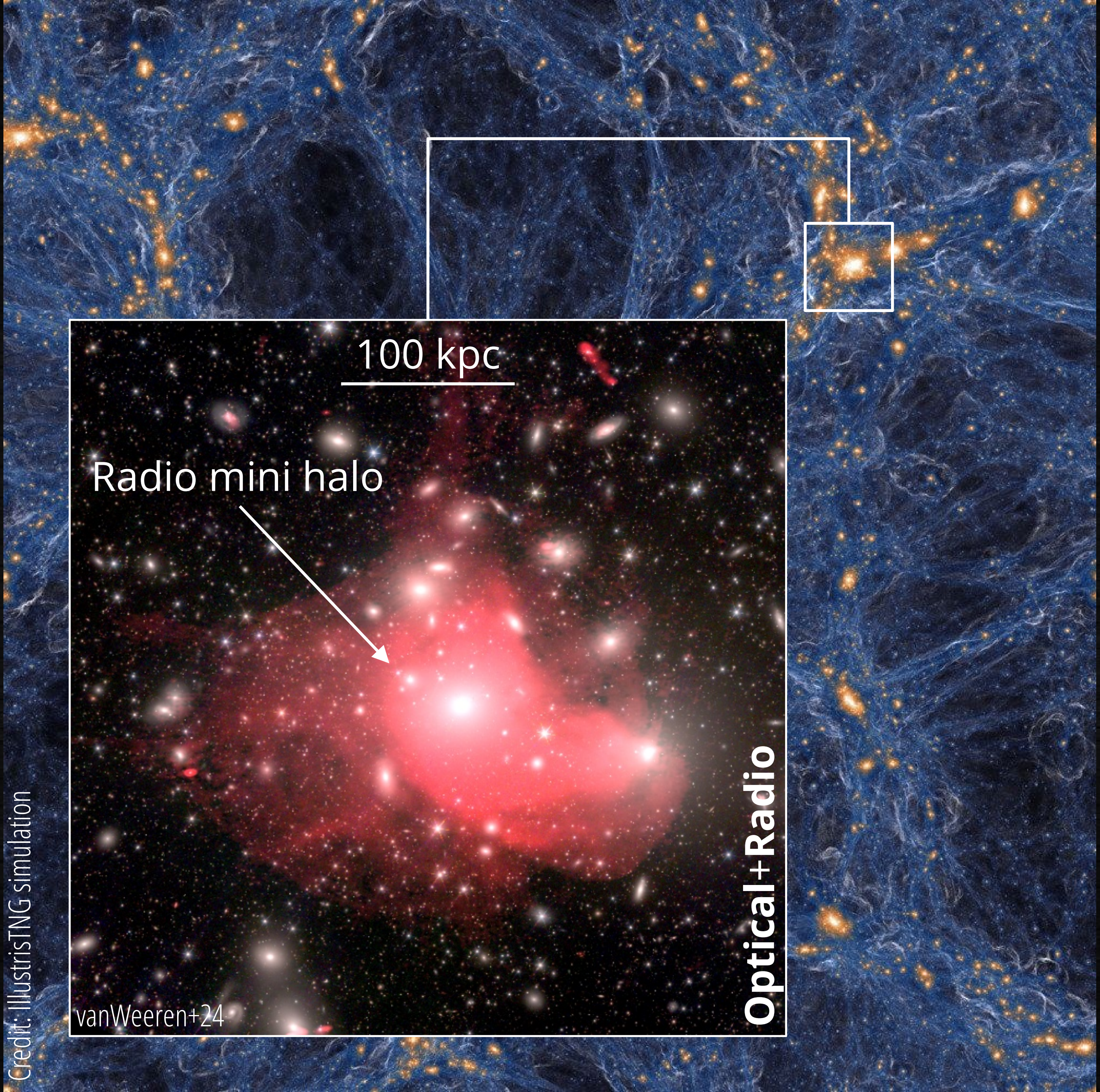
In this scenario, the new relic may trace a **shock** driven by the squeezed gas compressed by the merger, outflowing in perpendicular directions

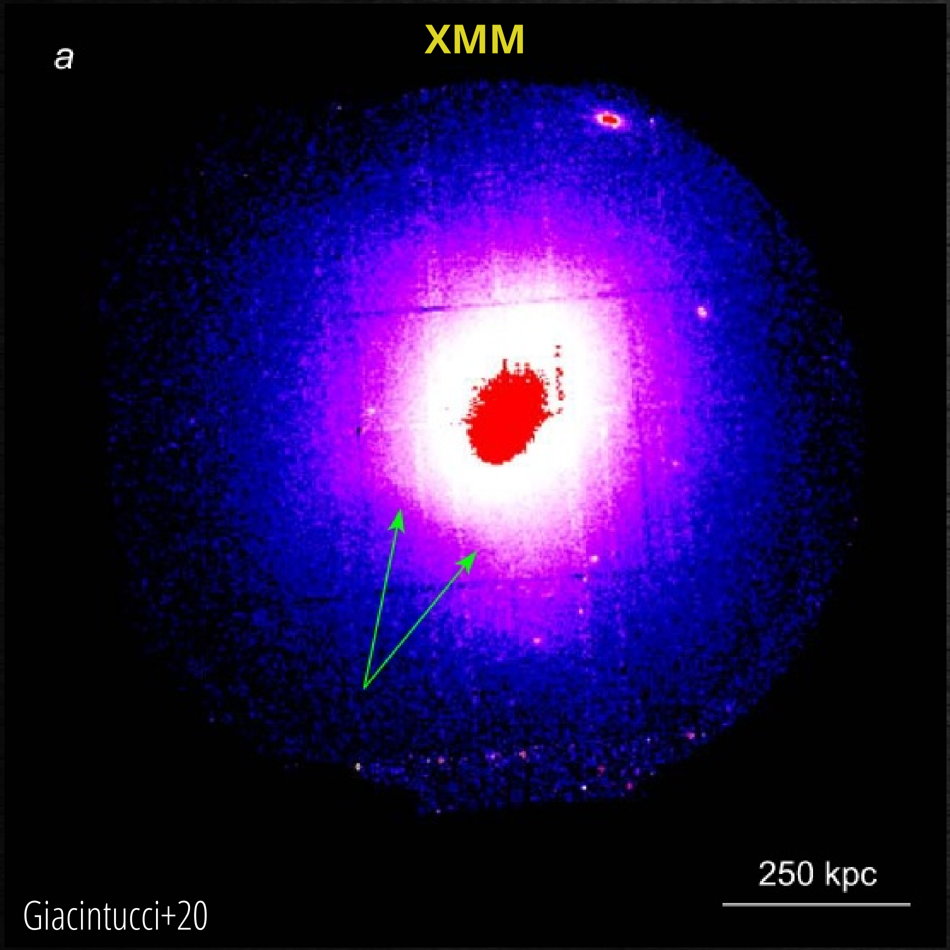

Credit: IllustrisTNG simulation

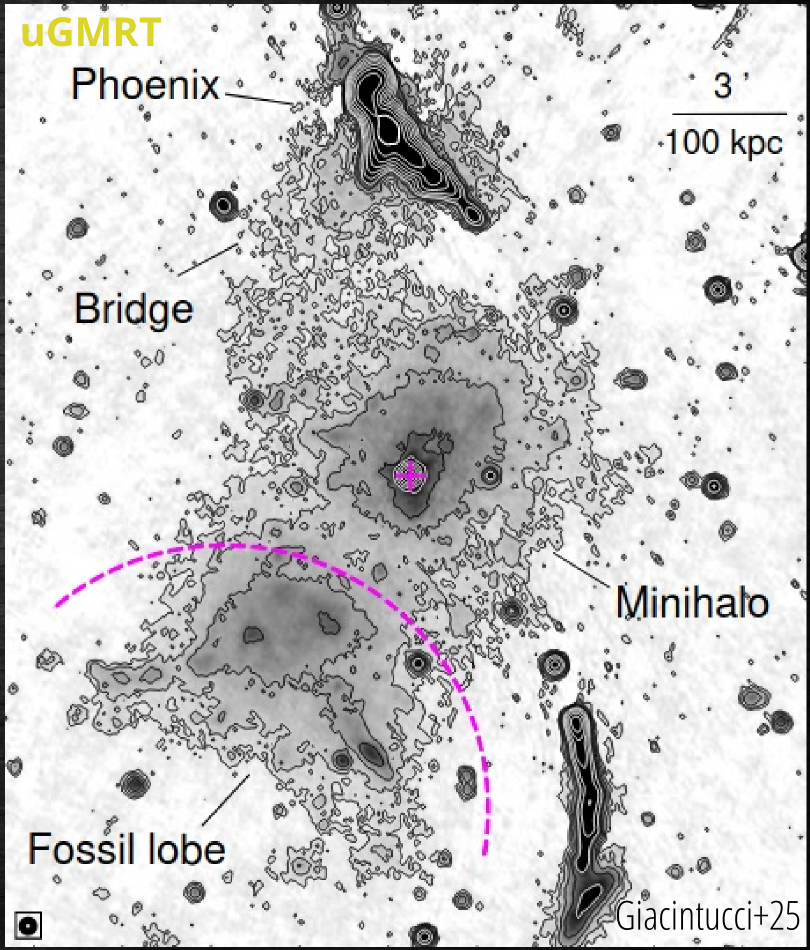

100 kpc
Radio mini halo
Optical+Radio
vanWeeren+24
Credit: IllustrisTNG simulation

Ophiuchus: a relaxed cluster

A **massive** and **relaxed** system in the **local** Universe (z=0.0296)

(Govoni+09, Murgia+10, Million+10, Durret+15, Werner+16, Giacintucci+20,25, Galdeano+22, Fuijta+25)





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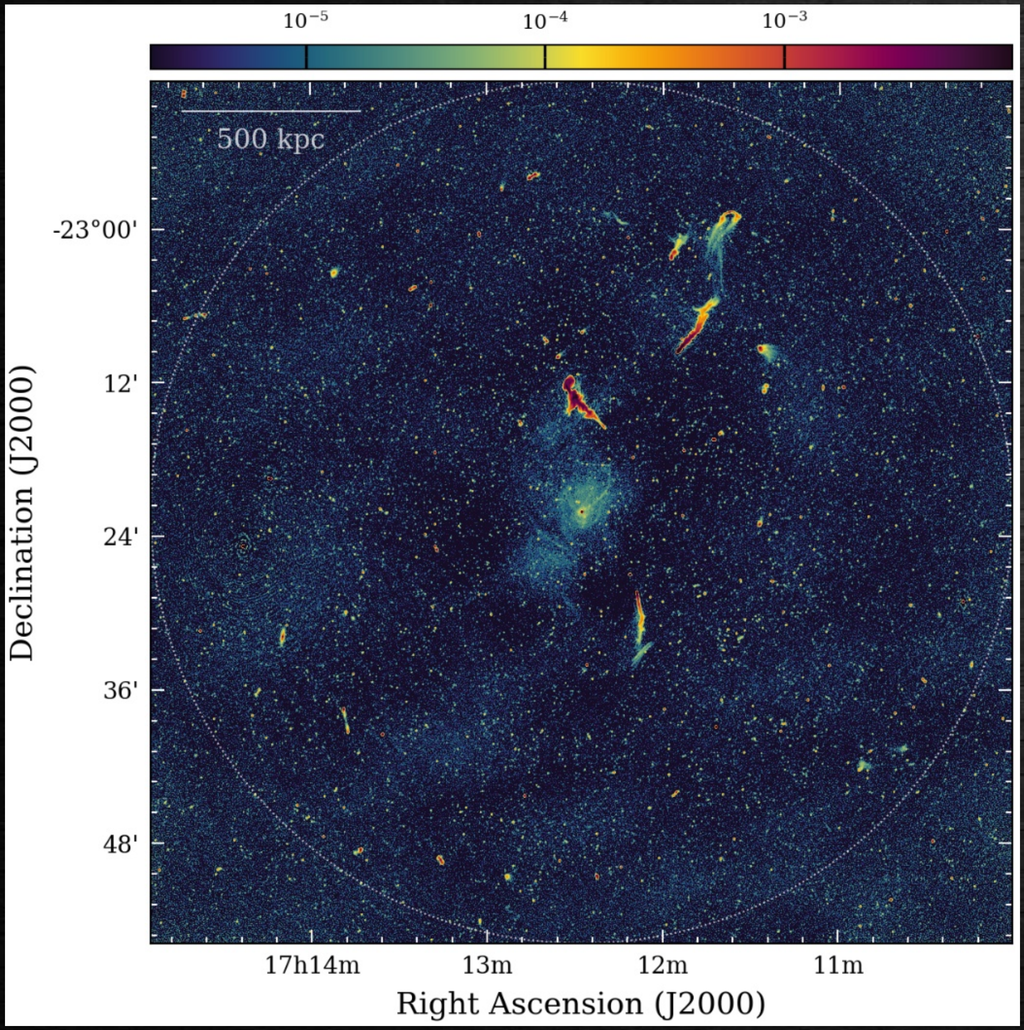
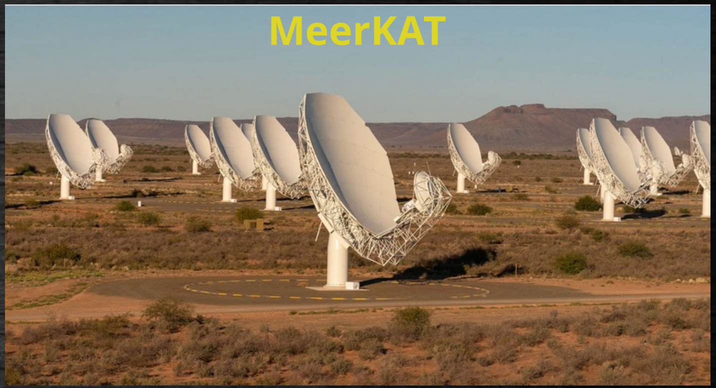
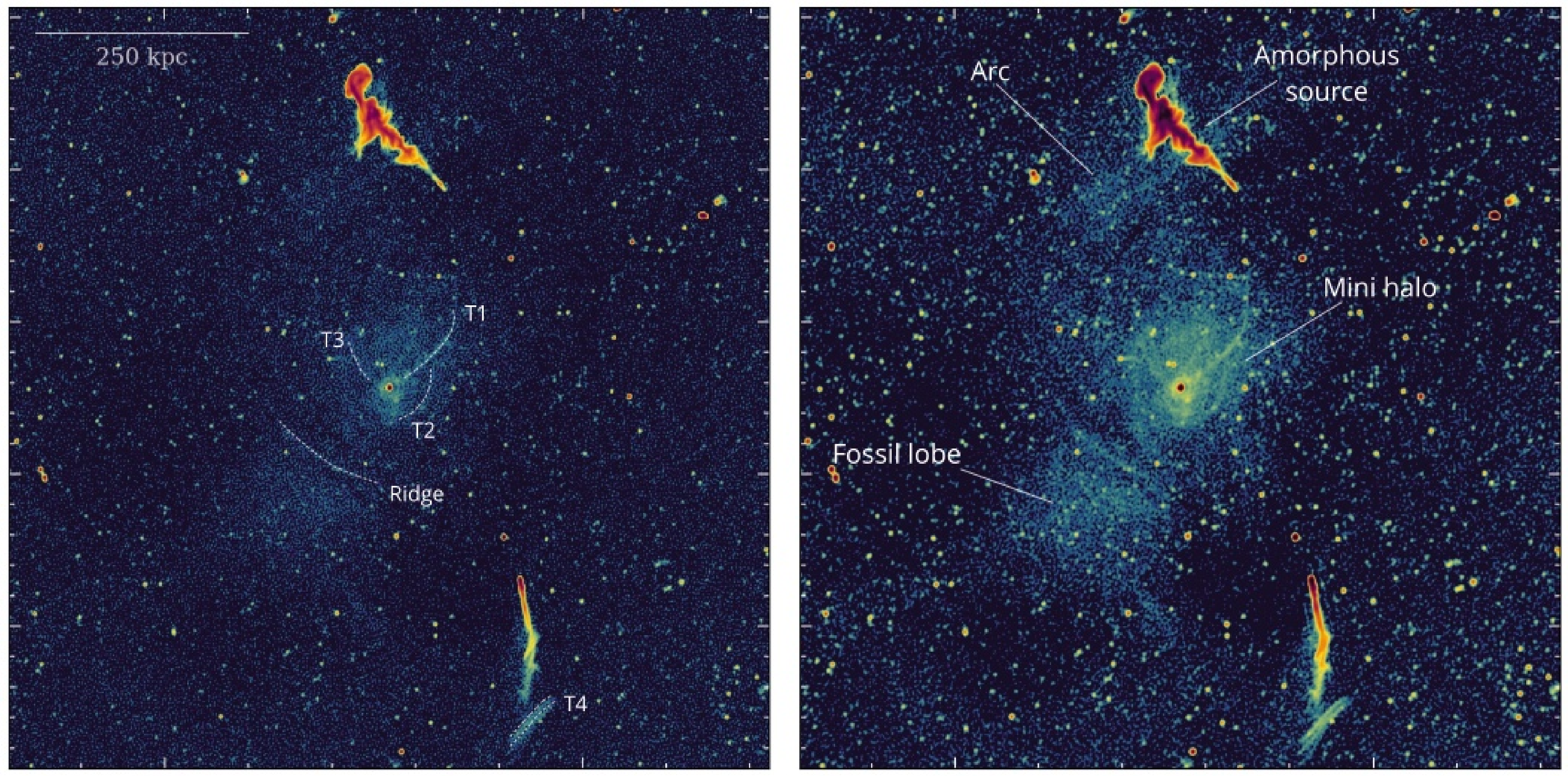




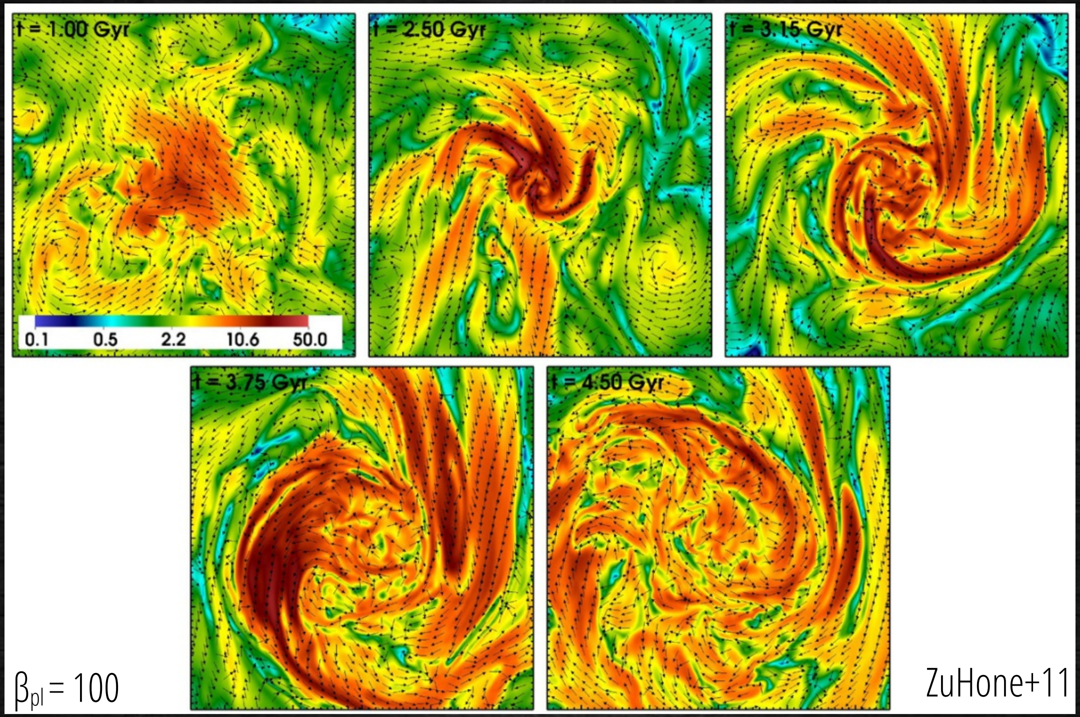
- MeerKAT 7.25h L-band (856-1712 MHz) observations
- Circle d = 67.3 arcmin (FWHM @ 1.28 GHz)
- Resolution: 6.1” x 5.5”
- Noise: 4.5 µJy/beam

