Constraining the origin of radio halos in galaxy clusters with LOFAR

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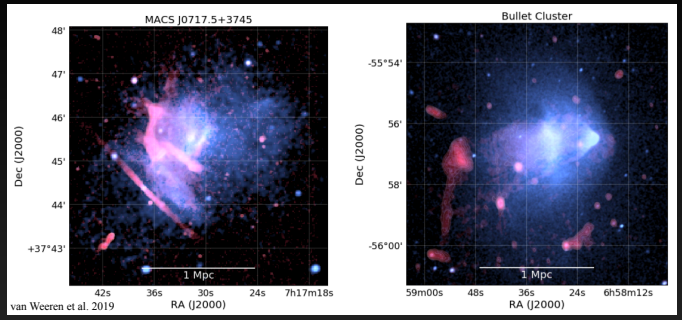
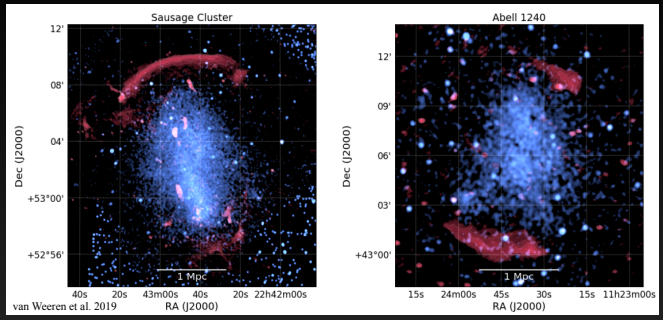
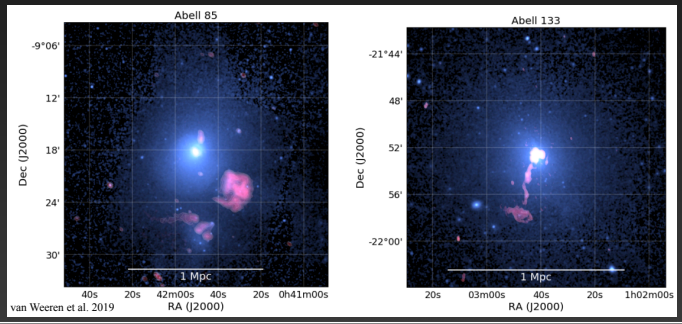
In collaboration with the LOFAR Clusters working group and the Surveys KSP

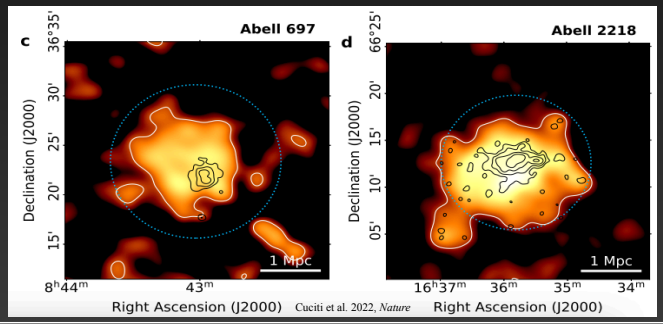
Pasini et al. 2022, A&A

Diffuse emission in galaxy clusters









Radio halos: formation models

Leptonic models:

(Major) merger

↓

MHD turbulence in cluster ICM

↓

Amplification of seed magnetic fields
Re-acceleration through Fermi-II

Main prediction:

Existence of ultra-steep spectrum RH ($\alpha < -1.5$)

Bonafede et al. 2022

Hadronic models:

Do not necessarily require mergers

Proton-proton collisions

↓

Injection of 'secondary' electrons

Main predictions:

