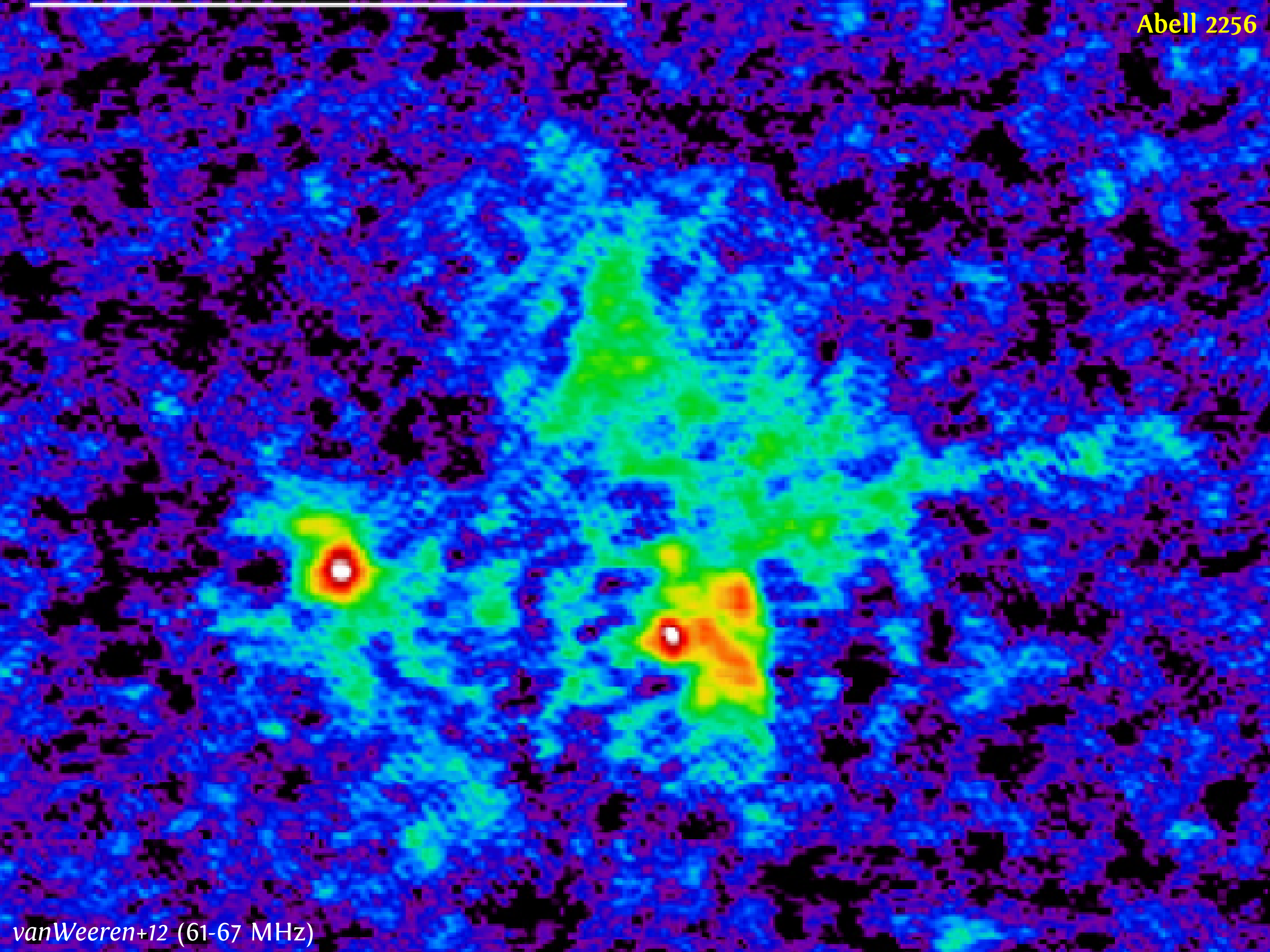
Galaxy clusters at LOFAR's turning point: lessons learned and open questions

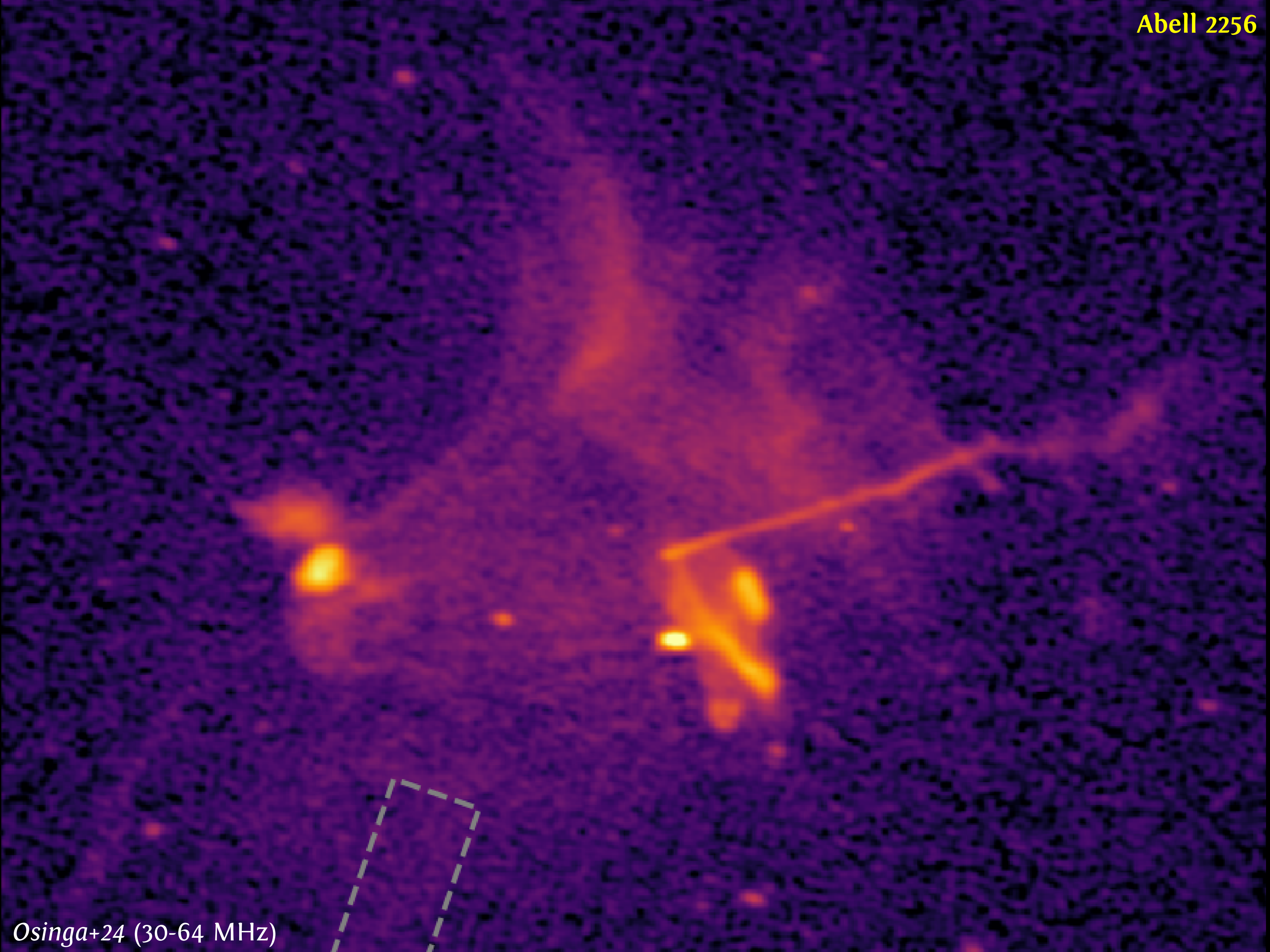
Andrea BOTTEON

INAF – IRA

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

June 5, 2024 – LOFAR Family Meeting, Leiden

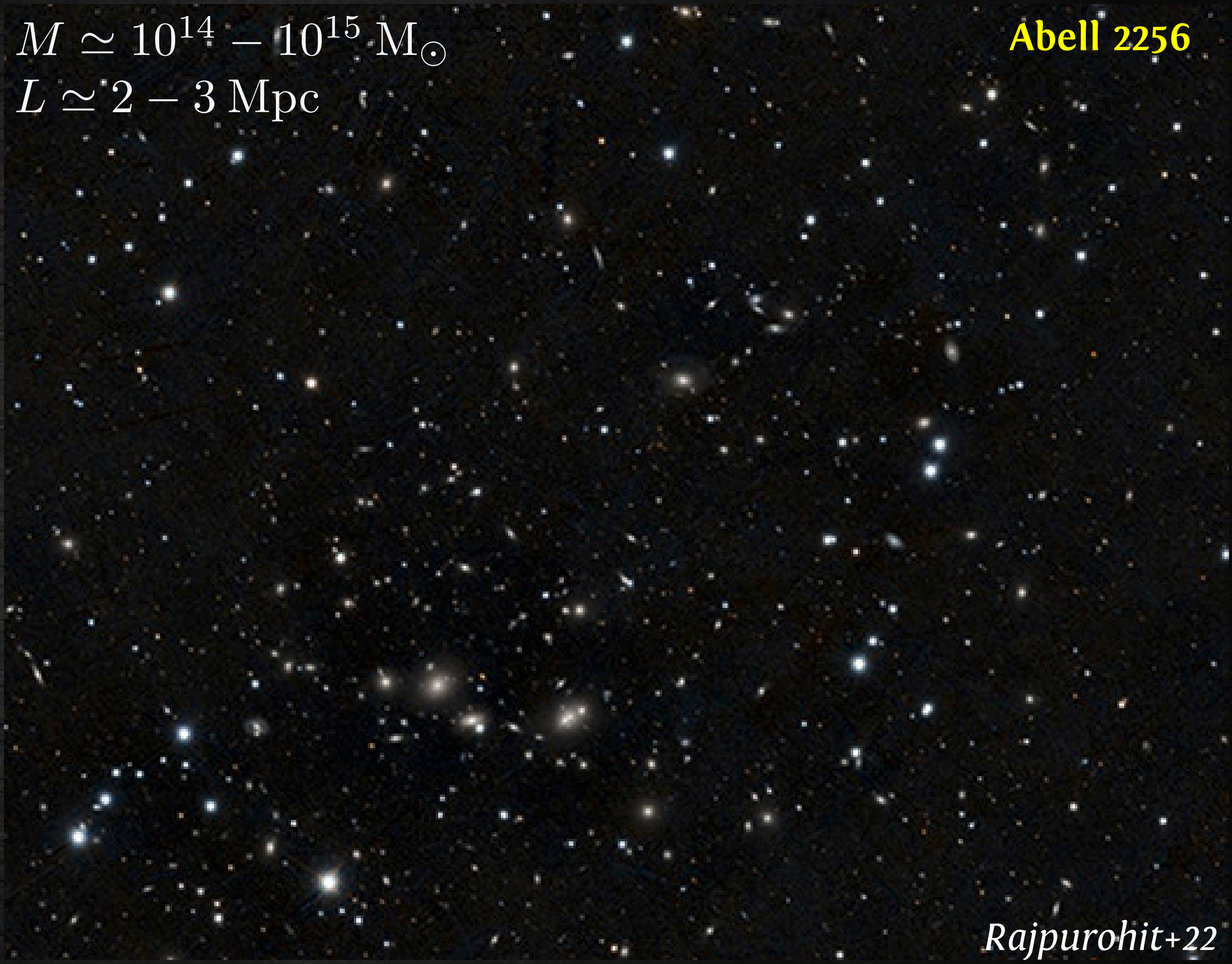

Abell 2256
vanWeeren+12 (61-67 MHz)


Abell 2256
Osinga+24 (30-64 MHz)

Galaxy clusters

Optical:
- 100-1000s galaxies
- Mass: a few % of total

Lensing:
- Trace dark matter
- Mass: 80% of the total



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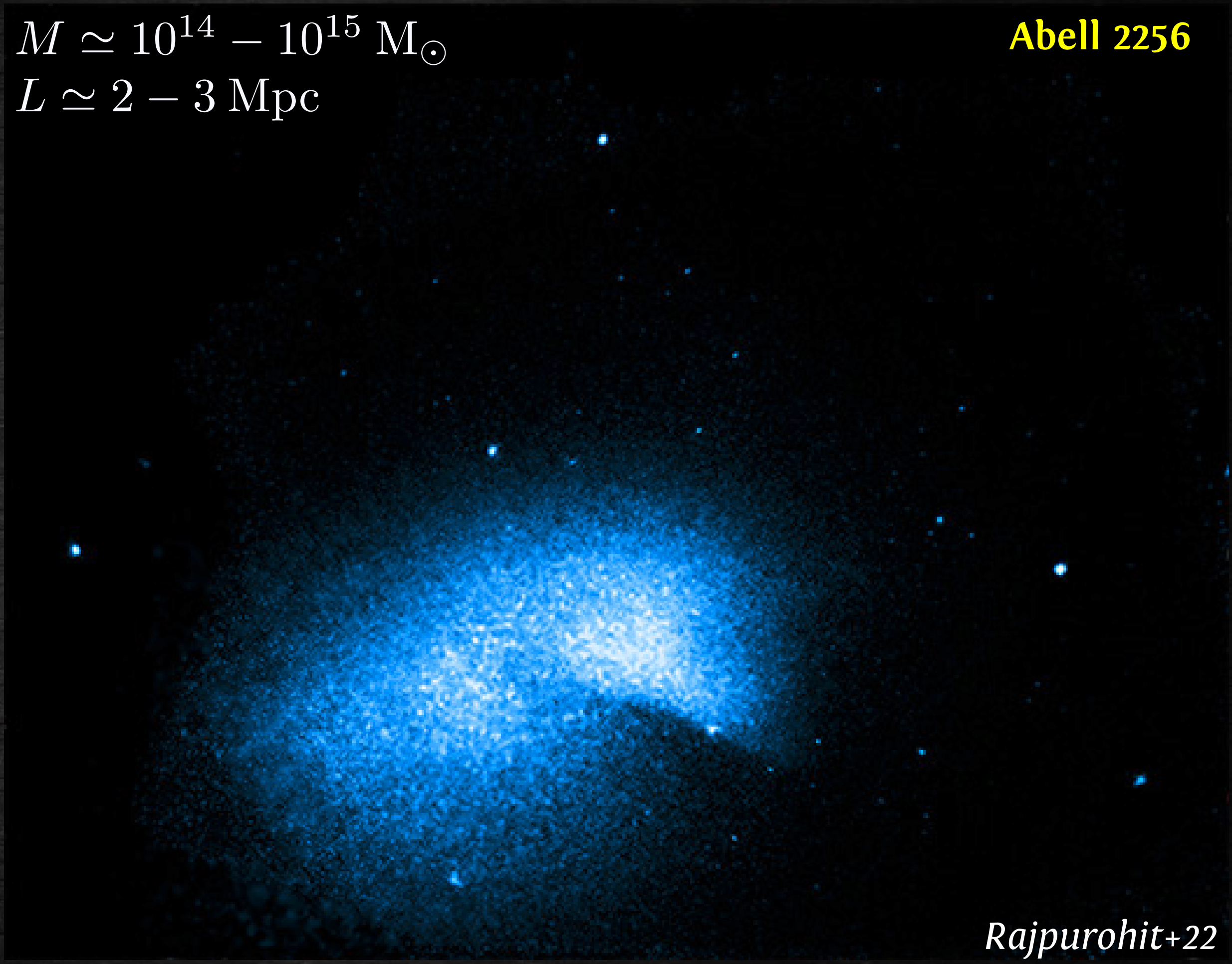
- Intra-cluster medium (ICM)
- Hot ($10^7 - 10^8$ K) and rarified ($10^{-3} - 10^{-4}$ cm^{-3})
- Thermal bremsstrahlung
- Mass: 15% of total



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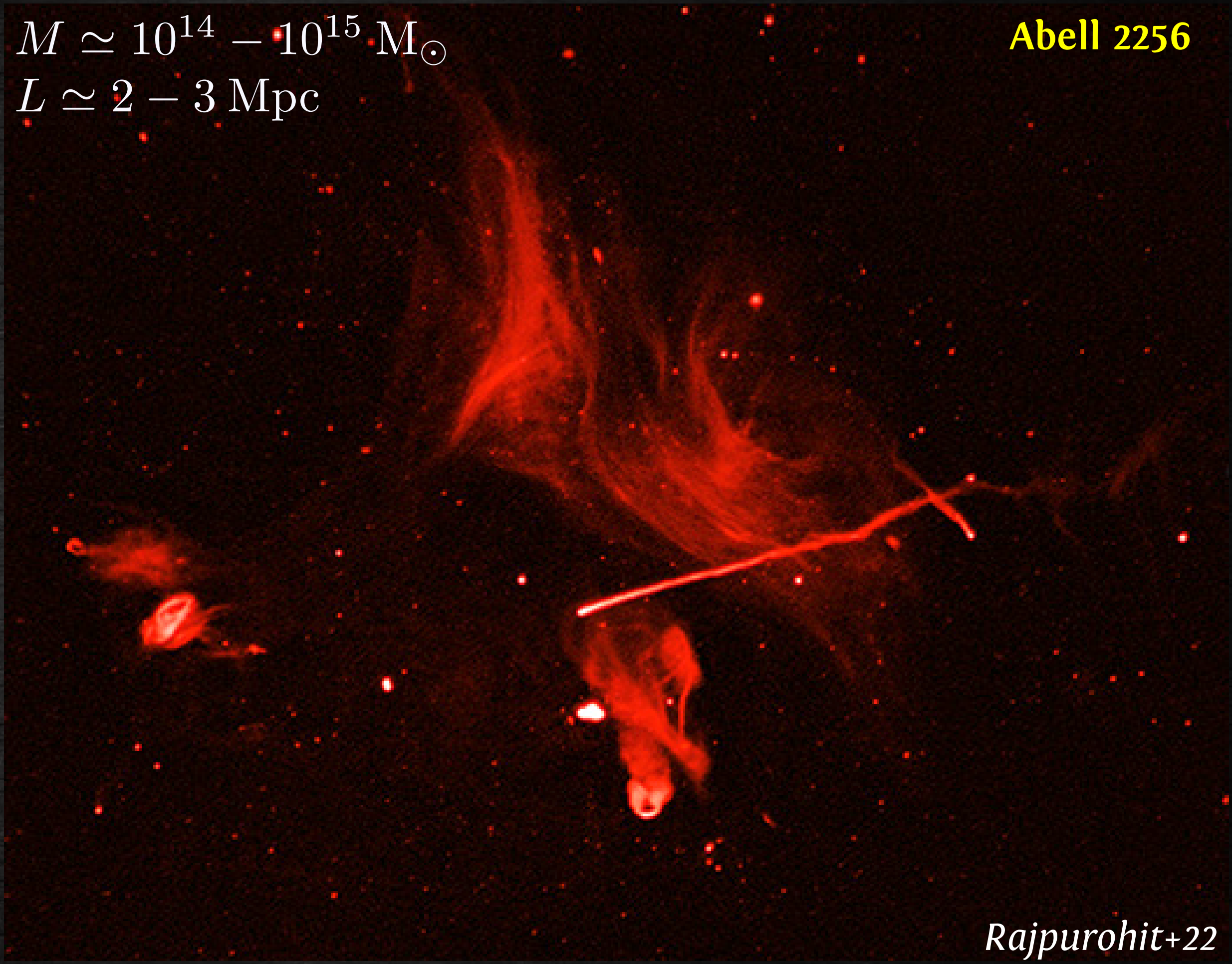
Radio:
- Relativistic electrons (GeV) and magnetic fields (μG)
- Non-thermal synchrotron emission



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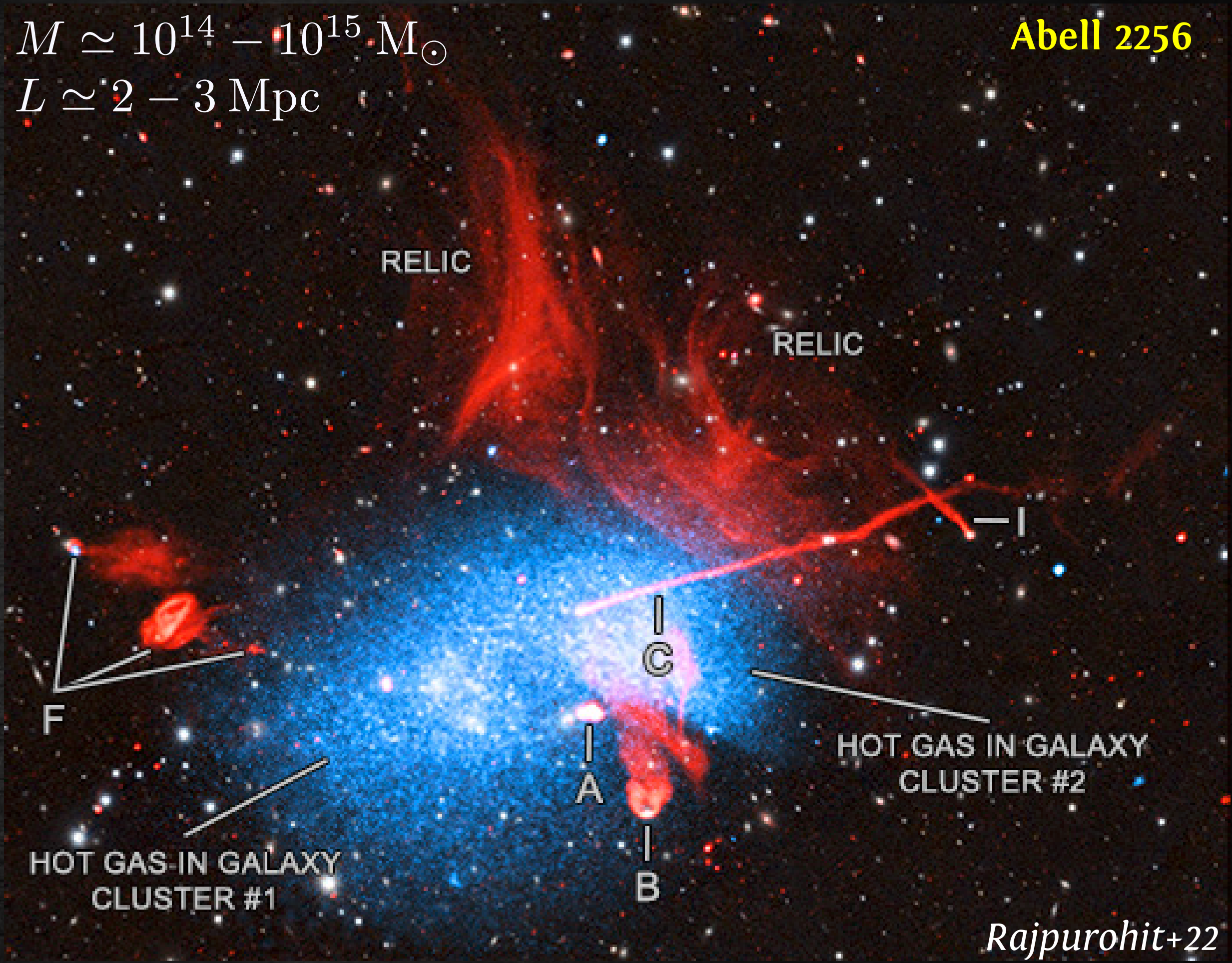

