Galaxy clusters in the radio band: the SKA perspective

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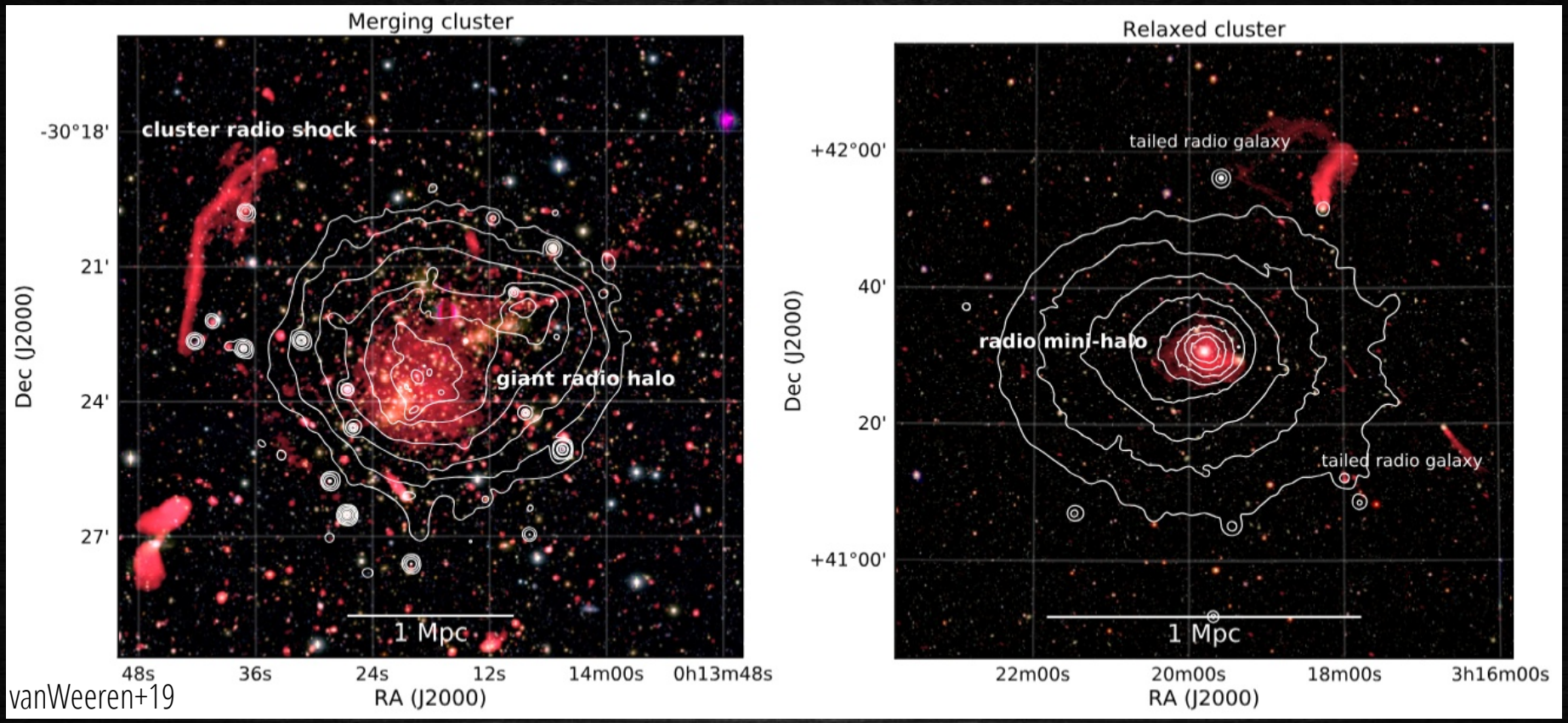
February 10, 2026 – Giornate del Raggruppamento INAF RSN1: Galassie e Cosmologia, Naples

Diffuse synchrotron sources in the ICM



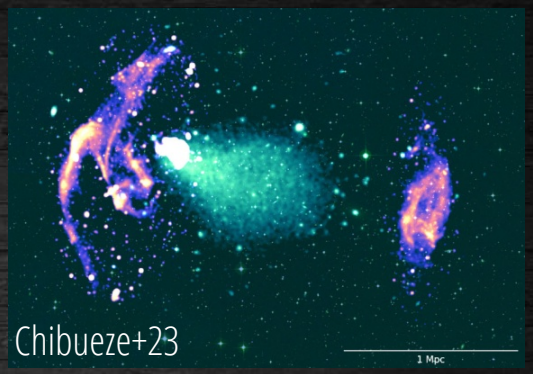
Halos: cluster-scale, located in cluster centers

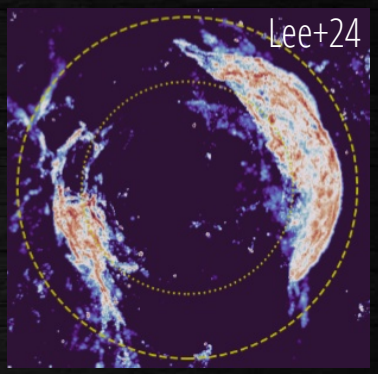
Mini halos: 50 kpc to $0.2 \times R_{500}$ in size, located in cluster centers

Relics: cluster-scale, arc-shaped, polarized, located in cluster outskirts

Emitting particles must be generated "in situ"
Possible origin: **turbulence**, **shocks**, **hadronic**

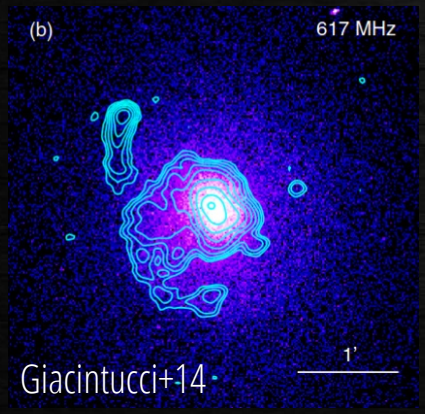
The current picture

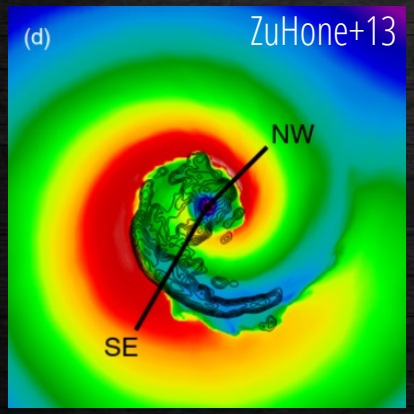




Energetic **cluster mergers** inject **shocks** and **turbulence** in the ICM producing relics and halos

- How the acceleration occurs?
- What is the origin of seeds CRe?
- What is the role of B?

