Paving the way to SKA observations of galaxy clusters with pathfinder and precursor instruments

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INAF – IRA

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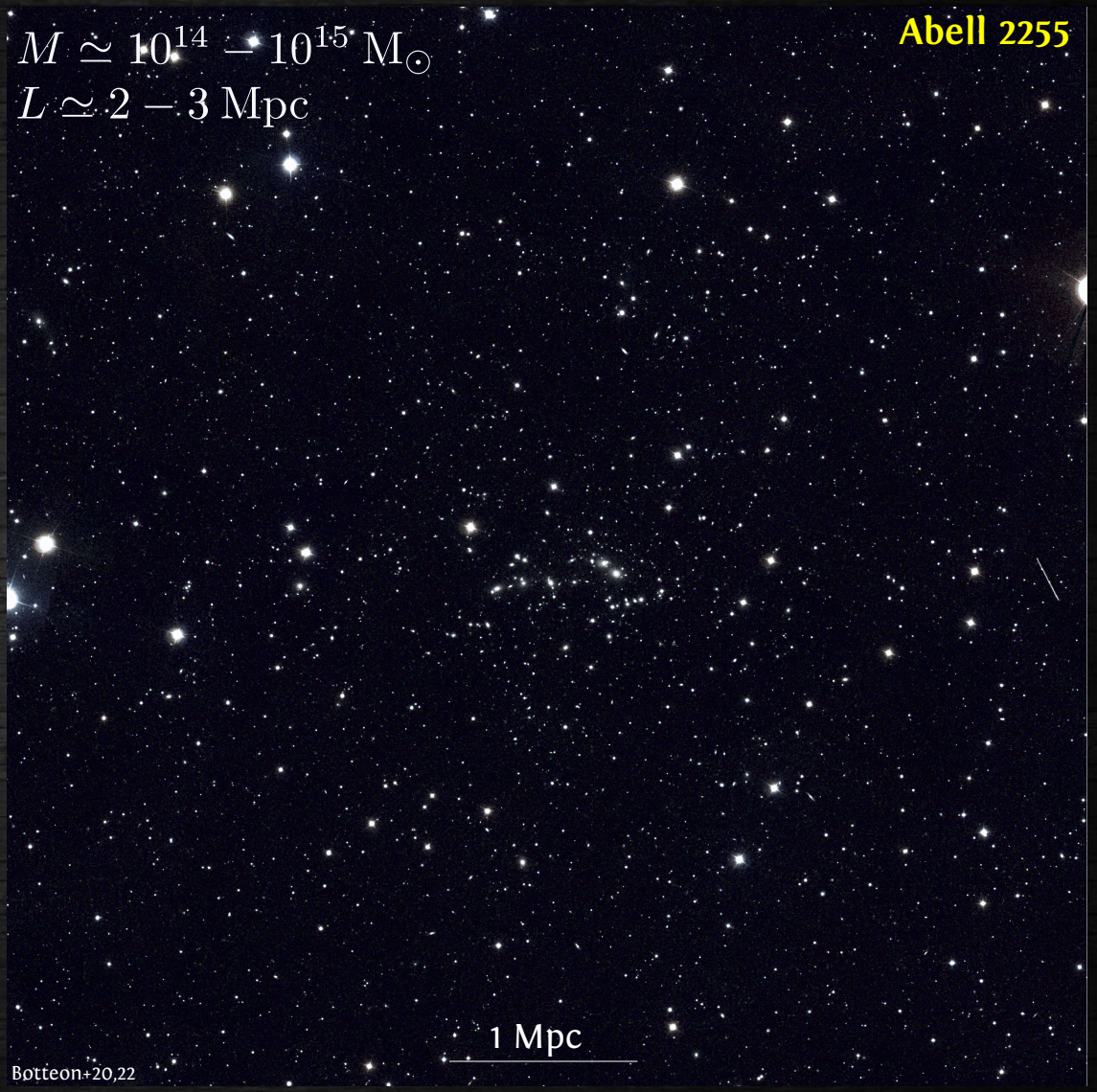
Galaxy clusters

Optical:
- 100-1000s galaxies
- Mass: a few % of total

Lensing:
- Trace dark matter
- Mass: 80% of the total



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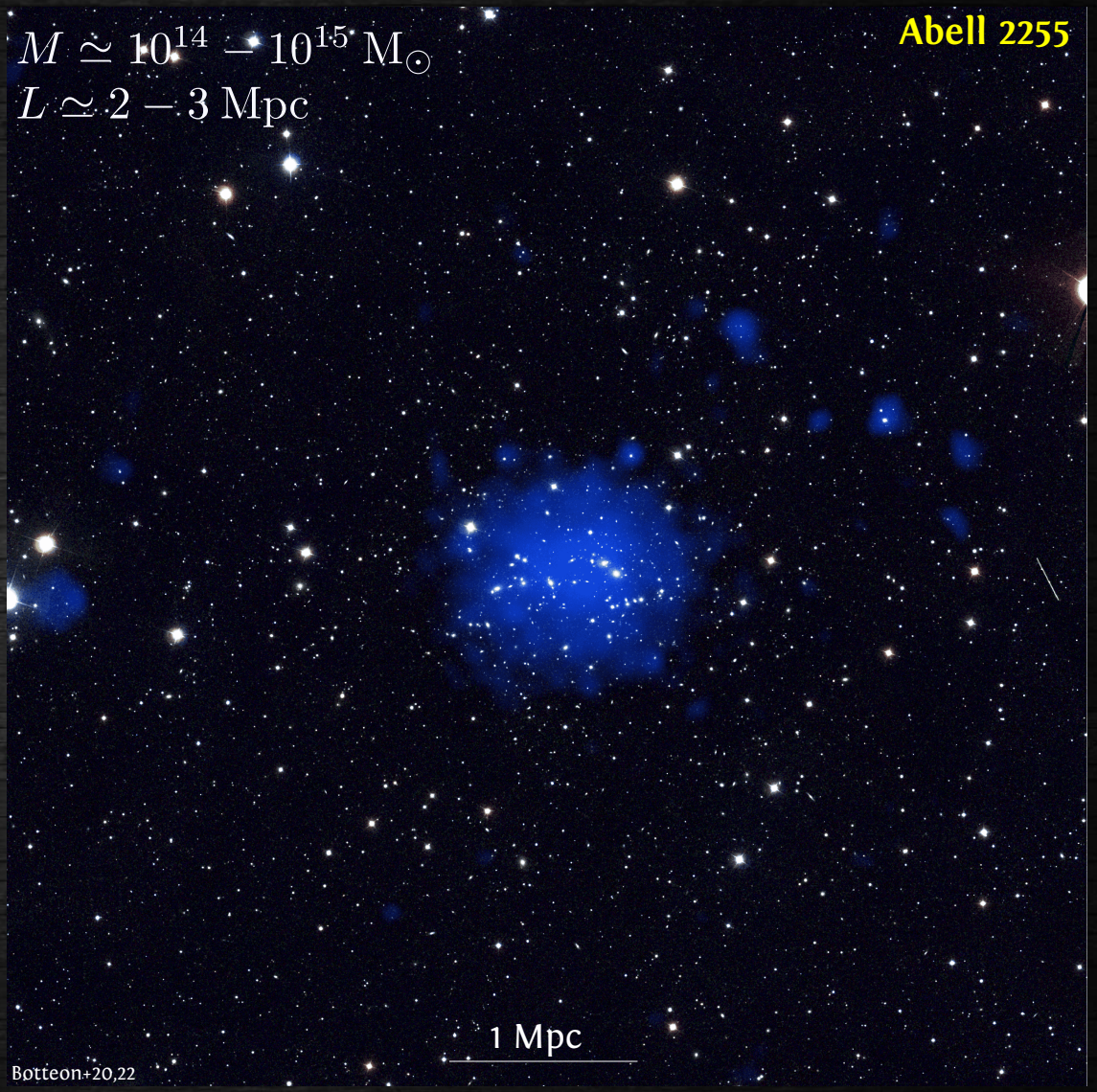
- Intra-cluster medium (ICM)
- Hot (10^7 – 10^8 K) and rarified (10^{-3} – 10^{-4} cm^{-3})
- Thermal bremsstrahlung
- Mass: 15% of total



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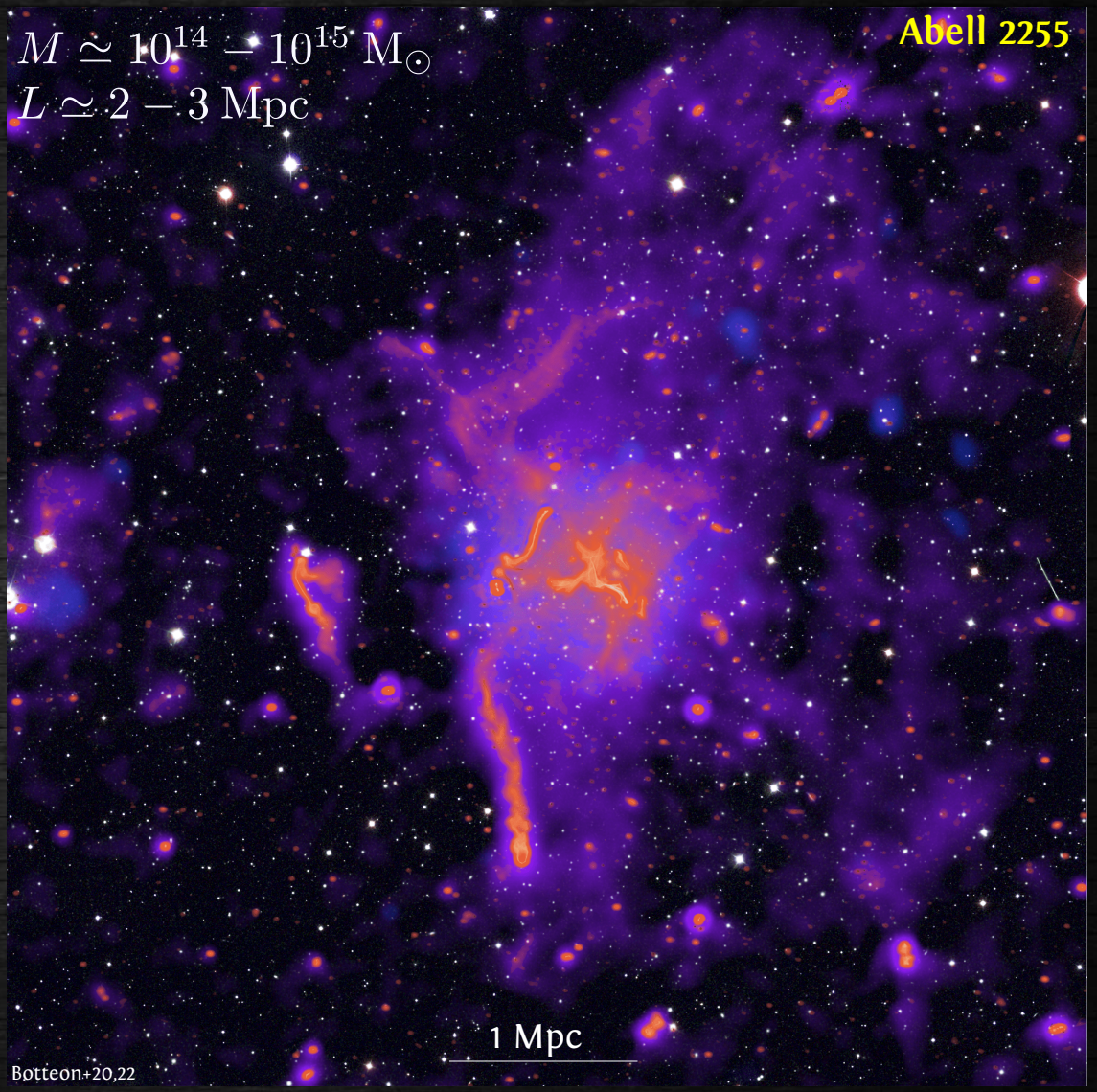
- Relativistic electrons (GeV) and magnetic fields (μG)
- Non-thermal synchrotron emission



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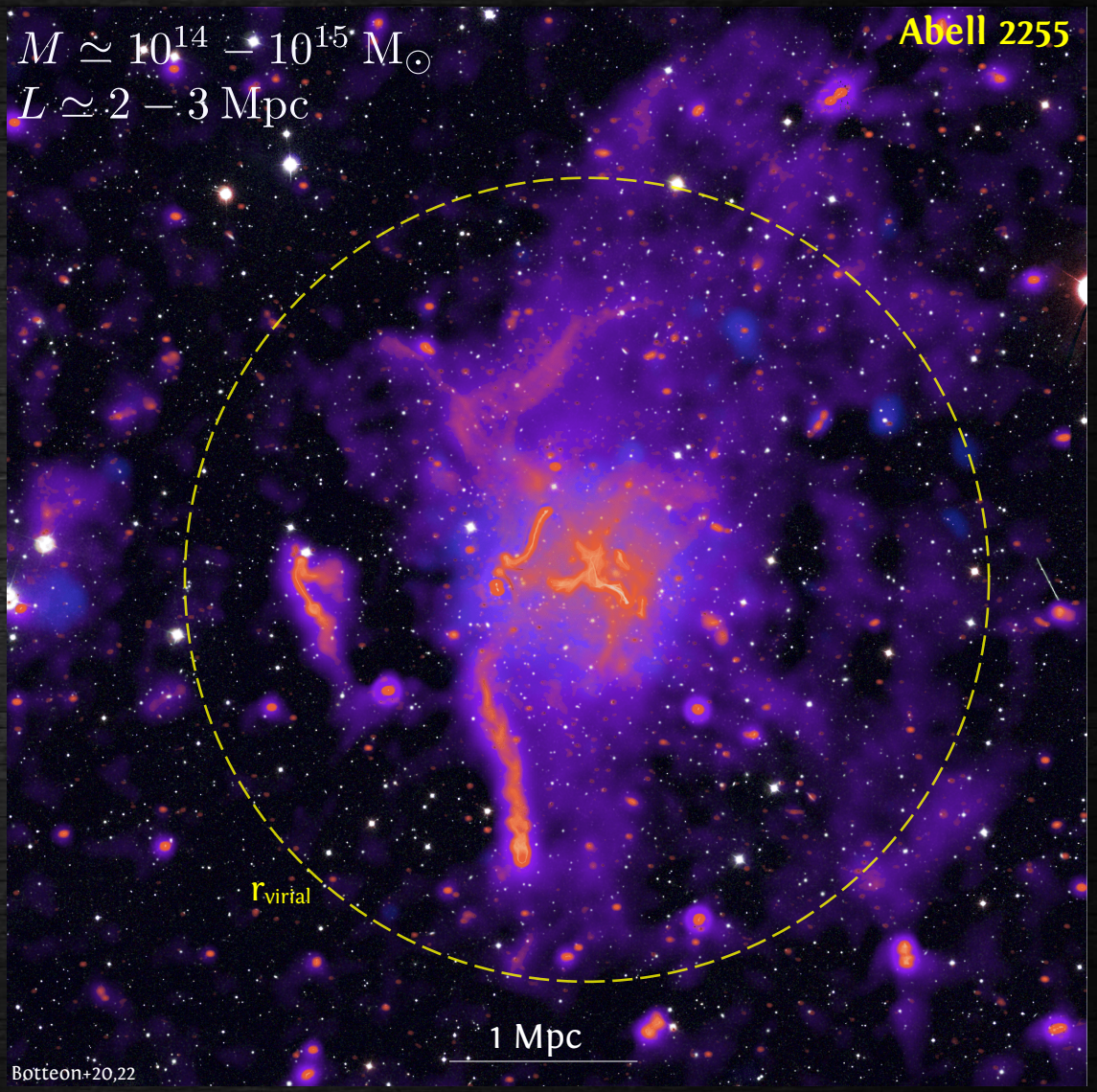

