Diffuse radio emission in galaxy clusters: a population view

Rossella Cassano

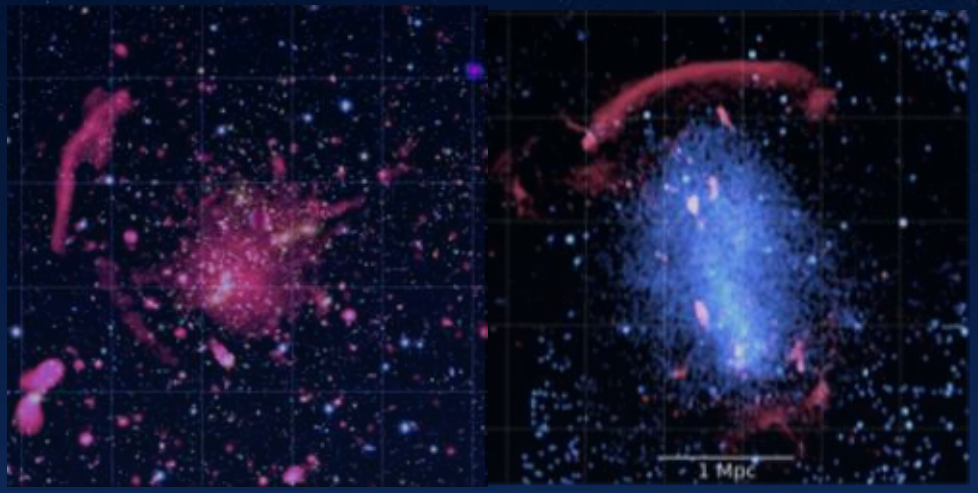
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19–23 Oct 2026

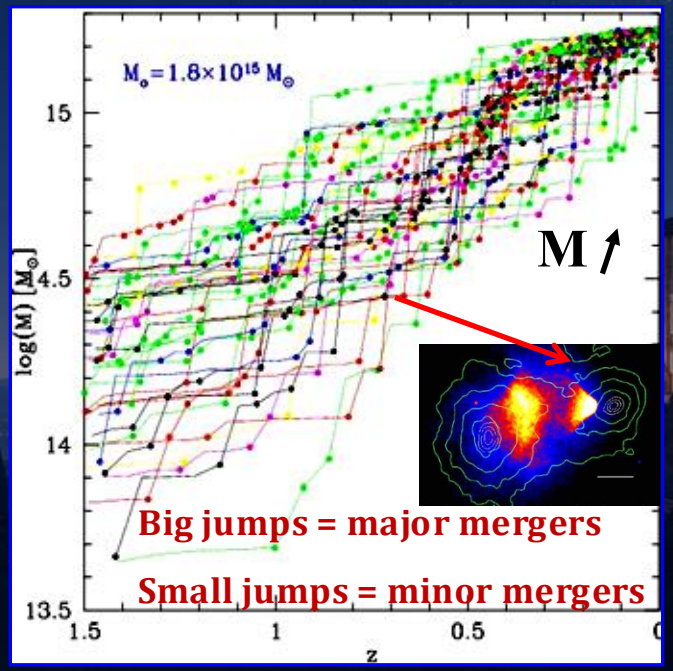
Diffuse radio emission as tracer of cluster assembly





$$\text{Merger Energy} \approx \frac{GM_1M_2}{R} \simeq 4\times10^{64}\left(\frac{M_{1\,2}}{10^{15}M_\odot}\right)^2 \times \left(\frac{2Mpc}{R}\right) erg$$

- clusters grow through mergers and accretion that drive turbulence and shocks in the ICM
- turbulence and shocks can power particle re-acceleration in the ICM (e.g. Brunetti & Jones 2014
- **Diffuse radio emission is one of the clearest observational signatures of these processes during cluster assembly.**



Roadmap for this lecture

1. Giant radio halos

Occurrence, mass, dynamics and radio power

2. The low-frequency view

LOFAR, spectral populations and high redshift

3. Other diffuse sources

Relics, mini-halos, megahalos and bridges

4. Local relations and future surveys

Radio–X-ray connection and SKA

Goal: use population statistics to understand how non-thermal emission traces cluster evolution.



From detections to populations

building a statistical RH sample

1. Parent sample

define clusters before radio

- X-ray selected
- known selection function
- mass / redshift cuts

2. Homogeneus radio data

Observe detections+non detections

- same frequency/depth
- surface brightness limit
- angular scale recovery

3. Population inference

turn maps into statistics

- detections+upper limits
- occurrence fractions
- scaling relations

GMRT Radio Halo Survey (Venturi + 07, 08)

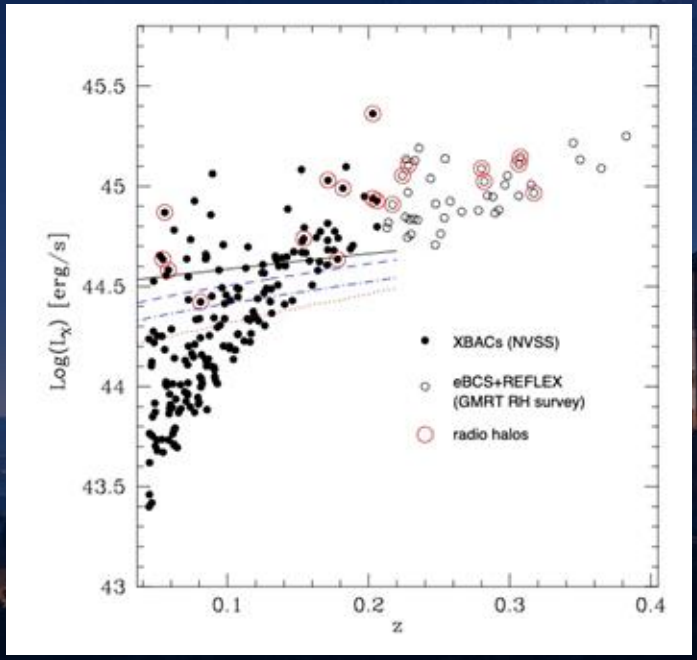
REFLEX + eBCS • X-ray selected

• z ≃ 0.2–0.4 • GMRT 610 MHz • halos and upper limits

Key message

The step forward was not simply to observe more clusters, but to:

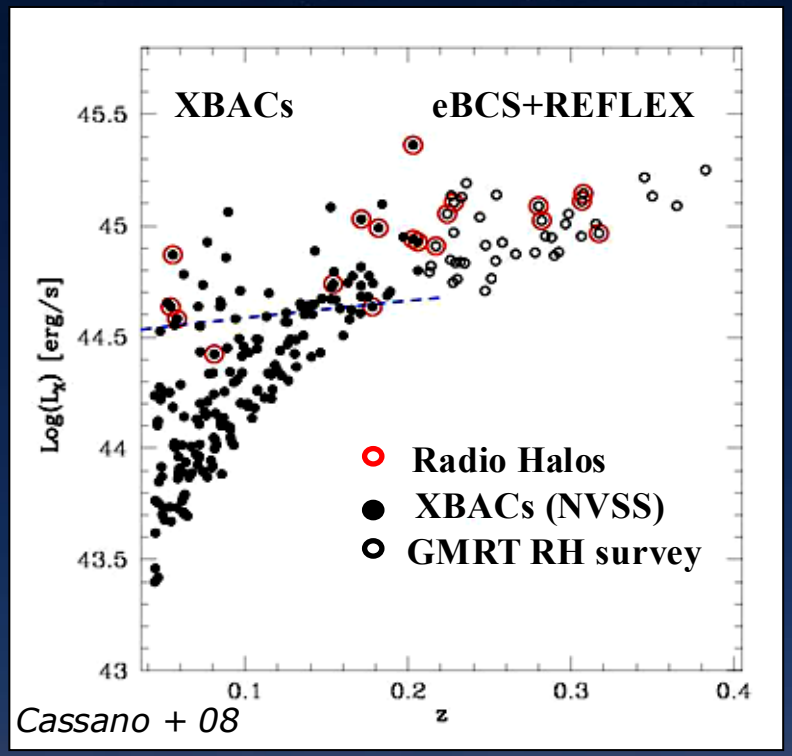
- define the parent sample
- treat the non-detections as information



The GMRT RH Survey the first systematic step

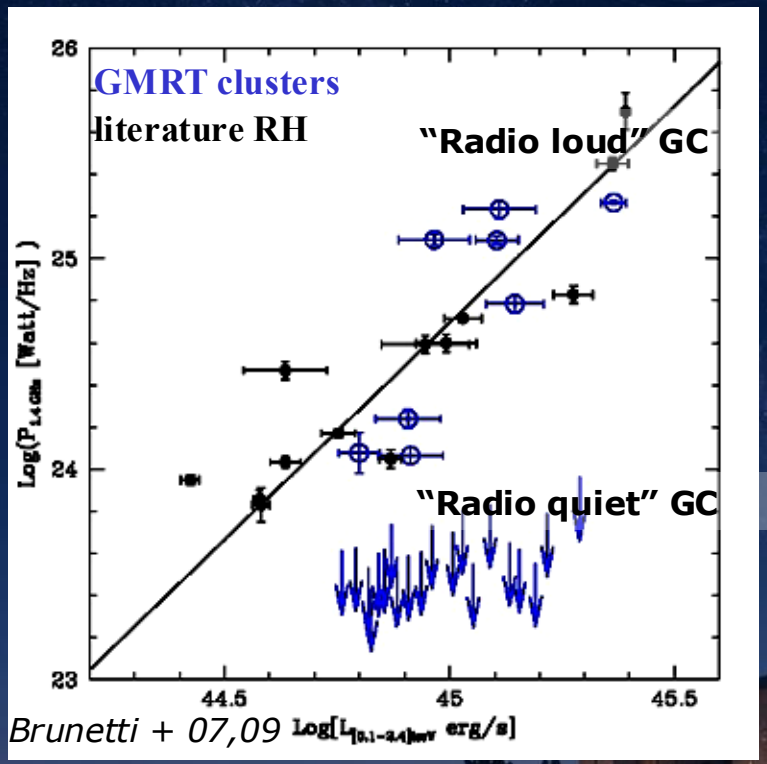
50 X-ray selected (0.2<z<0.4) REFLEX + eBCS clusters (0.2 < z < 0.4), GMRT at 610 MHz ends up in halos, non-detections, upper limits (*Venturi + 07, 08; Kale +13, 15*)

occurrence of RH in GC



Cassano + 08

Radio bi-modality of GC



Brunetti + 07,09

Key results

- RH occurrence: only ~20–30% of X-ray luminous clusters host giant halos host a RH
- Radio halos clusters traces the $P_{1.4}$-L_x correlation
- Non-detections lie significantly below it

Key methodological advance: homogeneous upper limits from model-halo injection.

From X-ray selection to mass selection

Why does selection matter?