Rajpurohit+22

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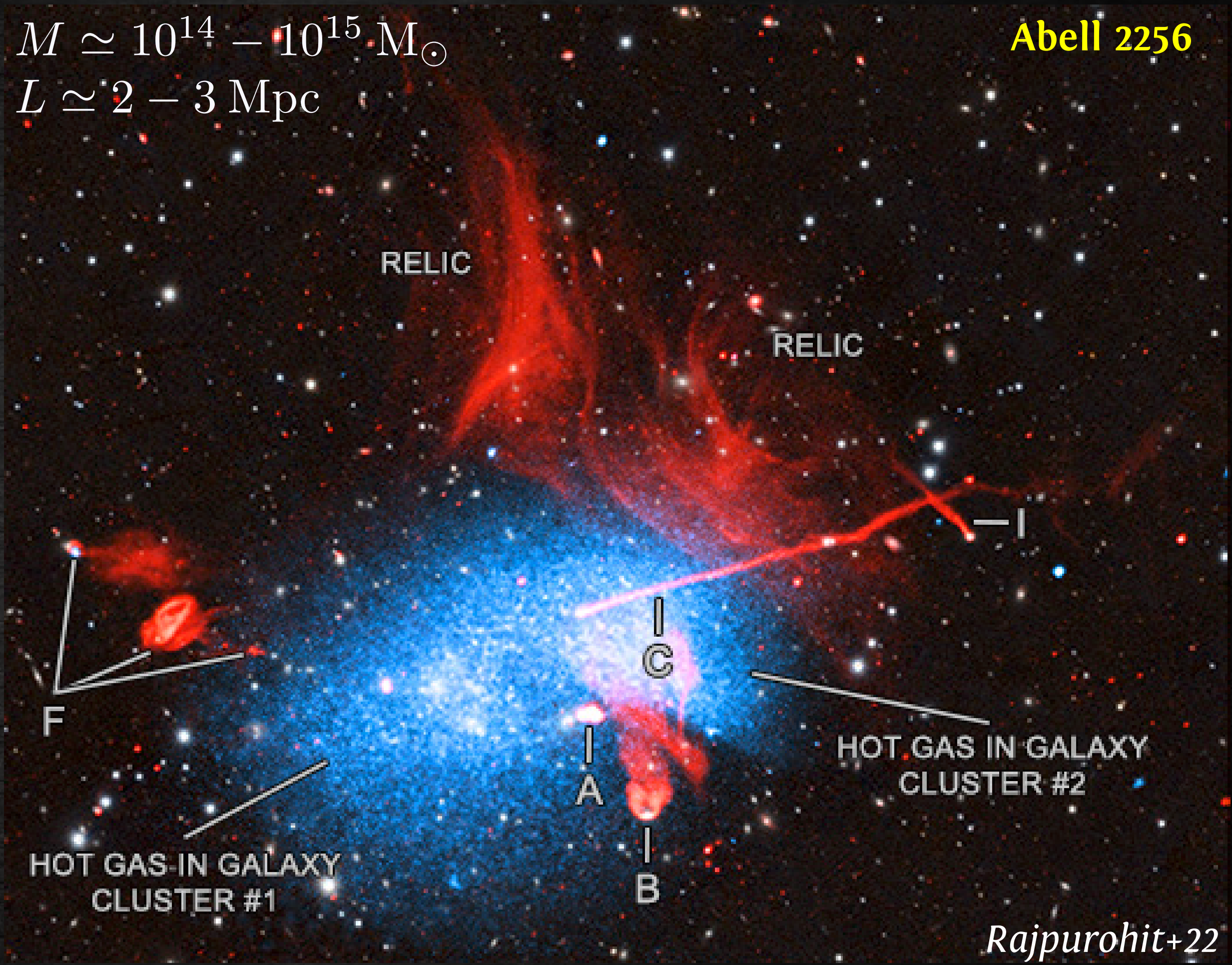


❓ *What is the origin of non-thermal components?*
❓ *What is their impact on the thermal ICM? (microphysics & dynamics)*

LOFAR Clusters WG results

1. *LOFAR, VLA, and Chandra Observations of the Toothbrush Galaxy Cluster,* van Weeren+
2. *A plethora of diffuse steep spectrum radio sources in Abell 2034 revealed by LOFAR,* Shimwell+

3. *Deep LOFAR observations of the merging galaxy cluster CIZA J2242.8+5301,* Hoang+
4. *Gentle reenergization of electrons in merging galaxy clusters,* de Gasperin+

5. *LOFAR discovery of an ultra-steep radio halo and giant head-tail radio galaxy in Abell 1132,* Wilber+
6. *Search for low-frequency diffuse radio emission around a shock in the massive galaxy cluster MACS J0744.9+3927,* Wilber+
7. *Discovery of large-scale diffuse radio emission in low-mass galaxy cluster Abell 1931,* Brüggen+
8. *LOFAR discovery of a double radio halo system in Abell 1758 and radio/X-ray study of the cluster pair,* Botteon+
9. *First evidence of diffuse ultra-steep-spectrum radio emission surrounding the cool core of a cluster,* Savini+
10. *LOFAR discovery of radio emission in MACS J0717.5+3745,* Bonafede+
11. *Radio observations of the double-relic galaxy cluster Abell 1240,* Hoang+

12. *The spectacular cluster chain Abell 781 as observed with LOFAR, GMRT and XMM-Newton,* Botteon+
13. *Ultra-steep spectrum emission in the merging galaxy cluster Abell 1914,* Mandal+
14. *A LOFAR study of non-merging massive galaxy clusters,* Savini+
15. *The evolutionary phases of merging clusters as seen by LOFAR,* Wilber+
16. *Radio observations of the merging galaxy cluster Abell 520,* Hoang+
17. *Characterizing the radio emission from the binary galaxy cluster merger Abell 2146,* Hoang+
18. *A massive cluster at z = 0.288 caught in the process of formation: The case of Abell 959,* Birzan+
19. *Signatures from a merging galaxy cluster and its AGN population: LOFAR observations of Abell 1682,* Clarke+
20. *LOFAR discovery of a radio halo in the high-redshift galaxy cluster PSZ2 G099.86+58.45,* Cassano+
21. *Particle acceleration in a nearby galaxy cluster pair: the role of cluster dynamics,* Botteon+

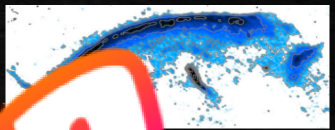
22. *Revived fossil plasma sources in galaxy clusters,* Mandal+
23. *LOFAR observations of X-ray cavity systems,* Birzan+
24. *The beautiful mess in Abell 2255,* Botteon+
25. *Reaching thermal noise at ultra-low radio frequencies. The Toothbrush radio relic downstream of the shock front,* de Gasperin+
26. *A giant radio bridge connecting two galaxy clusters in Abell 1758,* Botteon+
27. *The great Kite in the sky: a LOFAR observation of the radio source in Abell 2626,* [illegible]sti+

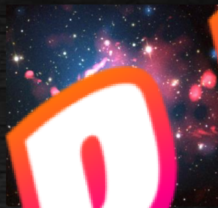
28. *Fast magnetic field amplification in distant galaxy clusters,* Di Gennaro+
29. *LOFAR detection of a low-power radio halo in the galaxy cluster Abell 990,* H[illegible]
30. *The Coma cluster at LOw Frequency ARray Frequencies: I. Insights into particle acceleration mechanisms in the radio bridge,* Bonafede+
31. *Understanding the radio relic emission in the galaxy cluster MACS J0717.5+3745: Spectral analysis,* Rajpurohit+
32. *Physical insights from the spectrum of the radio halo in MACS J0717.5+3745,* R[illegible]
33. *Diffuse radio emission from galaxy clusters in the LOFAR Two-metre Sky Survey Deep Fields,* Osinga+
34. *Non-thermal phenomena in the center of Abell 1775. 800 kpc head-tail, revived fossil plasma, and slingshot radio halo,* Botteon+
35. *LoTSS jellyfish galaxies. I. Radio tails in low redshift clusters,* Rober[illegible]
36. *Radio relics in PSZ2 G096.88+24.18: a connection with pre-existing plasma,* [illegible]
37. *LOFAR observations of galaxy clusters in HETDEX,* vanWeeren+
38. *Discovery of a radio halo (and relic) in a $M_{500} < 2 \times 10^{14}$ $M_{\odot}$ cluster,* B[illegible]on+
39. *LoTSS jellyfish galaxies. II. Ram pressure stripping in groups versus clusters,* R[illegible]
40. *Abell 1430: A merging cluster with exceptional diffuse radio emission,* [illegible]ft+
41. *A unique snapshot of the oldest AGN feedback phases,* Brienza+
42. *A LOFAR-uGMRT spectral index study of distant radio halos,* Di Gennaro+
43. *The ultra-steep diffuse radio emission observed in the cool-core cluster RX J1720.1+2638 with LOFAR at 54 MHz,* Biava+
44. *A 3.5 Mpc-long radio relic in the galaxy cluster ClG 0217+70,* Hoang+

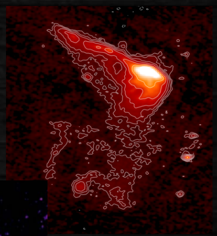
45. *LoTSS jellyfish galaxies. III. The first identification of jellyfish galaxies in the Perseus cluster,* Roberts+
46. *Spectral study of the diffuse synchrotron source in the galaxy cluster Abell 523,* Vacca+
47. *A LOFAR view into the stormy environment of the galaxy cluster 2A0335+096,* Ignesti+
48. *The Planck clusters in the LOFAR sky. I. LoTSS-DR2: new detections and sample overview,* Botteon+
49. *Deep low-frequency radio observations of Abell 2256. I. The filamentary radio relic,* Rajpurohit+
50. *A MeerKAT-meets-LOFAR study of MS 1455.0+2232: a 590 kiloparsec 'mini'-halo in a sloshing cool-core cluster,* Riseley+
51. *The eROSITA Final Equatorial-Depth Survey (eFEDS). LOFAR view of brightest cluster galaxies and AGN feedback,* Pasini+
52. *The galaxy group NGC 507: newly detected AGN remnant plasma transported by sloshing,* Brienza+
53. *The Coma cluster at LOFAR frequencies II: the halo, relic, and a new accretion relic,* Bonafede+
54. *Particle re-acceleration and diffuse radio sources in the galaxy cluster Abell 1550,* Pasini+
55. *Diffuse radio emission from non-Planck galaxy clusters in the LoTSS-DR2 fields,* Hoang+
56. *Galaxy clusters enveloped by vast volume of relativistic electrons,* Cuciti+

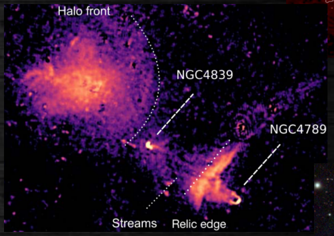
2016 2017 2018 2019 2020 2021 2022

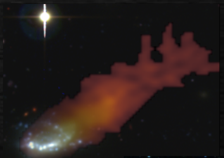
LFM 2022

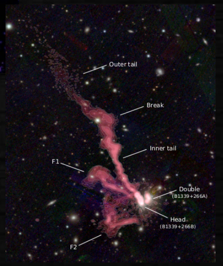


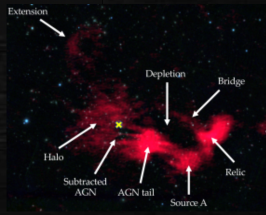




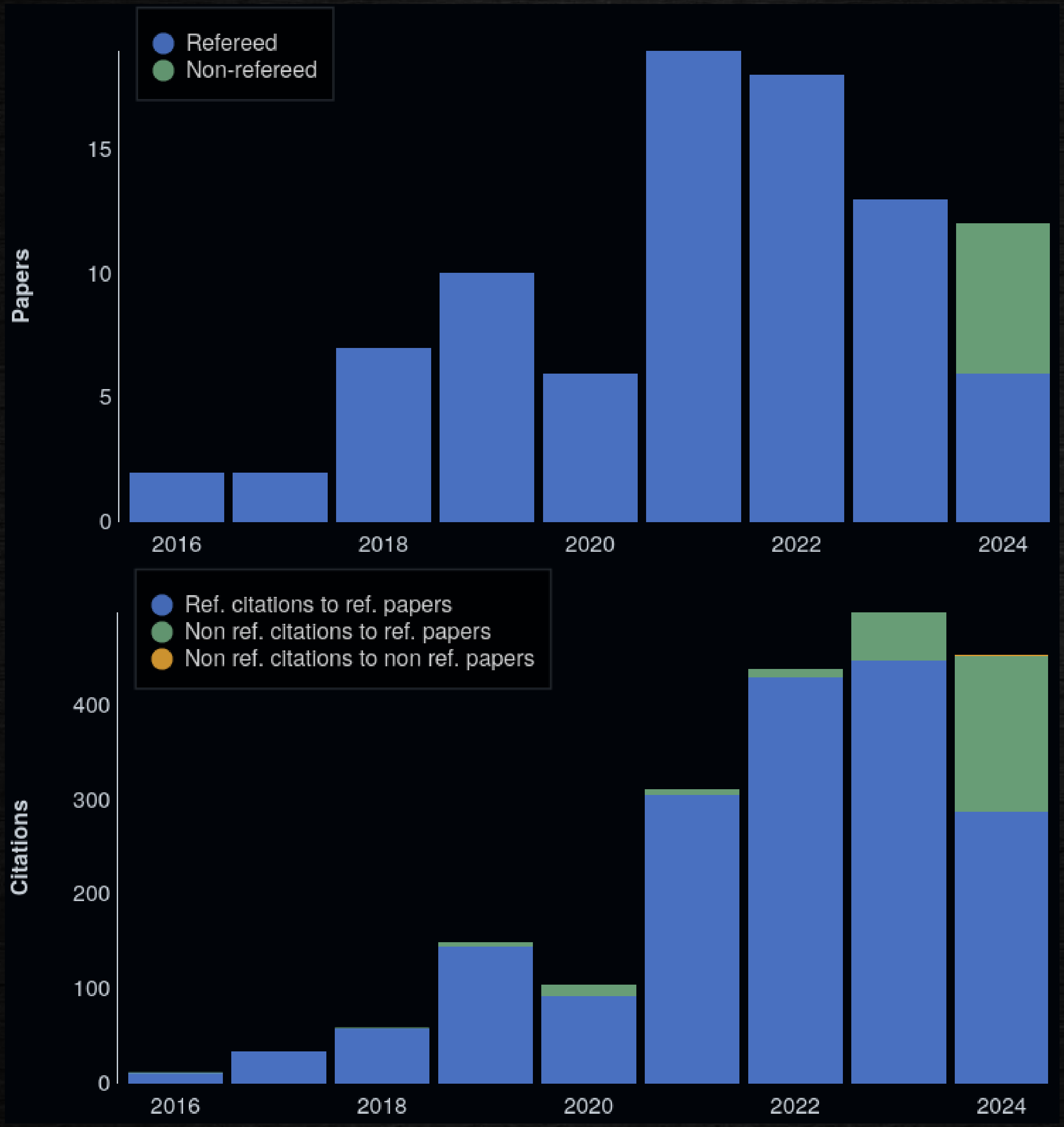








LOFAR Clusters WG in numbers



Total papers: **89**

Total citations: **~2060**

Average: **~23** per paper

Median: **~17** per paper

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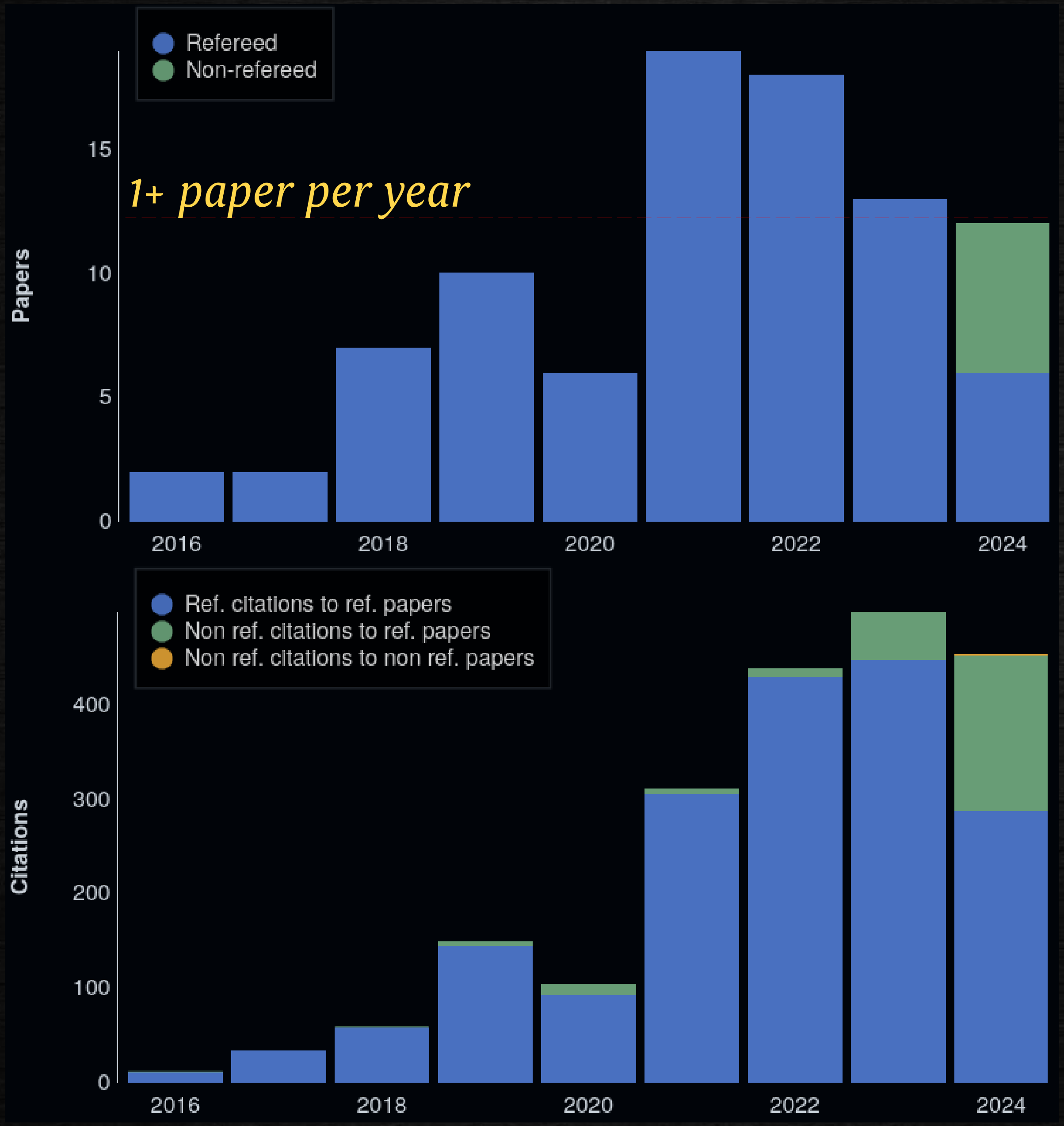

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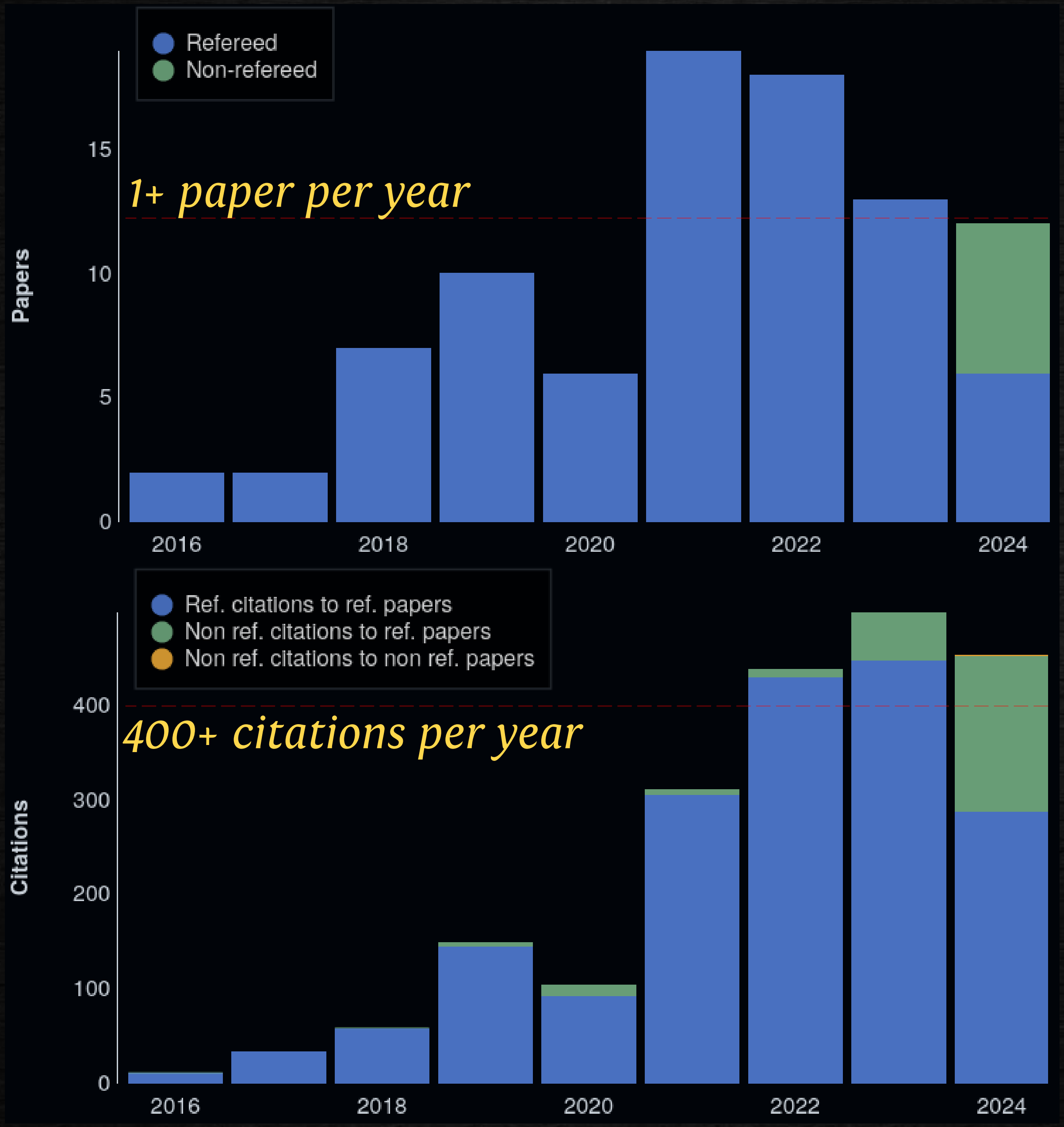

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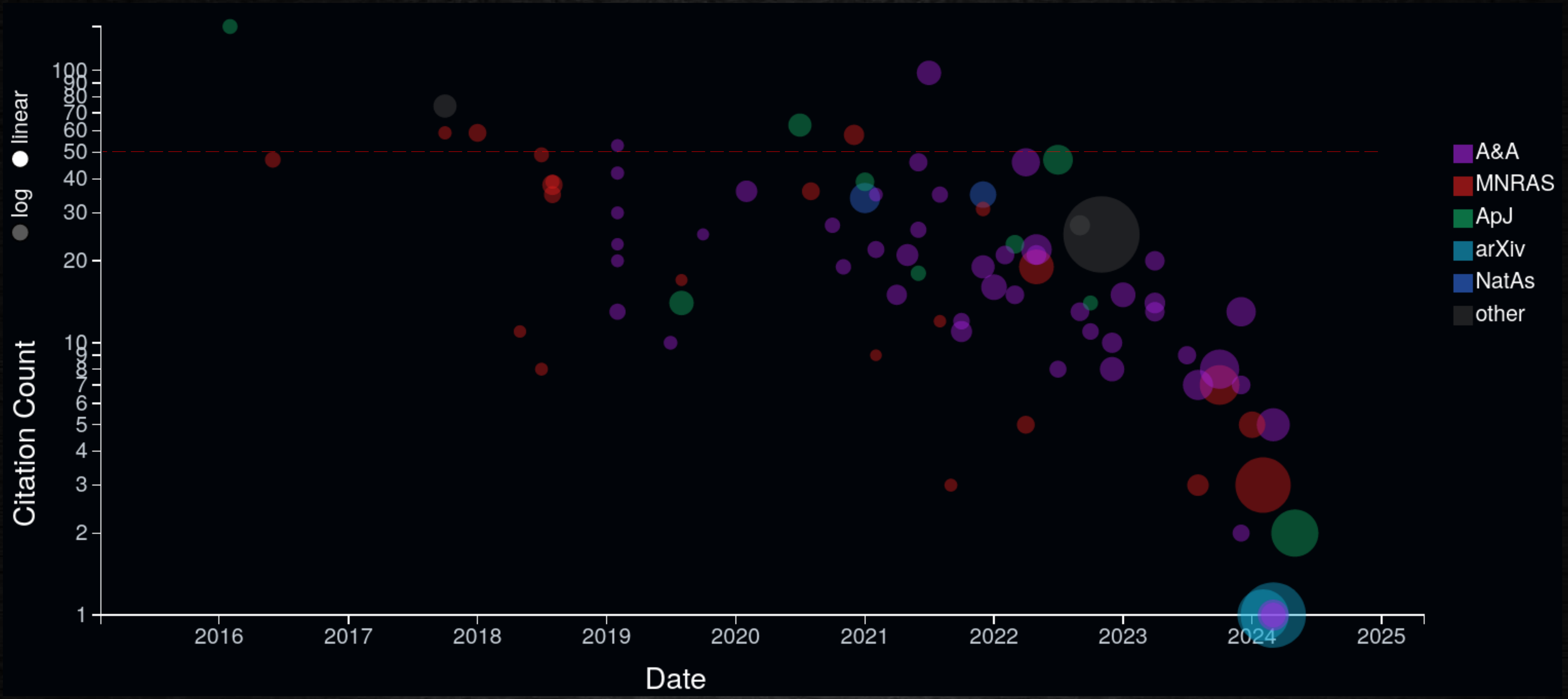

