

Galaxy clusters with LOFAR: recent results and new perspectives

LOFAR Annual Meeting 2026

11 June 2026

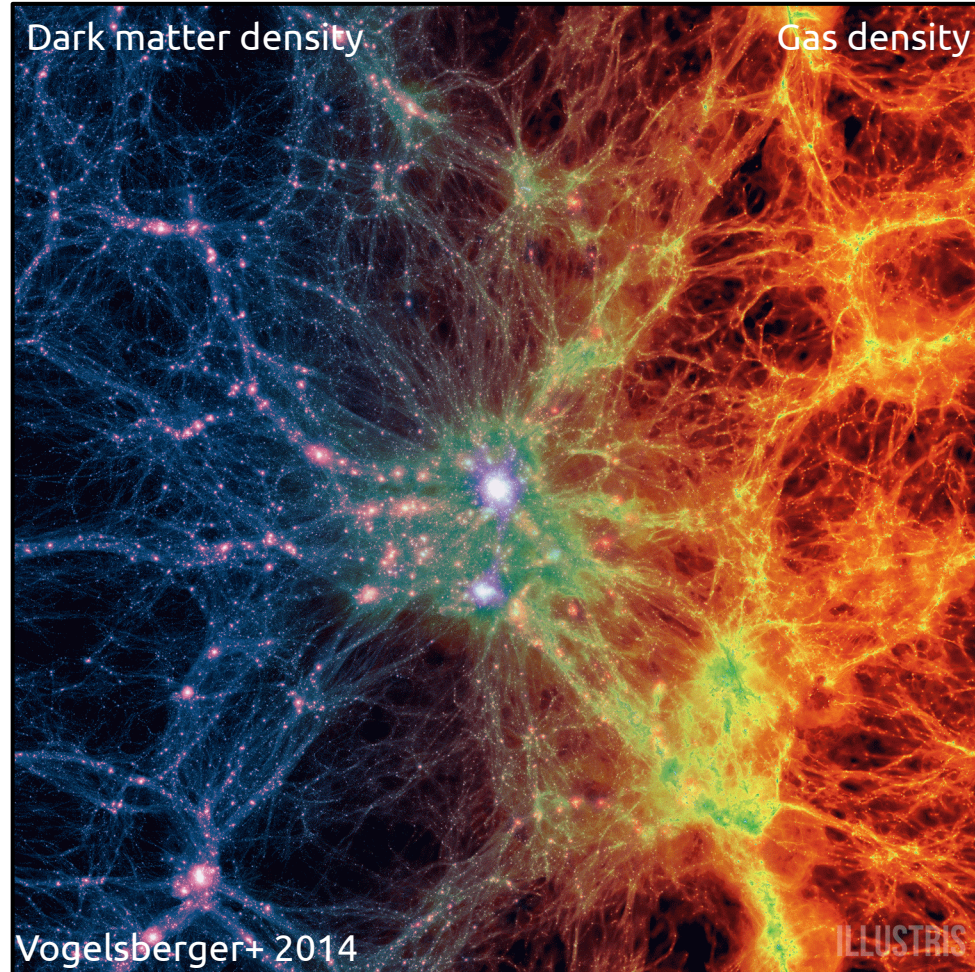
Chiara Stuardi

INAF - Istituto di Radioastronomia (Italy)

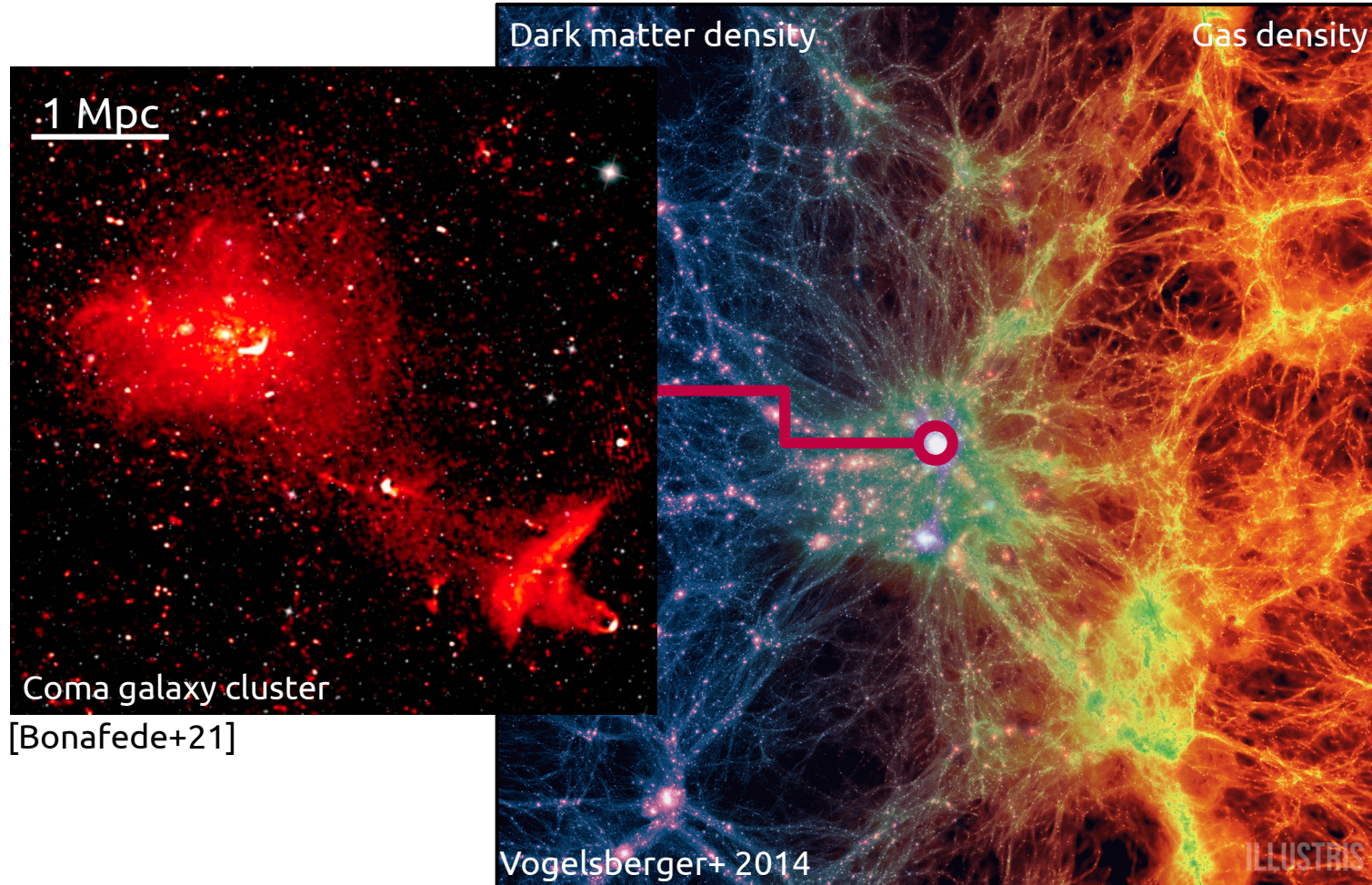
With: LOFAR Surveys Galaxy Clusters Scientific Working Group

They are at the nodes of the cosmic web

Galaxy clusters are ideal laboratories to study large-scale structure formation processes and plasma physics



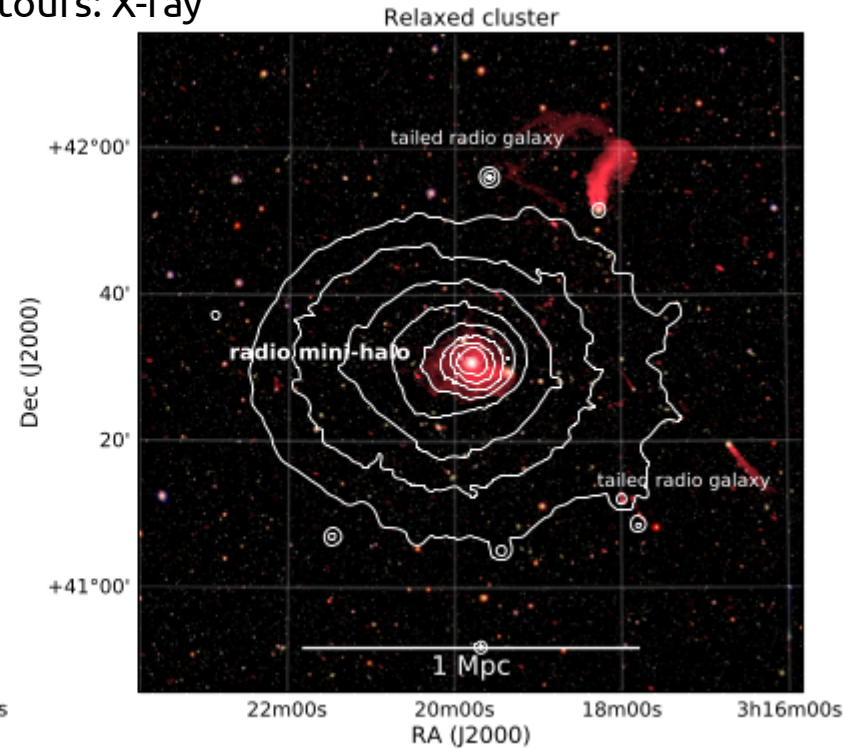
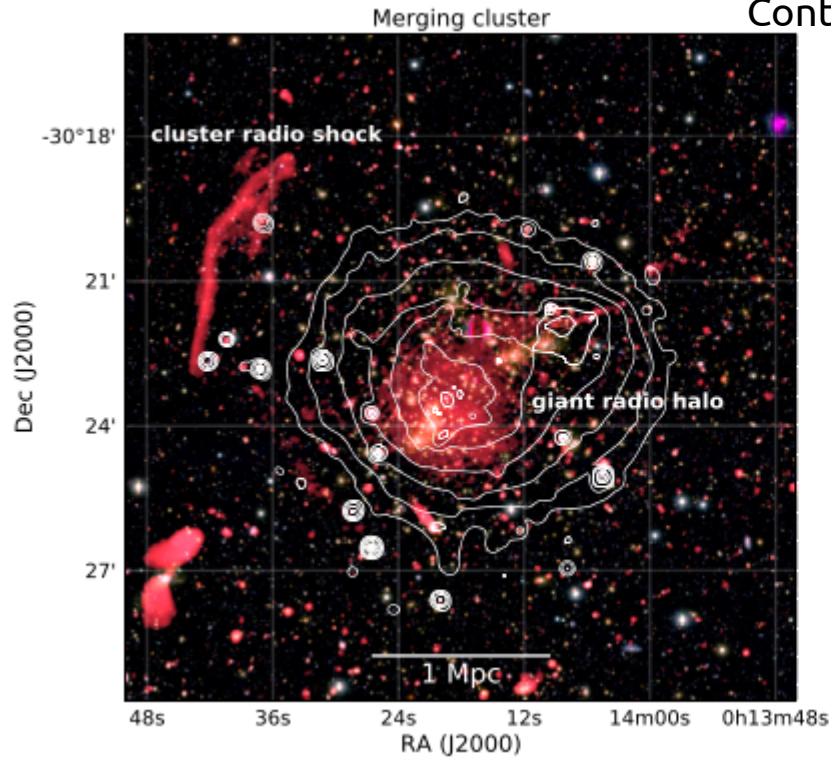
Some of them exhibit diffuse synchrotron radio emission



Diffuse radio sources provide evidences of **μG magnetic fields** and **GeV electrons** on **Mpc scales**

Traditionally classified as

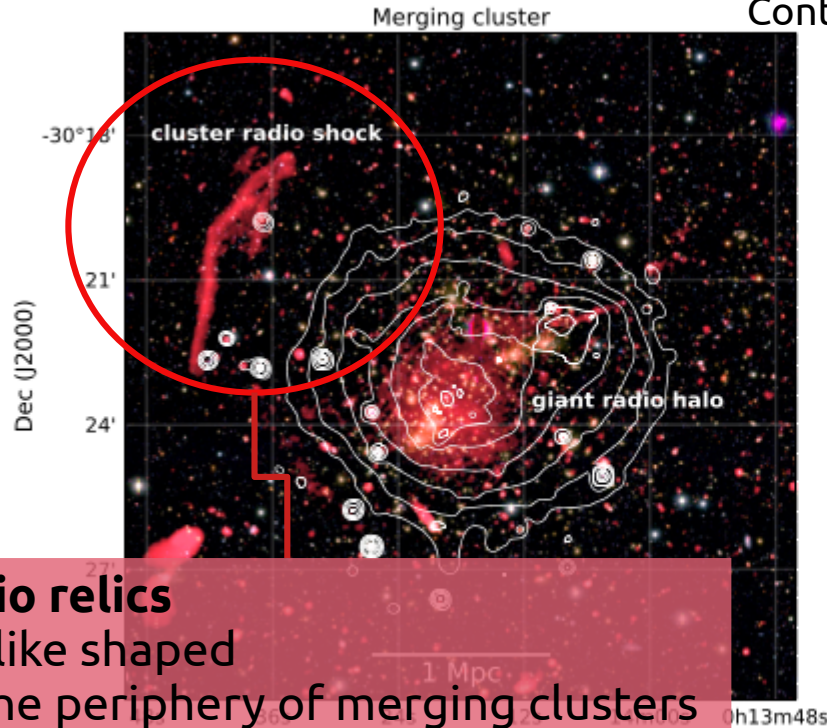
Red: radio
Contours: X-ray



[review: Van Weeren+19]

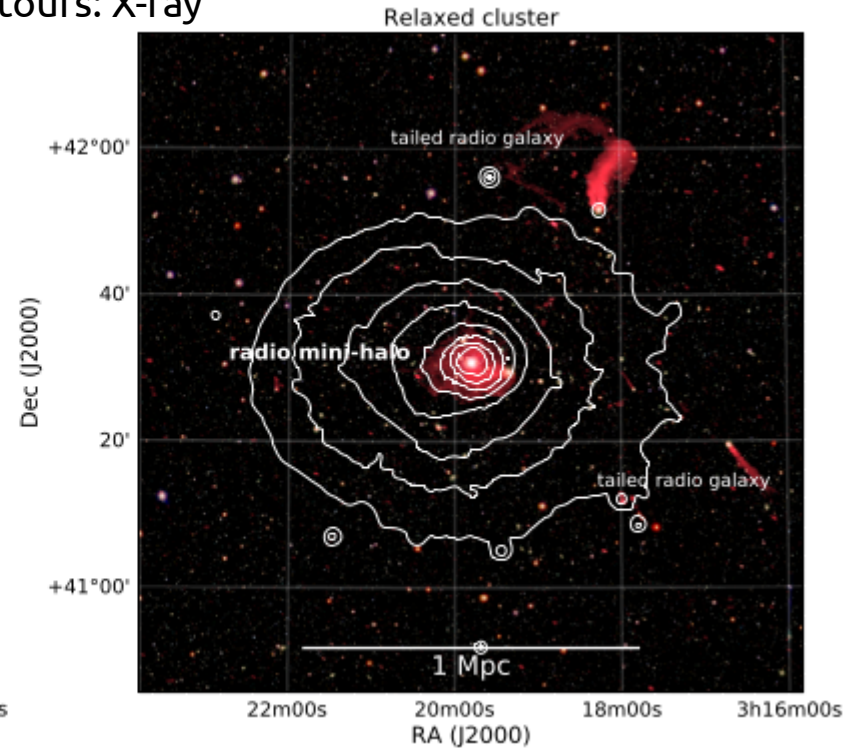
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Radio relics

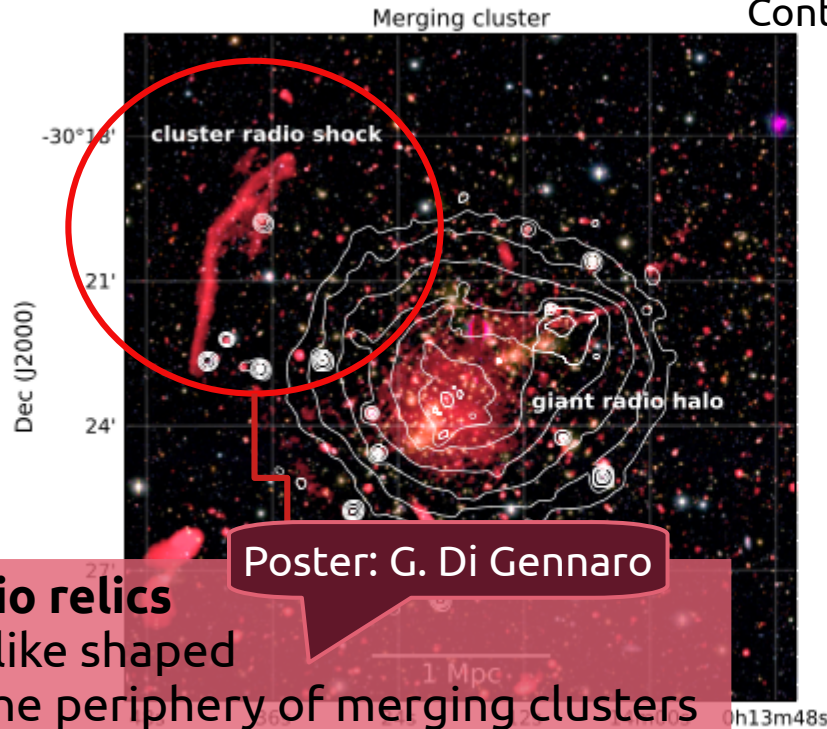
- Arc-like shaped
- At the periphery of merging clusters
- Linearly polarized (up to 60% at GHz)
- Connected to X-ray detected shocks
- Fermi I acceleration



[review: Van Weeren+19]

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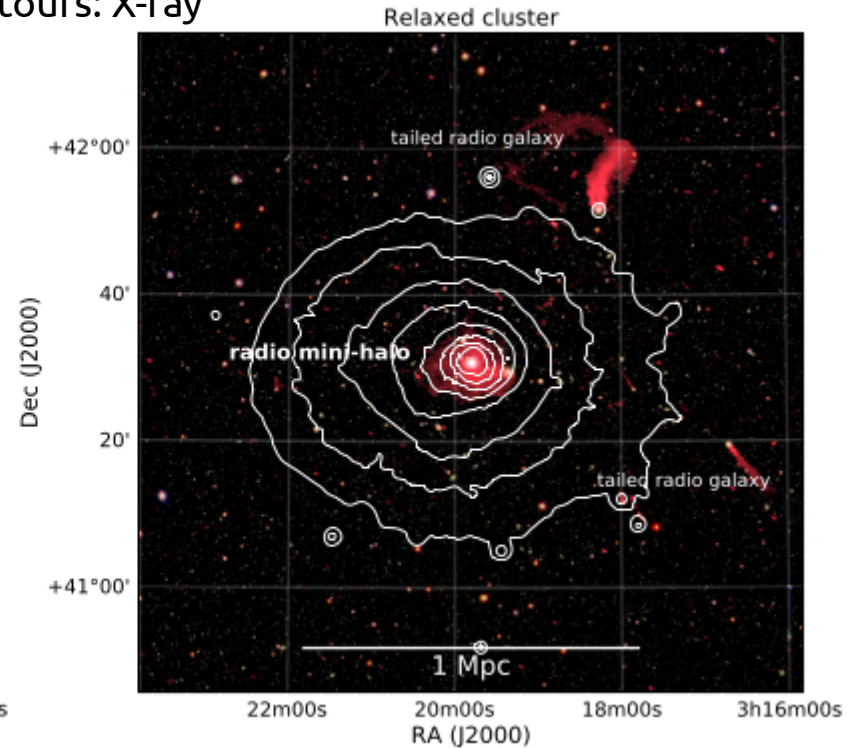
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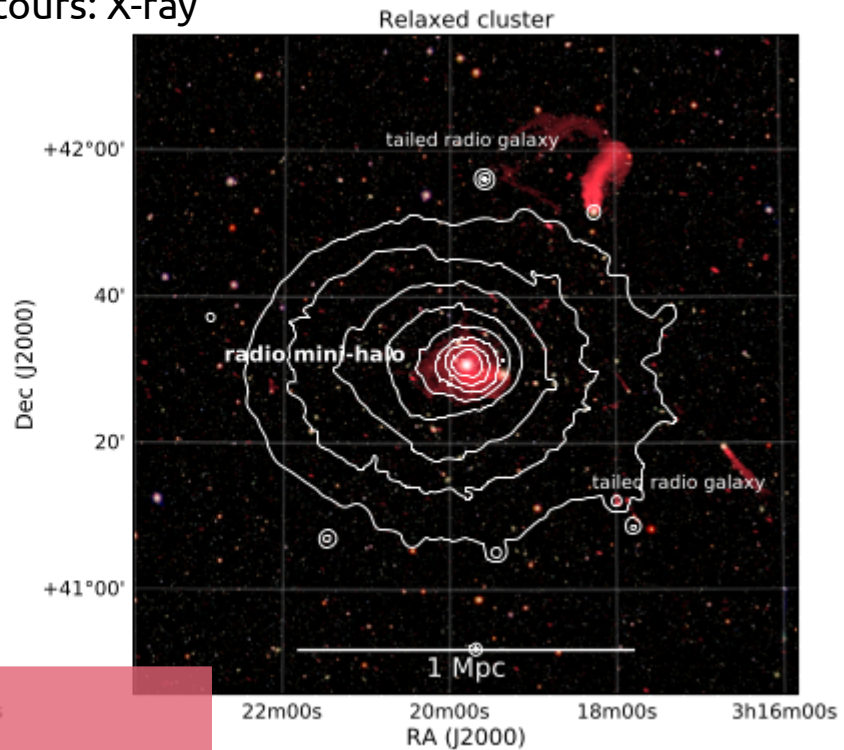
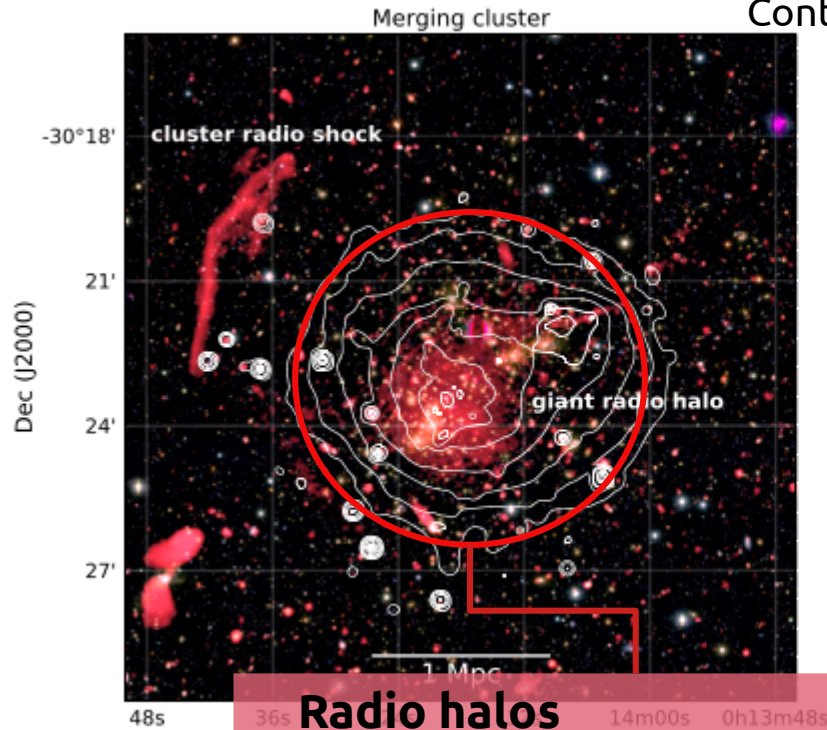
Poster: G. Di Gennaro



