

Radio mini-halos and AGN heating in cool core clusters of galaxies

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The brightest cluster galaxy (BCG) in the majority of relaxed, cool core galaxy clusters is radio loud, showing non-thermal radio jets and lobes ejected by the central active galactic nucleus (AGN). Such relativistic plasma has been unambiguously shown to interact with the surrounding thermal intra-cluster medium (ICM) thanks to spectacular images where the lobe radio emission is observed to fill the cavities in the X-ray-emitting gas. This ‘radio-mode AGN feedback’ phenomenon, which is thought to quench cooling flows, is widespread and is critical to understand the physics of the inner regions of galaxy clusters and the properties of the central BCG. At the same time, mechanically-powerful AGN are likely to drive turbulence in the central ICM which may contribute to gas heating and also play a role for the origin of non-thermal emission on cluster-scales. Diffuse non-thermal emission has been observed in a number of cool core clusters in the form of a radio mini-halo surrounding the radio-loud BCG on scales comparable to that of the cooling region. This contribution outlines the main points covered by the talk on these topics. In particular, after summarizing the cooling flow regulation by AGN heating and the non-thermal emission from cool core clusters, we present a recent study of the largest collection of known mini-halo clusters (~ 20 objects) which investigated the scenario of a common origin of radio mini-halos and gas heating. We further discuss the prospects offered by future radio surveys with the Square Kilometre Array (SKA) for building large ($\gg 100$ objects), unbiased mini-halo samples while probing at the same time the presence of radio-AGN feedback in the host clusters.

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†A footnote may follow.

1. Introduction

An important discovery from early *Chandra* and *XMM-Newton* observations of relaxed galaxy clusters was that the amount of gas radiatively cooling to low temperatures is much less than what is predicted by the standard cooling flow model (e.g., Peterson & Fabian 2006). The implication is that the central intra-cluster medium (ICM) must experience some kind of heating to balance cooling. The source of this heating, and understanding when and how it takes place, has become a major topic of study in extragalactic astrophysics. The most promising candidate has been identified as feedback from energy injection by the active galactic nucleus (AGN) of the central galaxy (e.g., McNamara & Nulsen 2007; Gitti et al. 2012). Radio jets and lobes from the AGN can interact strongly with the ICM, carving X-ray cavities and also driving turbulence. In a number of cases, the radio-loud AGN are surrounded by radio mini-halos extending on cluster-scales (e.g., Feretti et al. 2012). The nature of these diffuse radio sources is still debated. One possibility is that they form through the re-acceleration of relativistic particles by turbulence, whose origin is however unclear (e.g., Brunetti & Jones 2014). If the turbulence is powered by the AGN activity itself, the mechanisms responsible for particles re-acceleration in mini-halos and for gas heating in cooling flows should be intimately connected.

In this paper, which outlines the main topics covered by the talk, we first summarize briefly the cooling flow regulation by AGN heating (Sect. 2) and the non-thermal emission from cool core clusters (Sect. 3). We then present the main results published in Bravi et al. (2016), who attempted for the first time to relate the turbulent re-acceleration powering mini-halos to the AGN heating quenching cooling flows (Sect. 4), and in Gitti et al. (2015), who discussed the developments expected in this field by future Square Kilometre Array (SKA) observations (Sect. 5).

2. Cooling flow regulation in galaxy clusters

The majority of baryons in galaxy clusters are in the form of diffuse, hot ($T \approx 10^8$ K) plasma, the ICM, which emits in X-rays due to thermal bremsstrahlung and line emission. The characteristic time of energy radiated in X-rays, that is the “cooling time”, t_{cool} , depends locally on the radial profiles of temperature, $T(r)$, and density, $n_e(r)$, as

