Farnesina
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RADIO SKY 2020

DRANOEL
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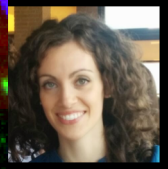

INSIGHTS AND PERSPECTIVES IN THE STUDY OF RADIO EMISSION IN GALAXY CLUSTERS

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with contribution by

Annalisa Bonafede
University of Bologna

Image credits A. Botteon

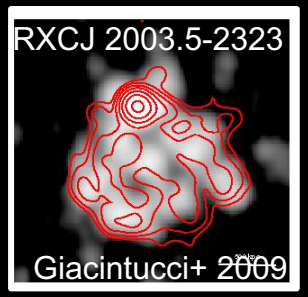
The Metre Wavelength Sky II – March 22nd, 2019

OVERVIEW

- Very broad introduction to the field
- Problems and established results
- Very sensitive view of diffuse radio emission in galaxy clusters and new issues
- Follow-up studies of some clusters in the GMRT Radio Halo Survey
- AGN science and galaxy cluster science
- uGMRT-MeerKAT synergy in the study of galaxy clusters
- The future?

Image credits A. Botteon

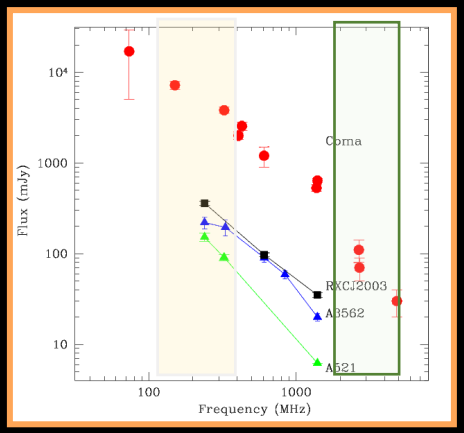
CLUSTER SCALE: GIANT RADIO HALOS



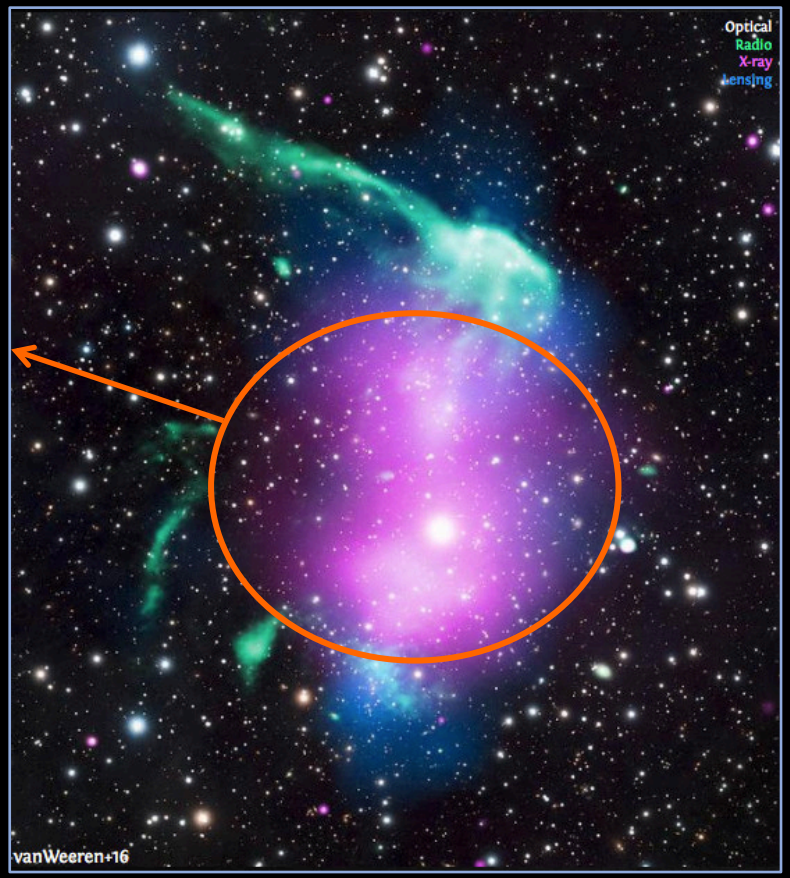
Relativistic particles and magnetic fields spread over Mpc volumes

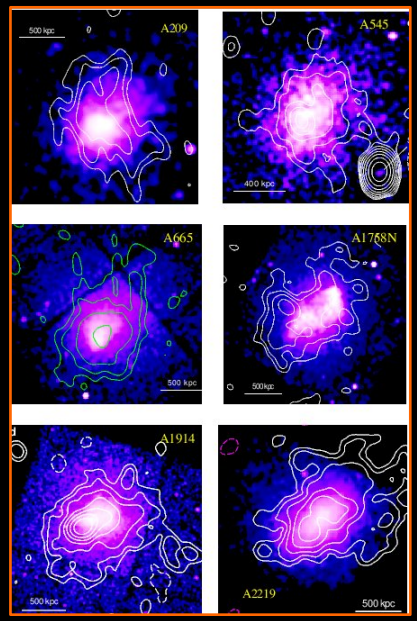
Present in few tens of galaxy clusters

~ Mpc size
- Steep spectrum (α~1.1-1.4 and steeper)
- sub μJy/"^{2} surface brightness
- Follow X-ray emission
- Unpolarized



From Venturi 2011



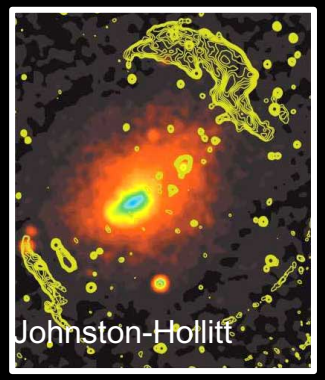


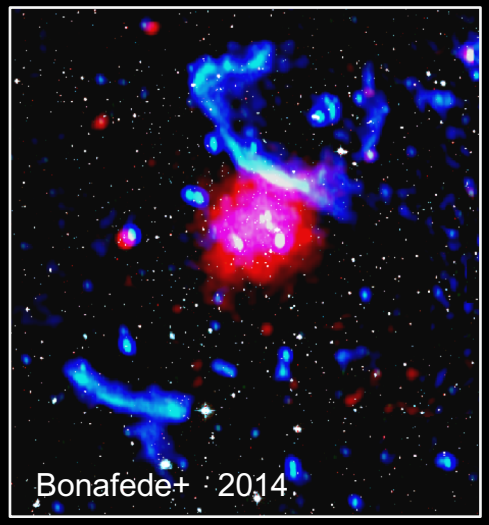
Images from S. Giacintucci

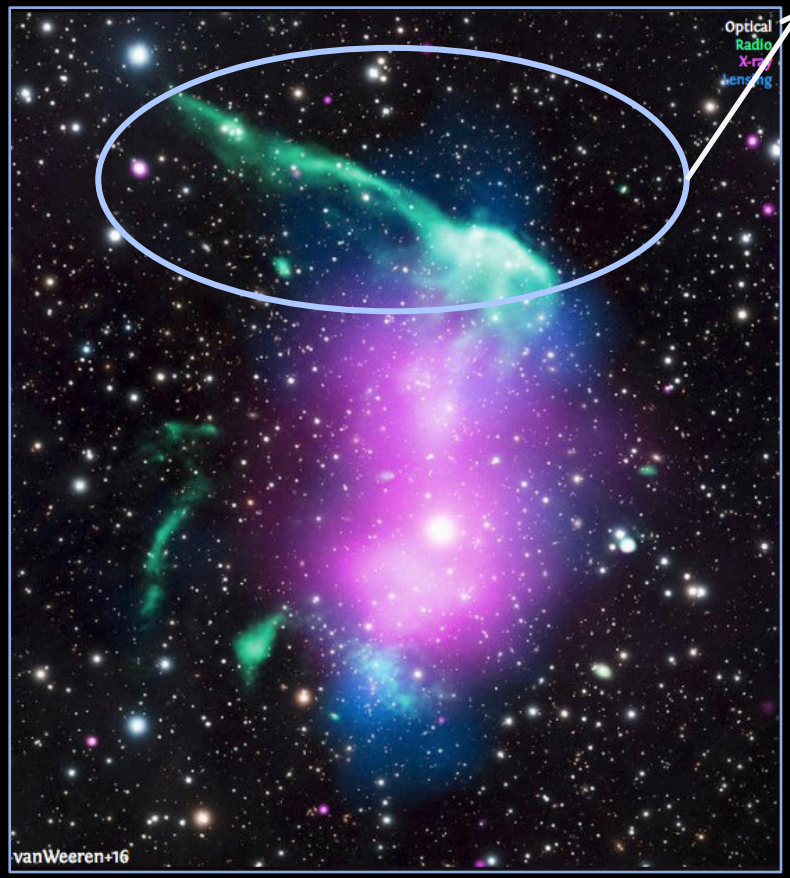
Detectability depends on frequency, array sensitivity, uv-coverage, multiresolution

CLUSTER OUTSKIRTS: RELICS

Relativistic particles and magnetic fields spread over Mpc volumes

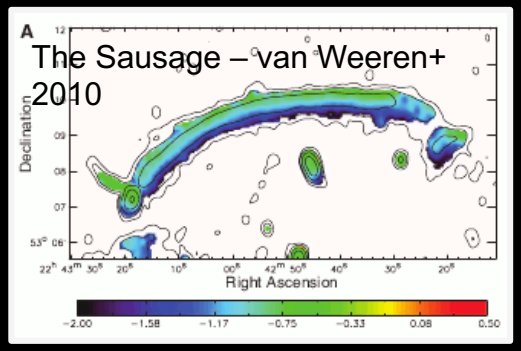






~few tens of relics & candidates
~ Mpc size
- Steep spectrum
- (α~1.2-1.5)
- Low surface brightness
- Elongated morphology

- Single & double relics
- Relics in clusters with and without radio halos

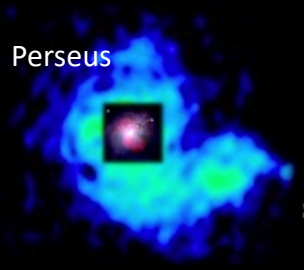


- Polarized (up to 30%)

⇩

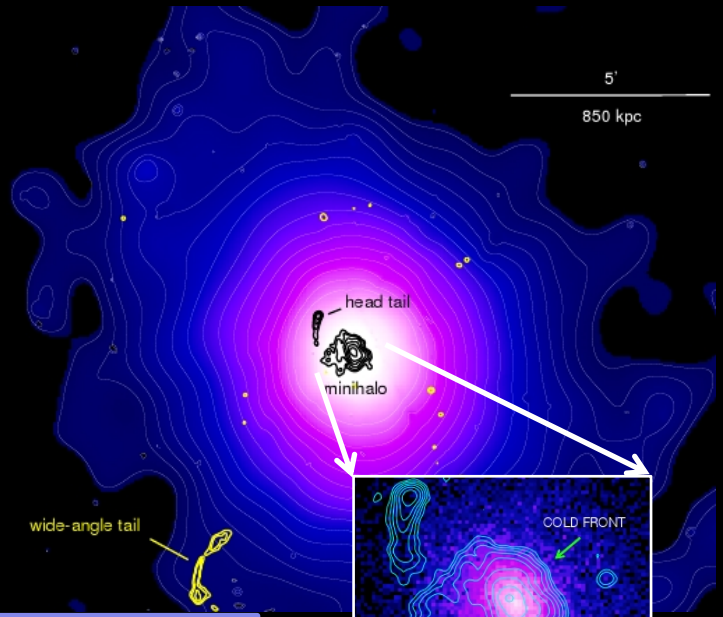
Mpc scale magnetic fields with some degree of order

CLUSTER CORES: RADIO MINI-HALOS

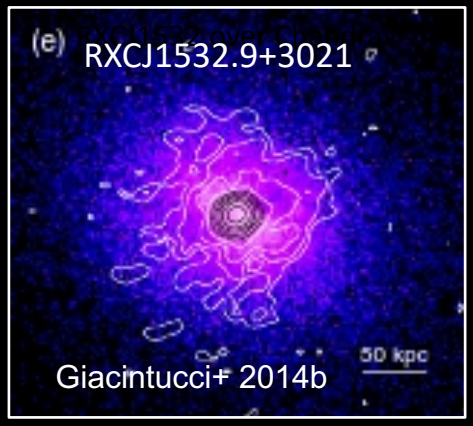


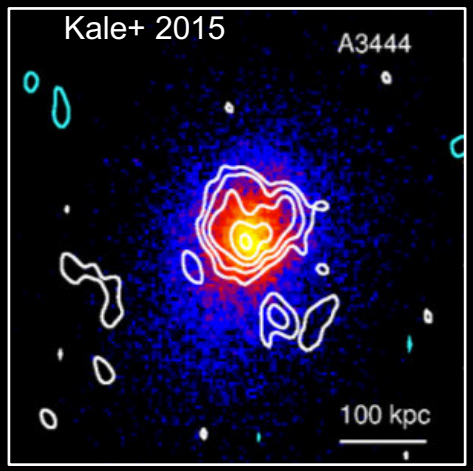
Present so far in ~ 20 galaxy clusters

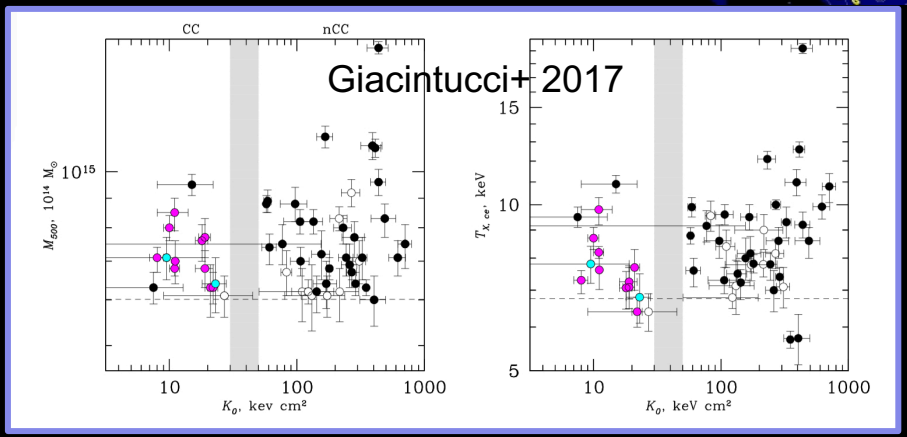
100 – 400 kpc in size
- Steep spectrum (α~1.2-1.5 and steeper)
- (sub) μJy/”^{2} surface brightness
- Sharp surface brightness cutoff
- Located at the peak of central X-ray brightness distribution
- Central BCG is always a radio source



RXCJ1720.1+2638
Giacintucci+ 2014a







Different properties of clusters hosting mini-halos and GRH known for a long time