X-ray selected surveys

- selection based on L_X
- L_X depends not only on mass
- cool cores / dynamical state can affect selection
- possible bias in occurrence studies

Venturi + 07,08; Kale+ 13,15

SZ/mass-selected surveys

- selection more closely related to total cluster mass
- less sensitive to core properties
- ideal to test:

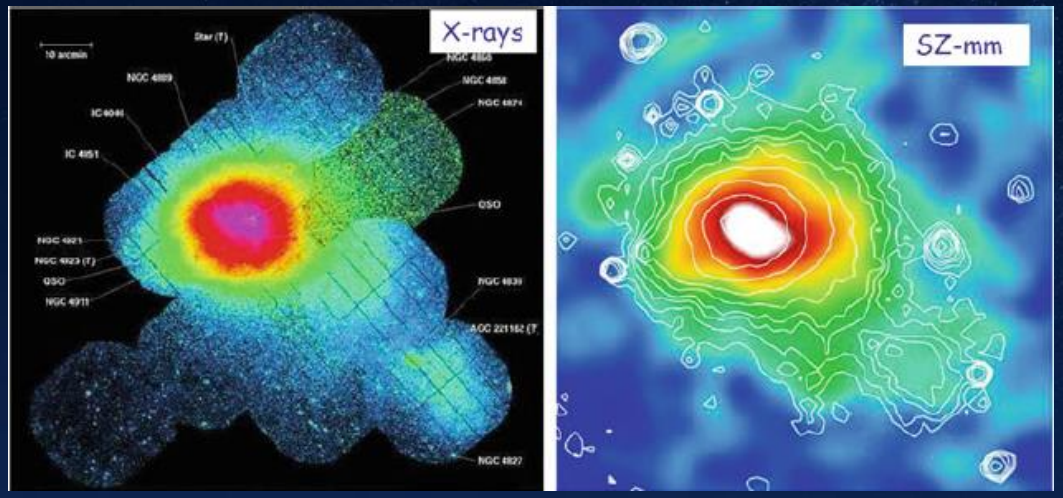
  - RH occurrence vs M_{500}
- radio power vs mass
- merger dependence at fixed mass

Cuciti + 15, 21

GRHS / EGRHS → Planck SZ-selected sample

The key question becomes: does the probability of hosting a radio halo depend on cluster mass?

X-ray vs SZ: two views of the thermal ICM



X-ray emission

$S_x \propto \int n_e^2 \Lambda(T)\, dl$

Sensitive to dense gas and cool cores

Thermal SZ effect

$y \propto \int n_e T_e\, dl$

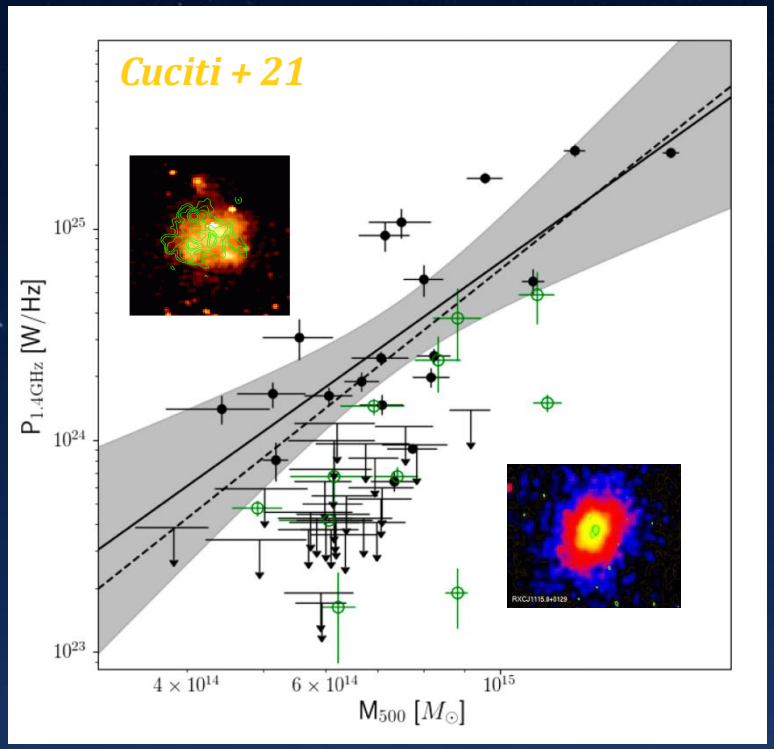
Integrated electron pressure

Integrated SZ signal → total ICM thermal energy ∝ Mgas T

$Y_s Z D_a^2 \propto M_{500}^{5/3} E(z)^{2/3}$ (self-similar)

SZ selection is closely related to cluster mass and less sensitive to cool-core properties than X-ray luminosity.

Radio halos & *radio-quiet* clusters in the $P_{1.4}$-M_{500} plane



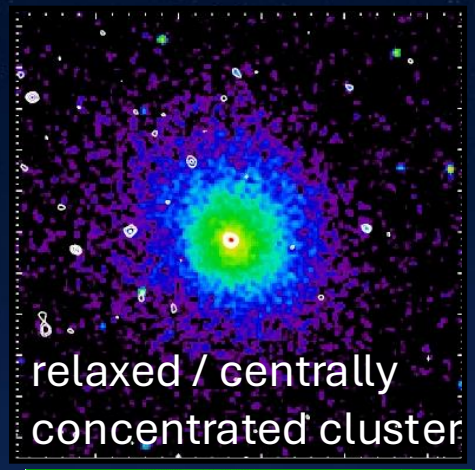
- RH detections
- upper limits
- best-fit correlation

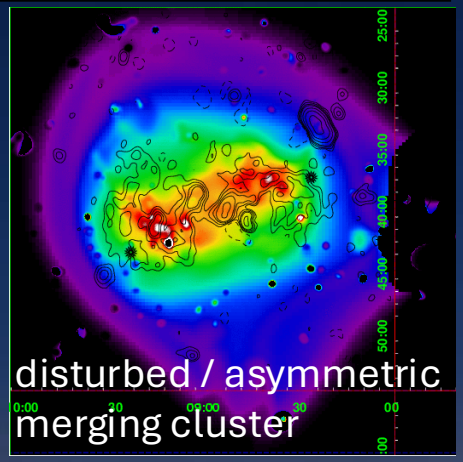
Two populations emerge

- RH clusters follow the $P_{1.4}$-M_{500} correlation
- clusters without detected halos populate the region below it

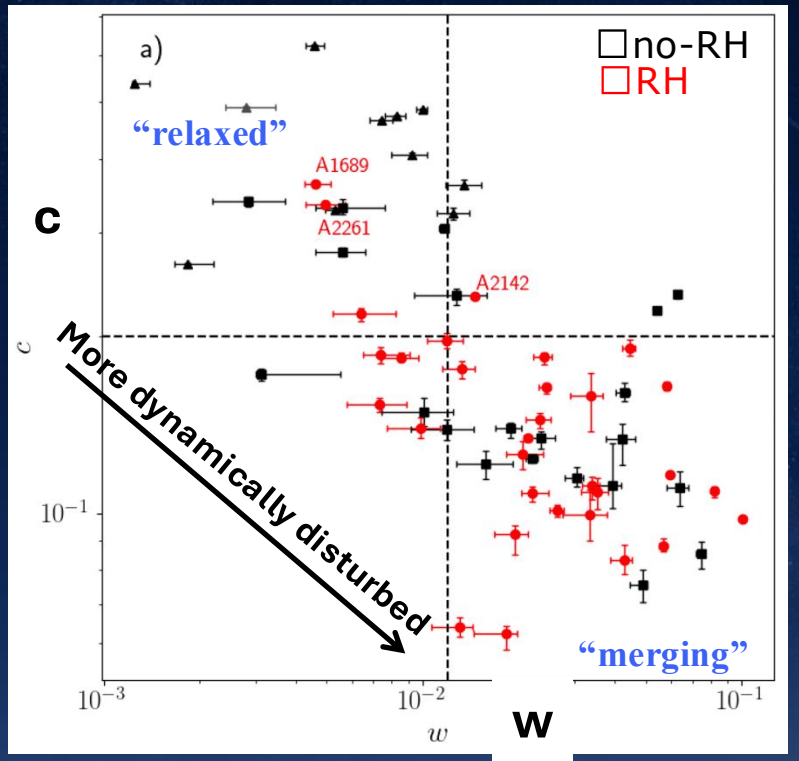
If clusters of comparable mass can be either radio loud or radio quiet, what distinguishes them?

Same mass, different radio properties - is the difference dynamical?





- concentration c → how peaked is the X-ray emission?
- centroid shift w → how disturbed/asymmetric is the cluster?
- P_3/P_0 → substructure / departure from symmetry



Radio halos preferentially occupy the dynamically disturbed region of parameter space, while radio-quiet clusters are predominantly more relaxed.

A quantitative measure of the cluster disturbance can be made with the analysis of sensitive X-ray images and derivation of the morphological parameters:

- the surface brightness concentration c (e.g., Santos et al. 08), the ratio of the peak over the ambient surface brightness, S:

$$c = \frac{S(r < 100kpc)}{S(< 500kpc)}$$

c ↘ relaxed → merger

- the centroid shift, w (e.g., Mohr et al. 1993),the standard deviation of the separation between the peak of the X-ray emission and the centroid in unit of R_{ap}:

$$w = \left[\frac{1}{N-1}\sum(\Delta_i - \langle\Delta\rangle)^2\right]^{1/2} \times \frac{1}{R_{ap}}$$

w ↗ relaxed → merger

- the power ratio, P_3/P_0 (e.g., Buote & Tsai 1995) a multipole decomposition of the X-ray surface brightness in a circular aperture (R_{ap}) centered on the cluster's centroid (X-ray brightness ≈ the mass distribution), power ratios are defined as P_m/P_0:

$$P_0 = [a_0\, ln(R_{ap})] \qquad a_0 = S(< R_{ap})$$

$$P_m = \frac{1}{2m^2 R_{ap}^{2m}}(a_m^2 + b_m^2)$$

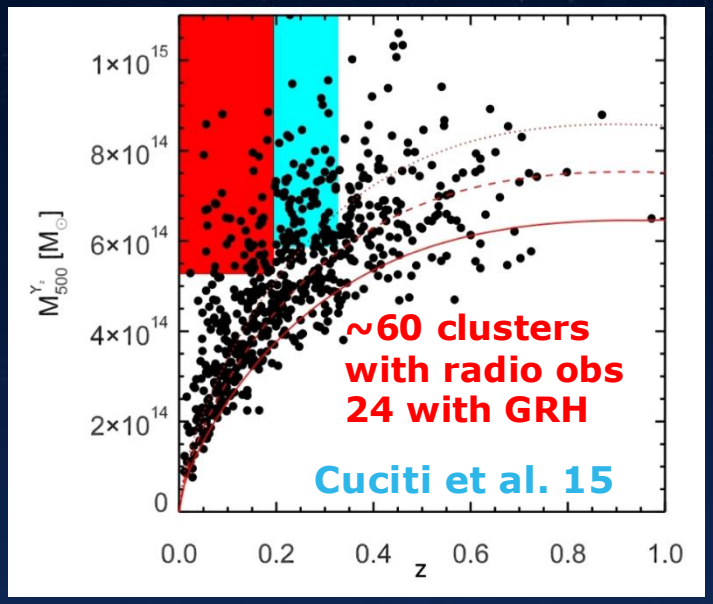
$$a_m(R) = \int_{R' \le R_{ap}} S(x')(R')cos(m\phi')d^2x'$$