- **Gamma-ray emission**
- **Only flat-spectrum halos**

Radio halos: challenges

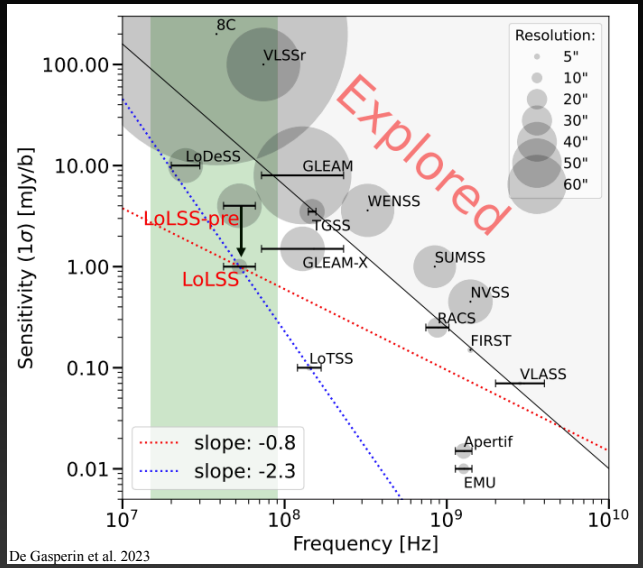
- Before LOFAR, USSRH were very rare: reality or bias?
- Necessity to use low-frequency observations to look for USSRH;
- The number of USSRH started to grow after the first LOFAR campaigns;
- No gamma-ray emission detected (e.g. Fermi);

↓

No conclusive result, although leptonic models seem favourites

LoTSS and LoLSS DR1: the HETDEX field

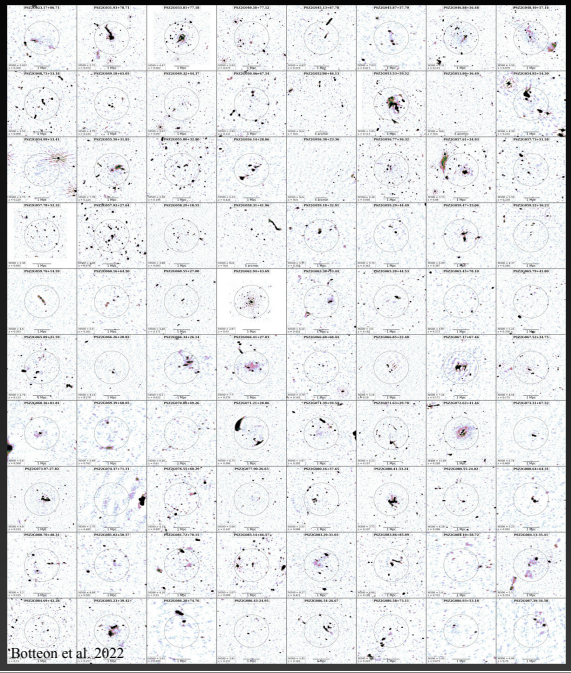
- LoTSS (144 MHz) and LoLSS (54 MHz) reach unprecedented sensitivity and resolution at (extremely) low-frequency;
- Unique opportunity to perform a spectral analysis of a large sample of radio halos, and constrain formation models;
- 50 PSZ galaxy clusters in DR1, will be extended to >300 clusters with DR2;