$$t_{\text{cool}}(r) \propto \frac{T(r)}{n_e(r) \Lambda(T(r))} \quad (2.1)$$

where $\Lambda(T(r))$ is the cooling function. The “cooling radius”, r_{cool} , is defined as the radius at which the cooling time is equal to the age of the system, which was originally assumed to be the Hubble time. Nowadays it is custom to consider a shorter time in which the system has realistically been relaxed, as for example the time since the last major merger event, $t_{\text{cool}}(r_{\text{cool}}) \approx 3$ Gyr. In the region inside r_{cool} , that is the so-called “cooling region”, t_{cool} is short by definition so the X-ray emission is an efficient process. Therefore the ICM cools down while flowing inwards with a mass inflow rate \dot{M} , and is compressed to maintain the pressure equilibrium at r_{cool} . Since the X-ray emission is proportional to the square of the density, $J_X(r) \propto n_e^2(r) \Lambda(T(r))$, this runaway process produces an increase of the central surface brightness. Indeed such clusters are characterized by a strongly peaked surface brightness profile in the center. In the framework of this standard “cooling flow” process, described by Fabian et al. (1994), it is possible to estimate the mass accretion rate directly from the cooling luminosity observed inside r_{cool} , L_{cool} , as $\dot{M} \propto L_{\text{cool}}/T$.

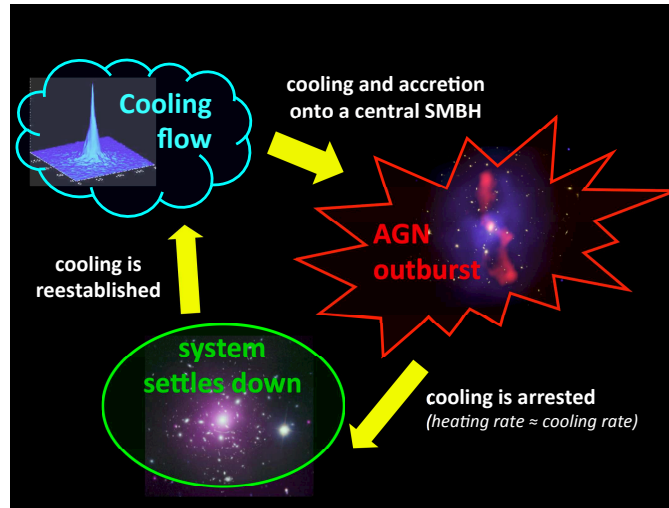


Figure 1: A sketch of the self-regulated feedback loop. A relaxed cluster develops a cooling flow, then the cool gas accreting into the central supermassive black hole (SMBH) triggers the AGN outburst. The associated mechanical heating is able to quench the cooling flow with a heating rate comparable to the cooling rate. After a while the system settles down and then the cycle starts again.

On the other hand, the observations tell us a different story. In particular, the high-resolution spectroscopic observations performed with *XMM-Newton* and *Chandra* revealed the lack of cold gas in the amount predicted by the standard cooling flow model (e.g., Peterson & Fabian 2006, for a review). What is observed, instead, is that the gas cools down only to a certain minimum temperature ($T_{\min} \approx$ one third of the ambient temperature) and that the actual mass accretion rate is only about one tenth of that predicted by the standard model. This has raised the so-called “cooling flow problem”, that is why, and how, is the cooling of gas below T_{\min} suppressed? This has also started a new nomenclature, as these clusters are now referred to as “cool core” instead of “cooling flow” clusters, but the reader should not be confused as both expressions refer to the same relaxed clusters, with a high brightness peak, low temperature and high density in the central region.

Among the many solutions proposed to solve the cooling flow problem, the main candidates have soon been identified in the radio-loud AGN. It had been known for decades that in most cool core clusters the brightest cluster galaxy (BCG) is radio-loud (Burns 1990). However, the unambiguous evidence of the strong impact that radio galaxies have on the ICM had to wait until the X-ray telescopes finally reached the same \approx arcsec angular resolution as the radio interferometers. Thanks to the spectacular overlays of *Chandra* and VLA images, indeed, it was soon realized that the central ICM in most cool core clusters is not smoothly distributed, but shows instead depressions often coincident with the BCG radio lobes. The obvious interpretation of such spatial anti-correlation between the X-ray and radio emission is that the “radio bubbles” displace the thermal ICM carving the so-called “X-ray cavities”, which are evident as deficit in the X-ray surface brightness distribution. By studying these systems it was realized that the *mechanical* AGN outburst has an energy budget able to balance the losses of the ICM. This has identified the so-called “radio-mode AGN feedback” as the main candidate to solve the cooling flow problem. The general picture envisions a sort of life-cycle in which the AGN is fueled by a cooling flow that is itself regulated by feedback from the AGN (see Fig. 1). This is the so-called “self-regulated feedback loop” – recurrent outbursts from the radio-loud AGN hosted by the BCG at the center of (almost)

every cool core cluster are able to heat the ICM. For general reviews on this topic we refer the reader to, e.g., McNamara & Nulsen (2007, 2012) and Gitti et al. (2012).