$$b_m(R) = \int_{R' \le R_{ap}} S(x')(R')sin(m\phi')d^2x'$$

P_3/P_0 ↗ relaxed → merger

e.g., Cassano et al. 2010, ApJ 721, 82

Radio halo occurrence vs cluster mass

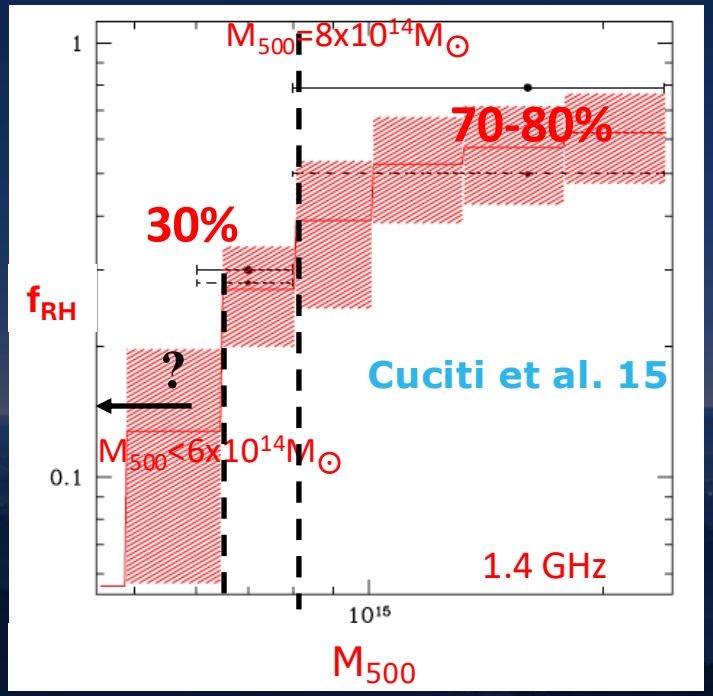


Mass-selected sample

Planck SZ-selected clusters

complete radio follow-up

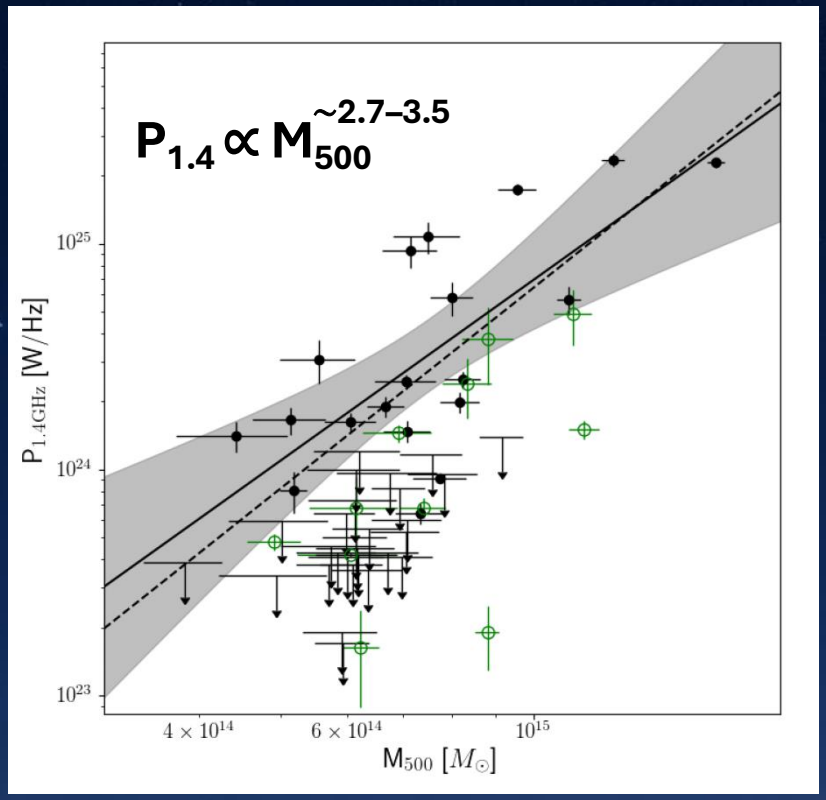
occurrence rises from ~35% to ~70%
(Cuciti et al. 2015, 2021)

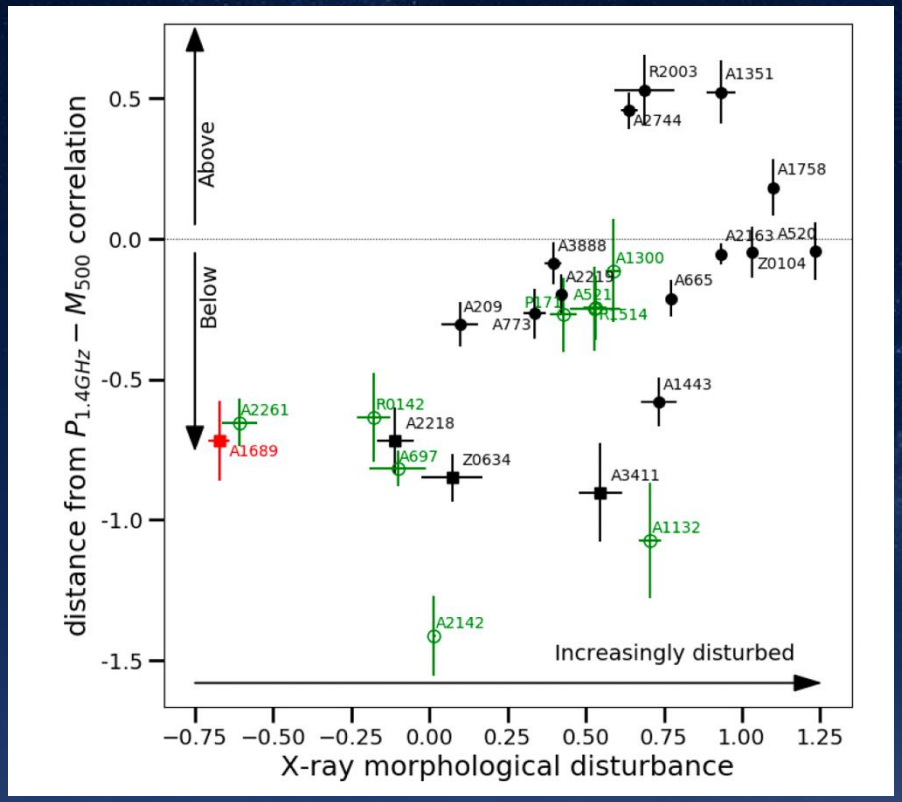


✓ the fraction of clusters hosting a RH increases with the cluster mass:
a clear drop in f_{RH} is seen at lower masses

Mass is one of the primary parameters controlling the probability of hosting a giant radio halo.

RH power -- mass correlation (~1 GHz)





The synchrotron power of radio halos increases rapidly with cluster mass, but with substantial scatter : ~ 0.3–0.4 dex → a factor of ~ 2–3 variation in radio power at fixed cluster mass.

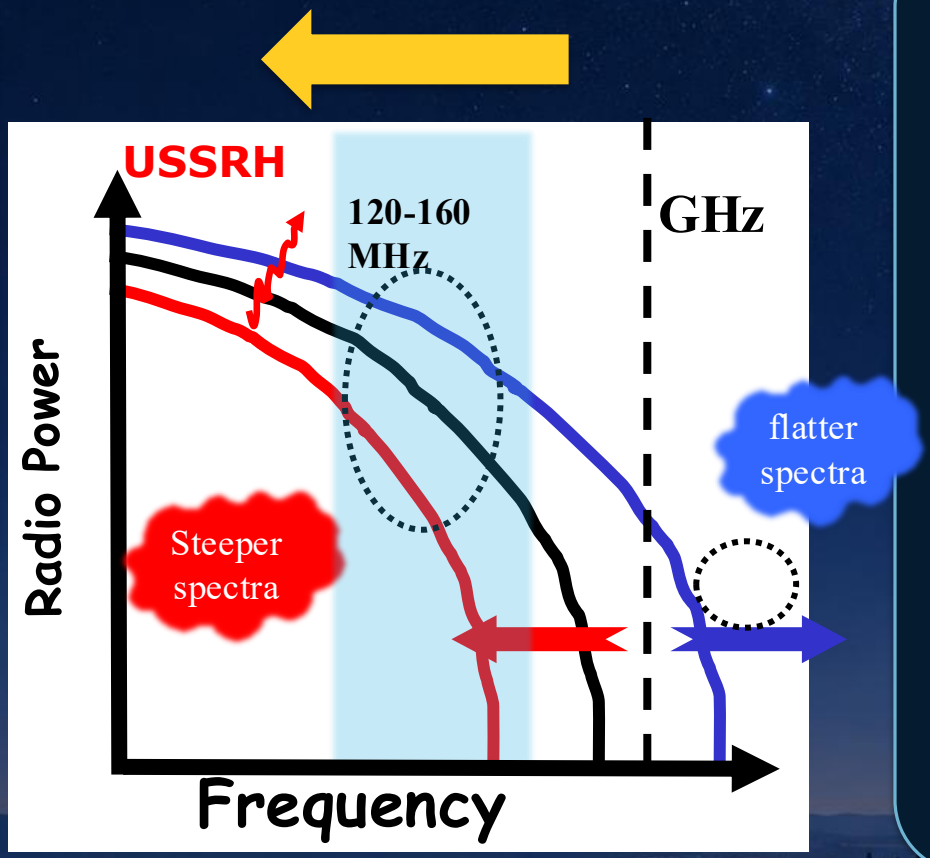
We found hints that the scatter around the correlation is related to the cluster dynamical "disturbance": more dynamically active clusters tend to scatter upward in the relation (Cuciti+21)

From GHz to LOFAR: frequency as a selection function

Changing observing frequency could changes which population enter in the sample

LOFAR view

- steep-spectrum emission boosted
- ultra-steep halos become visible
- faint, extended plasma easier to detect



