Galaxy clusters in the LOFAR Two-meter Sky Survey (LoTSS)

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

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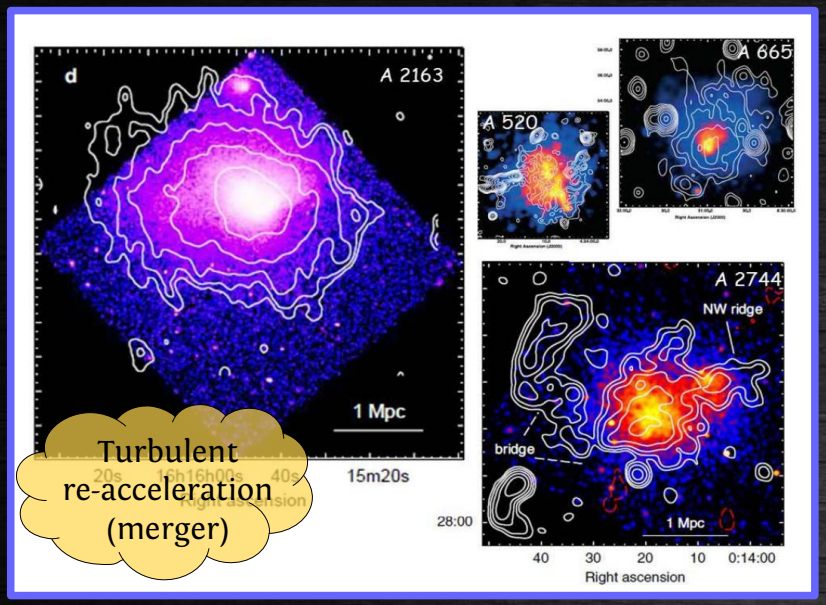
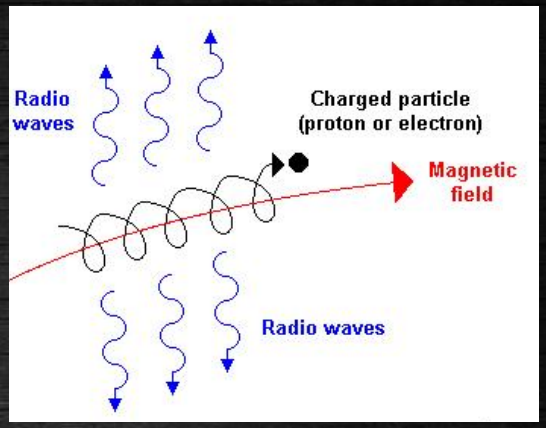
Radio halos and relics

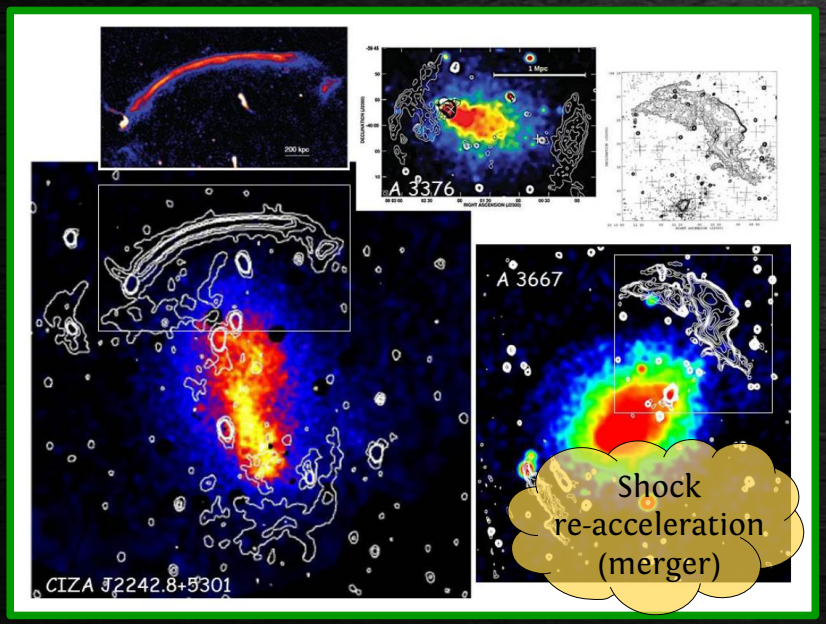


Brunetti+Jones14, vanWeeren+19 for reviews

HALOS



- *Low SB*
- *No optical counterpart*
- *Not ubiquitous*
- *α>1, with $S_\nu \propto \nu^{-\alpha}$*



RELICS

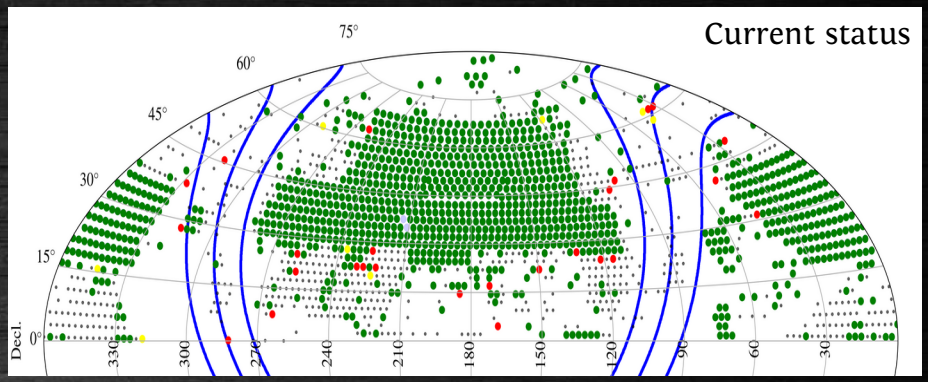
GMRT

VLA

WSRT

GMRT, VLA, WSRT studies have been focused mainly on *massive* (M_{500} > 5 x 10^{14} $M_\odot$) and *nearby* (z < 0.4) clusters

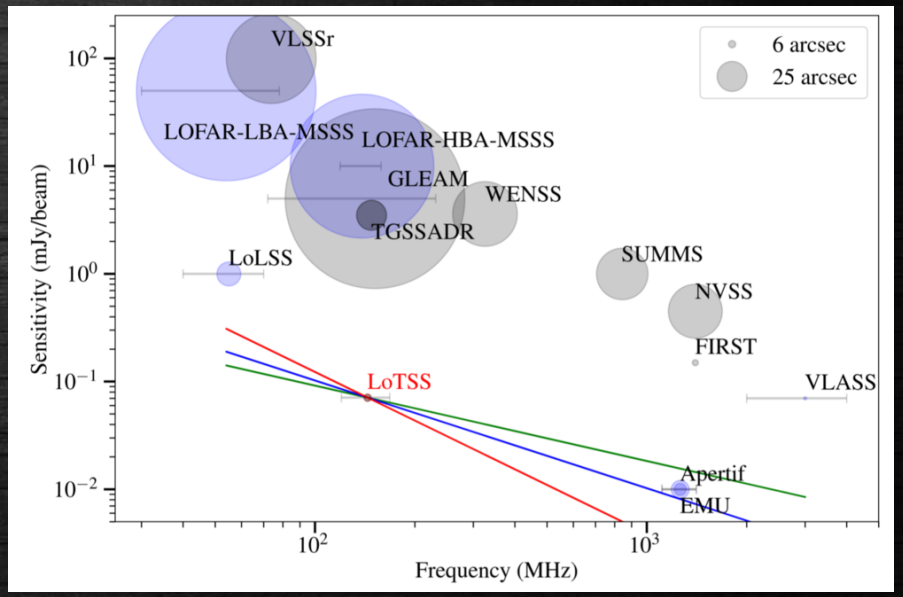
LOFAR Two-meter Sky Survey



LOFAR Two-metre Sky Survey (LoTSS):

