Statistical studies of diffuse radio emission in galaxy clusters with LOFAR

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on behalf of the Galaxy Clusters WG &
the LOFAR Survey KSP

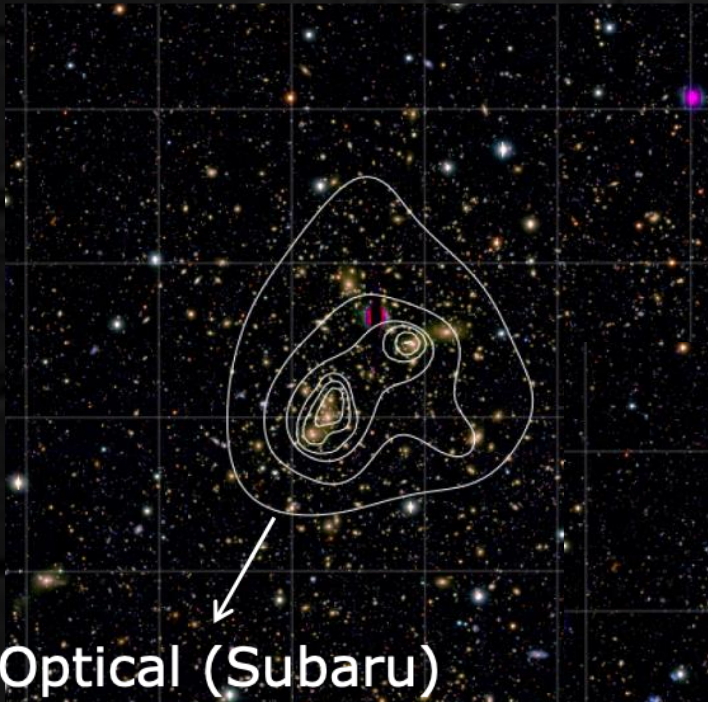
Outline of the talk

- ★ Galaxy clusters and their diffuse Mpc-scale radio emissions
- ★ Present picture and importance of statistical studies
- ★ A big project: Planck clusters in LoTSS DR2
- ★ RH statistics and comparison with model expectations
- ★ Radio-power mass correlation and cluster dynamics
- ★ Summary and future prospects

Clusters of galaxies

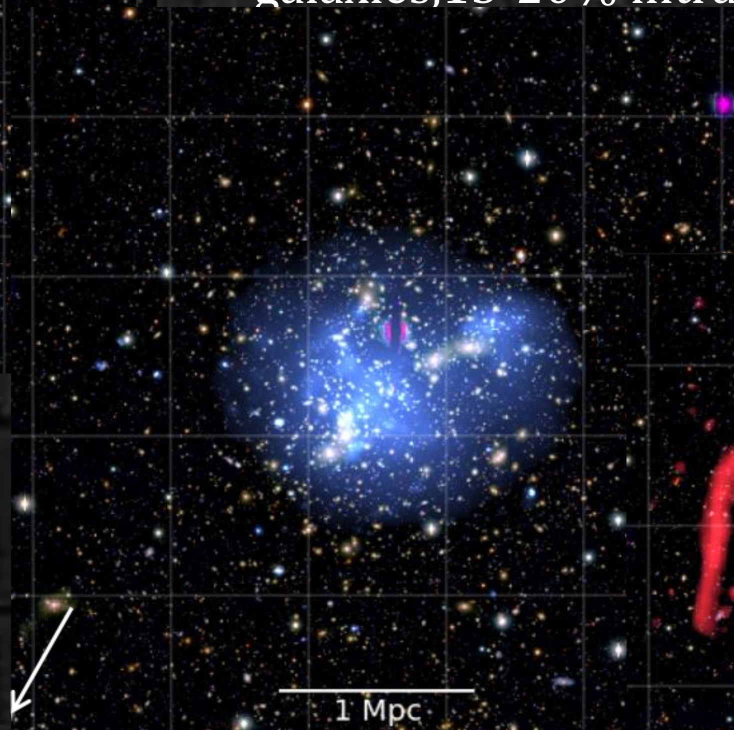
✓ Largest concentration of matter in the Universe, L~2-3 Mpc, $M \sim 10^{14}$-$10^{15}\ M_\odot$

✓ Made of : 70-80% of dark-matter, few % galaxies,15-20% intra-cluster medium (ICM)



Optical (Subaru)

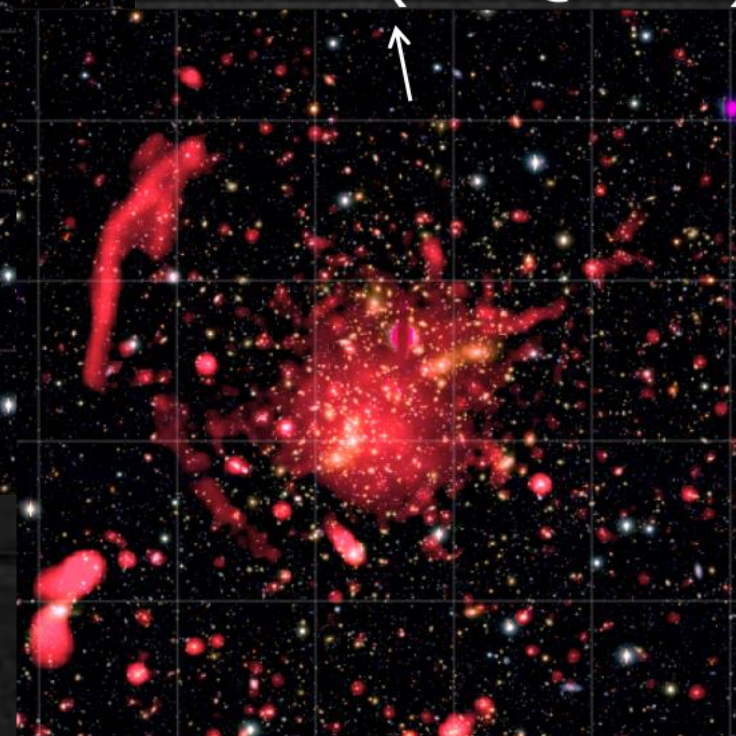
galaxies (stars)
+
DM (indirect)



X-rays (Chandra)

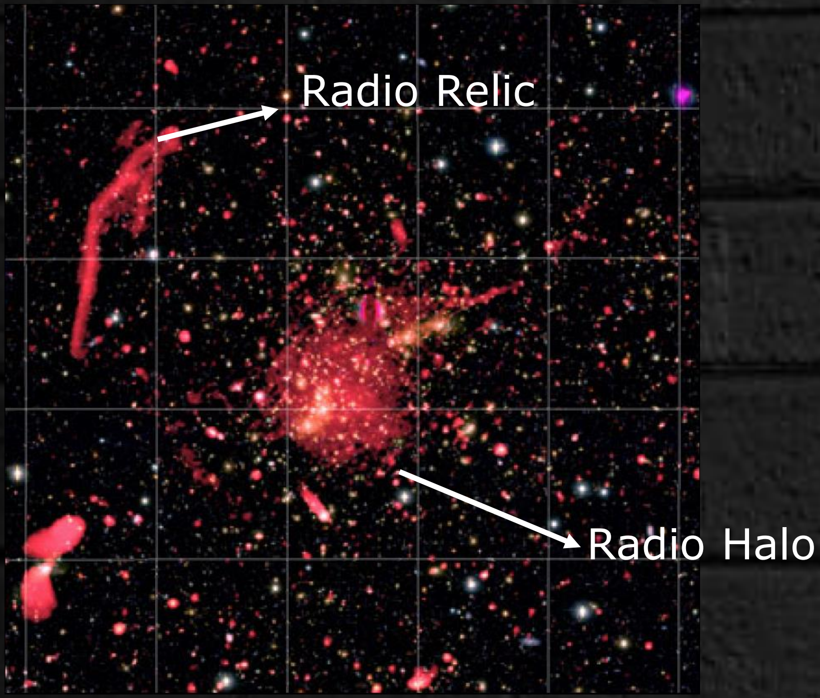
Hot ICM:
$n_e \sim 10^{-1}$-10^{-4} cm^{-3} ,
$T \sim 10^8$ °K

radio (VLA @1GHz)



Abell 2744, image credits: van Weeren + 19

Cluster-scale diffuse emission



van Weeren + 19

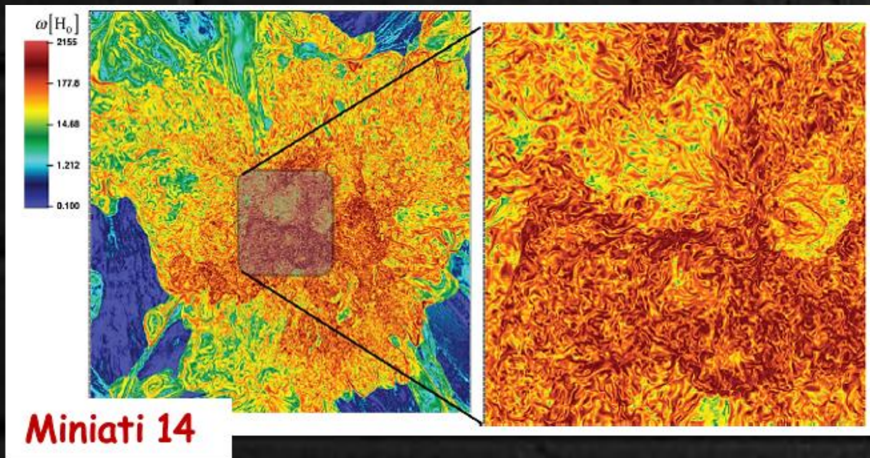
- diffuse synchrotron radio emission in the form of Radio Halos and Radio Relics
- steep spectrum sources (α >1, with $F(\nu) \propto \nu^{-\alpha}$)
- proof of the presence of non-thermal components, GeV electrons ($\gamma \sim 10^4$) and μ**G** magnetic field, mixed with the thermal ICM on Mpc scales.

Syn+IC lifetime of radio e^-

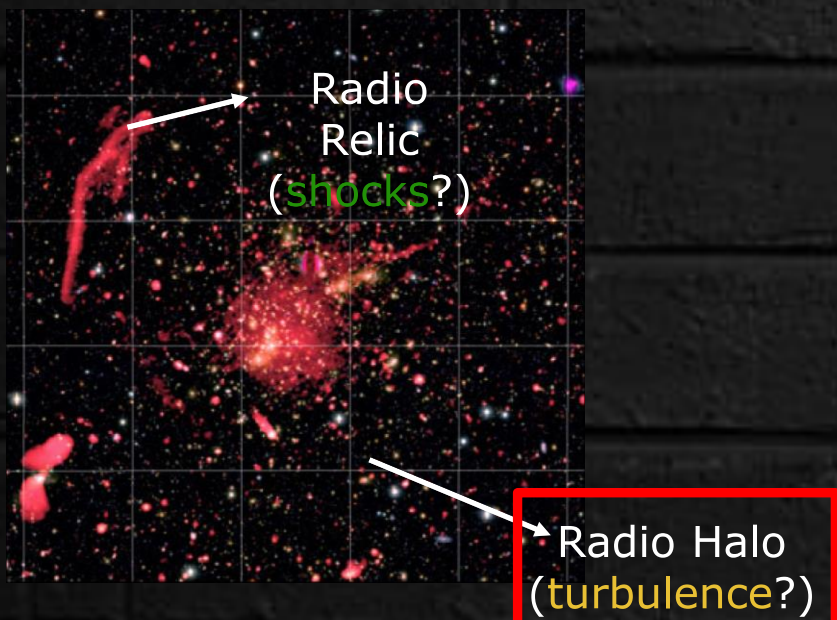
$T_{rad} \sim$100-300 Myr << diffusion time

ICM acceleration site !

Cluster-scale diffuse emission

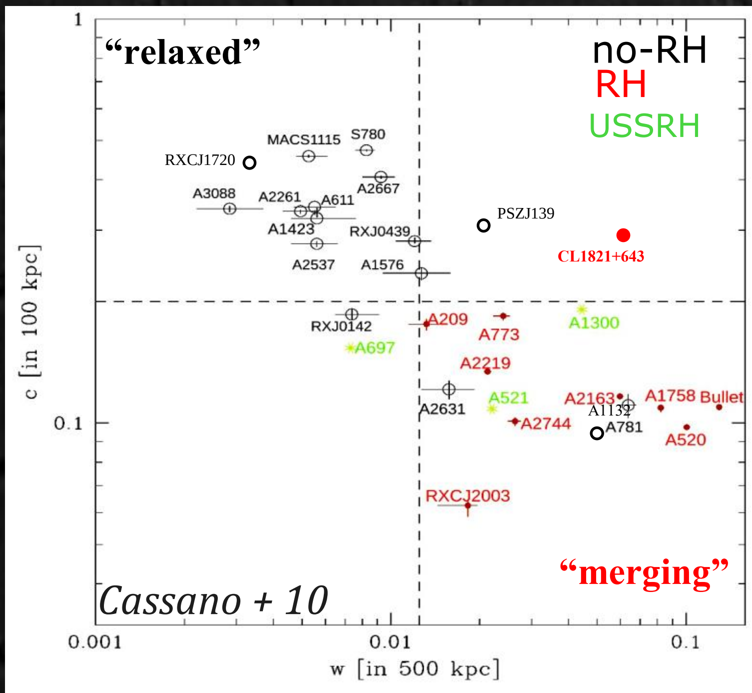


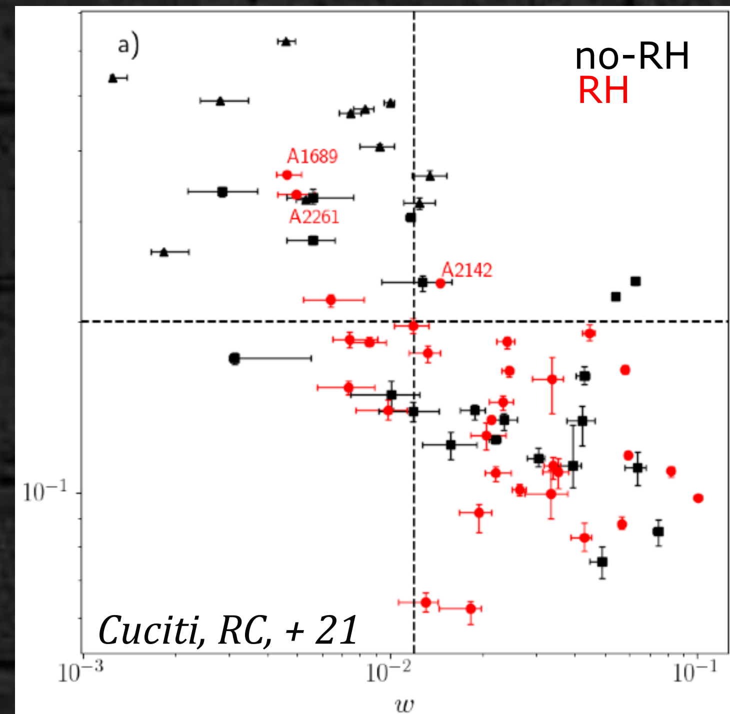
- Galaxy clusters form via a hierarchical sequence of mergers and accretion of smaller systems driven by DM
- Mergers drive **turbulence** and **shocks** in the ICM
- Turbulence and shock can power mechanisms of particle re-acceleration in the ICM (e.g. *Brunetti & Jones 2014*)



- Fundamental questions:
  - ➢ ORIGIN ??
  - ➢ IMPACT on thermal ICM ?? (microphysics & dynamics)

RH cluster - merger connection





see also e.g., Rossetti + 11, Wen & Han 14; Parek +15, Eckert 17, Cuciti + sub.

Cuciti, RC, + 21

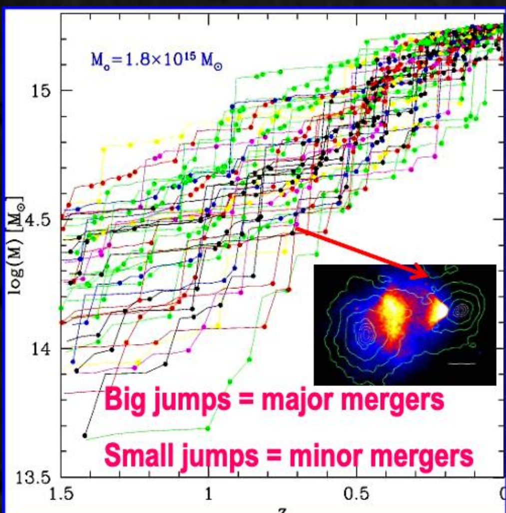
A statistical connection between RH and the clusters dynamical status: RH in the most **dynamically "disturbed"systems**, clusters without diffuse radio emission more "relaxed".

Turbulence generated during cluster mergers re-accelerates relativistic e- in the ICM to the energy necessary to produce the observed radio emission (e.g. Brunetti & Jones 2014)

Basic theoretical expectations (turbulence)

Cassano & Brunetti 05; Cassano et al. 2006, 2010, 2012

⋆ Monte-Carlo approach based on <u>semi-analytic</u> models (e.g. Lacey & Cole 93) to describe the formation history of GCs



⋆ *Turbulence* injected during cluster mergers (E_t derived from the PdV work of the infalling subclusters)

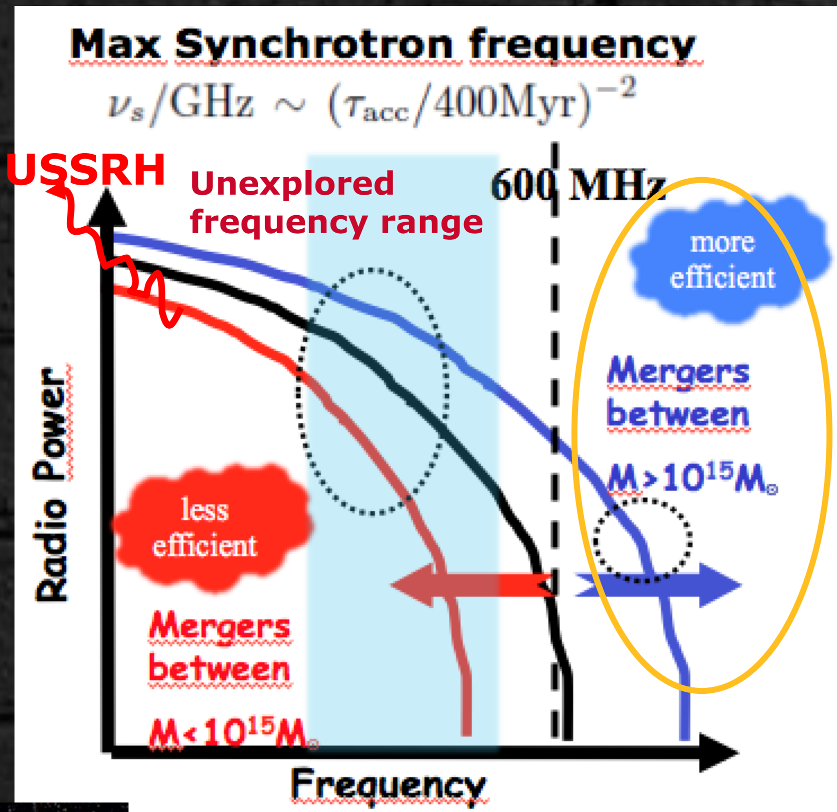
Turbulent energy flux

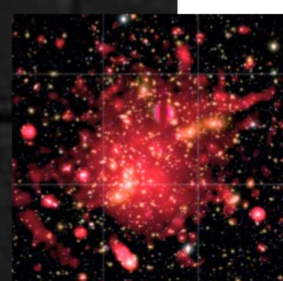
Particles heating/ acceleration rate

$$\rho_{ICM}\delta V^3 L^{-1}\eta_{CRe} \sim \int d^3 p E \frac{\partial f_e}{\partial t}$$

Radiation: Syn + ICS

⋆ FERMI II like acceleration mechanisms not efficient ! => max synchrotron ν_s





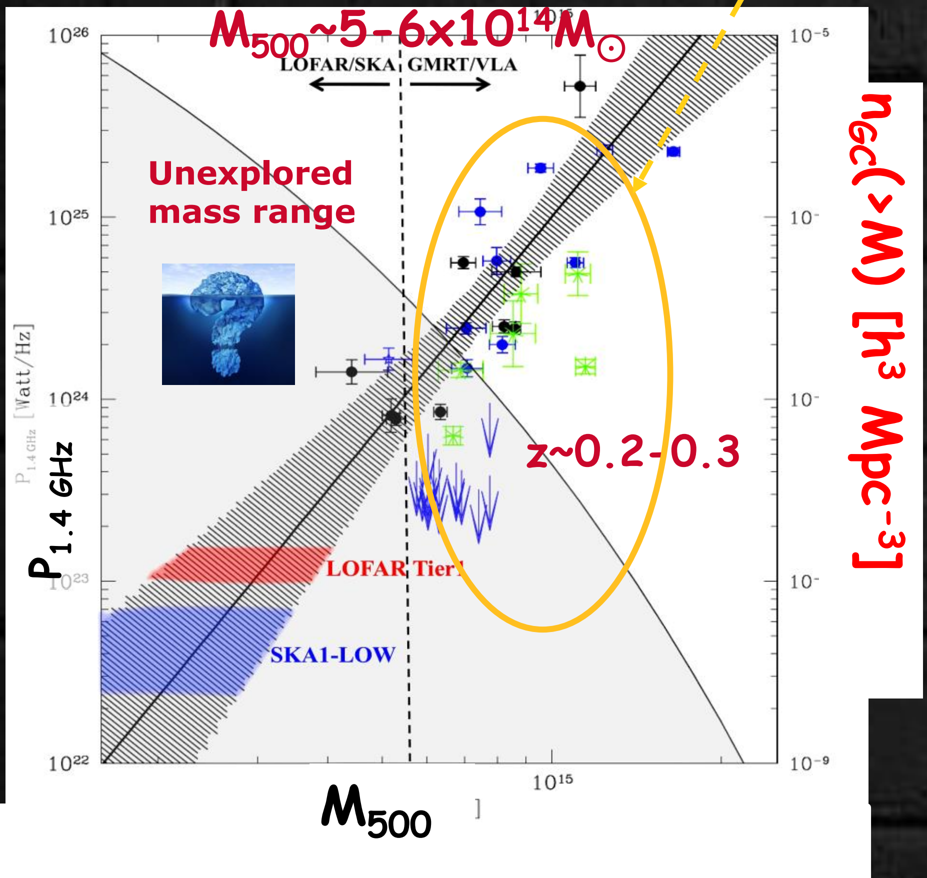
Radio Halos predicted to be a mix of different populations including *very steep spectrum* sources «invisible» at classical frequencies.

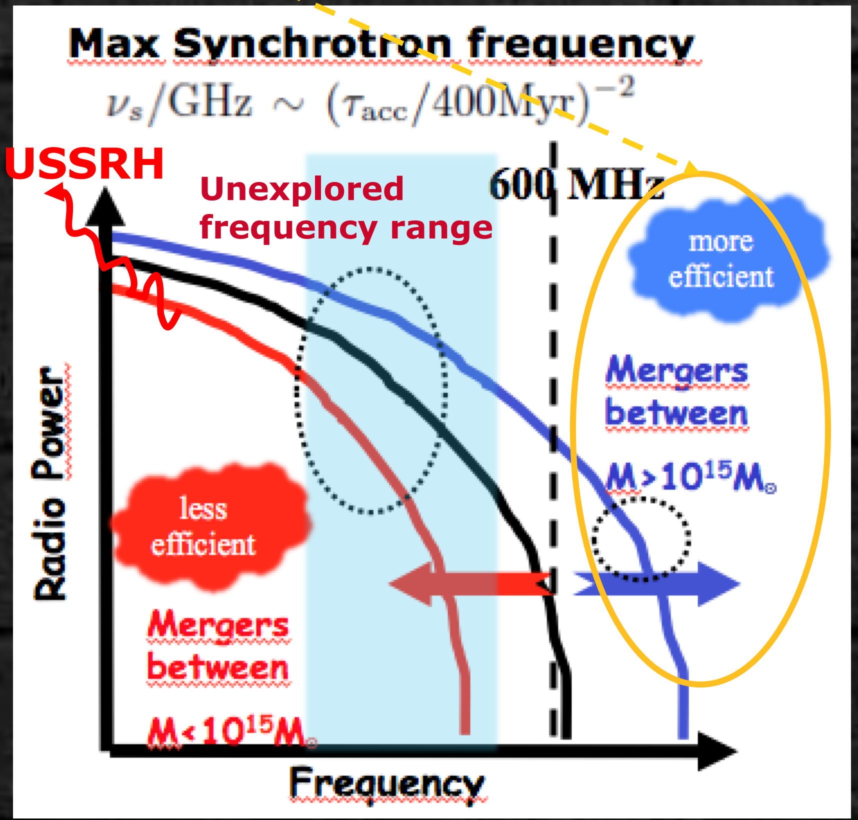
(Cassano + 06; Brunetti+ 08 Nature)

How much the present view is biased?

pre-LOFAR era: high mass, high frequency (low-z)

Cassano + 15



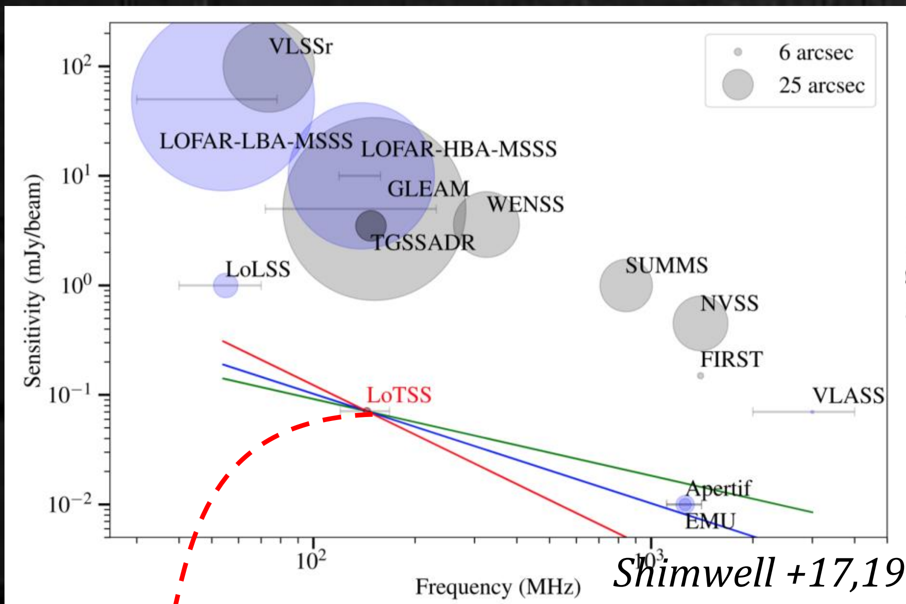


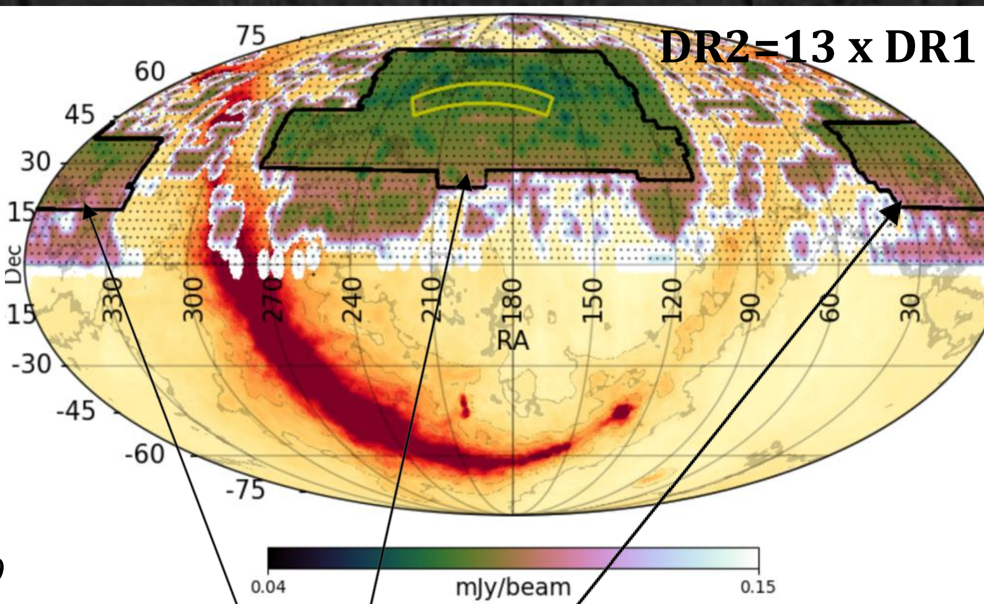
Current statistical studies **limited to massive M_{500}~5-6x$10^{14}M_\odot$ (and ~ nearby) systems** which are only a small fraction of the clusters in the Universe !