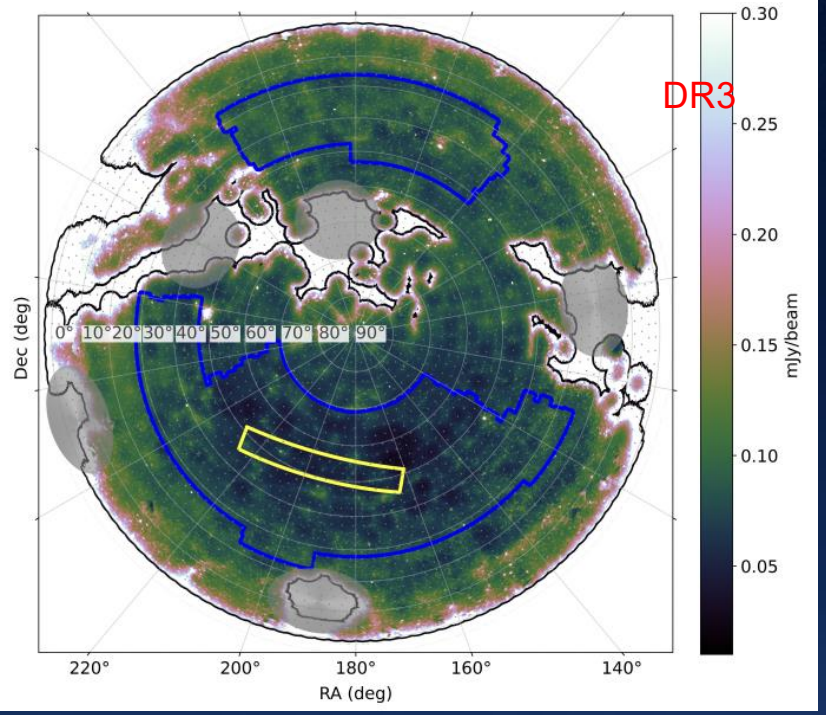
GHz view

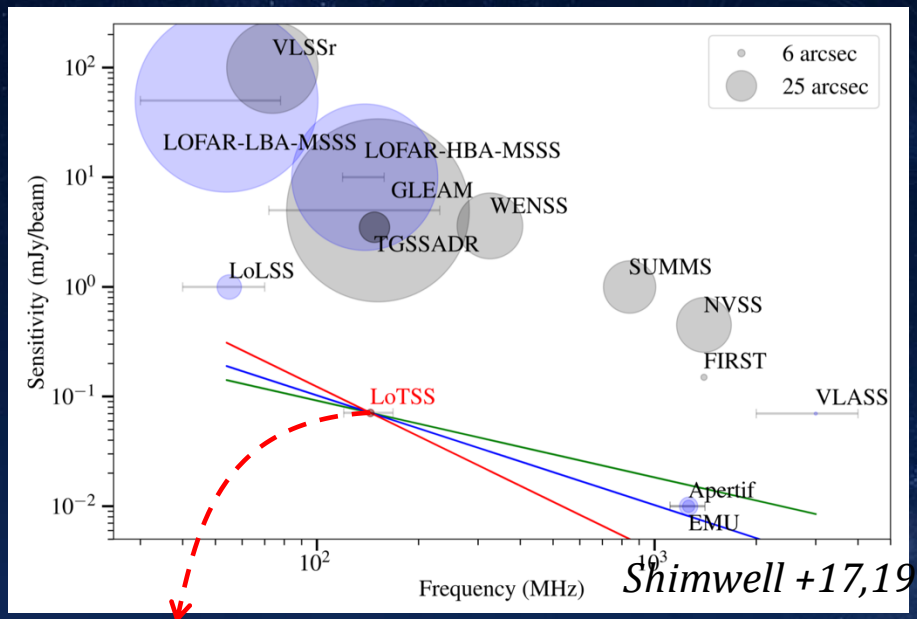
- flatter / brighter halos
- higher surface-brightness systems
- classical RH population
- steeper-spectrum sources easily missed

Key message: the low-frequency population is not simply the GHz population observed deeper.

LoTSS: the LOFAR Two-metre Sky Survey

(Shimwell+ 17,19, 22, 26) DR1, DR2…DR3





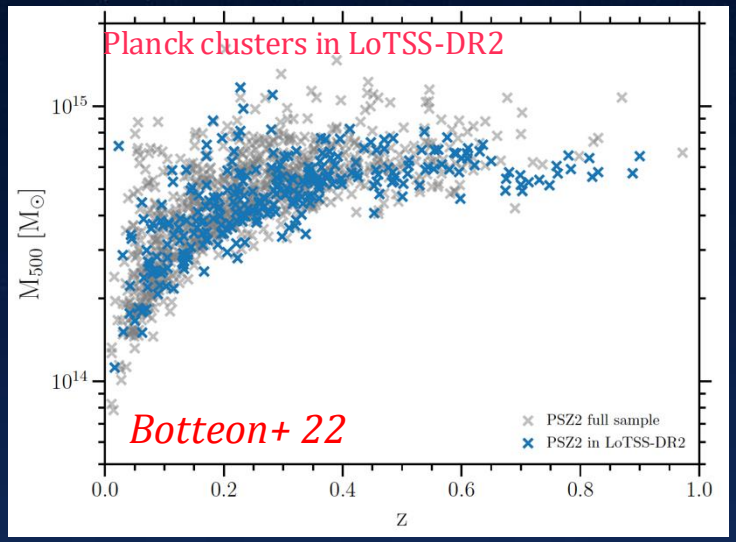
Unprecedented combination of sensitivity, resolution and sky coverage at low frequencies.

LoTSS-DR3 in numbers

- 19,035 deg^2 — 88% of the northern sky
- 120–168 MHz
- 6″ resolution — 92 μJy beam^{-1} median rms
- 2,551 pointings × 8 h
- 13.7 million radio sources

A game changer for detecting diffuse, steep-spectrum emission in galaxy clusters

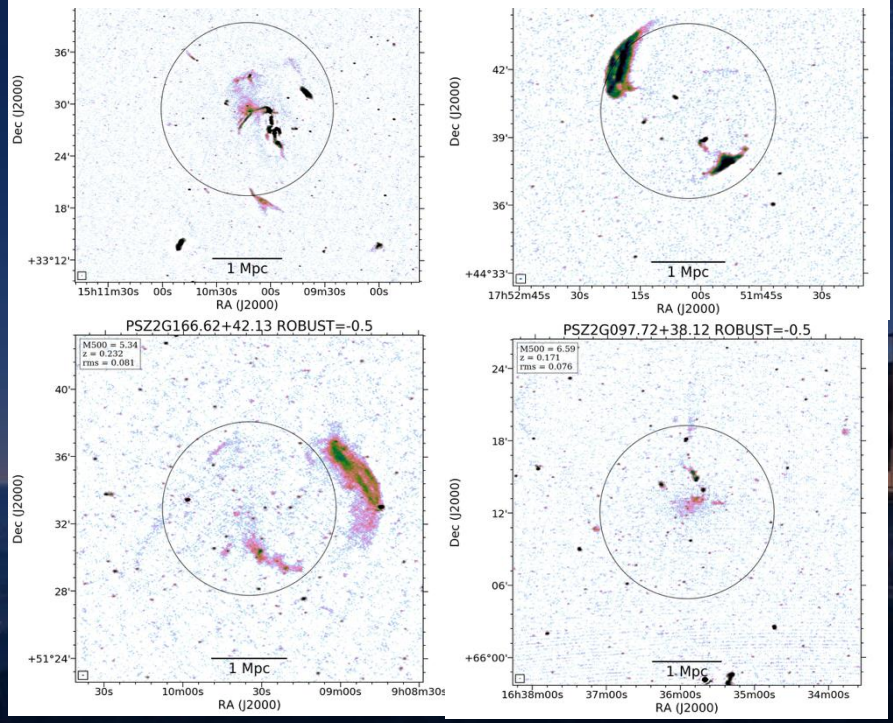
LoTSS: from discoveries to population studies



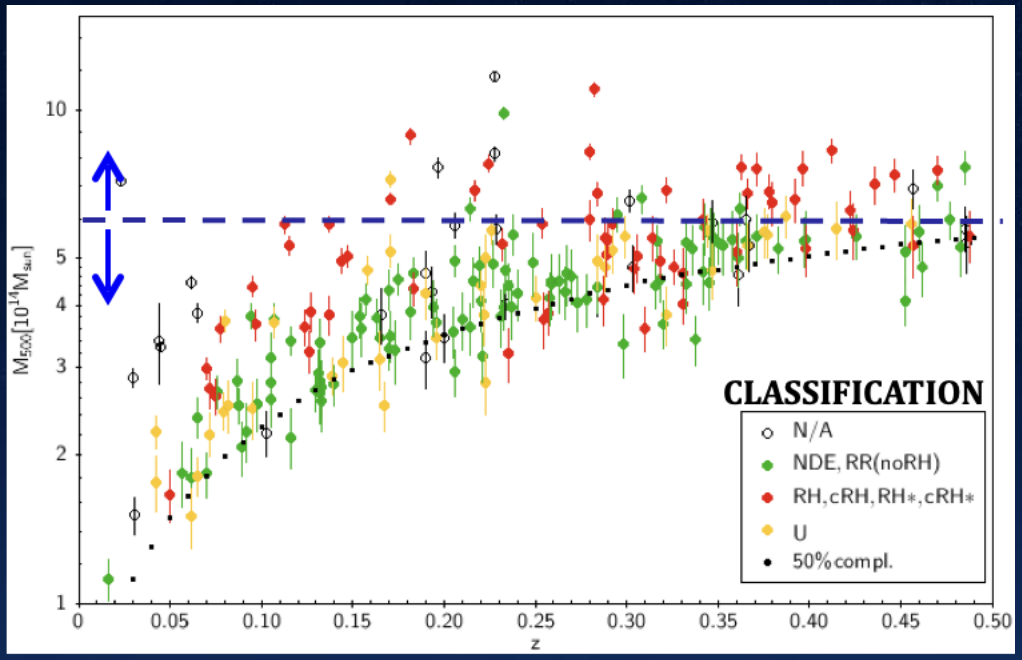
This is the largest low-frequency census of diffuse radio emission in galaxy clusters !

- 309 Planck SZ-selected clusters observed in LoTSS-DR2
- 83 radio halos and 26 relic-hosting clusters
- ≈50% of the diffuse sources were new discoveries
- the first large low-frequency census of cluster diffuse emission

Diffuse radio emission in Planck clusters with LoTSS-DR2



LoTSS: statistical analysis of PSZ2 clusters

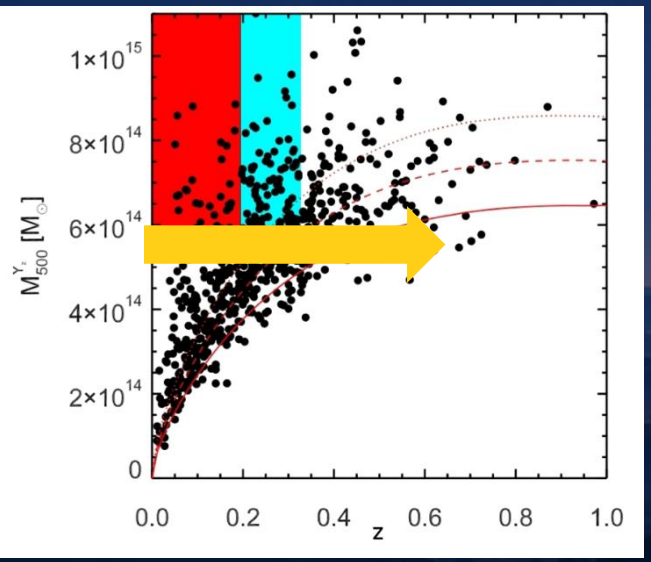


Cassano + 23

For the statistical analysis of RHs:

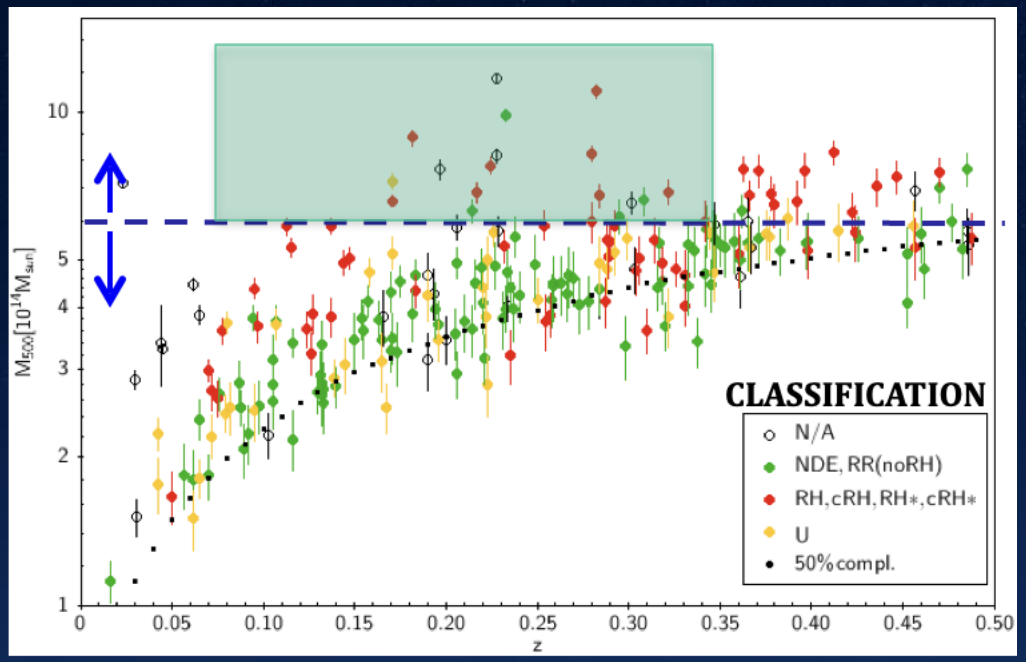
- sub-samples of **164** clusters with $0.07 < z < 0.5$
- M_{500} >Planck 50% completeness
- 164 clusters:
  71 NDE (43%)
  55 RH (31%)
  13 RR (8%)
  25 U (15%)

Classification of the diffuse emission made in *Botteon + 22*



This sample allows, *for the first time*, a statistical investigation of RH in an unprecedented range of cluster masses, including clusters down to M_{500} **~2.5-3·10^{14} $M_\odot$**, breaking down the wall of M_{500} **~6·10^{14} $M_\odot$**, that limited previous statistical studies (e.g., *Cassano+13, Cuciti+ 21*).

Radio-halo occurrence at low frequency



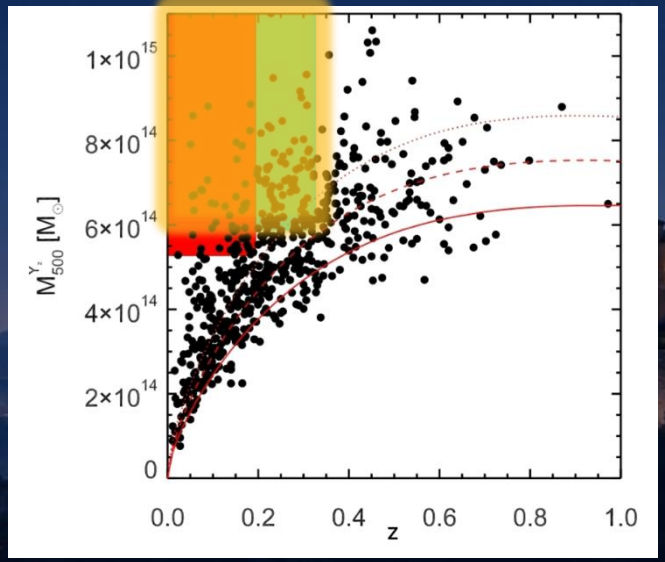
Cassano + 23

Cuciti+ 2021 (GMRT obs of PSZ2 $M_{500}>6\times10^{14}M_{\odot}$ clusters)

We compare the occurrence of RH in this sample with that derived from a sample of PSZ2 clusters with $M_{500}>6\cdot10^{14}\,M_{\odot}$ and $z\leqslant0.35$ observed with GMRT at 610 MHz (Cuciti+21).

LOFAR: 67-70%

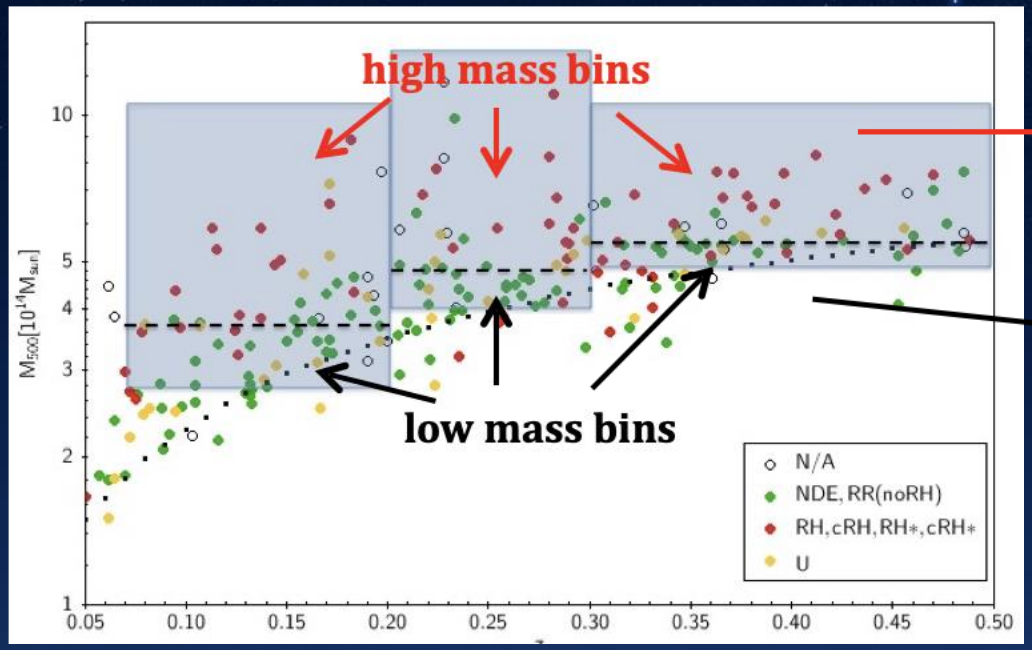
GMRT: 41-48%

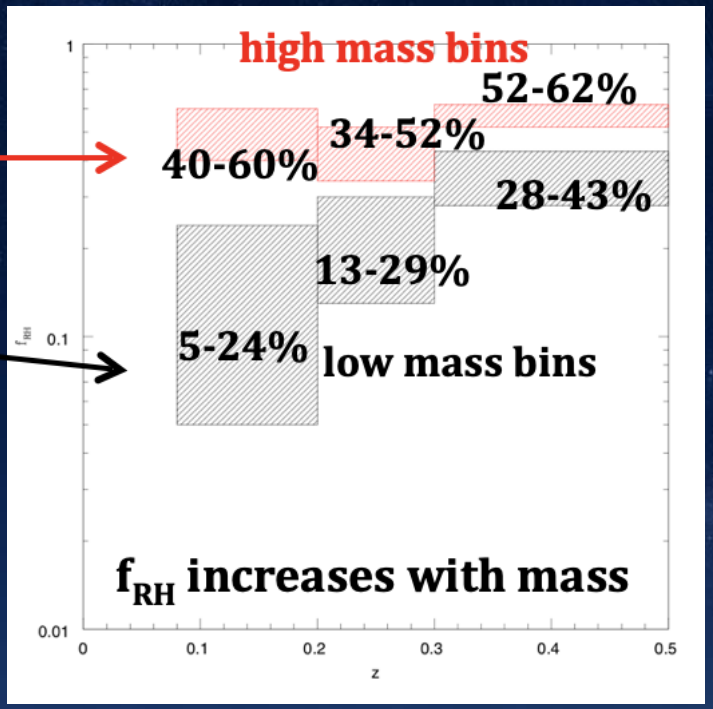


The fraction of clusters hosting RH increases at low radio frequency.

RH occurrence with the cluster mass

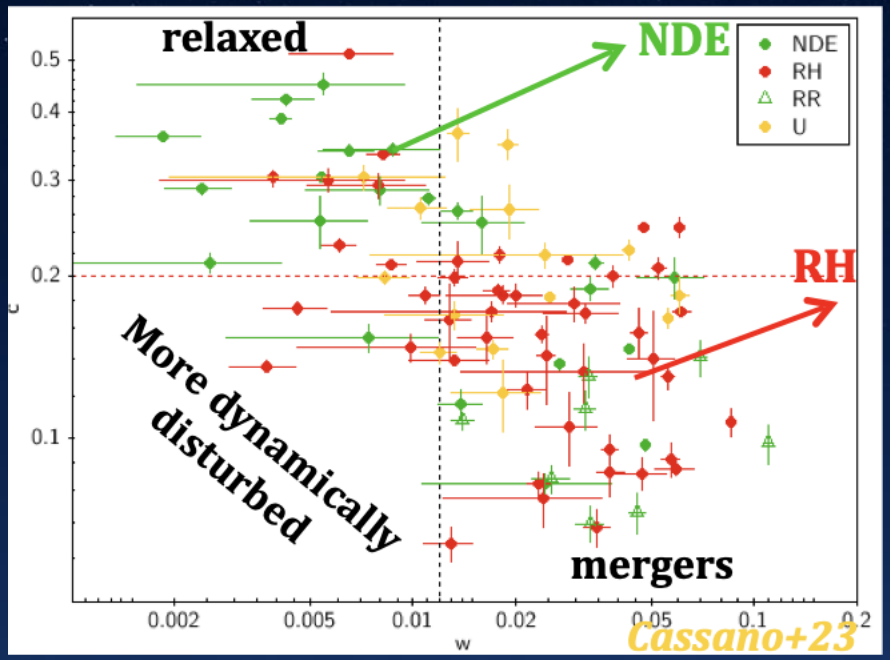
Cassano + 23





The observed fraction of clusters hosting radio halos increases with the cluster mass in different redshift bins.