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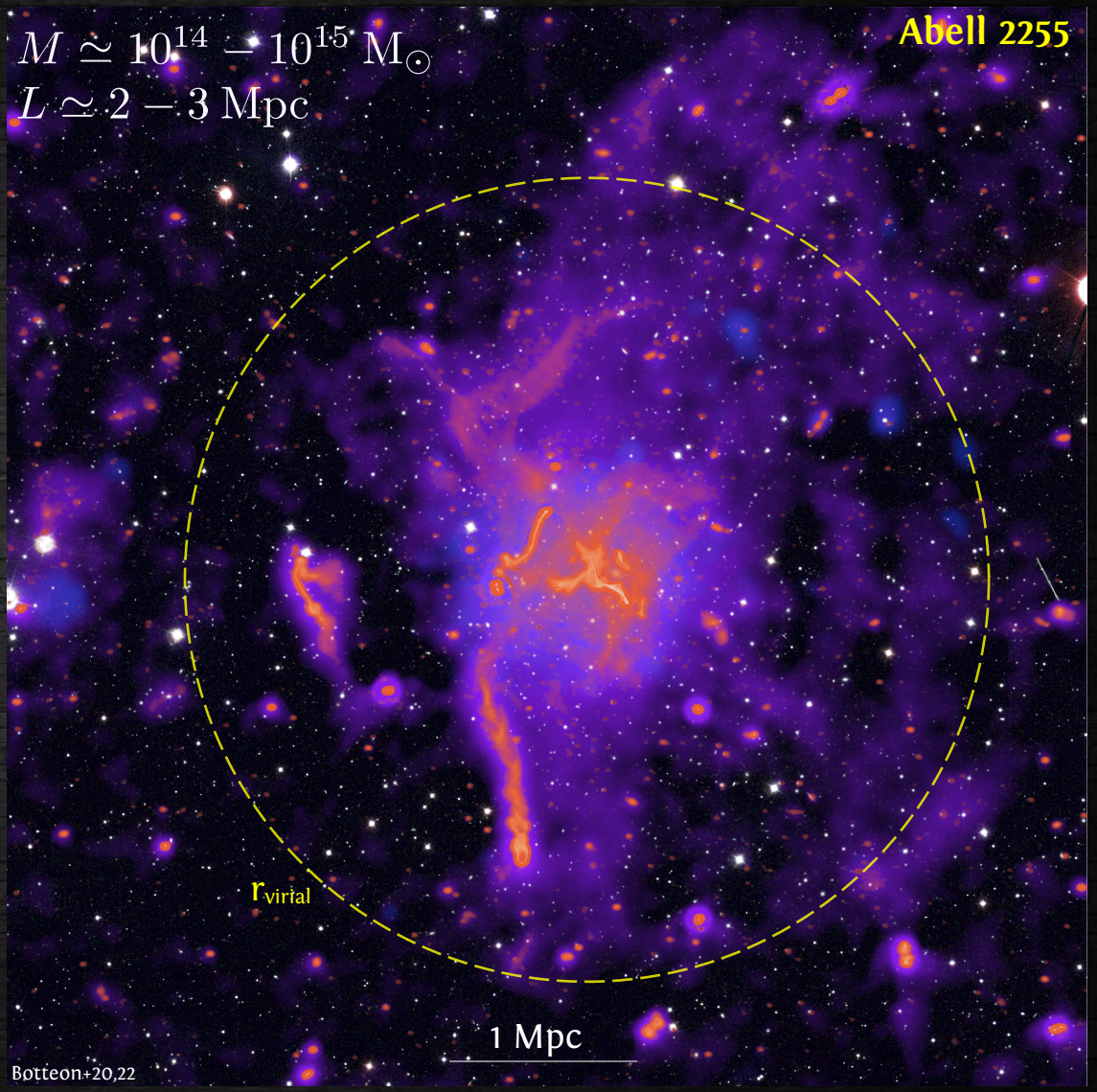
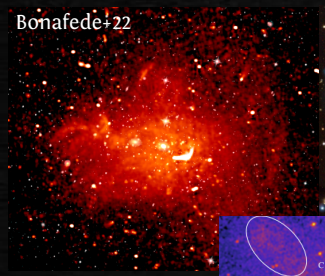
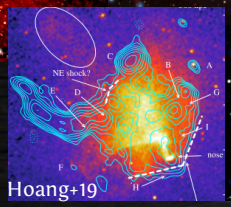


? *What is the origin of non-thermal components?*
? *What is their impact on the thermal ICM?* (microphysics & dynamics)

SKAO

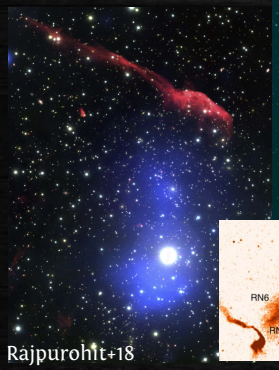
Diffuse cluster sources

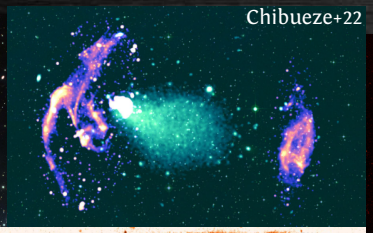


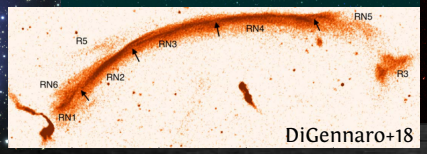


Radio halos:

- Cluster-scale, in the center
- Follow X-ray morphology
- Unpolarized
- Steep spectra (α~1.2-1.3 but also α>1.5)

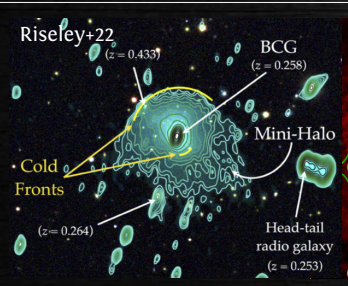


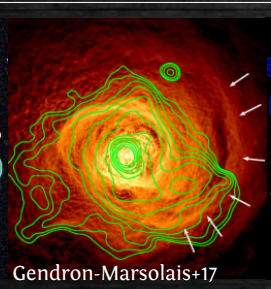


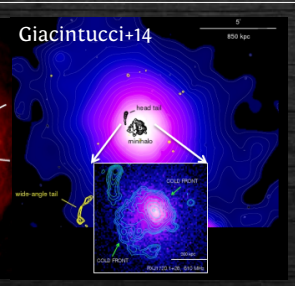


Radio relics:

- Cluster-scale, in the outskirts
- Elongated
- Polarized
- Steep spectra (α~1.0-1.3)
- Single and double relics







Radio mini-halos:

- 100-400 kpc in size, cluster centers
- Surround BCG
- Sharp surface brightness edges
- Steep spectra (α~1.0-1.5 and steeper)

Feretti+12, Brunetti+Jones14, vanWeeren+19 for reviews

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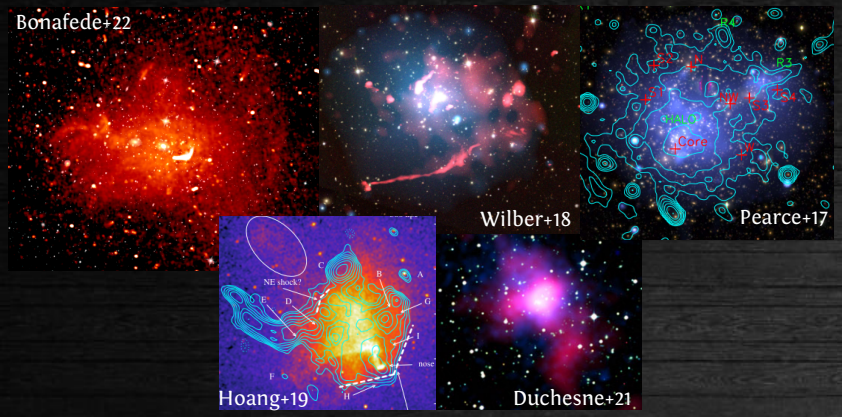

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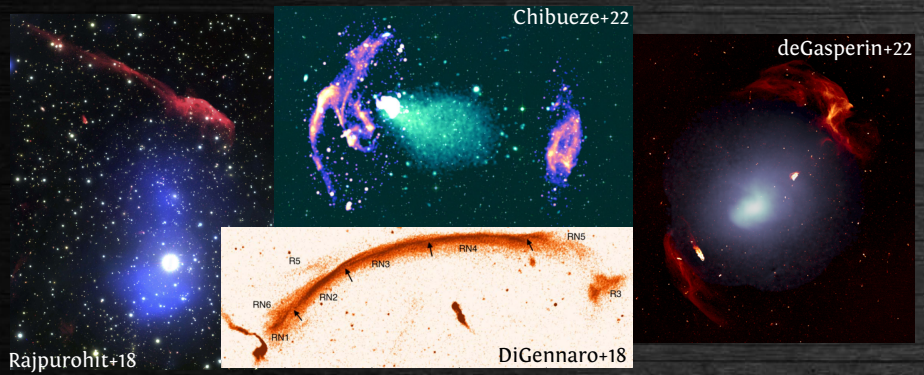

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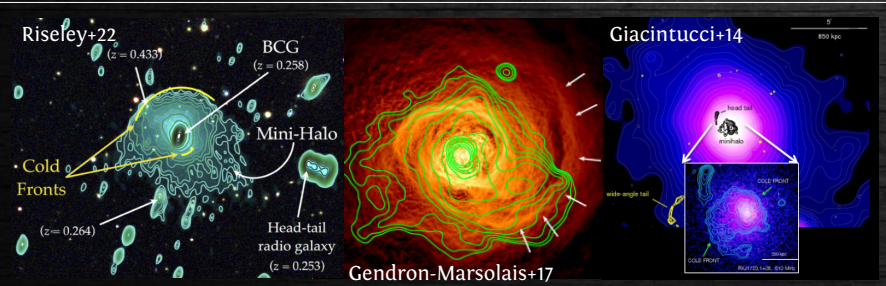

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Diffusion problem (e.g. Jaffe77)

$\tau_{\rm diff}(\sim 10\,{\rm Gyr}) \gg \tau_{\rm rad}(\sim 0.1\,{\rm Gyr})$ $\longrightarrow$ Emitting particle must be generated *"in situ"*

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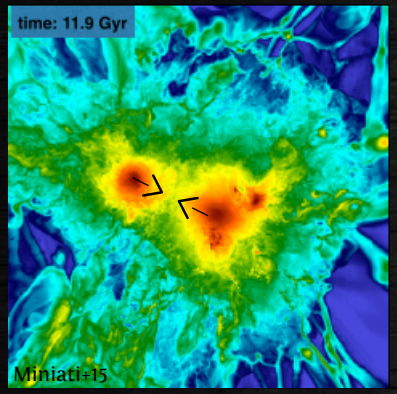
Origin of halos and relics

Observational milestones:

- *halos* and *relics* are **not ubiquitous** in galaxy clusters
- clusters hosting *halos* and *relics* are **merging** systems

The generation of **giant** diffuse cluster sources is linked to the *formation process* (mass growth) of galaxy clusters



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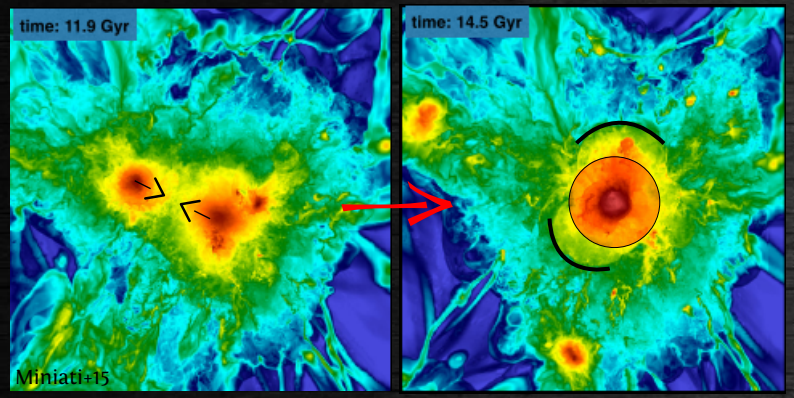

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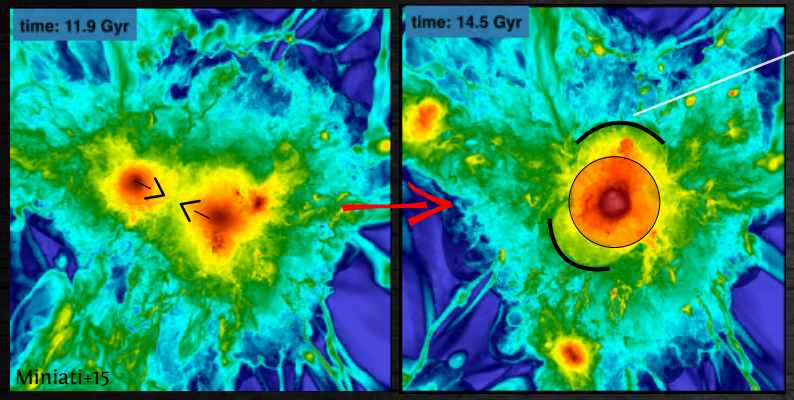

Shocks:

accelerate relativistic particles (Fermi I)

CRe → **Radio relics**

CRp → π^0 decay → gamma-rays (not detected)

→ $\pi^{\pm}$ decay → secondary $e^{\pm}$

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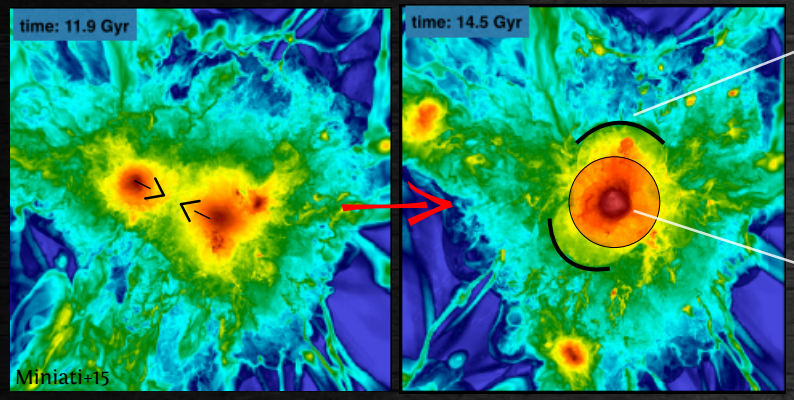

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accelerate seed CRe & secondary $e^{\pm}$ (Fermi II) → **Radio halos**
dynamo amplification of B

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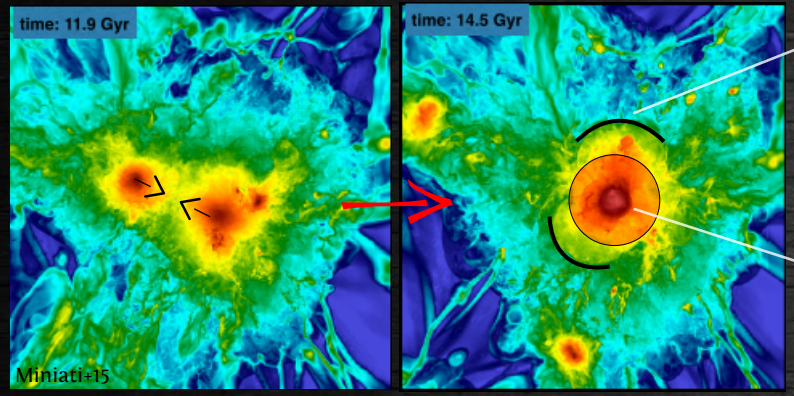