- *frequency 120-168 MHz*
- *resolution 6”*
- *rms 100 μJy/beam*
- *FoV 6.4 deg²*
- *3170 pointings*
- *8 hr observations*

(Shimwell+17,19)



Study and detection of *new* **diffuse radio sources** in galaxy clusters

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+

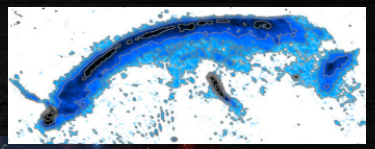
5. *LOFAR discovery of an ultra-steep radio halo and giant head-tail radio galaxy in Abell 1132,* Wilber+
6. *Search for low-frequency diffuse radio emission around a shock in the massive galaxy cluster MACS J0744.9+3927,* Wilber+
7. *Discovery of large-scale diffuse radio emission in low-mass galaxy 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+

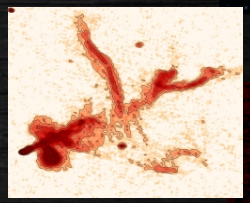
12. *The spectacular cluster chain Abell 781 as observed with LOFAR, GMRT and XMM-Newton,* Botteon+
13. *Ultra-steep spectrum emission in the merging galaxy cluster Abell 1914,* Mandal+
14. *A LOFAR study of non-merging massive galaxy clusters,* Savini+
15. *The evolutionary phases of merging clusters 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+

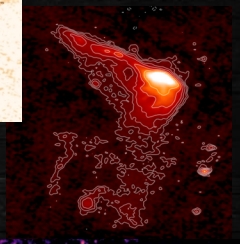
22. *Revived fossil plasma sources in galaxy clusters,* Mandal+
23. *LOFAR observations of X-ray cavity systems,* Birzan+
24. *The beautiful mess in Abell 2255,* Botteon+
25. *Reaching thermal noise at ultra-low radio frequencies. The Toothbrush radio relic downstream of the shock front,* de Gasperin+
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,* Ignesti+

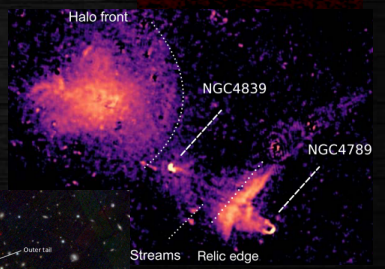
28. *Fast magnetic field amplification in distant galaxy clusters,* Di Gennaro+
29. *LOFAR detection of a low-power radio halo in the galaxy cluster Abell 990,* Hoang+
30. *The Coma cluster at LOw Frequency ARray Frequencies: I. Insights into particle acceleration mechanisms in the radio bridge,* Bonafede+
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,* Rajpurohit+
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,* Roberts+
36. *Radio relics in PSZ2 G096.88+24.18: a connection with pre-existing plasma,* Jones+
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,* Botteon+
39. *LoTSS jellyfish galaxies. II. Ram pressure stripping in groups versus clusters,* Roberts+
40. *Abell 1430: A merging cluster with exceptional diffuse radio emission,* Hoeft+
41. *The eROSITA Final Equatorial-Depth Survey (eFEDS). LOFAR view of brightest cluster galaxies and AGN feedback,* Pasini+
42. *A unique snapshot of the oldest AGN feedback phases,* Brienza+
43. *A LOFAR-uGMRT spectral index study of distant radio halos,* Di Gennaro+
44. *The ultra-steep diffuse radio emission observed in the cool-core cluster RX J1720.1+2638 with LOFAR at 54 MHz,* Biava+
45. *A 3.5 Mpc-long radio relic in the galaxy cluster ClG 0217+70,* Hoang+