Low-frequency halos and cluster dynamics



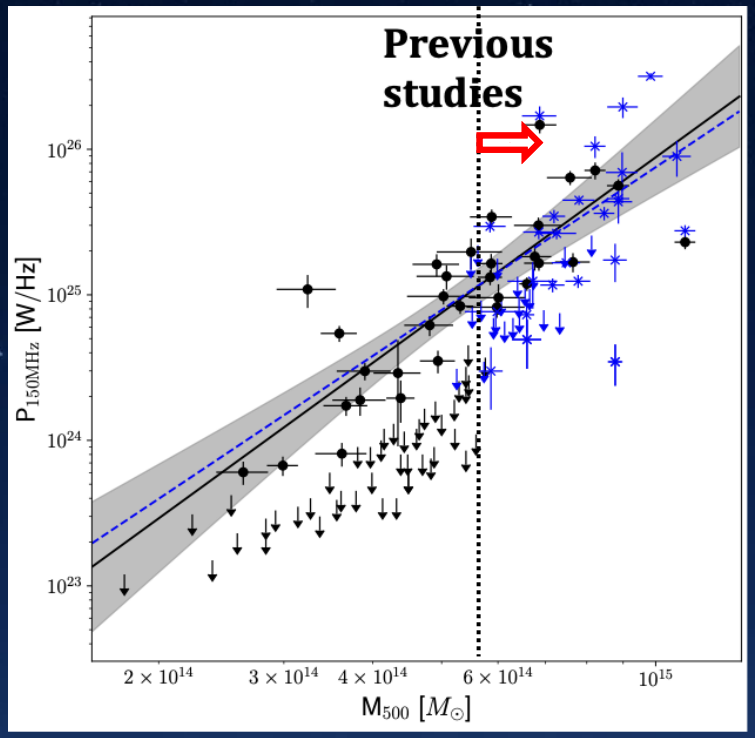
☆ The fraction of clusters with RH increases going towards more dynamically disturbed (*merging*) systems;

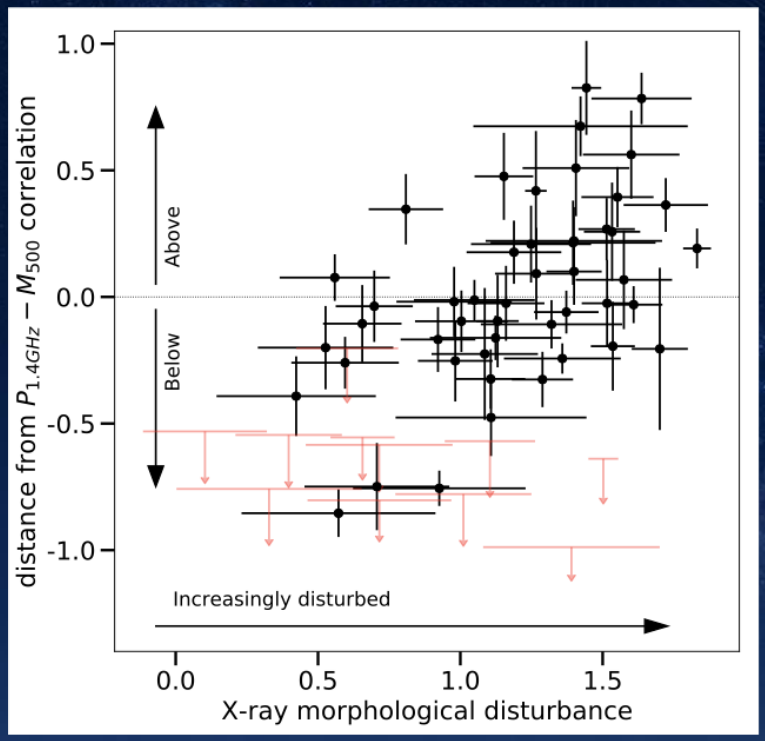
☆ The fraction of clusters without diffuse radio emission increases towards more relaxed systems

☆ Low frequency observations found radio halos also in less extreme mergers / less perturbed systems fraction

Low-frequency observations extend the radio-halo population to less dynamically disturbed clusters, while preserving the overall merger connection.

RH power mass correlation

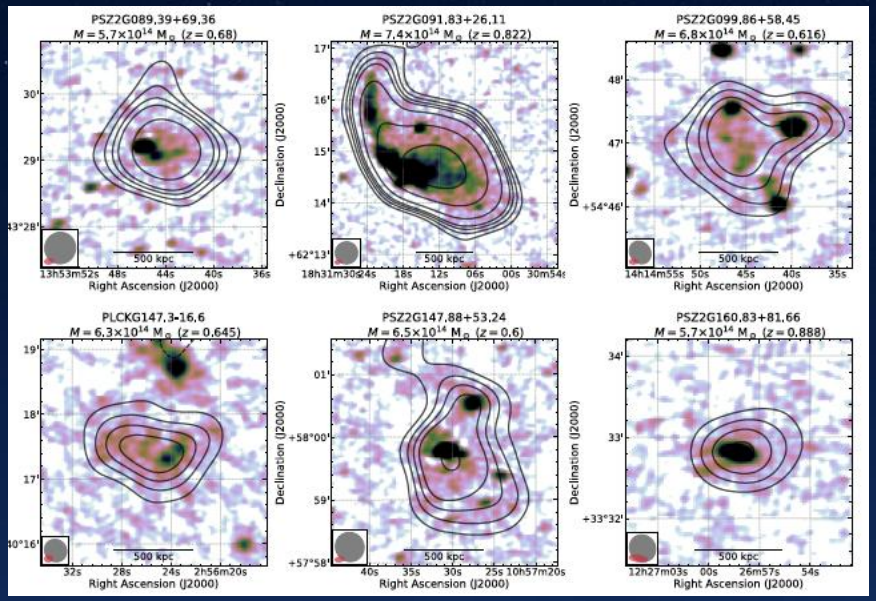




Cuciti, et al 23

- P_{150} increases with cluster mass
- LoTSS opens the lower-mass / lower-power region
- scatter is larger than the one observed at high-frequency
- scatter contributed by cluster dynamics with more dynamically active clusters being scattered up in the correlations

LOFAR opens a new window halos at high redshift



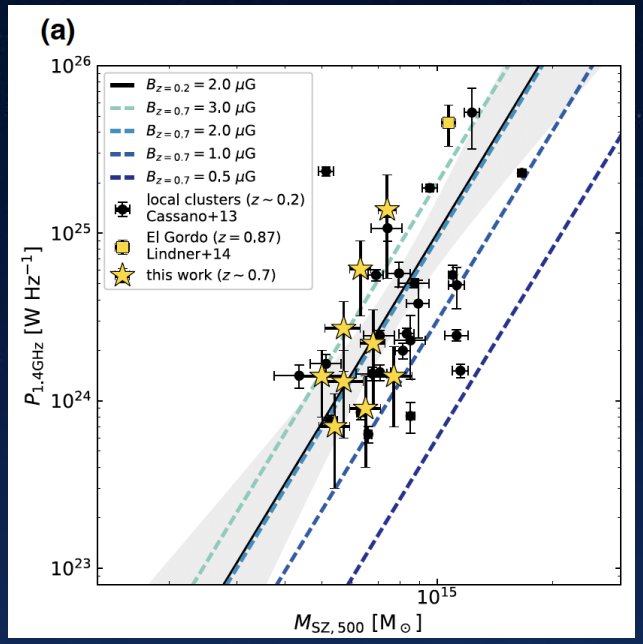
Di Gennaro et al 21

Massive SZ-selected clusters

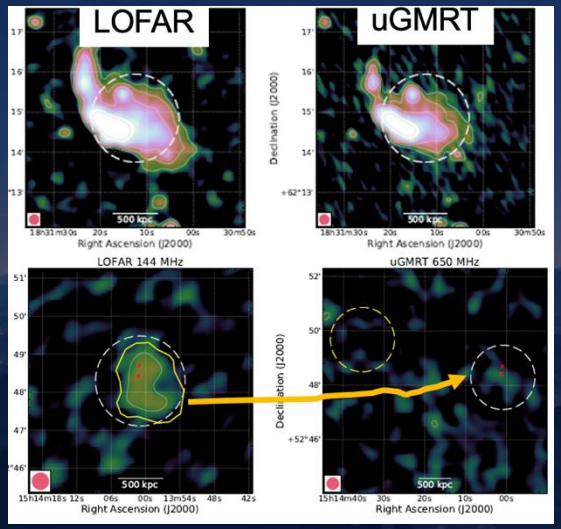
- **0.6 <z < 0.9**
- **M_{500} ~4-8 x 10^{14} $M_{\odot}$**
- **diffuse radio emission in 9/19 clusters**
- **most halo hosts are dynamically disturbed**

Massive merging clusters already host Mpc-scale radio halos when the Universe was only about half its present age.

What do high-z radio halos tell us?



Di Gennaro et al 21



<u>High-z halos are not strongly underluminous</u>

- radio powers are broadly consistent with the low-z $P_{1.4}$–M_{500} relation
- despite the less favourable high-z conditions for synchrotron emission
- implies μG-level magnetic fields already at z ~ 0.7–0.9

Fast amplification of cluster-scale magnetic fields

The follow-up at higher frequencies with the uGMRT reveals that **50% of these RHs are characterised by very steep radio spectra (α>1.5).**

What have we learned about the radio halo population?

1. Radio halos are not ubiquitous

At GHz frequencies, only a fraction of massive clusters host giant radio halos.

The occurrence fraction increases at lower observing frequencies.

2. Cluster mass matters

Both radio-halo occurrence and radio power increase with cluster mass.

LOFAR extends population studies to lower-mass and lower-power systems.

3. Cluster dynamics plays a key role

Radio halos preferentially occur in dynamically disturbed, merging clusters.

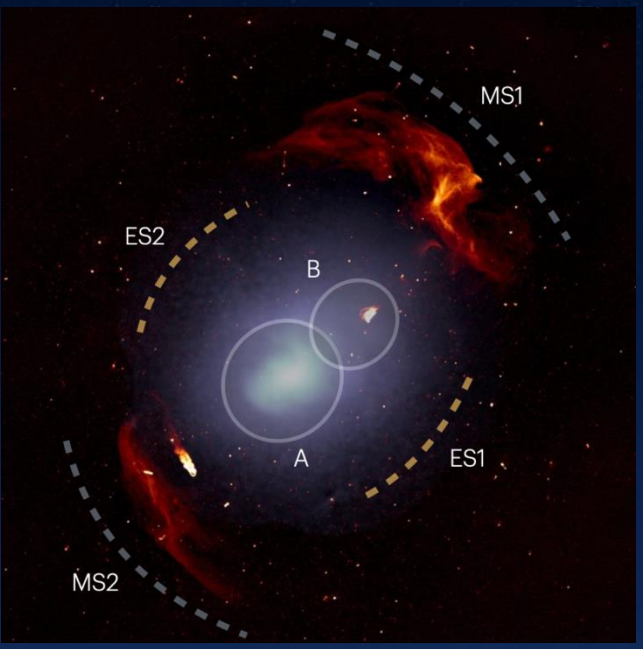
Low-frequency surveys also reveal halos in less extreme mergers.

4. The observed radio-halo population depends on observing frequency

Low-frequency observations uncover faint and steep-spectrum halos missed by GHz surveys.

High-redshift observations reveal luminous halos despite increasingly severe inverse-Compton losses.

