Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA
INAF ISTITUTO NAZIONALE DI ASTROFISICA

Unveiling the spectral properties of radio halos in the galaxy clusters of the LOFAR sky survey

The Fifth National Workshop on the SKA Project
Nov 27, 2025

Supervisors

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PhD cycle 39 (A.Y 2023-2026)
IRA-INAF BOLOGNA

Progetto PNRR
STILES
Proposta IR0000034
CUP: C33C22000640006

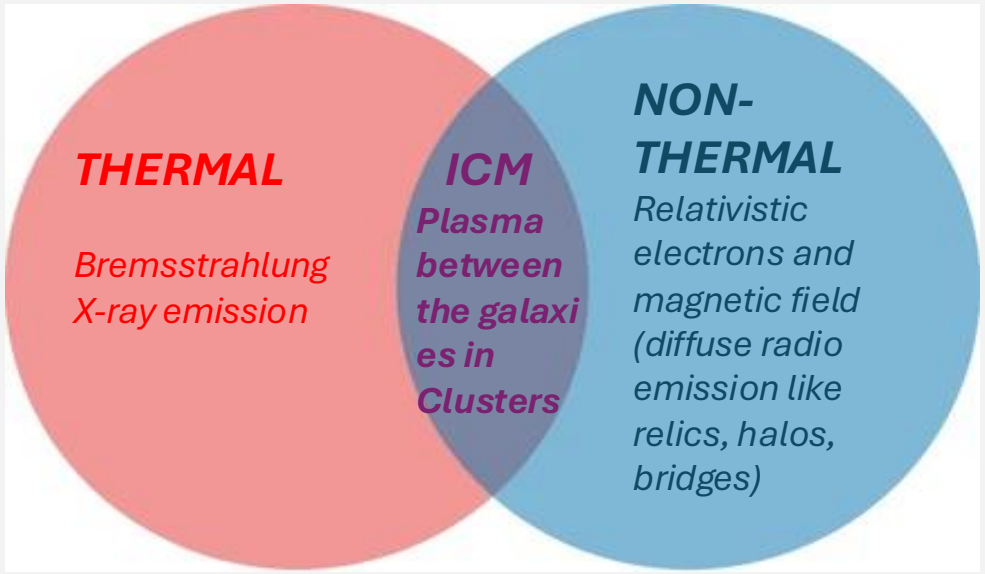
Missione 4 Istruzione e Ricerca
Componente 2 Dalla ricerca all'impresa
Linea di investimento 3.1

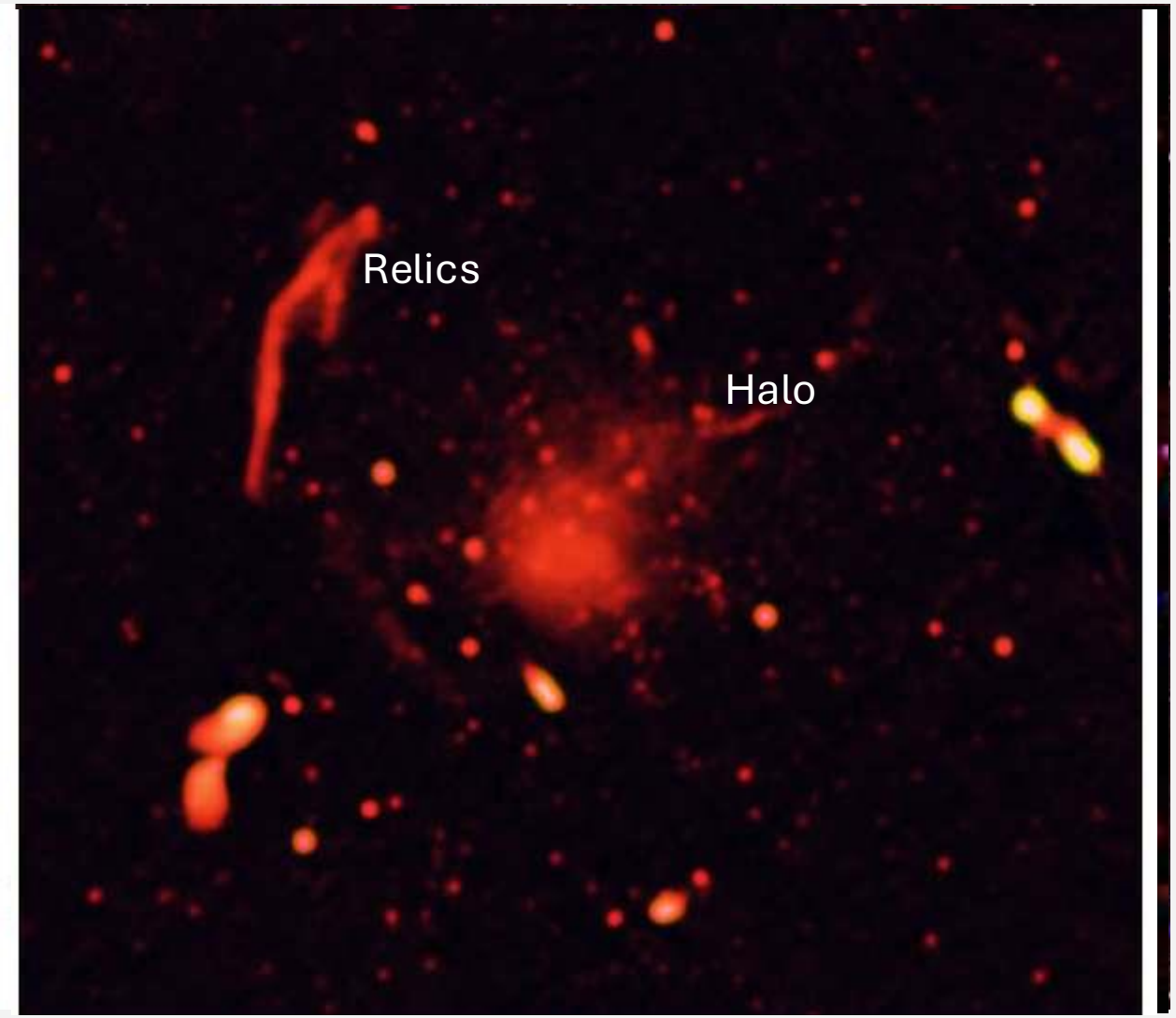
RADIO HALOS IN GALAXY CLUSTERS

COMPONENTS IN GALAXY CLUSTERS

- Galaxy clusters are massive gravitationally bound structure with a mass range of : 10^{14} - 10^{15} $M_{\odot}$.
- They are composed of galaxies, baryonic matter, hot gas, dark matter (70%-80%).

INTRA CLUSTER MEDIUM





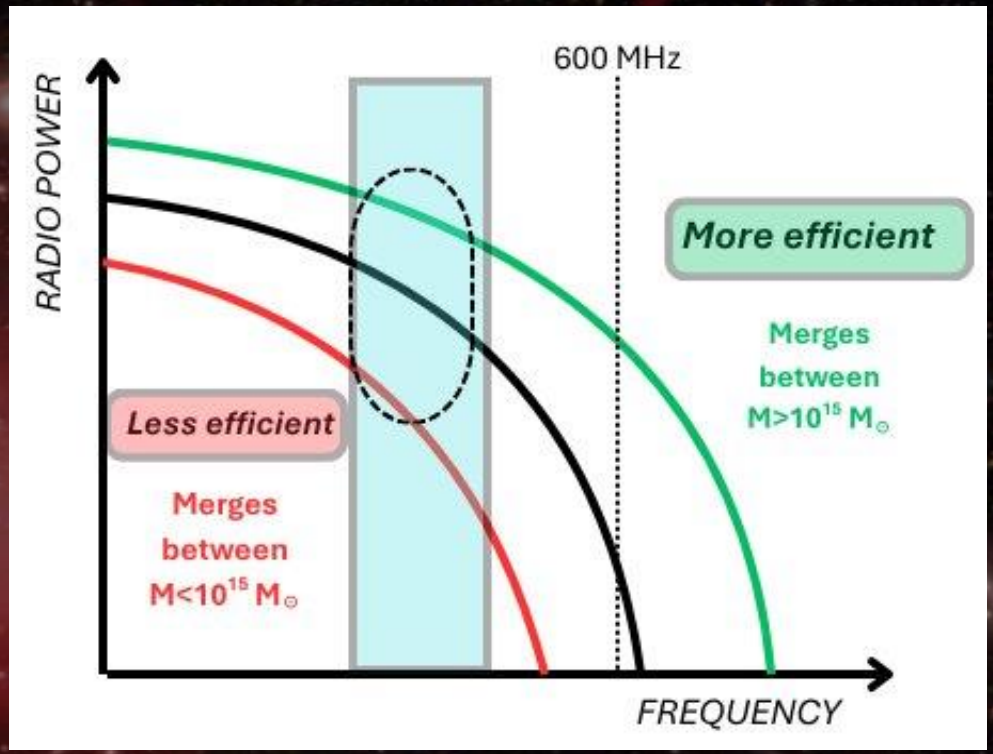
A2744 Optical + Xray + Radio

RADIO HALOS

Diffuse, ~ Mpc Unpolarised synchrotron radio sources

Origin - Turbulence by merging of clusters of galaxies (Fermi II)

- Turbulent energy
- Mass of the merging clusters



RADIO HALOS

Diffuse, ~ Mpc Unpolarised synchrotron radio sources

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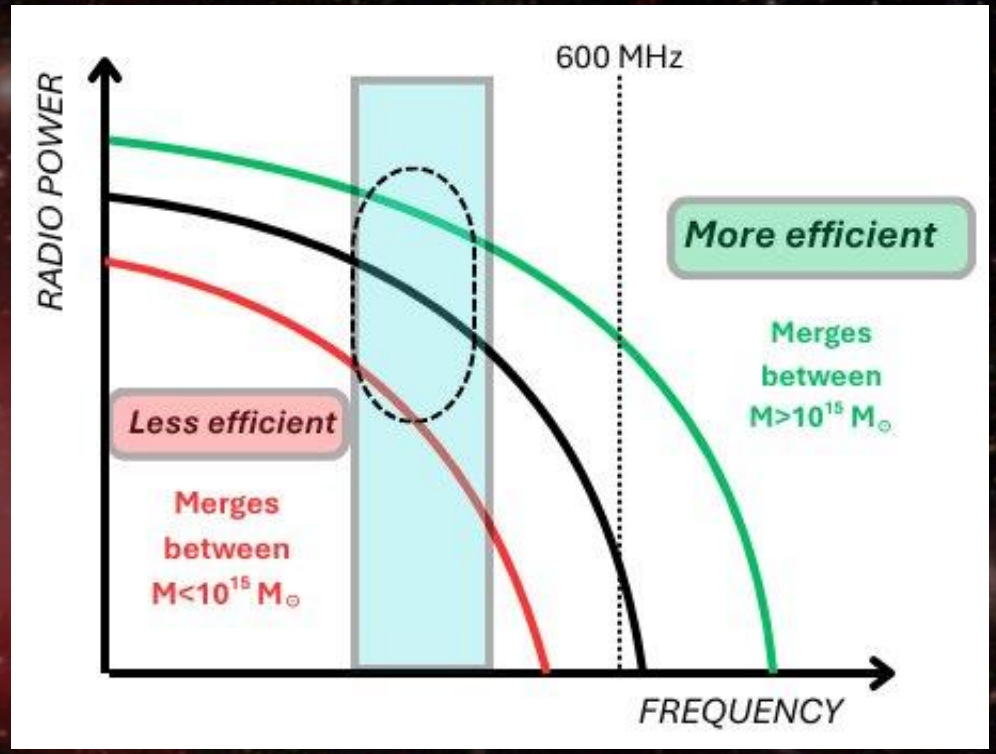
Expectations (model)

- Very low steepening frequency
- Brighter at lower frequency regime



RADIO HALOS

Diffuse, ~ Mpc Unpolarised synchrotron radio sources

Origin - Turbulence by merging of clusters of galaxies (Fermi II)

- Turbulent energy
- Mass of the merging clusters

Expectations (model)

- Very low steepening frequency
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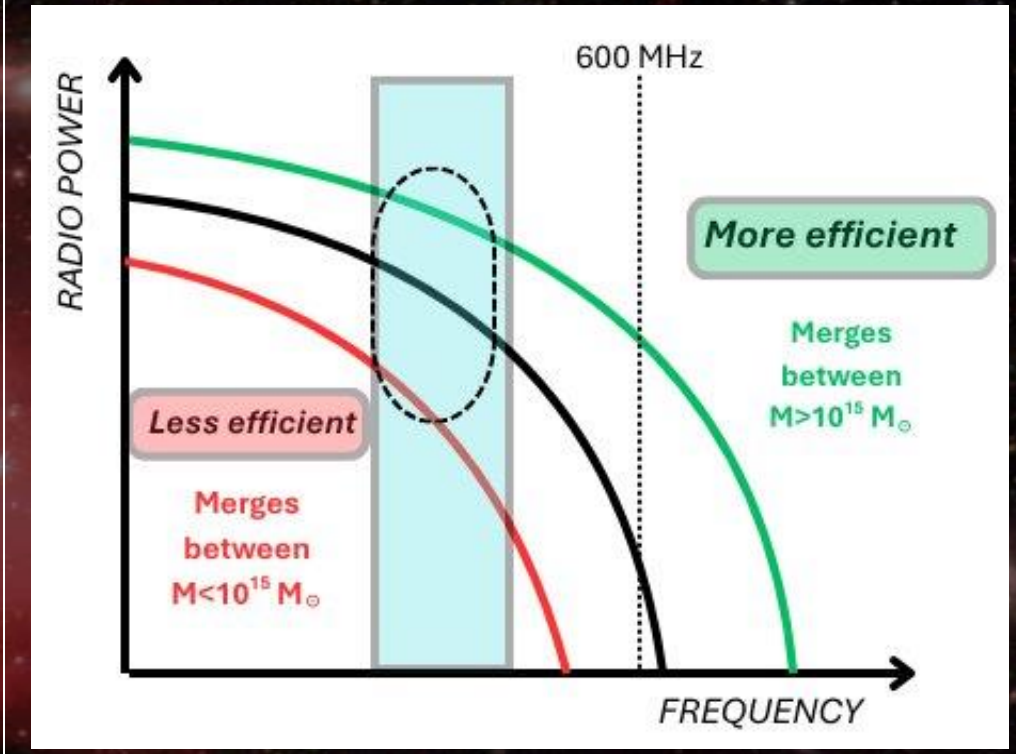
Observational proof ?

- **No**
- Analyzing a large sample of galaxy clusters in LOFAR and uGMRT
- **First systematic study of 45 radio halos observed in LoTSS-DR2-uGMRT. (My PhD work)**



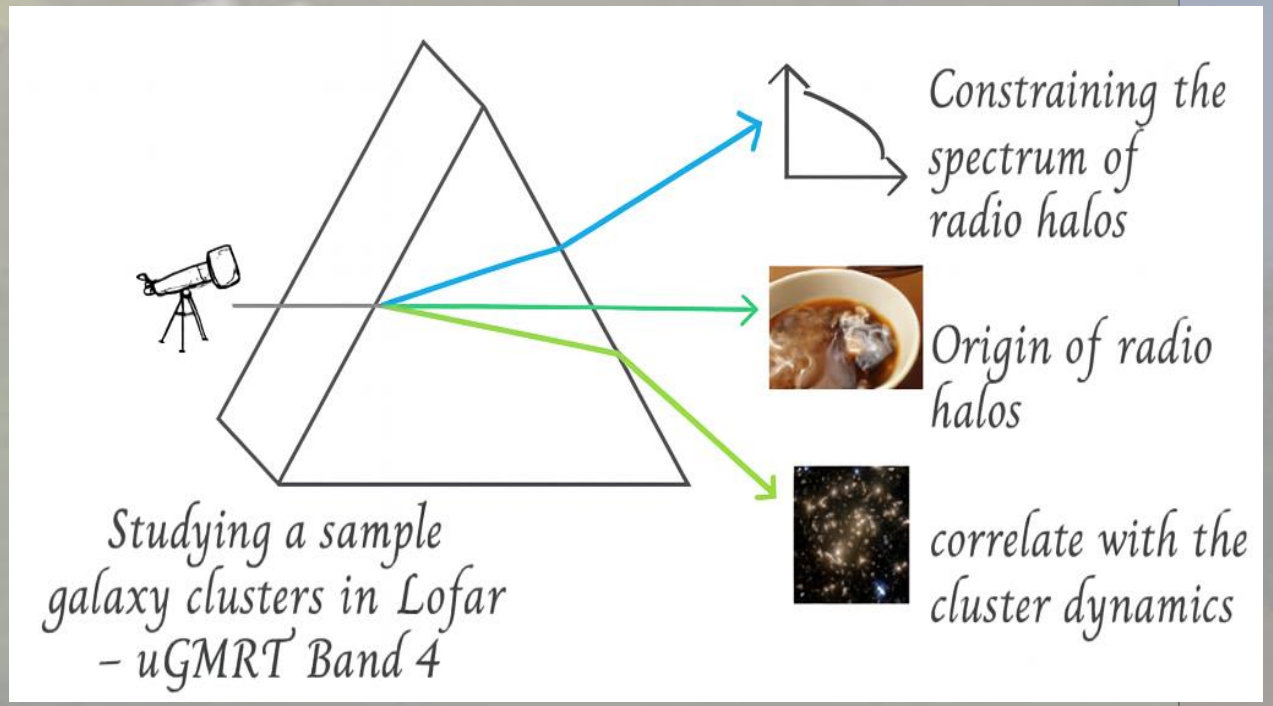
THE *PLANCK* CLUSTERS IN THE LOFAR SKY SURVEY

