Outline

- Radio emission from the Intra Cluster Medium
- The MACS sample: massive and distant galaxy clusters
- Radio observations at the GMRT
- Comparison with cosmological simulations
- LOFAR observations of the most distant and powerful radio halo
Radio halos

Synchrotron emission on Mpc scale
Low surface brightness
\( \sim 1 \, \mu\text{Jy/arcsec}^2 \) at 1.4 GHz
Usually unpolarized \( \rightarrow \) depolarization

- always found in merging clusters

\( \rightarrow \) particles generated or accelerated everywhere in the cluster

Feretti et al. (2001),
Govoni et al. (2004)
Radio halos: models

Models
- Re-acceleration models (e.g. Brunetti et al. 2001, Petrosian 2001)
- Hadronic models (e.g. Dennison 1980, Keshet 2010; Ensslin et al. 2010)

process
- Fermi II mechanism
- Fermi I mechanism
- Unefficient process

Particle spectrum
- curved spectral index
- straight spectral index
Radio halos: models

Re-acceleration models

Hadronic models

A Coma-like cluster

Brunetti et al. 2009

From Donnert et al. 2010
Radio halos: models

Re-acceleration models

Hadronic models

A Coma-like cluster

Brunetti et al. 2009

A2256 – 1st halo observed by LOFAR
Van Weeren et al. 2012

From Donnert et al. (2010)
Radio relics

Synchrotron emission on Mpc scale in the cluster outskirts

Low surface brightness $\sim 1 \mu$Jy/arcsec$^2$ at 1.4 GHz

Polarized $\sim 20\%$ at 1.4 GHz

$\rightarrow$ particles accelerated and/or magnetic field amplified. shocks?

Bonafede et al. (2009)
Radio relics:

Model predictions
→ DSA
→ Magnetic field compressed by the shock
→ $t_{\text{acc}} \sim 10^5 \text{ yr}$
→ $t_{\text{loss}} \sim 10^8 \text{ yr}$

Radio observable signatures
→ injection spectral index $> 0.5$
→ detectable polarization
- magnetic field aligned with shock surface
→ steady state reached, power-law spectrum steepening of the spectral index as particles move from the acceleration site

van Weeren et al. 2010
Distribution of halos and relics

Feretti et al. 2012

Feretti et al. 2012

Halos

$\langle z \rangle = 0.20$

Relics

$\langle z \rangle = 0.17$  Elongated

$\langle z \rangle = 0.06$  Roundish

Feretti et al. 2012
Aim of the work:
Extend our knowledge of halos and relics to $z > 0.3$

MACS catalog (Ebeling et al. 2007, 2010):

- From ROSAT Bright Source Catalog (Voges et al. 99)
- $z > 0.3$
- $L_x > 2 \times 10^{-12}$ erg/s/cm$^2$ [0.1 - 2.4 keV]

128 clusters

Most promising candidates selected on the basis of
- Chandra / XMM-Newton data available
- merging signature
- hints of diffuse emission from NVSS
Radio Observations

Giant Metrewave Radio Telescope GMRT

Frequency: 325 MHz
256 channels
8s integration time

Time: 6 hours per cluster (net ~ 3.5 - 4)
MACSJ1731.6+2252

$z = 0.389$

$L_x = 2.5 \times 10^{45}$ erg/s

Ebeling et al. 2010
MACSJ\text{1731.6+2252} \quad \text{z}=0.389

L_x = 2.5 \times 10^{45} \text{ erg/s}

Contours: 323 MHz
rms 0.3 mJy/beam Beam ~ 10.6” x 6.6”
Colors: DSS 2

Contours: 323 MHz
rms 0.5 mJy/beam Beam ~ 26” x 17”
Colors: Chandra (Ebeling et al. 2010)
MACSJ1149.5+2223

$z = 0.544$

$L_x = 1.4 \times 10^{45} \text{ erg/s}$

Ebeling et al. 2007
MACSJ1149.5+2223

$z = 0.544$
$L_x = 1.4 \times 10^{45} \text{ erg/s}$

**Lensing:**
7 multiply images
galaxies

Main halo
$M(500 \text{ kpc}) \sim 7 \times 10^{14} M_{\odot}$

+ 3 sub-halos

Tangential critical curves
At $z = 1.49, 1.89, 2.45$

Smith et al 2009
MACSJ\text{J1149.5+2223}

$z=0.544$

$L_x = 1.4 \times 10^{45}$ erg/s

High resolution Image

Contours: 323 MHz
rms $0.3 \text{ mJy/beam}$
Beam $\sim 11.5'' \times 7.8''$
Colors: SDSS dr7
MACSJ1149.5+2223, z=0.544

