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Chapter 1

Introduction

The formation history of our Universe has been a topic of discussion since ancient times. With the advancement in science and technology, humankind has been able to untie a few knots in the vast web of mystery. The Big Bang is the accepted cosmological theory that describes how the Universe began before undergoing a sequence of complex hierarchical structure formation. The theory asserts that the Universe started about 13.7 billion years ago in an initial state of very high temperature and density (Komatsu et al. 2011, Planck Collaboration et al. 2016). The ΛCDM : current standard model of cosmology, states that our Universe consists of baryonic matter (5%), cold dark matter (22%) and dark energy density (73%). This model successfully describes some of key observed phenomena such as the abundance of the light elements (Helium, Hydrogen and Lithium), the Cosmic Microwave Background (CMB) radiation (Smoot et al. 1992, Bennett et al. 1996 Planck Collaboration et al. 2016), the accelerated expansion of the universe (Riess et al. 1998) and the large-scale structures.

A key ingredient of the ΛCDM model is the theory of cosmic inflation (Guth 1981, Guth & Steinhardt 1984) that suggests, our Universe, in its first few moments, went through an extremely rapid exponential expansion. In a tiny fraction of a second ($\sim 10^{-32}$s), the linear size of the Universe increased by a factor of 10^{26}. This explains that distant regions of the Universe were actually much closer together prior to inflation and could have been causally connected, thus having same physical properties. This sudden expansion as invoked by inflation, also results in a flat-space geometry. This could also explain that, during this process the density of the magnetic monopoles dropped exponentially making their detection highly unlikely.

Our Universe is remarkably homogeneous and isotropic on larger scales. The CMB radiation has a spectrum consistent with that of a black body at a temperature of $T_{\rm CMB} = 2.725K$ (Fixsen 2009). However, tiny variations in the CMB temperature indicate that at that time there were small-scale density fluctuations (Smoot et al. 1992, Mather et al. 1994, Kovac et al. 2002). These tiny fluctuations are thought to be related with the quantum fluctuations of matter density that are present immediately after the Big Bang. Under the influence of gravity, these small scale primordial CMB density fluctuations can grow hierarchically. First, halos of cold dark matter formed and these merged with each other to accrete more mass (Springel et al. 2006). The baryonic matter that primarily follows the dark matter halos, then cooled and collapsed, forming clouds of gas, stars, galaxies and eventually the largest structures of all, namely clusters of galaxies. These clusters are the focus of this thesis.

Galaxy clusters

Galaxy clusters are the largest gravitationally bound systems of the Universe, with masses up to $10^{15} M_{\odot}$. Even though clusters can contain up-to thousands of galaxies, the majority (80%) of the cluster-mass is constituted by dark matter (Blumenthal et al. 1984). Dark matter only interact with the baryonic matter (∼20%) through gravitational force. Of the baryonic mass, 85% is comprised of a hot ($10^7 - 10^8$ K), rarefied ionised plasma, that fills the entire volume of the cluster, referred as intra-cluster medium (ICM). This dilute plasma emits thermal Bremsstrahlung radiation that is visible at X-ray wavelengths. Stars, cold gas and dust in galaxies form the remaining 15% of the baryonic mass.

Galaxy clusters are continuing to grow via the accretion of smaller groups of galaxies and through major merger events with other cluster of galaxies (Kravtsov & Borgani 2012). This process of cluster mergers and continuous accretion of gas from the inter-galactic medium (IGM), can create shock waves in and around galaxy clusters. The most spectacular are events where two massive clusters merge. This releases a huge amount ($\sim 10^{64}$ ergs) of gravitational energy into the ICM. The released binding energy strongly affects the physical properties of the system including density distribution & velocity dispersion of member galaxies and temperature, metallicity & density distribution of the X-ray emitting thermal ICM. Direct evidence of associated density, pressure and temperature jumps are seen with X-ray observations (Markevitch & Vikhlinin

2007). Merger driven shocks, bulk flows and turbulence can amplify the magnetic field ($\sim \mu$G) strength (Roettiger et al. 1996, Roettiger et al. 1997) and affect the spatial transport of the relativistic ($\gamma > 1000$) particles (also known as cosmic rays, CRs). In the presence of magnetic fields, these relativistic charged particles can emit synchrotron radiation that can be observed at radio frequencies. Radio observations reveal giant diffuse synchrotron emission that traces the CRs in the ICM (see Feretti et al. 2012, van Weeren et al. 2019, for reviews).