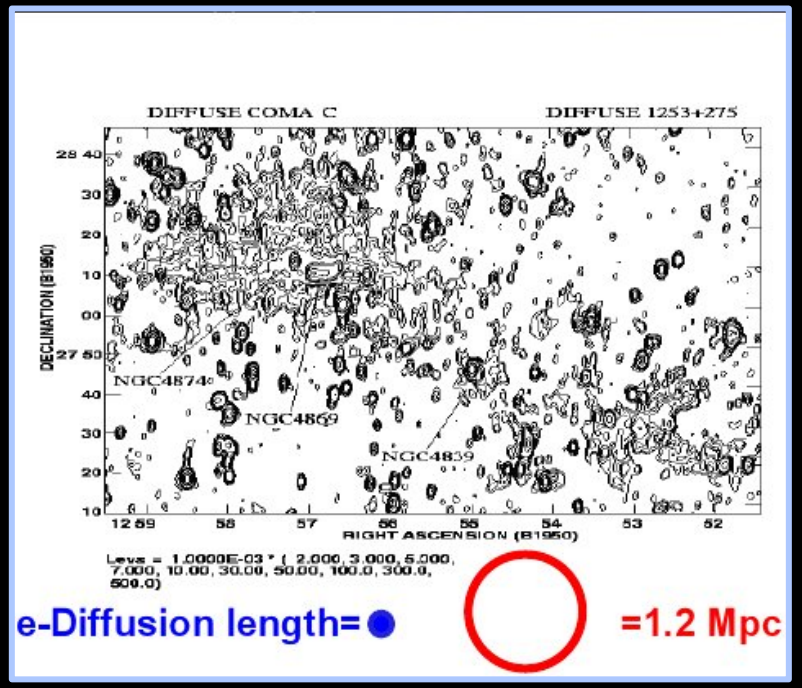
Diffusion problem

Crossing time of electrons ~ 10 Gyr

but radiative lifetime ~ 0.1 Gyr

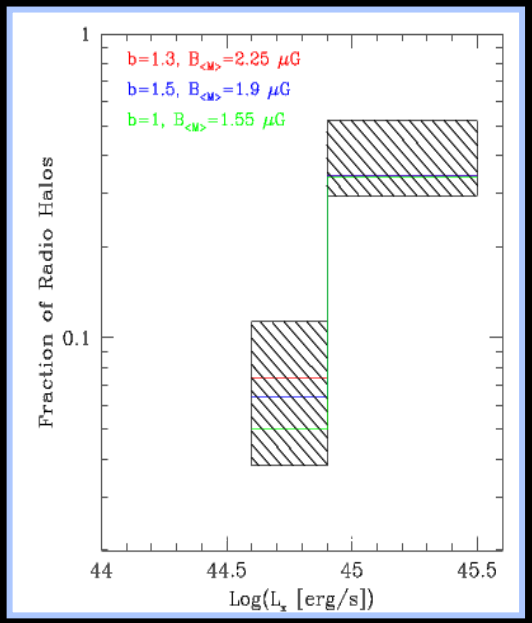
$t_{diff} >> t_{rad}$

Re-acceleration needed



Diffuse cluster sources not ubiquitous in galaxy clusters: why?

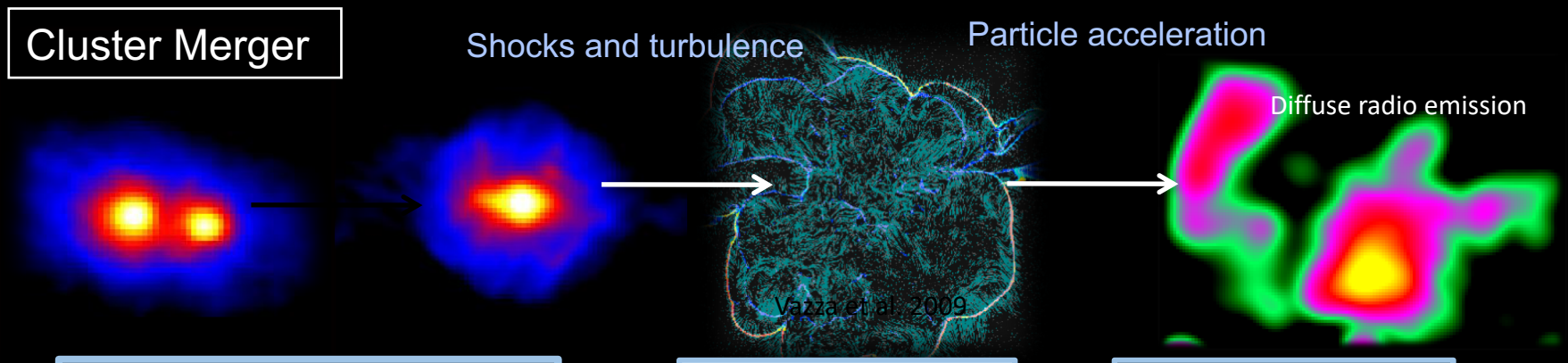
Fraction of observed radio halos and dependence on mass

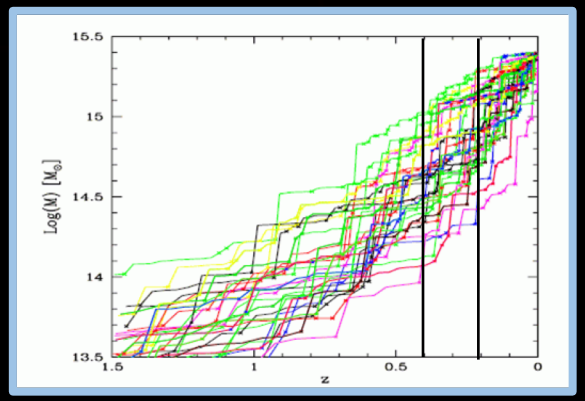


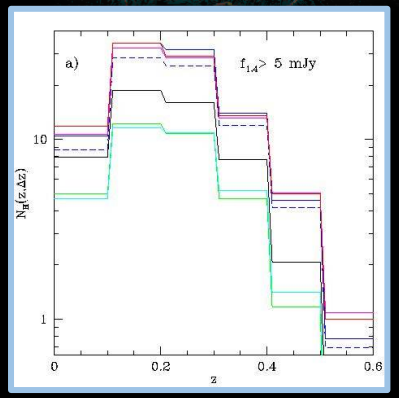
Origin of relativistic electrons

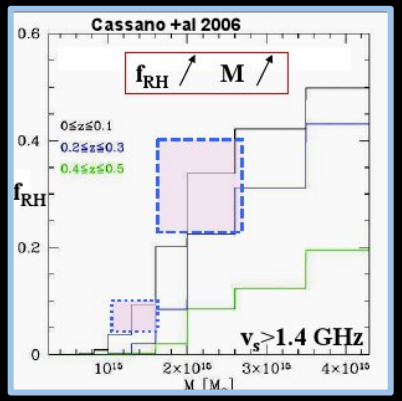
Secondary models – relativistic electrons continuously injected in the ICM by inelastic proton-proton collisions through production and decay of charged pions in the ICM

Primary models - in-situ re-acceleration of relativistic electrons by MHD turbulence
(e.g., Brunetti et al. 2001, 2004; Petrosian 2001; Fujita et al. 2003; Petrosian & Bykov 2008…)









Background of the E-GMRT Radio Halo Survey

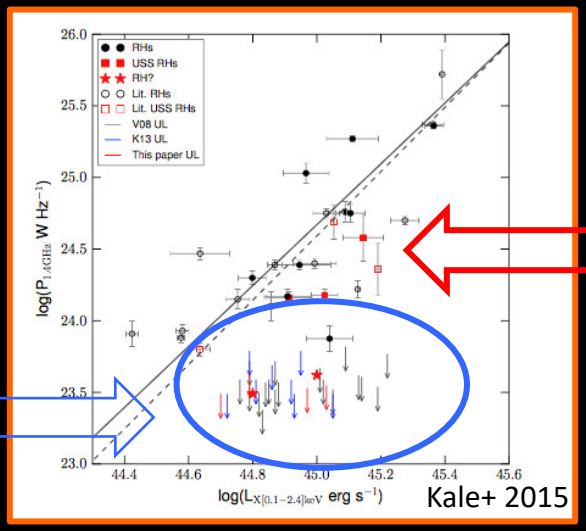
Venturi et al. 2007-2013; Giacintucci et al. 2005-2010; Kale et al. 2013, 2015; Brunetti et al. 2007, 2008; Cassano et al. 2008-2013; Dallacasa et al. 2009

Established results

BIMODALITY for giant radio halos

Upper limits of radio halo power

RELAXED CLUSTERS



Kale+ 2015

Radio power - cluster X-ray luminosity correlation

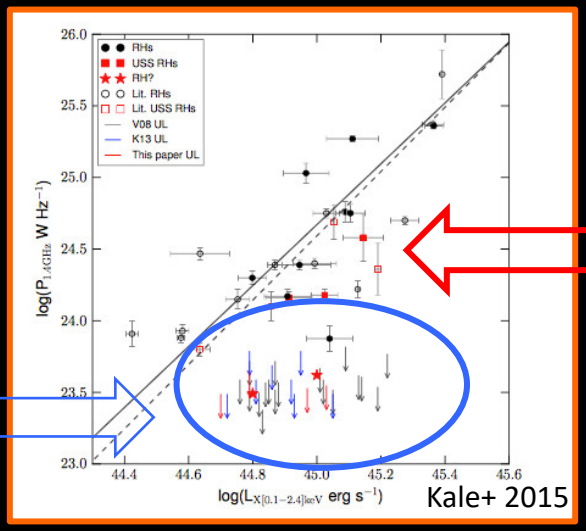
MERGING CLUSTERS

Established results

BIMODALITY for giant radio halos

Upper limits of radio halo power

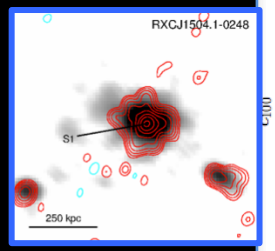
RELAXED CLUSTERS

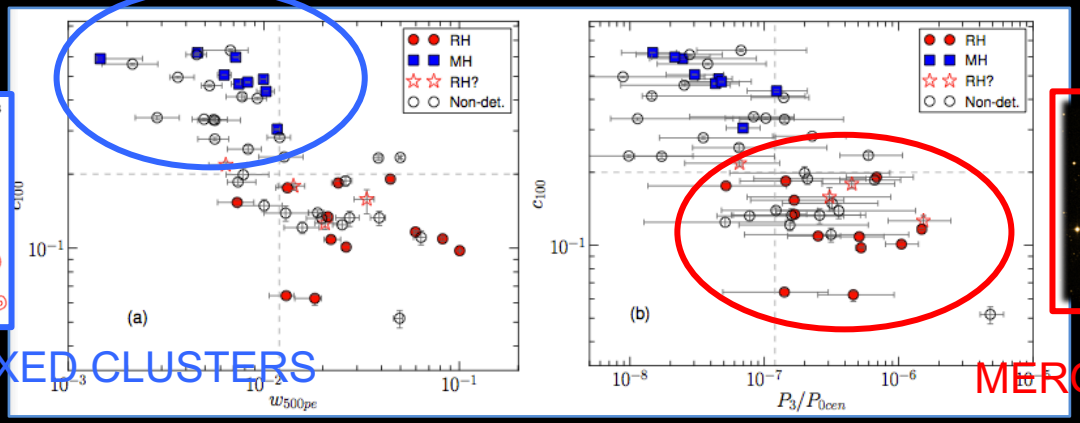


Radio power - cluster X-ray luminosity correlation

MERGING CLUSTERS

Quantitative assessment of the **CLUSTER DYNAMICS AND** presence of **DIFFUSE EMISSION** in the form of giant radio halos and mini-halos





RELAXED CLUSTERS

MERGING CLUSTERS

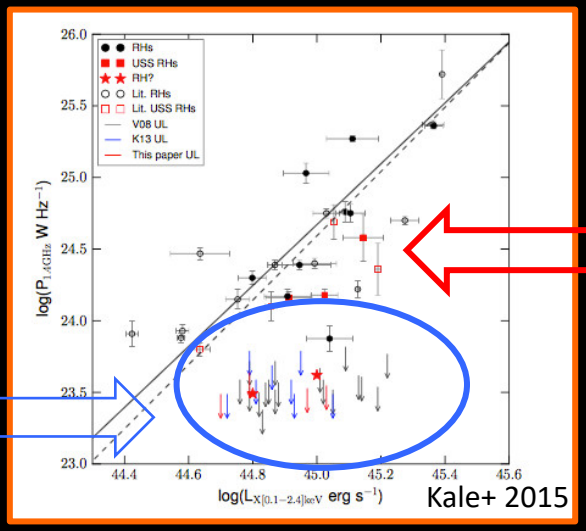
Cassano et al. 2010, Kale et al. 2015

Established results

BIMODALITY for giant radio halos

Upper limits of radio halo power

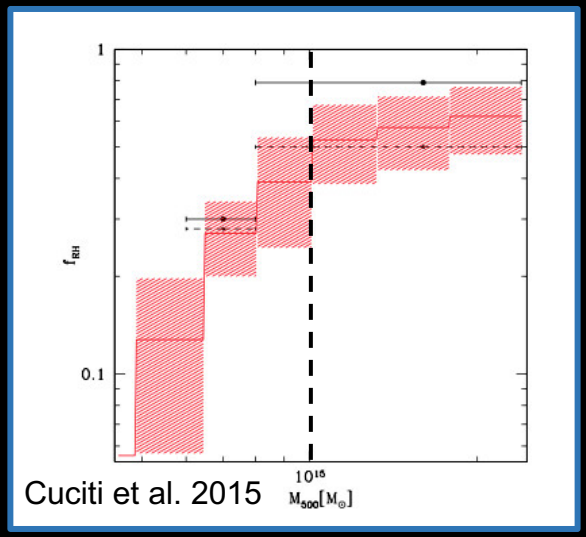
RELAXED CLUSTERS



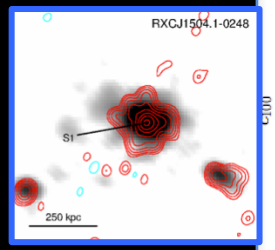
Radio power - cluster X-ray luminosity correlation

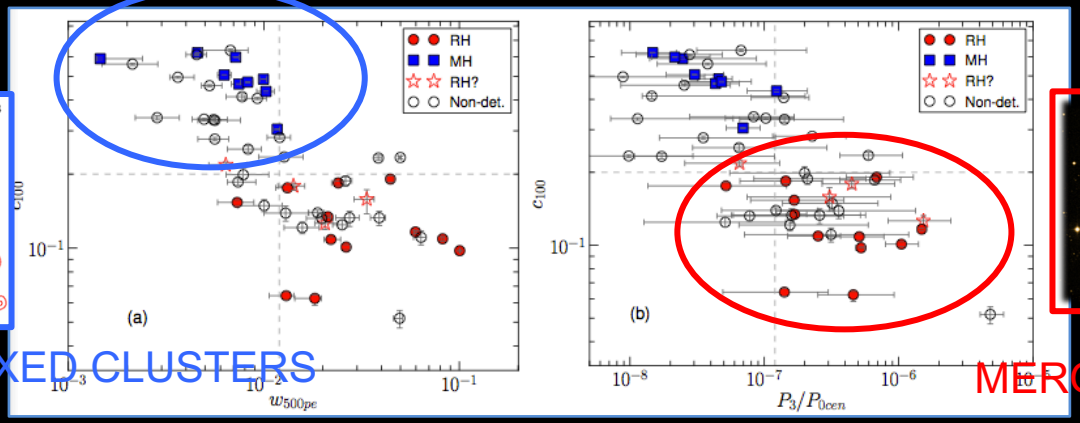
MERGING CLUSTERS

OCCURRENCE with cluster mass



Quantitative assessment of the **CLUSTER DYNAMICS AND** presence of **DIFFUSE EMISSION** in the form of giant radio halos and mini-halos





