



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

LOFAR ANNUAL MEETING

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Supervisors

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PhD cycle 39 (A.Y 2023-2026)

IRA-INAF BOLOGNA

FOCUS OF THE TALK

- 1. Statistics of Spectral properties of RHs**
- 2. A rare double halo emission in A2069**

RADIO HALOS IN GALAXY CLUSTERS

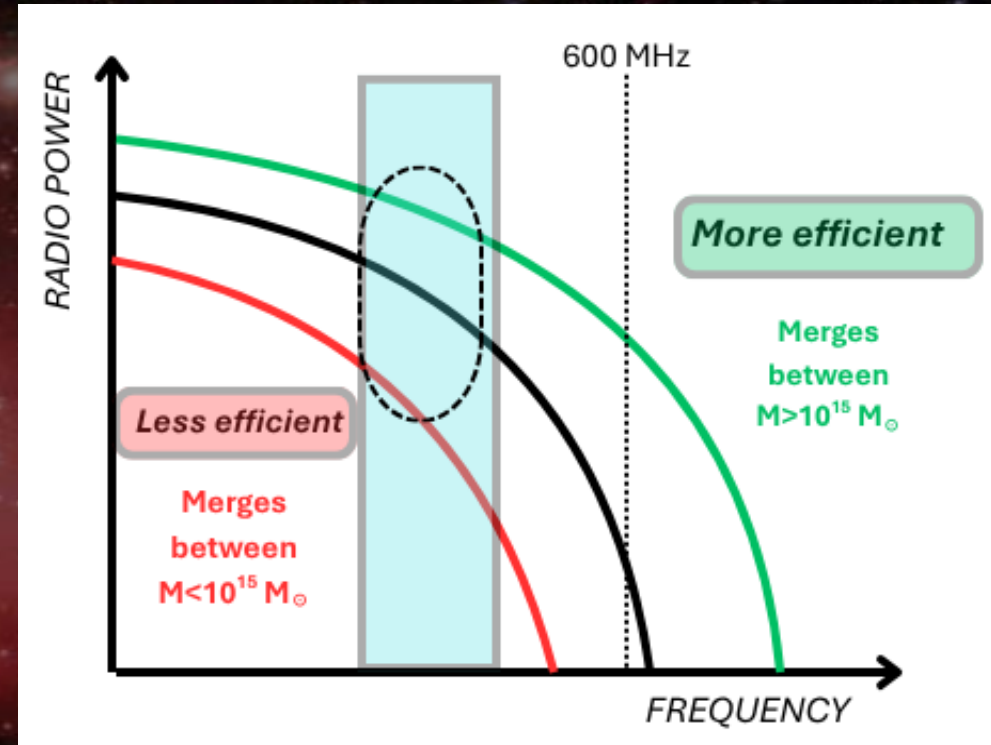
RADIO HALOS

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

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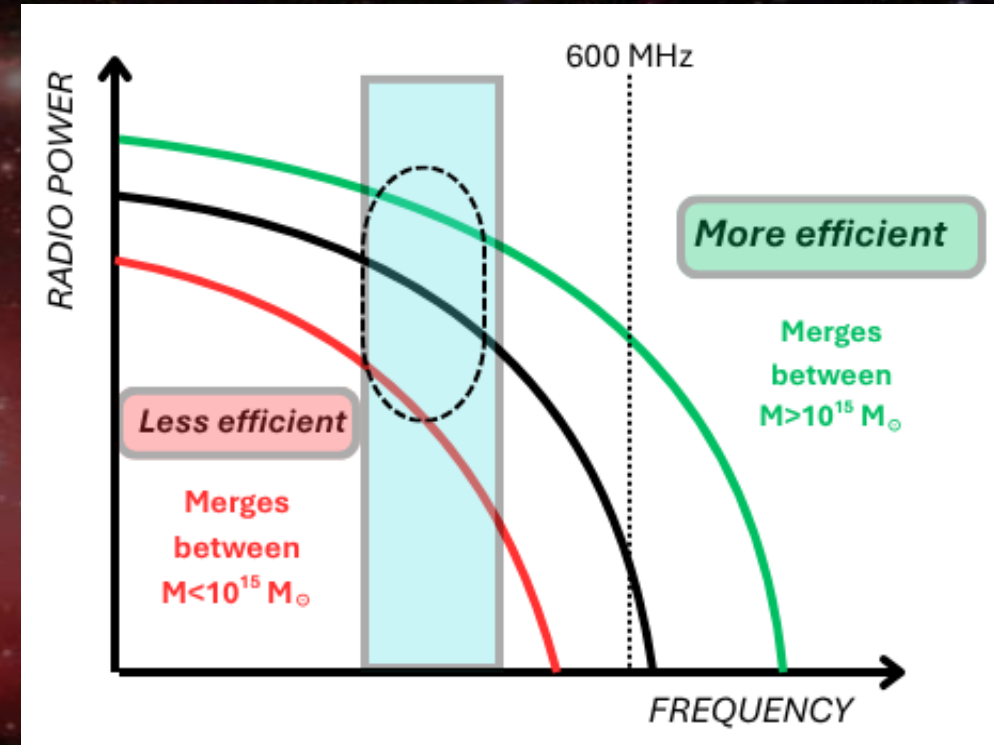
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Turbulence by merging of clusters of galaxies (Fermi II)

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- Mass of the merging clusters

Expectations (model)

- Low steepening frequency - Steeper spectral index
- Brighter at lower frequency regime



RADIO HALOS

Diffuse, ~ Mpc Unpolarised synchrotron radio sources

Origin -

Turbulence by merging of clusters of galaxies (Fermi II)

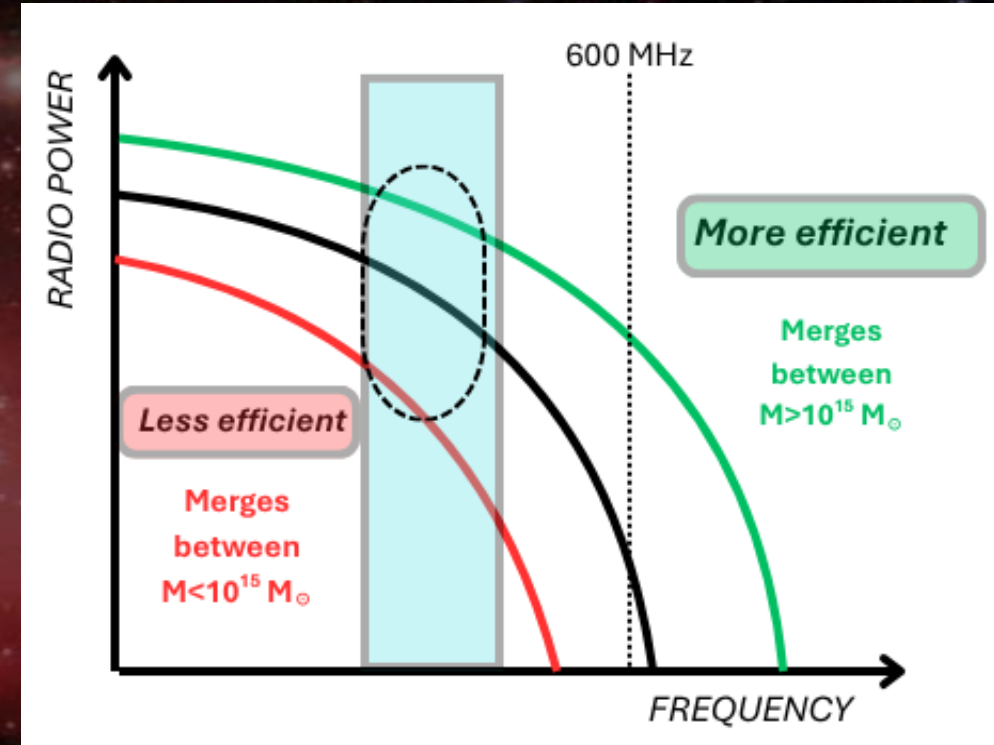
- Turbulent energy
- Mass of the merging clusters

Expectations (model)

- Low steepening frequency - Steeper spectral index
- Brighter at lower frequency regime

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

MODEL EXPECTATIONS

309 clusters



164 clusters

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

UNVEILING THE SPECTRAL PROPERTIES BY LOFAR-uGMRT

MODEL EXPECTATIONS

309 clusters



164 clusters



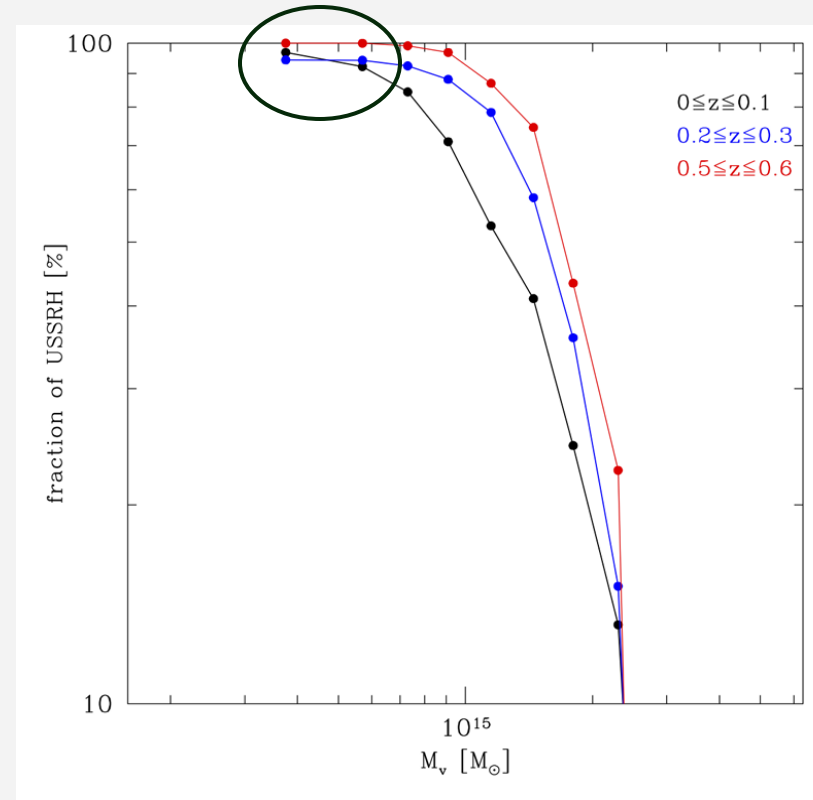
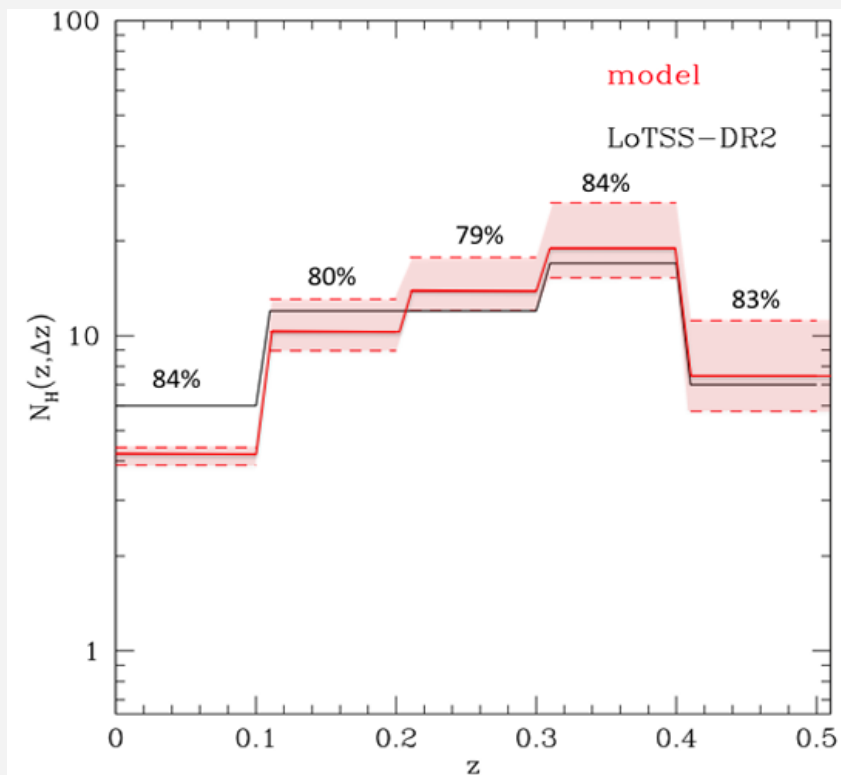
Statistics of radio haloes and reacceleration model (Cassano et al 2023)



Main outcomes

USSRH irrespective of the Z , RHs increases with cluster M , most of the RHs in disturbed system

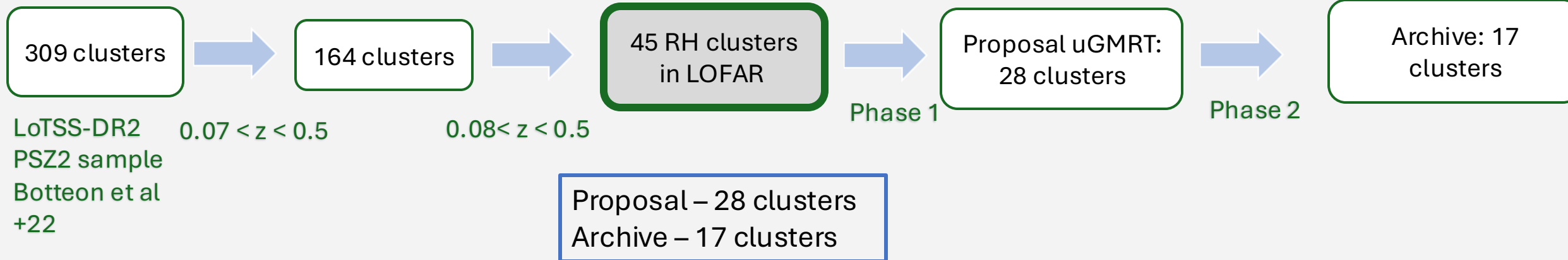
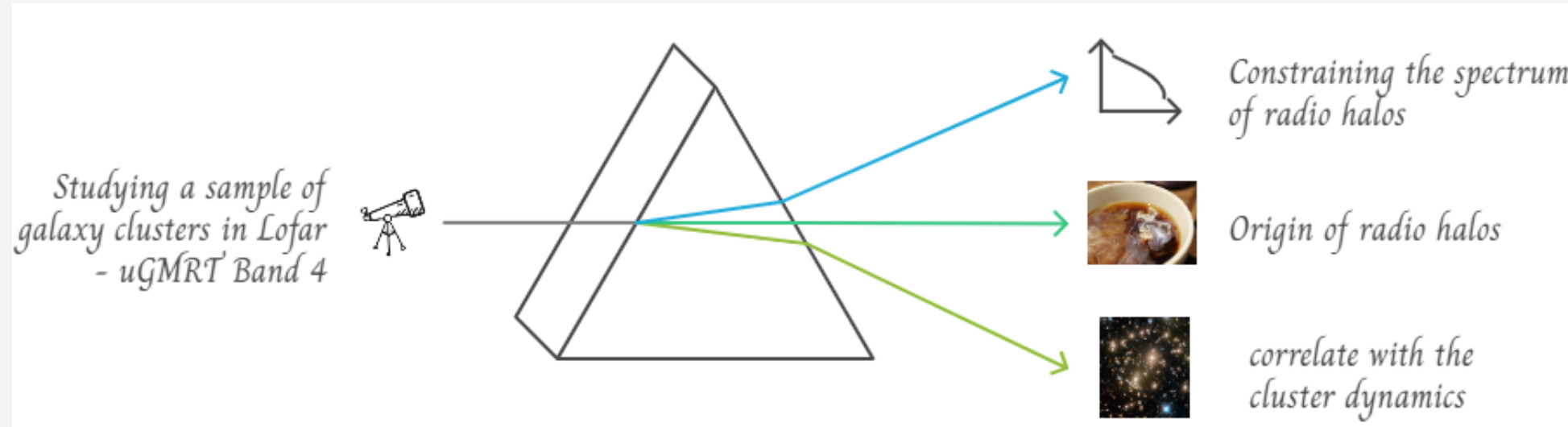
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Cassano et al 2023

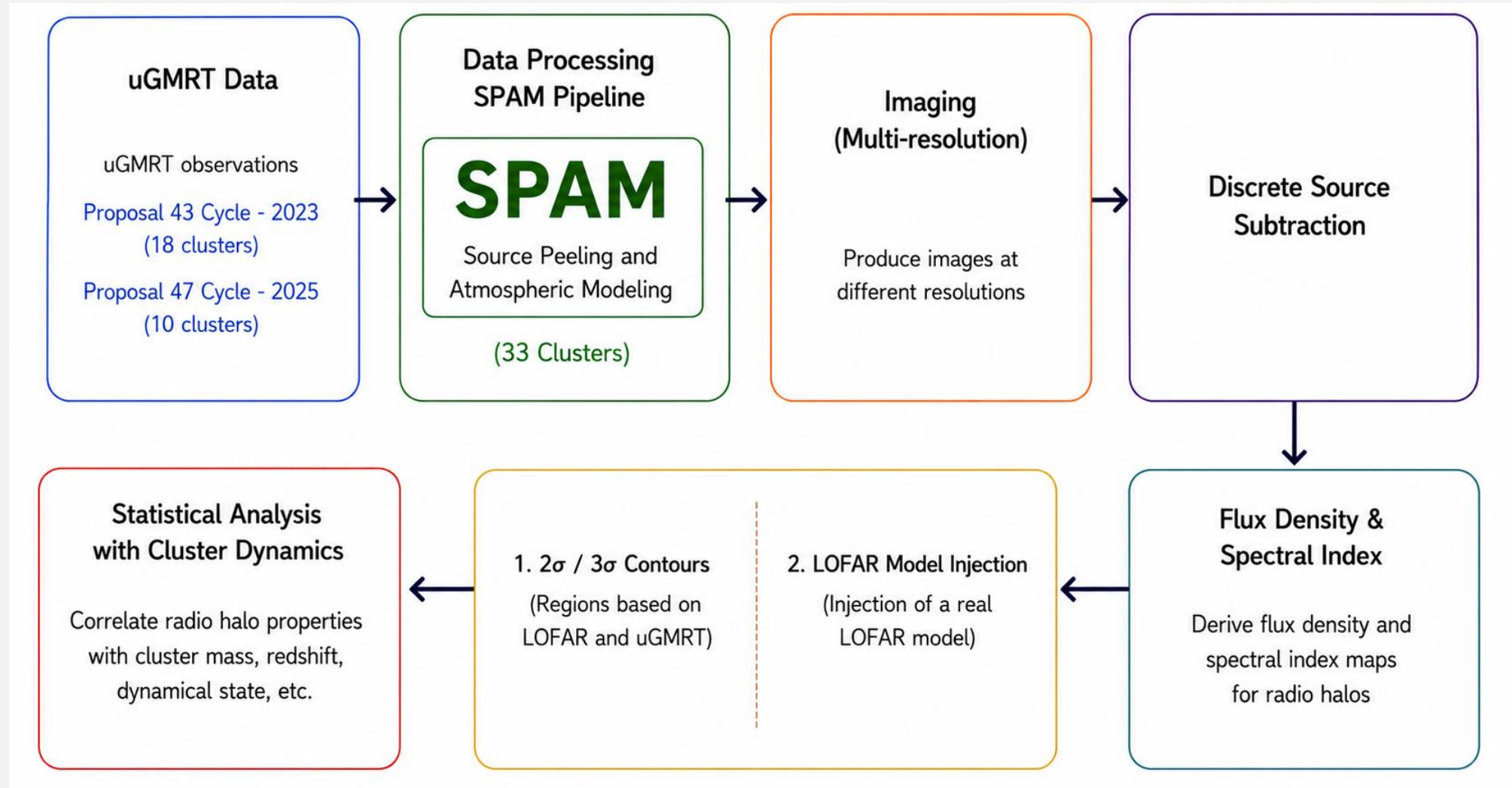
UNVEILING THE SPECTRAL PROPERTIES BY LOFAR-uGMRT