Low resolution Image (briggs Scheme + uvtaper)

Contours: 323 MHz
rms 0.5 mJy/beam
Beam ~ 24.5” x 20”
Colors: Chandra (Ebeling et al. 2007)
Double relics

- the most distant discovered so far -
- peculiar position

**E- relic**
LLS ~ 800 kpc
Distance ~ 1.4 Mpc
S = 23 +/- 2 mJy

**W- relic**
LLS ~ 800 kpc
Distance ~ 1.1 Mpc
S = 17 +/- 1 mJy
Double relics
- the most distant discovered so far -
- peculiar position

E- relic
LLS ~ 800 kpc
Distance ~ 1.4 Mpc
S = 23 +/- 2 mJy

Radio halo (?)

W- relic
LLS ~ 800 kpc
Distance ~ 1.1 Mpc
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Double relics

- the most distant discovered so far -

- peculiar position

MACSJ\,1149.5+2223, \ z=0.544

Radio halo (?)

LLS \sim 1.3 \ Mpc
MACSJ1149.5+2223, $z=0.544$

- Double relics - the most distant discovered so far - peculiar position

GMRT 2 sigma

VLA 1.4 GHZ

Radio halo (?)

LLS $\sim 1.3$ Mpc

$\alpha \sim 2$

The steepest spectrum observed in halos so far

$\alpha > 1.5$ rules out hadronic models (Brunetti et al. 2008+DallaCasa et al. 2009)

But see Ensslin et al (2010)
MACSJ1149.5+2223, \( z = 0.544 \)

Spectral index maps

\[ \alpha = 1.15 \pm 0.08 \]

\[ \alpha = 0.75 \pm 0.08 \]
MACSJ0553.4-3342

$L_x = 1.7 \times 10^{45}$ erg/s

$z = 0.431$

Mann & Ebeling 2012
**MACSJ0553.4-3342**

$L_x = 1.7 \times 10^{45}$ erg/s  \hspace{1cm} $z = 0.431$

Binary Head-On Merger

Merger in the plane of the sky

Just after the core passage
(distance between the 2 gas cores
$\sim 200$ kpc)

Mann & Ebeling 2012

SDSS colors + Chandra contours
MACSJ0553.4-3342, \( z = 0.431 \)

High resolution Image  
(Briggs scheme, Robust=0)

Contours: 323 MHz  
rms 0.15 mJy/beam  Beam \approx 14'' x 9''  
Colors: UH2m
MACSJ0553.4-3342, $z=0.431$

Low resolution Image
Briggs scheme, Robust=3
+ uvtaper

Contours: 323 MHz
rms 0.25 mJy/beam
Beam ~ 23" x 21"
Colors: Chandra (Mann & Ebeling 2012)
MACSJ0553.4-3342, \( z=0.431 \)

Radio halo detected!

**LLS \sim 1.3 \text{ Mpc}**

**\( S = 62 \pm 5 \text{ mJy} \)**
Radio halo detected!

\[ \text{LLS } \sim 1.3 \text{ Mpc} \]
\[ S = 62 \pm 5 \text{ mJy} \]

Time-scale for particle (re)acceleration

Merger in the plane of the sky
Distance between the 2 cores: 200 kpc

\[ M \sim 10^{15} \text{ M}_\odot \]

Collision \sim 0.08 \text{ Gyr ago}

\[ t_{\text{cross}} \text{ (= cascade time for turbulent eddies; Cassano & Brunetti 05)} \sim 0.5 \text{ Gyr} \]

Turbulent re-acceleration scenarios: \rightarrow Turbulence starts to develop well in time before the core passage
MACSJ0553.4-3342, \( z=0.431 \)

Radio halo detected!