RELAXED CLUSTERS

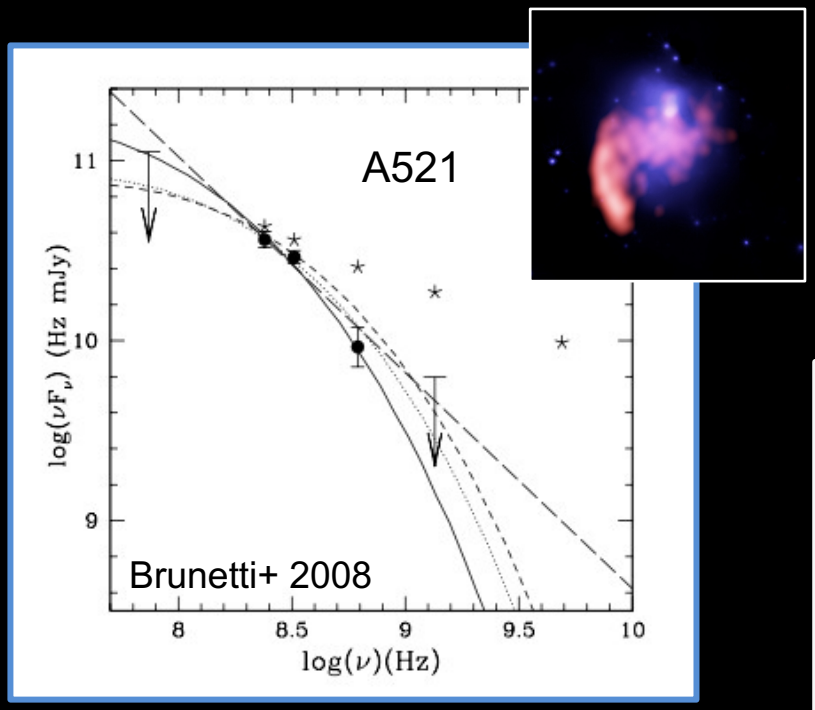
MERGING CLUSTERS

Cassano et al. 2010, Kale et al. 2015

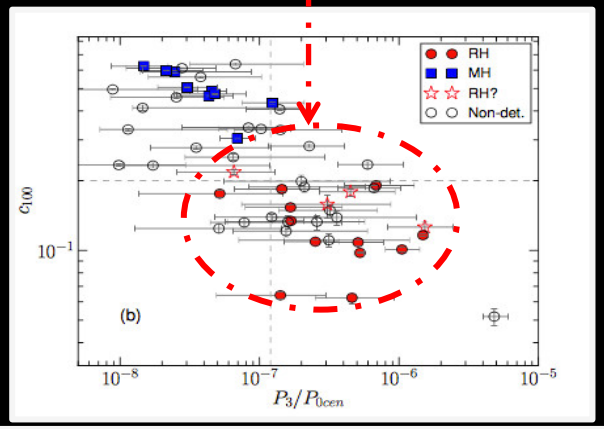
Established results

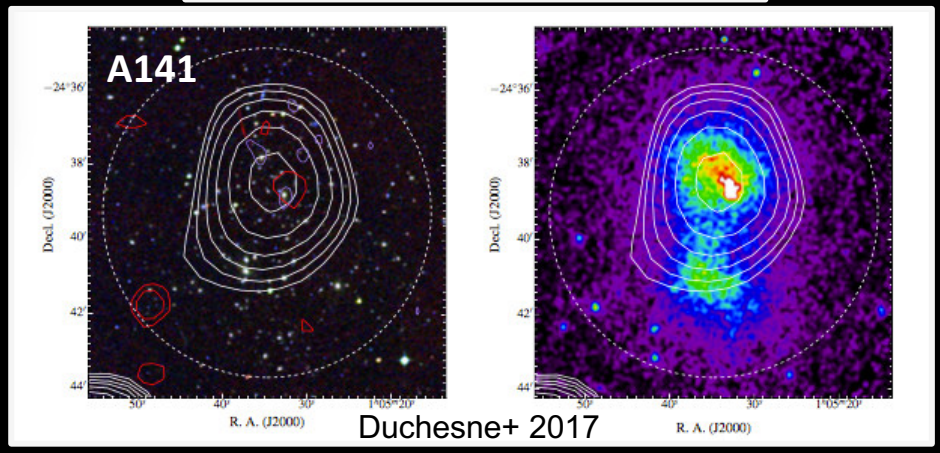
Prediction of the turbulent re-acceleration model:
From GHz radio halos to **USSS radio halos in minor/less massive merging systems**

Still few cases known, but the statistics is changing now with LOFAR, uGMRT and MWA



Cluster in the GMRT RH sample – Upper limit at 610 MHz (Venturi et al. 2007), but morphological parameters of a very disturbed cluster ⇨ MWA detection at 168 MHZ

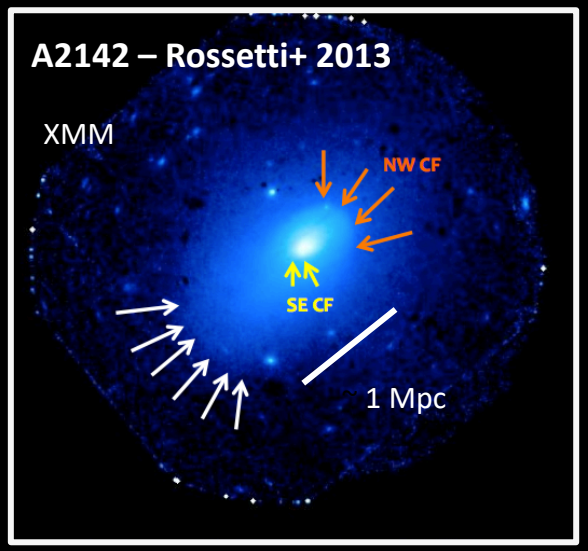


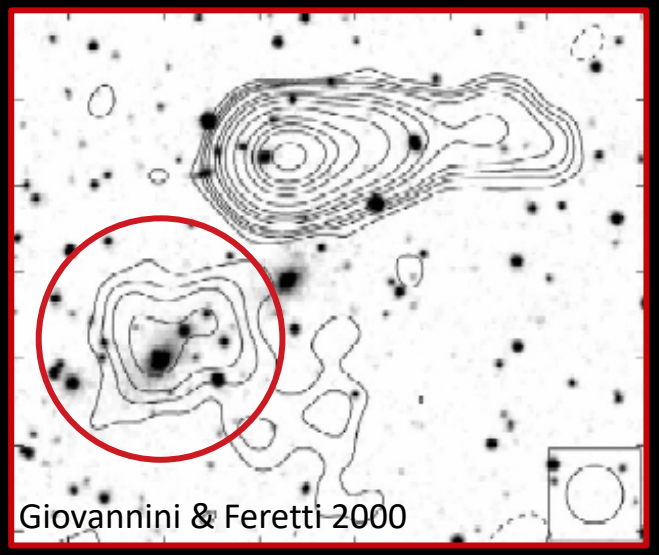


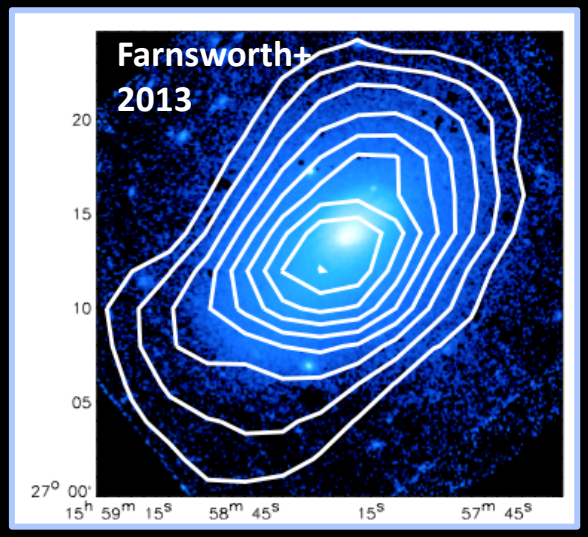
Duchesne+ 2017

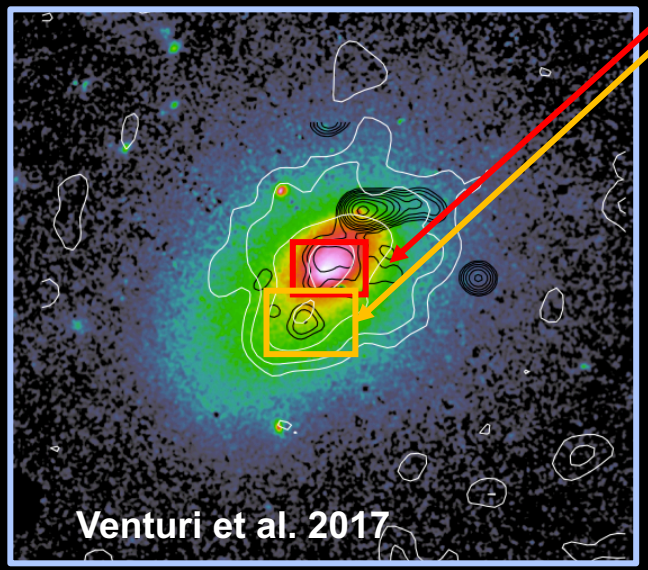
Life is getting more complicated…

The case of A2142 - Venturi et al. 2017









Formerly classified as a mini-halo

GBT, JVLA, GMRT observations show it is a multi component Mpc-scale radio halo

A component coincident with the former "mini-halo", and a second broader component most likely associated with the minor merger/accretion activity on the full cluster scale

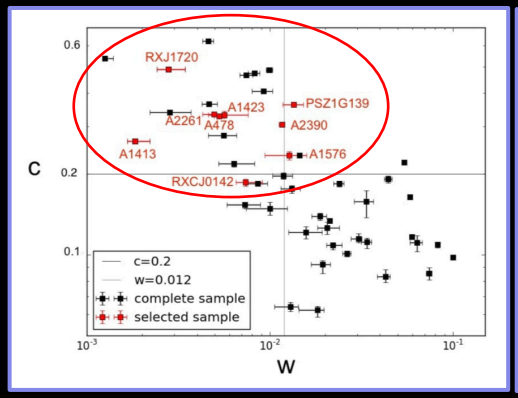
α~1.5-1.6, slightly steeper in the second component

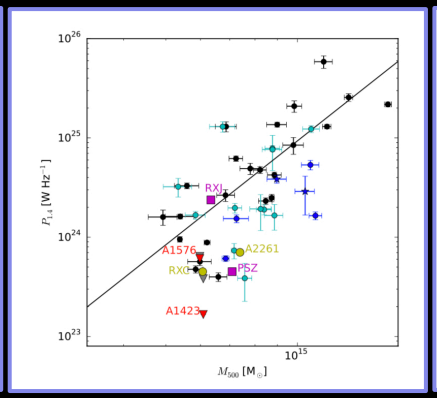
SLOSHING ON THE CLUSTER SCALE?

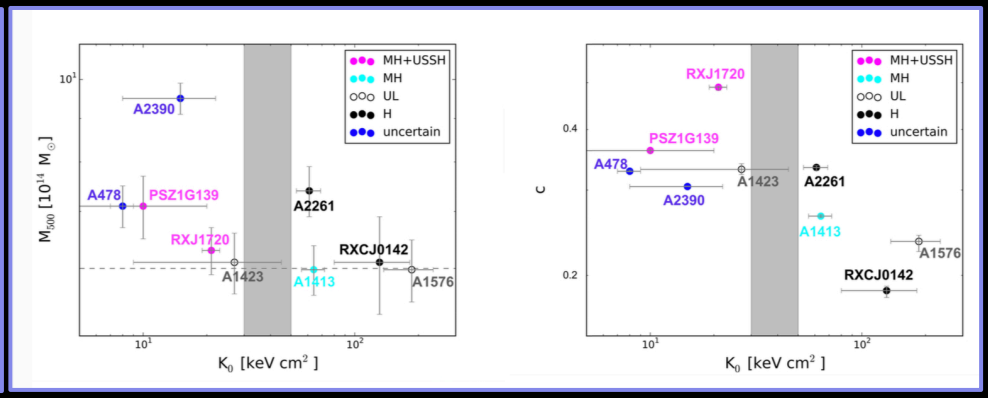
Life is getting more complicated…

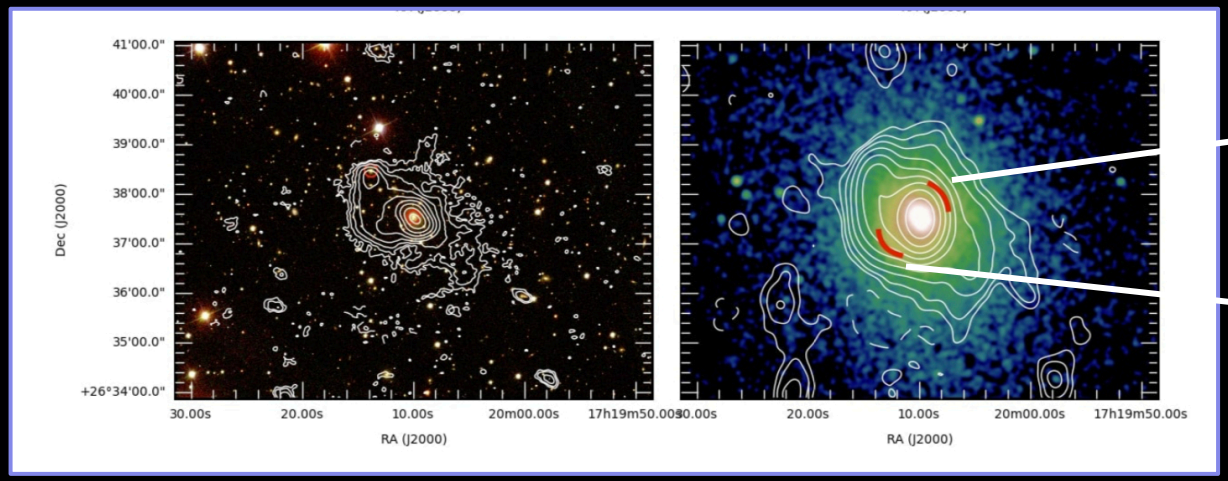
Sample of 9 non merging clusters observed at 144 MHz with LOFAR –
Savini, Bonafede et al. 2019

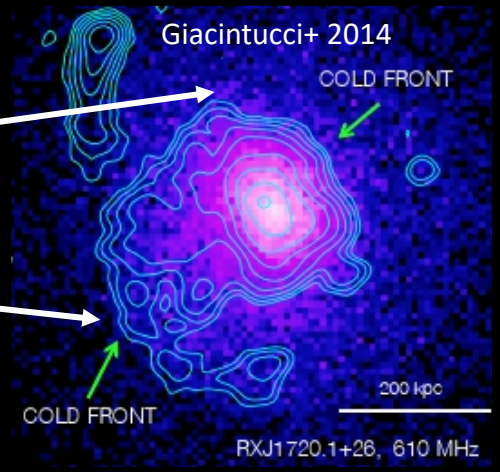
- ✓ Two clusters with USS radio halo surrounding the previously known mini-halo
- ✓ Two USS radio halos in non merging non-CCC
- ✓ 1 mini-halo in a non-CCC