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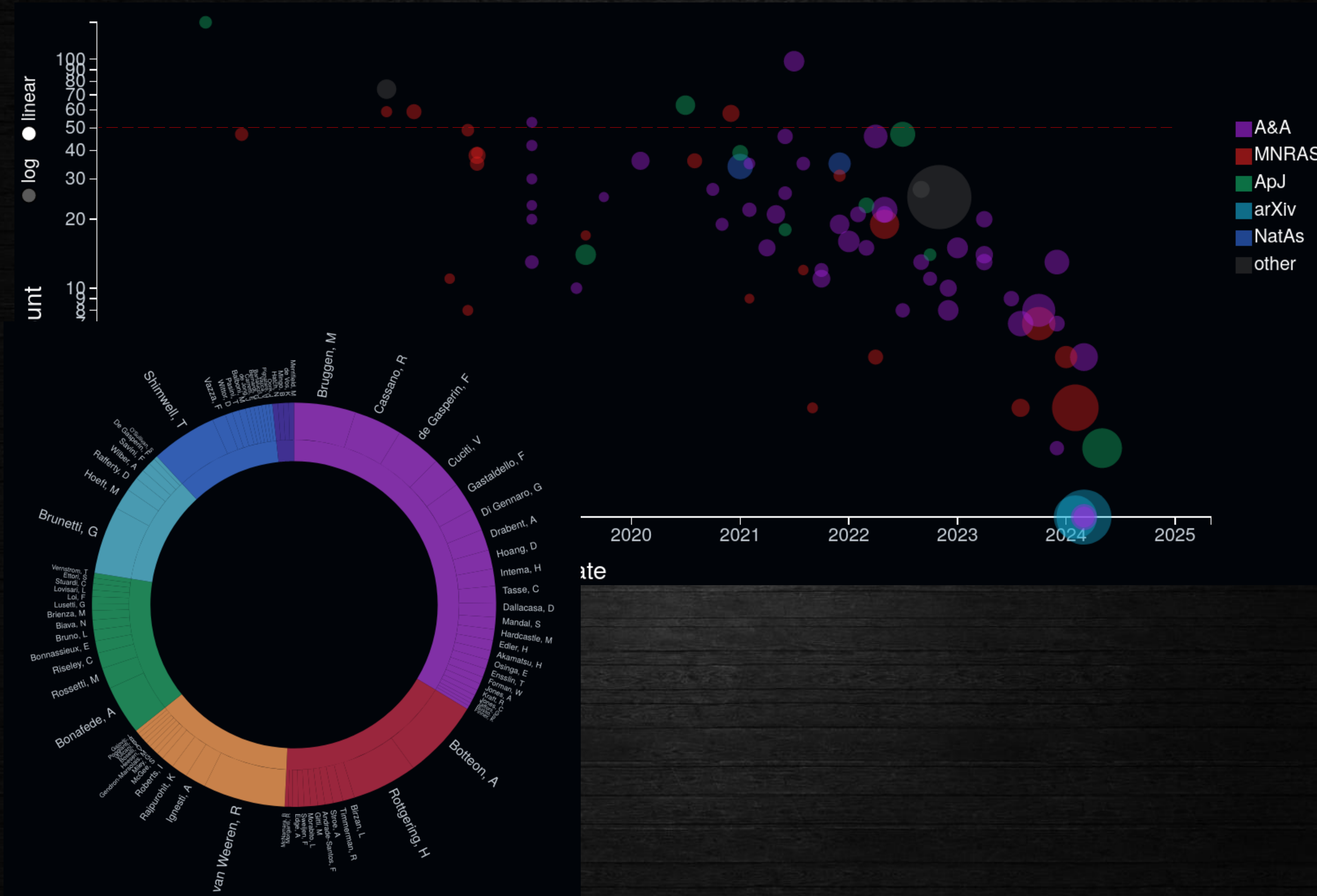

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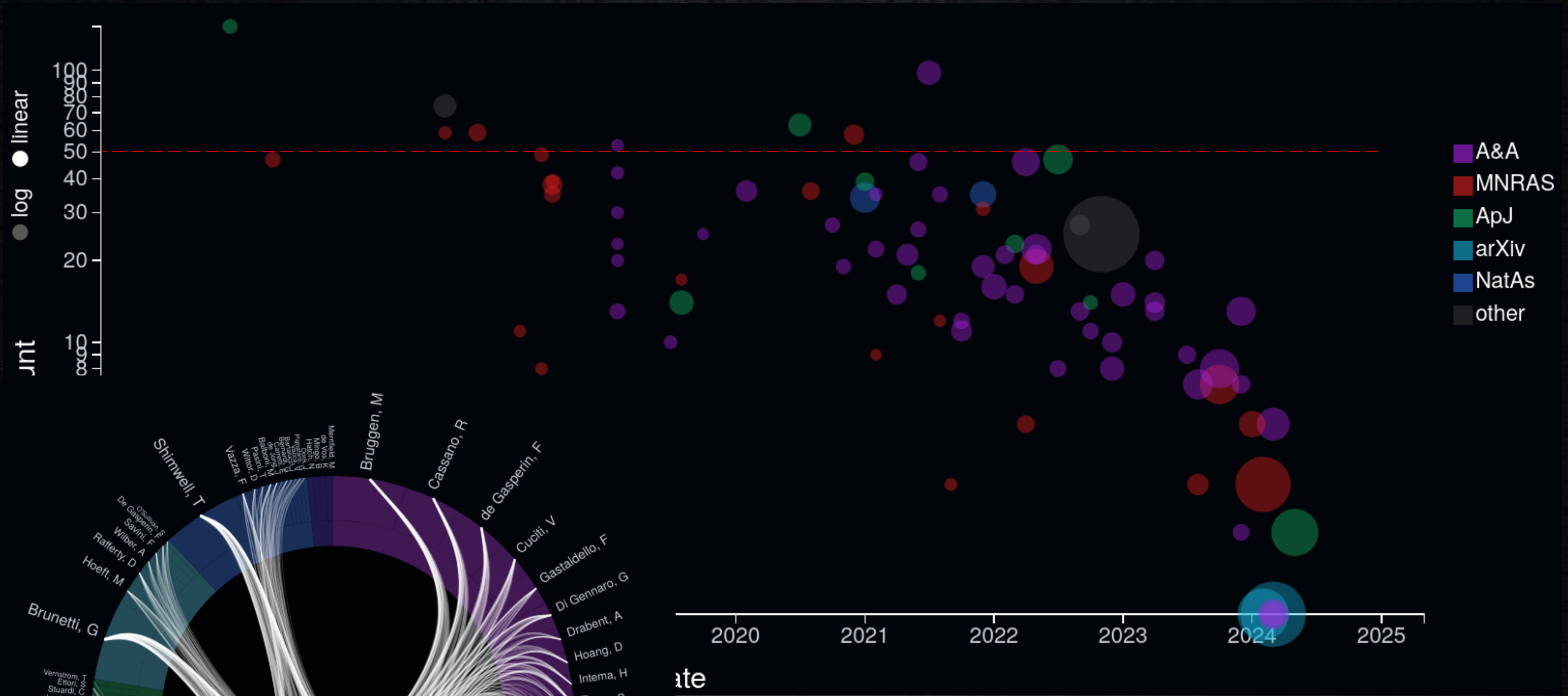
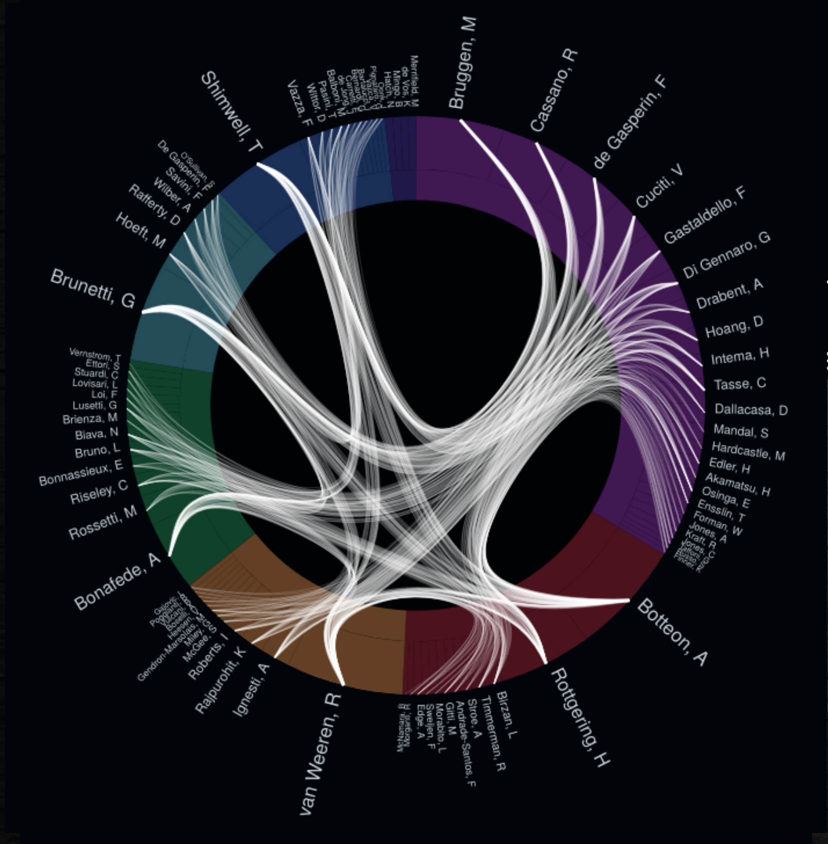
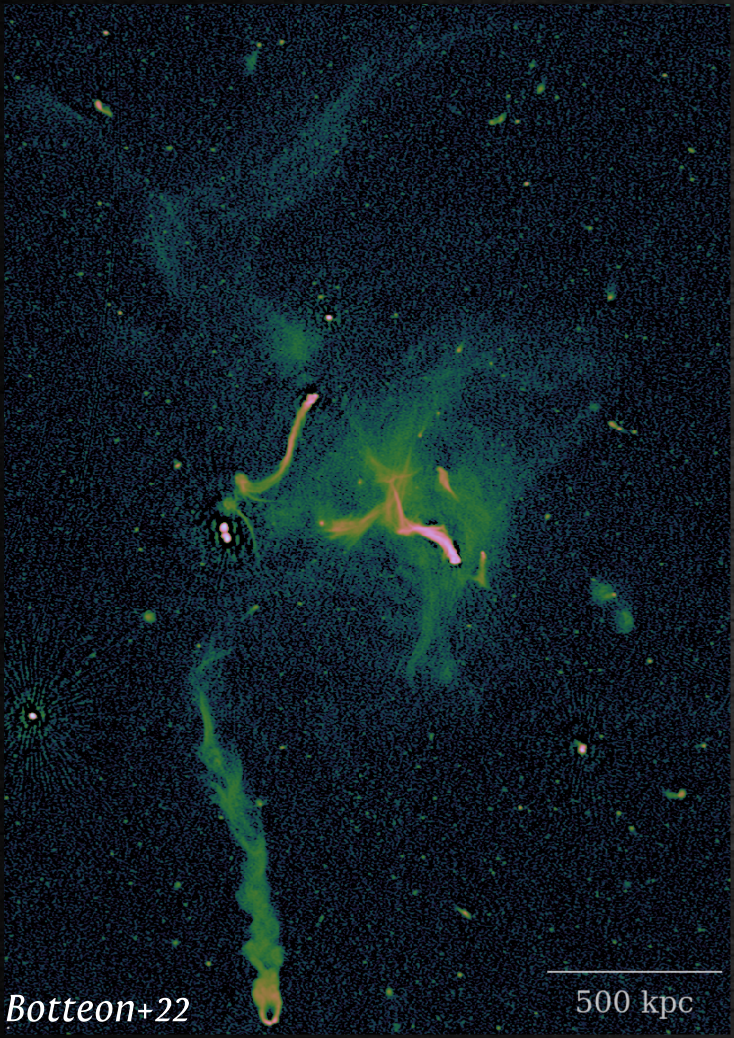
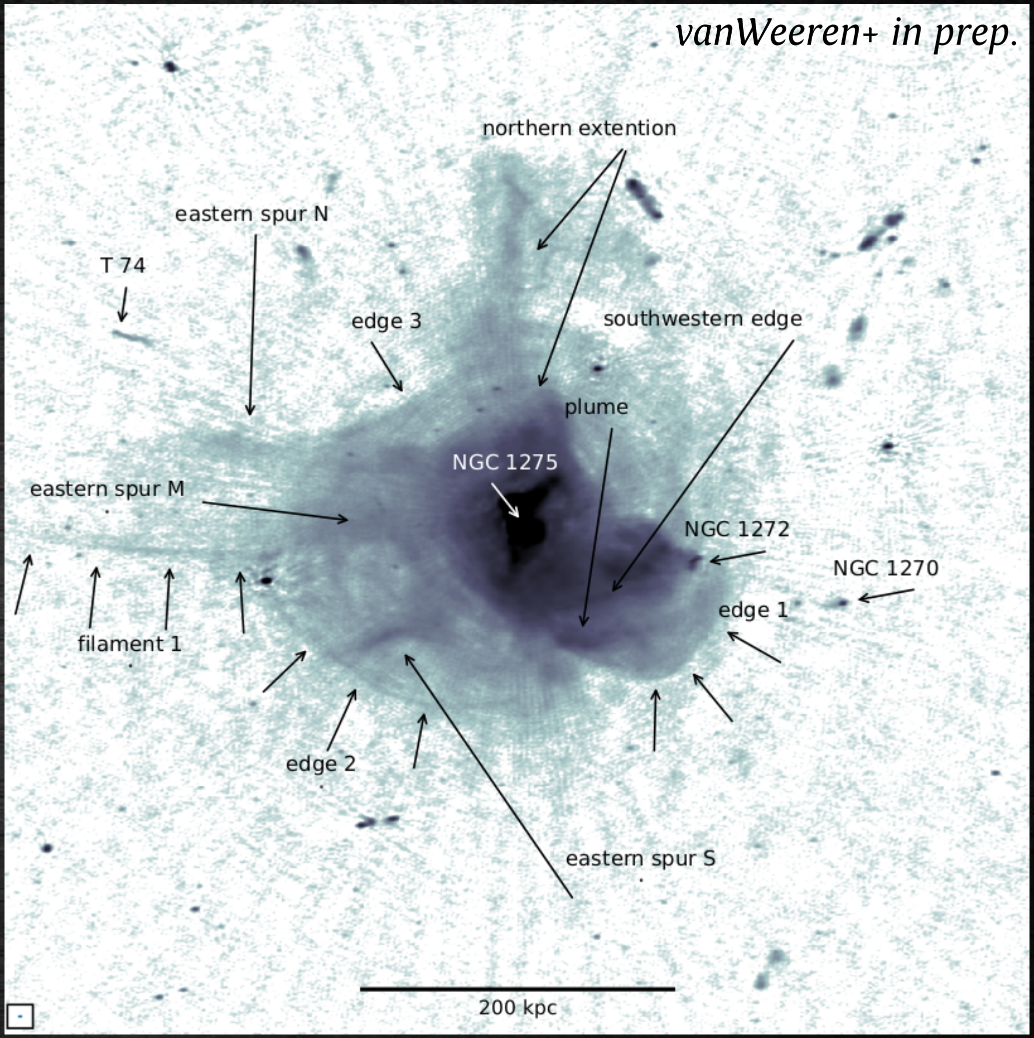




Cluster radio sources



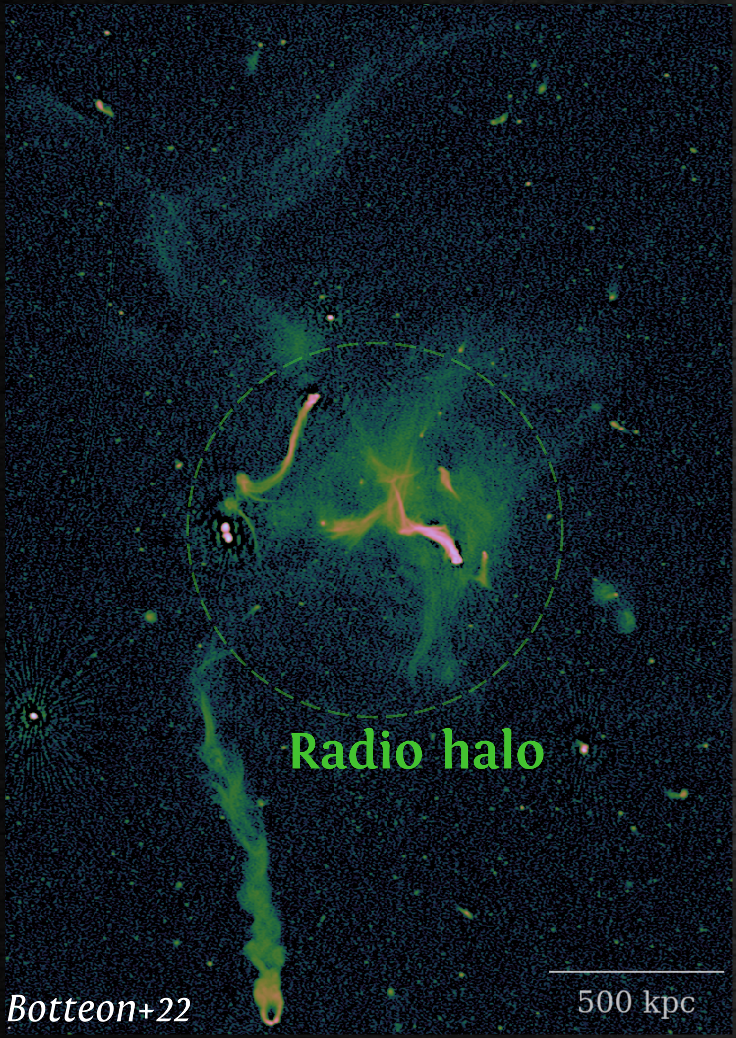


Disturbed cluster (A2255)

Relaxed cluster (Perseus)

Feretti+12, Brunetti+Jones14, vanWeeren+19 for reviews

Cluster radio sources



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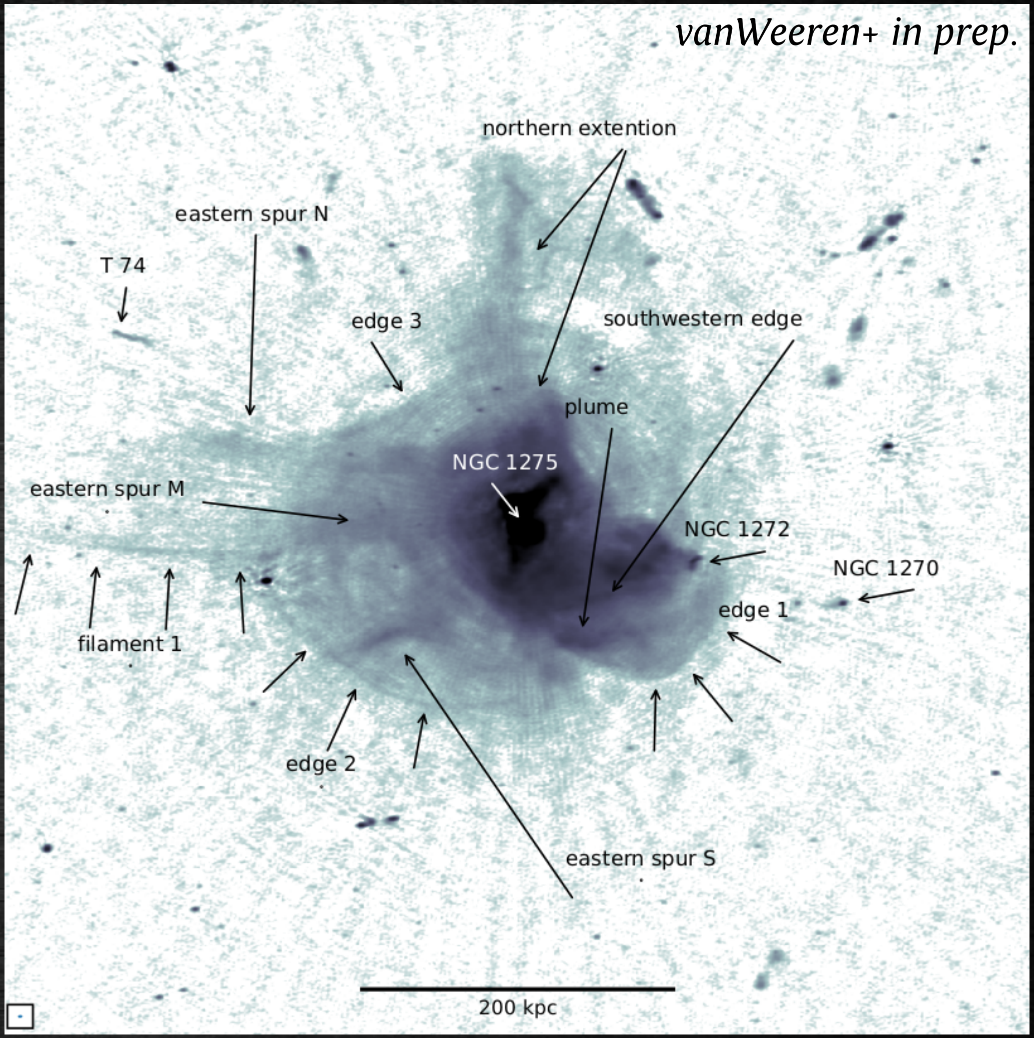

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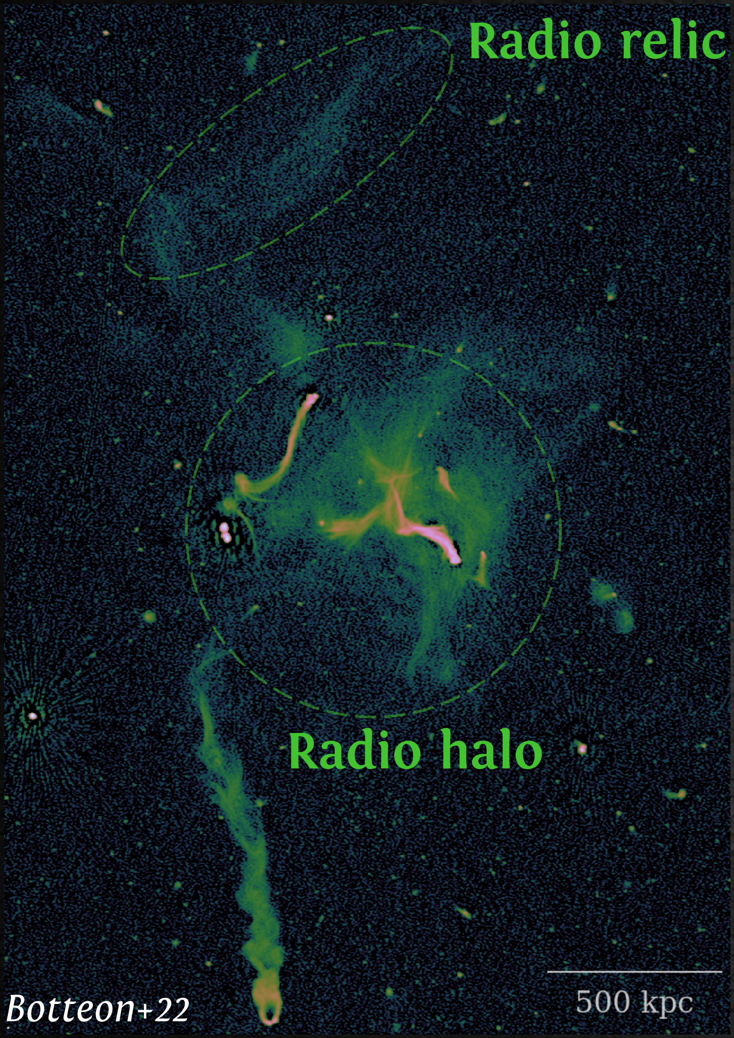