[review: Van Weeren+19]

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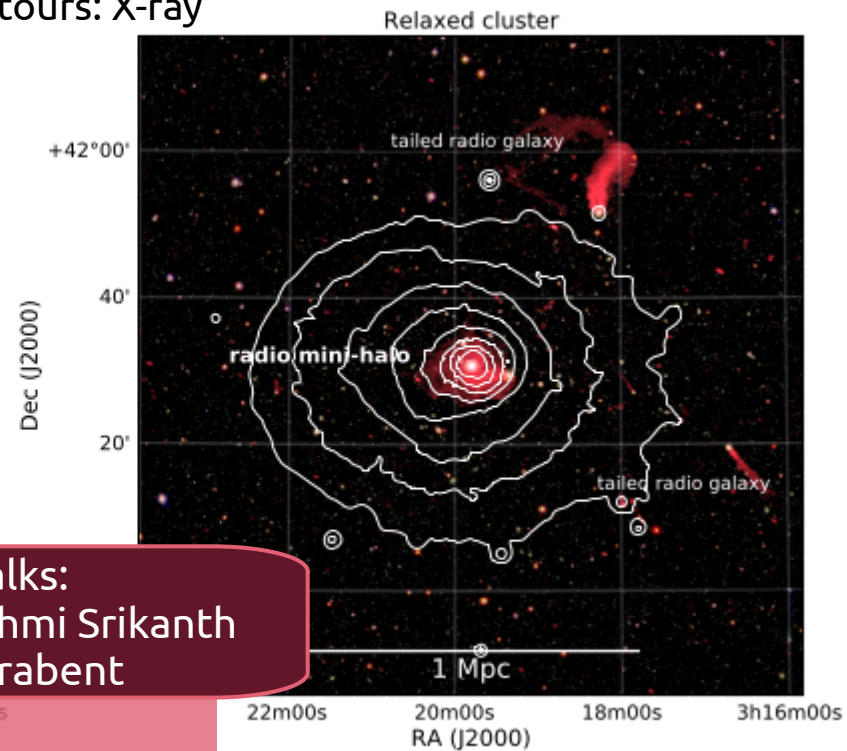
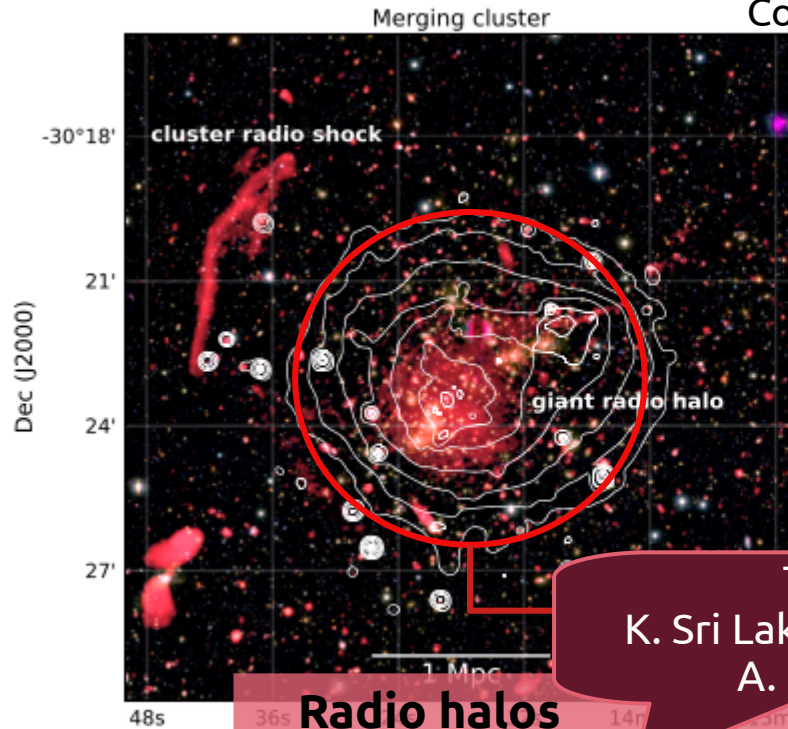
Radio halos

- Roundish
- At the center of merging clusters
- Fermi II acceleration (turbulence)

[review: Van Weeren+19]

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Talks:

K. Sri Lakshmi Srikanth
A. Drabant

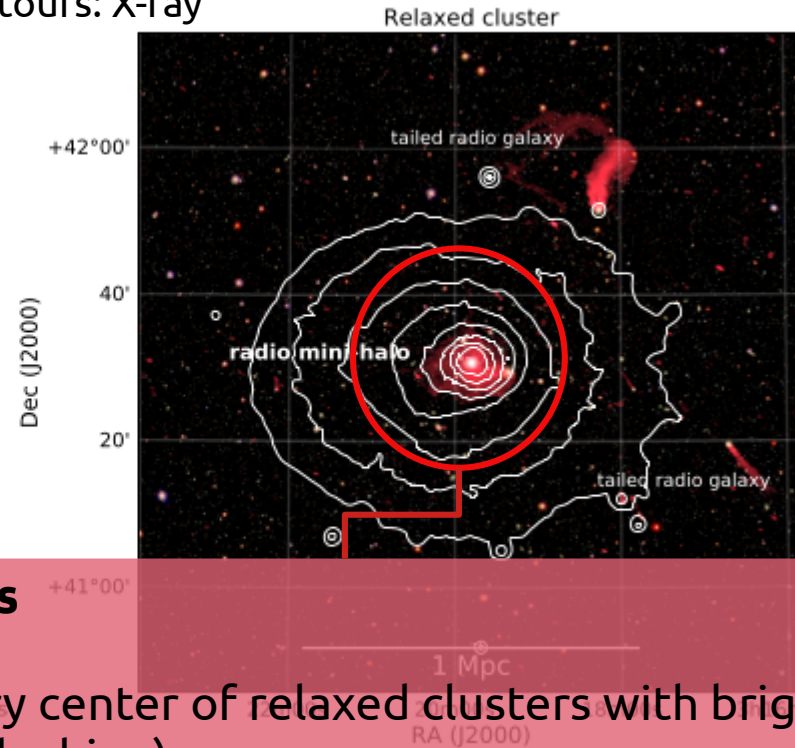
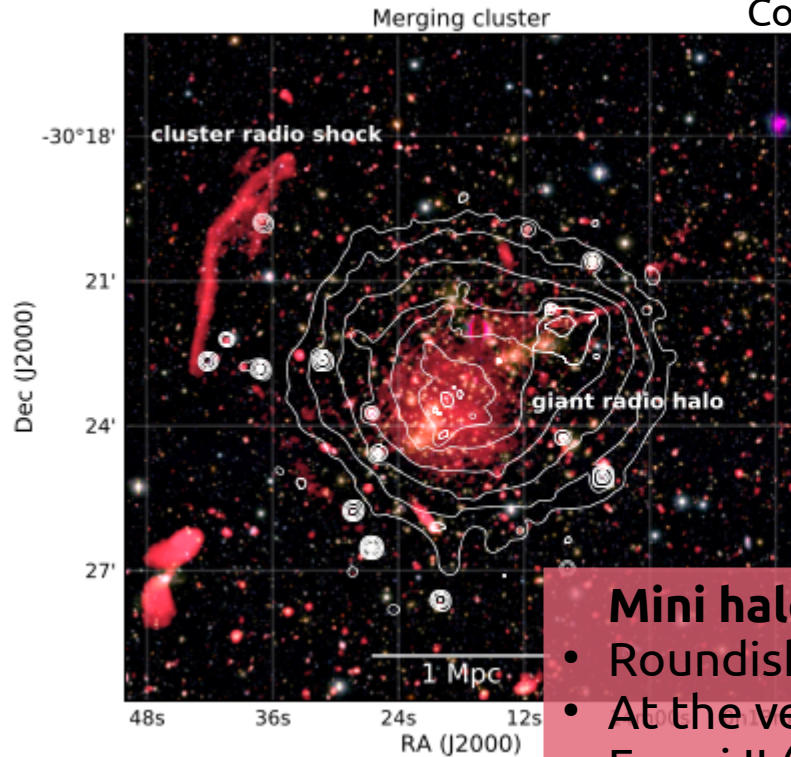
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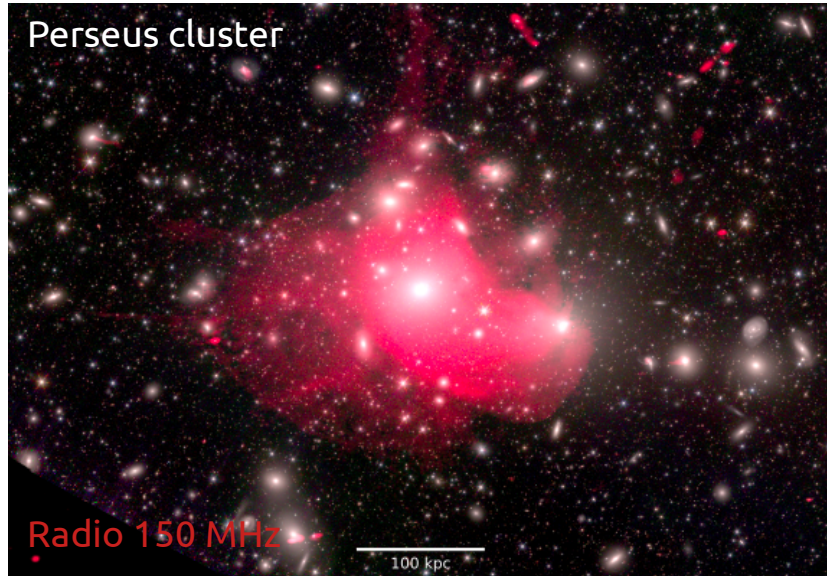
Mini halos

- Roundish
- At the very center of relaxed clusters with bright BCG
- Fermi II (sloshing)
- Hadronic acceleration models

[review: Van Weeren+19]

But reality is beyond classification

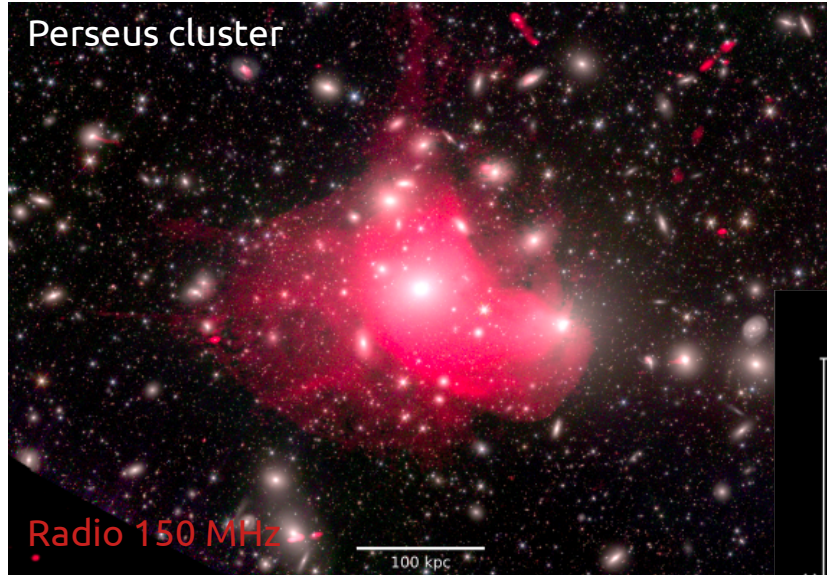
Giant radio halos in relaxed clusters



[Van Weeren+24]

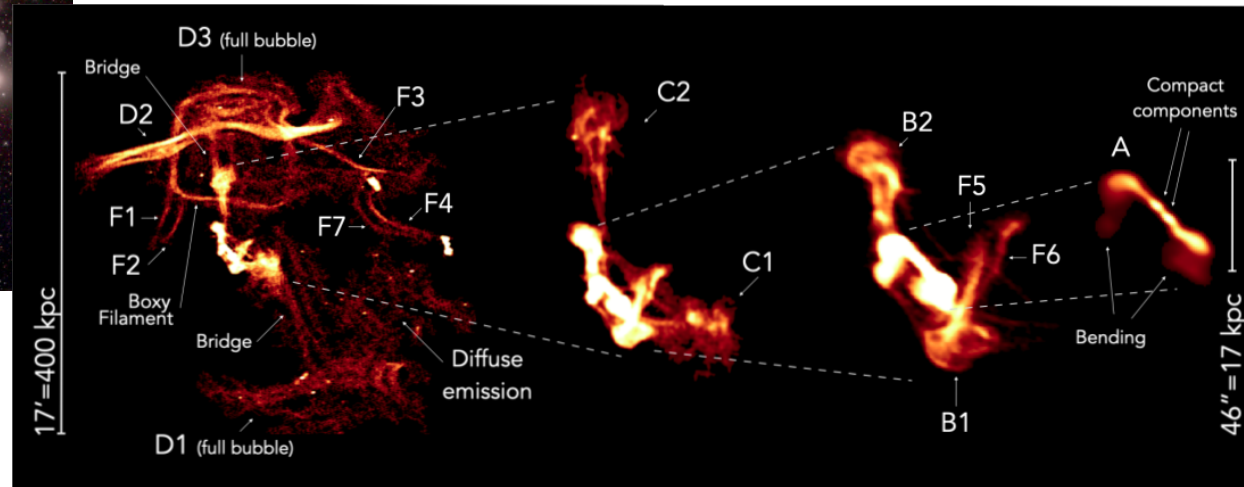
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[Van Weeren+24]

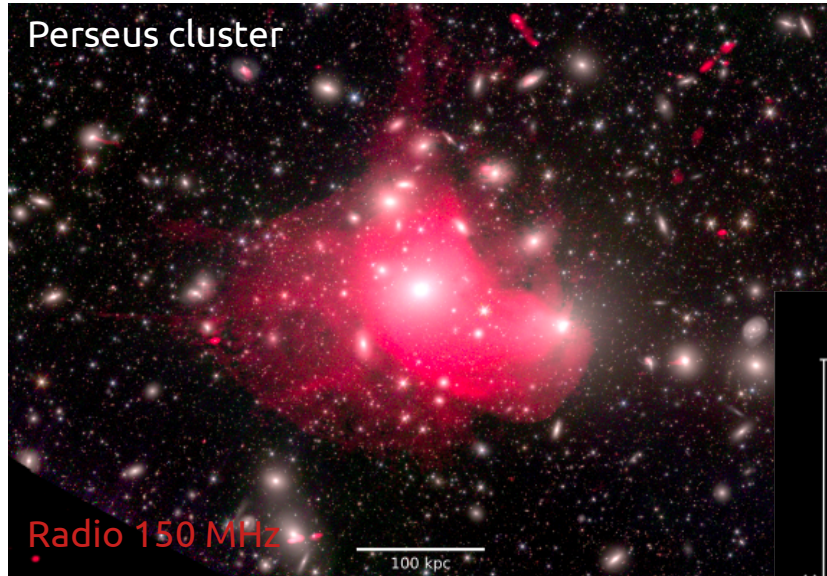
[Brienza+25]



Phoenixes, remnant plasma sources, GReET, filamentary AGN tails...

But reality is beyond classification

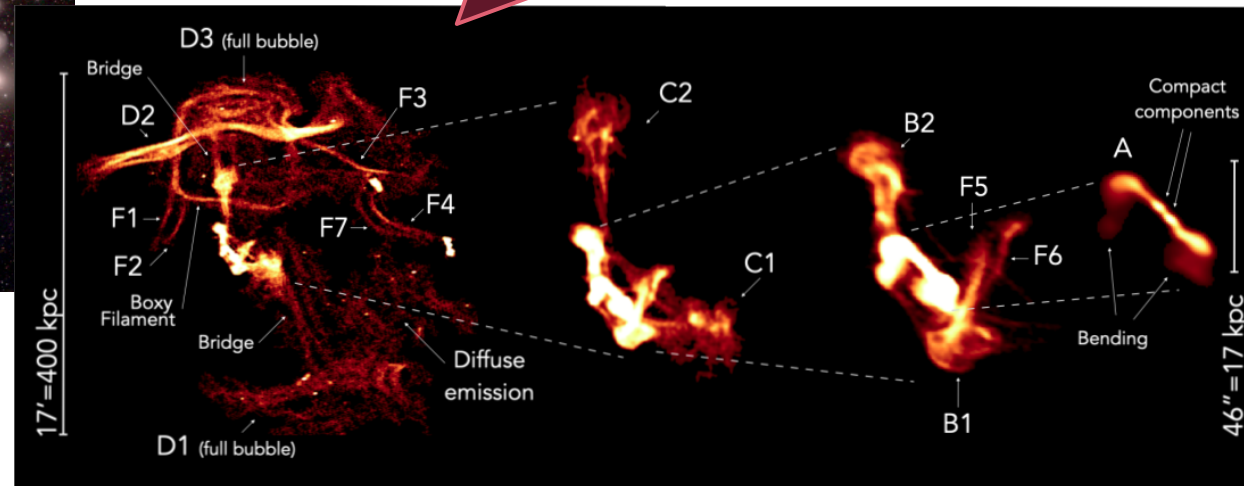
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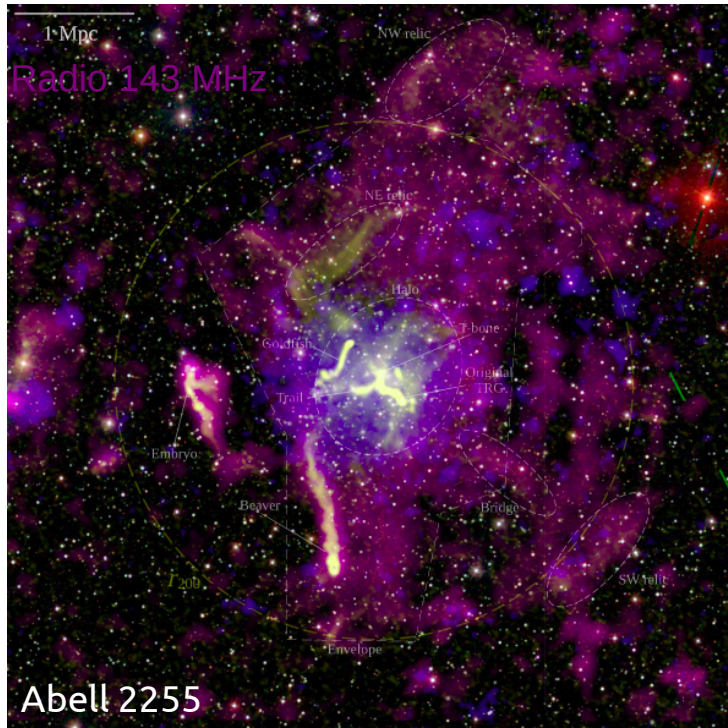
Talk: N. Biava (phoenixes)
Poster: T. Pasini (AGN in groups)

[Brienza+25]



Phoenixes, remnant plasma sources, GReET, filamentary AGN tails...