De Gasperin et al. 2023

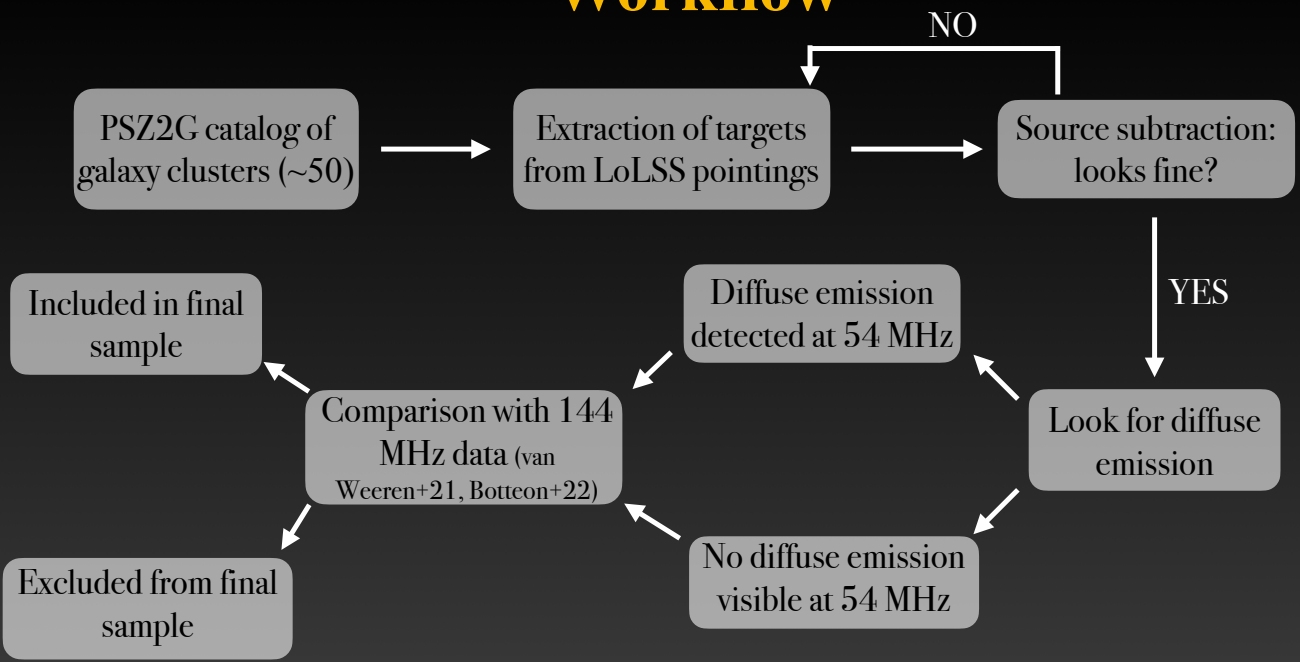
Radio halos at 144 MHz: DR1 and DR2

- A census of radio halos detected by LoTSS has recently been made for DR1 (van Weeren+21) and for DR2 (Botteon+22);
- DR1: 10 radio halos, 12 candidates;
- DR2: 83 radio halos (including candidates - e.g. no X-ray data available);
- We aim to do the same for LoLSS (DR1 coverage slightly larger than LoTSS);