Synchrotron threads in Ophiuchus



- T1: 70 kpc long, constant width of ~8 kpc
- T1 and T3 seem connected with the BCG
- T4: two parallel threads, likely connected with the tailed AGN
- The “ridge” is observed between the mini halo and fossil lobe (Giacintucci+20)

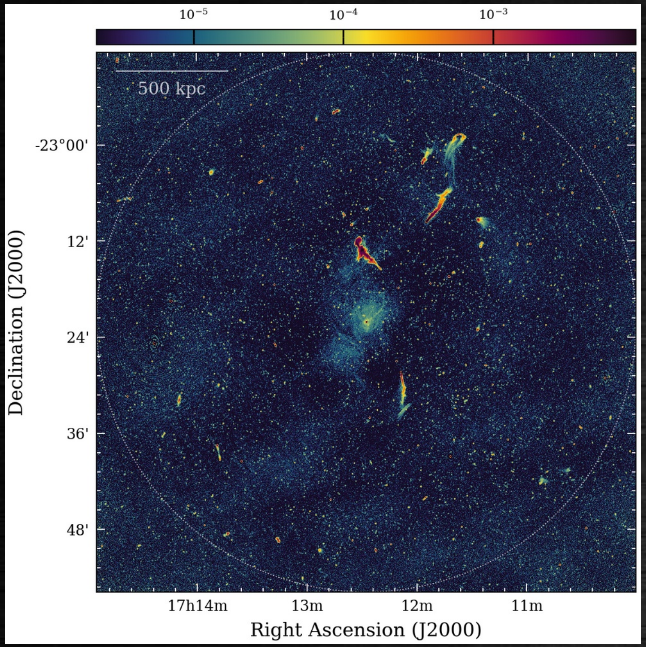
Sloshing of the magnetized ICM

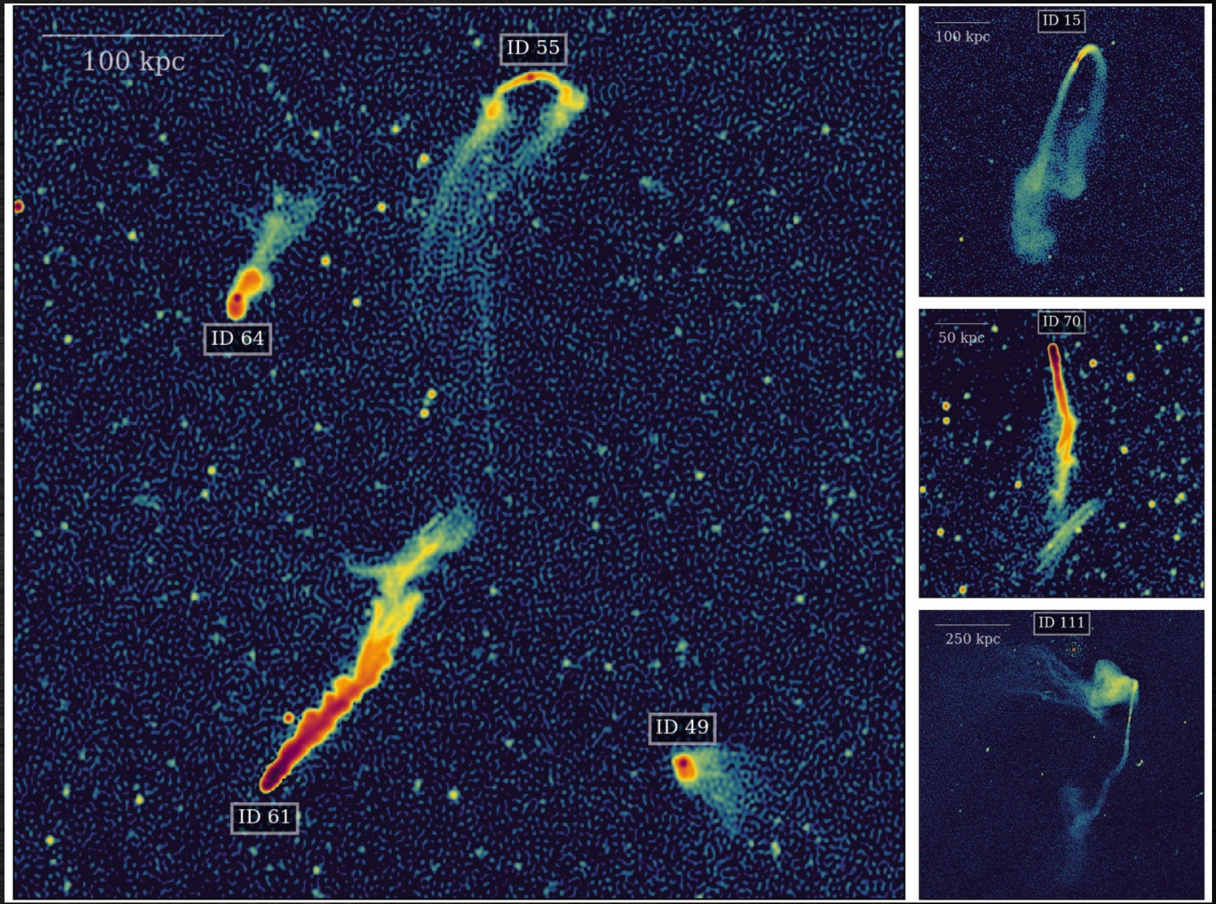


In **sloshing** clusters, shear flows stretch and amplify the field generating highly magnetized layers

The synchrotron threads may trace **magnetic field structures** or regions with **enhanced CRe density** and/or **re-acceleration sites**

A "potpourri" of radio tails



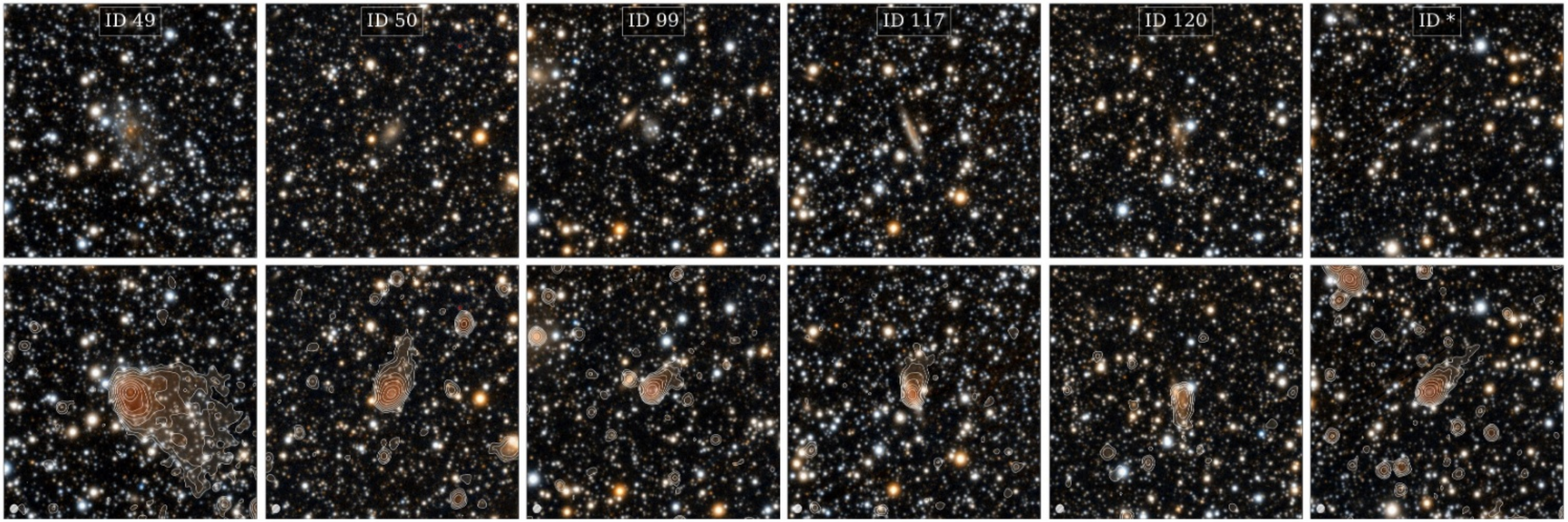


Tails can originate from:

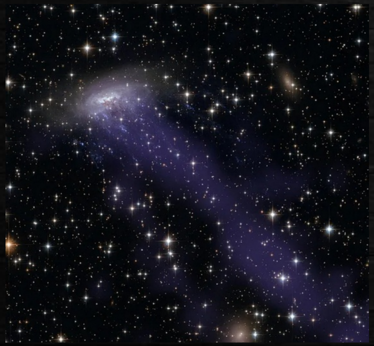
- AGN (WAT, NAT, HT)
- SFG (jellyfish galaxies)

65 radio galaxies in the field belong to Ophiuchus
(cross-match with Durret+15 and Galdeano+22)

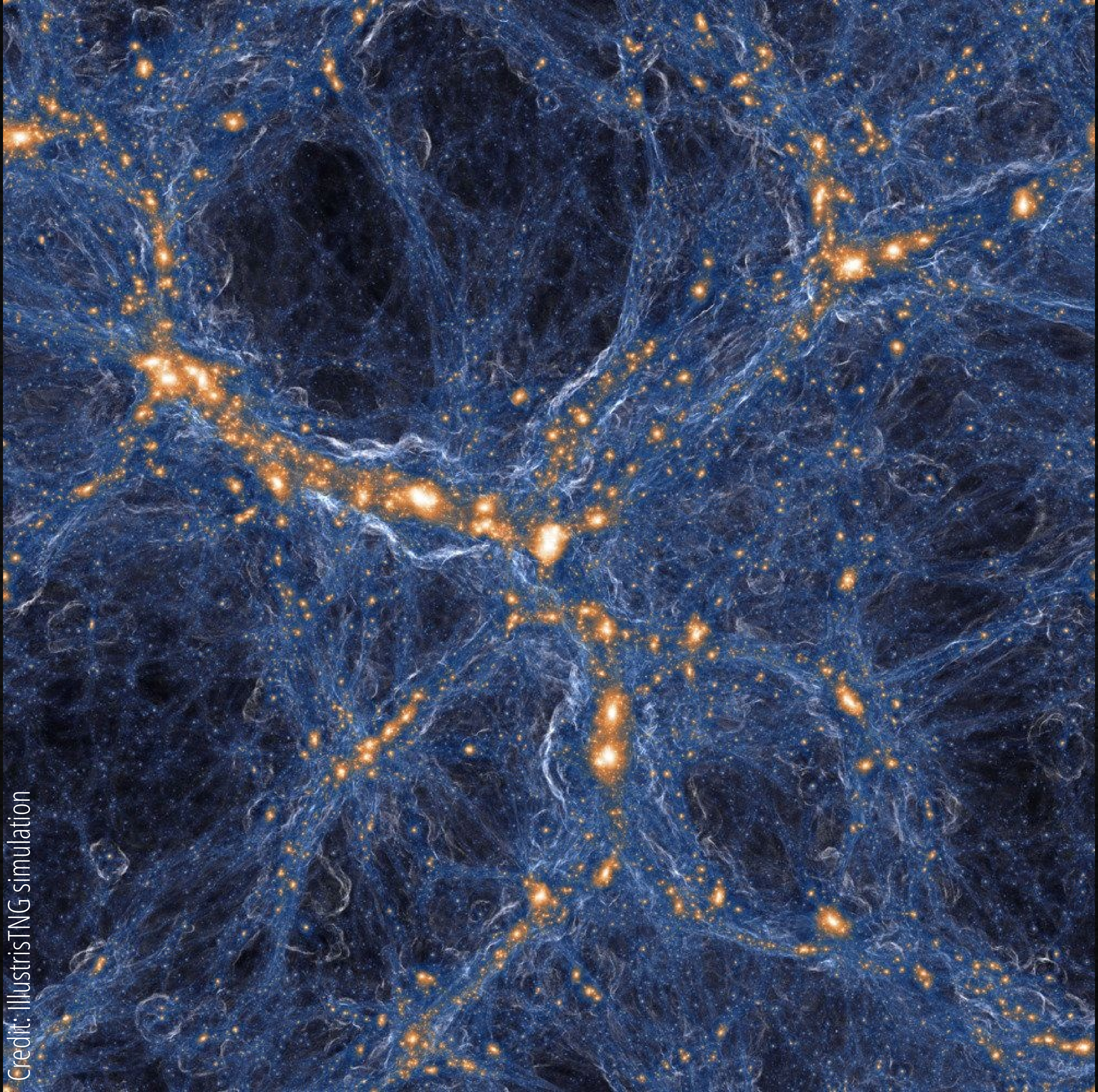
Jellyfish galaxies

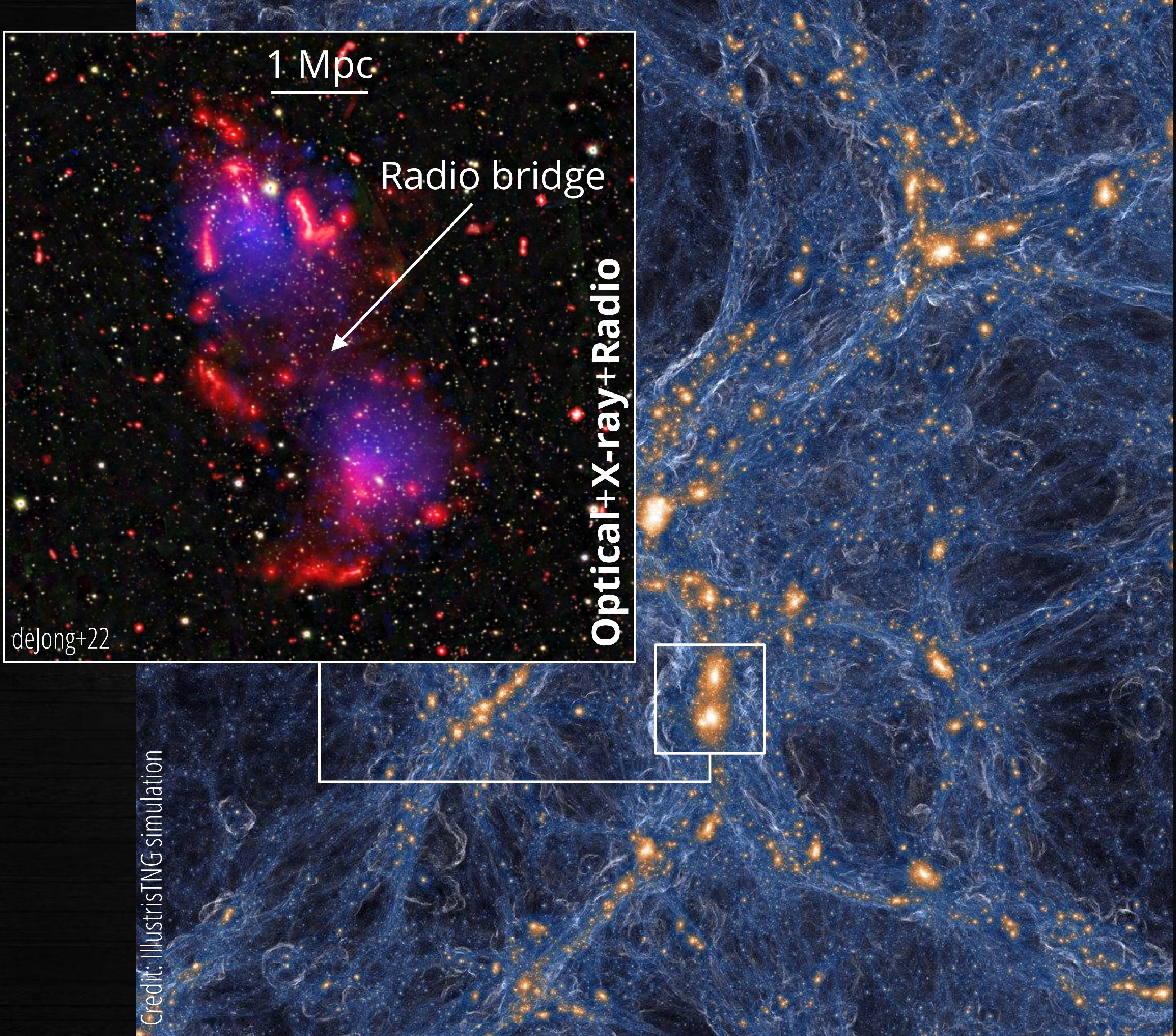


These are the **first** jellyfish galaxies identified in Ophiuchus

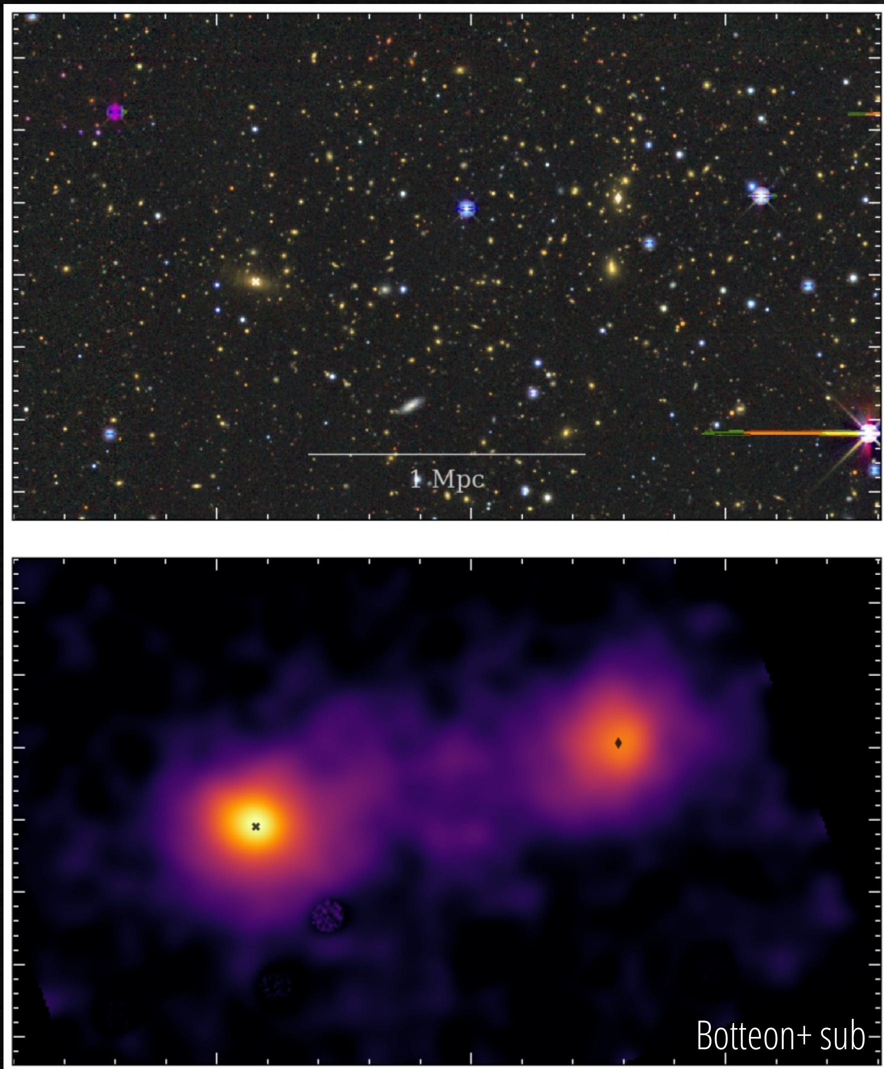


These detections demonstrate that **radio continuum** observations are especially valuable for discovering jellyfish galaxies as, in other bands, the detection is hampered by **Galactic absorption**