Typically diffuse radio sources in clusters have a steep spectral index[1] ($\alpha \leq -1$). The spectral shape is related to the physics of the (re)acceleration mechanism and the electron synchrotron and inverse Compton (IC) energy losses (Sarazin 1999, Brunetti & Jones 2014). Energy losses limit the life-time of CR electrons in the ICM and the maximum energy at which they can be accelerated by various mechanisms. The presence of CR electrons and magnetic fields in the ICM that generate large-scale diffuse radio sources via synchrotron emission, has fundamental implications on both the physics of the ICM and the evolution of galaxy clusters (e.g. Brunetti & Jones 2014, for a review).

Diffuse radio emission in clusters

In the last decades, with the advent of low-frequency telescopes and X-ray satellites, significant progress has been made to classify diffuse radio sources in the ICM and study the particle acceleration mechanisms. Diffuse radio sources can broadly be classified into two sub-categories based on their morphology and location of the sources in the cluster: *radio halos* and *radio relics*.

Radio halos are extended (~Mpc) diffuse radio sources that are located at the centre of merging clusters (Cassano et al. 2008; Cuciti et al. 2015, Kale et al. 2018). They typically have a morphology similar to the X-ray morphology of the ICM. More than 70 radio halos have been discovered (e.g. Feretti et al. 2012; van Weeren et al. 2019). Observational evidence to date suggests that radio halos are caused by continuous acceleration of CR electrons in the turbulent gas (Brunetti et al. 2001, Petrosian 2001, Brunetti & Lazarian 2007). These CR electrons (also known as primary electrons) are injected into the ICM by, for example, radio galaxies, supernovae, or galactic winds. Also, proton-proton collision could be responsible for the generation of secondary electrons (Hadronic model: Dennison 1980, Enßlin et al. 2011) that can be re-accelerated together with primary CR electrons (Brunetti & Lazarian 2011; Pinzke et al. 2017) and generate large-scale radio halos.However, current upper limits on the

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[1] $S_\nu = \nu^\alpha$; S_ν is the measured flux density of a radio source at the observed frequency ν

γ-ray emission in galaxy clusters puts constraints on the hadronic origin of radio halos (Jeltema & Profumo 2011; Ackermann et al. 2016; Brunetti et al. 2017).

Radio relics are $\sim$1-2 Mpc long and are located in the cluster outskirts Feretti et al. 2012, van Weeren et al. 2019). Typically they have a convex morphology with respect to the cluster centre, are linearly polarized (20% to 30% at GHz frequencies) and exhibit a radio spectral steepening towards the cluster centre (e.g. van Weeren et al. 2010, Bonafede et al. 2012, Stroe et al. 2013, Hoang et al. 2017, Kierdorf et al. 2017 etc.). Cluster radio relics are thought to be tracers of merger induced shock waves (e.g. Finoguenov et al. 2010, Shimwell et al. 2015, Botteon et al. 2016 etc.). Typically, the spectra of radio relics are well represented by a power-law; however, it is now a matter of debate if radio relics have a curvature at frequencies higher than $\sim$2 GHz (Stroe et al. 2016, Loi et al. 2017).

Nowadays, the connection between radio relics and shocks is well established. However, the underlying acceleration mechanism is still debated. Primarily shocks are thought to accelerate particles via diffusive shock acceleration (DSA, Krymskii 1977; Bell 1978a; Bell 1978b etc.). DSA is also known as Fermi-I mechanism and asserts that CR particles are scattered in the upstream and downstream regions of a shock by plasma irregularities. Due to these repeated reflections at the shock fronts, CR electrons gain their non-thermal energy (Fermi 1949). It was originally thought that electrons in the thermal pool could be accelerated by DSA to produce the observed (radio) emission. However, the acceleration efficiency via DSA is found to be low, and insufficient to generate bright radio relics (van Weeren et al. 2016a, Botteon et al. 2016 etc.). Also, a connected problem with the large acceleration efficiencies concerns the lack of γ-ray emission from galaxy clusters (Vazza et al. 2014; Vazza et al. 2015; Wittor et al. 2017).