MY PhD WORK - MOTIVE



PROGRESS

PROGRESS

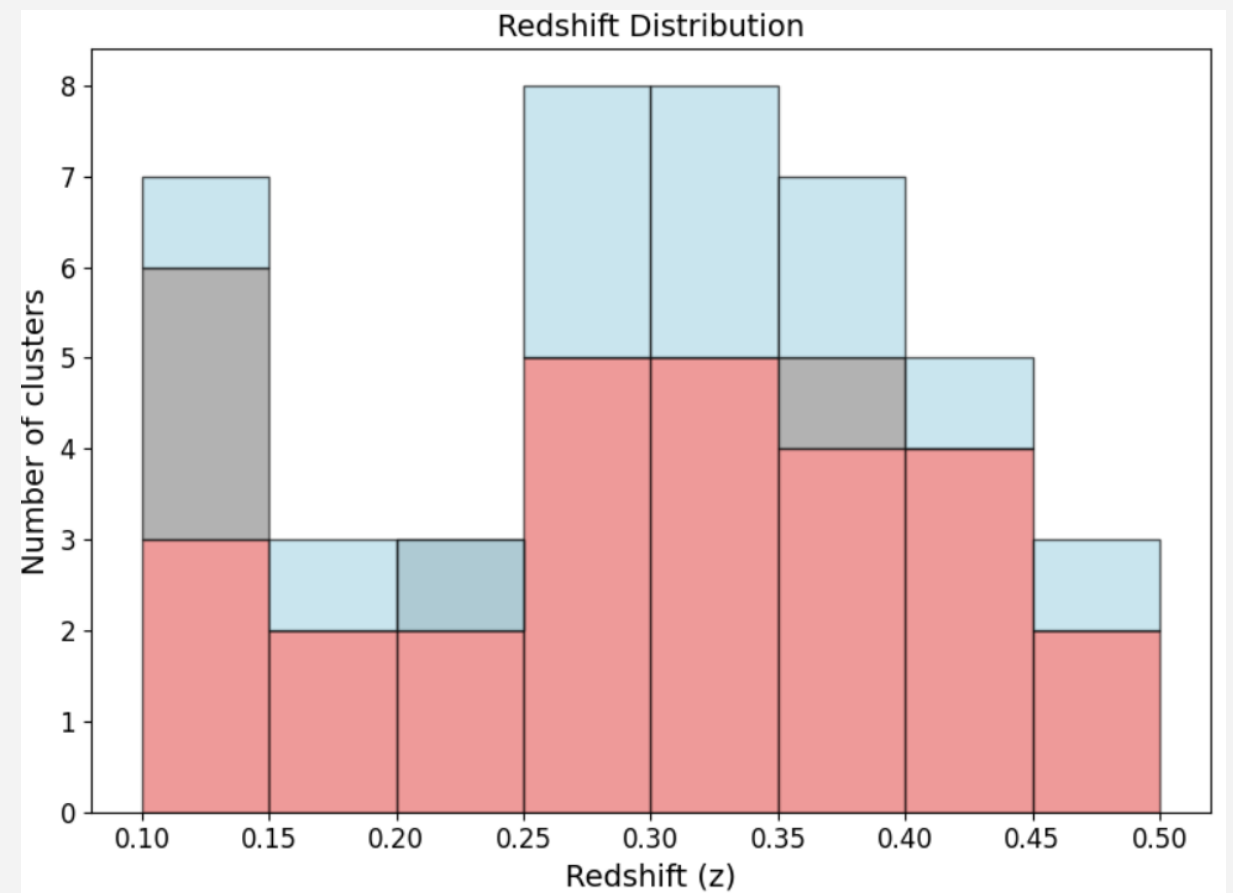
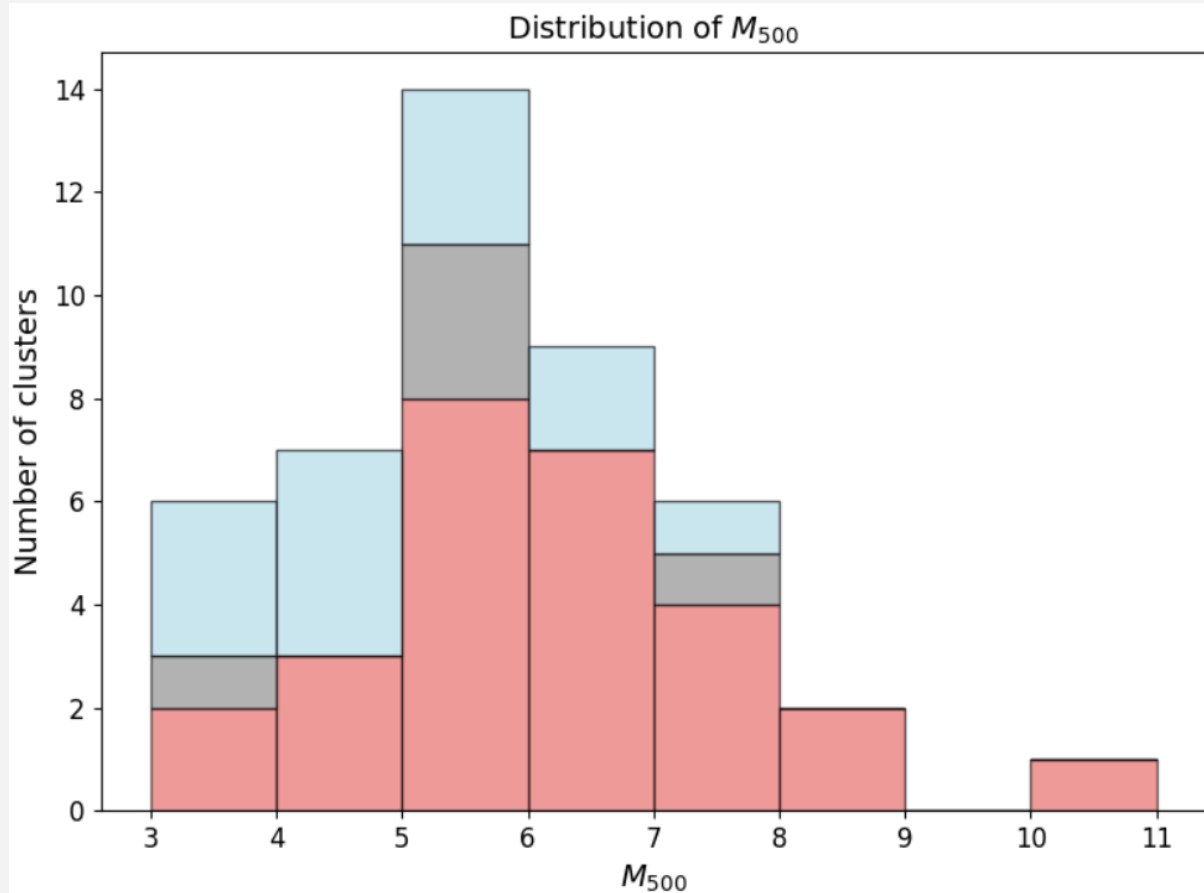


- 6/33 clusters – unsuccessful α measurement

- 27+5 (literature spectral index) = 32 clusters

STATISTICAL ANALYSIS OF THE SAMPLE

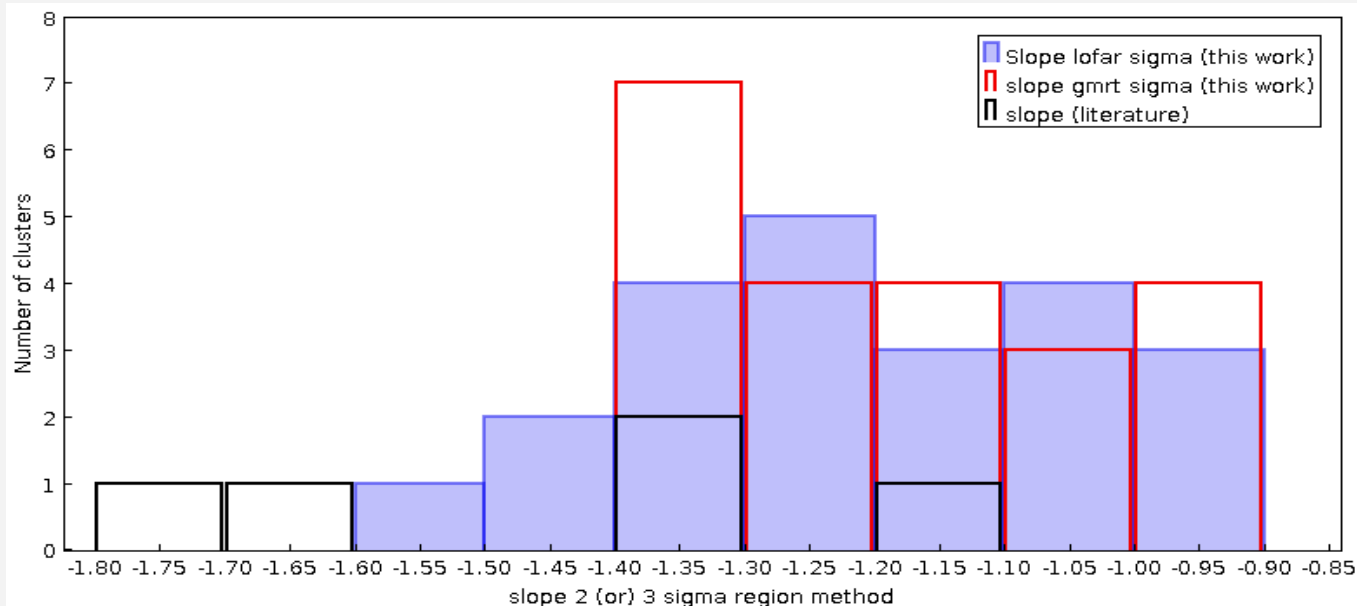
DISTRIBUTION OF MASS AND REDSHIFT



- 27 clusters (this work)
- 5 clusters (literature)
- Remaining clusters

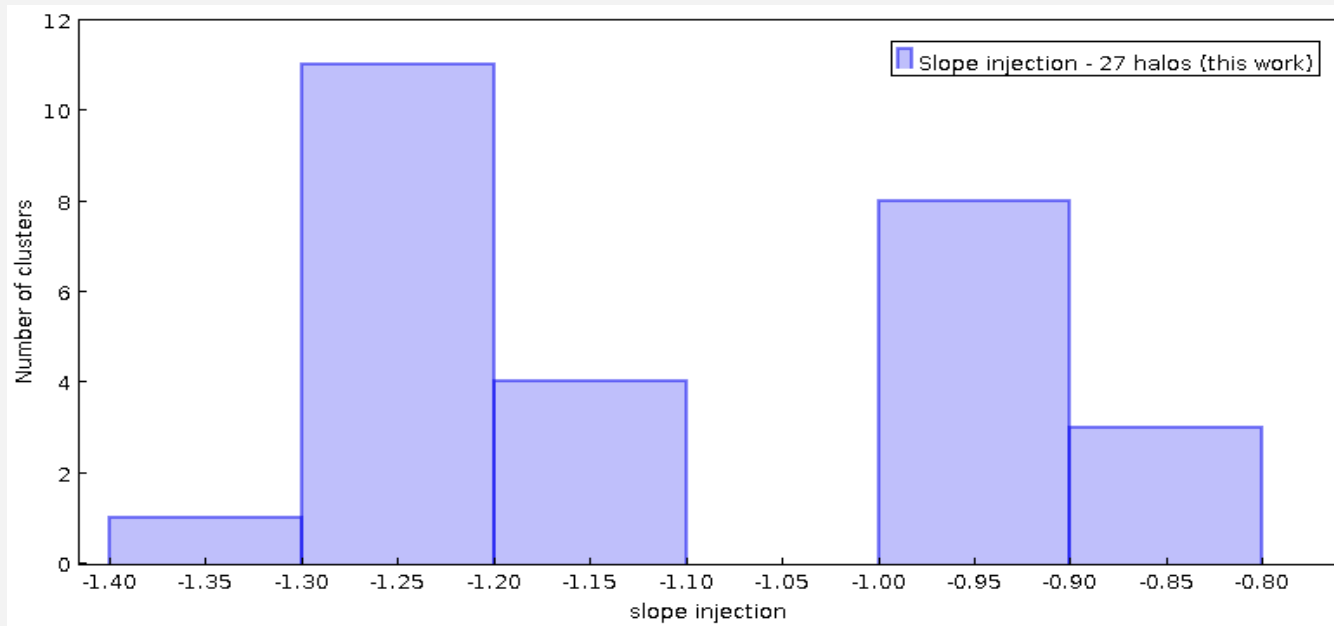
DISTRIBUTION OF SLOPE FOR THE SUBSAMPLE

2 or 3 σ region method + lit values



- 5 clusters I did not detect the halo in uGMRT – Upper limit.
- Lofar 2 σ might cover larger regions giving a steeper slope !

LOFAR MODEL INJECTION

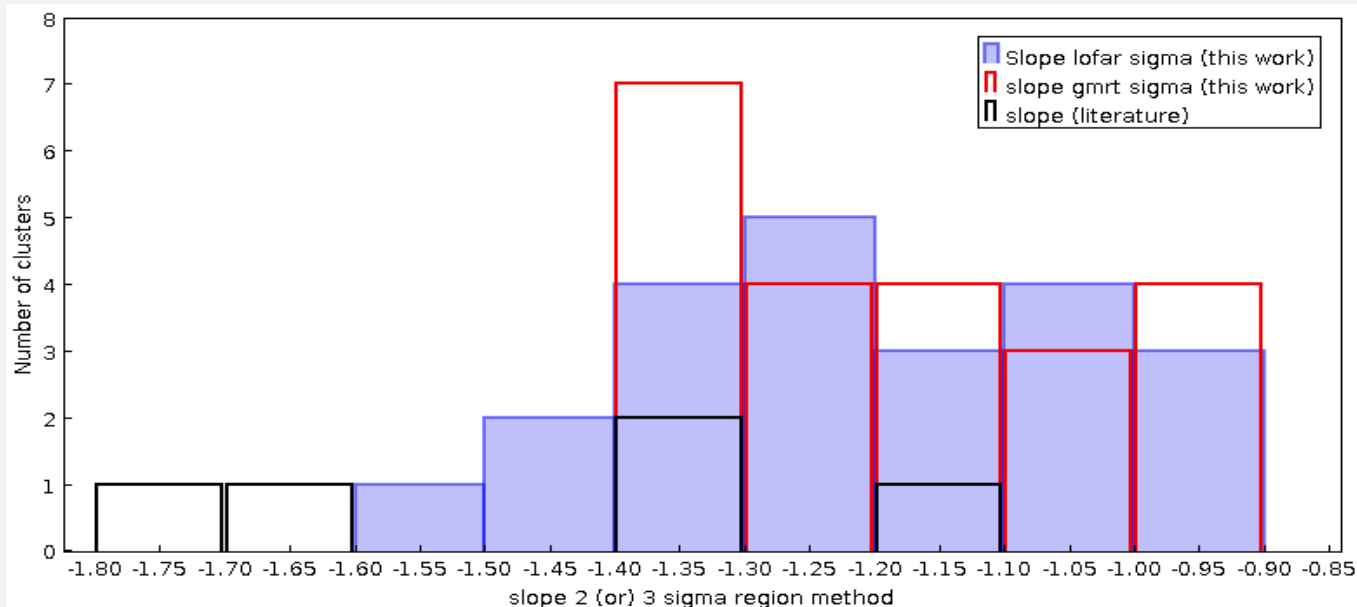


Literature spectral values available for clusters from the sample:

- A2034 ($\alpha=1.6$; Bonafede et al. in prep; LOFAR HBA - UHF)
- A1033 ($\alpha=1.65$; Edler et al. 2022; LOFAR LBA - HBA)
- A1132 ($\alpha=1.75$; Wilber et al. 2017; LOFAR - GMRT B3)
- A1550 ($\alpha=1.4$; Pasini et al. 2022, LOFAR - uGMRT B4)
- PSZ2G113.91-37.01 ($\alpha=1.13$; Campitiello et al 2024, LOFAR HBA- uGMRT B4)

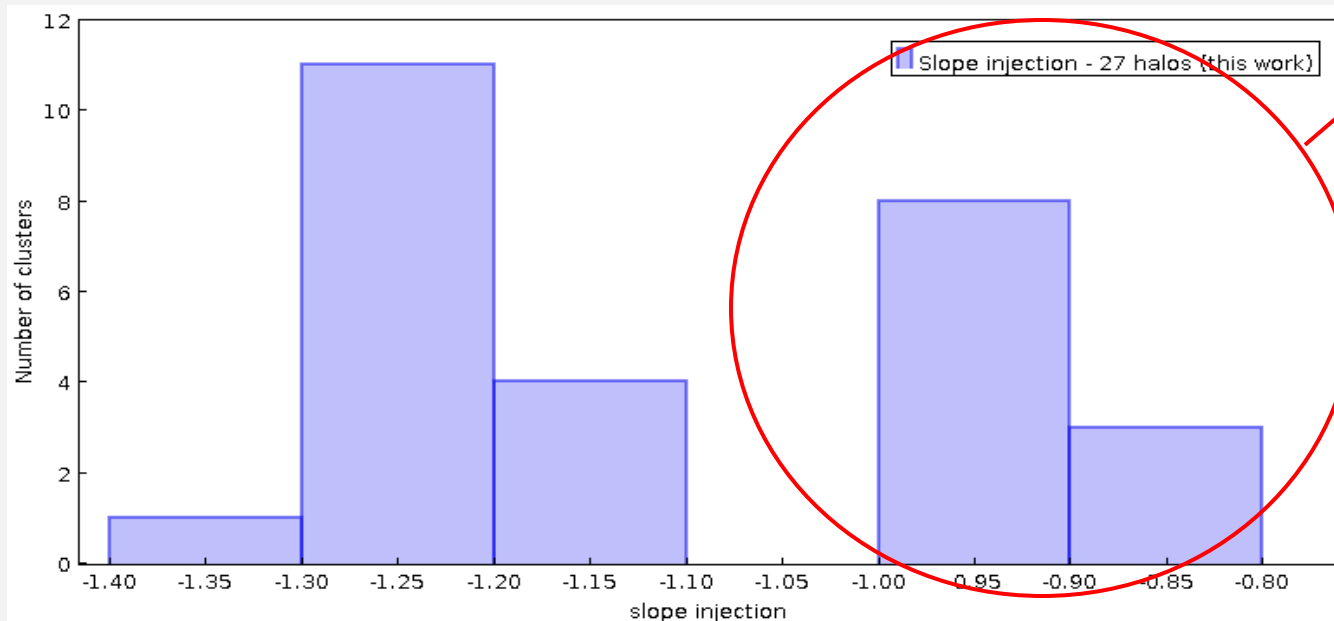
DISTRIBUTION OF SLOPE FOR THE SUBSAMPLE (27)

2 or 3σ region method + lit values



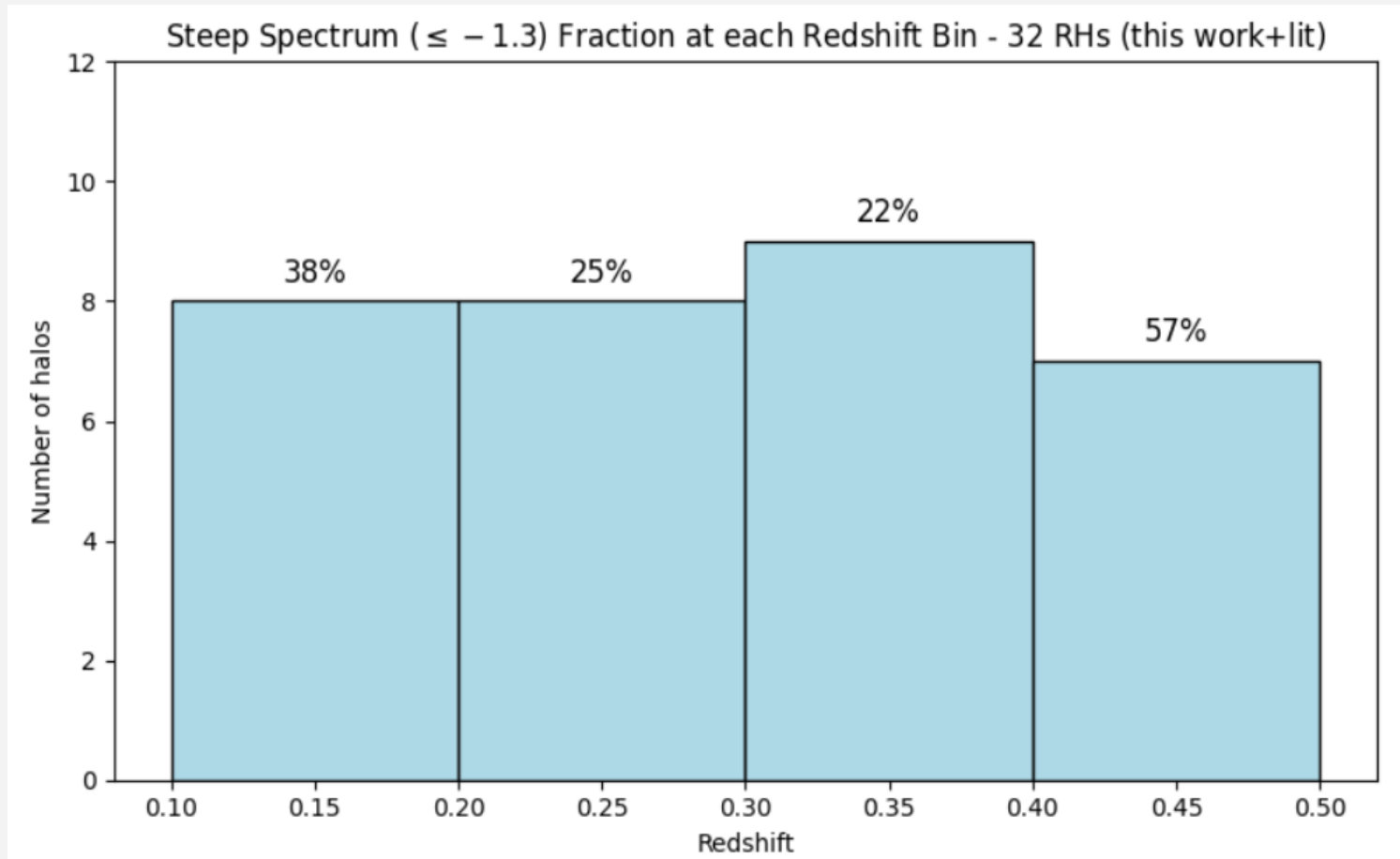
- uGMRT radio halo fluxes found by injection of LOFAR model is higher than what is measured from observation.
- Slopes from the lofar model injection method is more promising as it is calculated between lofar flux and gmrt flux without any losses.