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Halos:

✔ Ultra steep spectrum radio halos (USSRH) (Brunetti+08)
✔ High-frequency spectral steepening (Thierbach+03)
✔ More common/powerful in massive clusters (Cassano+13)
✔ Pure hadronic models discarded (Brunetti+17)

? *What is the role of secondary electrons?*
? *What are the composition and origin of seed particles?*
? *How does turbulence cascade to particle-scale?*

Relics:

✔ Co-location with (weak) shocks (Finoguenov+09)
✔ Head-on collisions generate double relics (Roettiger+97)
✔ Radial spectral steepening (aging) (vanWeeren+10)
✔ DSA of thermal electrons ruled out (Botteon+20)

? *What is the role of seed electrons?*
? *What is the magnetic field strength in cluster outskirts?*
? *Where are the CRp?*

Origin of mini-halos

Observational milestones:

- *mini-halos* are **not ubiquitous** in galaxy clusters
- clusters hosting *mini-halos* are somehow **relaxed** systems

Mini-halos *are not* associated with **energetic** merging events! Need processes that can *preserve* the cool core

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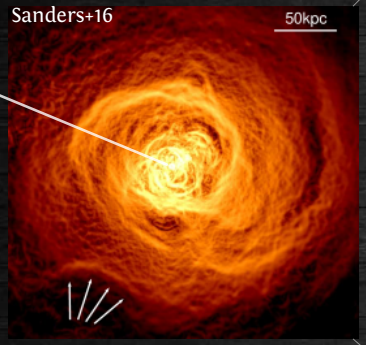
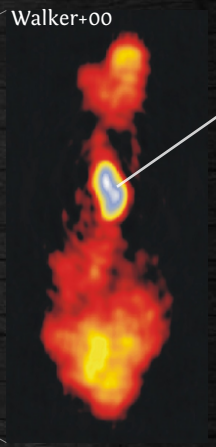
Sloshing:
cold fronts
turbulence





AGN:
turbulence
shocks
CRp+CRe

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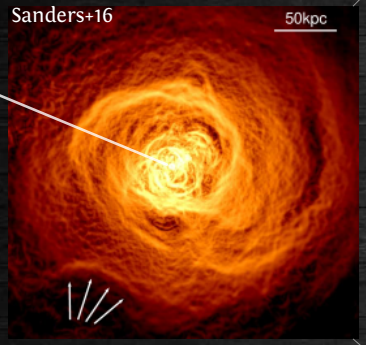

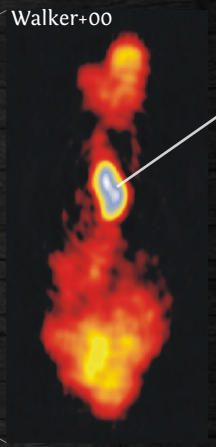

AGN:
turbulence
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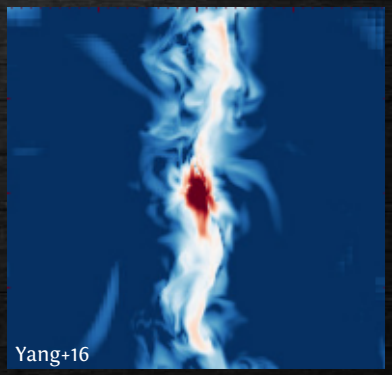
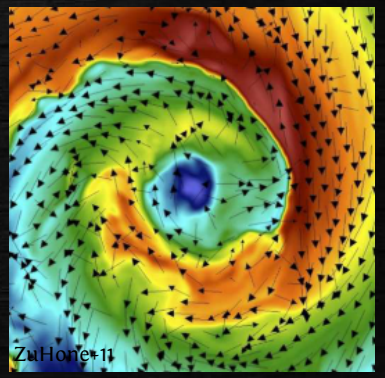
Mini-halos:

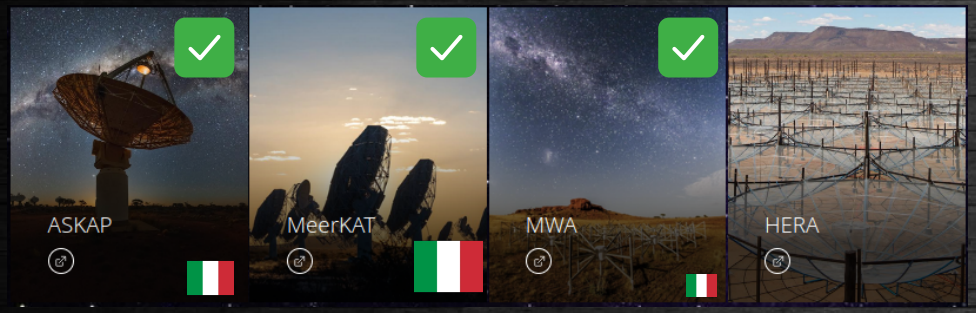
✔ Quite common in massive and cool-core clusters (Giacintucci+17)
✔ Connection with central AGN (Richard-Laferriere+20)
✔ Connection with sloshing cold fronts (Mazzotta+Giacintucci07)

❓ *What is the role of secondary electrons?*
❓ *What is the source of turbulence?* (AGN vs minor/off-axis merger)

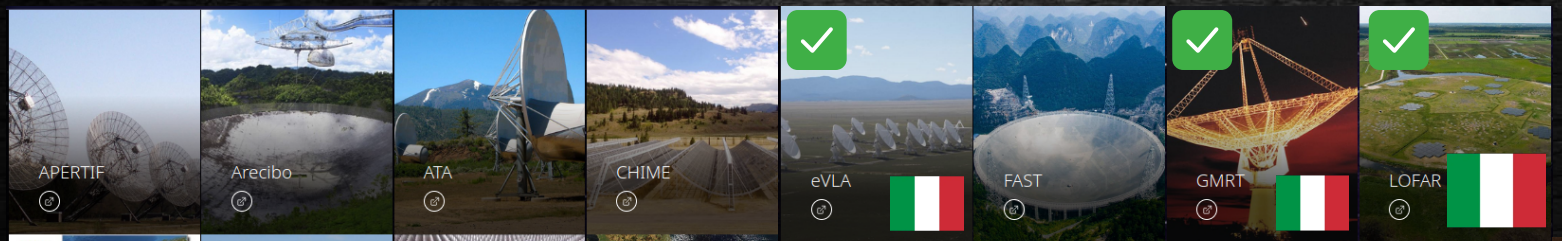


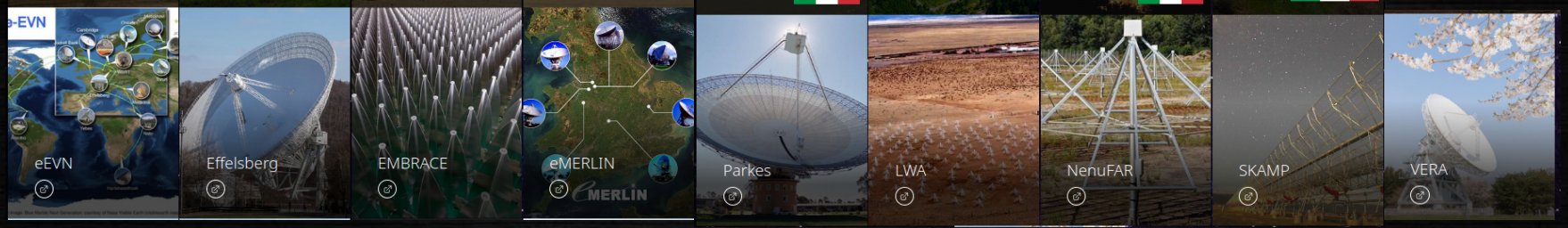


SKA precursors and pathfinders



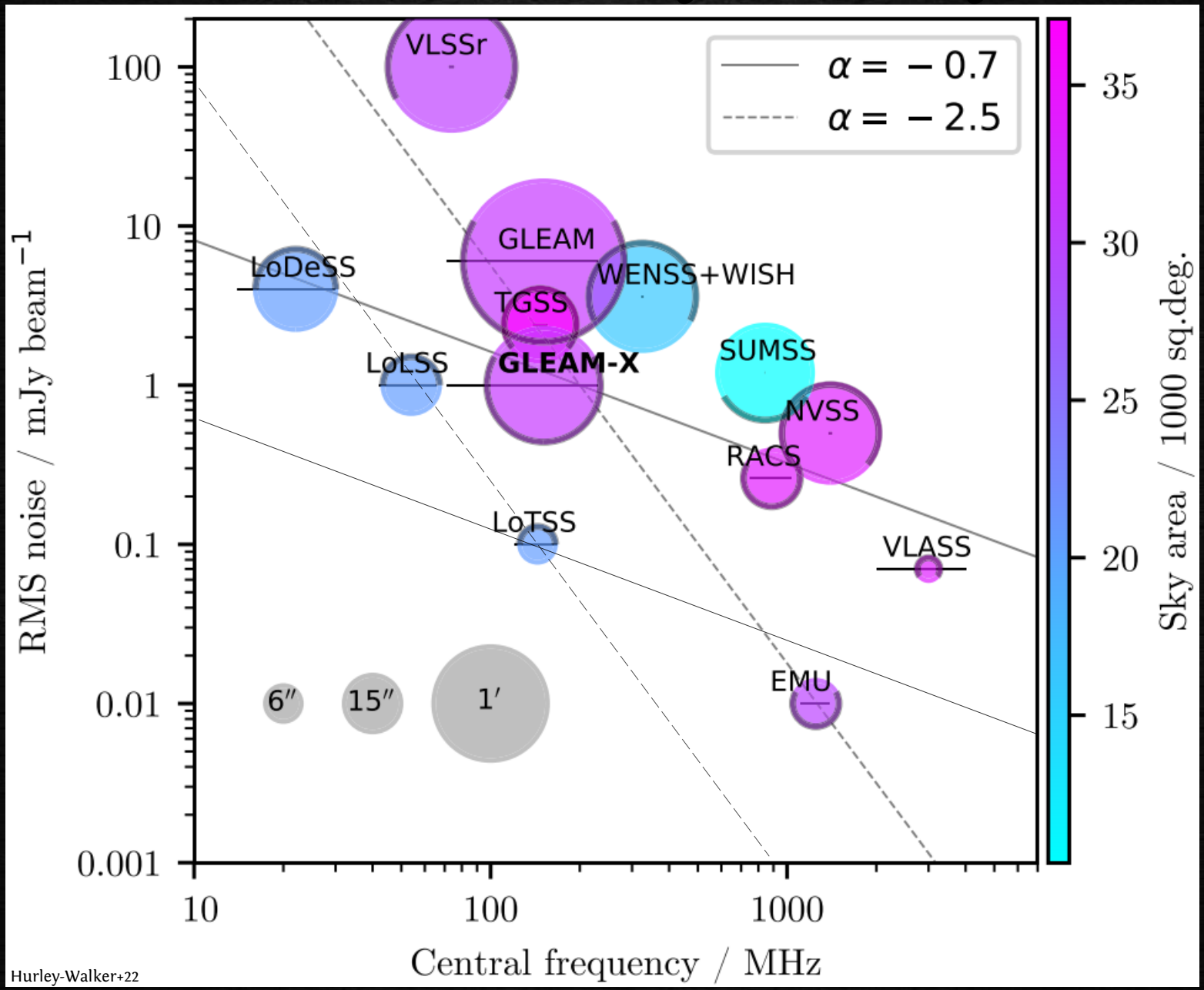
Precursors





Pathfinders

Wide-area sky surveys



Hurley-Walker+22

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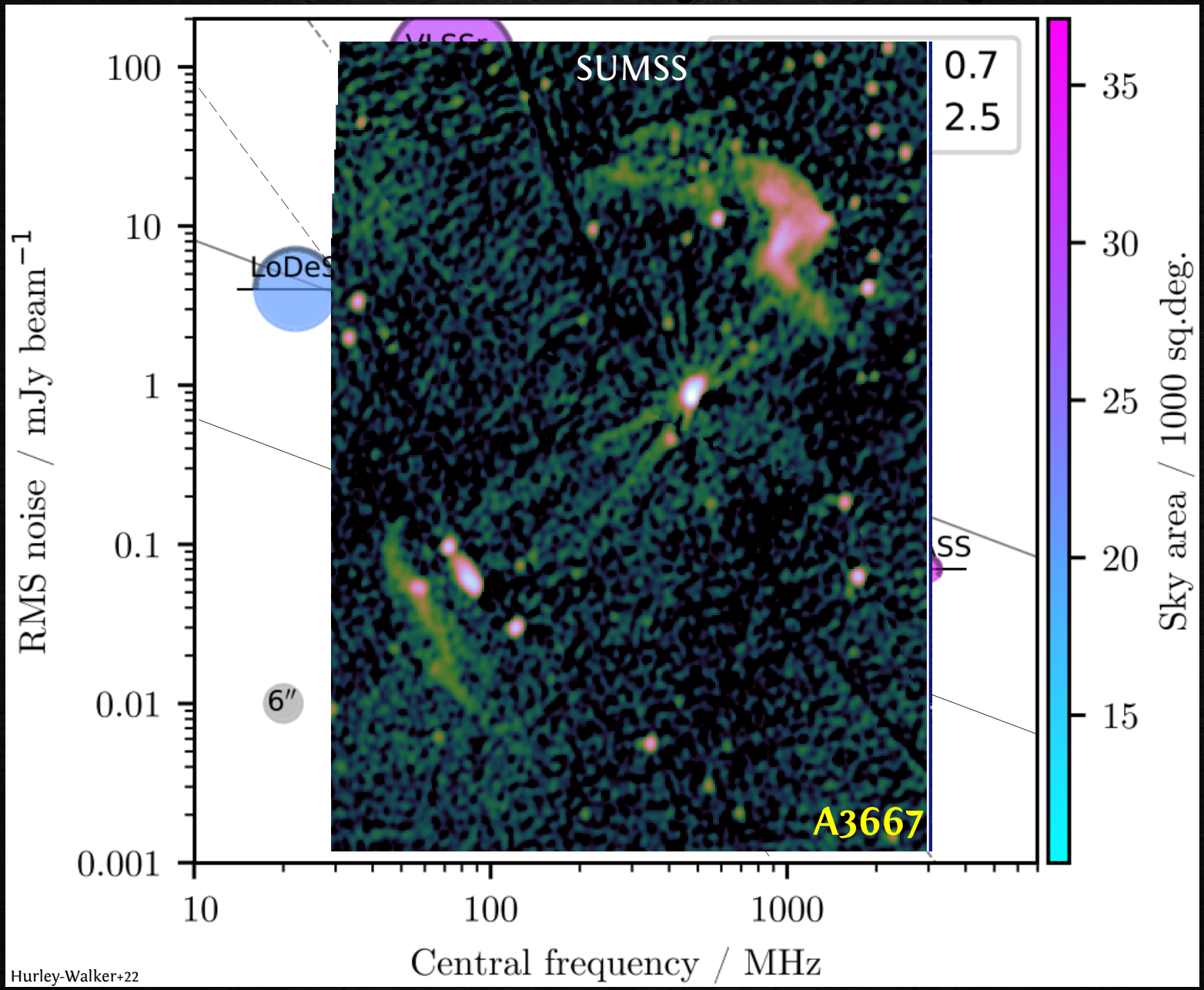