Radio Halos predicted to be a mix of different populations including *very steep spectrum* sources «invisible» at classical frequencies.

(Cassano + 06; Brunetti+ 08 Nature)

LOFAR Two-Meter Sky Survey second data release (DR2)





LOFAR Two-metre Sky Survey (LoTSS) *(Shimwell+ 17,19)*:

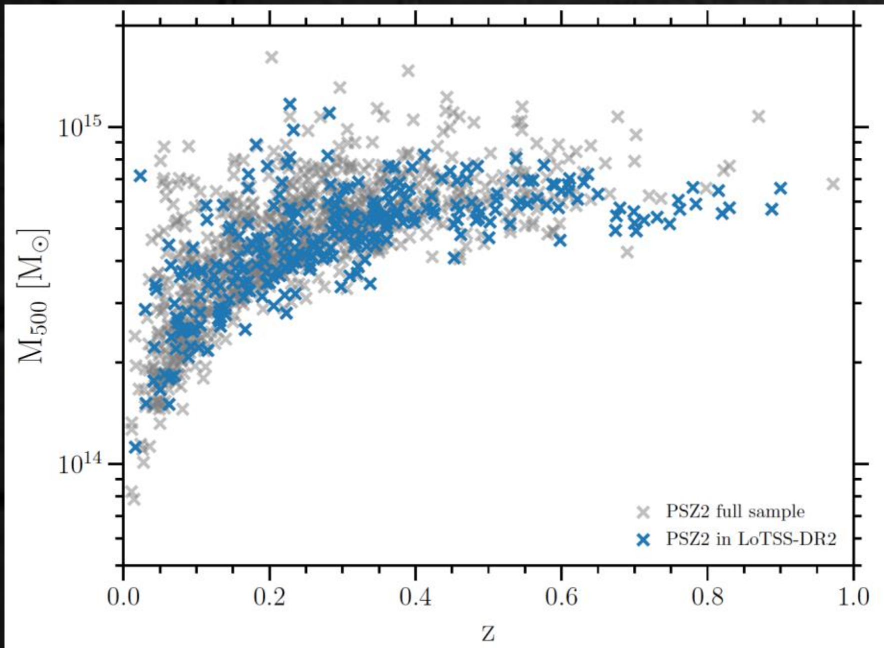
Frequency 120-150 MHz
resolution ~5 arcsec
sensitivity 100 μJy/beam
FoV 6.4 deg^2
3170 pointings 8 hrs observation each
2π str (all northern sky)

LoTSS-DR2 *(Shimwell+ 22)*

new pipeline, improving source fidelity, dynamic ranges…

5634 deg^2 (27% of the northern sky)

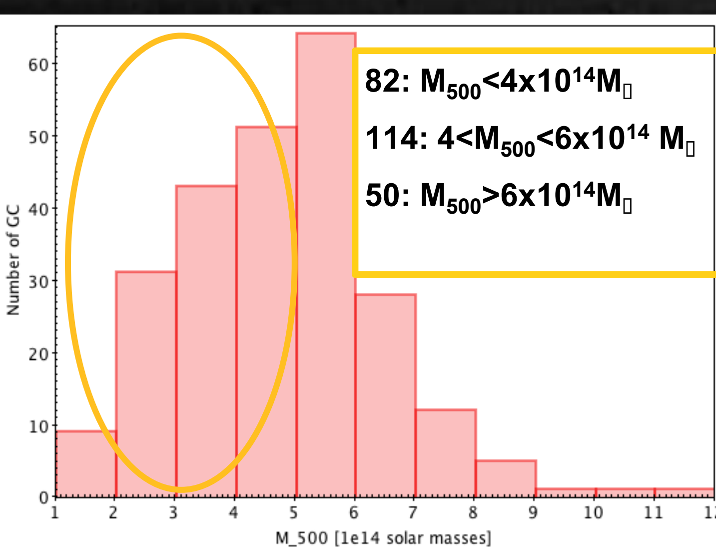
The Planck clusters in the LOFAR SKY

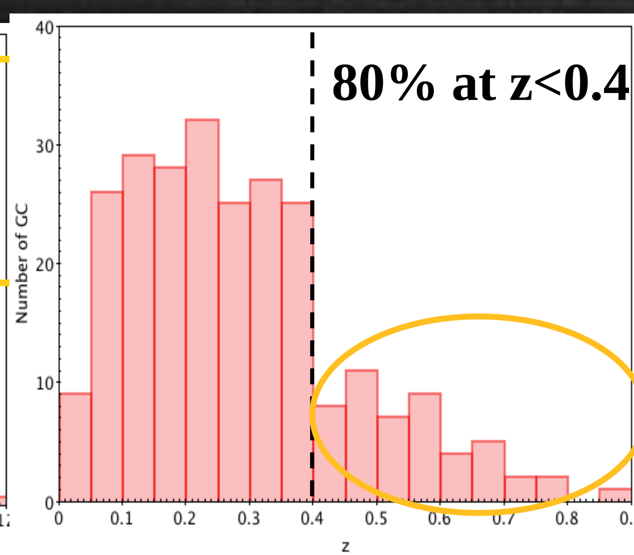


LoTSS-DR2 PSZ2 sample (*Botteon + 22*)

- 309 PSZ2 clusters in DR2 (12x PSZ2 DR1)
- 280 have M_{500} and z
- 70% have X-ray data (Chandra and/or XMM)
- classification of diffuse radio sources in GC

This is the largest statistical study of diffuse radio emission in clusters with deep low-frequency radio observations!





It allows to explore new mass and redshift ranges.

A collaborative effort

A group spread over three countries

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

Paper I: New detections and sample overview (*Botteon+ 22*)

Paper II: Recovering diffuse extended emission with LOFAR (*Bruno+ 22*)

Paper III: Dynamical states and density fluctuations of the ICM (*Zhang + 23*)

Paper IV: Statistics of radio halos and re-acceleration models (*Cassano + 22*)

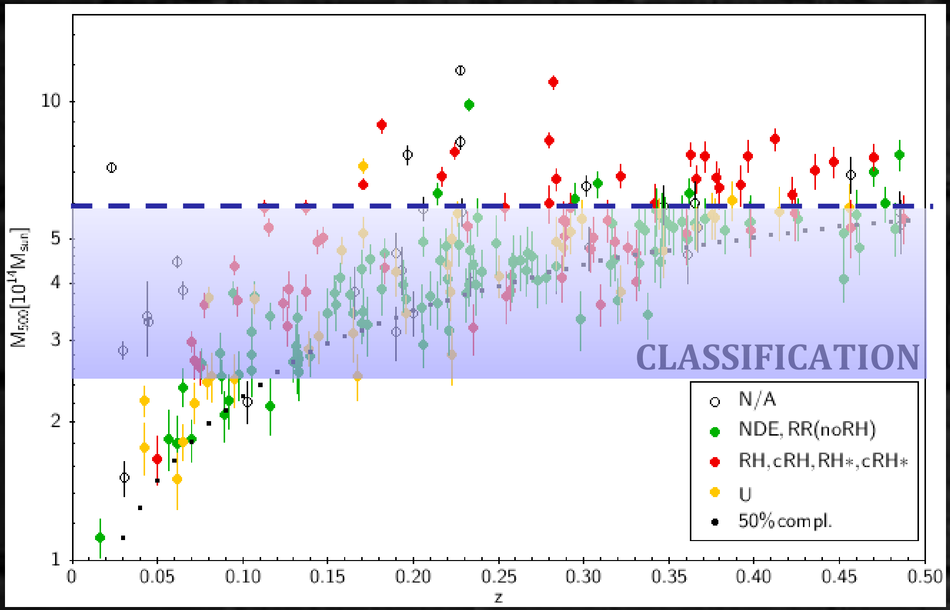
Paper V: Mass- radio halo power correlation at low radio frequency (*Cuciti + sub*)

Paper VI: Properties of radio relics (*Jones+ 23*)

https://lofar-surveys.org/planck_dr2.html

Statistical analysis

Cassano + 23



For the statistical analysis of RHs:

- sub-samples of **164** clusters with $0.07 < z < 0.5$

- M_{500} > Planck 50% completeness (M_{500}, z)
  (no significant differences between the completeness functions for regular and disturbed clusters; *Planck coll. 2016*).

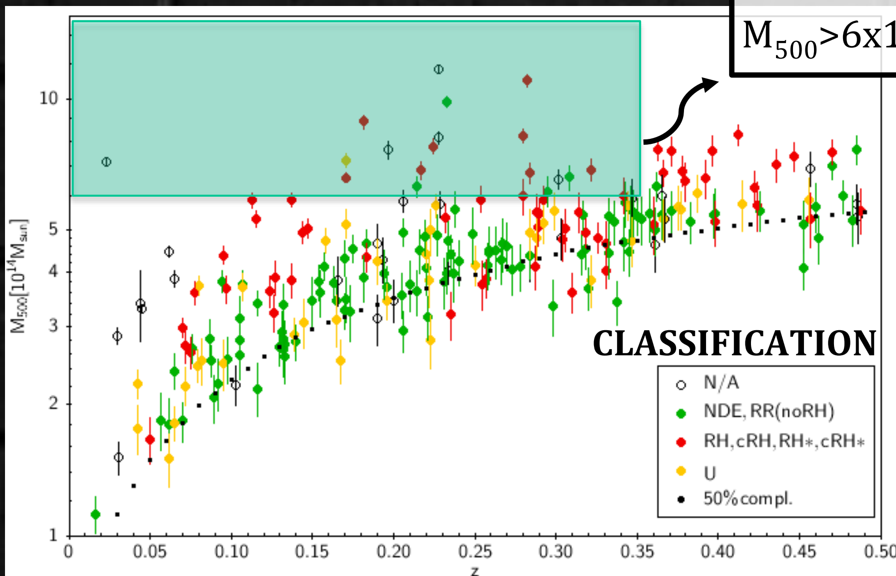
- 164 clusters:
  71 NDE (43%)
  55 RH (31%)
  13 RR (8%)
  25 U (15%)

Classification of the diffuse emission made in *Botteon + 22*

This sample allows, *for the first time*, to make a statistical study of RH in an unprecedented range of cluster masses, including clusters down to $M_{500} \sim 2.5\text{-}3 \cdot 10^{14}\ M_\odot$, breaking down the wall of $M_{500} \sim 6 \cdot 10^{14}\ M_\odot$, that limited previous statistical studies (e.g., Cassano+13, Cuciti+ 21).

Statistical analysis

Cassano+ 23



Cuciti+ 2021 (GMRT obs of PSZ2 M_{500}>6x10^{14} M_{sun} clusters)

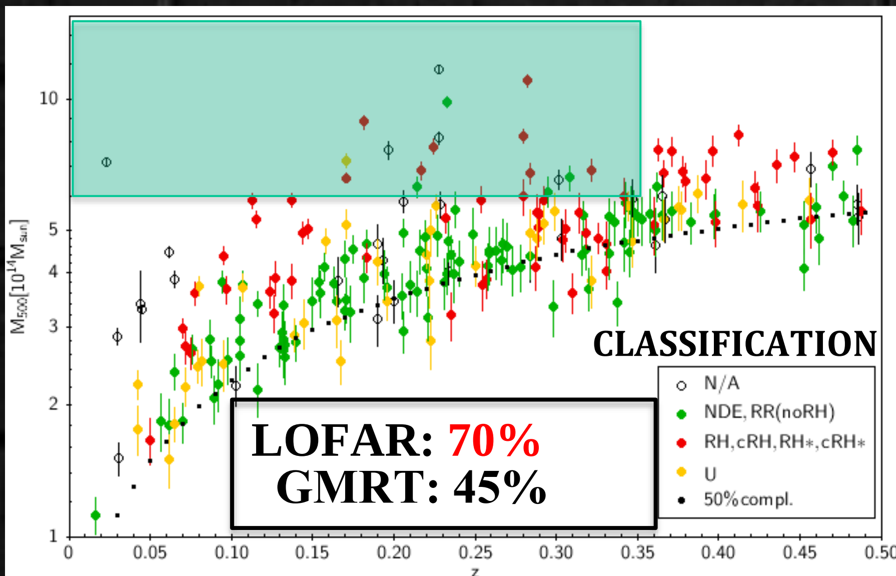
We compare the occurrence of RH in this sample with that derived from a sample of PSZ2 clusters with $M_{500}>6\cdot10^{14}\ M_{\odot}$ and $z\leqslant0.35$ observed with GMRT at 610 MHz (*Cuciti+21*).

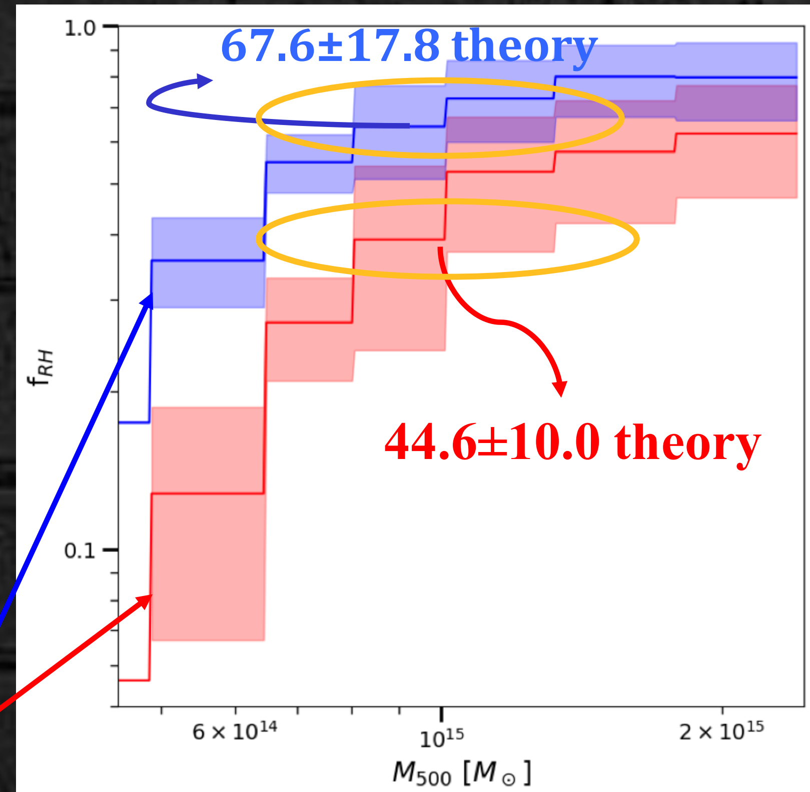
LOFAR: 70%
GMRT: 45%

The fraction of clusters with RH increases at low radio frequency.

Statistical analysis

Cassano+ 23





Expected fraction of clusters with Radio Halos

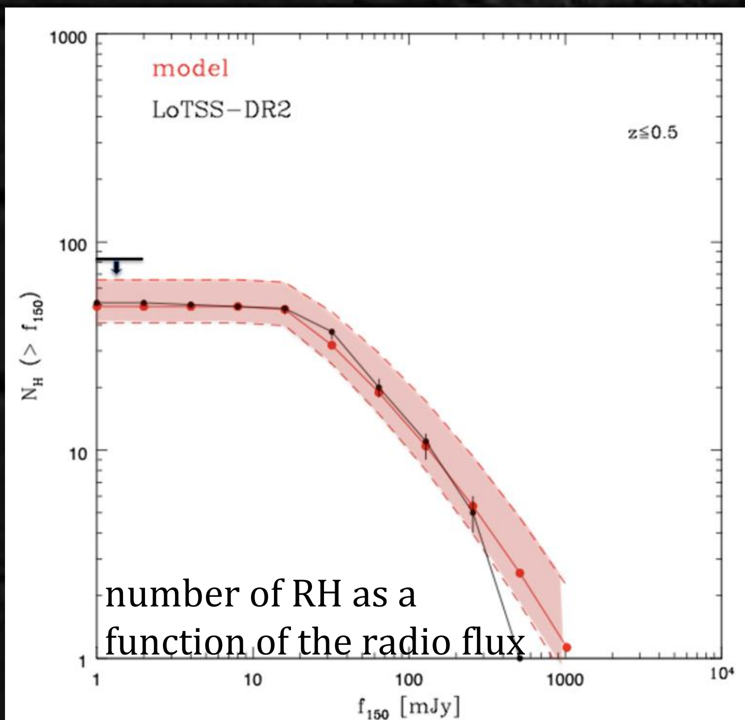
with obs. at 600 MHz

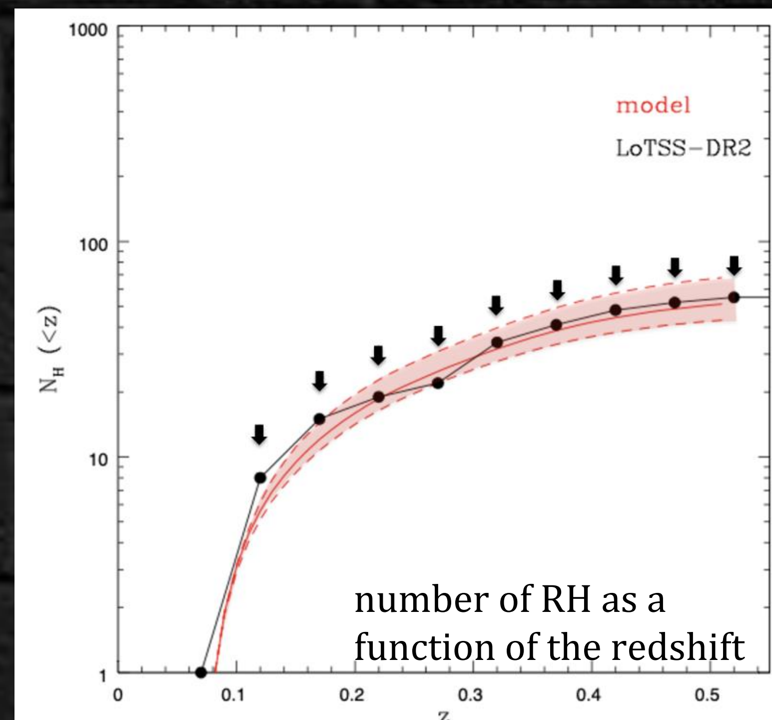
with obs. at 150 MHz

The observed increase of the occurrence of RH at low frequency is in line with model expectations which implies that **more RHs should be visible at lower frequency because of their very steep spectra.**

Testing merger-turbulent models against statistics

- semi-analytic models (statistical version of turbulent re-acceleration scenario; *Cassano & Brunetti 05, Cassano+06, Cassano+10*)
- mass and redshift limit of the observed sample
- normalise the number of clusters in the theoretical model to match the observed number of clusters

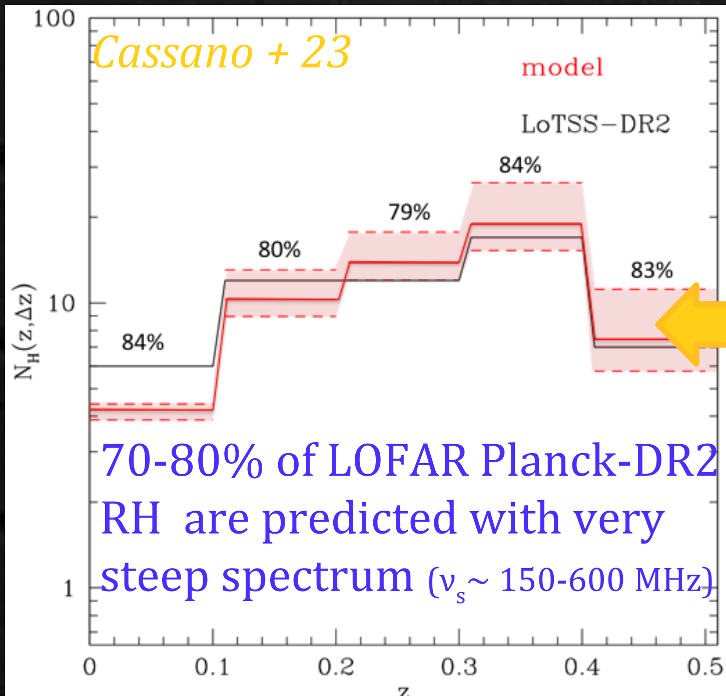




- we can reproduce the cumulative number of RHs (40-70 expected RH), their flux density and redshift distributions

-predict that 100-200 RH could be detected in PSZ2 clusters by the **full LoTSS**

The quest of very steep spectrum halos



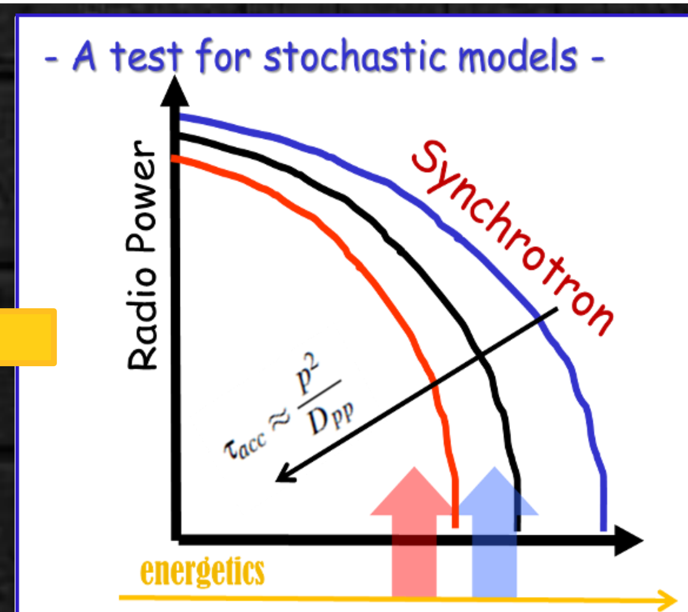
f_{RH} increases with mass

Caption

The **same** models predict a population of radio halos with different spectra, including a large number of very-steep spectrum halos (e.g. Cassano+06, Brunetti+08).

Numerous RH with very steep spectrum discovered at low radio frequencies (Brunetti+08, Macario+10, Wilbert +18 , Savini+ 18, Duchesne+20 ,21, Bruno+21, di Gennaro+21, Rajpuorhit+21, Biava+21, etc..)

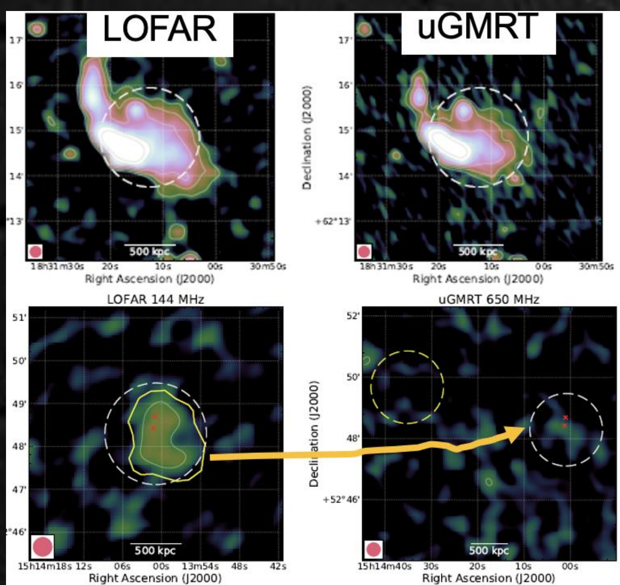
We are working on data at other frequencies, with LOFAR LBA (see Pasini's talk) and uGMRT, MeerKAT to measure RH spectrum in *unbiased* samples (from LOFAR surveys + mass selection)

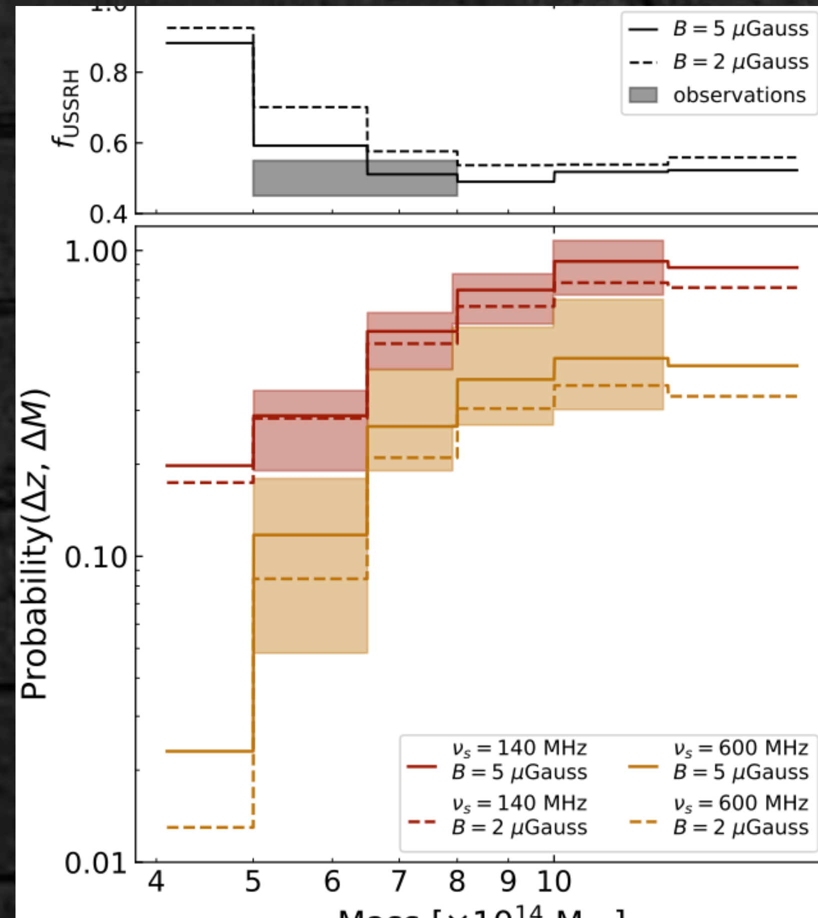


The quest of very steep spectrum halos

di Gennaro+ 21

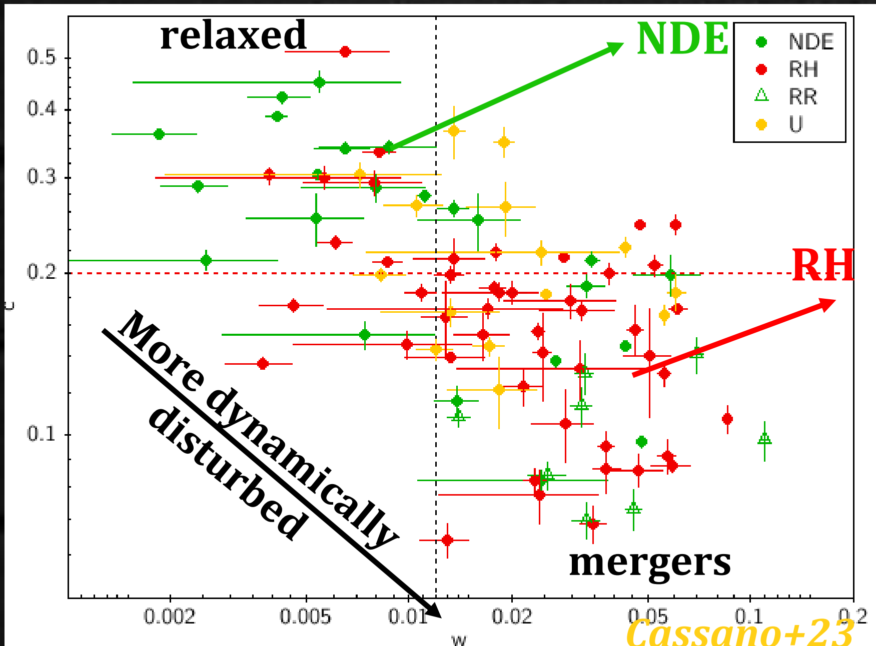
The **same** model (and with the same parameters) explain the RH fraction measured in a sample of massive high-z clusters (z=0.6-0.9) observed with LOFAR and followed-up at higher frequencies with the uGMRT (*di Gennaro +21*).