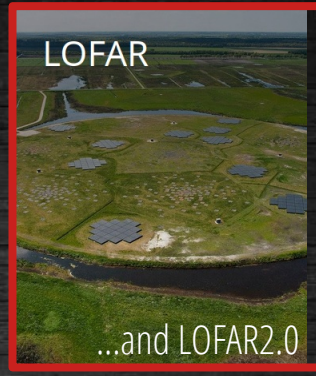


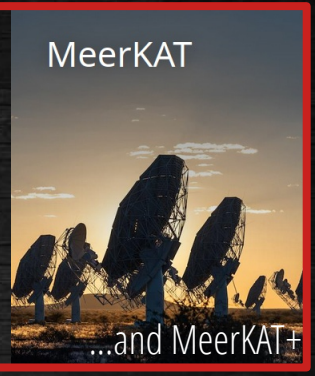


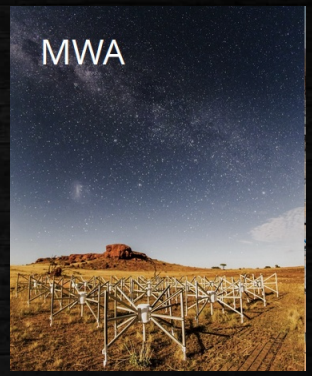
"Gentle" turbulence (e.g. sloshing) *may* reaccelerate CRe in **cool-core clusters** hosting mini halos

- What is the source of turbulence?
- Does the BCG have a role?
- What is the role of hadronic collisions?

The radio astronomy landscape

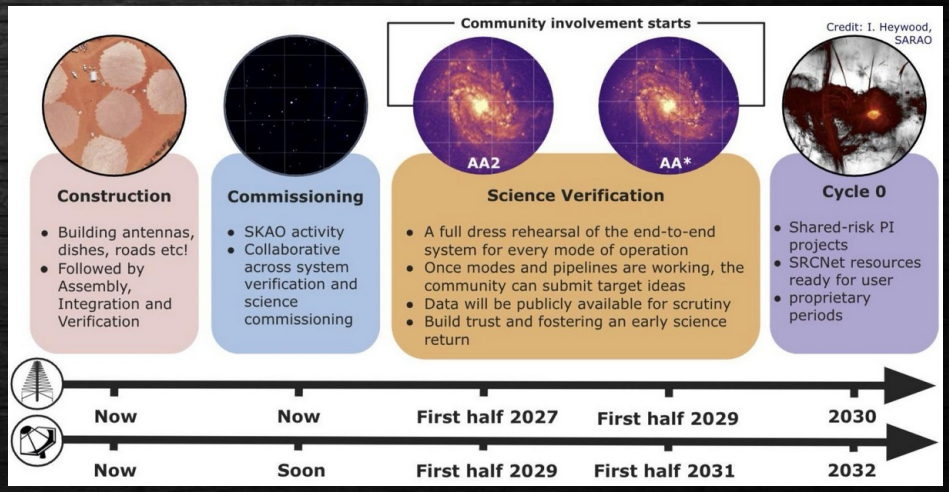






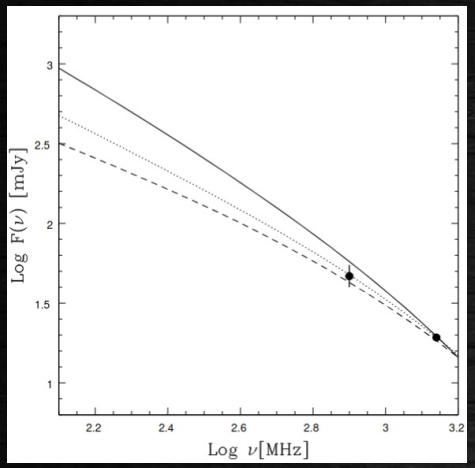
SKAO

Telescope	Band	Frequency Range (MHz)	Available Bandwidth (MHz)
SKA1-Low	N/A	50 - 350	300
SKA1-Mid	1	350 - 1050	700
	2	950 - 1760	810
	3	1650 - 3050	1400
	4	2800 - 5180	2380
	5a	4600 - 8500	3900
	5b	8300 - 15400	2 x 2500