Radio relics in population studies



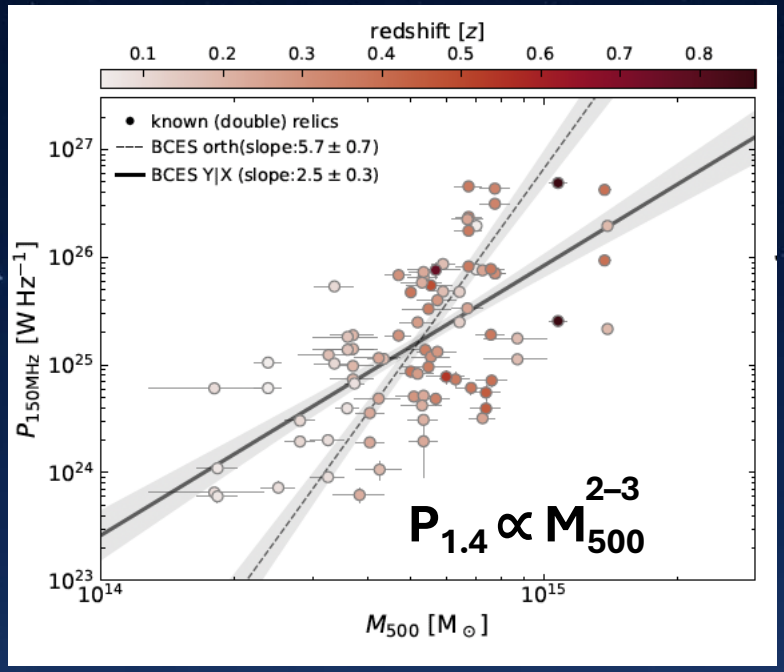
De Gasperin +22, Pal+26

Occurrence

- relics are rare: only **~10%** of merging clusters host bright relics (preferentially cluster outskirts)
- detectability depends strongly on merger geometry, shock orientation, surface brightness and seed electrons
- often associated with X-ray/SZ shock signatures

Radio relics are not ubiquitous tracers of mergers: only some merger shocks become radio bright.

Relic properties scale with the host cluster



Jones et al. (2023)

Occurrence

Relic-hosting clusters are relatively rare (~10% in LoTSS samples).

Radio power vs mass

More massive clusters can host brighter relics, but the scatter is large.

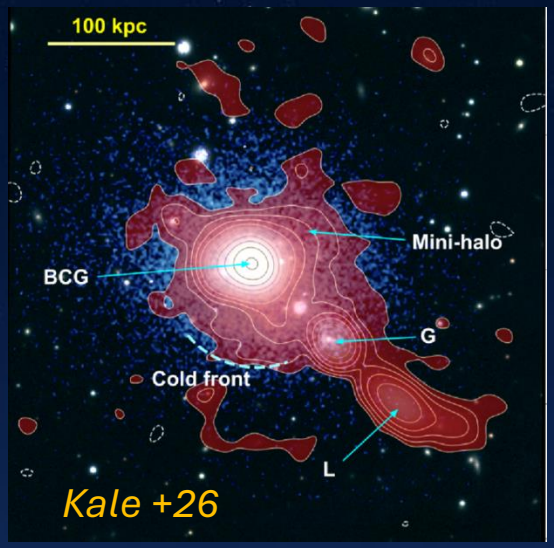
Size and location

Larger relics tend to lie farther from cluster centres.

Selection effects: surface brightness, projection and source geometry strongly affect relic detectability.

Cluster mass sets the energetic scale, but shock physics, geometry and selection shape the observed relic population.

Mini-halos: the cool-core population



Occurrence only a few tens known today

- Massive CC clusters $M_{500}>6x10^{14}M_{\odot}$ → 12/15 (~80%) host a mini-halo (*Giacintucci +18)*
- at lower masses the occurrence is still poorly constrained

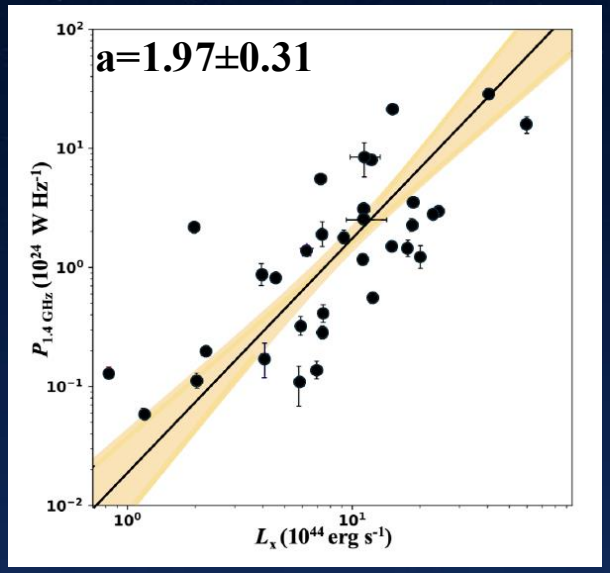
Where do we find them?

- almost exclusively in cool-core clusters
- typically surround a radio-loud BCG
- cluster-scale environment is generally much more relaxed than for giant radio halos
- mild gas motions / sloshing may still be present

Selection / observational challenge?

- mini-halo emission is faint and low-surface-brightness
- it must be separated from the much brighter central BCG
- requires both short and long baselines / high dynamic range

Mini-halos: diffuse emission in cool cores



Gitti +26, Richard-Laferrière + 20

What do they scale with?

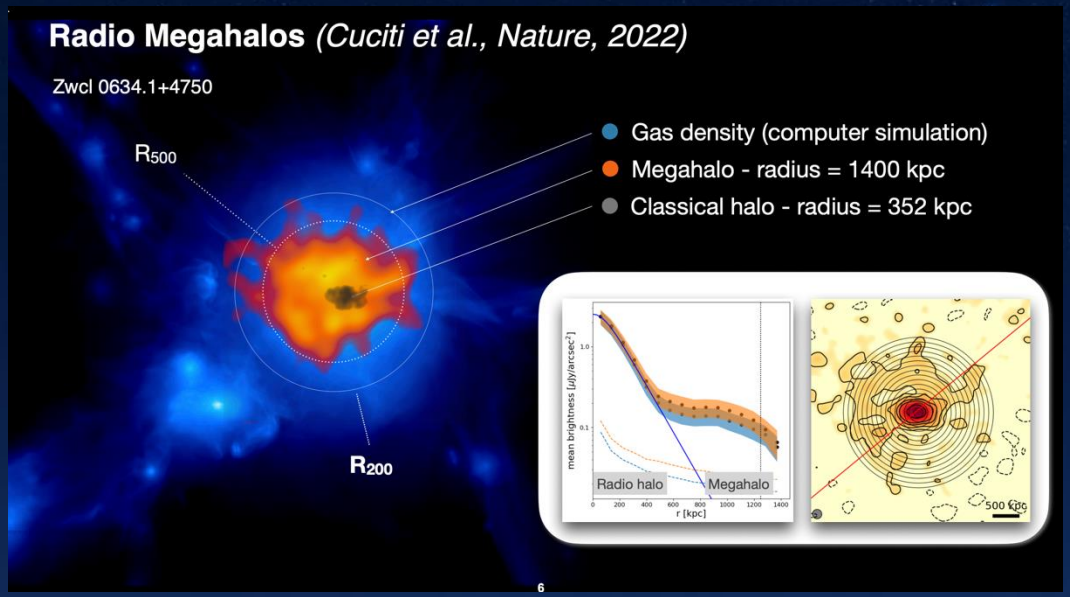
- mini-halo radio power correlates with cluster X-ray luminosity
- the $P_{1.4}$-L_X relation suggests a connection between thermal energy reservoir and non-thermal emission
- scatter remains significant
- likely reflects core thermodynamics, magnetic field, turbulence and AGN/ICM coupling

Core properties matter

- earlier studies found a particularly strong relation with core X-ray luminosity (Giacintucci +19)
- no equally clear relation with total cluster mass was found in those samples
- For giant halos the relevant scale is the cluster; for mini-halos it may be the core.

Mini-halo emission appears to be more closely linked to the **thermodynamics and dynamics of the cool core** than to the global merger state of the cluster.

Beyond radio halos: the emerging population of megahalos



What do we observe?

- diffuse emission extending to $\geq R_{500}$
- emitting volume > 30 times larger than the classical halo
- emissivity 20–30 times lower
- much flatter surface-brightness profile than the inner halo

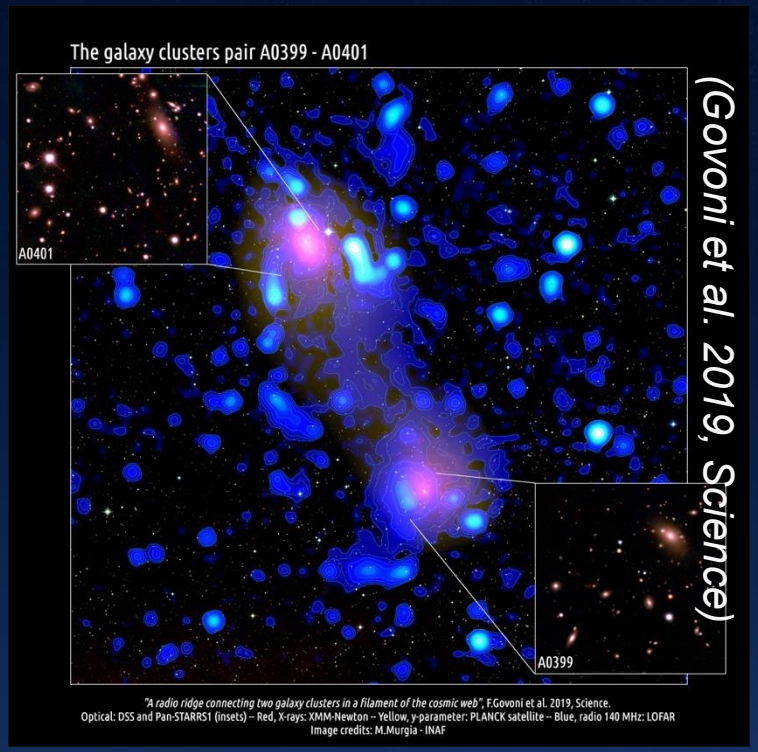
How common are they?

- first 4 systems found with LOFAR
- additional detections/candidates are now emerging
- all known cases lie in massive clusters
- current detections occupy exactly the region of the M-z plane where LoTSS is sensitive enough

Key message

Megahalos may reveal a widespread, very low-emissivity non-thermal component filling the whole cluster volume — but current statistics are strongly sensitivity-limited.

Beyond clusters: radio bridges and the cosmic web



What have we observed?

DIRECT DETECTIONS

Very faint, Mpc-scale synchrotron emission between interacting cluster pairs (A399–A401; A1758N–S, A2067/A2061)
Govoni +19; Botteon + 20; Pignataro + 24

THERMAL–NON-THERMAL CONNECTION

Emission associated with hot intercluster gas: relativistic particles and magnetic fields beyond cluster centres

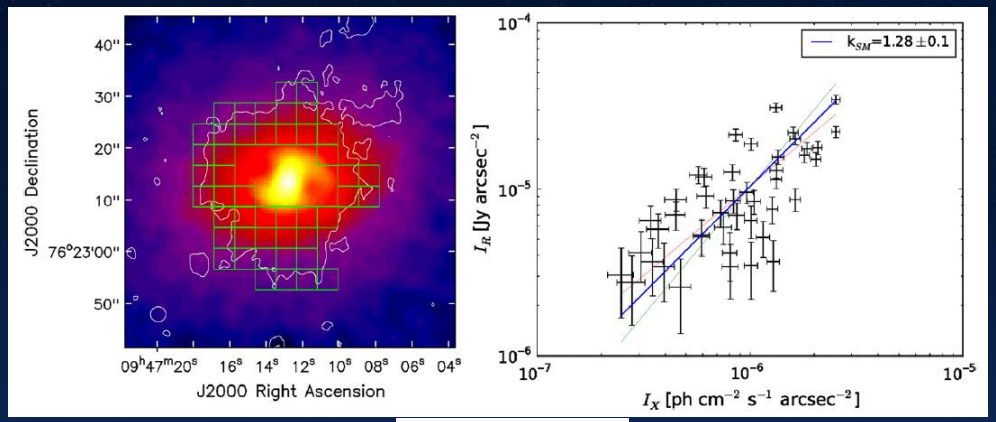
Towards the cosmic web

Only a handful of individual bridges are known. Statistical stacking (on >3 Mpc) probes faint, average intercluster radio emission *(Vernstrom + 21)*; direct detection of generic cosmic filaments remains challenging.