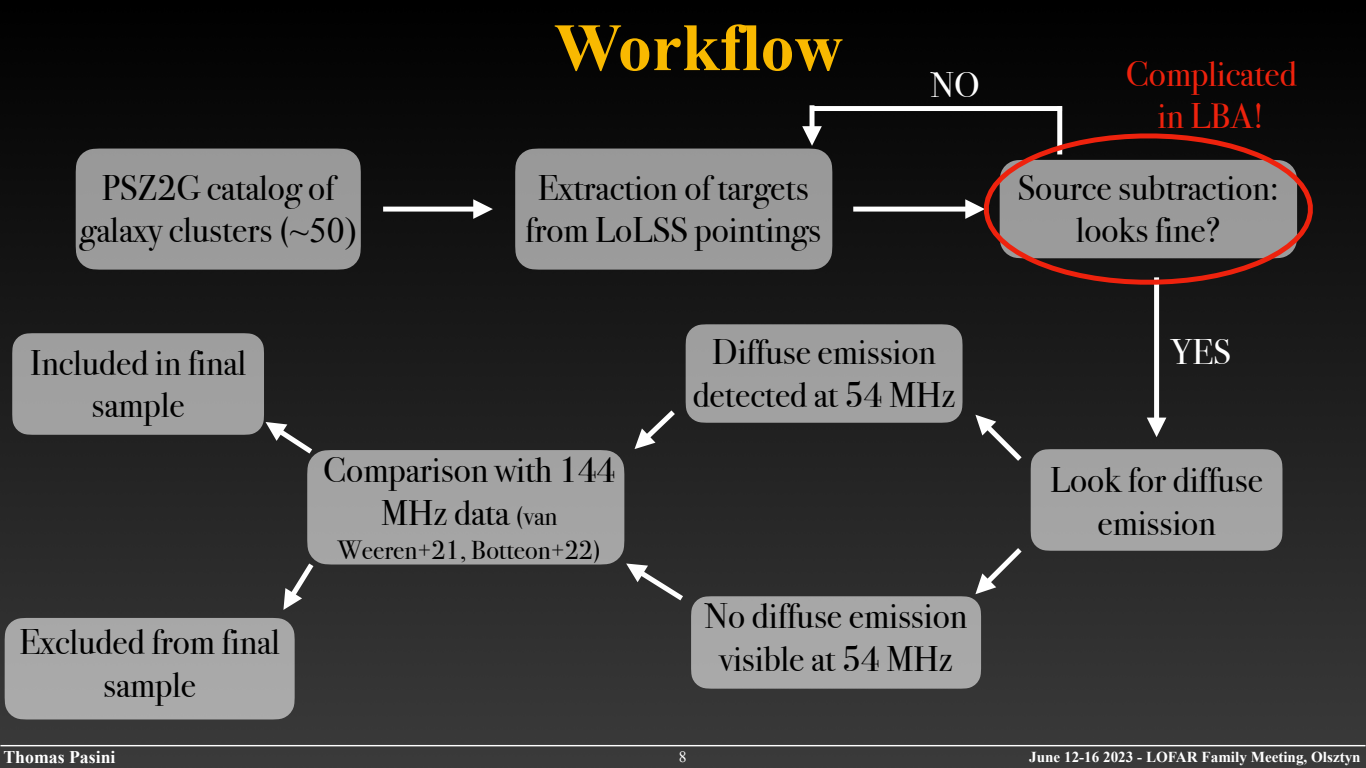


Botteon et al. 2022

Workflow


NO
PSZ2G catalog of galaxy clusters (~50)
Extraction of targets from LoLSS pointings
Source subtraction: looks fine?
YES
Look for diffuse emission
Diffuse emission detected at 54 MHz
Included in final sample
Comparison with 144 MHz data (van Weeren+21, Botteon+22)
No diffuse emission visible at 54 MHz
Excluded from final sample

Workflow


NO
Complicated in LBA!
PSZ2G catalog of galaxy clusters (~50)
Extraction of targets from LoLSS pointings
Source subtraction: looks fine?
YES
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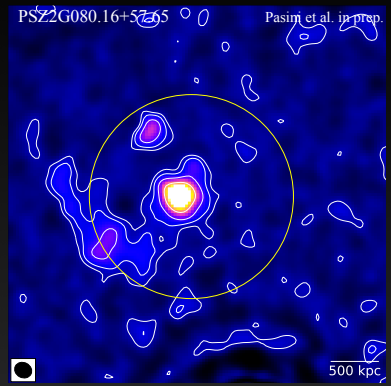
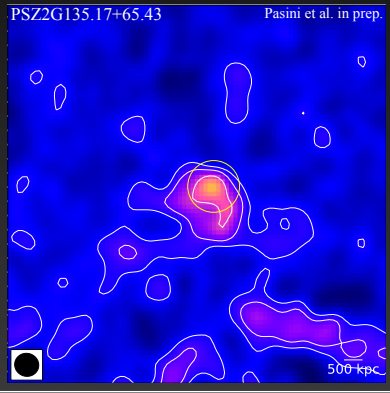
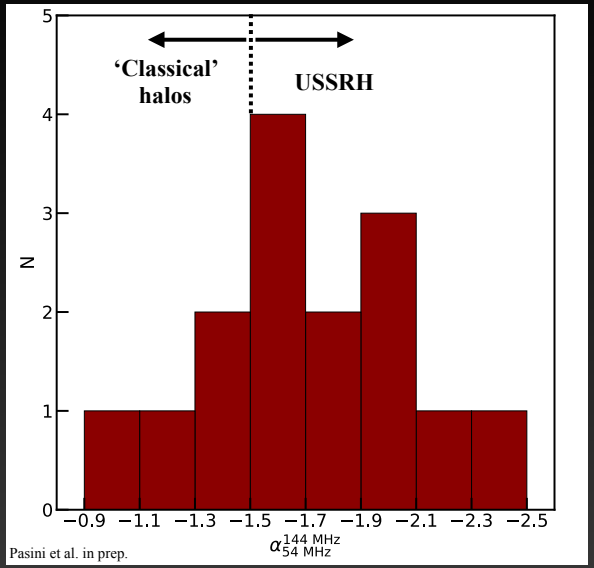
Flux density and spectral index