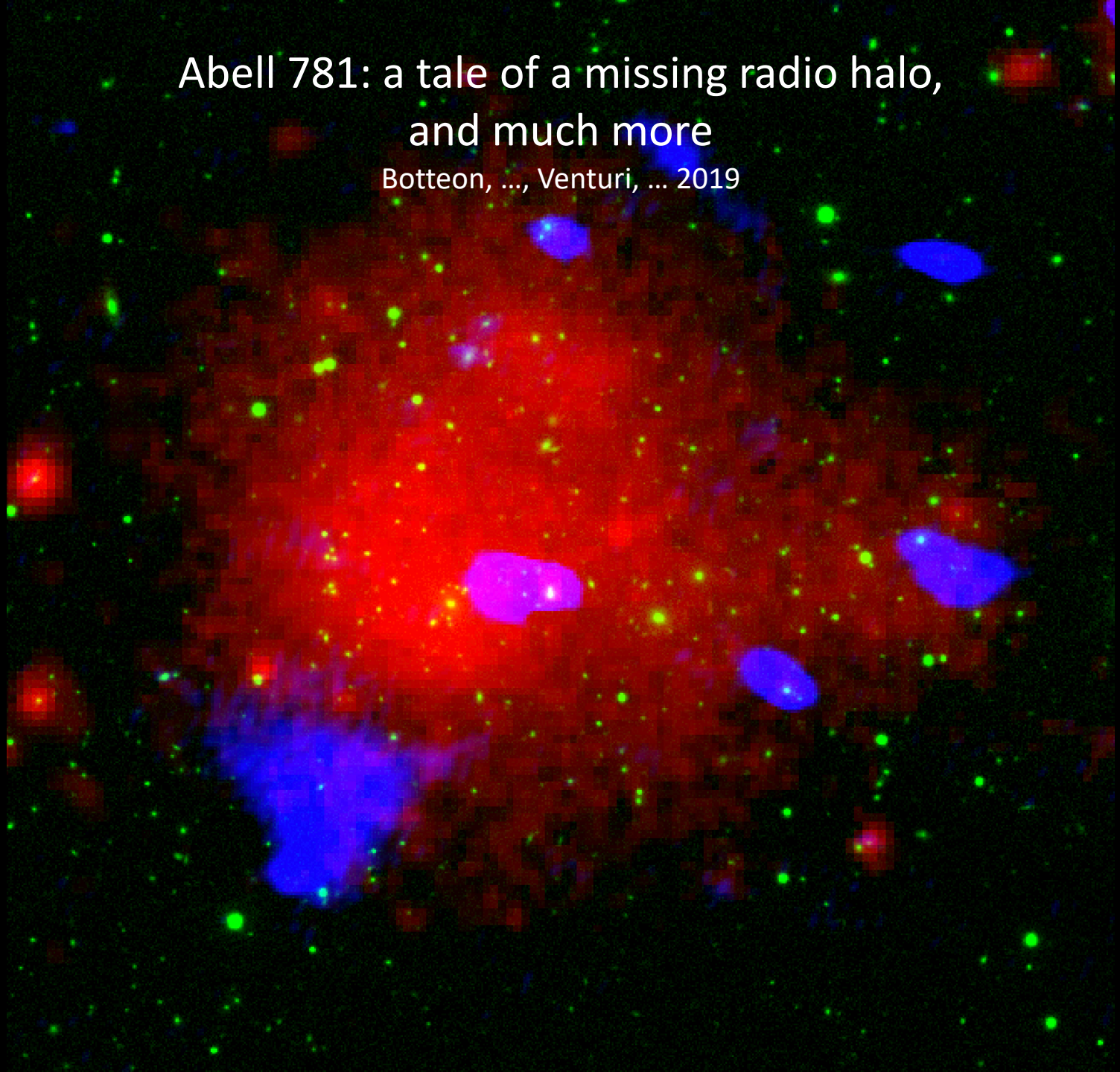











Abell 781: a tale of a missing radio halo,
and much more
Botteon, …, Venturi, … 2019

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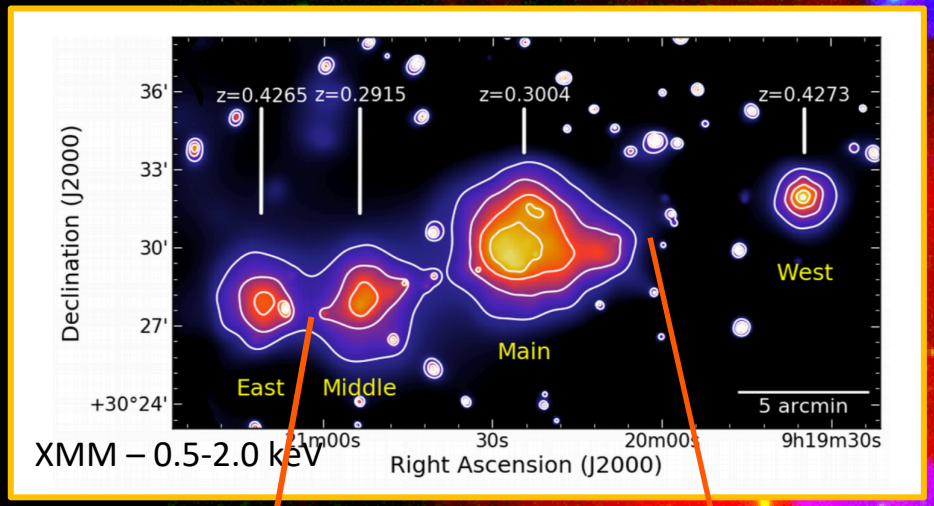
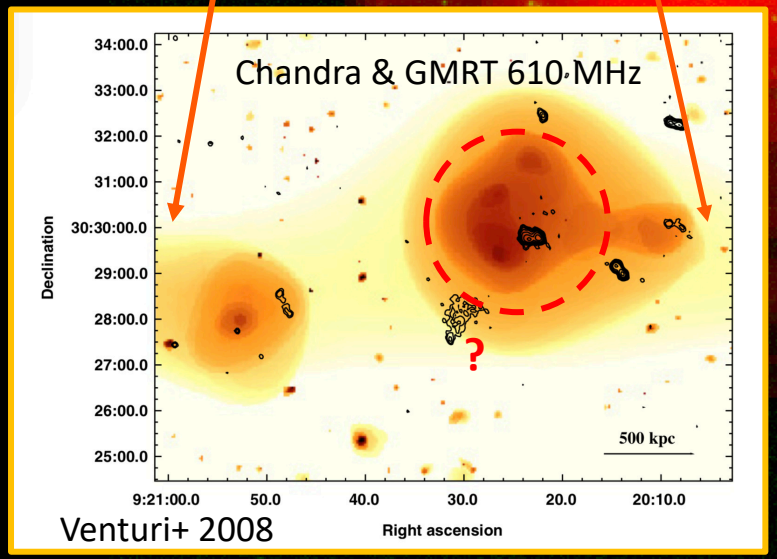


XMM – 0.5-2.0 keV

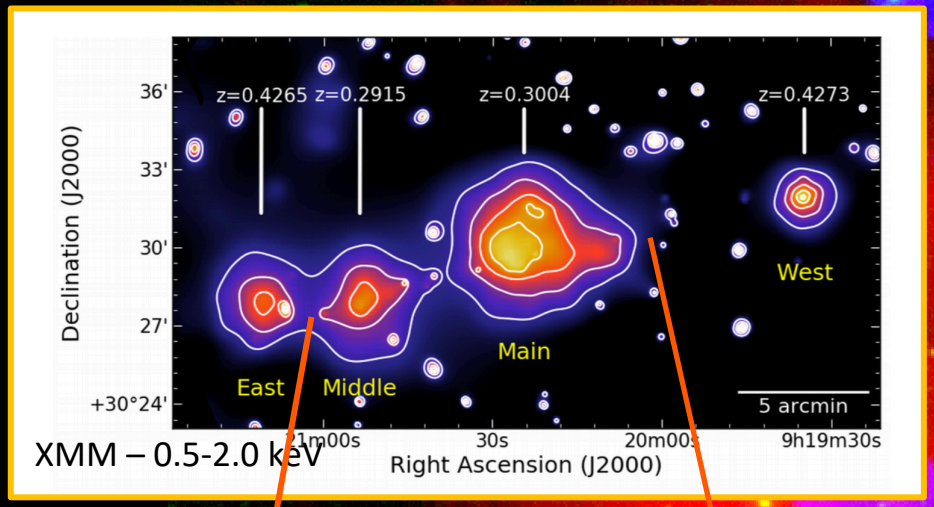


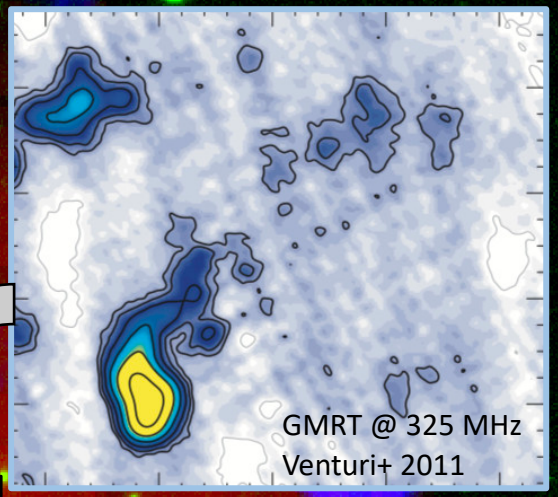
Venturi+ 2008

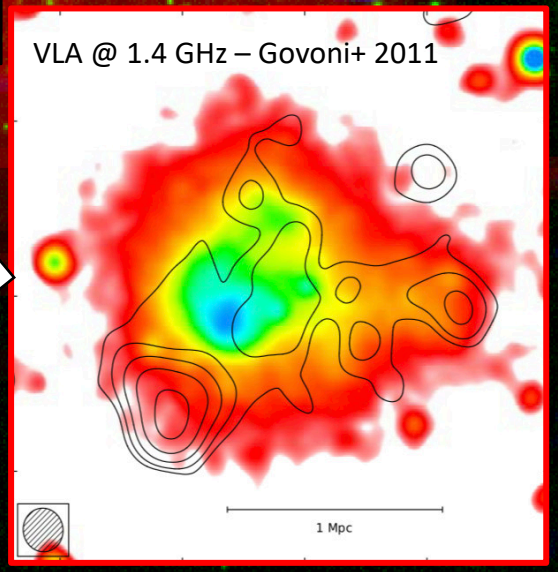
L_X ~10^{45} erg/s

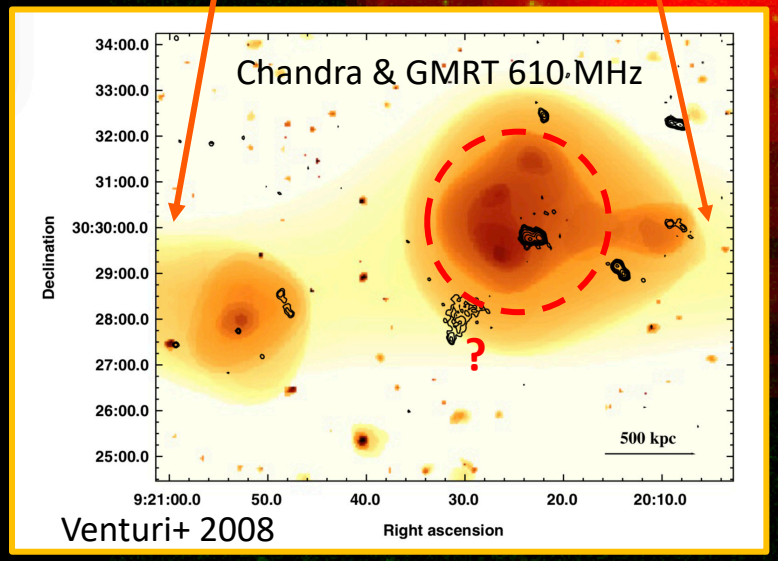
Abell 781: a tale of a missing radio halo, and much more

Botteon, …, Venturi, … 2019



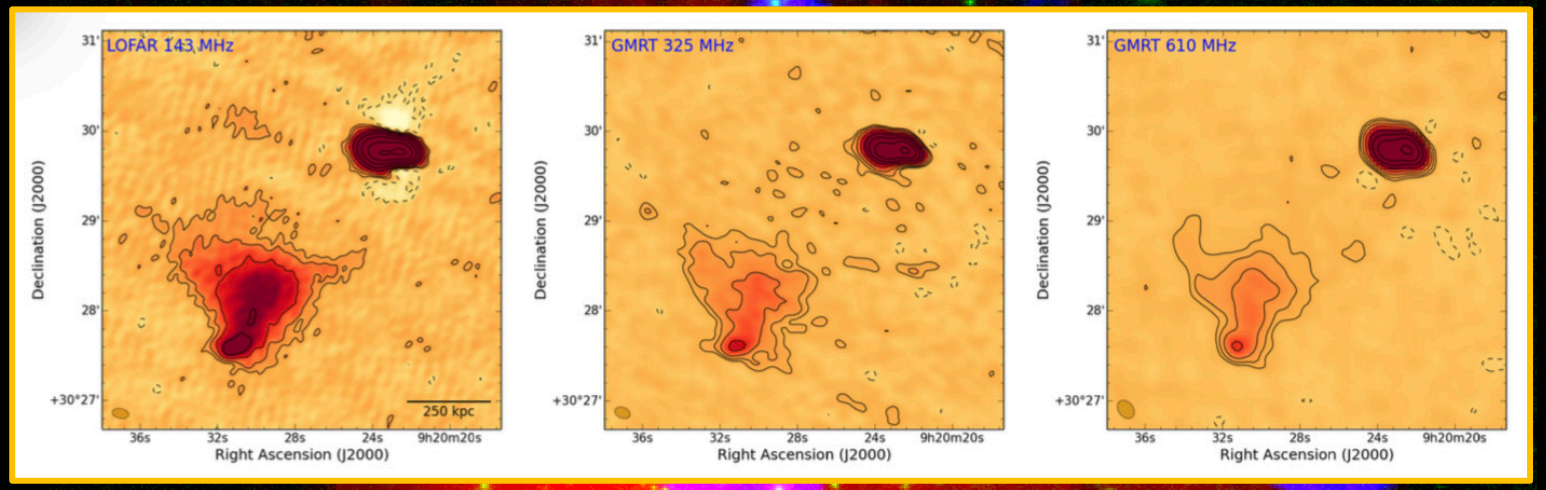






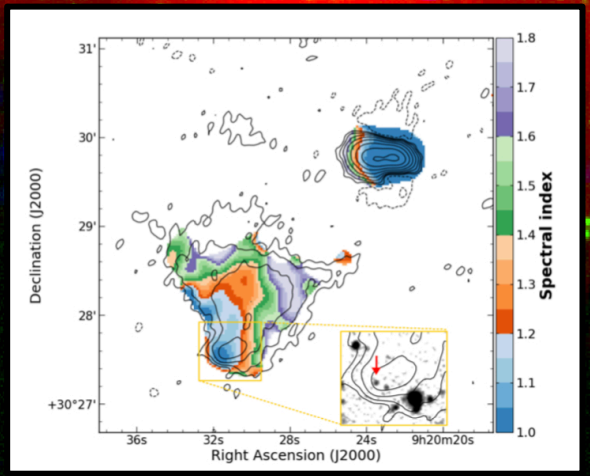
Abell 781: a tale of a missing radio halo, and much more