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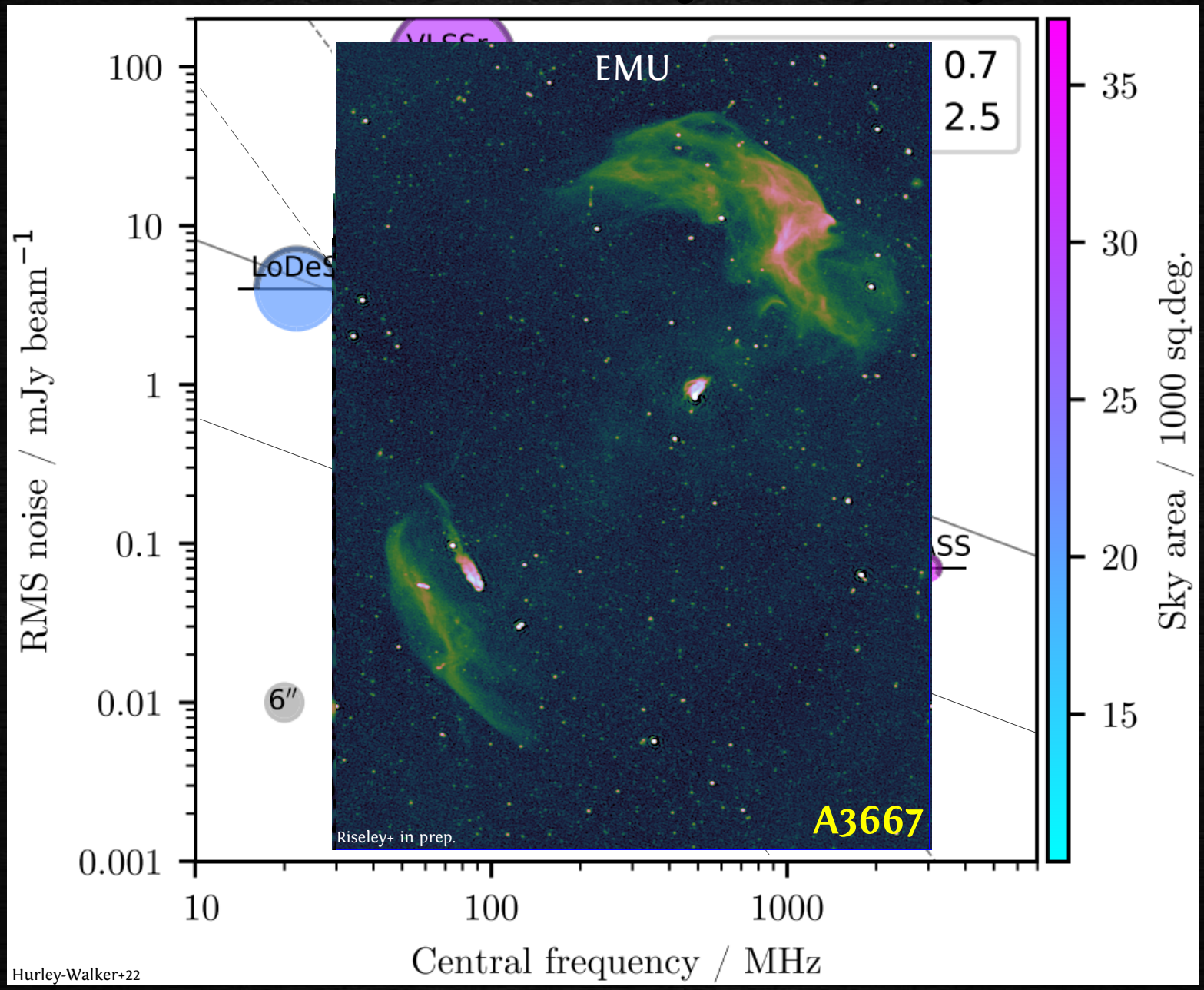
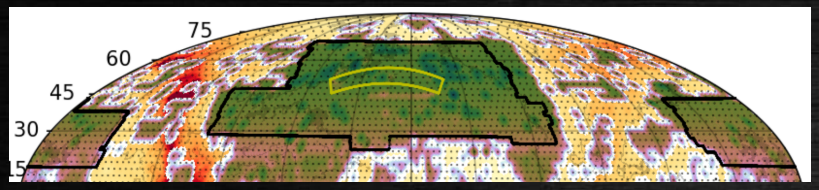


Large statistical samples



LOFAR

LoTSS-DR2, 5634 deg^2, **309** PSZ2 clusters

(Botteon+22)

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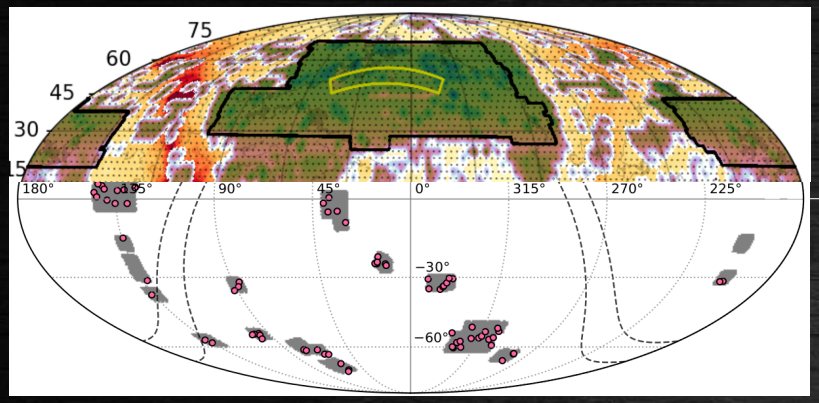

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ASKAP

EMU, 1990 deg^2, **71** PSZ2 clusters

(Duchesne+ sub.)

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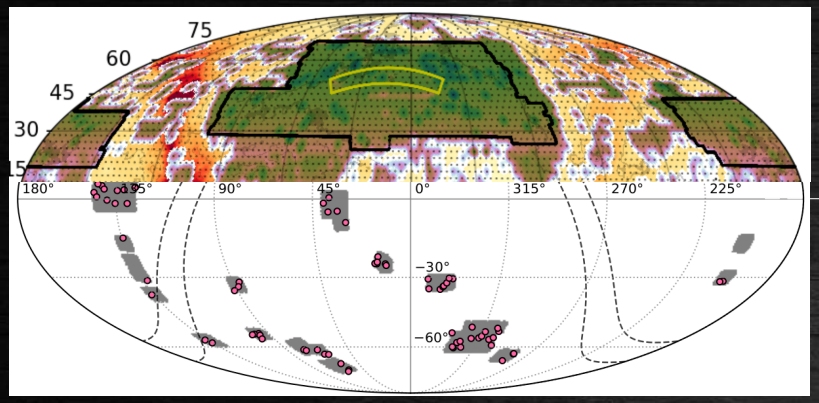

LOFAR

LoTSS-DR2, 5634 deg², **309** PSZ2 clusters
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EMU, 1990 deg², **71** PSZ2 clusters
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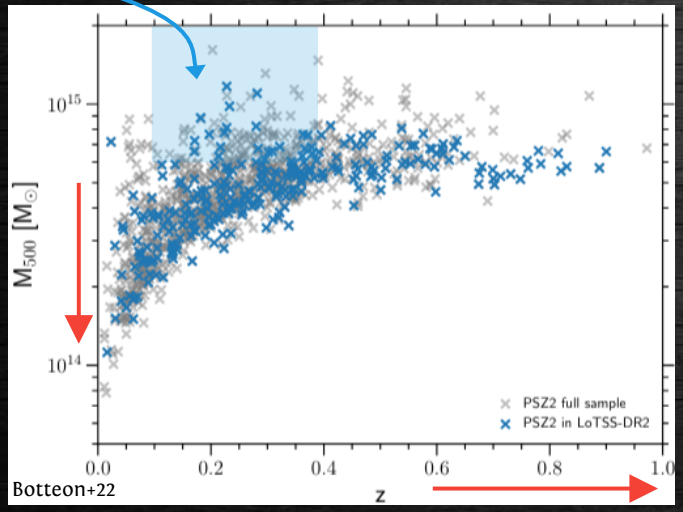
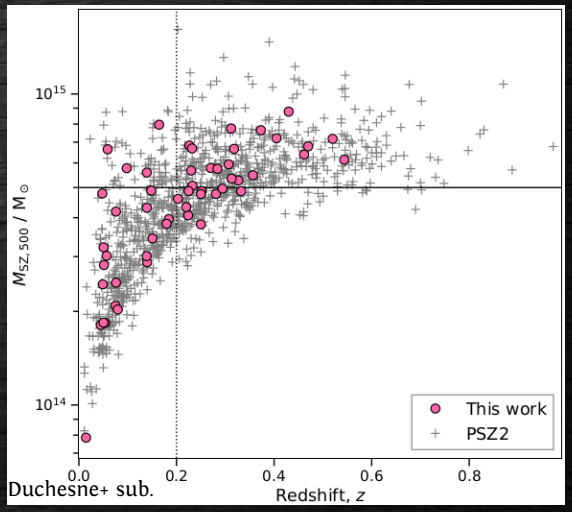
Planck provides a *mass-selected* cluster sample

Previous studies





The Planck clusters in the LOFAR sky
(6 papers in A&A)

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

Highlights

LoTSS-DR2 (Botteon+22): **83** halos, **26** relics
EMU (Duchesne+ sub.): **21** halos, **11** relics

About *half* are **new**

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→ All *LoTSS*+*EMU*: ~**500** halos, ~**160** relics

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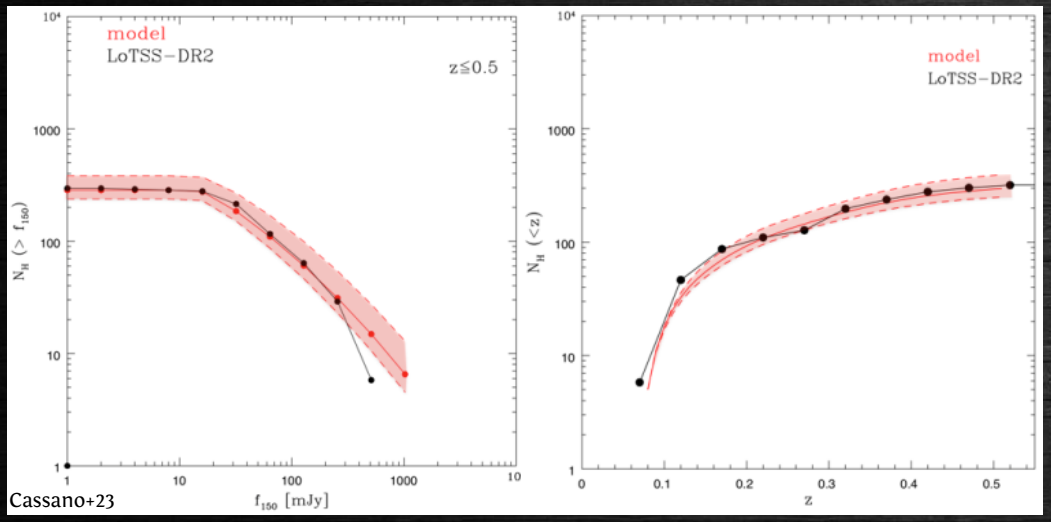
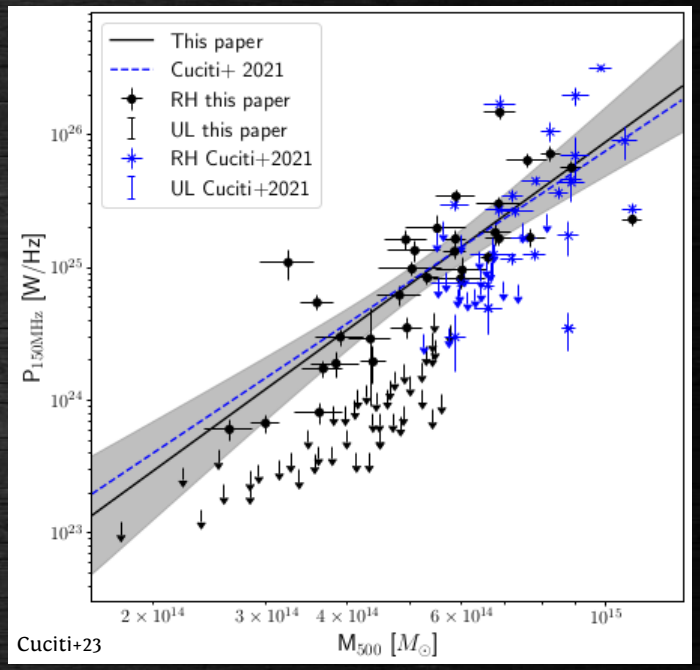


Cassano+23



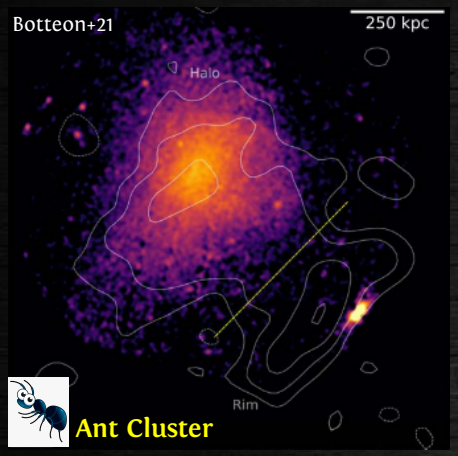
Cuciti+23

- Number, flux density, and z distribution of **halos** OK with *turbulent re-acceleration* models
- Ongoing: tests on spectral properties using *LoLSS*, *uGMRT*, and *MeerKAT*

- P-M relation at *low*-frequency
- *Wider* range of mass probed
- Scatter related to cluster **disturbance**

Low-mass and high-z radio halos

Low-mass →
$M_{500} < 2e14\ M_{\odot}$



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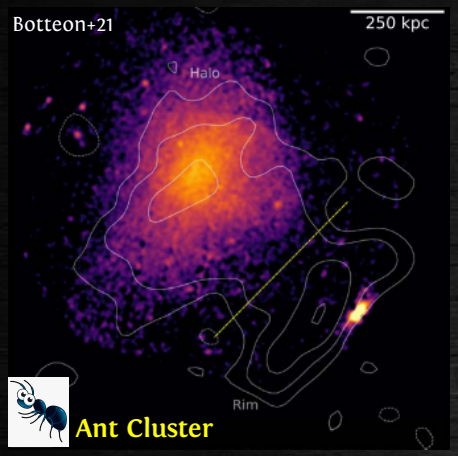

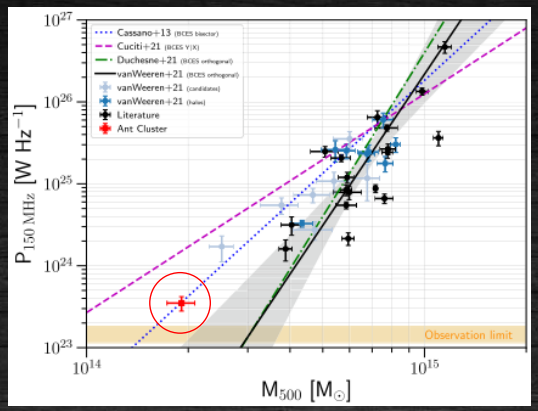

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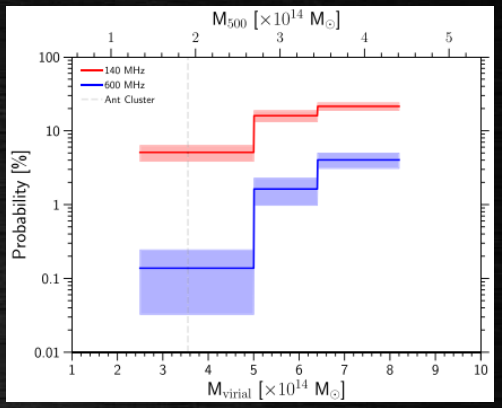