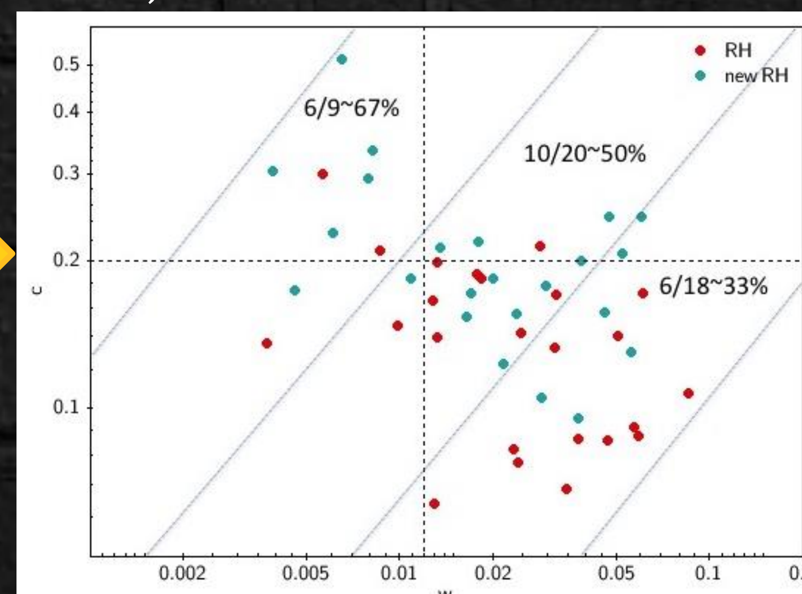
50% of the LOFAR detected RHs were found to be characterised by very steep radio spectra (α>1.5), in line with model expectations.

RH connection with cluster dynamics



- We investigate for the first time the RH-cluster merger connection at low radio frequencies.
- *Observations at low radio frequency are expected to find RH also in less disturbed systems.*

☆ The fraction of clusters with **RH increases** going towards more dynamically disturbed (*merging*) systems;



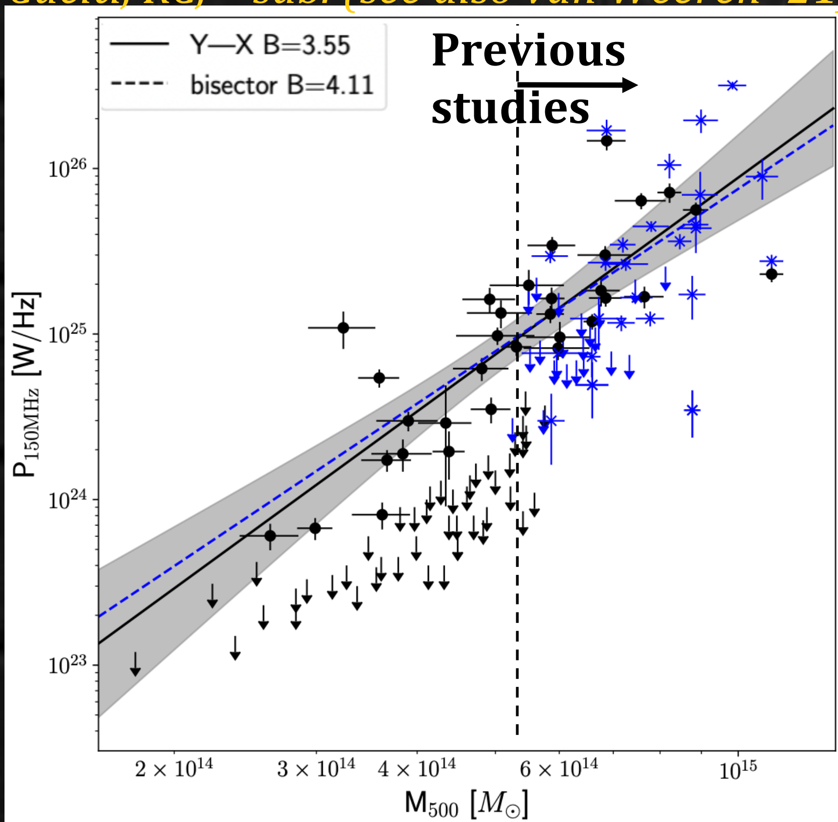
☆The fraction of newly detected RHs by LOFAR increases going from merging to more relaxed GCs.

☆LOFAR starts to observe RHs in less disturbed systems, possibly unveiling RHs with very steep radio spectra.

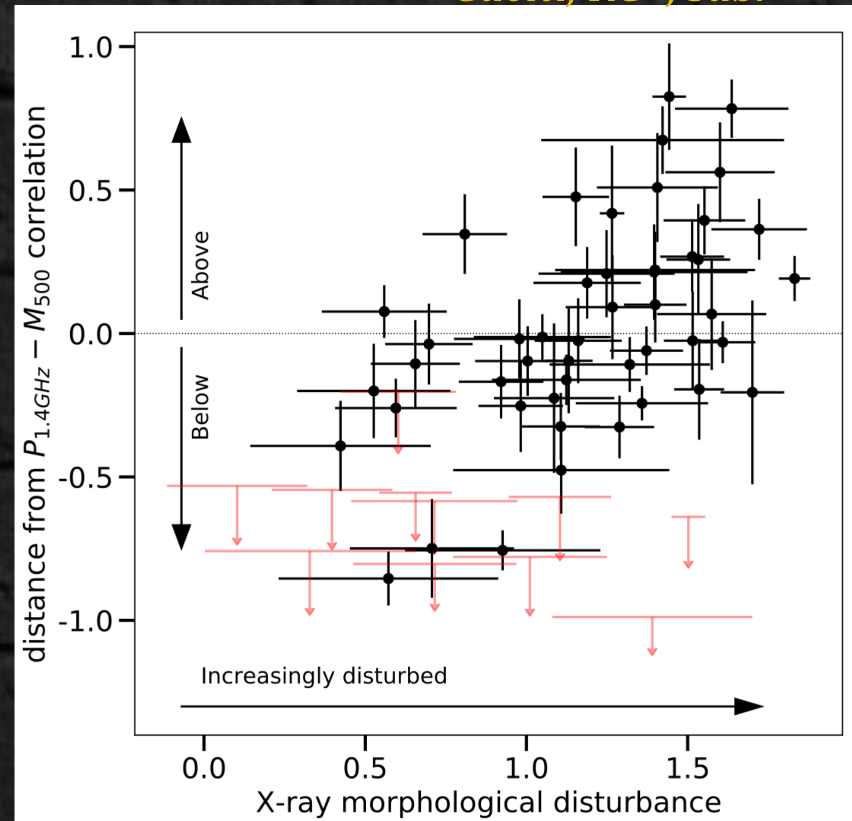
see also *talk by Biava*

RH power mass correlation

Cuciti, RC, + sub. (see also van Weeren+21)



Cuciti, RC+, sub.



We extend the radio-power -- cluster mass correlation towards **lower masses** with respect to previous works (*e.g.; Cassano+13; Cuciti+21*)

The **scatter** of the correlation is related to the cluster "***disturbance***": with more dynamically active clusters being scattered up in the correlations (hints in *Cuciti+21*)

Summary

The **largest statistical** study of RH with deep (~83 μJy/beam), low-frequency (150 MHz) observations.

A simple version of the re-acceleration models, that is based on homogeneous conditions in the ICM and Monte Carlo simulations of merger-turbulent connection, and that uses reference parameters already adopted in the past, provides an excellent description of the LOFAR observations:

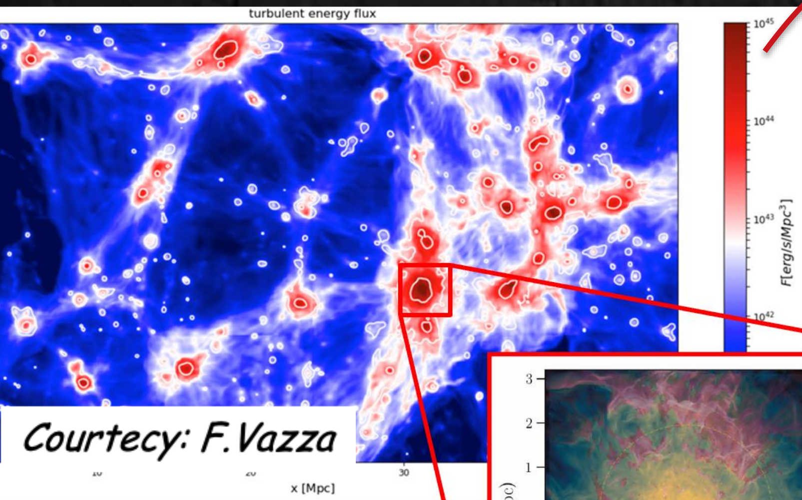
- The increase of the occurrence of RH at **low frequency**
- The occurrence of RH at **high-redshift** and the fraction of **very steep spectrum RH (50% of USSRH)**
- The number of RH and their **flux density** and z distributions

Radio power of halos increases with the cluster mass; the large scatter of the correlation is related to the **cluster dynamical status**.

Spectral studies are ongoing and are mandatory to complete the picture.

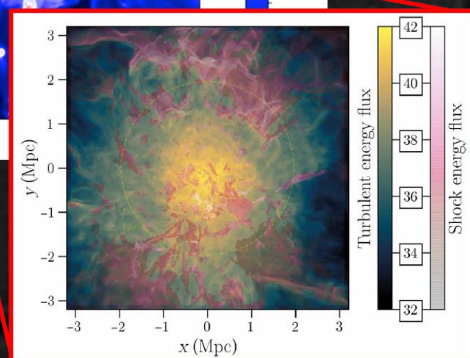
TURBULENCE, SHOCKS & B IN LSS

Brunetti & Vazza 2020; see also talk by Nishiwaki

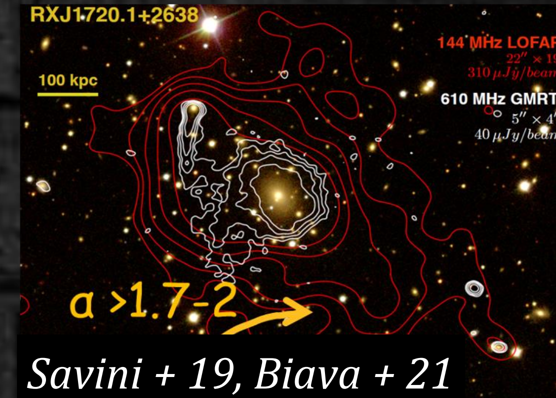


turbulent energy flux

$$F = \frac{1}{2}\rho\frac{\delta V^3}{L}$$



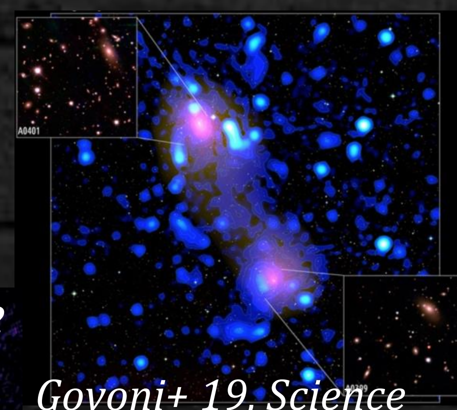
Diffuse emission on entire cluster volume and beyond



Savini + 19, Biava + 21

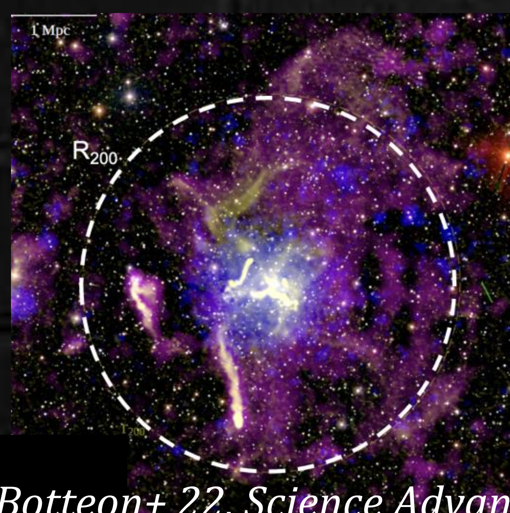
steep spectrum halos around cool-core clusters

radio bridges between pre-merging GCs

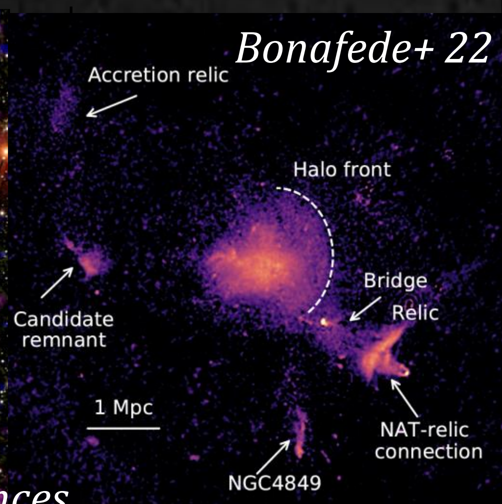


Govoni+ 19, Science

Botteen+ 20

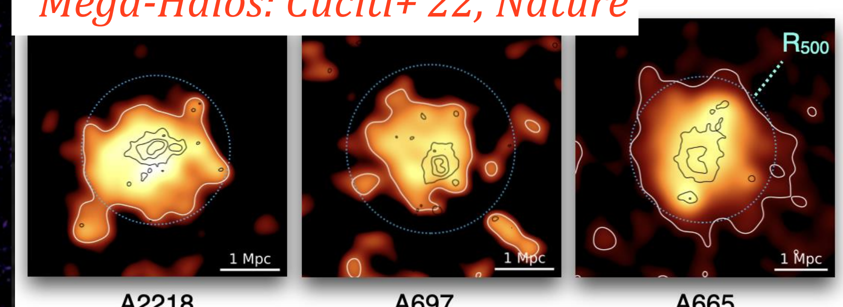


Botteen+ 22, Science Advances

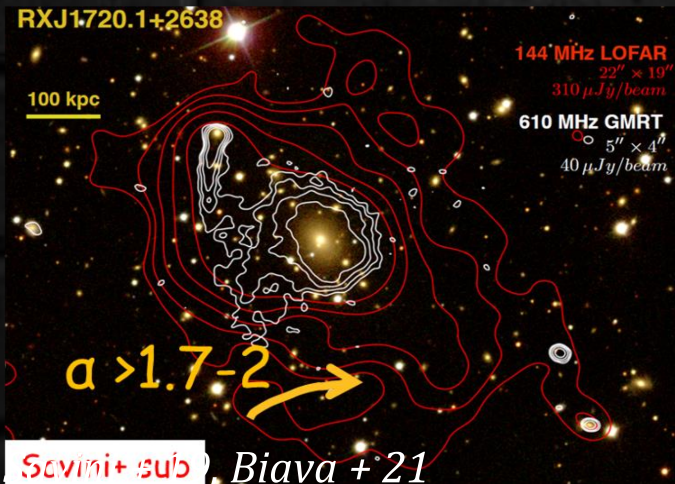


Bonafede+ 22

Mega-Halos: Cuciti+ 22, Nature

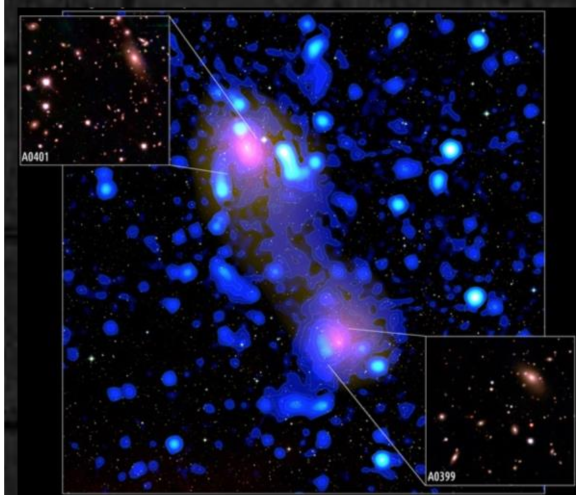


Cluster-scale diffuse emission
in the *LOFAR era*

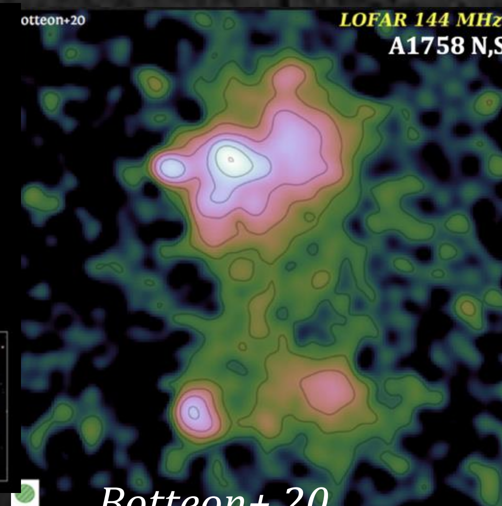


Savini+ sub, *Biava + 21*

steep spectrum halos around cool-core clusters



Govoni+ 19, Science

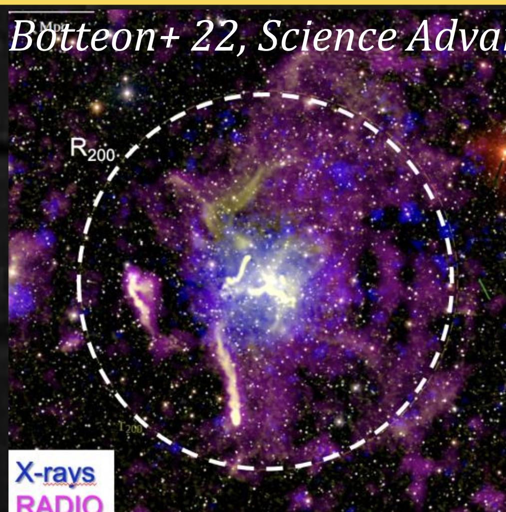


Botteon+ 20

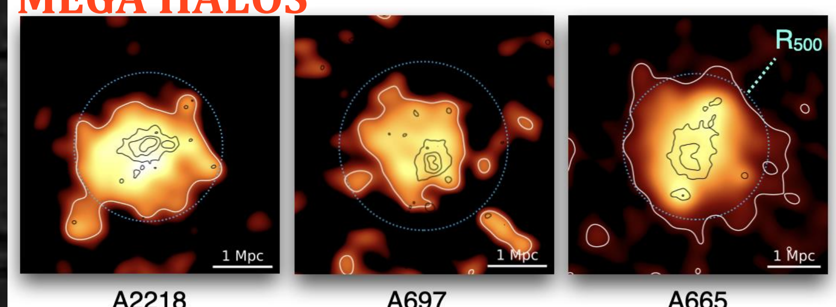
radio bridges between pre-merging clusters

Diffuse emission on entire cluster volume and beyond

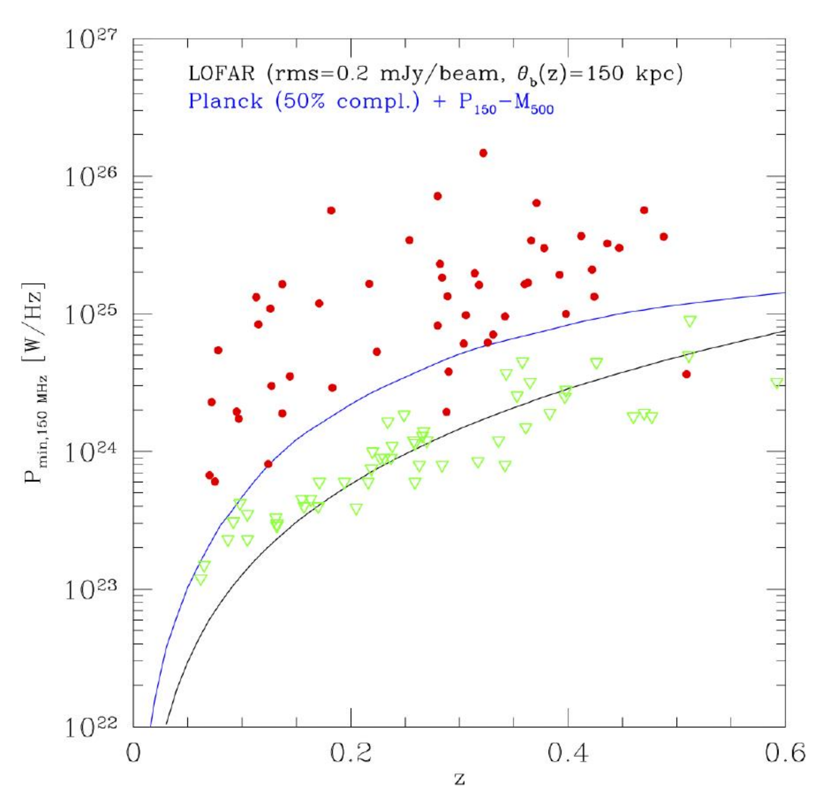
Botteon+ 22, Science Advances



MEGA HALOS



Cuciti+ 22, Nature

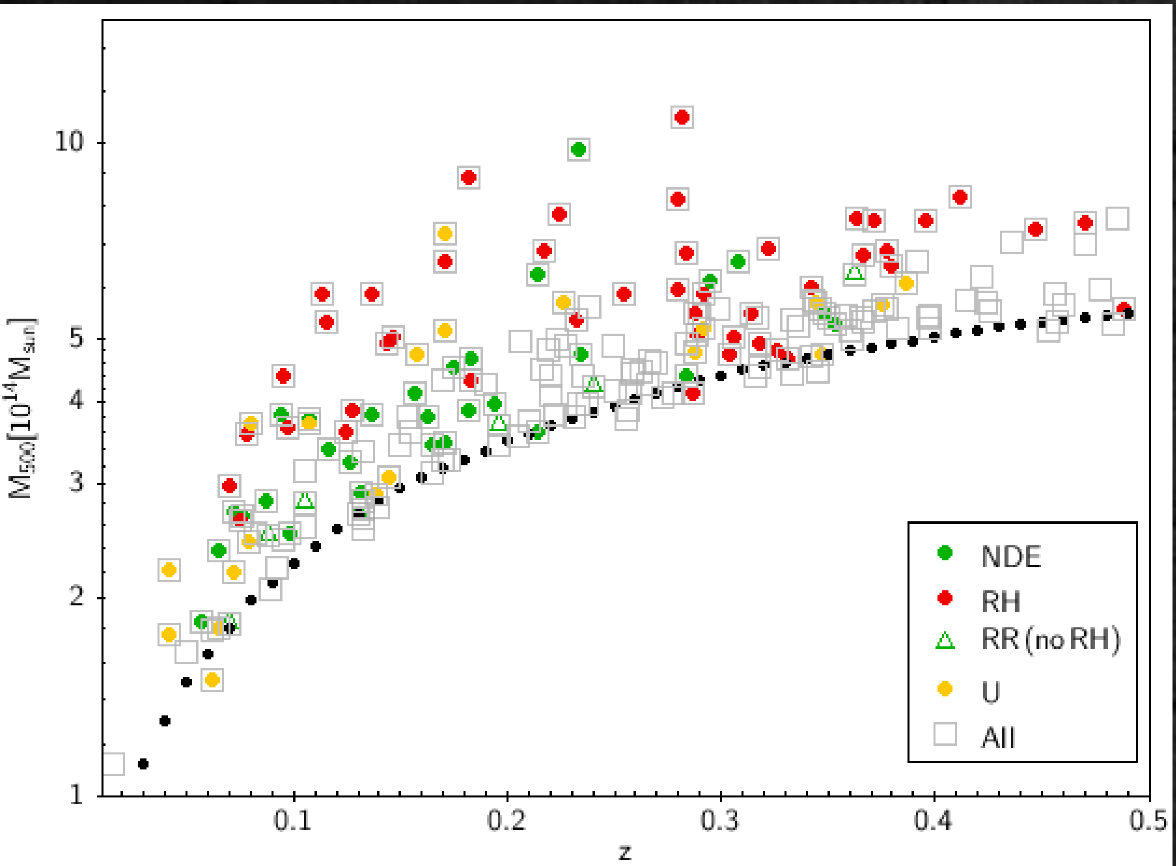


This plot allows determining the minimum power of a RH that could be detected in LoTSS-DR2. We also report an analytic expression that we used in previous papers (Cassano et al. 2010a, 2012) to estimate the minimum flux density of an RH that can be detected in a given survey by assuming that the halo is detectable when the integrated flux within $2\times\theta_e$ (θ_e is the angular size corresponding to the e-folding radius r_e) gives a signal-to-noise ratio ξ, i.e. $f_{min}(<2\,\theta_e) \simeq 0.75\,f_{min}(<3\,\theta_e) \simeq \xi\,\sqrt{N_b} \times F_{rms}$, where N_b is the number of independent beams within $2\,\theta_e$. It follows that

$$f_{min}(<3\,\theta_e, z) \simeq 4.44 \times 10^{-3}\,\xi \left(\frac{F_{rms}}{10\,\mu Jy}\right)\left(\frac{10\,arcsec}{\theta_b}\right)\left(\frac{\theta_e(z)}{arcsec}\right)\ [mJy], \tag{2}$$

where F_{rms} is the rms noise in μJy, and θ_b is the beam angular size in arcsec. The corresponding minimum radio power $P_{min}(z)$ is reported in Fig. 2 as the black line assuming F_{rms} = 200 μJy beam^{-1}, $\theta_b = \theta_b(z)$ depending on redshift with a fixed linear size of 150 kpc (see the data reduction strategy described in Paper I) and θ_e corresponding to r_e = 170 kpc (which is about the median values of r_e in our sample). With this parameter choice, Eq. (2) with ξ = 5 roughly describes the behaviour of the upper limits as a function of redshift. The blue line in Fig. 2 was obtained by applying the $P_{150\,MHz}-M_{500}$ best-fit relation to the 50% *Planck* completeness line reported in Fig. 1. It indicates the minimum power of RHs in PSZ2 clusters under the assumption that they follow the radio power-mass correlation. The fact that this line is always above the line traced by the upper limits indicates that LOFAR would be able to detect RHs in clusters with a mass above the 50% completeness line. As a consequence, to compare model expectations with observations, we used the blue line to determine the minimum power of a detectable RH in PSZ2 clusters that lie above the 50% completeness line at each redshift (see Sect. 5, for details).