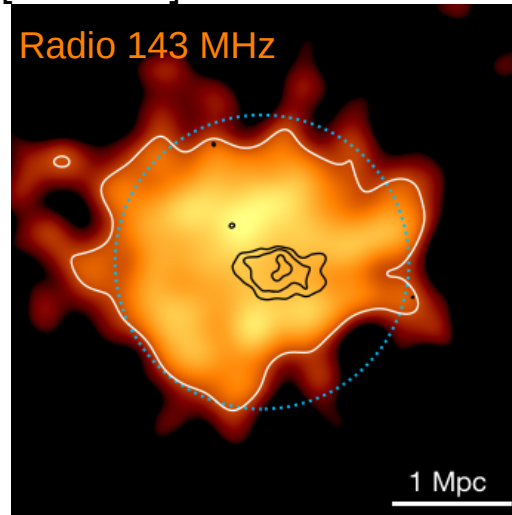
And new sources await discovery



[Botteon+22]

Diffuse radio emission
around classical
radio halos
up to 5 Mpc in size

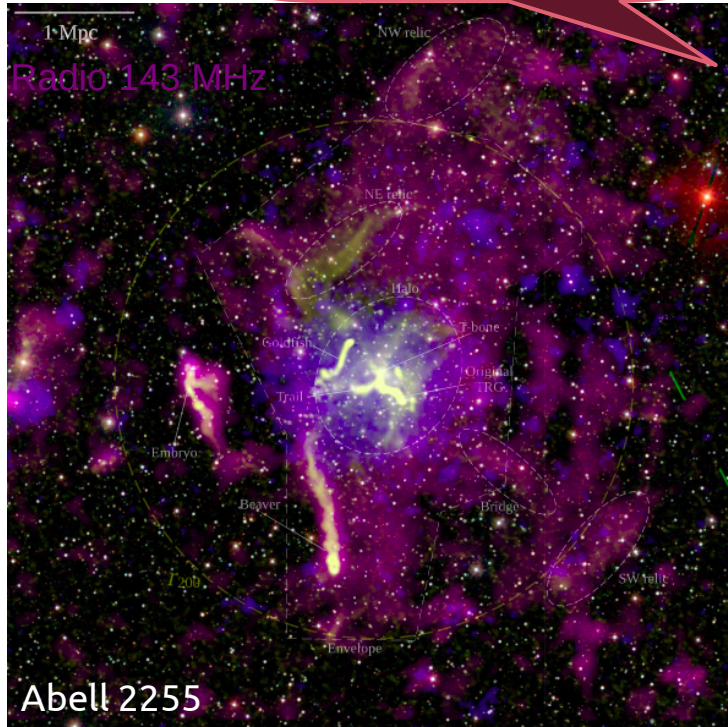
[Cuciti+22]



Bridges between
galaxy clusters

And new sources await discovery

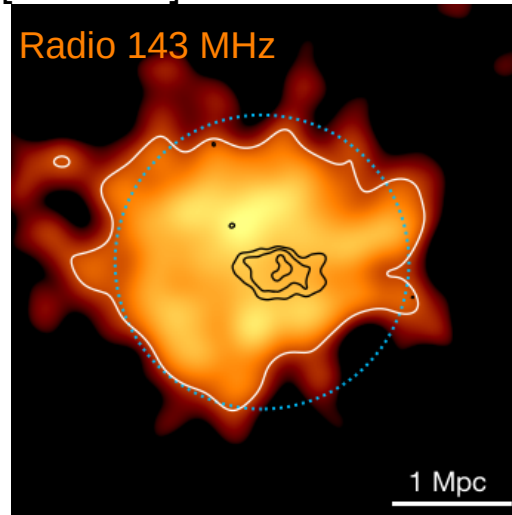
Talk: M. Cianfaglione



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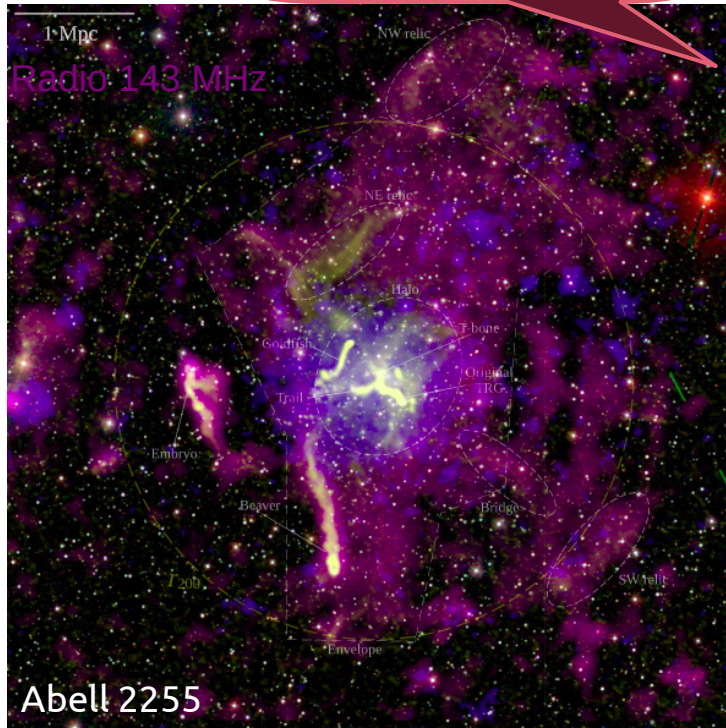


Bridges between
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And new sources await discovery

[Govoni+19]

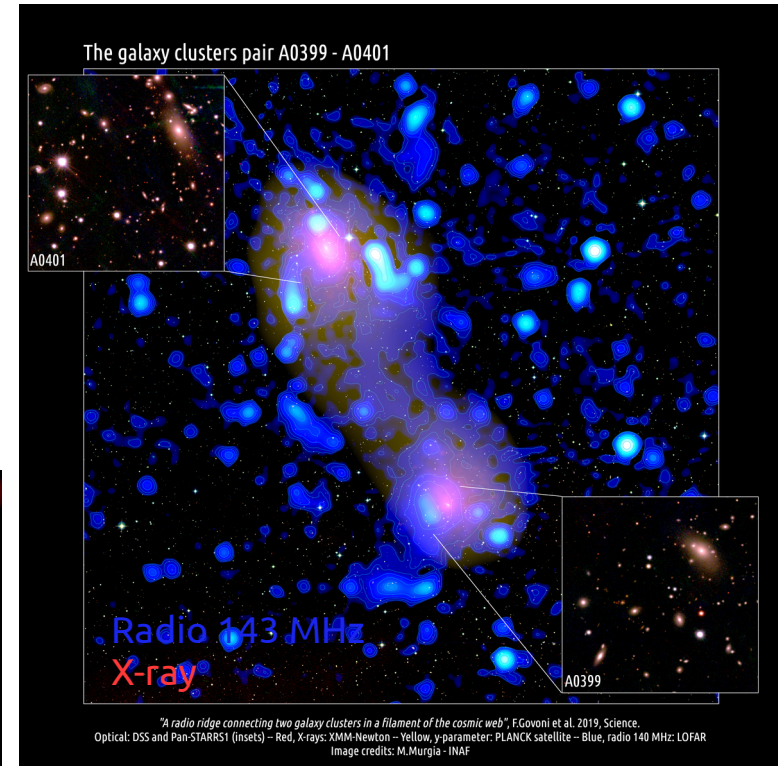
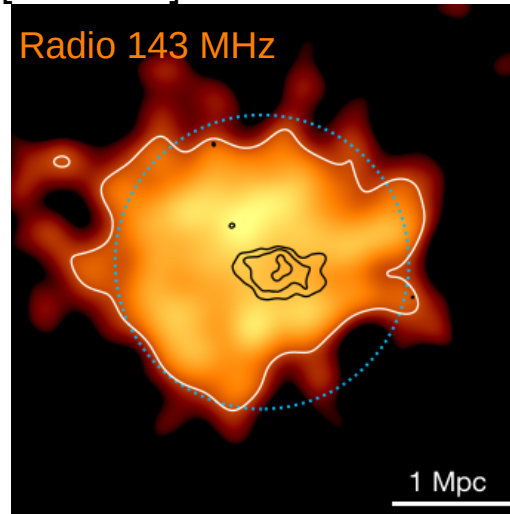
Talk: M. Ciani



[Botteon+22]

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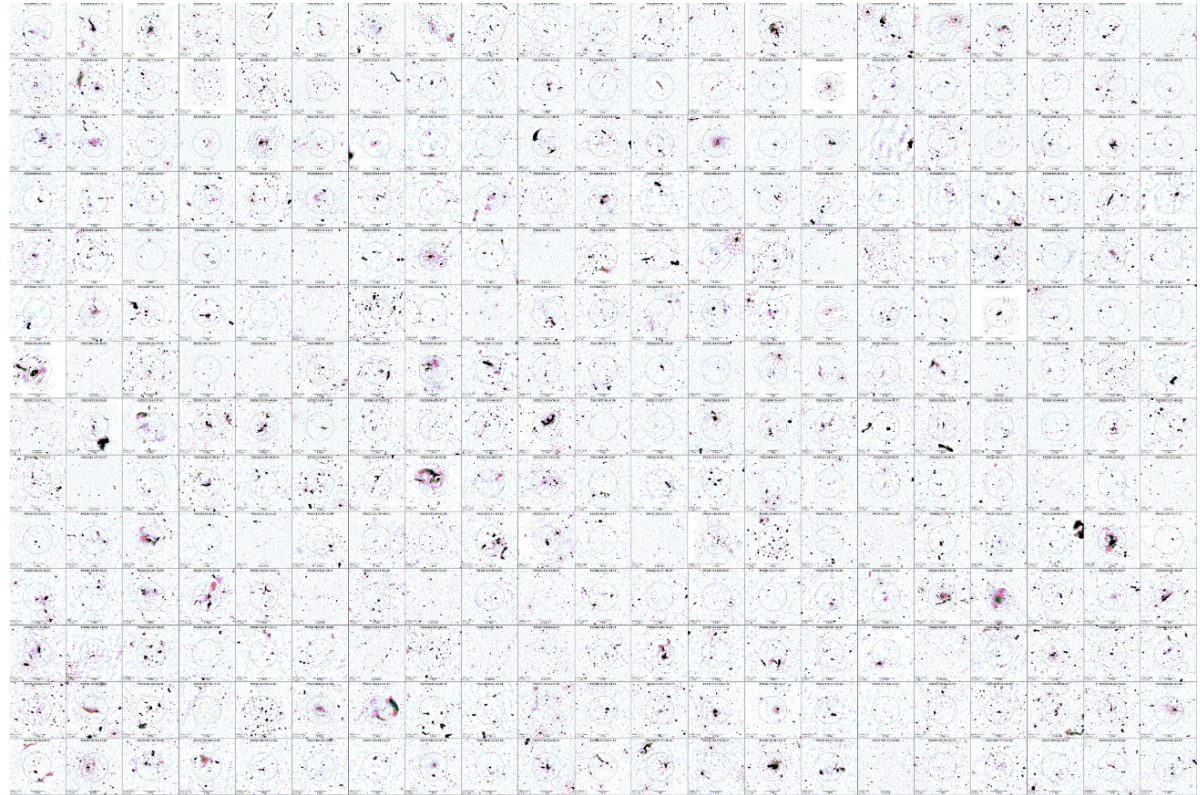


Bridges between
galaxy clusters

LOFAR, LOFAR...and still LOFAR

- LOFAR has opened up new avenues for discovery
→ new physics related
to **rare and peculiar objects**

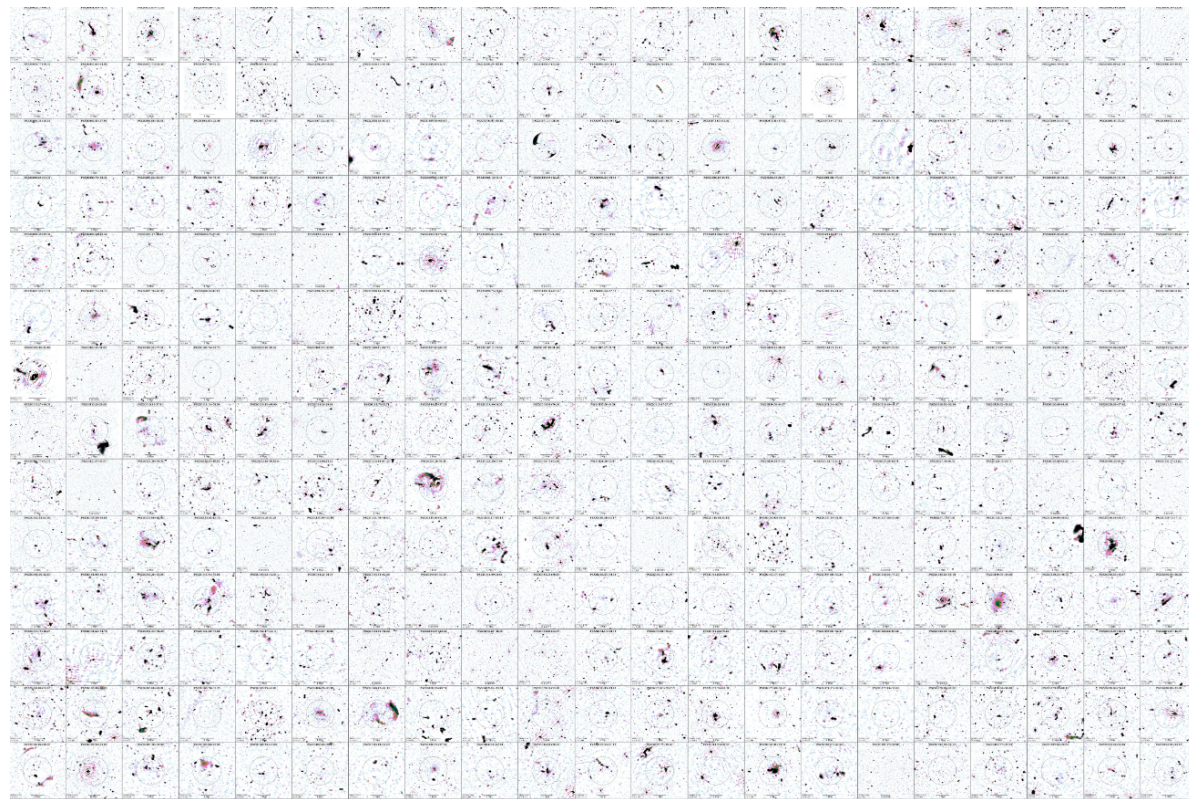
[Botteon+22]



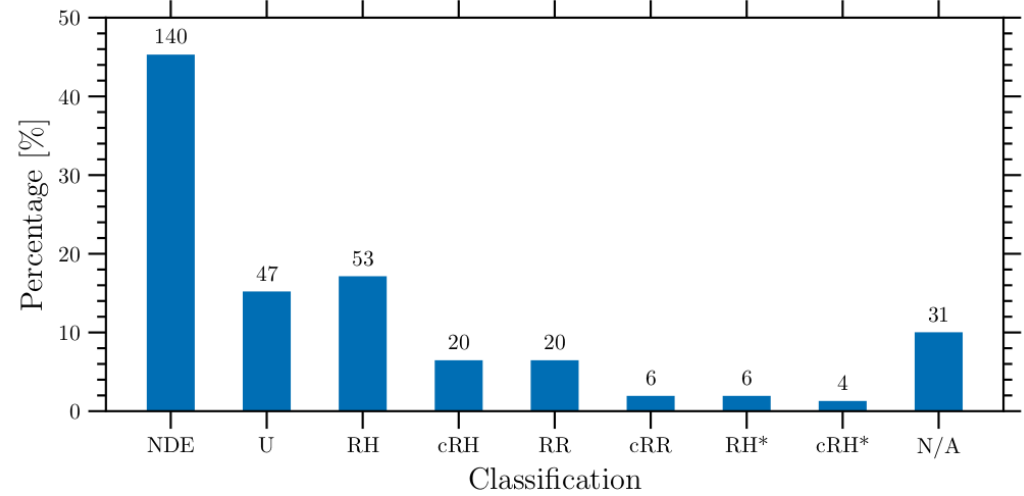
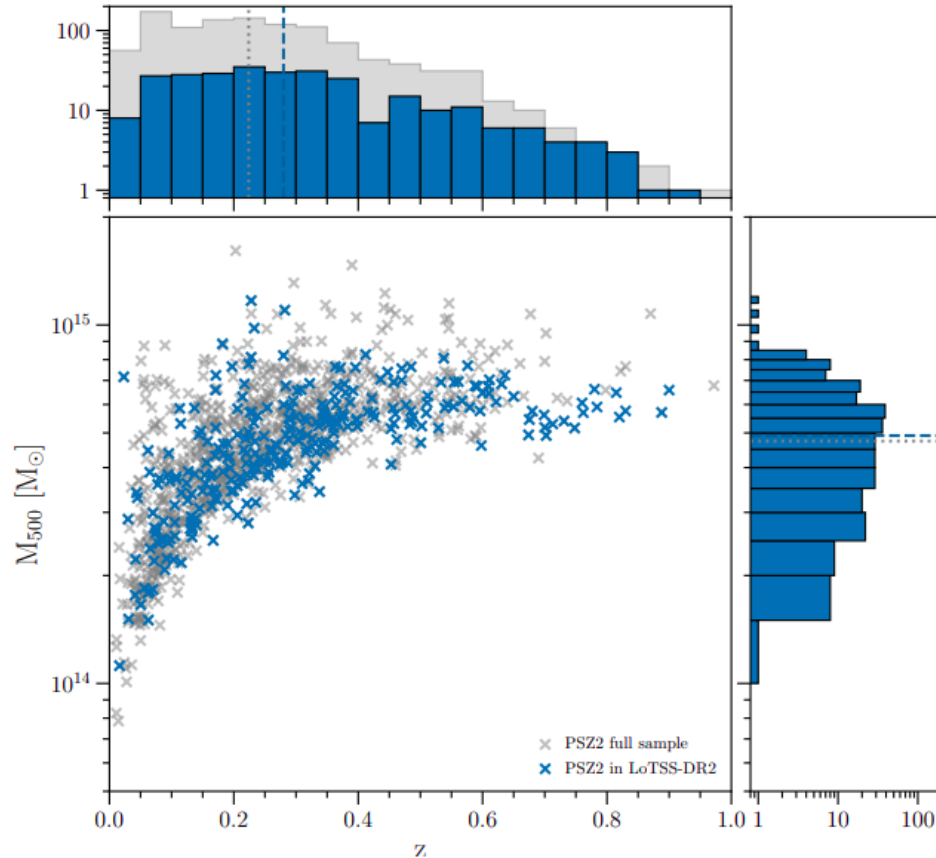
LOFAR, LOFAR...and still LOFAR

- LOFAR has opened up new avenues for discovery
→ new physics related
to **rare and peculiar objects**
- But also allowed for **statistical studies** based
on solid samples
→ test theoretical models

[Botteon+22]



LOTSS-DR2/PSZ2 project



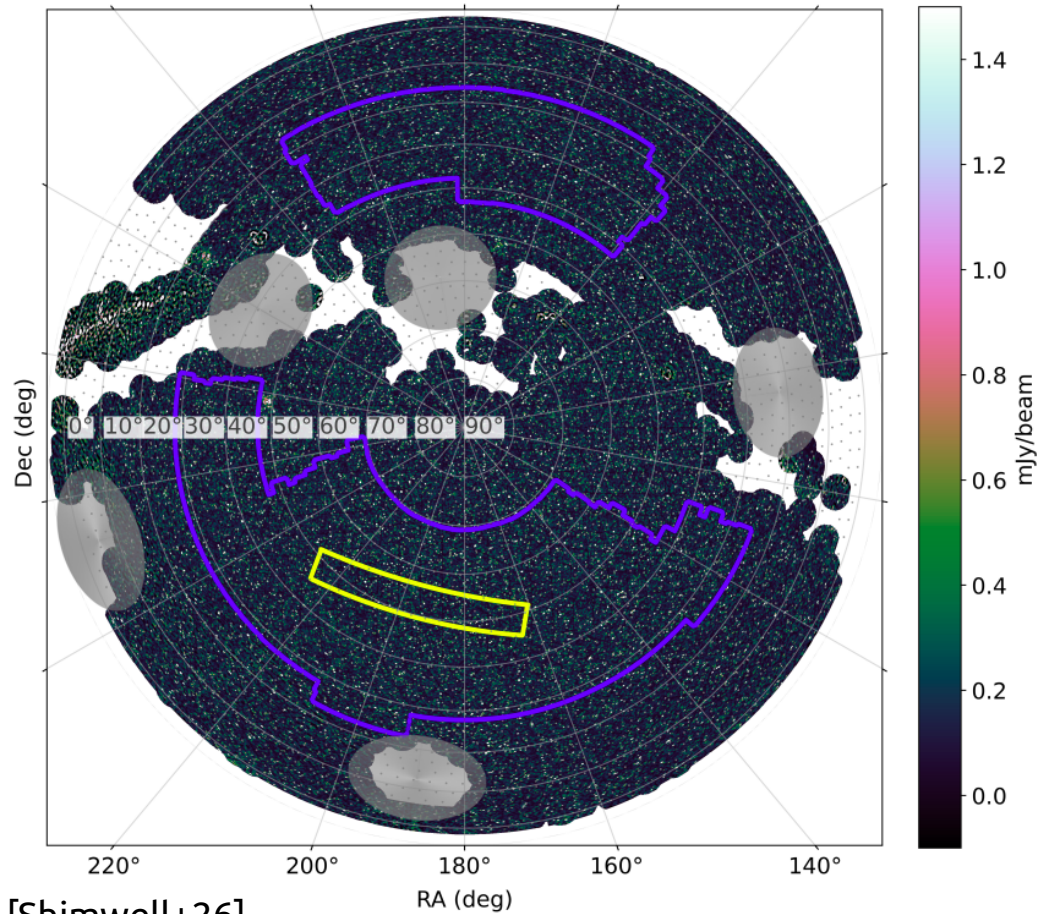
309 galaxy clusters belonging to the second Planck catalog of Sunyaev-Zel'dovich sources (PSZ2)