Credit: IllustrisTNG simulation

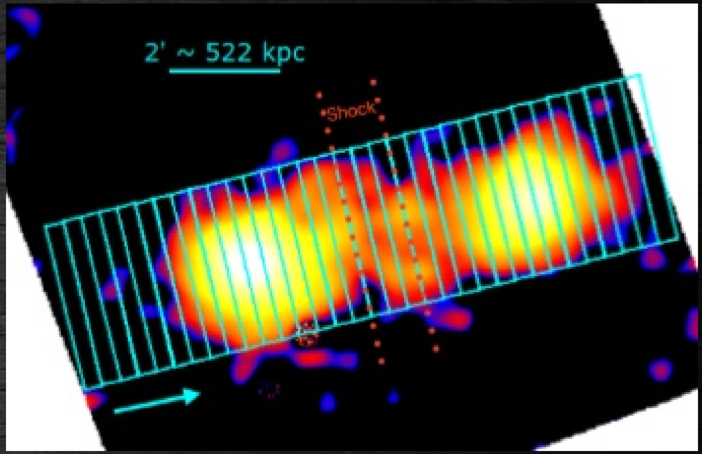

1 Mpc
Radio bridge
Optical+X-ray+Radio
deJong+22
Credit: IllustrisTNG simulation

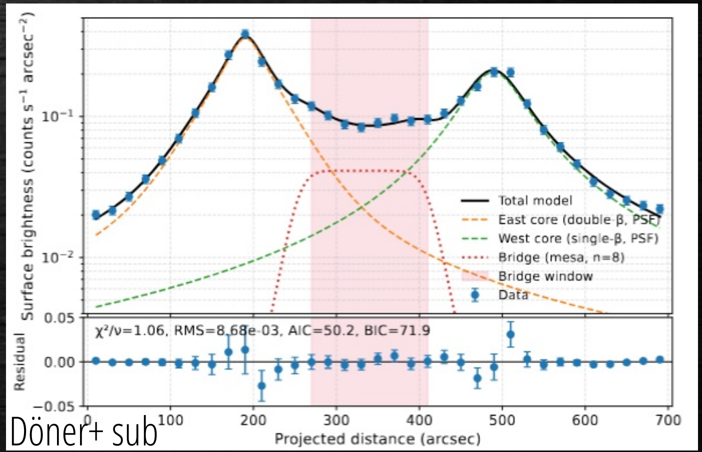
PSZ2 G279.79+39.09: a cluster pair



Not clear if observed **before** or **after** the core passage…

- z = 0.29
- R_{2D} ~ 1.3 Mpc
- $M_{500} = 6.1 \times 10^{14}\ M_{\odot}$ (PSZ2)

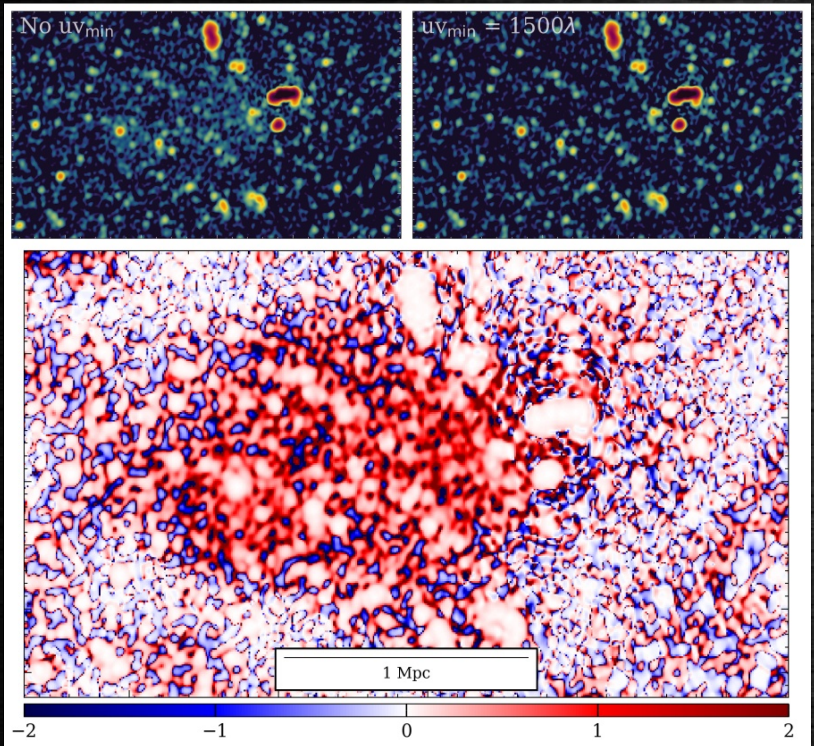




A&A, submitted

Enhanced radio emission between a galaxy cluster pair

Andrea Botteon[1], Turgay Caglar[2,3], Sibel Döner[4,2], Reinout J. van Weeren[3], and Krista Lynne Smith[2]



Radio follow-up: **MeerKAT** 7.5 h (UHF) + uGMRT 8 h (band 3)

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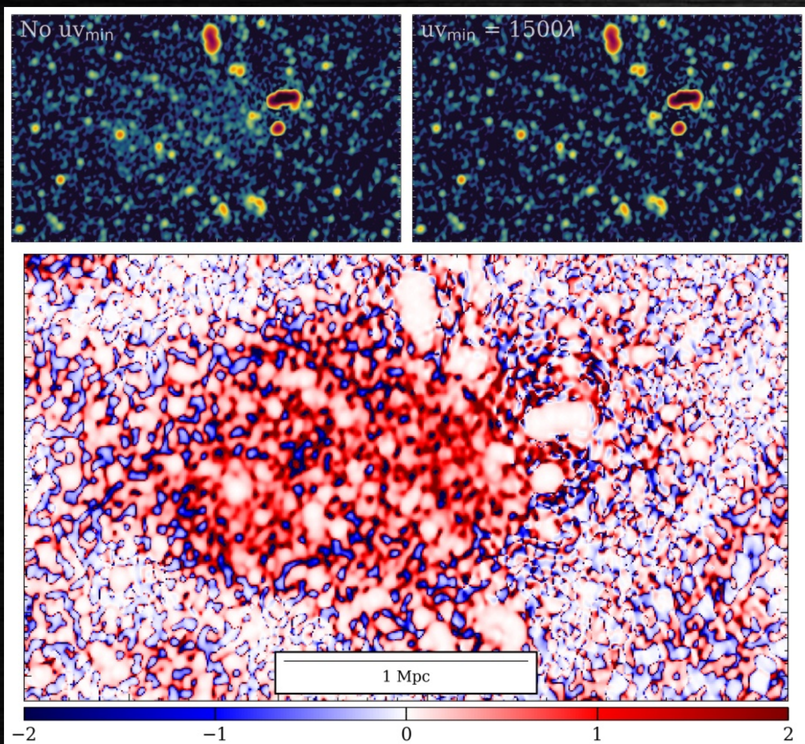
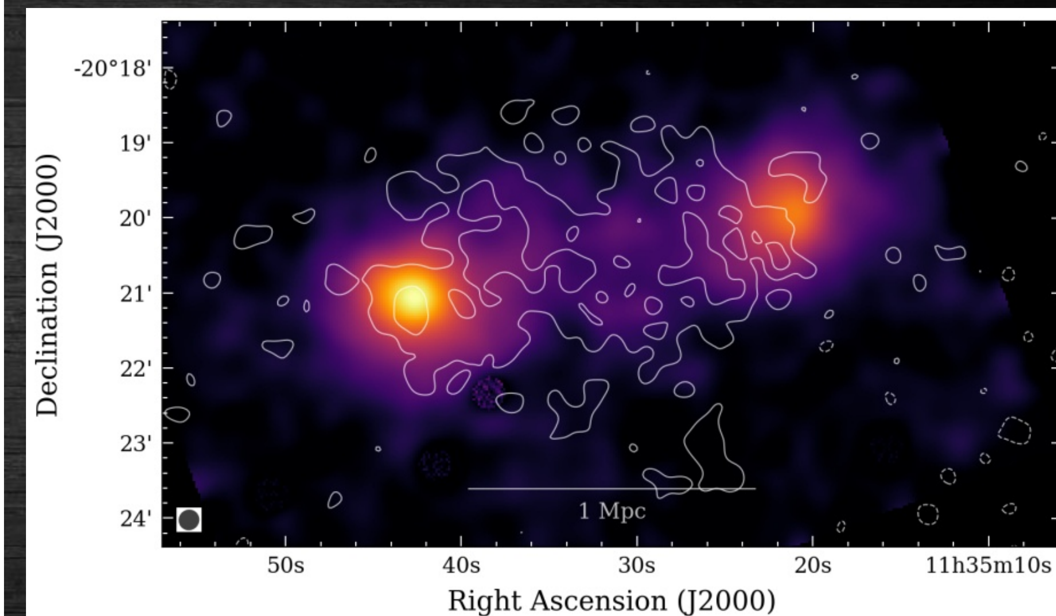
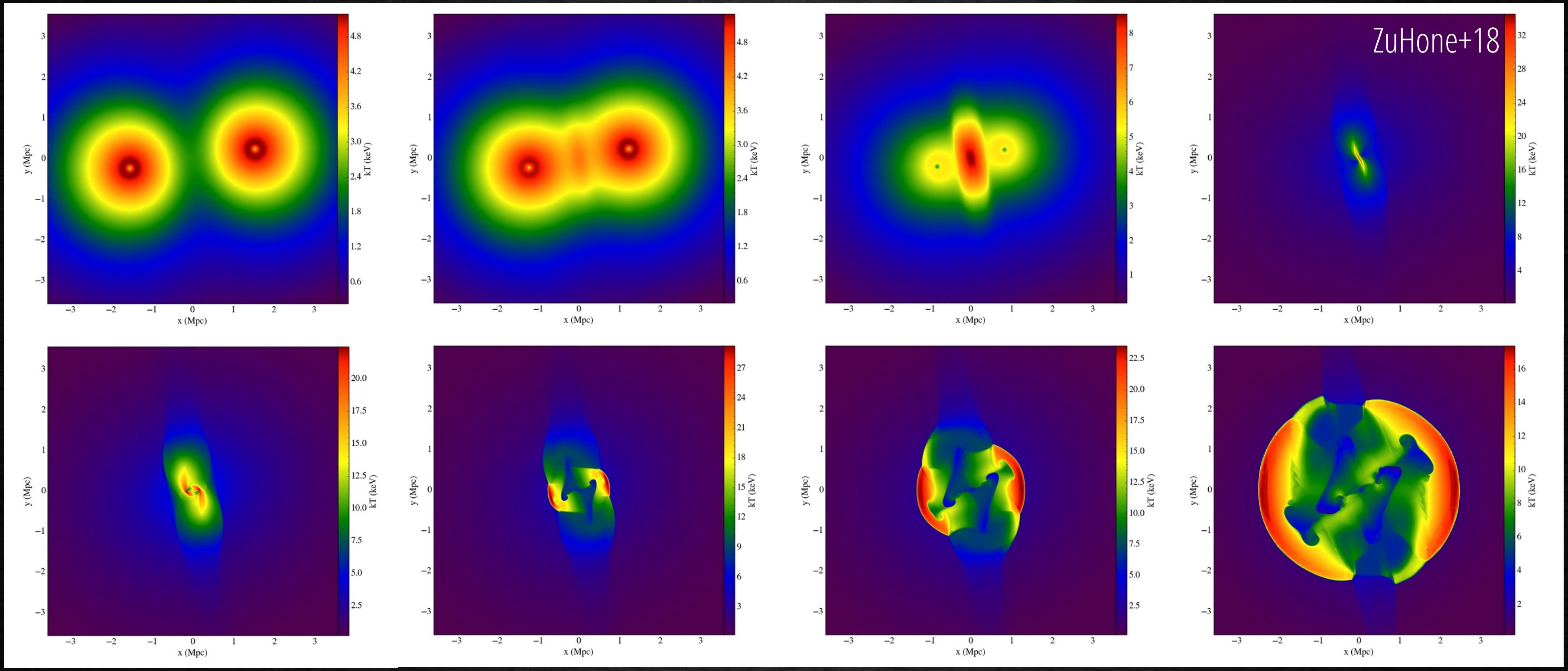




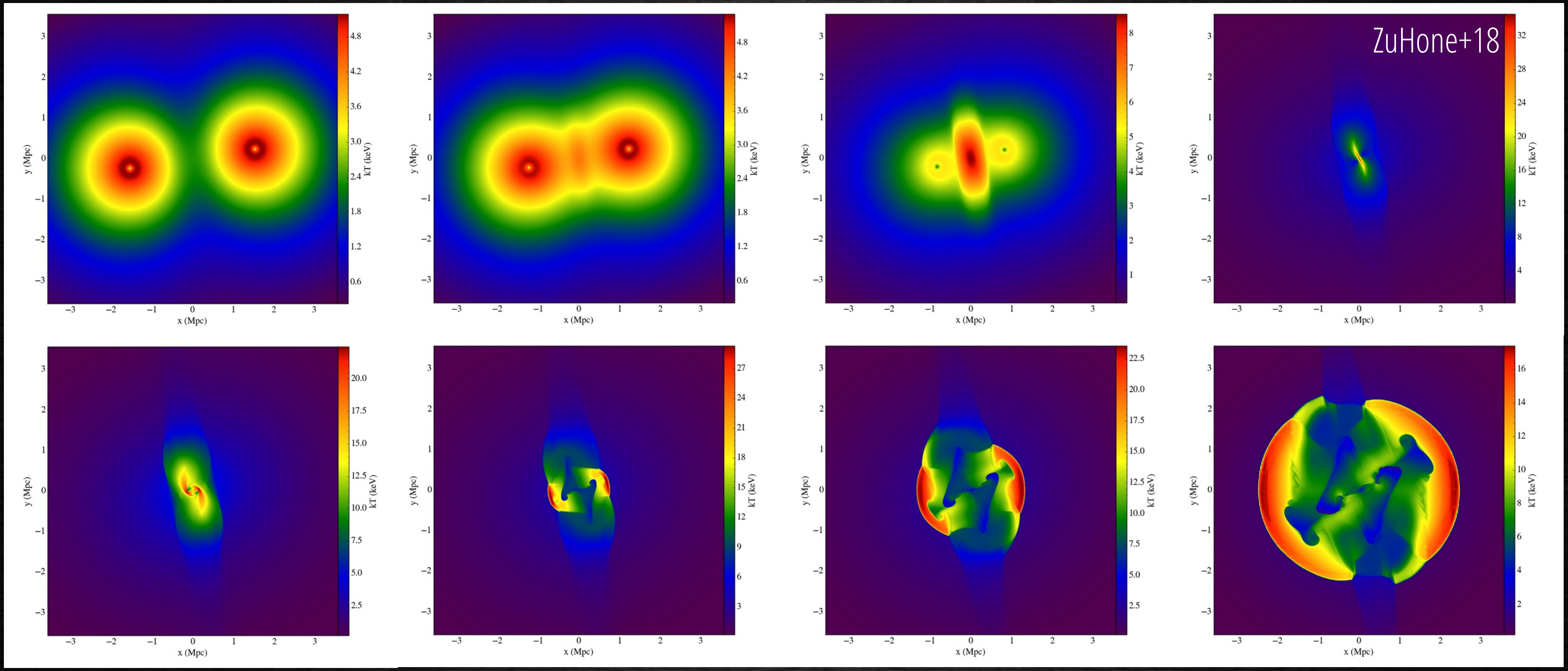
Radio follow-up: **MeerKAT** 7.5 h (UHF) + uGMRT 8 h (band 3)

Possible origin of the bridge



Possible origin of the bridge

Pericenter



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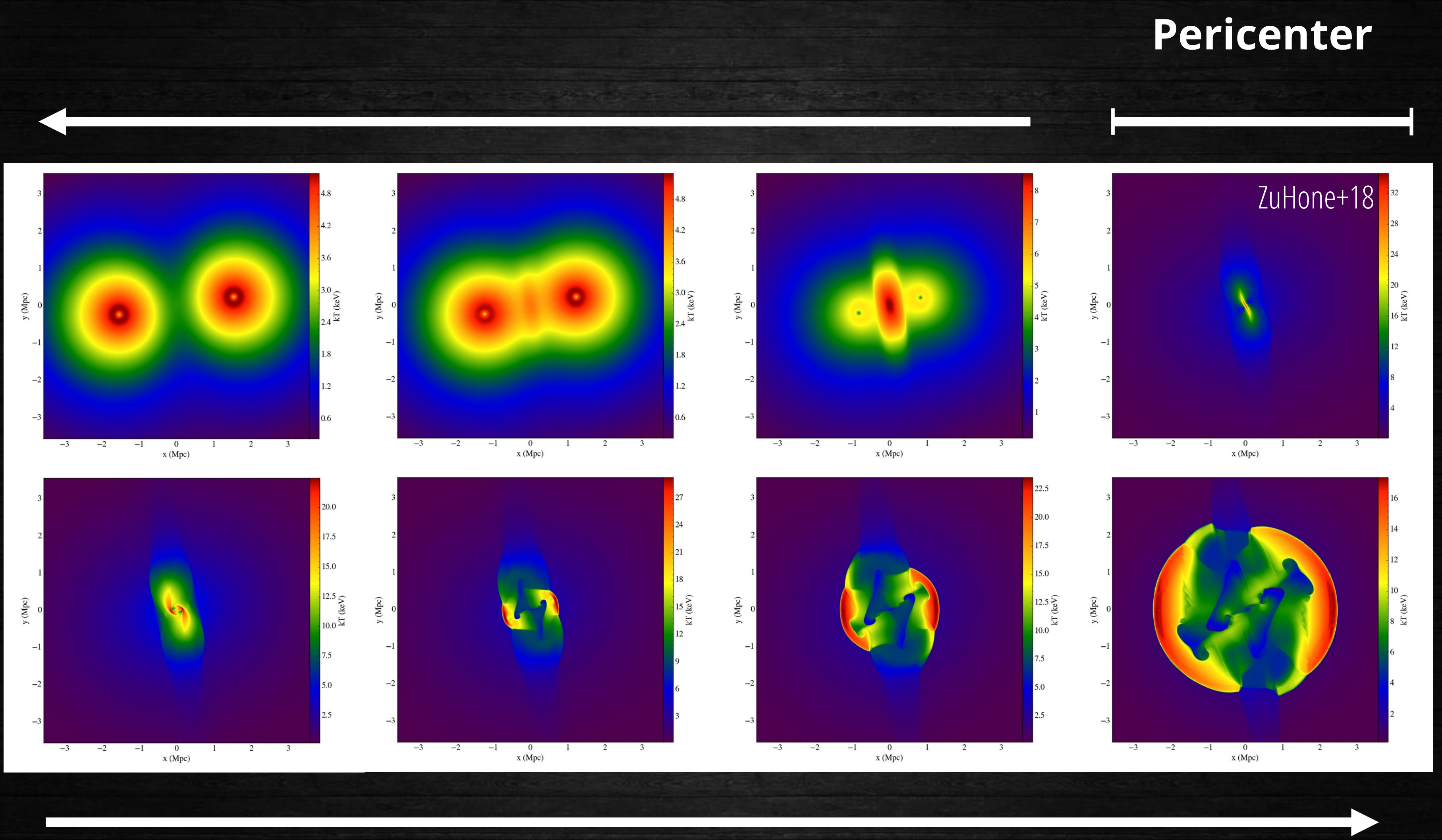
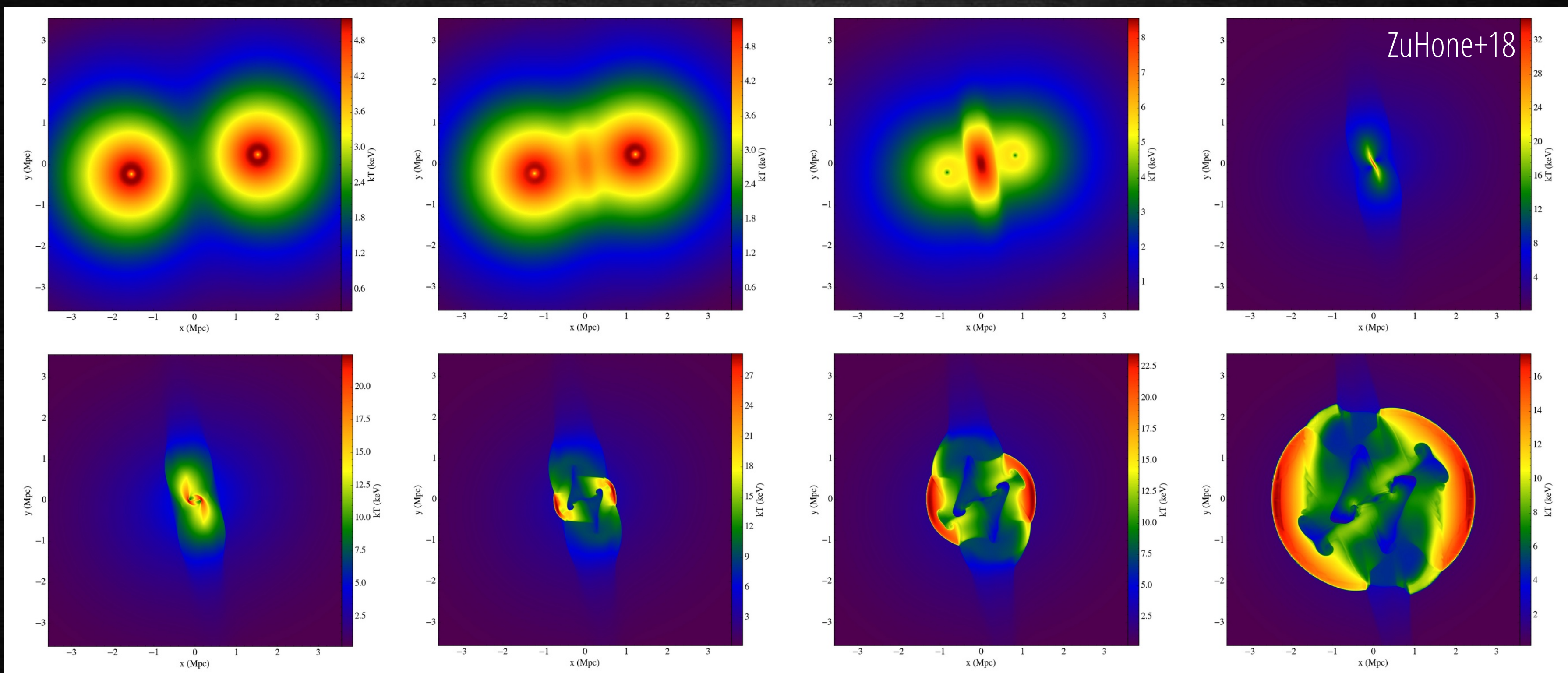