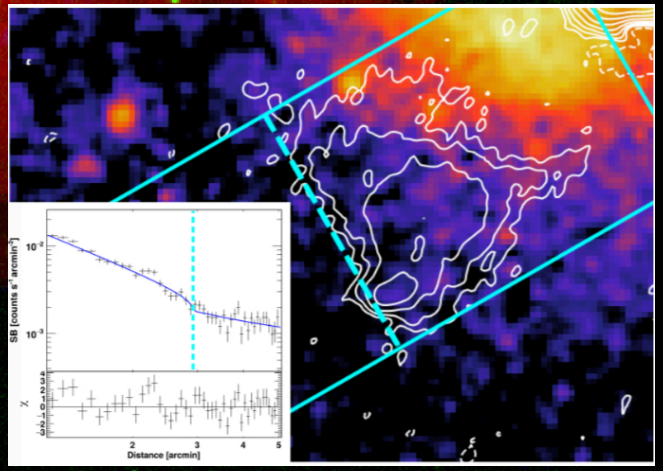
Botteon, …, Venturi, … 2019



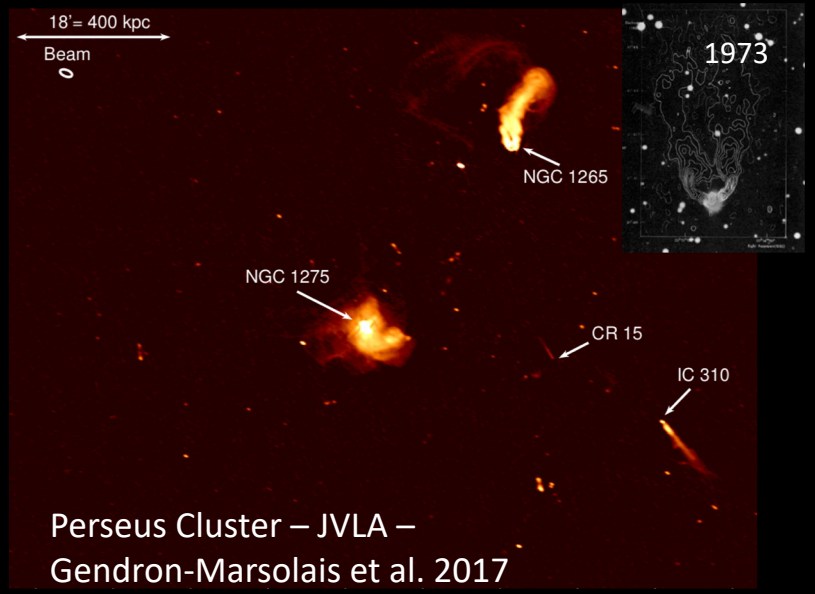
alpha=1.4

- Relic?
- Interaction between a shock and radio plasma from a tailed radio galaxy?

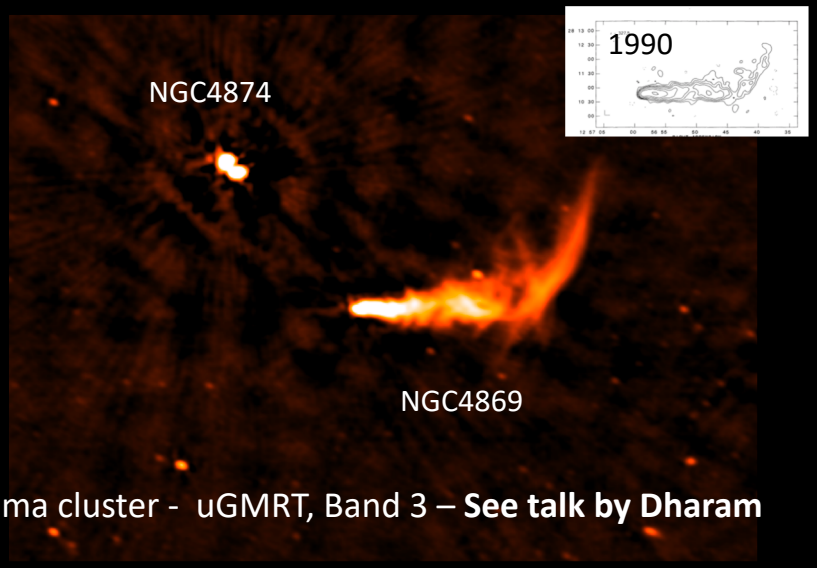




Where AGN science and galaxy cluster science meet



Perseus Cluster – JVLA – Gendron-Marsolais et al. 2017

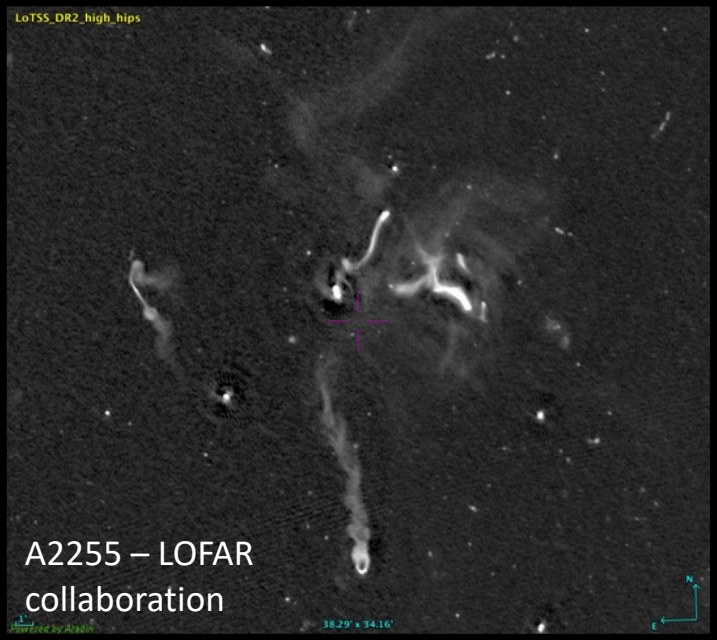


Coma cluster - uGMRT, Band 3 – **See talk by Dharam**

The sensitivity of the present observations show impressive tails of emission from cluster radio galaxies

⇩

- Radio plasma and ICM interaction
- Trajectories of galaxies in their motion within the cluster
- Reservoir of relativistic particles in the ICM

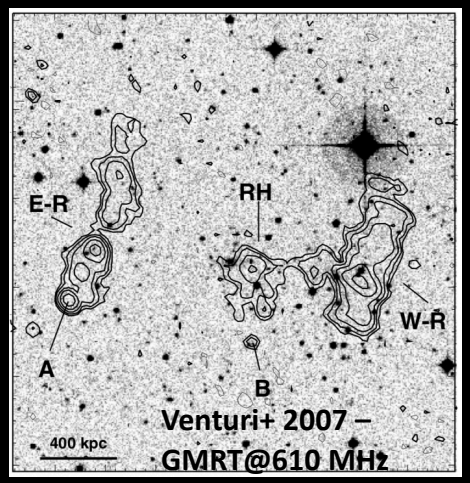


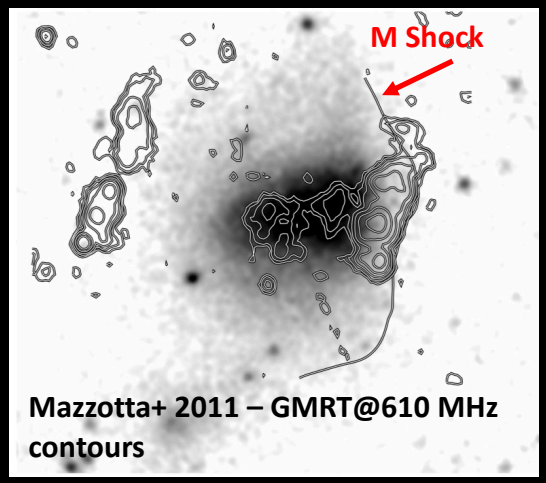
A2255 – LOFAR collaboration

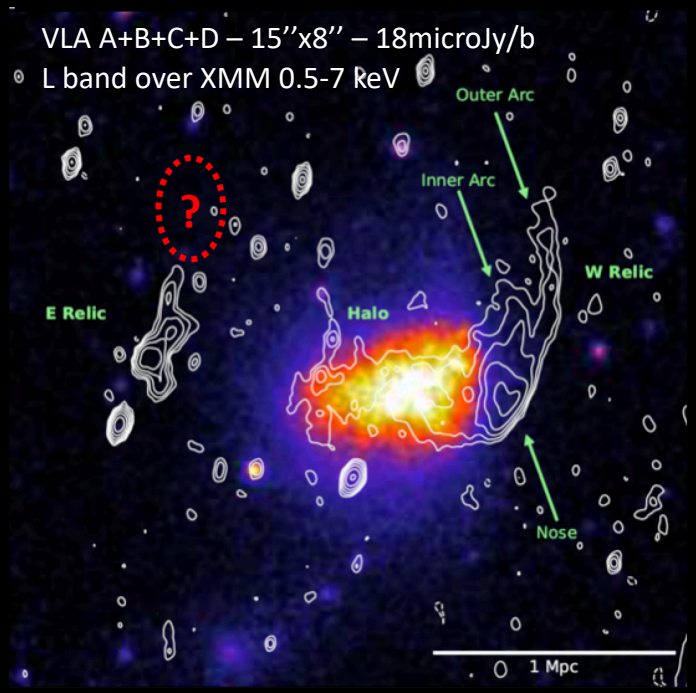
Where AGN science and galaxy cluster science meet

The case of RXCJ1314-2515

Stuardi (PhD student), Bonafede et al. in prep.







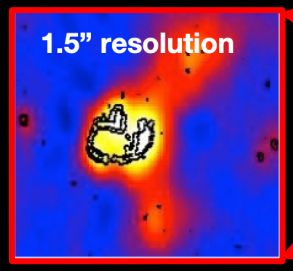
- Structure in the W relic, with two arcs
- Very steep spectrum of the northern part of the E relic (alpha steeper than 1.7)
- Radio halo confined within the brightest X-ray central region even at the very high sensitivity of the VLA L band image

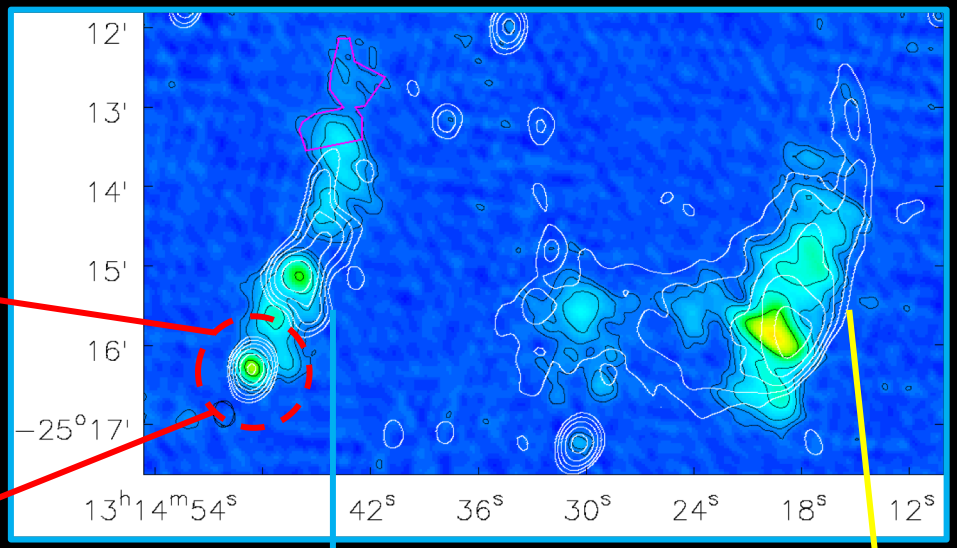
Where AGN science and galaxy cluster science meet

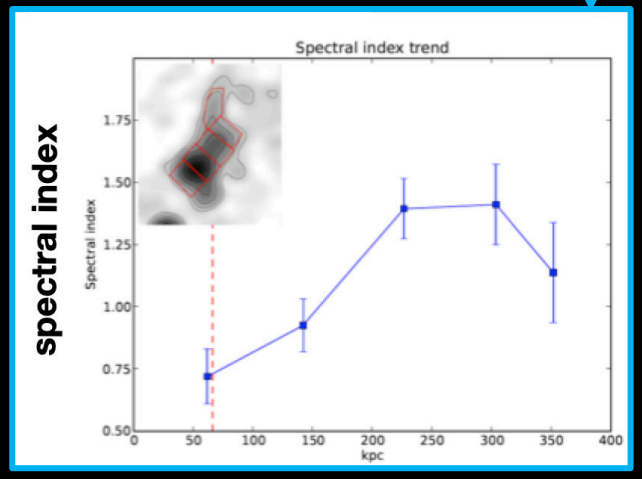
The case of RXCJ1314-2515

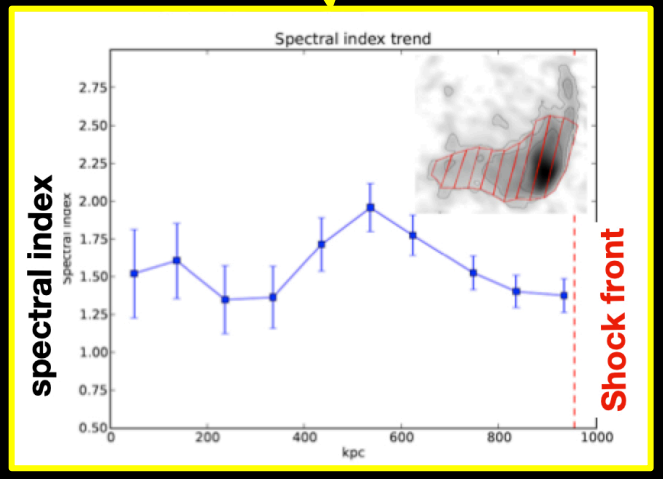
Stuardi (PhD student), Bonafede et al. in prep.