- We need to measure the flux density at the two frequencies within the exact same region (e.g. no Halo-FDCA);
- We estimate it within 3 HBA e-folding radii (Botteon+22);
- We mask spurious sources when present, and compare our results with flux density measurements from Botteon+22;





Spectral index of radio halos: results

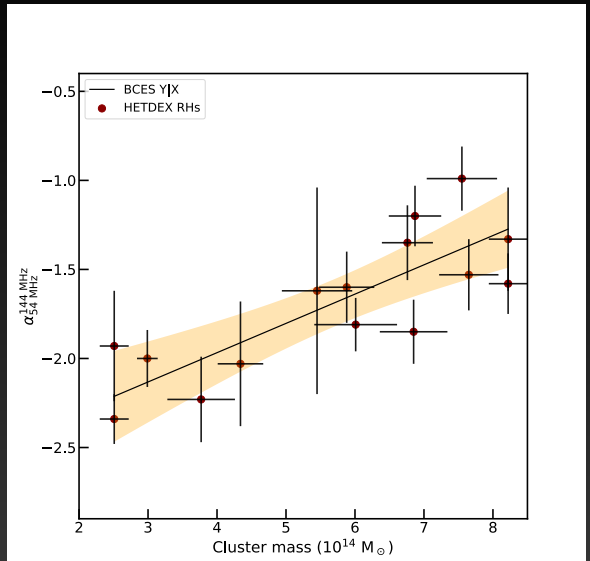


- The final sample includes 14 galaxy clusters hosting 15 radio halos (A1758 hosts two);
- Out of 15 halos, 11 (75%) shows $\alpha < -1.5$ and are classified as USSRH;
- The majority of radio halos detected at low-frequency have a steep spectrum!

Agreement with leptonic models, hard to explain if purely hadronic origin;

A correlation between mass and spectral index?

- If turbulent origin (e.g. mergers are involved), some kind of connection between mass and spectral index is expected;
- Surprisingly clear trend between cluster mass and halo spectral index;
- We need a larger sample (DR2!) to accurately assess the existence of the correlation;
- Furthermore, we need to work on reproducing the observed trend with our models;



Pasini et al. in prep.