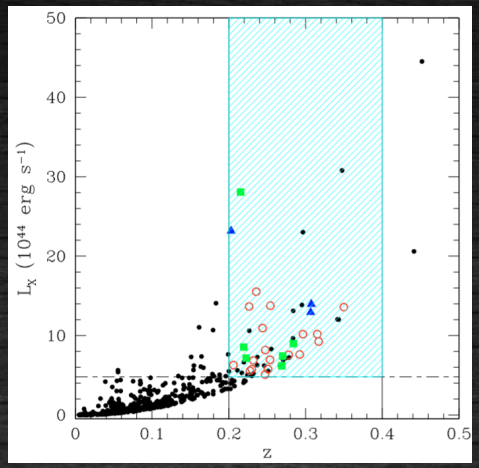


A paradigm shift

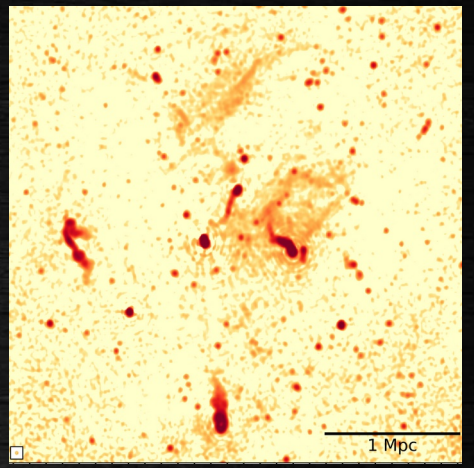
Venturi+03



Venturi+07



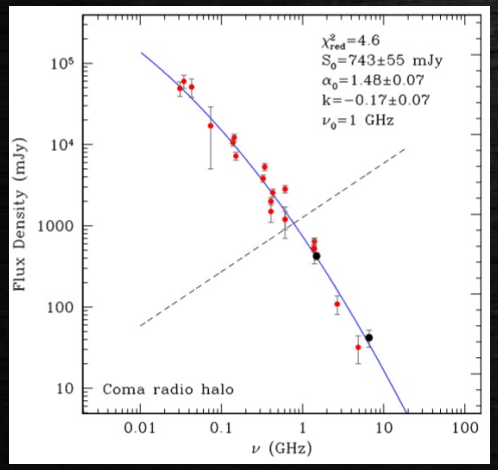
Pizzo+09



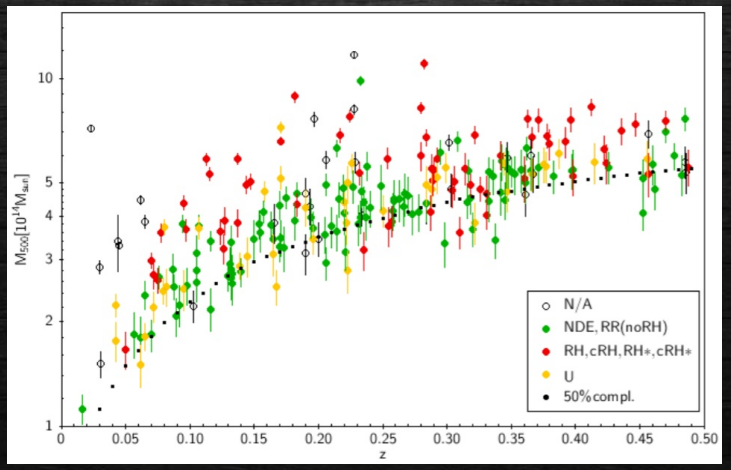
Before

vs

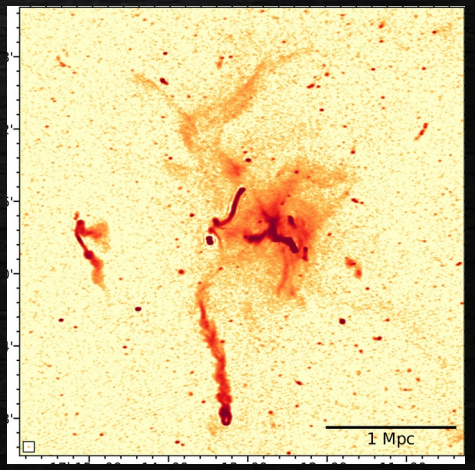
Now



Murgia+24



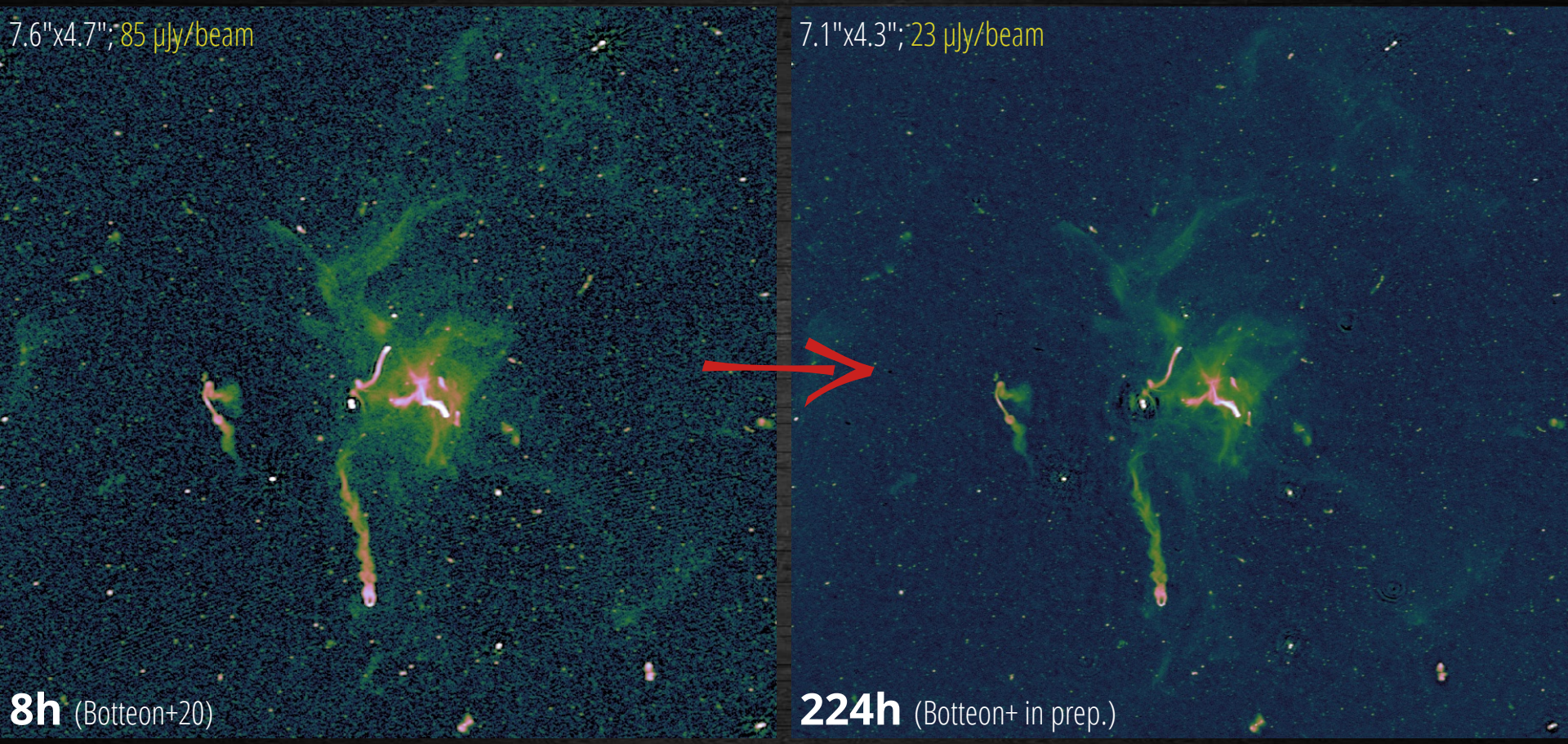
Cassano+23



Botteon+20

A taste of SKA

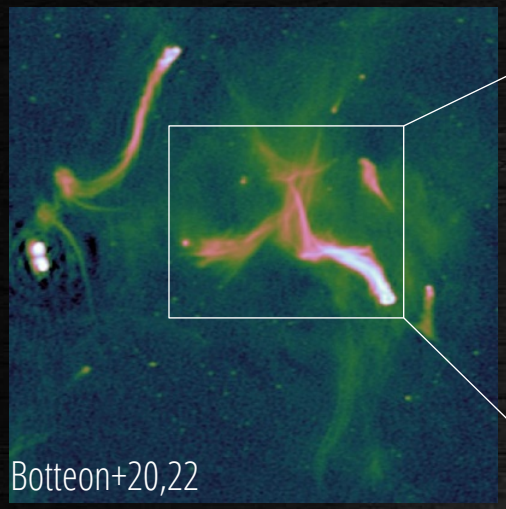
LOFAR Galaxy Cluster Deep Field: 336h @ 120-168 MHz

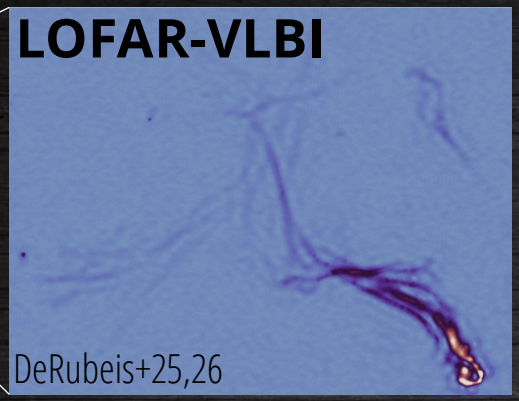


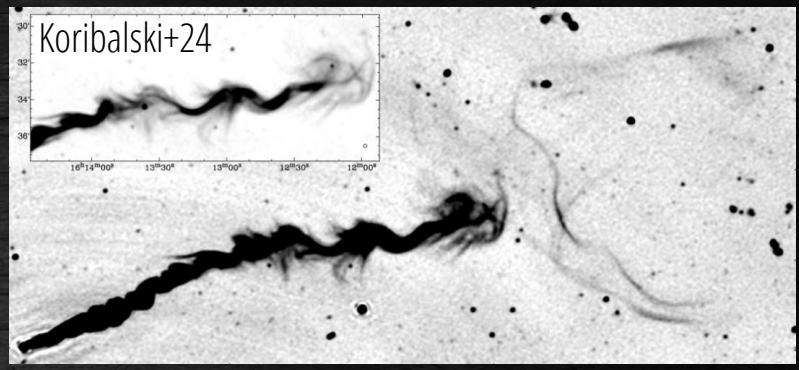
Comparison with 1h of **SKA-LOW** (AA4, @150 MHz, BW: 200 MHz):