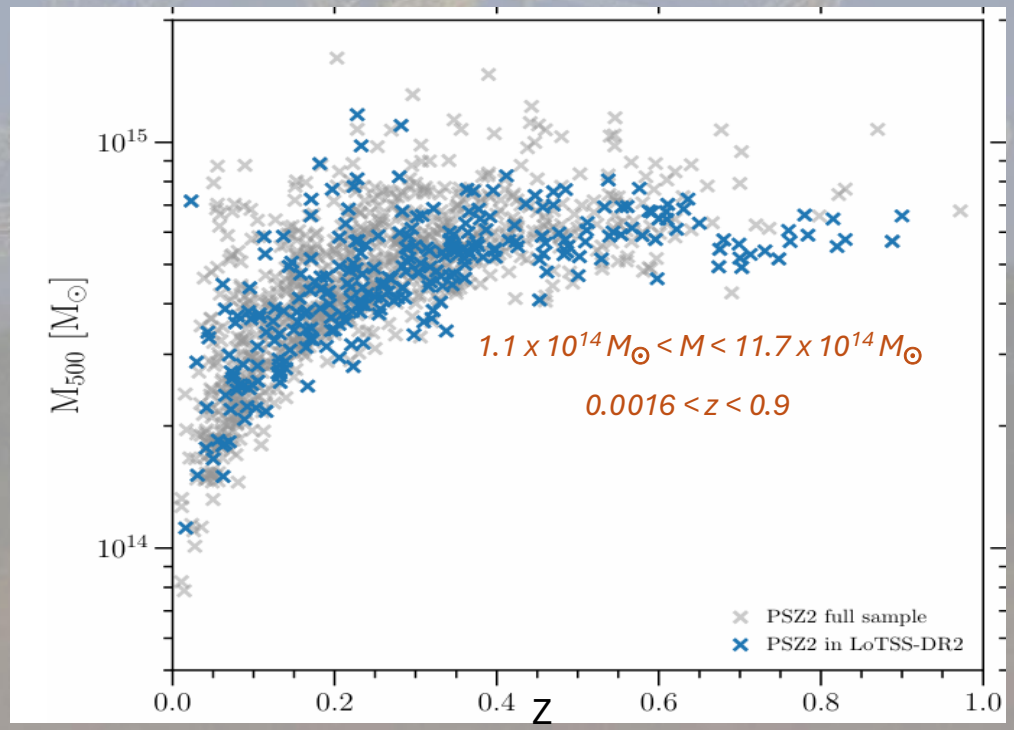
UNVEILING THE SPECTRAL PROPERTIES BY LOFAR-uGMRT

LoTSS DR2 survey
- Freq – 120-168 MHz
- Resolution – 6'',
- Rms – 100 μJy
- 5634 deg^2

GOAL – CONSTRAINING THE SPECTRUM/ORIGIN OF RADIO HALOS AND CORRELATE WITH CLUSTER DYNAMICS

SAMPLE SELECTION (LoTSS DR 2 - PSZ2 catalogue) - 309 clusters





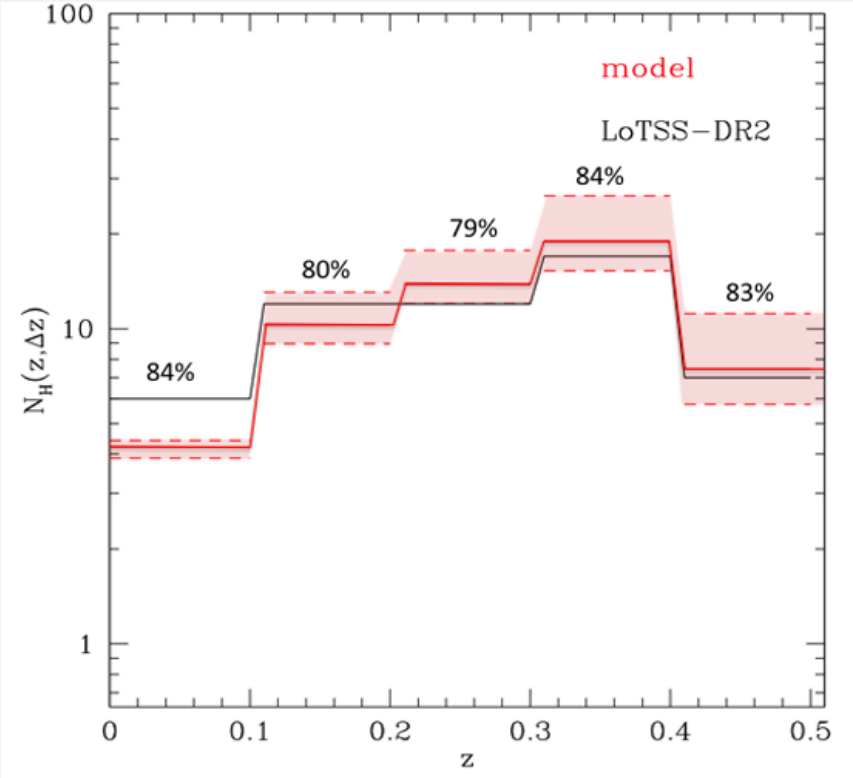
Redshift-mass distribution of PSZ2 sources

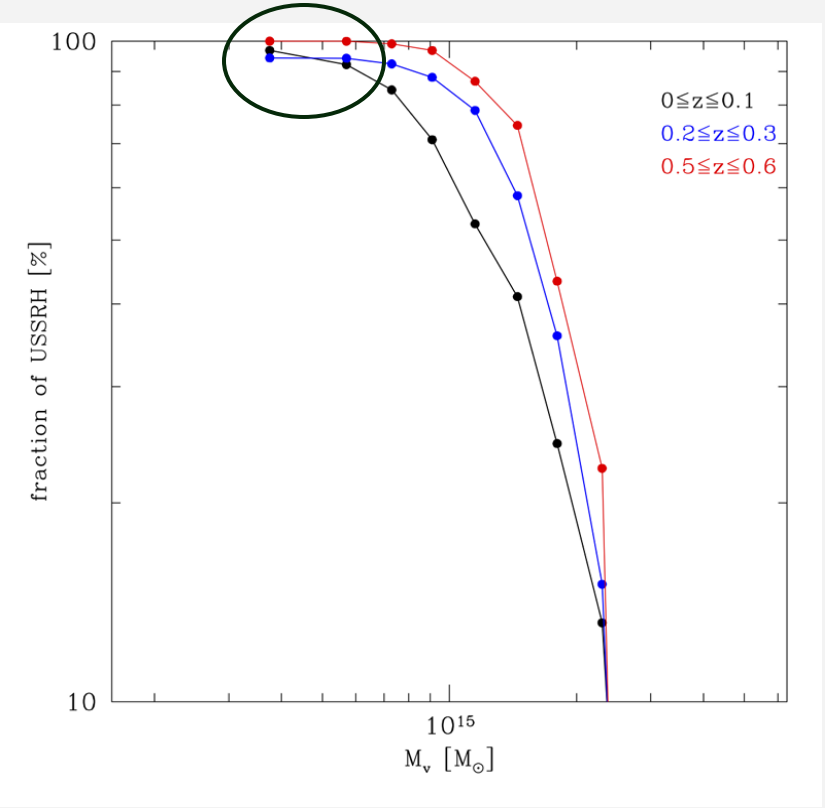
UNVEILING THE SPECTRAL PROPERTIES BY LOFAR-uGMRT

MODEL EXPECTATIONS

309 clusters → 164 clusters (71 NDE, 55 RH, 13 RR, and 25 U) → Statistics of radio haloes and reacceleration model (Cassano et al 2023) → Main outcomes → USSRH irrespective of the Z, RHs increases with cluster M, most of the RHs in disturbed system

LoTSS-DR2 $0.07 < z < 0.5$
PSZ2 sample
Botteon et al +22

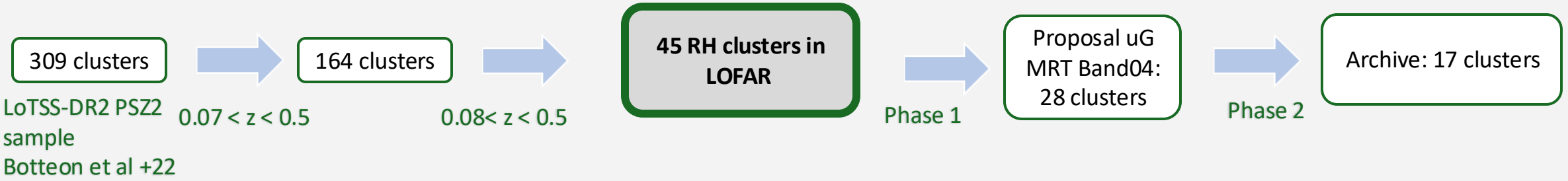




Cassano et al 2023

UNVEILING THE SPECTRAL PROPERTIES BY LOFAR-uGMRT

MOTIVE – CONSTRAINING THE SPECTRUM OF RADIO HALOS



Proposal – 28 clusters
Archive – 17 clusters

PROGRESS

PROGRESS

Processed the uGMRT data with SPAM pipeline (22 clusters)

Produced images at different resolutions

Discrete source subtraction to study the radio halos

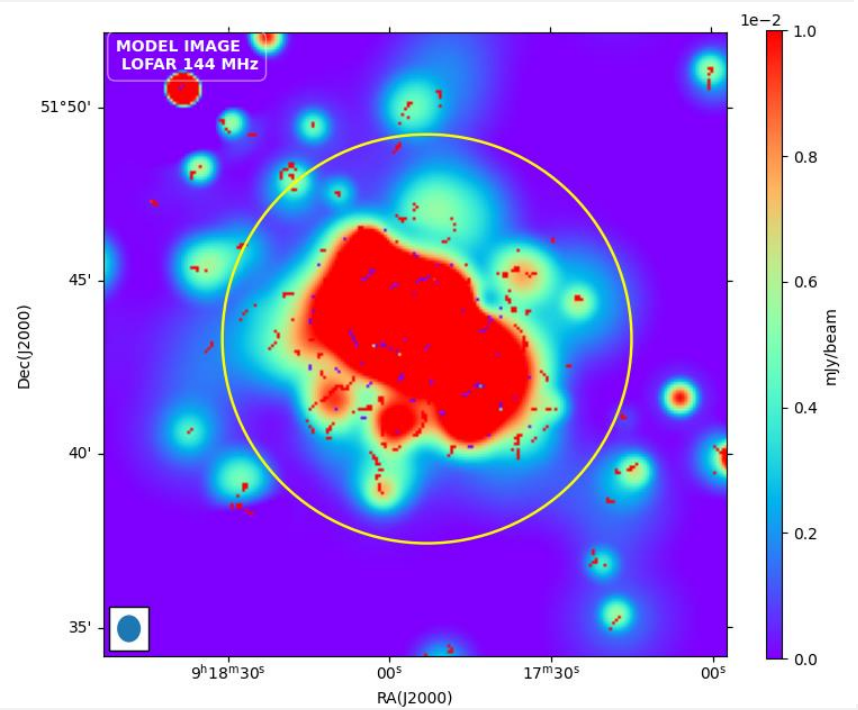
Found the FLUX DENSITY and SPECTRAL INDEX

1. *2 sigma contours (regions based on LOFAR and uGMRT)*
2. *LOFAR model injection (injection of a real LOFAR model instead of an exponential model)*

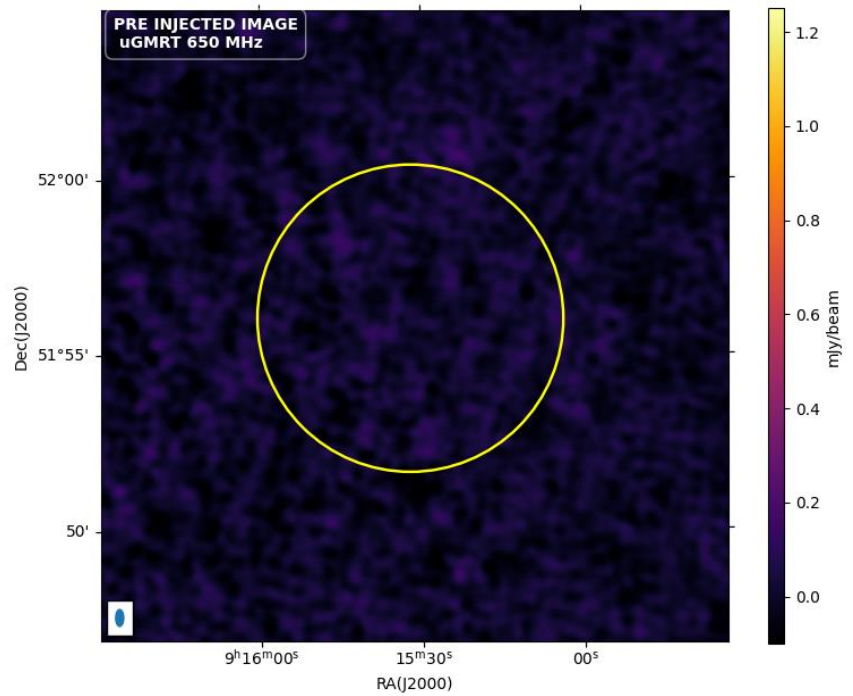
Statistical analysis with cluster dynamics

PROGRESS

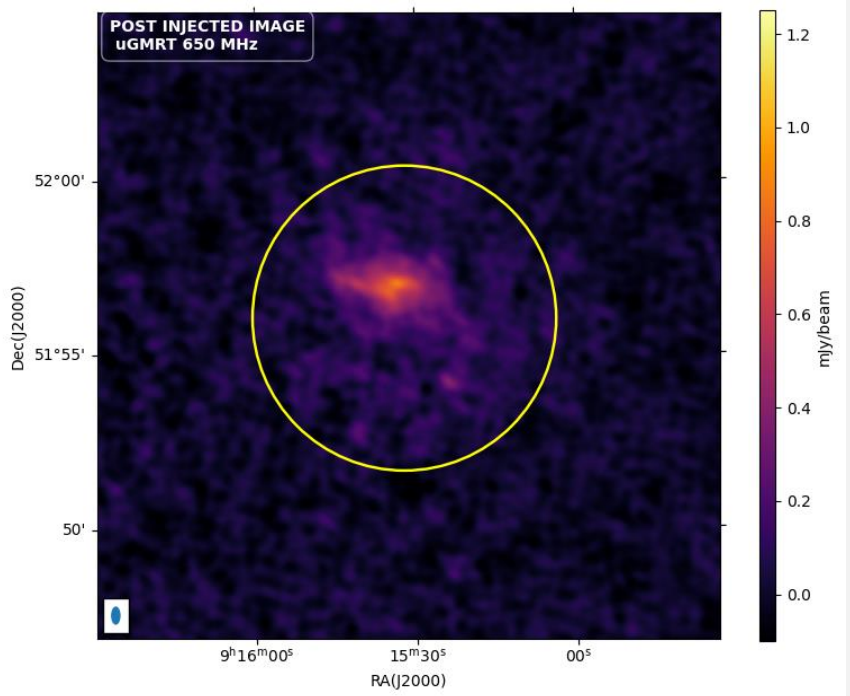
LOFAR MODEL



PRE INJECTION



POST INJECTION



Found the flux density and spectral index

1. *2 sigma contours (regions based on LOFAR and uGMRT)*
2. *LOFAR model injection (injection of a real LOFAR model instead of an exponential model)*