Key question: how are electrons sustained and magnetic fields amplified over Mpc scales?

From global scaling relations to the local thermal–non-thermal connection

point-to-point radio–X-ray analysis



Ignesti + 20

$$I_{\mathrm{R}} \propto I_{\mathrm{X}}^{k}$$

- **k = 1 — radio and X-ray brightness vary proportionally**
- **k < 1 — radio brightness decreases more slowly than X-rays → the radio emission is relatively more extended**
- **k > 1 — radio brightness decreases more rapidly than X-rays → the radio emission is relatively more centrally concentrated**

Giant radio halos

k<1

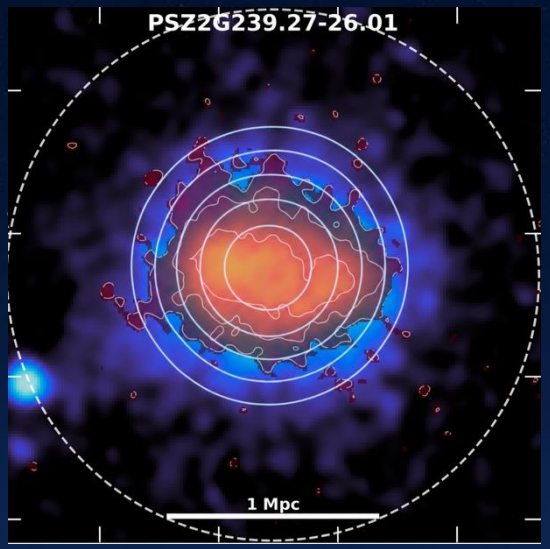
- positive radio–X correlation
- generally sub-linear
- radio emission declines more slowly than X-rays
- non-thermal component is spatially more extended

Mini-halos

k>1

- linear / super-linear relation
- radio emission follows the thermal core more closely
- in some cases radio declines faster than X-rays

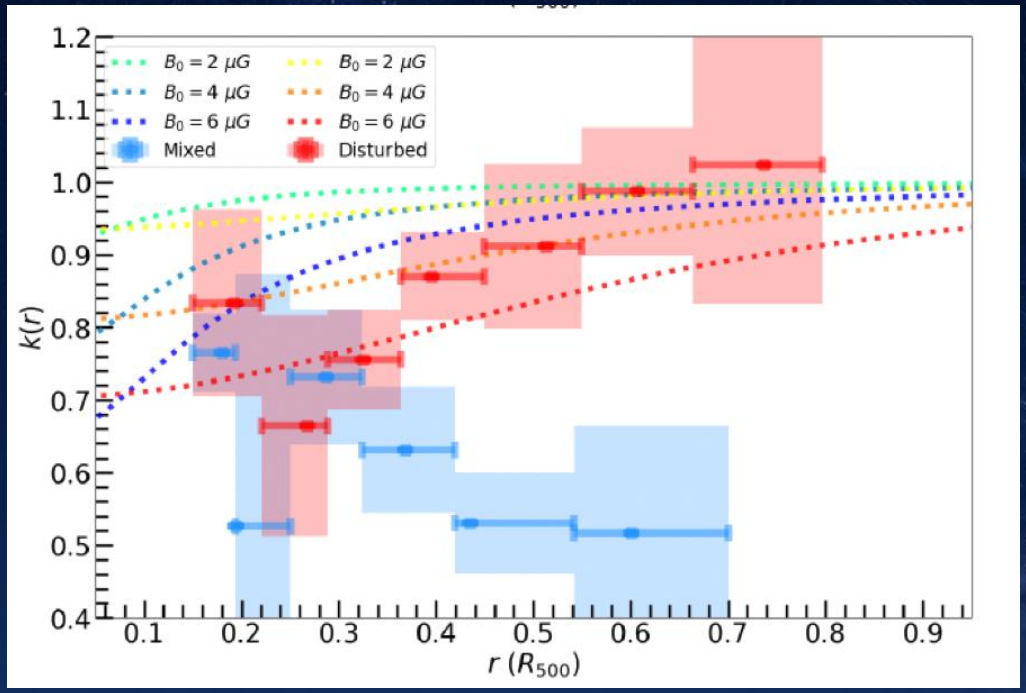
Does the radio – X-ray connection change with radius?



$$k(r) = \frac{\Delta \ln I_R}{\Delta \ln I_X}$$

k(r) measures how the relative decline of radio and X-ray surface brightness changes across the halo.

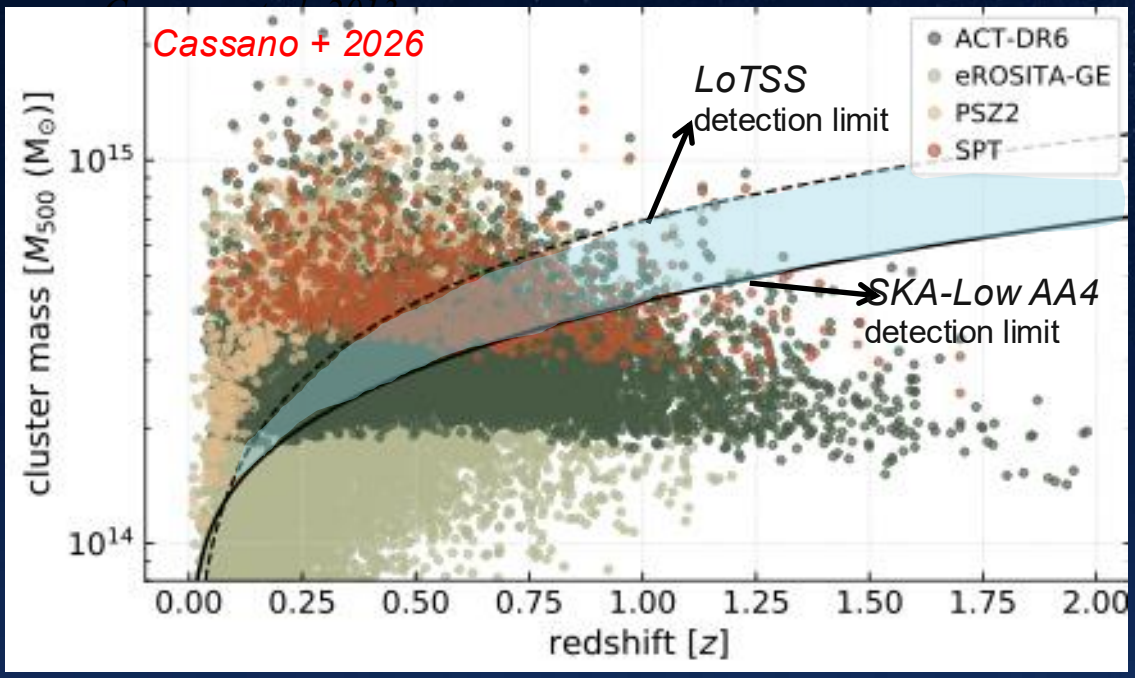
- k(r)<1 → radio declines more slowly than X-rays
- k(r)=1 → similar radial decline
- k(r)>1 → radio declines more rapidly than X-rays



Balboni + 26

The global radio–X-ray correlation hides different radial behaviours, linked to cluster dynamics.

The future: the non-thermal Universe in the SKA era



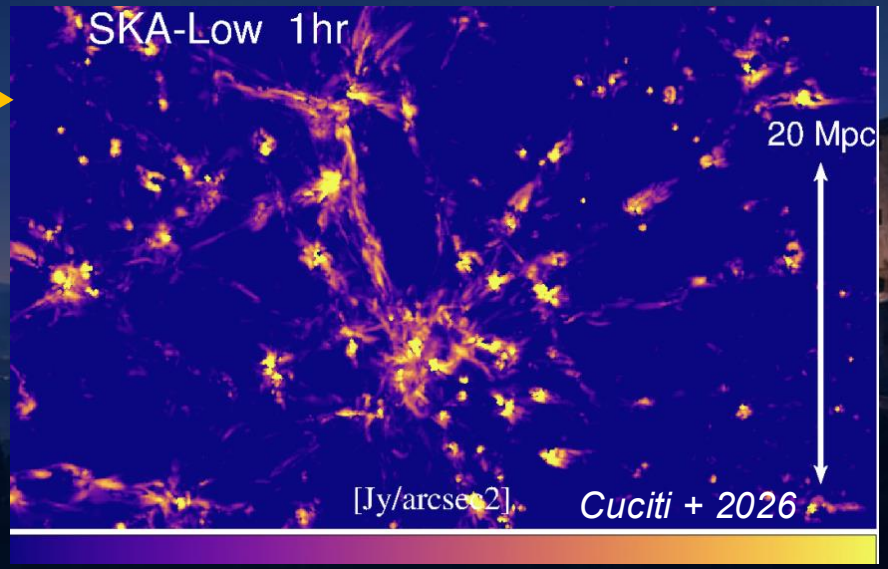
SKA-Low will push towards…

- Lower masses $M_{500} \sim 10^{14}\ M_\odot$
  probe groups and weaker mergers

- Higher redshifts $z \sim 1$
  trace the evolution of non-thermal components

- Much larger samples
  ≥ 2500 radio halos expected up to $z \simeq 0.6$
  including ≥ 1000 ultra-steep-spectrum halos

- Probing the synchrotron cosmic web
  SKA-Low → brightest filaments



SKA-Low will open new frontiers in the non-thermal Universe
from galaxy groups to high-redshift clusters and the synchrotron cosmic web

From observations to physics: the key questions



Observed synchrotron emission from ≈ 100 kpc – Mpc scales



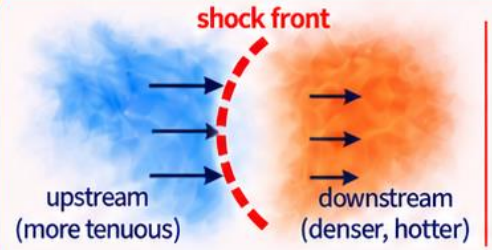
Can the electrons live long enough?

losses • lifetime • confinement



Where do the particles come from?

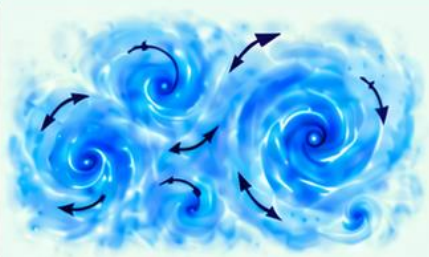
CR sources • seed electrons



SHOCKS

How are particles accelerated at shocks?

1st-order Fermi → **relics**



TURBULENCE

How are particles re-accelerated in the ICM?

2nd-order Fermi → **halos**