3. Non-thermal emission from cool core clusters

3.1 Radio-loud AGN

As we have discussed above in Sect. 2, the main non-thermal emission observed from cool core clusters is that of radio-loud AGN, that inflate large cavities, heat the ICM and induce a circulation of cool gas and metals on hundred-kpc scale (for more details on this latter topic, not covered here, see e.g. Gitti et al. 2012). Although we currently reached a good understanding of the general framework of the cooling flow regulation in galaxy clusters, many details of this process are still unclear, as for example the detailed microphysics of how the heat is transferred to the ICM. The common belief is that the heating mechanisms must be distributed in the core, with a gentle energy dissipation acting at a heating rate that cannot be much higher than the cooling power, otherwise the cool core would be disrupted. In this context, it has recently been proposed that the observed outflows from mechanically-powered AGN can drive turbulence in the ICM which can contribute to heat it. In particular, Zhuravleva et al. (2014) showed that the dissipation of such a turbulence produces a heating rate which is able to balance the cooling rate locally at any radius.

3.2 Radio mini-halos

In some cases the radio-loud BCG at the center of cool core clusters is surrounded by a diffuse, faint, amorphous (roundish) radio source classified as “radio mini-halo”, which extends on scales (total size) $\sim 100\text{-}500$ kpc comparable to that of the cooling region. Although the AGN is likely to play a role in the initial injection of the relativistic particles, the mini-halo emission is not directly connected with the BCG radio bubbles, but on the contrary is truly generated from the ICM on larger scales. Furthermore, while in the case of the BCG the thermal and non-thermal components are clearly spatially separated, in the case of mini-halos such components are mixed (see in the left panel of Fig. 2 the example of the cluster RBS 797 which hosts both a mini-halo, in green contours, and a cavity-bubble system, in blue contours).

The problem of the origin of radio mini-halos stems from the so-called “slow diffusion problem”, that is the fact that the radiative lifetime of the radio-emitting particles is too short ($\lesssim 10^8$ yr) for the relativistic electrons to cover the distances (\approx hundreds kpc) on which the radio emission is observed. This can be explained in the framework of leptonic models, which envision *in situ* particle re-acceleration by turbulence in the cool core region, or alternatively by hadronic models, in which secondary electrons are continuously generated by p - p collisions in the cluster volume (see e.g. Brunetti & Jones 2014, for a recent review).

In the framework of leptonic models, Gitti et al. (2002) originally proposed that the cooling flow process itself may power radio mini-halos through the compressional work done on the ICM and the frozen-in magnetic fields. This model considers particle re-acceleration by Fermi II mechanisms associated to MHD turbulence in the cool core region, thus envisioning a connection between the radio properties of mini-halos and the X-ray properties of the hosting clusters. Remarkably, a trend between the mini-halo radio power and the cooling flow power has been observed in the first, small collections of mini-halos, in which it appears evident that the strongest radio mini-halos are associated with the most powerful cooling flows (Gitti et al. 2004, 2007, 2012).