- classification
- flux measurements (and upper limits)
- scaling relations for halos and relics

[Botteon+22, Bruno+23, Zhang+23, Cassano+23, Cuciti+23, Jones+23]



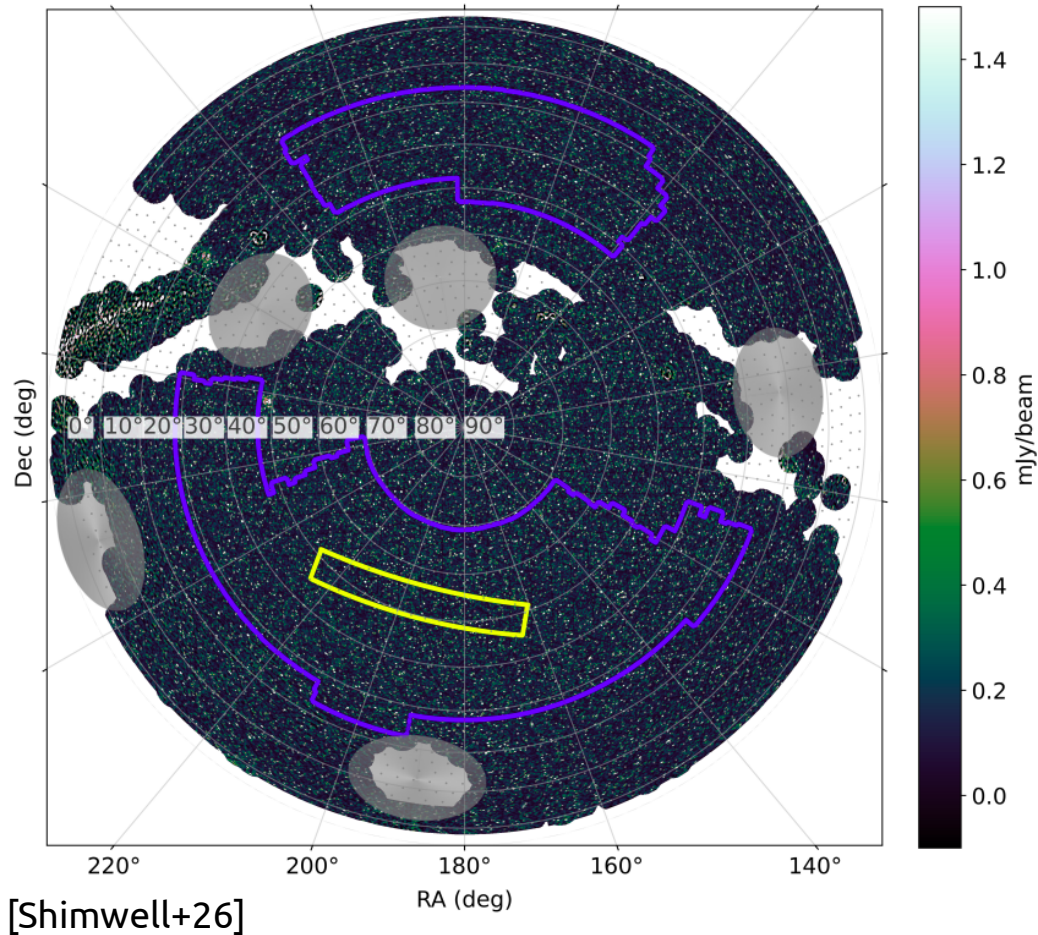
LOTSS-DR3



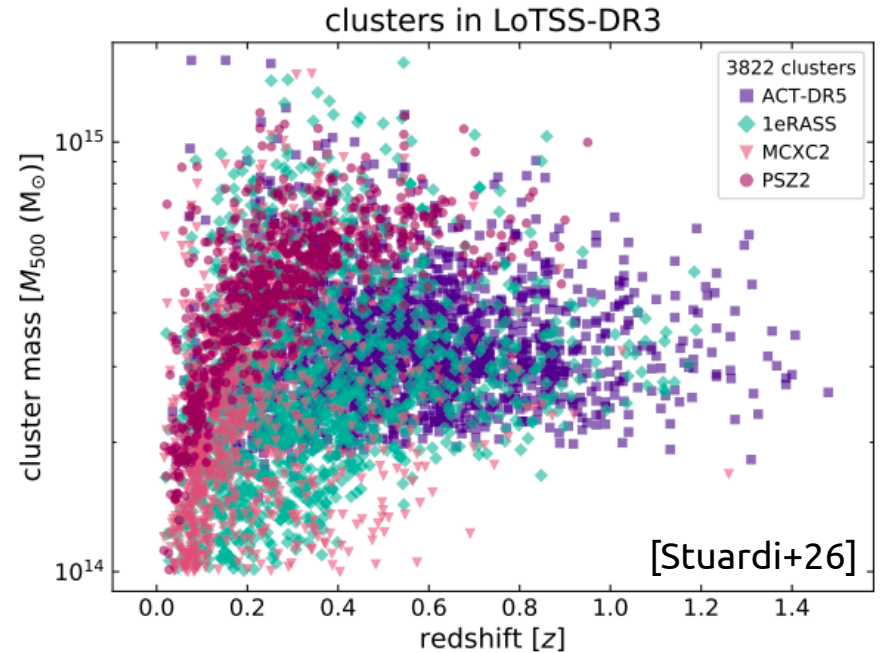
x 2.5 data size
x 3 area
x 10 number of clusters

[Shimwell+26]

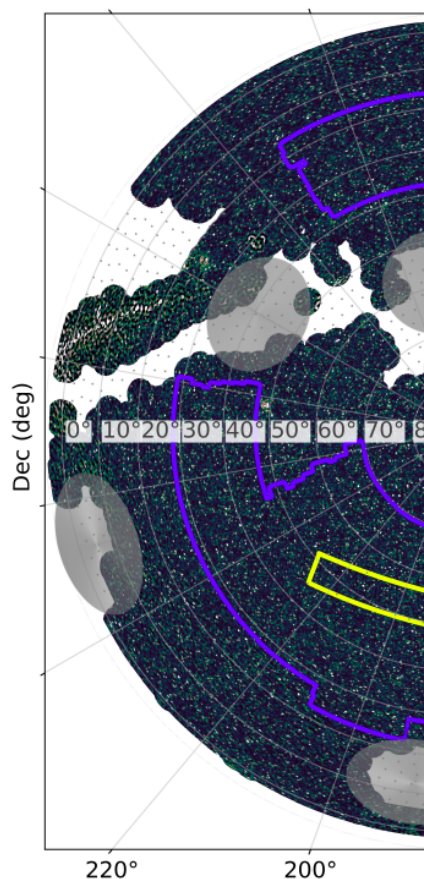
LOTSS-DR3



x 2.5 data size
x 3 area
x 10 number of clusters



LOTSS-DR3

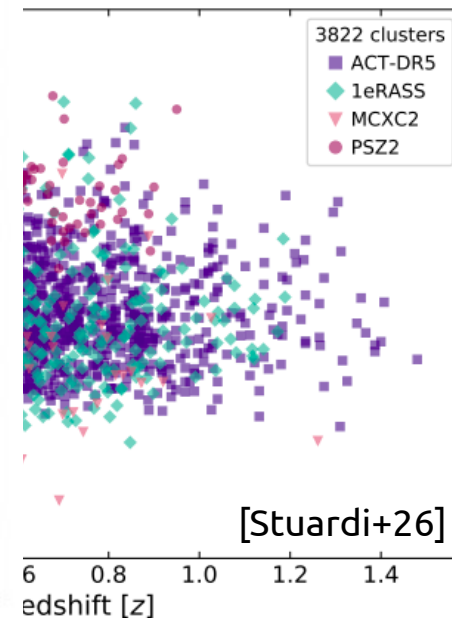


[Shimwell+26]



usters

s in LoTSS-DR3



Machine learning: a possible solution to the problem of big data

Many efforts in the LOFAR community, mostly towards radio galaxies

- Supervised methods: learning from prepared examples
[on LOFAR data: Alegre+22,24, Stuardi+24,26]
- Self-supervised methods: learning groups from a lot of raw data
[on LOFAR data: Mostert+21,23,24, Baron-Perez+25]

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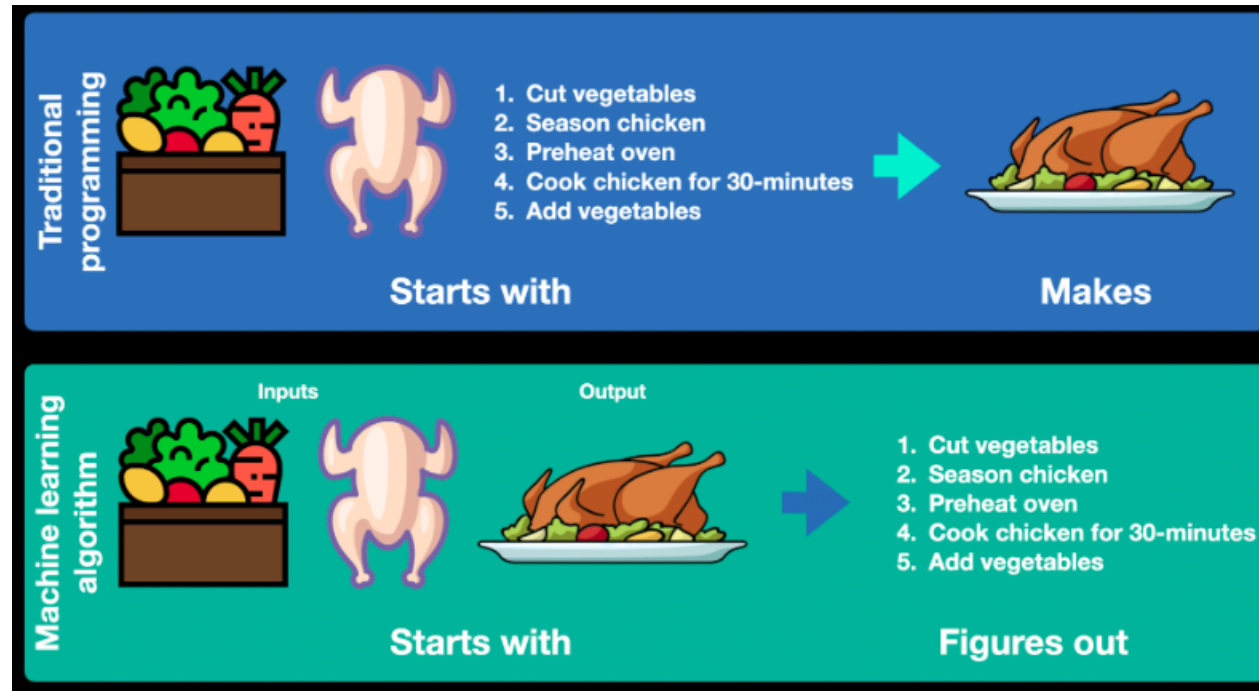
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[on LOFAR data: Alegre+22,24, Stuardi+24,26]

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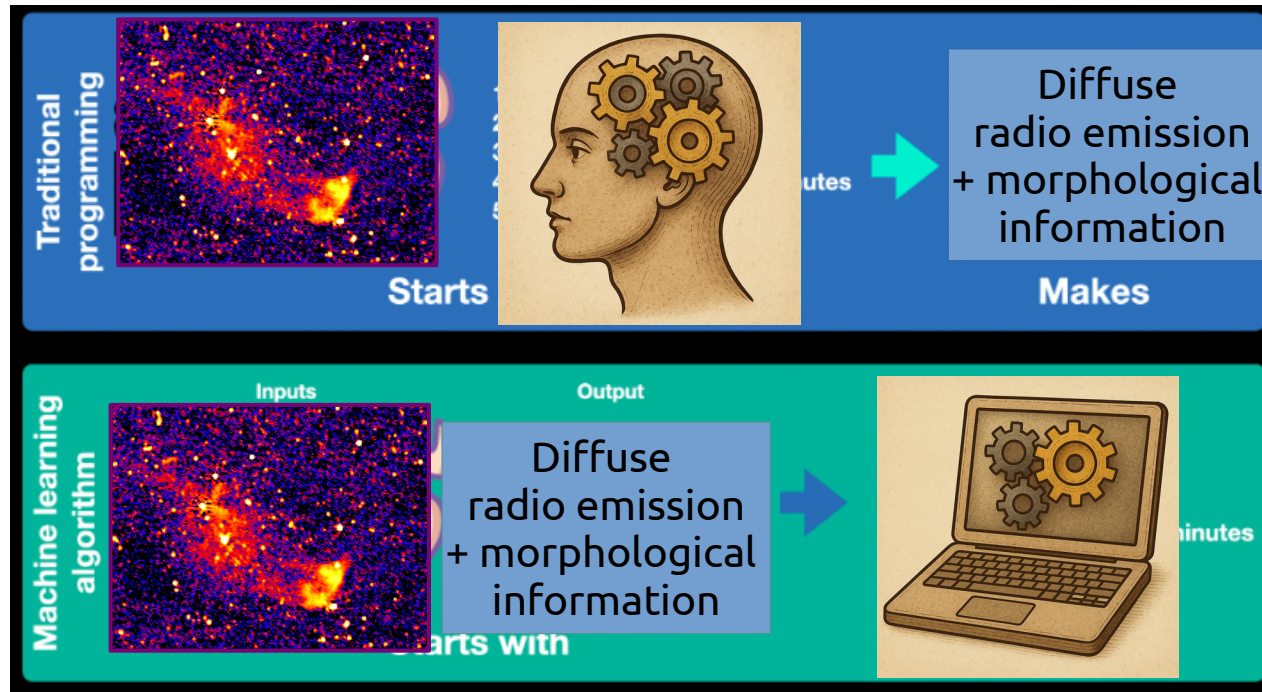
[on LOFAR data: Mostert+21,23,24, Baron-Perez+25]

Supervised machine learning concept



Need for a **large dataset** of input and output for the training

Supervised machine learning concept



Need for a **large dataset** of input and output for the training

Our approach: Radio U-Net

Convolutional neural network based on the U-net architecture [Ronneberger+15]
to perform the segmentation of diffuse radio emission in radio astronomical surveys

Radio U-Net: architecture and training strategy

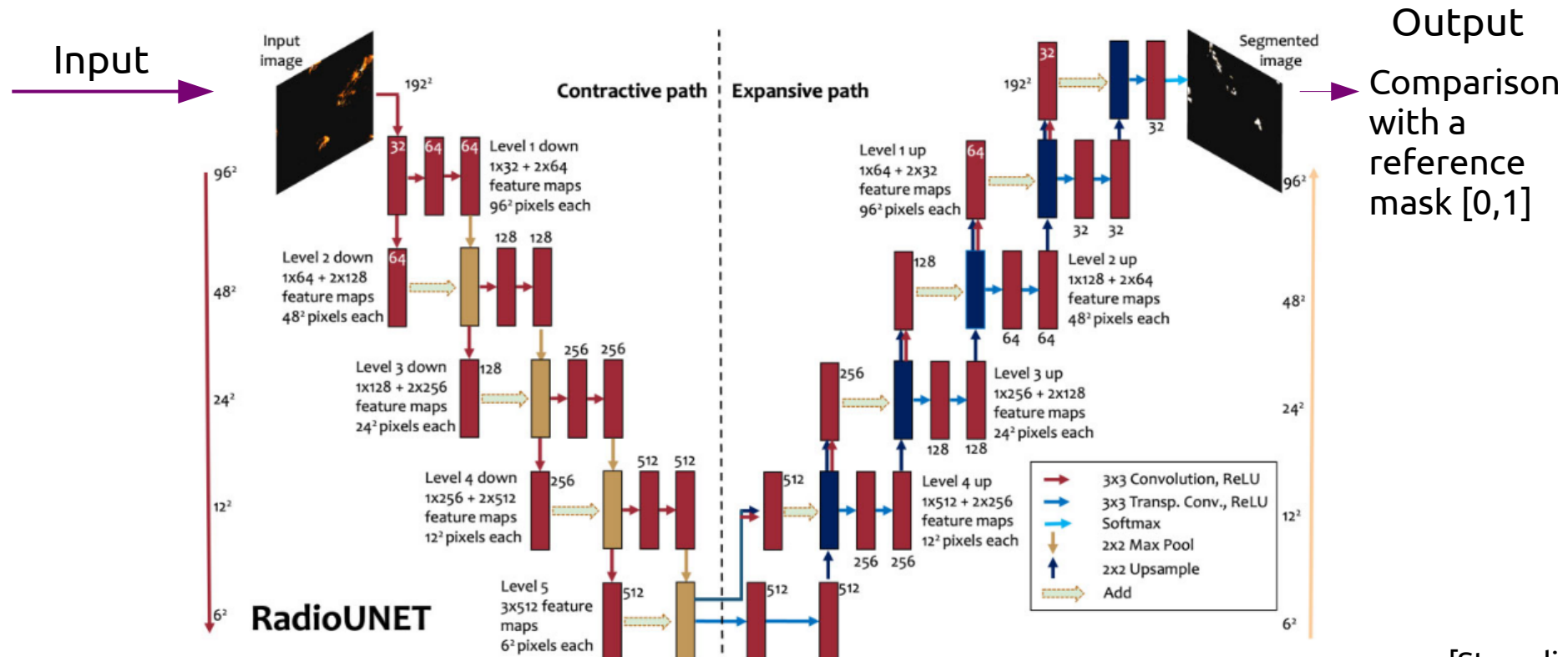
Convolutional neural network based on the U-net architecture [Ronneberger+15]
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Learns image features
by itself via filter (or kernel)
optimization

Radio U-Net: architecture and training strategy

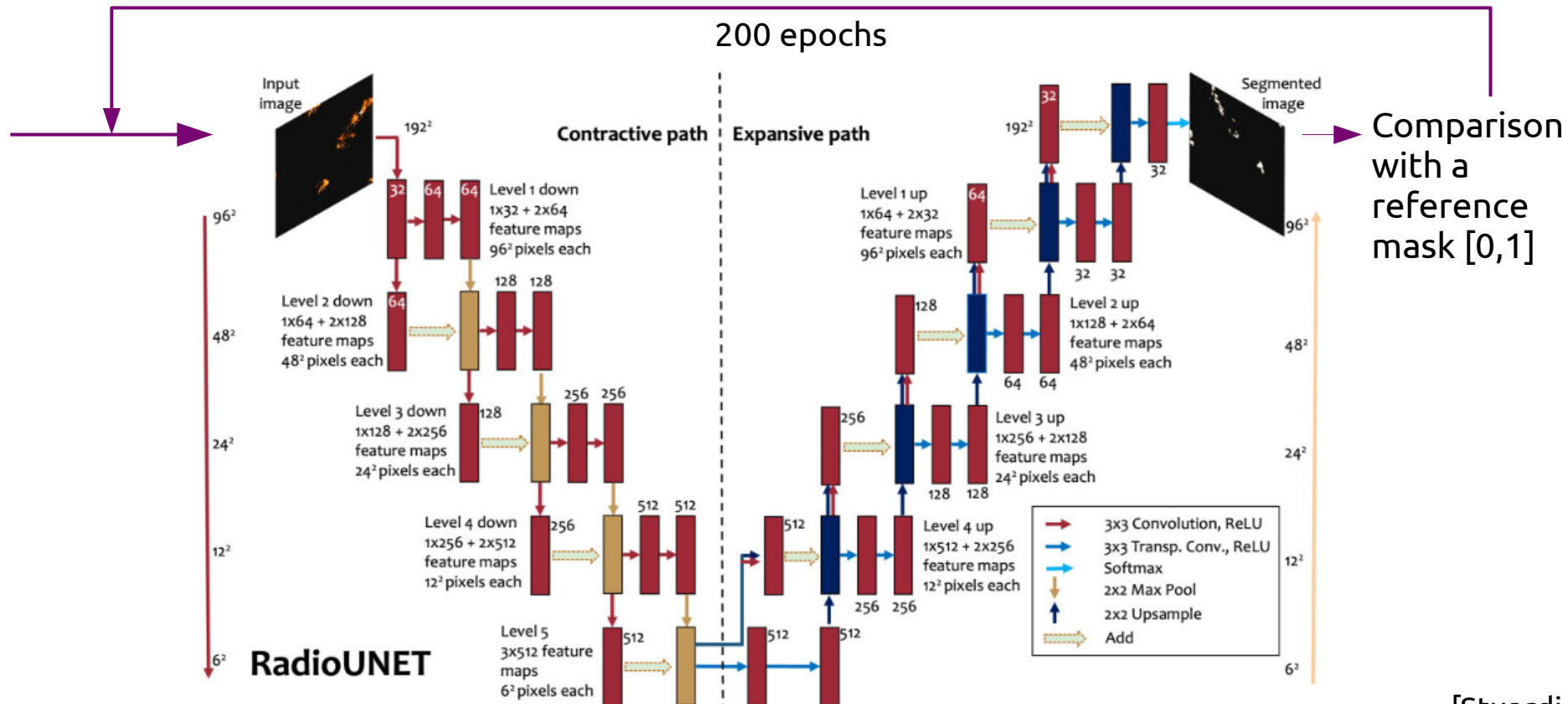
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[Stuardi+24]