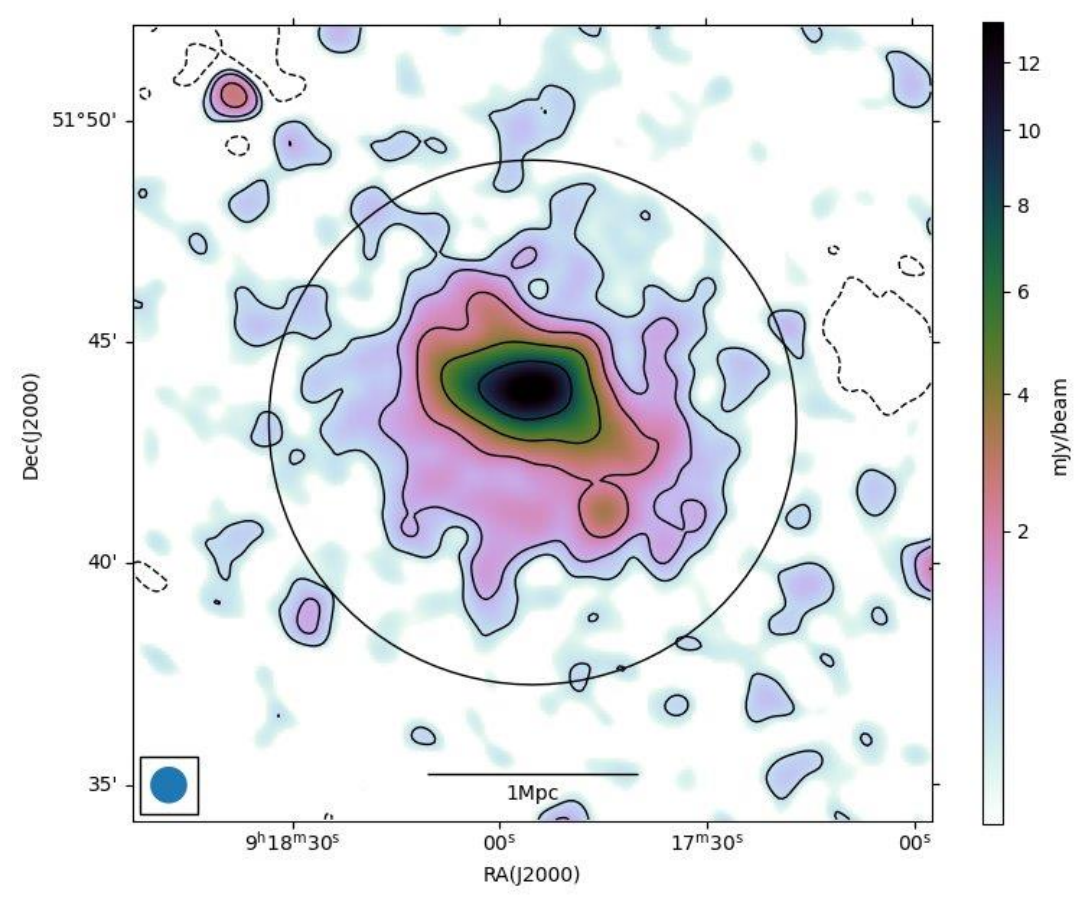
Diffuse radio emission in the massive clusters Abell 773 and Abell 1351(Srikanth et al)

A773

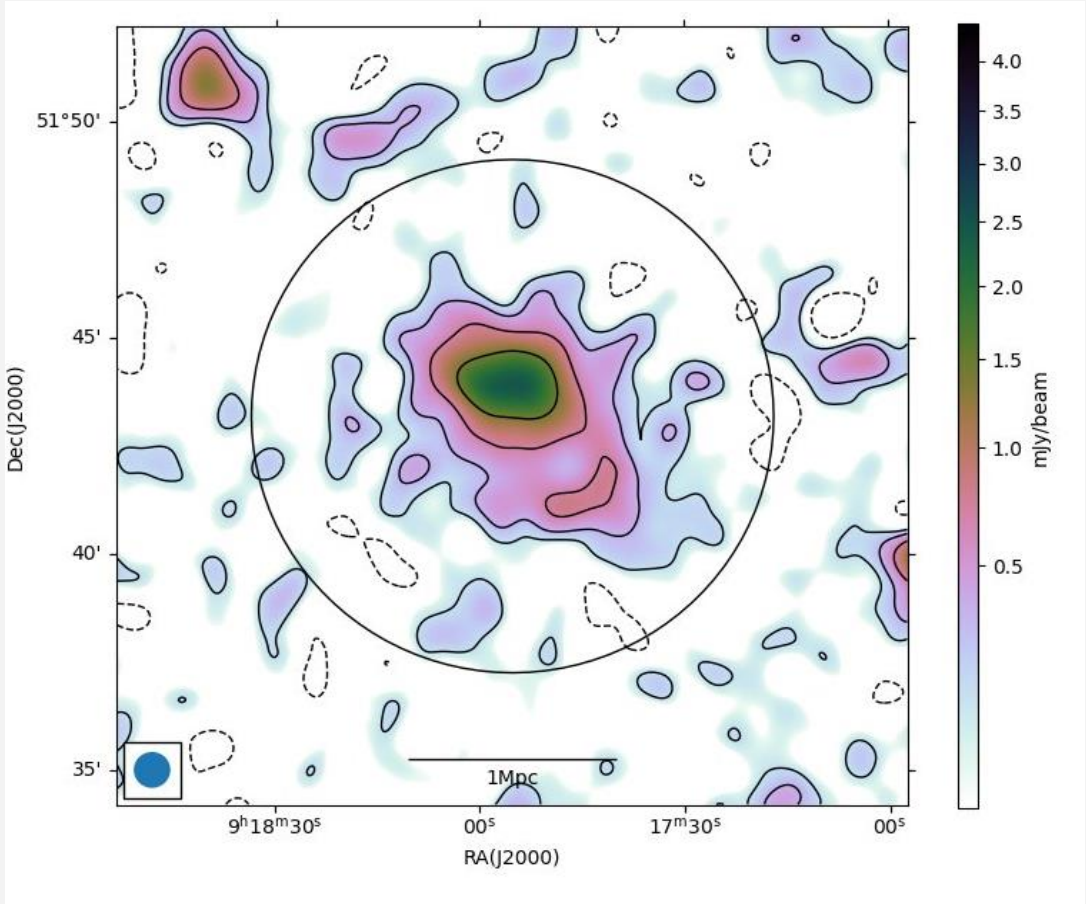
Cluster redshift z = 0.217
M500 =6.85 × $10^{14}M_{\odot}$

High resolution – 10'' × 10''
Low resolution – 50 '' × 50''

LOFAR



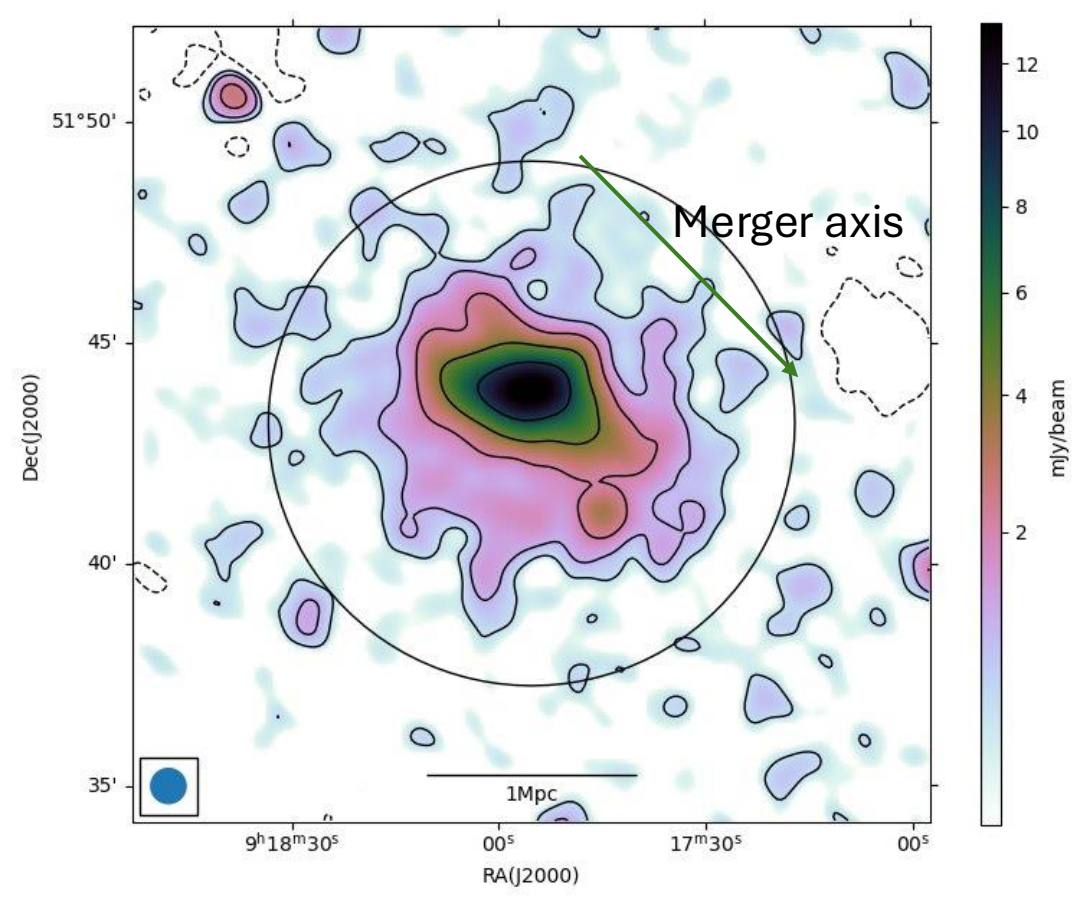
uGMRT



(Srikanth et al)

A773

LOFAR



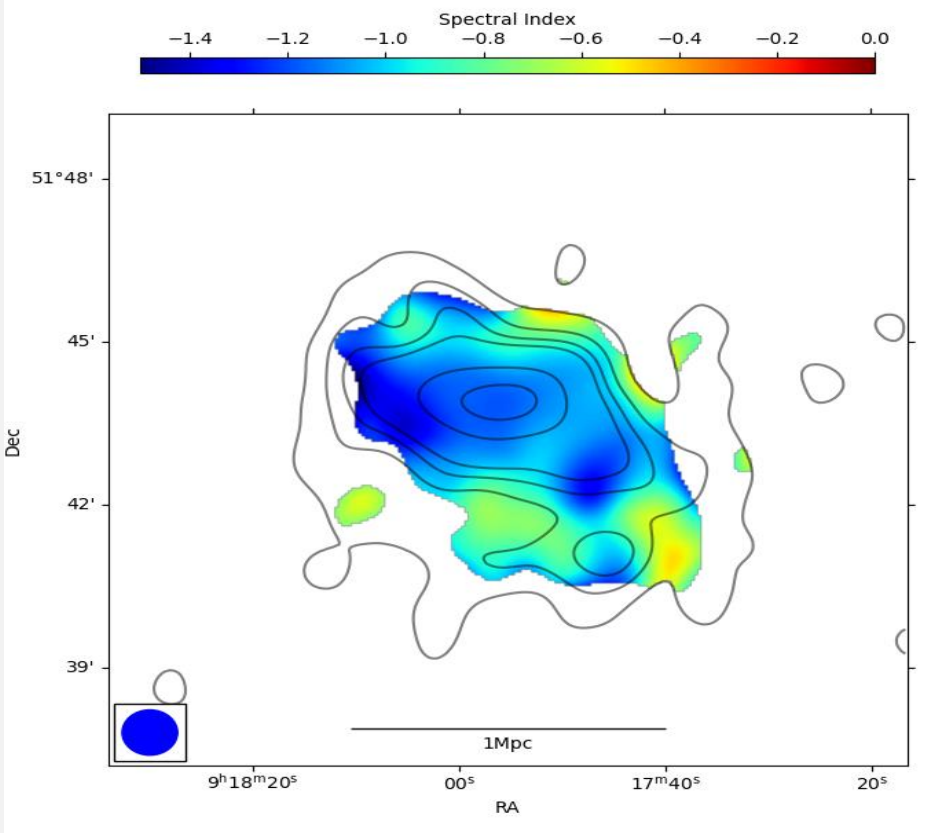
- Active merging cluster.
- Halo is very bright and at the center of the cluster.
- Size of the halo ~2Mpc from LOFAR and uGMRT analysis. ~1.6 Mpc at VLA (F. Govoni et al 2001).
- Halo is extended along NE-SW direction.

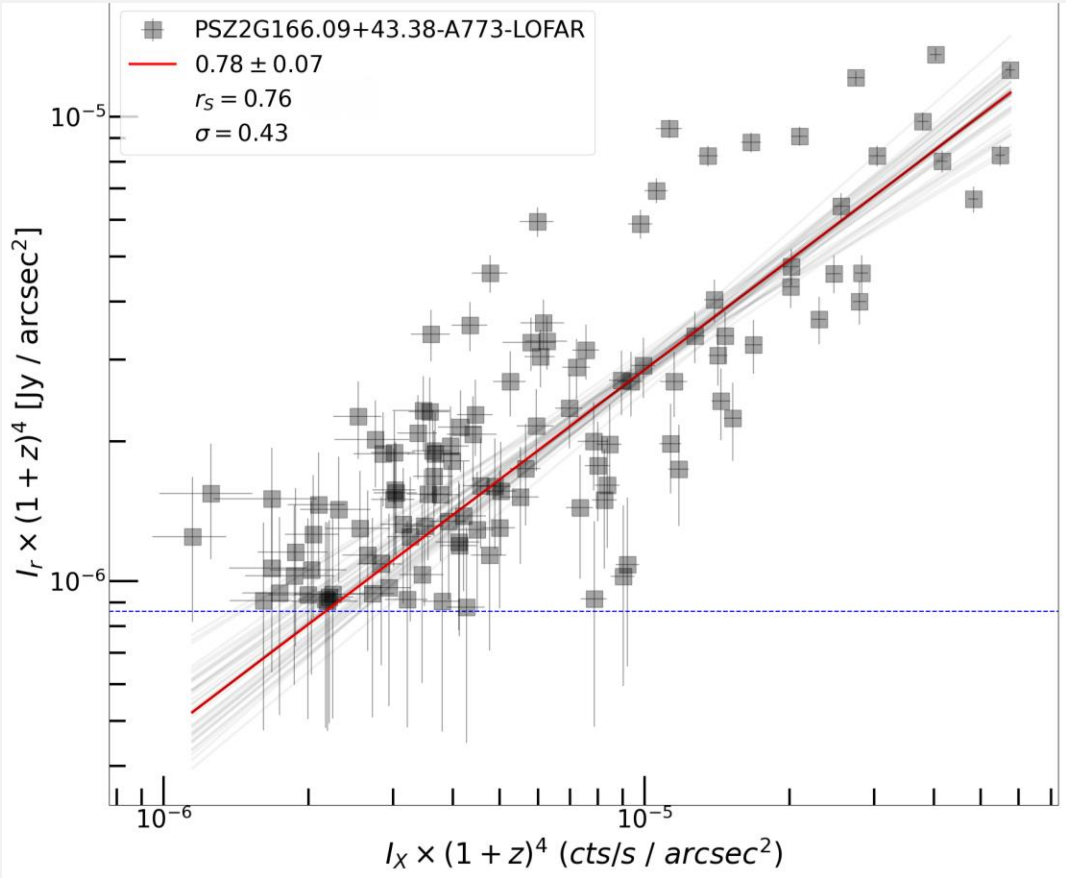
Method	LOFAR (mJy)	uGMRT (mJy)	Slope
LOFAR 2 sigma	143.4 ± 14.5	27.1 ± 1.5	-1.1 ± 0.08
uGMRT 2 sigma	141.1 ± 14.3	26.5 ± 1.5	-1.1 ± 0.08
LOFAR injection	149.2 ± 15.1	28.9	-1.1 ± 0.07

Flux loss in uGMRT : ~7%

(Srikanth et al)

A773 SPECTRAL INDEX MAP AND POINT TO POINT ANALYSIS

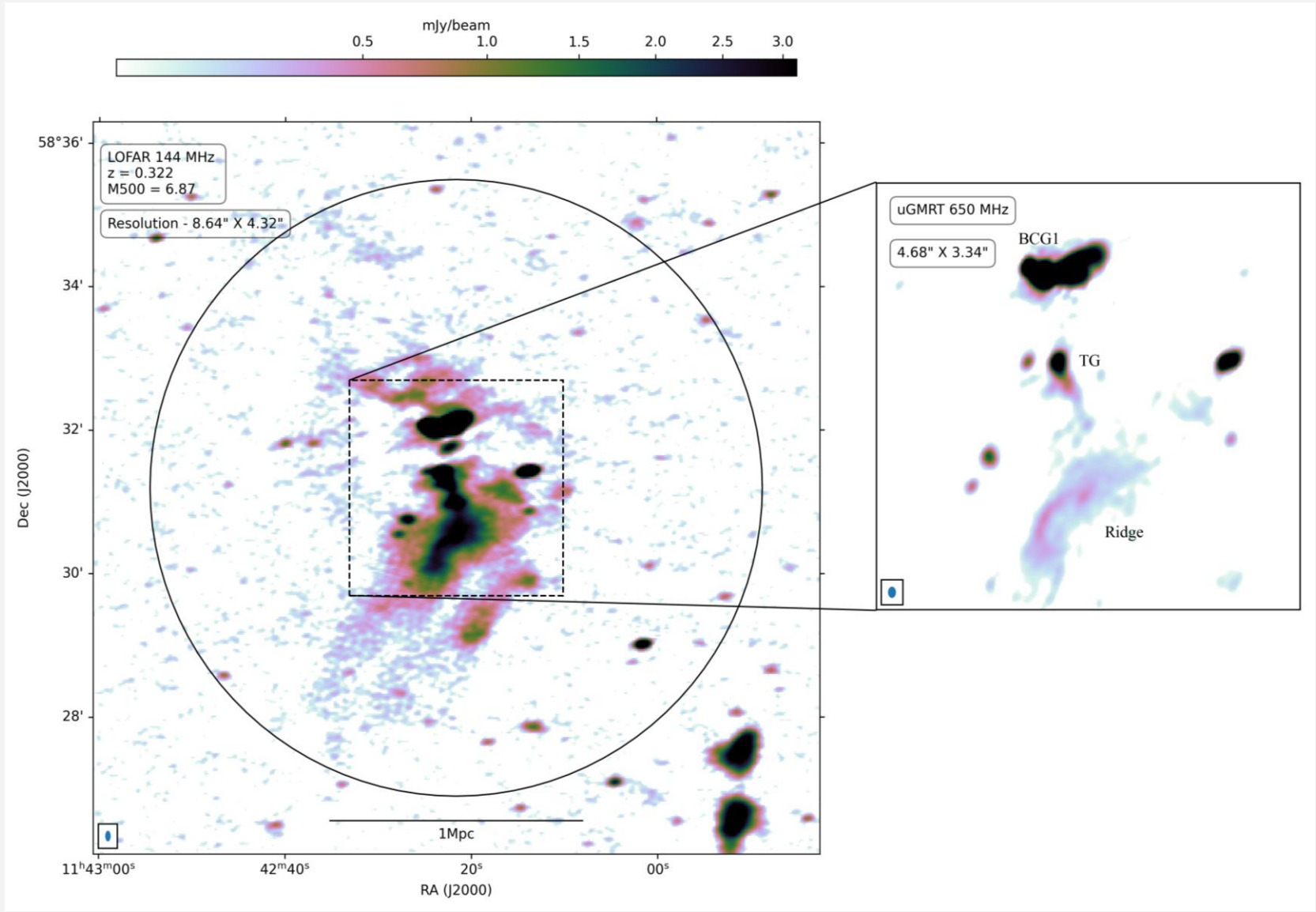




- Spectral index –1.1 in the center region of the halo.
- Sublinear relation – turbulent reacceleration model.