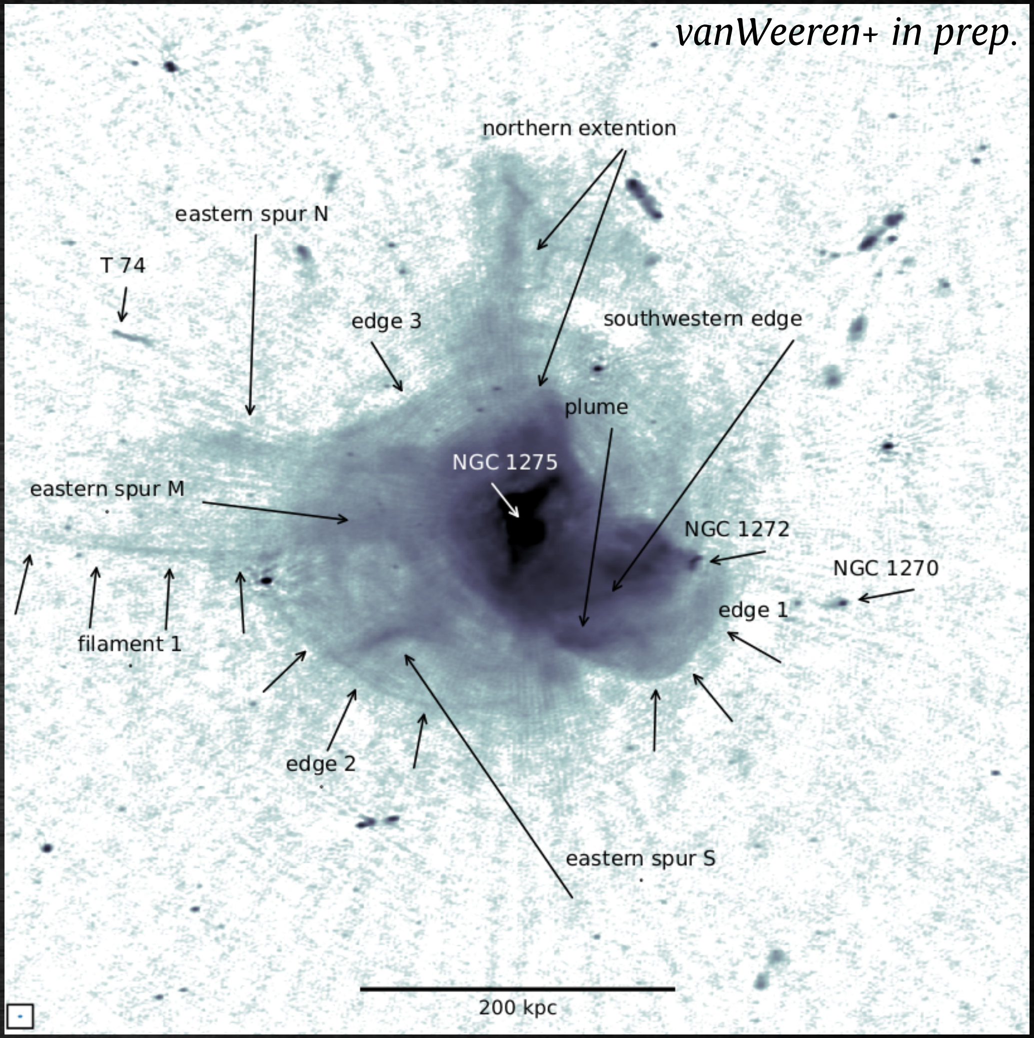

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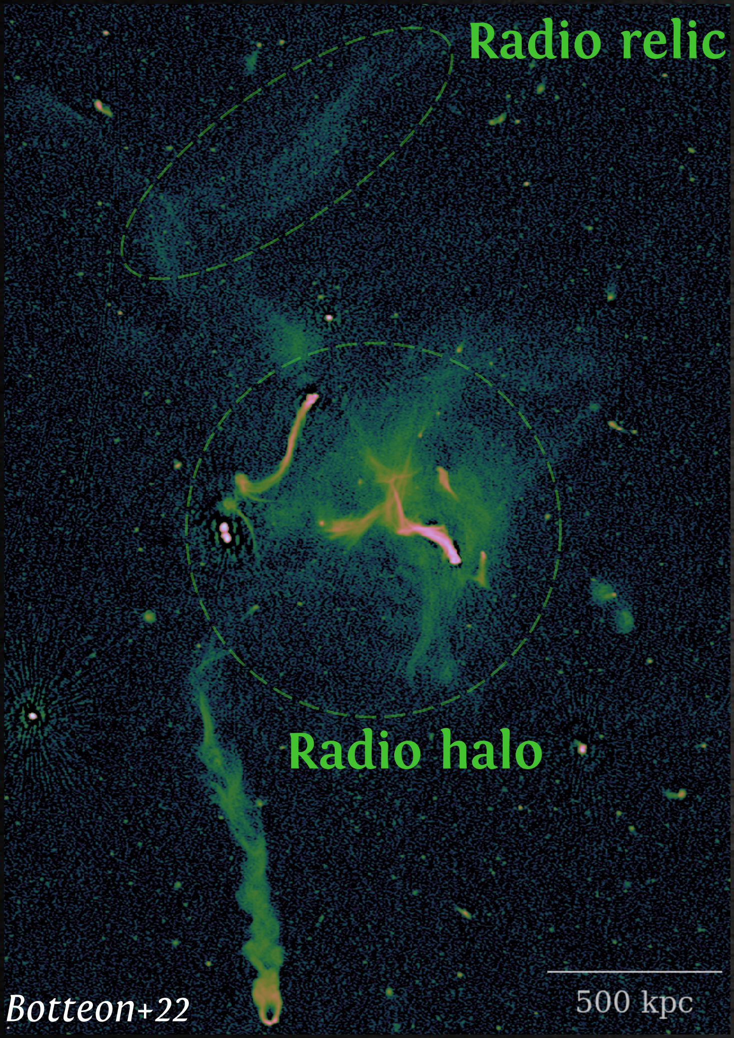

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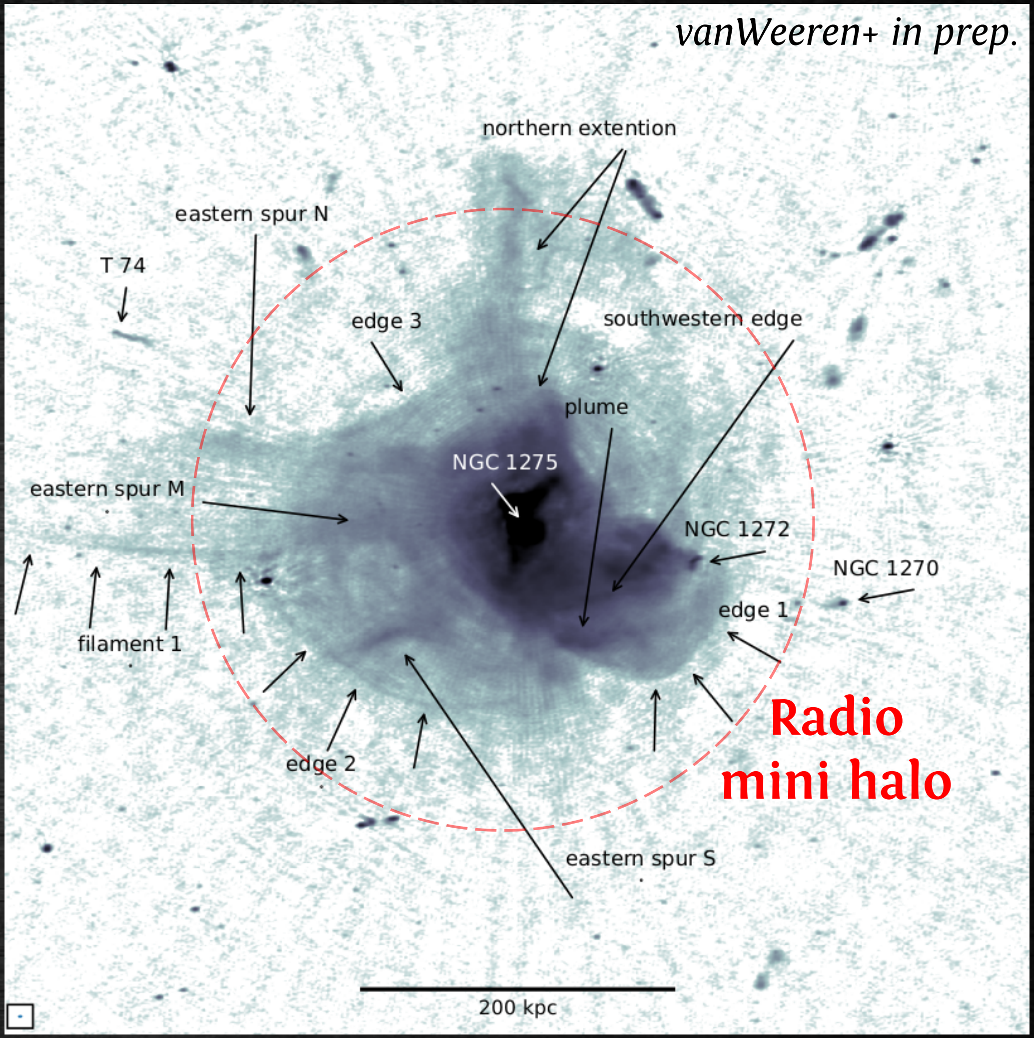

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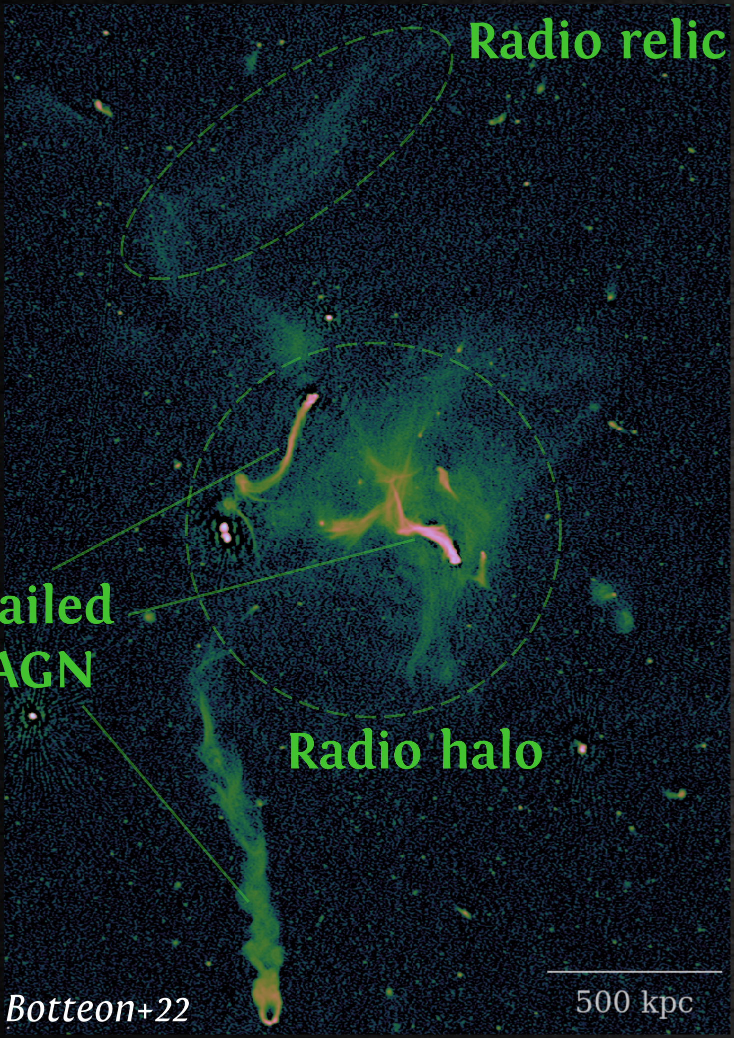
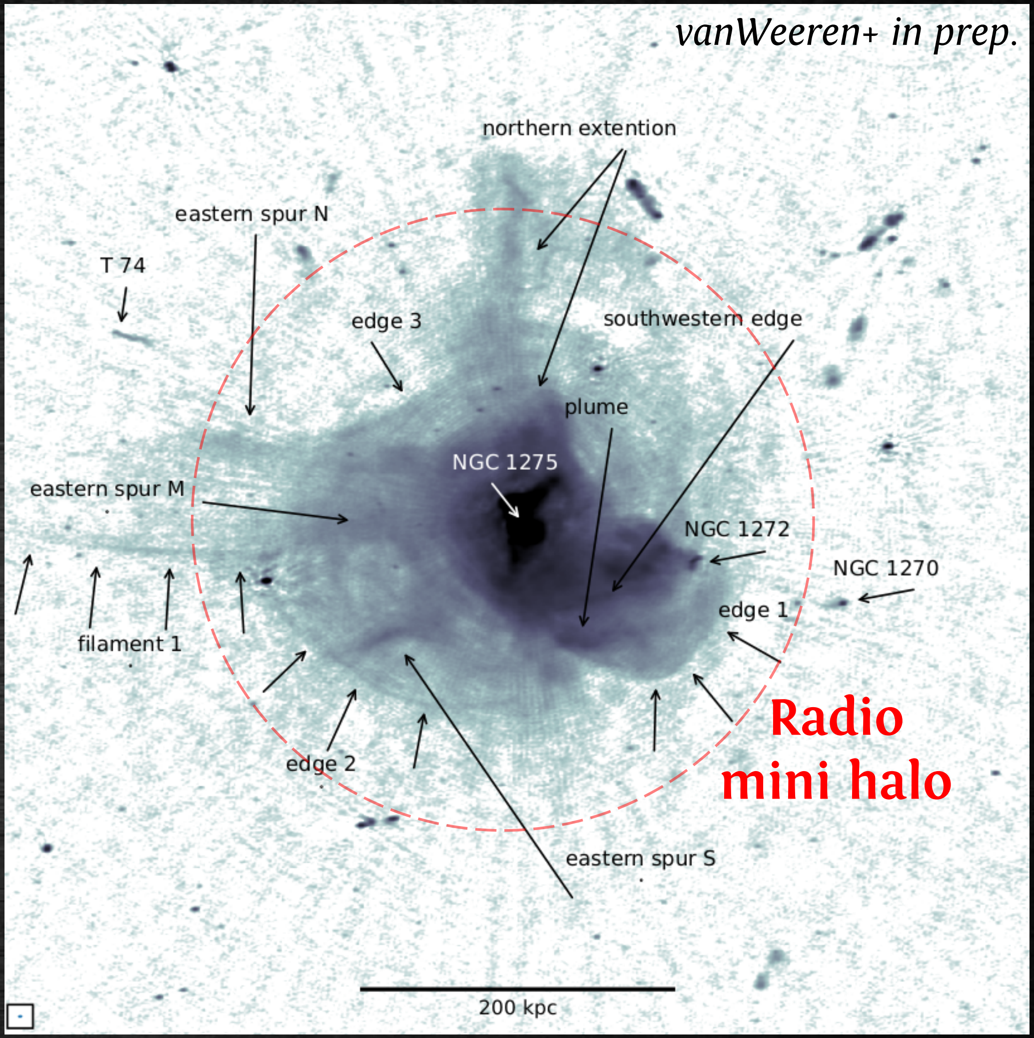


Tailed AGN

Disturbed cluster (A2255)



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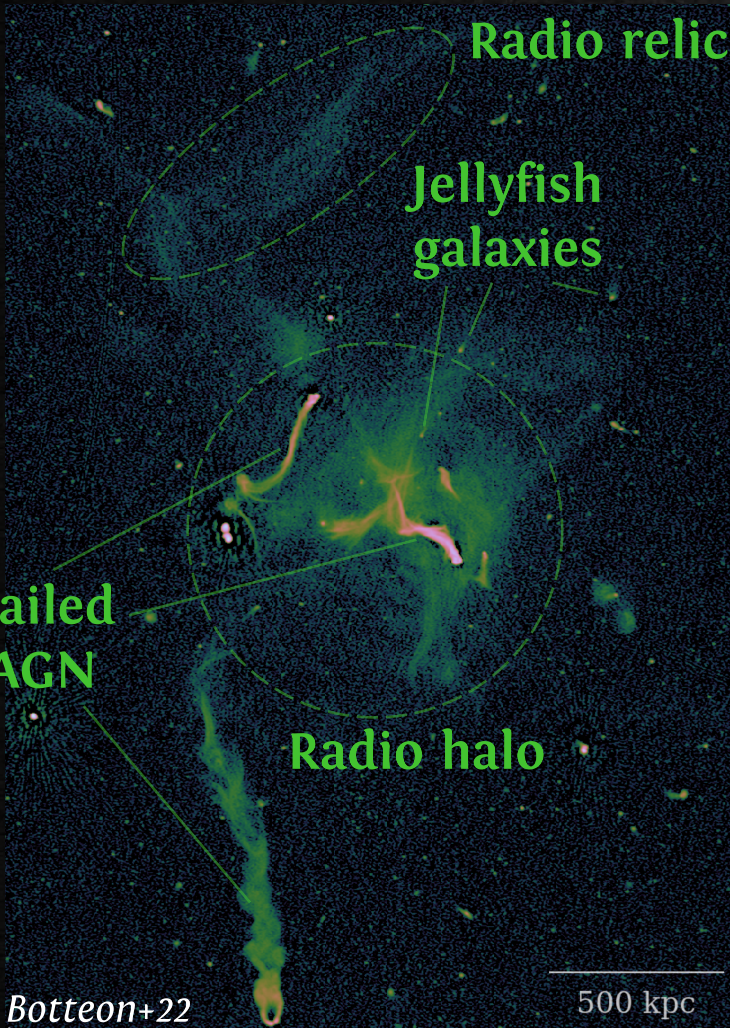

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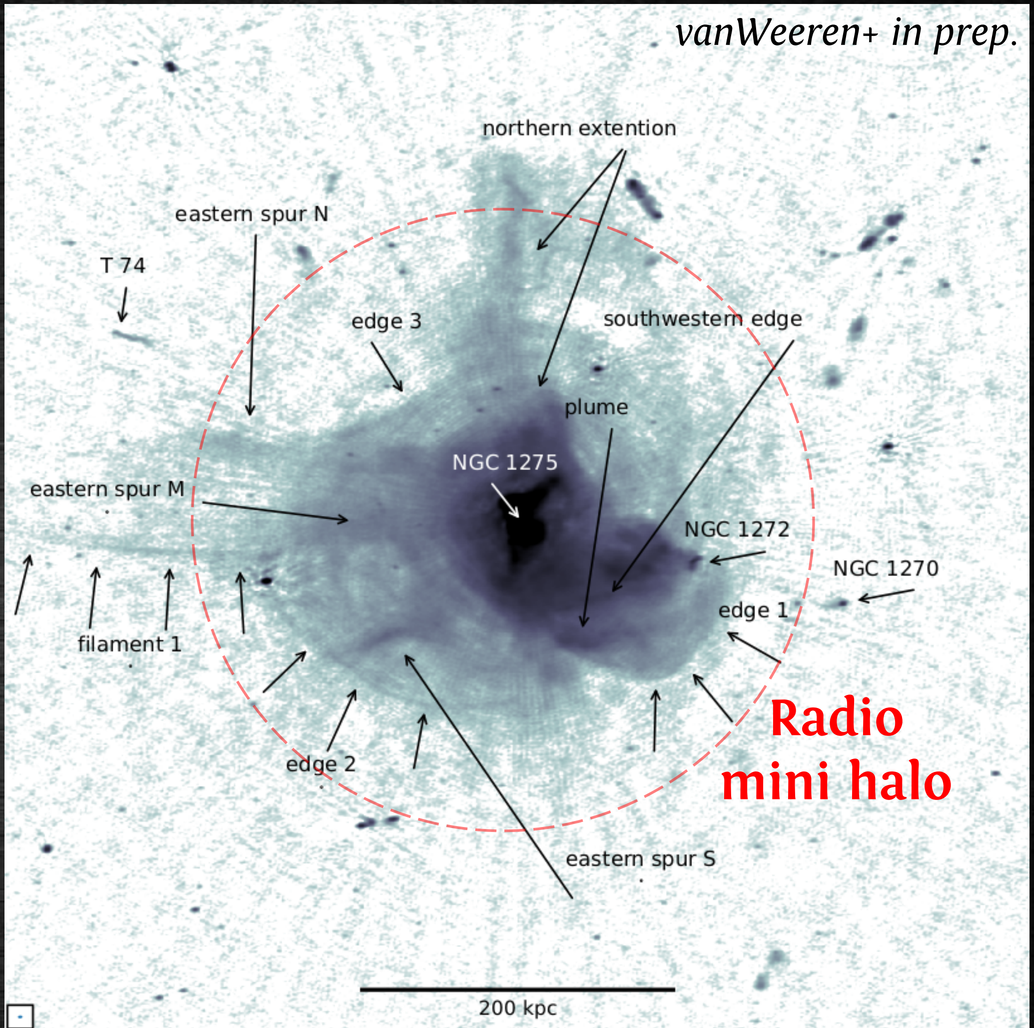

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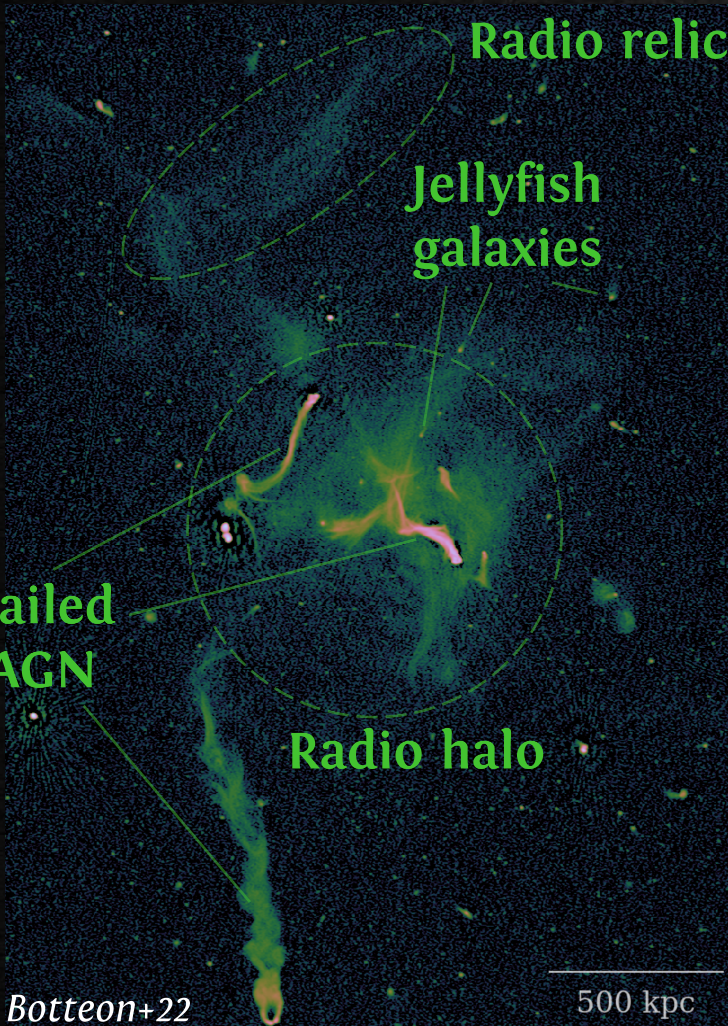