For these reasons, the role of **'fossil plasma'** or seed particles have been invoked, as recent simulations indicate that re-acceleration of seed relativistic particles is more efficient than the DSA (e.g: Kang & Ryu 2015). A similar issue has also been suggested for the generation of radio halos that may require an initial pool of mildly relativistic CR electrons for turbulent re-acceleration (Brunetti & Jones 2014). A key question that needs to be answered is what are the source of these fossil electrons in the ICM? It is clear that galaxy clusters host active galactic nuclei (AGN). These AGNs can inject CR electrons into the ICM and in the presence of magnetic fields can generate synchrotron radio emission (Vantyghem et al. 2014). Such AGNs that are very luminous at radio wavelengths are known as radio galaxies and are often accompanied by single or twin radio lobes that can extend up-to Mpc scales. These energetic CR electrons from the lobes of a radio galaxy can provide the seed populations of relativistic electrons and a possible connection between radio galaxies and re-acceleration mechanisms in radio halos or radio relics (Kang & Ryu 2016). Such tentative morphological connections of radio galaxies with radio relics have been proposed by Bonafede et al. (2014), Shimwell et al. (2015) and most clearly has been shown by van Weeren et al. (2017) in the galaxy cluster pair Abell 3411–3412.

Studying the population of fossil electrons is not trivial. When the central AGN of a radio galaxy switches off and there is no supply of freshly injected particles, the so-called 'AGN remnant lobes' can diffuse into the surrounding medium. Due to synchrotron and radiative losses, after a few tens of Myr, their spectrum becomes steep ($\alpha \leq -1.2$) and curved. The fossil plasma becomes invisible and hard to detect, even at the lowest observable frequencies (Brienza et al. 2017, Hardcastle 2018, English et al. 2019). However, in a cluster environment, these low-energy relativistic ($\gamma \sim$100) electrons can still be poorly mixed with the ICM (Sarazin 1999; Petrosian 2001; Pinzke et al. 2013). Merger driven turbulence, shocks and ICM bulk motion can adiabatically compress these old fossil electrons (Ensslin et al. 1998; Enßlin & Brüggen 2002) and emit observable (sub GHz) radio waves again. These revived fossil plasma sources, which are known as **radio phoenices**, provide us with a unique opportunity to study these otherwise invisible population of electrons (Kempner et al. 2004). To date, only a few radio phoenices have been discovered (Slee et al. 2001, van Weeren et al. 2009, de Gasperin et al. 2015). In order to understand the acceleration mechanisms responsible for the generation of radio phoenices, it is crucial to identify their common observational and physical properties and compare them with that of radio halos and relics. This will also help in establishing radio phoenices as a distinct class of objects and enable us to better understand the nature of this relatively unexplored population.

Faint radio population

Radio source counts that are derived from deep 1.4 GHz surveys, had shown a sudden steepening below 1 mJy (Windhorst et al. 1990, Prandoni et al. 2001b). This is interpreted as a result of the emergence of a faint radio population; which is different in nature from the ones that dominate at higher flux densities (such as radio loud AGNs). The faint radio population most likely consists of several types of objects such as: faint (radio-quiet) AGNs, starburst galaxies, distant clusters, normal spirals and ellipticals. The physical and evolutionary properties of faint radio sources and the relative importance of the different class of objects are still being debated and their redshift distribution and luminosity properties are not well known (Prandoni et al. 2001a). This is mainly because the current samples of such objects are small. Moreover, optical follow up of these sources are highly incomplete in terms of spectroscopic information (Gruppioni et al. 1999, Gregorini & Prandoni 2000). Therefore, it is evident that wider and deeper (low-frequency) radio sky surveys with optical follow-up are strongly needed in order to asses the evolution and the nature of the faint radio population. Observations at low-radio frequencies not only have large field of views, that allow to construct a larger statistical sample and provide more robust statistical constraints but also are more sensitive to (steep spectrum) star forming galaxies that dominate the faint radio population.

Low-frequency radio data processing and advancements

In the last decades, significant progress has been made in order to understand the physics of galaxy clusters. Cluster mergers are the largest particle accelerators of the Universe and these conditions (such as large scales, weak shocks and magnetic fields) cannot be found in other astronomical events or be reproduced on Earth. It is now well established that shocks and ICM motions generated through cluster mergers can produce large-scale synchrotron emission that usually has a very low-surface brightness and steep spectra. Therefore, it is clearly beneficial to study these systems at the low-radio (sub GHz) frequencies.