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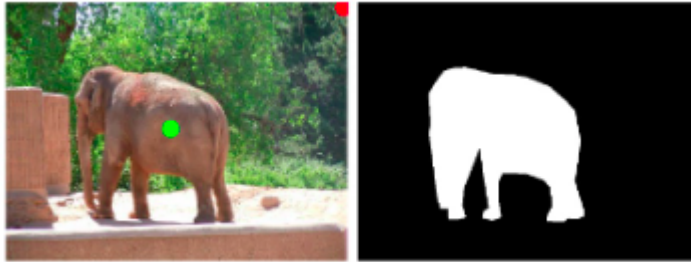
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Radio U-Net: architecture and training strategy

Convolutional neural network based on the U-net architecture [Ronneberger+15] to perform the segmentation of diffuse radio emission in radio astronomical surveys



Identifies interesting regions of an image ← Supervised training

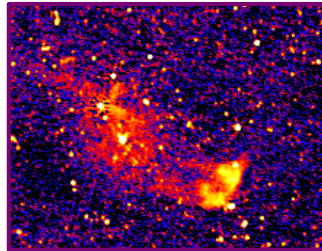


Radio U-Net: architecture and training strategy

Convolutional neural network based on the U-net architecture [Ronneberger+15] to perform the segmentation of diffuse radio emission in radio astronomical surveys



Identifies interesting regions of an image



Supervised training
- large dataset
- reference (mask)

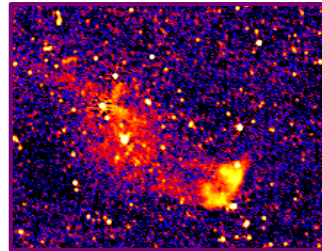


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Supervised training

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**Not available for
cluster radio sources!!**

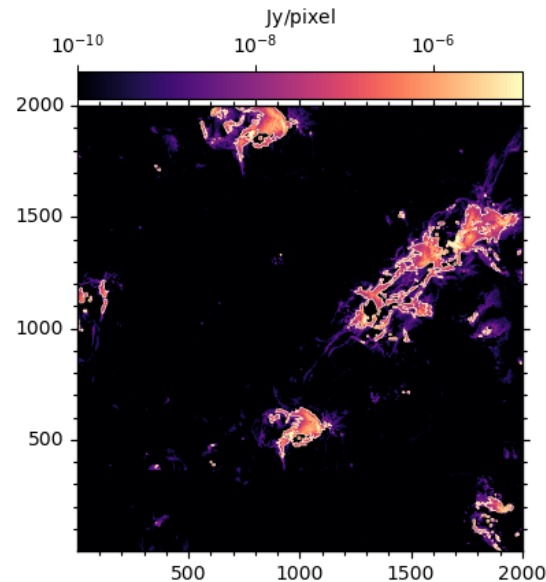


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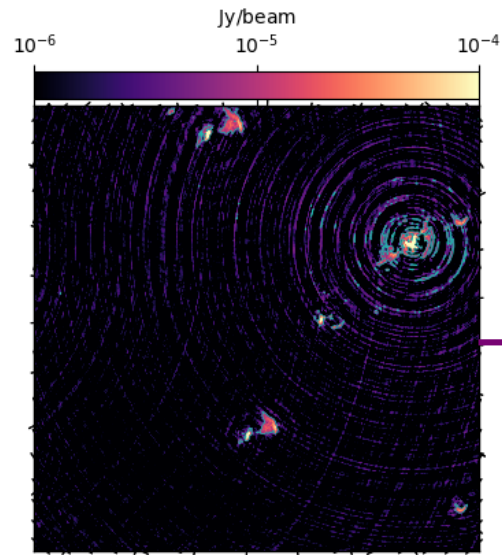
Convolutional neural network based on the U-net architecture [Ronneberger+15] to perform the segmentation of diffuse radio emission in radio astronomical surveys

Training on synthetic LoTSS observations built on cosmological simulations [Gheller&Vazza22]

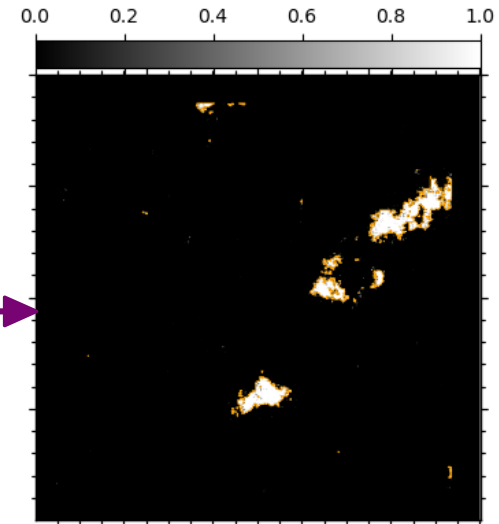
- reference mask at 10^{-3} noise of the input image
- residual imaging artifacts



Sky image – Reference mask



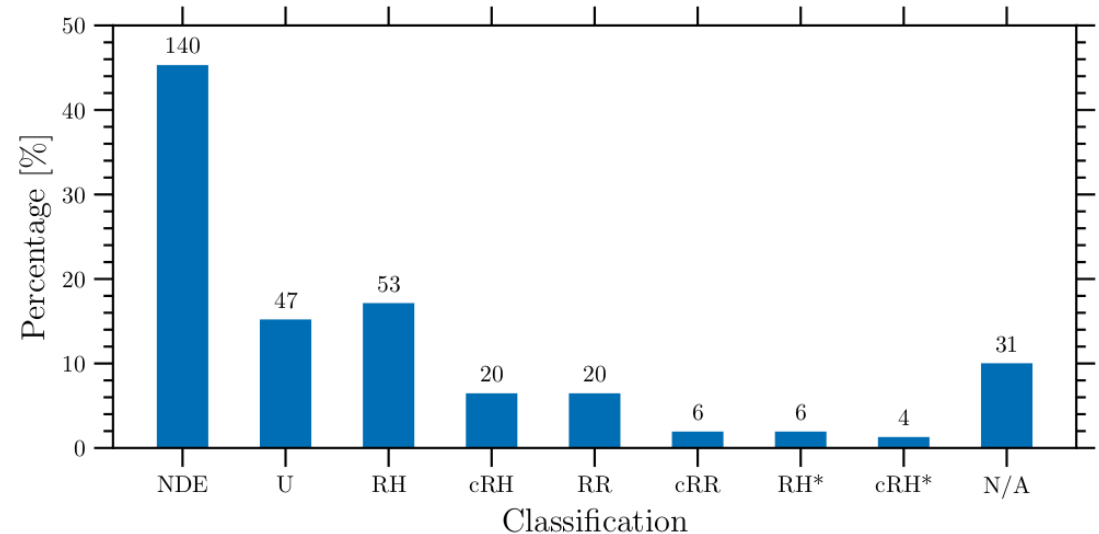
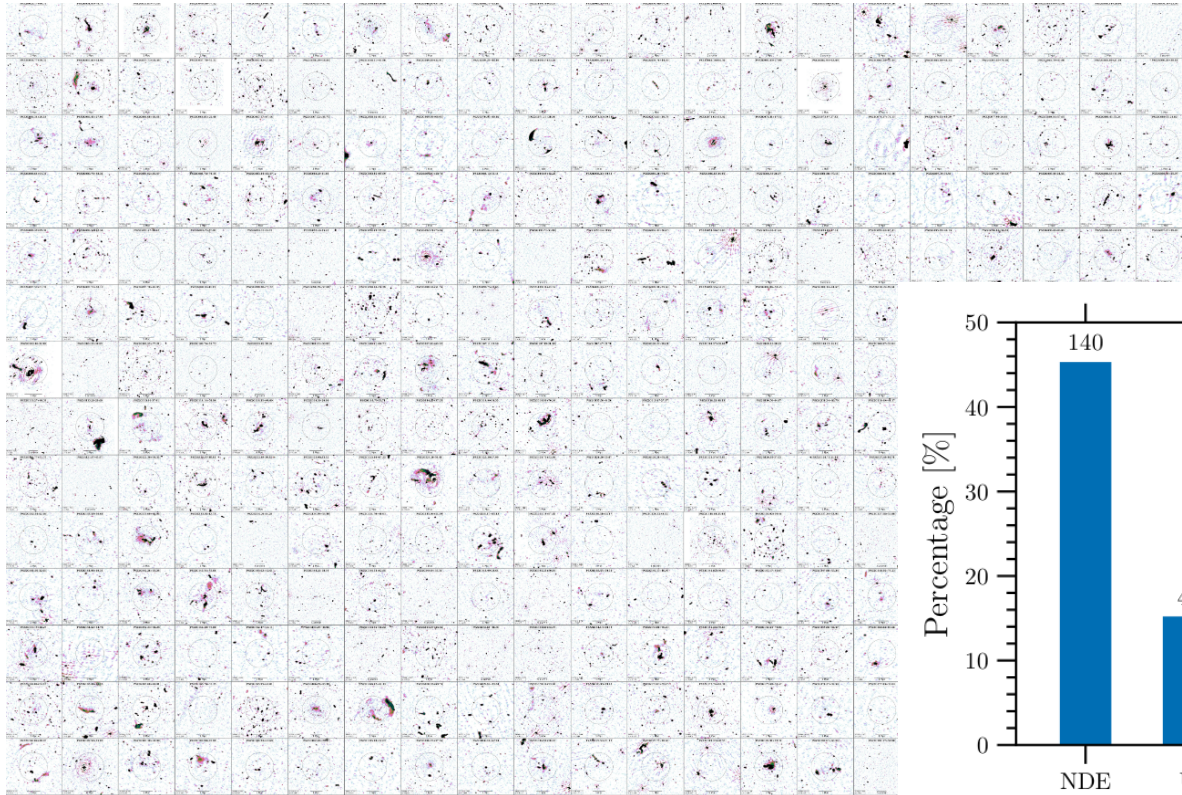
Input image



Output probability image [Stuardi+24]

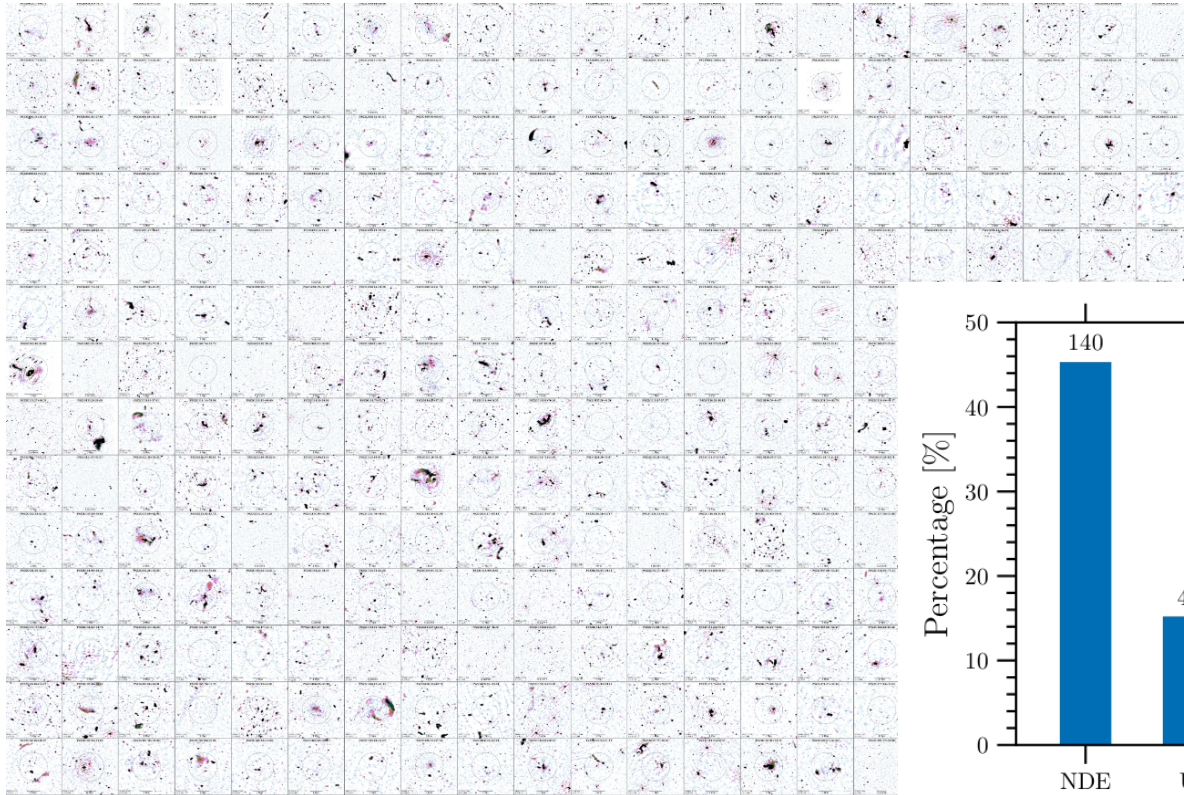
Radio U-Net: performance verification on LoTSS-DR2

LoTSSDR2/PSZ2: 309 galaxy clusters with visual detection and classification [Botteon+22]
Images directly downloaded from the survey archive without any tailored processing



Radio U-Net: performance verification on LoTSS-DR2

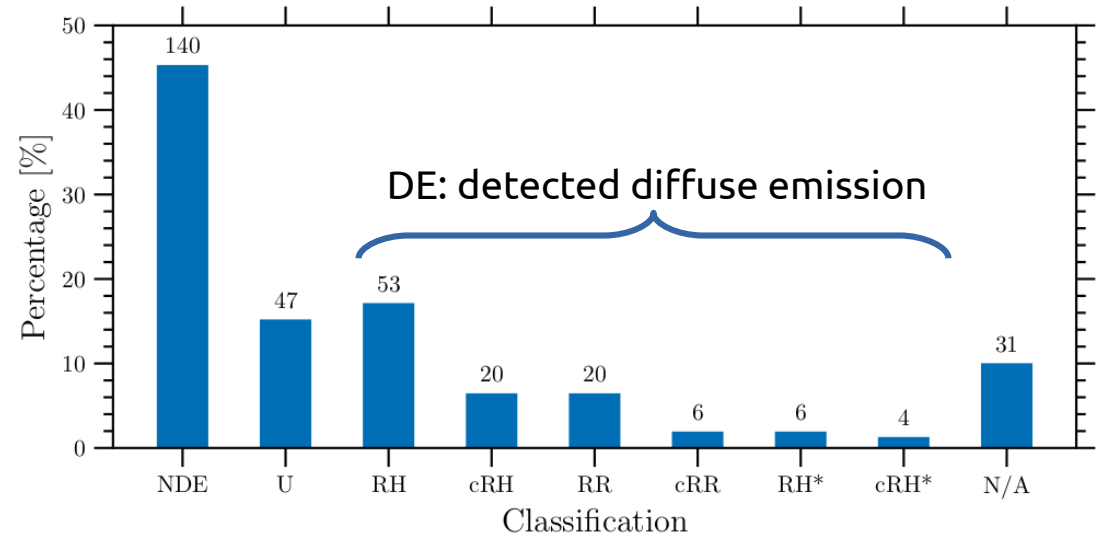
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Applied to all 309 clusters

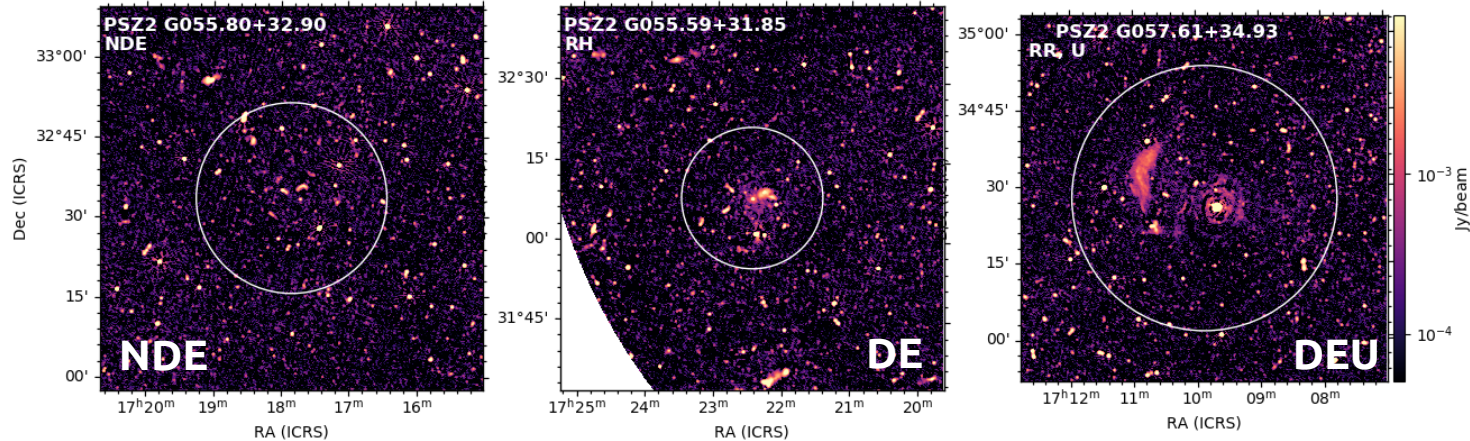
+

Test sample: 114 NDE, 85 DE, 47 U
- all with z and good data quality

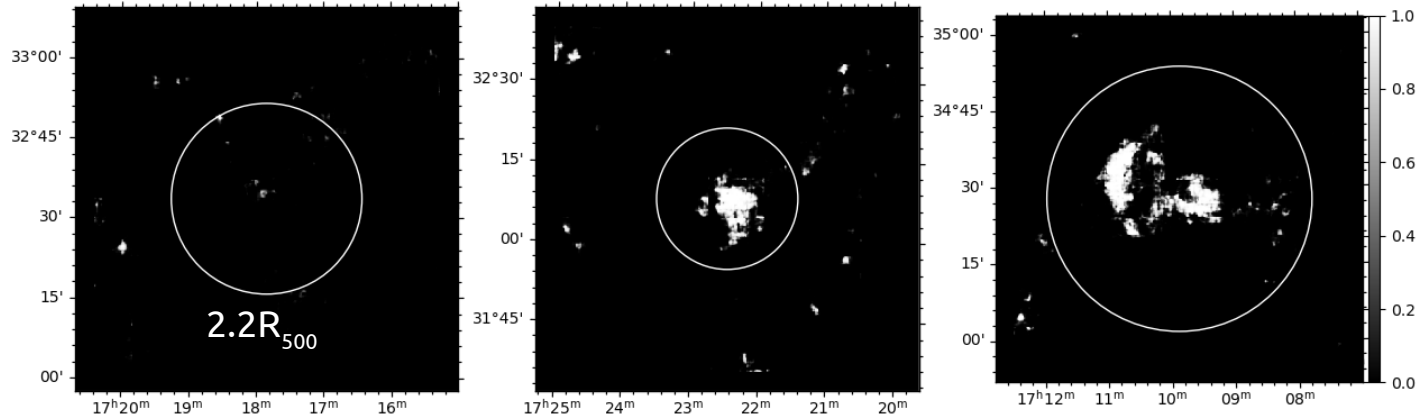


Radio U-Net: performance verification on LoTSS data

LoTSS data



Radio U-Net segmented



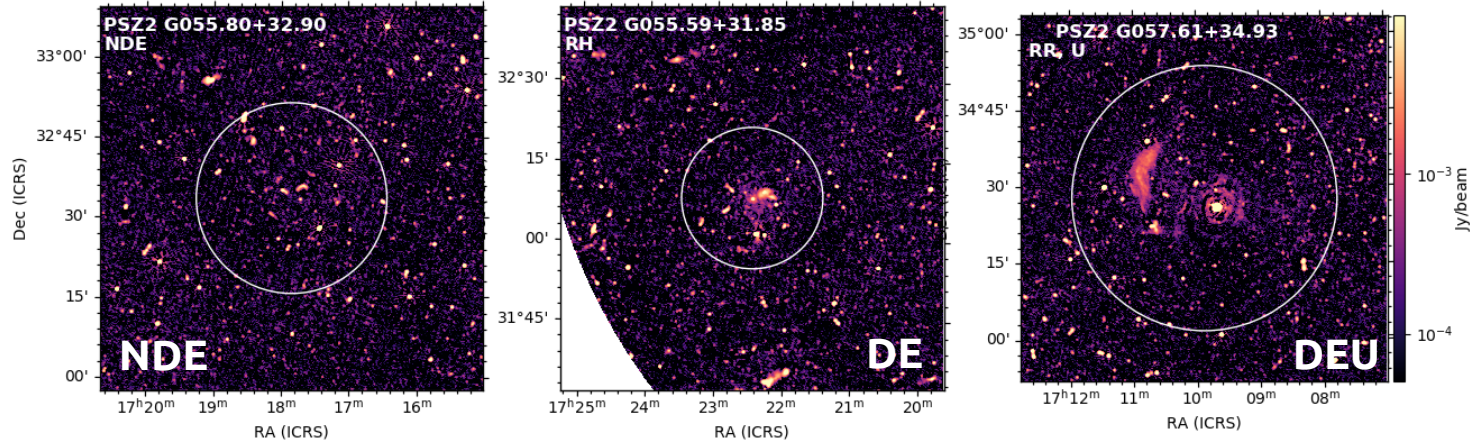
Detection ratio to test the detection with labeled galaxy clusters

$$R = (\text{sum probability/number of pixels})_{2.2R_{500}}$$

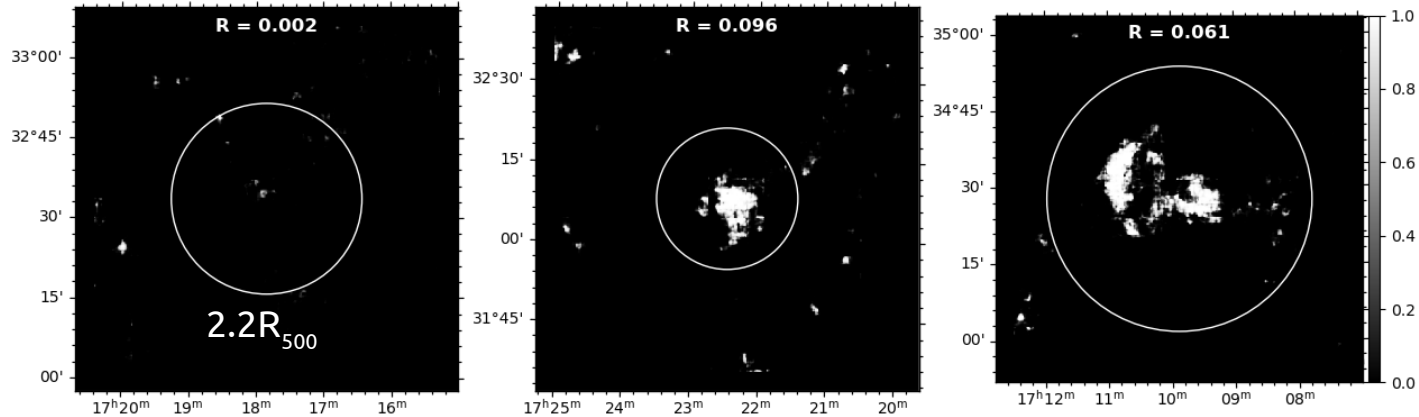
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Radio U-Net: performance verification on LoTSS data