LOFAR MODEL INJECTION

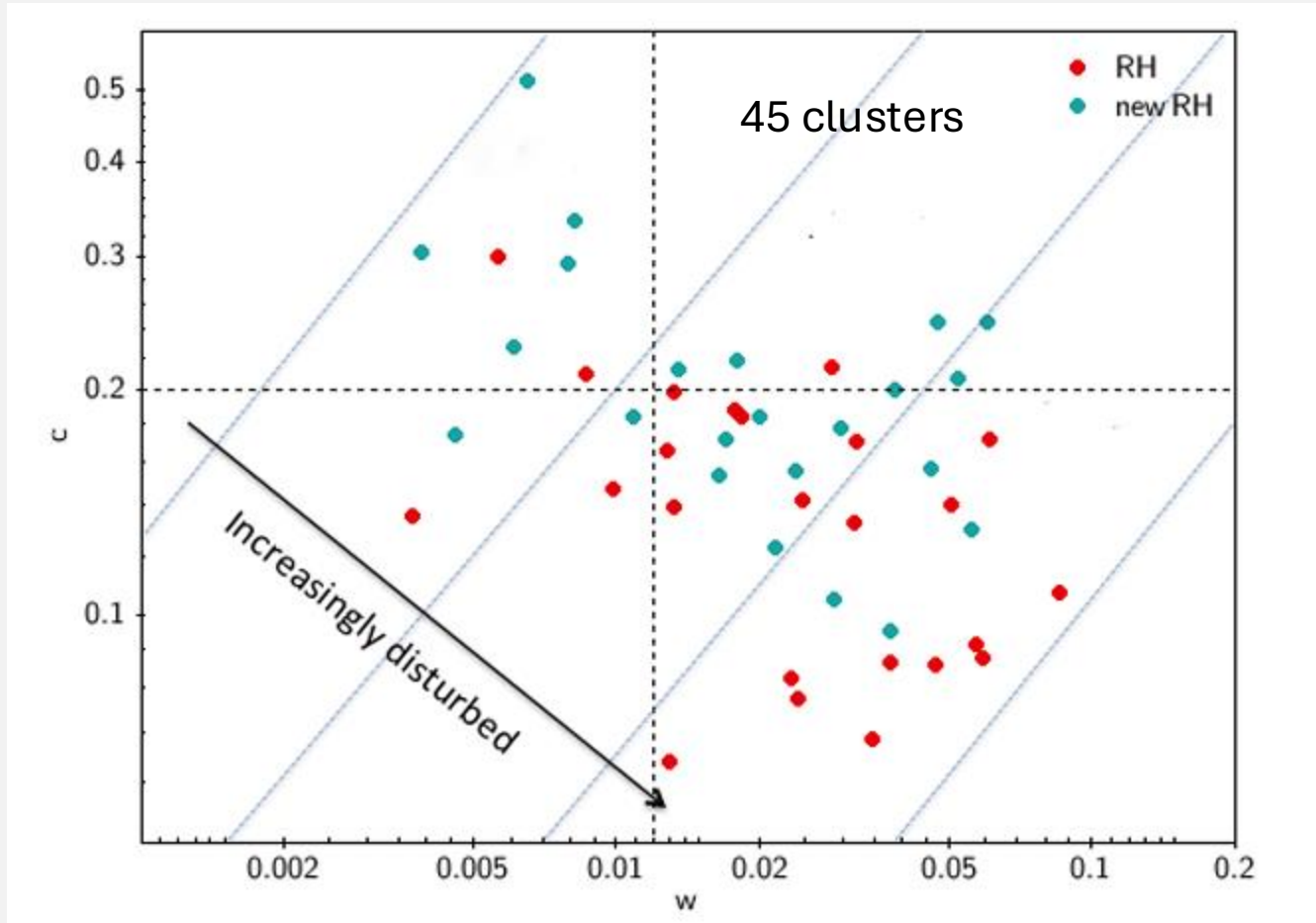


- Most of the halos detected in uGMRT suffers from a flux loss of ~15-20%.
- Flux loss increases for faint halos.

Fraction of steep spectra RHs in redshift bins



CORRELATION WITH CLUSTER DYNAMICS

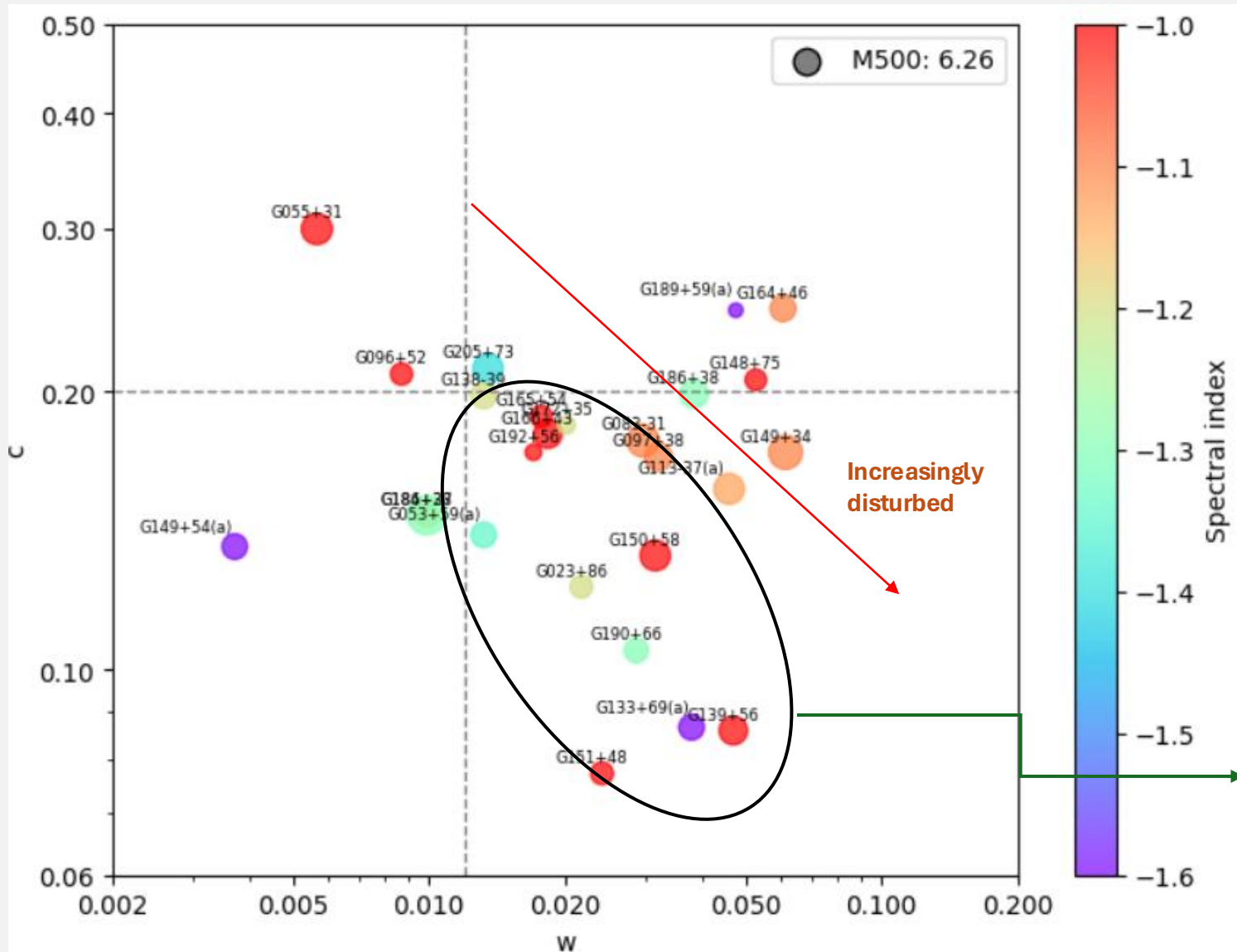


Cassano et al 2023

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



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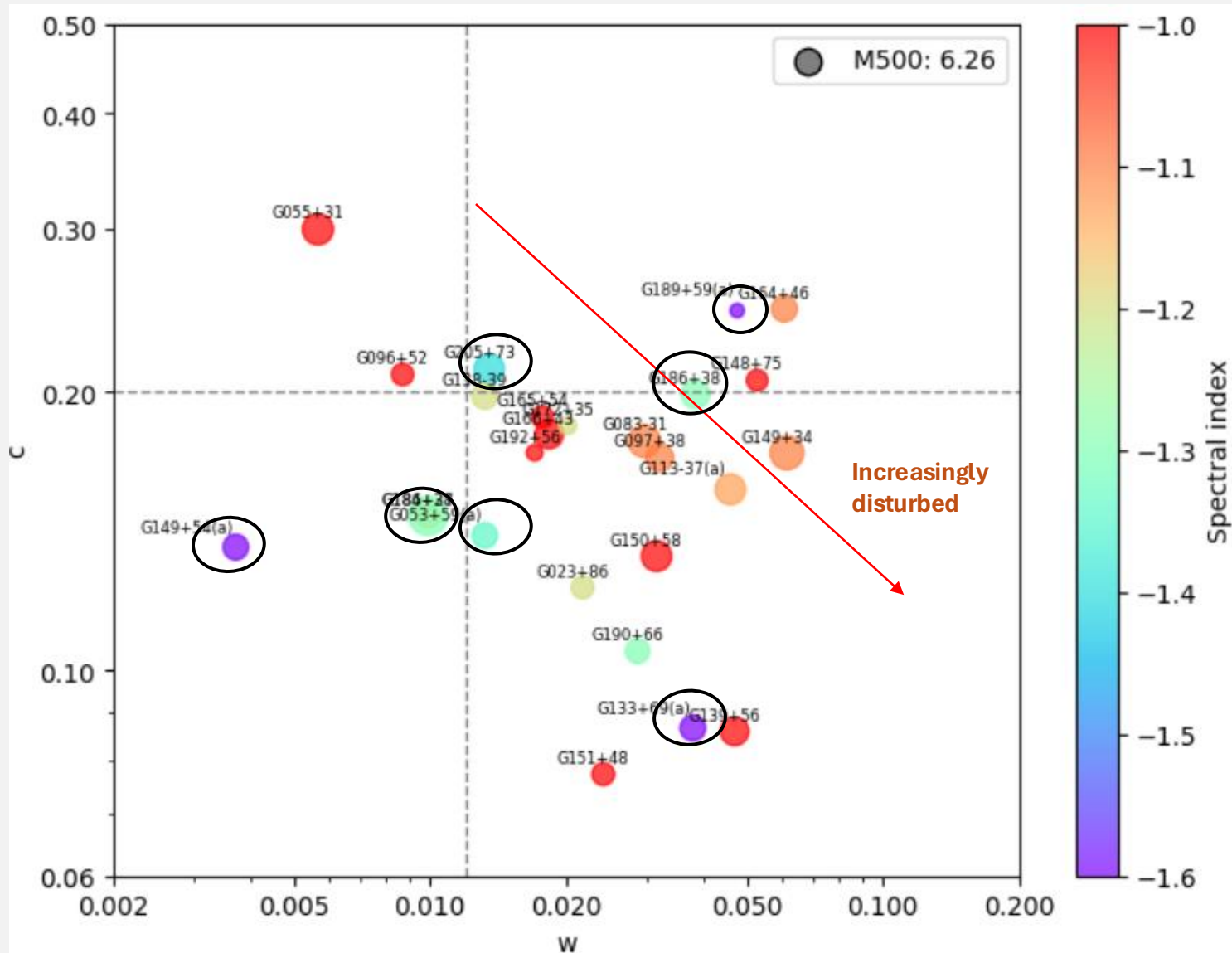
w – centroid shift (presence of substructures) Maughan et al 2008.

Slope – slope from injection measurements

- 26/32 clusters have dynamical info from X-rays

Most of the radio halos are in disturbed/merging clusters have flat α

CORRELATION WITH CLUSTER DYNAMICS



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

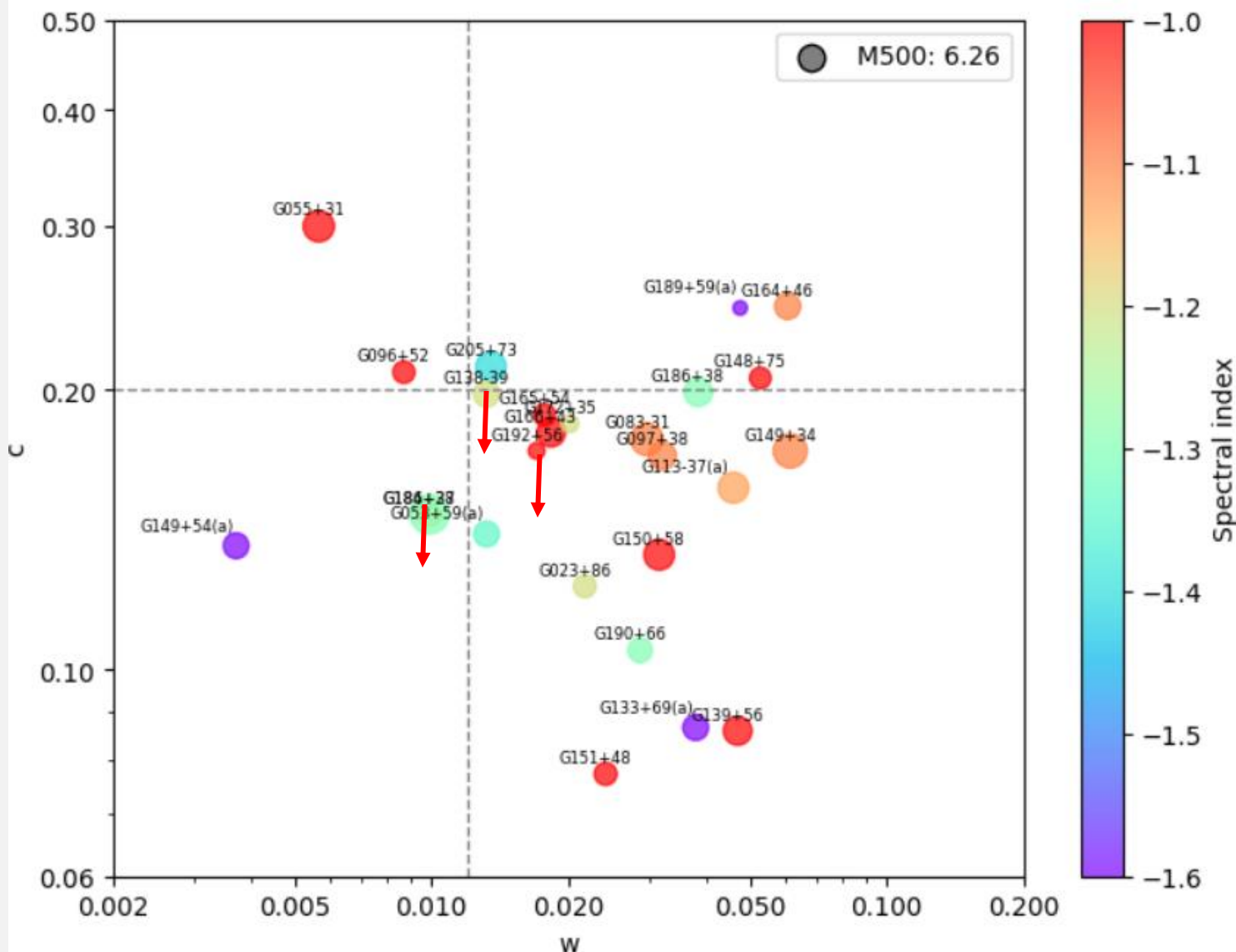
w – centroid shift (presence of substructures) Maughan et al 2008.

Slope – slope from injection measurements

- 26/32 clusters have dynamical info from x-rays

Some of the radio halos in relaxed clusters have steeper α

CORRELATION WITH CLUSTER DYNAMICS



FOR CLUSTERS WITHOUT RADIO HALO IN uGMRT

- Among the 5 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) - $\alpha = -1.2$
- G192+56 (lowest mass cluster in my subsample) - $\alpha = -1$ (uGMRT was not sensitive)
- G138-39 (The halo was also not detected in EGRHS)- $\alpha = -1.2$
- G183+34 - $\alpha = -1.3$ (cRH, same upper limits even with exponential models)
- G063+53 - $\alpha = -1.3$ ($z = 0.422$, uGMRT was not sensitive)

SUMMARY

FIRST COMPLETE-SAMPLE STUDY

First study on a complete sample about the spectral properties of radio halos to constrain the model

FLATTER SPECTRA

- Most of the RHs have flatter spectra.
- Turbulent reacceleration model is a homogeneous model and thus expected α was steeper.

OBSERVATIONAL EFFECTS MATTER

- α should be considered with the flux loss that happens in an instrument.

COMPLETE SAMPLE = STRONGER CONSTRAINTS

- Completing the entire sample will help constrain the origin of RHs effectively.

REDSHIFT DEPENDENCE

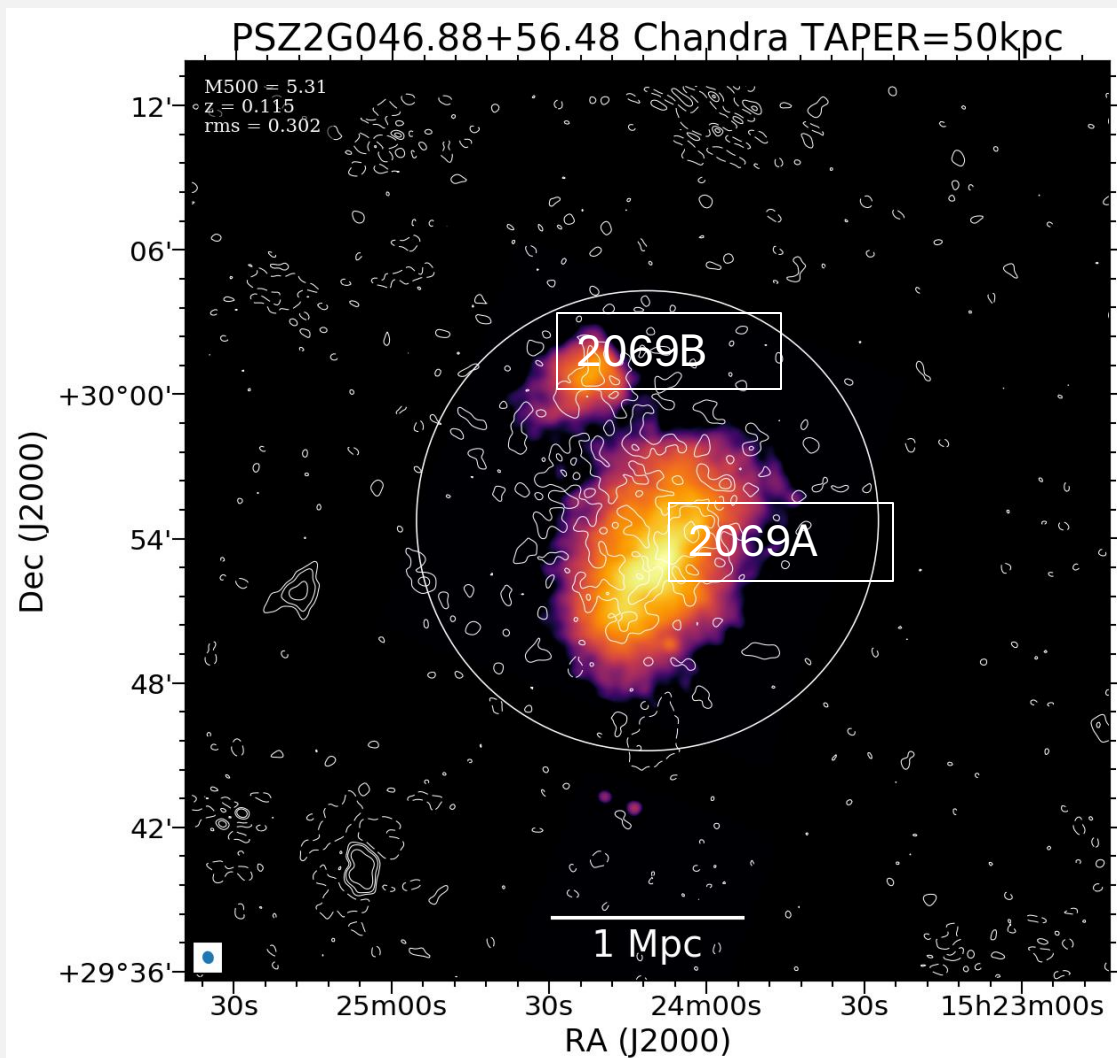
- IC/synchrotron losses at higher z can cause steeper spectra of RHs than at lower z cases