- LLS \(~ 1.3\) Mpc
- \( S = 62 \pm 5\) mJy

Time-scale for particle (re)acceleration

Merger in the plane of the sky
Distance between the 2 cores: 200 kpc

\( M \sim 10^{15}\) M\(_{\odot}\)

Collision \(~ 0.08\) Gyr ago

\( t_{\text{cross}} \) (= cascade time for turbulent eddies; Cassano & Brunetti 05) \(~ 0.5\) Gyr

Turbulent re-acceleration scenarios: \( \rightarrow \) Turbulence starts to develop well in time before the core passage
MACSJ $1752.0+4440$

$L_x = 8.2 \times 10^{44} \text{ erg/s}$

$z = 0.366$

XMM-Newton image

Ebeling et al. (in prep)
MACSJ\textsubscript{1752.0+4440}, $z=0.336$

High resolution Image
(Briggs scheme, Robust=0)

Contours: 323 MHz
rms 0.2 mJy/beam
Beam $\sim 9.9'' \times 8''$
Colors: SDSS
MACSJ1752.0+4440, $z = 0.336$

Low resolution Image (Briggs scheme 3)

Contours: 323 MHz
rms 0.5 mJy/beam
Beam $\sim 14'' \times 10''$
Colors: XMM-Newton(a) (Ebeling et al. In prep)
Double relics

**E- relic**
- LLS $\sim 1130$ kpc
- Distance $\sim 1.3$ Mpc
- $S = 410 \pm 33$ mJy

**W- relic**
- LLS $\sim 910$ kpc
- Distance $\sim 0.8$ Mpc
- $S = 166 \pm 16$ mJy
MACSJ1752.0+4440, z=0.366

Double relics

E-relic
LLS ~ 1130 kpc
Distance ~ 1.3 Mpc
S = 410 +/- 33 mJy

Radio halo
LLS ~ 1650 kpc
S = 164 +/- 16 mJy

W-relic
LLS ~ 910 kpc
Distance ~ 0.8 Mpc
S = 166 +/- 16 mJy
MACSJ1752.0+4440, z=0.366

GMRT + WSRT observations @ 1.7 GHz (van Weeren, Bonafede, Ebeling et al, in press)

Spectral index map

Relic E
$\alpha = 1.21 \pm 0.06$

W relic
$\alpha = 1.12 \pm 0.07$

Spectral steepening toward the cluster centre $\rightarrow$ particle aging
MACSJ1752.0+4440, z=0.366

Polarization properties

$F_{\text{pol}} \sim 20\%$

$F_{\text{pol}} \sim 10\%$

Magnetic field aligned with the relics' main axes

1.7 GHz Image from WSRT

Contours: $I_{\text{pol}}$
3-sigma

Colors:
Fractional polarization
Mach numbers from radio spectral index

DSA regime

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

Blandford & Eichler 87

W relic: \( M \sim 3.3 \)

E relic: \( M \sim 4.6 \)

0.67 1.15 1.64
Mach numbers from radio spectral index

DSA regime

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

Blandford & Eichler 87

E relic: \( M \sim 3.3 \)

W relic: \( M \sim 4.6 \)

Rare Events!

Vazza et al. 2010

0.67  1.15  1.64
Rare Events... but they exist:

Sample of high resolution cosmological simulations with ENZO (Vazza et al. 2010,2011)

X-ray maps from simulations

1 case of morphological similarity (shock with $M \sim 5$)
Sample of high resolution cosmological simulations with ENZO (Vazza et al. 2010, 2011)

→ convert to radio emission

projected map of energy flux

\[ \Phi_{\text{shock}} = \int \rho v_s^3 dx^2 / 2 \]
\[ \Phi_{\text{turb}} = \int \rho \sigma_t^3 dx^3 / (2 \cdot l_t) \]

A fraction of the energy is converted into radio emission:

\[ P_{\text{relic}} \sim A_s \Phi_{\text{shock}} \]
\[ P_{\text{halo}} \sim A_t \Phi_{\text{turb}} \]

At and As tuned to reproduce the observed emission
At and As tuned to reproduce the observed

\[ P_{\text{relic}} \sim A_s \Phi_{\text{shock}} \]

\[ P_{\text{halo}} \sim A_t \Phi_{\text{turb}} \]

\[ A_s \approx 10^{-5} \]

Electron to proton acceleration efficiency
(e.g. Hoeft & Brüggen 2007)

\[ R_{e/p} \sim 10^{-3} - 10^{-4} \]
At and As tuned to reproduce the observed emission

\[ P_{\text{relic}} \sim A_s \Phi_{\text{shock}} \]

\[ P_{\text{halo}} \sim A_t \Phi_{\text{turb}} \]

\[ A_s \approx 10^{-5} \]

\[ A_t \approx 0.05 \]