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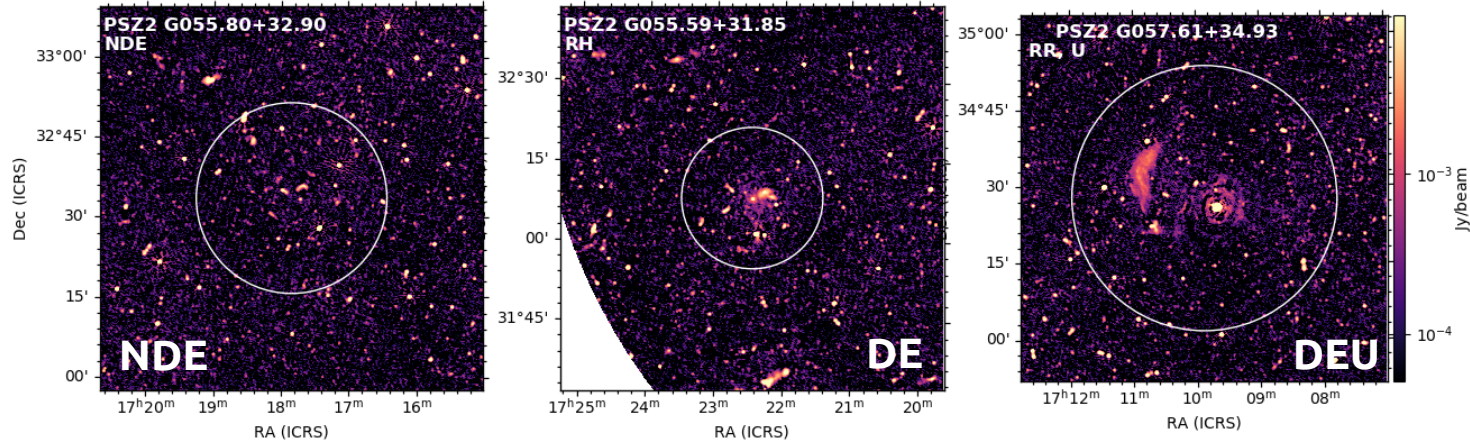
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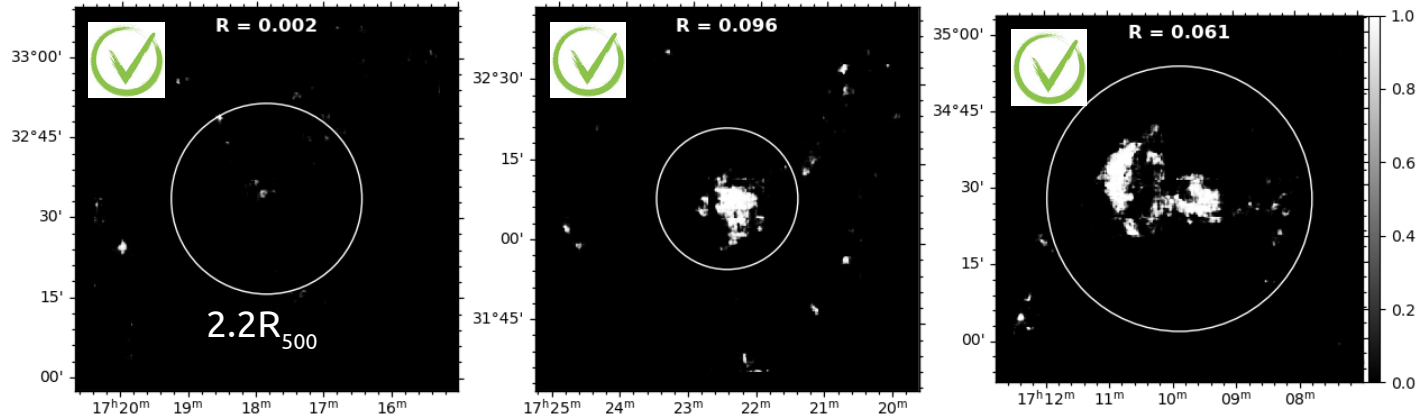
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Radio U-Net: performance verification on LoTSS data

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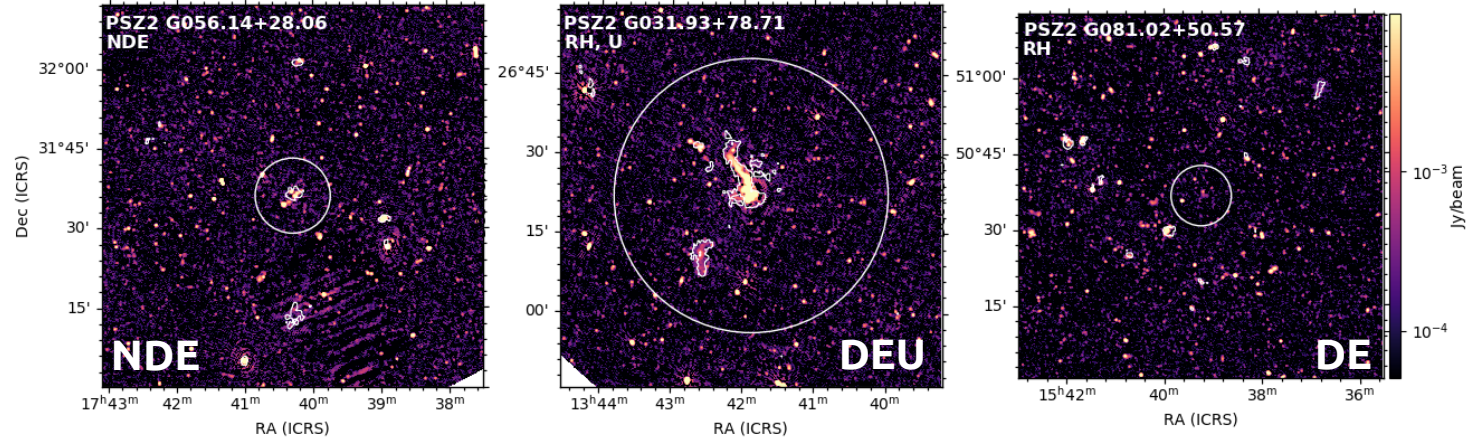


Radio U-Net segmented

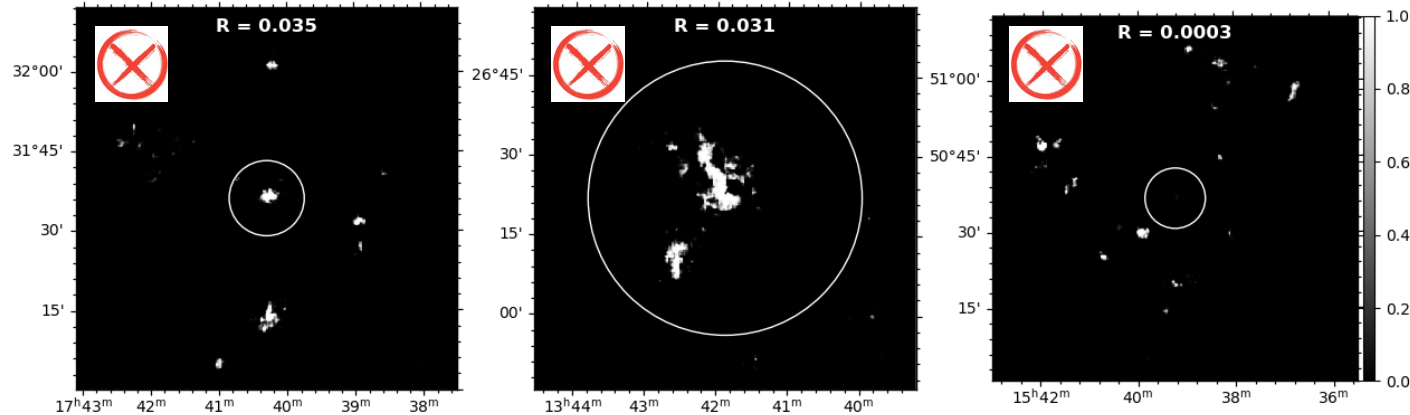


It is not always working (73% accuracy)

LoTSS data



Radio U-Net segmented

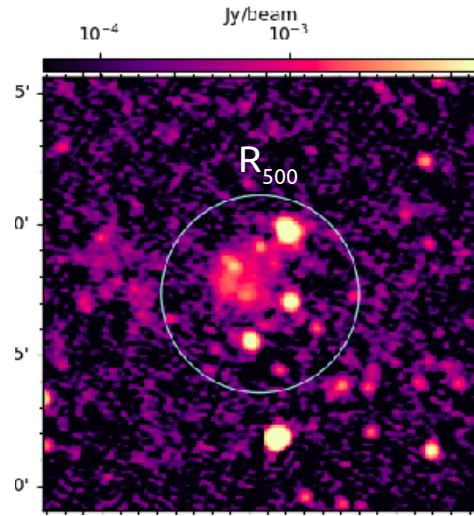


False positive mostly due to galaxy over-densities
and/or **extended radio galaxies**

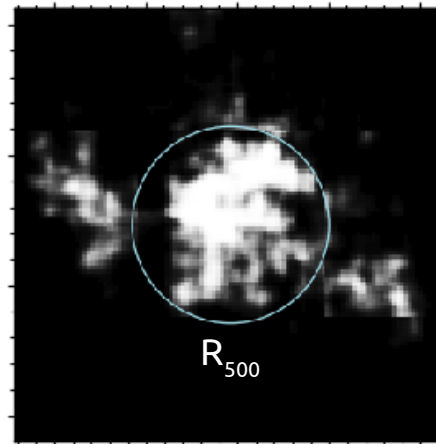
False negative for **high redshift**
or **low mass clusters**

Detection beyond galaxy clusters

LoTSS data



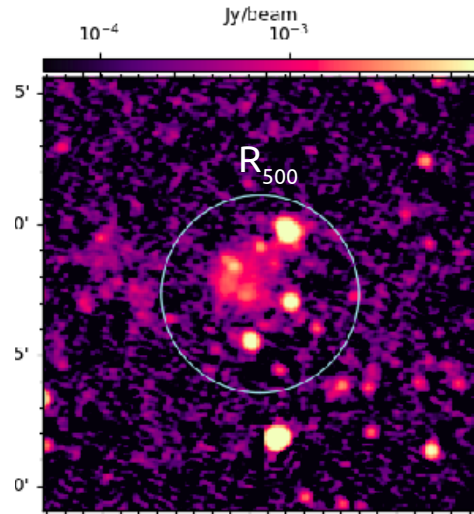
Radio U-Net segmented



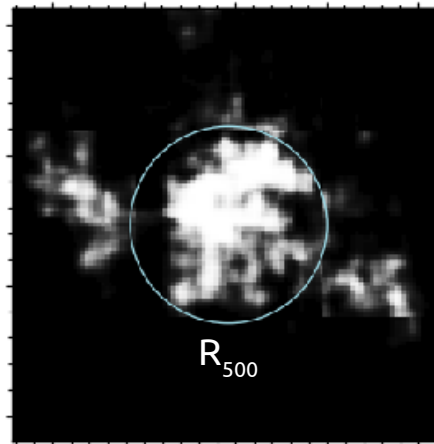
Detection of diffuse radio emission beyond galaxy clusters and below classical detection limits

Detection beyond galaxy clusters

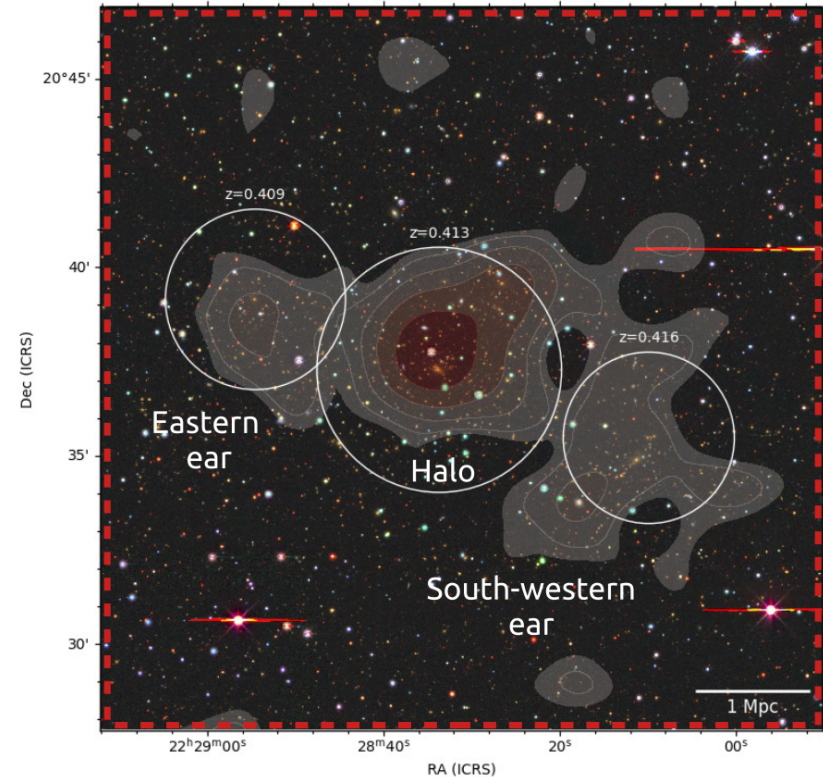
LoTSS data



Radio U-Net segmented



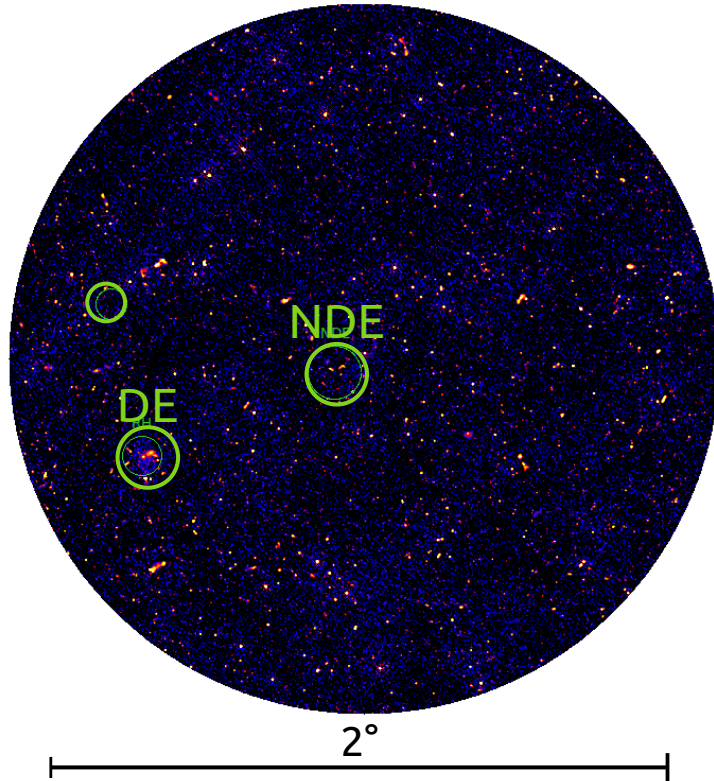
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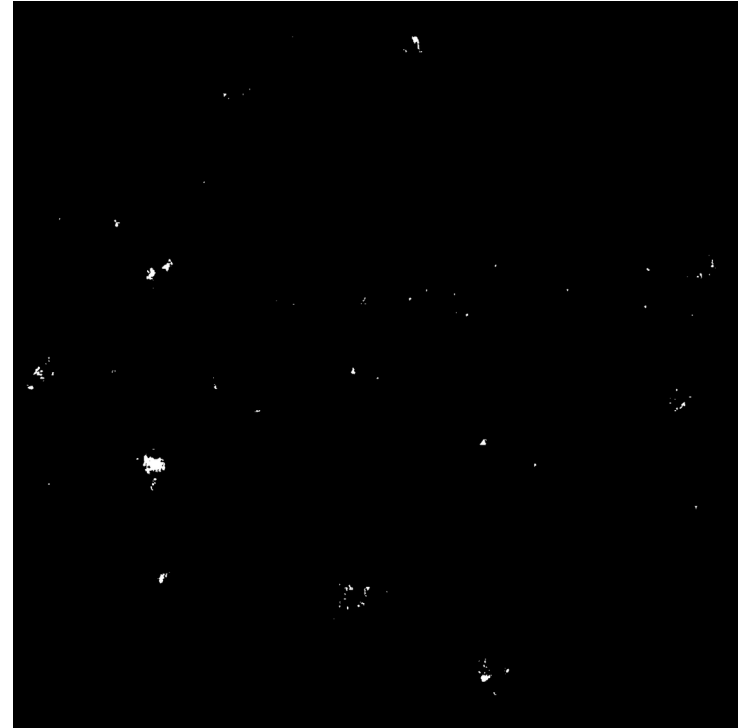
[Stuardi+25]

Radio U-Net: towards the LoTSS-DR3

LoTSS data: entire pointing



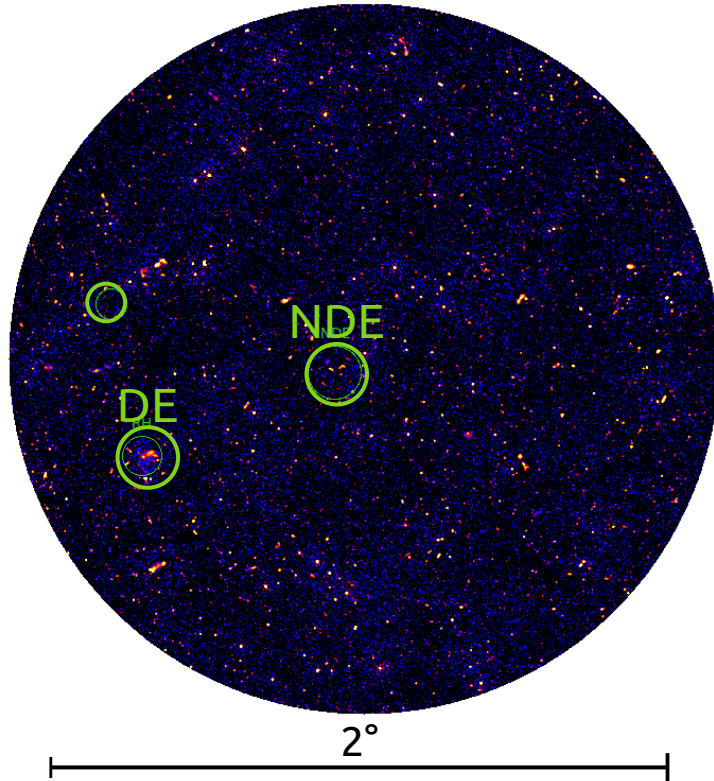
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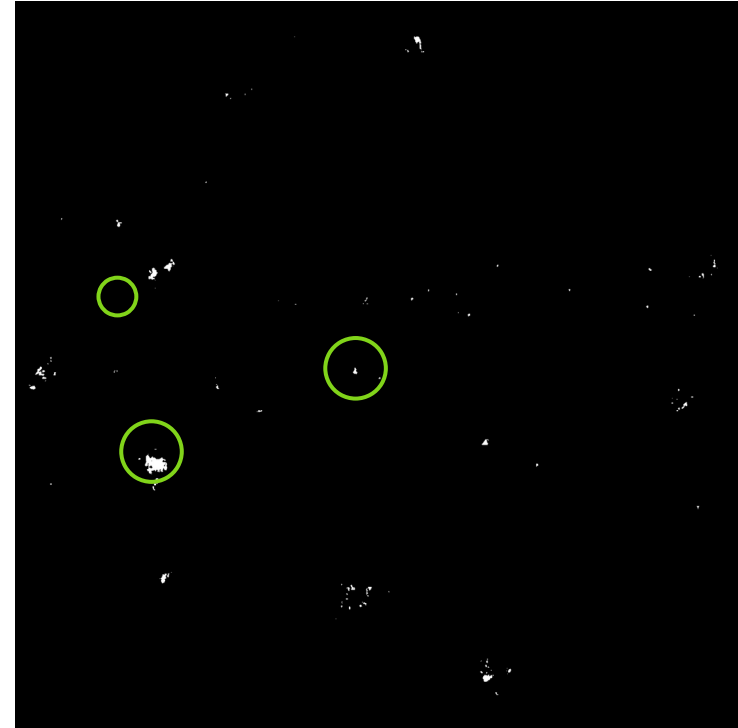
- ML guided blind search