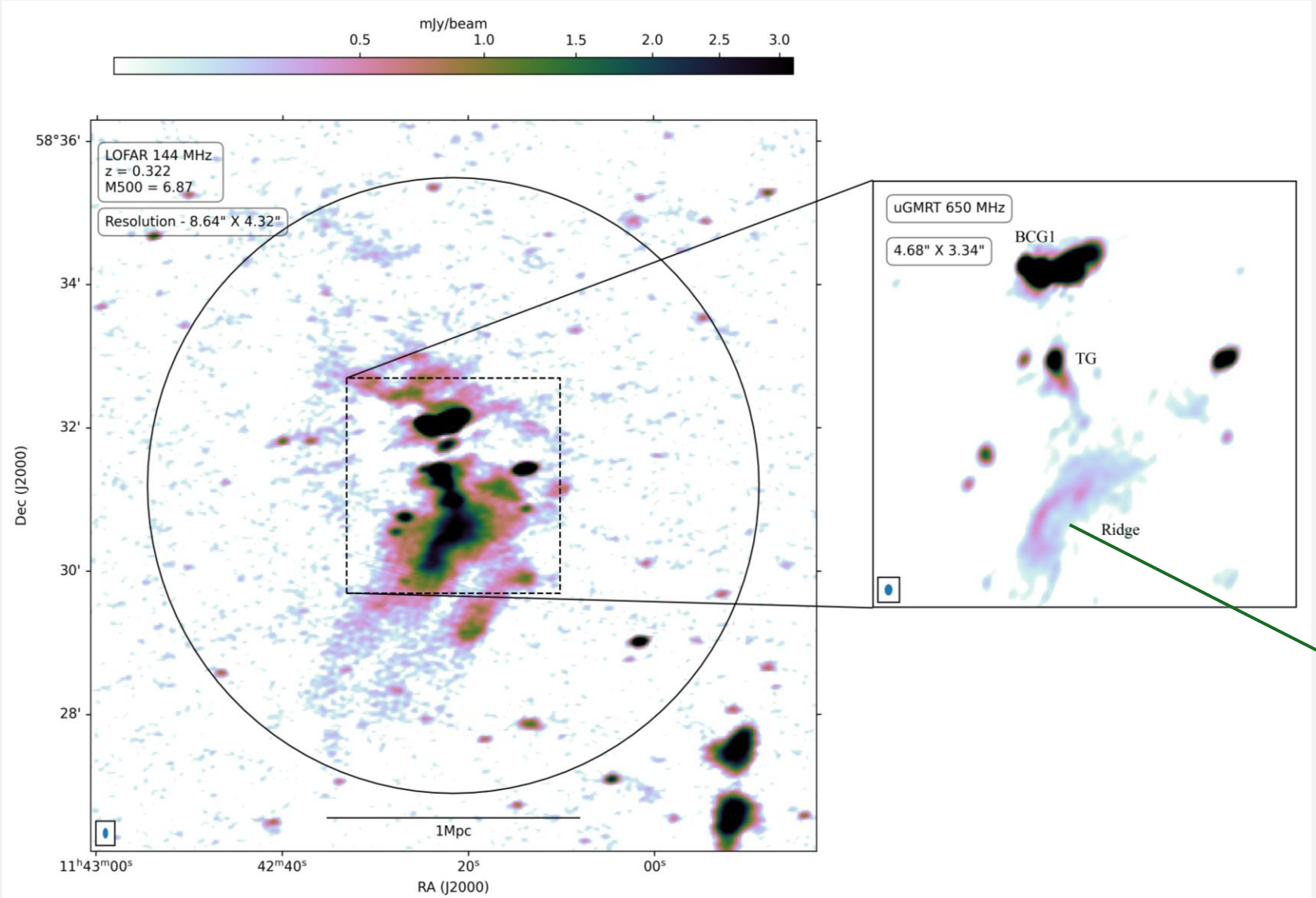
(Srikanth et al)

A1351



(Srikanth et al)

A1351

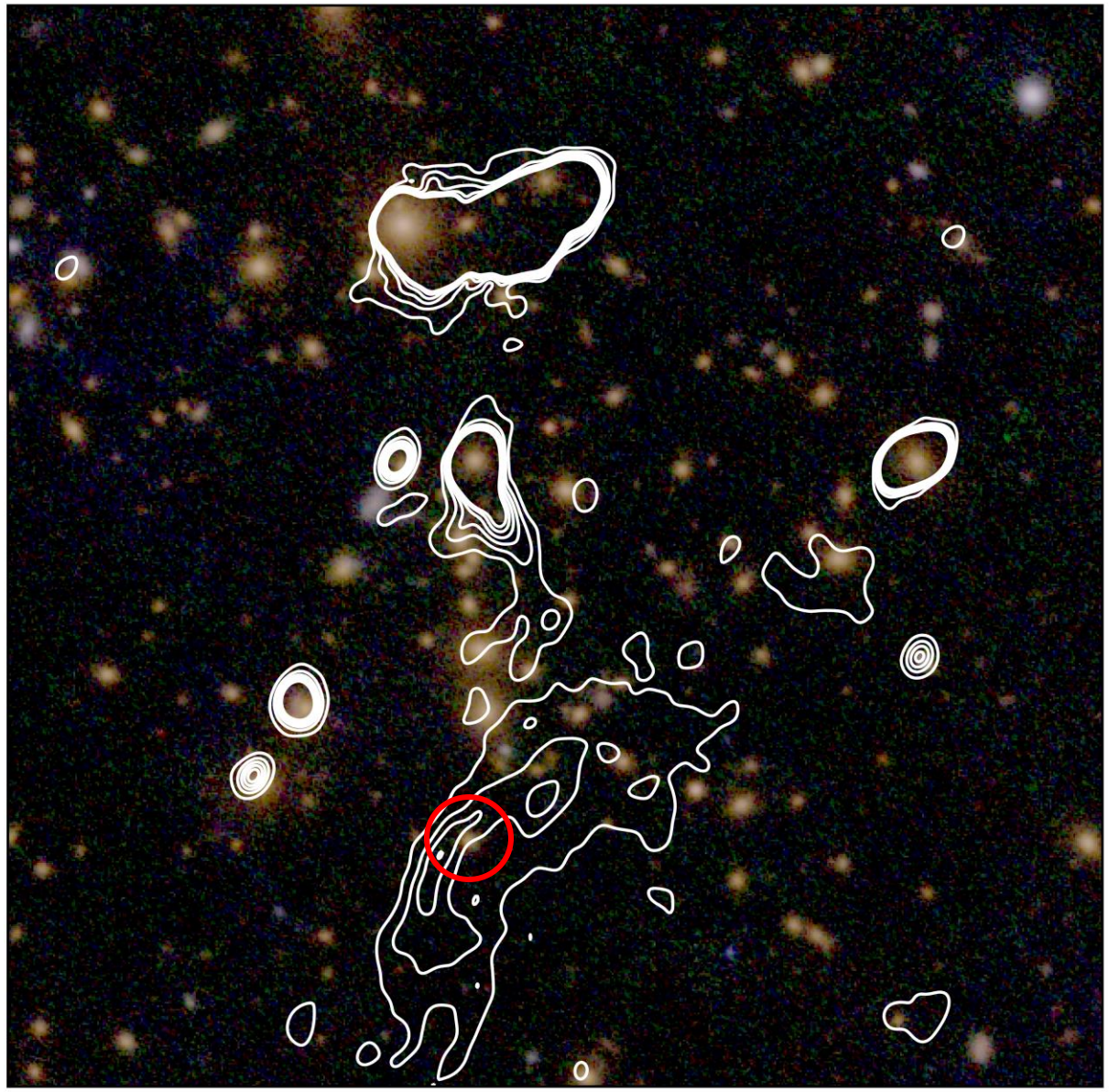


The source subtraction is difficult and can still leave some residuals in the final subtracted image

Claimed as a relic in the literature (Chatterji 2022, Giacintucci 2009, Barrena 2014)

(Srikanth et al)

A1351



Presence of a galaxy on the center of the ridge with optical overlay.

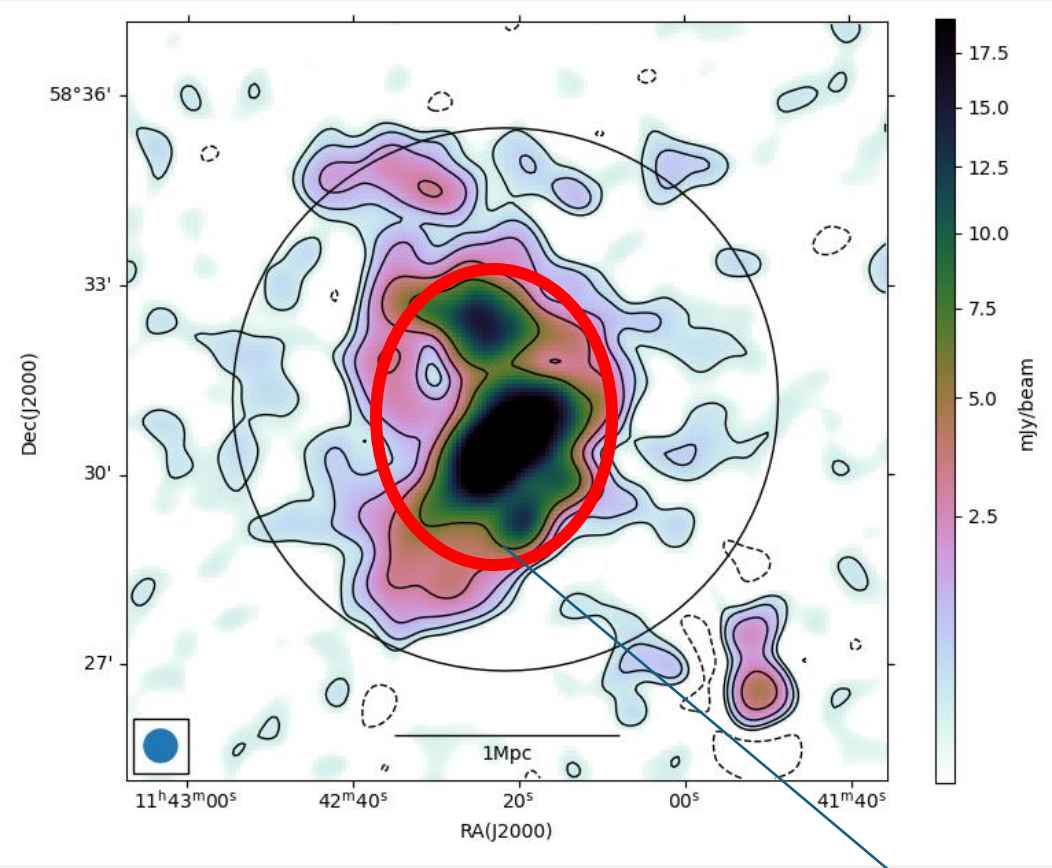
(Srikanth et al)

A1351

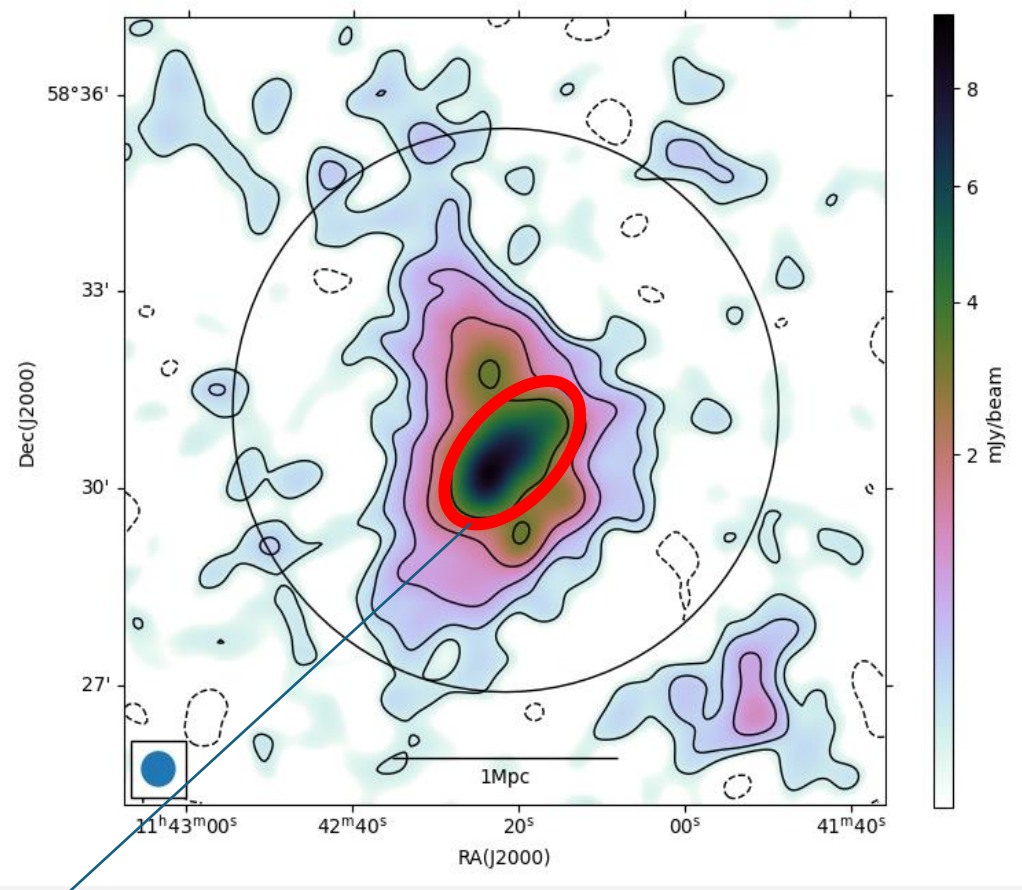
Cluster redshift z = 0.322
M500 =6.87 × $10^{14}M_{\odot}$

Resolution – 33" × 33"

LOFAR



uGMRT

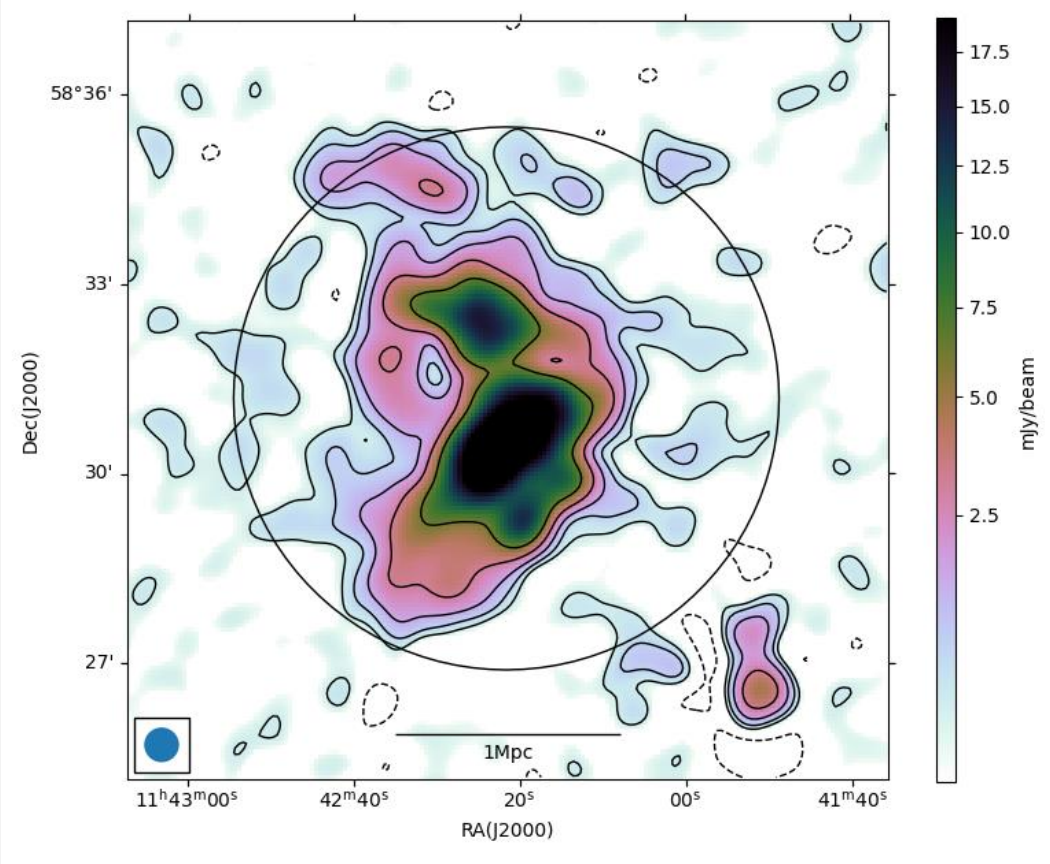


contaminants

(Srikanth et al)

A1351

LOFAR



- Merging cluster.
- Size of the halo ~2 Mpc.
- Merger axis NE-SW.