- Crucial test for turbulent *re-acceleration* models

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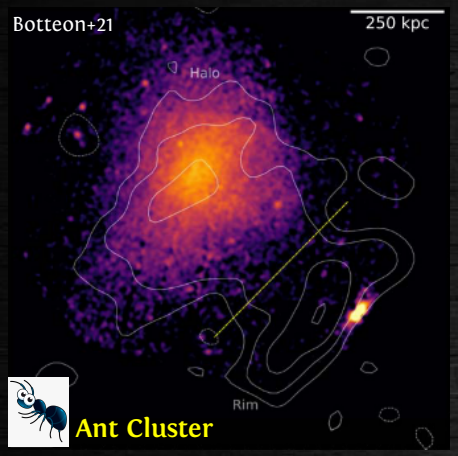

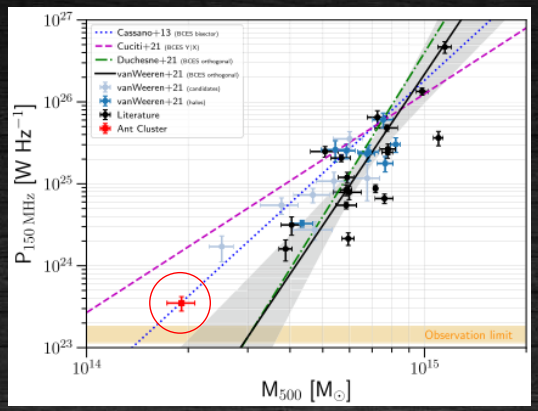

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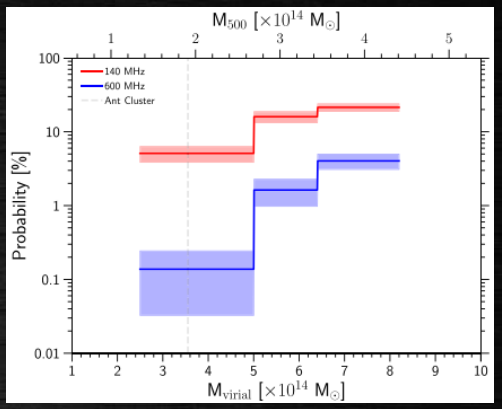
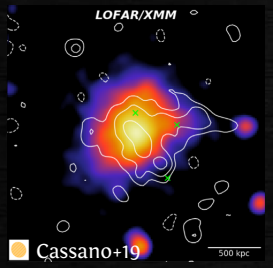
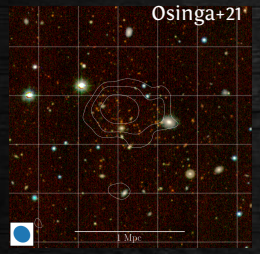
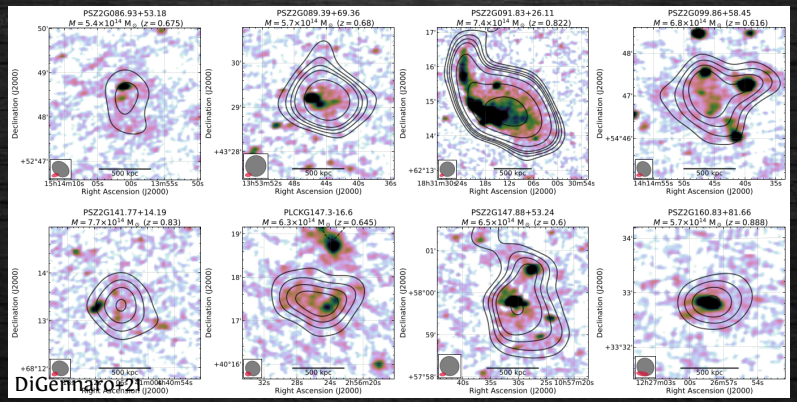


- Crucial test for turbulent *re-acceleration* models

High-redshift → z › 0.6







$$\frac{d\gamma}{dt} \propto -\left(B_{\rm cmb}^2 + B^2\right)\gamma^2$$

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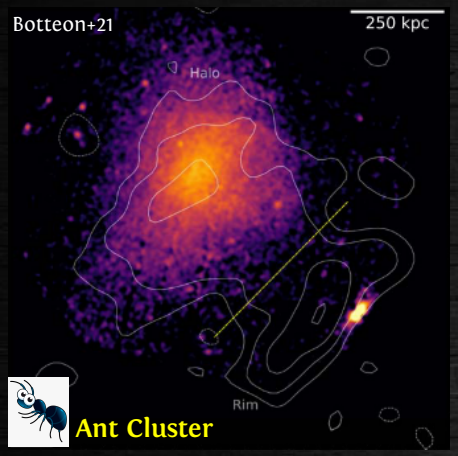

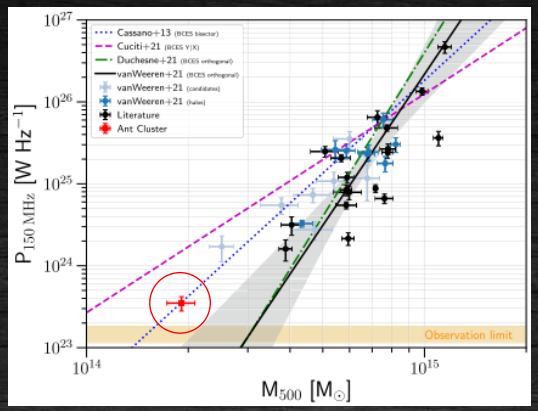

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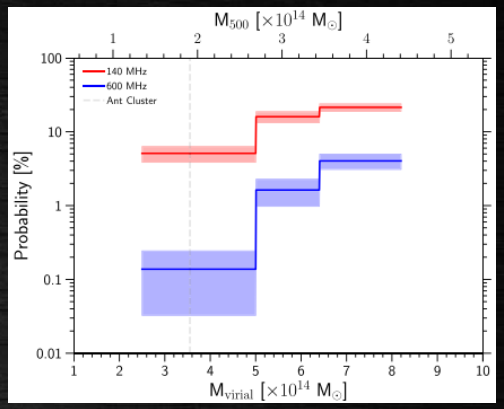

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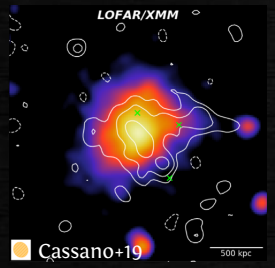

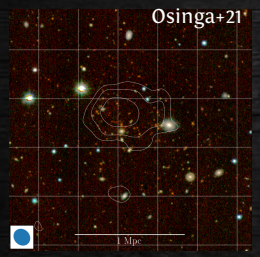

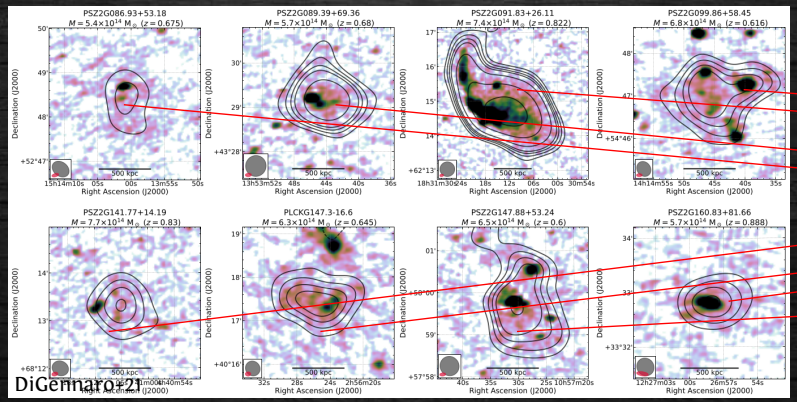

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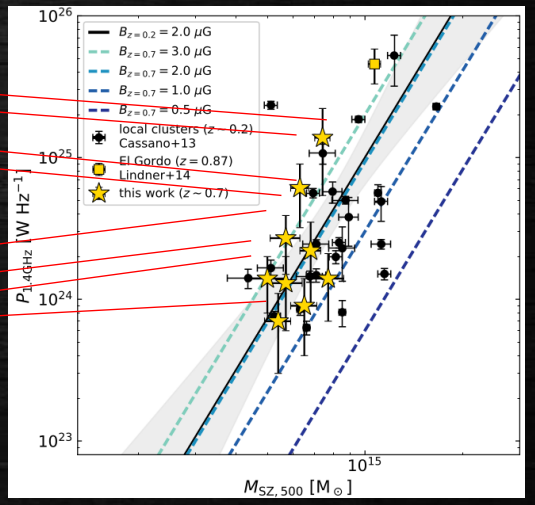

Fast magnetic field amplification in *distant* galaxy clusters

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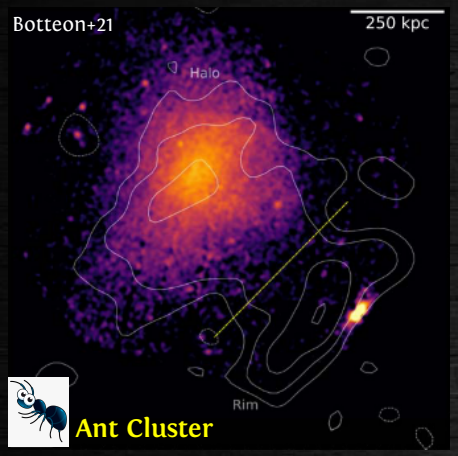

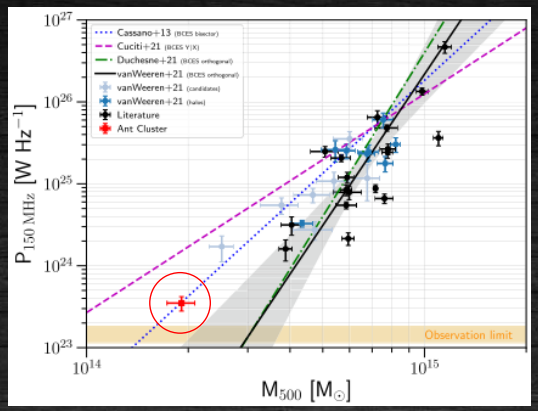

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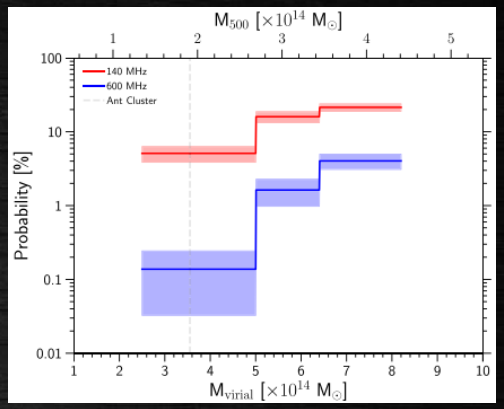

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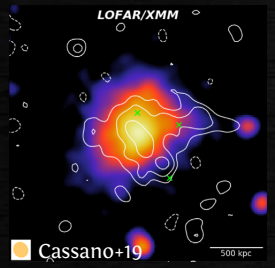

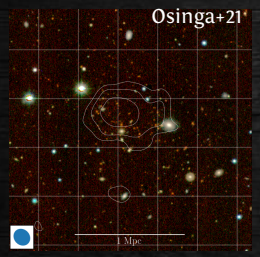

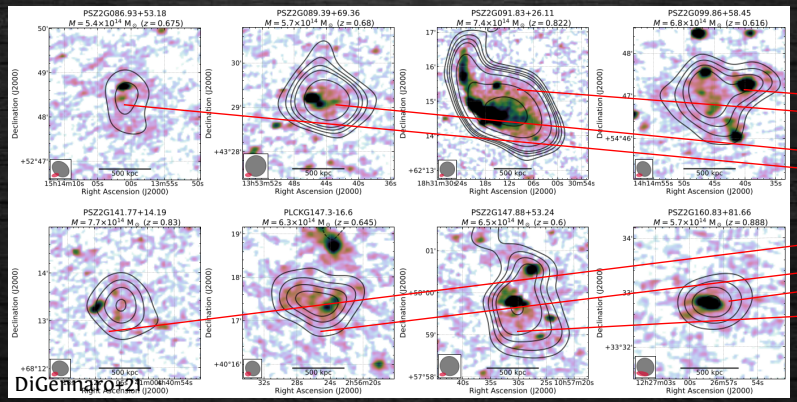

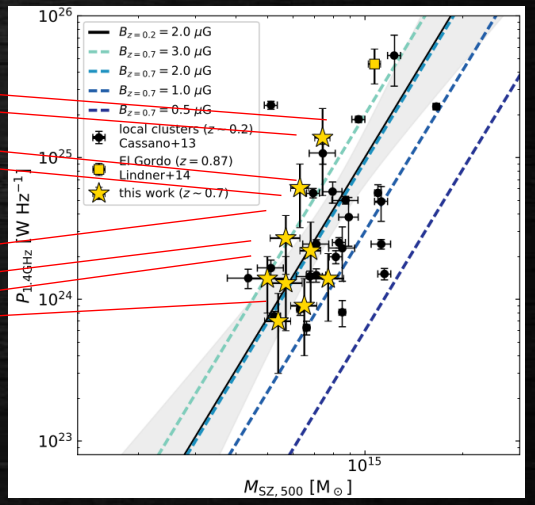

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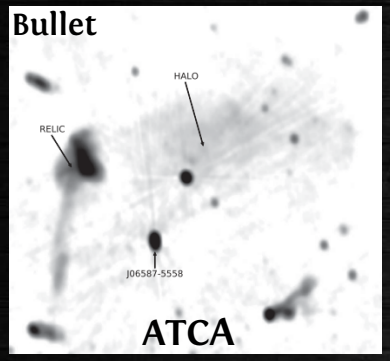
Fast magnetic field amplification in *distant* galaxy clusters

- *How low can we go in mass?*
- *How far can we go in redshift?*

Halos & relics (sub)structures

We can now recover extended emission at *high resolution*



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→ not true anymore

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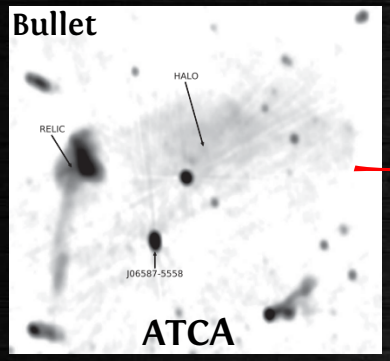