However, calibration of low-frequency radio data is not trivial due to the direction dependent, time varying effects of the ionosphere that affects both the amplitude and the phase of the radio signal. These ionospheric effects are more dominant towards the lower part of the radio spectrum making it one of the main limiting factors for high-resolution low-frequency radio observations. In addition, the field-of-view at these frequencies, is much larger than at higher frequencies. Therefore, applying a unique correction factor using traditional techniques (such as self-calibration; Pearson & Readhead 1984) to correct these phase and amplitude effects for the entire field of view is too simplistic and is not sufficient. Below, a brief description of two of the pioneer low-frequency radio telescopes: **GMRT** and **LOFAR** is given. These two radio telescopes are also two of key the pathfinders of the future generation radio telescope Square Kilometre Array (SKA; Schilizzi 2005).

The Giant Meterwave Radio Telescope (GMRT; Swarup et al. 1991) is a radio interferometer that is located in India and consists of 30 parabolic dishes of 45 meter diameter each. The GMRT started to improve the low-frequency view of the radio sky in terms of angular resolution and sensitivity. This has been shown in a few low-frequency surveys centred around 150 MHz (e.g.: Ishwara-

Chandra et al. 2010, Sirothia et al. 2009). Most importantly, in the last 10 years, the development of the Source Peeling and Atmospheric Modeling (SPAM; Intema et al. 2009, Intema 2014), have made a significant improvement on the ionospheric calibration of the low-frequency radio data. This fully automated pipeline includes state-of-the-art calibration, radio frequency interference (RFI) mitigation schemes, direction-dependent calibration, and ionospheric modeling. One of the most important data products of this pipeline is the 150 MHz TIFR GMRT Sky Survey (TGSS ADR; Intema et al. 2017). The TGSS is the most sensitive (2-5 mJy/beam rms noise) radio sky survey at such low-frequency till date, that covers almost 90% (–53° to +90°) of the whole sky.

The Low Frequency Array (LOFAR; van Haarlem et al. 2013) is the largest pathfinder to the SKA that operates at the lowest observable frequency range of 30-240 MHz. LOFAR is a new-generation radio telescope that uses phased aperture array technique in which the antenna primary beam is formed electronically. This is different from traditional radio telescopes that use mechanical steering of antennas. Most of the LOFAR antennas are based in the Netherlands, with baseline lengths ranging from 100 meters to 120 km. Additional remote stations are located throughout Europe. The longest European baseline of LOFAR can provide a resolution of $0.5''$ at 150 MHz. The combination of LOFAR's large field of view, wide range of baseline lengths, and large fractional bandwidth makes it a powerful instrument for performing large area and deep sky surveys. These enormous capabilities of LOFAR also make the challenges to tackle the radio data calibration and imaging (at such low frequencies) more complicated since, the ionosphere and its associated Faraday rotation and sky structure are heavily direction dependent and time varying. In the last few years, novel algorithms have been developed to overcome these challenges; such as SAGECal (Yatawatta et al. 2013), Facet Calibration (van Weeren et al. 2016b), KillMS (kMS; Tasse 2014; Smirnov & Tasse 2015), DDFacet (Tasse et al. 2018). Specifically KillMS and DDFacet are now being used for the completion of the LOFAR Two Meter Sky Survey (LoTSS; Shimwell et al. 2017) where the whole northern radio sky is observed with a sensitivity better than 100μJy/beam at the resolution of $5''$. This upcoming deep and sensitive low-radio-frequency survey will be an excellent tool to further investigate the nature of diffuse radio emission in clusters and of the faint radio population.

This Thesis

With the advent of new generation low-frequency telescopes and better calibration techniques, we have now started to unveil the sub GHz radio sky with unprecedented depth and sensitivity. Diffuse radio emission have steep synchrotron spectra, meaning that they are brighter at low frequencies and are the ideal targets for LOFAR. LOFAR has been thought to have the potential to make major breakthroughs in the field of cluster science (Rottgering et al. 2006, Röttgering et al. 2011, Cassano et al. 2012, Nuza et al. 2012). Even if the number of such observations are very limited at this stage, the complexity of objects observed has put the traditional taxonomy of diffuse radio sources into question (de Gasperin et al. 2017). Recent LOFAR observations have also strengthened the claim of presence of **fossil radio plasma** in the ICM that could provide the seed particles and can be accelerated to generate large-scale diffuse radio emission (van Weeren et al. 2016a, Shimwell et al. 2016, Hoang et al. 2017, Wilber et al. 2018). Cluster science with LOFAR also includes the fate and evolution of radio lobes/bubbles, the interplay between cluster radio galaxies (AGNs) and the ICM and the distribution of the ICM magnetic fields. In this regard, open questions in this field that are to be answered, are:

- How common is the presence of fossil radio plasma in clusters?
- Do ultra-steep spectrum fossil plasma sources in galaxy clusters have a common origin and is there a connection between radio galaxies and re-acceleration mechanisms in radio halos and relics?
- What is the occurrence of diffuse radio sources as function of cluster mass and dynamical state?
- How useful are the upcoming deep radio surveys in order to understand the nature of faint radio source population?