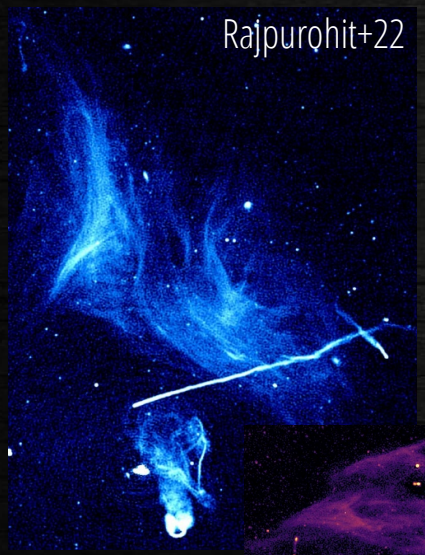
- uniform weighting | beam ~ 5″x4″ | rms ~ 105 μJy/beam (confusion 2.75 μJy/beam)
- Briggs 0 | beam ~ 12″x10″ | rms ~ 23 μJy/beam (confusion 21 μJy/beam → confusion noise limited)

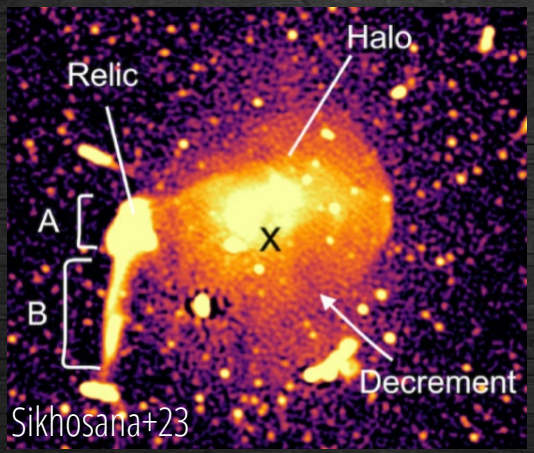
Surface brightness structures

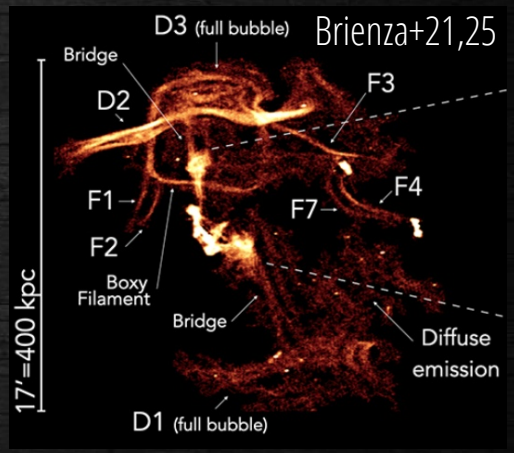








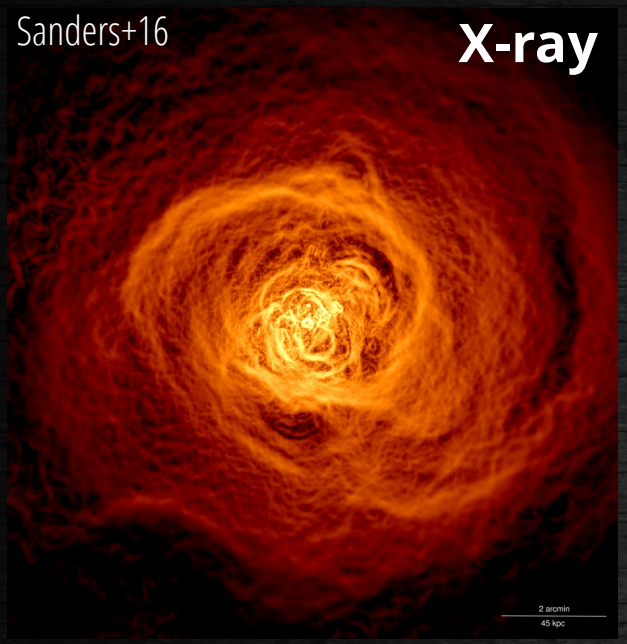


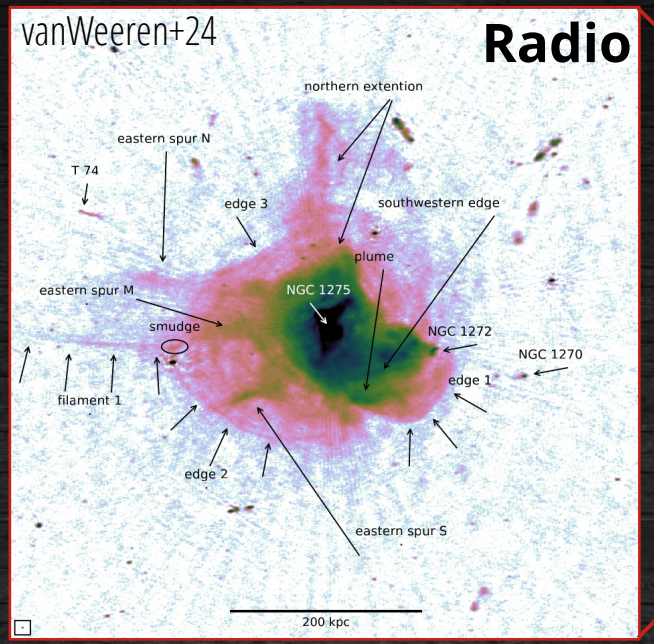


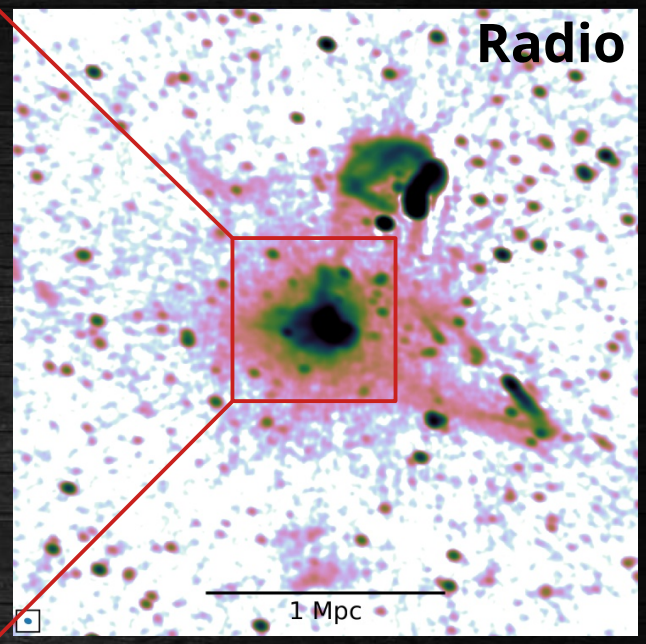
Edges, enhancements, depletions, ribbons, filaments, threads, sheets...