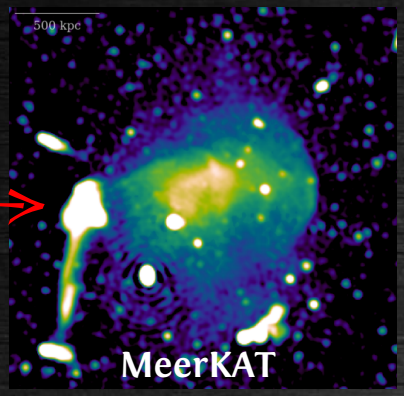

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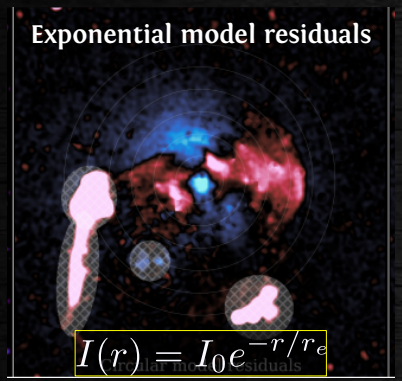

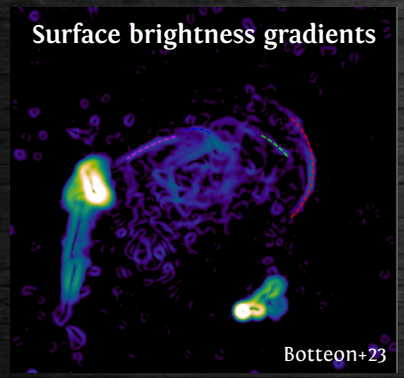

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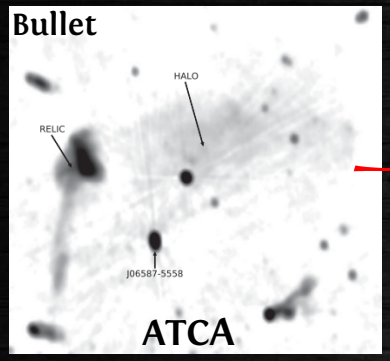

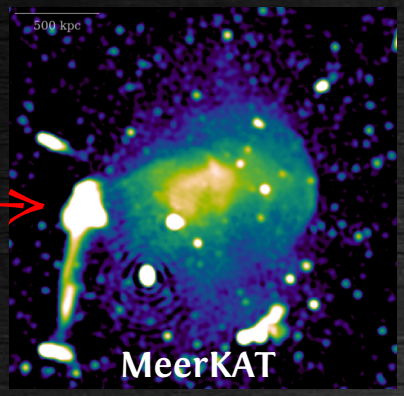

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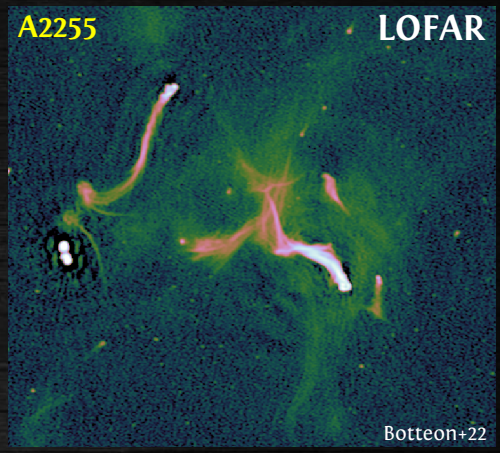

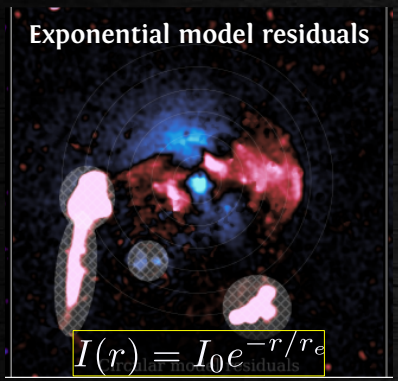

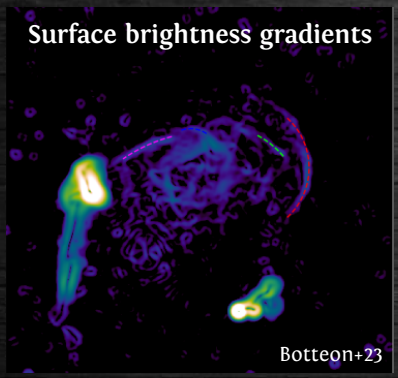

Halos are actually rich of **substructure**, including prominent surface brightness *edges* and *filamentary* structures

Halos & relics (sub)structures

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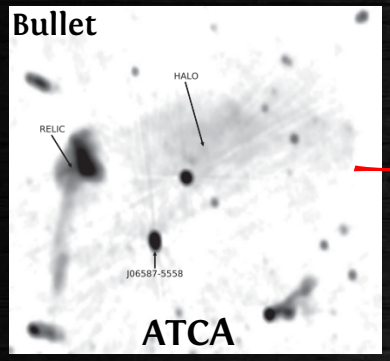

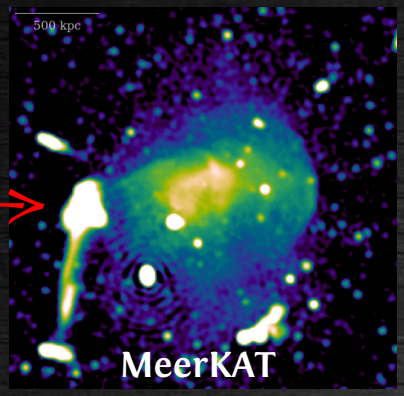

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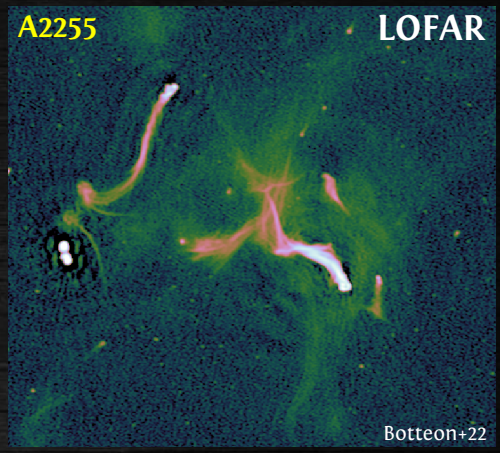
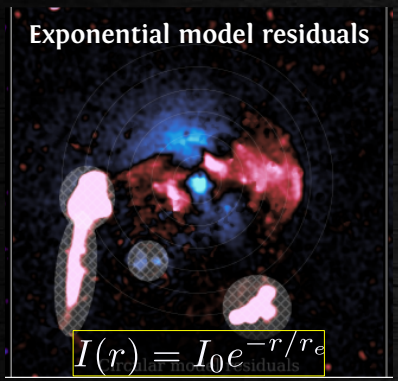
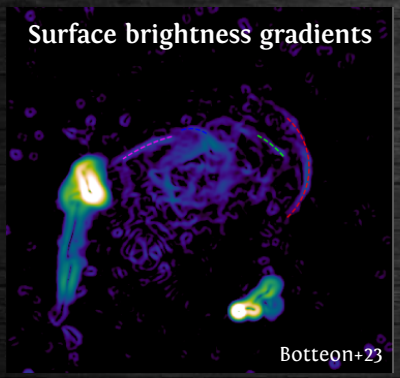
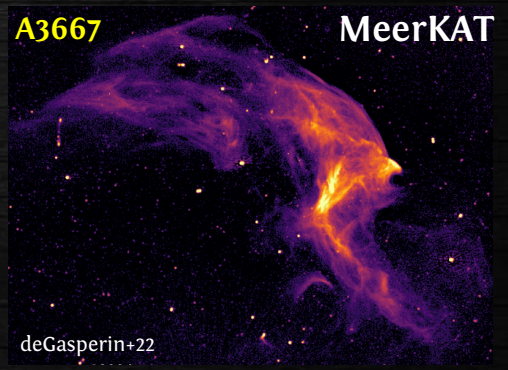






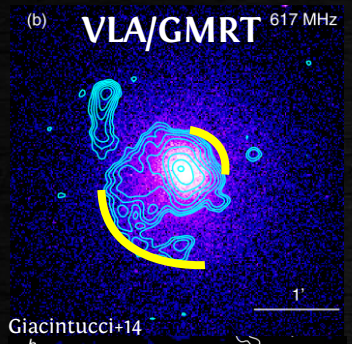
Halos are actually rich of **substructure**, including prominent surface brightness *edges* and *filamentary* structures

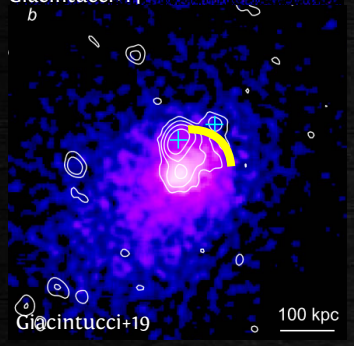
Radio relics?
Full of *filaments*!

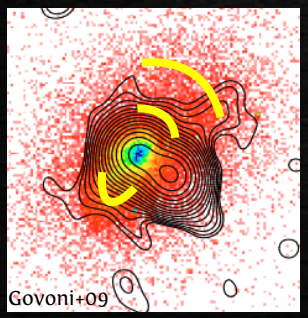


❓ *What is their connection with particle acceleration and magnetic field amplification mechanisms?*

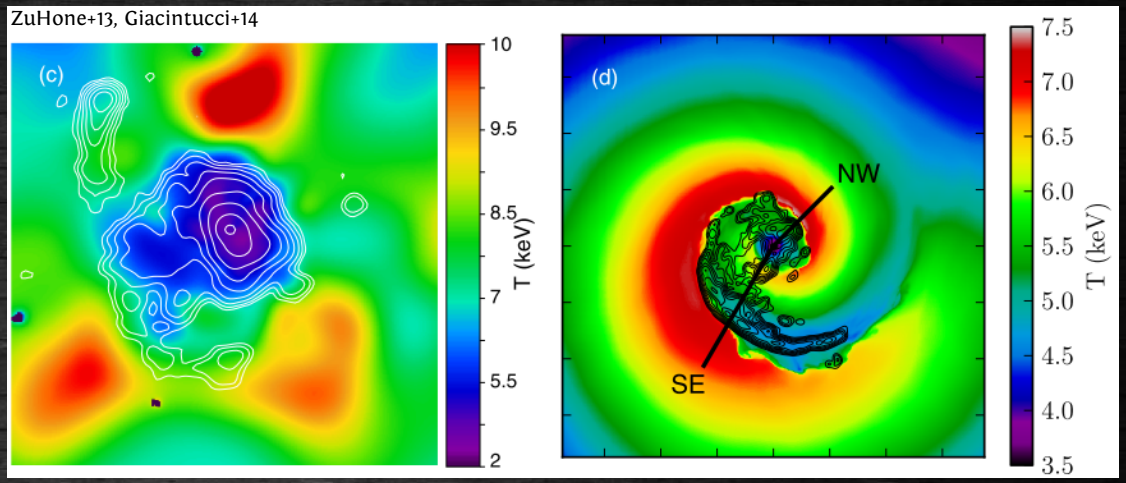
Mini(?) halos







Confinement of **mini-halos** in sloshing *cold fronts*



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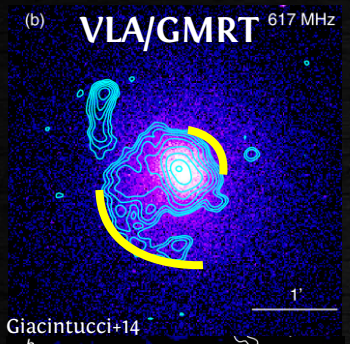
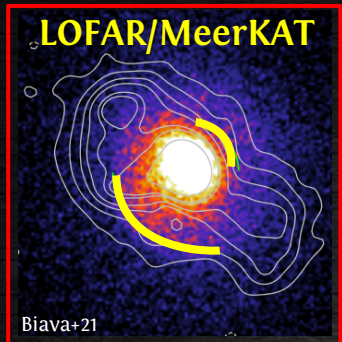
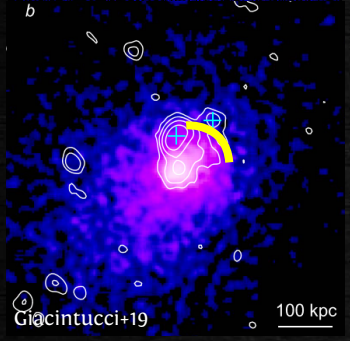
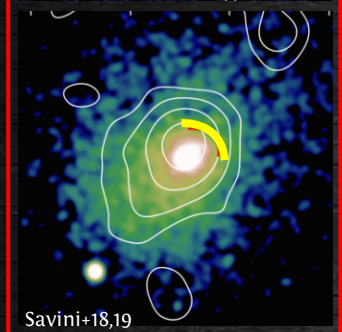
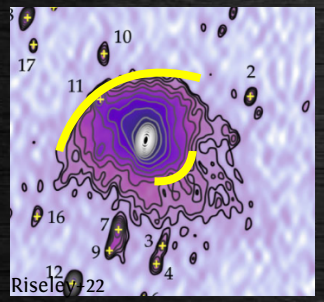
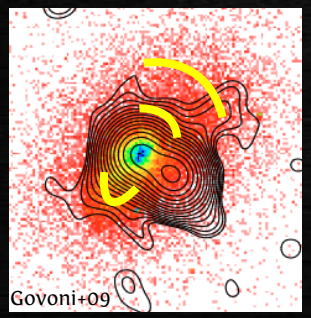


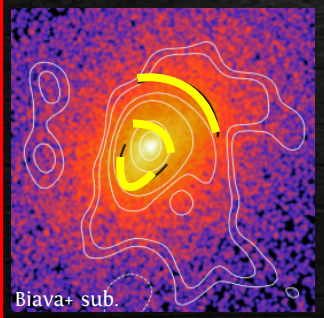




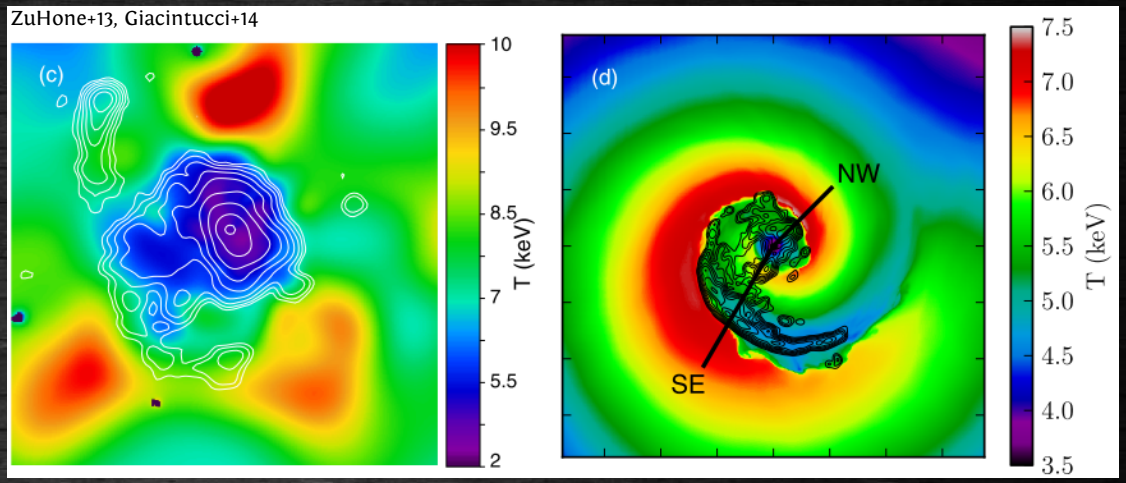








Confinement of **mini-halos** in sloshing *cold fronts*



Some **mini-halos** are surrounded by *steep spectrum* emission

- ? *Two components with different origin?*
- ? *Low levels of turbulence outside the central region?*

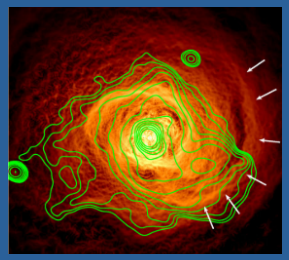
Re-defining giant & mini halos?