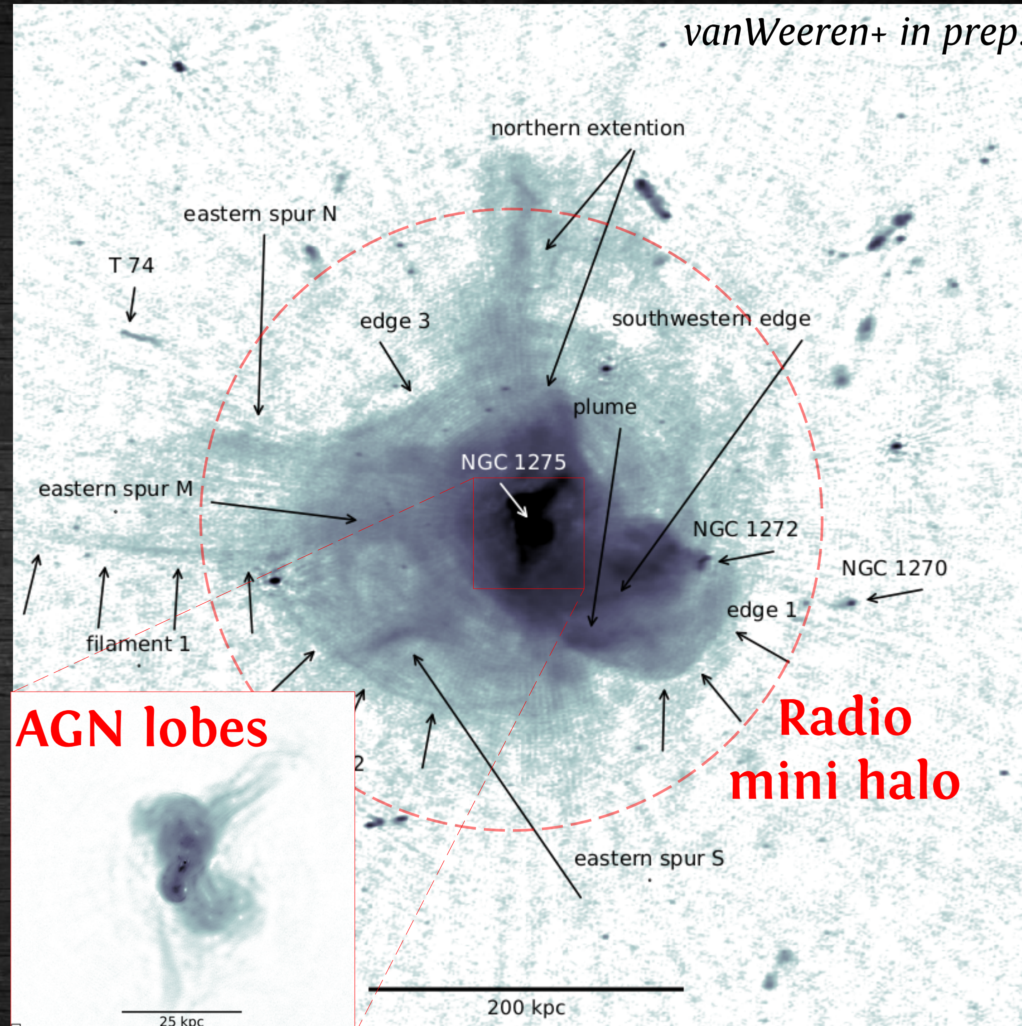

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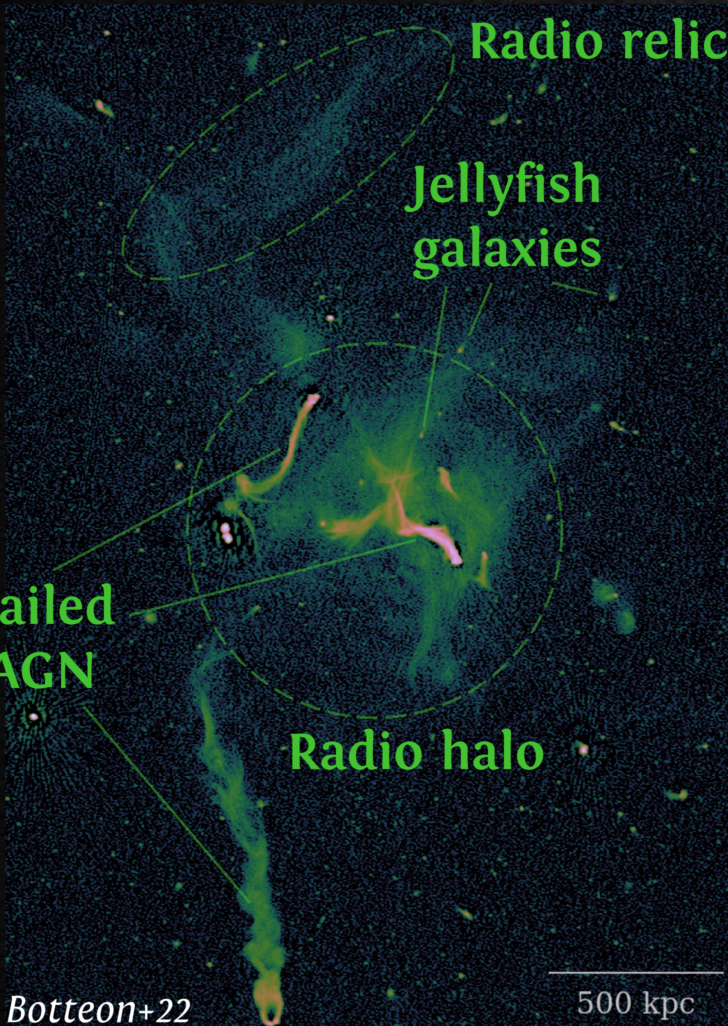

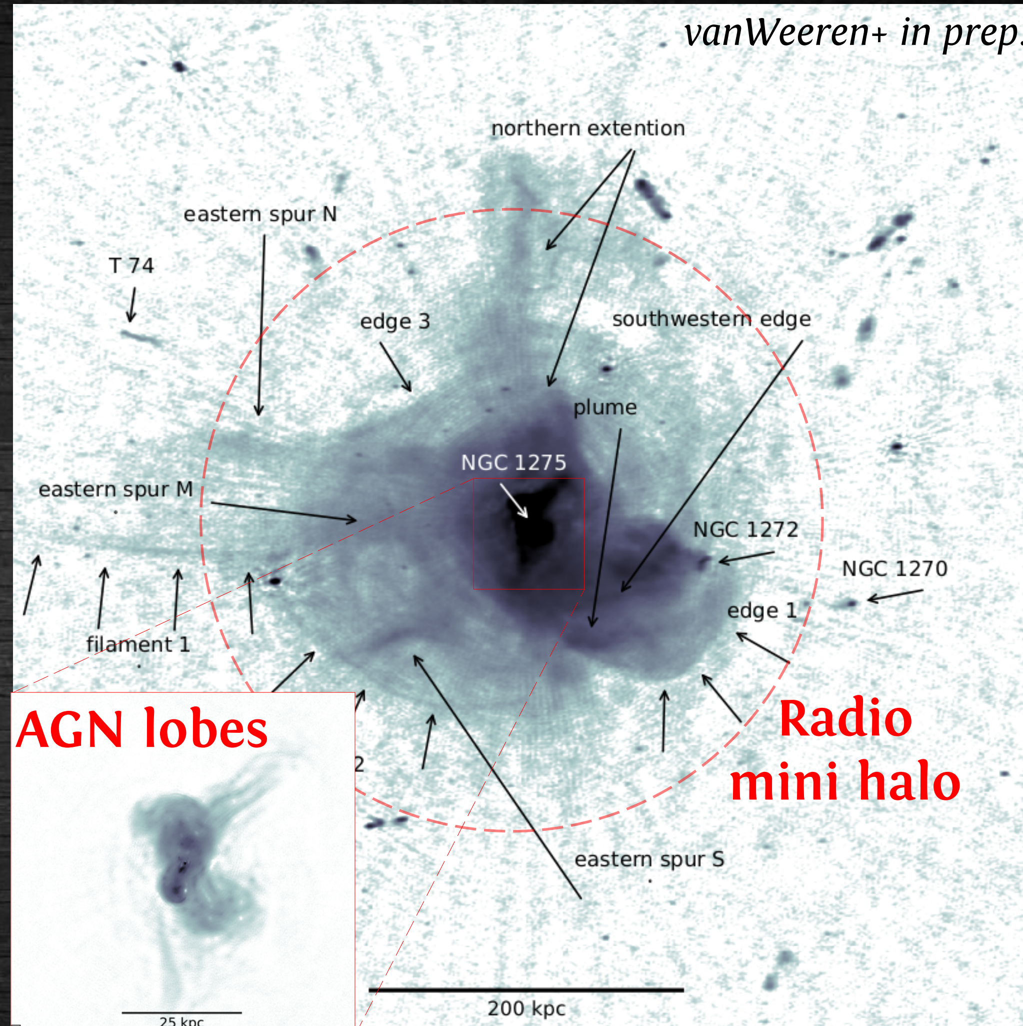

Disturbed cluster (A2255)

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WG interests: ~80% *diffuse emission*, ~20% *cluster galaxies*

WG (original) goals

Exploitation of LOFAR surveys to study galaxy clusters
(~2012)

M. Brüggen (Bremen), **G. Brunetti** (Bologna), T.A. Enßlin (Garching), C. Ferrari (Nice), H.J.A. Röttgering (Leiden), G. Miley (Leiden), P. Best (Edinburgh), A. Edge (Durham), M. Arnaud (Saclay), L. Feretti (Bologna), R.F. Pizzo (Groningen), E. Orrú (Nijmegen), R.J. van Weeren (Leiden, ASTRON), M. Wise (Amsterdam), A. Bonafede (Bremen), M.A. Brentjens (ASTRON), G. Macario (Nice), R. Cassano (Bologna), J. Croston (Southampton), K. Ferriere (Toulouse), M. Hoeft (Tautenburg), K. Chyzy (Krakow), L. Birzan (Leiden), D. Rafferty (Leiden), C. Horellou (Onsala), E. A. Valentyn (Kapteyn) (*Cluster Science Team*)

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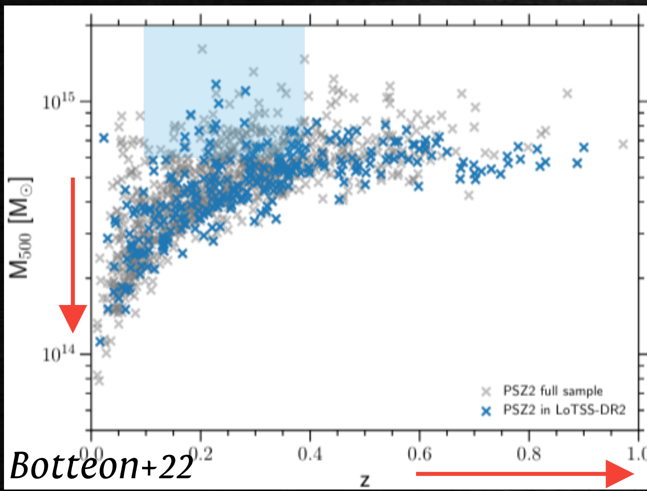
3 Observational goals and survey design

The main observational goals of the present proposal are :

- Discover diffuse emission in a unprecedently large number of clusters (up to large distances, z≈1) and relate observations to models of cluster evolution
- Make detailed maps and spectral studies of diffuse emission at low frequencies to address the magnetic-field structure and the coupling between CR and magnetic fields
- Study the interaction of radio sources with the cluster gas (e.g. radio-blown cavities) in order to constrain physical processes and the evolutionary history of clusters
- Map the 3-dimensional distribution of magnetic fields in nearby clusters via Faraday synthesis and polarization studies of background radio sources
- Detect the cosmic web in the radio via shocked synchrotron filaments in very deep surveys
- Study starburst galaxies in clusters

- Discover diffuse emission in a unprecedently large number of clusters (up to large distances, z≈1) and relate observations to models of cluster evolution ✓

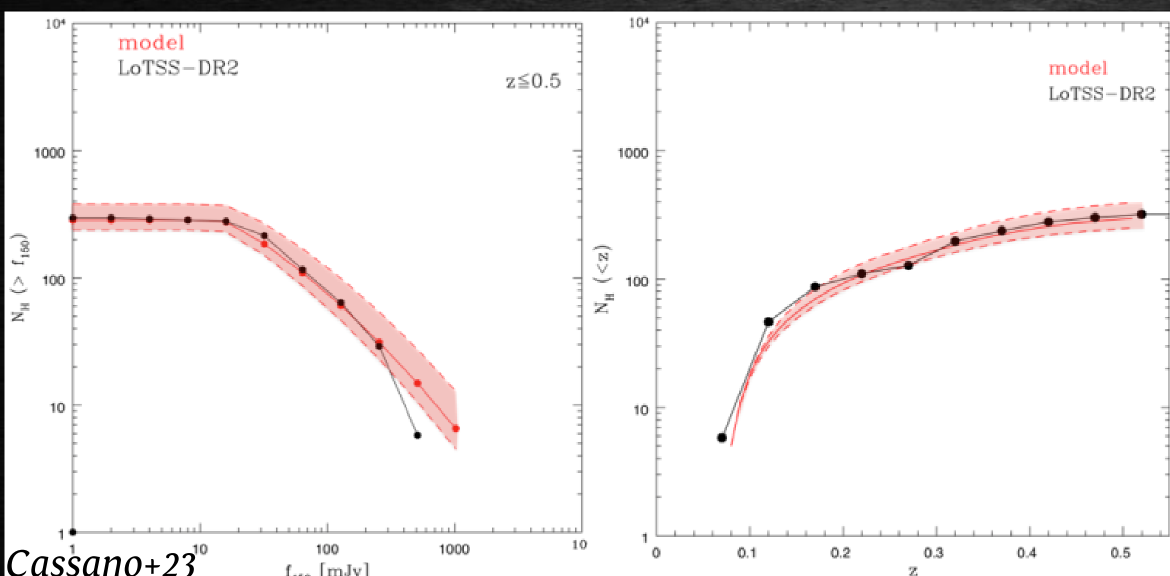
The Planck clusters in the LOFAR sky *(6 papers in A&A)*



Botteon+22

Statistical analysis of PSZ2 *galaxy clusters* exploring new ranges of *redshift* and *mass*

309 clusters: **83** *halos*+**26** *relics*, half are **new**!
Halos observed up to *z~0.9*



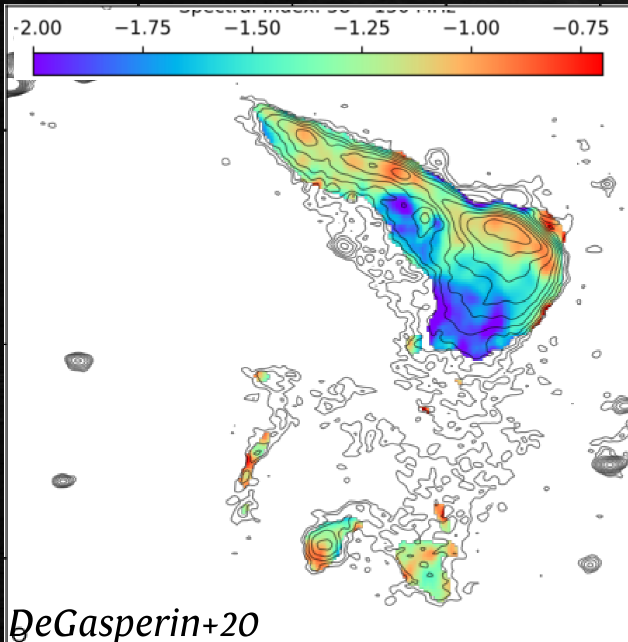
Cassano+23

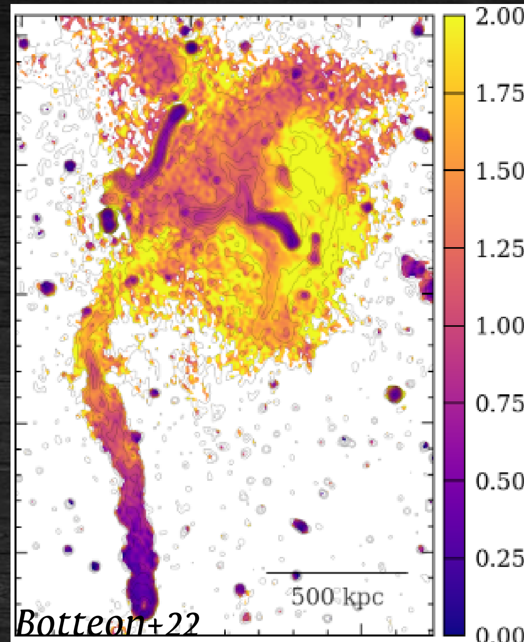
Number, flux density, and z distribution of **halos** OK with *turbulent re-acceleration* models

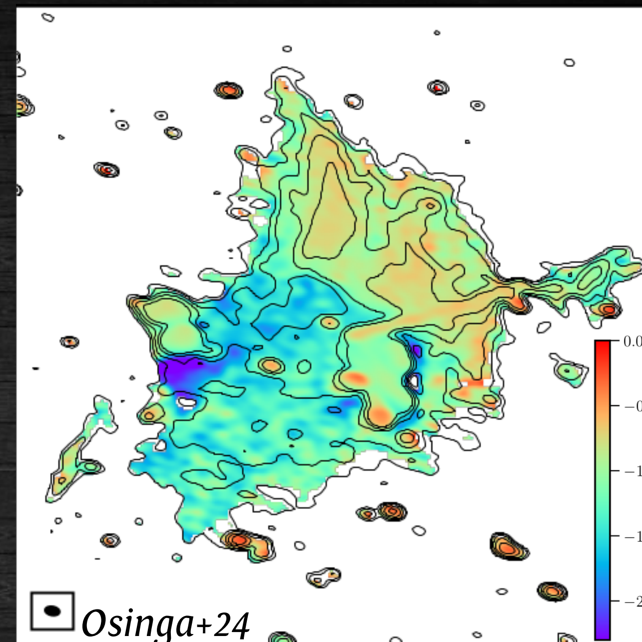
↓

Ongoing: tests on spectral properties using *LoLSS*, *uGMRT*, and *MeerKAT*

- Make detailed maps and spectral studies of diffuse emission at low frequencies to address the magnetic-field structure and the coupling between CR and magnetic fields







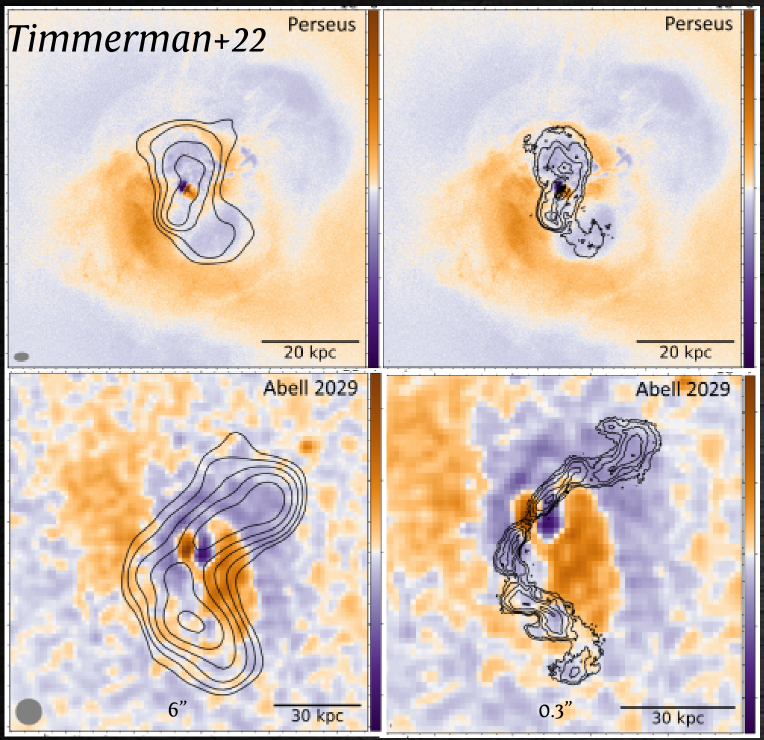
LBA-HBA spectral index maps have been produced for *a few* bright targets

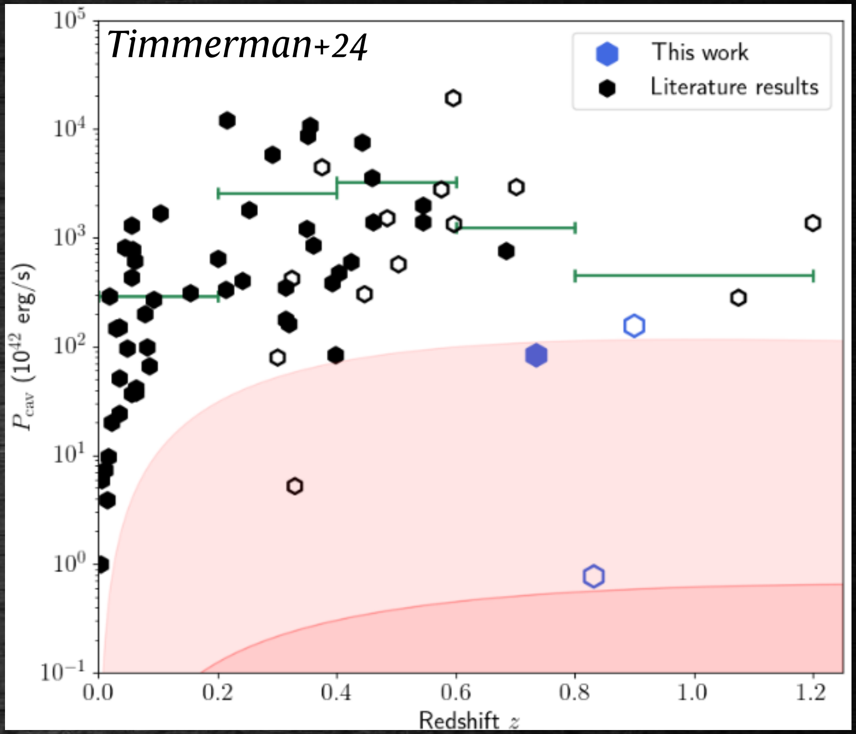
HBA-uGMRT/JVLA spectral index maps have been produced for *many* targets

Halos and **relics** are rich of *(sub)structures* which are often mirrored in the spectral index maps

What is their connection with particle acceleration and magnetic field amplification mechanisms?

- Study the interaction of radio sources with the cluster gas (e.g. radio-blown cavities) in order to constrain physical processes and the evolutionary history of clusters





Hybrid radio/X-ray method to estimate P_{cav}, push studies of radio-mode feedback at *z > 0.6* thanks to the **ILT**

Other kind of interactions between **AGN** and **ICM** observed with LOFAR...

(e.g. phoenixes, tails...see later)

- Map the 3-dimensional distribution of magnetic fields in nearby clusters via Faraday synthesis and polarization studies of background radio sources

NOT DONE: strong Faraday depolarization!