→ intersection between ICM, AGN, and plasma physics

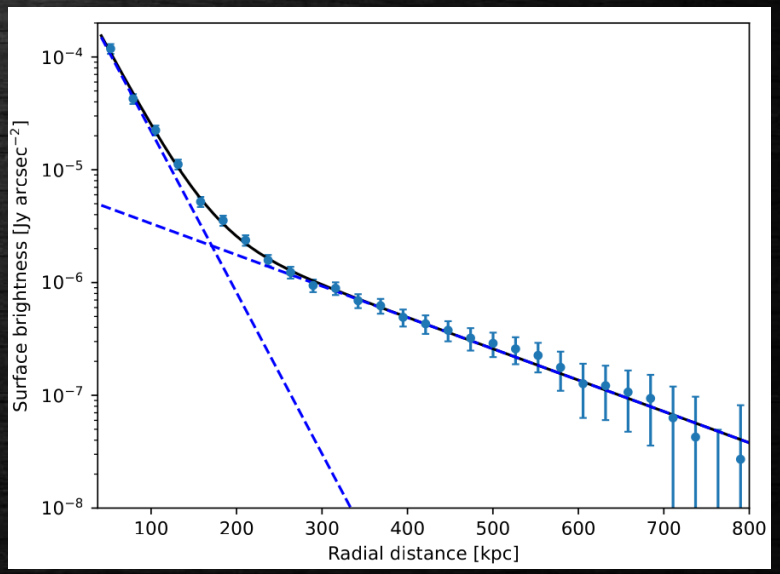
A Mpc-scale halo in Persus







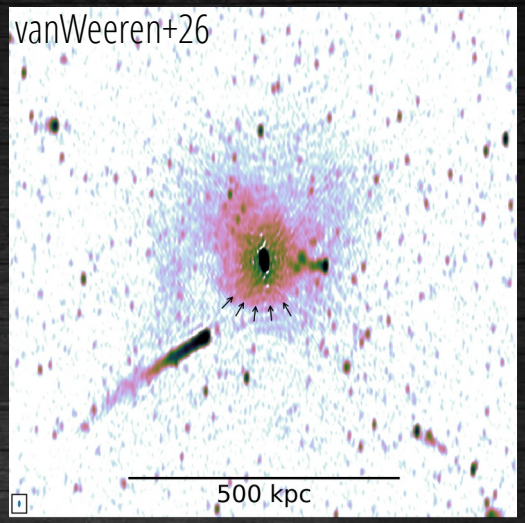
- Mini and giant halos: are they different?
- Do the two halo components have different origins?
- Transition between more efficient and less efficient acceleration?
- How common are Mpc-scale halos in relaxed clusters?

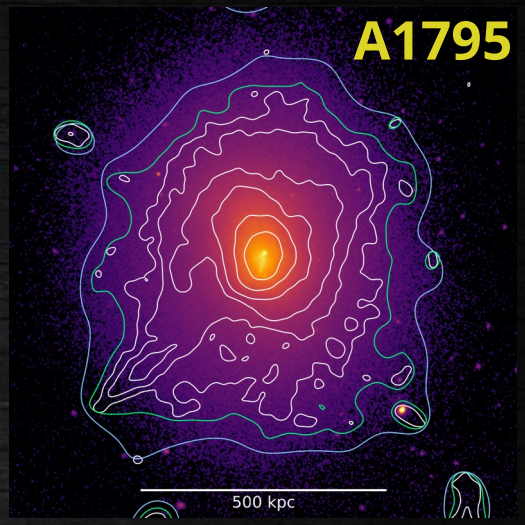


Radio ~~mini~~ halos in relaxed clusters

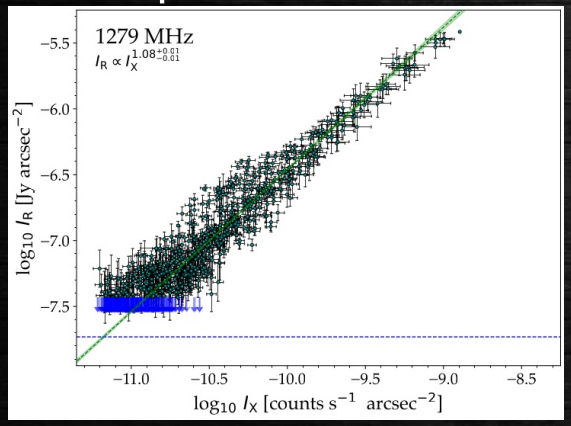
Cluster-scale emission is not unique to merging systems!

Bonafede+14, Kale+16,19, Venturi+17, Savini+18,19 Riseley+22,23,24, Bruno+23, Biava+24, Lusetti+24, Trehaeven+25, Hoang+25