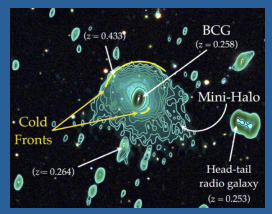
Mini-halos

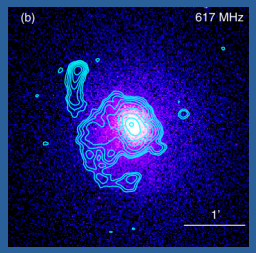
Giant halos

Re-defining giant & mini halos?

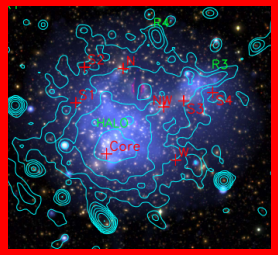
Mini-halos

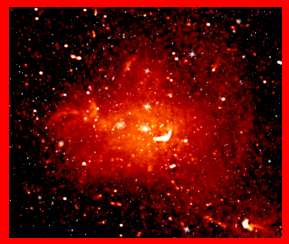






Giant halos





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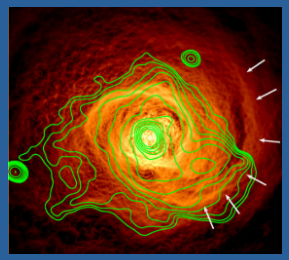
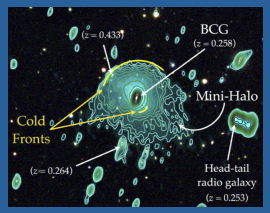
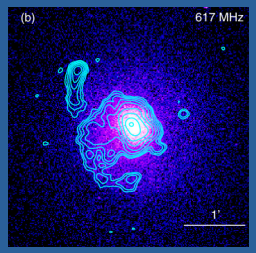
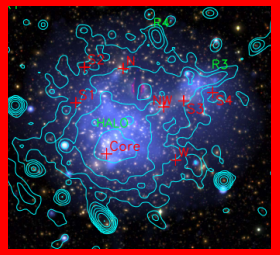


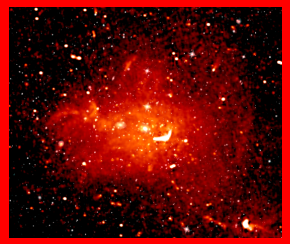




The prototypical “mini” halo is **~1 Mpc** in size

Giant halos





“Giant” halos in low-mass clusters are **~500 kpc** in size

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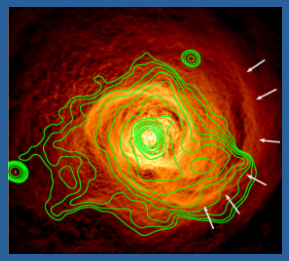
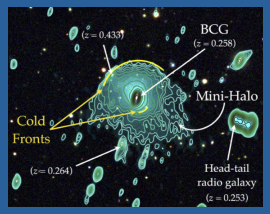
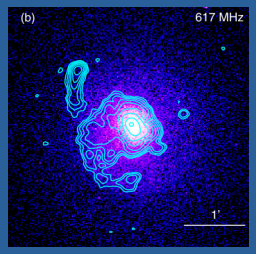
Mini-halos







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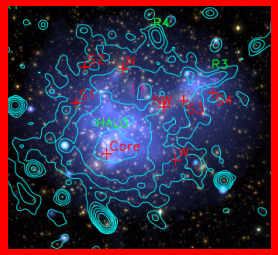

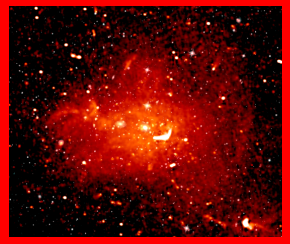

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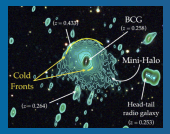

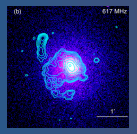

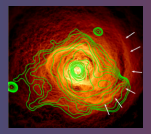

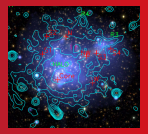

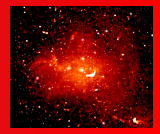

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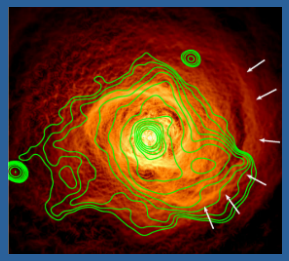

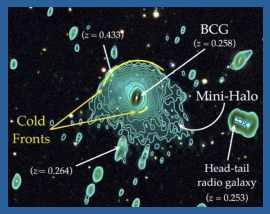

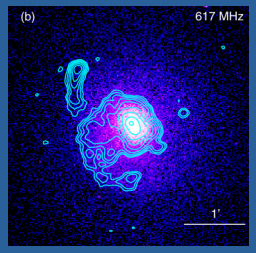

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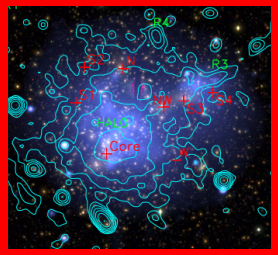

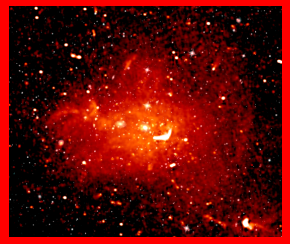

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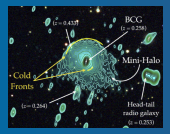
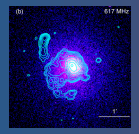
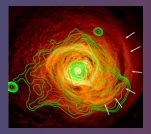
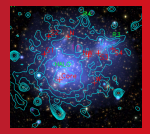
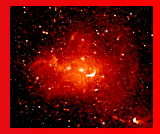










galaxies

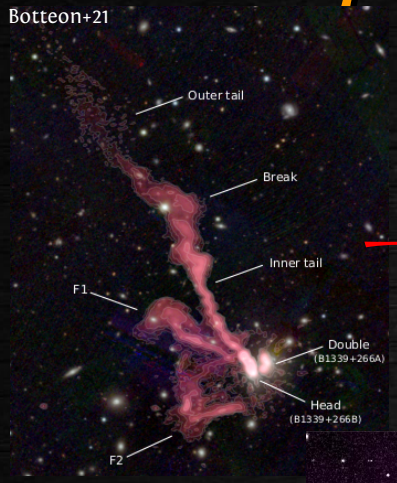
Article

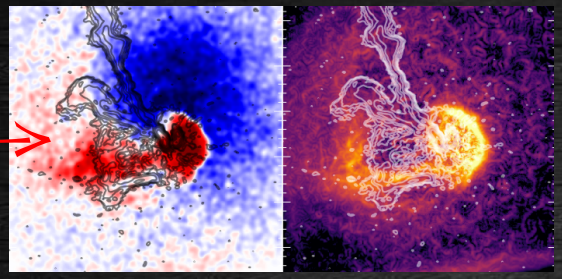
Radio Galaxy Classification: #Tags, Not Boxes

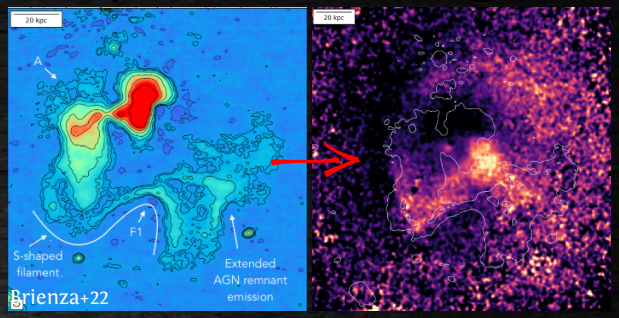
Lawrence Rudnick

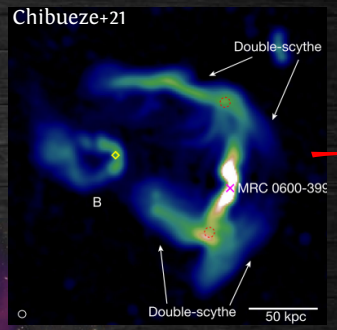
Instead of trying to place them into “boxes”, we should assign them #tags, a system that is easy to understand and apply, that is flexible and evolving, and that can accommodate conflicting ideas with respect to what is relevant and important.

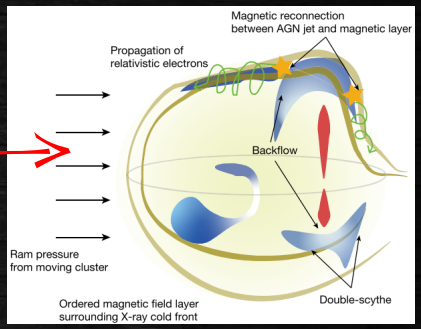
AGN/ICM interaction (seeding)

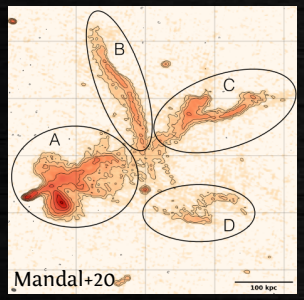


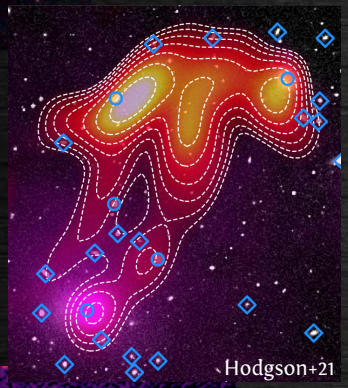


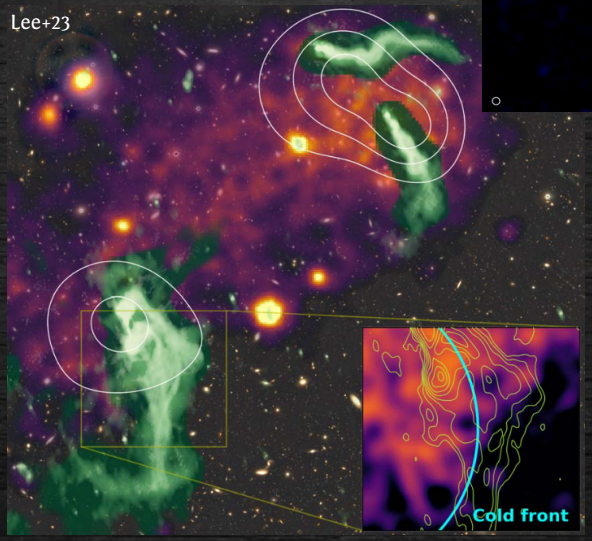


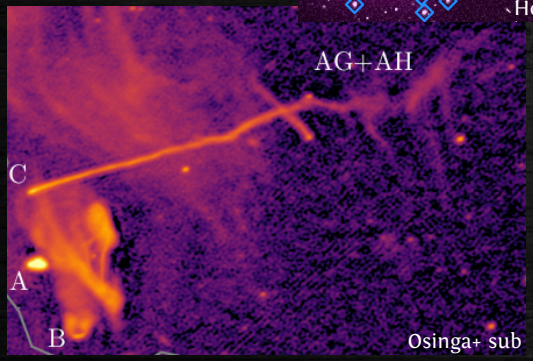


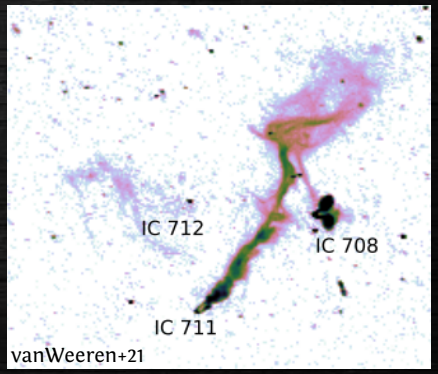








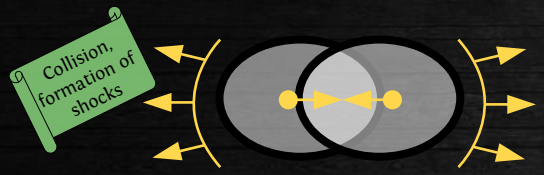


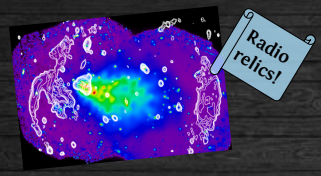


Complex interactions between *non-thermal components* and *ICM motions*
→ transport of **seeds** and **B**

Beyond clusters

- **Relics** are found in the cluster *outskirts*
  (vanWeeren+10, Bagchi+11, Bonafede+14,22, Hoang+21, Riseley+22, Jones+23)





- **Halos** have extensions of 2 Mpc and *beyond*
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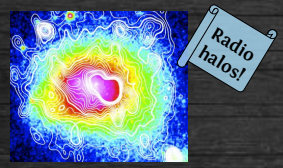

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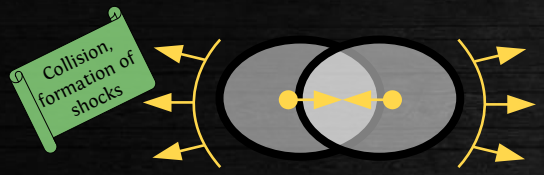

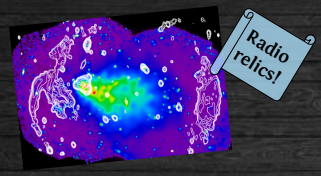

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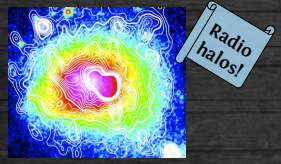

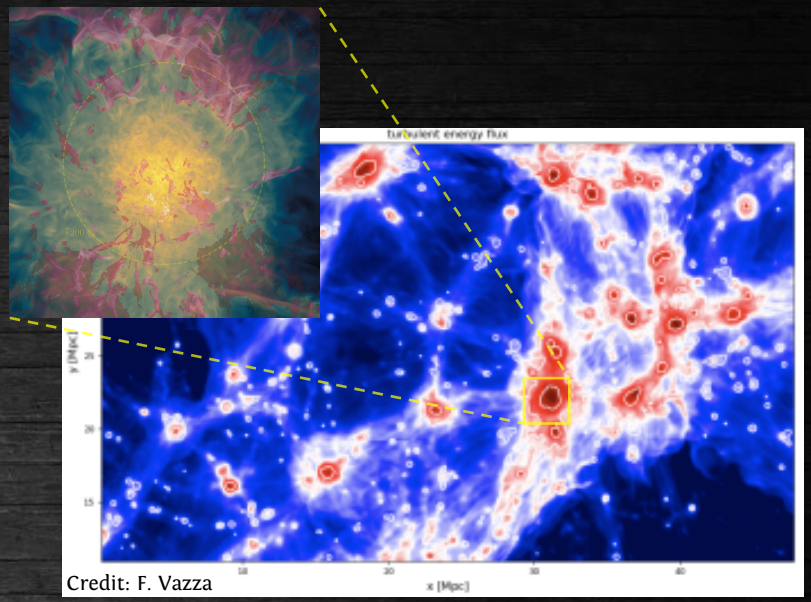

Probing particle acceleration at *large distances* from the cluster center

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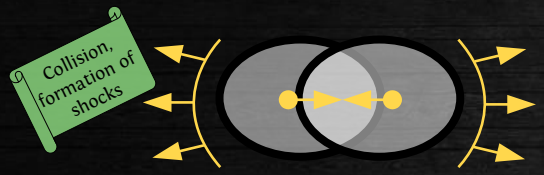

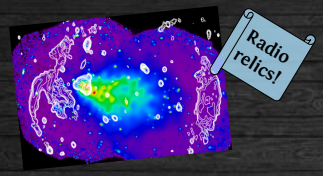

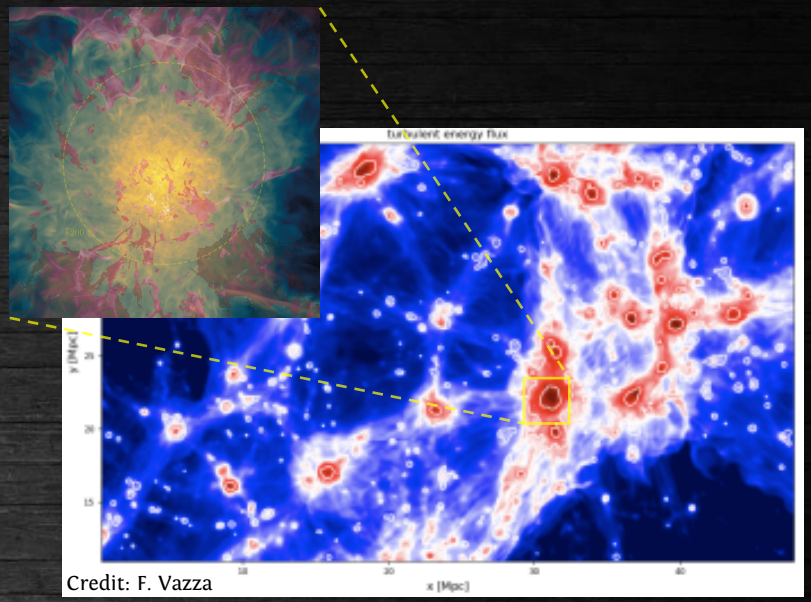

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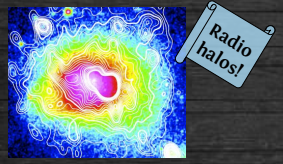


Probing particle acceleration at *large distances* from the cluster center

What about diffuse emission *outside* clusters?