A rare double halo emission, a curious case of A2069

Supervisor: Reinout J Van Weeren

A2069

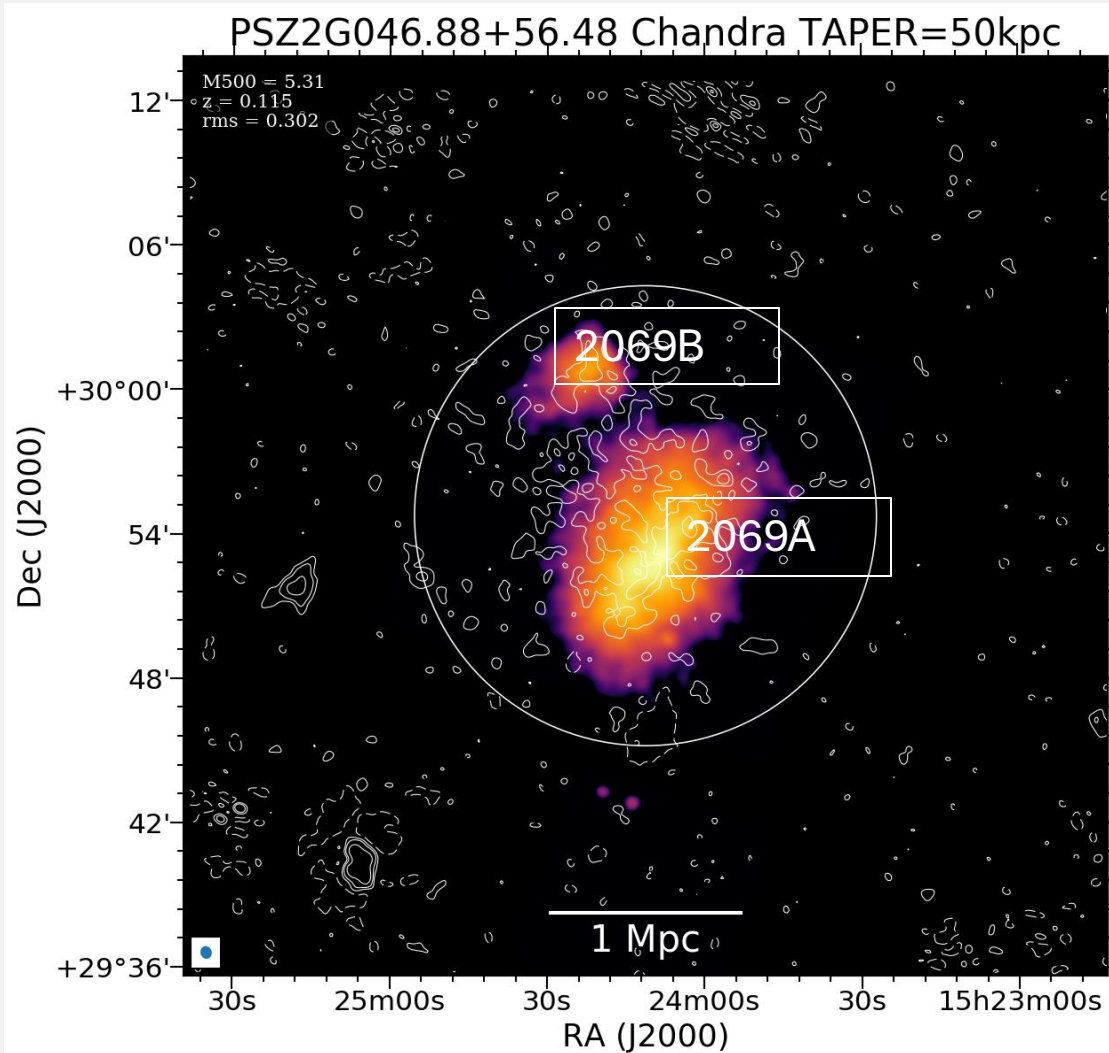
$$M_{500} = 5.31 \times 10^{14} M_{\odot}$$
$$Z = 0.115$$



- *Part of the supercluster 2069 with Corona Borealis in the foreground*
- *Bimodal cluster (subcomponent/subcluster).*

A2069

$$M_{500} = 5.31 \times 10^{14} M_{\odot}$$
$$Z = 0.115$$



GBT (1.4 GHz)

Farnsworth et al. (2014)

Diffuse extended emission detected

WSRT (346 MHz)

Drabent et al. (2015)

Radio halo reported

Emission nature in component B
remains uncertain

LOFAR LoTSS-DR2 (144 MHz)

Diffuse emission engulfs
the entire system

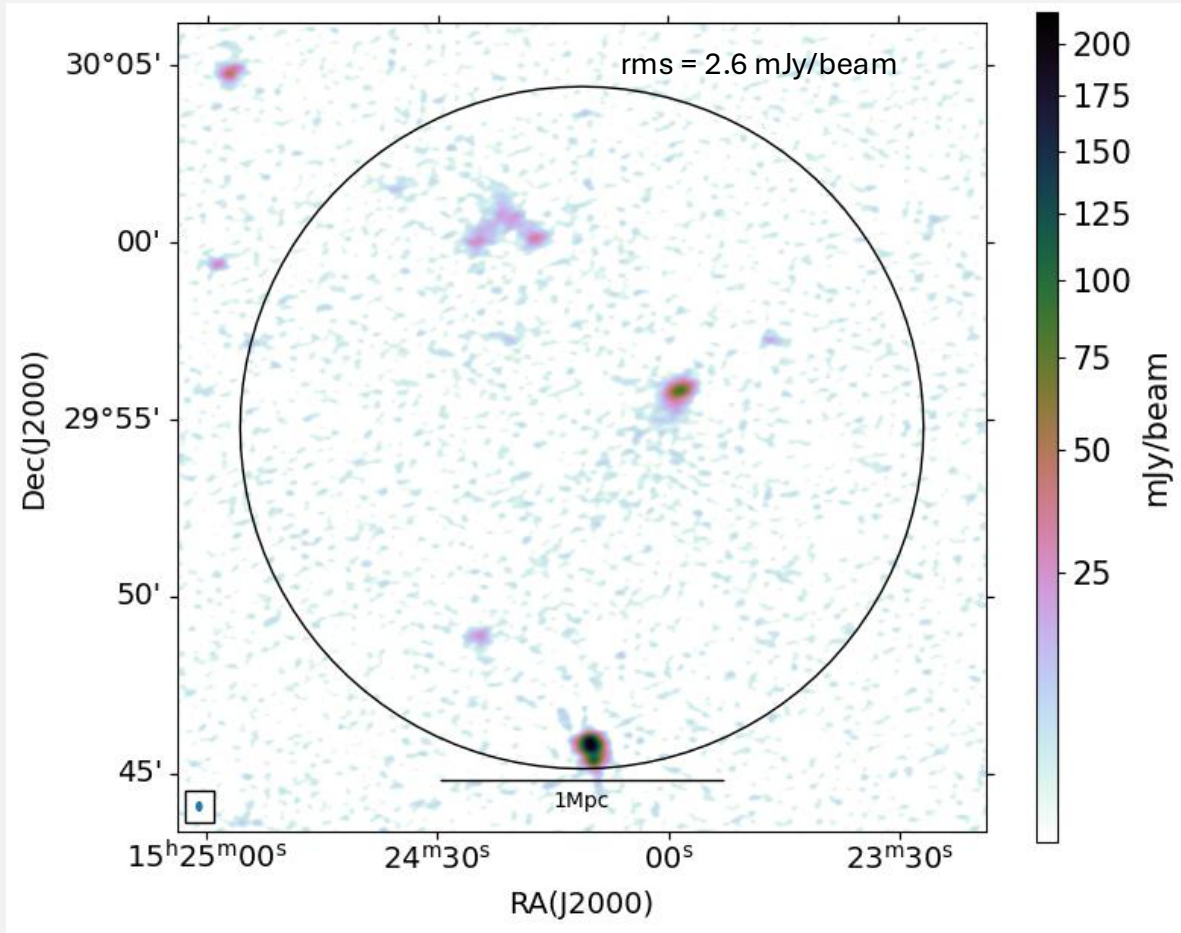
No clear distinction between
RH and mRH

- *No multifrequency spectral index analysis has been carried out yet.*

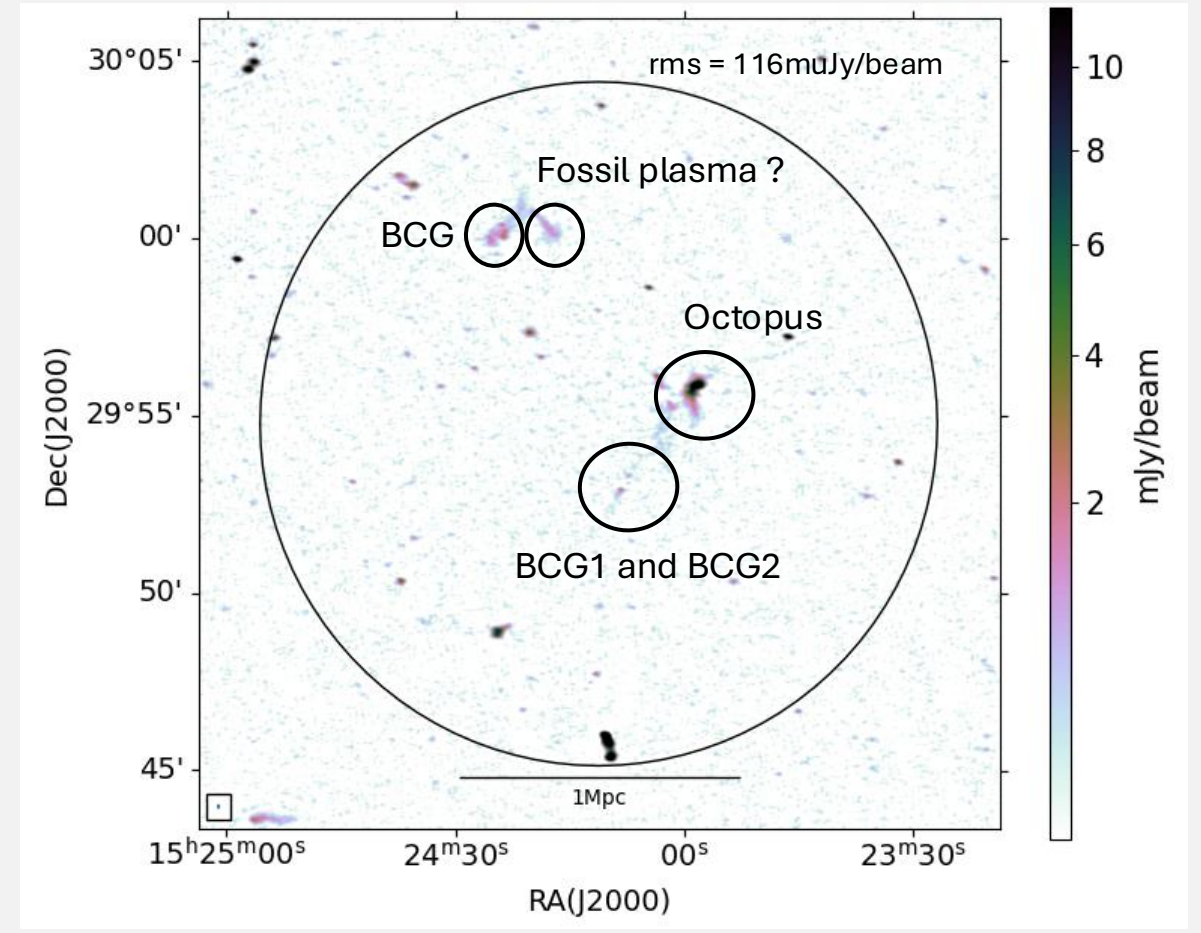
HIGH RESOLUTION

$$M_{500} = 5.31 \times 10^{14} M_{\odot}$$
$$Z = 0.115$$

LBA – 54 MHz



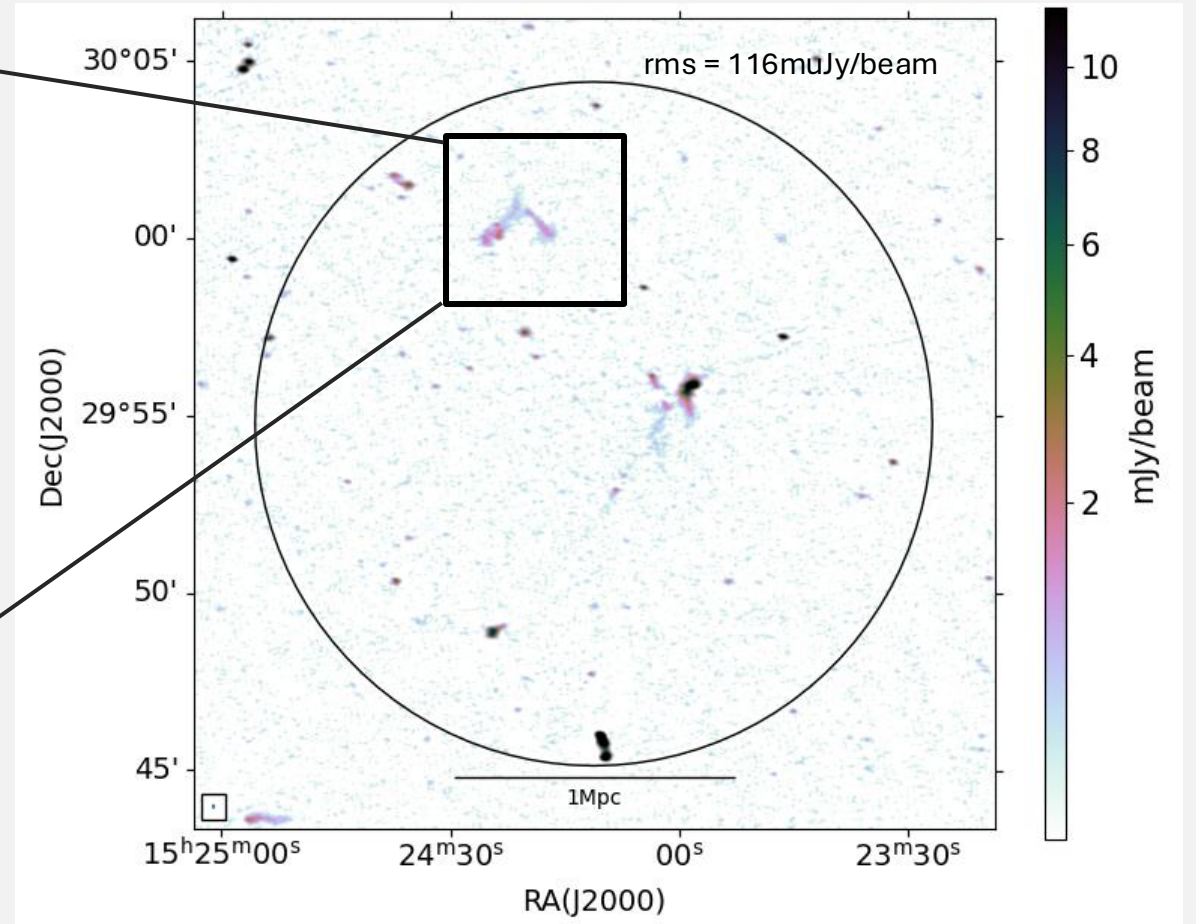
HBA - 144MHz



HIGH RESOLUTION

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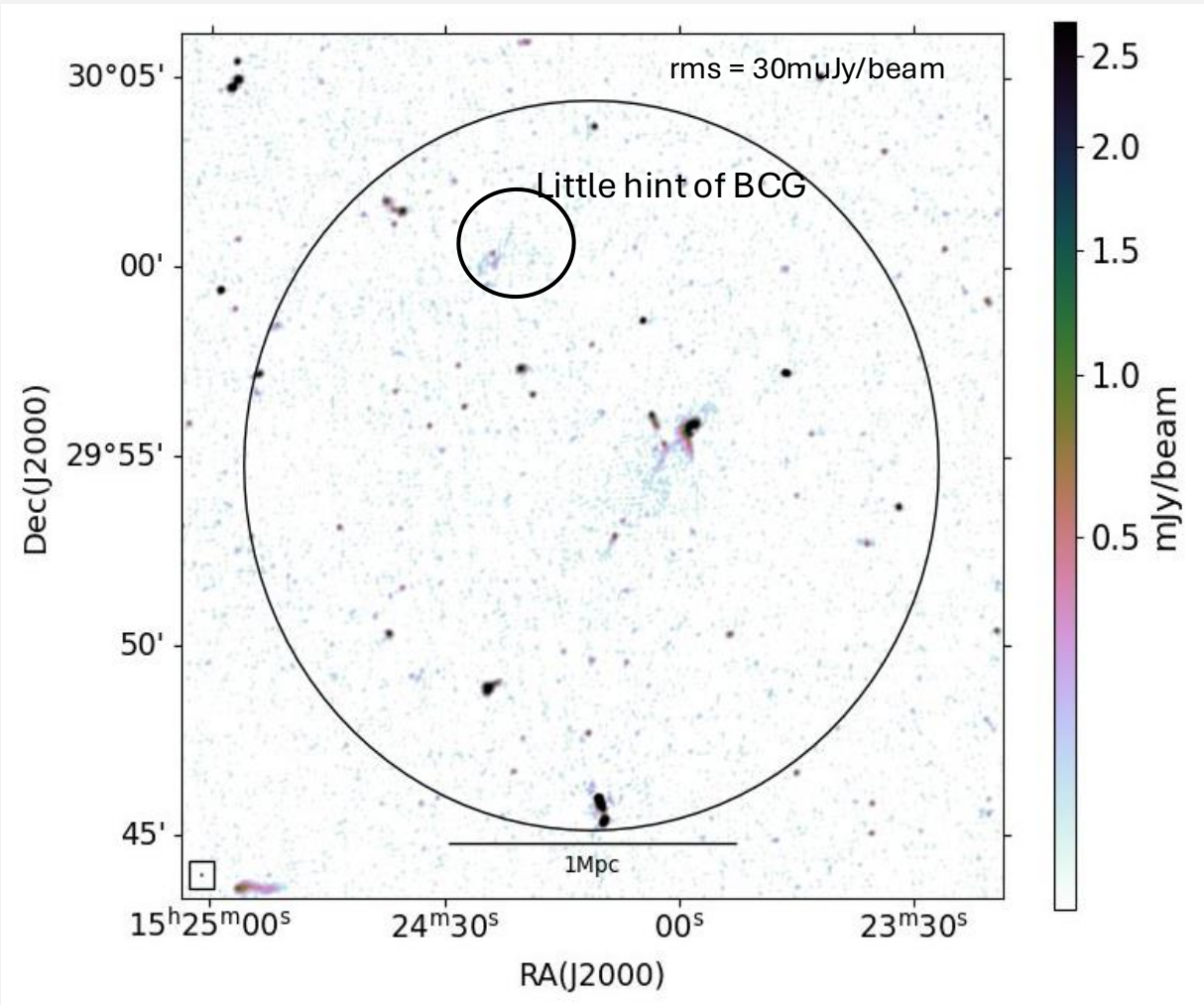
HBA - 144MHz



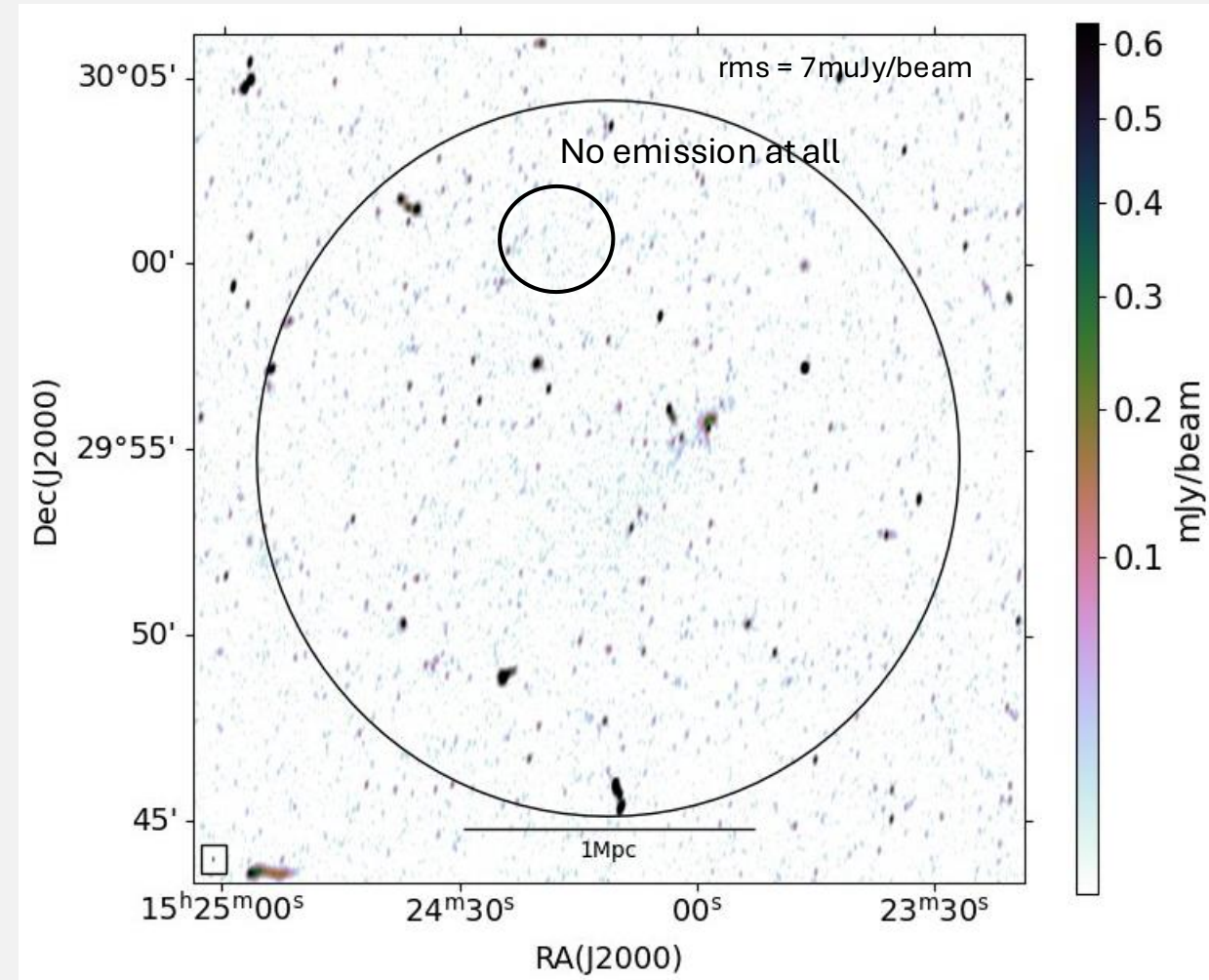
HIGH RESOLUTION

$$M_{500} = 5.31 \times 10^{14} M_{\odot}$$
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uGMRT Band03 - 400MHz