Wide-angle tail source at the southern tip of the E relic









uGMRT – MeerKAT
Synergies and potentials for galaxy cluster and AGN science

RADIO-CLASH-GCAV Project – Diffuse emission and radio galaxy populations
Terni de' Gregory (PhD student), Venturi, Nonino & collaborators

ESO Large Programme **Galaxy Clusters at VIRCAM** – CLASH and RELIC cluster samples (P.I. Nonino)
Proprietary and archival GMRT data
Meerkat-16 and **uGMRT** data for **MACSJ1931** (CCC with mini-halo) and **A1300** (unrelaxed cluster with giant radio halo and at least one relic)

Central region of MACSJ1931 – MeerKAT-16 overlaid on VIRCAM images in filters B, RC and Z – Terni, Venturi, Nonino et al et al. in prep

uGMRT – MeerKAT
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RADIO-CLASH-GCAV Project – Diffuse emission and radio galaxy populations

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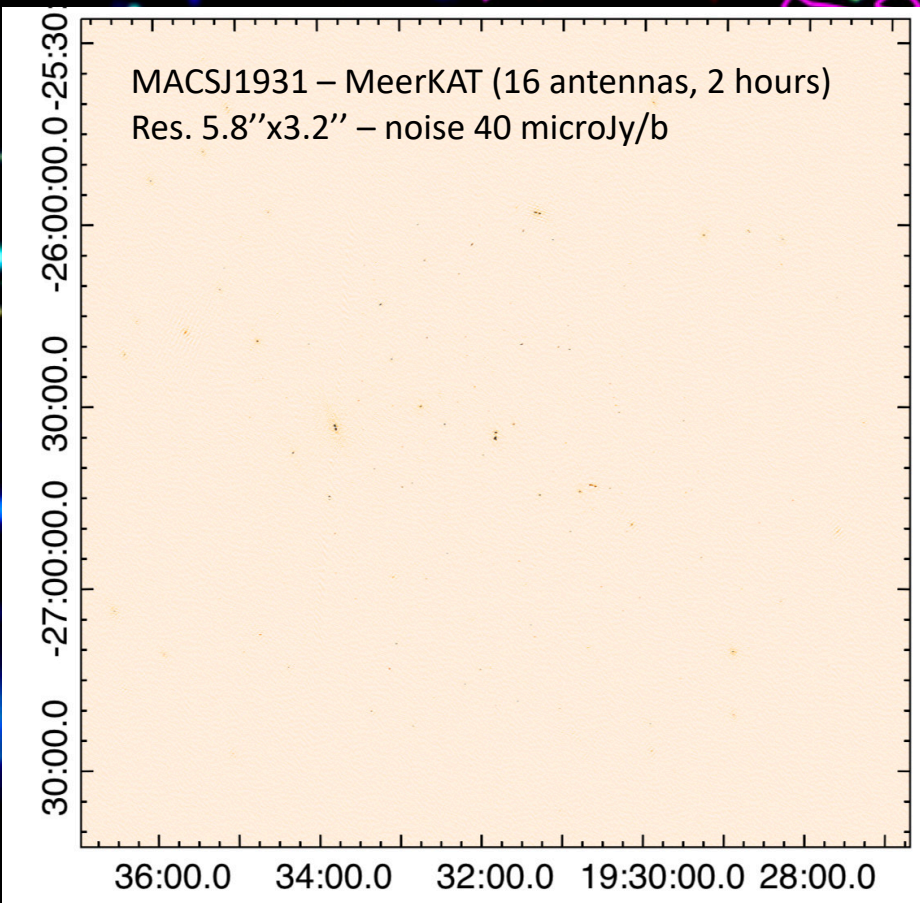

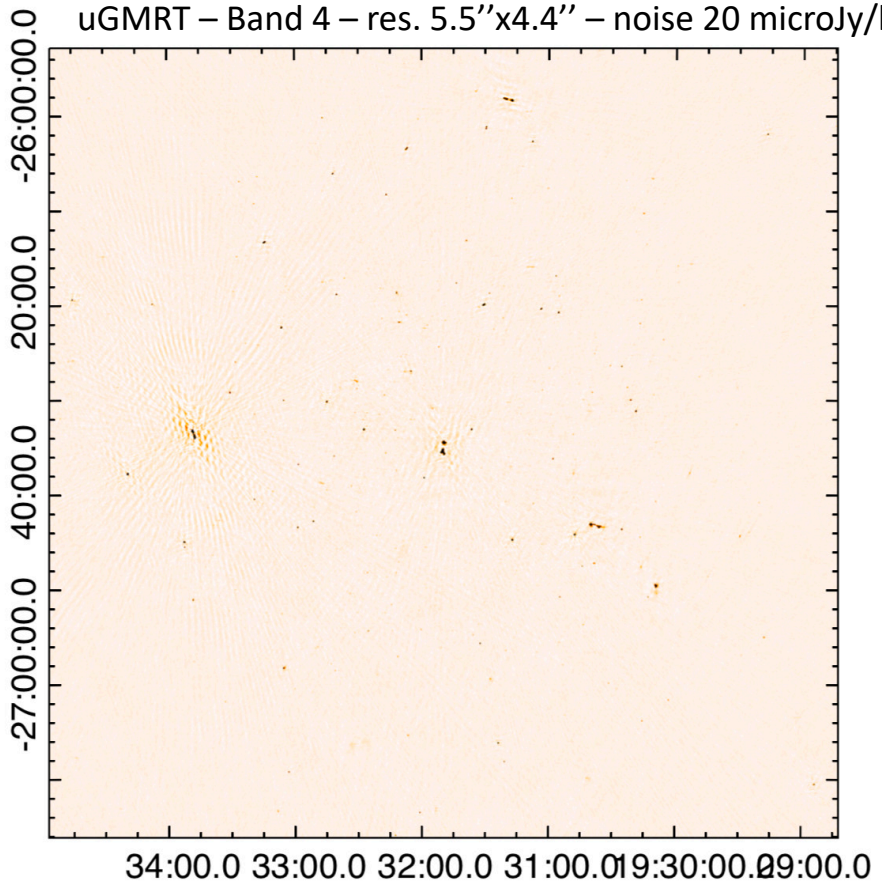

uGMRT – MeerKAT
Synergies and potentials for galaxy cluster and AGN science

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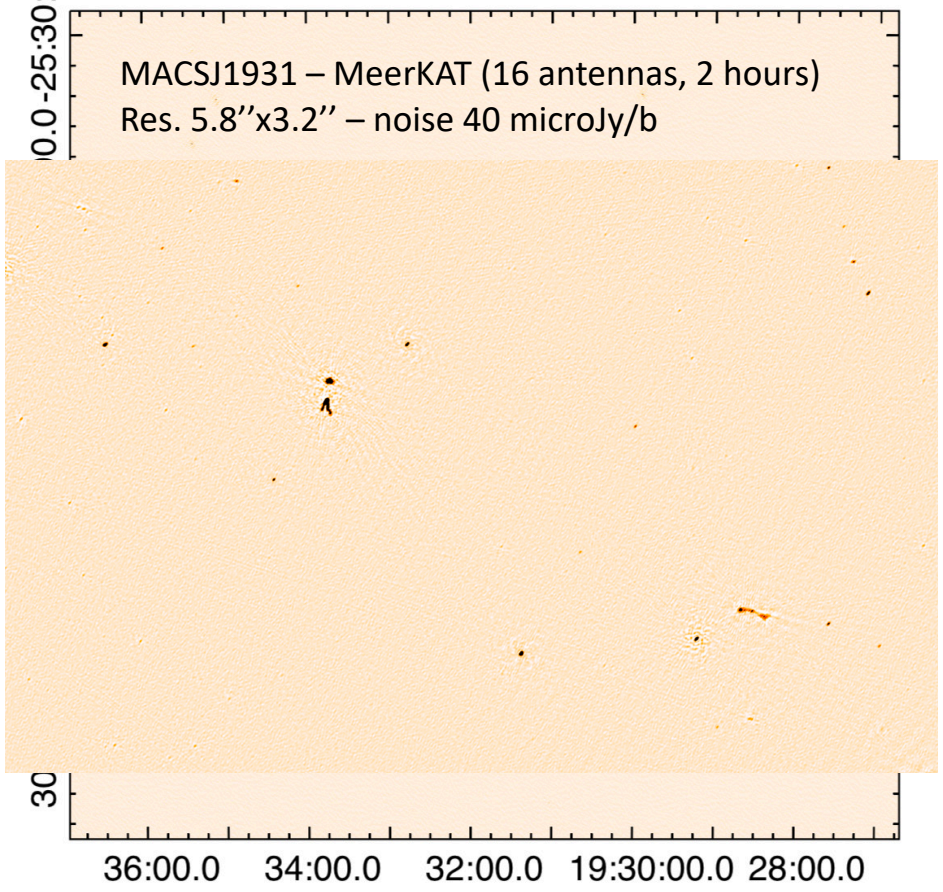
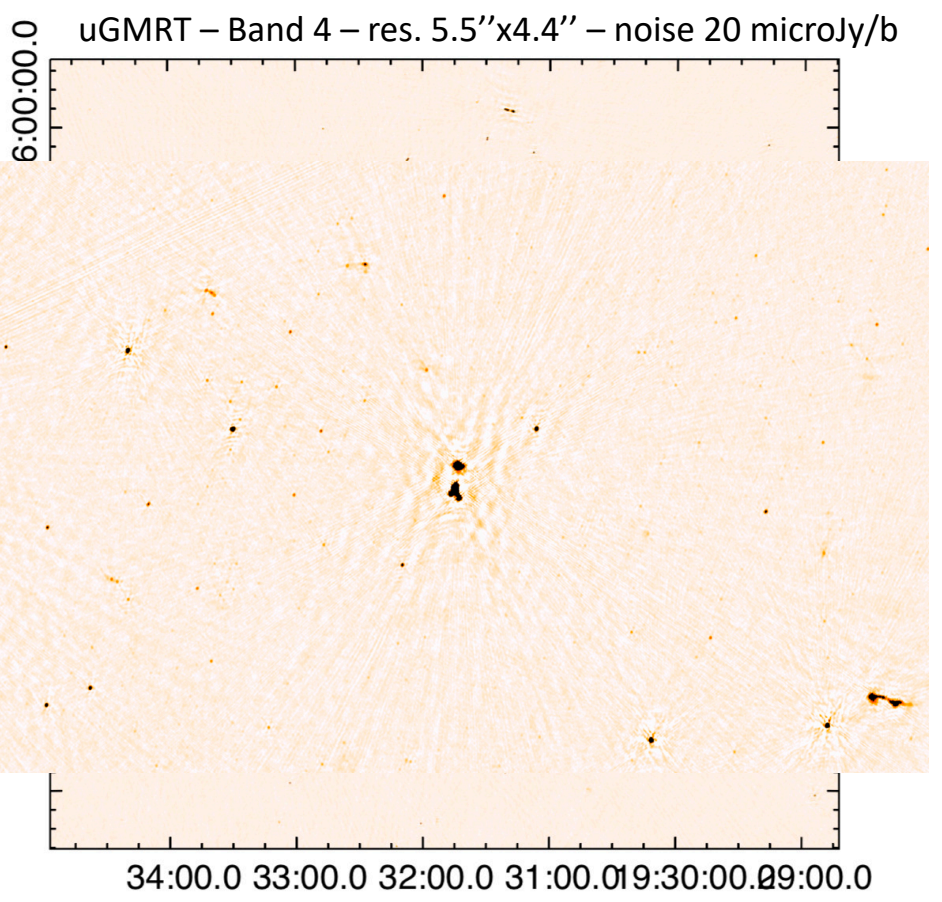




Some final considerations

- Our current knowledge of the origin of diffuse emission in galaxy clusters is solid but still incomplete to account for the variety of the new observational results

- New high sensitivity observations at low frequency show extended USS radio emission surrounding previously classified mini-halos in an increasing number of clusters, pointing to the role of less energetic events and minor mergers in galaxy clusters

- Cluster science and AGN science are meeting: extended/tailed radio galaxies of amazing sizes and beauty provide a direct link to the reservoir of relativistic electrons needed to form diffuse cluster-scale radio sources during cluster mergers and large scale structure formation

✓ The synergy between uGMRT and MeerKAT is very promising for the study of galaxy clusters over a broad range of redshifts and angular scales

A1300 – MeerKAT 16 -2 hours – rms 25 microJy/b – 12.0''x4.6 '' – Terni, Venturi, Nonino et al. in preparation

Some final considerations

Clusters, Relics, and Halos - Chandrasekhar Auditorium (14:15-16:00)

-Conveners: Marc Verheijen

time	title	presenter
14:15	Insight and perspectives in the study of radio emission in galaxy clusters	VENTURI, Tiziana
14:40	Exploring particle (re-)acceleration at low frequencies in merging galaxy clusters	DI GENNARO, Gabriella
14:41	Surveys at ultra-low frequencies: a first look at cosmic rays fate in galaxy clusters	DE GASPERIN, Francesco
15:01	Diffuse Radio Emission in ACTPol Clusters	SIKHOSANA, Sinenhlanhla Precious
15:21	The Corona Borealis supercluster as seen by LOFAR	DRABENT, Alexander

Tea break - Chandrasekhar Auditorium (16:00-16:30)

Clusters, Relics, and Halos - Chandrasekhar Auditorium (16:30-17:55)

-Conveners: Marc Verheijen

time	title	presenter
16:30	A closer look at particle acceleration in galaxy clusters with the Upgraded GMRT	KALE, Ruta
16:55	Diffuse Radio Emission in 'off-state' galaxy clusters.	DWARAKANATH, K
17:15	Searching for Ultra Steep Spectrum Radio Halos with the uGMRT and LOFAR	CUCITI, Virginia
17:35	Insights into cosmic magnetic fields from radio relic observations at metre wavelengths	HOEFT, Matthias

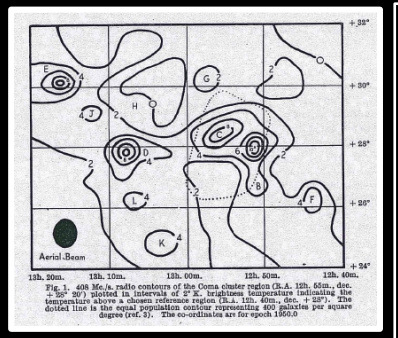
Snacks and poster viewing - NCRA Lawns (17:55-19:00)

- ✓ The results which will be presented in this section clearly show where we are now going with the current generation of radio interferometers
- ✓ We'll miss Simona and Tracy…

A1300 – MeerKAT 16 -2 hours – rms 25 microJy/b – 12.0''x4.6 '' – Terni, Venturi, Nonino et al. in preparation

Brief historical background of observations and knowledge of diffuse cluster scale sources - Halos

Coma C – Large* 1959; Willson 1970



1959 – Discovery of diffuse emission in the Coma cluster

TABLE 1. Parameters of halos

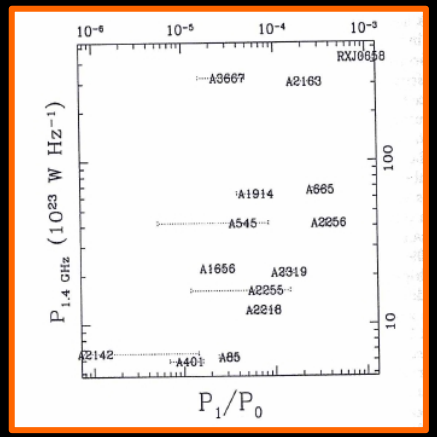
Clus	Size kpc	$P_{1.4}$ W Hz^{-1}	P_{tot} erg s^{-1}	α	u_{min} erg cm^{-3}	U_{min} erg	H_{eq} μG	Ref
A1656	550	3.2×10^{23}	6.1×10^{40}	1.34	2.4×10^{-14}	5.0×10^{58}	0.5	[3]
A2163	500	-	3×10^{41}	-	5.4×10^{-14}	8.0×10^{58}	0.8	[4]
A2218	250	7.9×10^{22}	9.0×10^{39}	1.1	4.3×10^{-14}	5.3×10^{57}	0.7	[5,2]
A2255	725	2.5×10^{23}	1.6×10^{41}	$\gtrsim$1.5	3.1×10^{-14}	5.3×10^{58}	0.6	[6,2]
A2256	900	1.2×10^{23}	1.6×10^{41}	1.9	1.1×10^{-14}	1.1×10^{58}	0.5	[7,8]
A2319	1660	5.1×10^{23}	9.2×10^{40}	1.3	3.7×10^{-14}	7.1×10^{58}	0.6	[2]

