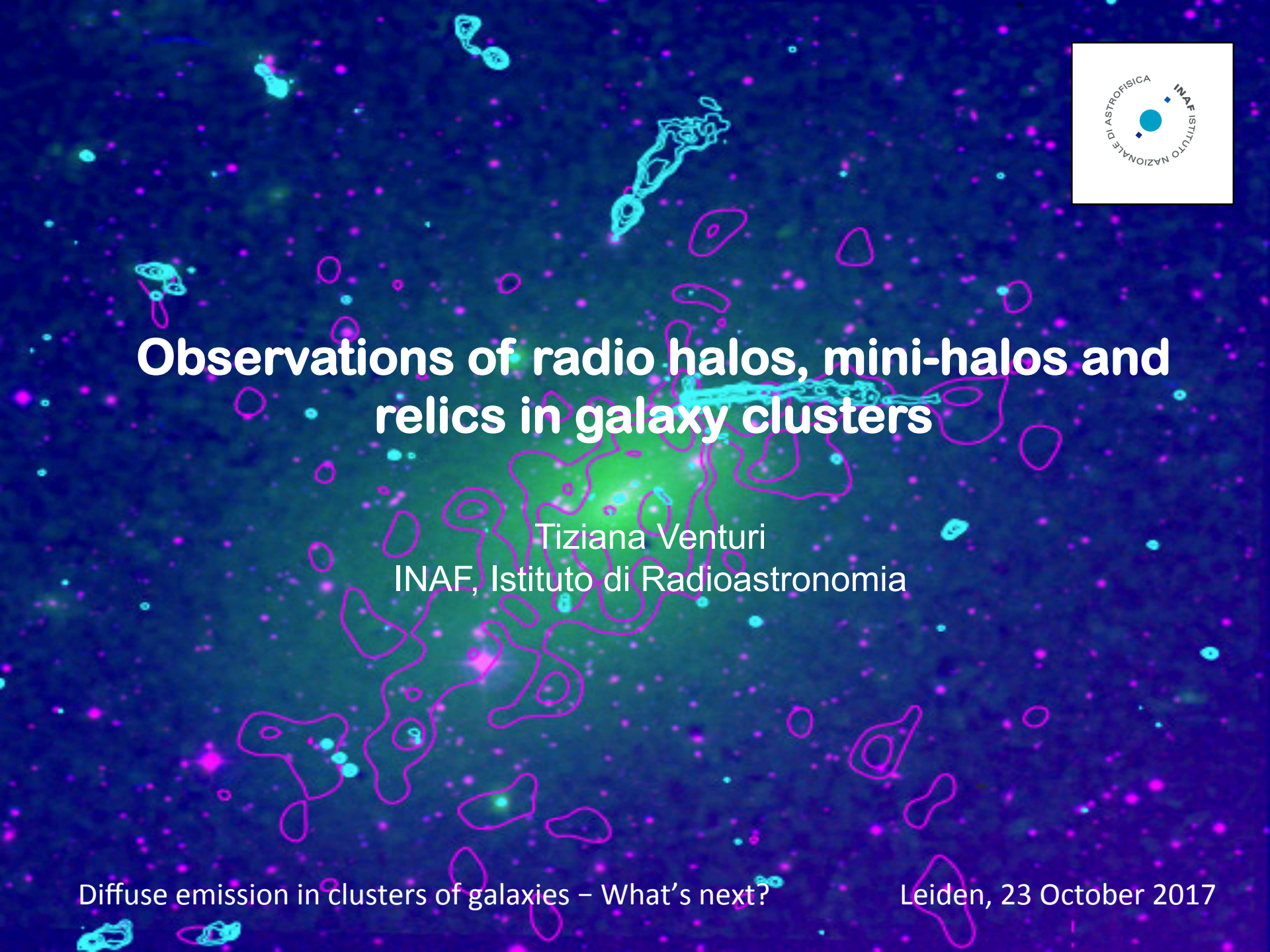
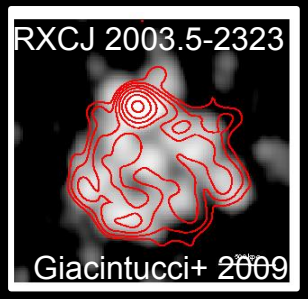


Observations of radio halos, mini-halos and relics in galaxy clusters

Tiziana Venturi
INAF, Istituto di Radioastronomia

Diffuse emission in clusters of galaxies – What's next? Leiden, 23 October 2017

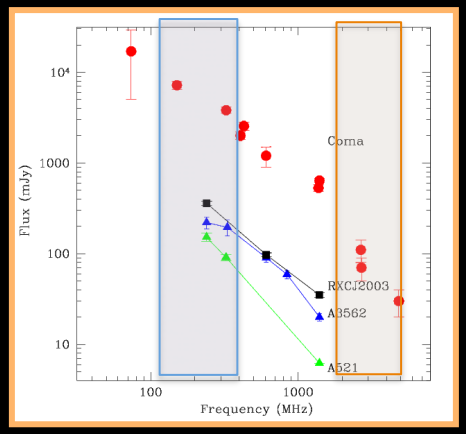


CLUSTER SCALE: GIANT RADIO HALOS

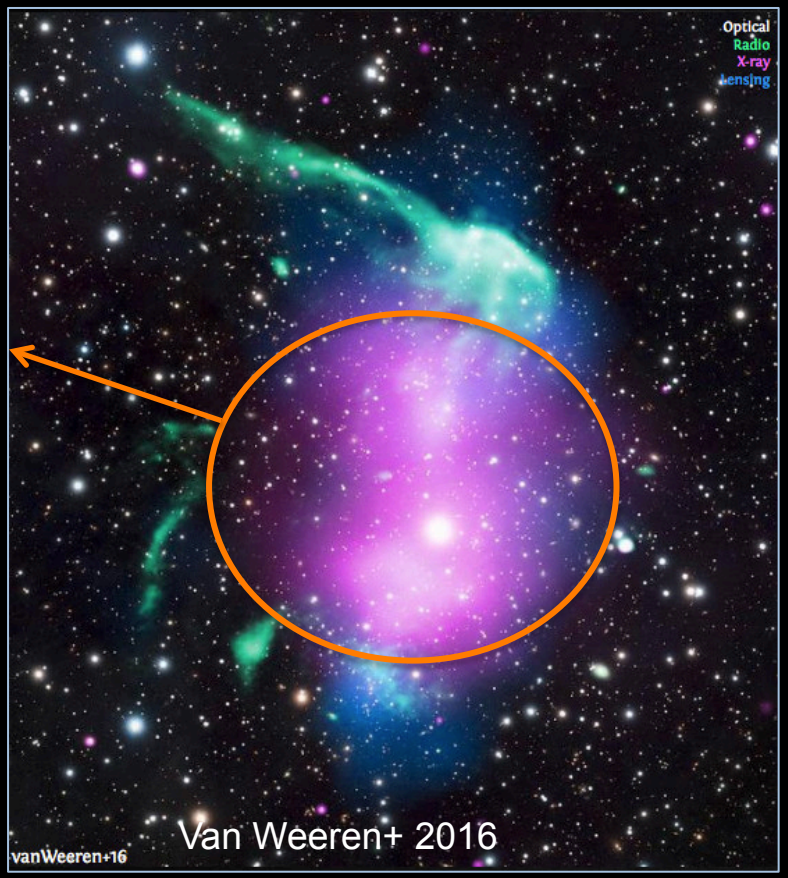
Relativistic particles and magnetic fields spread over Mpc volumes

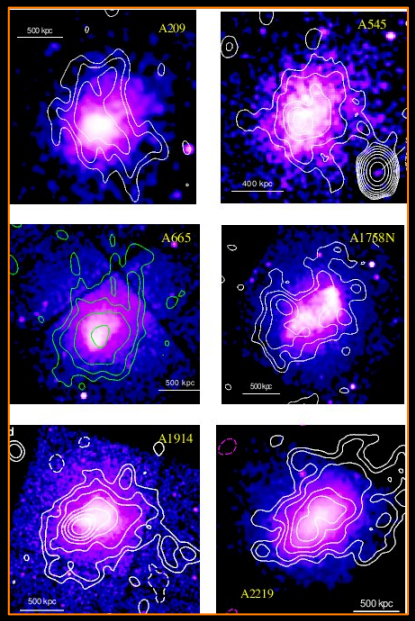
Present in few tens of galaxy clusters

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



From Venturi 2011



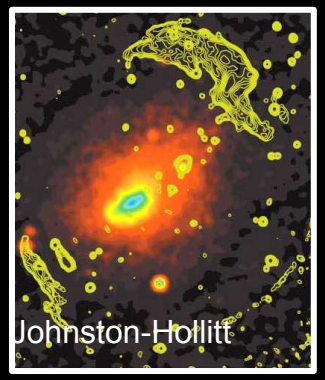


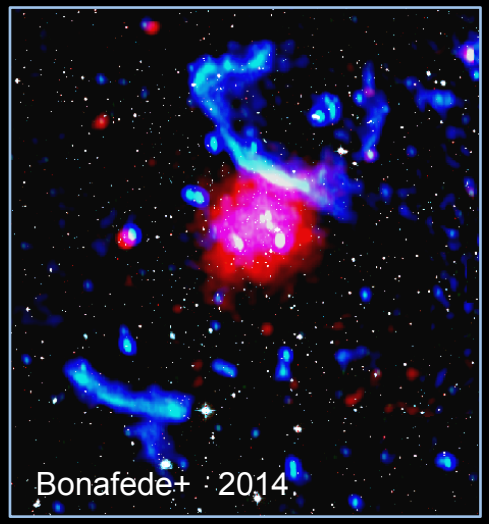
Images from S. Giacintucci

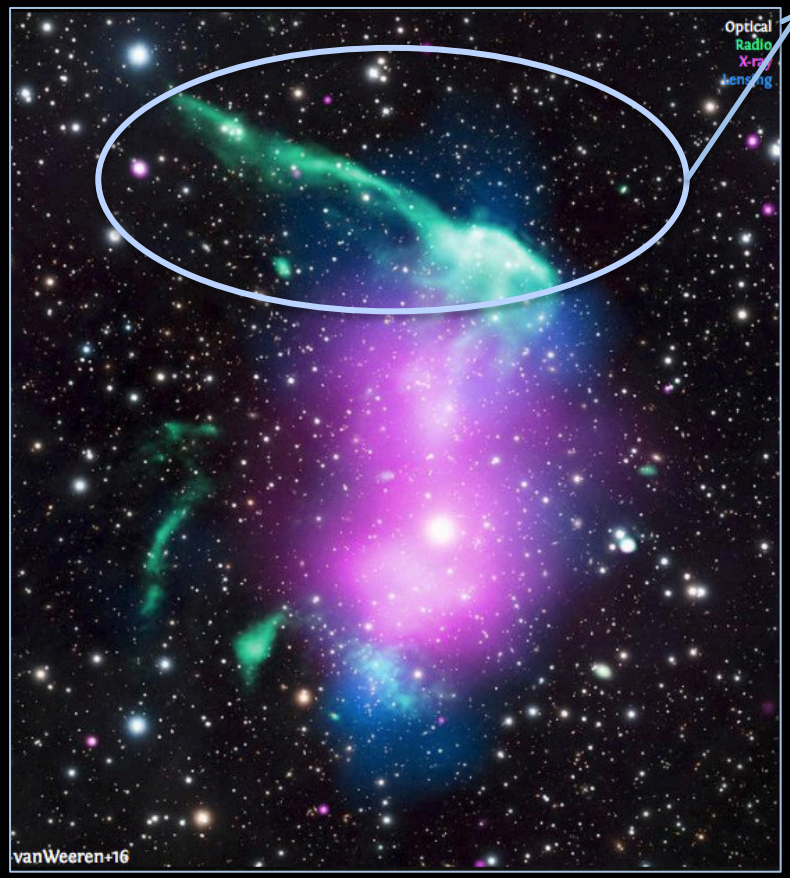
Detectability depends on frequency, array sensitivity, uv-coverage, multiresolution

CLUSTER OUTSKIRTS: RELICS

Relativistic particles and magnetic fields spread over Mpc volumes



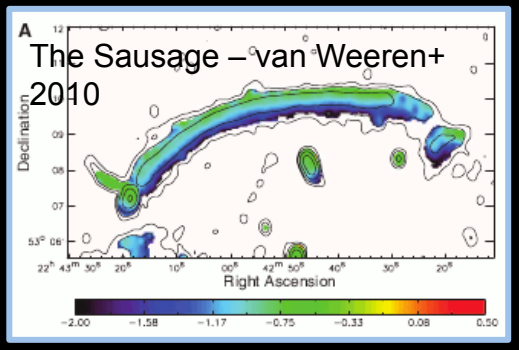




~few tens of relics & candidates

~ 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

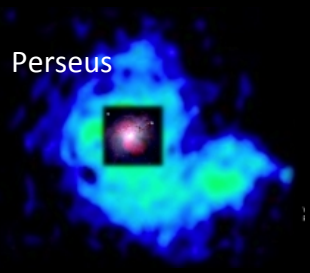


- Polarized (up to 30%)

↓

Mpc scale magnetic fields with some degree of order

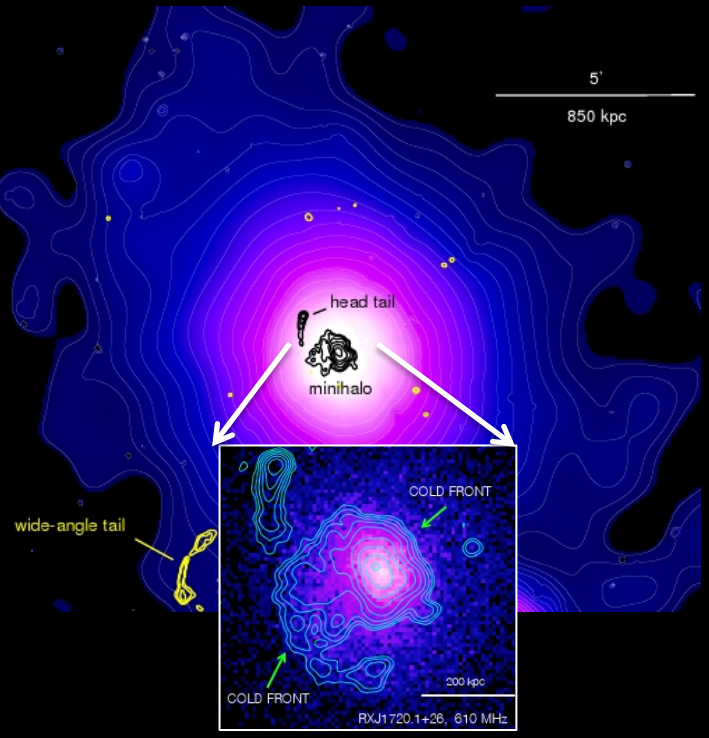
CLUSTER CORES: RADIO MINI-HALOS



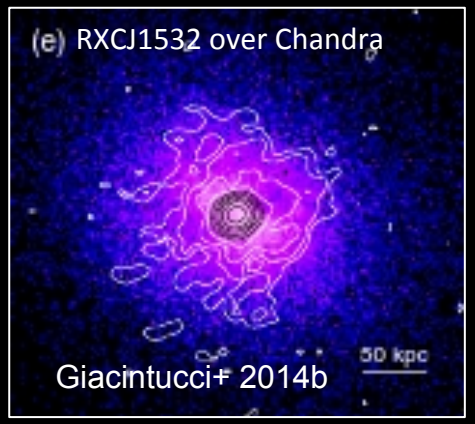
Present so far in ~ 20 galaxy clusters

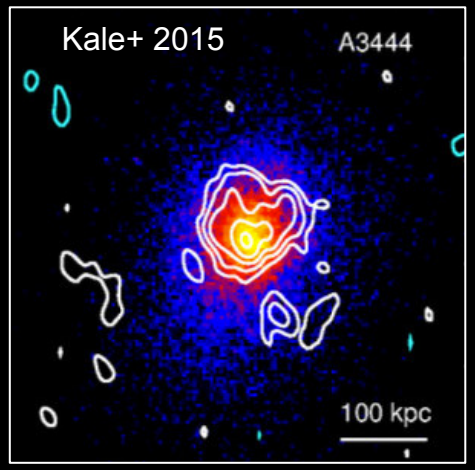
~ 100 – 400 kpc in size
- Steep spectrum (α~1.2-1.5 and steeper)
- (sub) μJy/”^{2} surface brightness
- Sharp surface brightness cutoff
- Located at the peak of central X-ray brightness distribution
- Central BCG is always a radio source

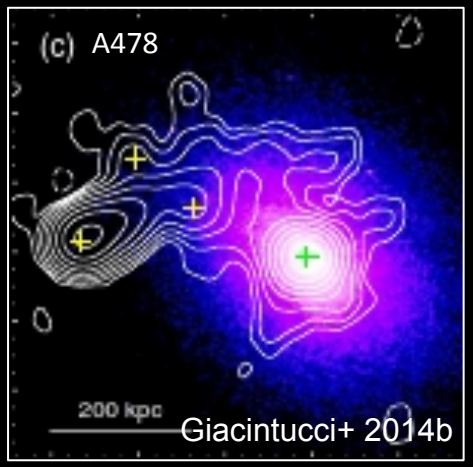
Different properties of clusters hosting mini-halos and GRH known for a long time



RXCJ1720.1+2638
Giacintucci+ 2014a







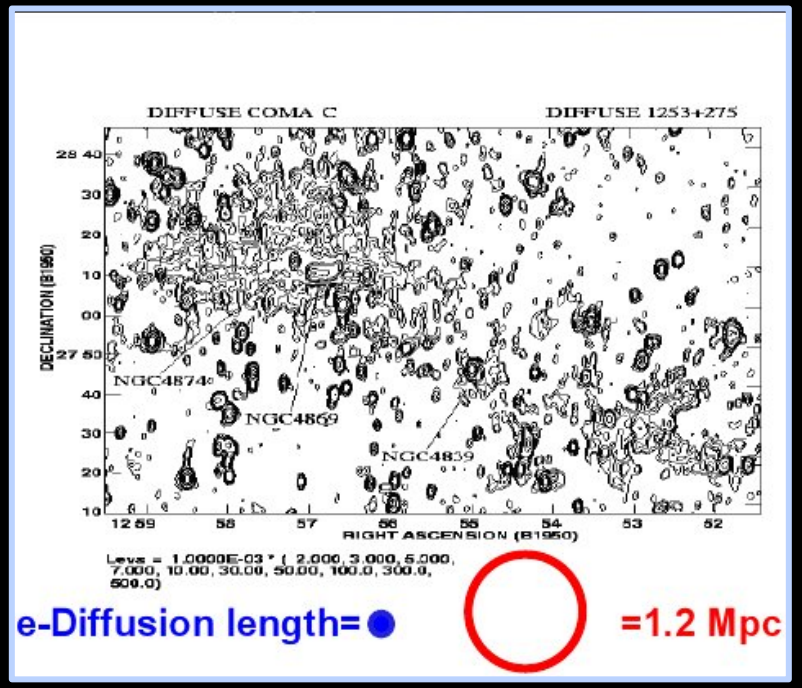
Diffusion problem

Crossing time of electrons ~ 10 Gyr

but radiative lifetime ~ 0.1 Gyr

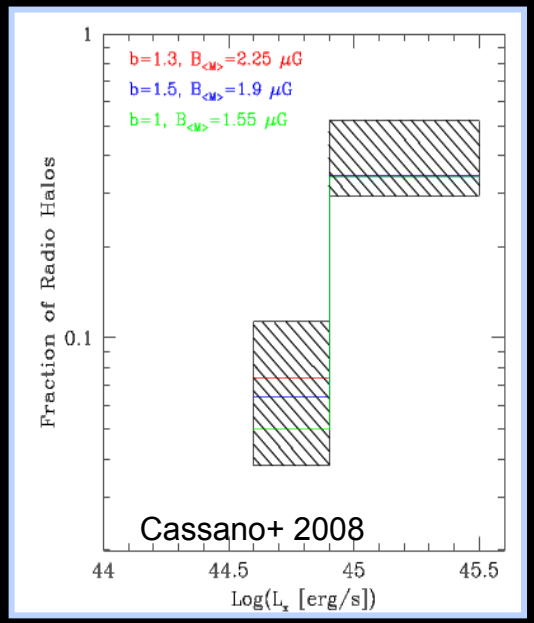
$t_{diff} >> t_{rad}$

Re-acceleration needed



Diffuse cluster sources not ubiquitous in galaxy clusters: why?