Possible origin of the bridge

Pre-collision: novel mechanisms operating in the intra-cluster region generate the radio emission (e.g. Brunetti+Vazza20), similarly to the cases of A399-A401 (Govoni+19) and A1758 (Botteon+20)

Pericenter



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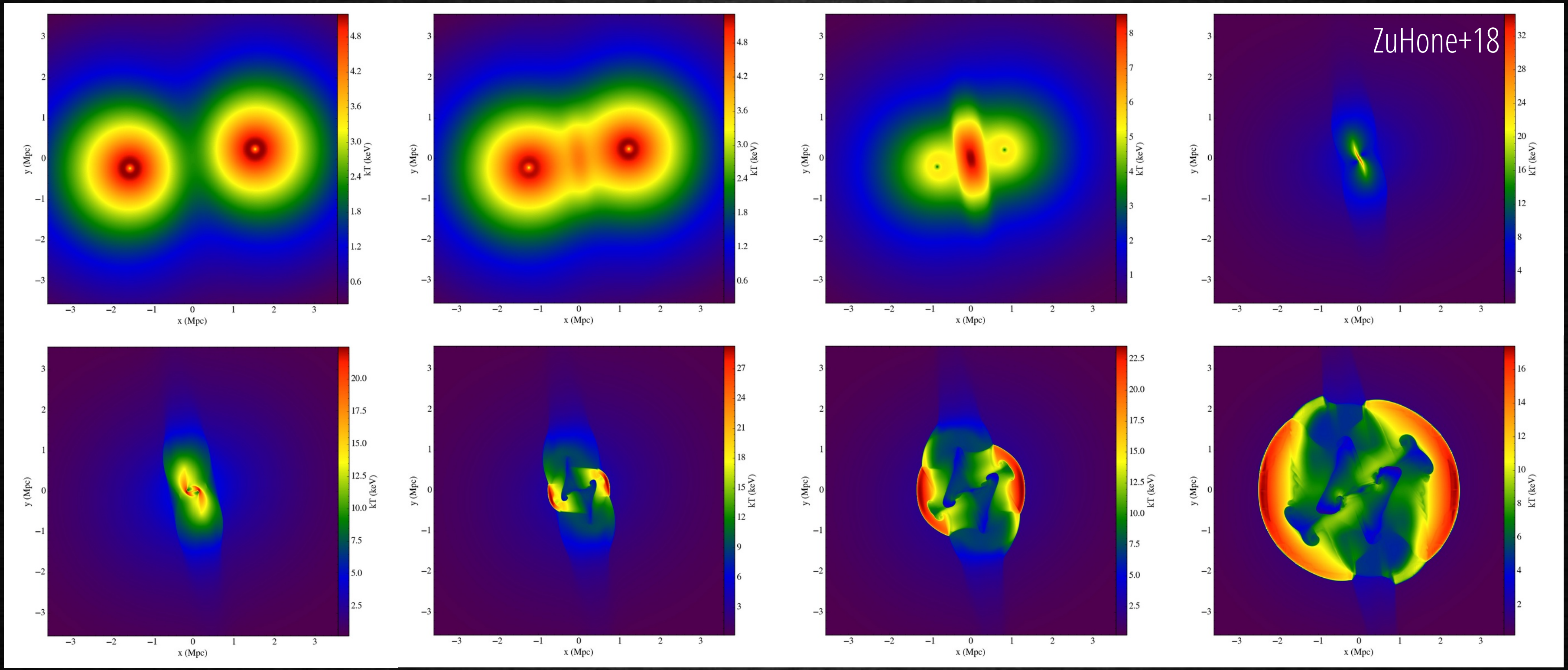


Post-collision: the turbulent wake in-between the clusters re-accelerates CRe, similarly to the cases of radio halo with surface brightness extensions due to the interaction with subclusters (e.g. Kim+89, Botteon+19, Pignataro+24)...also called “bridges” (e.g. Coma)

Conclusions

- Galaxy clusters host diffuse synchrotron sources in the ICM

- **A754:** an energetic merger
  - A case of halo-shock connection
  - Discovery of a faint distant radio relic
  - New merger scenario

Botteon+24

- **Ophiuchus Cluster:** a relaxed, sloshing cluster
  - Detection of synchrotron threads
  - Discovery of jellyfish galaxies

Botteon+25

- **G279+39:** a cluster pair close to pericenter passage
  - Detection of a radio bridge connecting the two clusters

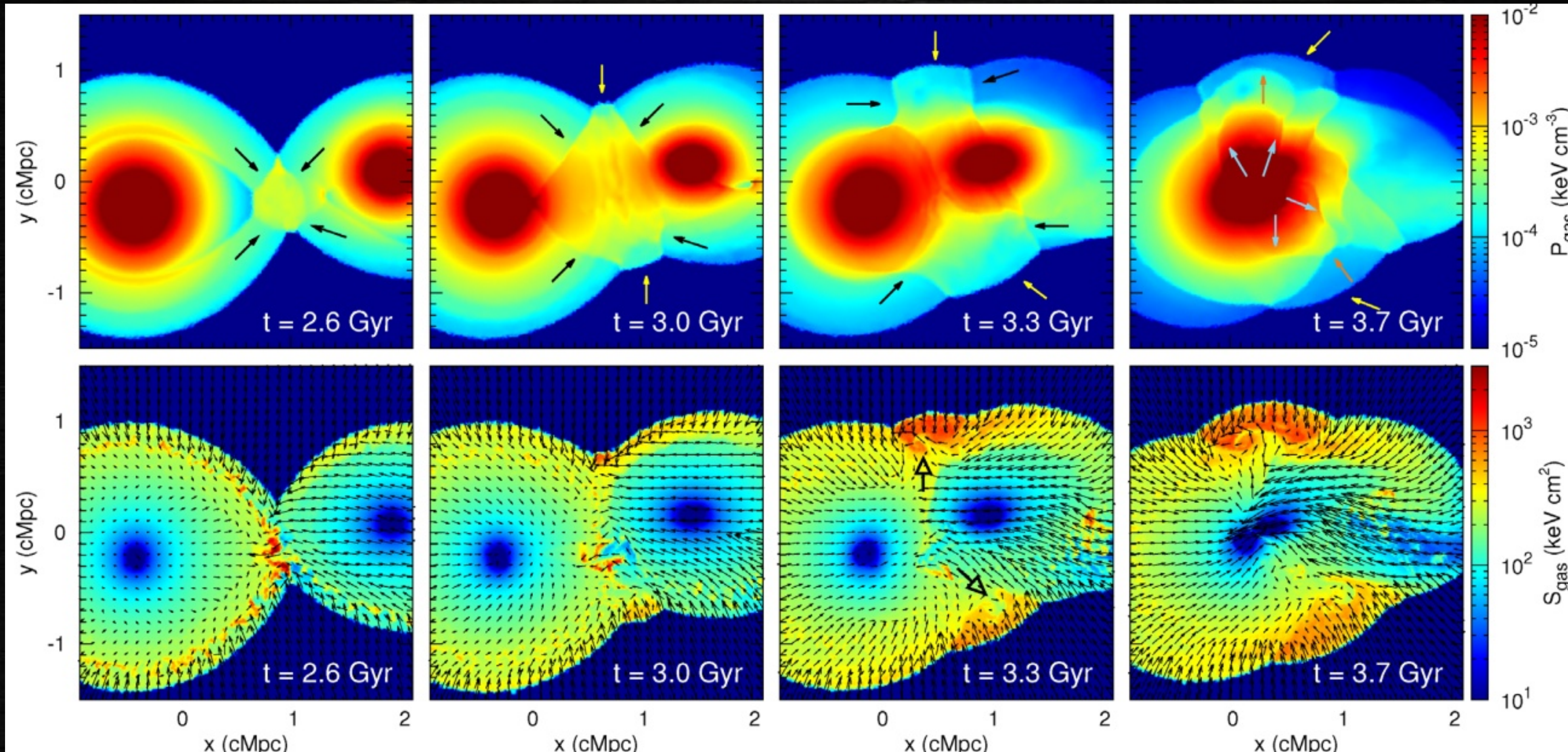
Botteon+ submitted

- MeerKAT can efficiently probe non-thermal phenomena in clusters in different dynamical states

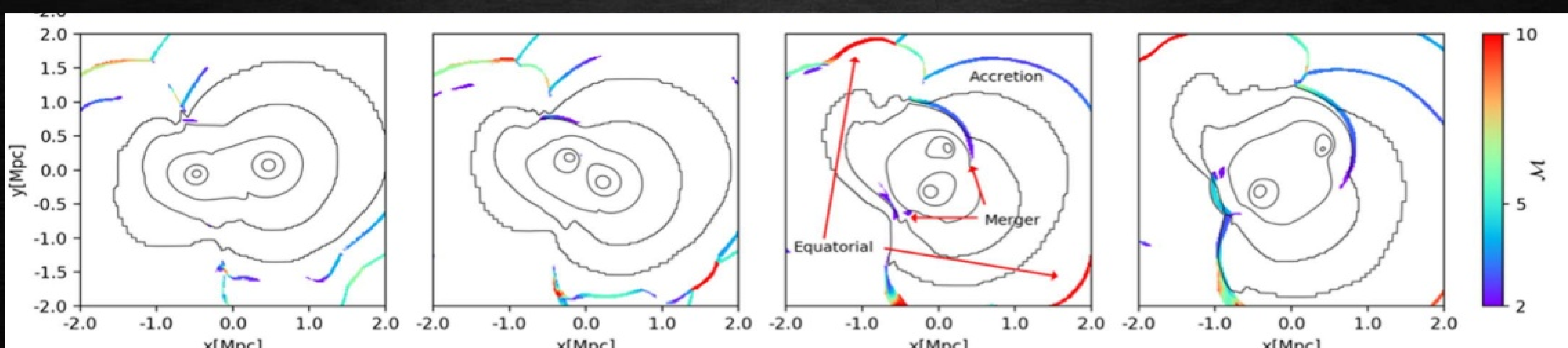
Thank you

Extra slides

Equatorial(?) shocks

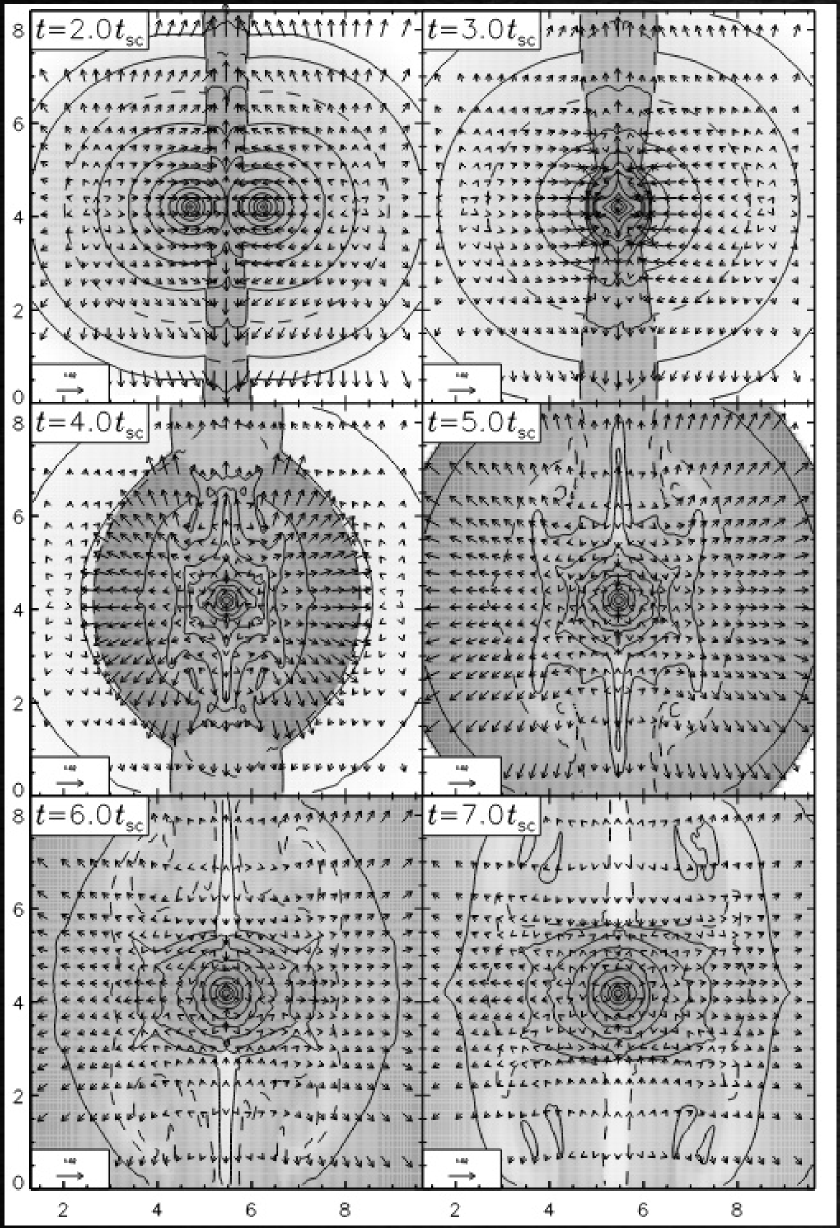


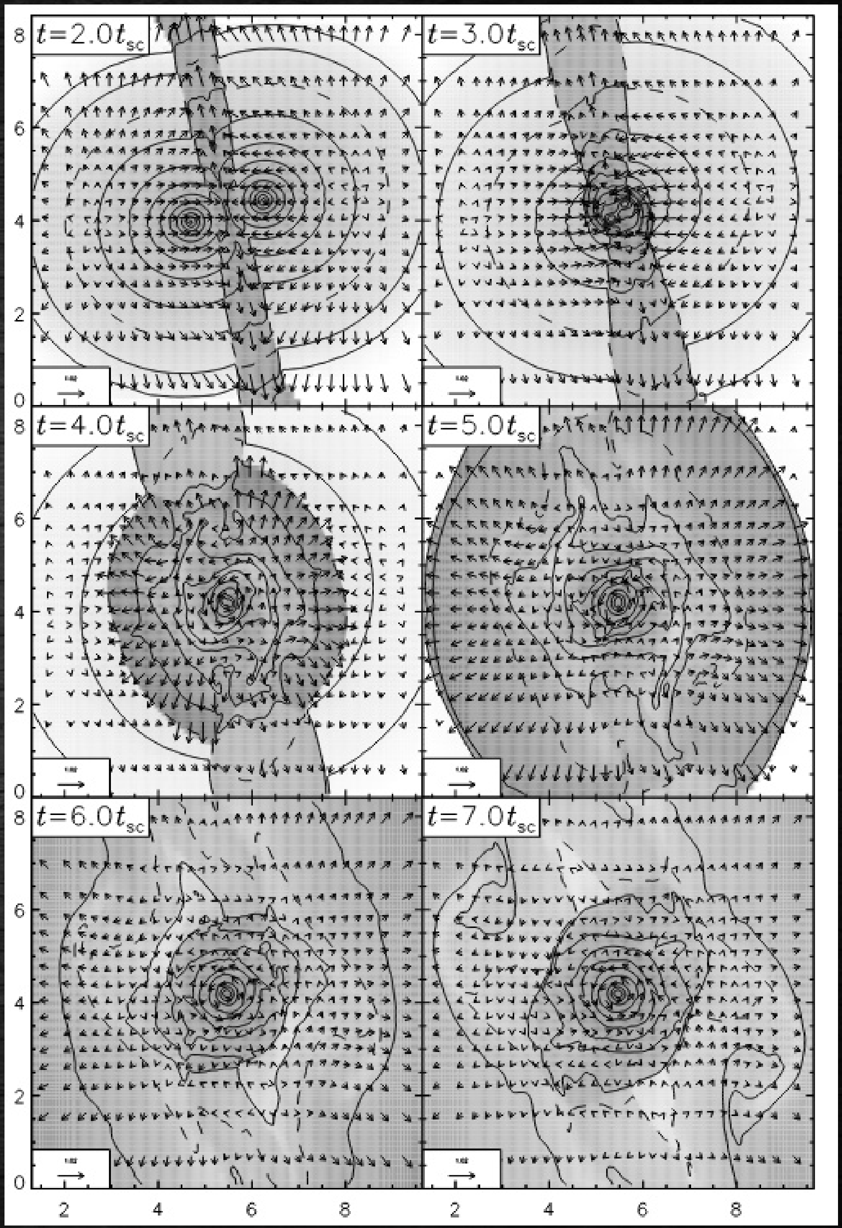
Zhang+21



Lee+20

Perpendicular outflows



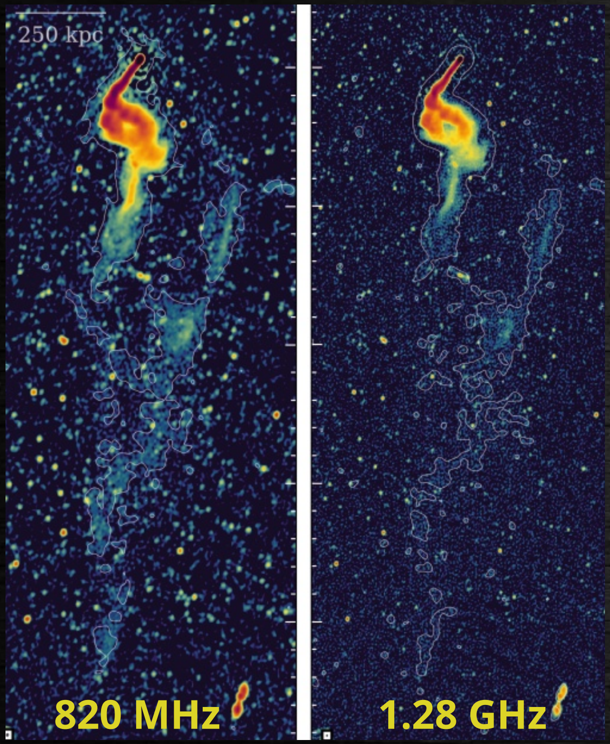


Ricker98

The relic

Acceleration of thermal e$^-$ via DSA is problematic at weak cluster shocks: generally we talk about **re-acceleration** of existing CRe

(Kang+Jones02,05, Vazza+14,15,16, Botteon+20a)



LLS = 1.6 Mpc

$\alpha = 1.24 \pm 0.39$

$P_{1.4} = 8.0 \times 10^{22}$ W/Hz

The relic

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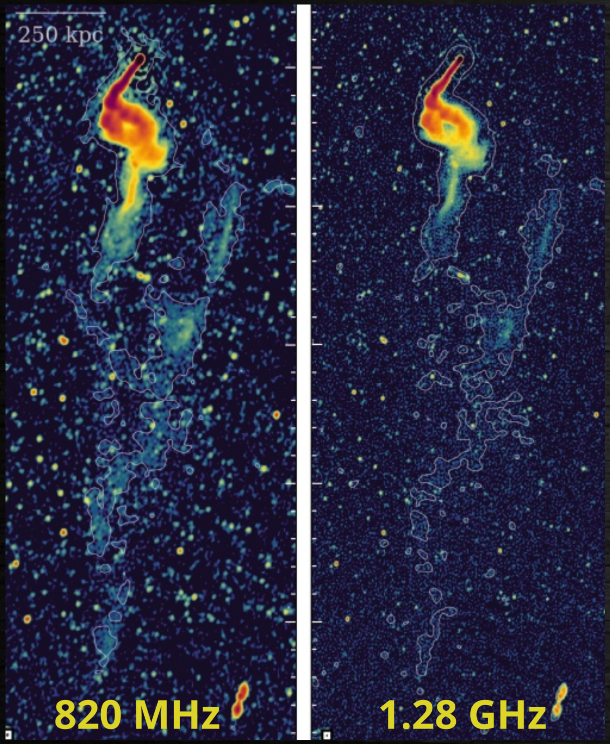

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Low $P_{1.4}$ but high F_{shock} $(\propto 0.5 \times V^3_{sh} \times \rho_u \times A)$

↓

Is DSA viable here?