Six radio halos known as of 1995 (Feretti & Giovannini)

1959 — 1995 — 2001 — 2002

First correlations between diffuse emission and dynamical status (Buote 2002)

and between radio and X-ray morhpology (Govoni et al. 2001)



Halo and Relic sources detection rate

L_x(0.1–2.4 keV) 10^{44} erg s^{-1}	Relics %	Halos %	Total %
0–3	1.3(1)	–	1.3
3–5	3.0(1)	3.0(1)	6.0
5–7	4.5(1)	4.5(1)	9.0
7–10	16.1(5)	9.7(3)	25.8
>10	8.3(1)	25.0(3)	33.3

Eight radio halos known as of 2002, new additions from NVSS (Giovannini & Feretti)

Brief historical background of observations and knowledge of diffuse cluster scale sources - Halos

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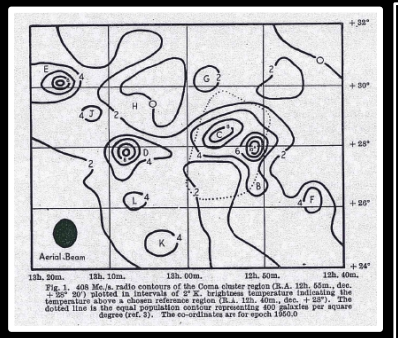

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1959 1995 2001 2005 2015 2002

Turbulent re-acceleration model and start of GMRT RH surveys

First correlations between diffuse emission and dynamical status (Buote 2002)

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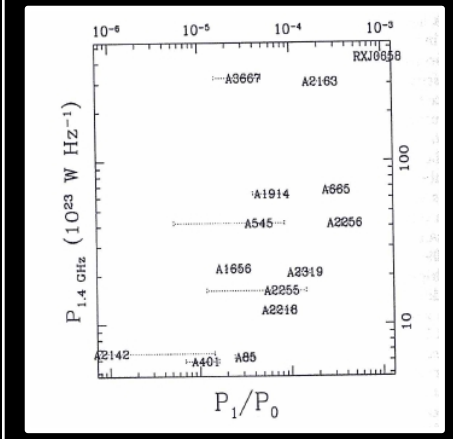

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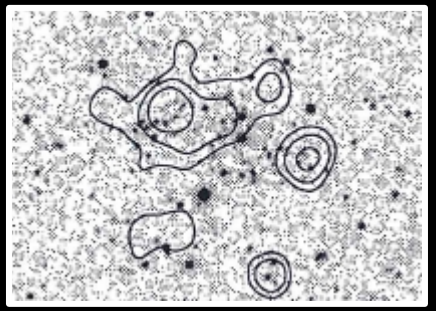
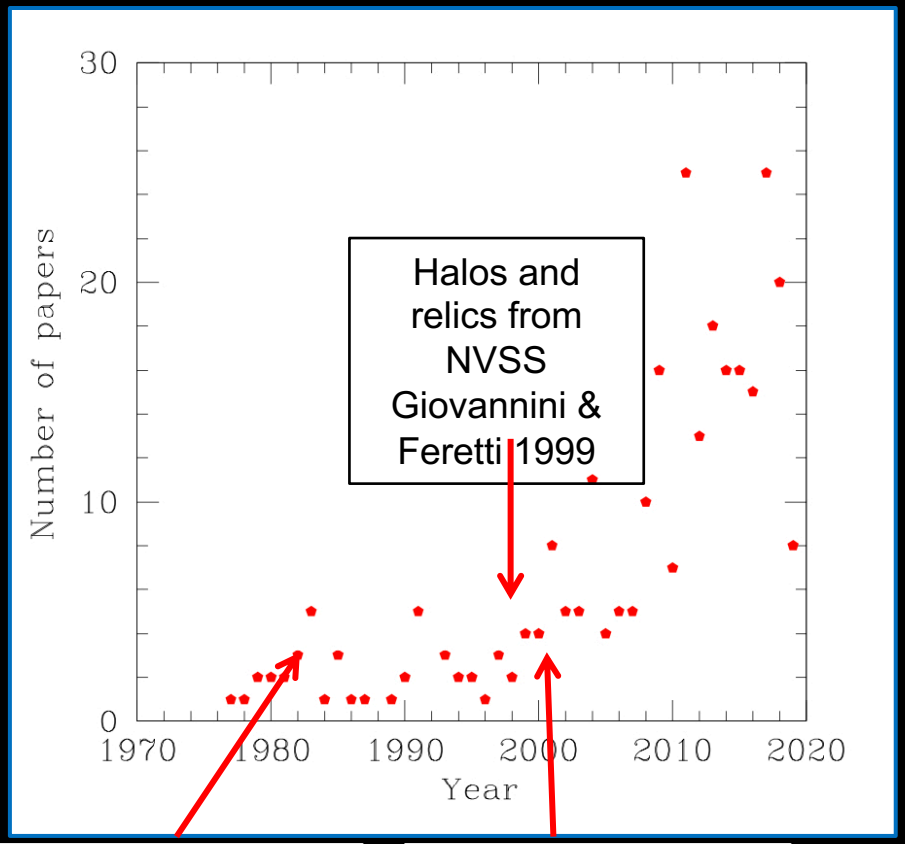
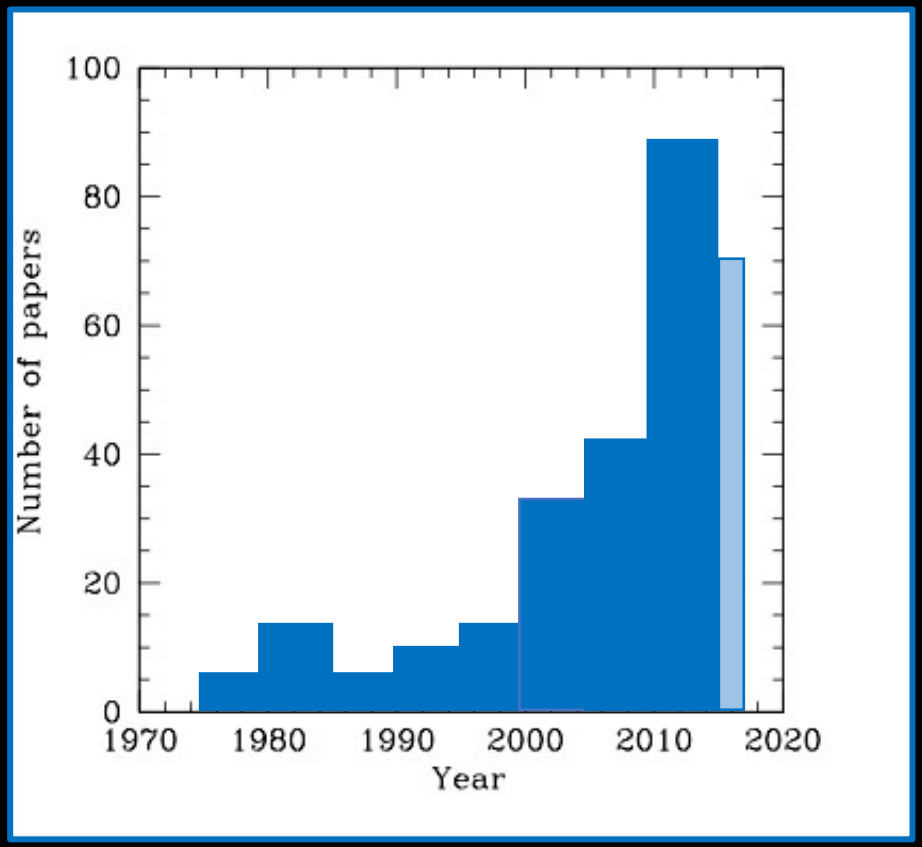


Eight radio halos known as of 2002, new additions from NVSS (Giovannini & Feretti)

Number of papers with the words “radio halo”, “mini-halo”, “relic”, “diffuse/extended emission” in the title





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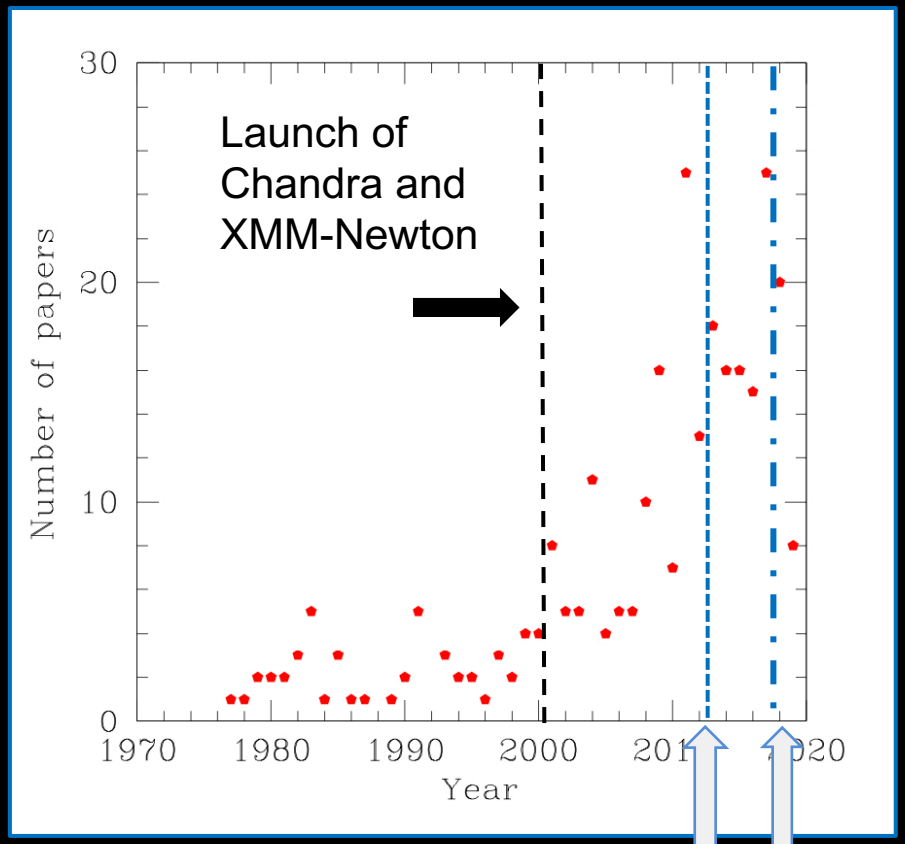
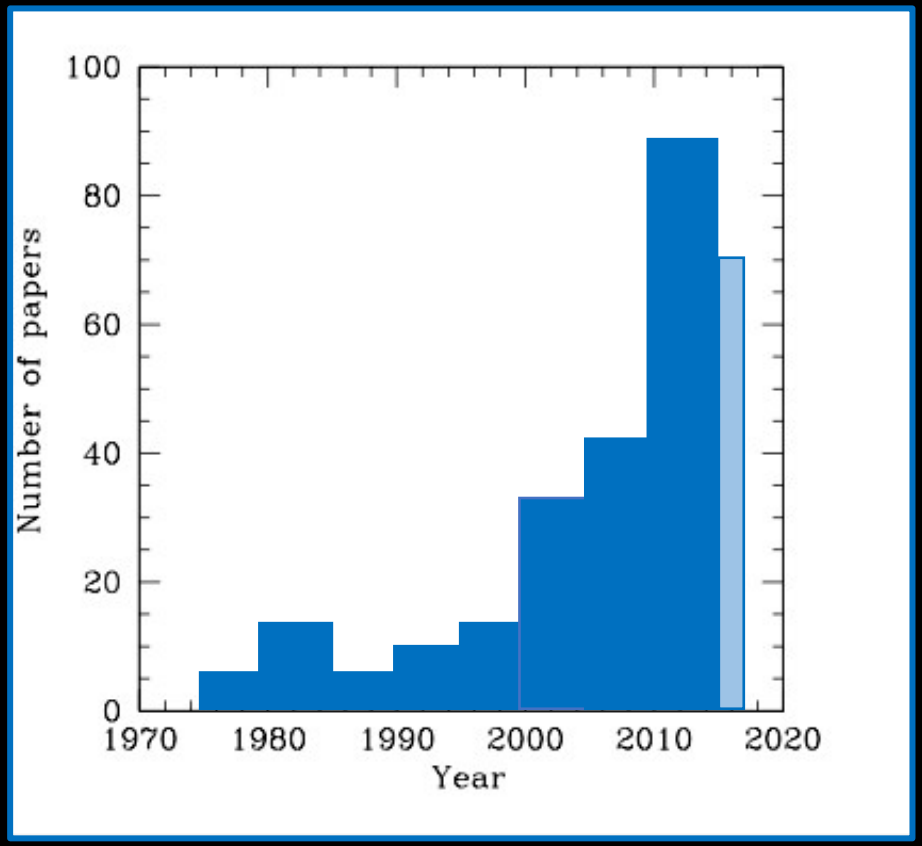
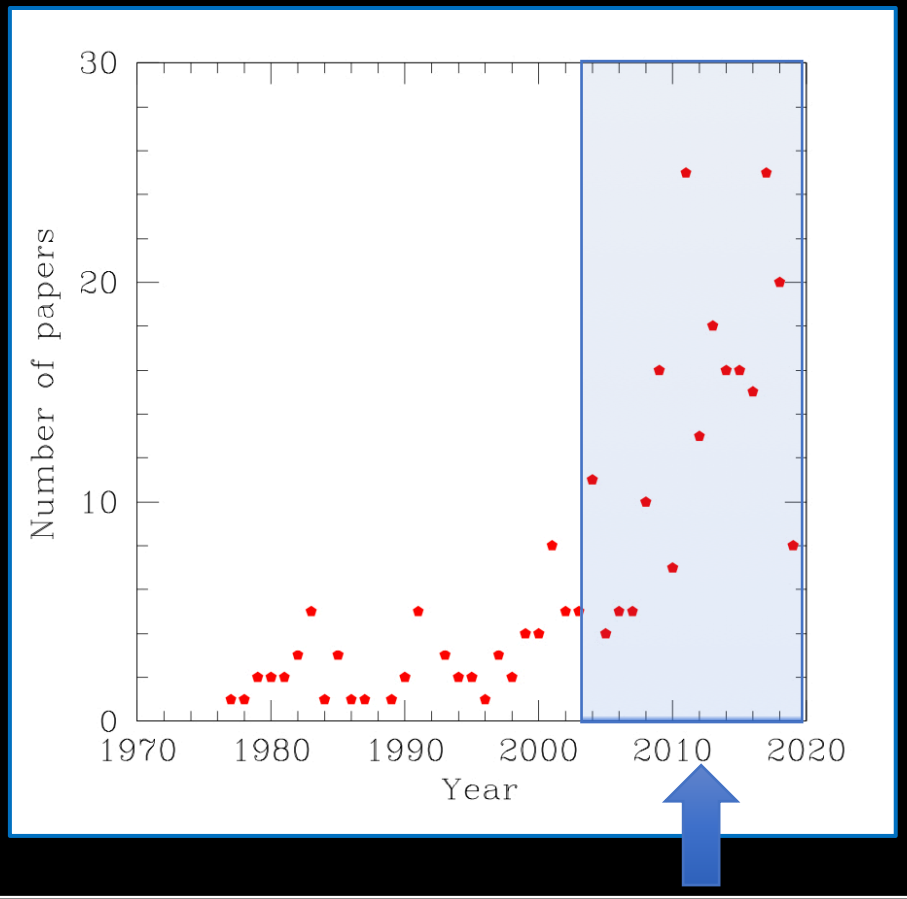