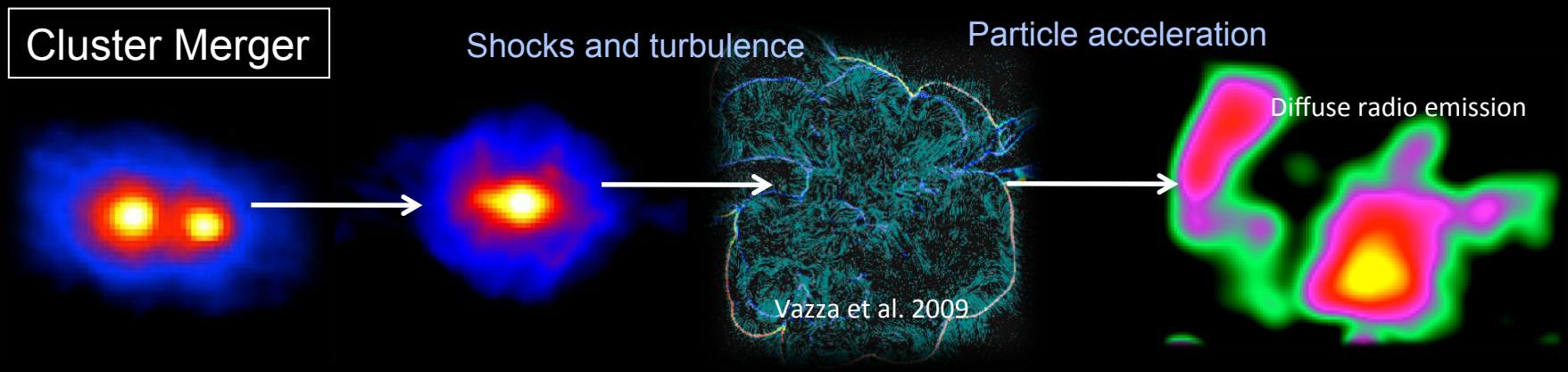
Fraction of observed radio halos and dependence on mass



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…)



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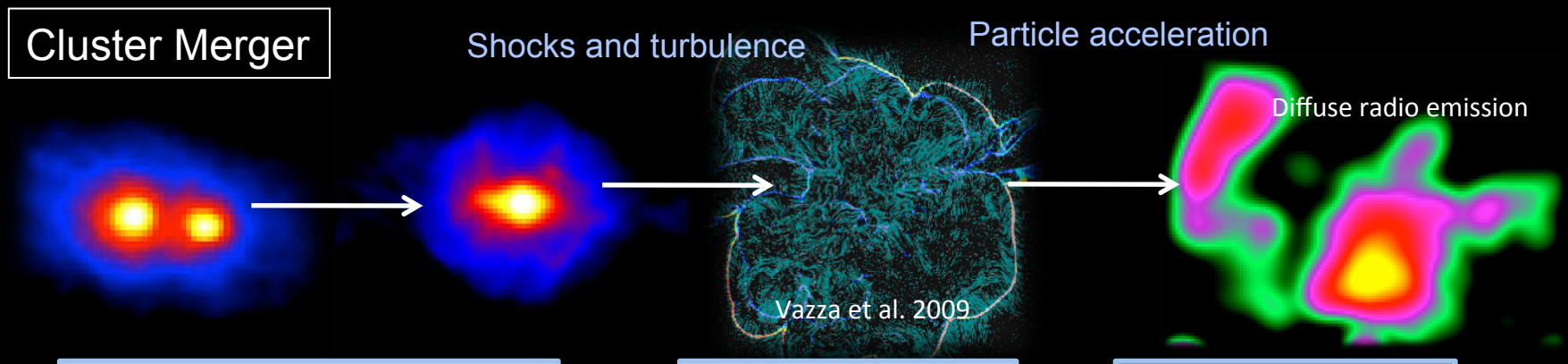
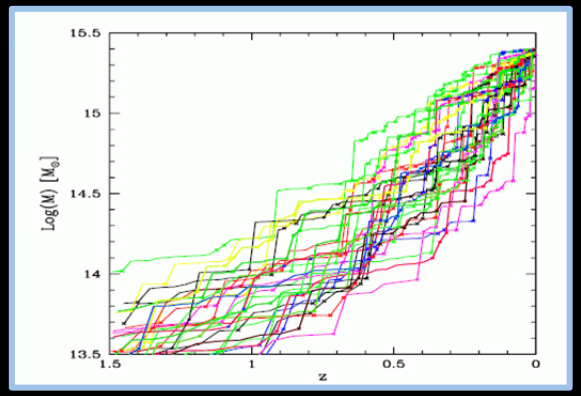
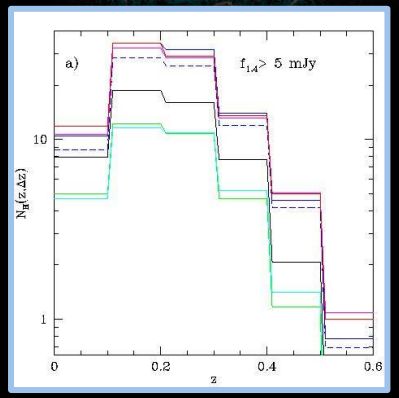
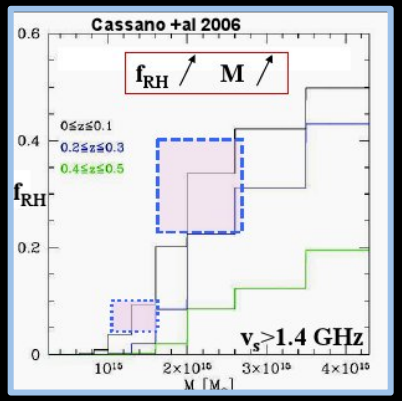






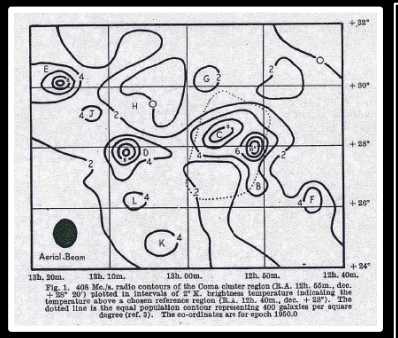


Background of the E-GMRT Radio Halo Survey

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

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

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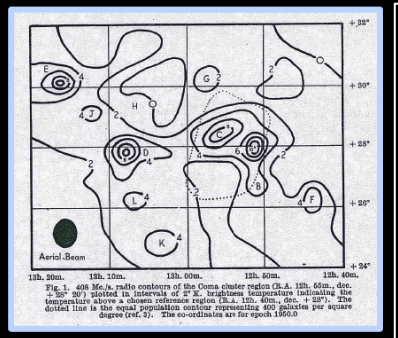

Fig. 1. 408 Mc/s. radio contours of the Coma cluster region (R.A. 12h. 55m., dec. + 28° 20′) plotted in intervals of 2° K. brightness temperature indicating the temperature above a chosen reference region (R.A. 12h. 40m., dec. + 23°). The dotted line is the equal population contour representing 400 galaxies per square degree (ref. 3). The co-ordinates are for epoch 1950.0

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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	600	-	3×10^{41}	-	5.4×10^{-14}	8.0×10^{58}	0.8	[4]
A2218	550	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	700	1.2×10^{23}	1.6×10^{41}	1.9	1.1×10^{-14}	1.1×10^{58}	0.5	[7,8]
A2319	660	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)

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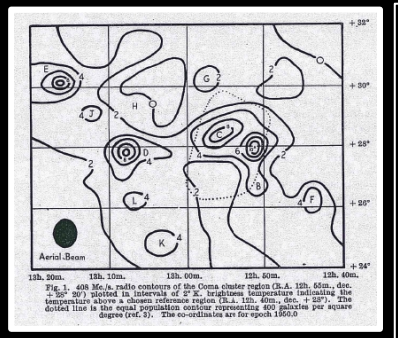

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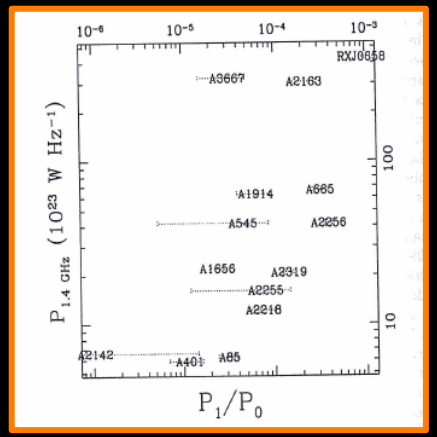

Halo and Relic sources detection rate

L_x(0.1–2.4 keV) 10^{44} erg s^{-1}	Relics %	Halos %	Total %
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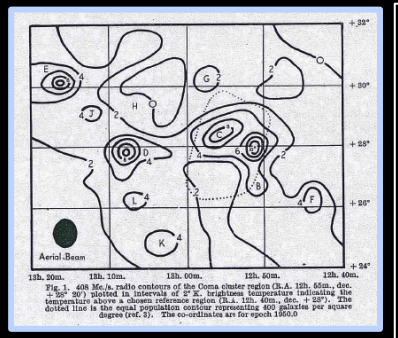

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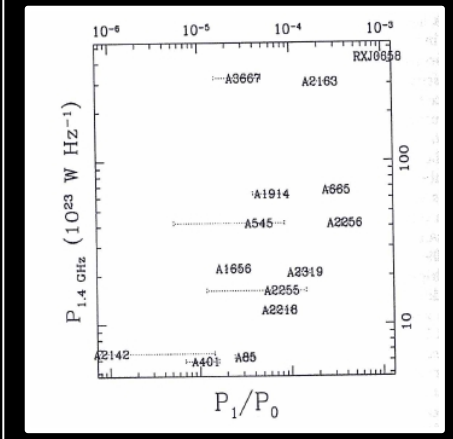

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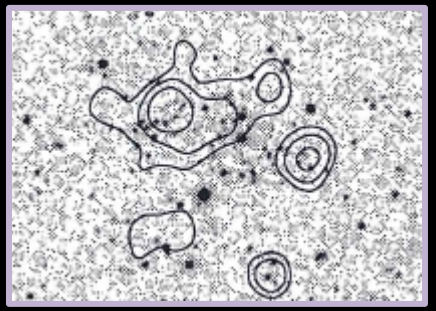

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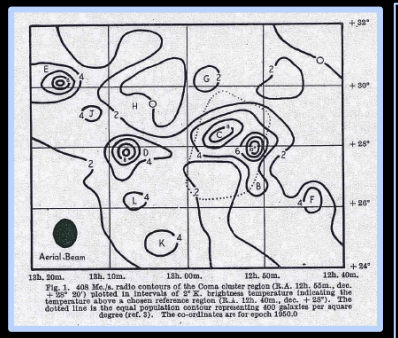

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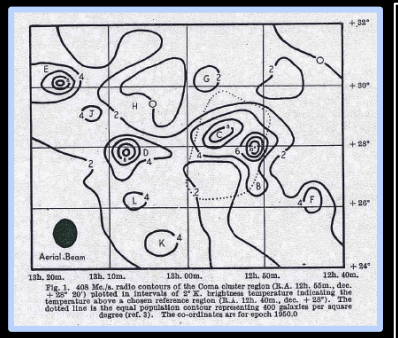

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1959 – Discovery of diffuse emission in the Coma cluster

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Name	Distance from c.c.	Cluster
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1253+275	1.35 Mpc	A1656
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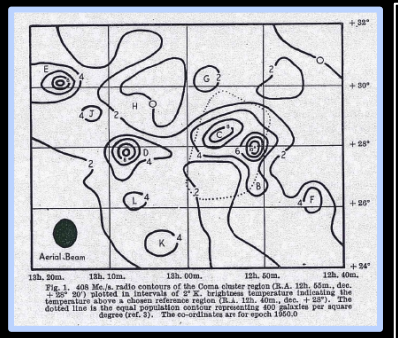

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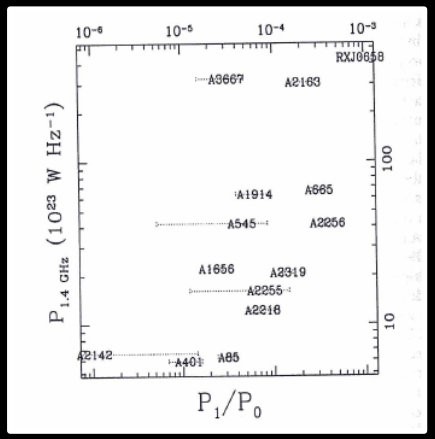

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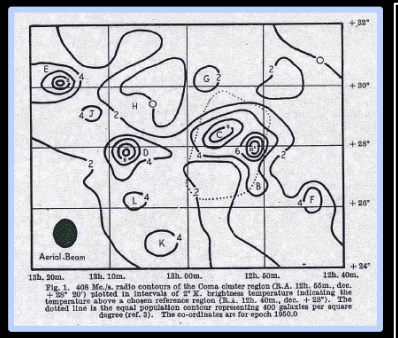

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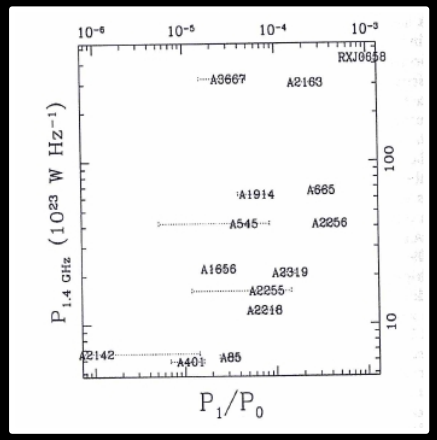
0917+75	2.5 Mpc	A786, Rood#27
1253+275	1.35 Mpc	A1656
Coma Bridge	1.1 Mpc	A1656
1401-33	90 kpc	S753
2006-56 region	1.04 Mpc	A3667

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

1959 — 1995 — 2001 — 2002 — 2005 — 2015

Numerical and theoretical work on relics starts (Ensslin et al., Brüggen et al., Vazza et al.

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

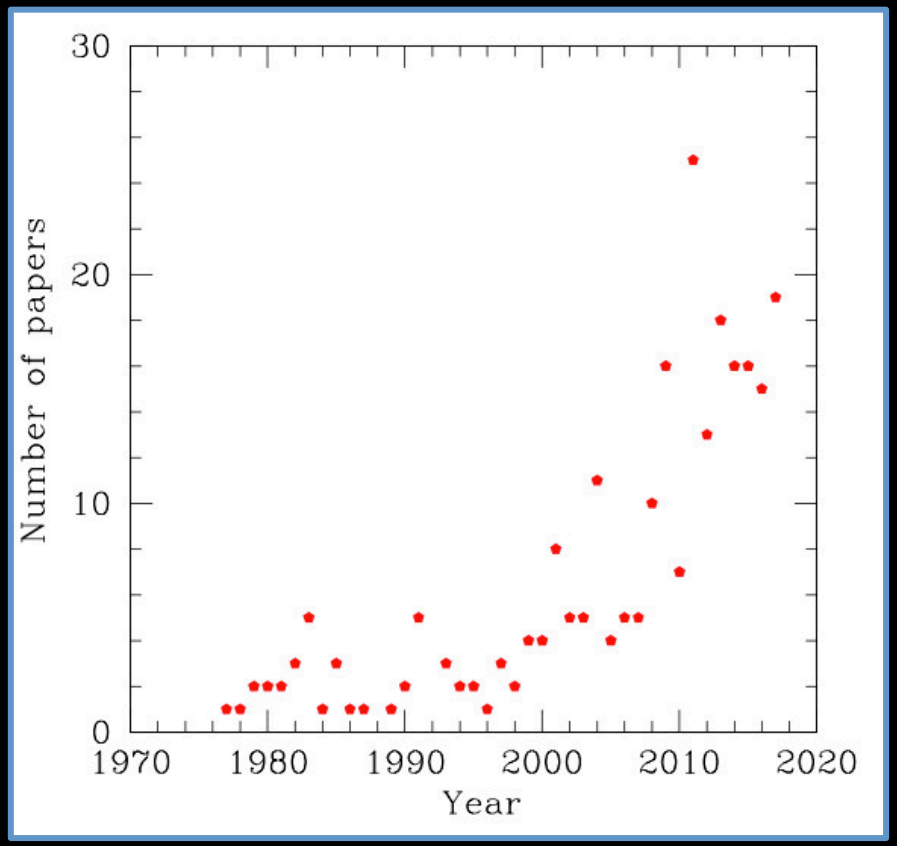


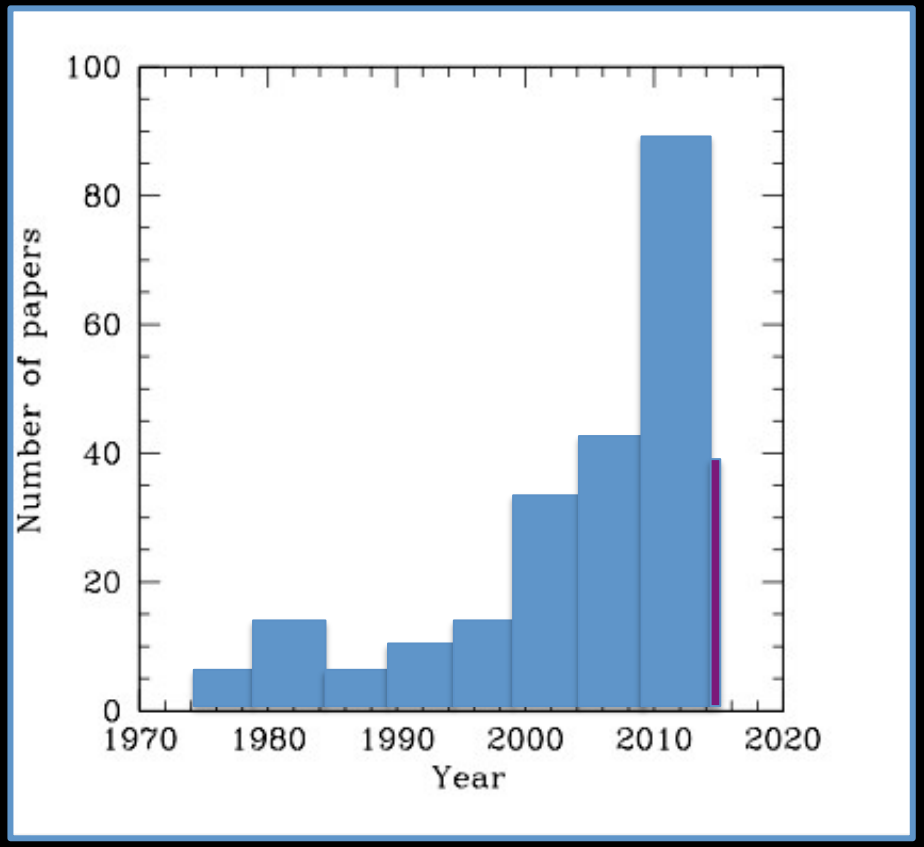
L_x(0.1–2.4 keV) 10^{44} erg s^{-1}	Relics %	Halos %	Total %
0–3	1.3(1)	–	1.3
3–5	3.0(1)	3.0(1)	6.0
5–7	4.5(1)	4.5(1)	9.0
7–10	16.1(5)	9.7(3)	25.8
>10	8.3(1)	25.0(3)	33.3