RH connection with cluster dynamics



Cassano+, in prep.

In the total sample:

31% have RH

47% have NDE

4% have RR

18% have U

In the "morphological" sample:

44% have RH

30% have NDE

6% have RR

20% have U

How many RH await discovery in LoTSS?

By considering the **fraction** of clusters with RH in PSZ2

f_{RH}~31% (f_U~17%)

and the number of PSZ2 clusters in the LoTSS (**835** clusters)

=> **260-400** RH in all LoTSS.

By considering the **number** of clusters with RH in PSZ2/DR2 clusters

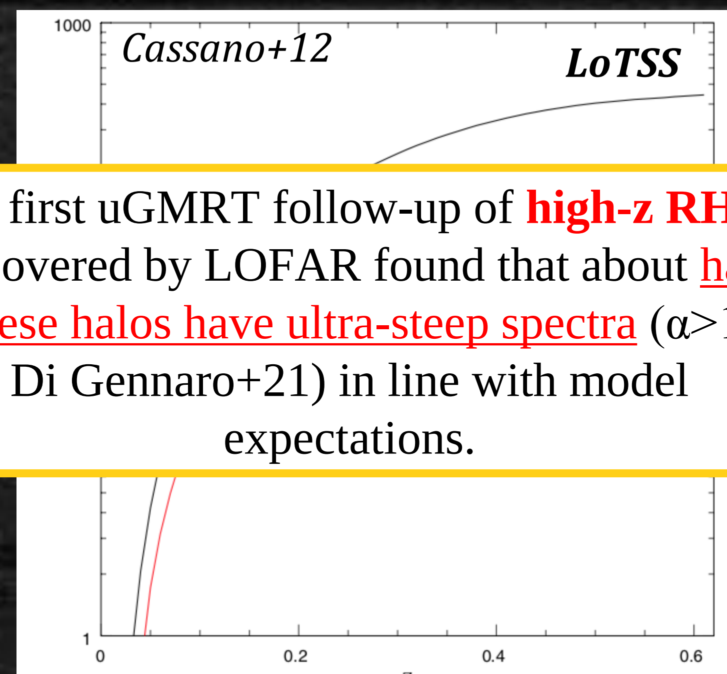
N_{RH}~83 (N_U~43)

and correcting for the ratio of the sky coverage (5634/21000)=**0.27**

=> **300-450** RH in all LoTSS

These extrapolations are in line with model expectations which give ~**350-500** RH in all LoTSS (*Cassano+10, 12, 15*).

About **half** of RH in PSZ2 clusters are new discovery. Model expectations imply that ~**50% of RH** in LoTSS is expected to **have ultra-steep spectra** (*Cassano+12*).



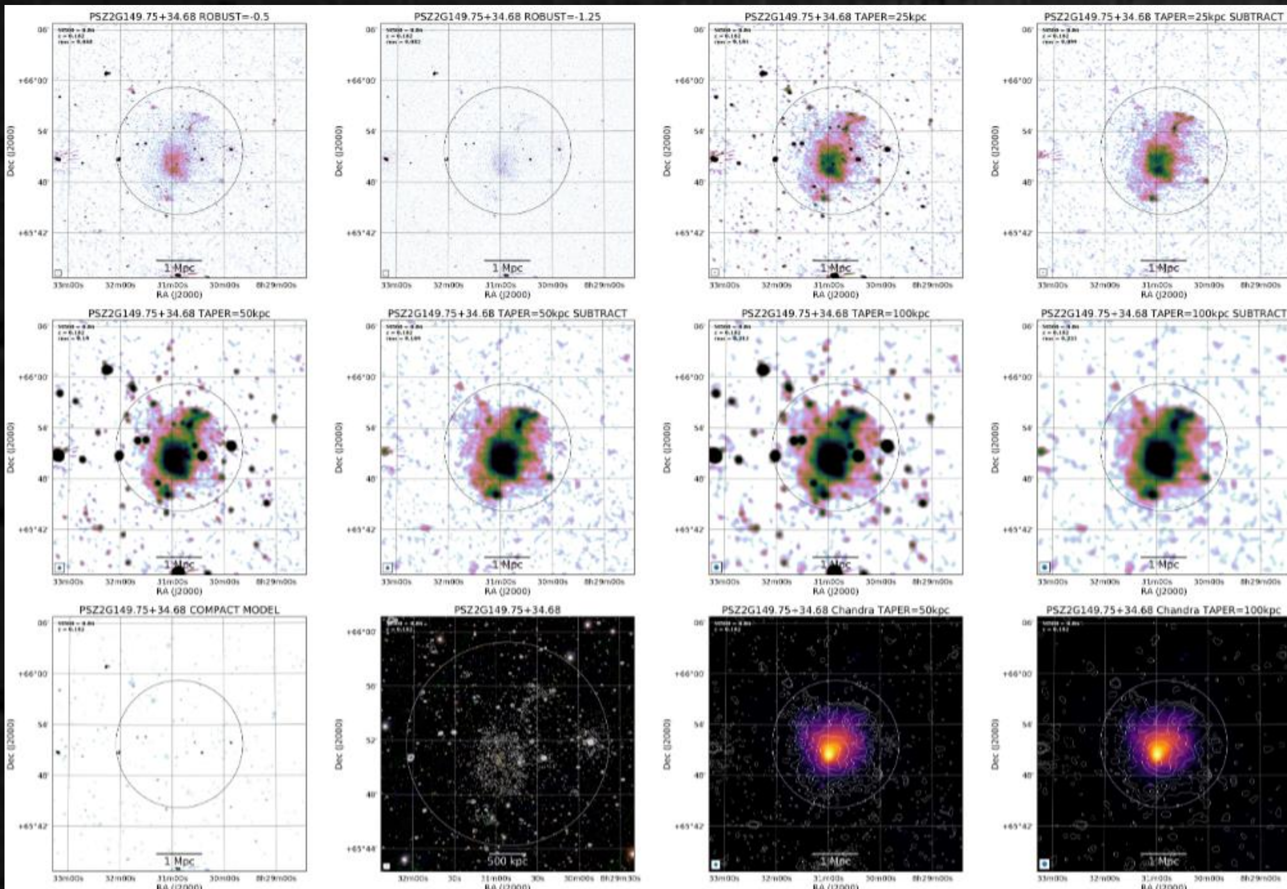
A first uGMRT follow-up of **high-z RH** discovered by LOFAR found that about half of these halos have ultra-steep spectra (α>1.5; Di Gennaro+21) in line with model expectations.

CLUSTER 3

Bologna, 20-23 September 2022

Images and classification

Botteon+ 22



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

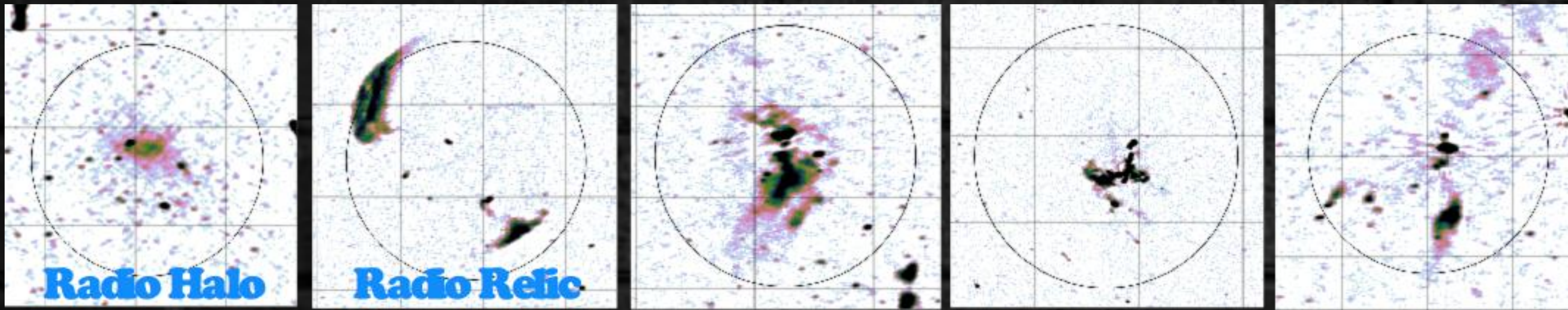
8) Chandra/XMM overlays

The *image quality* was improved compared with that of **LoTSS-DR2**

“Extraction+selfcal” method (vanWeeren+21)

Images and classification

Botteon+, in prep.

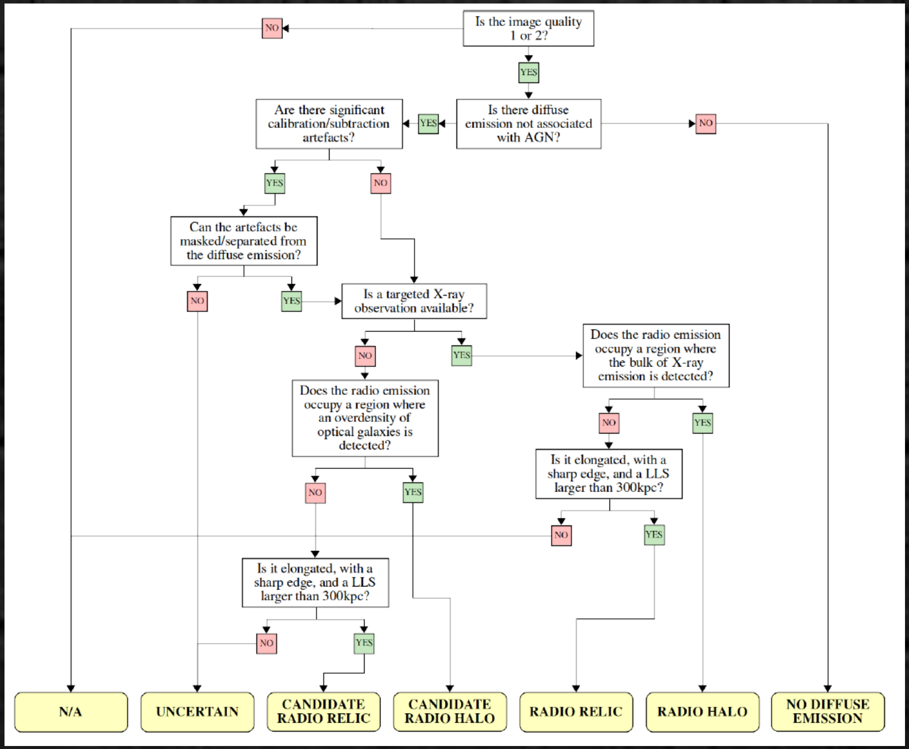


Classification was not an easy task!

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

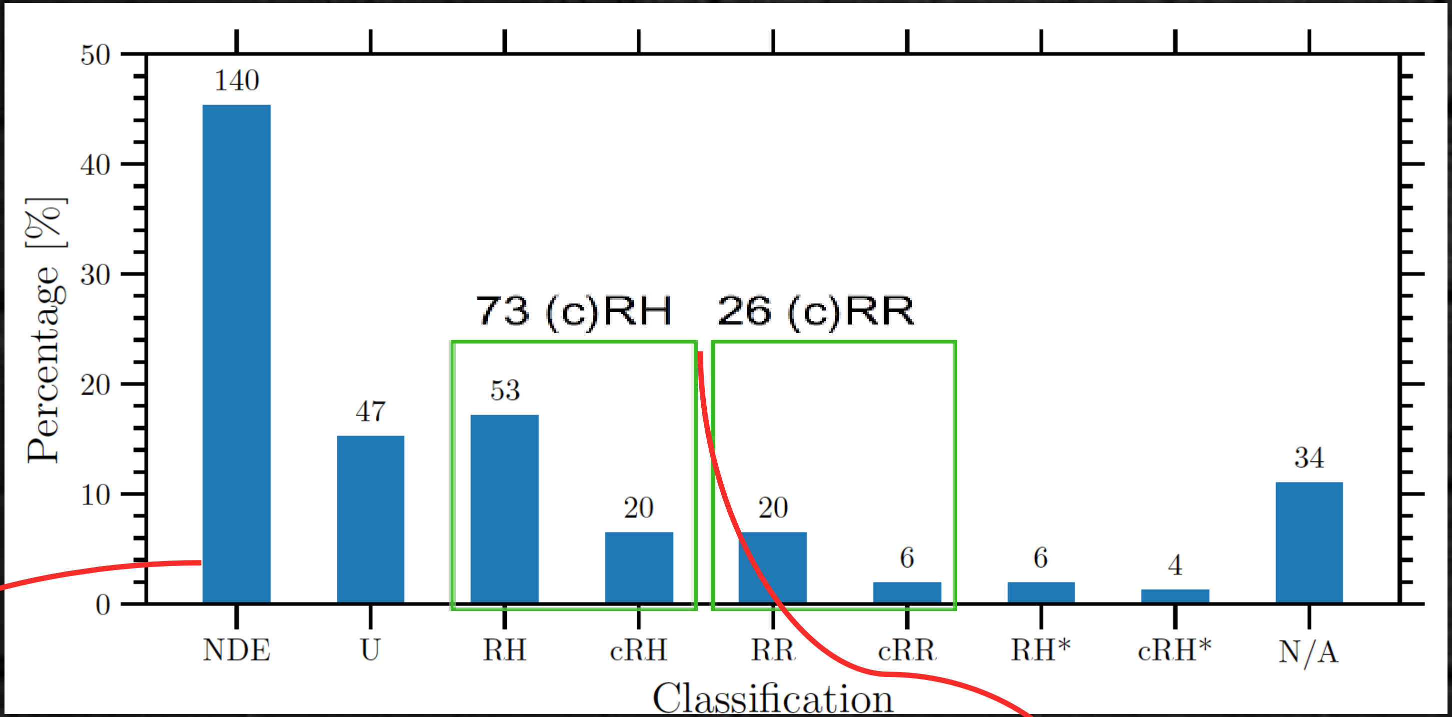
- *No diffuse emission* (NDE)
- *Radio halos* (RH) → (candidate, if X-ray is missing)
- *Radio relics* (RR) → (candidate, if X-ray is missing)
- *Uncertain* (U)
- *Not applicable* (N/A)

CLASSIFICATION TREE



Numbers and fractions

Botteon+, in prep.



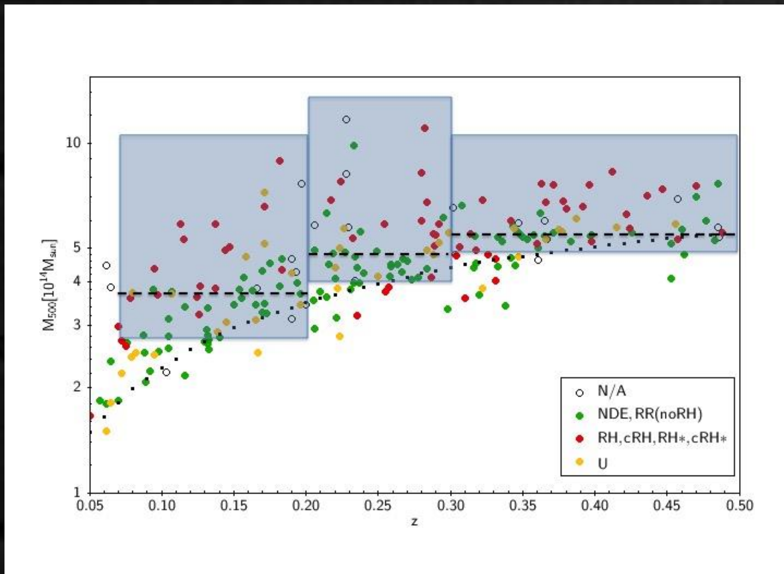
About half of the clusters in the sample does not host diffuse emission not associated with AGN

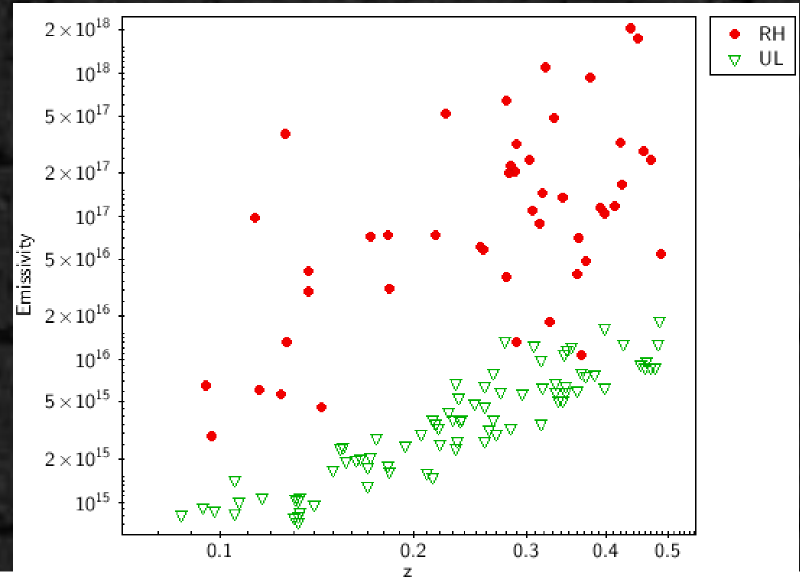
Computation of **UL** *(Bruno+, in prep.)*

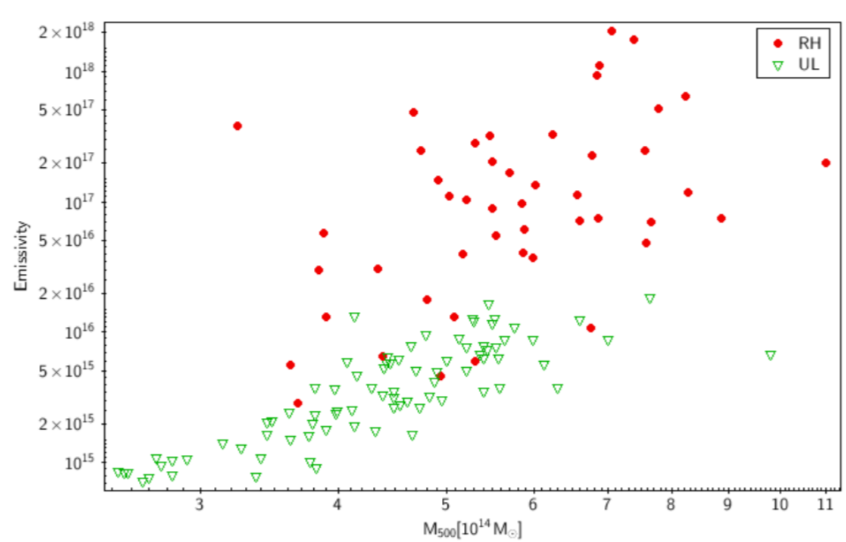
About *half* of the *(c)RH* and *(c)RR* are **new discoveries**!

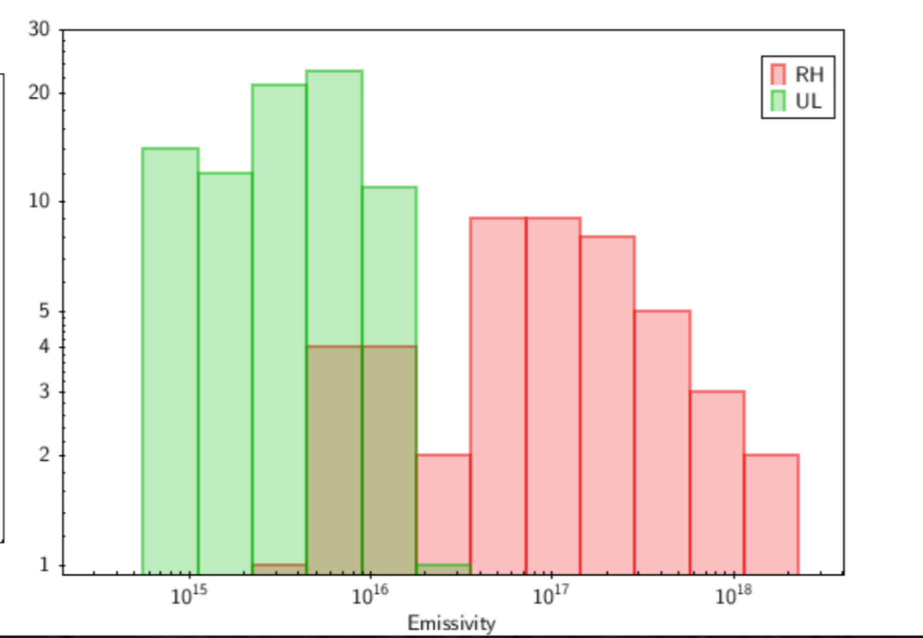
RH emissivity

WORK IN PROGRESS

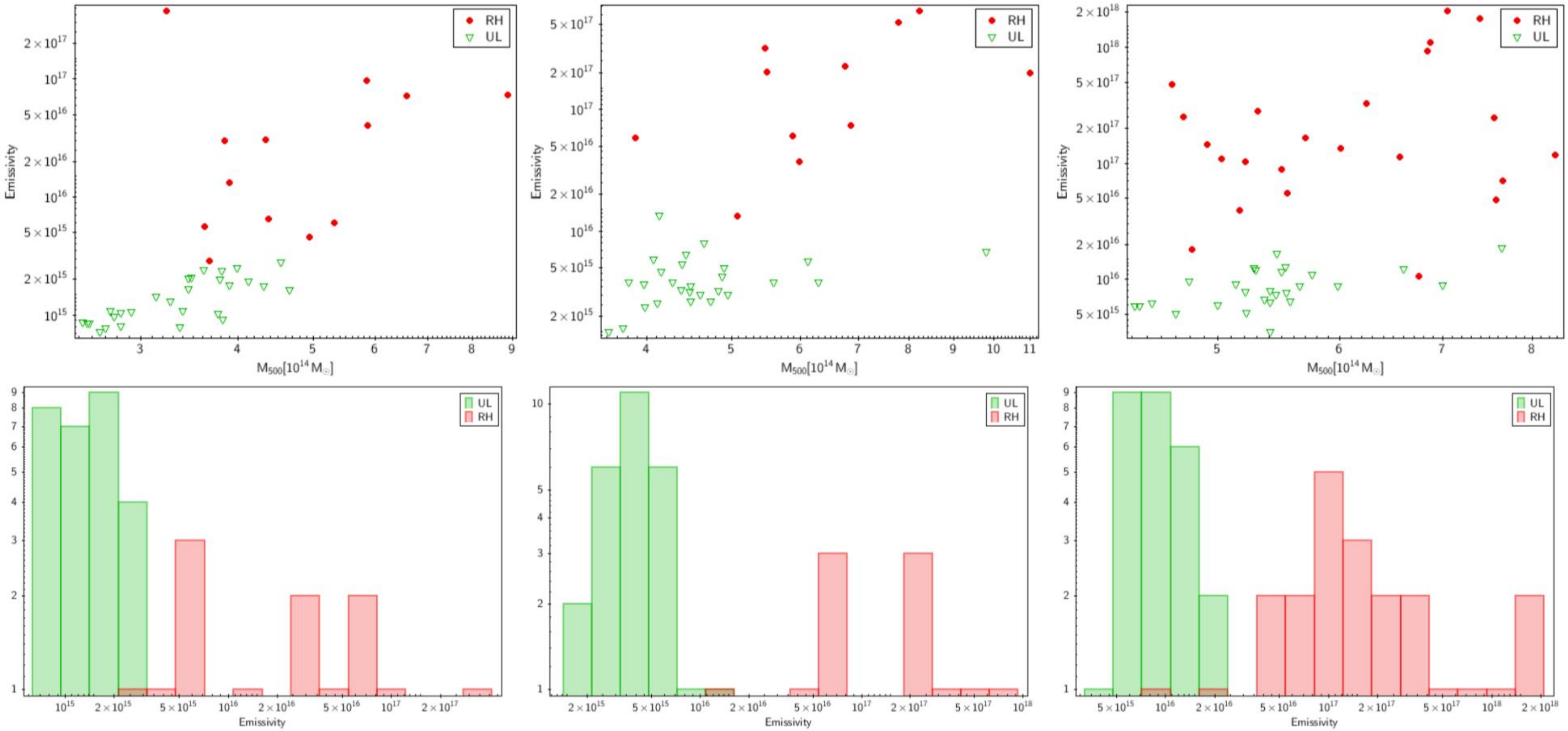








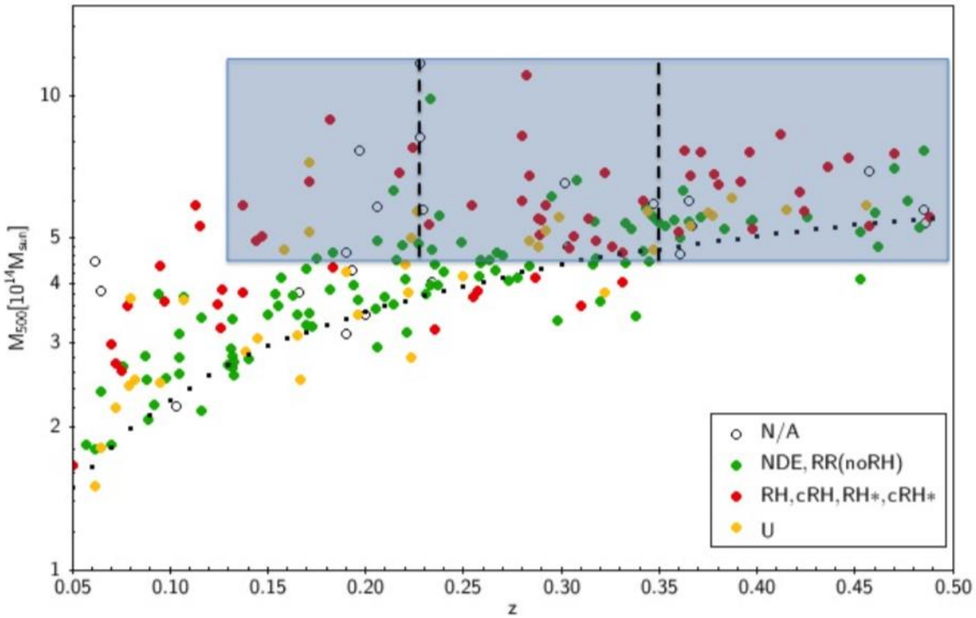
RH emissivity

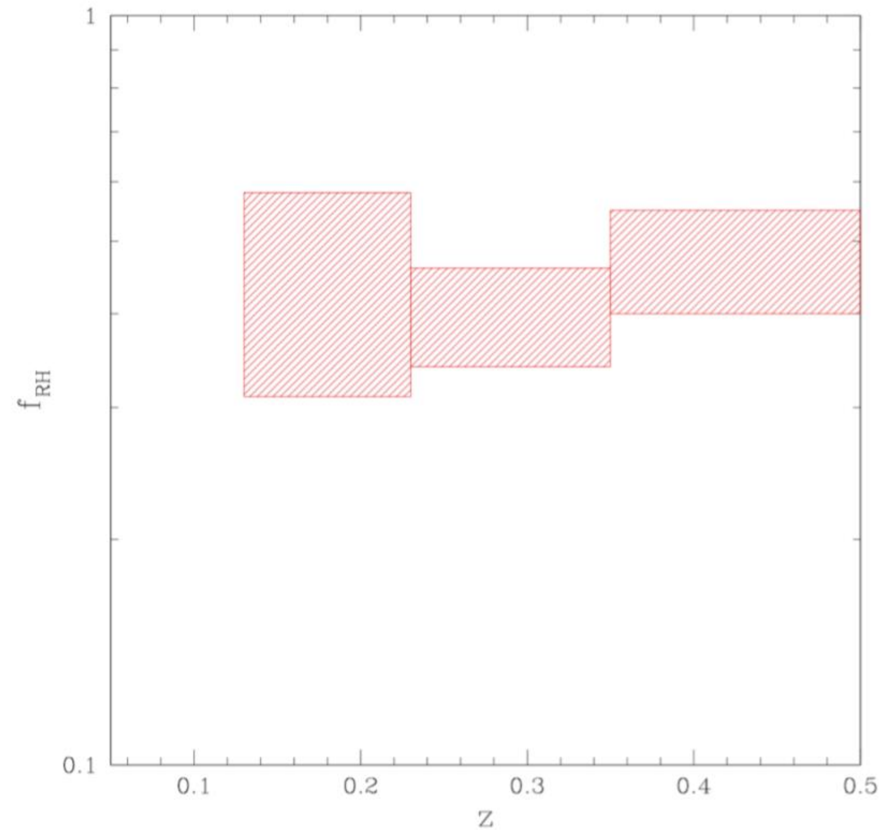


“Science at low frequency - SALF VIII”