Radio U-Net: towards the LoTSS-DR3

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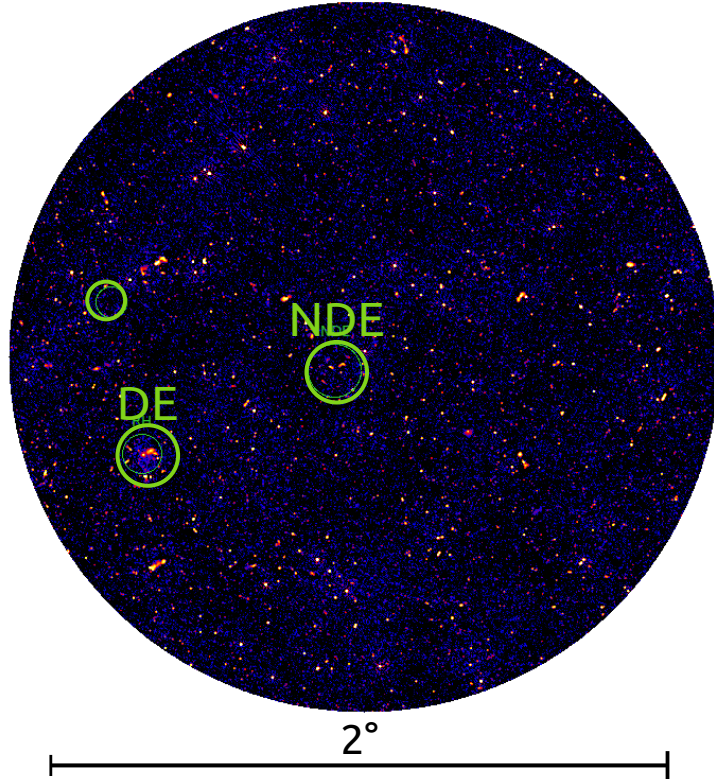
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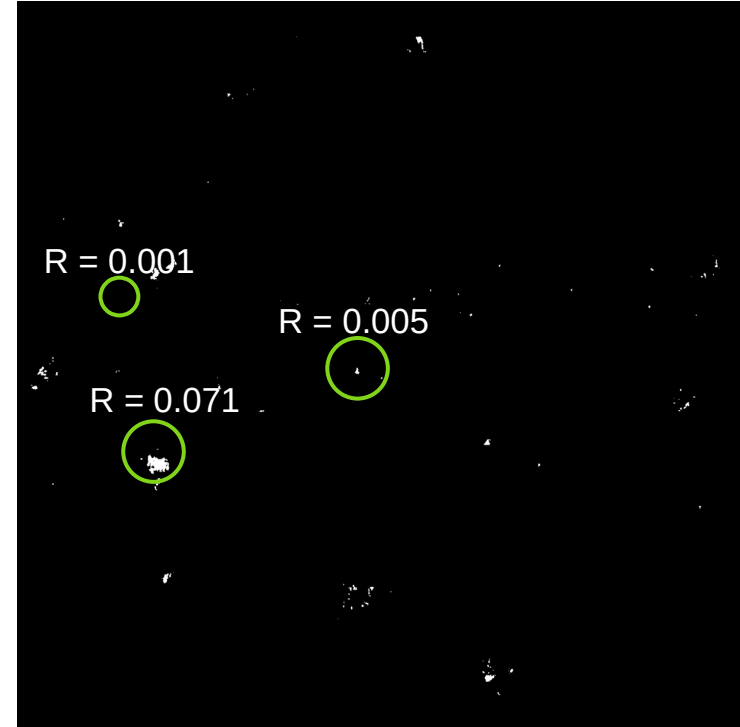
- ML guided blind search
- Cross-match with cluster catalogues

Radio U-Net: towards the LoTSS-DR3

LoTSS data: entire pointing



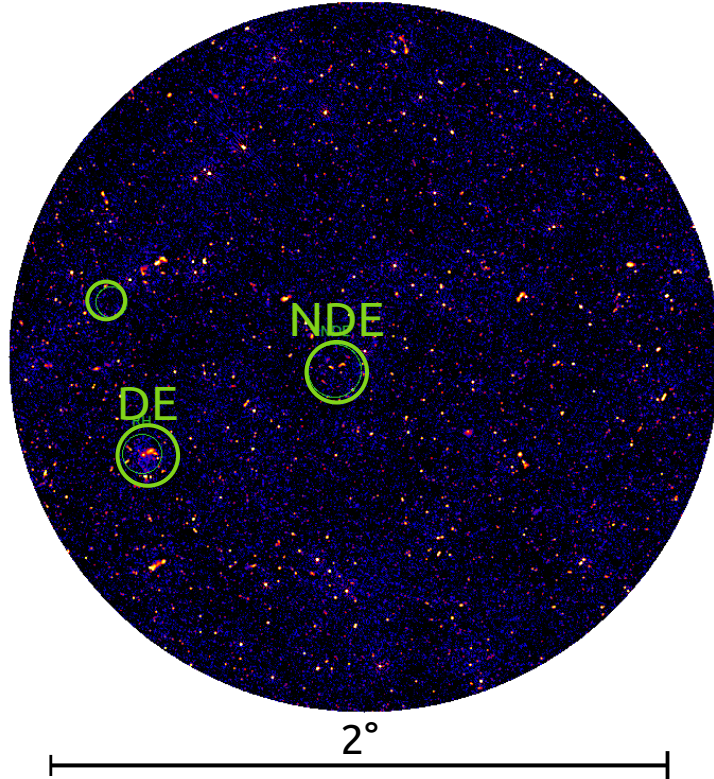
Radio U-Net segmented



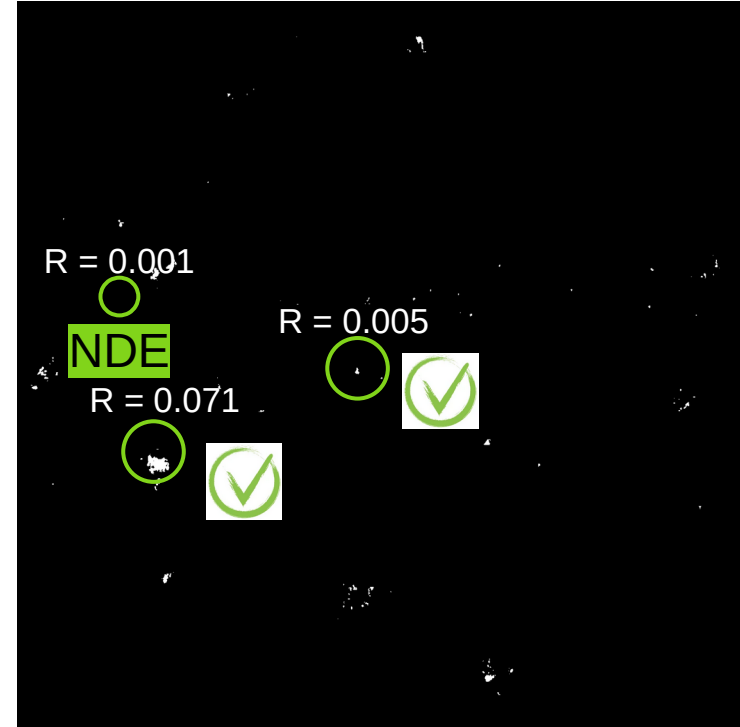
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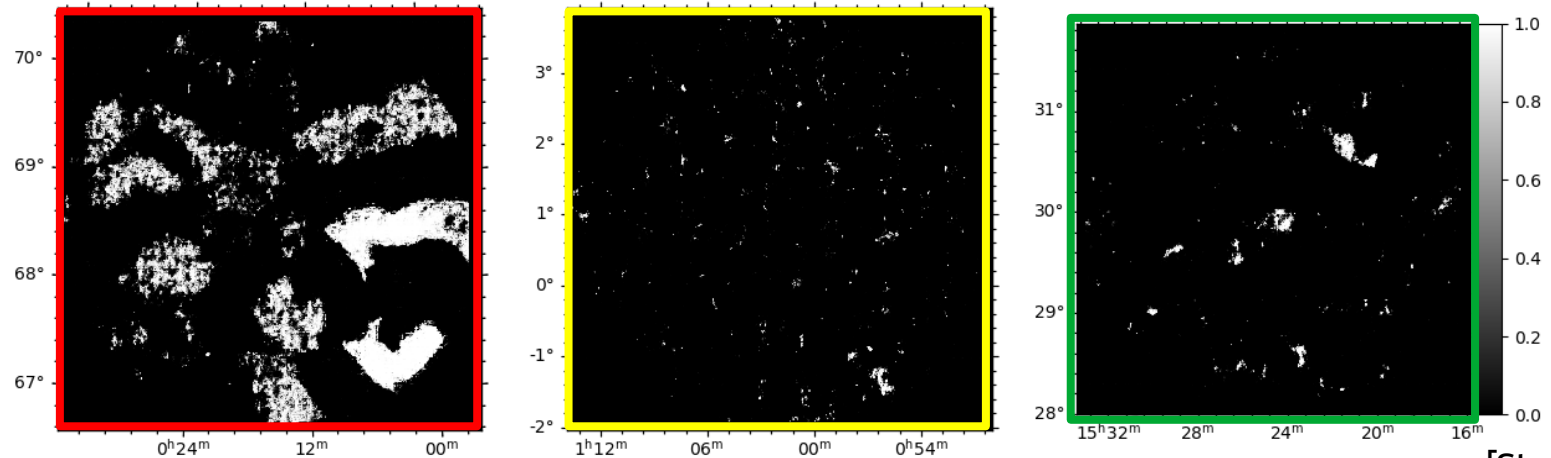
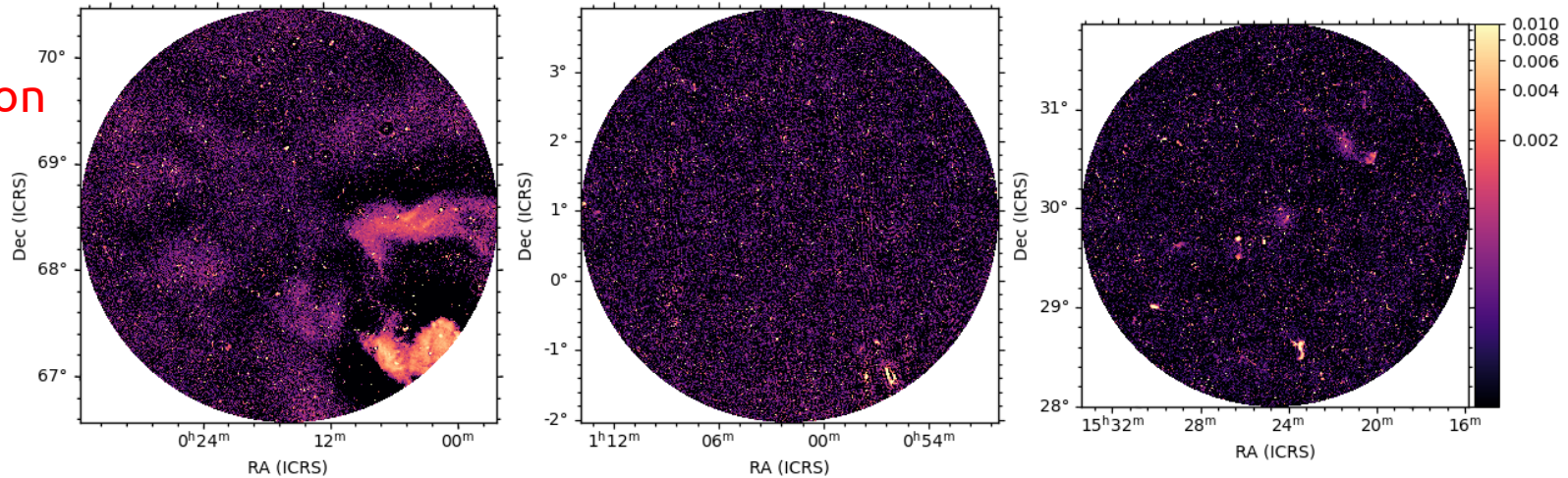
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Again: it is not always working!

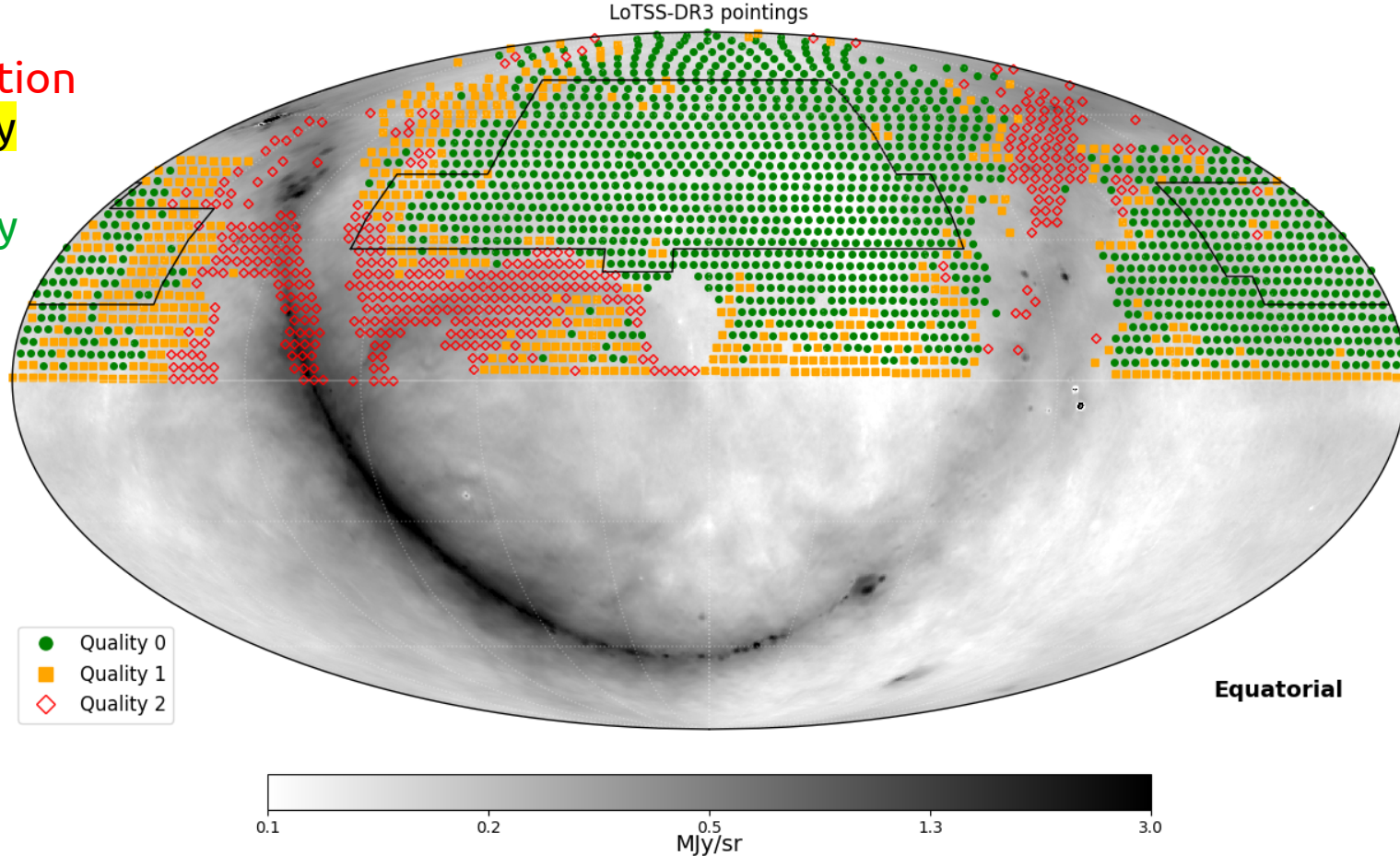
- Galactic contamination
- Low quality images
- DR2 quality images



[Stuardi+26]

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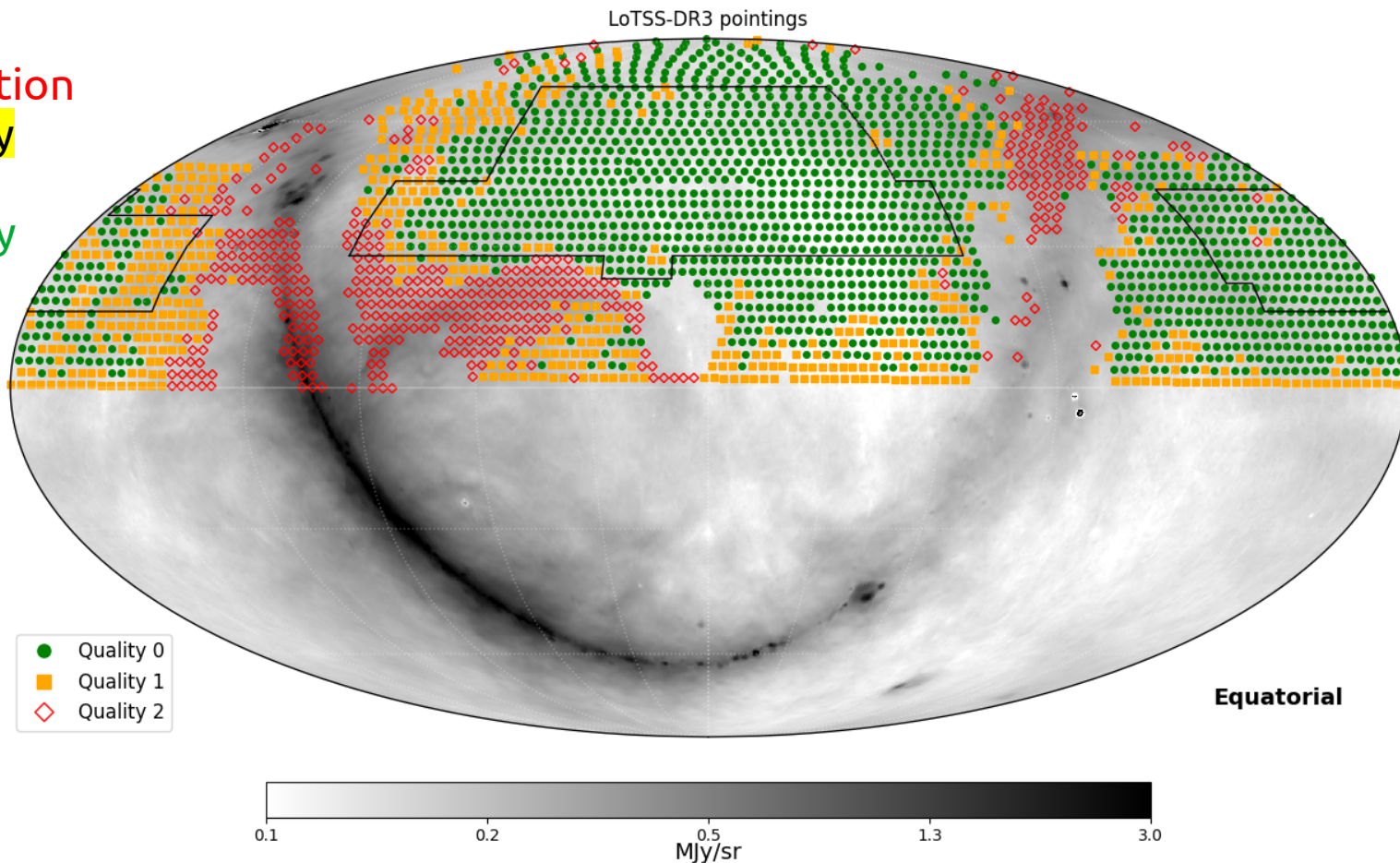
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[Stuardi+26]