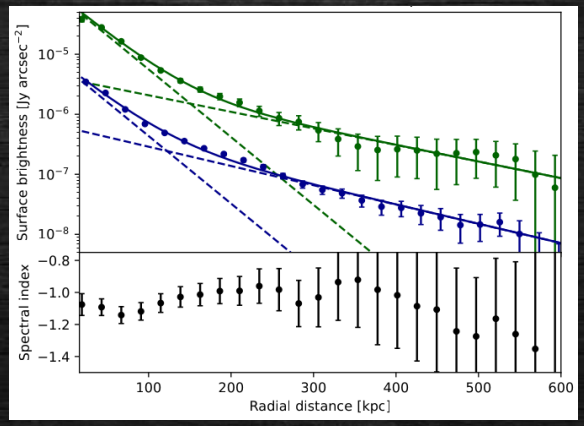




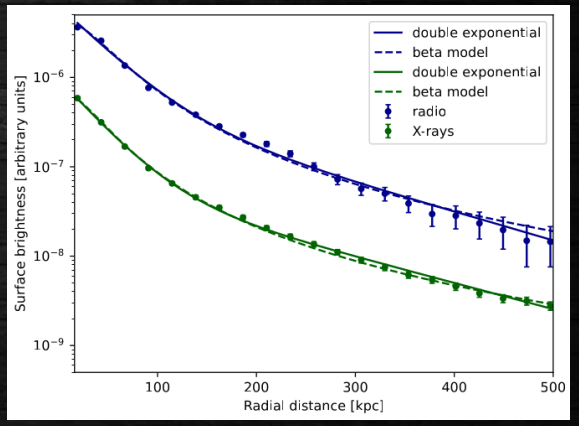
Superlinear I_R-I_X



Almost constant α ~ 1.1

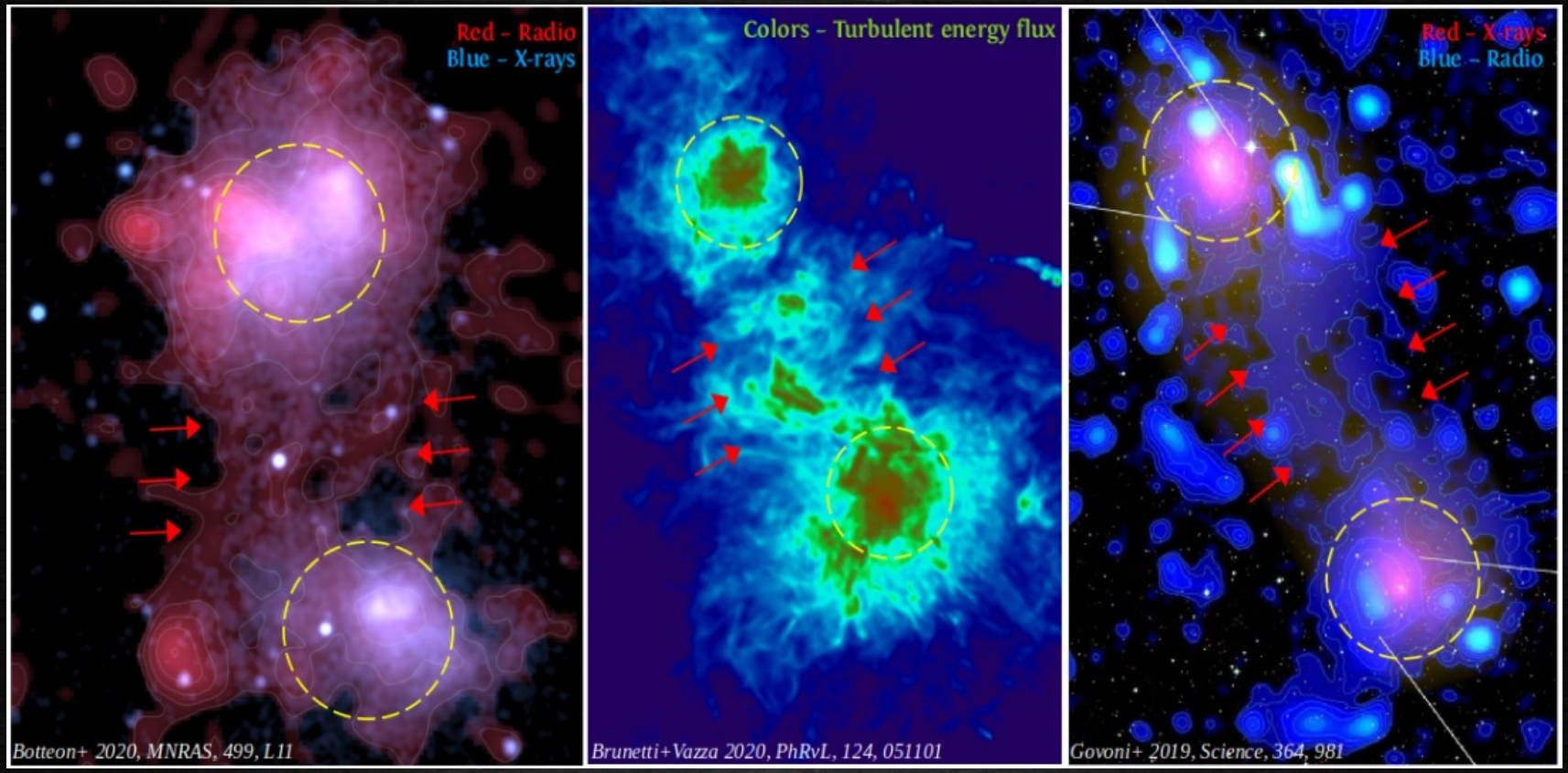


Thermal = non-thermal



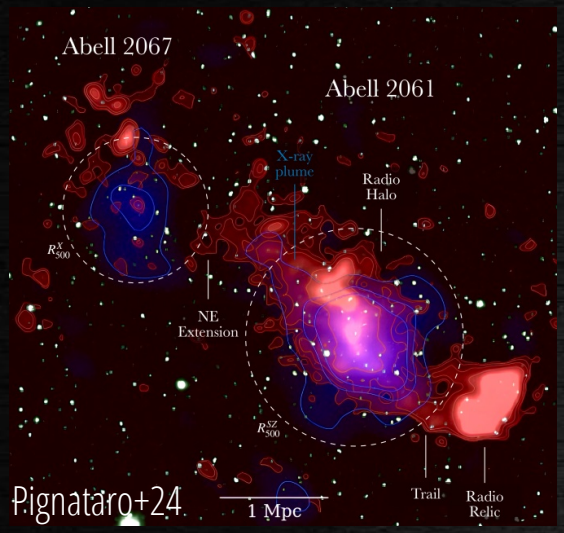
A1795 may be a **hadronic** radio halo

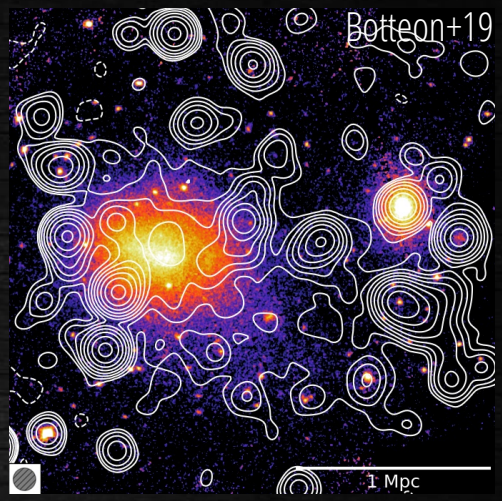
Cluster pairs: radio bridges and more

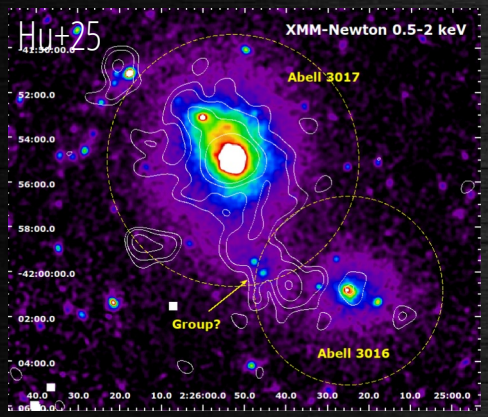


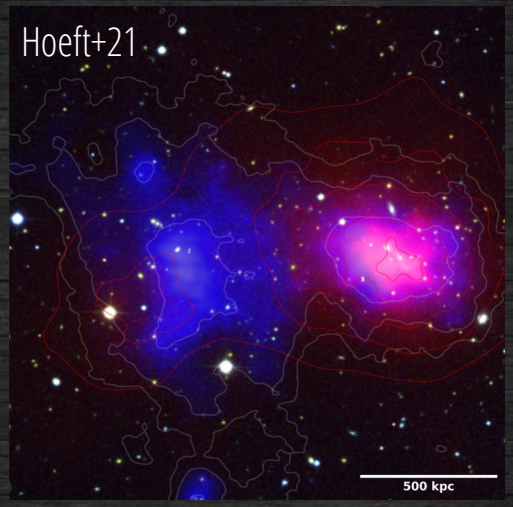
Radio bridges connect pairs of galaxy clusters in a pre-merger phase

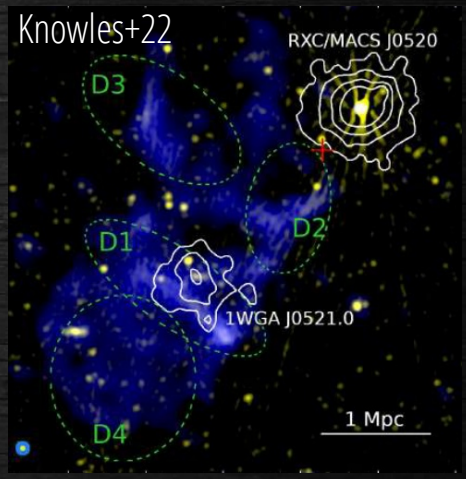
- Are bridges common in cluster pairs?
- What are the properties of the emission?
- What are the particle acceleration mechanisms?