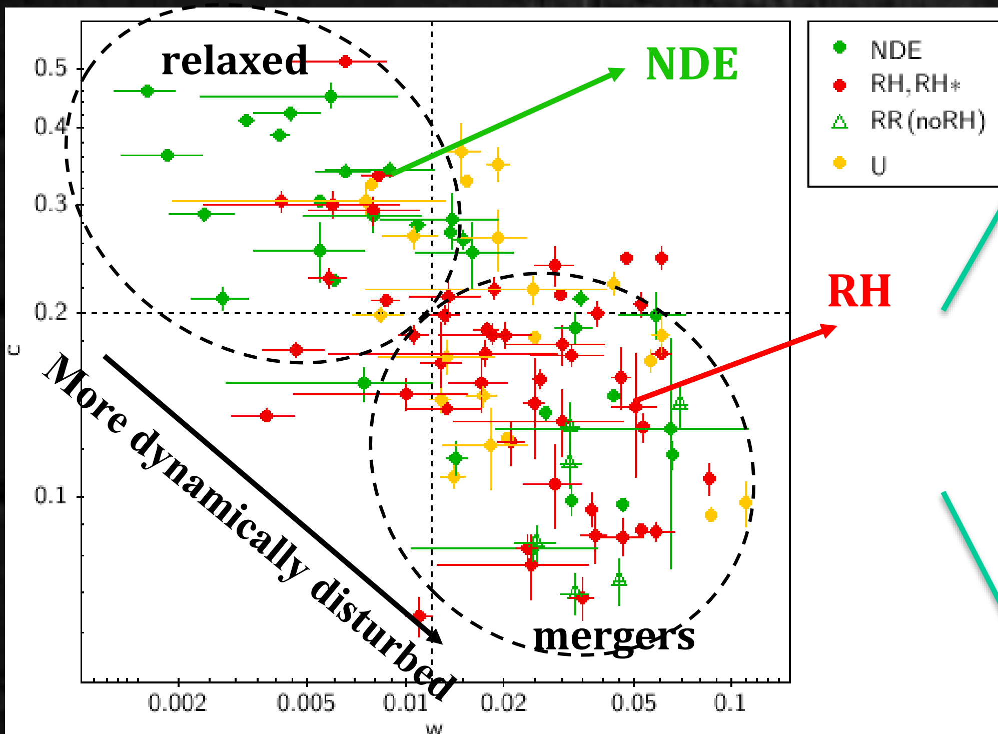
6-9 Dicember 2021

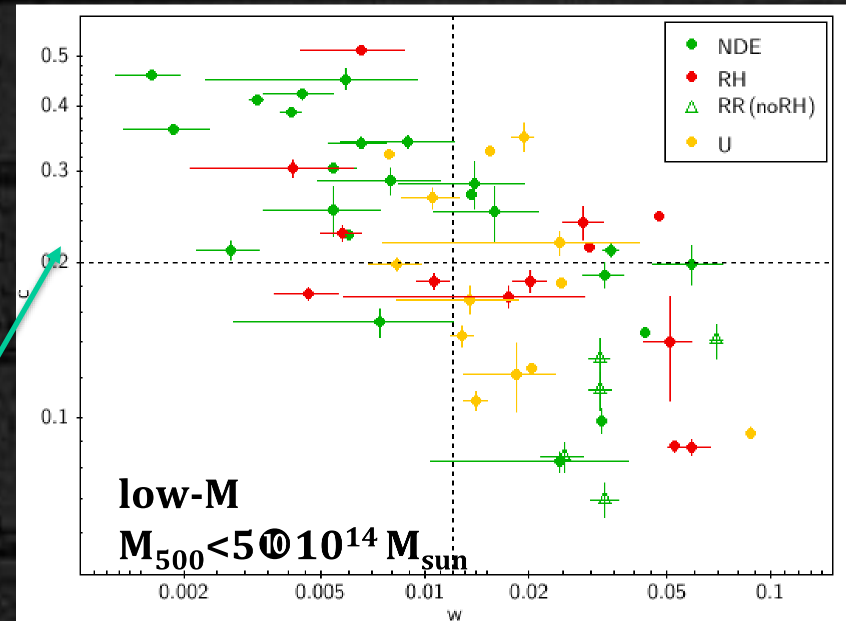
RH occurrence with redshift

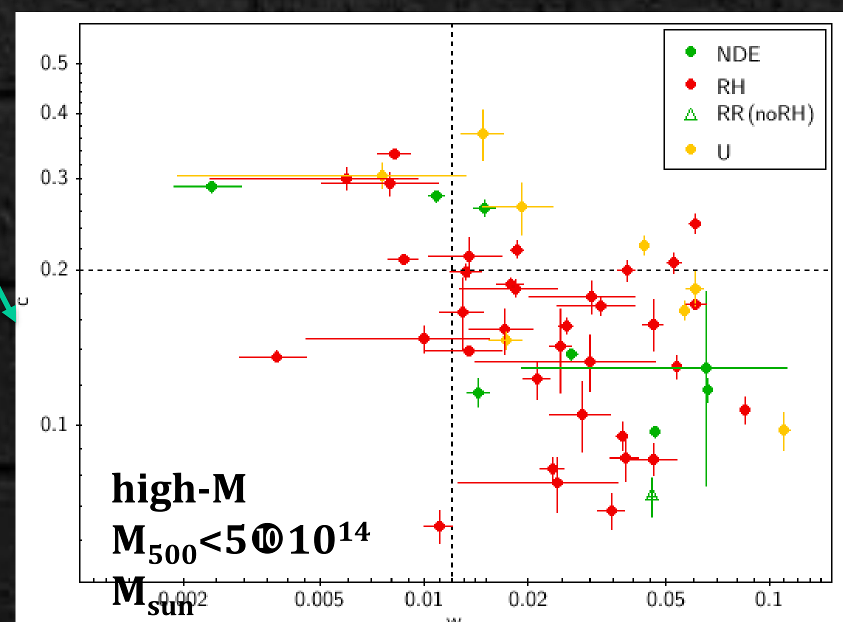




RH occurrence with redshift

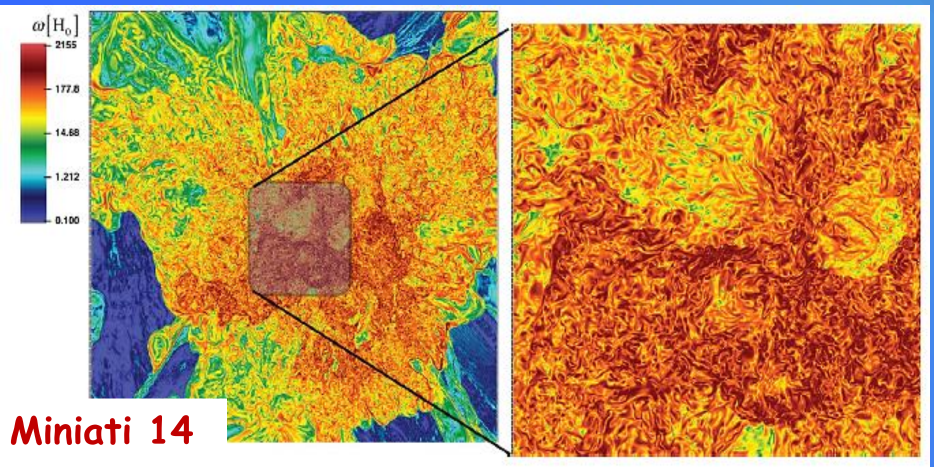






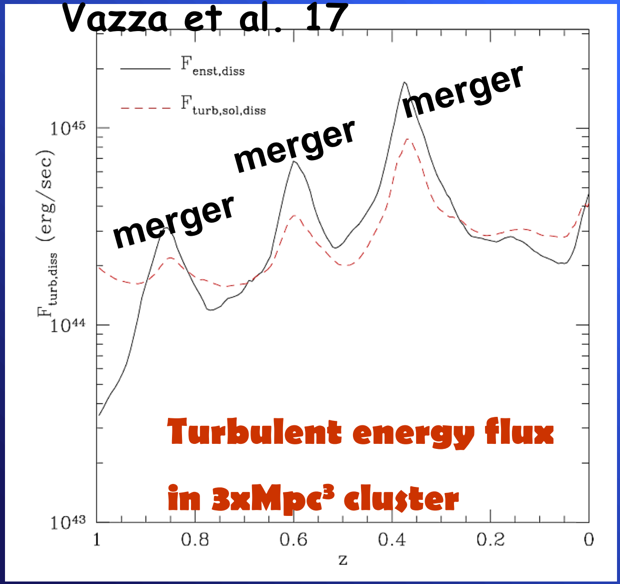
PRESENT PICTURE for Giant Radio Halos

Brunetti & Jones 14, van Weeren + 19, reviews



Turbulent Luminosity ≈ 10^5 x Radio Luminosity

- Galaxy clusters form via a hierarchical sequence of mergers and accretion of smaller systems driven by DM
- Mergers drive **turbulence** and **shocks** in the ICM
- Turbulence power reacceleration mechanisms based on second-order Fermi

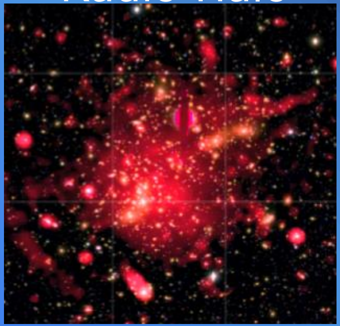


Turbulent energy flux

Particles heating/acceleration rate

$$\rho_{ICM}\delta V^3 L^{-1}\eta_{CRe} \sim \int d^3 p E \frac{\partial f_e}{\partial t}$$

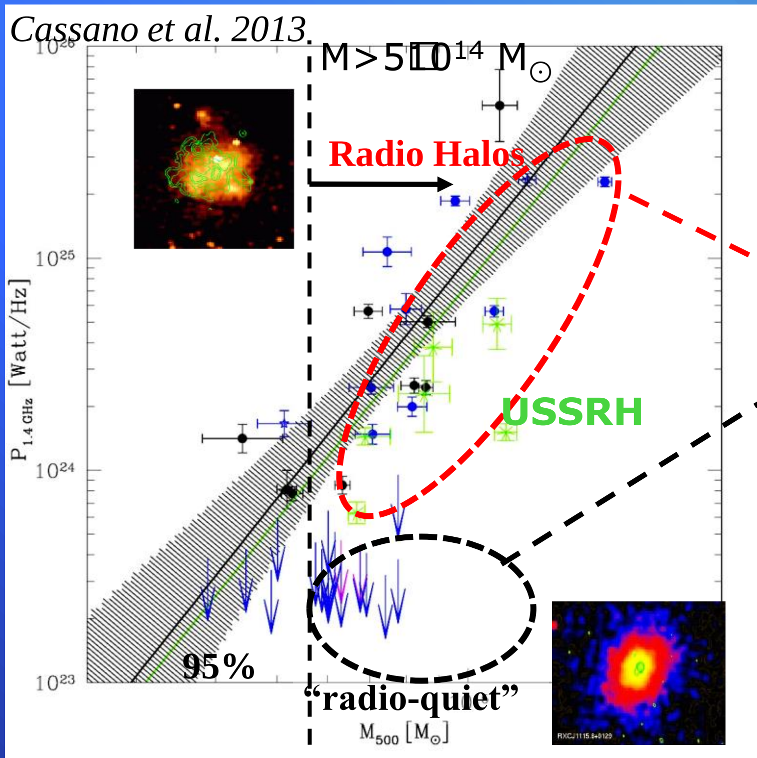
Radio Halo

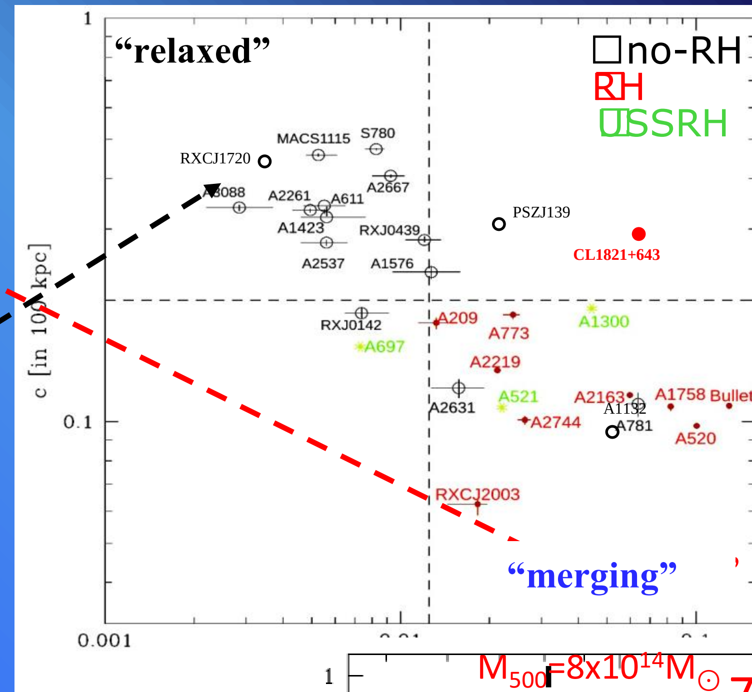


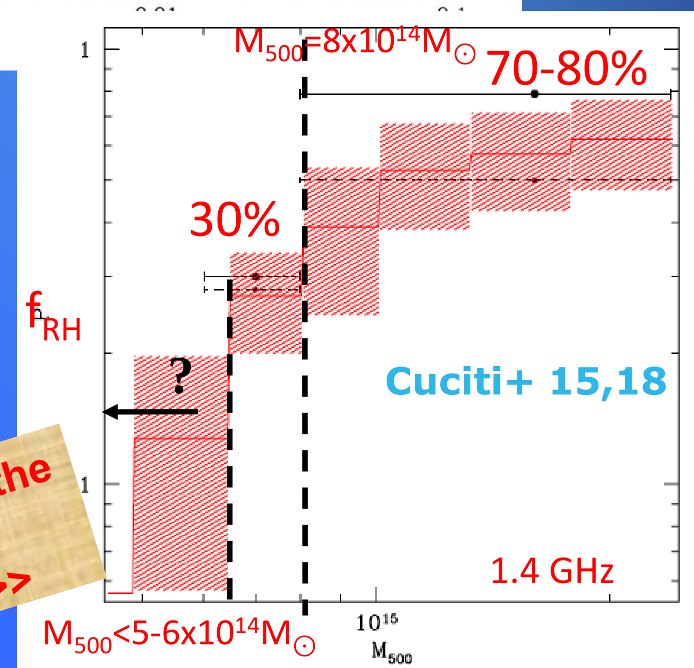
Radiation: Syn + ICS

GRH in merging clusters of galaxies

RH – cluster merger (GHz frequency)







- ✓ RH in the most **dynamically "disturbed" systems**, clusters without diffuse radio emission more "relaxed"
- ✓ fraction of clusters with RH increases with the cluster mass**:** **drop of f_{RH} at lower masses**

<<Mass sets the energy available>>

PRESENT PICTURE for Giant Radio Halos

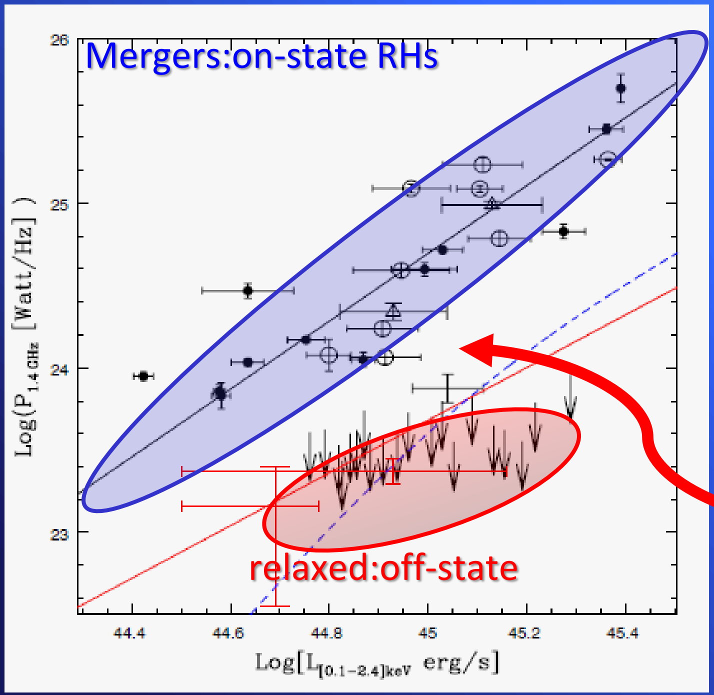
Brunetti & Jones 14, van Weeren + 19, reviews

Hadronic interactions produce secondary electrons *(e.g., Dennison 80; Blasi & Colafrancesco 99).*

: $p_{th} + p_{CR} \rightarrow \pi^{\pm} + \pi^0 + ... \rightarrow \pi^0 \rightarrow \gamma\gamma \rightarrow$ gamma ray emission

$\pi^{\pm} \rightarrow e^{\pm} \rightarrow$ synchrotron radio emission

Radio and gamma-rays (FERMI) studies indicate that secondaries have not a dominant role in the generation of giant radio halos *(e.g., Brunetti et al. 08; Ackermann +13, 15)*

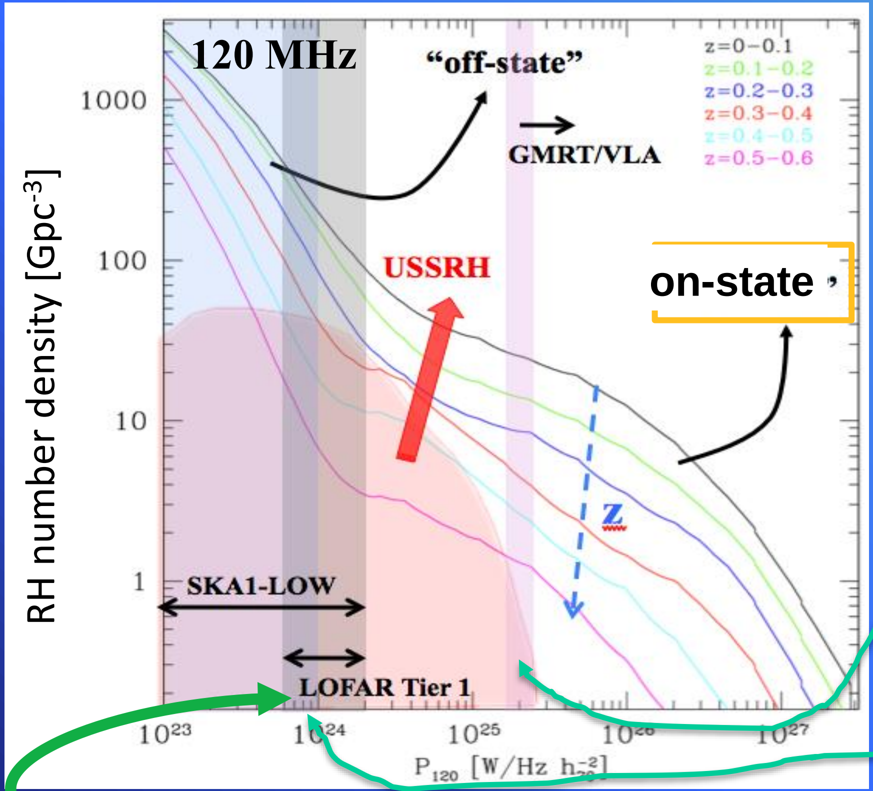


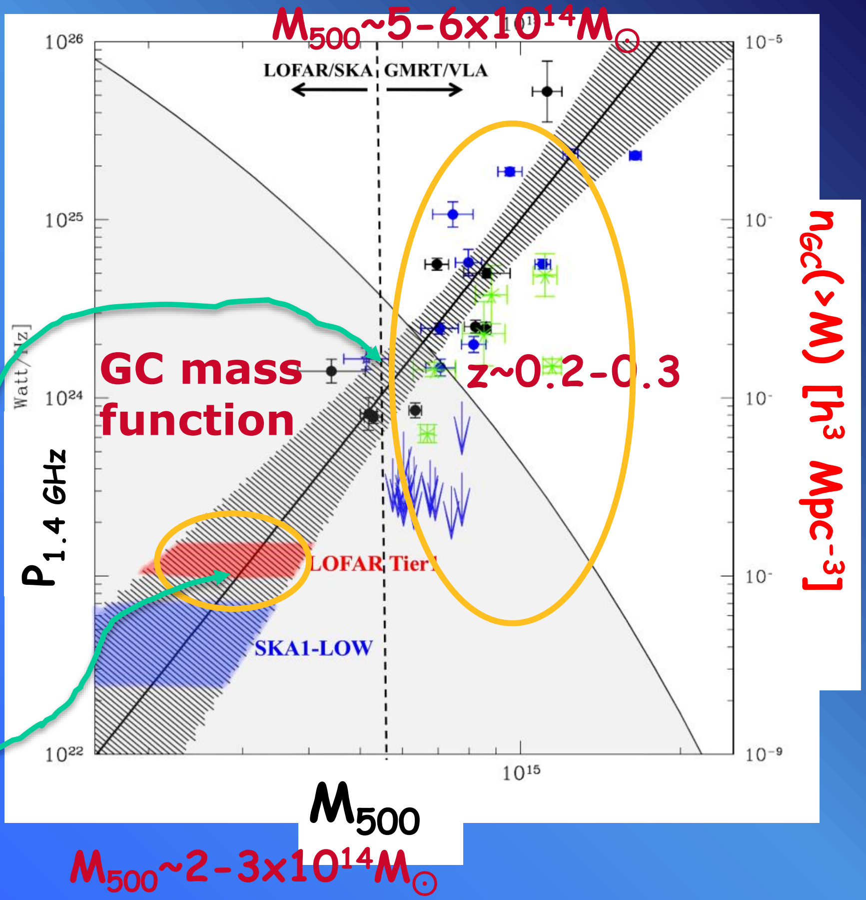
More relaxed clusters are expected to produce low power "off state" halos, fainter than classical RHs *(Brunetti & Lazarian 11; Donnert +13).*

✓ Possible detection of **"off-state" halos** from stacking analysis (*Brown + 11*) and a likely detection in CIZAJ1938.3 (~8 times below the correlations; *Bonafede + 15*).