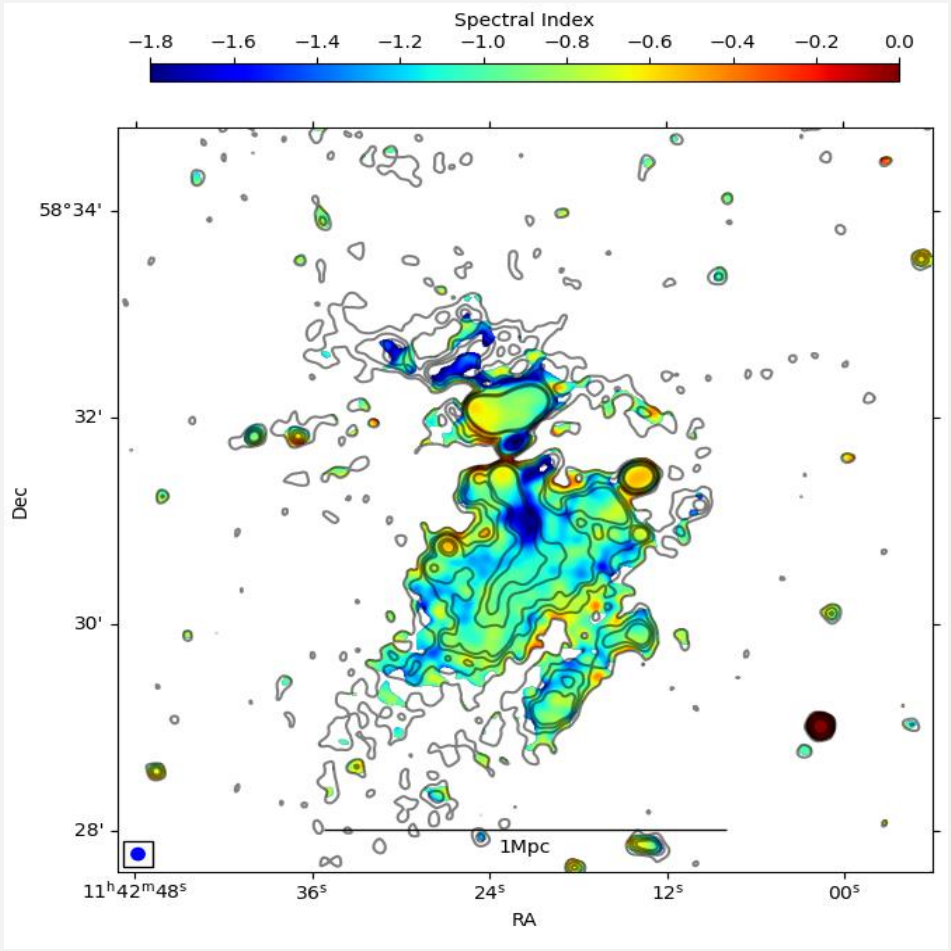
Method	LOFAR (mJy)	uGMRT (mJy)	Slope
LOFAR 2 sigma	392.6 ± 39.3	93.4 ± 4.7	-0.95 ± 0.07
uGMRT 2 sigma	385.2 ± 38.56	91.5 ± 4.6	-0.95 ± 0.07
LOFAR injection	408.6 ± 40.9	97.6	-0.95 ± 0.07

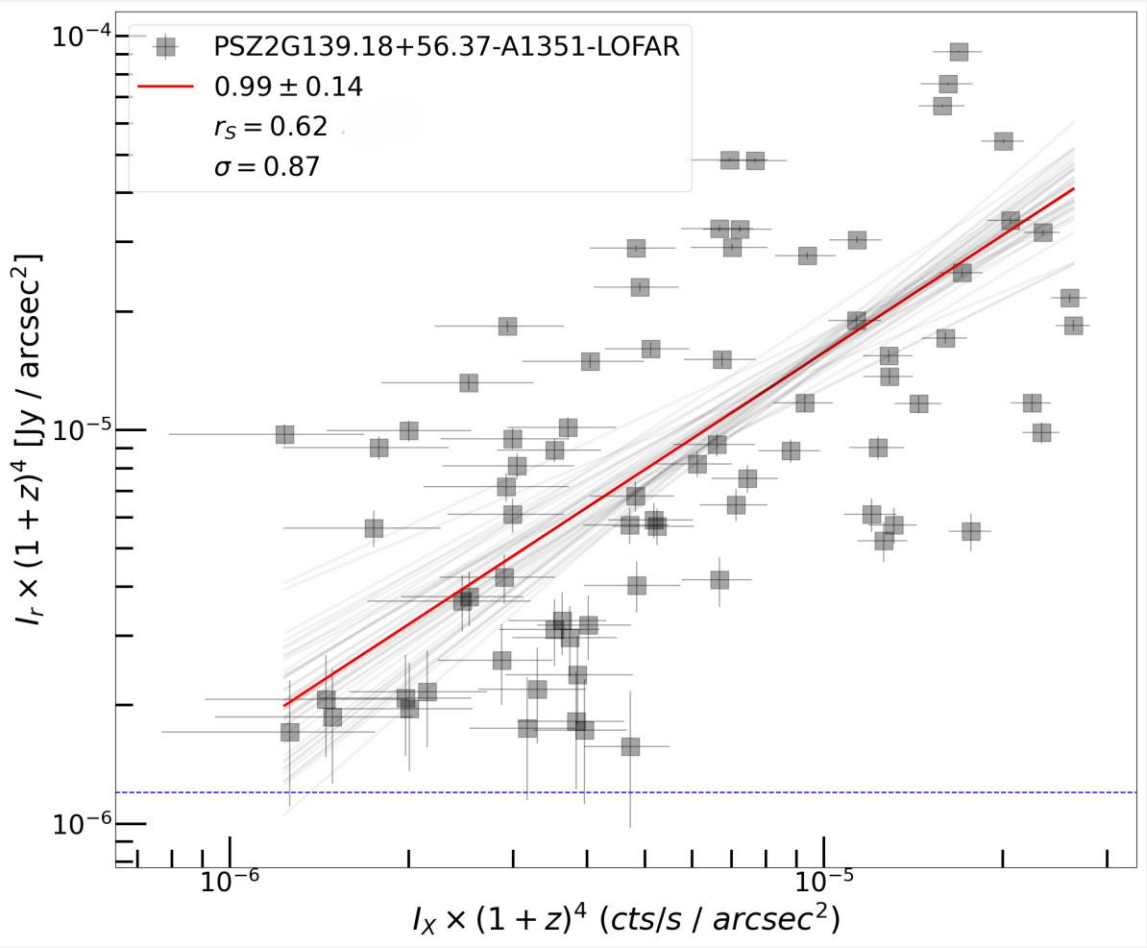
Flux loss in uGMRT : ~4-7%

(Srikanth et al)

A1351

Resolution - 7 " × 7 "

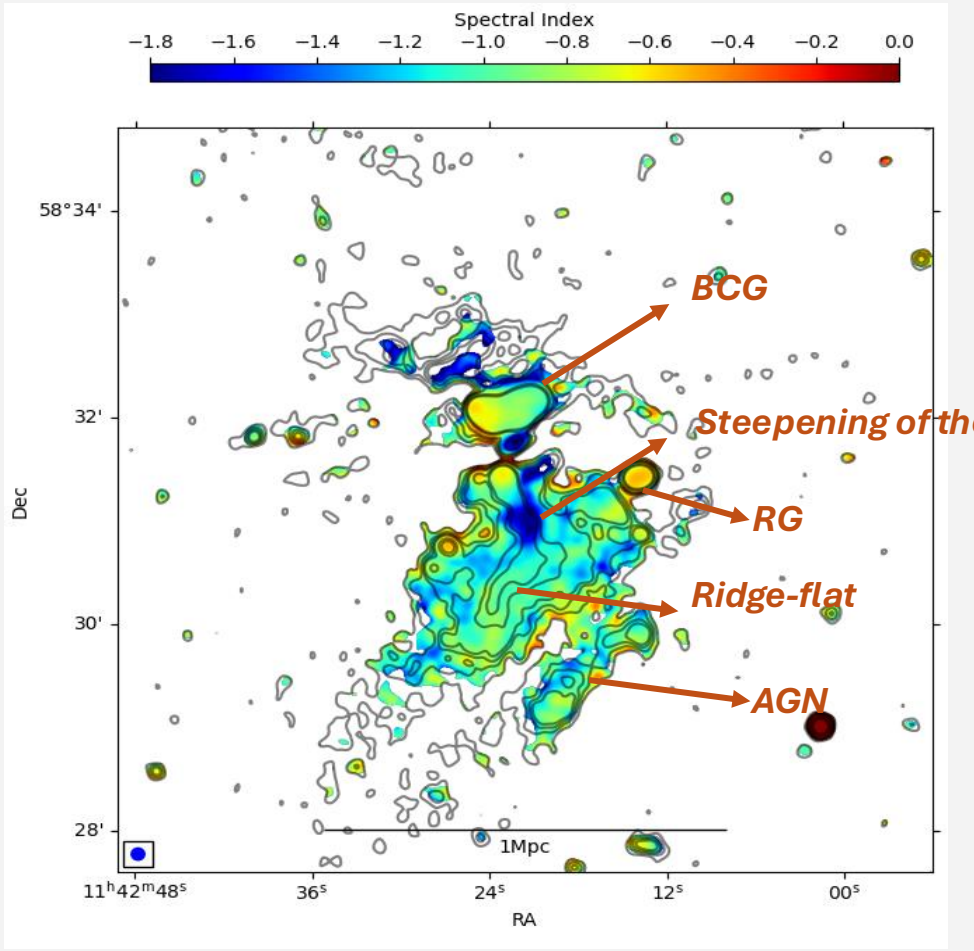


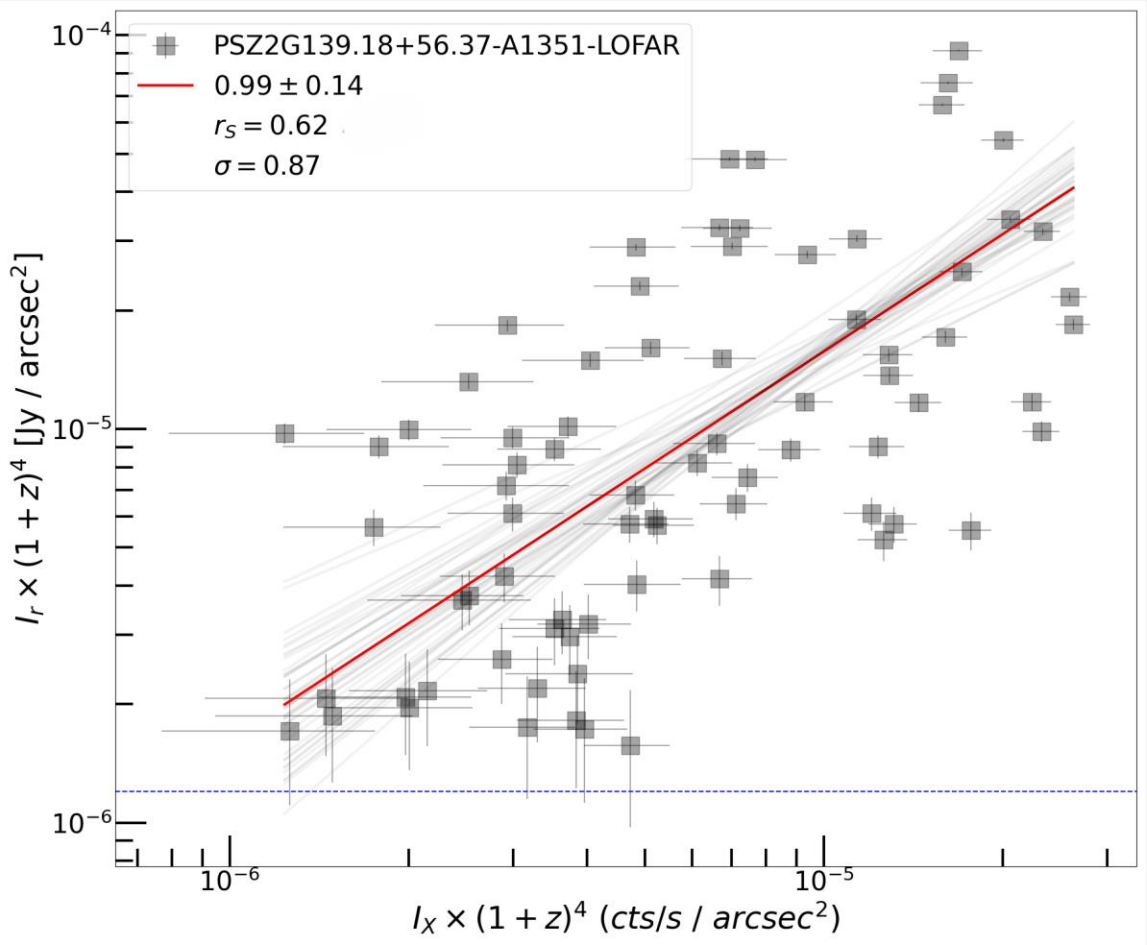


(Srikanth et al)

A1351

Resolution - 7 " × 7 "