Two new additions from NVSS (Giovannini & Feretti 2000)

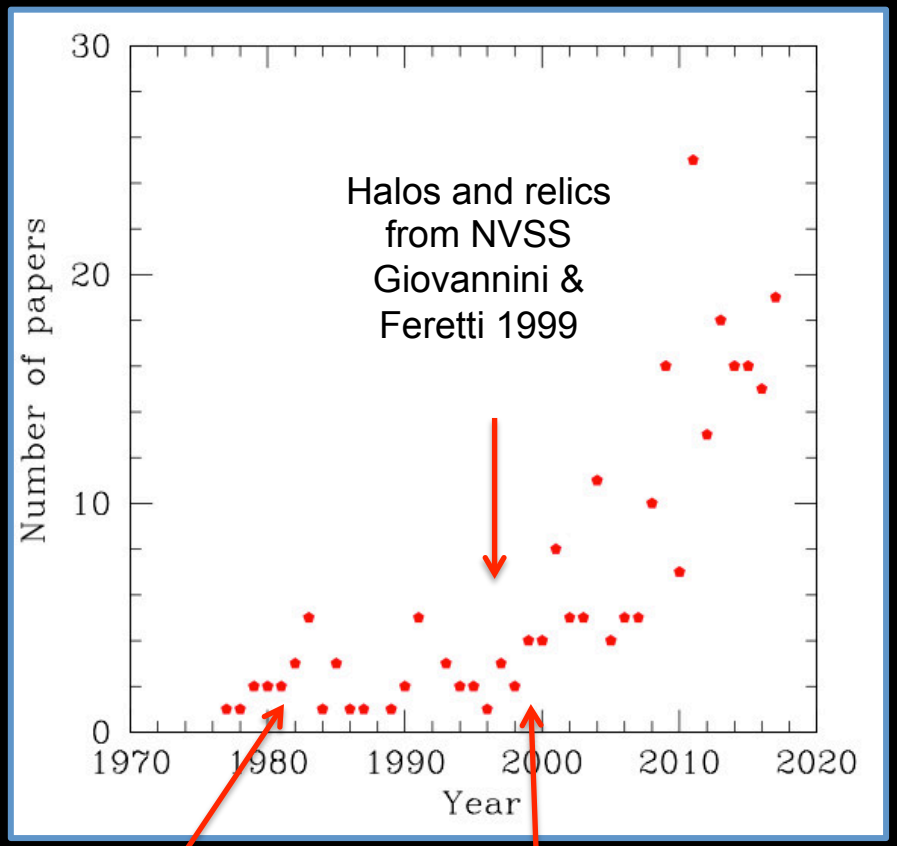
Sistematic searches for relics start (WSRT, GMRT, ...) (van Weeren & collaborators)

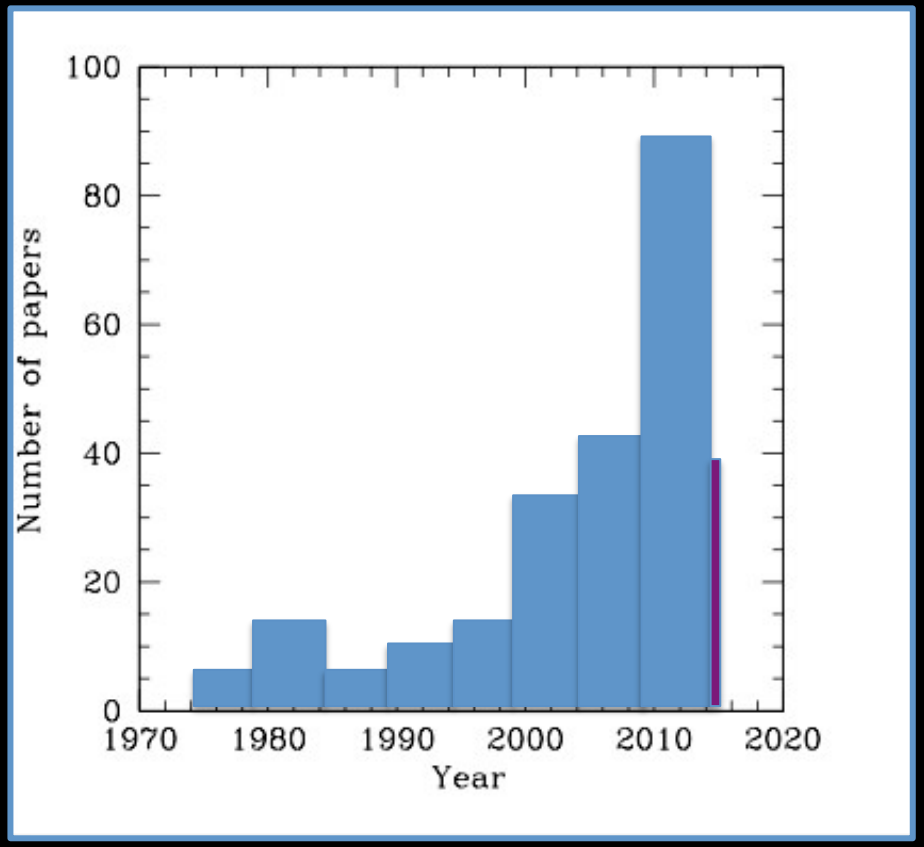
Number of papers with the words “radio halo”, “mini-halo”, “relic”, “diffuse emission” in the title



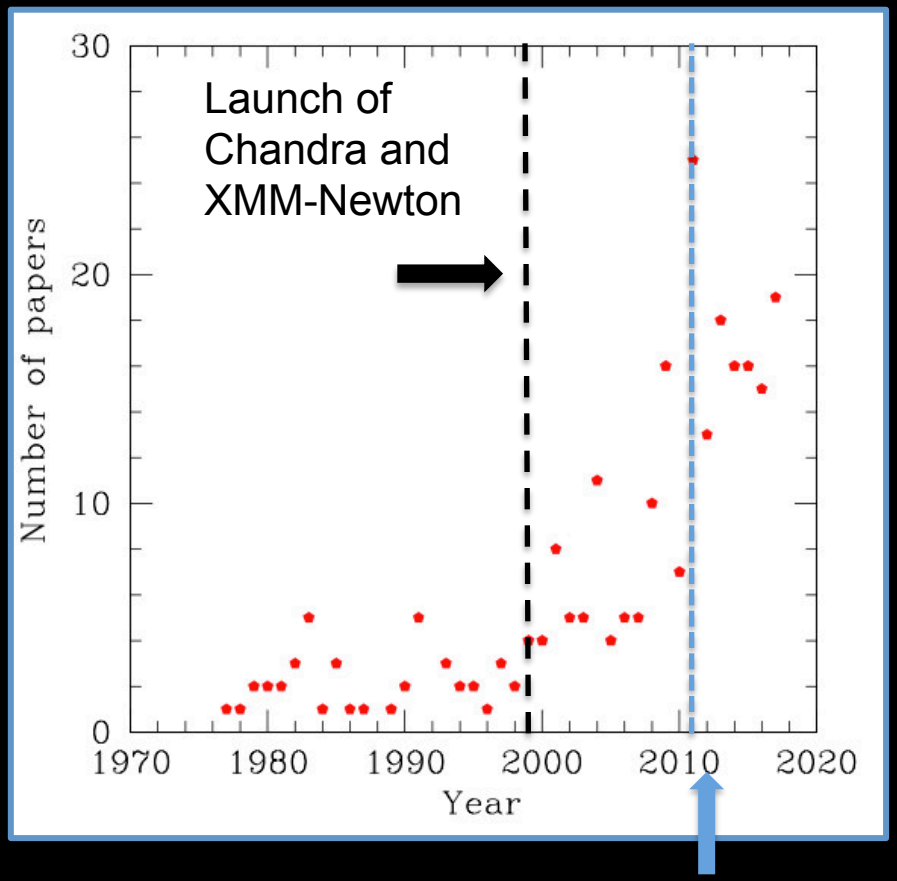


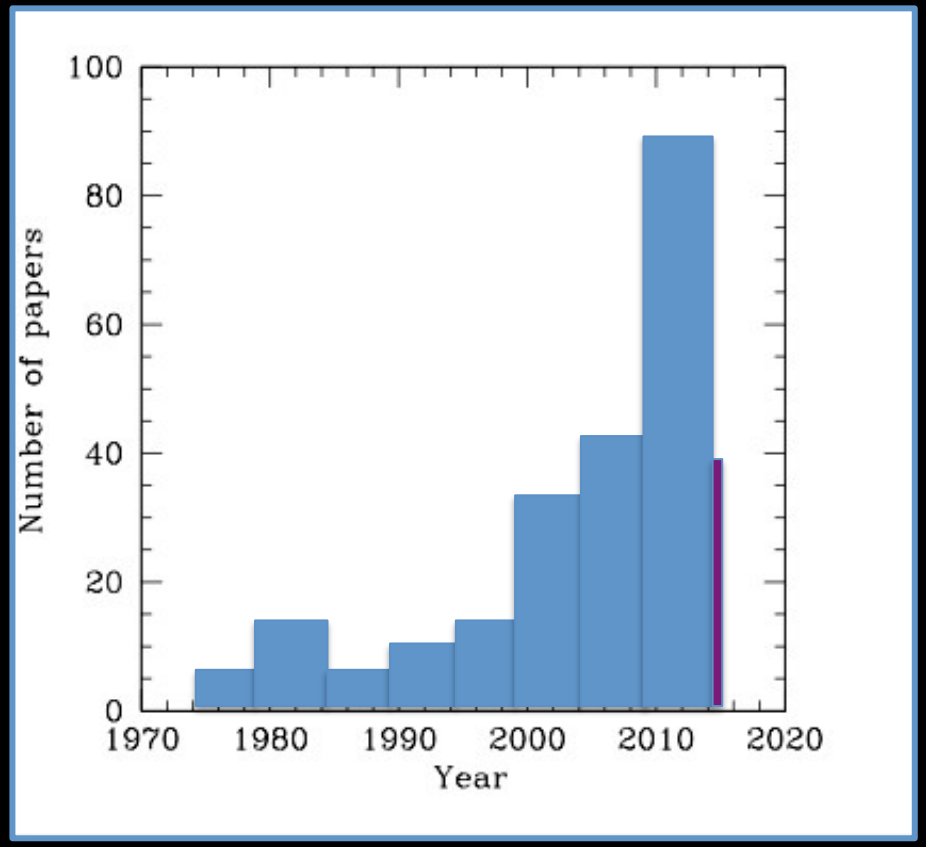
Number of papers with the words “radio halo”, “mini-halo”, “relic”, “diffuse emission” in the title





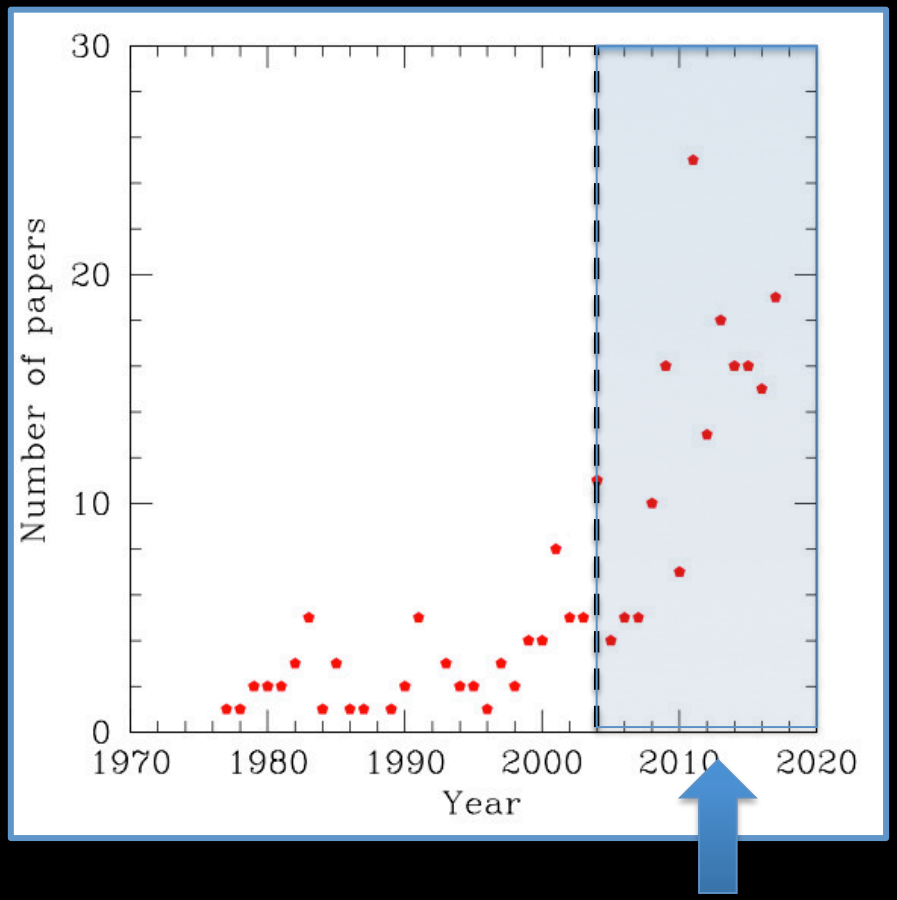
Number of papers with the words “radio halo”, “mini-halo”, “relic”, “diffuse emission” in the title

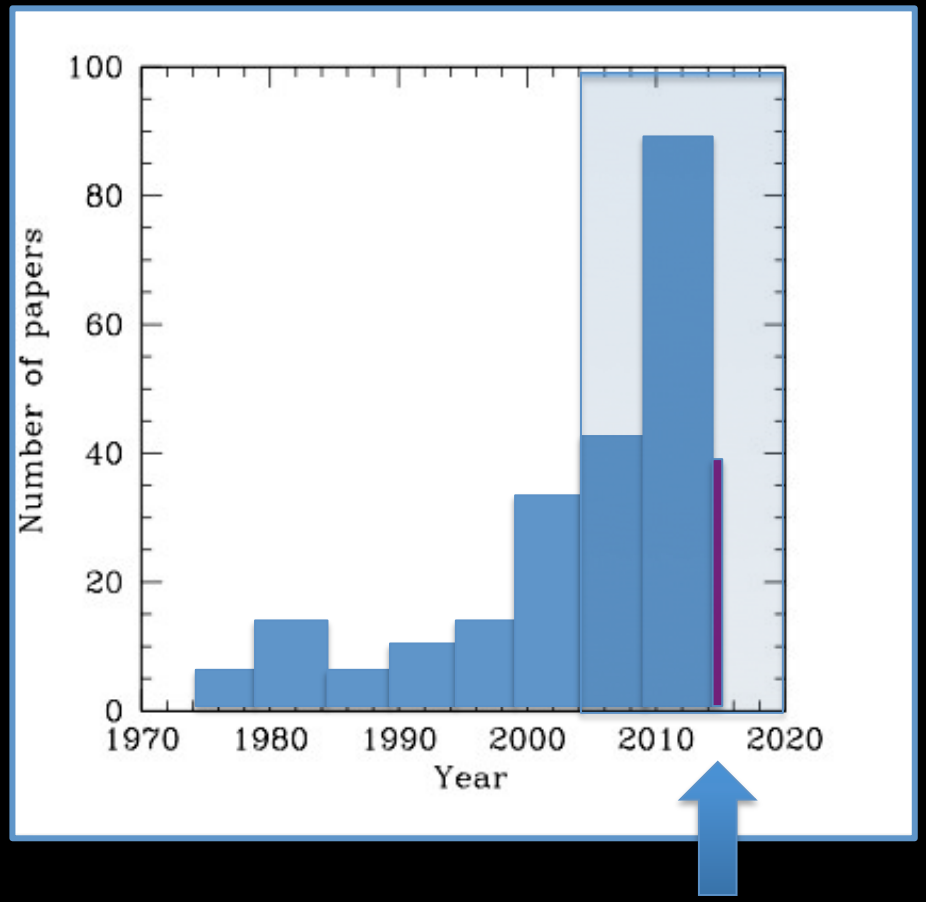




First release of Planck SZ catalogue

Number of papers with the words “radio halo”, “mini-halo”, “relic”, “diffuse 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) radio sky surveys

What makes the difference?