How much the present view is biased?

from Monte Carlo simulations
(see also Cassano et al. 10, 12, 15)





LOFAR rms sensitivity ≃ 200 μJy/b at 20 arcsec res. (*e.g. van Weeren + 16).*

Complex population of GRH: depending on sensitivity of the observations

High sensitivity low-frequency obs. : ***USSRH*** and ***off-state*** **hadronic** halos dominate low radio powers

Statistical exploitation of GCs in LoTSS

LOFAR Two-metre Sky Survey (LoTSS, Shimwell+17, 19)

Area: all the northern sky (~20,627 deg²)

Frequency: 120-168 MHz,

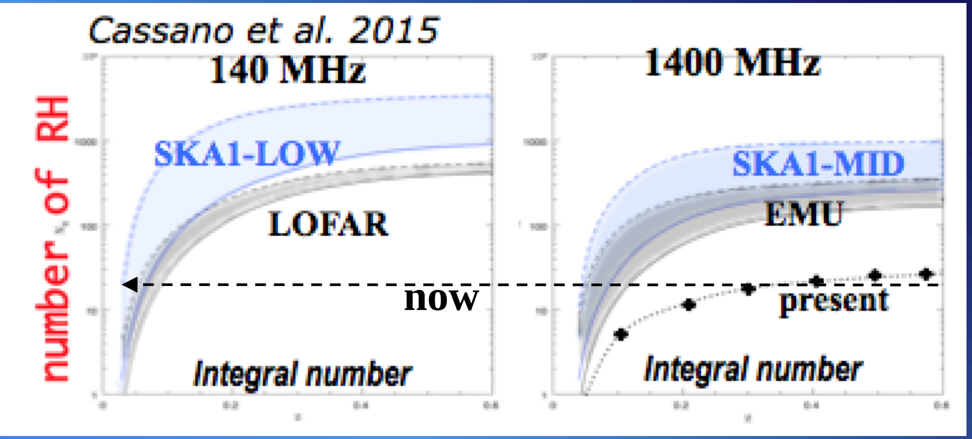
resolution~6",

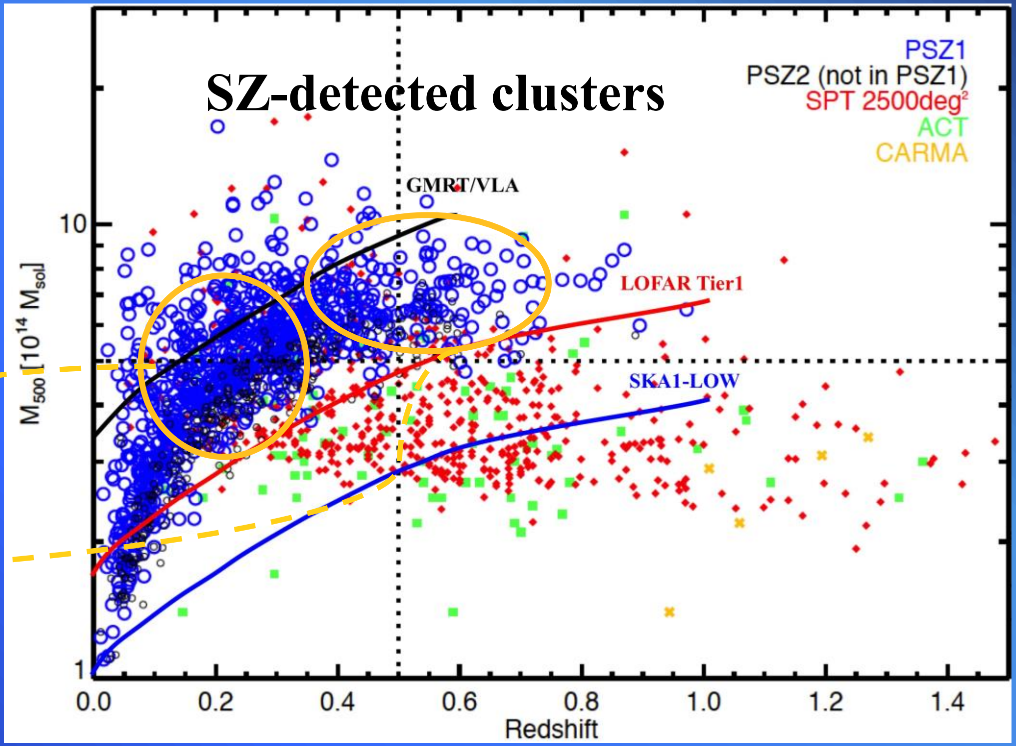
rms=100 μJy/beam

FoV: 6.4 deg²

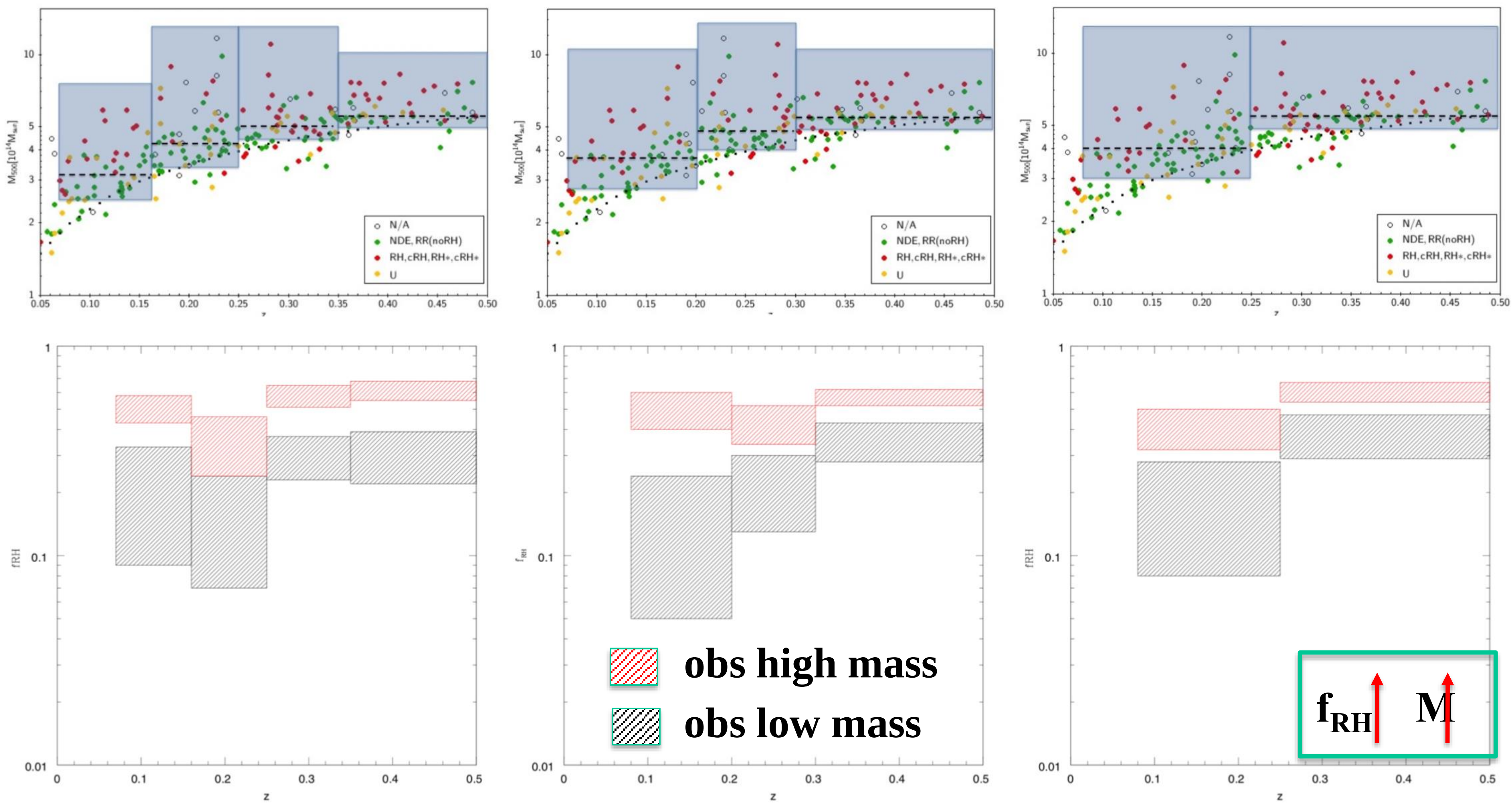
LoTSS could discover up to ~500 RH: M_{500} > 2-3x10^{14}M$_{\odot}$ (z~0.2-0.3)

M_{500} ≥ 5x10^{14}M$_{\odot}$ (z>0.4-0.5)



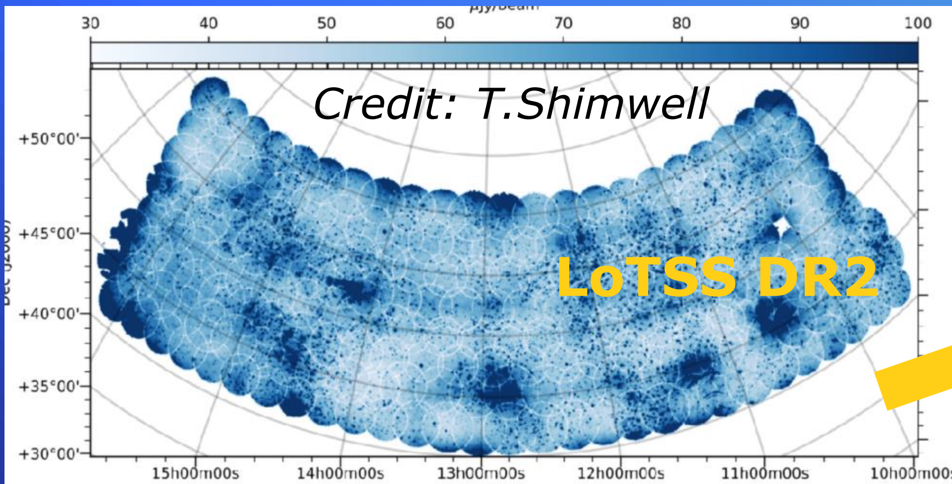


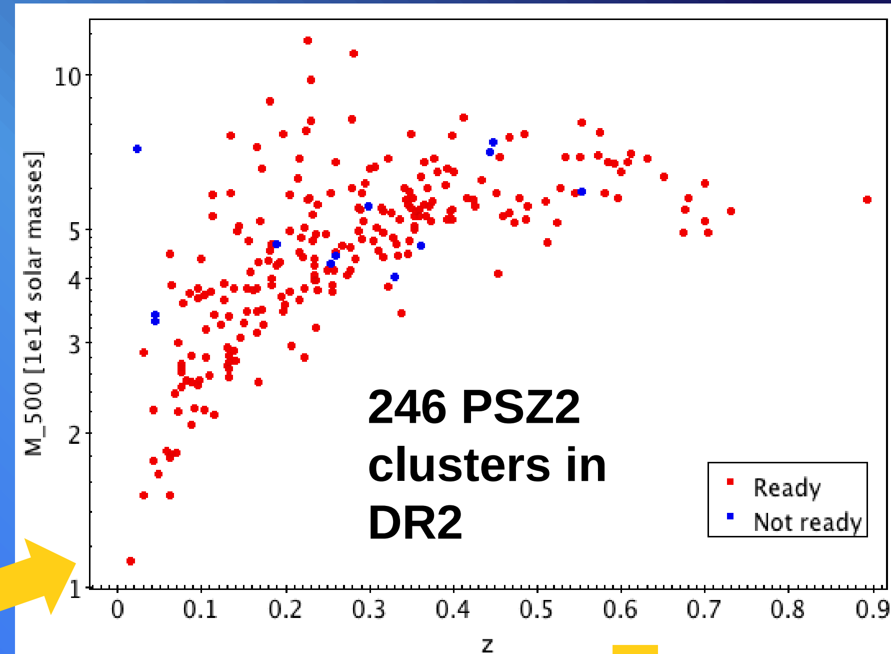
RH occurrence with the cluster mass



Statistical exploitation of LoTSS DR2 area

*LoTSS DR2 ~ **5720 square degrees** (27 % of the northern sky), new pipeline, improving source fidelity, dynamic ranges, …*

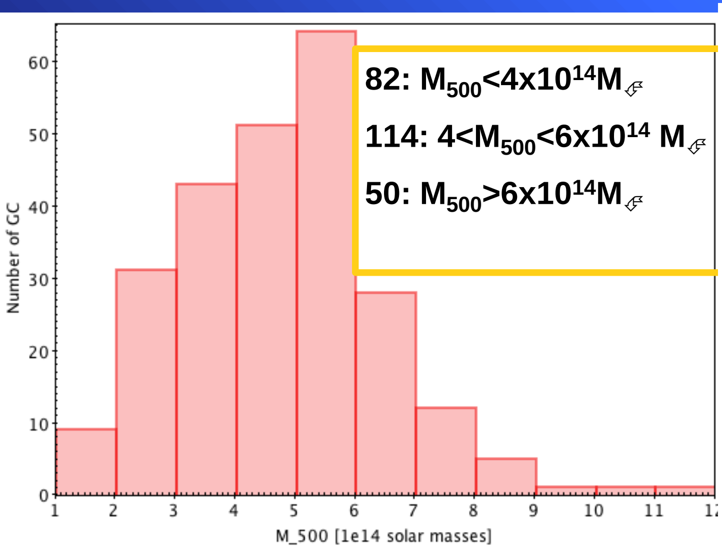


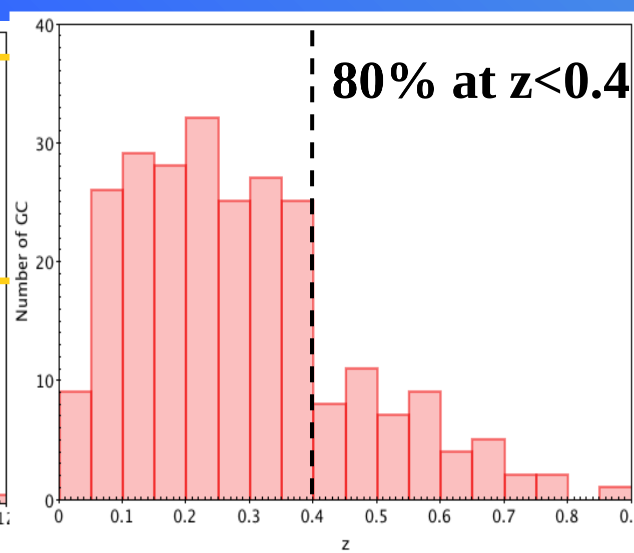


308 PSZ2 clusters in DR2, of this:

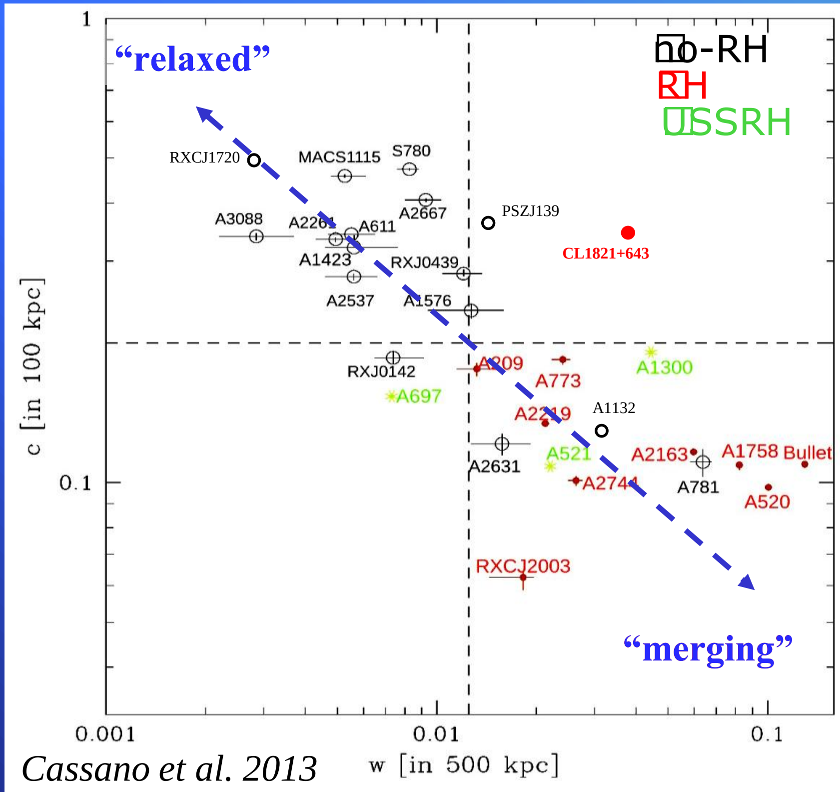
246 have M_{500} and z

~70% have X-ray data (mainly Chandra + XMM-Newton)

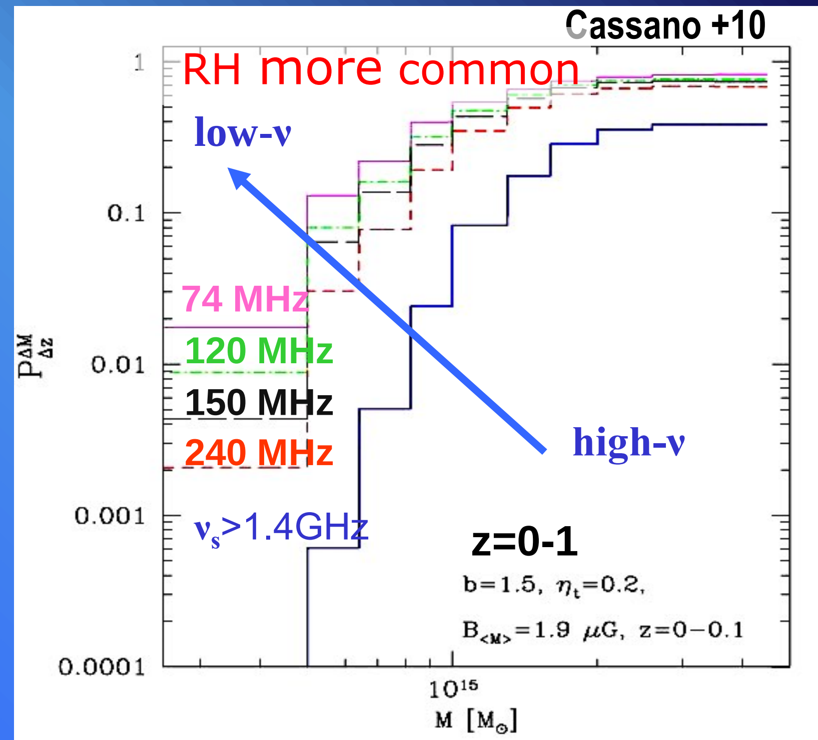




Some immediate objectives



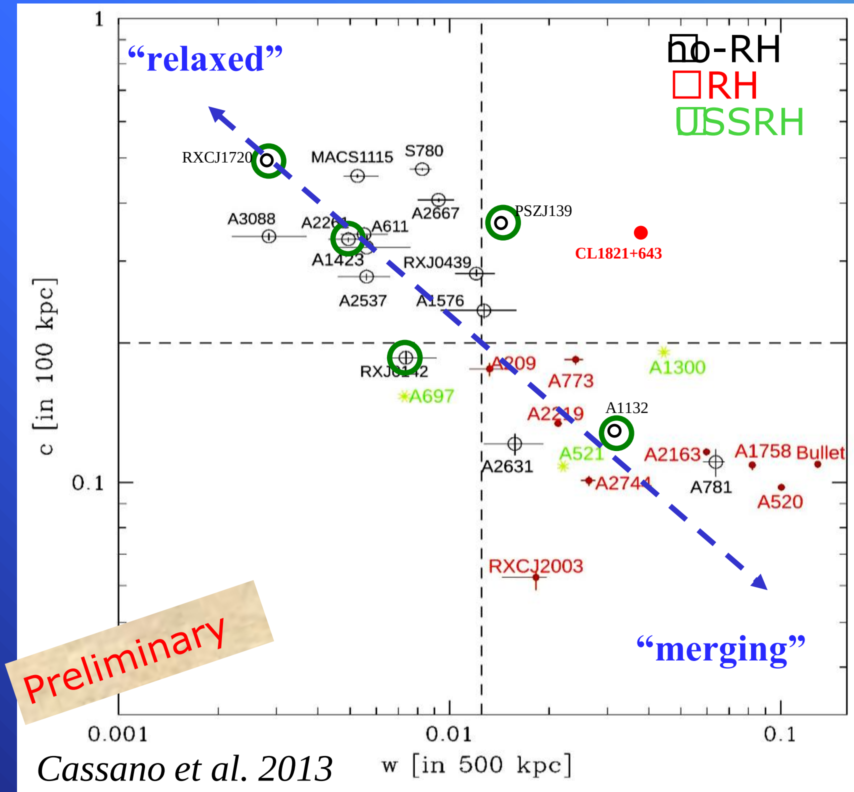
Cassano et al. 2013



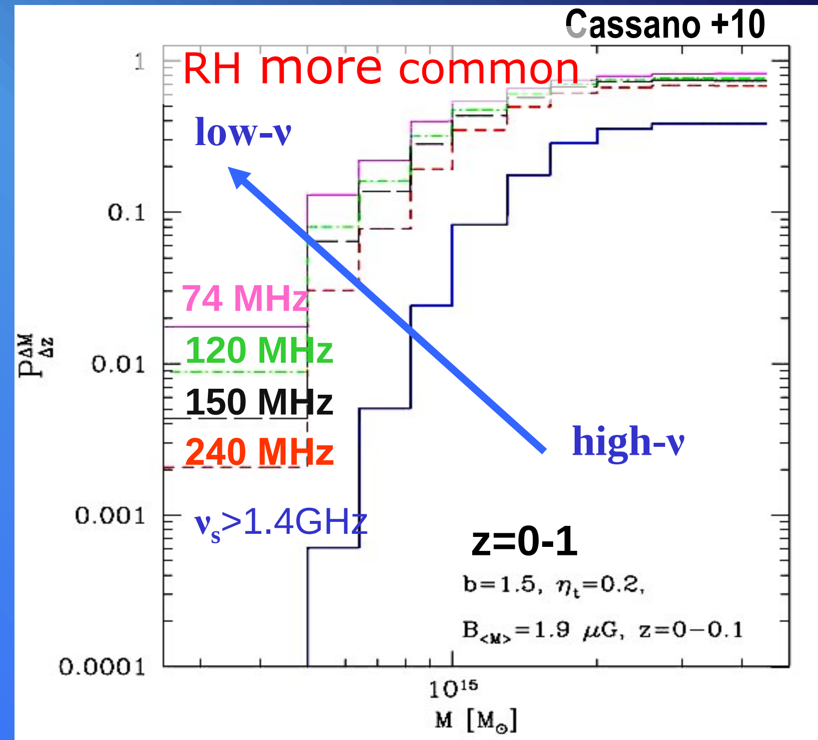
RH – merger connection:
✓ RH (especially USSRH) in less "perturbed" galaxy clusters.

Occurrence of radio halos with mass:
✓ increase of the occurrence with respect to high-ν
✓ less pronunced mass drop

Some immediate objectives



USSRH from *Wilber et al. 18; Savini et al. 18*



RH – merger connection:
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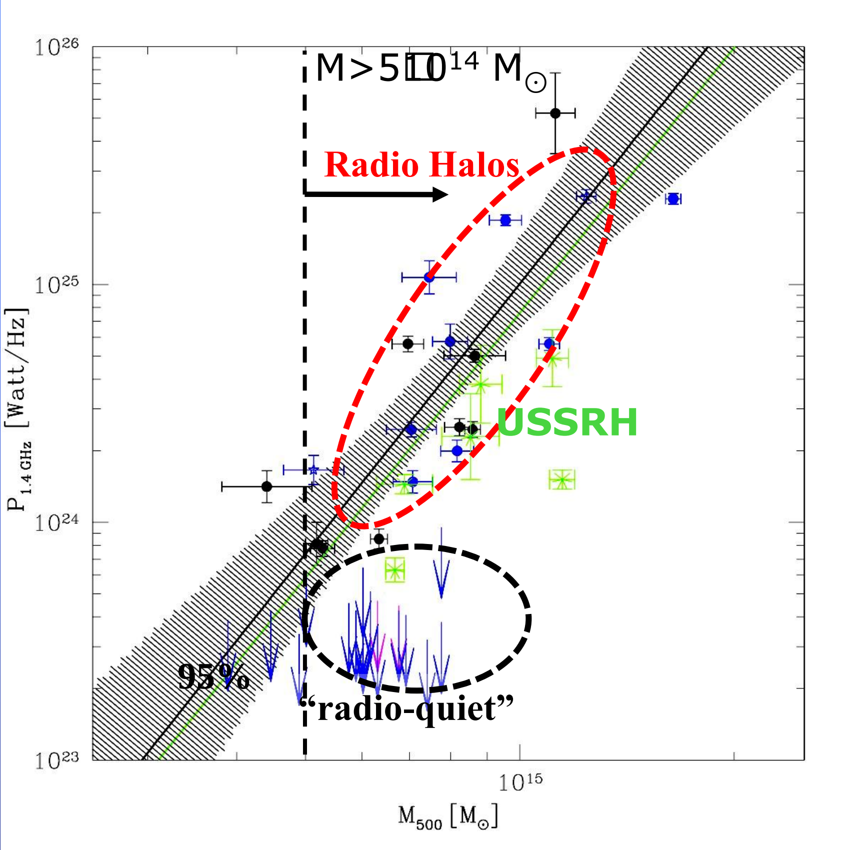
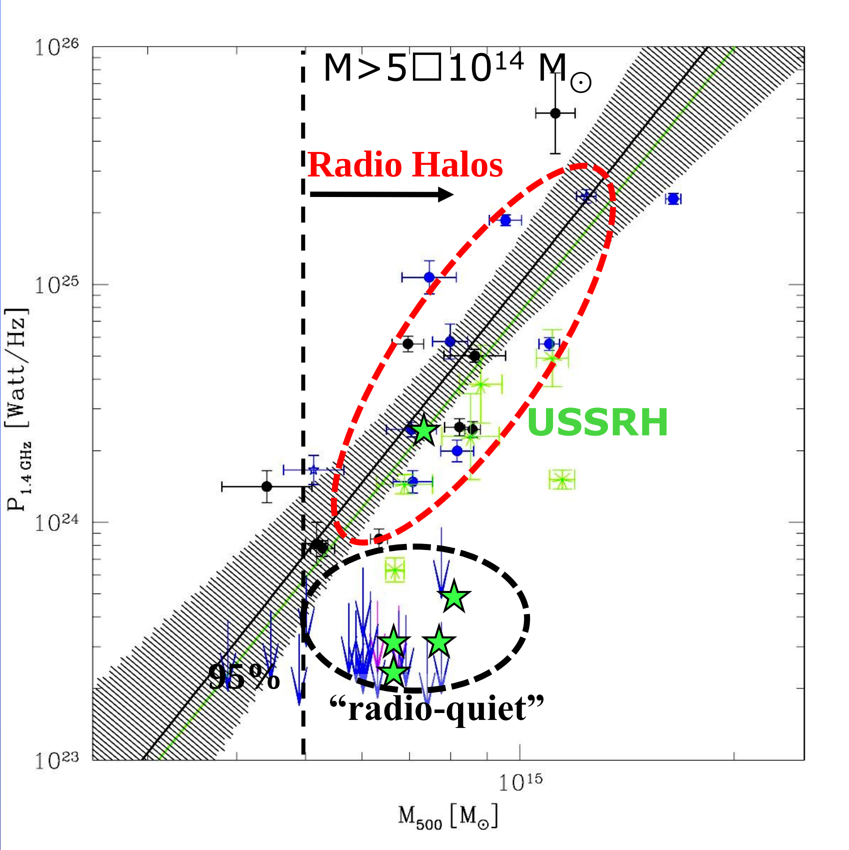
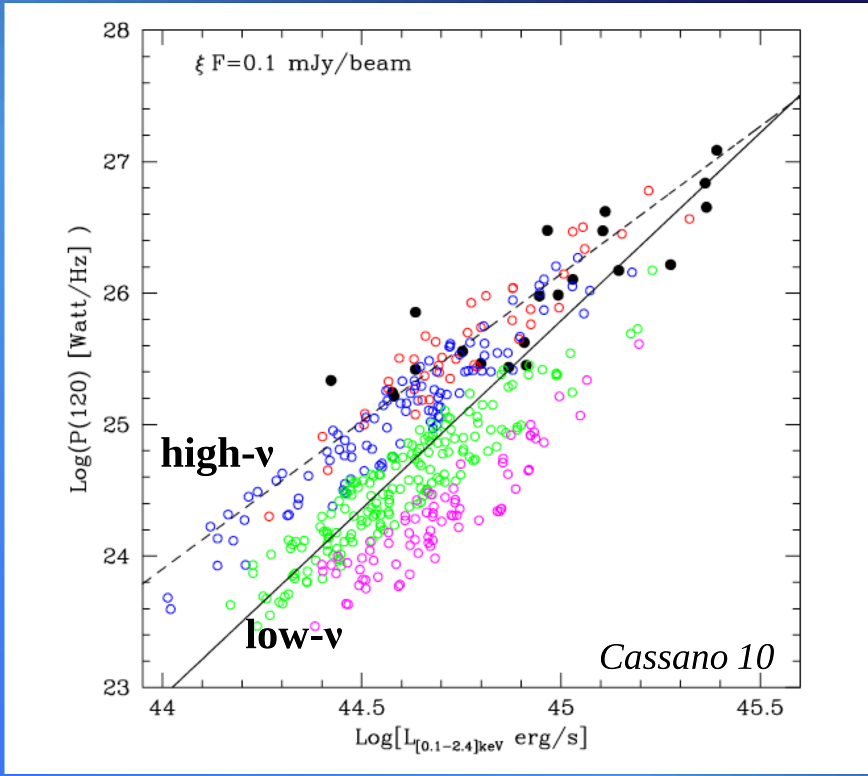
Some immediate objectives



RH power – cluster mass correlation:
✓ RH (especially USSRH) in less massive galaxy clusters would make steeper and broader the correlation at low frequency.