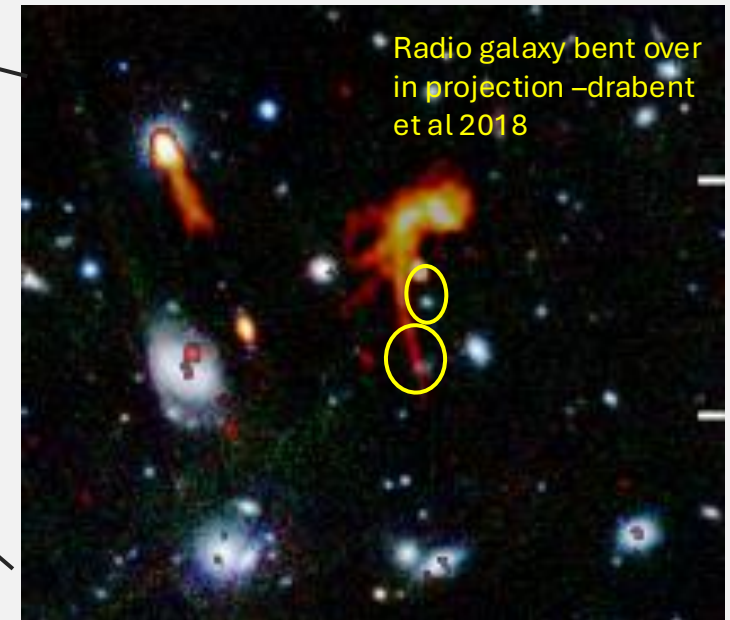
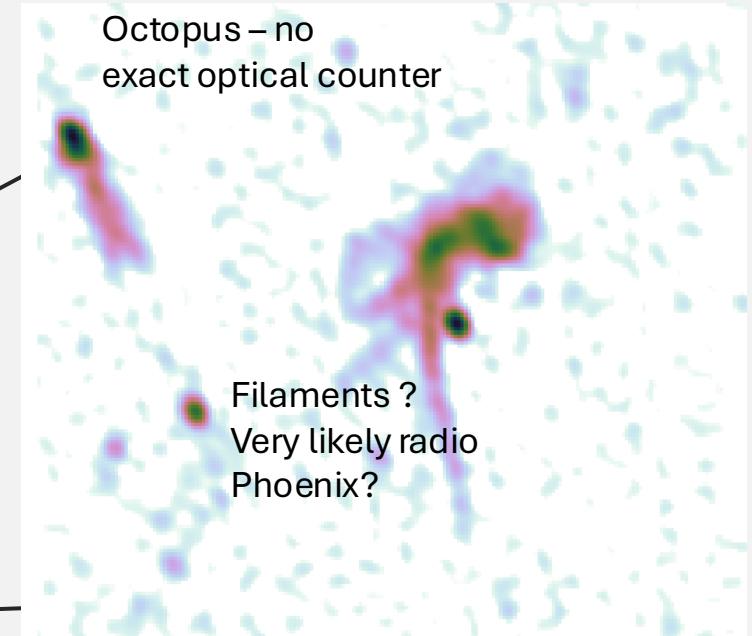
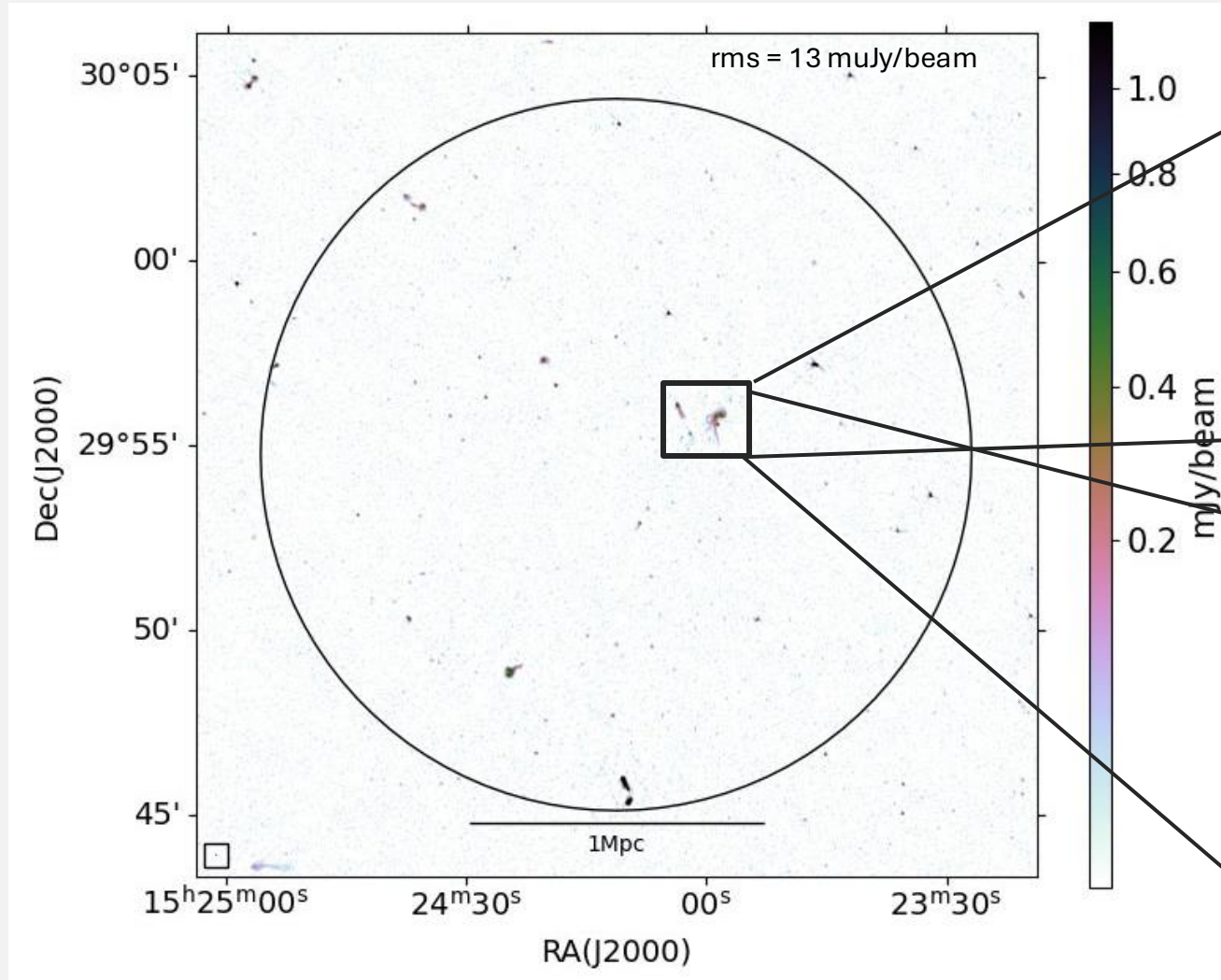


MeerKAT L Band – 1.2 GHz



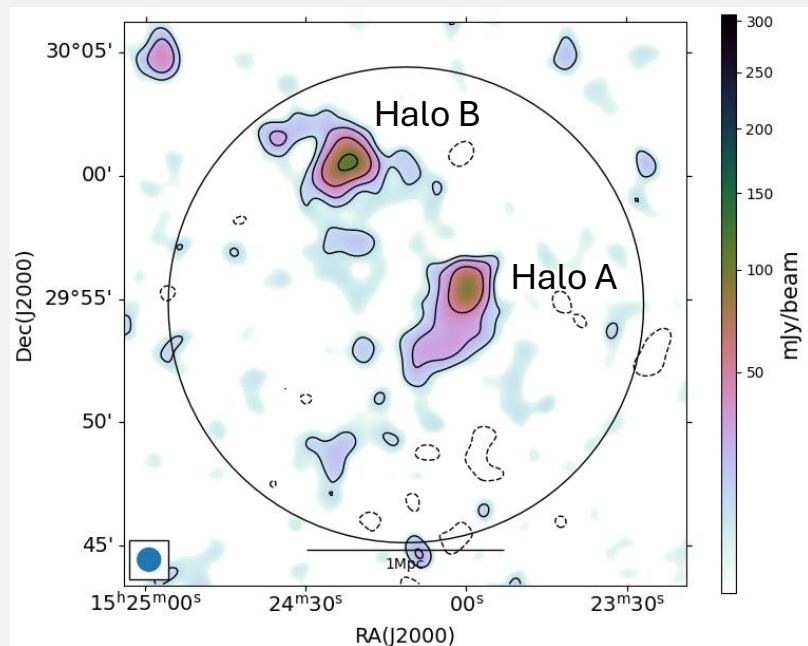
HIGH RESOLUTION

uGMRT Band04 – 650MHz; 3.5" x 2.8 "

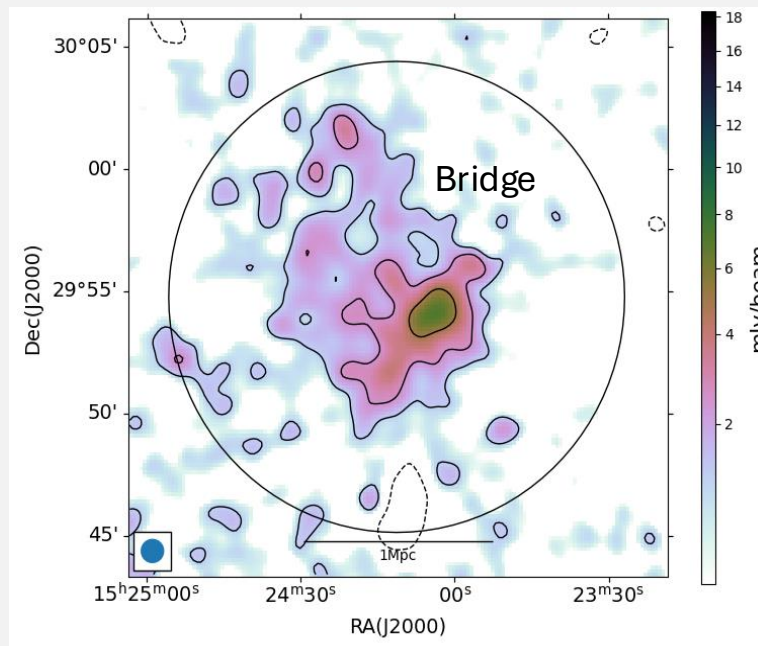


LOW RESOLUTION – 60 ''

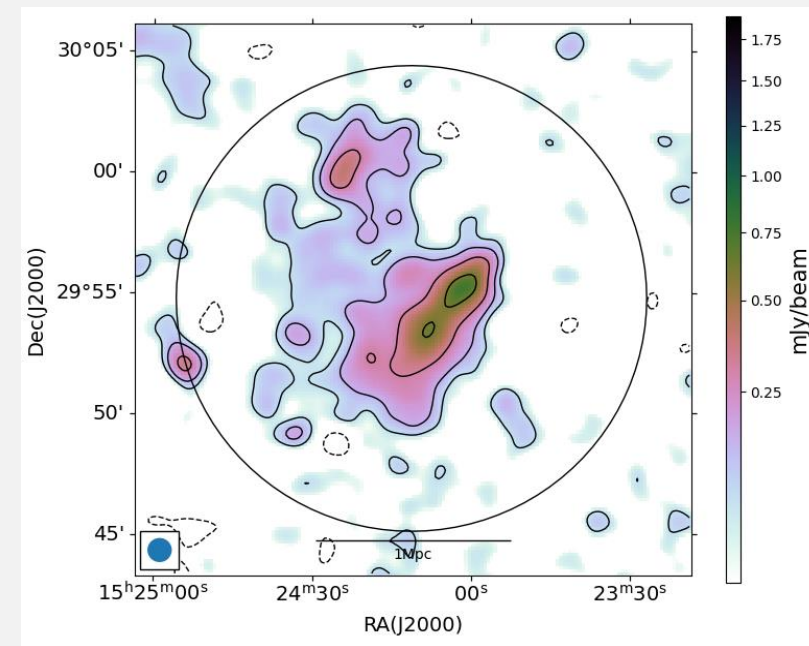
LBA – 54 MHz



HBA - 144MHz



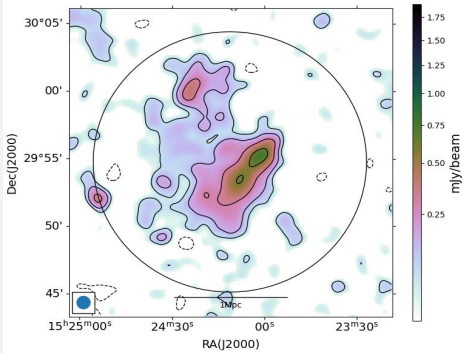
MeerKAT L Band – 1.2 GHz



- LBA – bridge emission insignificant.
- LBA fluxes and *α with LBA are not reliable* due to strong source subtraction residuals

SPECTRAL INDEX

RH MeerKAT L Band – 1.2 GHz

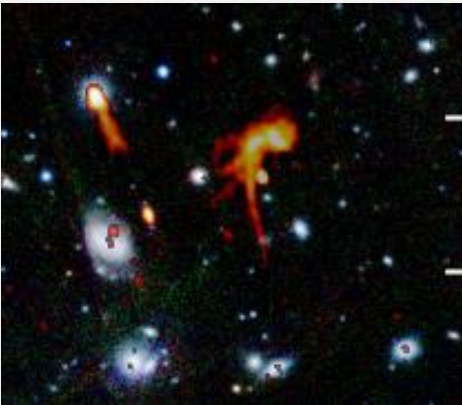


Spectral index



	Slope LBA-HBA	Slope HBA-MeerKAT
Entire emission	-1.50 pm 0.15	-1.12 pm 0.08
Halo A	-1.28 pm 0.16	-1.12 pm 0.08
Halo B	-2.47 pm 0.19	-1 pm 0.11
Bridge		-1.24 pm 0.10