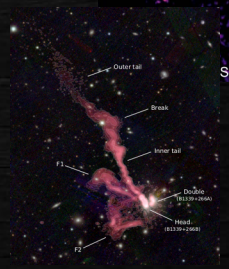
2016 2017 2018 2019 2020 2021





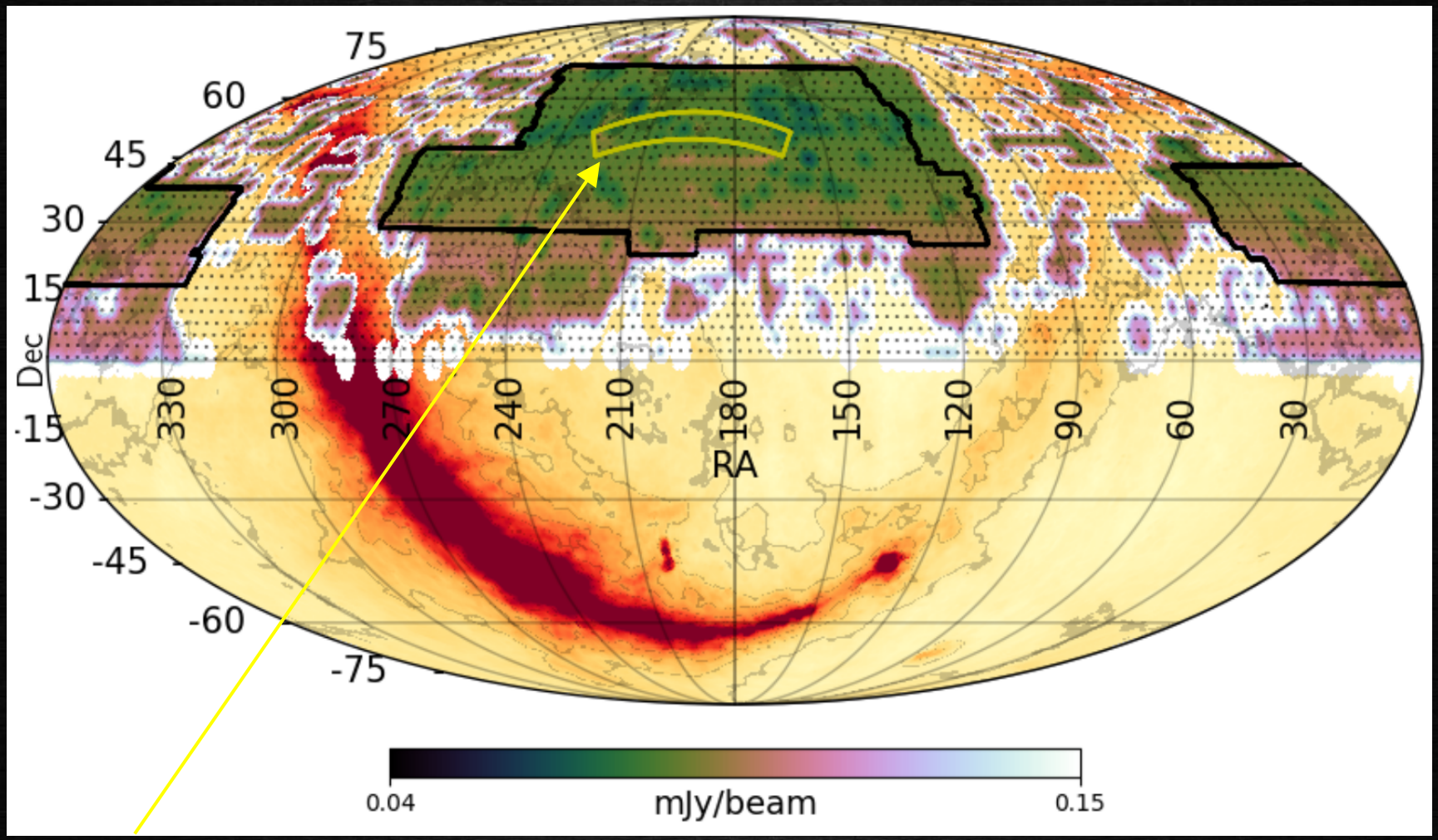






LoTSS DR1 & DR2

The first LoTSS DR occurred in *February 2019*

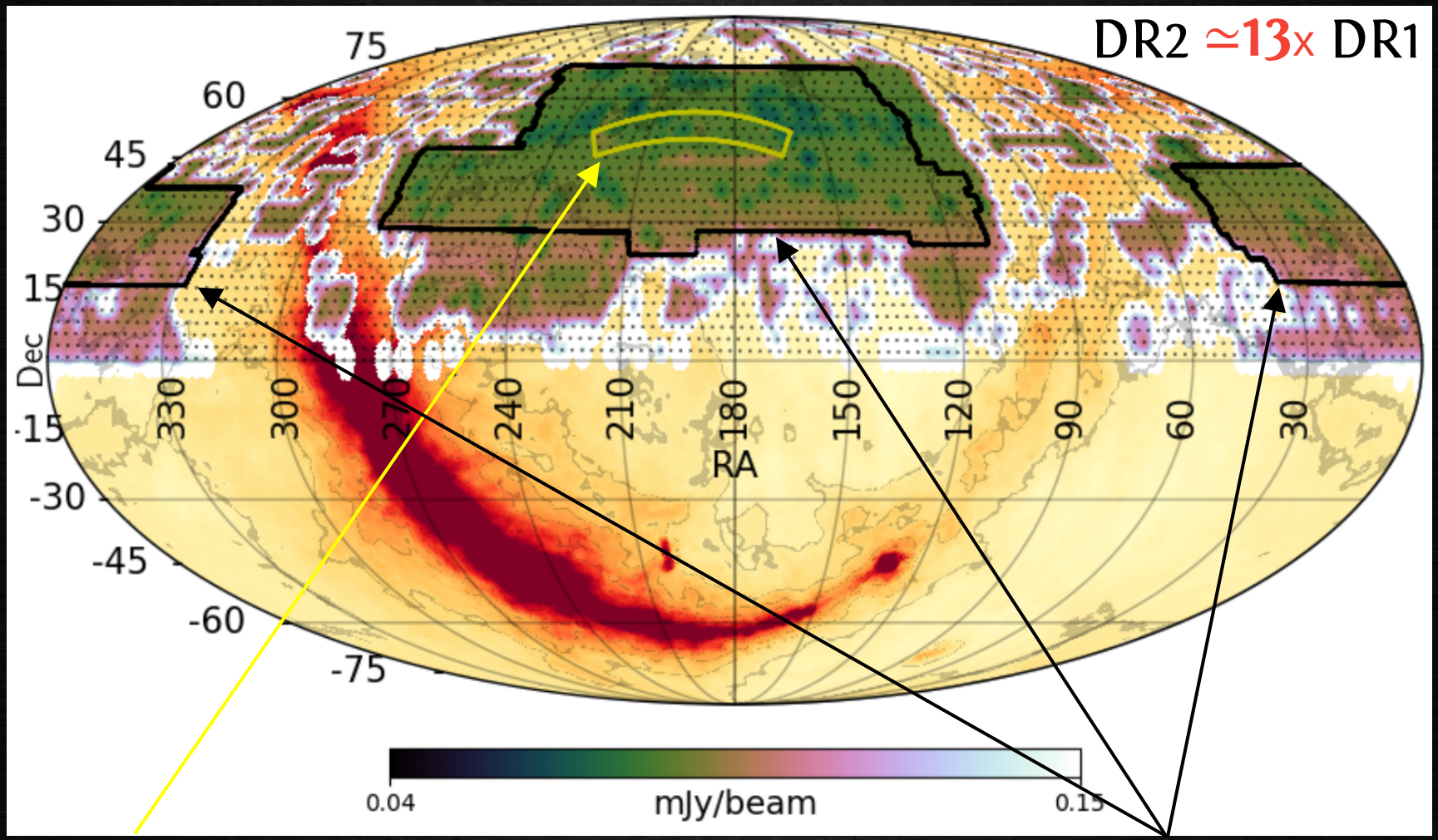


LoTSS-DR1 (Shimwell+19):

- *424 deg²*
- *325,694 sources detected*

LoTSS DR1 & DR2

The **second** LoTSS DR will occur in the *early 2022*



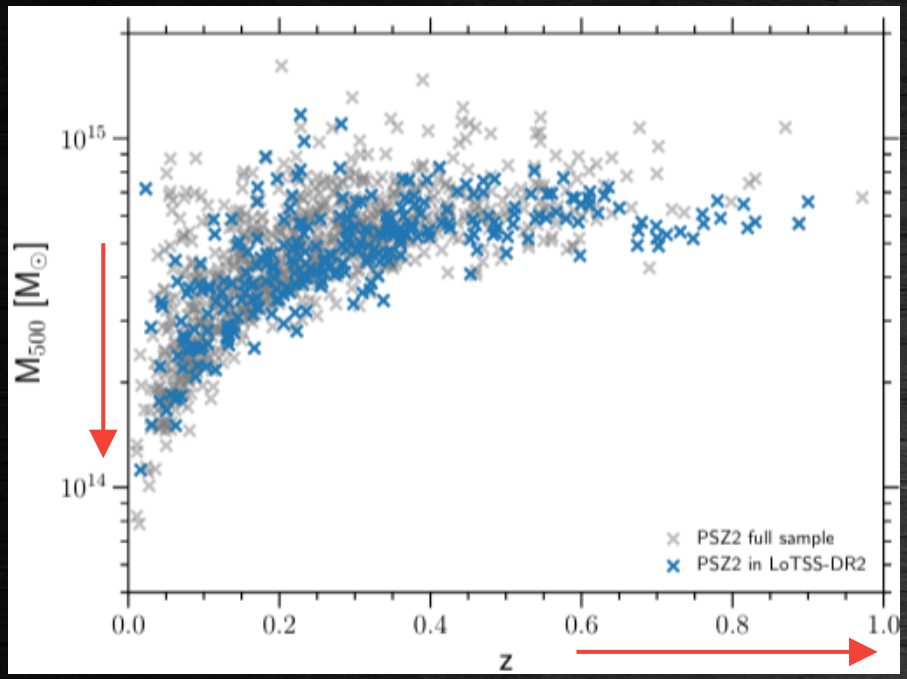
LoTSS-DR1 (Shimwell+19):