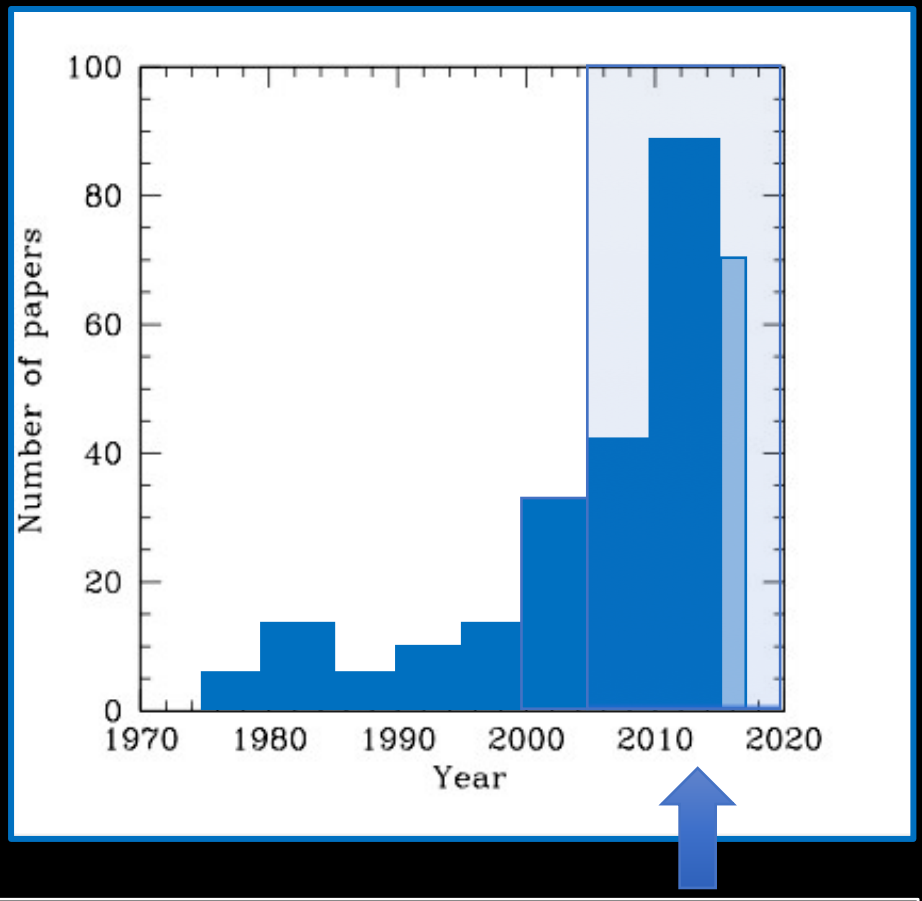


First release of Planck SZ catalogue

LOFAR SPLASH papers

Number of papers with the words “radio halo”, “mini-halo”, “relic”, “diffuse/extended emission” in the title





Dedicated radio surveys of samples of clusters selected following a number of different criteria (X-ray luminosity, mass, redshift)
Exploitation of existing (i.e. NVSS, WSRT) and new (i.e. MWA, TGSS, LOFAR) radio sky surveys

Brief historical background of observations and knowledge of diffuse cluster scale sources - Halos

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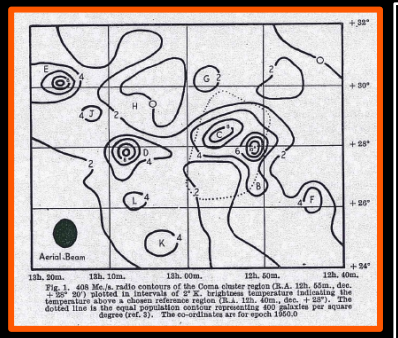
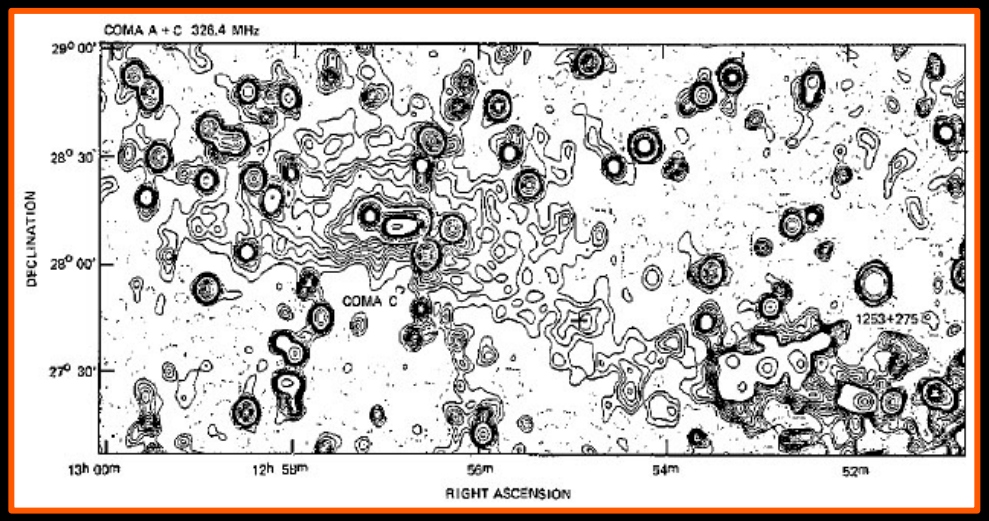


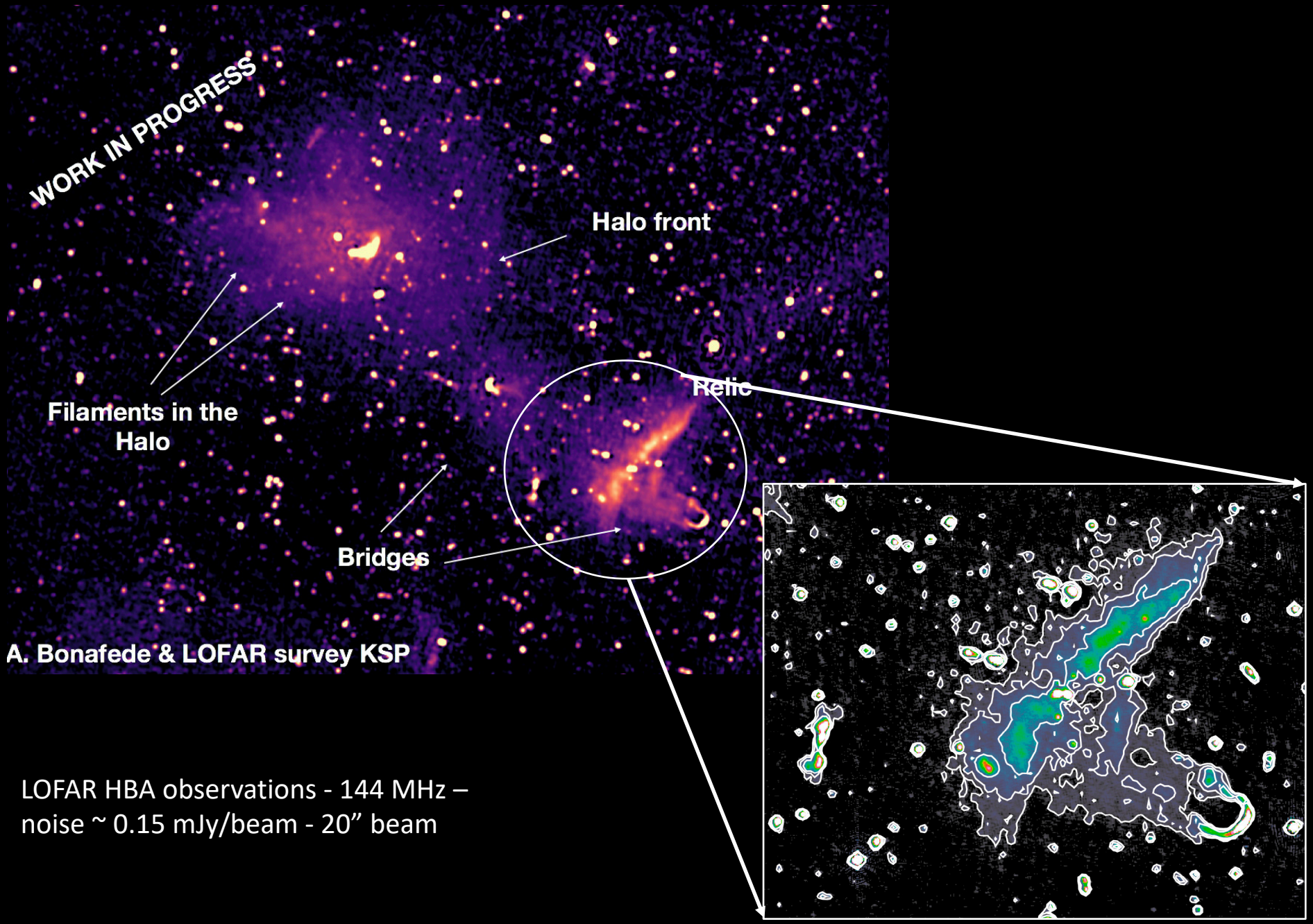
1959 – Discovery of diffuse emission in the Coma cluster

1959 — 1989 — 1995 — 2001 — 2002 — 2005 — 2015



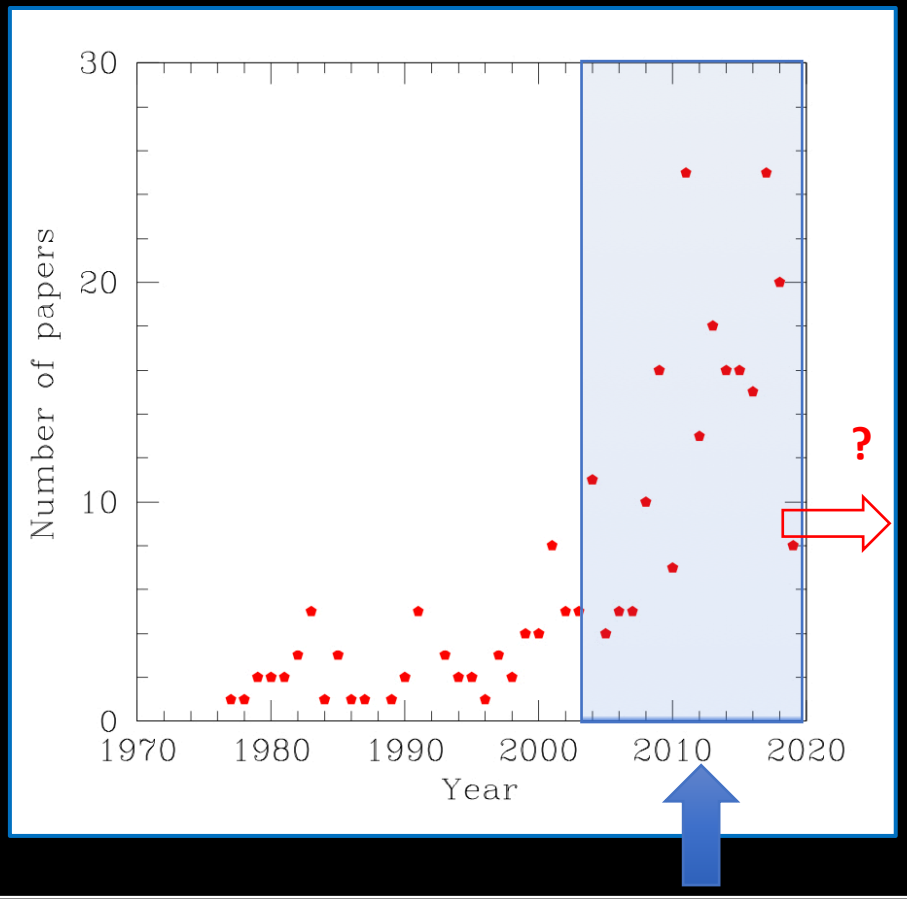
Kim, …, TV, 1989

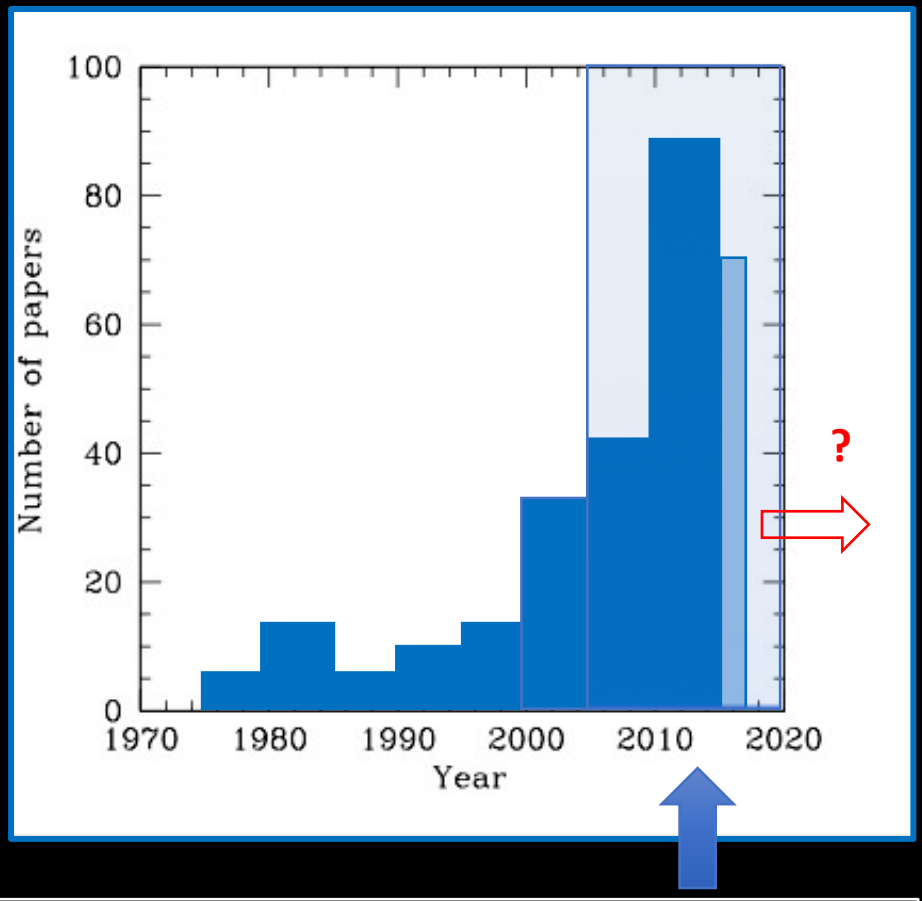
Start of cluster science with LOFAR, uGMRT, JVLA



LOFAR HBA observations - 144 MHz –
noise ~ 0.15 mJy/beam - 20” beam

Number of papers with the words “radio halo”, “mini-halo”, “relic”, “diffuse/extended emission” in the title





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Exploitation of existing (i.e. NVSS, WSRT) and new (i.e. MWA, TGSS, LOFAR) radio sky surveys

THANK YOU FOR YOUR ATTENTION