octopus



Spectral index



	Slope HBA-B4	Slope B4-MeerKAT
Octopus	-1.61 pm 0.07	-1.83 pm 0.11

Fossil plasma



Spectral index

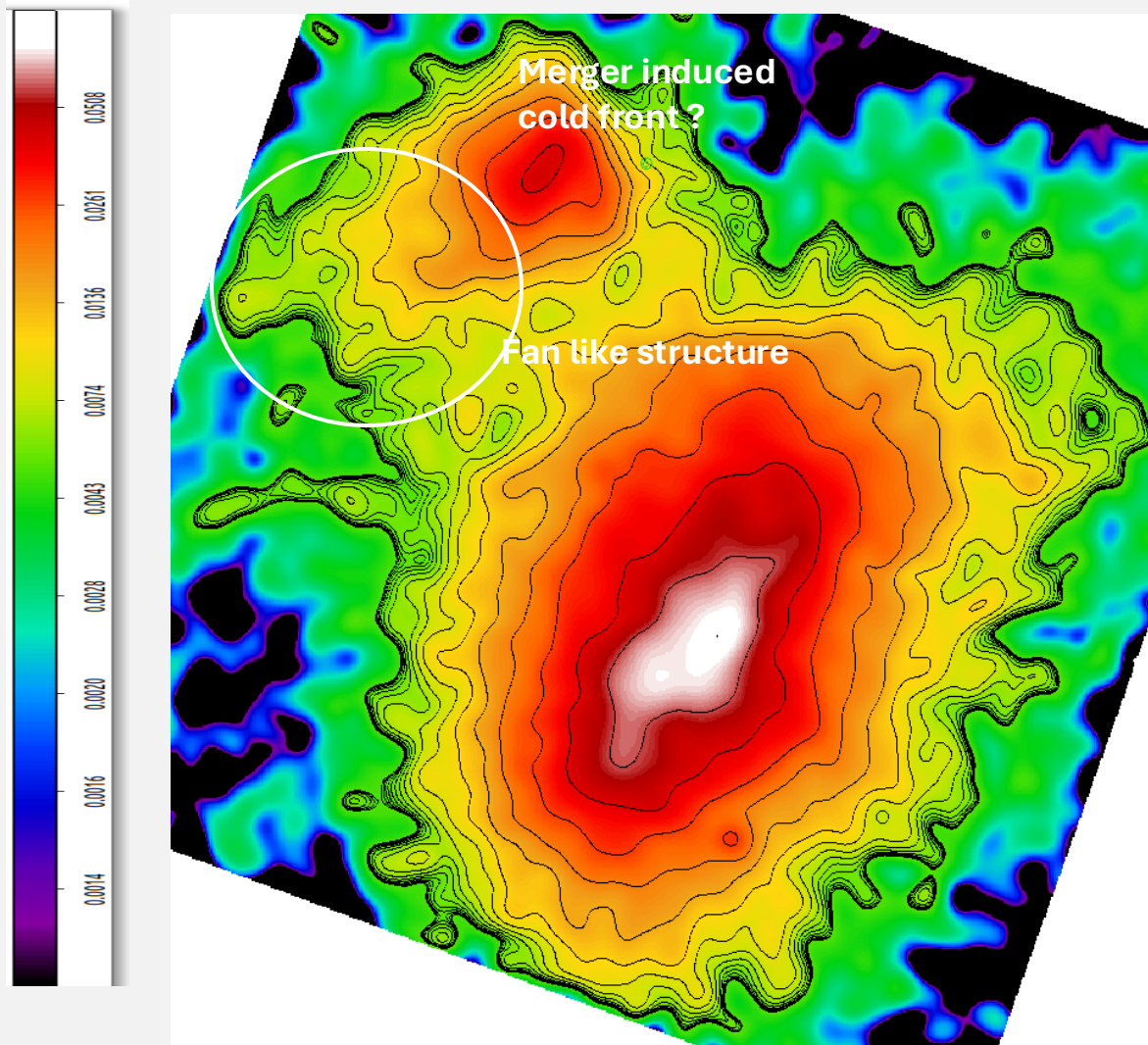


	Slope LBA-HBA
Fossil plasma	-2 pm 0.15

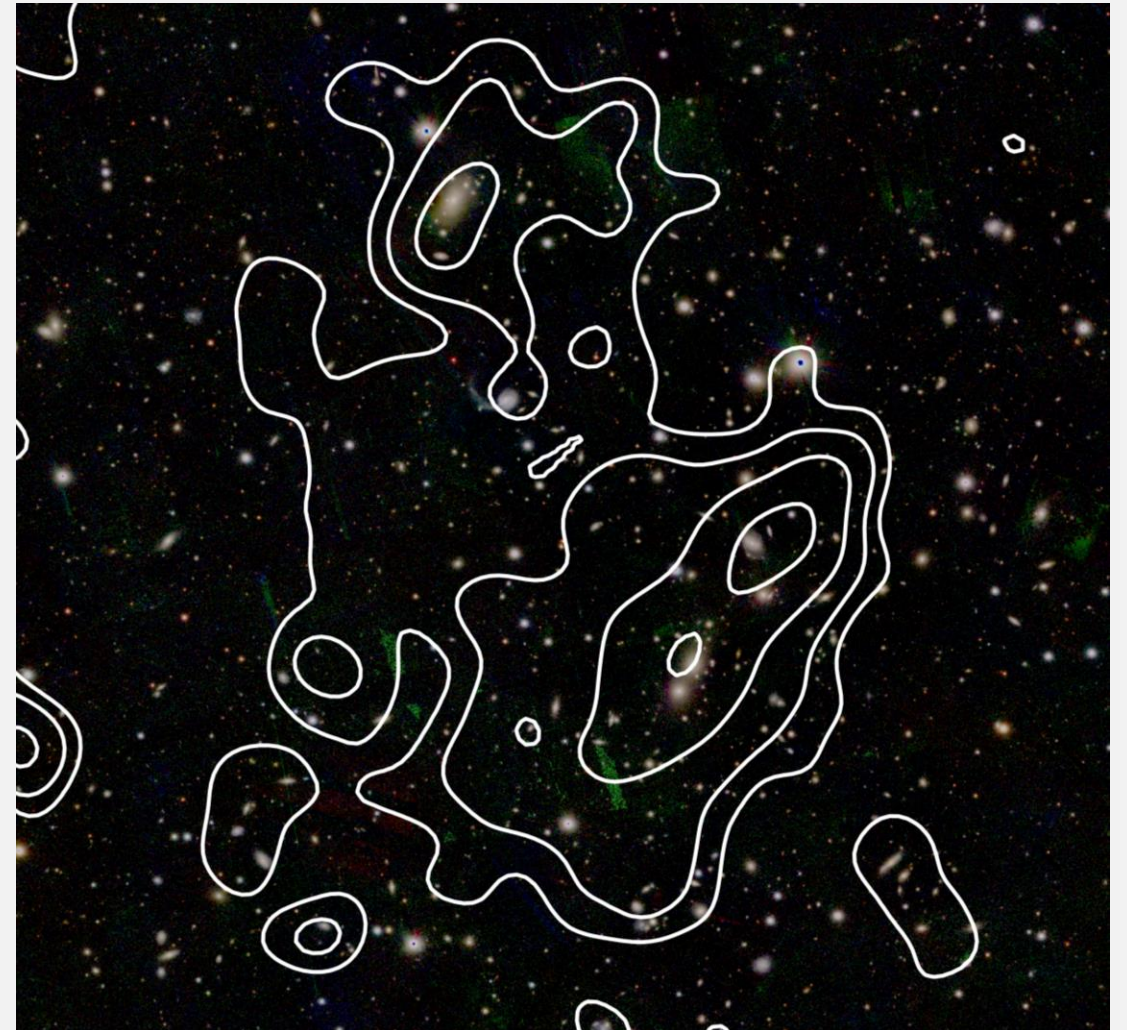
No information from SI maps

Cluster dynamics

X-ray image CHANDRA



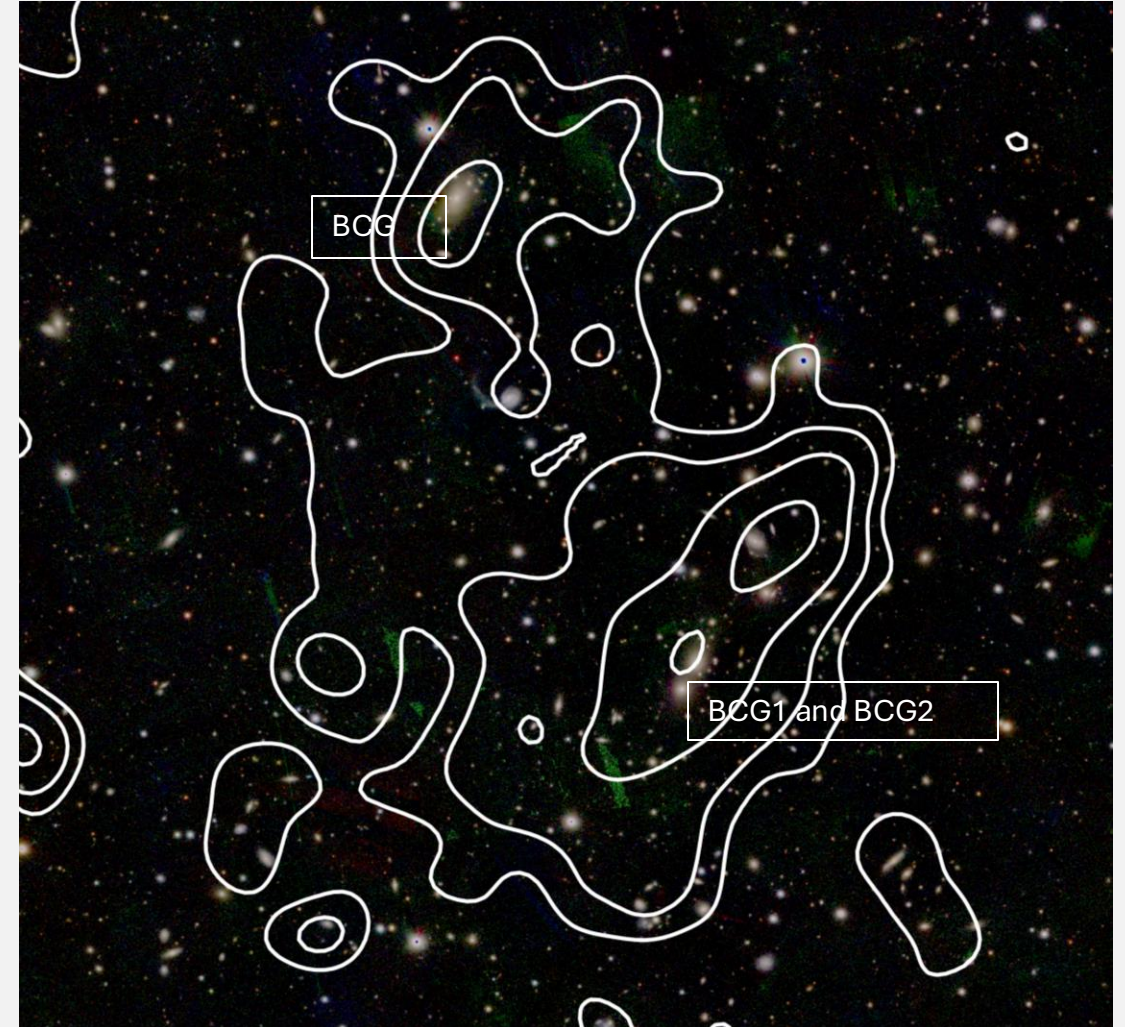
PanSTARRS – MeerKAT RH overlay



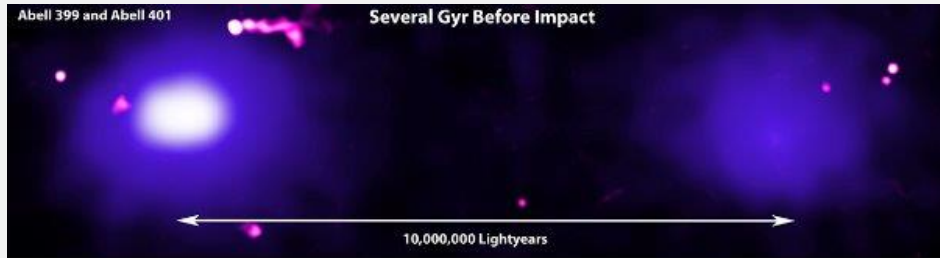
Cluster dynamics

- Subcomponent A – RH A - Merging by itself
- Subcomponent B – comparatively cooler (not cool core) - RH B - offset merger
- Sub A and Sub B in the plane of the sky (*Drabent et al 2014*)
- Bridge compression between A and B
- No clear bimodality distribution of galaxy velocities.
- Temperature at the bridge has high uncertainty – XMM image

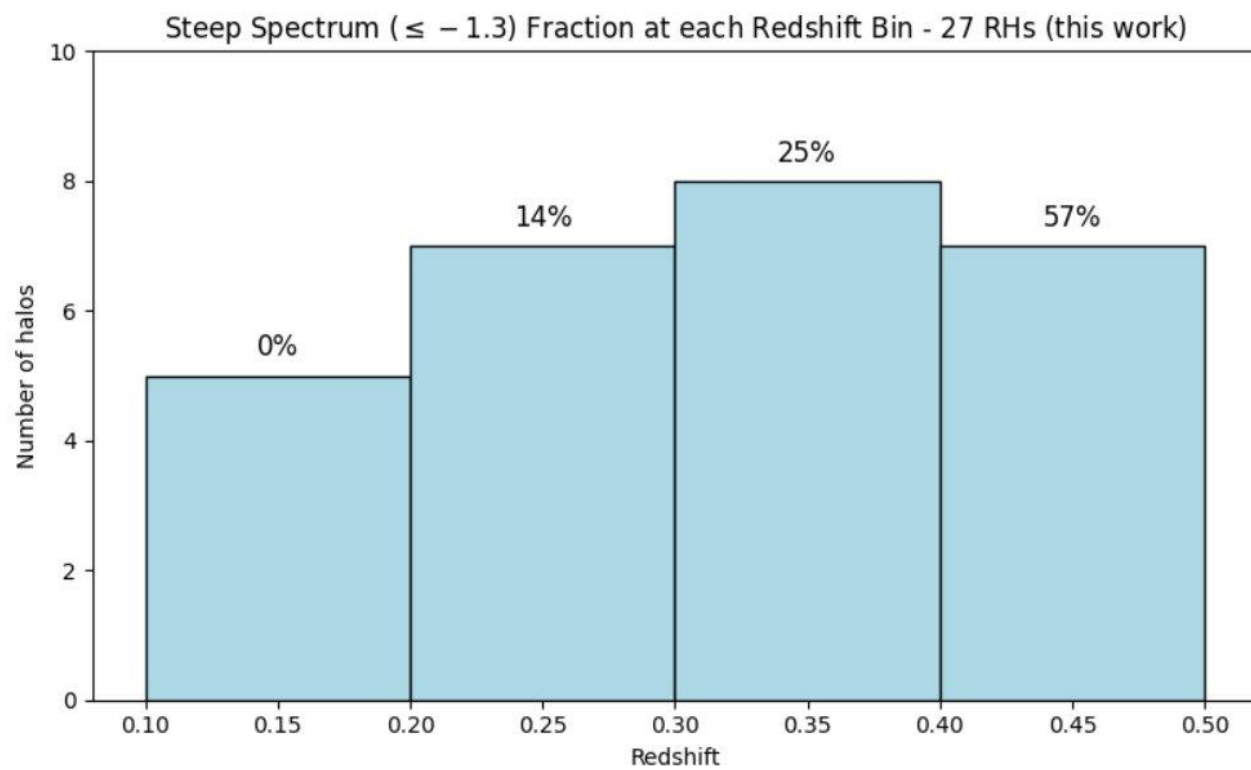
PanSTARRS – MeerKAT RH overlay



CONCLUSION



- Double halo within R_{500} with complicated merging scenario and scenario.
- Merger induced cold front.
- Origin of octopus – probably phoenix? Detailed analysis required.
- Presence of fossil plasma in LBA-HBA.



UNVEILING THE SPECTRAL PROPERTIES BY LOFAR-uGMRT

Previous literature studies

Fraction of clusters with radio haloes in high-mass clusters

(Cuciti et al 21)

Presence of diffuse emission in LOFAR-GMRT
PSZ2 clusters $M_{500} \geq 6 \times 10^{14} M_{\odot}$ and $z \leq 0.35$

Instrument	Observed f_{RH}	f_{RH} from model
LOFAR	67–73%	$67.0 \pm 17.8\%$
GMRT	41–48%	$44.6 \pm 10.0\%$

Notes. Ranges in the observed f_{RH} values were obtained considering the U cases once as RH clusters and once as clusters without RH.

Steep spectral Haloes at high redshift clusters

(Di Gennaro et al 21)

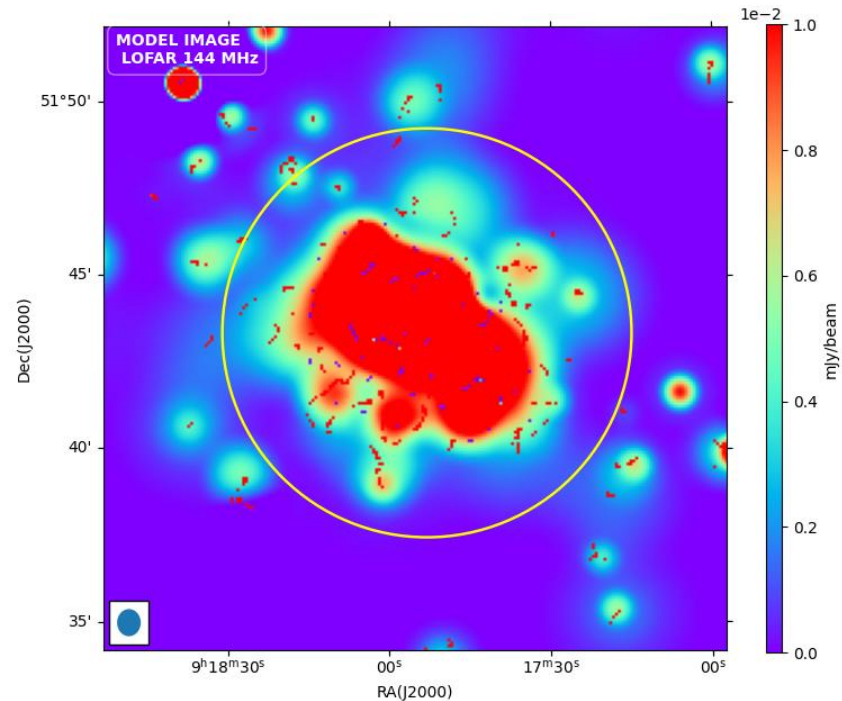
LOFAR- GMRT analysis of 9 PSZ2 clusters $z \geq 0.6$

- 5/9 clusters – show spectral index between -1 and -1.4 (massive clusters)
- 4/9 clusters – upper limits steeper than -1.5 .

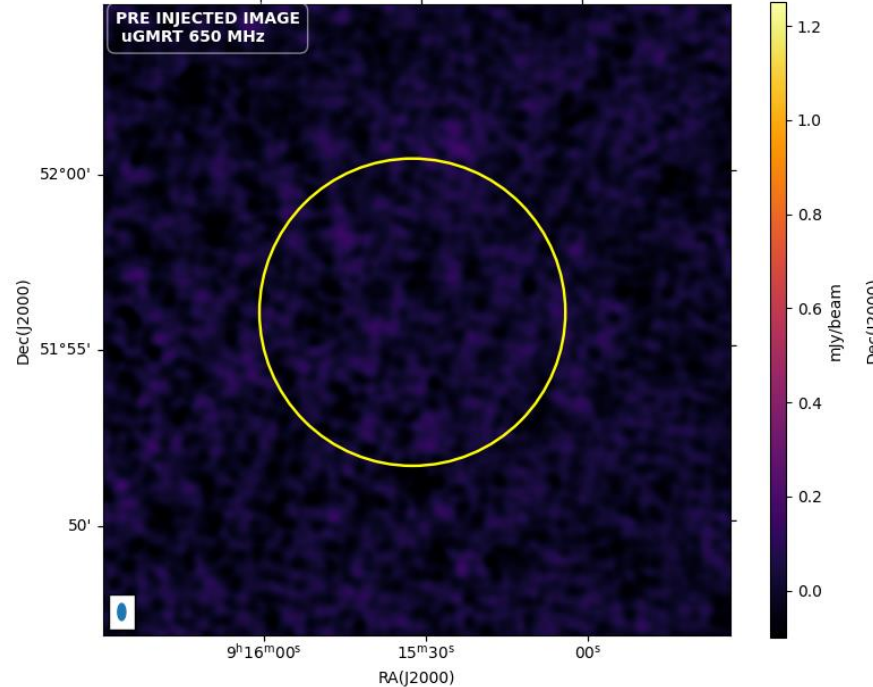
Open
questions ?

PROGRESS

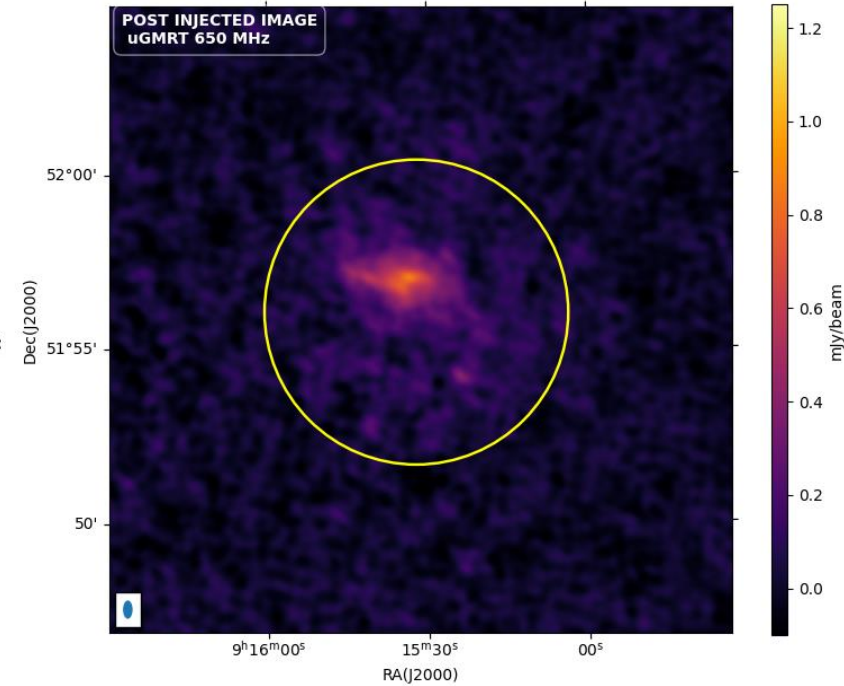
LOFAR MODEL



PRE INJECTION -uGMRT



POST INJECTION -uGMRT

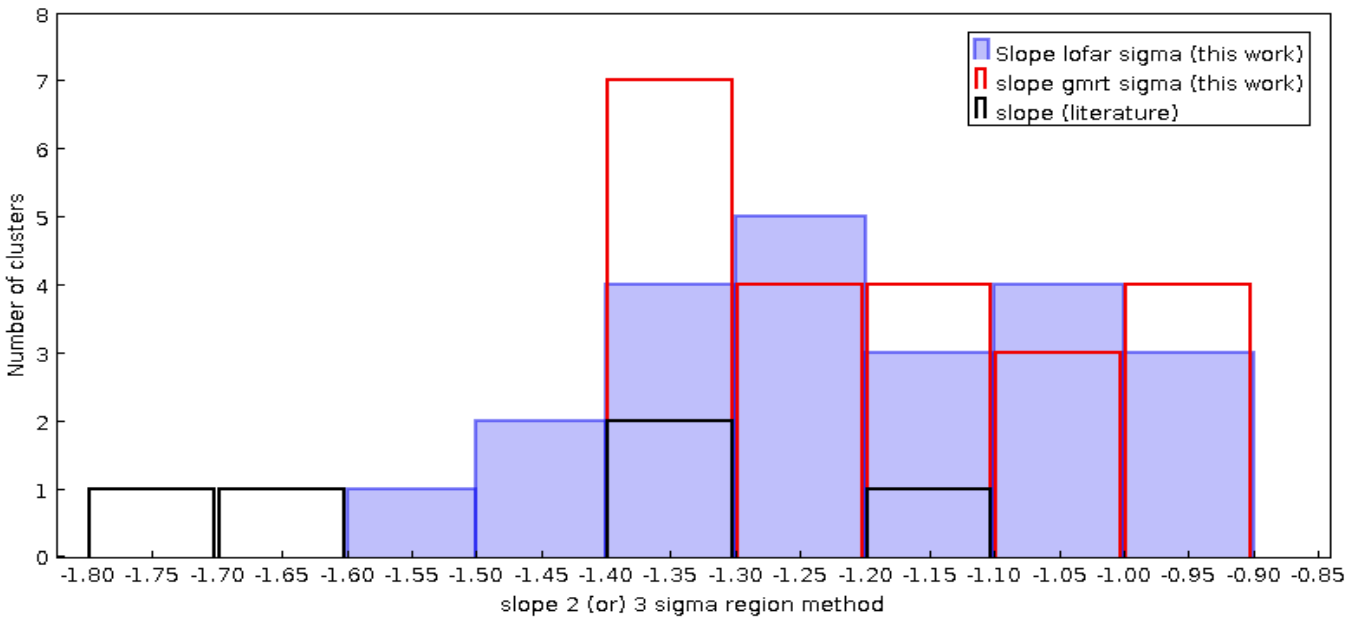


Found the flux density and spectral index

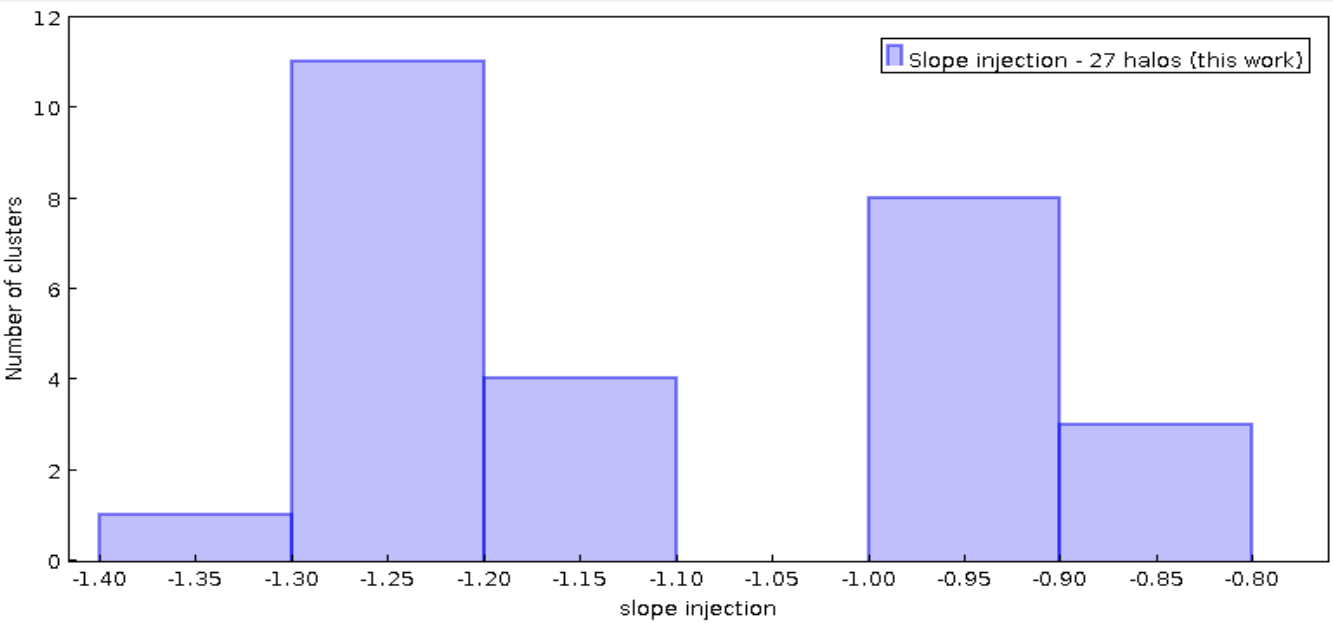
1. 2 sigma contours (regions based on LOFAR and uGMRT)
2. LOFAR model injection (injection of a real LOFAR model instead of an exponential model)