But it is fast: survey processed in 4h @LEONARDO-CINECA

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- DR2 quality images

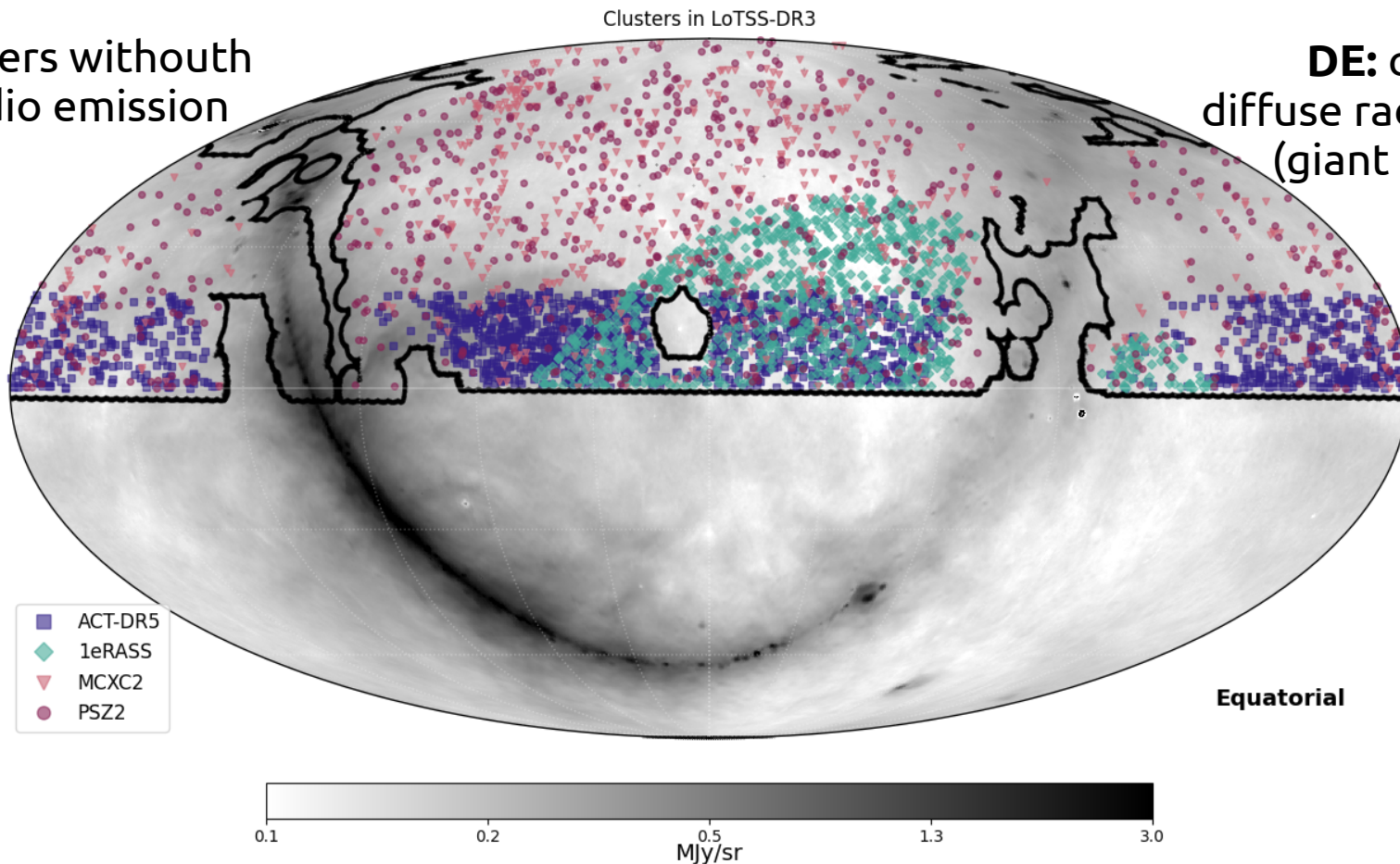


[Stuardi+26]

Cross-match with galaxy clusters catalogues

NDE: clusters without
diffuse radio emission

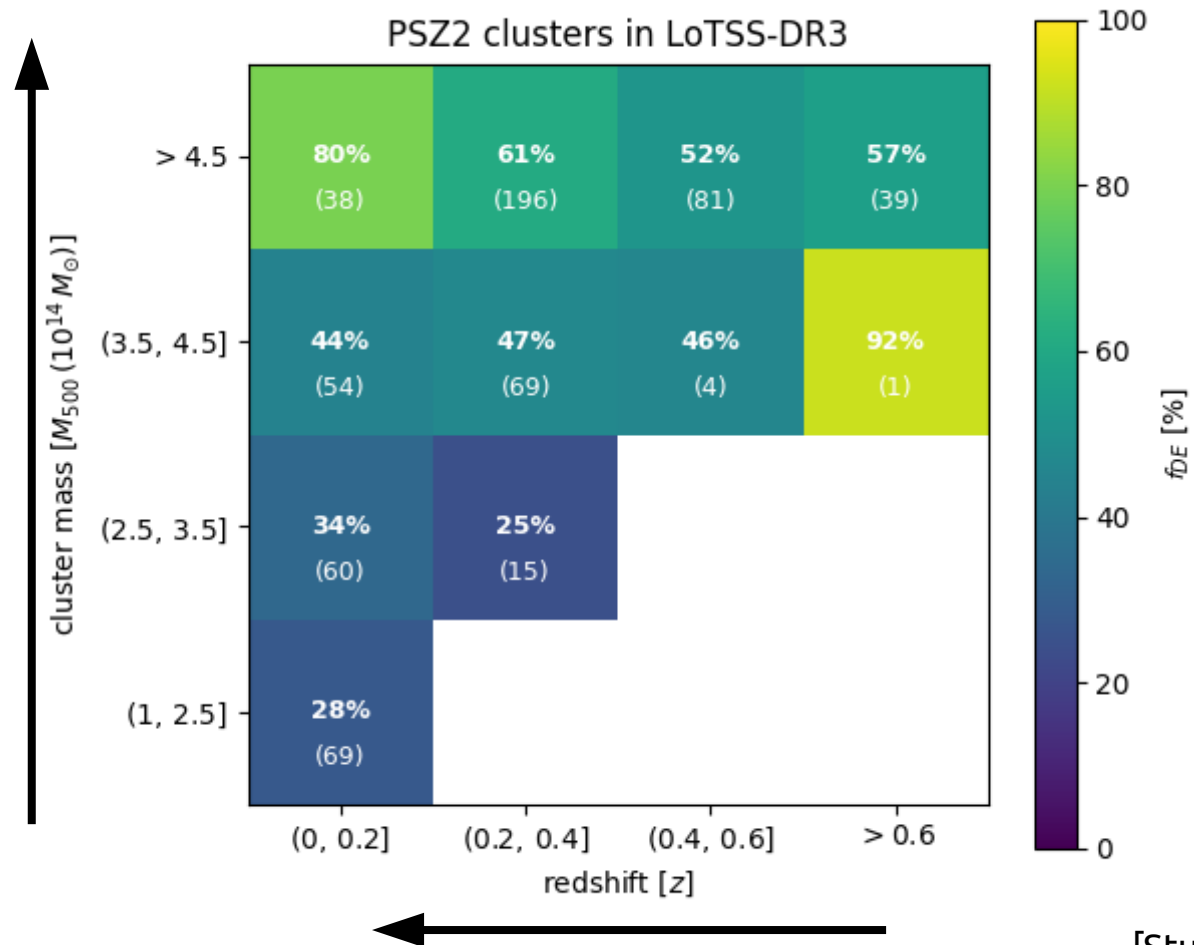
DE: clusters with
diffuse radio emission
(giant halos, relics,
mini-halos,
phenixes,
uncertain...)



[Stuardi+26]

Result 1) test detection rate on very large samples

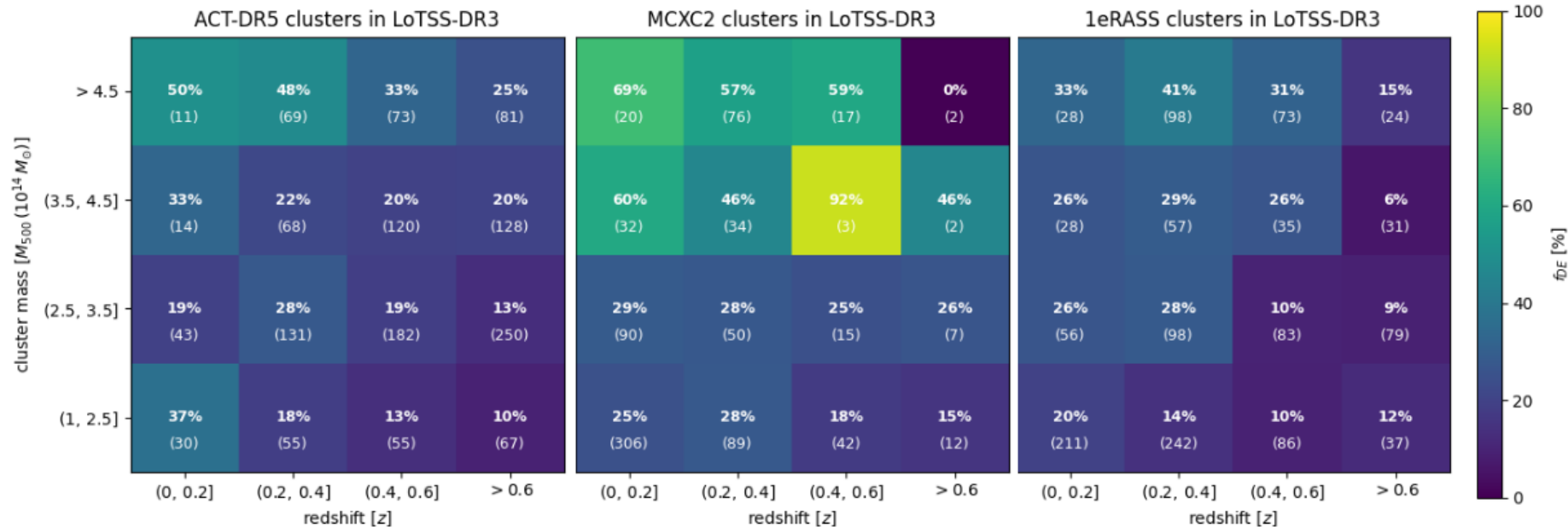
Catalogue	$N_{\text{LoTSS-DR3}}$	f_{DE}
PSZ2	686	50%
ACT-DR5	1699	22%
MCXC2	874	32%
1eRASS	1324	21%



[Stuardi+26]

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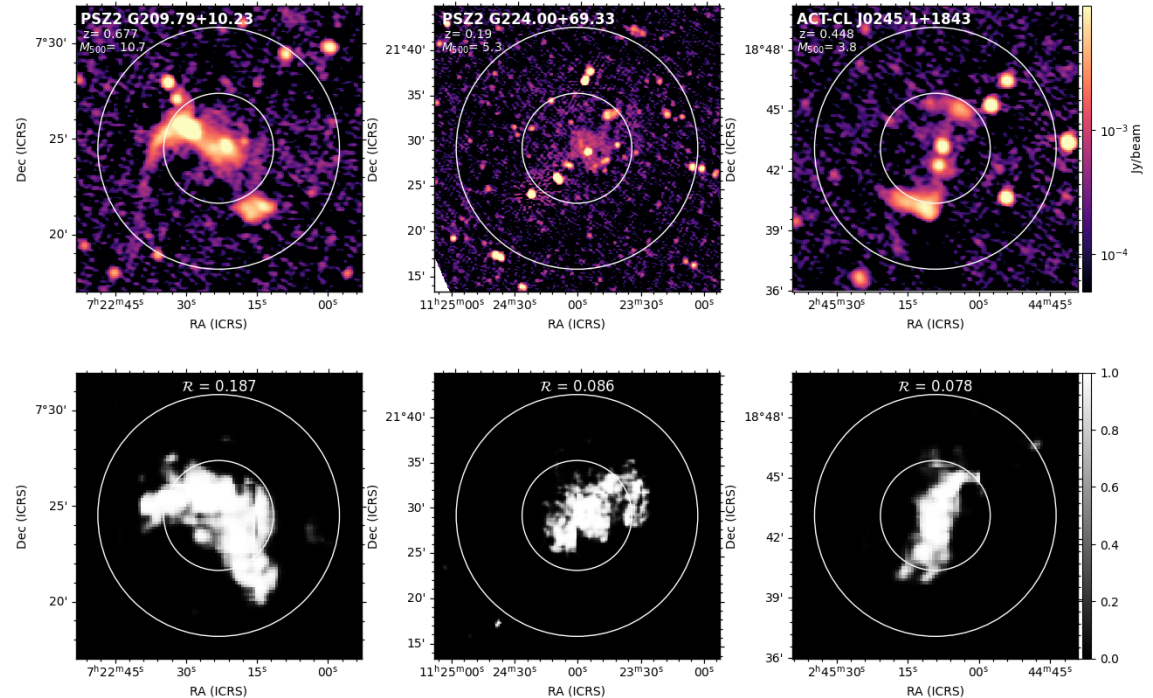
[Stuardi+26]

Result 2) extraction of interesting sub-samples

- Selection of **357** galaxy clusters with highly confident DE classification
19 clear false detection (due to AGN)
109 with literature confirmation of some kind of diffuse radio emission (comprising known bridges and phoenixes)
229 possible new discoveries
NB: extraction and self-calibration of each target is necessary

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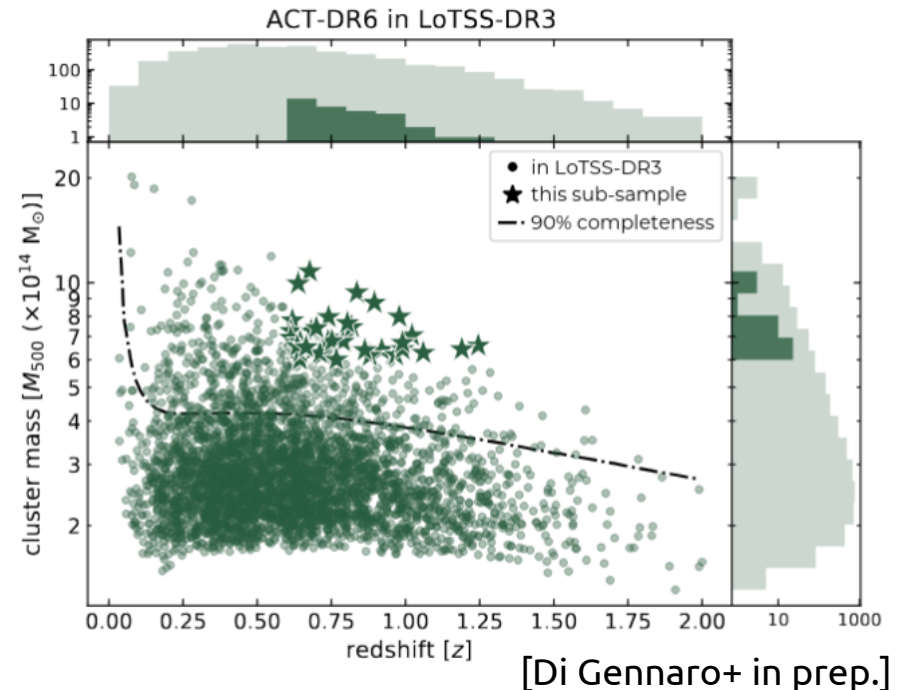


[Stuardi+26]

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- Follow up on single clusters
(Pfeifer, Hoang, Drabent, Cianfaglione...)
- First step towards more focused sample studies
 - high-redshift systems (G. Di Gennaro)
 - low-mass systems
 - bridges
 - phoenixes (N. Biava)



https://lofar-surveys.org/clusters_dr3.html



Galaxy clusters in LoTSS DR3

In this page, we present the results of the analysis of galaxy clusters covered by the third LOFAR Two-metre Sky Survey Data Release (LoTSS-DR3). The sample is constructed by cross-matching clusters listed in four major catalogues: the second Planck Sunyaev–Zel’dovich cluster catalogue, the fifth data release of the Atacama Cosmology Telescope cluster catalogue, the second Meta-Catalogue of X-ray detected Clusters of galaxies, and the first SRG/eROSITA All-Sky Survey cluster catalogue.

The merged catalogue contains 3822 galaxy clusters and represents the largest sample to date used to search for diffuse synchrotron emission in the intra-cluster medium. The detection pipeline is based on Radio U-Net, a convolutional neural network introduced by [Stuardi et al. \(2024\)](#). The corresponding Radio U-Net segmentation map of LoTSS-DR3 is also provided as a HiPS dataset for visualisation.

A curated sub-sample of 357 clusters, identified as hosting diffuse radio emission at the highest network accuracy (76%), is additionally provided. This sub-sample is available both as a downloadable fits file and as a searchable table, including associated postage-stamp images.

When using any of these data products, please cite [Stuardi et al. \(2026\)](#), where a full description of the methods and results is presented.

Tables

- [All clusters FITS table](#)
- [Curated subsample FITS table](#)
- [DR3 quality table](#)

HiPS image

[HiPS image](#)

<https://github.com/ICSC-Spoke3/Radio-U-Net>

Conclusions

- Machine learning is a valuable tool for identifying interesting targets and creating statistical samples from huge datasets

Possible improvements:

- integrate datasets at different frequencies/multi-wavelength
- test self-supervised methods
- improve the training dataset

However:

- human supervision remains indispensable
- data extraction and self-calibration represent a bottleneck for scientific exploitation of large datasets
- source classification is still a dream (or a nightmare?)

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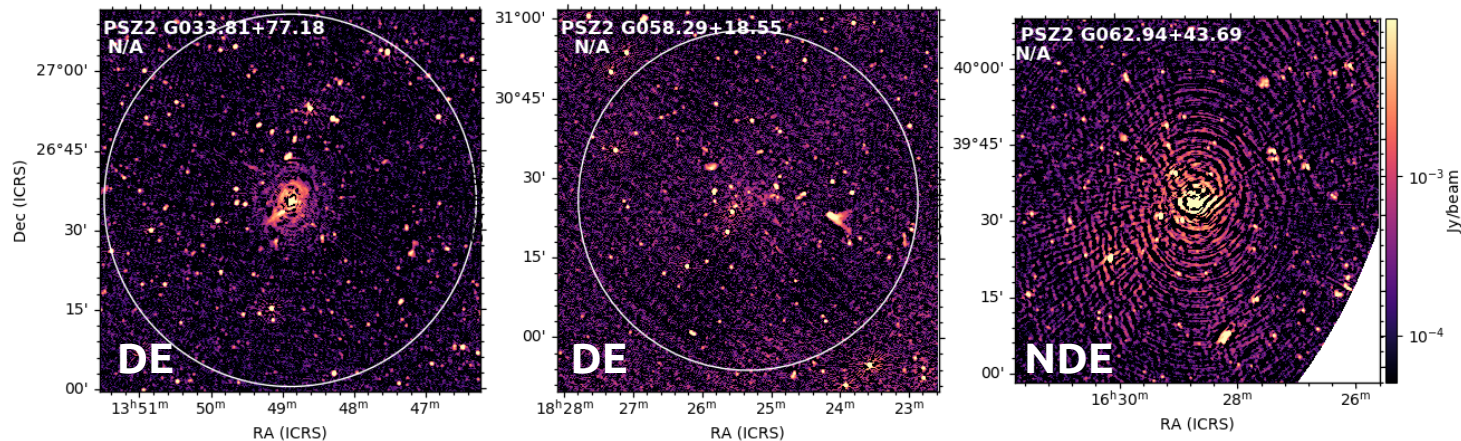
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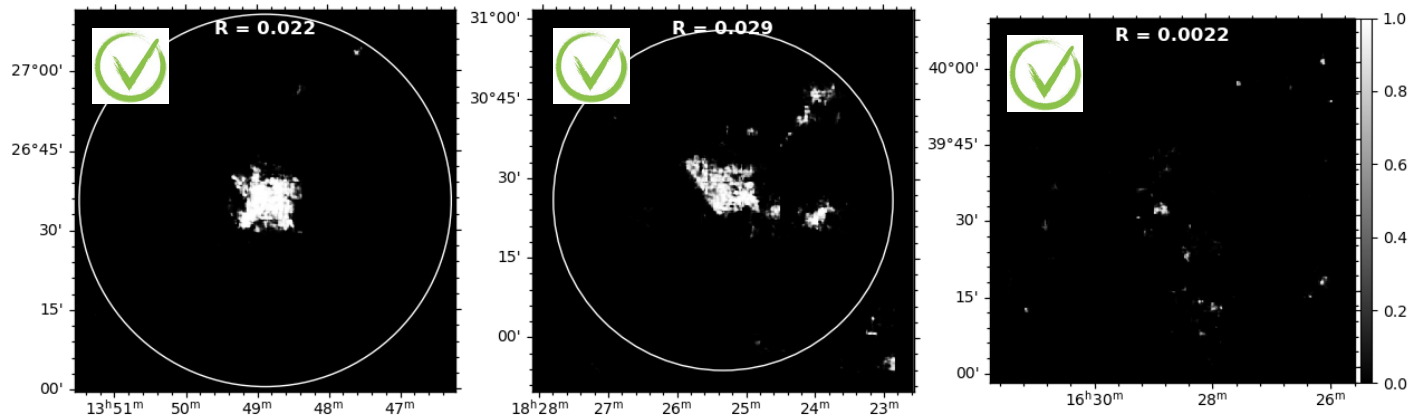
Thank you for your attention!

Low quality images

LoTSS data



Radio U-Net segmented



Correct segmentation of low-quality images

[Stuardi+24]