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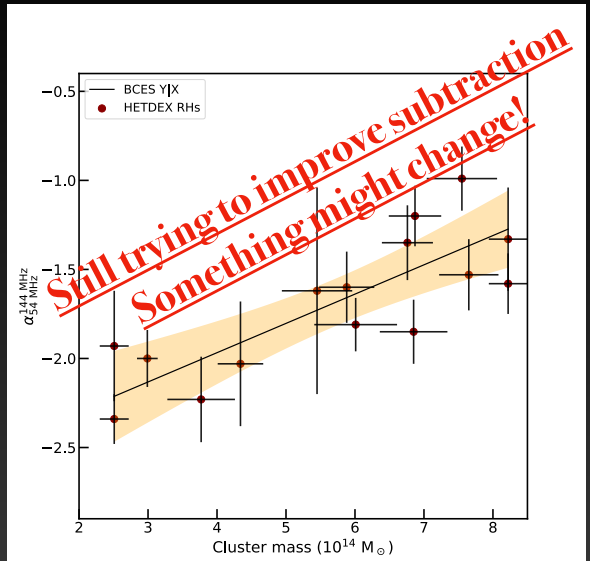
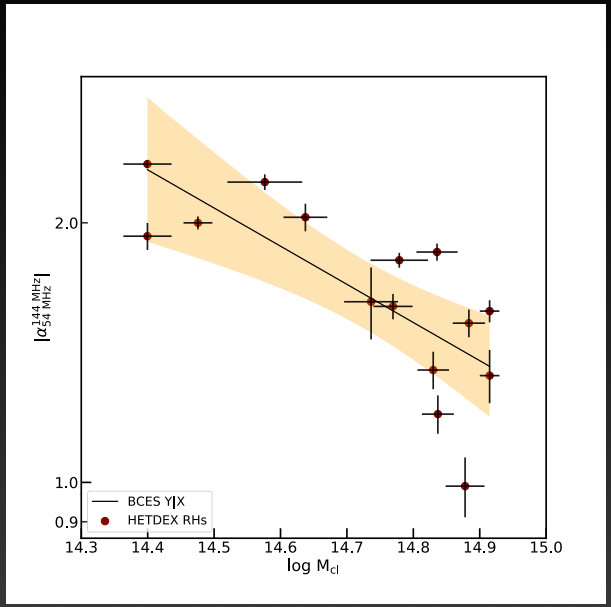


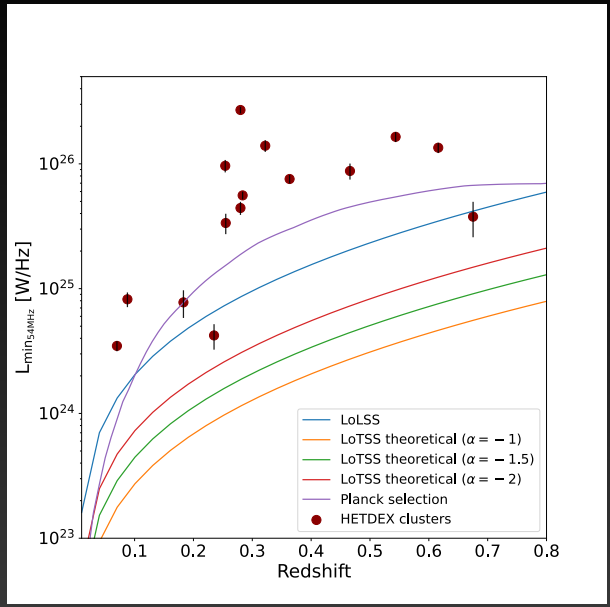
Pasini et al. in prep.

Conclusions

- Thanks to LOFAR (specifically LoTSS and LoLSS), we are able to perform the first low-frequency spectral index study of a relatively large sample of radio halos;
- We measure the flux density at both frequencies in a region that encompasses 3 e-folding radii, and calculate the spectral index;
- Out of 15 radio halos, 11 (75%) shows $\alpha < -1.5$, and are therefore classified as USSRH;
- We find a clear trend between cluster mass and halo spectral index, with more massive clusters hosting flatter halos (but we need more data!);
- Our results strongly support turbulent models, while purely hadronic models struggle to explain what observed.

Backup


2.0
1.0
0.9
$|\alpha_{54\ MHz}^{144\ MHz}|$
14.3
14.4
14.5
14.6
14.7
14.8
14.9
15.0
log M_{cl}
BCES Y|X
HETDEX RHs


10^{26}
10^{25}
10^{24}
10^{23}
$L_{min_{54MHz}}$ [W/Hz]
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Redshift
LoLSS
LoTSS theoretical ($\alpha = -1$)
LoTSS theoretical ($\alpha = -1.5$)
LoTSS theoretical ($\alpha = -2$)
Planck selection
HETDEX clusters