DISTRIBUTION OF SLOPE FOR THE SUBSAMPLE (27)

2 or 3 σ region method

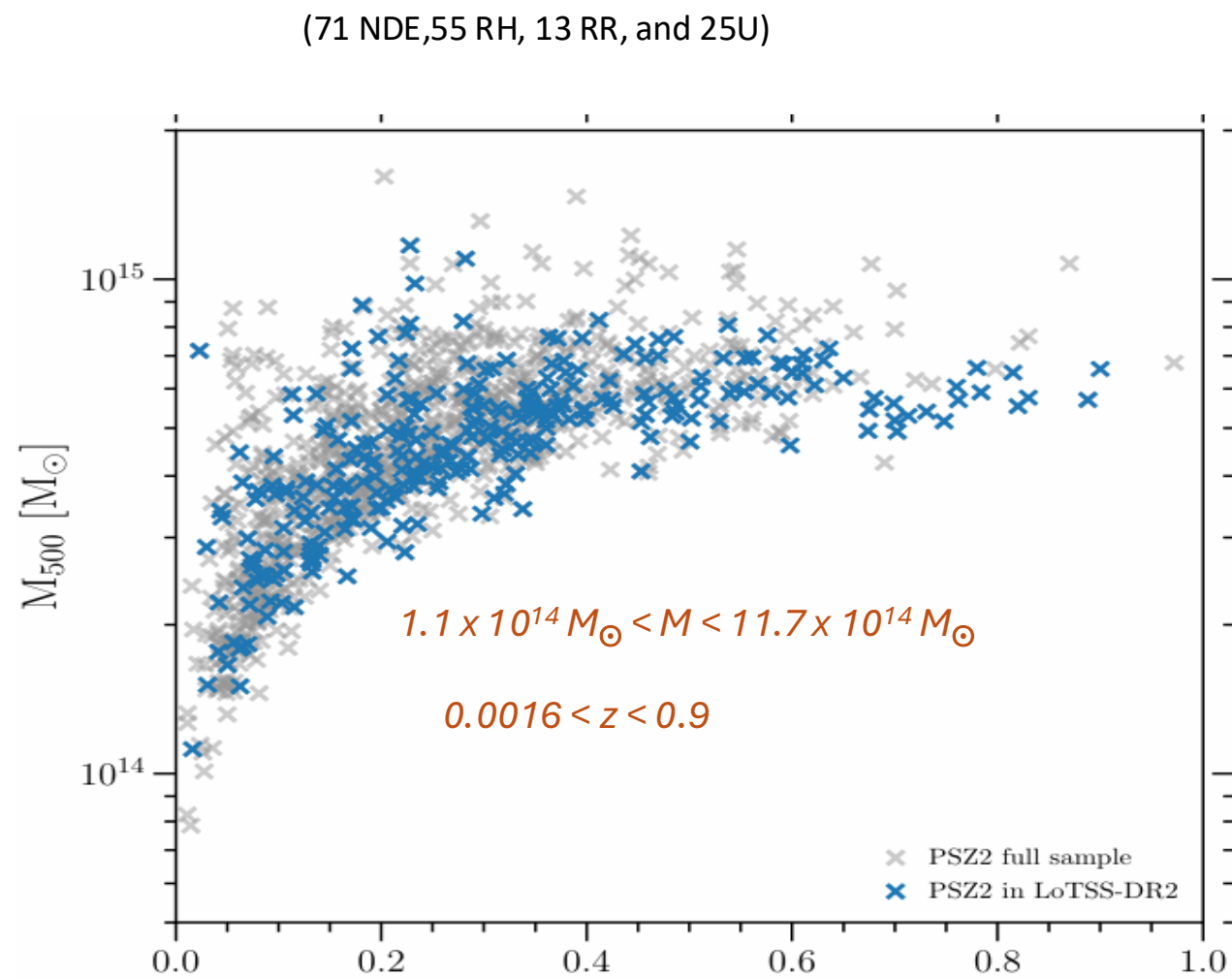


LOFAR MODEL INJECTION



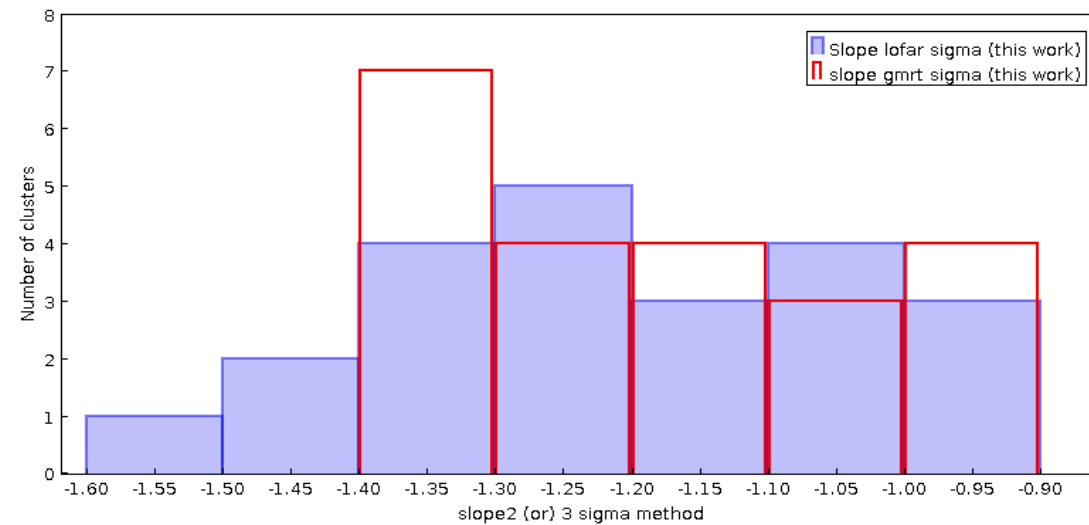
Deviation from literature reported Spectral index values

Cluster name	Literature spectral index	Spectral index (this work)
A773	-2.1	-1 (srikanth et al 2026)
A1351	-1.6	-1 (srikanth et al 2026)
A697	-1.8	-1.3

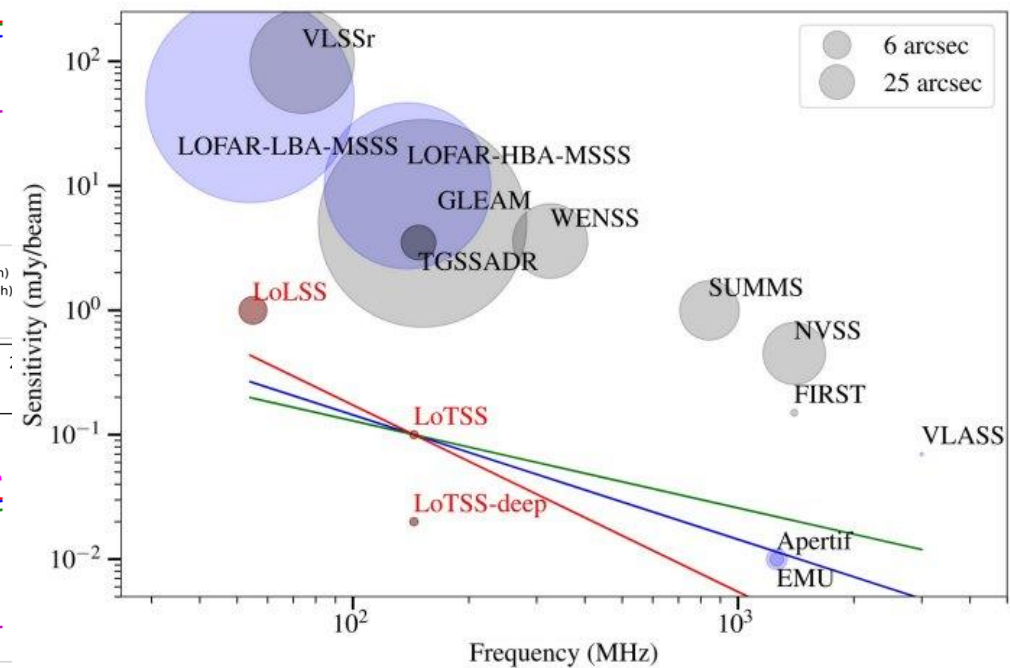
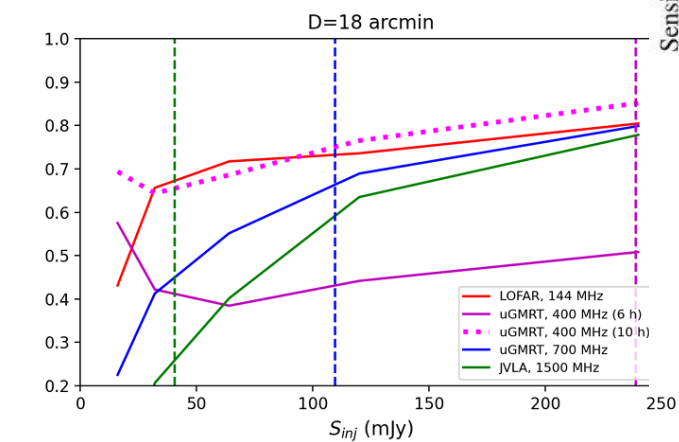
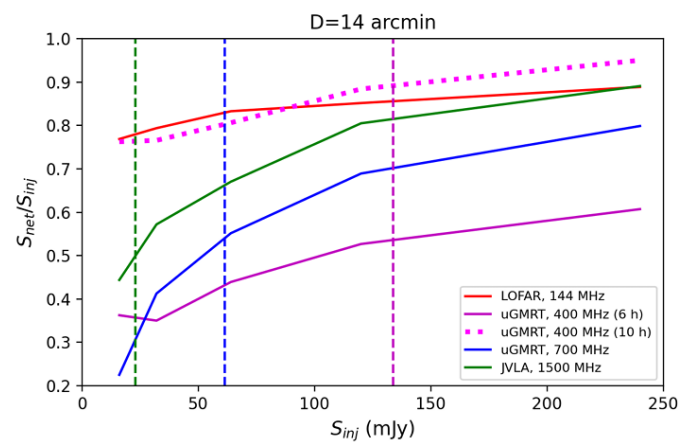
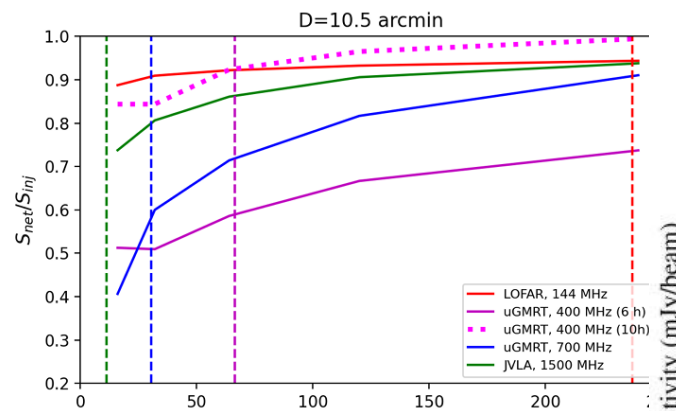
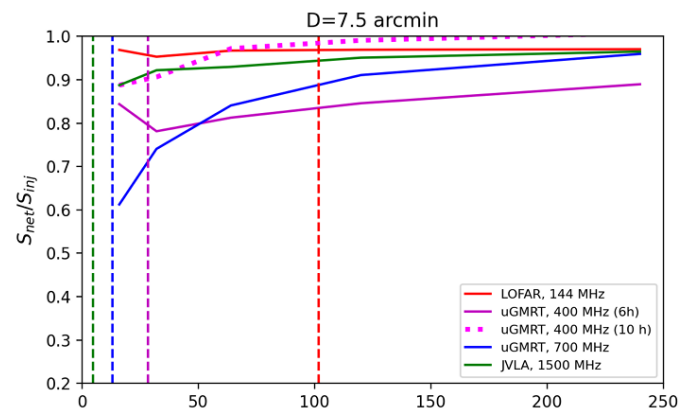


Redshift-mass distribution of PSZ2 sources

2 or 3 σ region method

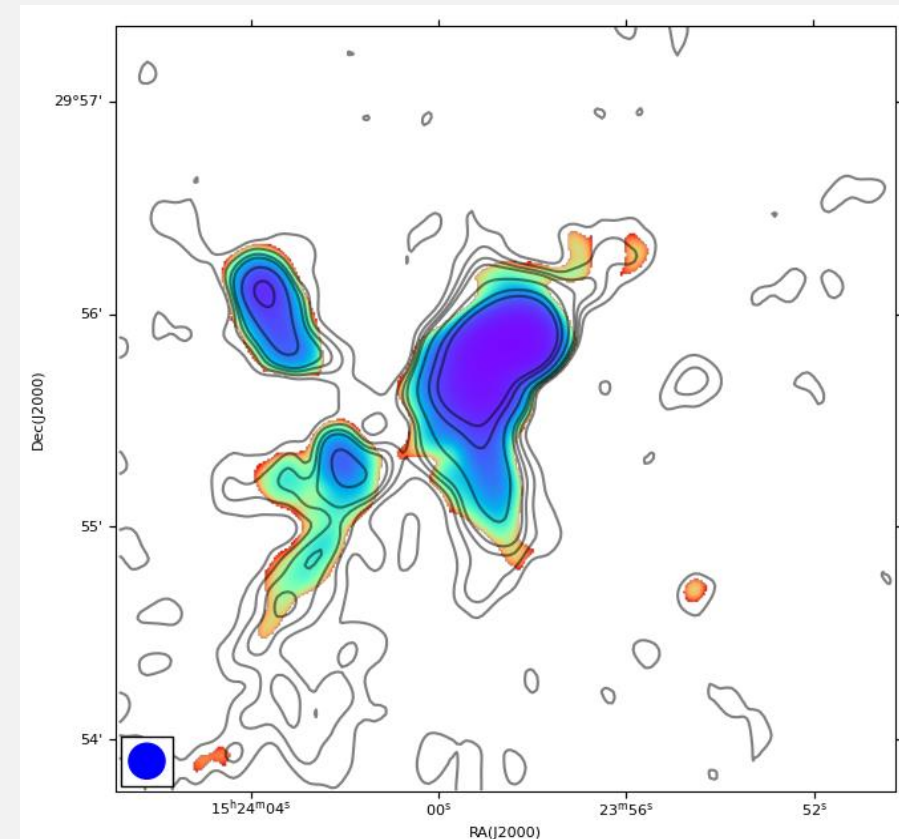
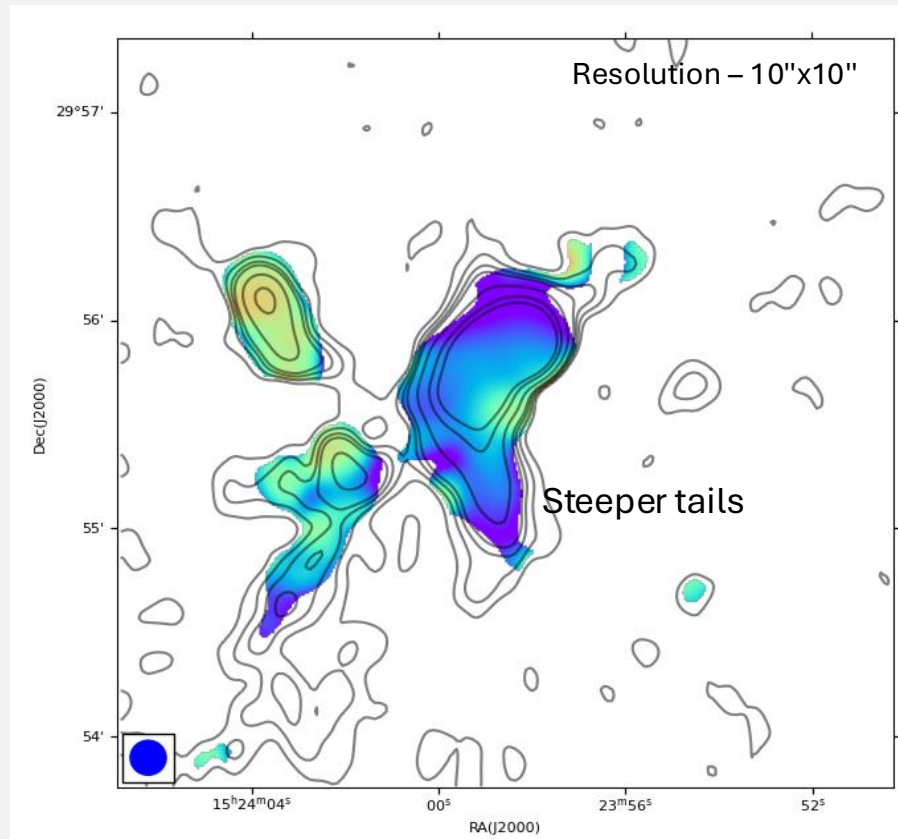
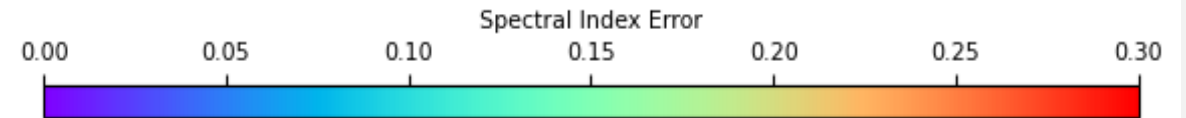
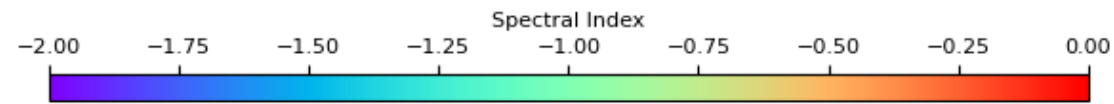


- 21 out of 27 clusters in the sample have info about dynamical status as derived from the X-ray images
- All the 5 clusters from lit have dynamical info