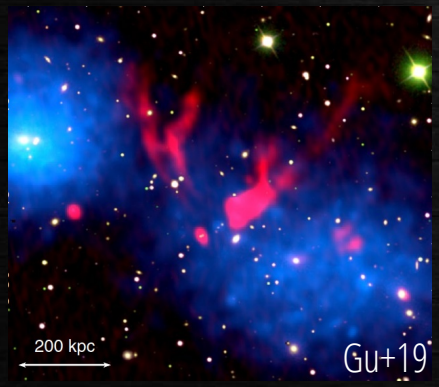


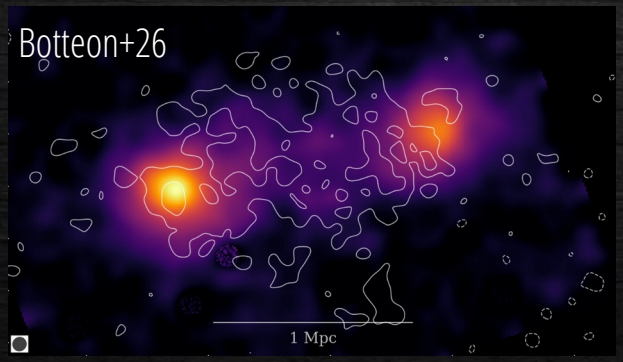










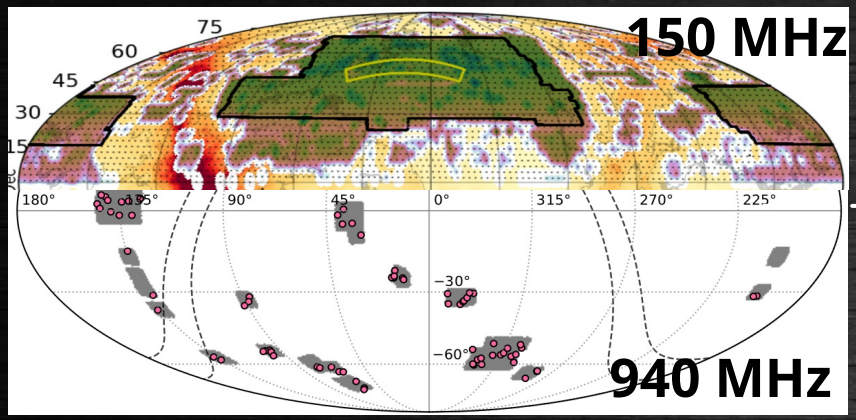


- Different morphologies…
- …different origin?

→ cluster pairs do not only show “bridges”

The “explosion” of cluster samples

Large cluster samples are needed to determine the statistical properties of diffuse cluster radio sources

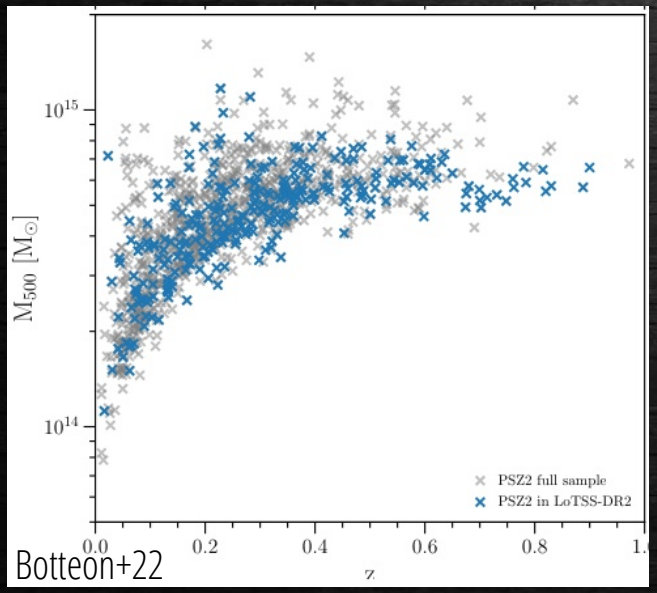


LOFAR

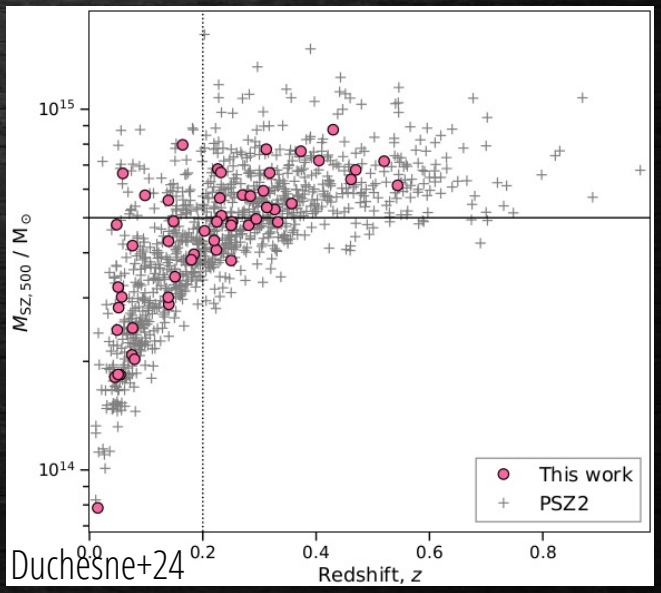
LoTSS-DR2, 5634 deg², 309 PSZ2 clusters (Botteon+22)

ASKAP

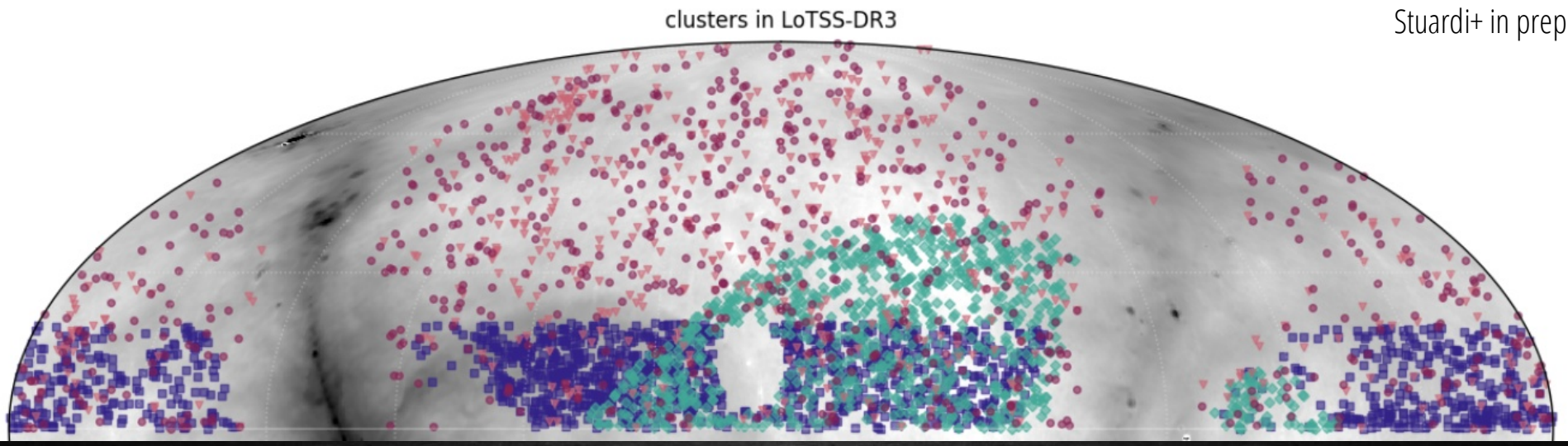
EMU, 1990 deg², 71 PSZ2 clusters (Duchesne+24)