Some immediate objectives





RH power – cluster mass correlation:
✓ RH (especially USSRH) in less massive galaxy clusters would make steeper and broader the correlation at low frequency.

Conclusions

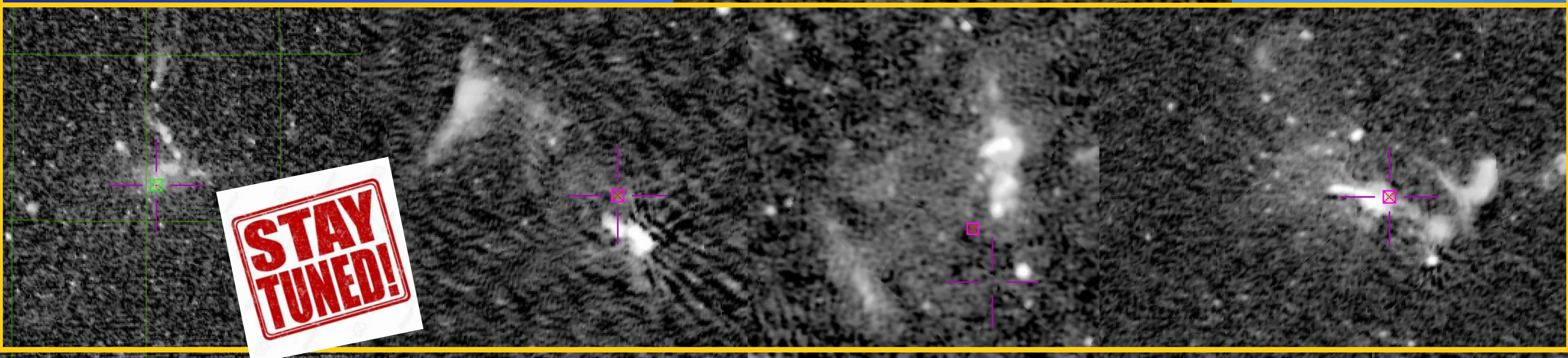
Present scenario: Radio Halos trace turbulent regions in the ICM where particles are trapped and accelerated during mergers

Partial view: present statistical investigation limited to massive clusters and to high-ν observations

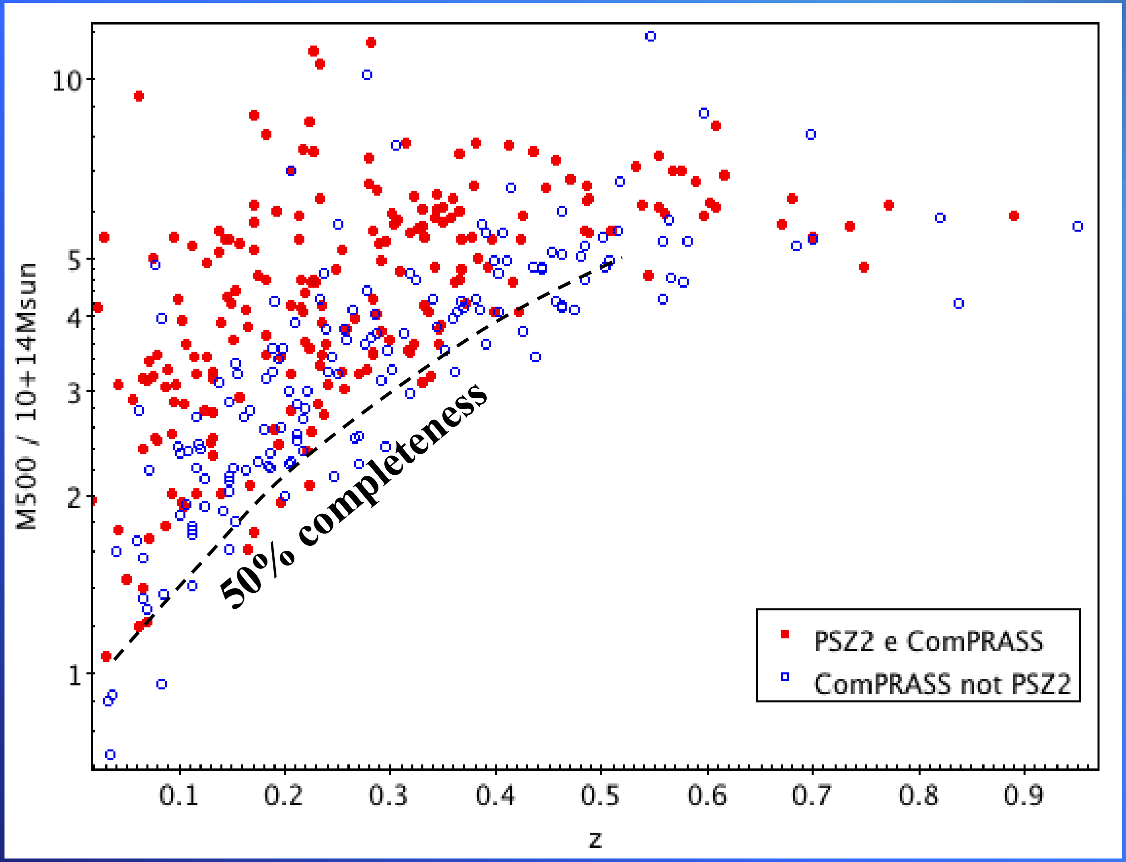
LoTSS, thanks to the combined low- and high-sensitivity, would allow to overcome present biases :

- ✓ USSRH and “off-state” (secondary) halos, RH in less perturbed systems
- ✓ increase of the occurrence with respect to high-ν + less pronunced mass drop
- ✓ steeper and broader RH power – cluster mass correlation

First statistical studies are in progress and will be based on the LoTSS DR2 (~27% of LoTSS) + PSZ2 clusters.



Can we increase the statistics and completeness?

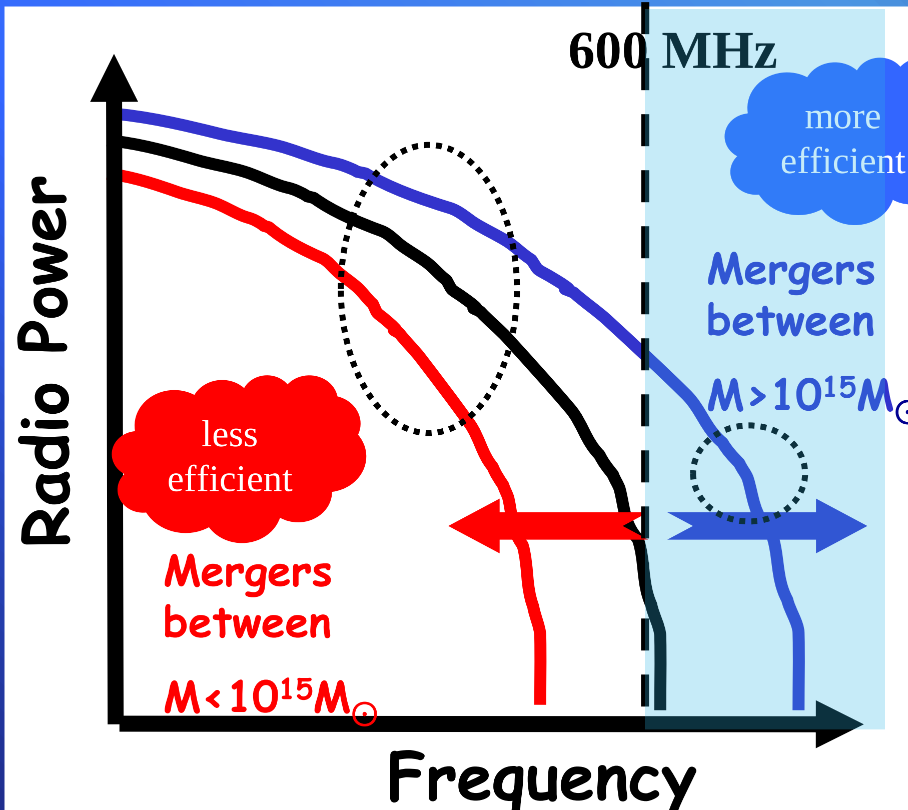


ComPRASS confirmed clusters in DR2 => total sample of 363

With respect to Planck catalogues, the ComPRASS catalogue is simultaneously more pure and more complete *(Tarrìo, Melin, Arnaud 2019)*.

Basic statistical expectations (turbulent GRH)

Cassano & Brunetti 05; Cassano et al. 06, 10, 12



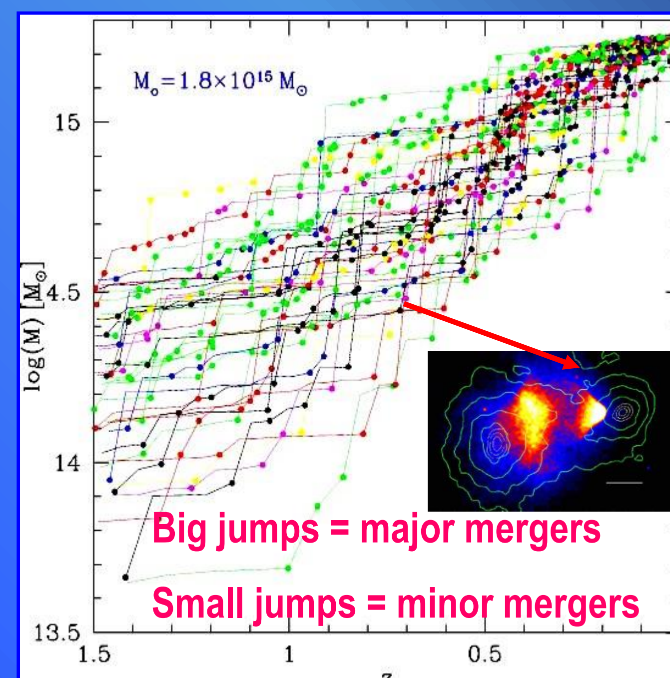
Acceleration efficiency

$X \approx 1/\tau_{acc}$

Steepening frequency

$$\nu_s \propto \langle B\rangle \gamma_{max}^2 \propto \frac{\langle B\rangle \chi^2}{\left(\langle B\rangle^2 + B_{cmb}^2\right)^2}$$

Semi-analytic models to describe the formation history of galaxy clusters



At **GHz frequency**:

✓ RH common in massive-merging GCs

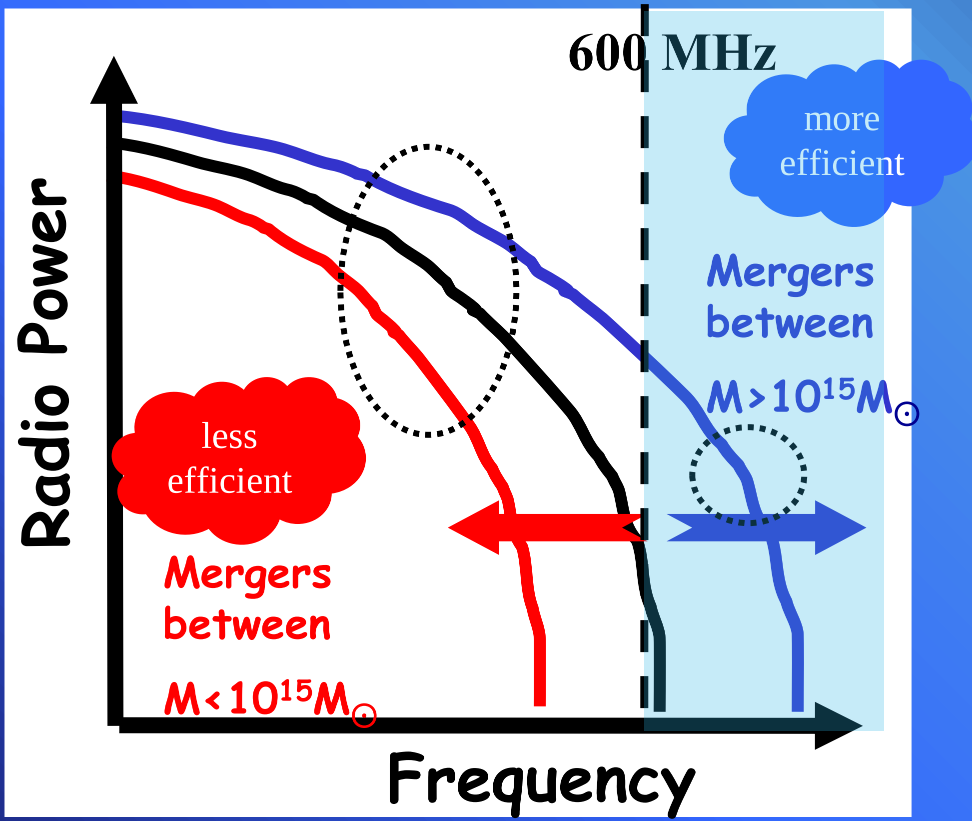
✓ RH rare in less massive-merging GC

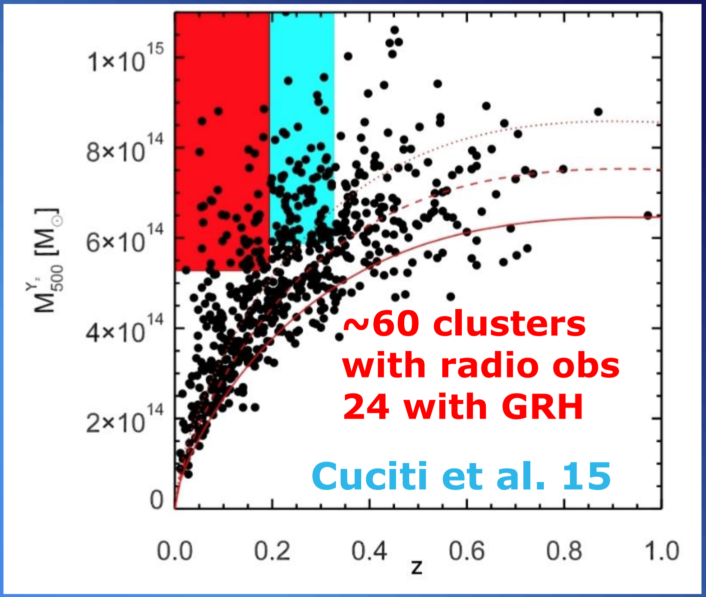
✓ **drop of fraction of RHs at lower masses**

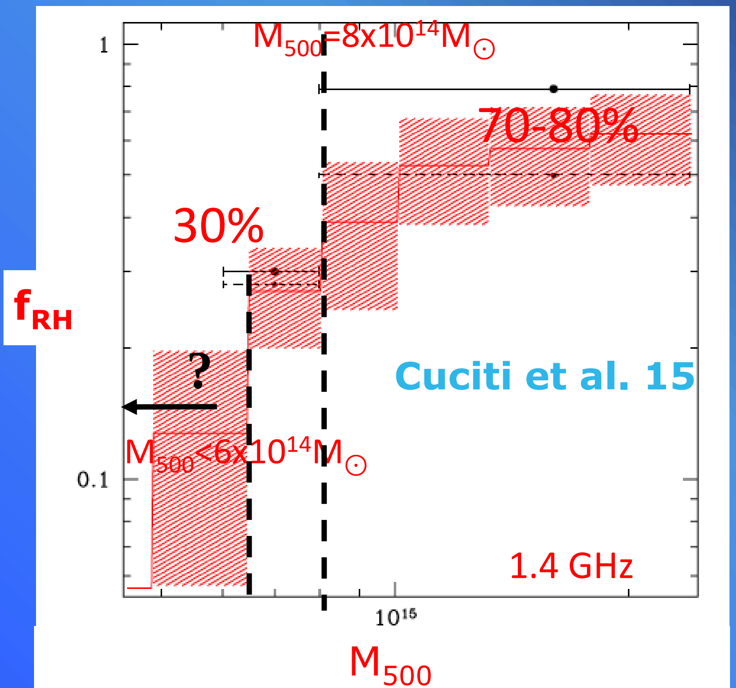
«mass sets the energy available»

Basic statistical expectations (turbulent GRH)

Cassano & Brunetti 05; Cassano et al. 06, 10, 12







At **GHz frequency**:

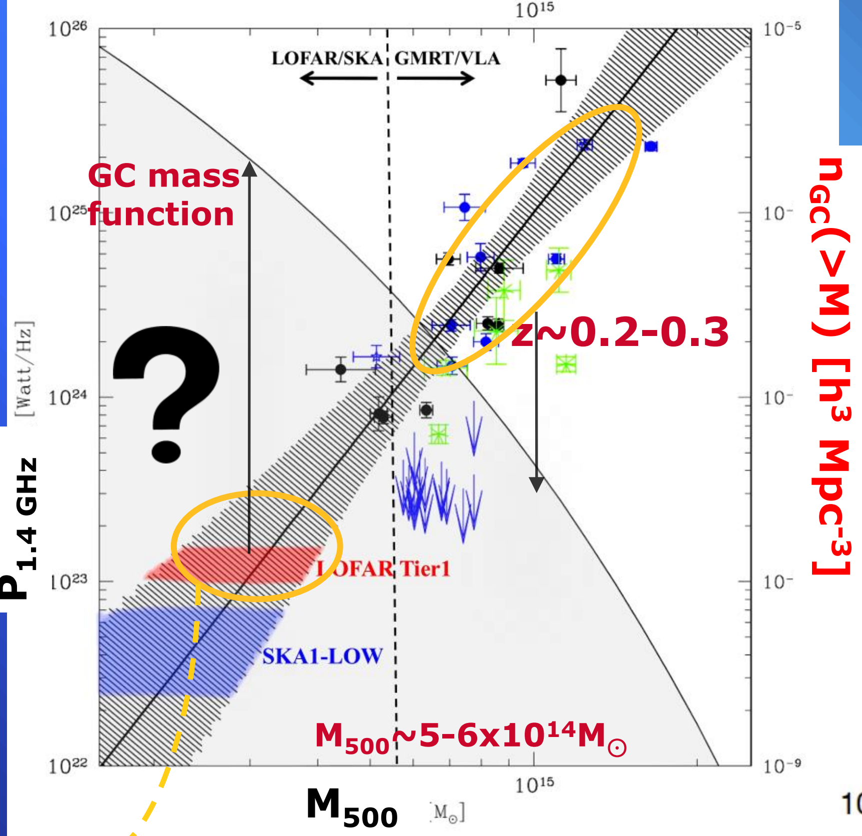
- ✓ RH common in massive-merging GCs
- ✓ RH rare in less massive-merging GC
- ✓ **drop of fraction of RHs at lower masses**

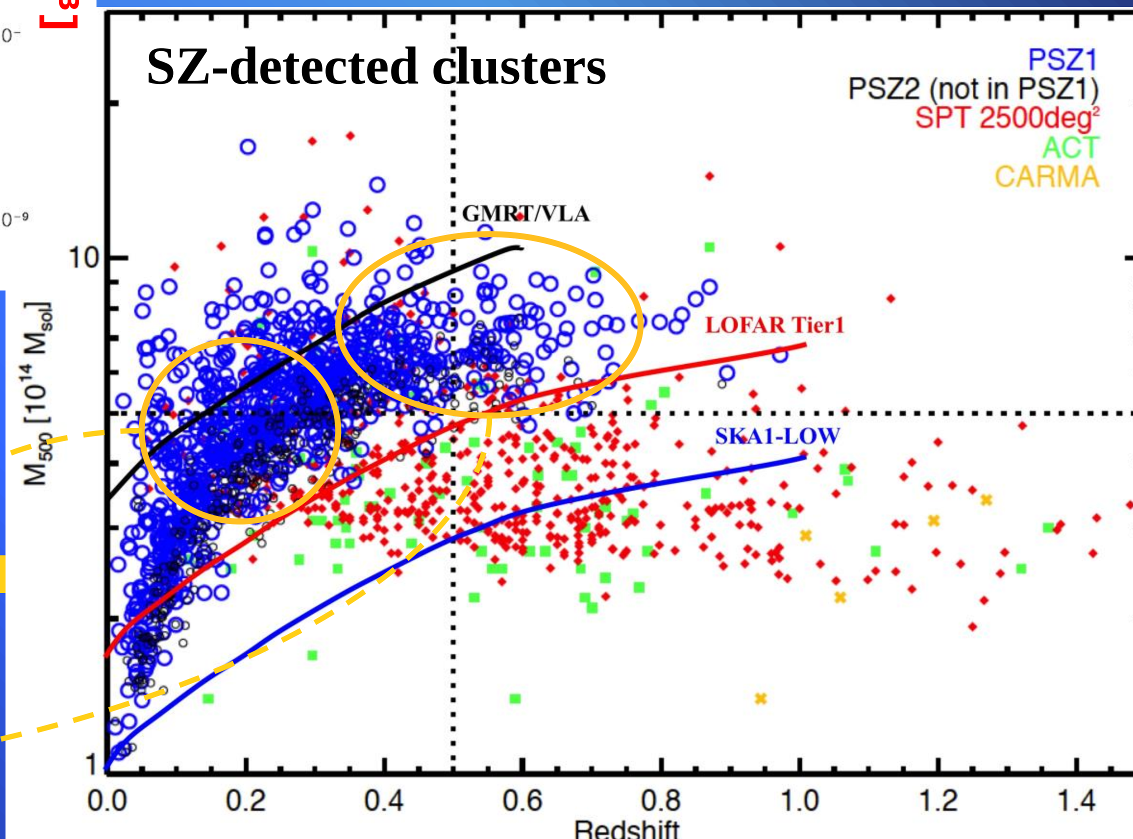
«mass sets the energy available»

Where do GRH live?

GRH in massive and merging GC (~nearby)

- How much the present view is biased ?
- Which are the typical masses and redshifts of GRH hosts?





LOFAR should discover GRH mainly in:

M_{500} = 2-3x$10^{14}M_\odot$ (z~0.2-0.3)

M_{500} ≥ 5x$10^{14}M_\odot$ (z>0.4-0.5)

from http://szcluster-db.ias.u-psud.fr

Expectations from a two population scenario

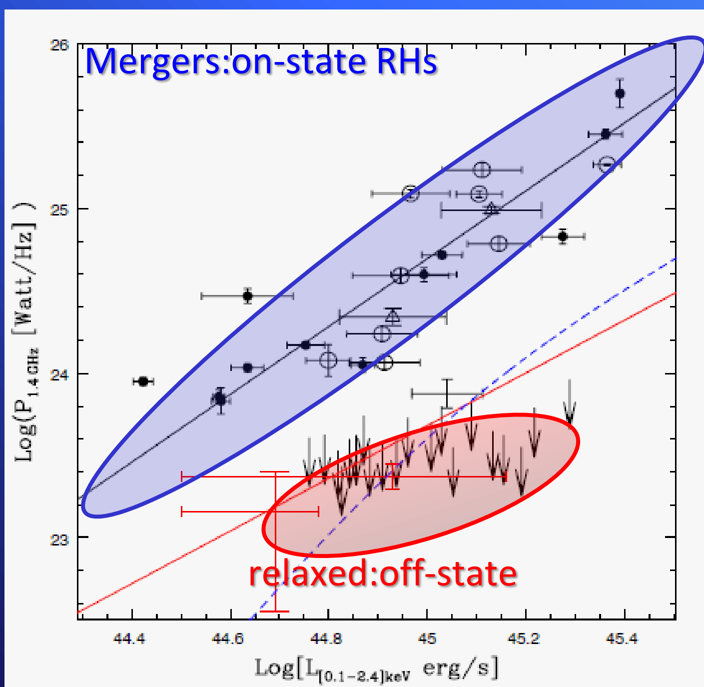
2-Population model:

- on-state RHs in turbulent clusters (including ultra-steep…)
- Off-state/hadronically induced emission in relaxed systems

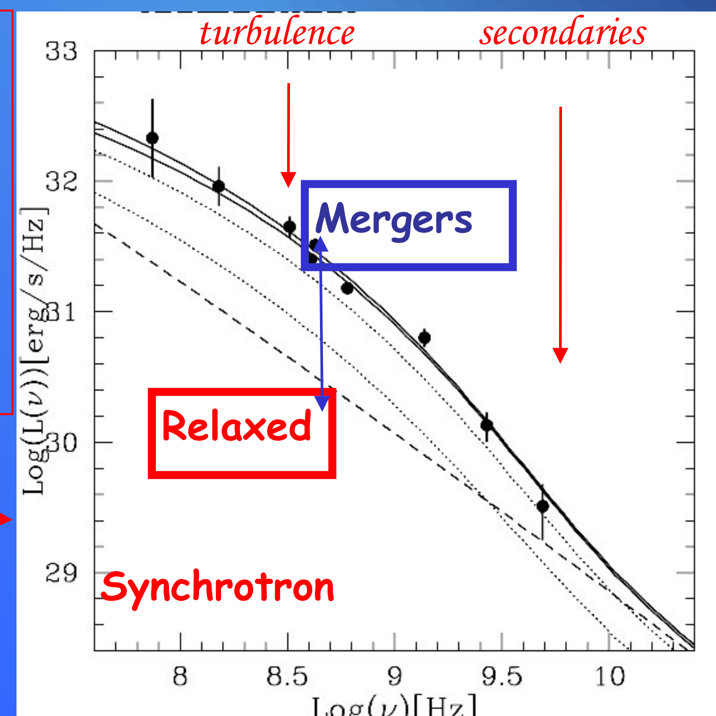
«On-state RHs» in merging (turbulent) systems