In order to answer these questions, systematic studies of different classes of radio sources are crucial. It is also very important to combine complementary multi-band data to understand the interaction between different components (such as thermal and non-thermal) of clusters. In addition, observations of these systems at different wavelengths, need to be compared with simulations.

Conducting wide and deep radio sky surveys is one of the main goals of LOFAR since its commencement. For this purpose, a three-tier approach had been adopted. Tier 1 includes the observation of the whole 2π steradians of the northern sky (LoTSS; Shimwell et al. 2017, Shimwell et al. 2019). In these radio images, the most prevalent population is the radio-loud AGN that dominates the bright radio sky. With deeper observations, it is indeed possible for LOFAR to open up a new regime of (much) fainter radio population (such as radio quiet quasars, distant star-forming galaxies, high-redshift clusters and faint diffuse radio emission). Therefore, deeper Tier 2 and Tier 3 observations were planned to cover smaller areas (over a sky area of 30 deg^2) with a higher sensitivity (10-15 μJy/beam; see Röttgering et al. 2011 for more details). In order to scientifically exploit these more sensitive surveys, complementary multi-wavelength data are necessary, most notably to identify the host galaxies of the extra-galactic radio sources and determine their redshift. For these reasons, observations were focused on fields with the highest quality multi-wavelength data available; such as the Lockman Hole, the Boötes and the European Large-Area ISO Survey-North 1 (ELAIS-N1) fields. Studying these deep fields would allow an extreme broad range of science that includes: star formation processes in the early Universe; characterisation of the distribution of star-formation across the galaxy population as a function of mass, luminosity, different environment and redshift; intra-cluster magnetic fields; determining the history of black hole accretion and its dependence with the star formation; the nature of radio filaments and bridges across galaxy clusters that could be related to the accretion shocks and etc. However, before addressing the science questions, it is very important to make sure that the sources in these radio images are properly deconvolved and have reliable flux densities. **Radio source-counts** is one of the immediate data products from these deep radio images that can be used as a sanity check for the data reduction and to study the statistical properties of the (faint) radio source population. Source counts derived from these wide area surveys would overcome uncertainties introduced by low statistics, cosmic variance effects (Heywood et al. 2013) and other systematics (Condon et al. 2012). These source counts can also be used to estimate the foreground contamination for Epoch of Reionization (EoR) experiments (Trott & Wayth 2016).

Thus, the aim of this thesis is two fold:

- To better understand the nature of revived fossil (radio) plasma sources in galaxy clusters and establish them as a distinct class of radio sources (Chapter 2,3 and 4).
- To derive the deepest radio source-counts at 150 MHz (to date) and compare with the other existing determinations, as well as with state-of-the-art evolutionary models (Chapter 5).

Below, the contents of each chapter and the topics discussed within, are described (in brief):

Chapter 2 deals with a detailed study of a merging galaxy cluster Abell 1914. Deep radio (LOFAR 150 MHz, GMRT 325 and 610 MHz and VLA 1.4 GHz), X-ray (*Chandra*) and optical (CFHT) data are presented. The analysis shows that the ultra-steep spectrum source (4C38.39; $\alpha \leq -2$) that previously was thought to be part of a radio halo, is a distinct source with properties that are consistent with revived fossil plasma sources. In addition, some diffuse emission to the west of the source 4C38.39 was also detected that could belong to a radio halo.