The relic

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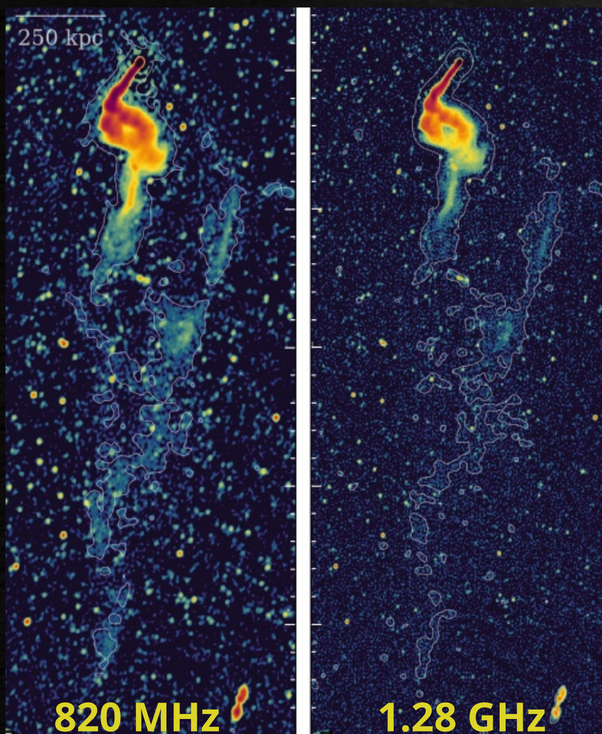

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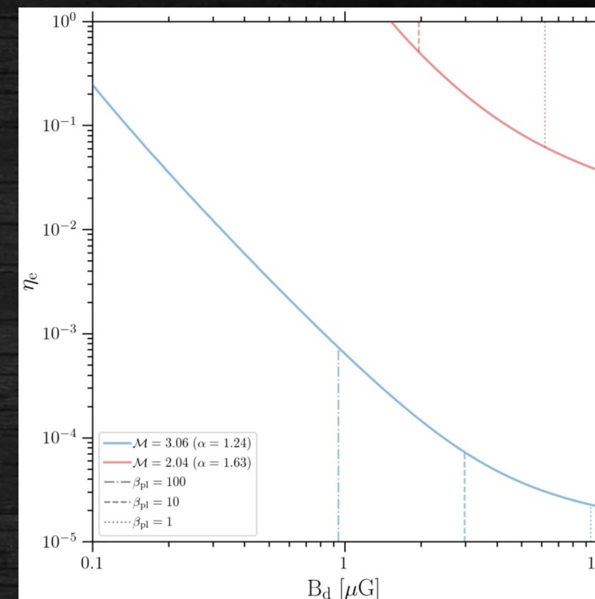

<10^{-3} of the kinetic energy dissipated at the shock surface (η_e) is needed to accelerate thermal electrons if B_d > 0.8 μG

The relic

Acceleration of thermal e⁻ via DSA is problematic at weak cluster shocks: generally we talk about **re-acceleration** of existing CRe

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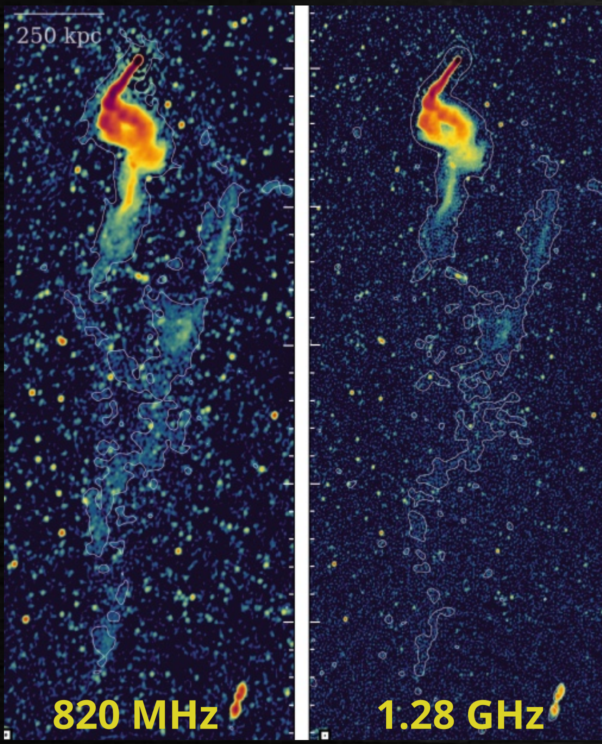

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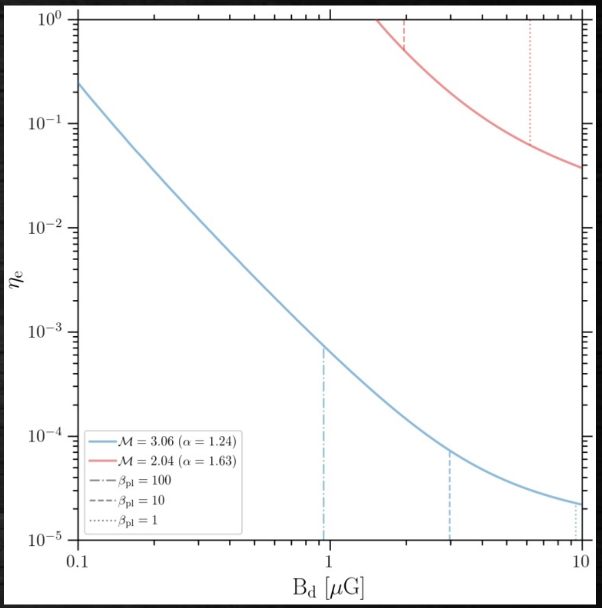
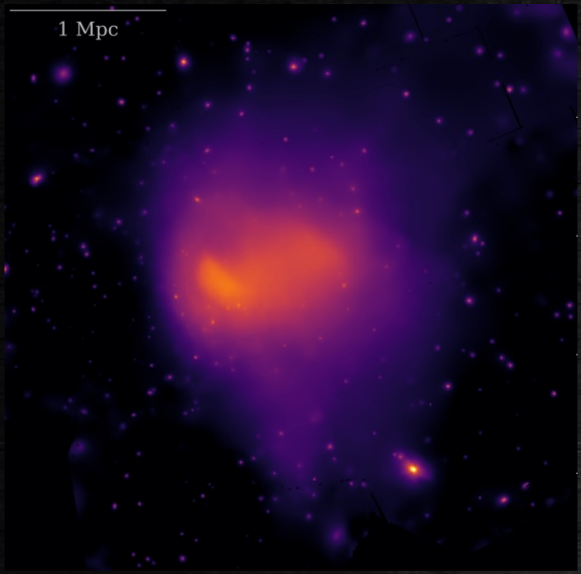
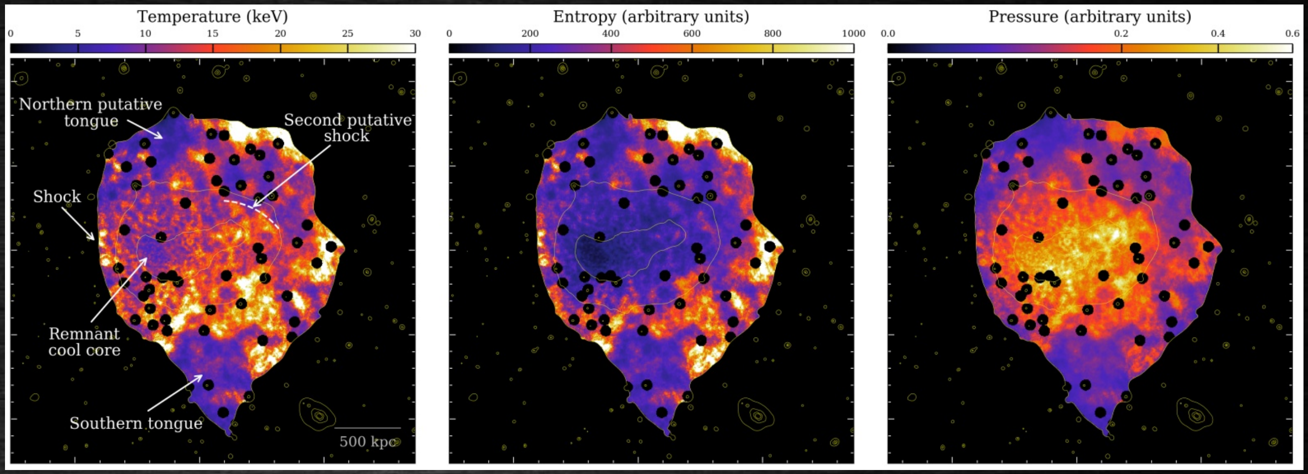


$<10^{-3}$ of the kinetic energy dissipated at the shock surface (η_e) is needed to accelerate thermal electrons if $B_d > 0.8$ μG

DSA <u>is not</u> ruled out: a weak radio relic powered by direct acceleration of thermal pool electrons?

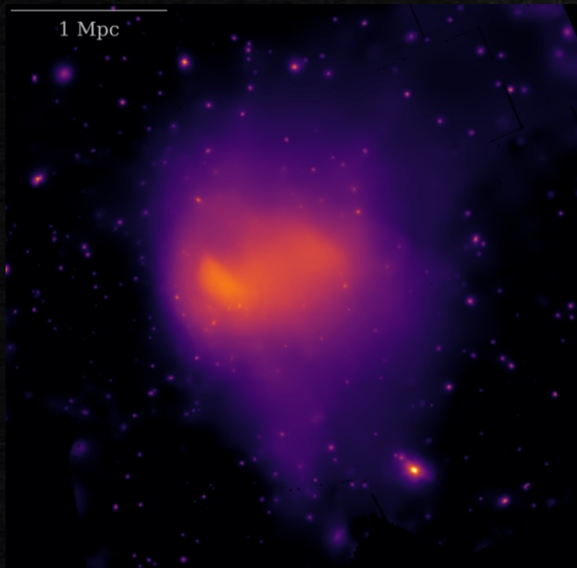
Thermal gas properties

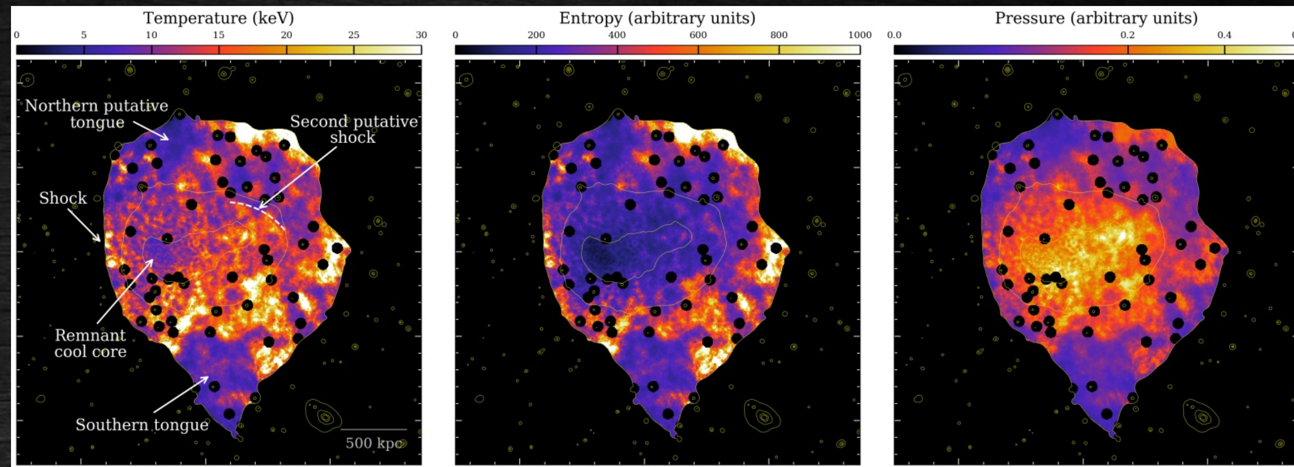




Low temperature/entropy/pressure "tongue" of emission in the south, with a putative counterpart in the north

Thermal gas properties





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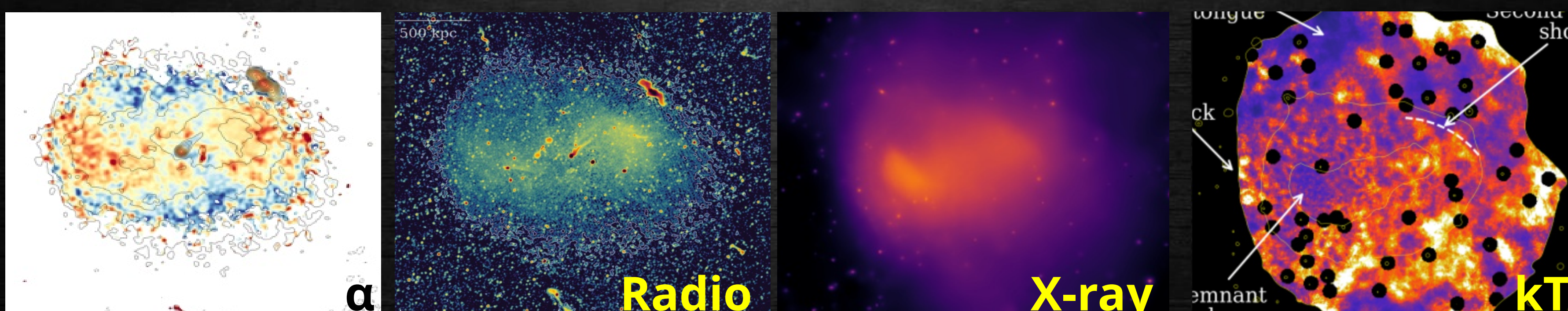
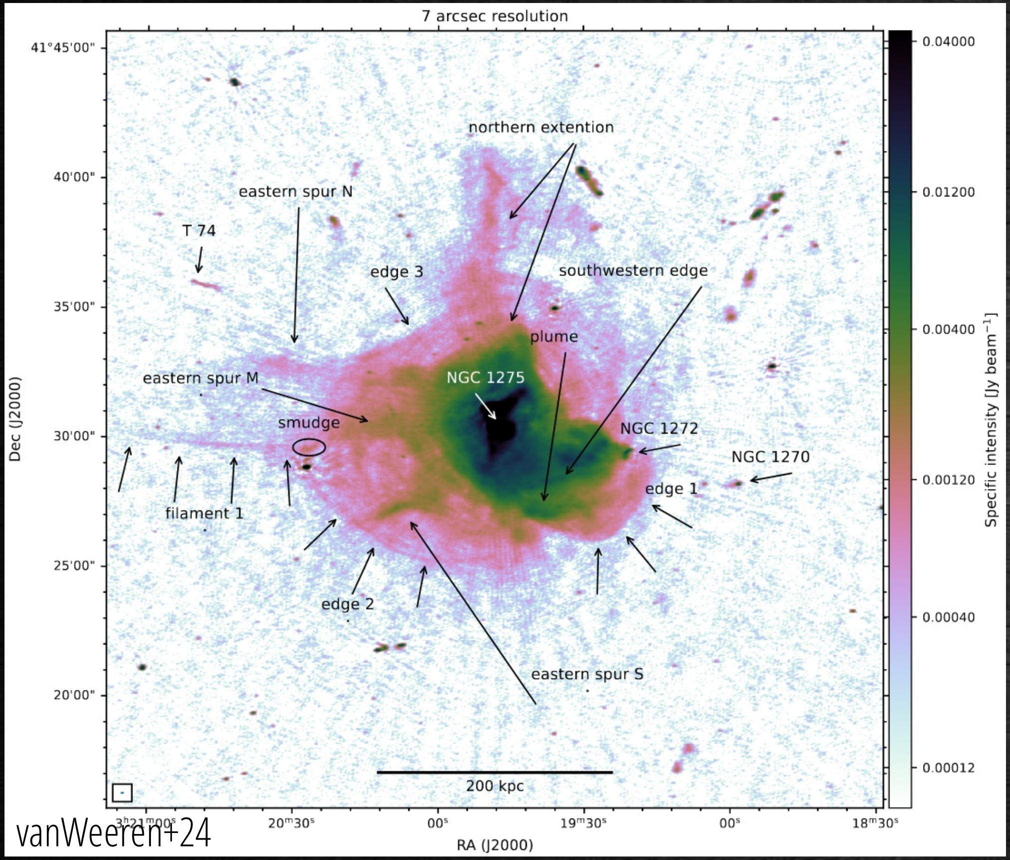


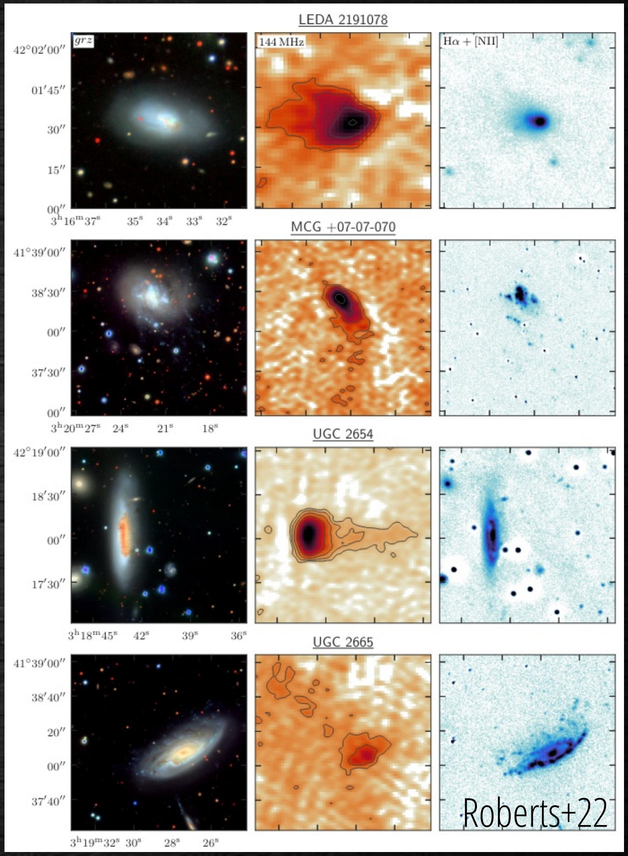
Signs of heated gas where the halo spectrum is flatter and where the radio/X-ray emissions possibly show a SB edge