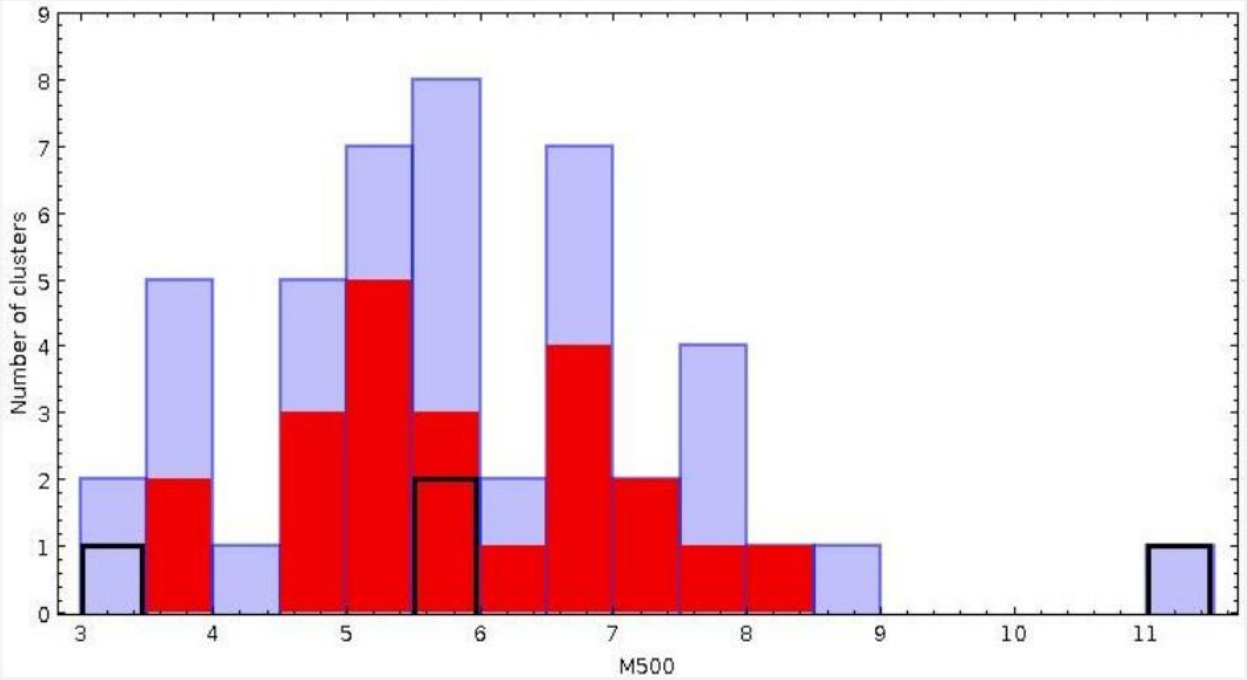


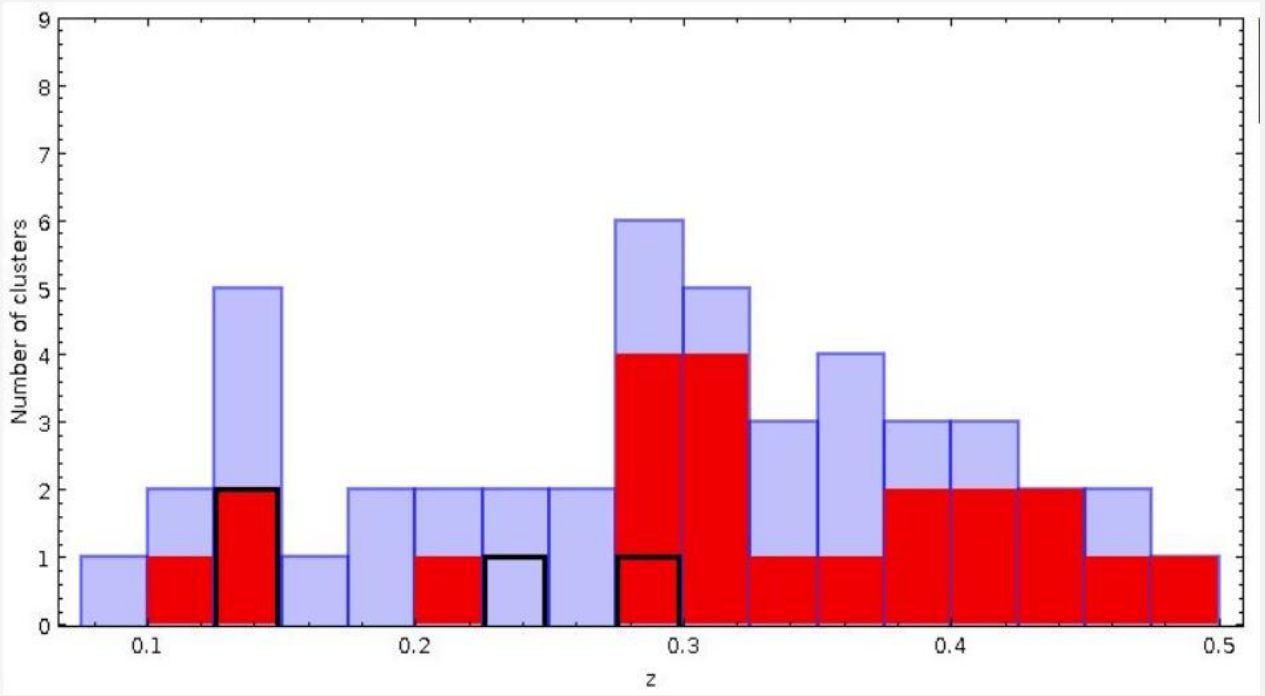
- No spectral steepening along the ridge – from our analysis hints of a radio galaxy-presence of a galaxy on the center of the ridge with optical overlay.
- No relation – high amount of scatter due to contaminants.

(Srikanth et al)

STATISTICAL ANALYSIS OF THE SAMPLE

DISTRIBUTION OF MASS AND REDSHIFT

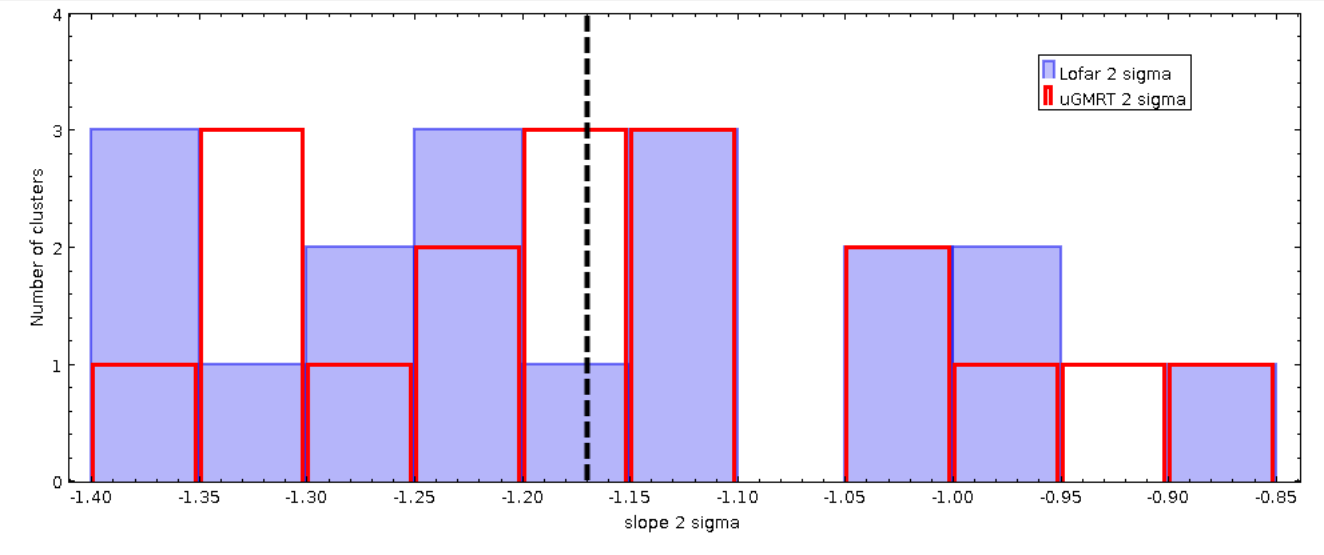




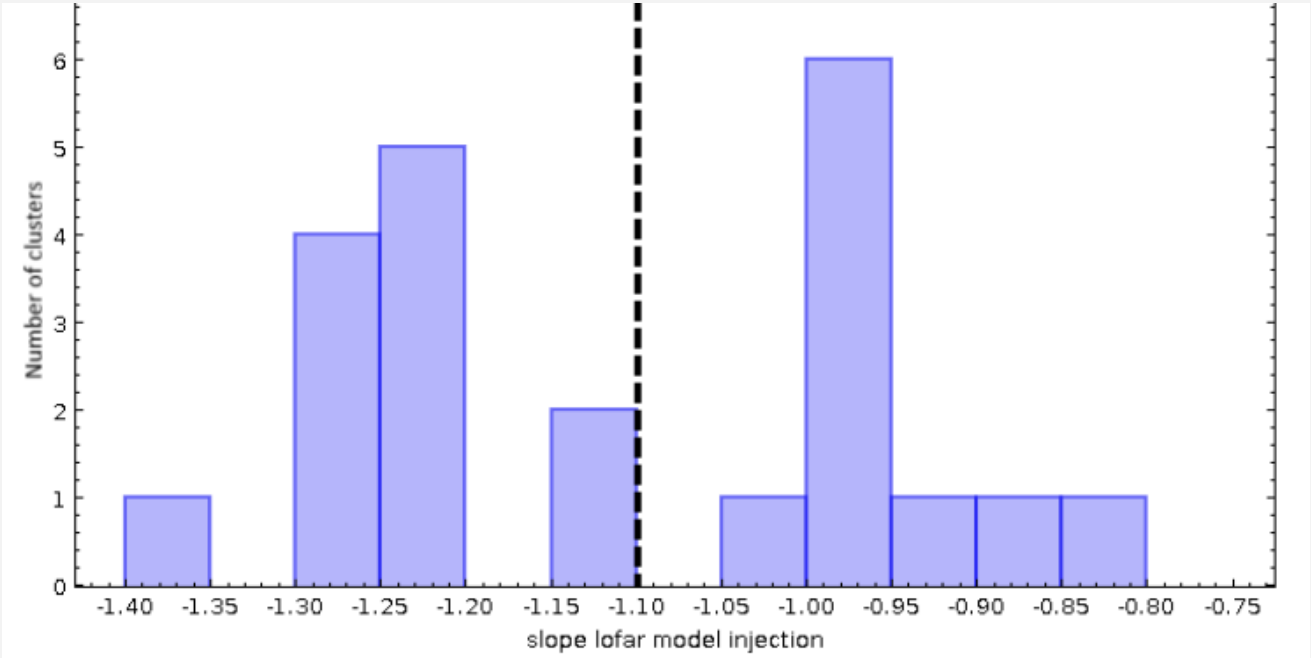
Entire sample (45)
Clusters analyzed (22)
Clusters with archival spectral information

DISTRIBUTION OF SLOPE FOR THE SUBSAMPLE (22)

2σ regions

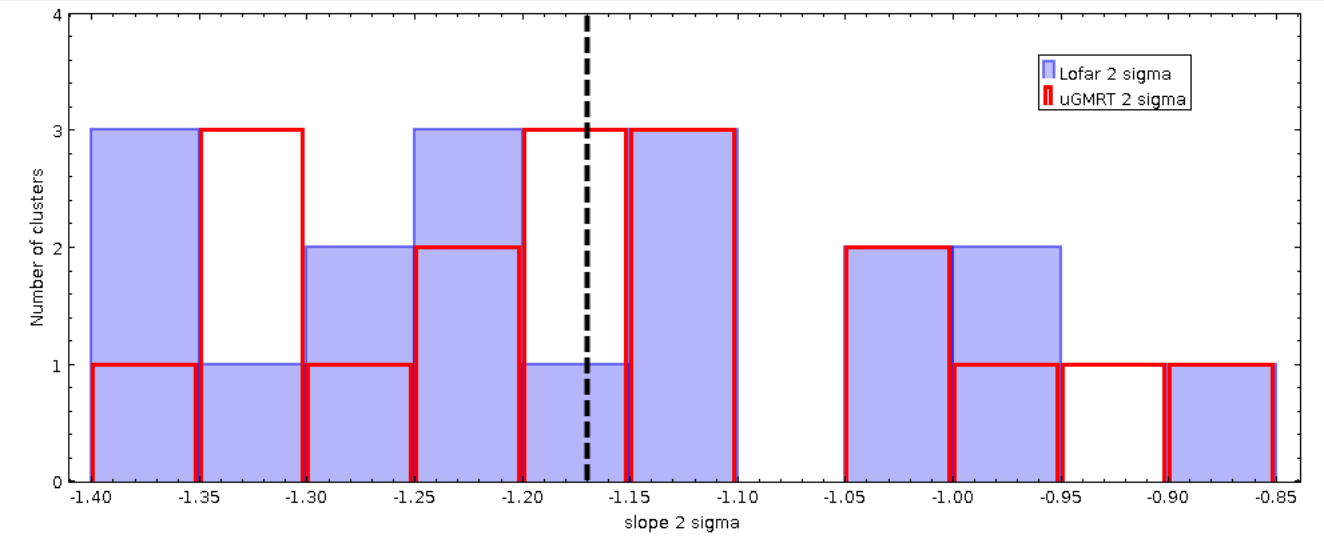


LOFAR MODEL INJECTION

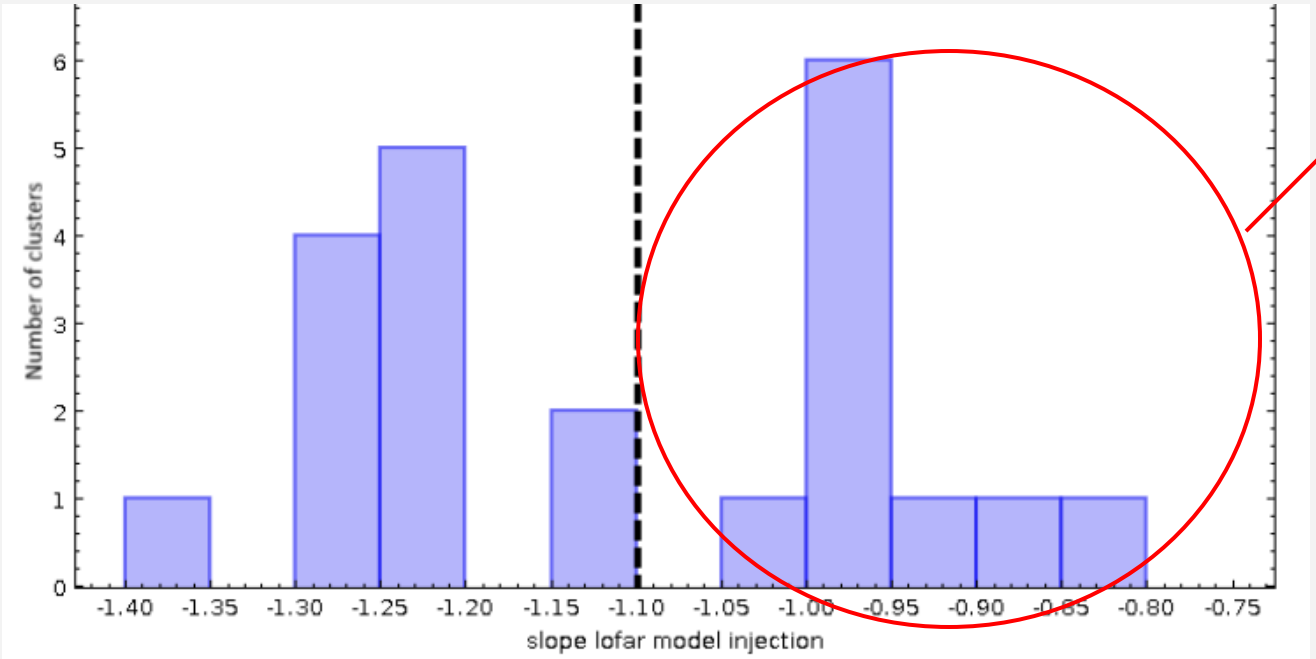


DISTRIBUTION OF SLOPE FOR THE SUBSAMPLE (22)

2σ regions



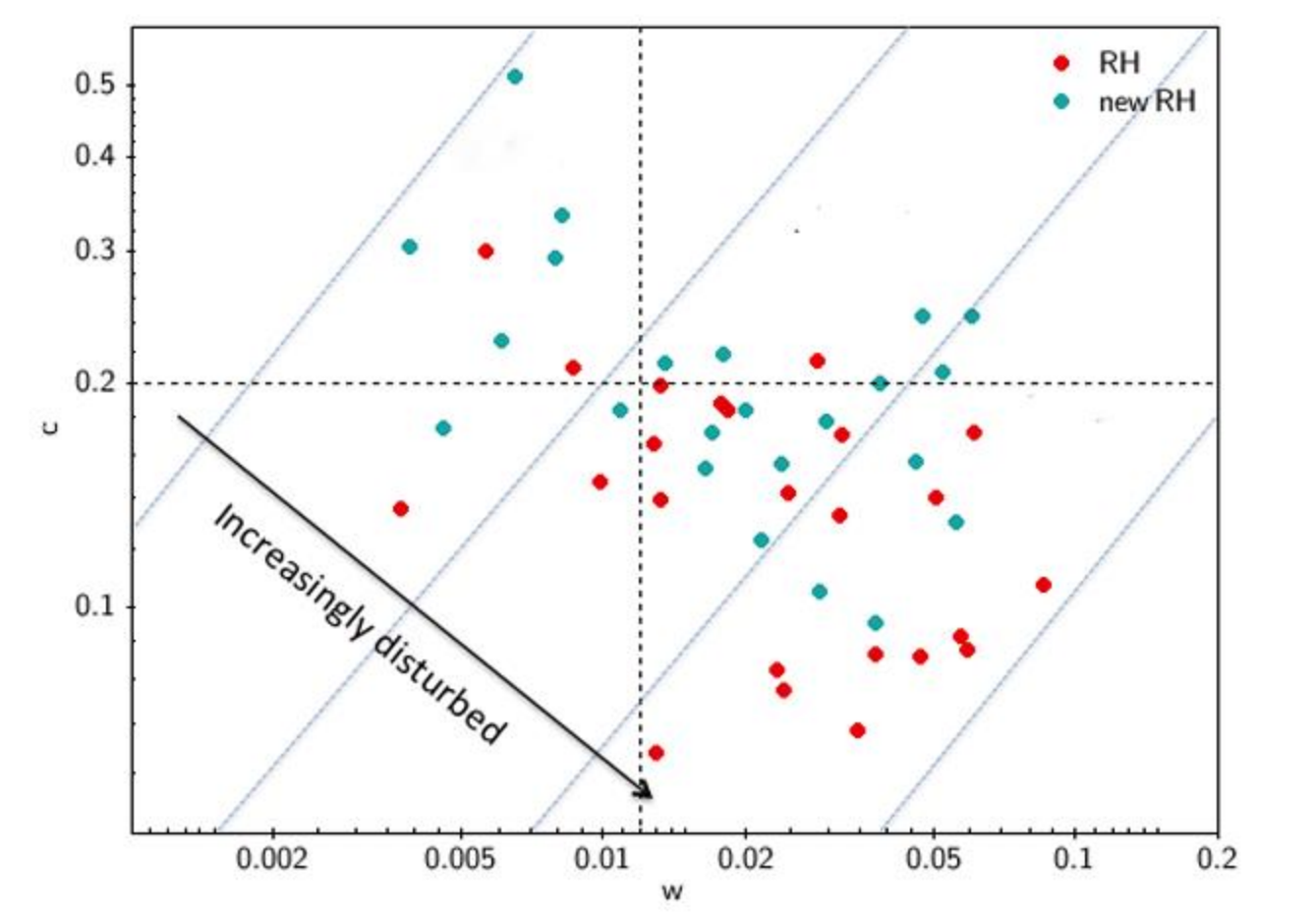
LOFAR MODEL INJECTION



- uGMRT radio halo fluxes found by injection of LOFAR model is higher than what is measured from observation.
- Slopes from the lofar model injection method is more promising as it is calculated between lofar flux and gmrt flux without any losses.