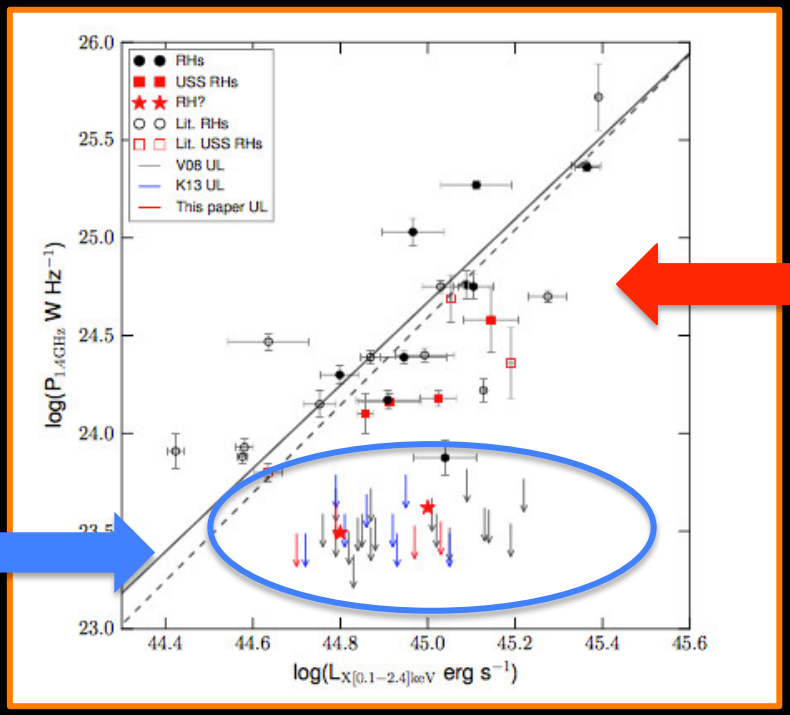
…

We now know where to look

Bimodality for GIANT RADIO HALOS

Region of upper limits of radio halo power

RELAXED CLUSTERS



Correlation between radio power of radio halos and cluster X-ray luminosity (or Mass)

MERGING CLUSTERS

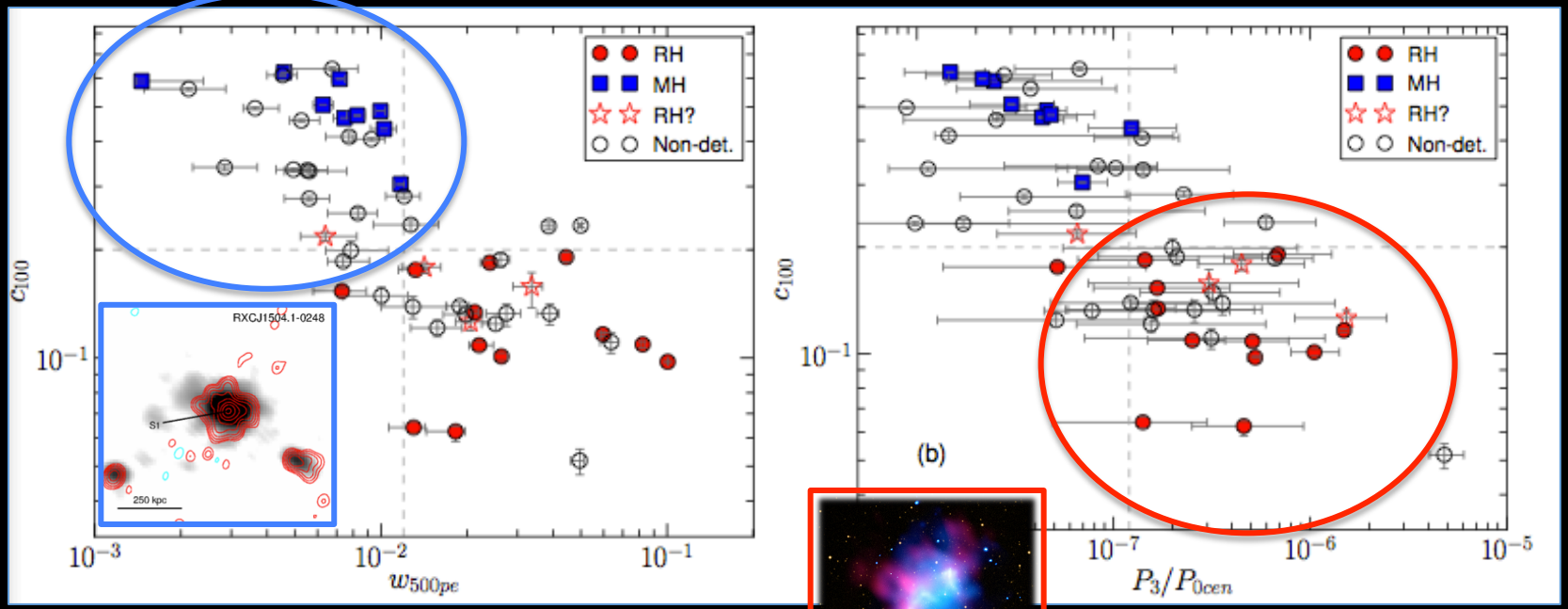
Plot from the final E-GMRT Radio Halo Survey analysis
Kale+ 2015

What makes the difference?

…

We now know where to look

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

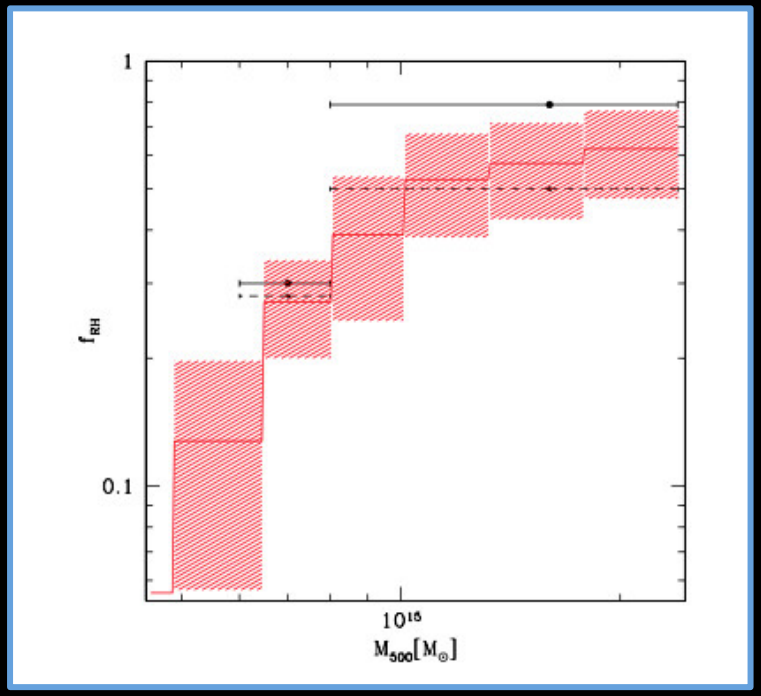
What makes the difference?

…

We now know where to look

Quantitative assessment of the OCCURRENCE OF GIANT RADIO HALOS and mass of the host cluster from mass selected samples

Quite low (<30%) below ~ 8×10^{14} M_{500} (M_{sun}) with a further drop below 6×10^{14} M_{500}



Quite high (>50%) above 10^{15} M_{500} (M_{sun})

Cuciti et al. 2015

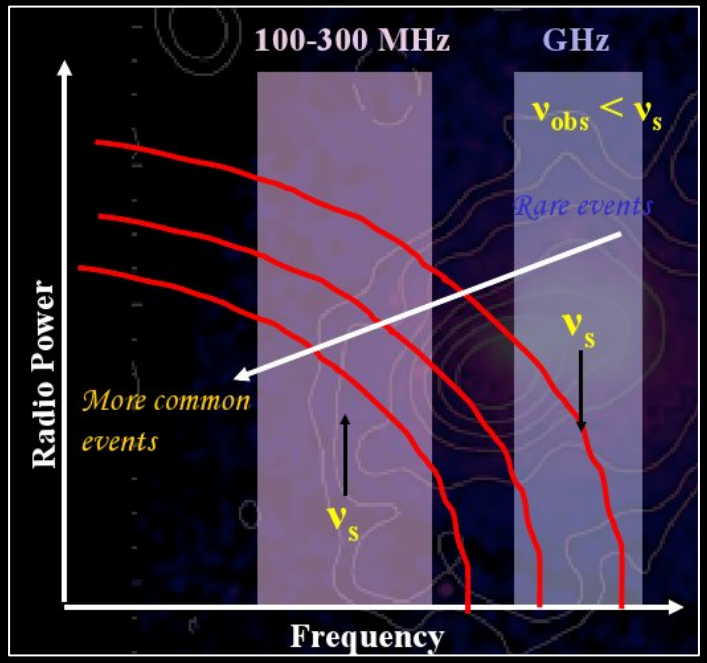
What makes the difference?

…

We now know where to look

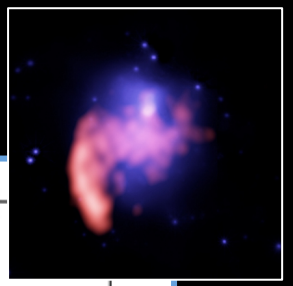
Ultra steep spectrum RHs in minor/less massive merging systems

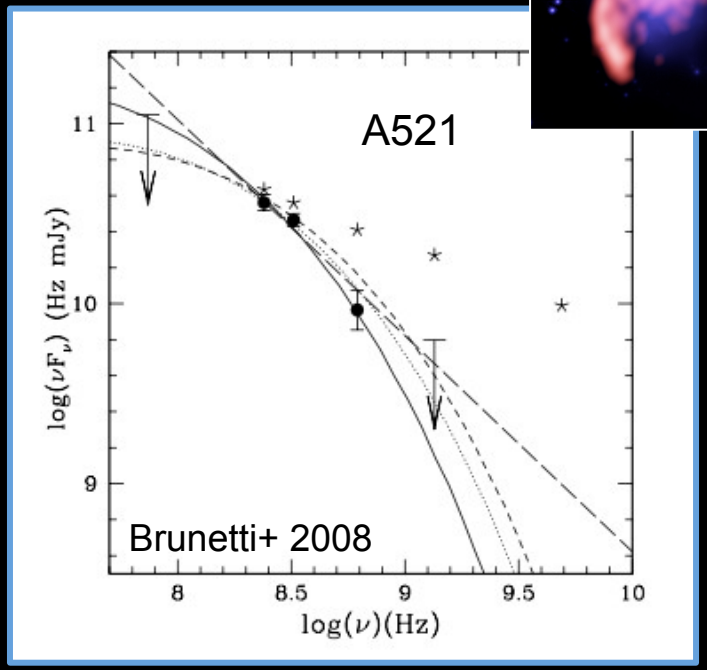
Prediction of the turbulent re-acceleration model:
From GHz radio halos to USSS radio halos



From Cassano

Still few cases known, but wait for LOFAR, uGMRT and MWA!





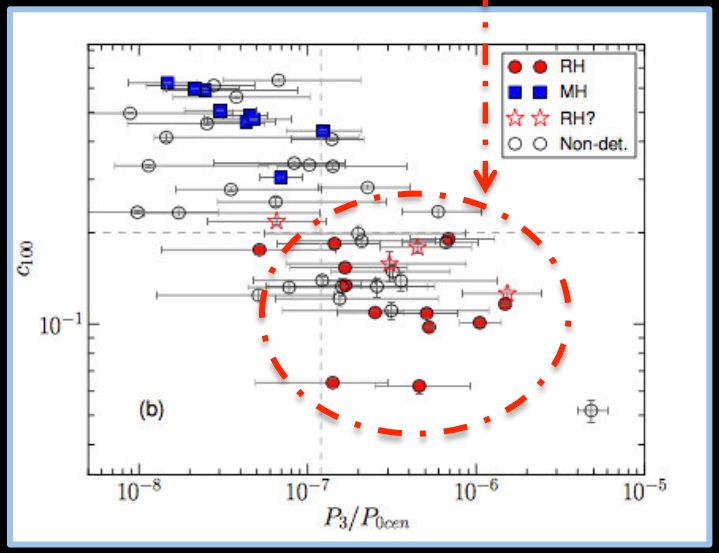
What makes the difference?

…

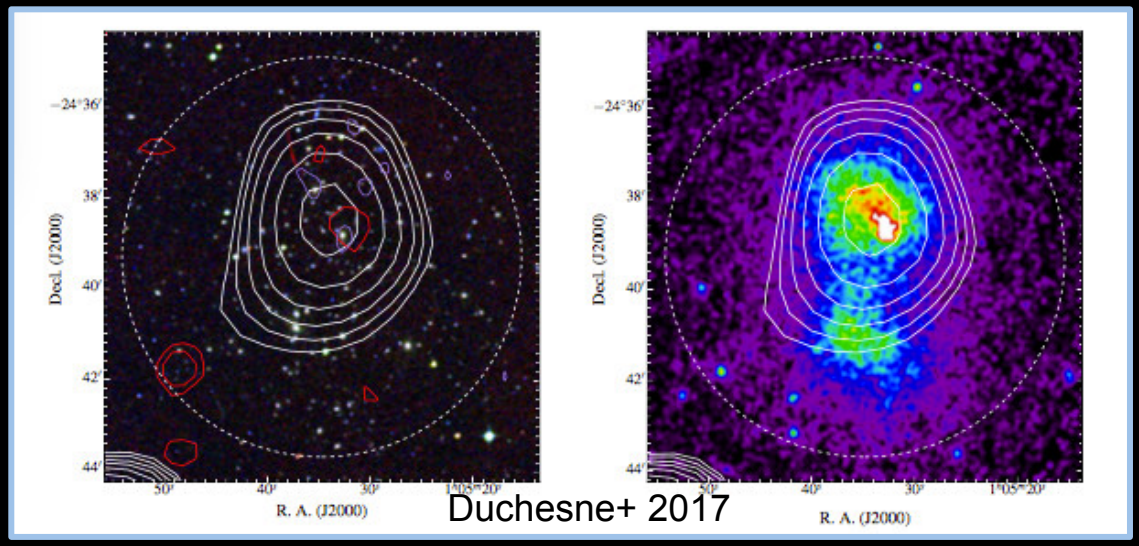
We now know where to look

The case of A141

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



Radio halo detected at 168 MHz with MWA
(Duchense et al. 2017)



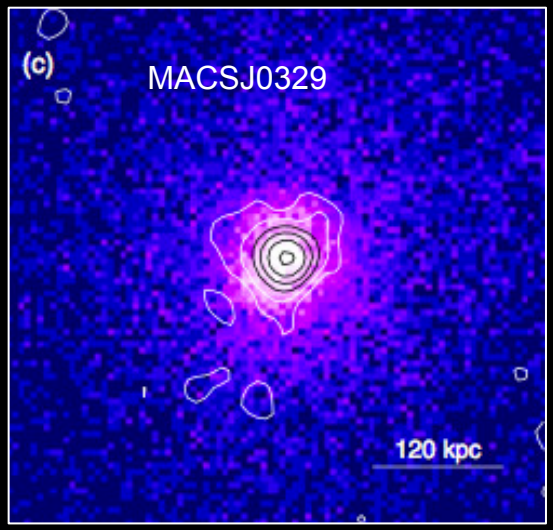
Duchesne+ 2017

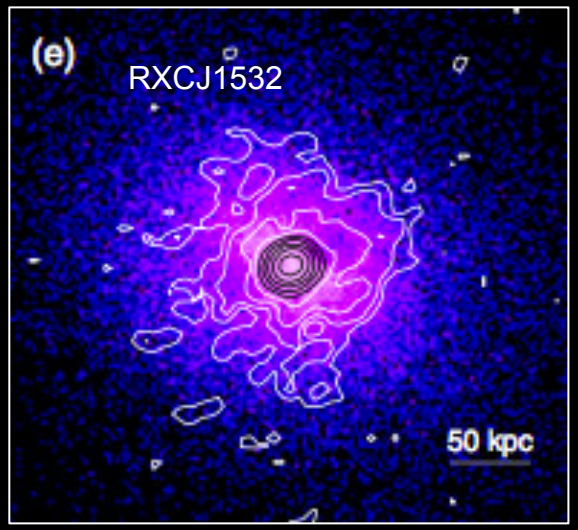
What makes the difference?

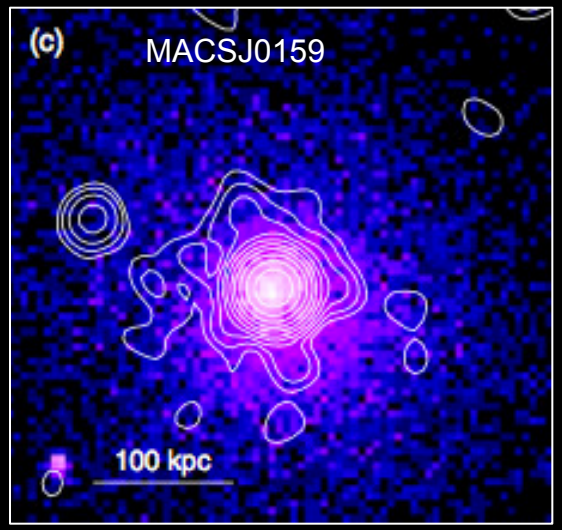
…

We now know where to look

MINI-HALOS, cool-core clusters and sloshing cores







Images from Giacintucci et al. 2014

Linear sizes of the order of few hundred kpc

Scales: ~1.2 kpc/” at z=0.06; ~5.8 kpc/” at z=0.45

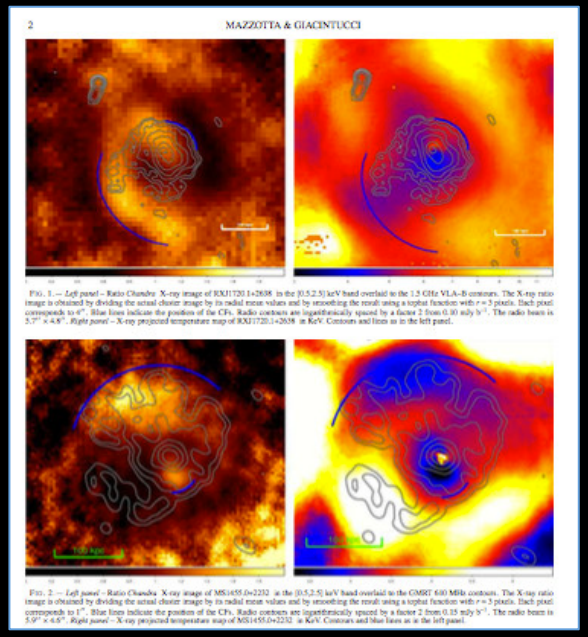
Need for multiscale high resolution and multifrequency observations to isolate the emission from the BCG

What makes the difference?

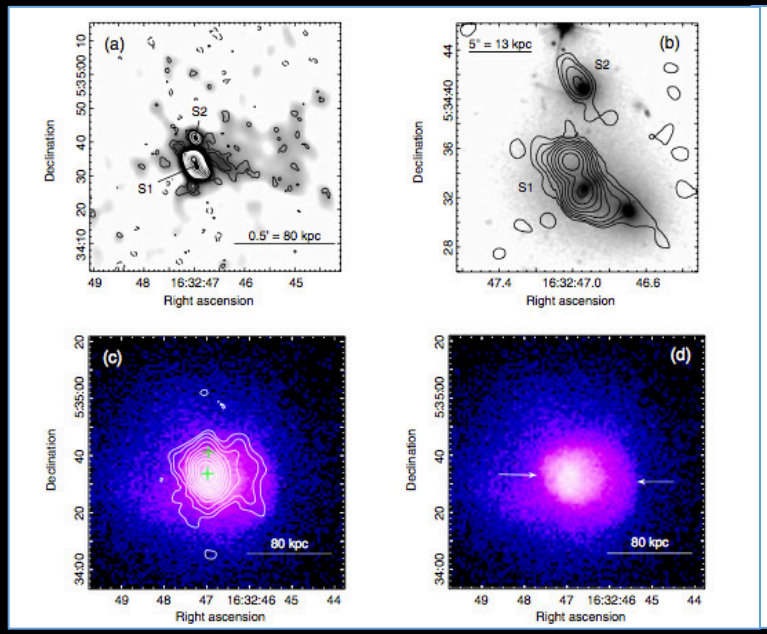
…

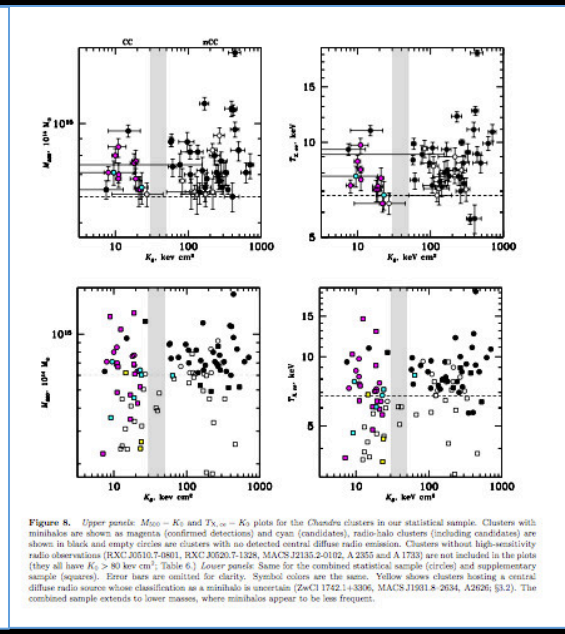
We now know where to look

MINI-HALOS, cool-core clusters and sloshing cores



Mazzotta & Giacintucci 2008





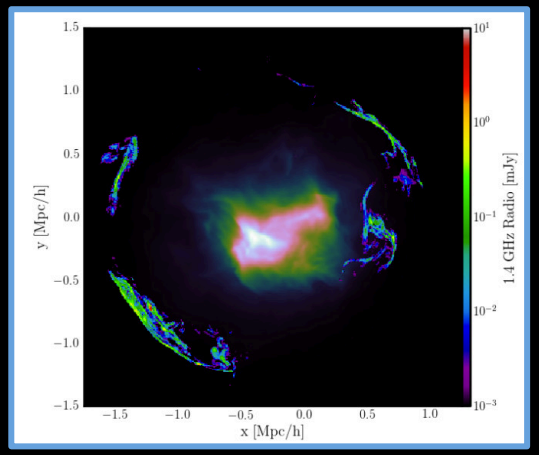
Giacintucci et al. 2014 & 2017

What makes the difference?