Botteon+22

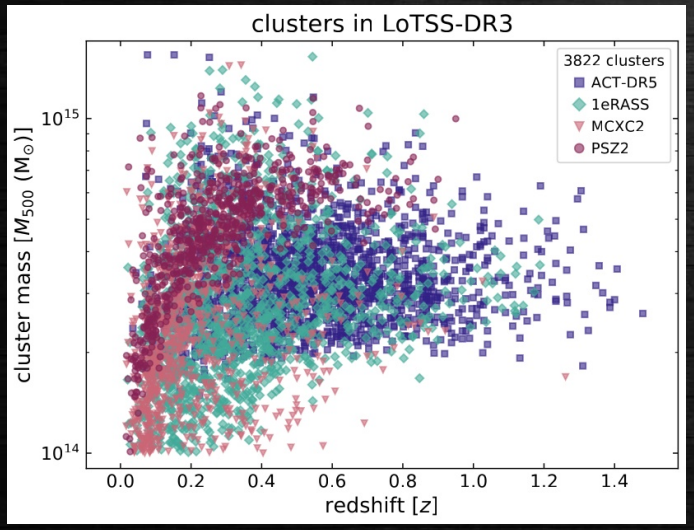


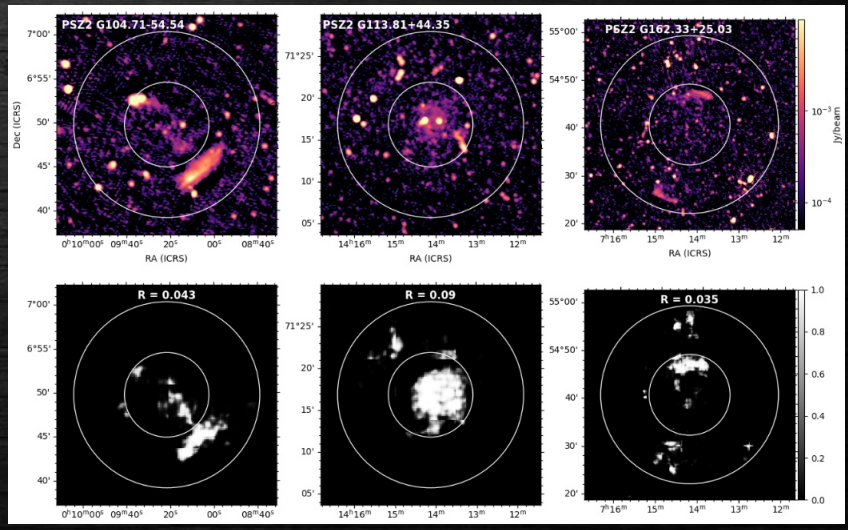
Duchesne+24



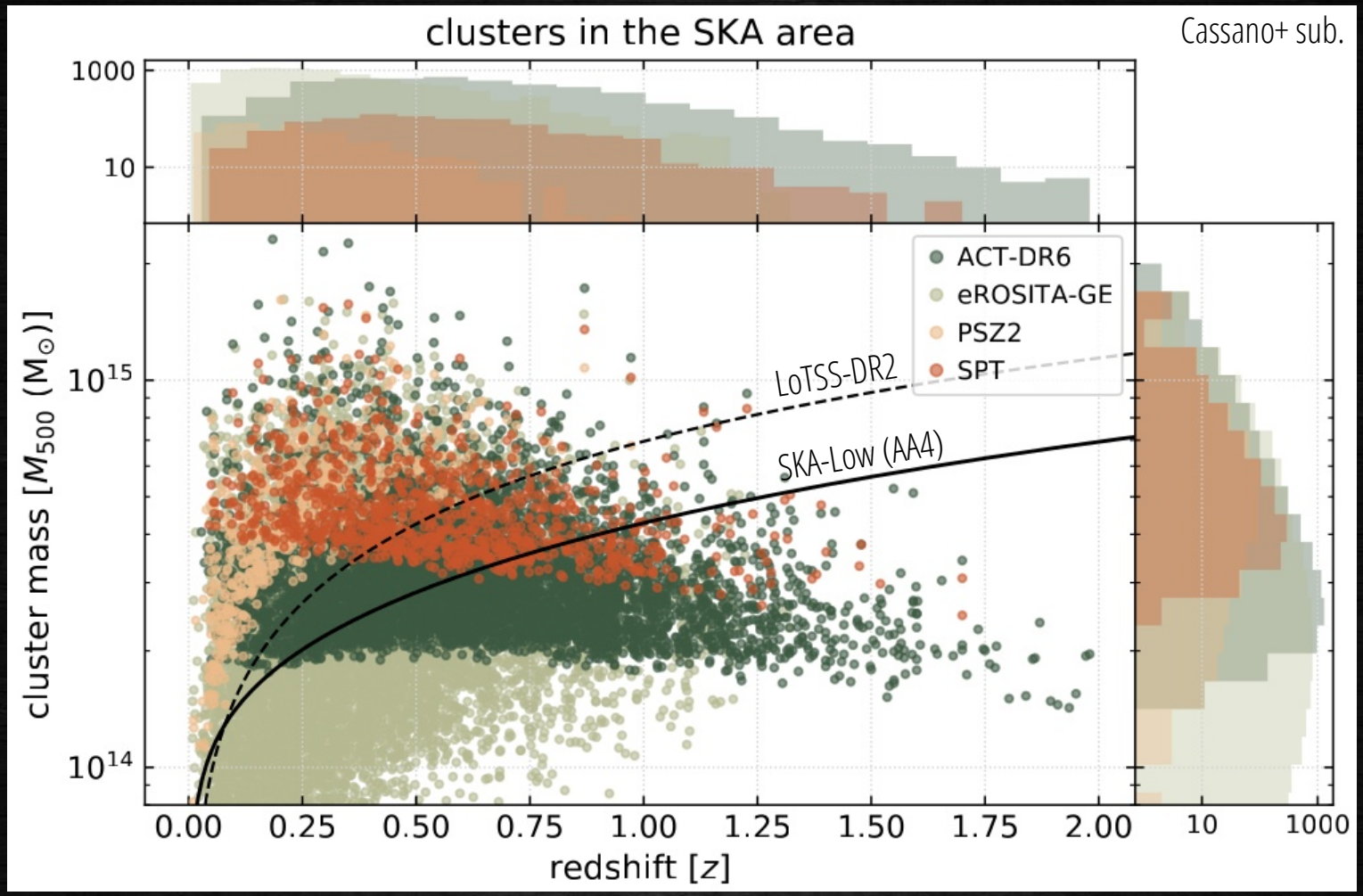
Stuardi+ in prep.

- LoTSS-DR3: 19035 deg^2 → will be public from Feb 19th!
- 3822 clusters from ACT-DR5, 1eRASS, MXCX2, PSZ2
- Deployment of machine-learning methods trained on DR2 results (Stuardi+24)
- Sub-sample of 357 clusters selected at the highest network accuracy





SKA predictions



With SKA-Low:

- ~2500 halos up to z~0.6 (1000+ USSRH)
- Halos at z~1 down to $M_{500} \sim 10^{14}\ M_\odot$

Take-home messages

- Non-thermal diffuse sources in the ICM: fast evolving field
- Dramatic progress in the last years due to new instruments

- INAF researchers are among the world leading experts in the field
- Involvement in: SKA, LOFAR(2.0), MeerKAT(+), Euclid, XRISM, AXIS, NewAthena...

- Very strong synergy with X-rays. Improve connections with SZ and Gamma-rays

- Interactions between cluster, AGN, and plasma communities could help to address some new results

- Data are incoming with fast rates:
  - Need specific computing resources
  - “Overflow” of data → new discoveries → interpretation challenges

Thank you