LOFAR results on Perseus

Perseus is similar to Ophiuchus: nearby, sloshing, it hosts a mini-halo…



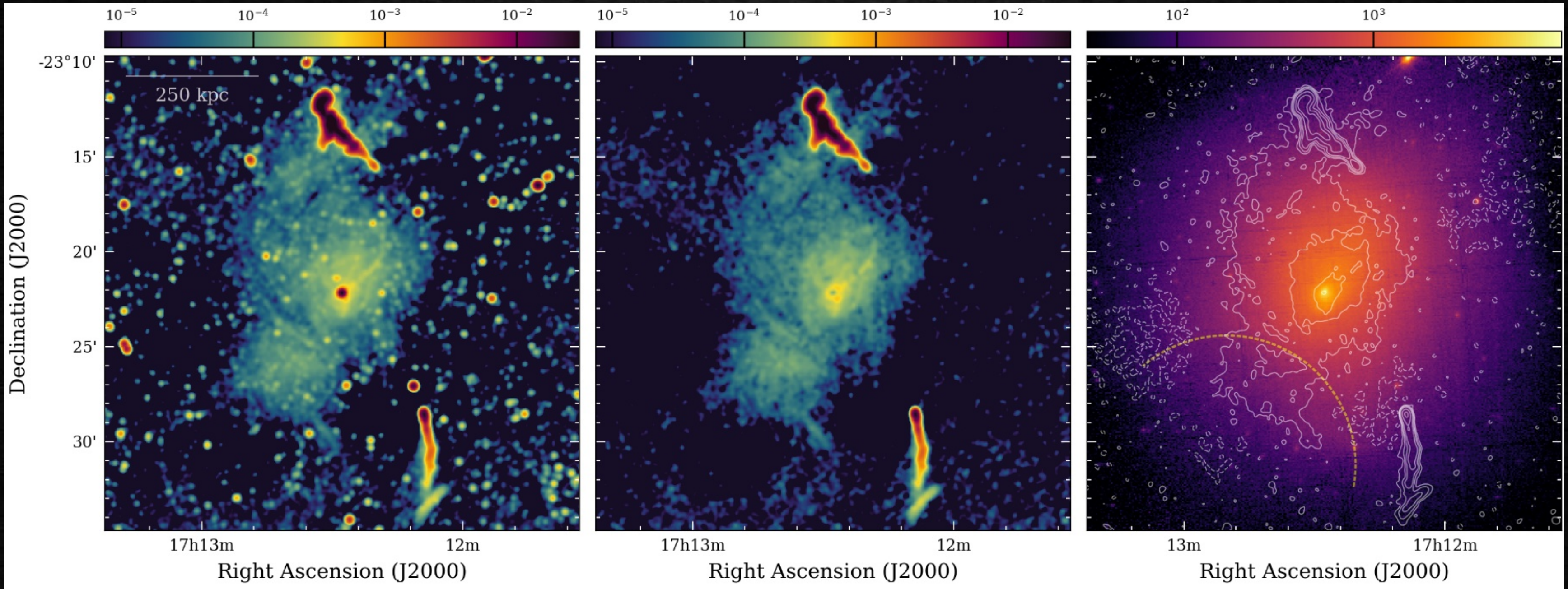
Detection of **filaments**



Detection of **jellyfish**

MeerKAT detects similar features in Ophiuchus

The cluster diffuse emission



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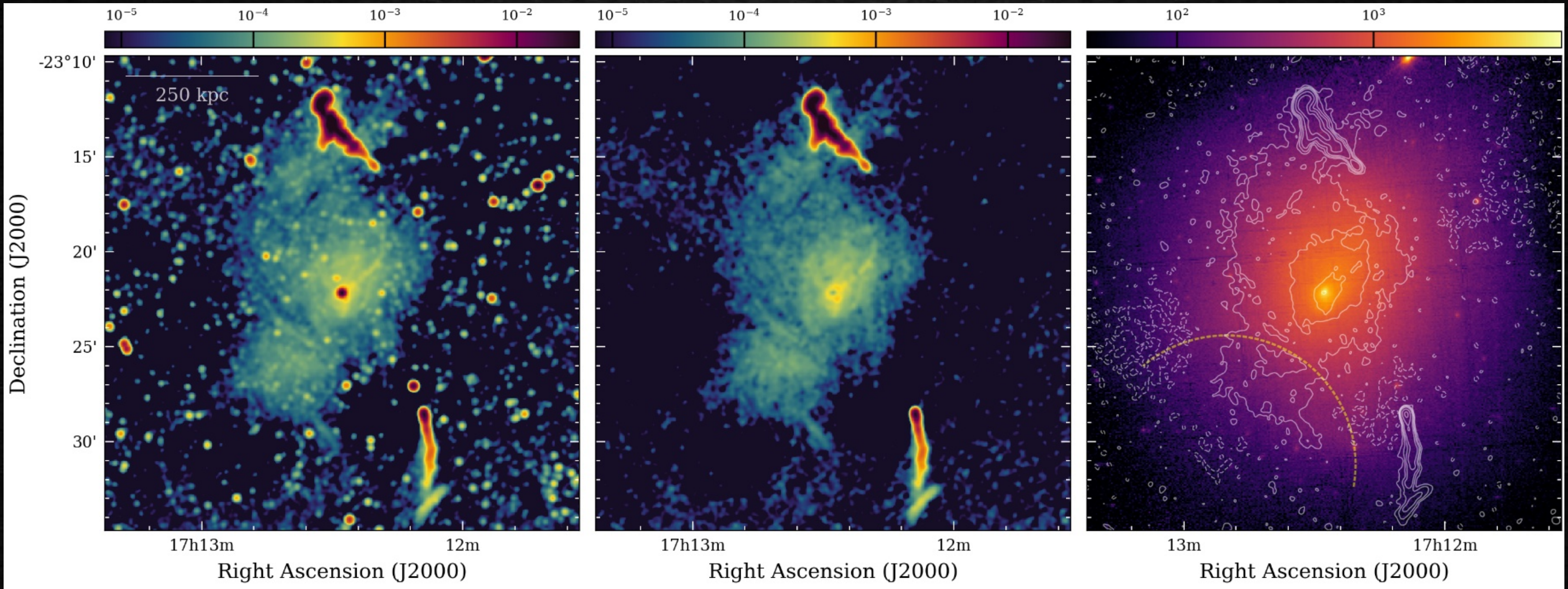
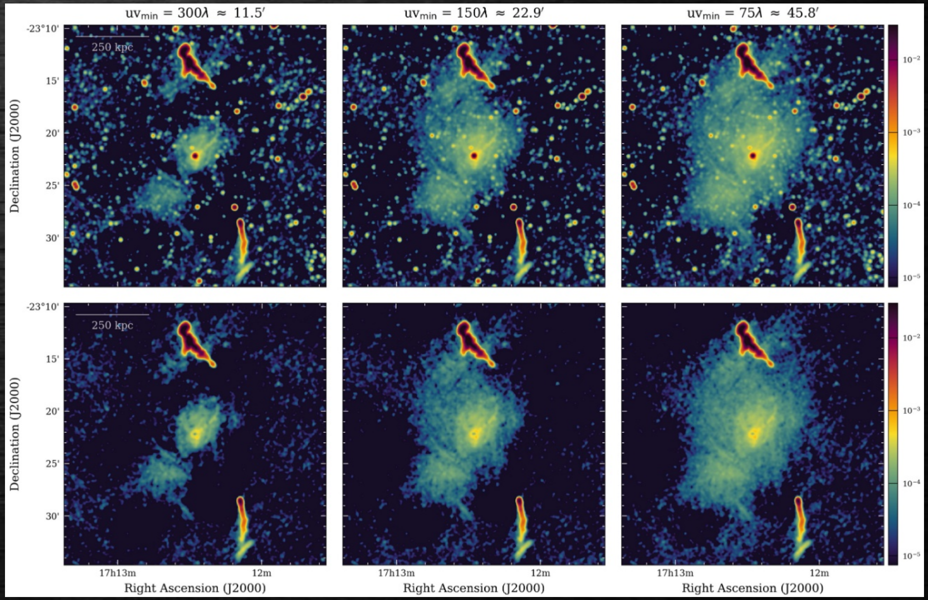
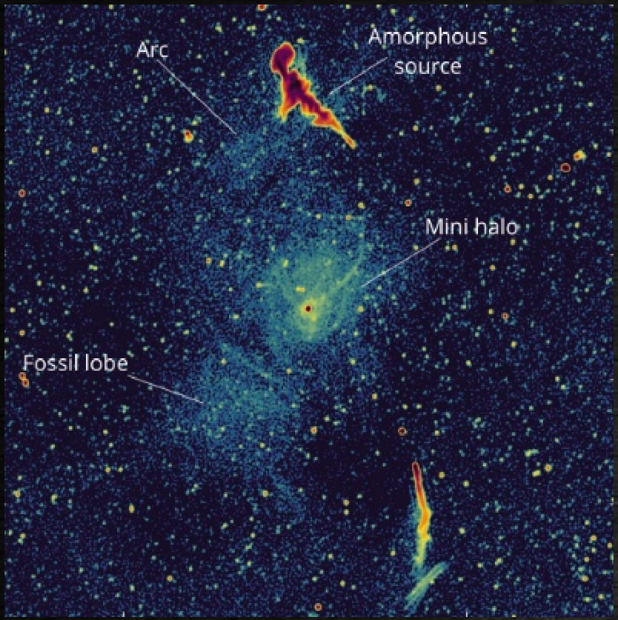
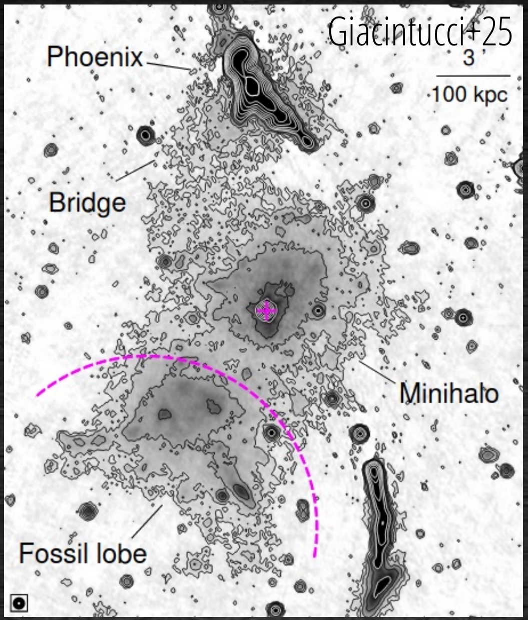


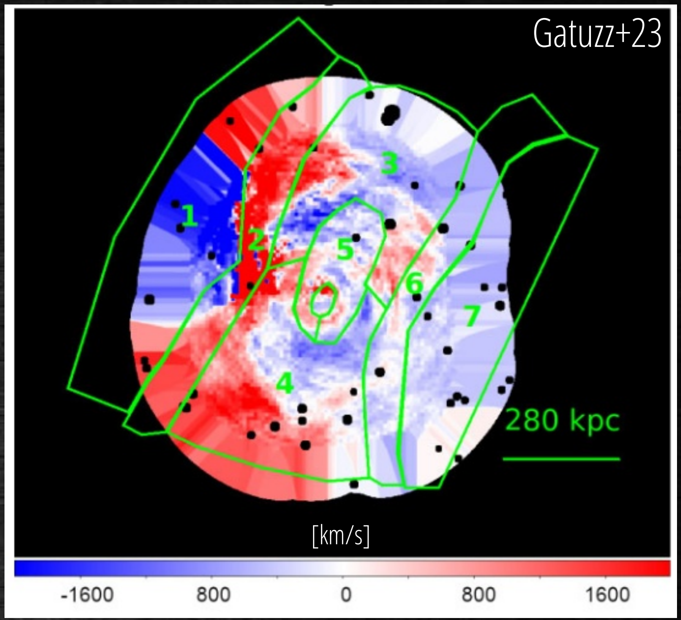
The detection of the extended emission from the **Ophiuchus cluster** is in competition with the necessity to filter out large-scale **Galactic** emission



Where is the counterpart lobe?







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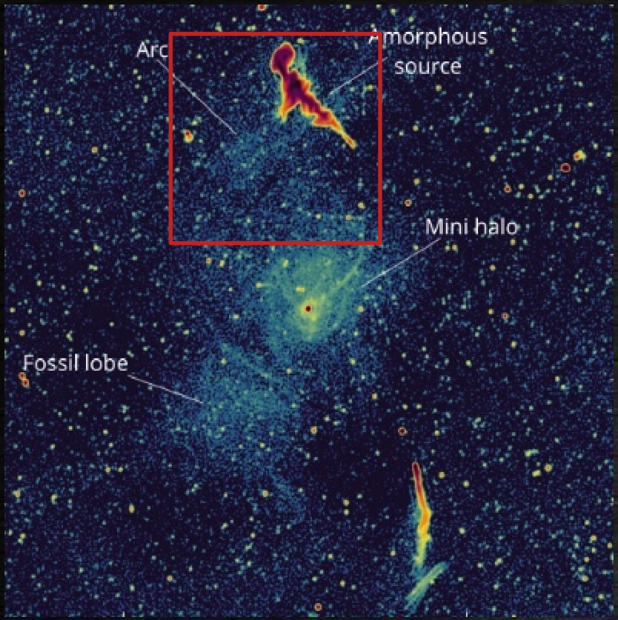

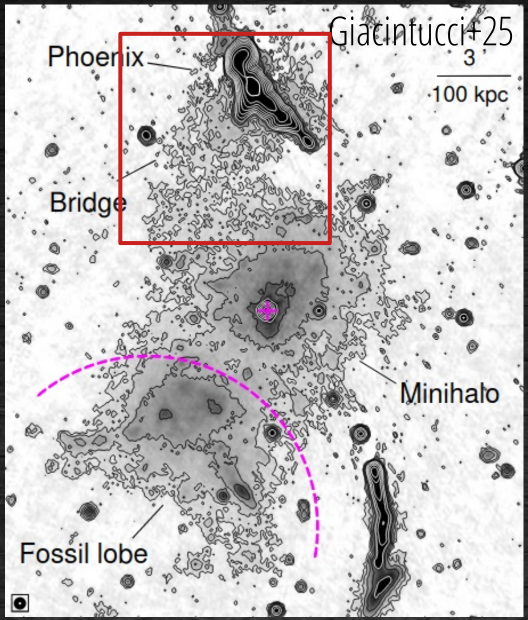

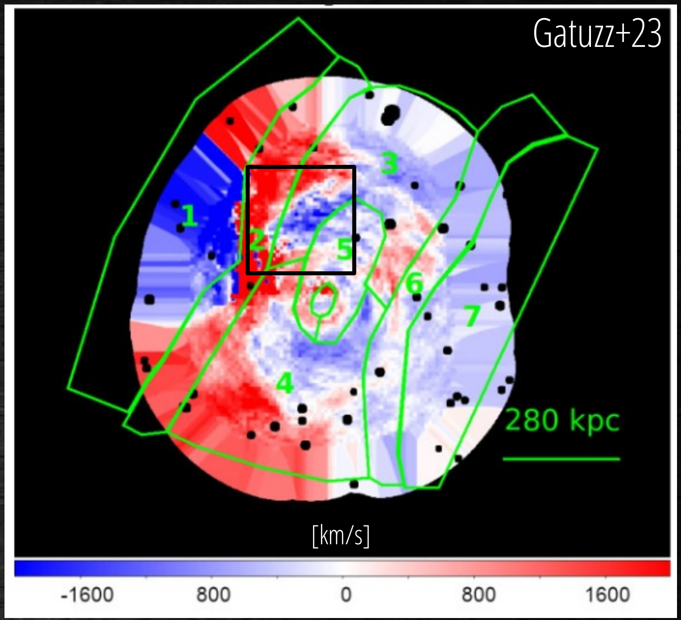

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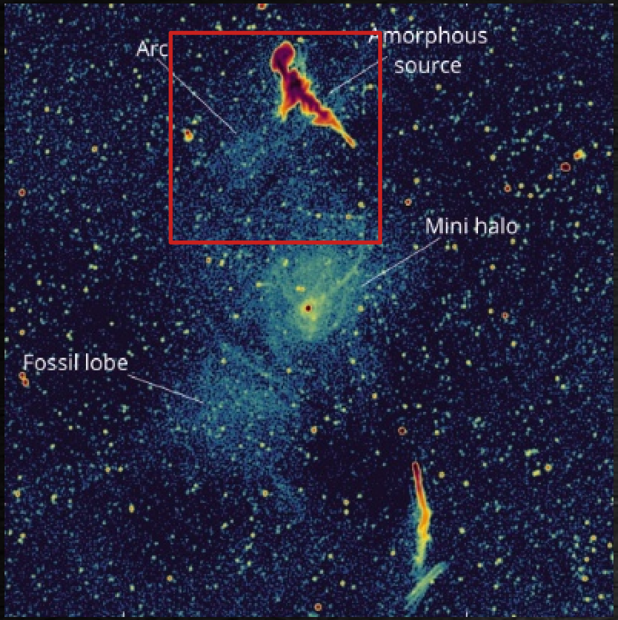
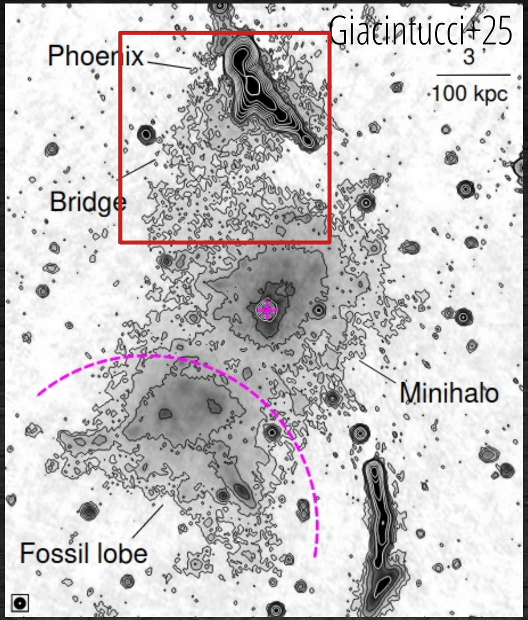
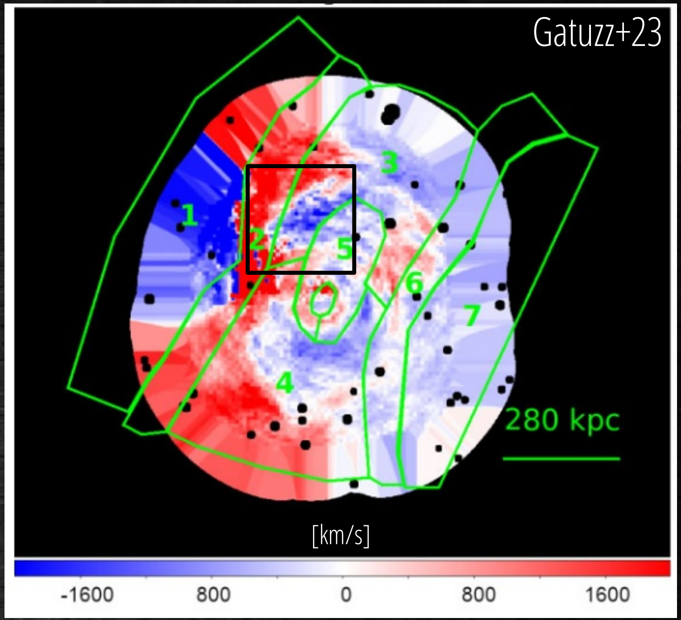
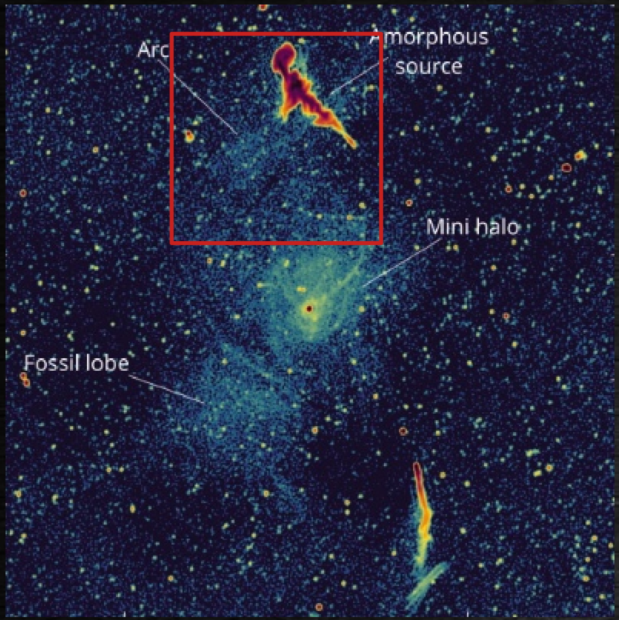


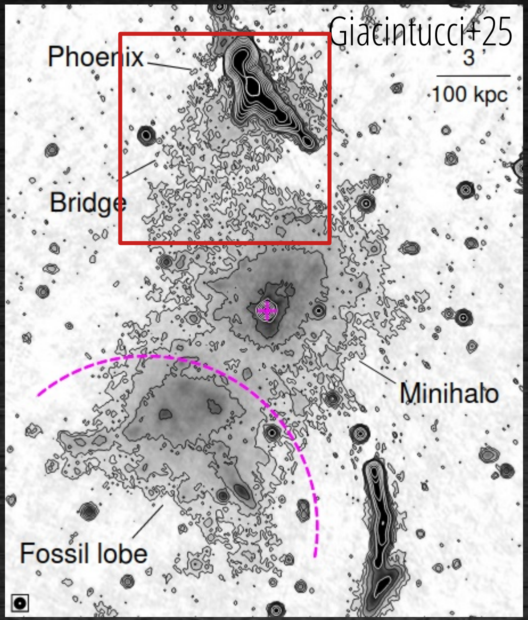


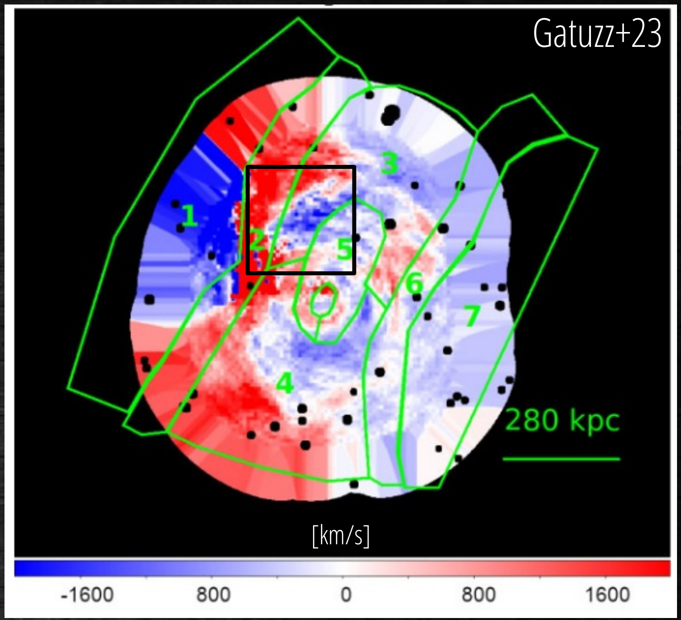


Is the arc old nonthermal plasma transported by shear flows?