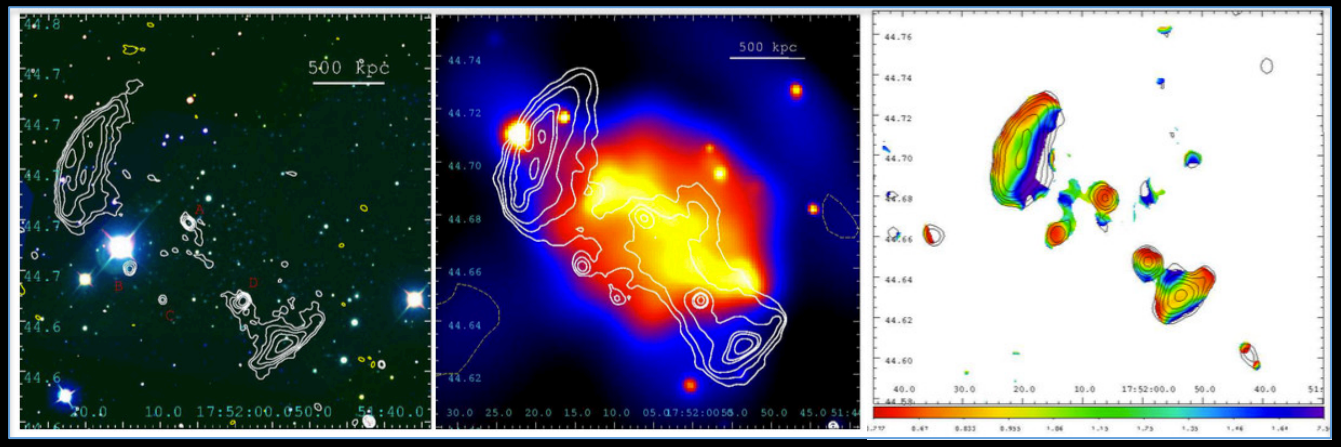
…

We now know where to look

RELICS, disturbed clusters and shocks



Simulations of merger shocks and formation of double relics
Skillmann+ 2013



Results for MACSJ1752+4440 consistent with simulations for a binary merger event in the plane of the sky with mass ratio 1:3 and DSA for the emission of relics - Bonafede+ 2012

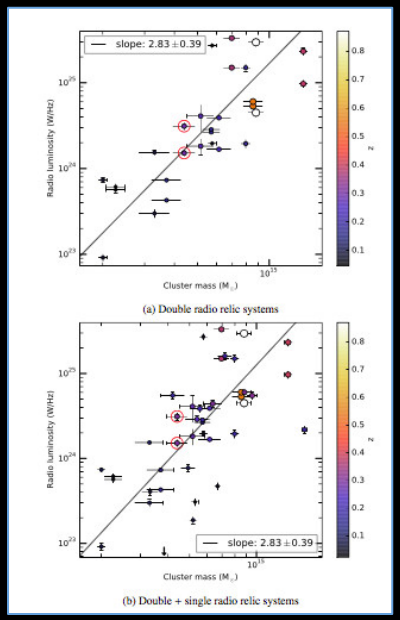
$$\alpha_i = -\frac{1}{2} + \frac{M^2 + 1}{M^2 - 1}$$

What makes the difference?

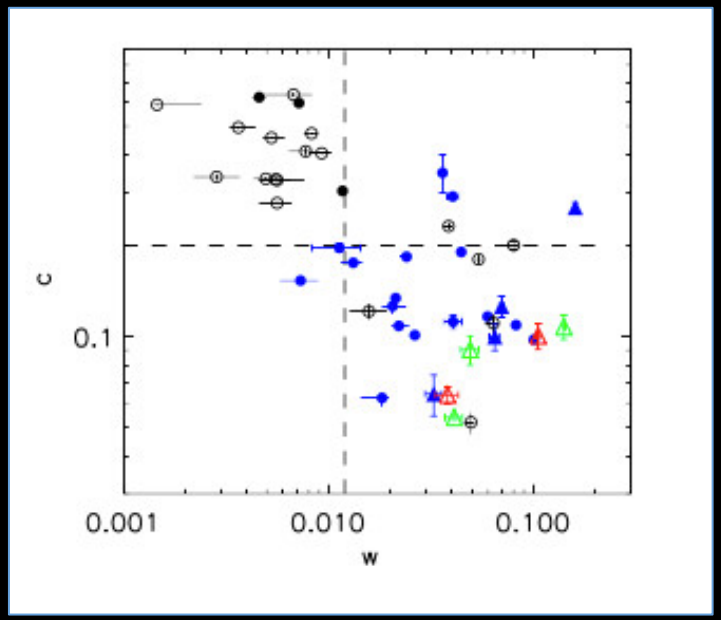
…

We now know where to look

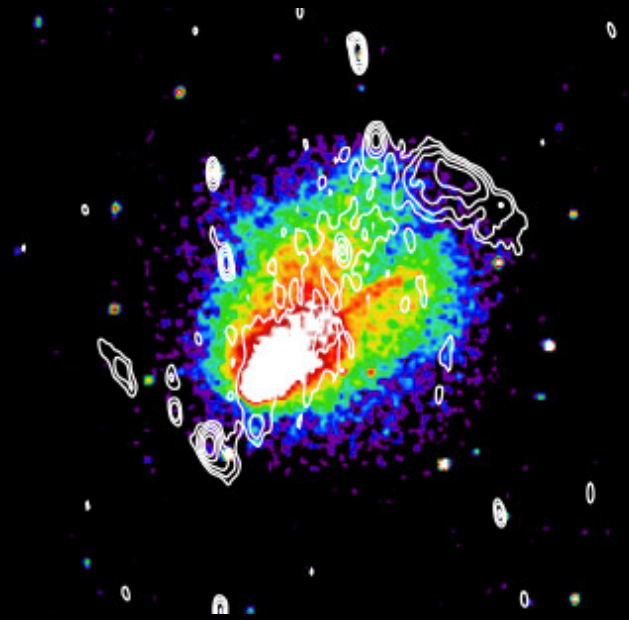
RELICS, disturbed clusters and shocks



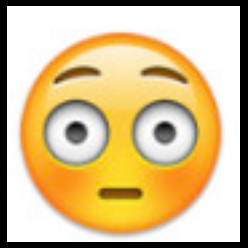
Mass-Luminosity correlation for relics (double and all) de Gasperin et al. 2014



Bonafede et al. 2017

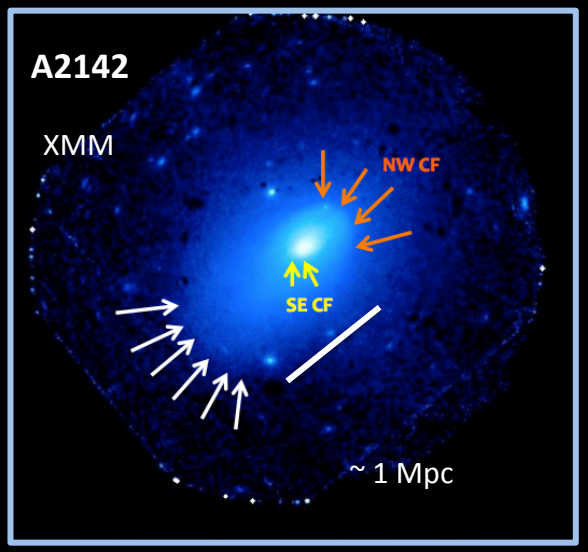


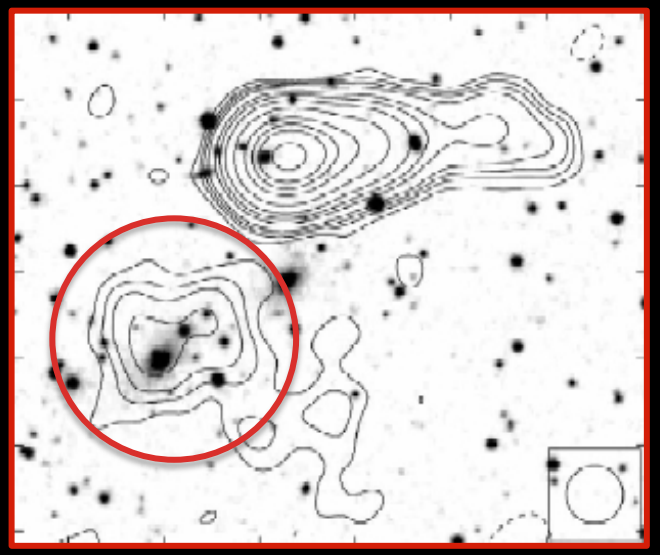
El Gordo, the most distant cluster with a radio halo and double relics Botteon et al. 2016

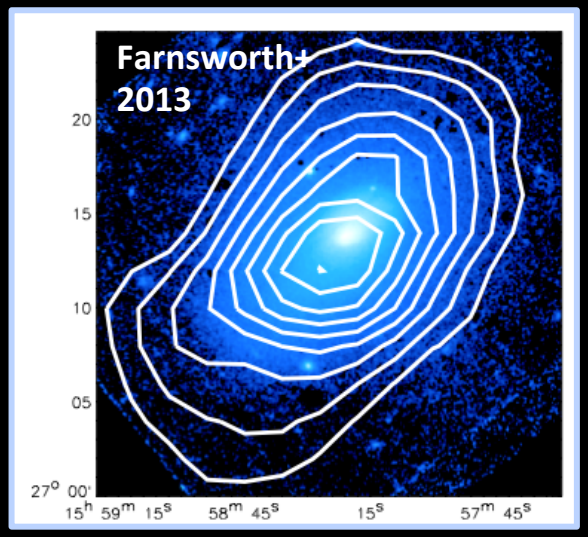


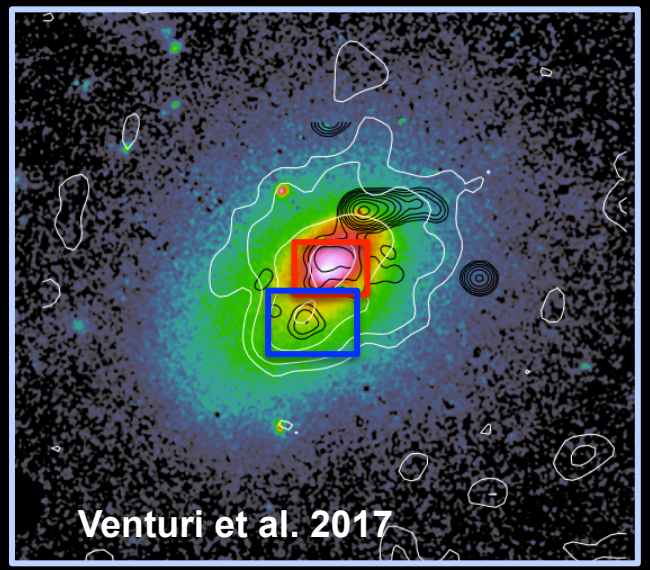
New open questions

Reality is not black or white… some gray zones







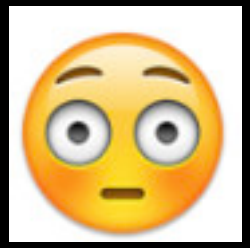


Formerly classified as a mini-halo

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

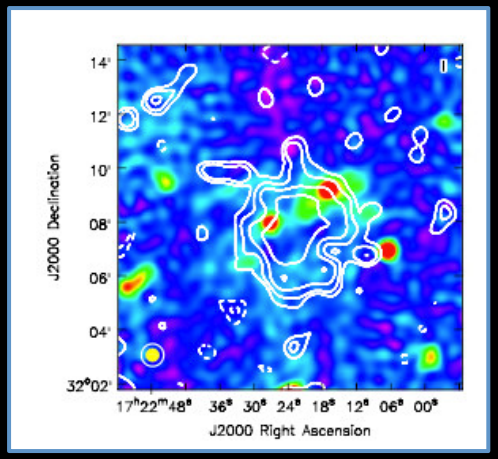
α~1.5-1.6, slightly steeper in the second component



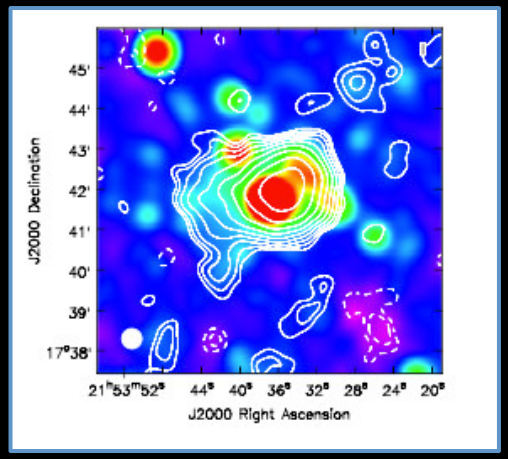
New open questions

Reality is not black or white… some gray zones

A2261

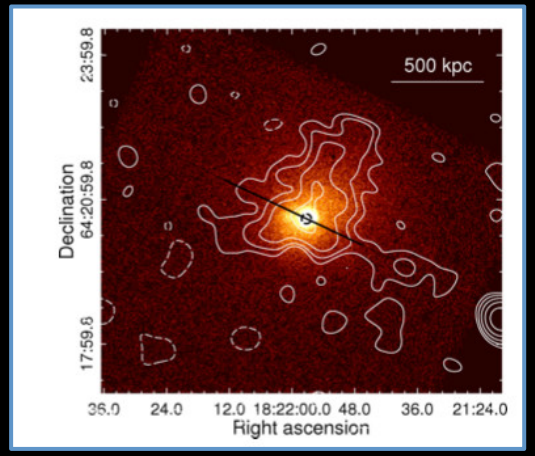


A2390

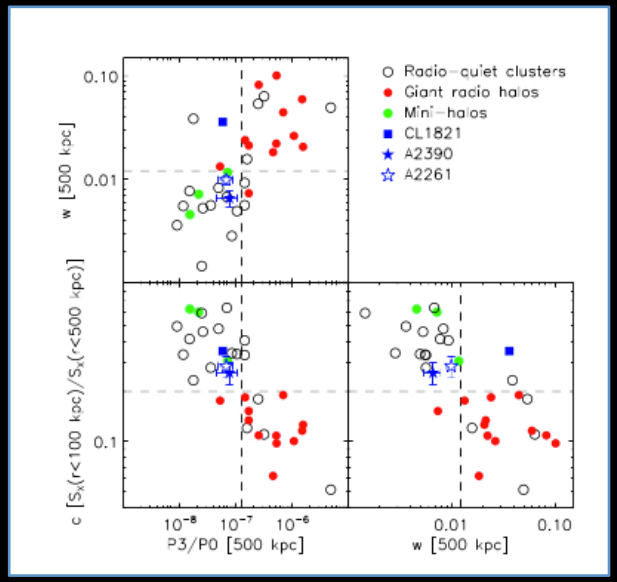


Sommer et al. 2017

CL1821+643



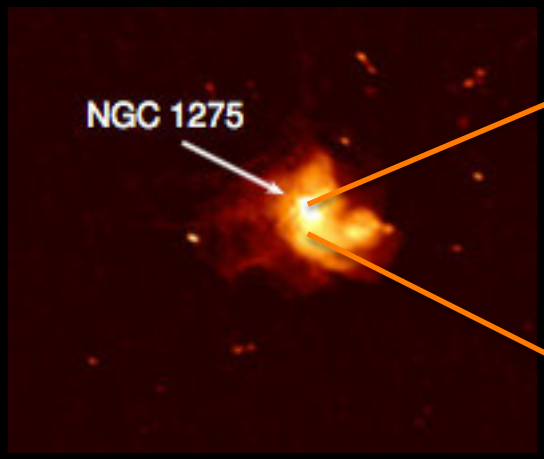
Bonafede et al. 2014



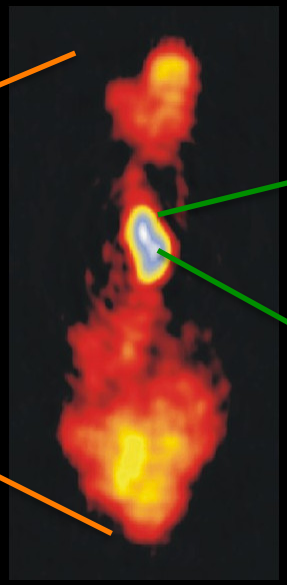
Giant radio halos in cool-core clusters

- ✧ Minor/off-axis mergers which have preserved the cool core and injected turbulence?
- ✧ Secondary model halos?/Transition phase?
- ✧ Mpc-scale sloshing (as suggested for A2142)?

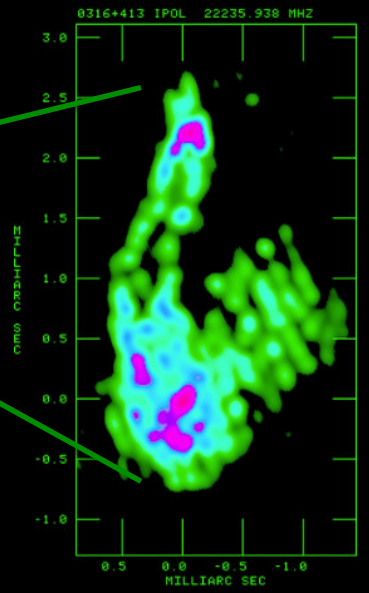
New open questions
Mini-halos and central AGN?