- *424 deg²*
- *325,694 sources detected*

LoTSS-DR2 (Shimwell+, in prep.):

- *5,634 deg²*
- *4,395,448 sources detected*

LoTSS-DR2/PSZ2 sample

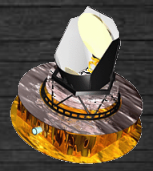


LoTSS-DR2 sample

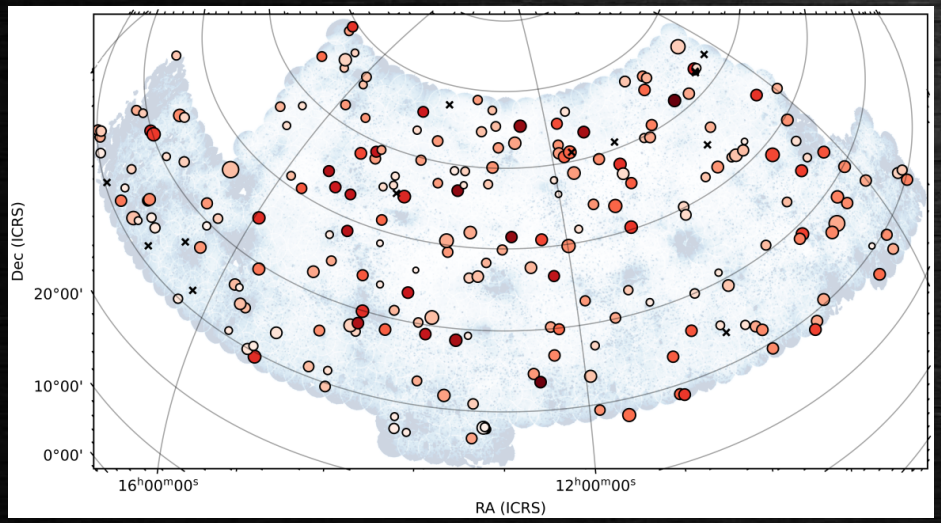
(Botteon+, in prep.)

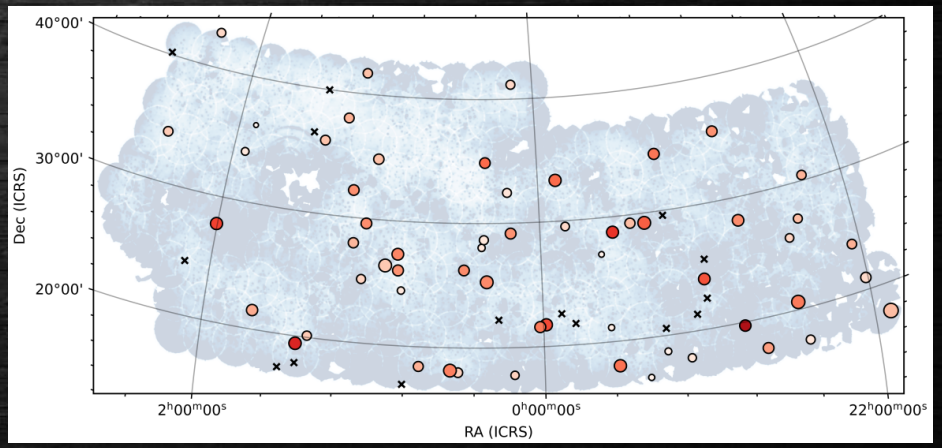
- *309 PSZ2 clusters*
- *12x more than in LoTSS-DR1* (vanWeeren+21)

Statistical analysis of **309** PSZ2 galaxy clusters exploring new ranges of *redshift* and *mass*