- Most of the halos detected in uGMRT suffers from a flux loss of ~10-15%.
- Flux loss increases for faint halos.

CORRELATION WITH CLUSTER DYNAMICS

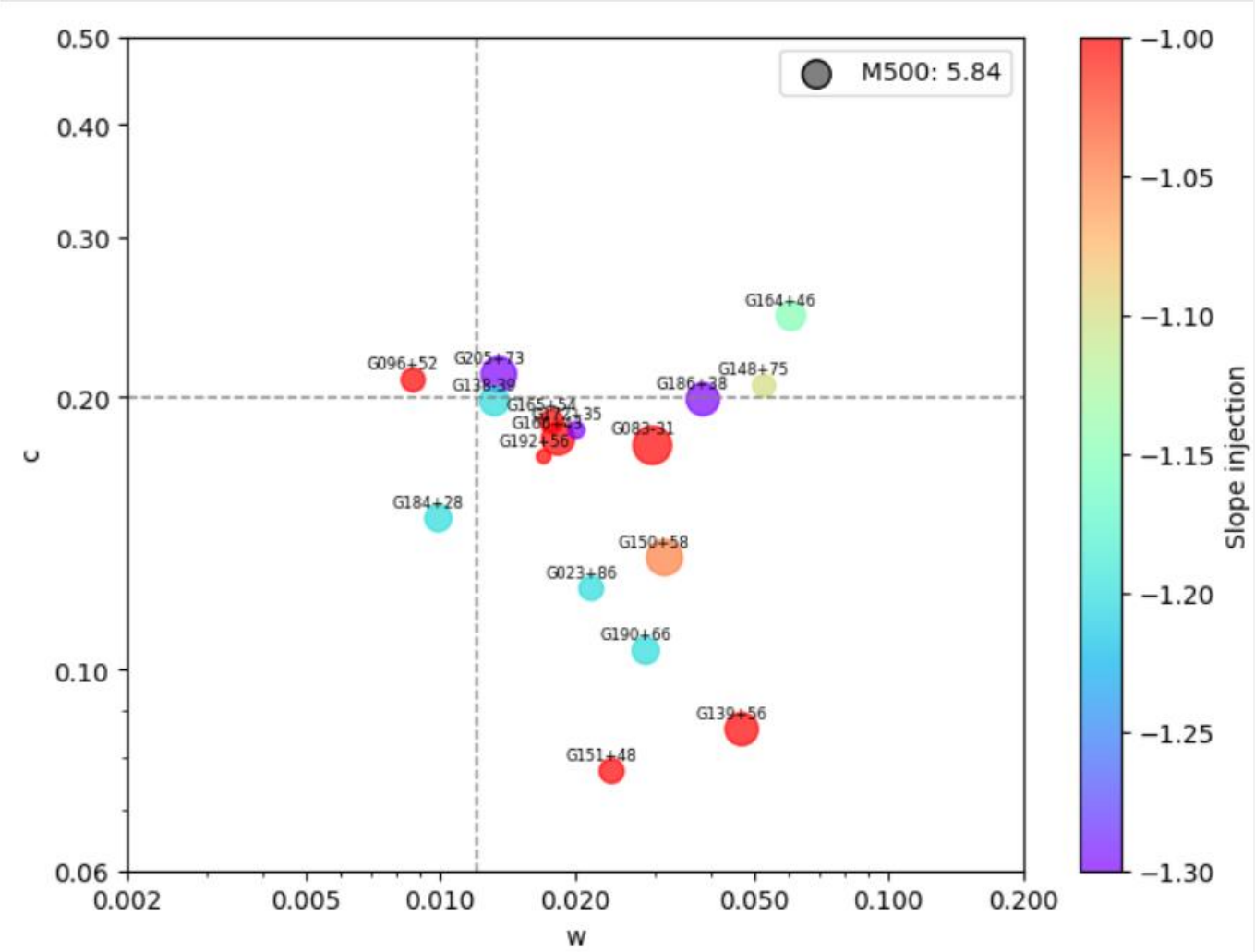


Cassano et al 2023

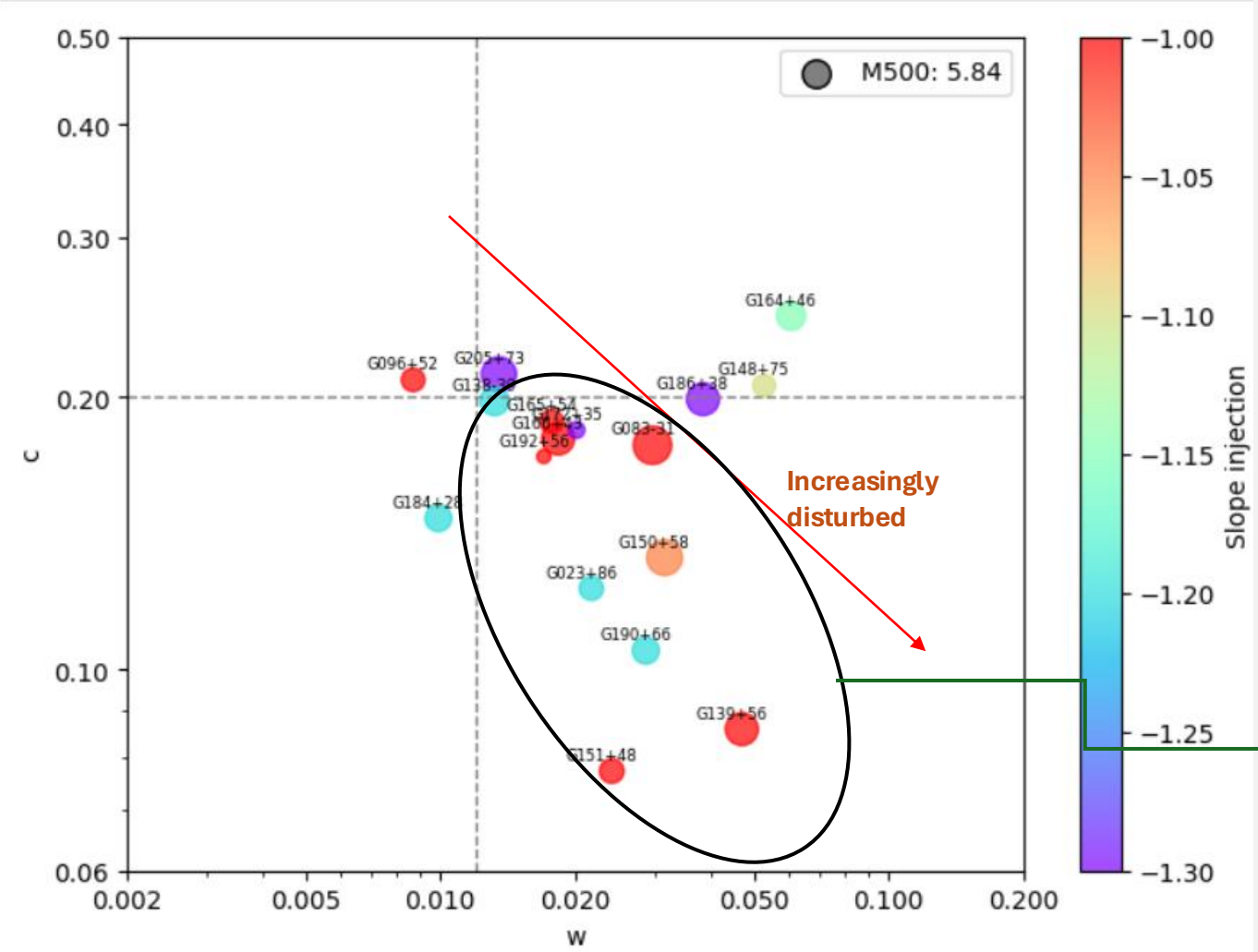
c – concentration parameter (if a cluster is cool core or non-cool core cluster) Santos et al 2008.

w – centroid shift (presence of substructures) Maughan et al 2008.

CORRELATION WITH CLUSTER DYNAMICS (22)



CORRELATION WITH CLUSTER DYNAMICS (22)



c – concentration parameter (if a cluster is cool core or non-cool core cluster) Santos et al 2008.

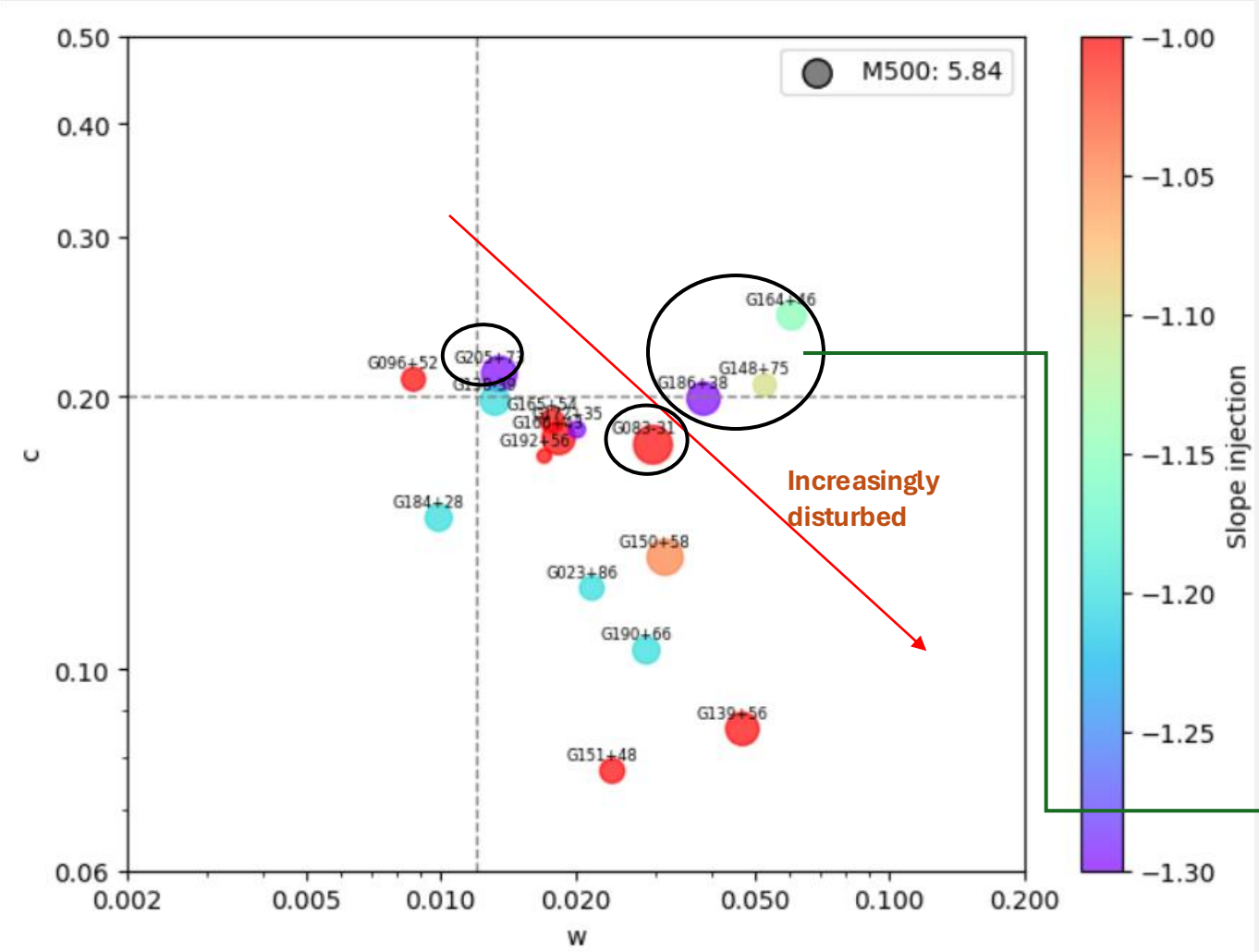
w – centroid shift (presence of substructures) Maughan et al 2008.

Slope – slope from injection measurements

- 17 out of 22 clusters in the sample have info about dynamical status as derived from the X-ray images

Most of the radio halos are in disturbed/merging clusters

CORRELATION WITH CLUSTER DYNAMICS (22)



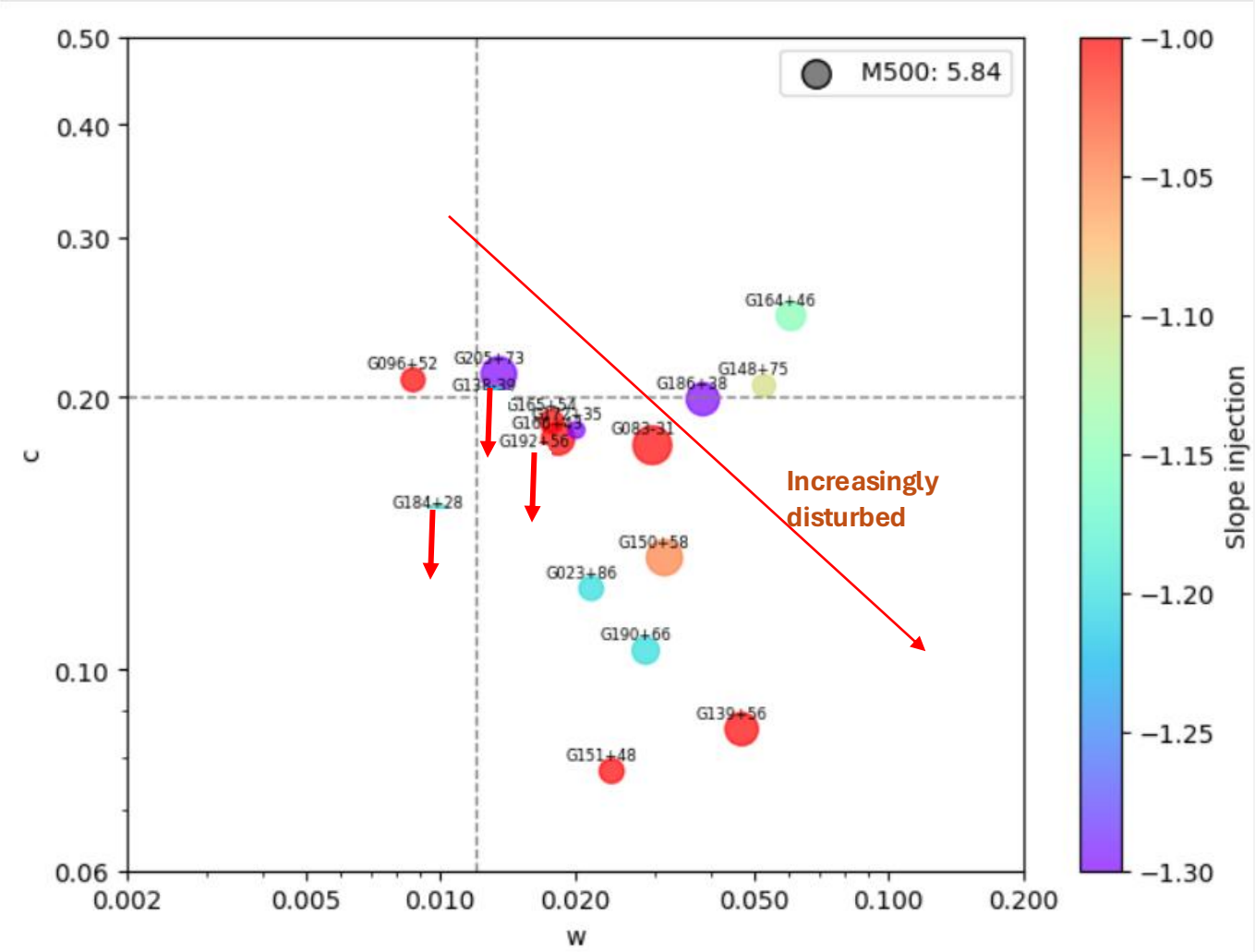
c – concentration parameter (if a cluster is cool core or non-cool core cluster) Santos et al 2008.

w – centroid shift (presence of substructures) Maughan et al 2008.

- 17 out of 22 clusters in the sample have info about dynamical status as derived from the X-ray images

These halos reside in more relaxed clusters and exhibit a steep spectral index.