Where is the counterpart lobe?







Is the arc old nonthermal plasma transported by shear flows?

Could the arc be the counter lobe stretched by gas sloshing?
(see also Giacintucci+25)

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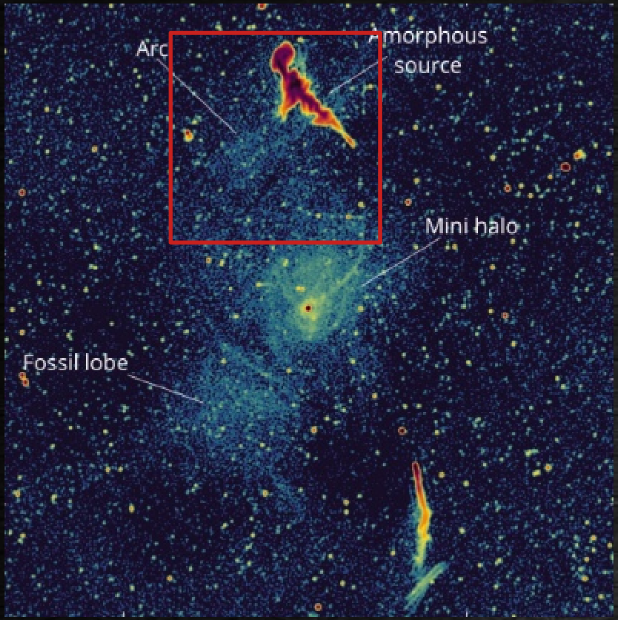

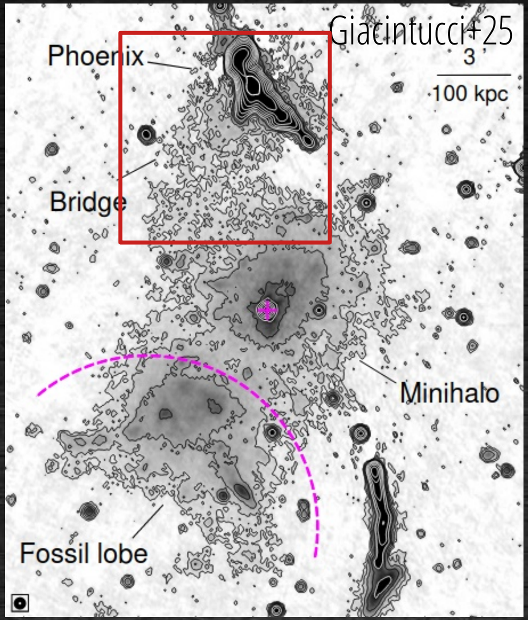

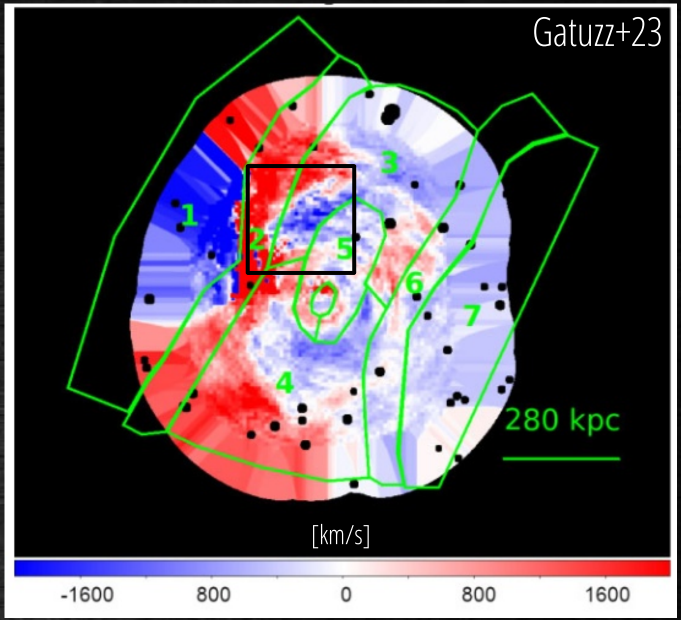

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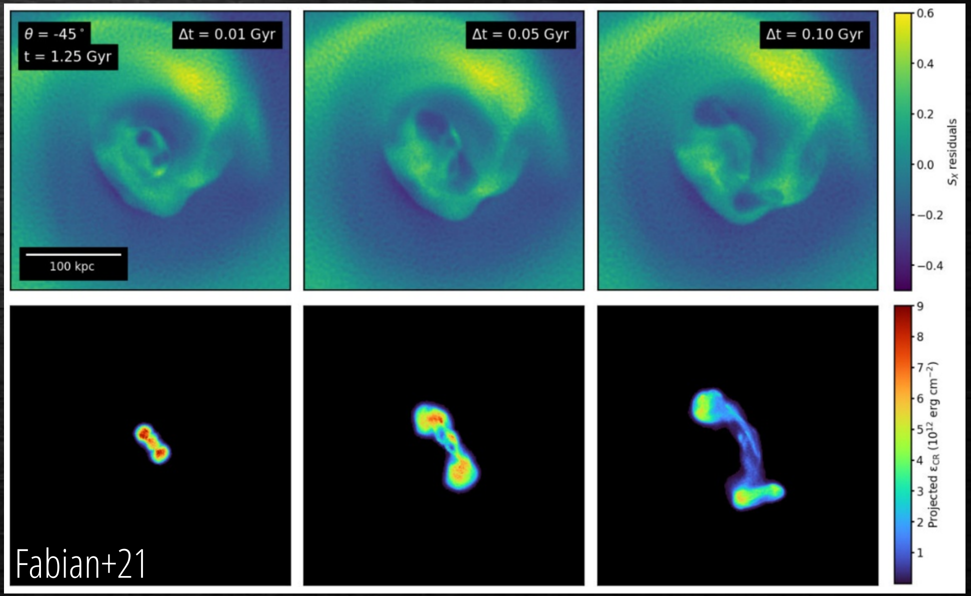
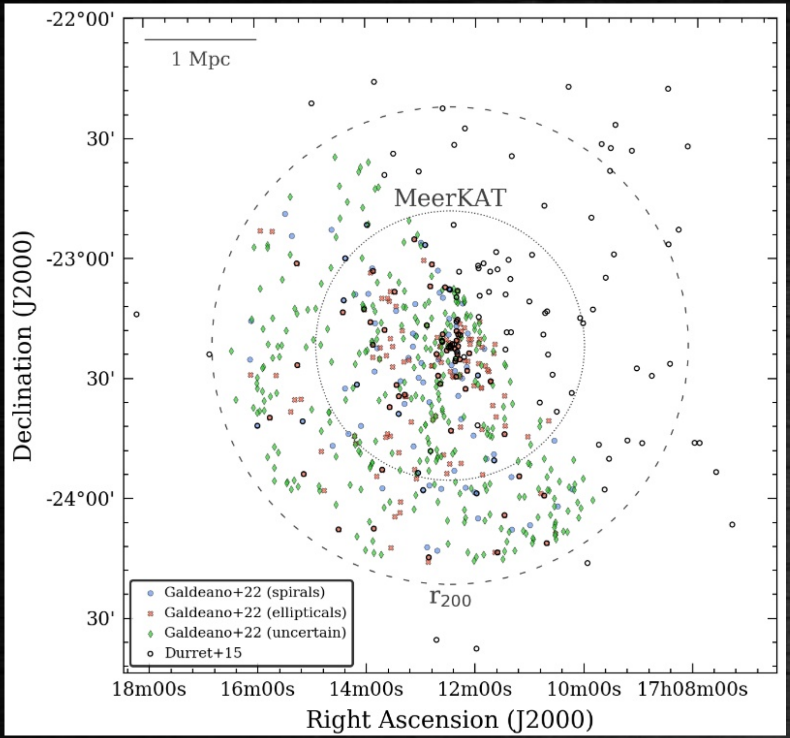


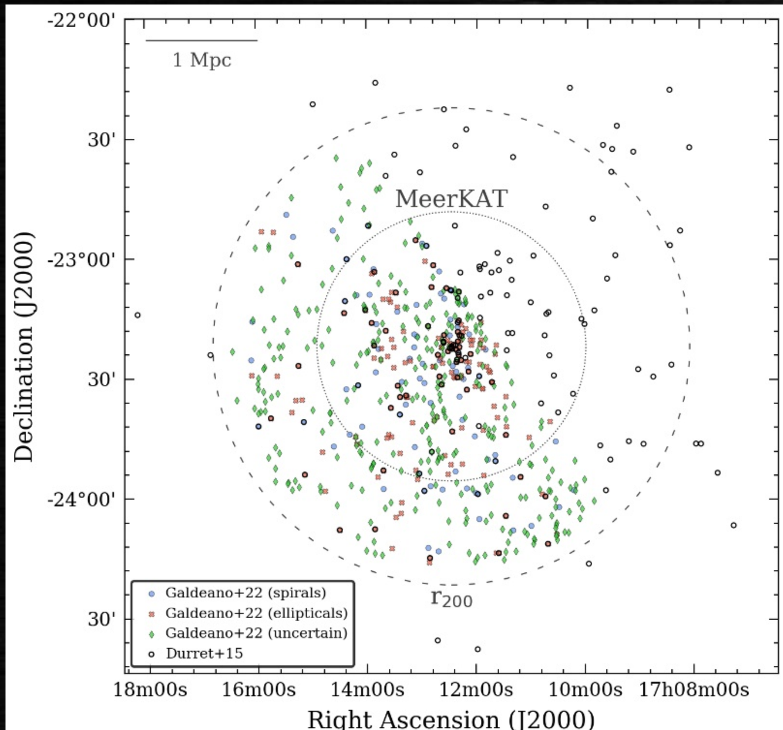
A catalog of cluster radio galaxies



- 152 spectroscopically confirmed members (Durret+15)
- 537 candidate photometric members morphologically classified as **elliptical**, **spiral** and **uncertain** (Galdeano+22)

→ 65 radio galaxies belong to Ophiuchus

A catalog of cluster radio galaxies



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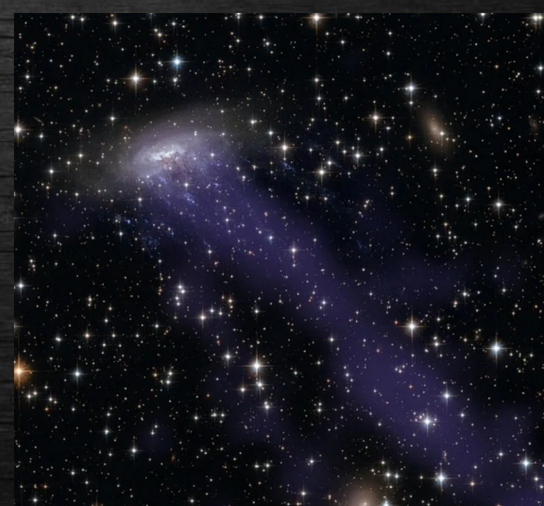
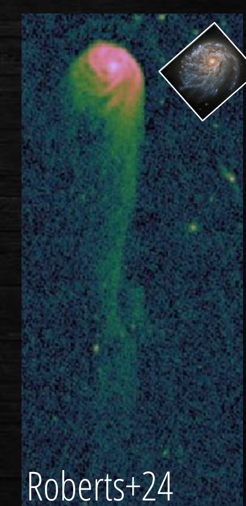
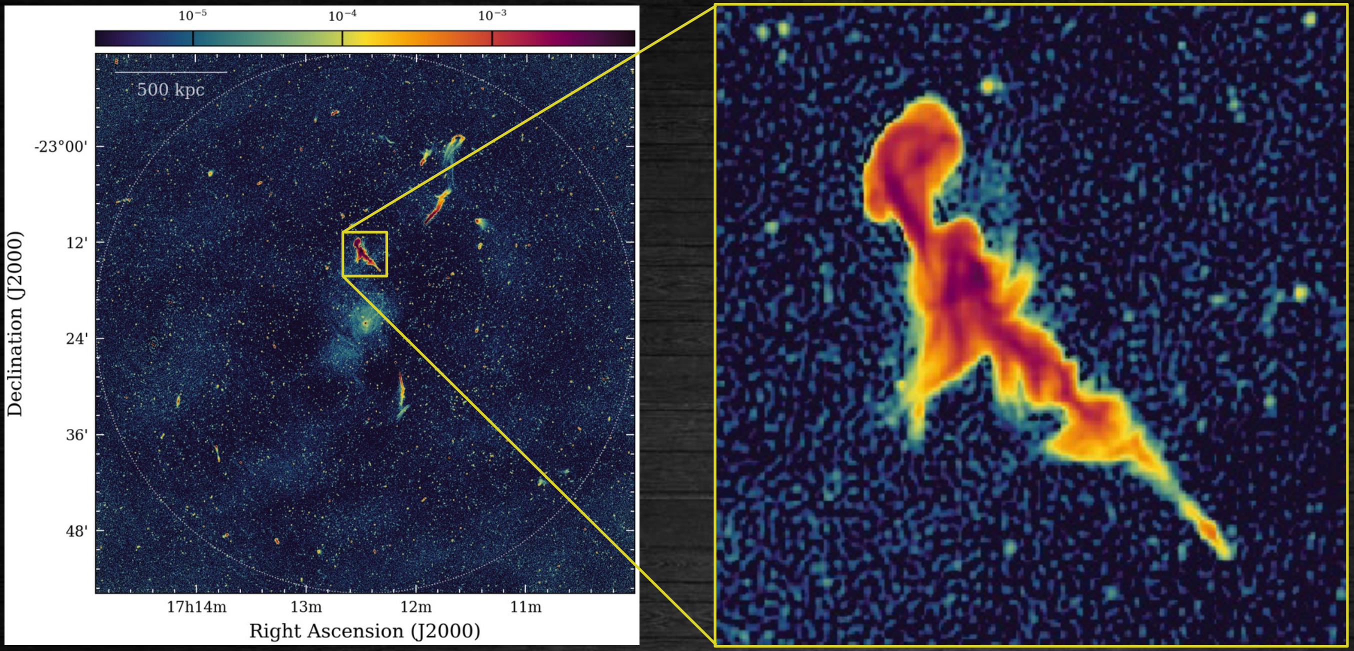
Among the cluster members with extended radio tails, we identified at least 6 **jellyfish galaxies**





The amorphous source in Ophiuchus



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Radio phoenix:

- AGN origin
- Very steep α
- Filamentary

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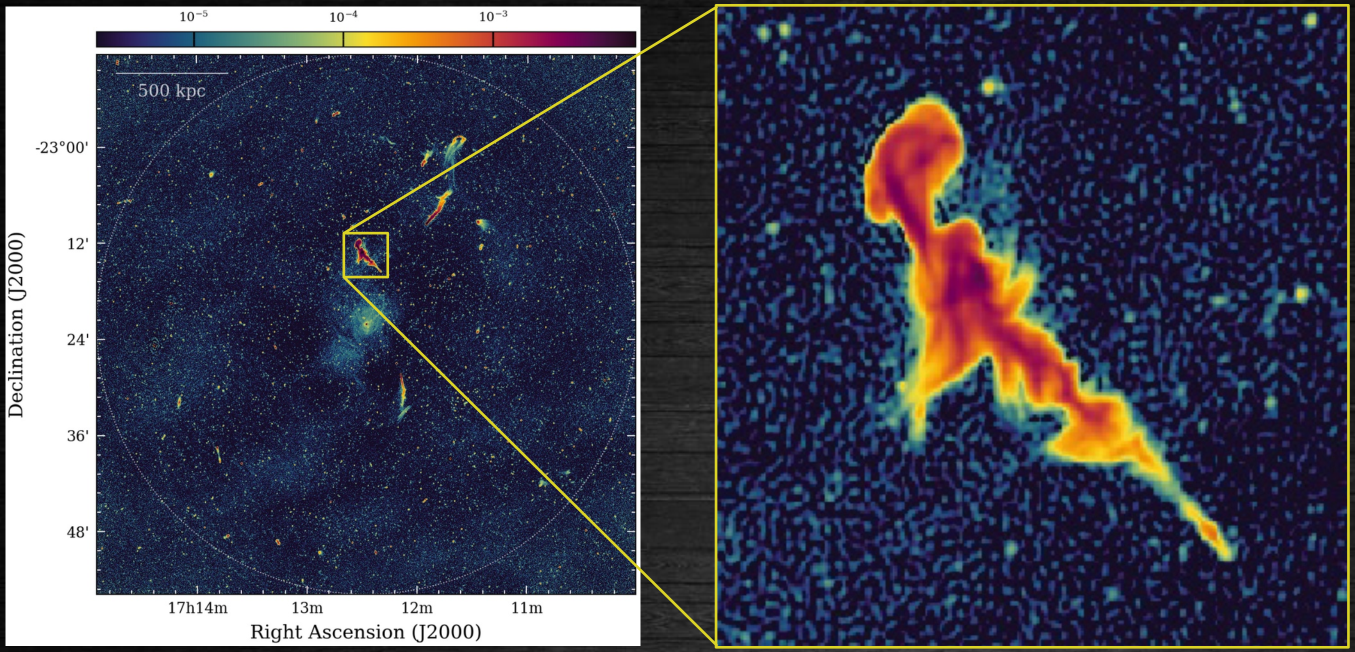