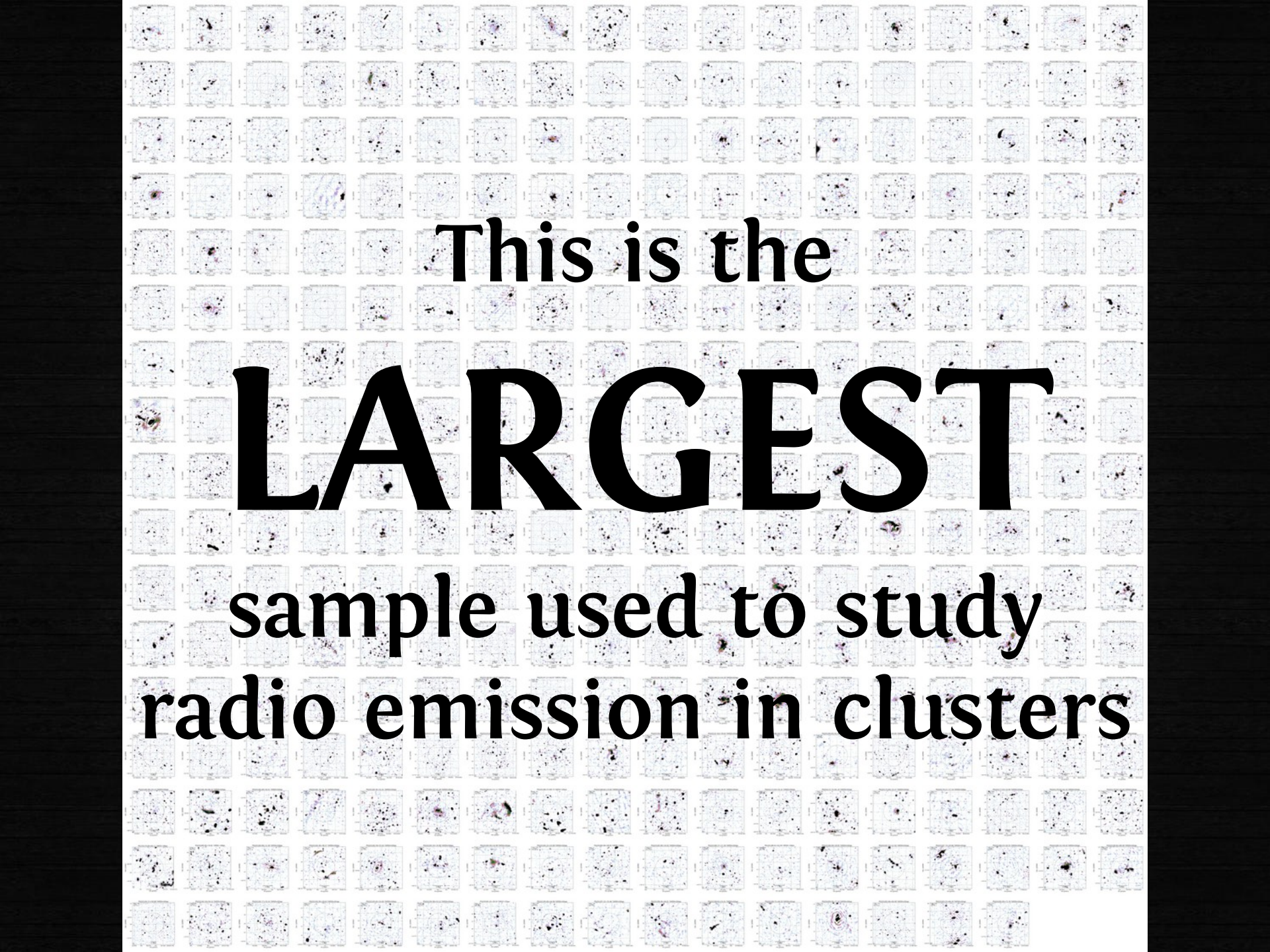


Planck provides a cluster sample that is close to be *mass-selected*





Circle ∝ M_{500}
Color ∝ z


This is the
LARGEST
sample used to study
radio emission in clusters

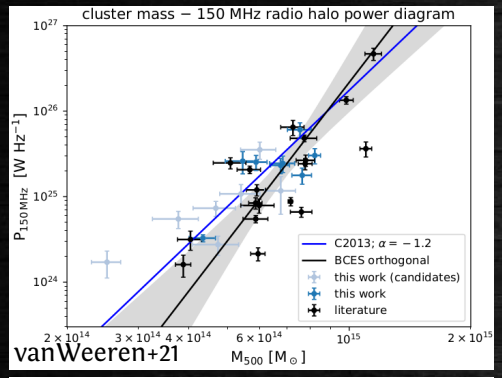
Goal

Understanding the origin of *diffuse* synchrotron sources in the **ICM**

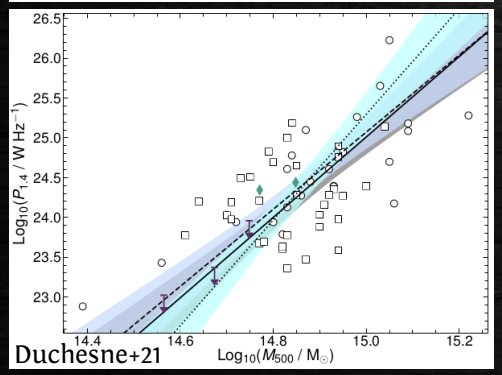
Compare with *statistical expectations* of models, study the *evolution*, the role of *mergers* and of *secondary processes* to probe the origin of **CRs** and **B** in clusters

Moving from *20-30* clusters to **300+**
...a *critical* improvement for statistics!

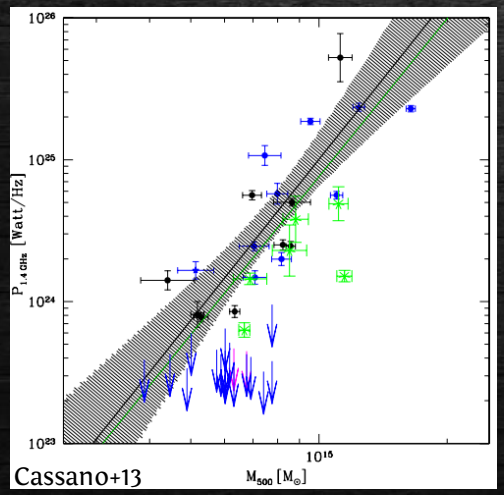
Scaling relations



vanWeeren+21

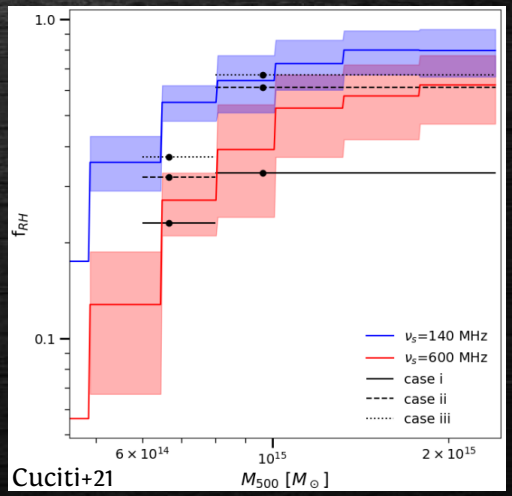


Duchesne+21



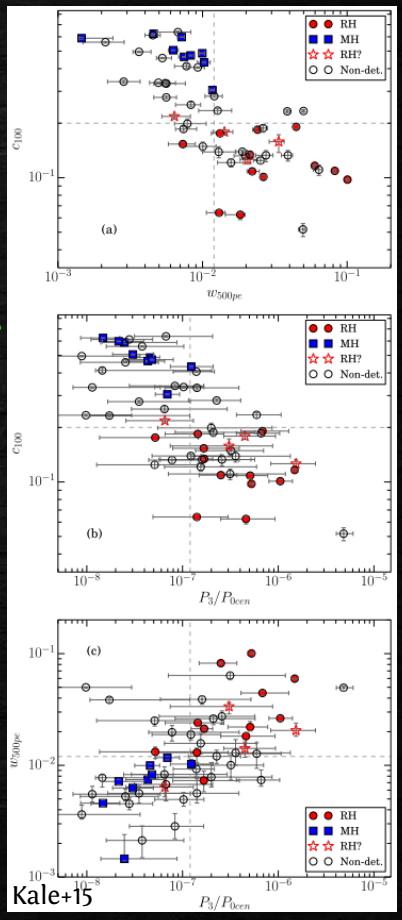
Cassano+13

Occurrence



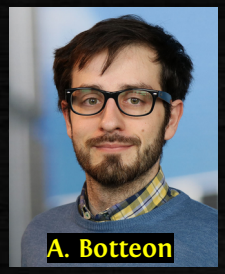
Cuciti+21

Connection with dynamical state



Kale+15

A collaborative effort

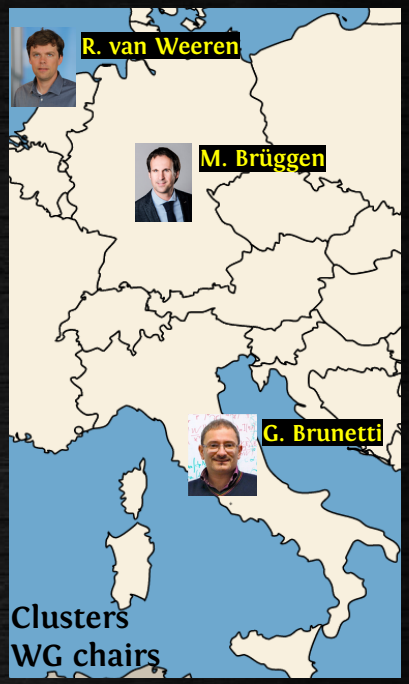


Radio group

X-ray group

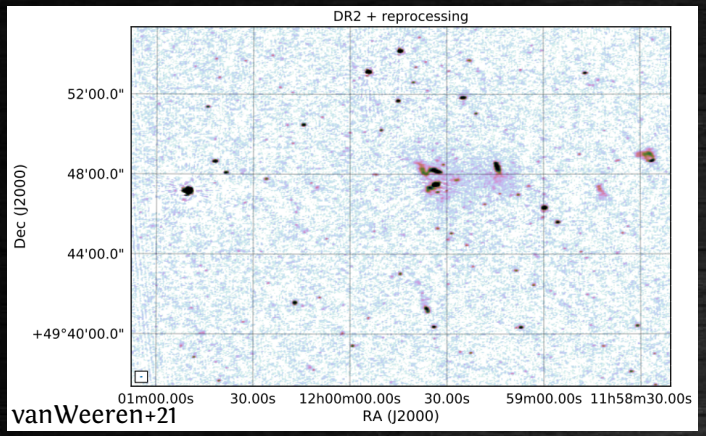
A group spread over three countries

Italy (INAF-IRA Bologna+INAF-IASF Milano), *Germany* (Hamburg), *Netherlands* (Leiden+SRON)