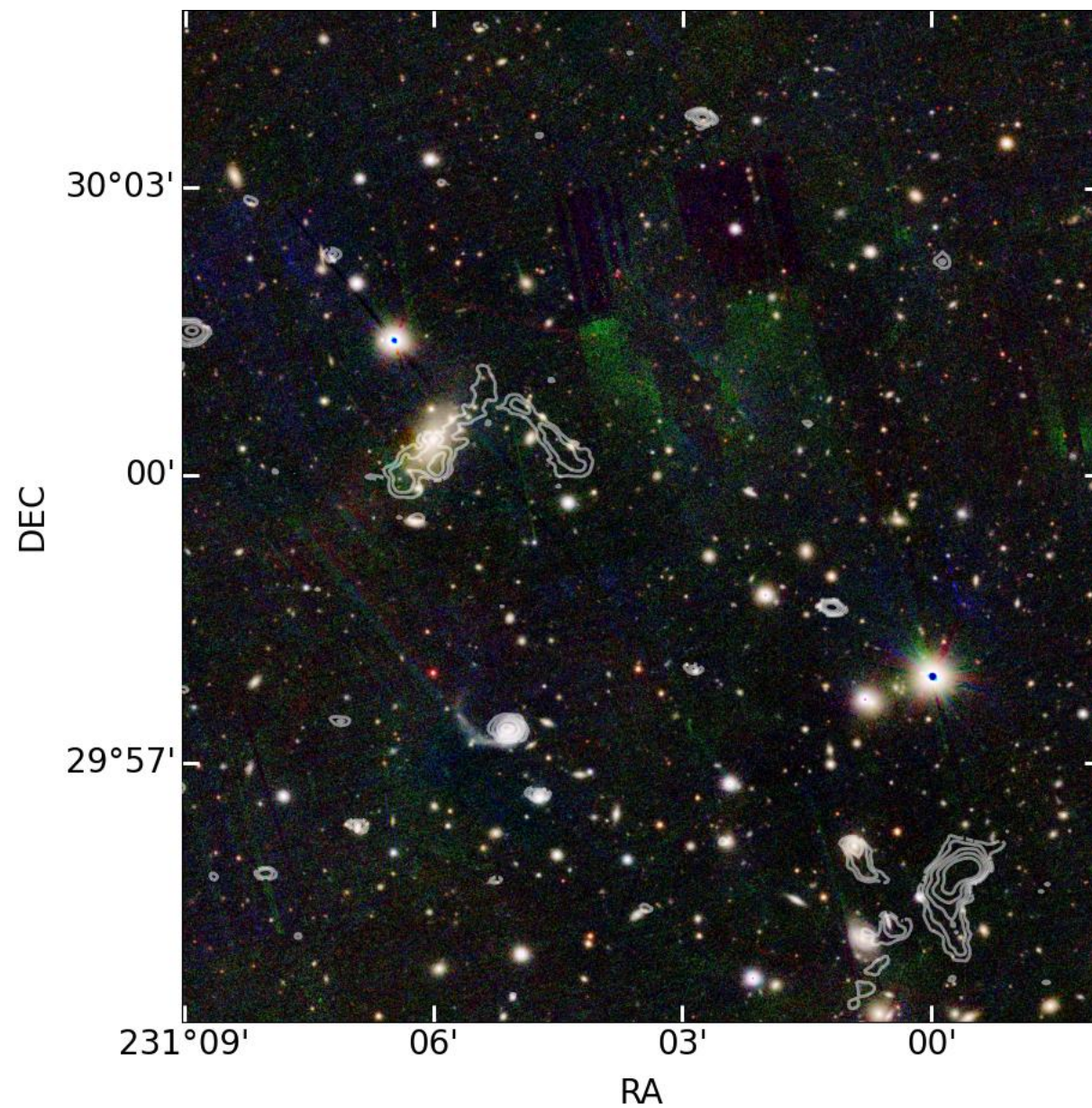
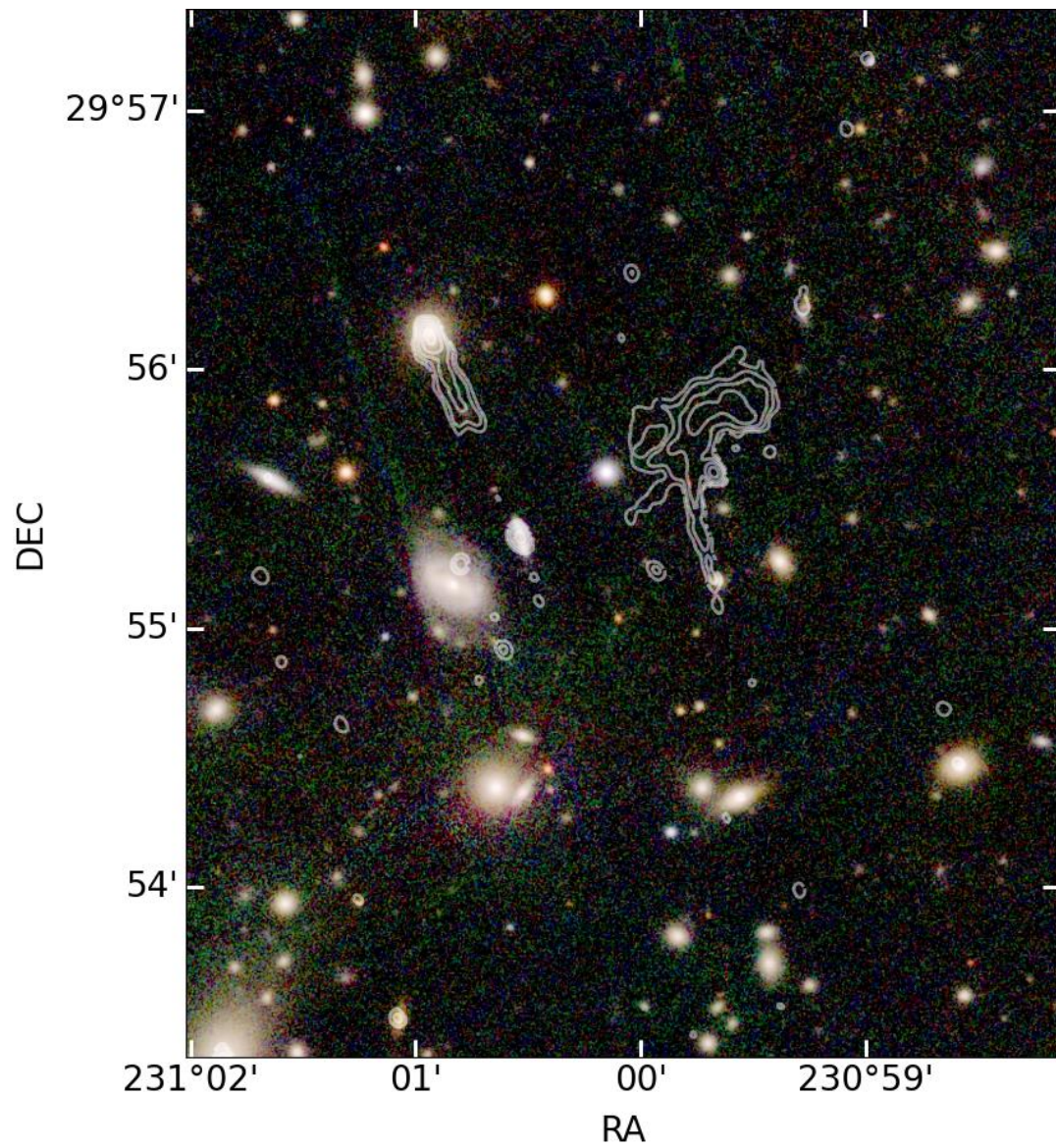


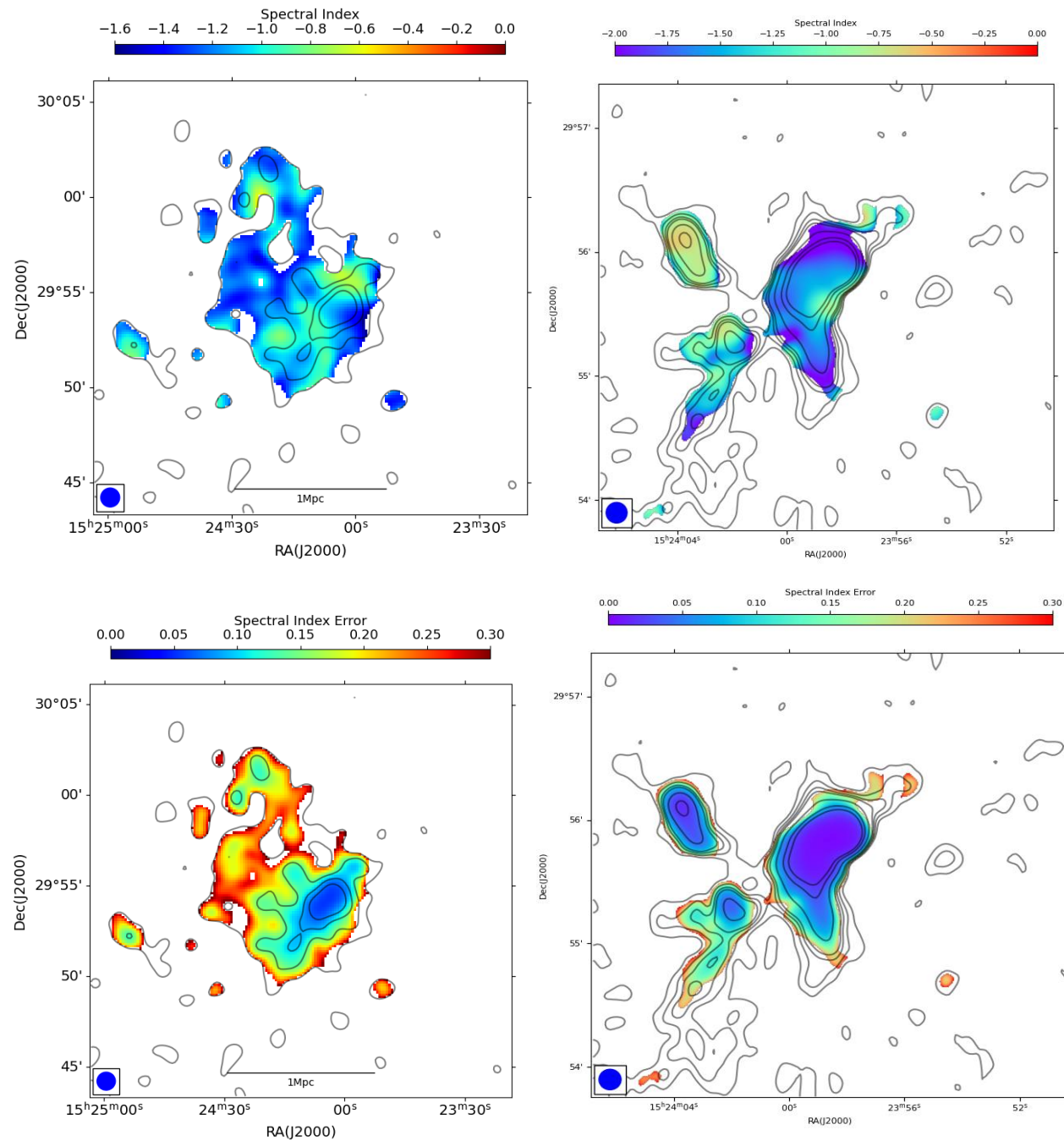
Green $\alpha = -0.7$, blue $\alpha = -1.0$, red $\alpha = -1.5$

SPECTRAL INDEX OCTOPUS –HBA - Band4



- No clear information regarding acceleration/ re-acceleration scenario from the SI maps

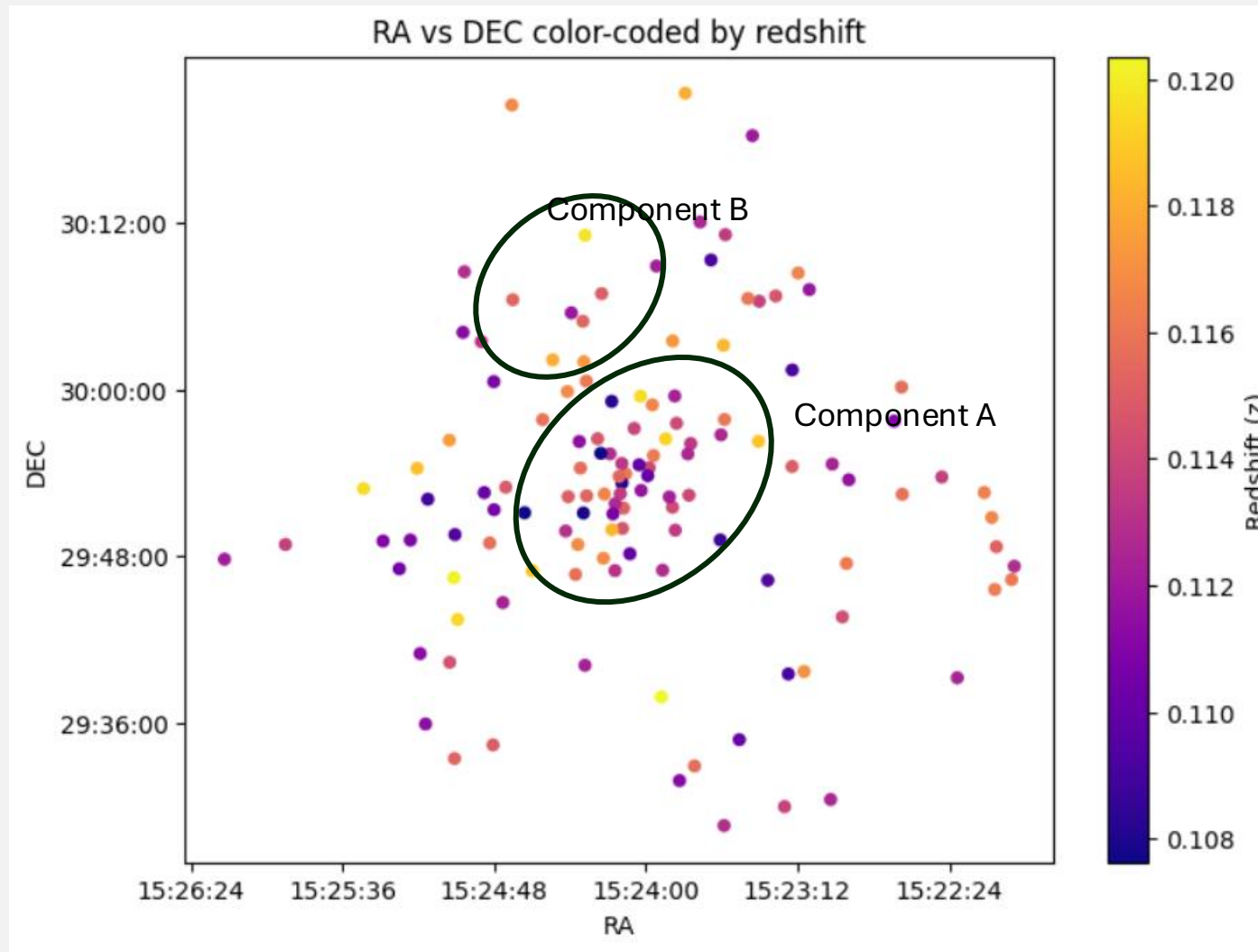




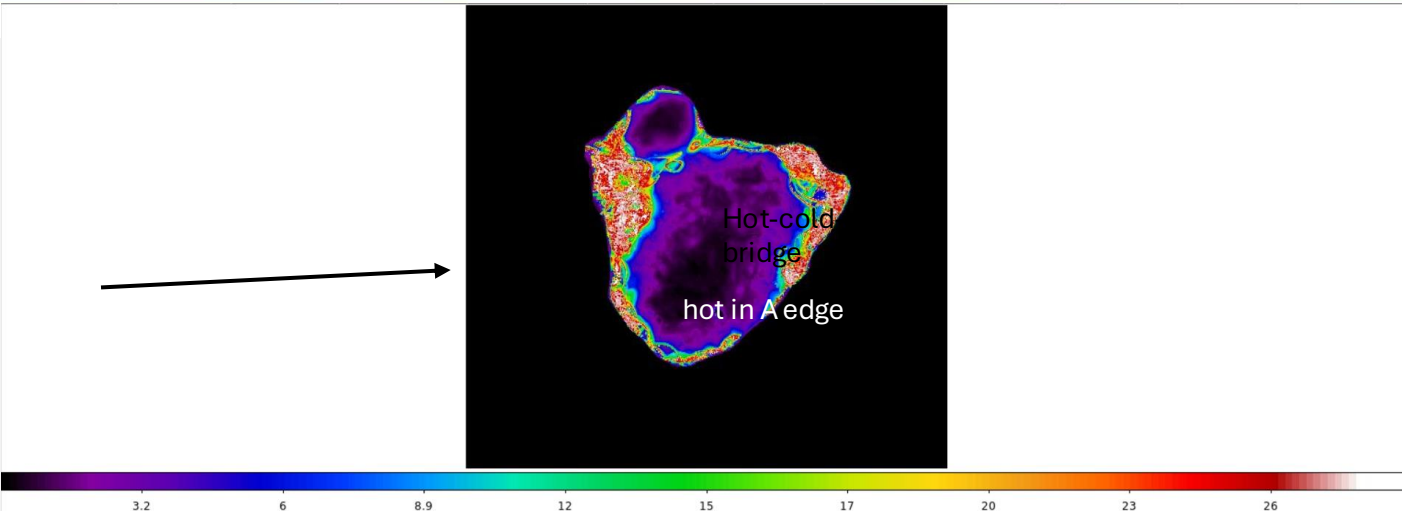
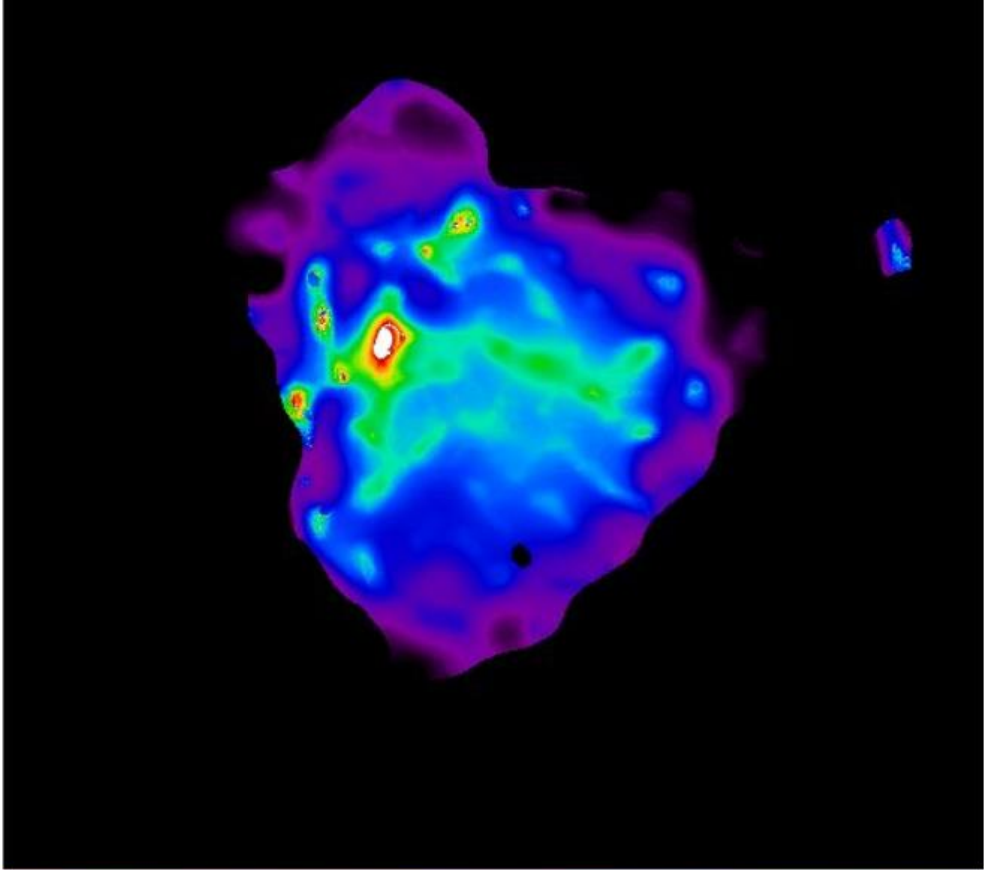
	LBA (mJy)	HBA (mJy)	MeerKAT (mJy)
Entire emission	665.83 pm 72.87	152.57 pm 16.07	13.18 pm 0.73
Halo A	334.03 pm 38.79	95.28 pm 10.24	8.18 pm 0.47
Halo B	232.05 pm 28.93	20.50 pm 2.89	2.28 pm 0.18
Bridge		37.03 pm 2.78	2.44 pm 0.17

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TAKEAWAYS



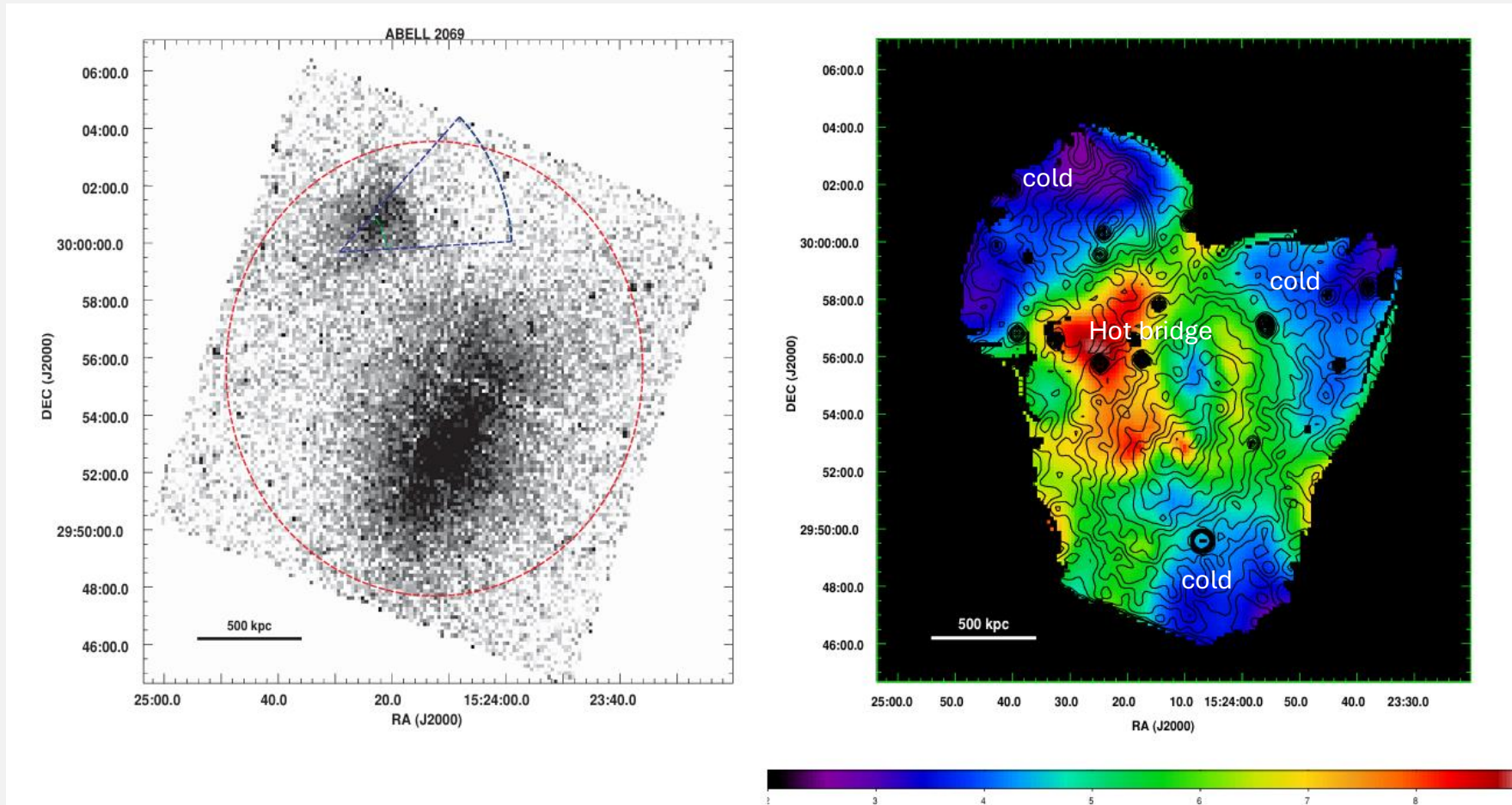
Temperature map from XMM..



- Very high error values for the bridge

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ANALYSIS FROM LITERATURE



(Owers et al 2009)

- Temp distribution is not uniform
- Component B is colder than the surrounding cannot be sure if it's cool core
- **Bridge is hot** – compression or stripped gas (also in Abell 3017-3016 Dan Hu et al 2025)
- Component A temp distribution is not clearly understandable – complicated merging