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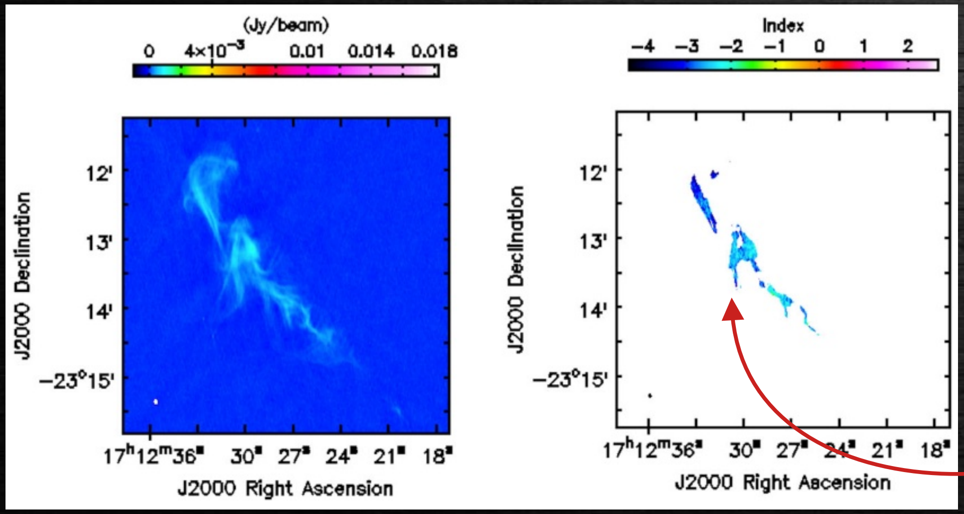
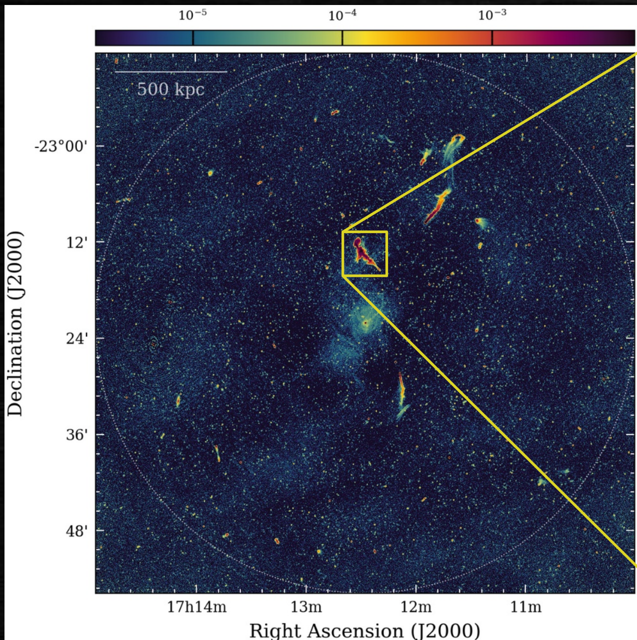
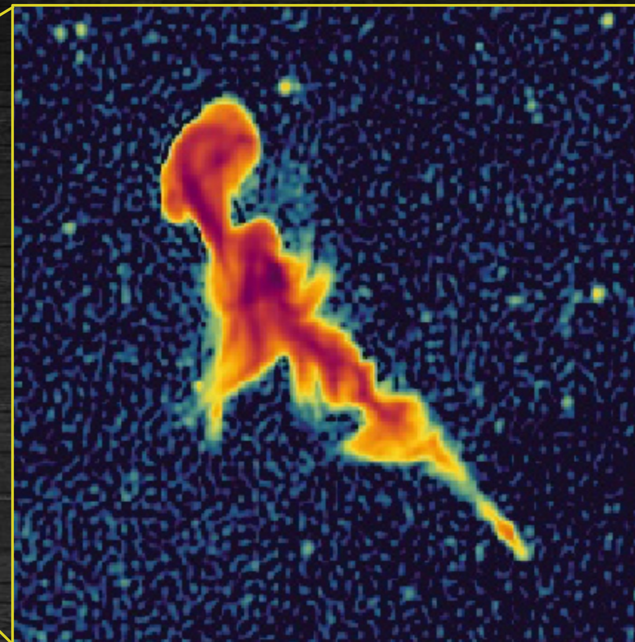


JVLA in-band spectra
(A array, L band)

Werner+16

The amorphous source in Ophiuchus





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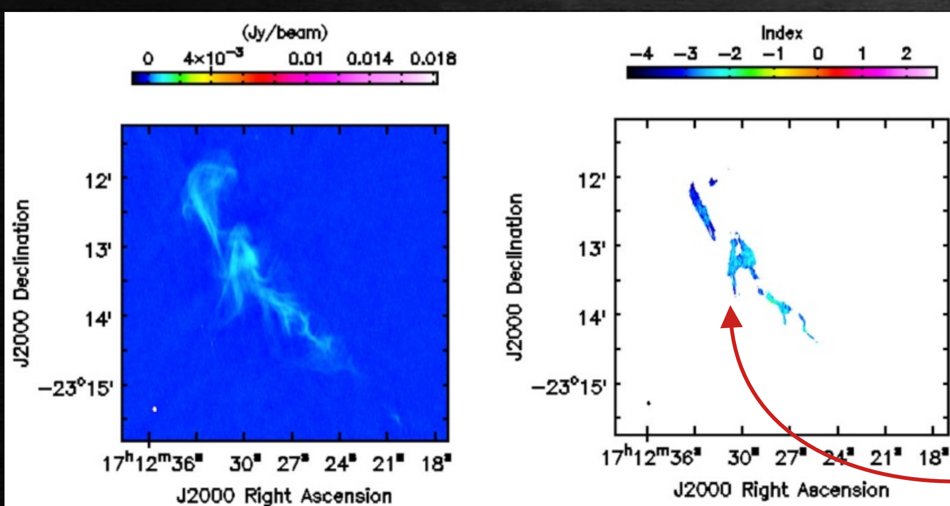

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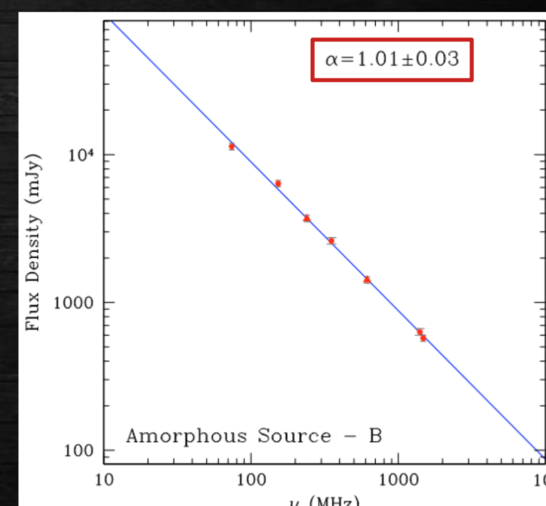
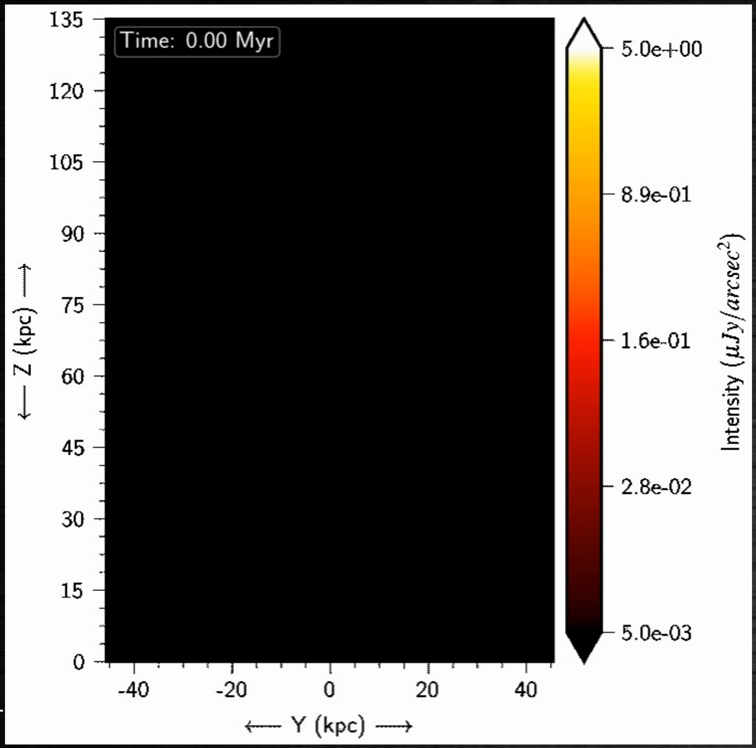


Werner+16

Murgia+10

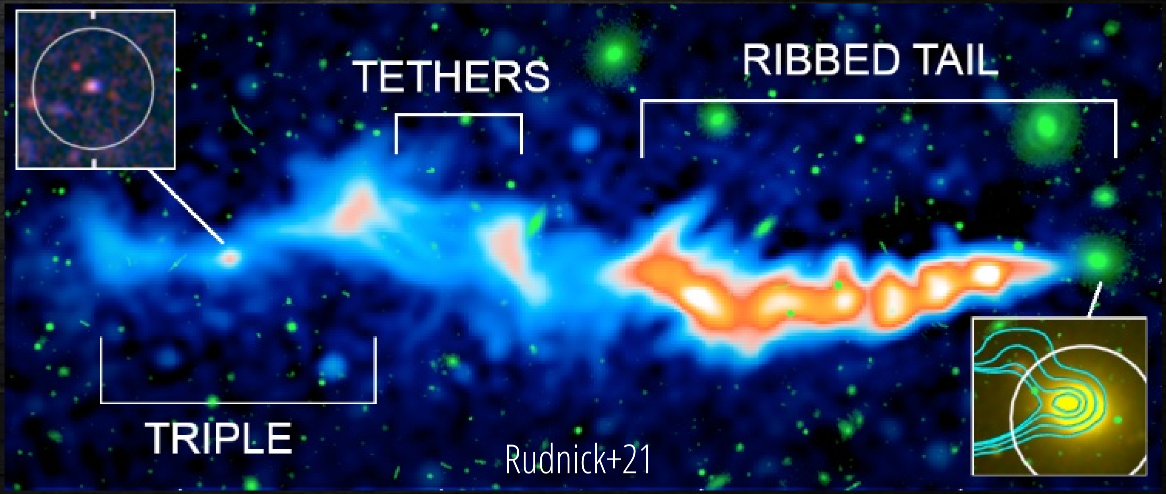
Numerical simulations



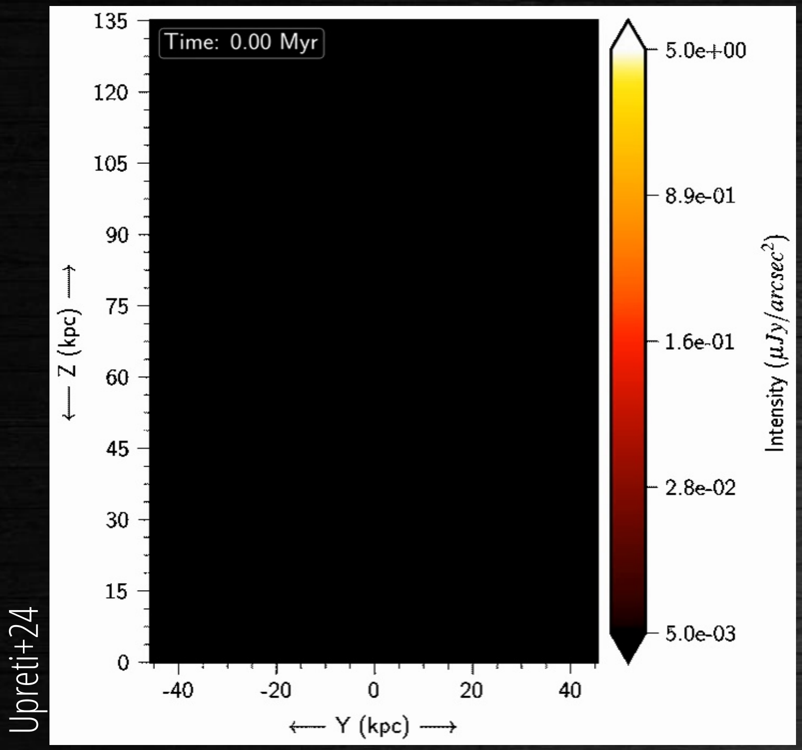
Upreti+24

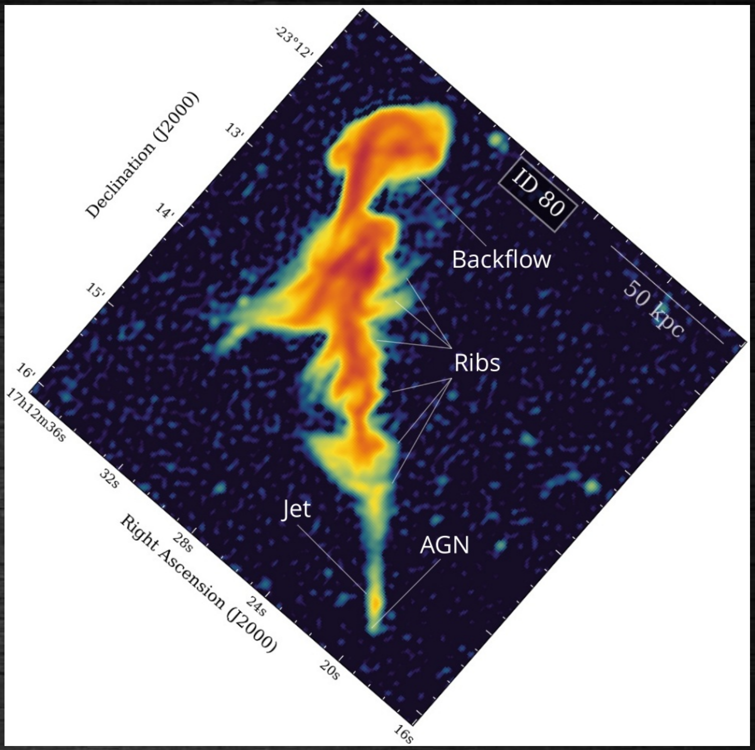
Simulations of a radio jet undergoing **kink instability**

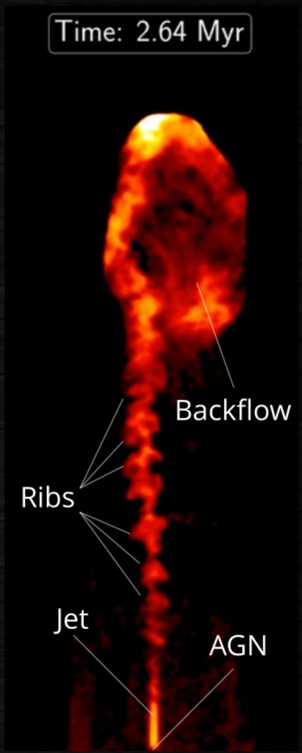
→ the case of the MysTail in Abell 3266



Numerical simulations

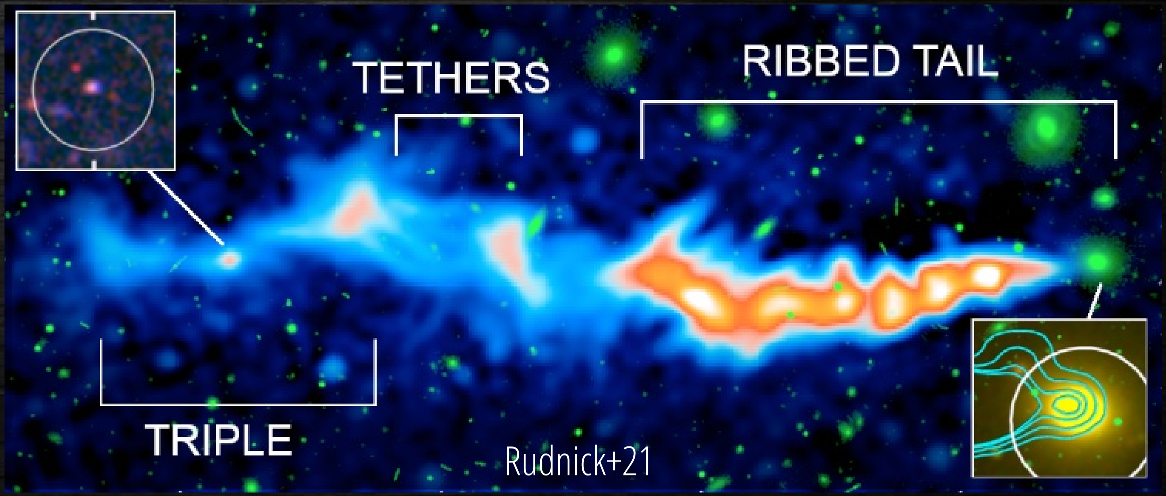




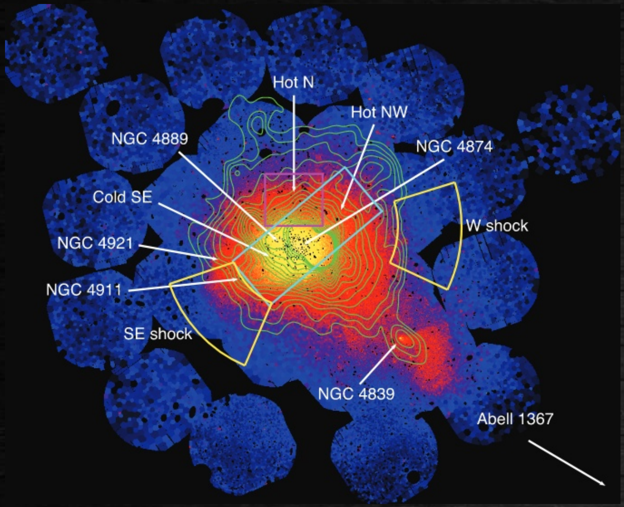


Simulations of a radio jet undergoing **kink instability**

→ the case of the MysTail in Abell 3266

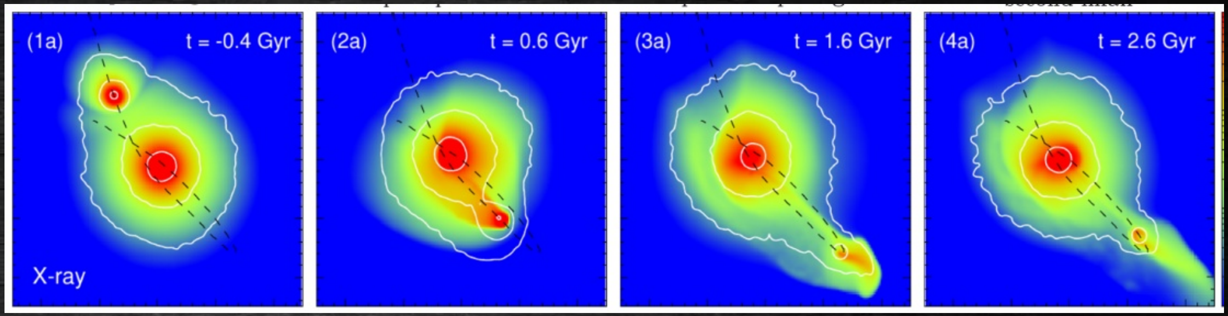


Radio halo extensions

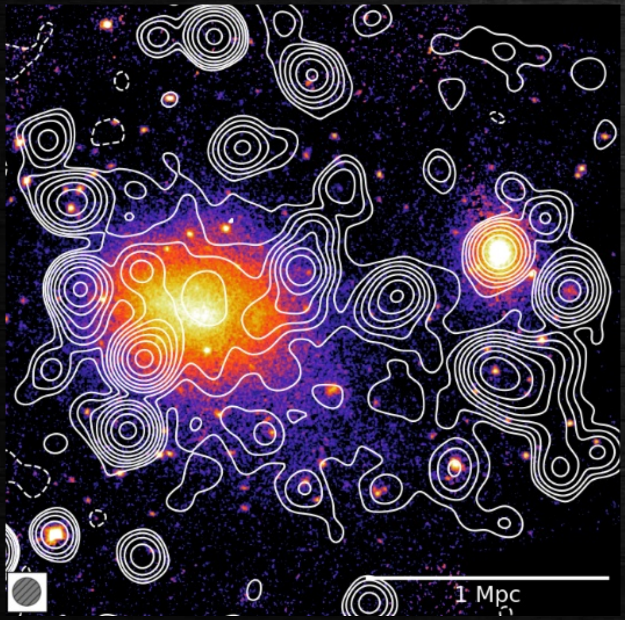


Mirakhor+Walker20

Coma cluster (z=0.023)

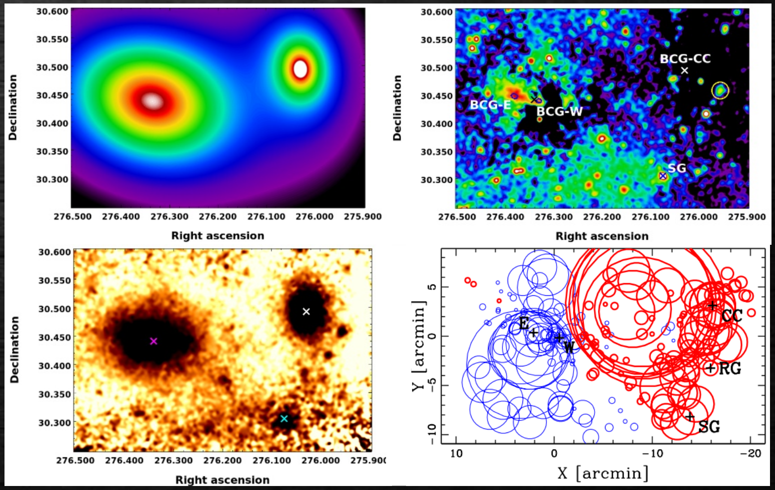


Lyskova+19



Botteon+19

RXC J1825.3+3026 (Lyra, z=0.064)



Clavico+19, Girardi+20