- **Paper I**: Presentation of the sample and new detections (Botteon+)
- **Paper II**: Occurrence of radio halos wrt mass and dynamical state (Cassano+)
- **Paper III**: Scaling relations of radio halos (Cuciti+)
- **Paper IV**: Statistical properties of radio relics (Jones+)
- **Paper V**: Methods to infer upper limits on the diffuse emission (Bruno+)
- **Paper VI**: X-ray study of the sample (Zhang+)
- ....

Images



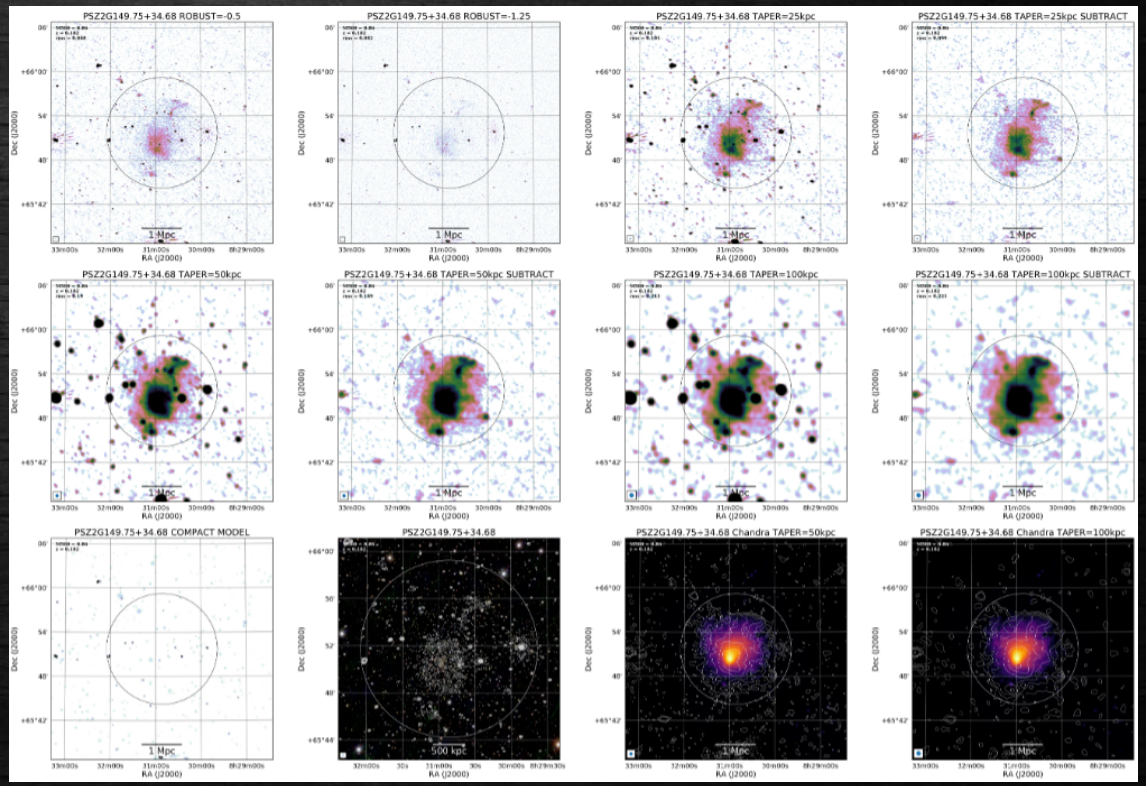
For selected targets, we can improve the *image quality* compared to that of **LoTSS-DR2**

"Extraction+selfcal" method (vanWeeren+21)

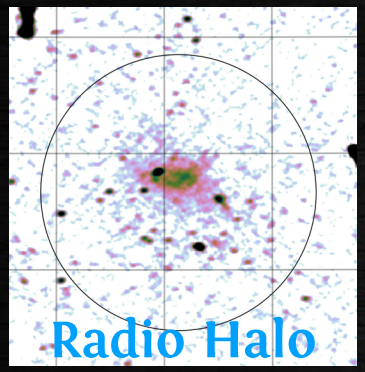
Each cluster was **re-processed** to *improve* the calibration towards its direction, and a number of images were produced for *science*:

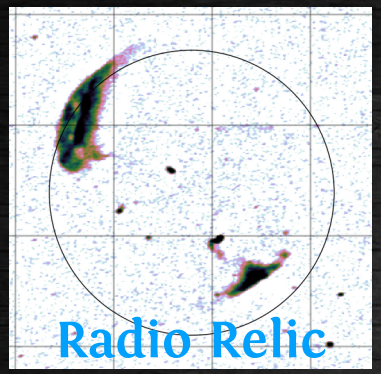
1) LoTSS-like image
2) High-resolution image
3) 25 kpc res images (with/without sources)
4) 50 kpc res images (with/without sources)
5) 100 kpc res images (with/without sources)
6) Model of compact sources
7) Optical overlay
8) Chandra/XMM overlays

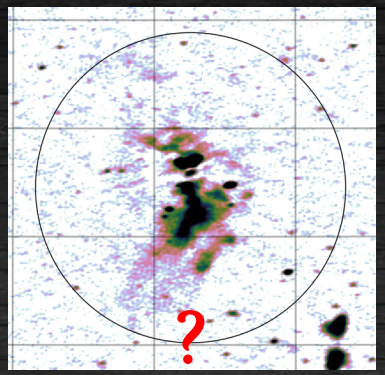
FITS images will be **publicly** available