Conversely, **LOFAR** data have been used to probe *magnetic fields* in the **IGM**

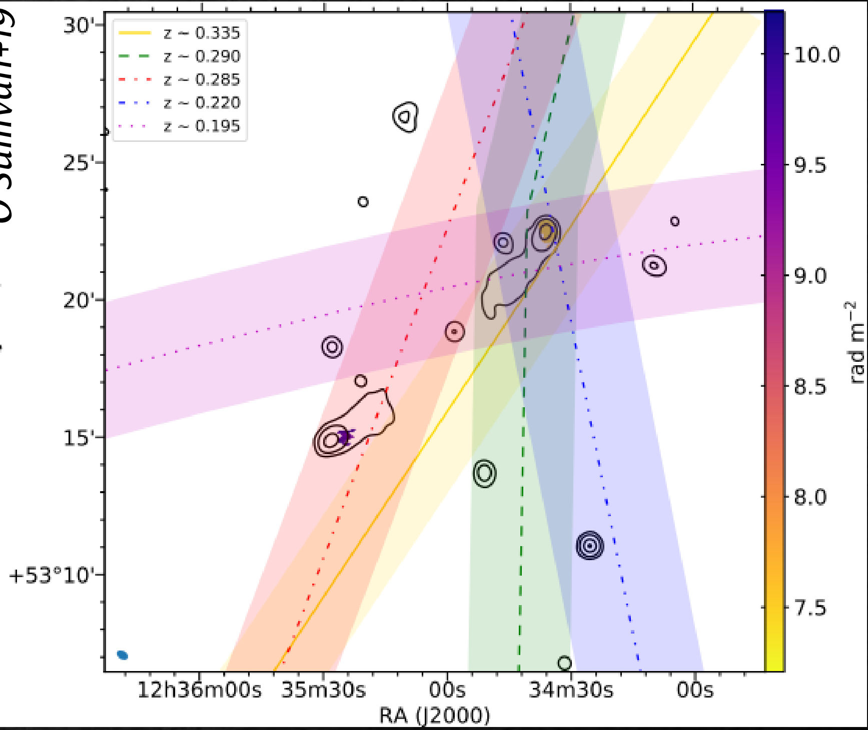
LOFAR Magnetism SKP results

Recent publications:

Credit: O'Sullivan

- Mahatma+21 (radio galaxy environments)
- Hutschenreuter+22 (Milky Way ISM)
- Stuardi+20 (giant radio galaxies)
- Sobey+22 (new pulsars)
- O'Sullivan+19, 20 (IGM magnetism)
- Carretti+22a,b (magnetisation of cosmic filaments)
- Pomakov+22 (evolution of cosmic magnetism)
- Heesen+23 (magnetised CGM of nearby galaxies)

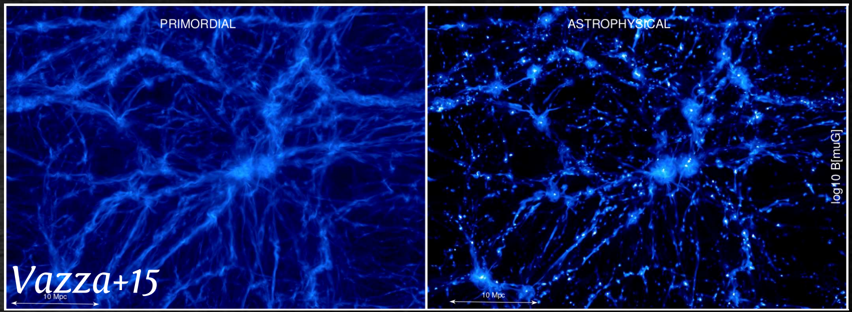
O'Sullivan+19

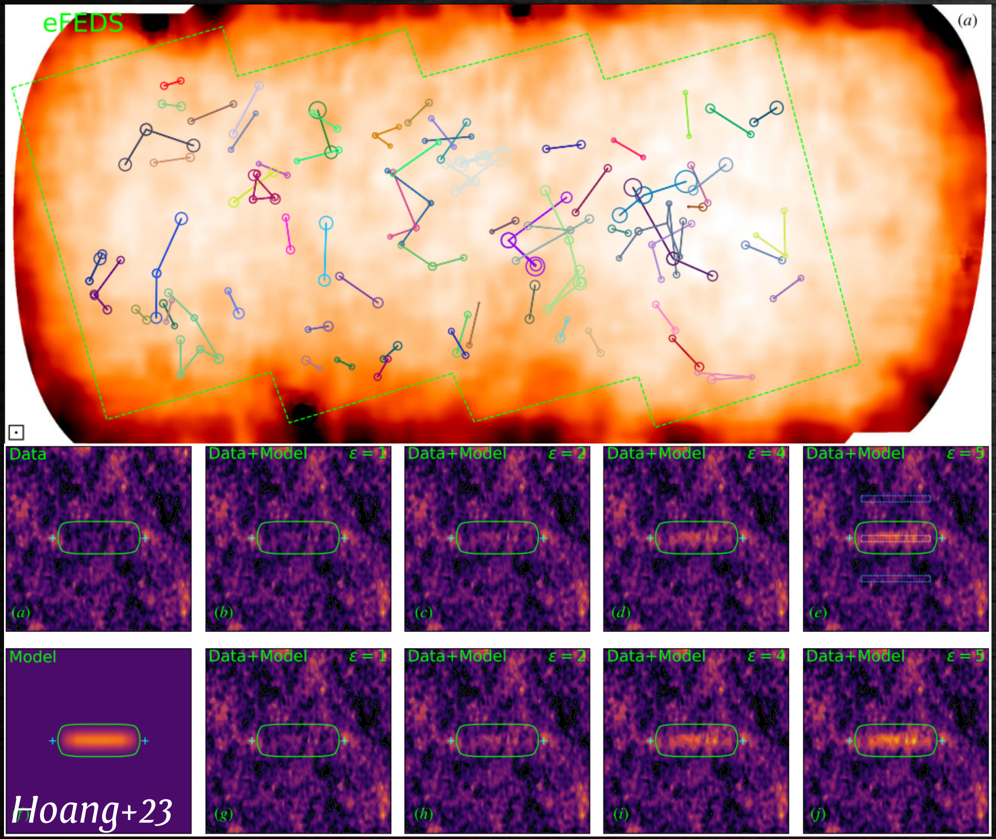


- Detect the cosmic web in the radio via shocked synchrotron filaments in very deep surveys

NOT DONE: radio emission from the *cosmic web* is beyond reach of *current* instruments

- *How did the Universe become magnetic?*
- *Where and when did it originate, and how has cosmic magnetism evolved?*





Solution(?): **stacking**

106 paired clusters (*LOFAR*, *eROSITA*)

- *ε < 1.2 x 10⁴⁴ erg/s/cm³/Hz*
- *B < 75 nG*

The detection with other instruments is **disputed**
(*Vernstrom+21, Hodgson+22*)

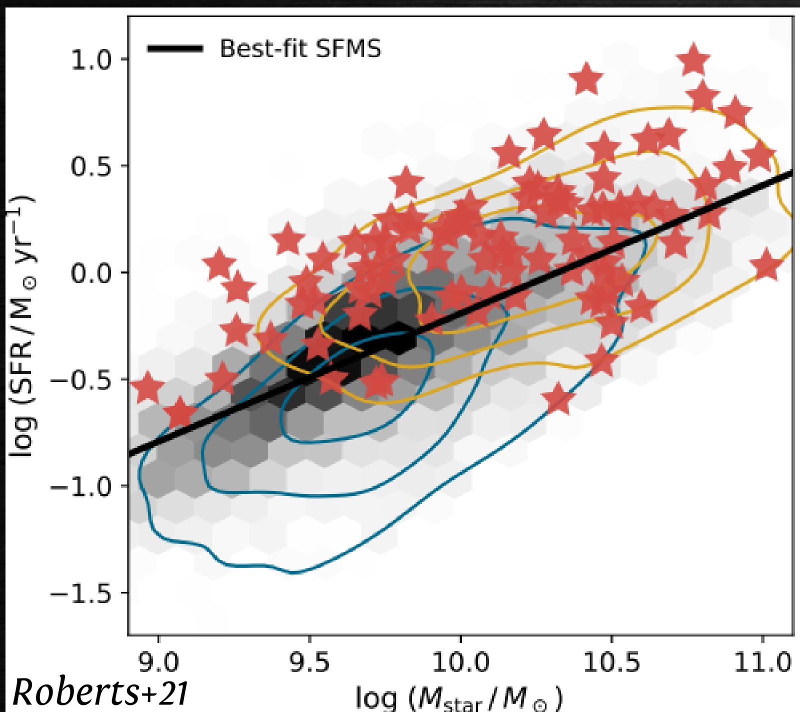
→ need to extend the **LOFAR** analysis to a *larger area*
(*Hoang+, in prep.*)

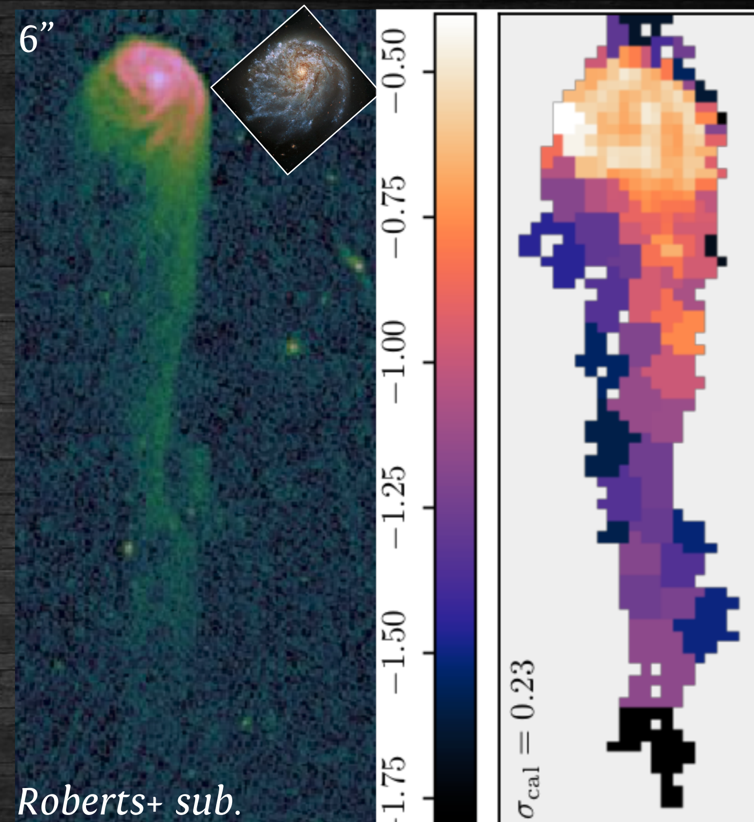
- Study starburst galaxies in clusters

Jellyfish galaxies: starburst galaxies undergoing RPS

LoTSS jellyfish galaxies

(4 papers in A&A)



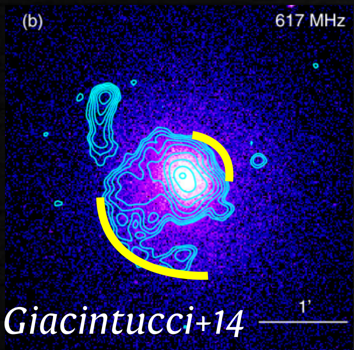


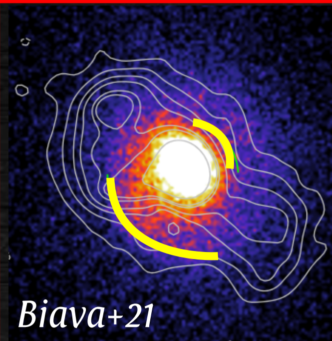
Enhanced SFR, tails up to 100 kpc, simple *radiative aging*

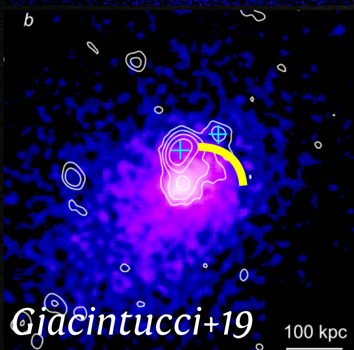
see Ignesti’s talk

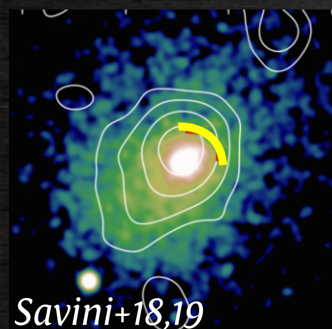
Some “unplanned” results

Mpc-scale halos in relaxed clusters





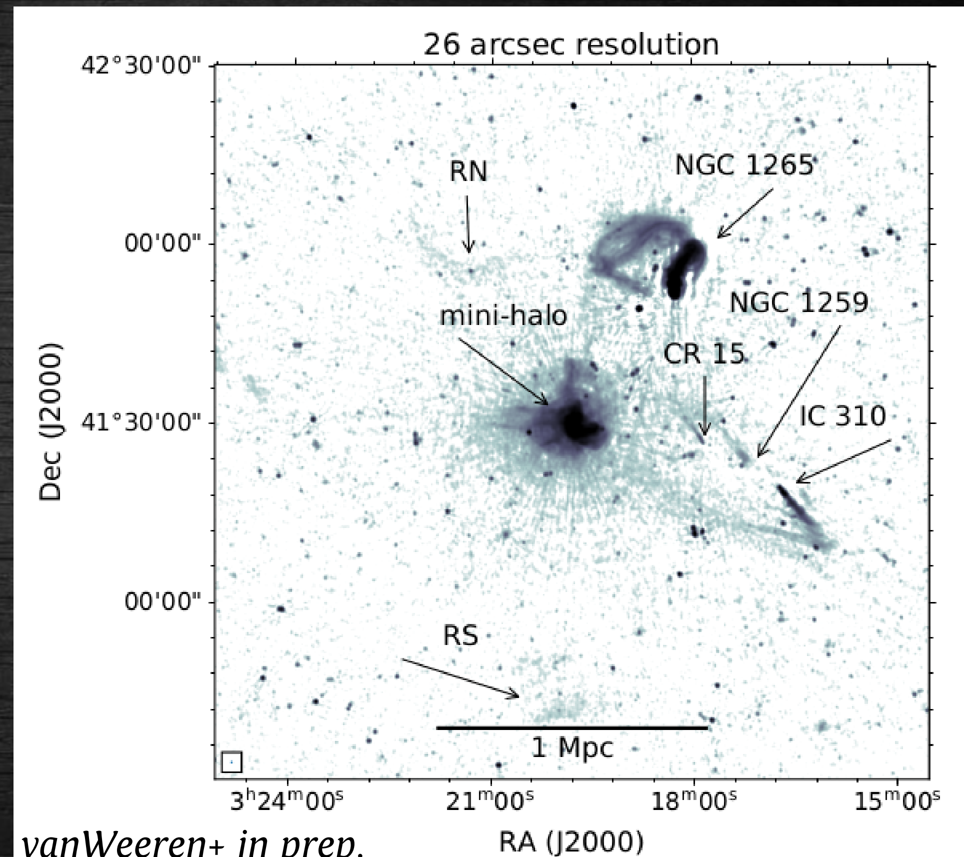




GMRT
610 MHz

LOFAR
144 MHz

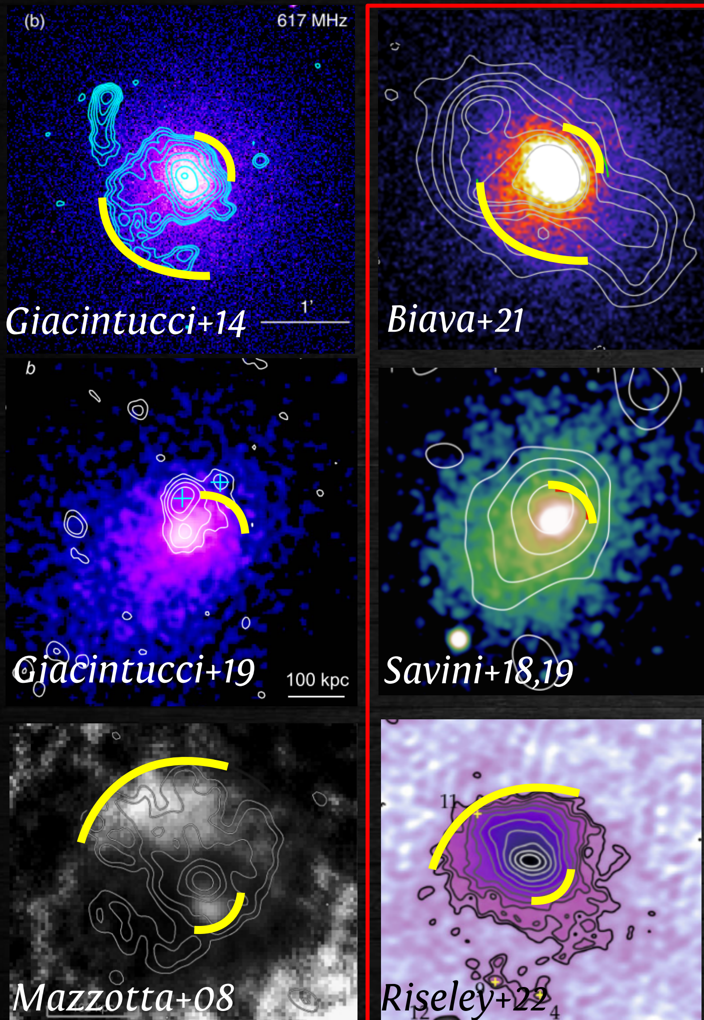
Some **mini-halos** are surrounded by *steep spectrum* emission



- *Two components with different origin?*
- *Low levels of turbulence outside the cold fronts?*

Mpc-scale halos in relaxed clusters

Some **mini-halos** are surrounded by *steep spectrum* emission



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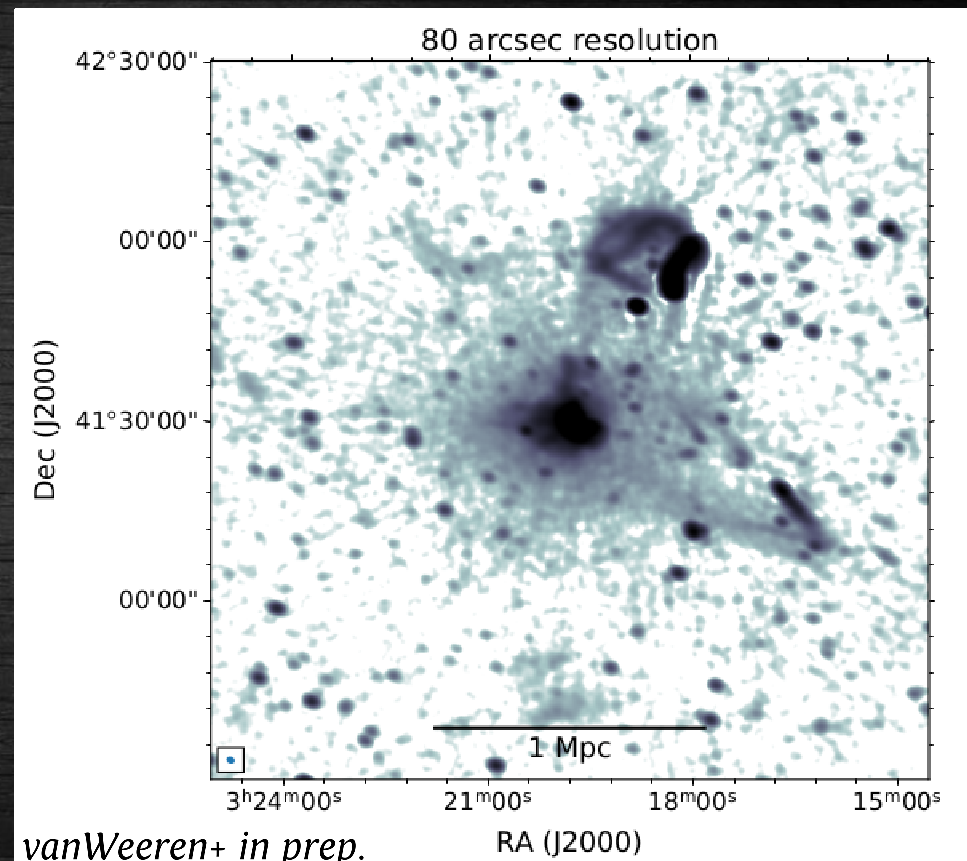
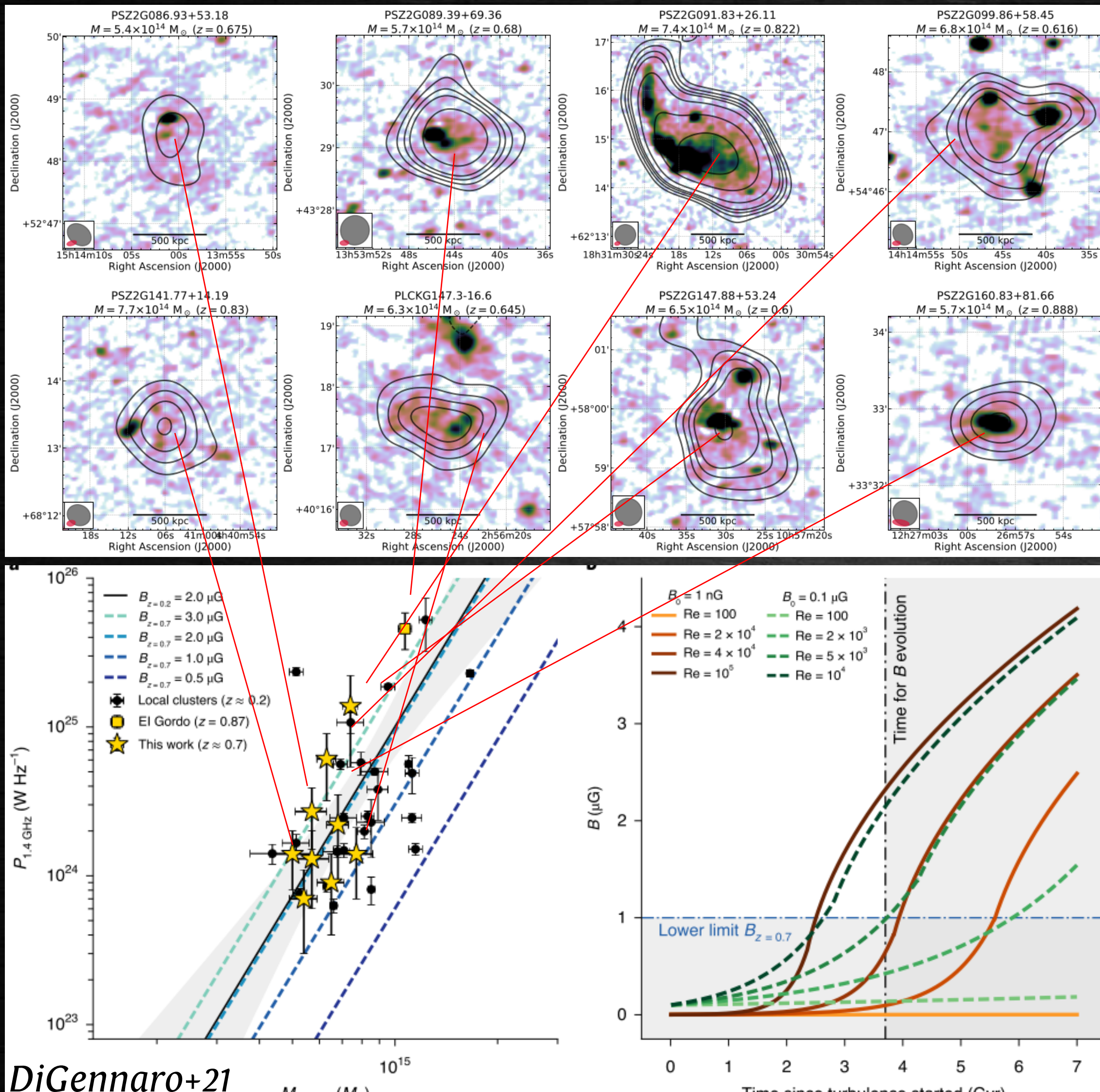


- *Two components with different origin?*
- *Low levels of turbulence outside the cold fronts?*

Magnetic field amplification



DiGennaro+21

High-redshift sample:
PSZ2 at *z > 0.6* in **LoTSS**

$$\boxed{\frac{d\gamma}{dt} \propto -\left(B_{\rm cmb}^2 + B^2\right)\gamma^2}$$

$$B_{\rm cmb} = 3.25(1+z)^2 \mu\mathrm{G}$$

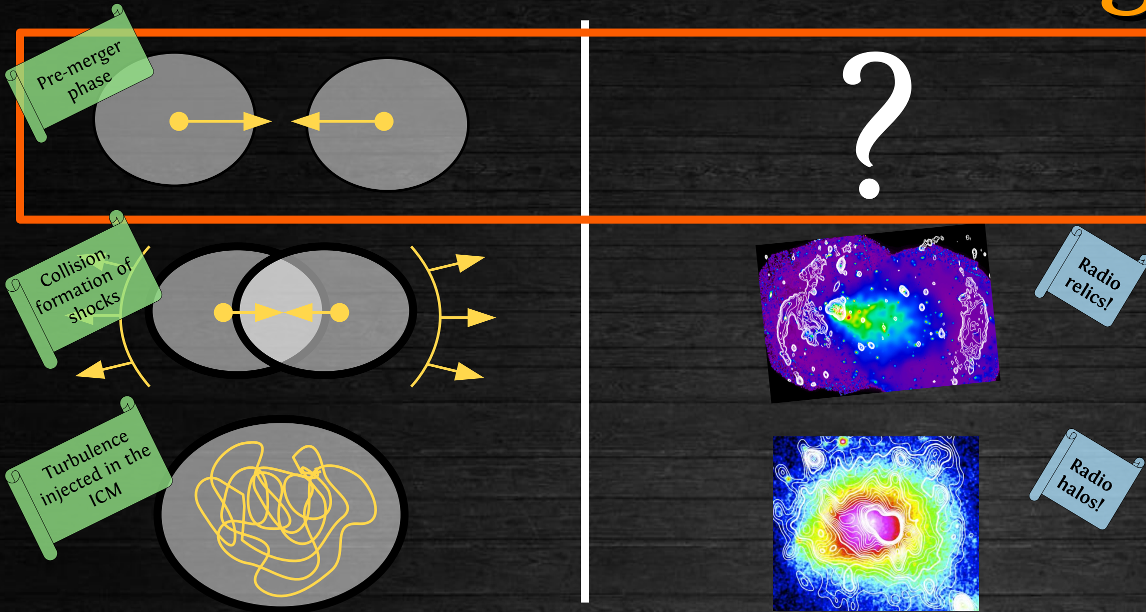
↓

Strong *IC* losses

see Di Gennaro's talk

Fast magnetic field amplification in *distant* galaxy clusters

Radio bridges



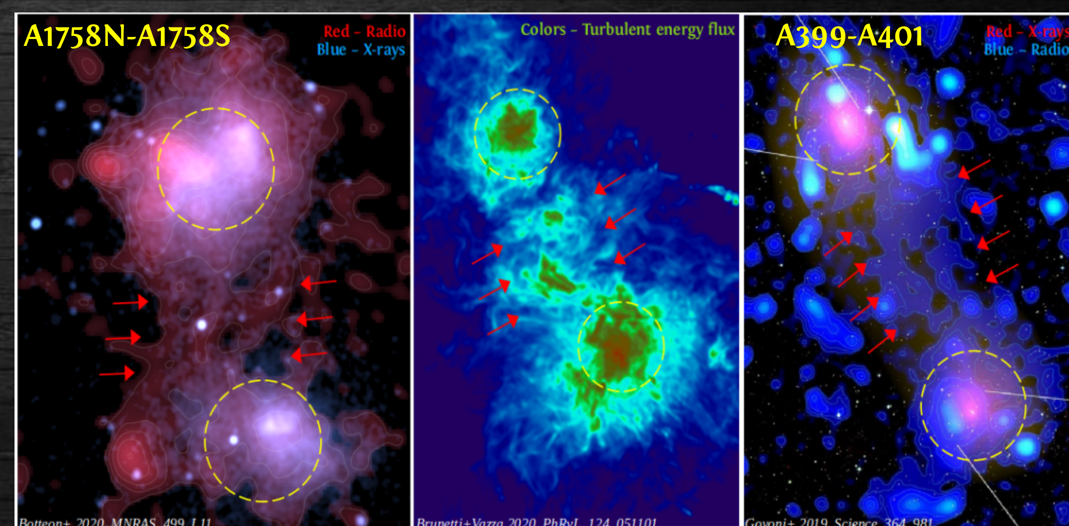
Can diffuse radio emission be generated *before* the merger phase?