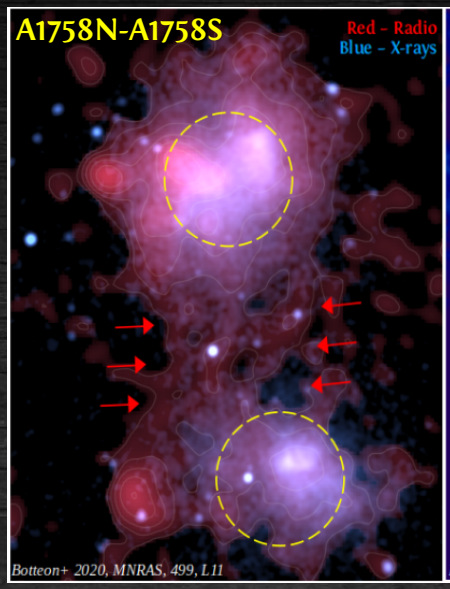
Radio bridges

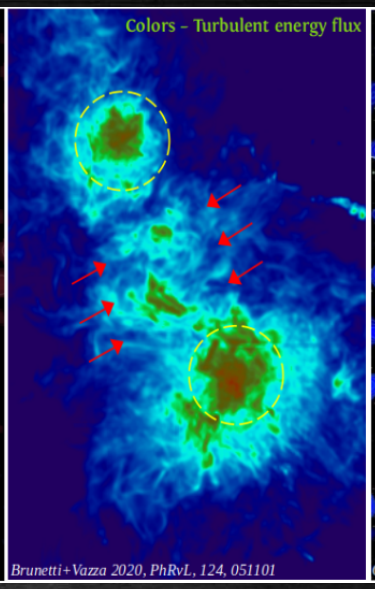
Radio bridges are **2-3 Mpc** long synchrotron sources connecting *pairs* of galaxy clusters

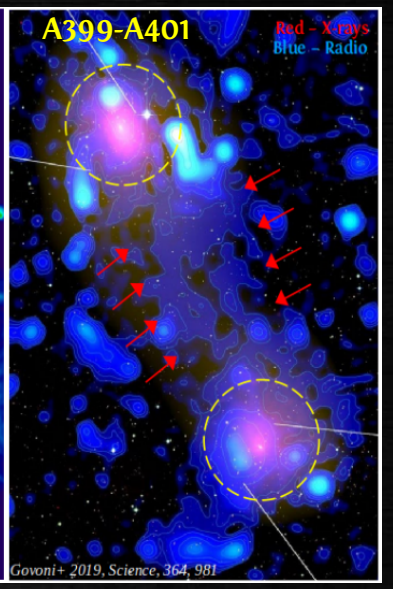
- *Are bridges common in cluster pairs?*
- *What are the properties of the emission?*
- *What are the particle acceleration mechanisms?*

Very *active* research field

(Wittor+19, Brunetti+Vazza20, de Jong+22, Radiconi+22, Nunhokee+23, Balboni+23, Pignataro+23)







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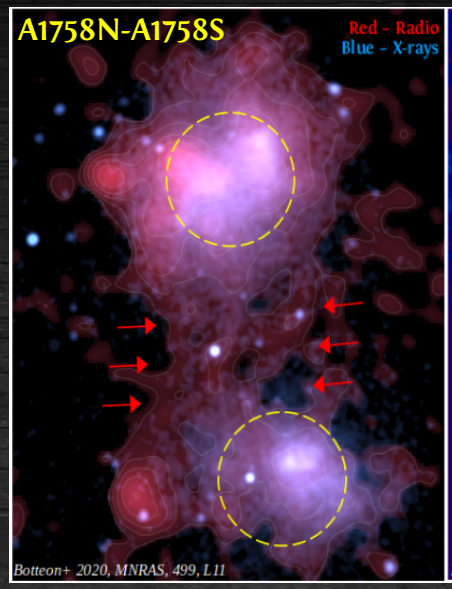
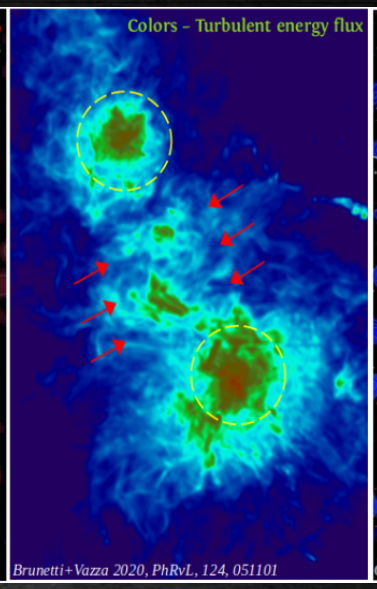
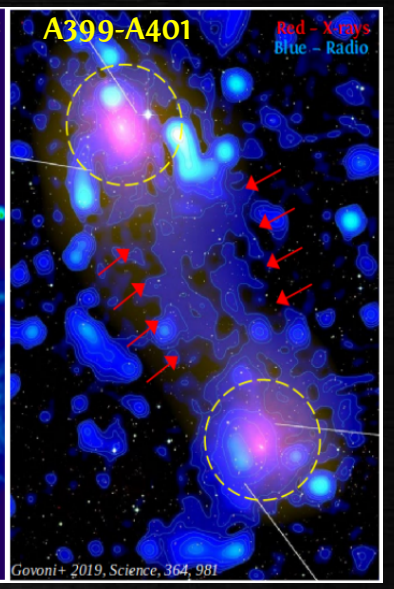
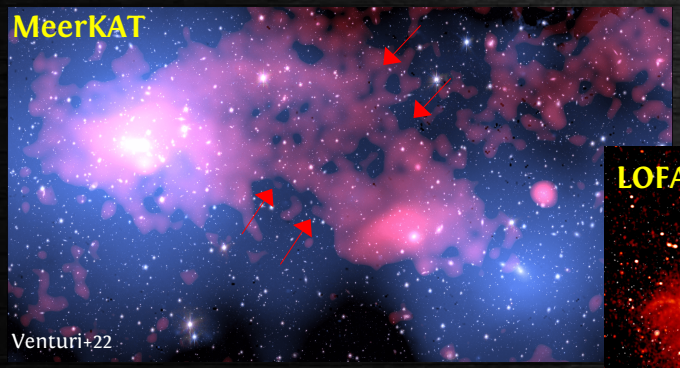
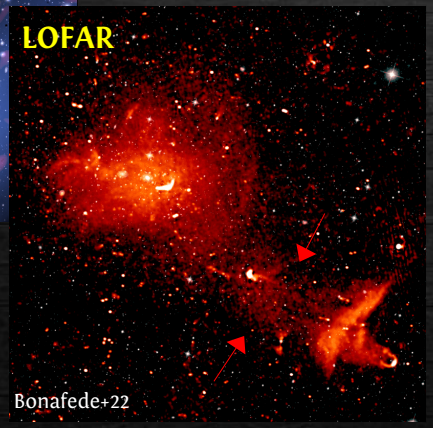


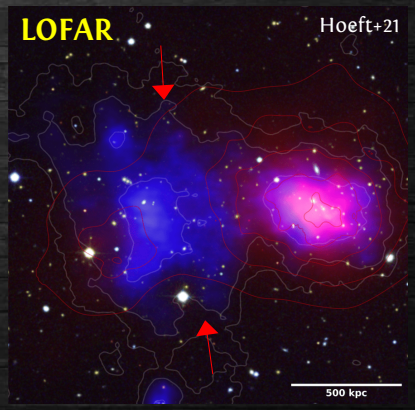


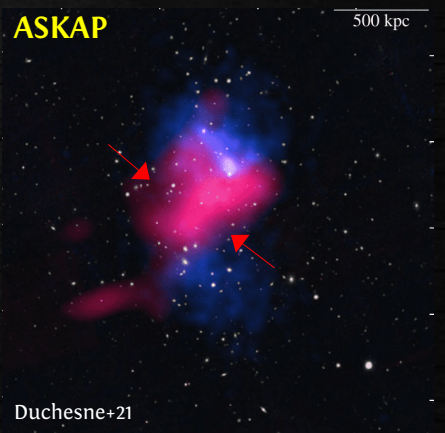


Other diffuse emission *in-between* clusters:









Cosmic web

- *How did the Universe become magnetic?*
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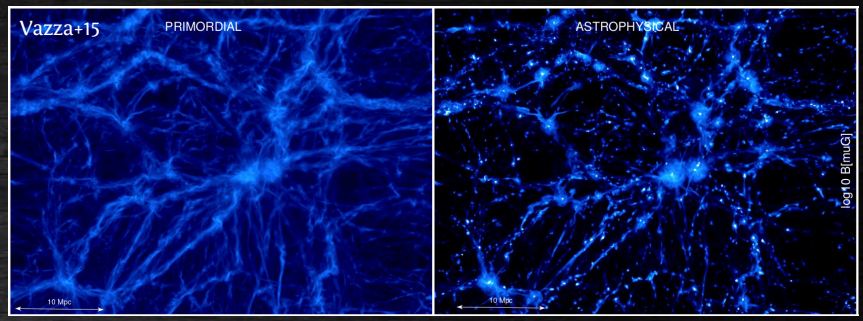
Radio emission from the *cosmic web* is beyond reach of *current* instruments

→ **stacking**



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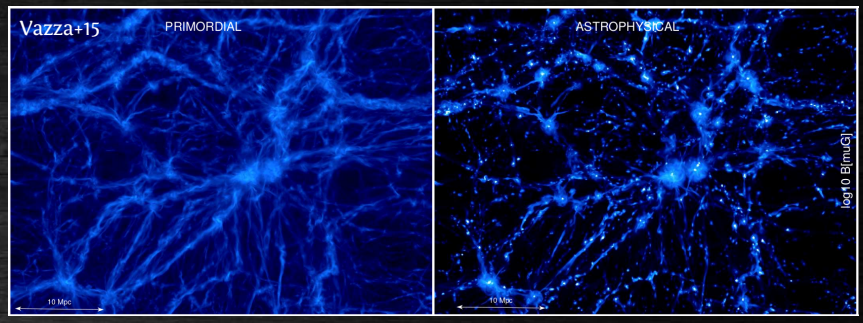

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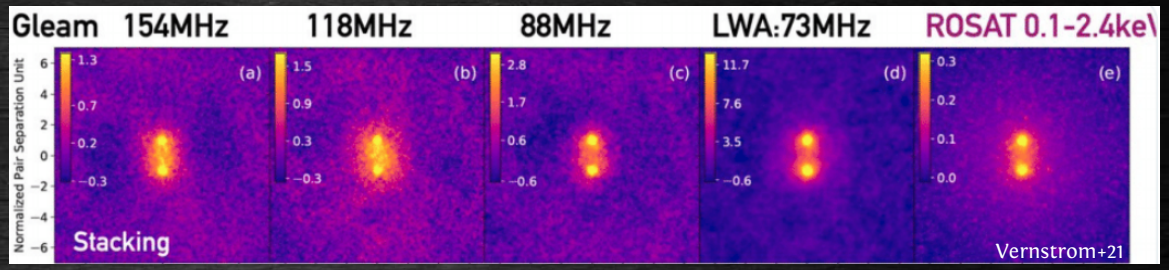


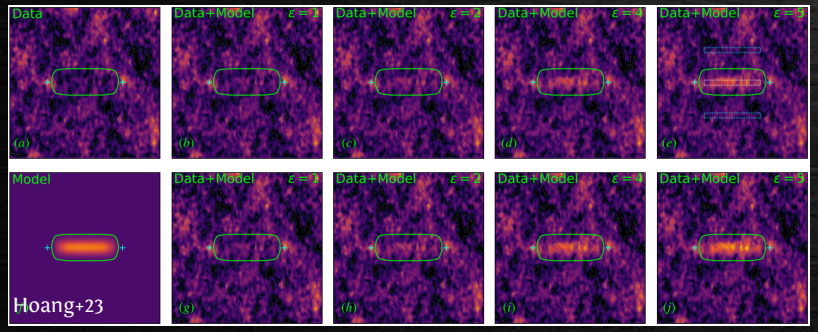
390k pairs of LRG (*MWA*, *LWA*, *ROSAT*)

- $\alpha \sim 1$
- $30\ nG < B < 60\ nG$

But see Hodgson+22

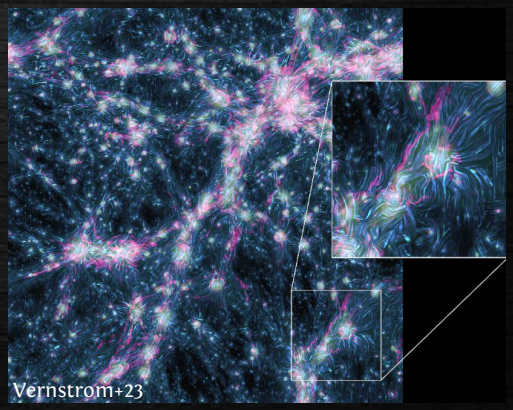
106 paired clusters (*LOFAR*, *eROSITA*)

- $\varepsilon < 1.2 \times 10^{44}\ erg/s/cm^3/Hz$
- $B < 75\ nG$



612k pairs of LRG+clusters (*GMIMS*, *Planck*)

- *Polarization fraction ›20%*
- *Shock origin*



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Thank you