Gendron-Marsolais+ 2017



VLBA image
Courtesy of NRAO



3C84 as imaged
by RadioAstron

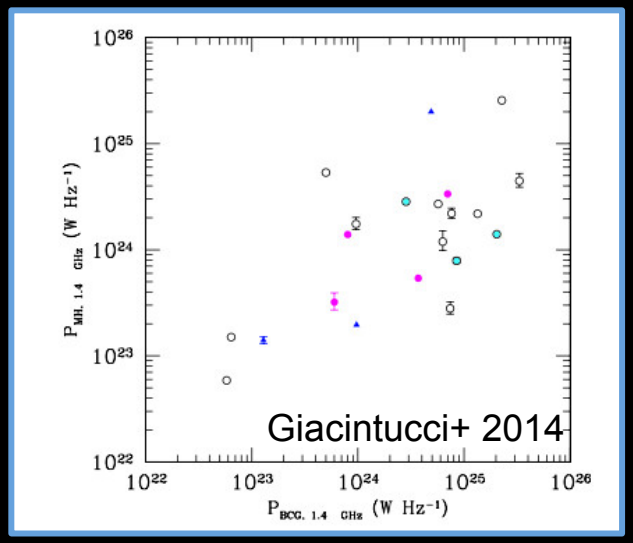
Table 1
List of Clusters

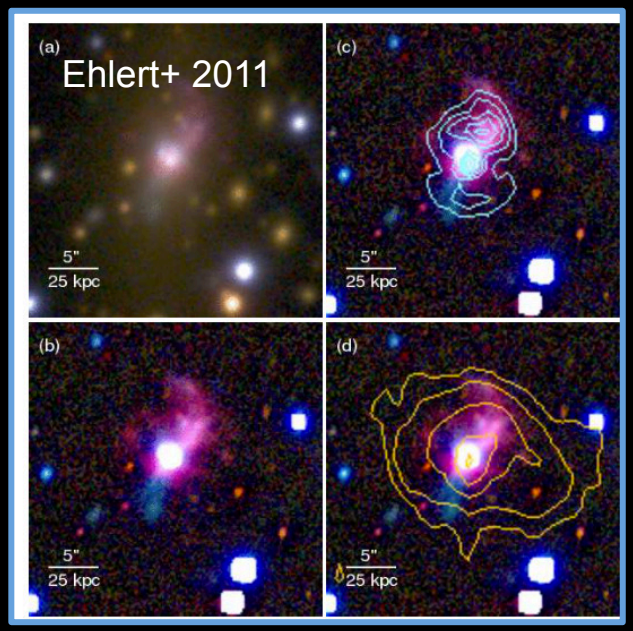
Cluster name	R.A.$_{J2000}$ (h, m, s)	Decl.$_{J2000}$ (°, ′, ″)	z	scale (kpc/″)
MACS J0159.8-0849	01 59 48.0	−08 49 00	0.405	5.413
MACS J0329.6-0211	03 29 40.8	−02 11 54	0.450	5.759
A 478	04 13 20.7	+10 28 35	0.088	1.646
ZwCl 3146	10 23 39.6	+04 11 10	0.290	4.350
A 1795	13 49 00.5	+26 35 07	0.062	1.195
RX J1532.9+3021	15 32 54.4	+30 21 11	0.362[a]	5.048
A 2204	16 32 45.7	+05 34 43	0.152	2.643
ZwCl 1742.1+3306	17 44 13.5	+32 58 55	0.076	1.441
MACS J1931.8-2635	19 31 48.0	−26 35 00	0.352	4.958

How common is Perseus?
z=0.0179 , 0.366 kpc/”

Giacintucci+ 2014

New open questions
Mini-halos and central AGN?

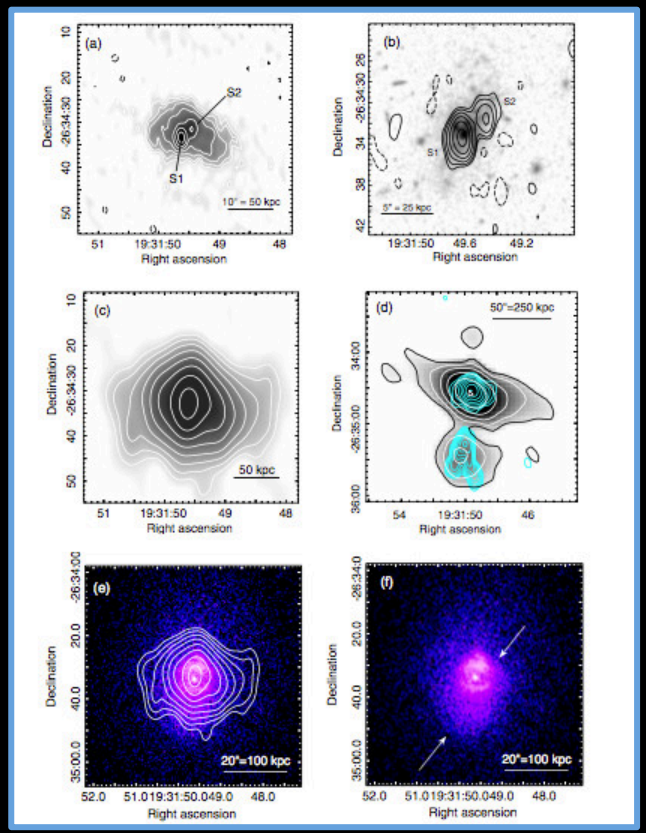




Recurrent AGN activity not uncommon in CCC BGCs

⇩

Potential reservoir of relativistic electrons?

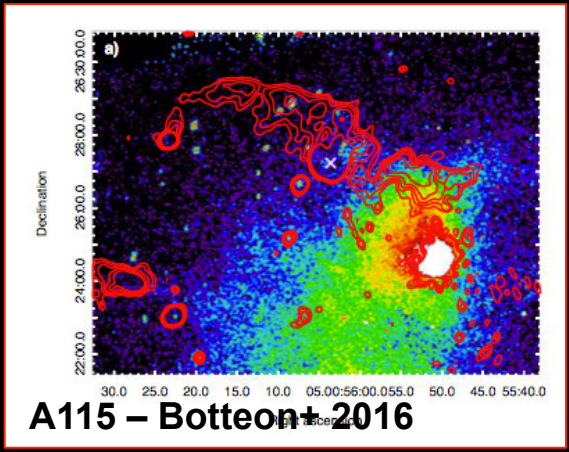


Extreme feedback and radio emission in the core region of the

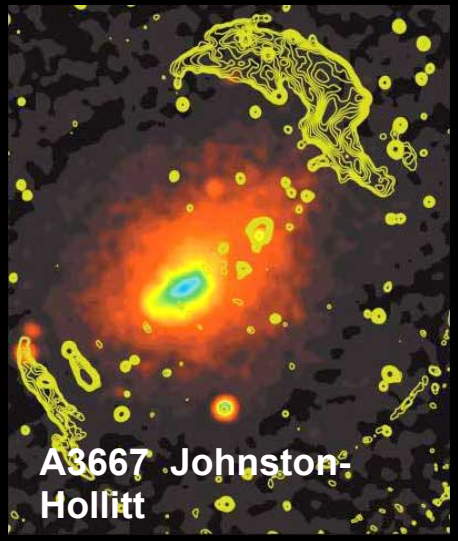
z=0.352
CLASH cluster
MACSJ1931.8-2635

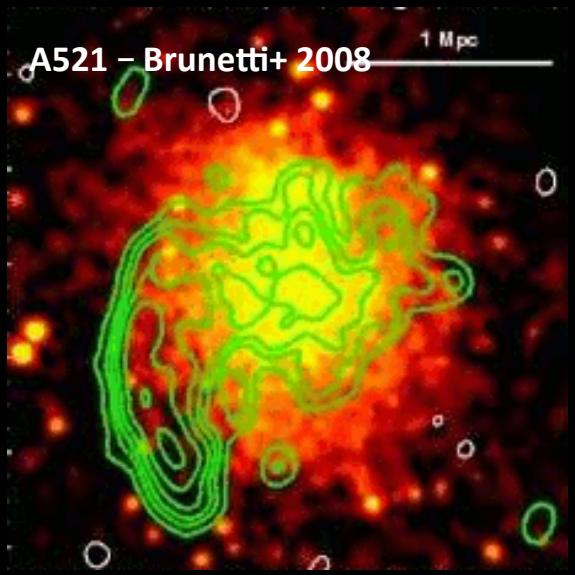
Giacintucci+ 2014

New open questions
Single relics, double relics & halos

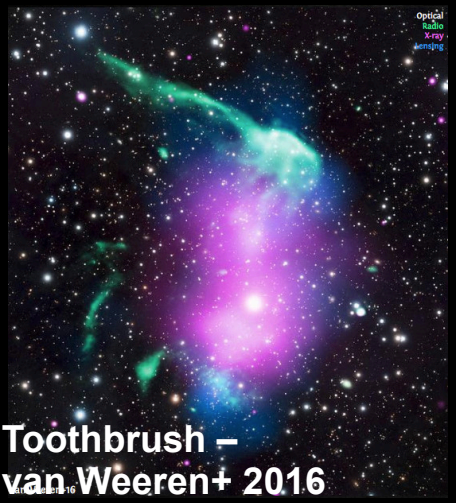


A115 – Botteon+ 2016


A3667 Johnston-Hollitt



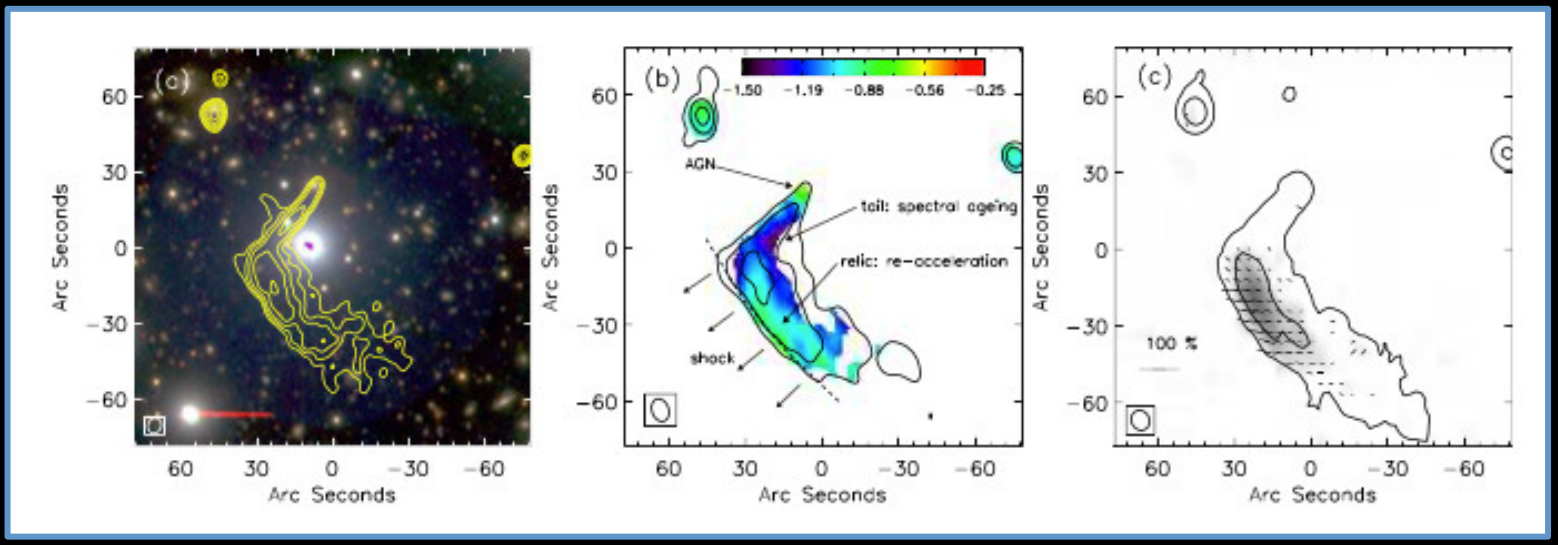
A521 – Brunetti+ 2008



Toothbrush – van Weeren+ 2016

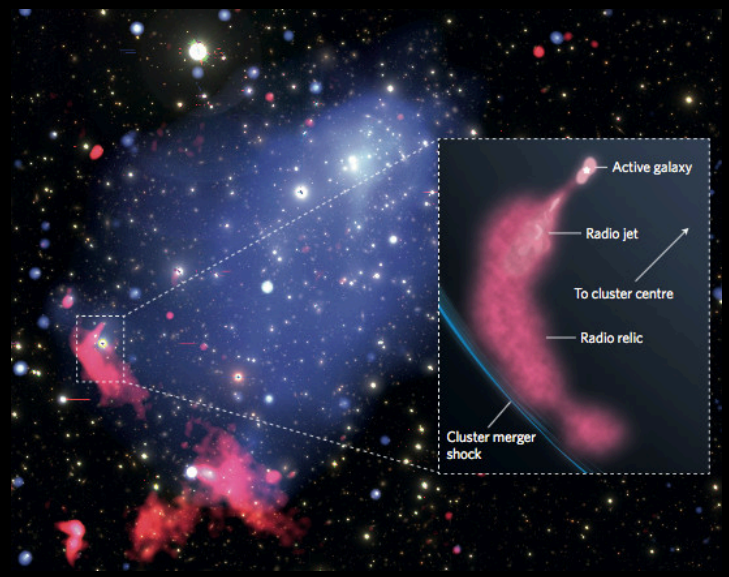
- ✧ Observed association with shocks still rare – MISSING SHOCKS
- ✧ Mismatch of Mach numbers as derived from radio and X-ray
- ✧ Re-acceleration from thermal pool sometimes problematic
- ✧ Population of relativistic electrons sometimes necessary
- ✧ Radio halo – double relic connection?

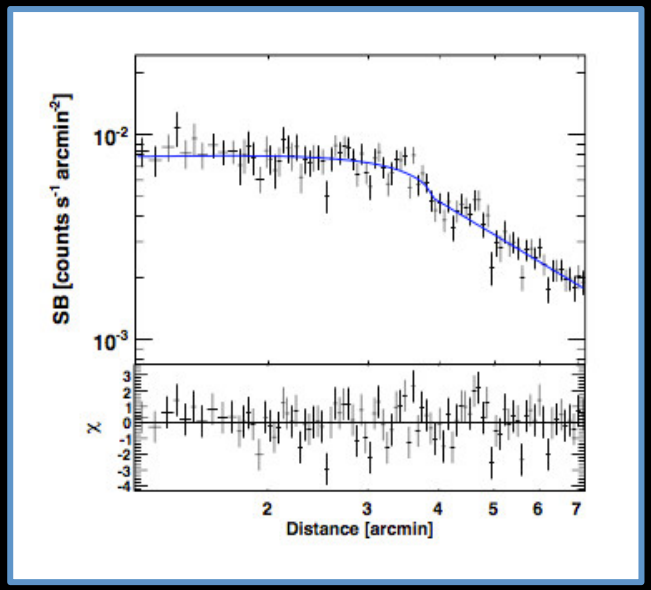
New open questions
Single relics, double relics & halos



The case of A3411-A3412

Possible evidence of relativistic electrons injected in the ICM by a radiogalaxy (previous cycle of activity?) and re-accelerated by a merger shock

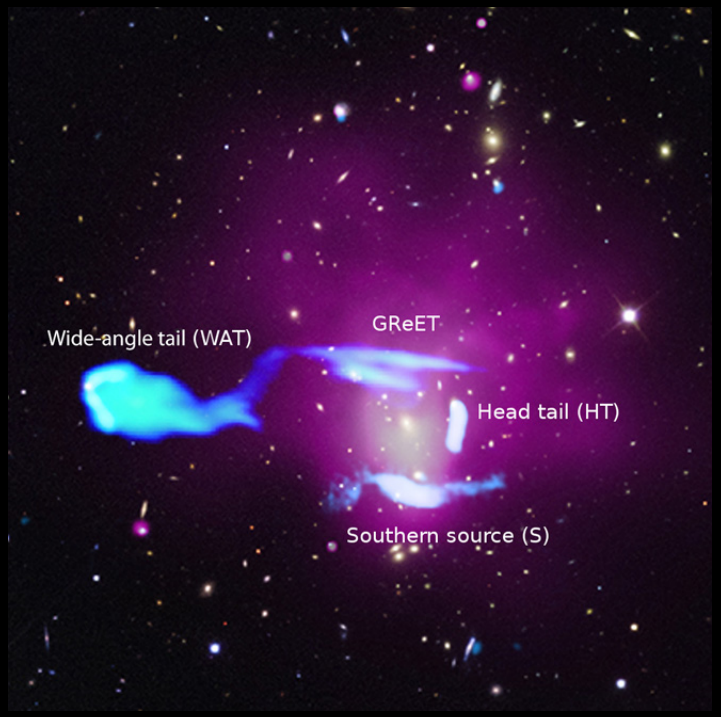




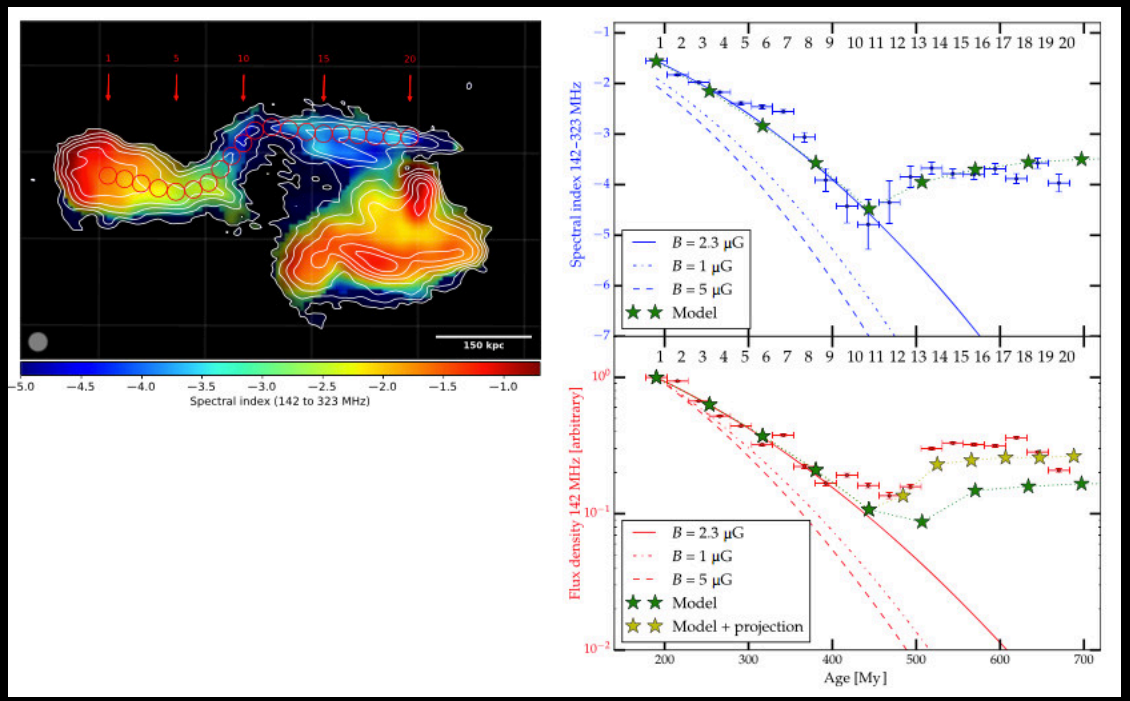
van Weeren+ 2016
Johnston-Hollitt 2017

New open questions

Ultrasteep emission in galaxy clusters and the case of A1033:
Gentle re-energisation of electrons in merging galaxy clusters



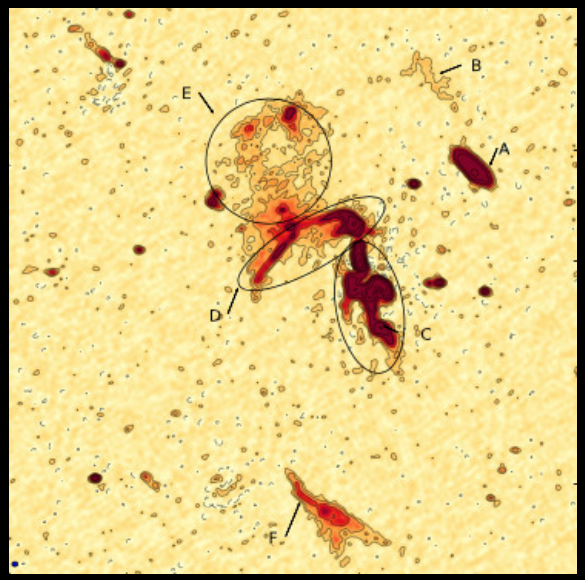
A1033 - de Gasperin et al. 2017



New open questions

Ultrasteep emission in galaxy clusters and the case of A2034

Where does it all come from?