YES,

in form of *radio bridges*!

Radio bridges are **2-3 Mpc** long synchrotron sources connecting *pairs* of galaxy clusters

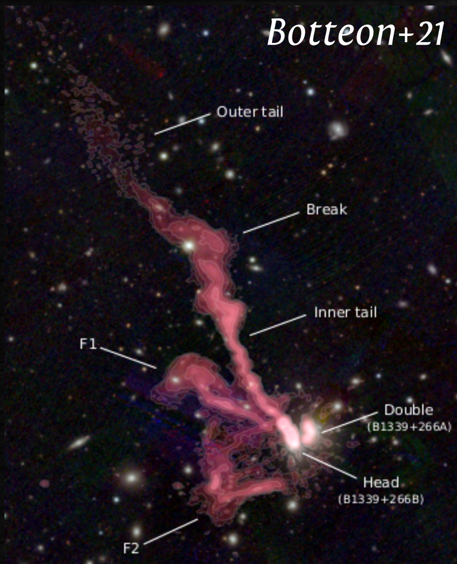
- *Are bridges common in cluster pairs?*
- *What are the properties of the emission?*
- *What are the particle acceleration mechanisms?* (shock vs turbulence)

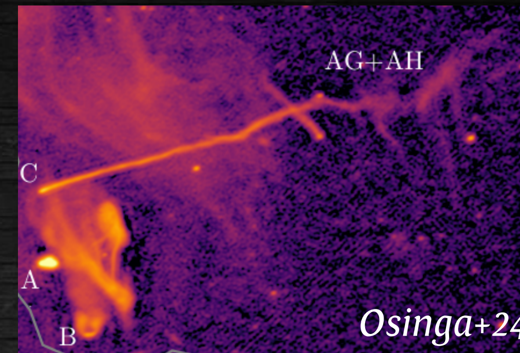


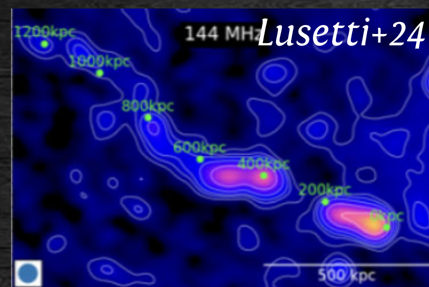
Very *active* research field

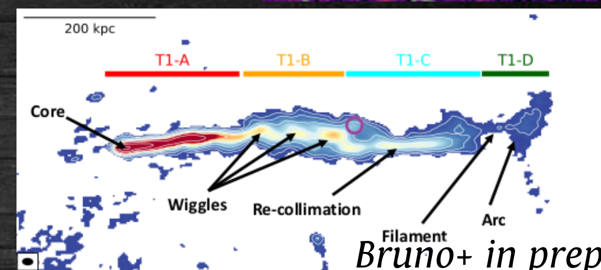
(Wittor+19, Brunetti+Vazza20, de Jong+22, Radiconi+22, Nunhokee+23, Balboni+23, Pignataro+23,24)

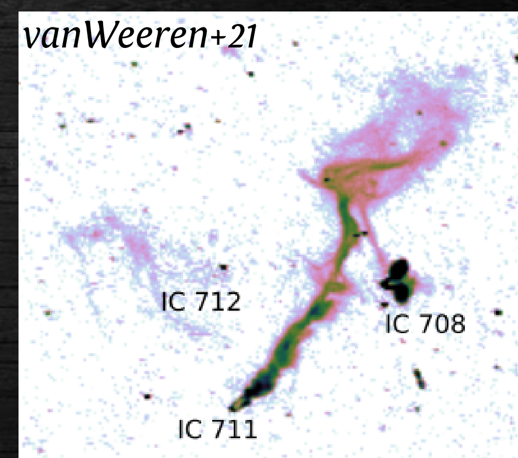
Tailed AGN and interplay with ICM

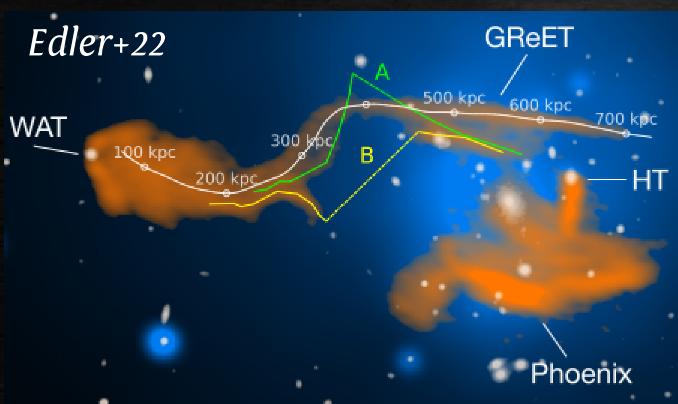


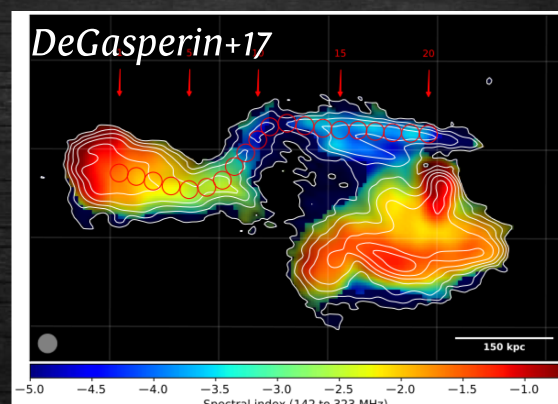






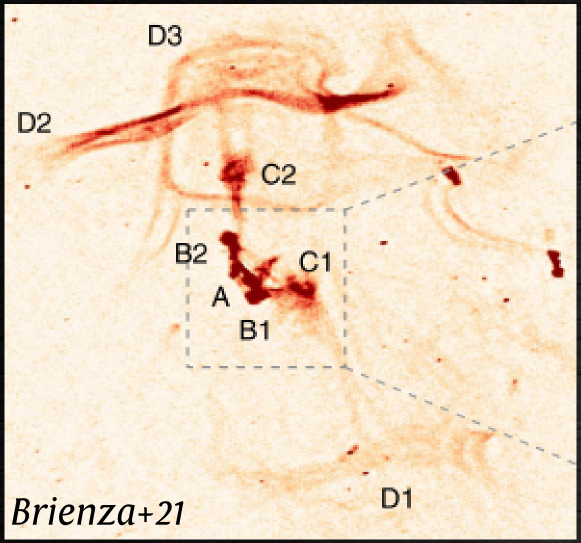


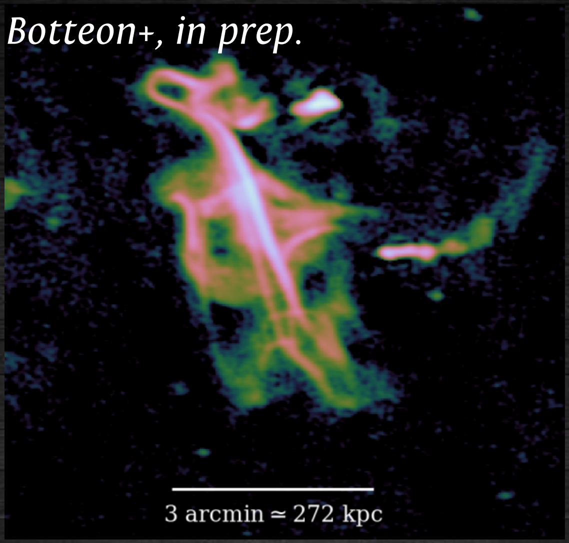


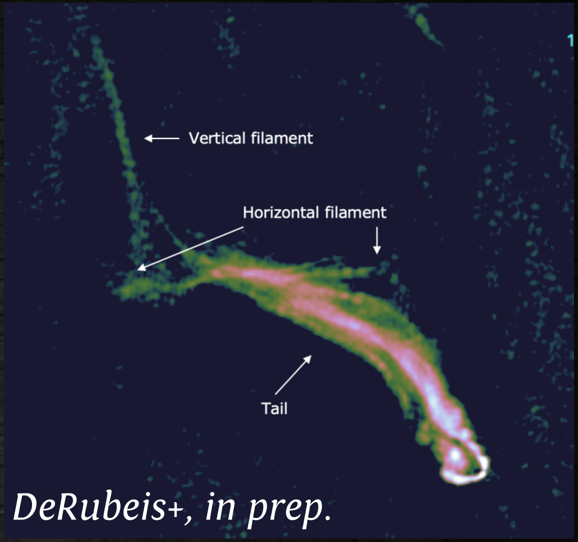


Tails are often *long* and *broken*, suggesting complex interactions between *non-thermal components* and **ICM motions** → transport of **seeds** and **B**

Filaments everywhere

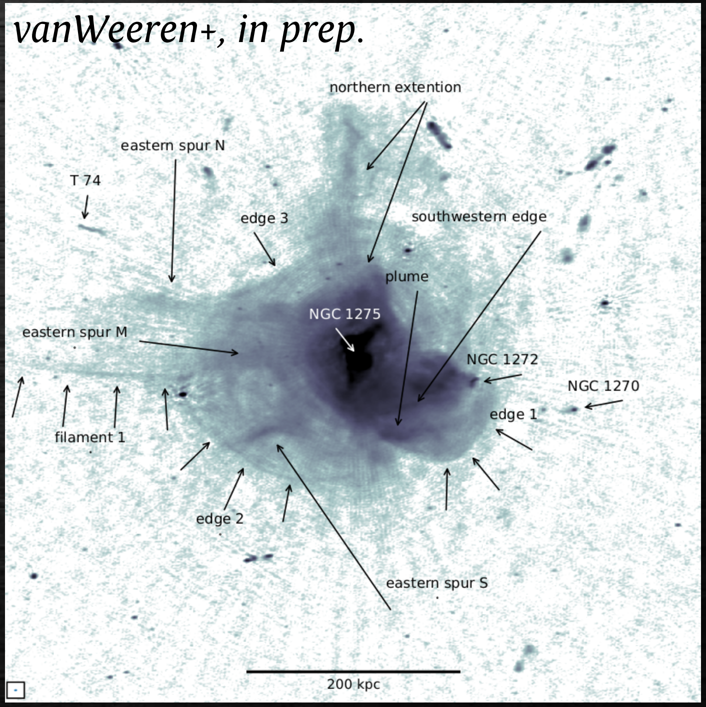






Tubes/filaments may be connected with *complex shock surfaces*, or mark *large-scale turbulent magnetic fields*, or be related to *flux tubes where the electron diffusion is faster*, or other

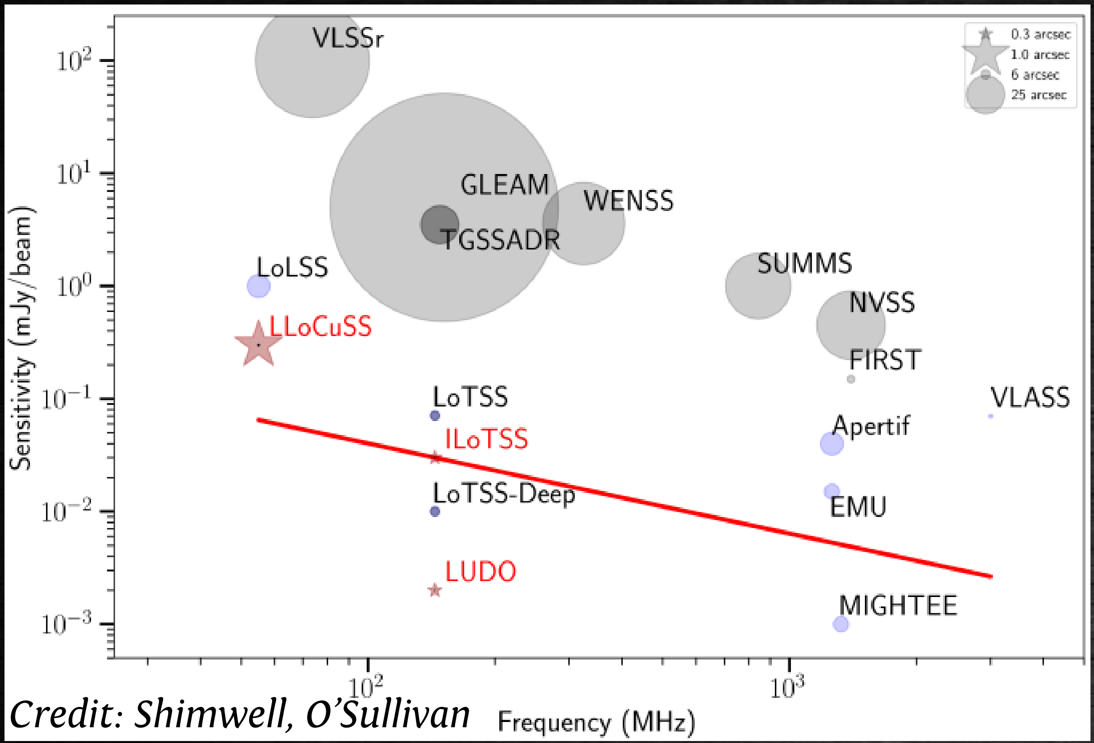
(e.g. Rudnick+22)



? *What is their connection with particle acceleration and magnetic field amplification mechanisms?*

see Brüggen’s talk

LOFAR2.0



Credit: Shimwell, O'Sullivan

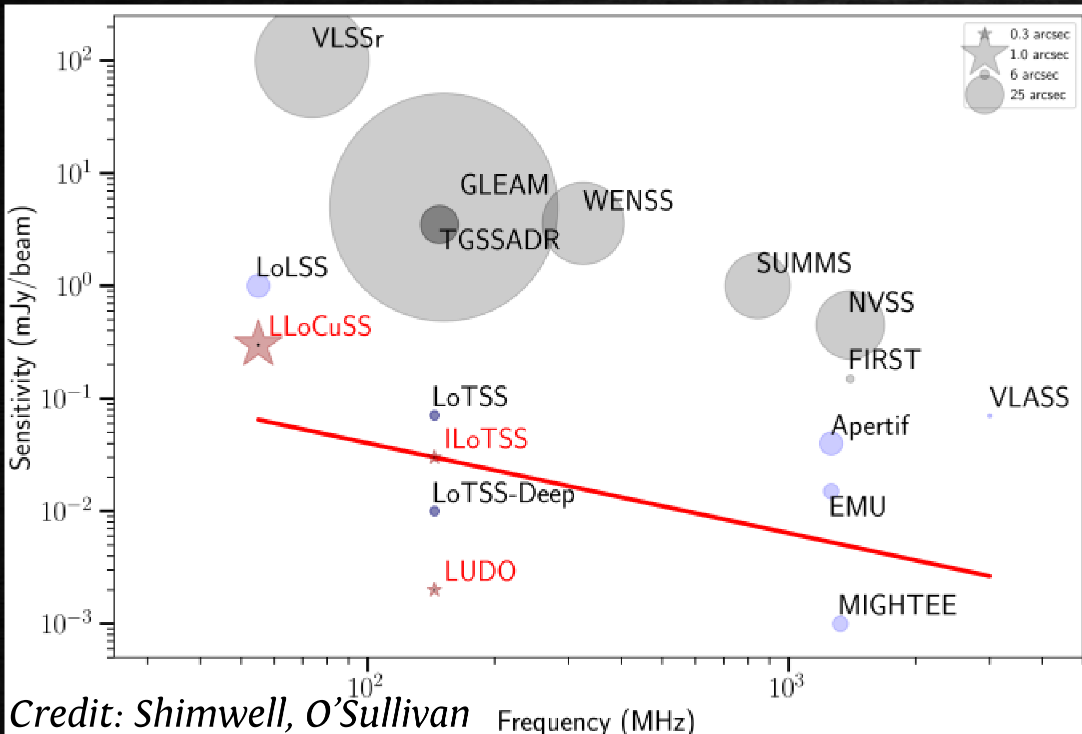
Spectral index studies with **LOFAR** are limited because of **LBA**

↓ **LOFAR2.0**

Improved *sensitivity* and *resolution* is critical to perform spectral studies of cluster sources

(e.g. Pasini+ sub.)

LOFAR2.0



Credit: Shimwell, O'Sullivan

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(e.g. Pasini+ sub.)

A survey like **LLoCuSS** will also allow to detect emission from the *oldest electrons*/*weakest magnetic fields* (AGN bubbles, tails, outskirts) and rare sources with *steep spectra*

A survey like **ILoTSS** will also allow to study *AGN-feeback* in a large numer of clusters and investigate the origin of *non-thrermal filaments*

Conclusions

- **Galaxy clusters** host a *multitude* of radio sources
- Halos, relics, mini-halos, bridges sources probe *non-thermal* phenomena in extremely dilute media
- *CRs acceleration* and *B amplification* in **unique** environments

Conclusions

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- LOFAR has **revolutionized** this field
- Important *advances* have been achieved
- Many *open questions* still remain (magnetic fields, synchrotron cosmic web, acceleration mechanisms)

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Thank you

Extra slides

The LOFAR Cluster Deep Field

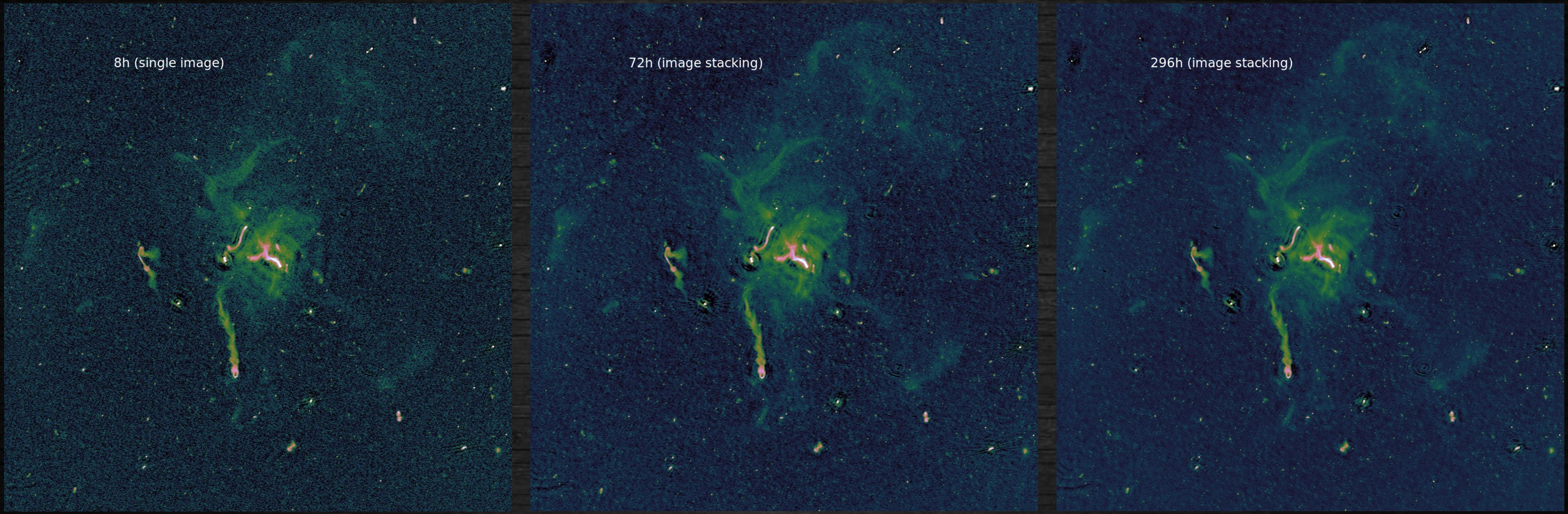
Abell 2255 *(z=0.08)*

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

Observed in different epochs with **LOFAR HBA**:

- **2018 → 8h** in the context of LoTSS *(Botteon+20)*
- **2019 → 72h** *(Botteon+22)*
- **2022-2023 → 226h** *(analysis in progress)*

= **336h**



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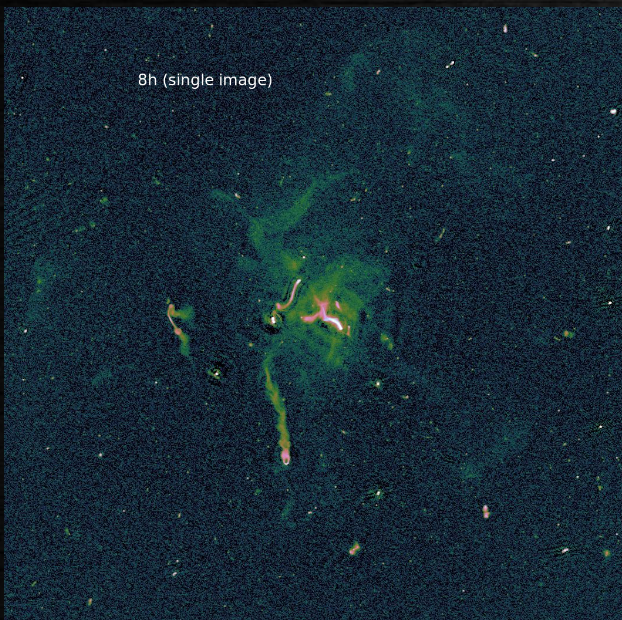