CORRELATION WITH CLUSTER DYNAMICS (22)



FOR CLUSTERS WITHOUT RADIO HALO IN uGMRT

- Among the 4 clusters without radio halo in uGMRT, 3 clusters have X-ray data.
- The slope values in the plot represents the upper limit found during Lofar model injection .
  - *G184+28 (Mini halo, relaxed cluster)* - α = -1.2
  - *G192+56 (lowest mass cluster in my subsample)* - α = -1 (uGMRT was not sensitive)
  - G138-39 *(The halo was also not detected in EGRHS)*- *α = -1.2*
  - *G183+34* - *α = -1.3 (cRH, same upper limits even with exponential models)*

SUMMARY

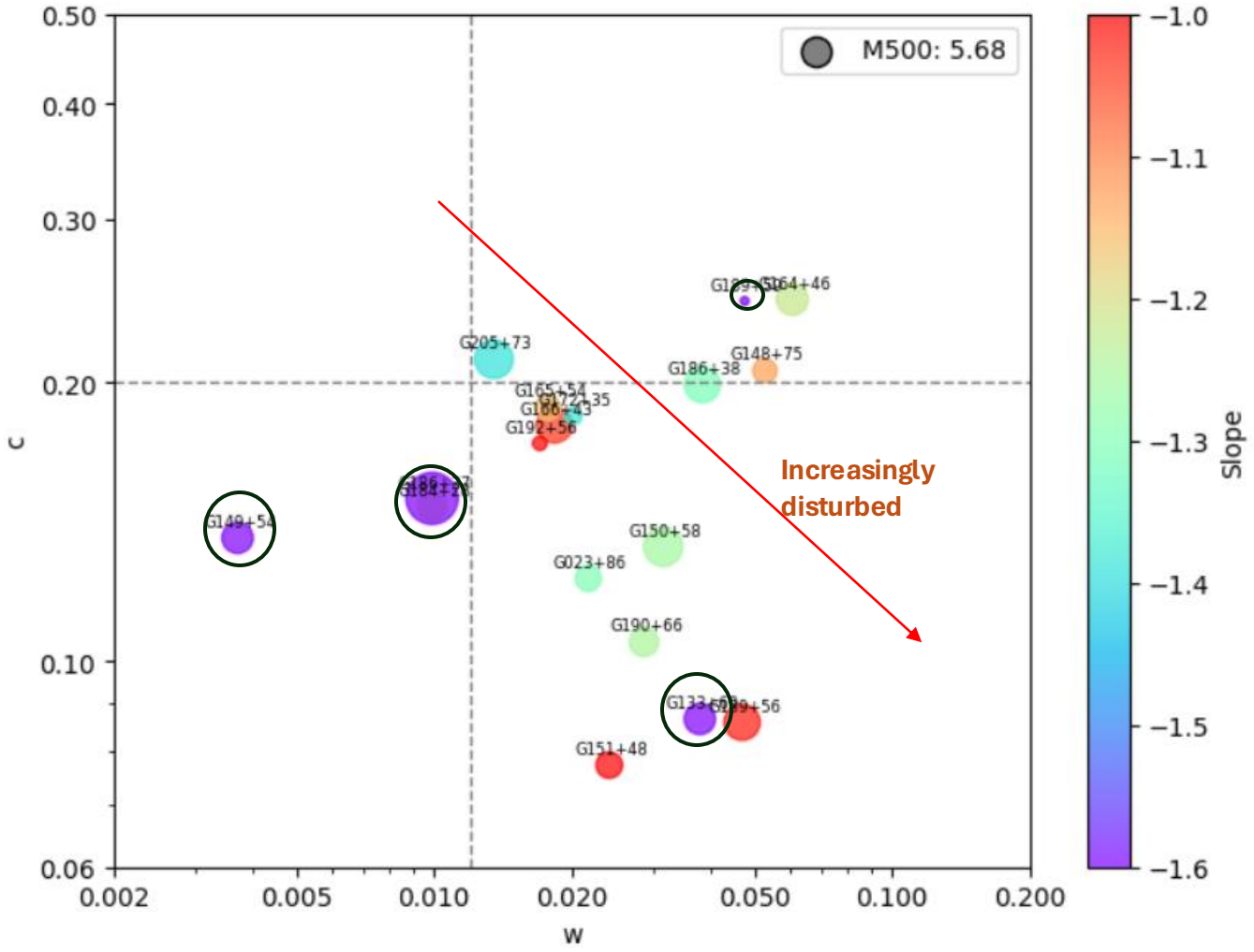
First study on a complete sample about the spectral properties of radio halos.

Completing the entire sample will help constrain the origin/model of radio halos effectively.

Complement the analysis of radio halos with future SKA-low surveys where we expect to see "more RHs".

Backup slides

CORRELATION WITH CLUSTER DYNAMICS



FOR CLUSTERS WITH ARCHIVAL SPECTRAL INFORMATION

- *G186+37 (A697)* - α = -1.7 (GMRT + VLA)
- *G189+59 (A1033)* - α = -1.65 (LOFAR + GMRT)
- *G149+54 (A1132)* - α = -1.75 (LOFAR + GMRT)
- *G133+69 (A1550)* - *α = -1.6 (LBA+HBA+GMRT+JVLA)*

detailed analysis needs to be carried out !!

Backup slides

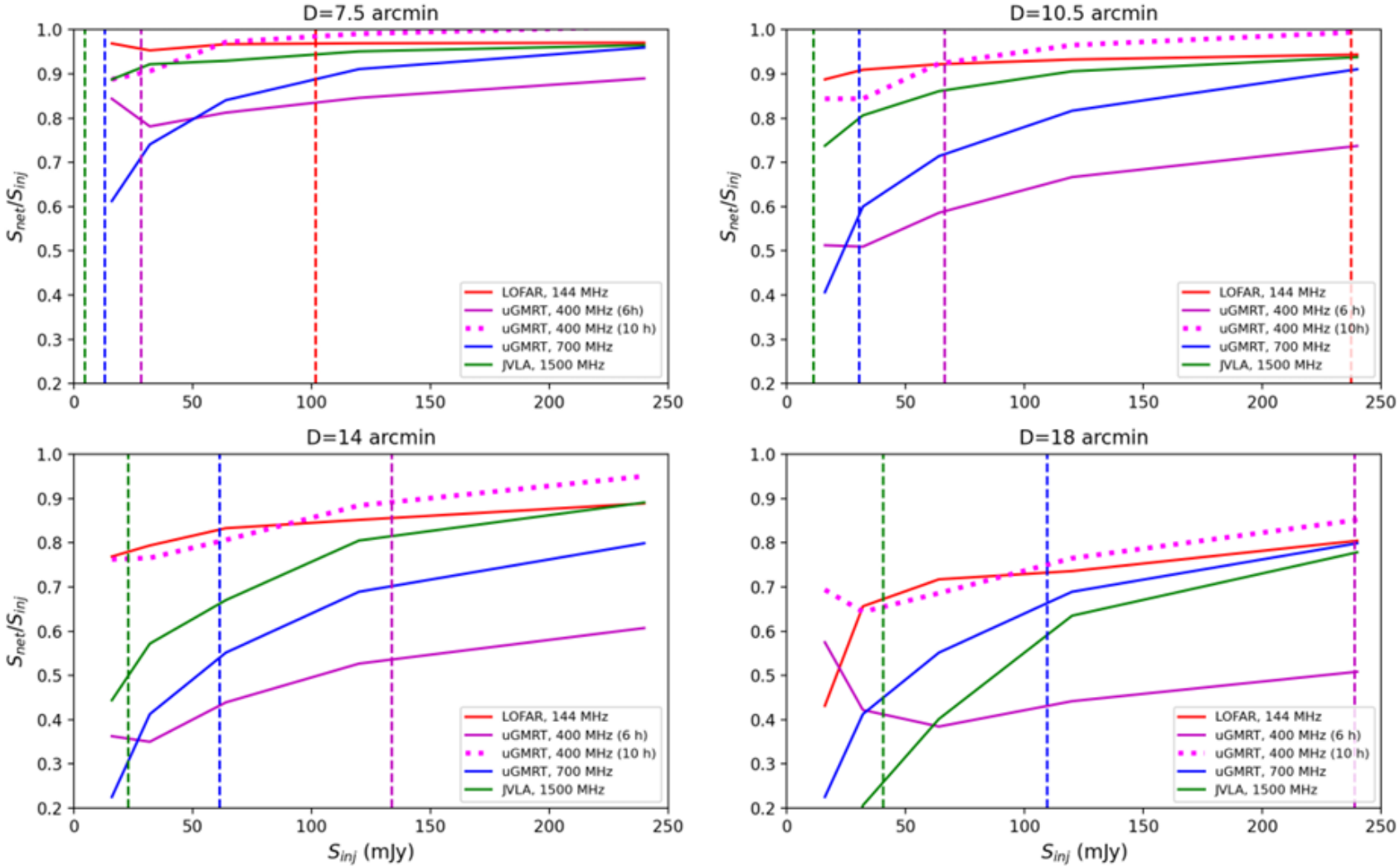
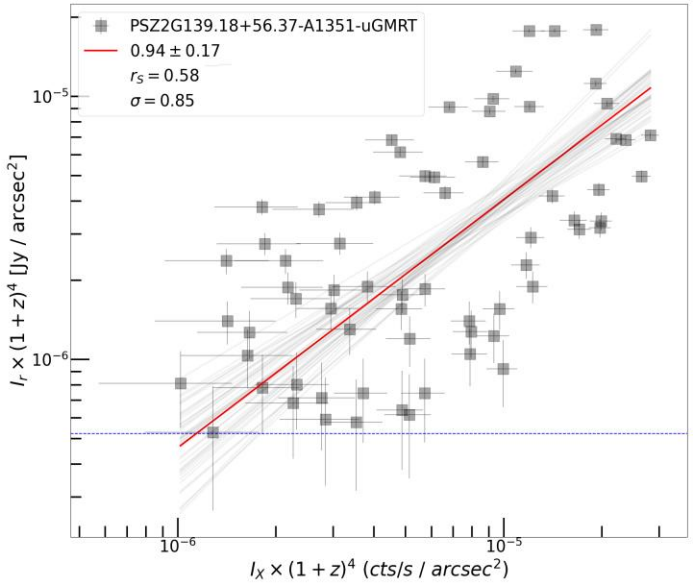
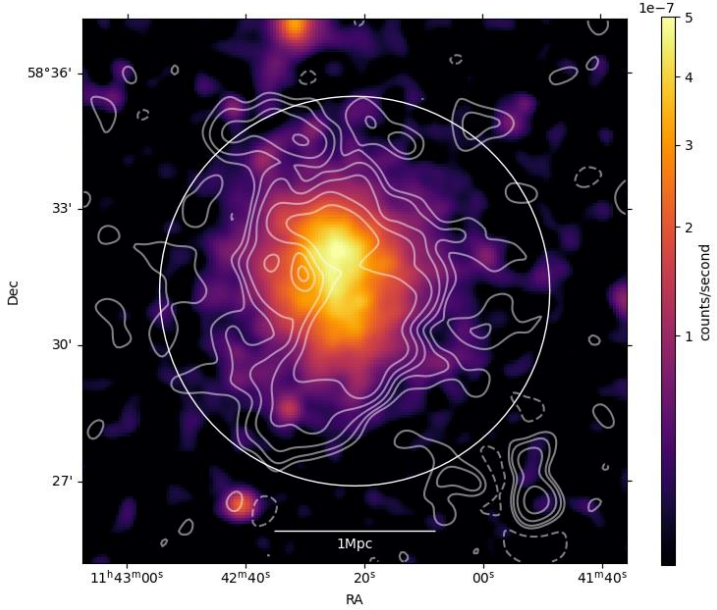
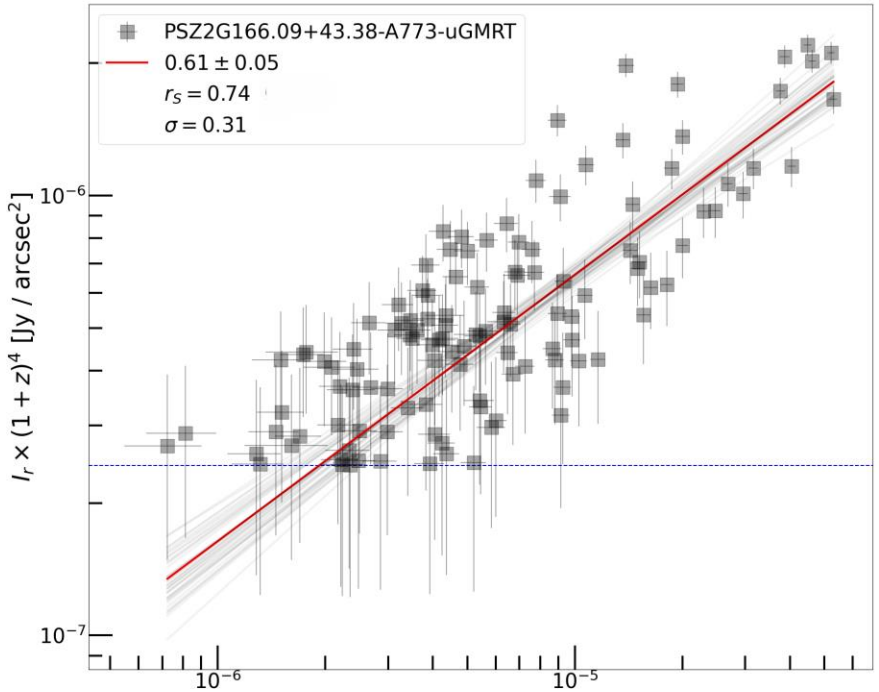


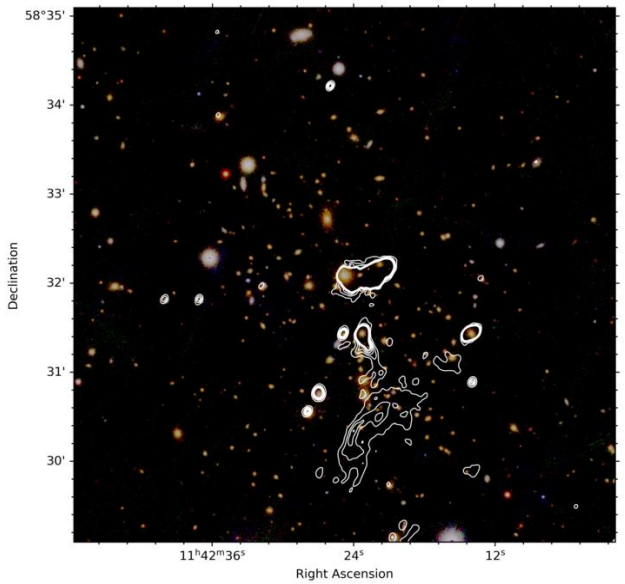
Fig. 14. Recovered net flux density as a function of the injected flux density for various angular diameters and instruments. Red, magenta, blue, and green curves are injections in LOFAR (HBA at 144 MHz), uGMRT (band 3 at 400 MHz, 6 and 10 h on source are shown with solid and dotted lines, respectively), uGMRT (band 4 at 700 MHz), and JVLA (DnC+BnC array, *L* band at 1.5 GHz) datasets, respectively. The expected flux density integrated up to $3r_c$ of a representative radio halo with $M_{500} = 5 \times 10^{14}\ M_\odot$ is indicated by a dashed vertical line and can be exploited to estimate effective losses (see Table 3 and discussion in Sect. 6).

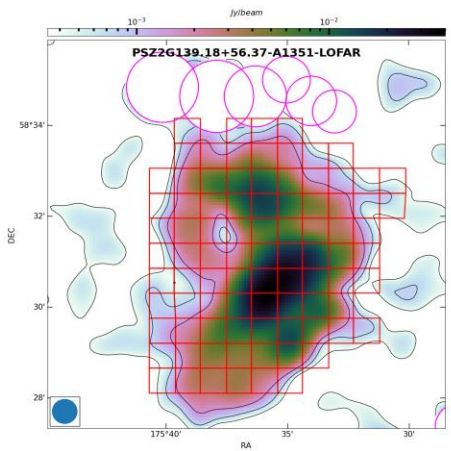
Backup slides

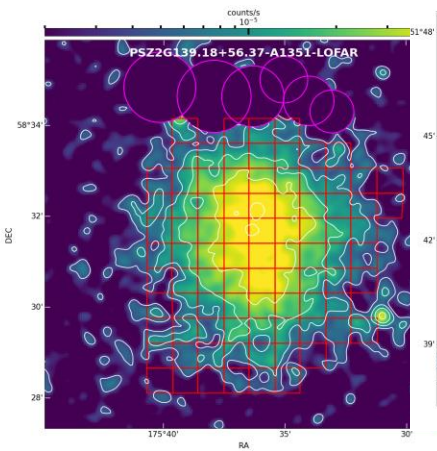


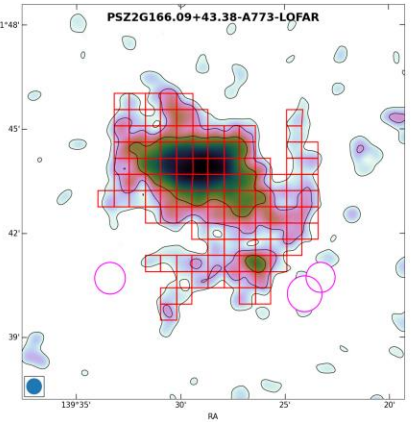


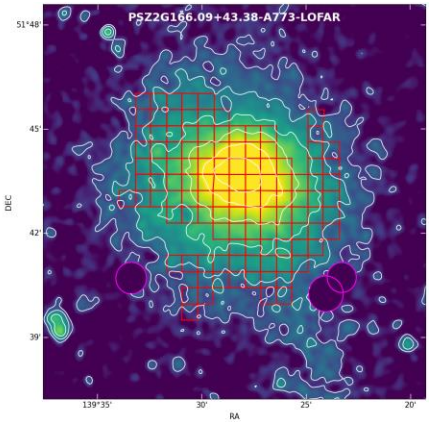












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