Merger-boosting

«Off-state » in relaxed systems

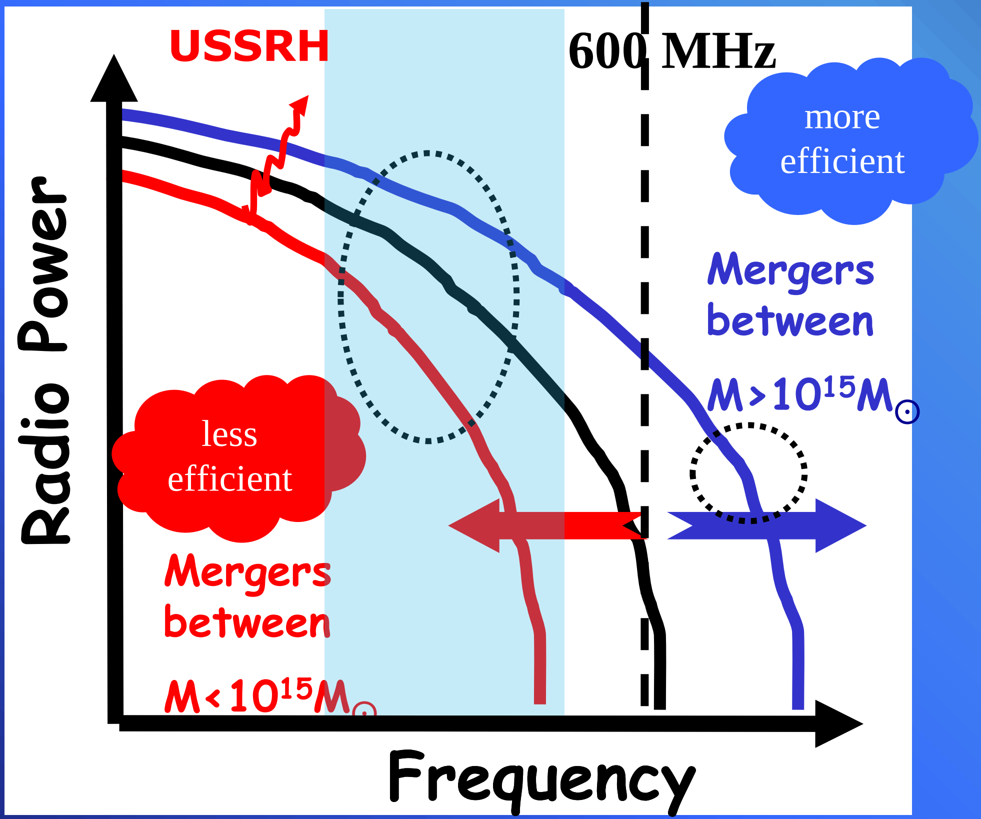


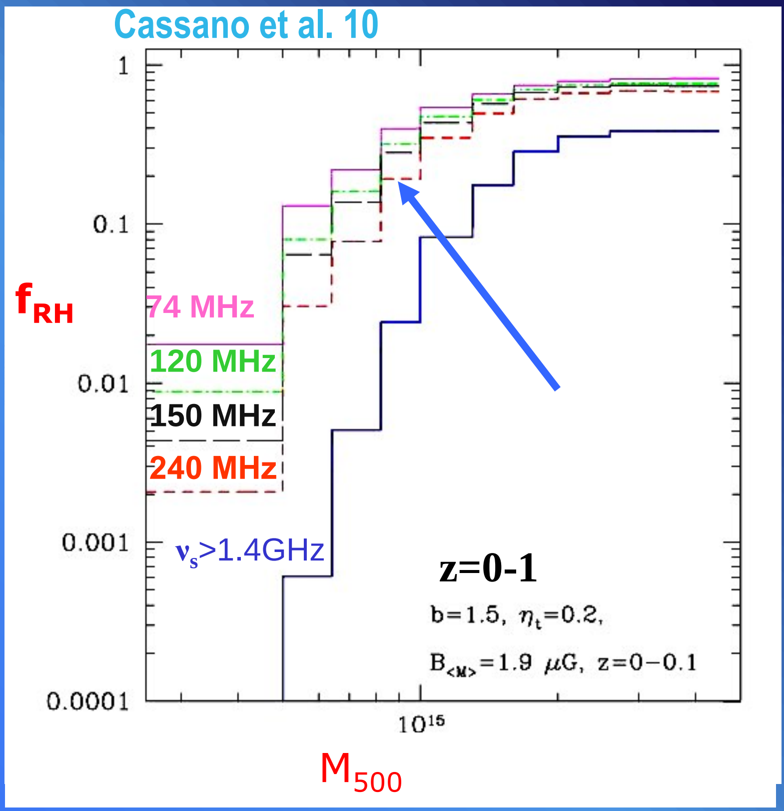
THEORETICAL MOTIVATION
Calculations based on *CRp* + *CRe* + MHD turbulence (Brunetti & Blasi 05, Brunetti & Lazarian 11)



Basic statistical expectations (turbulent GRH)

Cassano & Brunetti 05; Cassano et al. 06, 10, 12



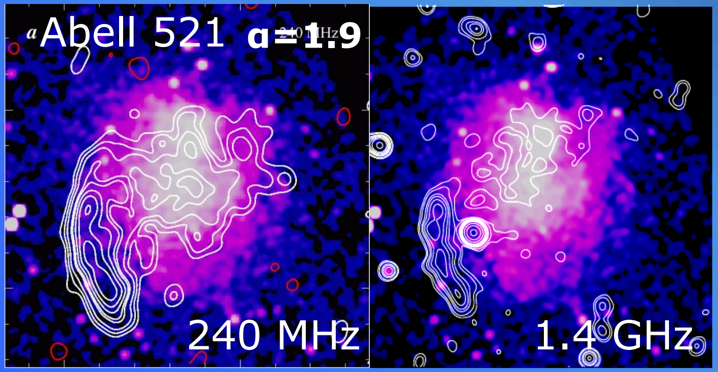


At **low (<1 GHz) frequency**:

✓ A complex population of RH (different spectra)

✓ RH more common, increase of the fraction of RH

✓ ultra-steep spectrum RH (USSRH, **α>1.5**)

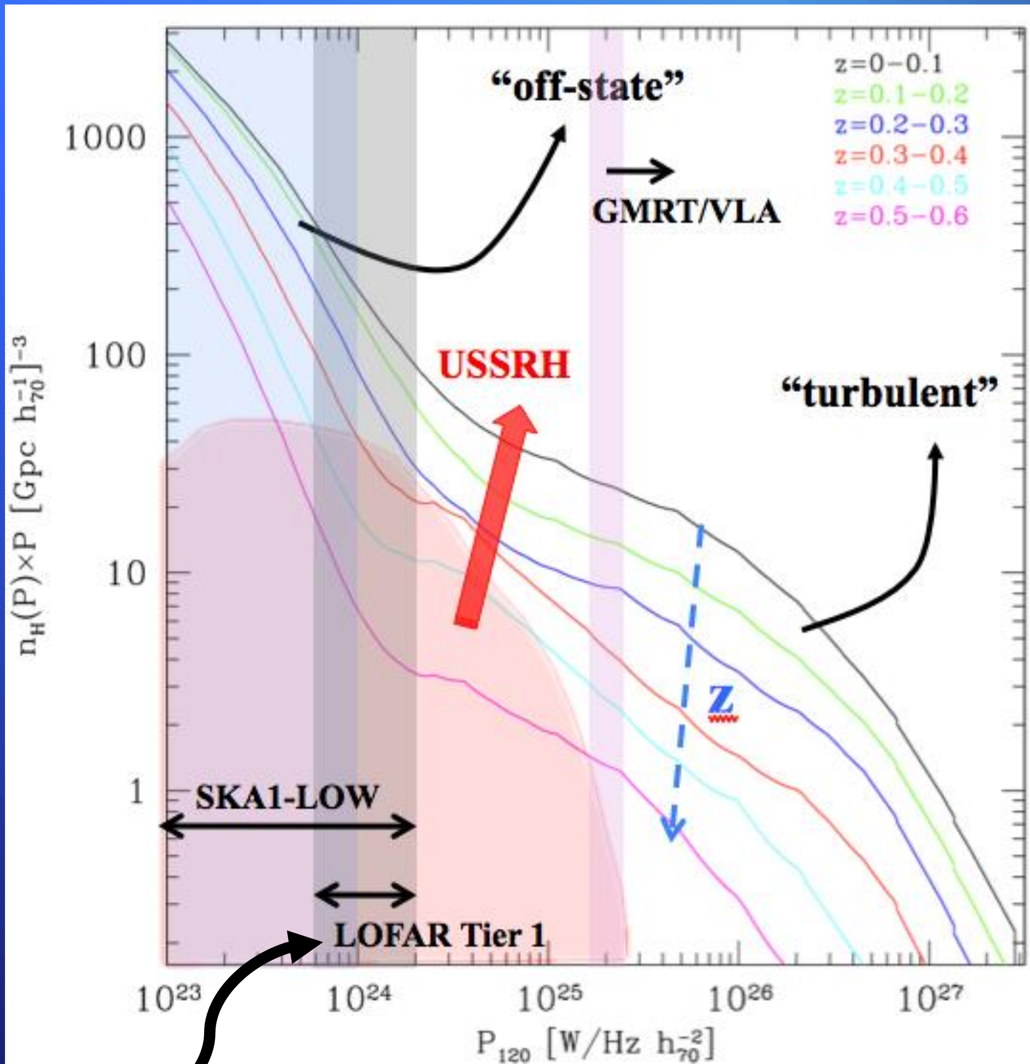


Brunetti et al. 08; Dallacasa et al. 09

Luminosity functions of GRH+"off-state" at low-ν

Cassano et al. 15,16

RH number density [Gpc^{-3}]



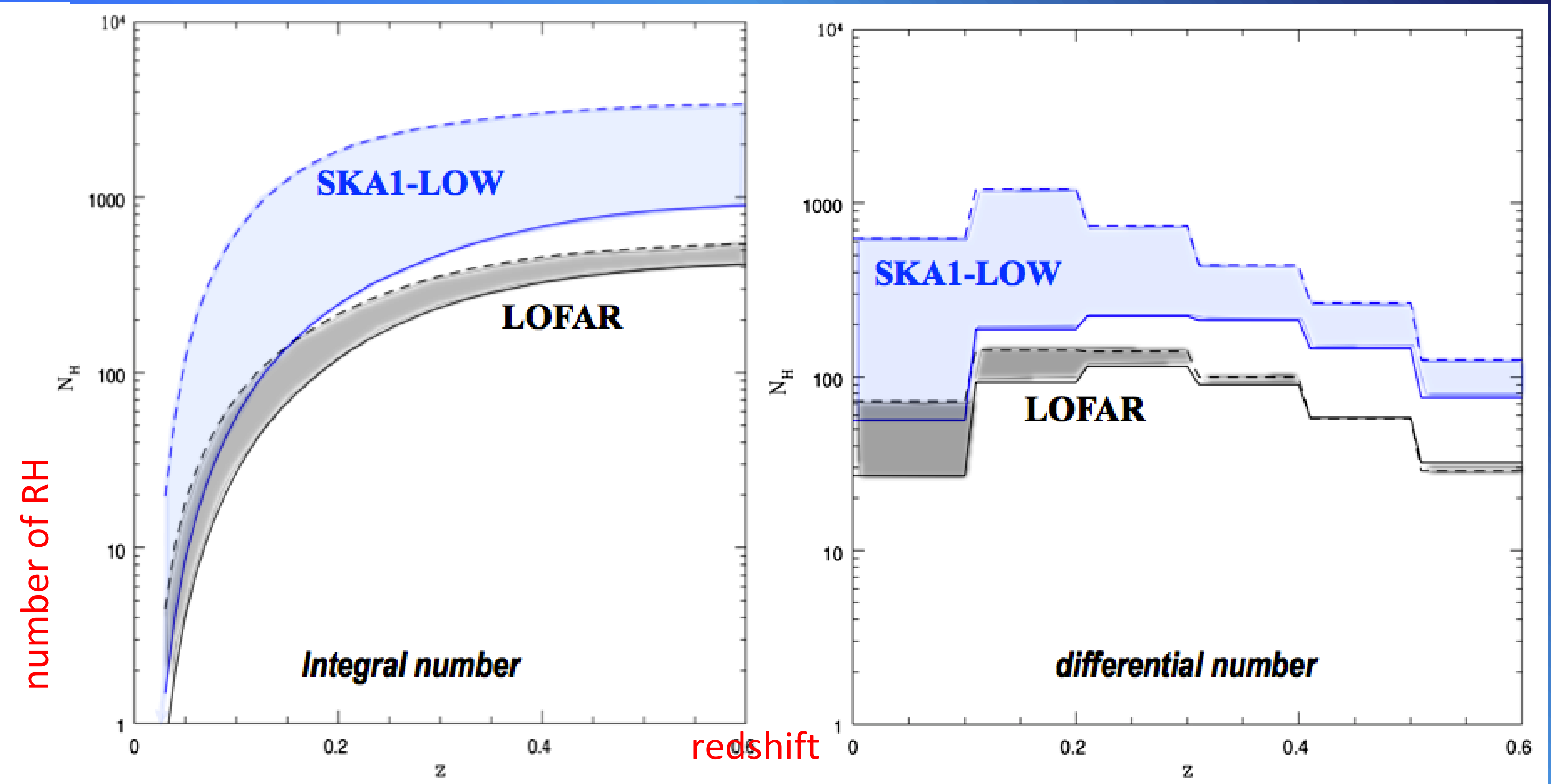
Complex **population of GRH: depending on sensitivity of the observations**

USSRH **and** ***off-state*** **halos dominate low radio powers**

LOFAR rms sensitivity ≃ 200 μJy/beam at 20 arcsec resolution (*e.g. van Weeren et al. 16).*

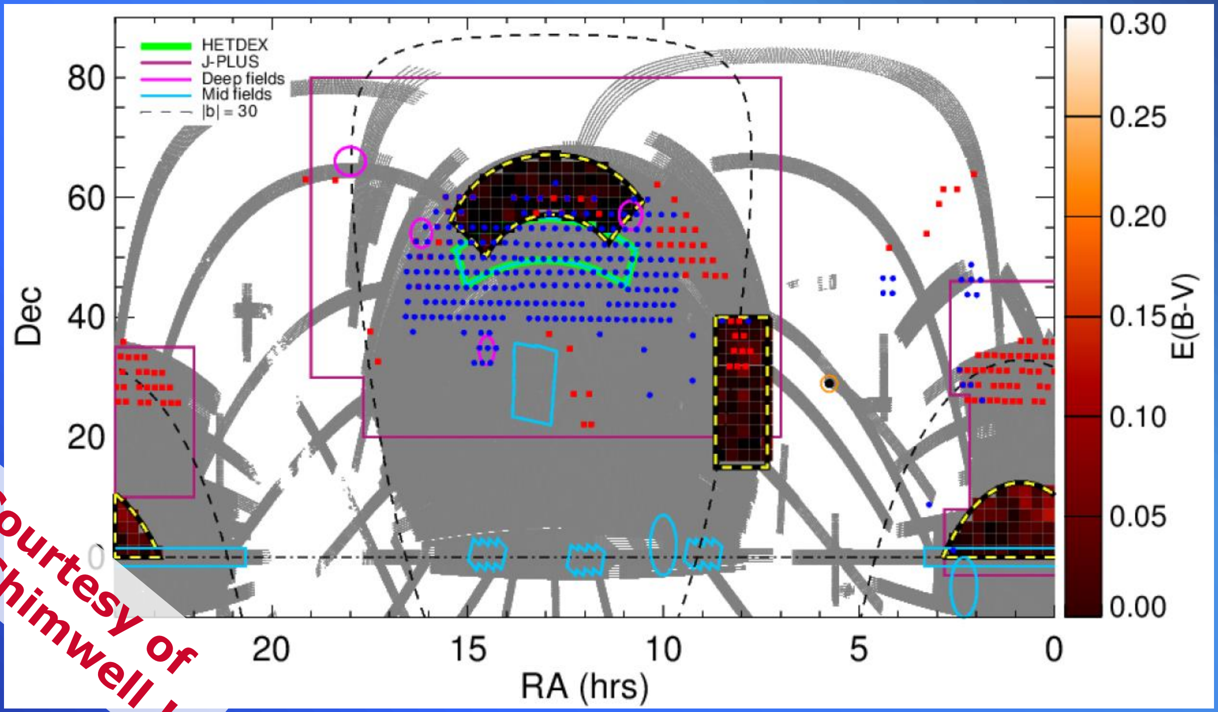
How many RHs await discovery in LOFAR surveys?

Cassano et al. 2015



- We presently know ~30-40 GRH !
- A LOFAR Survey on 2π sr with rms~0.4 mJy/beam and res~25” => with 250 GRH on 2π sr
-

LOFAR plan for surveys and Galaxy Clusters (see talk by Tim Shimwell)



Courtesy of T.Shimwell !

- **HETDEX region** tot. coverage ~**350 deg²**, with 0.5 mJy/beam and 25" res=> **30 massive clusters** (*Shimwell et al. 16*) => ~**3-4 GRH**

- **End of 2016** (blue and red regions), tot. coverage ~**2,300 deg²** => **~190 massive clusters** => **~60 RH** (with 0.2 mJy/beam and ~20")

- **End of 2017**: (black and yellow regions), extension to the WEAVE fields (increase of the sky coverage by 1,000-1,500 deg²), tot. coverage ~ **3,800 deg²** => **~300 massive clusters** => **~90 RH** (with 0.2 mJy/beam and ~20")

- **LoTSS (LOFAR Two-metre Sky Survey)** will cover 2π sr **(~20,627 deg²)**, with 0.1 mJy/beam and 5" => **~1700 massive clusters** =>
~**240 GRH** (with 0.5 mJy/beam and 25")
~**400-500 GRH** (with 0.2 mJy/beam and ~20" or with 0.1 mJy/beam and ~10")

LOFAR plan for surveys and Galaxy Clusters (see talk by Tim Shimwell)

- HETDEX region
~350 deg^2, 0.5 mJy/beam and 25" =>
30 massive clusters (*Shimwell et al. 16*) => ~**3-4 GRH**

- statistical studies: **no**
a) study of interesting targets in the field by producing high sensitivity and high resolution (~0.2 mJy/b, 10") images

- End of 2016
~**2,300 deg^2** =>~10% of LoTSS
~190 massive clusters => **~60 RH**
(with 0.2 mJy/beam and ~20")

- statistical studies : **yes**
b) occurrence of RH with cluster mass
c) correlations (as synchrotron power vs Mass)
d) GRH-cluster merger connection (needs X-ray/weak lensing data)

- End of 2017
~ **3800 deg^2** =>~20% of LoTSS
~300 massive clusters => **~90 RH**
(with 0.2 mJy/beam and ~20")

- statistical studies : **yes**
b)+c)+d)
b)+c)+d) at high-redshift (if res. ~ 5-10" and rms~0.1 mJy/beam)

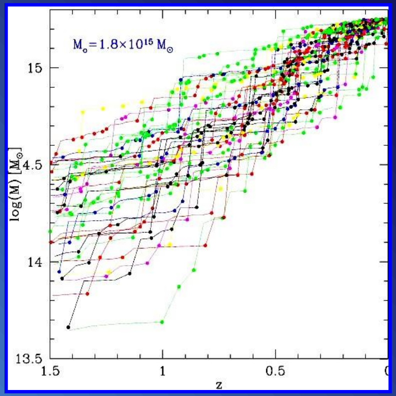
- **LoTSS**
~20,627 deg^2 with 0.1 mJy/beam and 5" =>
~1700 massive cluster=>
~**400-500 GRH** (with 0.1 mJy/beam and ~10")

- statistical studies : **yes**
b)+c)+d)
b)+c)+d) at high-redshift (if res. ~ 5-10" and rms~0.1 mJy/beam)
f) *GRH as probe of cluster merging rate with cosmic time* (as a function of M and z; *see Cassano et al. 16, A&A in press) +g?-h?*

Statistical Modeling of cluster RH:

(Cassano & Brunetti 2005)

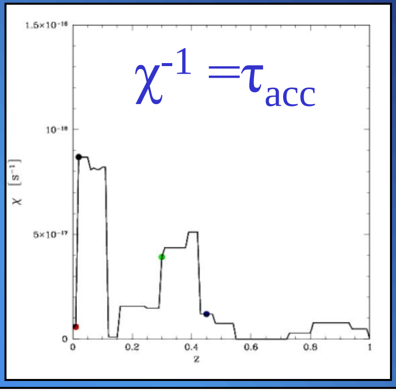
(cosmological "version" of turbulent-acceleration model)



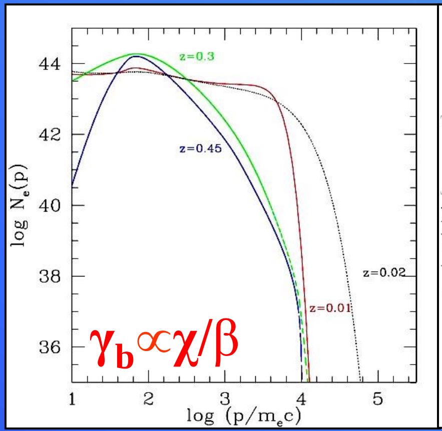
INGREDIENTS

- Semi-analitic model of cluster formation ⇒ merger trees
  (Press & Schecther 1974; Lacey & Cole 1993)

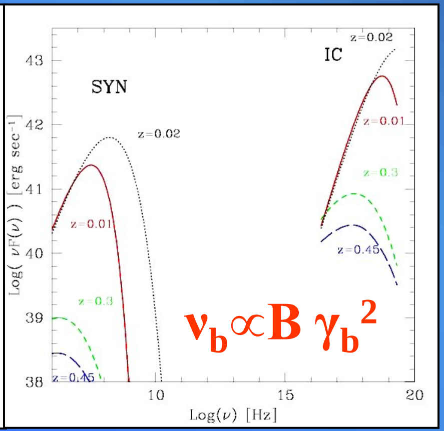
- Estimate of the turbulent energy injected in the cluster volume during merger events (*Ram Pressure Stripping)* and the acceleration efficiency (τ_{acc}^{-1}) due to MS waves. The cosmological evolution of the magnetic field is accounted for by scaling the field with the cluster mass (cosmological MHD simulations; e.g. *Dolag et al. 2002*). ⇒



- Calculate the **acceleration** of fossil $e^{\pm}$ due to the interaction with the turbulent waves and the ensuing **Synchrotron** and **Inverse Compton** emission spectra from the resulting electron spectra ⇒

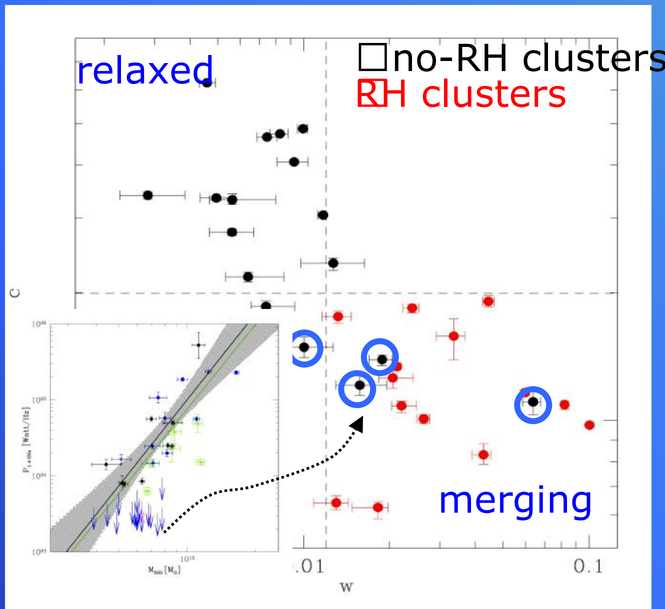


electron spectra



radiation spectra

Merging clusters without RHs



We note "radio anomalies", i.e., merging clusters that do not host RHs, on the low mass-end of the sample: $6\times10^{14}M_\odot<M_{500}<7\times10^{14}M_\odot$

These can be explained:

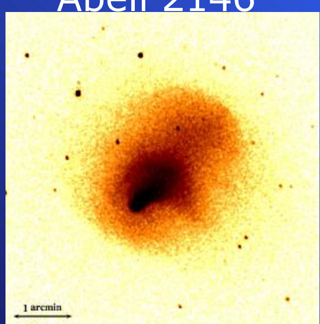
-phases of merger where turbulence (and particle acceleration) is still not fully developed;

-less energetic merger => less massive systems mergers with lower mass ratio?

USSRH => need low v_0 obs. (LOFAR)

Merging clusters without RH are also found in studies of single objects:

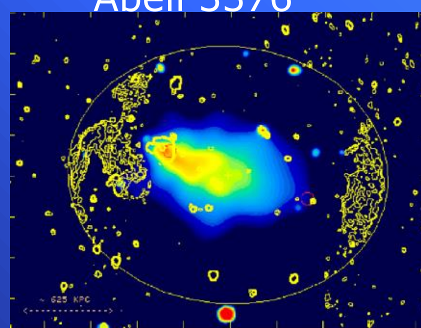
Abell 2146



Russell et al. 11

$M_{500}\sim3.9\times10^{14}M_\odot$ z~0.23

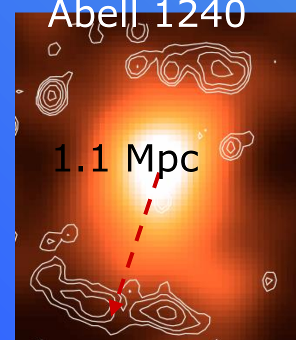
Abell 3376



Bagchi et al. 06

$M_{500}\sim2.3\times10^{14}M_\odot$, z~0.05

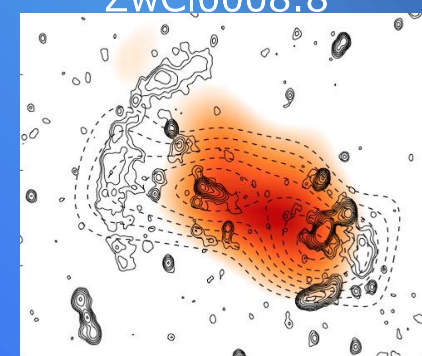
Abell 1240



Bonafede et al. 09

$M_{500}\sim3.7\times10^{14}M_\odot$ z~0.16

ZwCl0008.8



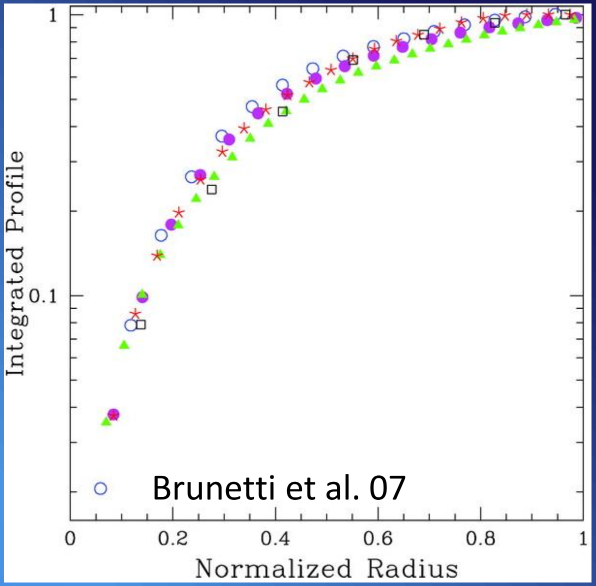
Van Weeren et al. 11

$M_{500}\sim3.3\times10^{14}M_\odot$, z~0.1

…these are even less massive systems, $M_{500}\leq4\times10^{14}M_\odot$!

Detecting giant RH in galaxy clusters (Cassano et al. 10,12)

From the brightness profiles of well studied RH, we find that ~50% of the total radio flux of a RH is within half radius (e.g., Brunetti et al. 2007)



We estimated the minimum flux of a RH (over ~1 Mpc) that can be detected detected in a survey:

★ brightness based-based method

$$f_{min}(z) \simeq 1.2 \times 10^{-4} \xi_1 \left(\frac{F_{rms}}{10\mu Jy}\right)\left(\frac{100\,arcsec^2}{\theta_b^2}\right)\left(\frac{\theta_H^2(z)}{arcsec^2}\right) [mJy]$$

★ flux based-based method

$$f_{min}(z) \simeq 1.43 \times 10^{-3} \xi_2 \left(\frac{F_{rms}}{10\mu Jy}\right)\left(\frac{10\,arcsec}{\theta_b}\right)\left(\frac{\theta_H(z)}{arcsec}\right) [mJy]$$

configurations	rms	θ_b
	μJy/beam	arcesc
LOFAR (120 MHz)	400	25
SKA1-low (120 MHz)	20	10
EMU (1.4 GHz)	13	15
SKA1-SUR (1.4 GHz)	5	15