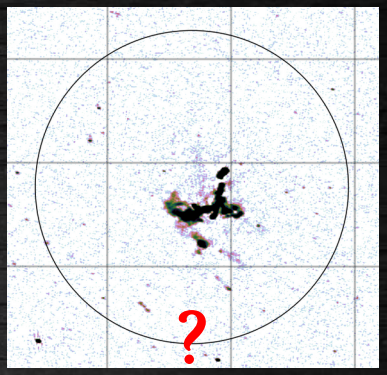


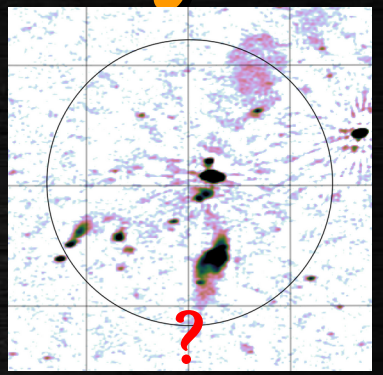
Classification is not easy





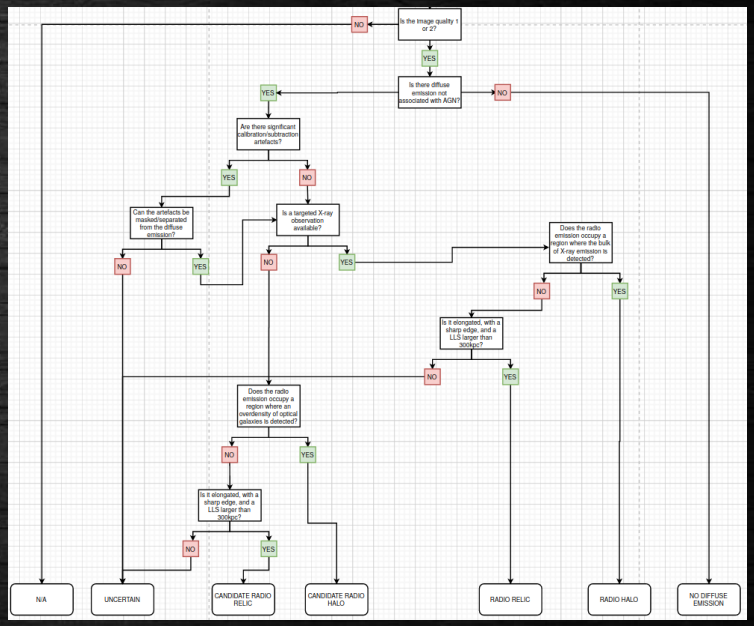




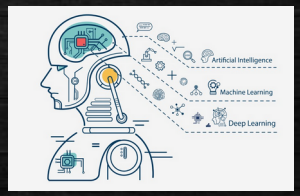


Classification of sources done by 4 persons (Botteon, Cassano, Cuciti, Shimwell), using a *decision tree* to be as **objective** as possible

- *No diffuse emission* (NDE)
- *Radio halos* (RH) → (candidate, if X-ray is missing)
- *Radio relics* (RR) → (candidate, if X-ray is missing)
- *Uncertain* (U)
- *Not applicable* (N/A)

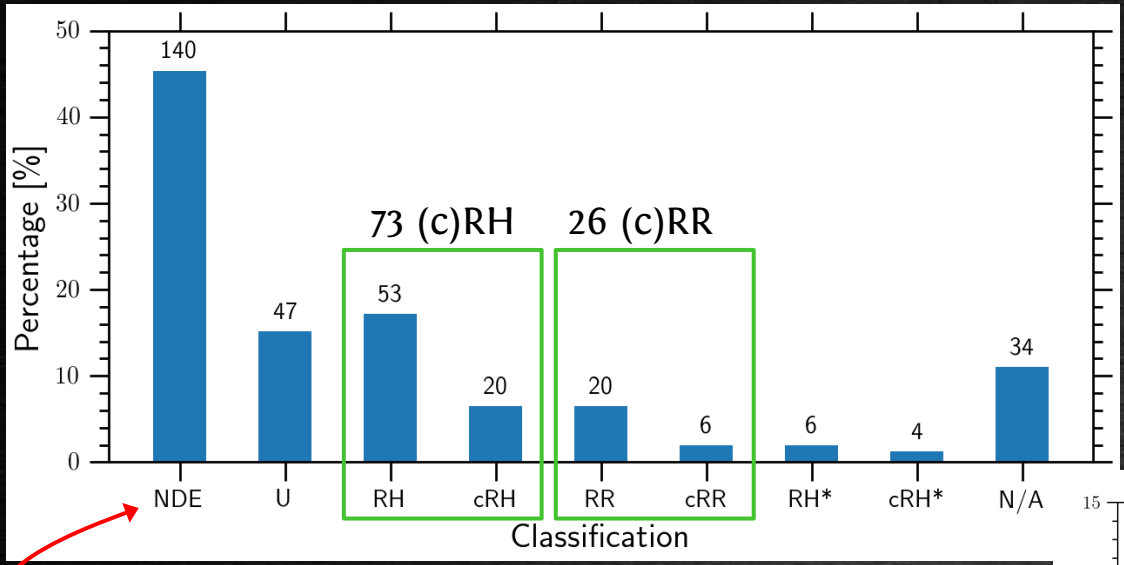


This will be *problematic* with **SKA** with $>10^3$ clusters to study



Automated methods?
Citizen science?

Results

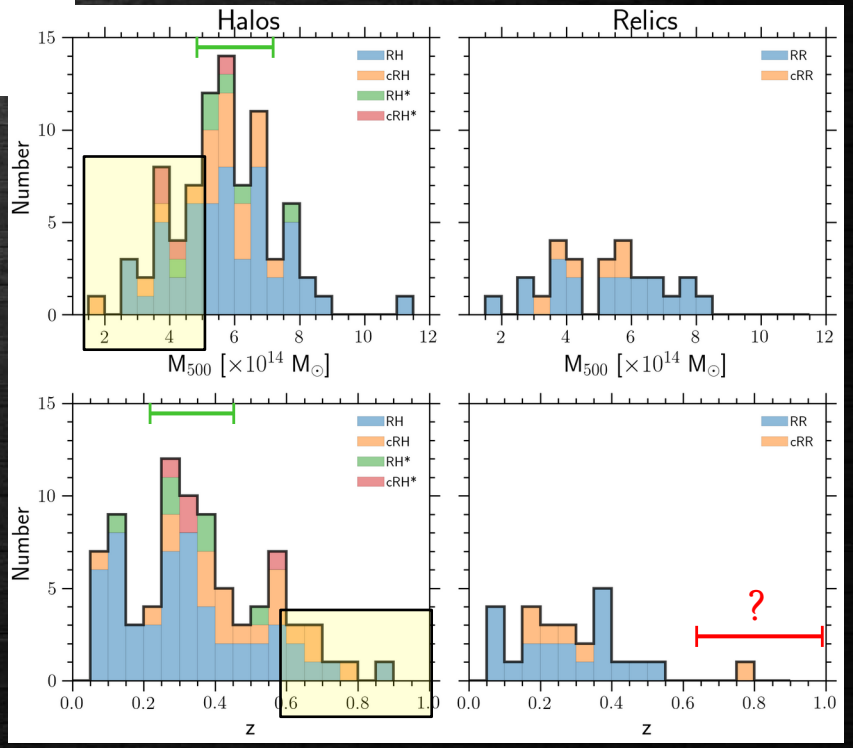


About *half* of the *(c)RH* and *(c)RR* are **new discoveries**!