Electron to proton acceleration efficiency
(e.g. Hoeft & Brüggen 2007)

Corresponds to efficiency \( \sim 1\text{e}-4 \)
(e.g. Fujita 2003; Cassano & Brunetti 2005)

\[ R_{e/p} \sim 10^{-3} - 10^{-4} \]
A tiny fraction of the energy injected by shocks and turbulence is required to reproduce the observed radio emission.
MACSJ0717+3745

\(z = 0.55\)

\(L_X[0.1-2.4 \text{ keV}] = 2.74 \times 10^{45} \text{ erg/s}\)

\(P_{[1.4 \text{ GHz}]} \sim 1.6 \times 10^{26} \text{ W/Hz}\)

The most distant and powerful radio halo

Bonafede et al. 09
1.4 Ghz VLA

van Weeren et al. 09
610 Mhz GMRT
LOFAR observations of MACS J0717+3745

Observations: 1-2 April 2012
Time: 12 hours
Integration time: 2s

22 Core Stations
9 Remote Stations

Low Band Observations

244 Sub-Bands
64 channels per Sub band

Multi-beam observation
122 SBs on the target, 122 SBs on 3C196

41 Sub-bands centered on 34 MHz
40 Sub-Bands centered on 58 MHz
41 Sub-Bands centered on 74 MHz
MACSJ0717+3745: calibration strategy

1) CasA demixed from the raw data
2) Calibration of 3C196 – every SB is calibrated separately
3) Amplitude Gains transferred to the target MACSJ0717+3745
4) Phase calibration of the target MACSJ0717+3745
   Against a VLSS model
   20 SBs within each band are combined together

No ionospheric calibration but solving for differential TEC

**Pro:** Robust determination of the amplitude Gains
   Possibility to solve for clock-TEC- FR
**Contra:** half of the Band spent on the calibrator
LOFAR observations of MACSJ0717+3745

$z = 0.55$

$L_{X[0.1-2.4 \text{ keV}]} = 2.74 \times 10^{45} \text{ erg/s}$

58 MHz image

Rms noise ~ 15 mJy/beam

Beam = 43" x 32" (robust 0 weighting scheme)
LOFAR observations of MACSJ0717+3745

$z = 0.55$
$L_x^{[0.1-2.4 \text{ keV}]} = 2.74 \times 10^{45} \text{ erg/s}$

58 MHz image

Rms noise ~ 15 mJy/beam

Beam = 43" x 32"
(robust 0 weighting scheme)

Robust = -0.2
HPBW = 12" x 38"
Rms noise 12 mJy/beam
MACSJ0717 - preliminary results

- colors: VLA 1.4 GHz
  White contour: LOFAR 34 MHZ

Additional extended emission detected at 34 Mhz
Spectral index - preliminary

- colors: VLA 1.4 GHz
  White contour: LOFAR 34 MHZ

Additional extended emission detected at 34 MHz

Spectral index of the whole emission:

\[ \alpha \approx 0.8 \]
\[ \alpha \approx 1.1 \]
\[ \alpha \approx 1.3 \]
Radio halos observed by LOFAR so far

**Abell 2256**
Van Weeren et al. 2012, in press

**MACSJ0717+3745**
Bonafede et al, in prep.

Spectral index of the whole emission:
MACSJ0717+3745: Plans to improve the calibration

Ionosphere: Clock + TEC + Faraday Rotation

From XX, YY to RR LL

RR+LL phase → affected by clock and TEC
\( (\sim \nu \text{ and } 1/\nu) \)

RR-LL phase → affected by Faraday Rotation
\( (\sim \nu^{-2}) \)

1) Fit clock and TEC and FR for a strong calibrator –
   !! Needs a lot of BW on a calibrator!!

2) Correct for clock on your target

3) Solve for FR and TEC on your target

Python script by R. van Weeren and B vd Tol to fit clock, TEC and FR
MACSJ0717+3745: clock and TEC separation

CS- CS baseline

![Graph showing phase vs freq with markers and lines for different data types.](image-url)
RS- CS baseline   PHASE UNWRAPPING NEEDED
(work in progress with R. van Weeren and Bas van der Tol)

MACSJ0717+3745: clock and TEC separation
Thanks!