- Ultrasteep spectrum radio halo
- A number of candidate relics
- Further very steep radio emission

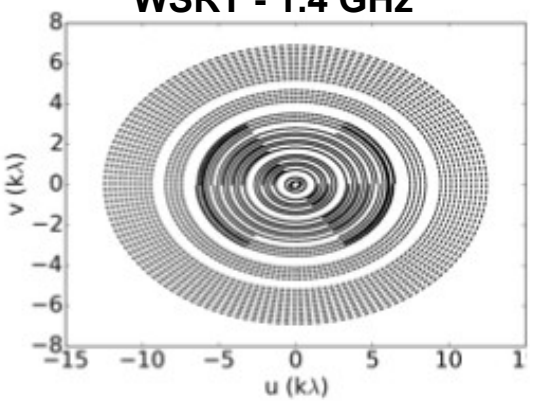
Thermal/Non-thermal interplay difficult to test

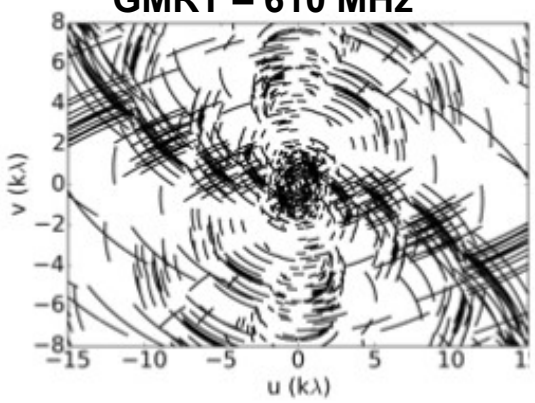
Shimwell+ 2016

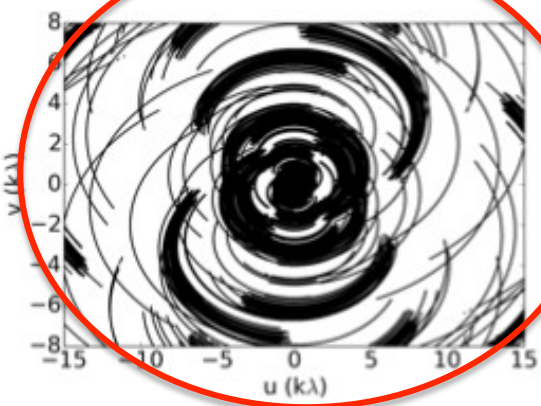
LOFAR – 150 MHz

WSRT - 1.4 GHz

GMRT – 610 MHz

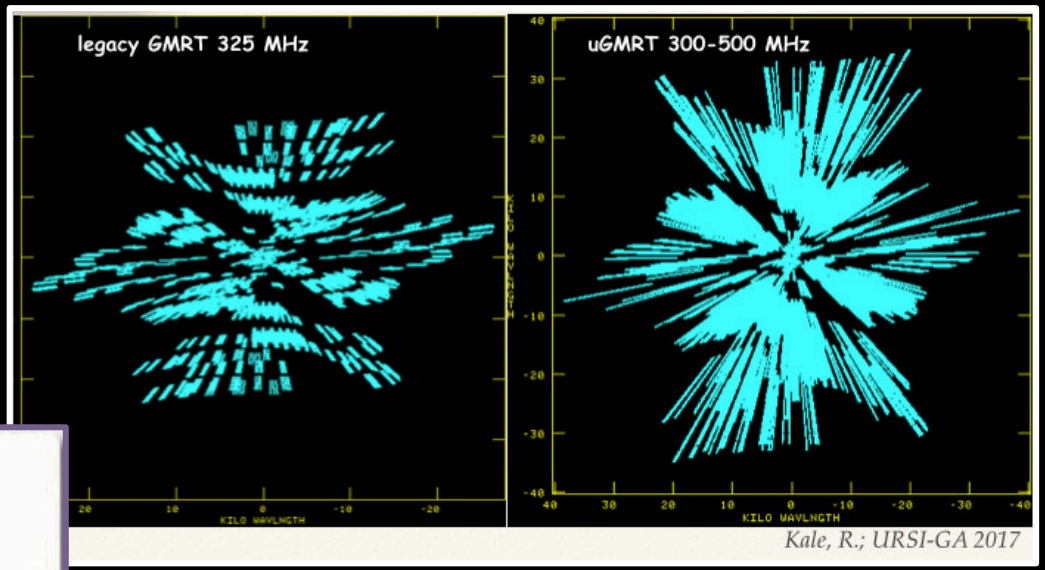




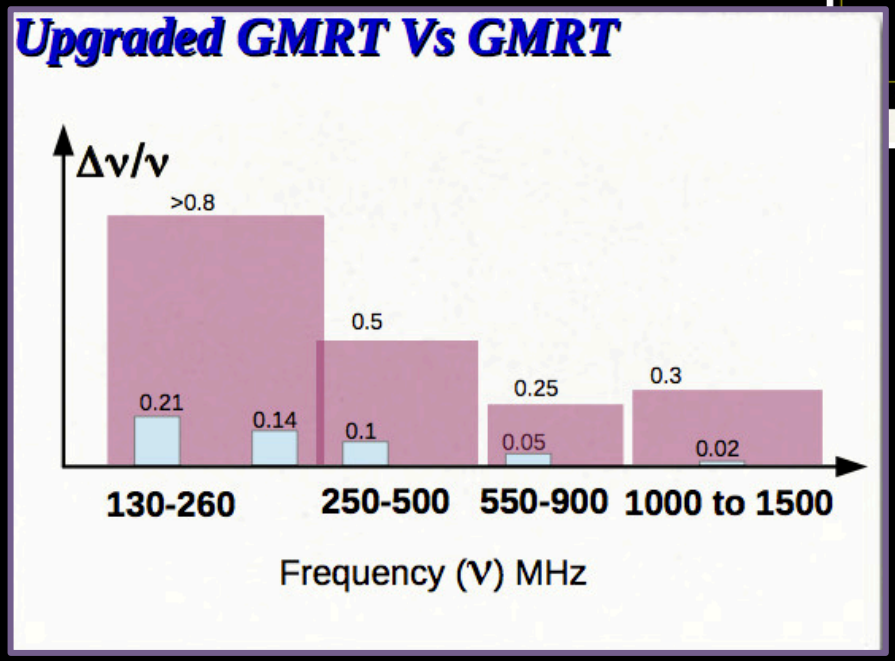


Potential of the current generation of radio interferometers

- Broad bands and u-v coverage
- Frequency range
- Field of view
- Sensitivity



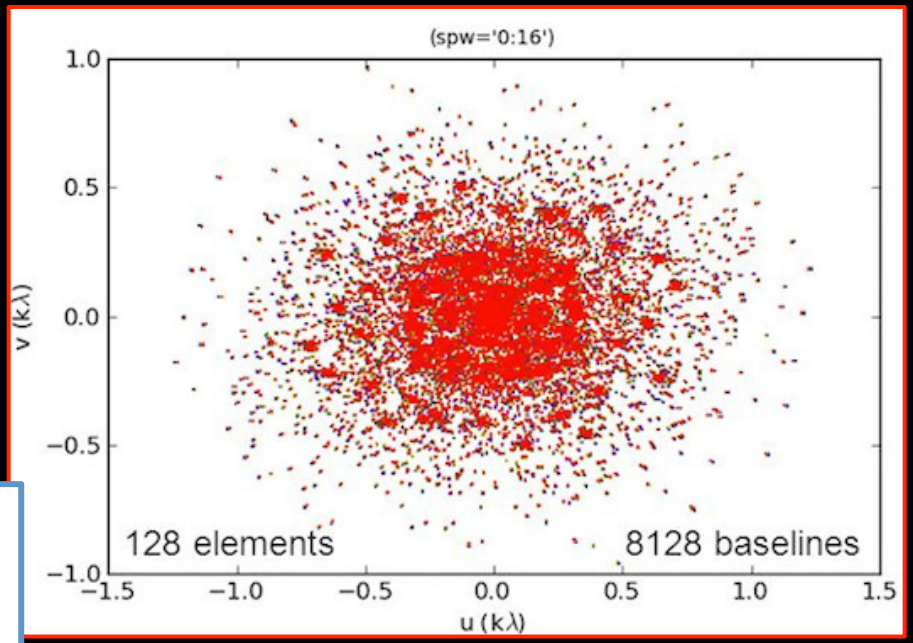
Plots from R. Kale

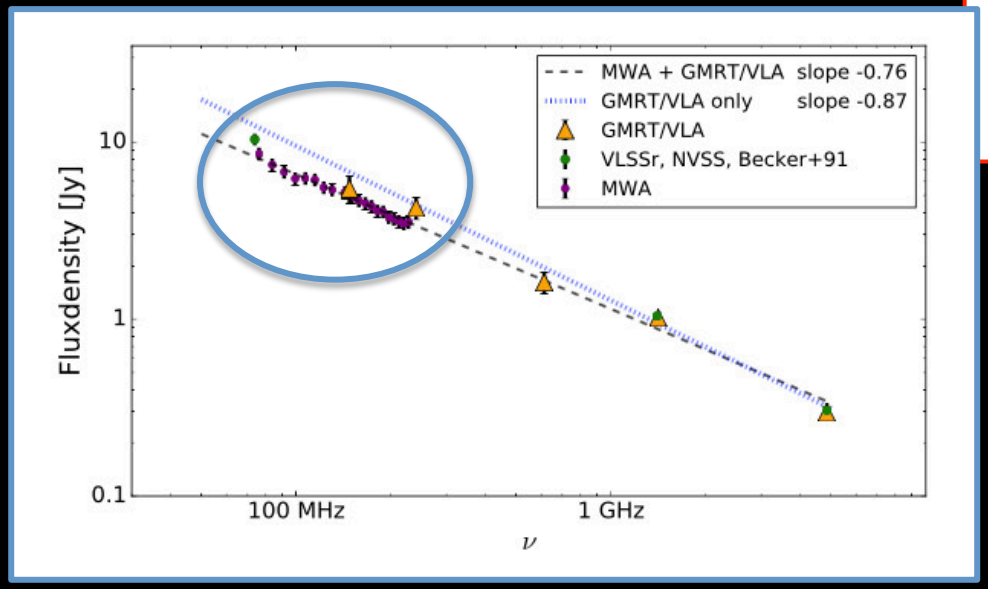


Continuous frequency coverage of uGMRT from 130 MHz to 1500 MHz

Potential of the current generation of radio interferometers

- Broad bands and u-v coverage
- Frequency range
- Field of view
- Sensitivity





Duchense+ 2017

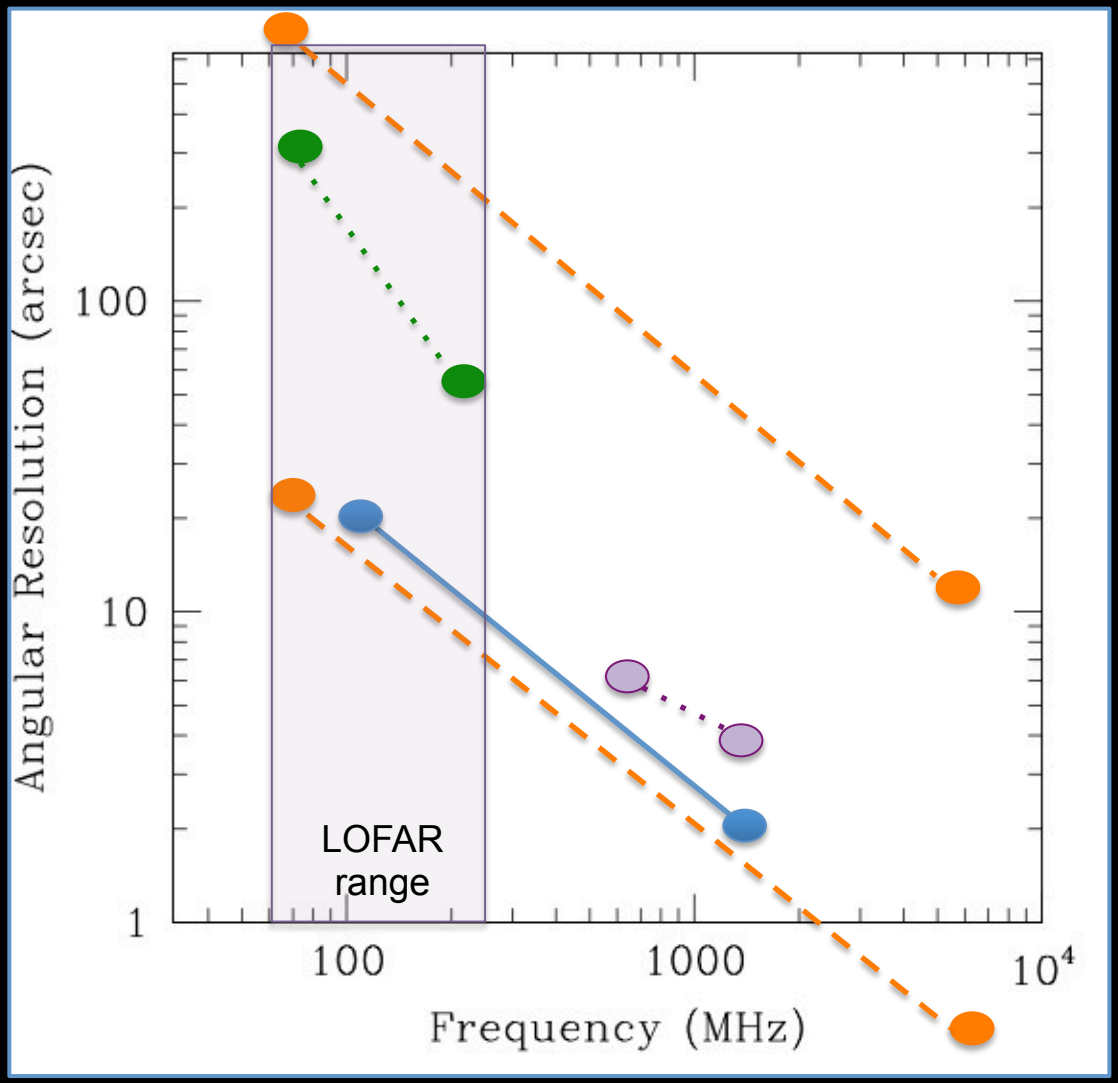
Continuous frequency coverage of MWA from 80 to 300 MHz

Potential of the current generation of radio interferometers

Arrays complementary to each other in terms of angular resolution

Excellent imaging on a broad range of angular scales

Much more reliable spectral studies



Potential of the current generation of radio interferometers

Arrays complementary to each other in terms of angular resolution

Excellent imaging on a broad range of angular scales

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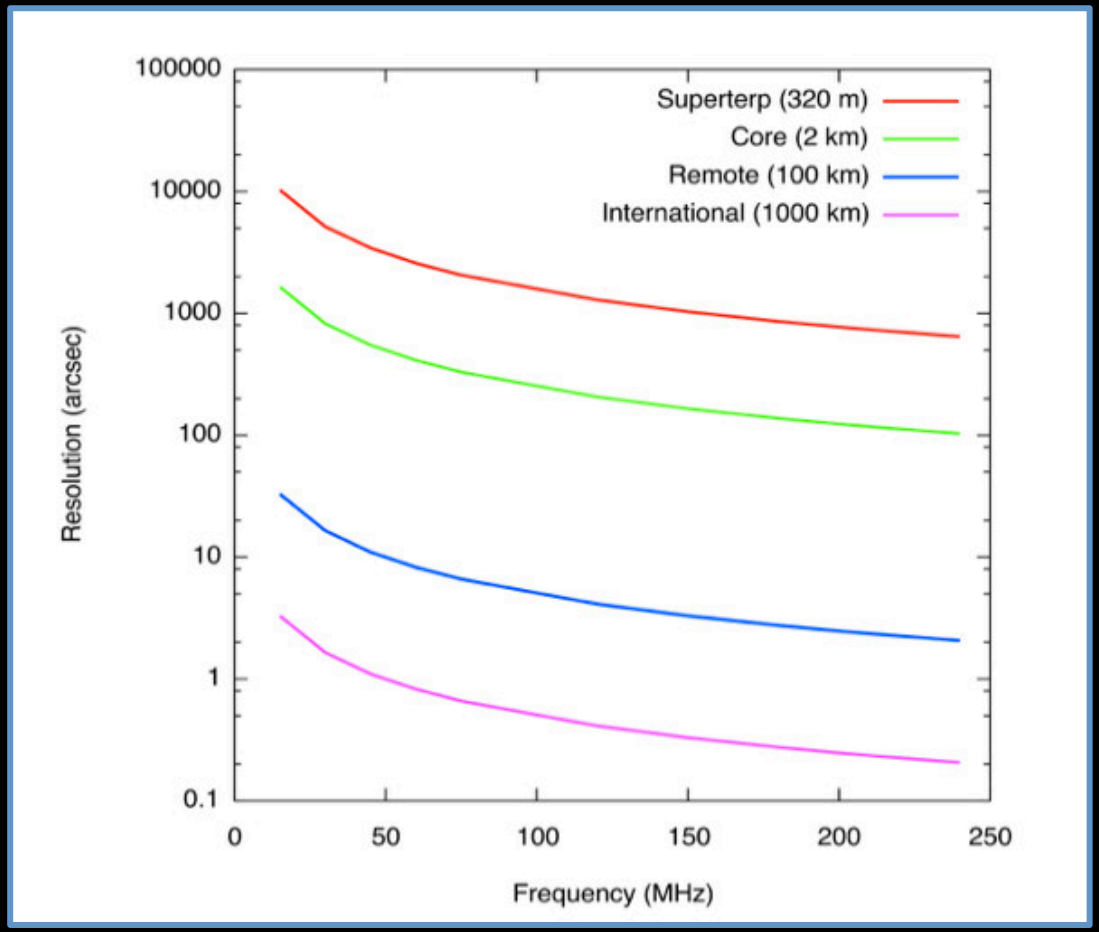
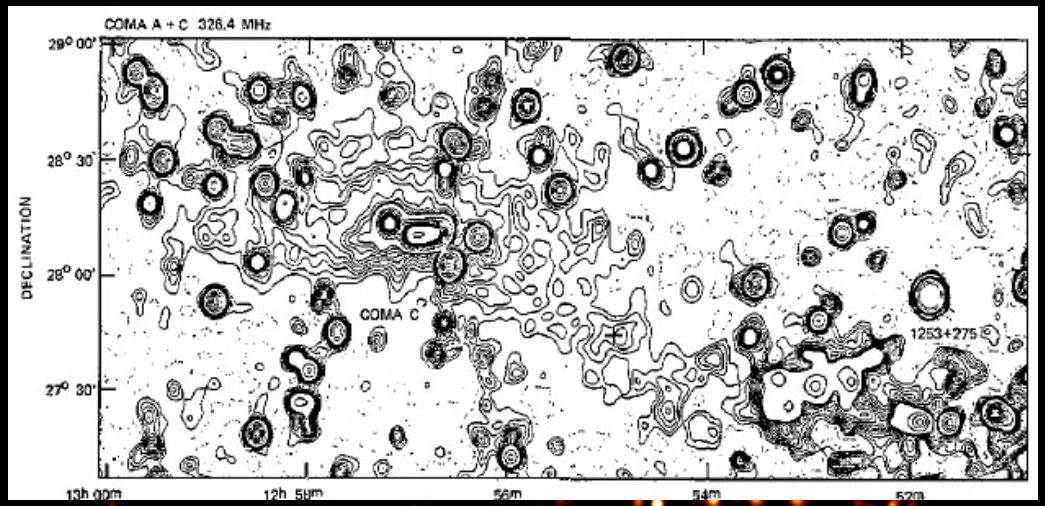