Chapter 3 and 4 present the first systematic study of revived fossil plasma candidates in galaxy clusters. **Chapter 3** demonstrates the discovery potential of the 150 MHz TIFR GMRT Sky Survey (TGSS) in combination with the 1.4 GHz NRAO VLA Sky Survey (NVSS) to find and study revived fossil plasma sources in galaxy clusters. A subset of three candidates (out of which two are new discoveries) was studied in detail using deep multi-band radio (LOFAR and GMRT), X-ray (*Chandra* or *XMM-Newton*) and archival optical observations. Tentative physical properties of these three sources were discussed based on the observations and they were categorised to be in the class of 'radio phoenices'. As the next step, in **Chapter 4**, an observational overview of all the known radio phoenices (either newly discovered or previously known) is presented. Out of 25 sources that are shown, 12 are new discoveries, for which new radio (GMRT and/or LOFAR) and, for a subset, X-ray observations have been shown. Common physical properties of the whole sample of radio phoenices (such as radio morphology, dynamical state of the host cluster, location of the phoenices inside the cluster and spectral behaviour) are studied for the first time, in order to establish the nature of this relatively unexplored class of objects. These radio phoenices are found to have AGN origin and are located well within the R_{500} of the clusters. Presence of dynamical disturbance in the cluster supports the formalism that they are associated with ICM motion and or shocks. Finally, even if these revived fossil plasma tend to have a curved spectra at higher frequencies, presence of non-uniform spectral indices suggests they should not be thought of a reservoir of uniform cosmic-ray population.

In **Chapter 5** the deepest radio source counts, that have ever been obtained at 150 MHz are presented for the Lockman Hole, The Boötes and the Elais-N1 fields. These three fields are the LOFAR Tier-3 depth survey fields (see Röttgering et al. 2011 for details). The derived source counts are compared with other existing determinations, as well as with state-of-the-art evolutionary models (e.g. Mancuso et al. 2017; Bonaldi et al. 2019). The expected flattening and upturn of the counts below ~1 mJy (as also seen in higher frequency surveys) is due to the emergence of the radio-quiet quasar and star-forming populations, which these deeper pointings will critically enable us to properly sample across luminosity and redshift space.

Future studies

In terms of fundamental physics, this century has seen some of the biggest breakthroughs such as discovery of Higgs Boson, detection of gravitational waves etc. and it has become clear that the advancement in technologies play a key role in this proess. In the field of radio astronomy, a similar trend in technological advancements had happened in the last decade. Many new generation radio telescopes (such as LOFAR, MWA, ASKAP, MeerKAT etc.) started to become operational and older telescopes have been upgraded (such as VLA, WSRT, GMRT). The LOFAR has already started to reveal the radio sky at frequencies around and even below 100 MHz and has clearly made a significant impact in our understanding of faint radio populations. The lowest observable window of the electro-magnetic radiation is a completely uncharted territory and therefore, is full of potential for new discoveries.

The future of cluster science with LOFAR is undoubtedly promising. The dense core of LOFAR provides excellent sensitivity towards low surface brightness diffuse emission. Furthermore, the arc-second resolution will allow appropriate disentanglement of the foreground/background emission and embedded sources that are projected onto the diffuse emission. In the next few years, few immediate objectives can be achieved:

- Already, from the shallow low-frequency surveys it has become clear that fossil radio plasma can occupy a significant fraction of the cluster volume and provide seed particles for re-acceleration. The known sample of revived fossil plasma sources is probably just the tip of the iceberg of the population and upcoming wider and deeper radio surveys (such as LoTSS; Shimwell et al. 2019 and LoLSS; de Gasperin et al. in prep) will be excellent tools to further investigate the nature of these fossil electron population. Also, studying the spectral behaviour of these diffuse sources would allow for detailed comparisons between the predictions from different particle re-acceleration models and the observational data.

- The brightness fluctuations in the diffuse radio emission reflect the underlying distribution of magnetic fields in the ICM. The high-resolution images from LOFAR are able to resolve scales smaller than the typical coherent scales of magnetic field in galaxy clusters. This will be crucial to probe the magnetic field power spectrum (Murgia et al. 2004, Vacca et al. 2012).

- Enßlin & Röttgering (2002) predicted that sensitive radio surveys at low radio frequencies will be crucial to draw an unbiased statistical population of radio halos that can provide unique information about galaxy cluster merger rates and associated non-thermal processes. Also, turbulent re-acceleration model predicts the existence of ultra-steep spectrum radio halos (Cassano et al. 2010) that will be picked up by upcoming low-frequency radio surveys.

Complementary radio observations at high frequencies is also important in order to distinguish between various models for the origin of synchrotron emitting electrons. In addition, following up large unbiased samples of diffuse radio sources at high frequencies will allow us to study the polarisation properties and magnetic field distribution in the ICM. Finally, it is of no doubt that combining X-ray data with radio observations is very important to study the interplay between thermal and non-thermal components in the ICM. Therefore, with the future generation radio (SKA) and X-ray telescopes (eROSITA, ATHENA), we expect to have a much better understanding of galaxy cluster physics.