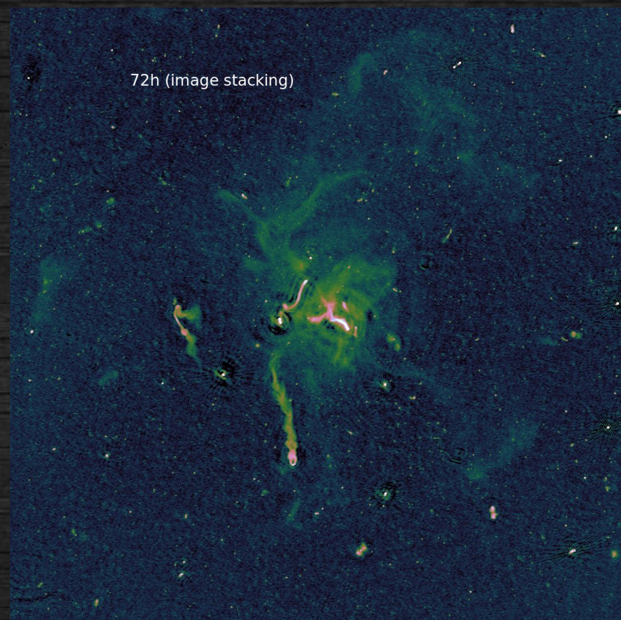

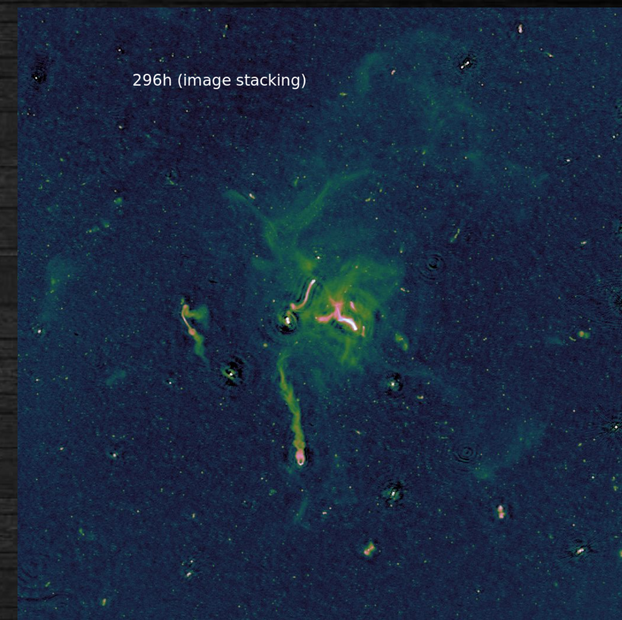

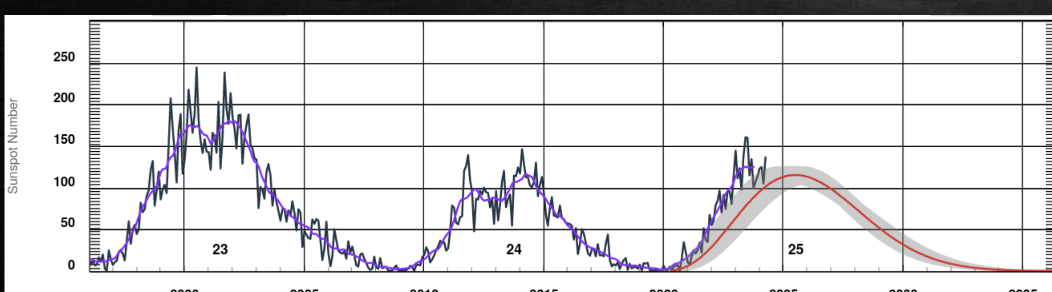

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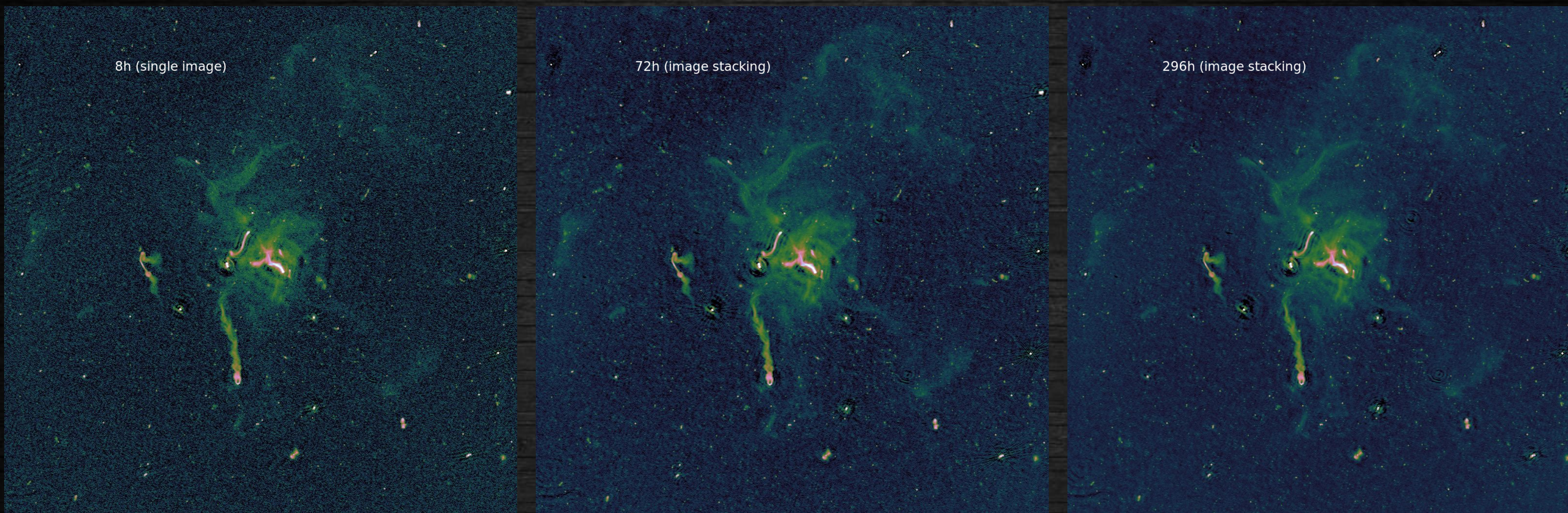
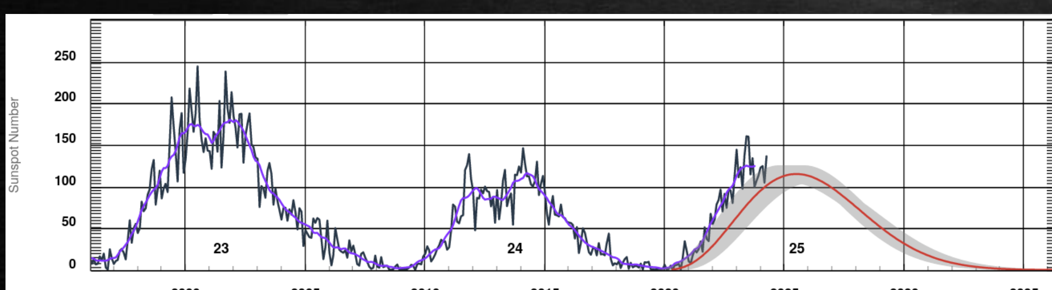
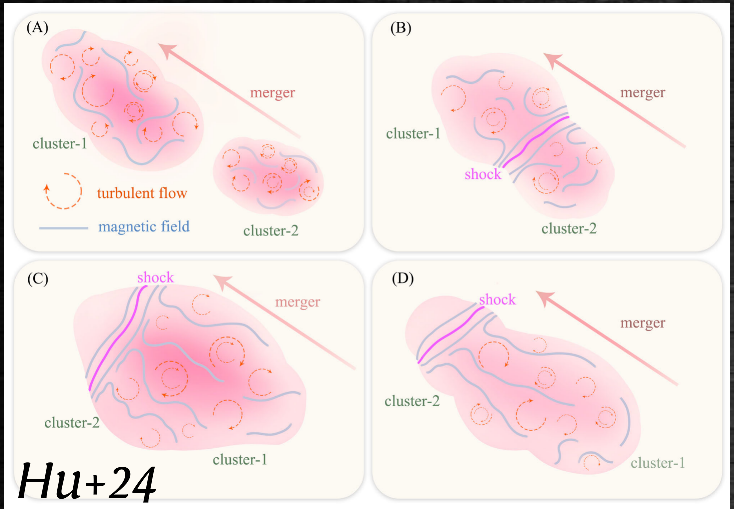


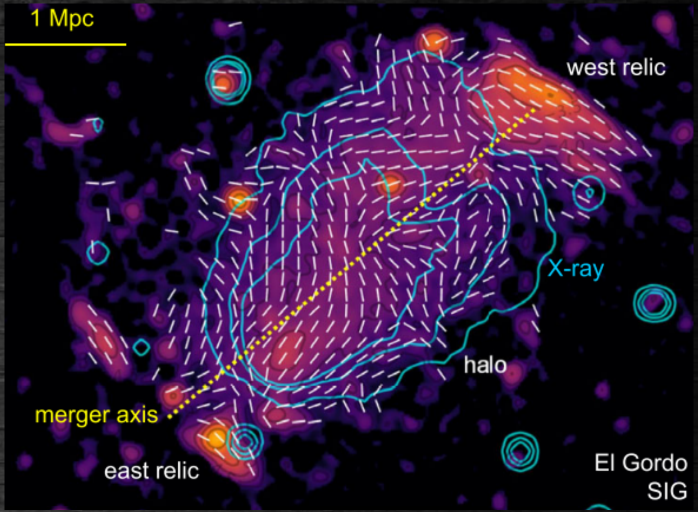


Nice northern lights pictures = *bad* radio data

Magnetic field topology

The direction of **synchrotron intensity gradient** (SIG) determines the magnetic field *orientation* *(Lazarian+17,18, Hu+20)*





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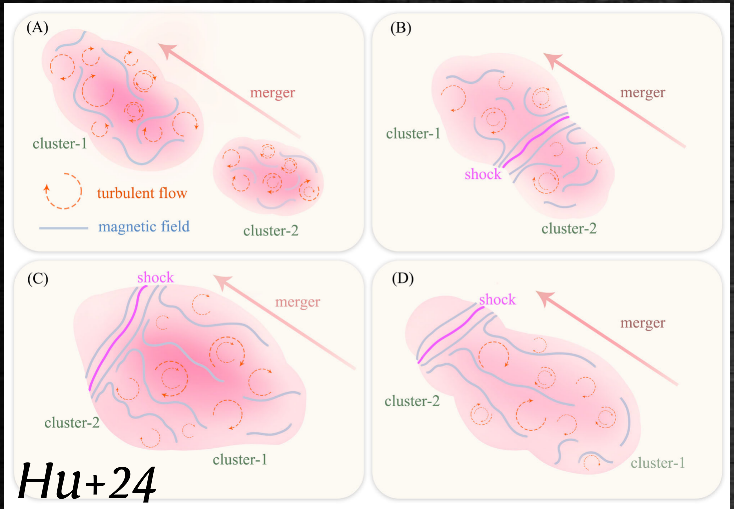
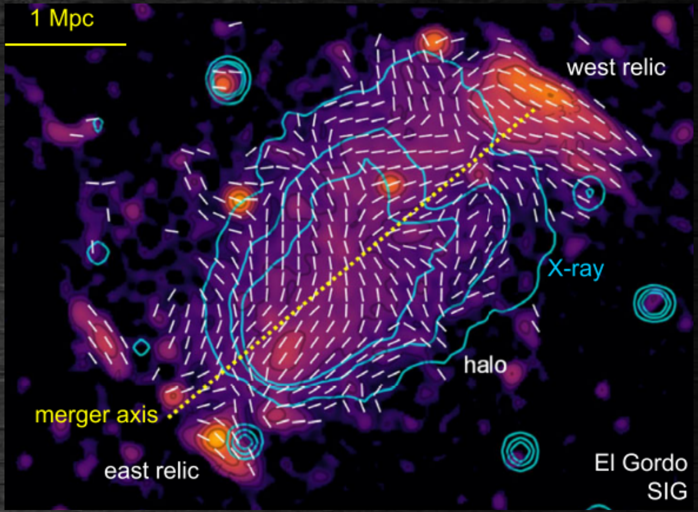
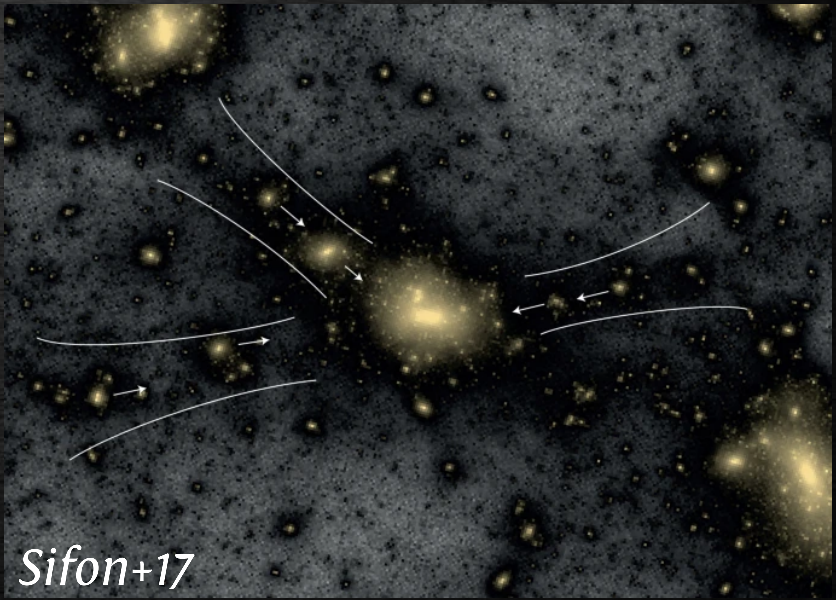




Can we map the *topology* of large-scale magnetic fields with **SIG**?



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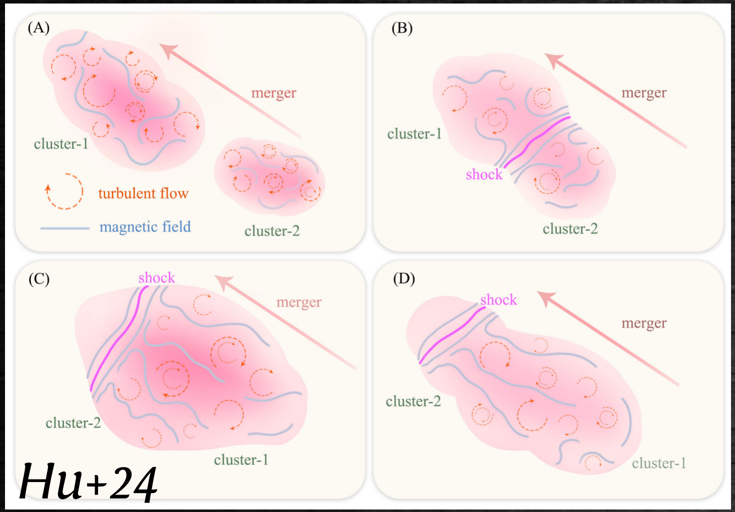

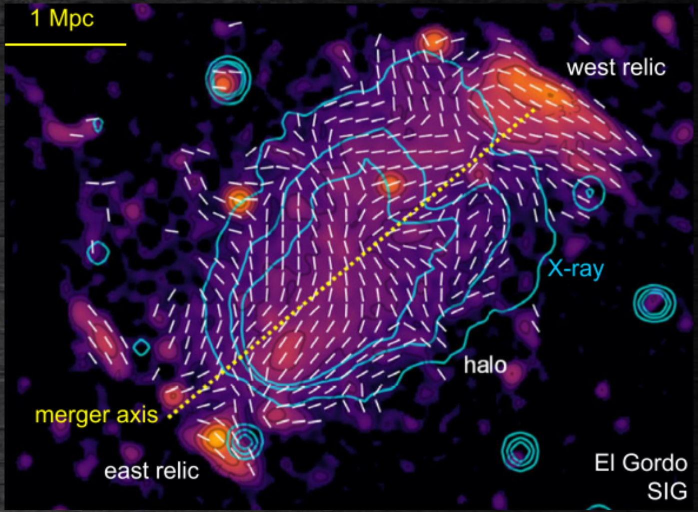

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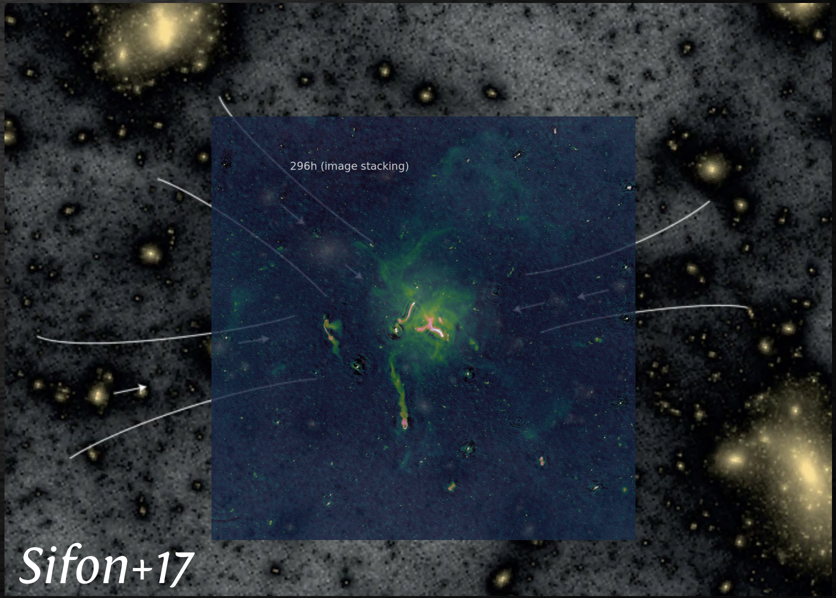
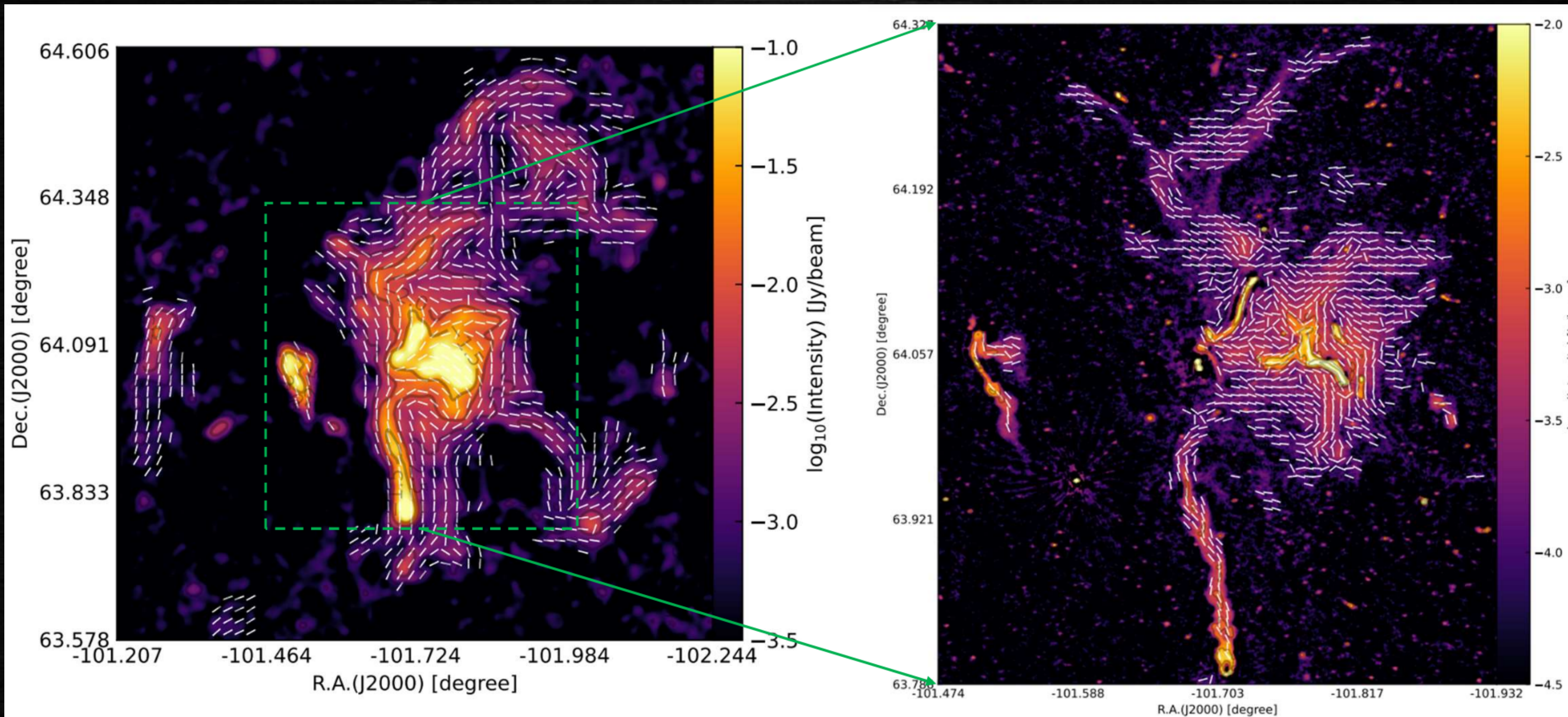


SIG on A2255



Credit: Y. Hu

low-resolution

high-resolution

WORK IN PROGRESS

Tested on the **72h** HBA image, will be applied on the **UDF** data

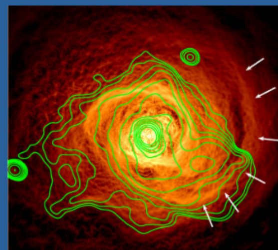
Re-defining giant & mini halos?

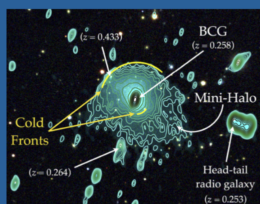
Mini-halos

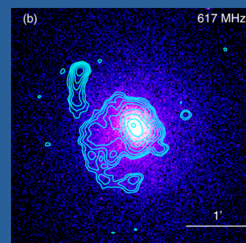
Giant halos

Re-defining giant & mini halos?

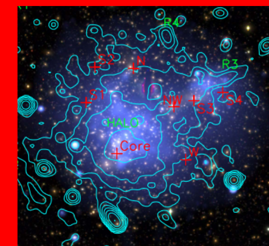
Mini-halos

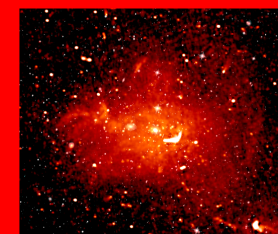






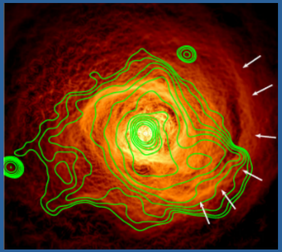
Giant halos

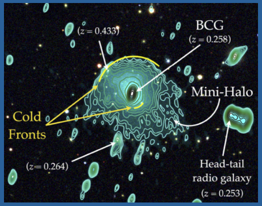


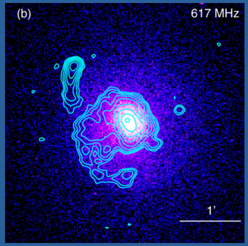


Re-defining giant & mini halos?

Mini-halos

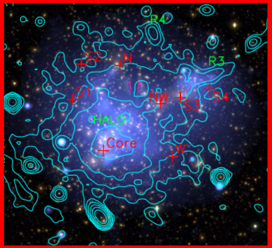


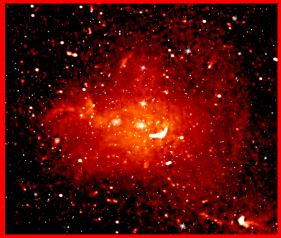




The prototypical "mini" halo is **~1 Mpc** in size

Giant halos

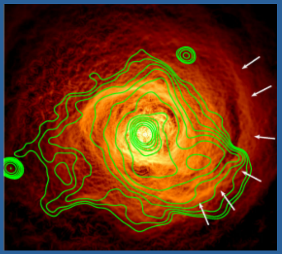


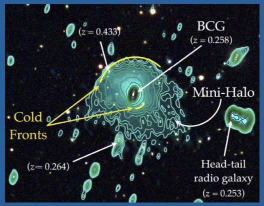


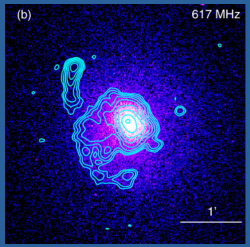
"Giant" halos in low-mass clusters are **~500 kpc** in size

Re-defining giant & mini halos?

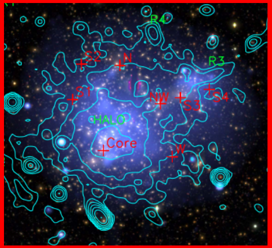
Mini-halos

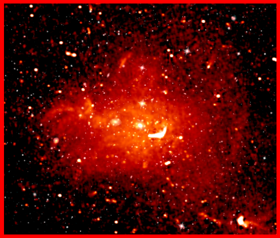






Giant halos





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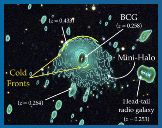
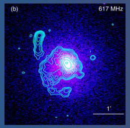
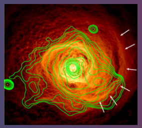
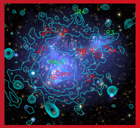
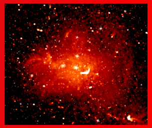
Halos.





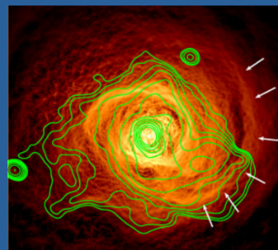


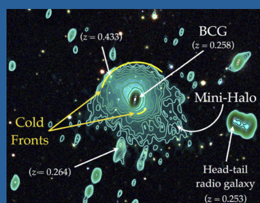


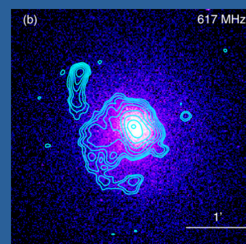


Re-defining giant & mini halos?

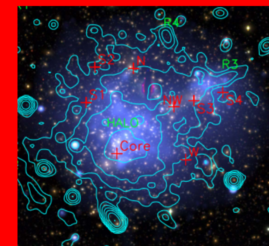
Mini-halos

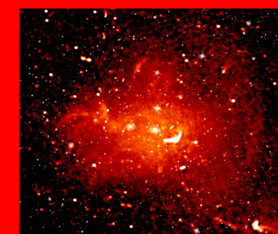






Giant halos





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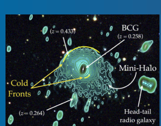

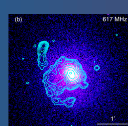

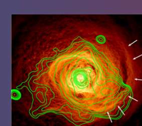

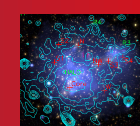

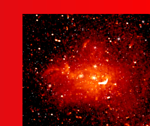

galaxies

Article

Radio Galaxy Classification: #Tags, Not Boxes

Lawrence Rudnick

Instead of trying to place them into "boxes", we should assign them #tags, a system that is easy to understand and apply, that is flexible and evolving, and that can accommodate conflicting ideas with respect to what is relevant and important.