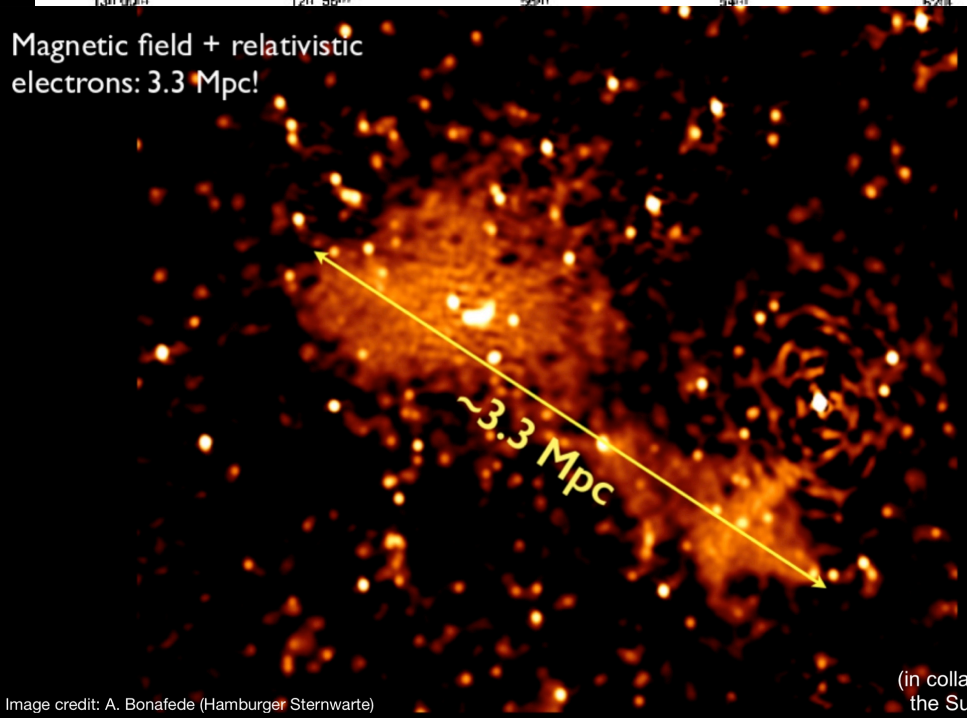
LOFAR

…30 years of Coma…



Giovannini, TV, … 1989

WSRT @ 325 MHz

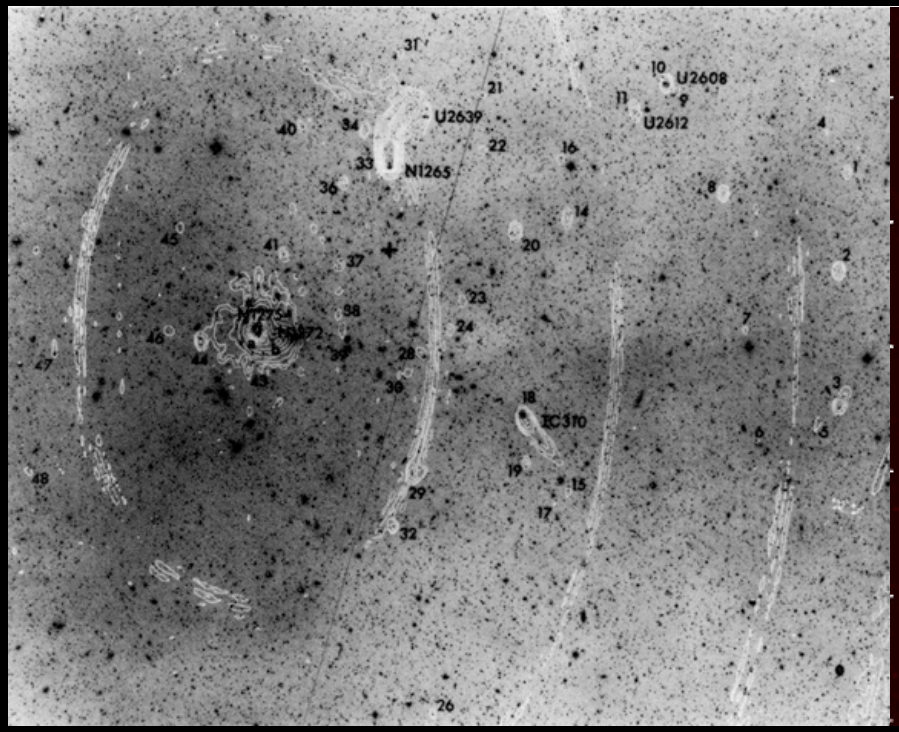


Bonafede et al.
LOFAR @ 140 MHz

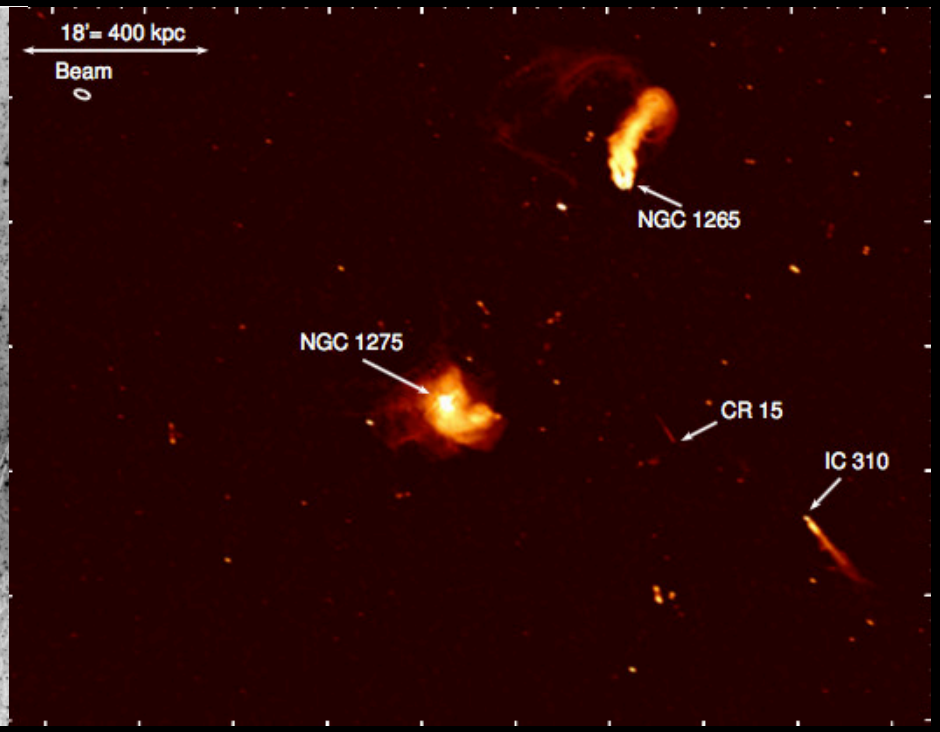
Image credit: A. Bonafede (Hamburger Sternwarte)

(in collaboration with the Surveys KSP)

… 40 years of Perseus…

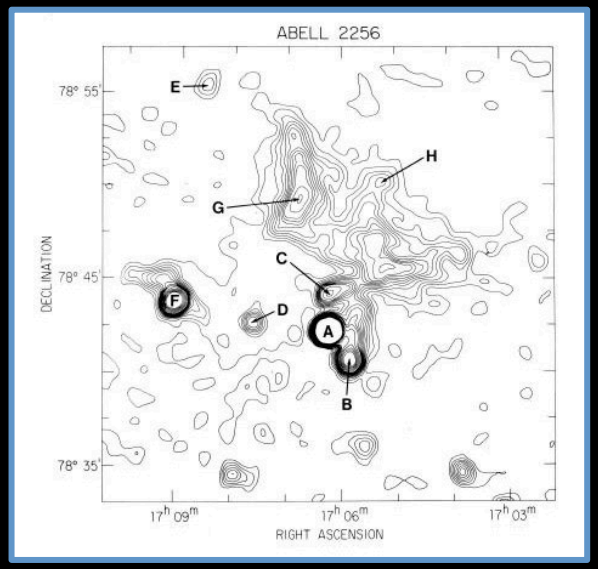


Gisler & Miley (1979) – WSRT @ 610 MHz

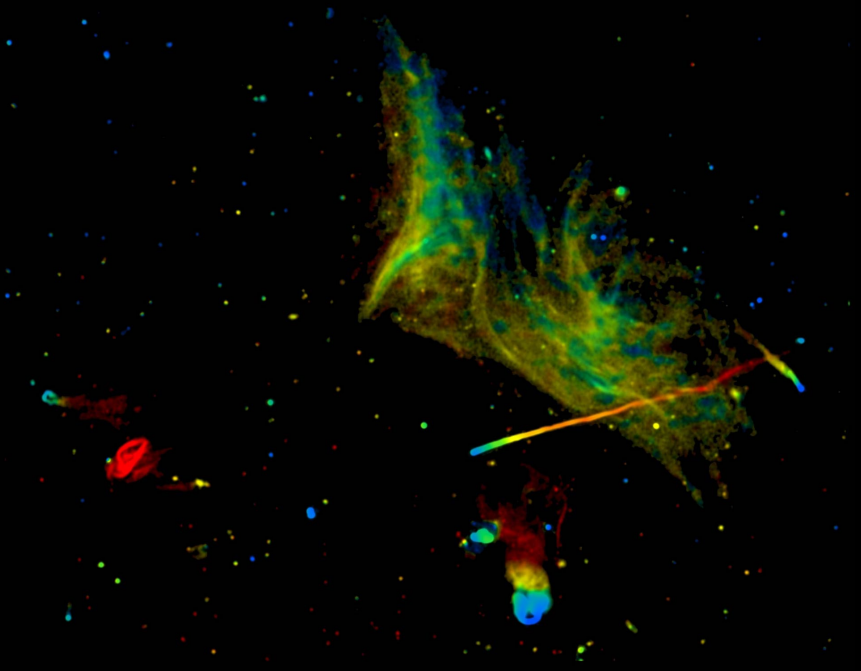


JVLA – Gendron-Marsolais+ 2017 –
JVLA @ 230-470 MHz

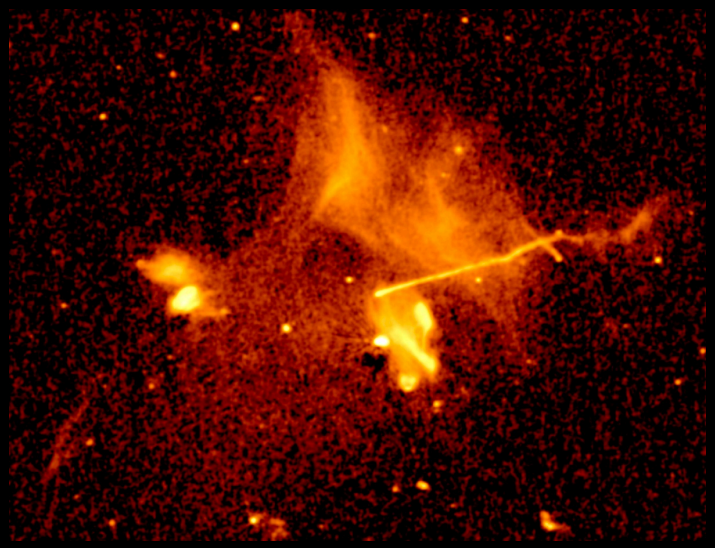
… 40 years of Abell 2256…



Bridle & Fomalont 1976
WSRT 610 MHz



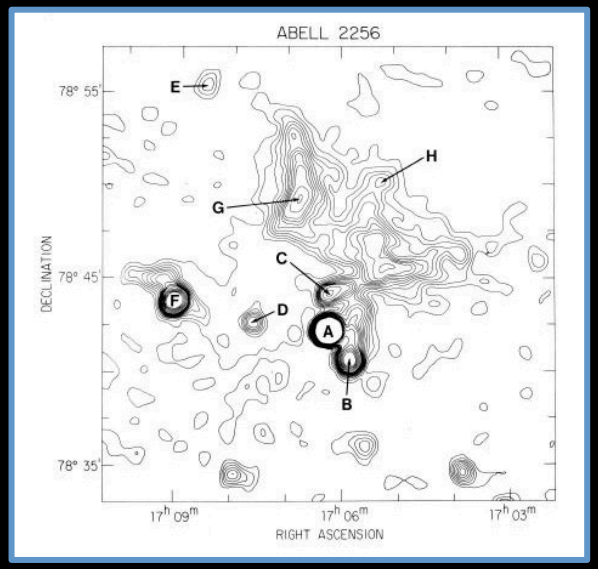
Owen, Eilek, Rudnick 2015 – VLA



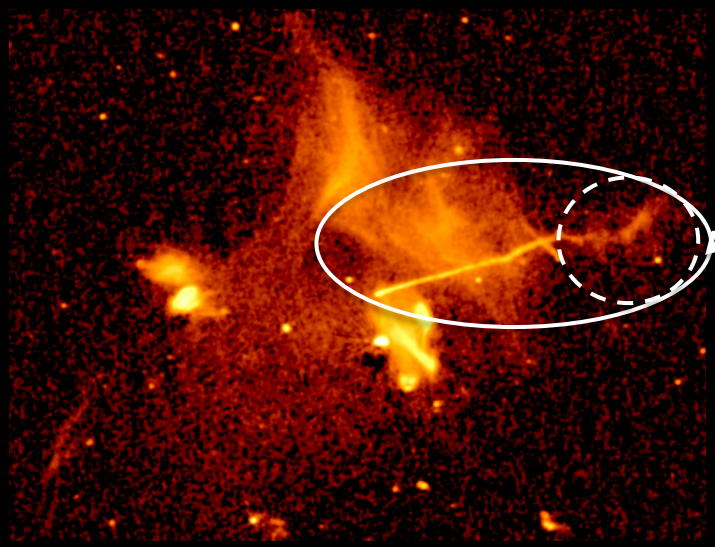
van Weeren 2015
LOFAR 120-180 MHz

… 40 years of Abell 2256…

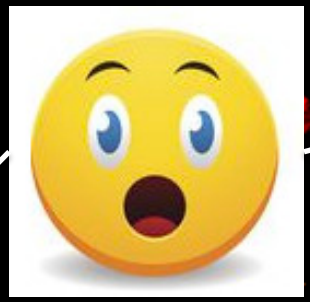
New insights from amazing tails in galaxy clusters?

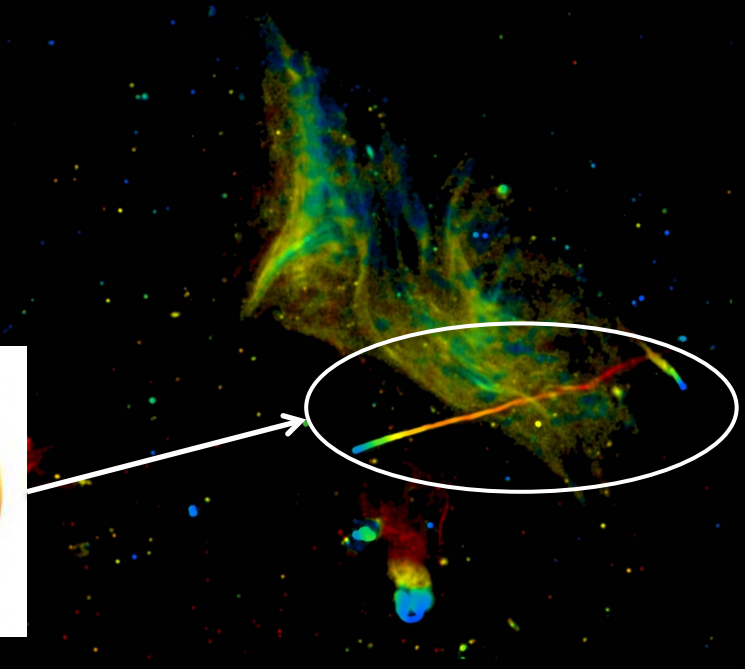


Bridle & Fomalont 1976
WSRT 610 MHz



van Weeren 2015
LOFAR 120-180 MHz





Owen, Eilek, Rudnick 2015 – VLA

FINAL GENERAL CONSIDERATIONS

Our progress in understanding the processes shaping the properties of the radio emission in galaxy clusters has been enormous. Such progress has been possible thanks

- ✓ to the SYNERGIC APPROACH of theory and observations
- ✓ to the collaboration between the radio, optical, X-ray, gamma-ray communities - MULTIMESSENGER APPROACH
- ✓ to the combination of SURVEY APPROACH and DEEP STUDIES OF INDIVIDUAL CLUSTERS/SOURCES
- ✓ to the TECHNICAL DEVELOPMENT in radio astronomy , which has led to an incredible improvement in the performances of radio interferometers
- ✓ to the huge investment in the calibration and data analysis techniques

THANK YOU FOR YOUR ATTENTION

THANKS TO THE SOC




AND TO MY COLLABORATORS





…and many others …