About half of the clusters in the sample does not host diffuse emission not associated with AGN

→ Computation of **UL**

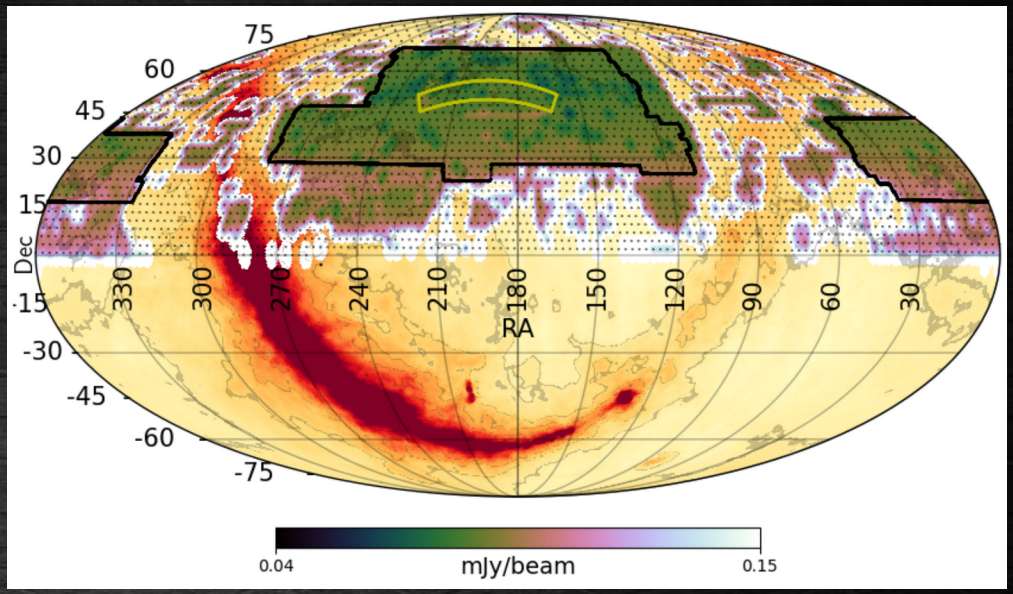
With **LOFAR**, we are expanding the "parameter space" of *galaxy cluster studies*



Predictions

The fraction of **RH** and **RR** is **21%** and **7%**, respectively, and increases to **27%** and **10%** if *candidates* are also included

Using **DR2** results to predict what LoTSS will detect at its *completion*



LoTSS should find:

~**260** halos

~**84** relics

x1.3

x30

Predictions from **models**:

~**350** halos (Cassano+10)

~**2500** relics (Nuza+12)

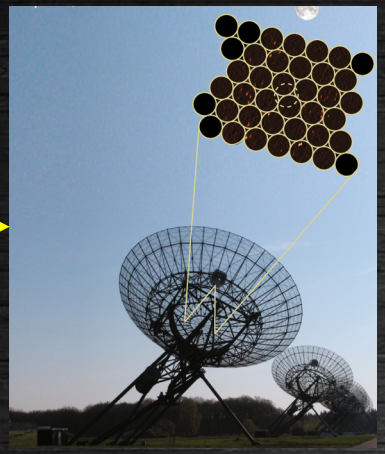
Halos: turbulent re-acceleration can explain the number of halos

Relics: shock acceleration in the ICM does not work as we thought

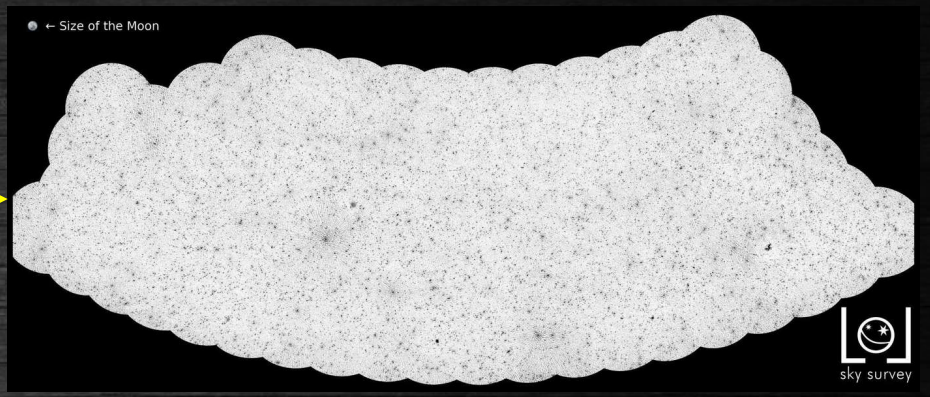
More details in Papers II, III, IV

Synergies with other surveys

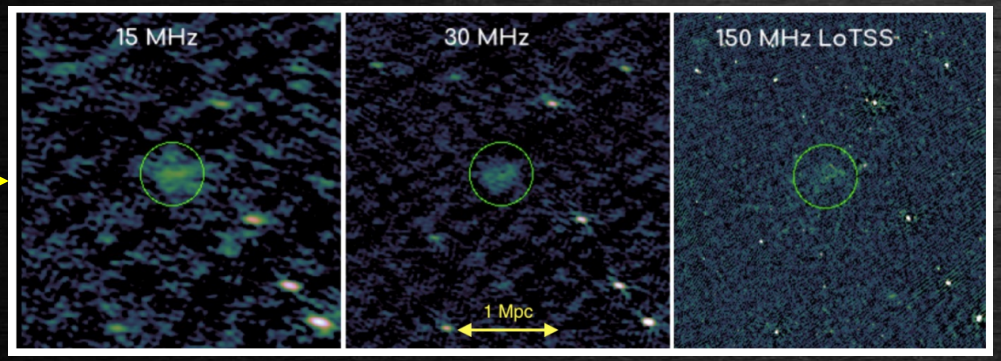
Apertif @ *1.4 GHz*
(Hess+, in prep.)



LoLSS @ *54 MHz*
(deGasperin+21)

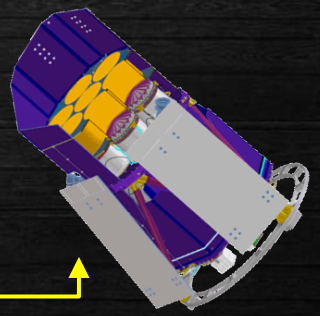


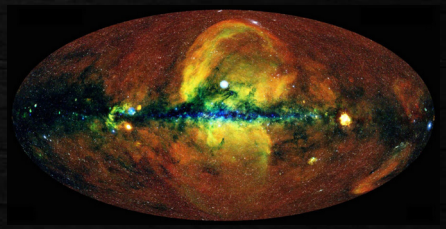
LoDSS @
15-30 MHz
(PI: vanWeeren)



Fundamental for
spectral studies

eROSITA All Sky Survey
detections of more *low-mass* and *high-z* clusters





Conclusions

- **LOFAR** is the *largest* pathfinder of the **SKA** at low-frequency
- **LoTSS-DR2** will occur in *early 2022*: *5600 deg²* and *4.4M sources*
- Great interest and participation of the **Italian** community working on *galaxy clusters*

- Analysis of **309** PSZ2 clusters in LoTSS-DR2
- **99** (c)RH+(c)RR, about *half* of them are **new discoveries**
- New ranges of *mass* and *redshift*

- Results will be presented in *a series of papers*
- Images will be **publicly** available

Thank you