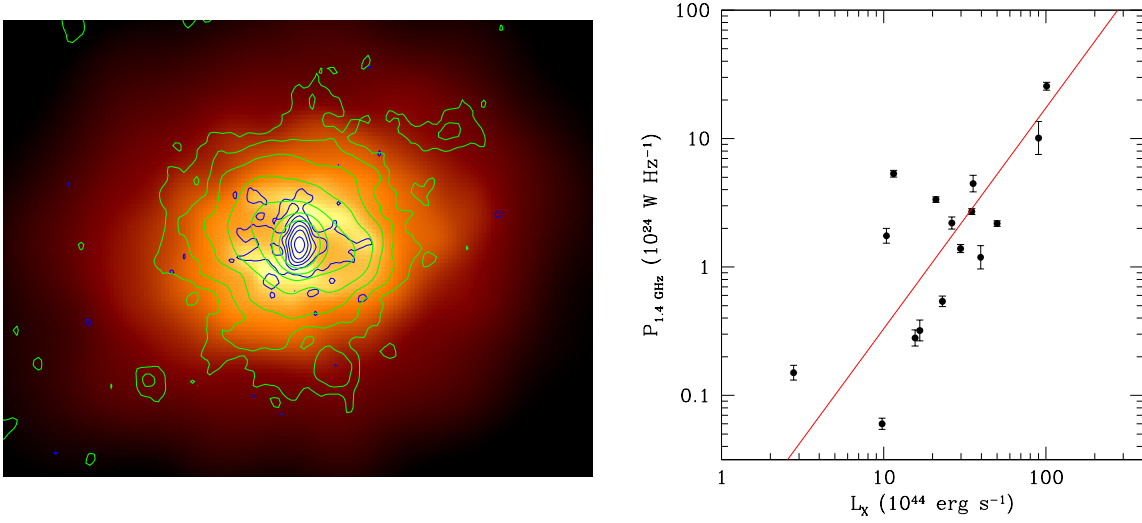


Figure 2: *Left panel:* X-ray *Chandra* image of the galaxy cluster RBS 797 at $z = 0.35$ with superimposed radio VLA contours at 1.4 GHz (in green, at $\sim 3''$ resolution, Gitti et al. 2012) and at 5 GHz (in blue, at $\sim 1''$ resolution, Gitti et al. 2013). The X-ray cavities in the ICM are observed to be coincident with the BCG radio lobes extending out for ~ 40 kpc (blue contours), which are surrounded by the large-scale emission of the diffuse radio mini-halo having a radius of ~ 90 kpc (green contours). *Right panel:* Radio power at 1.4 GHz, $P_{1.4}$, versus the X-ray luminosity, L_X , for the sample of 16 confirmed mini-halos. The red solid line is the best fit relation $P_{1.4} \propto L_X^{1.72}$ (see text). Adapted from Gitti et al. (2015).

4. A new study of the largest mini-halo sample

We note that previous studies of mini-halos face some issues. One caveat is that the observational investigations were based only on small ($\ll 10$ objects), heterogeneous samples, analyzed in different ways by starting from data obtained by different instruments. The second caveat is that the origin of turbulence and in particular its connection with the thermodynamical properties of the cool core is still unclear. In Bravi et al. (2016) we attempted to address both these issues. In particular, we exploited the increased mini-halo statistics currently available in literature (~ 20 objects, mostly from Giacintucci et al. 2014) and performed a homogeneous *Chandra* analysis of the host clusters in order to accurately derive the spectral properties of the cool cores to be compared with the radio properties of the mini-halos. We found a correlation between the integrated radio luminosity at 1.4 GHz (expressed in terms of νP_ν)¹ and the cooling flow power $P_{CF} = \dot{M}kT/\mu m_p$ (where k is the Boltzmann constant, T the ICM temperature at r_{cool} , m_p the proton mass, and $\mu \approx 0.61$)² in the form $[\nu P_\nu]_{1.4} \propto P_{CF}^{0.8}$ (see Bravi et al. 2016, and these proceedings). This confirms a connection between the thermal energy reservoir in cool cores and the non-thermal energy of mini-halos.

4.1 Turbulent re-acceleration scenario: a common origin for mini-halos and gas heating?

We further argued that the particle re-acceleration producing mini-halos and the gas heating by AGN in cool cores are due to the dissipation of the same turbulence. As discussed above in Sect. 3.1, the (turbulent) heating power must be slightly higher, but in general very close, to the cooling flow power: $P_{turb} \gtrsim P_{CF}$. Therefore, if we assume that a fraction of P_{turb} is channelled into particle acceleration and non-thermal radiation, P_{CF} can be seen as an upper limit to the non-thermal

¹ $[\nu P_\nu]_{1.4} = 1.4 \times 10^{40} (P_{1.4}/10^{24} \text{ W Hz}^{-1}) \text{ erg s}^{-1}$.

² $P_{CF} \sim 10^{41} (\dot{M}/1M_\odot \text{ yr}^{-1}) (kT/1 \text{ keV}) \text{ erg s}^{-1}$.

luminosity of mini-halos, L_{NT} . On the other hand, when we observe synchrotron emission we know that at the same time the relativistic electrons are losing energy through Inverse Compton (IC) scattering with CMB photons, therefore the total non-thermal luminosity must be higher than that observed in radio : $L_{\text{NT}} = L_{\text{radio}} [1 + (B_{\text{CMB}}/B)^2]$, where $B_{\text{CMB}} = 3.2(1+z)^2 \mu\text{G}$ is the magnetic field equivalent to the CMB in terms of IC losses, and B is the magnetic field intensity in the mini-halo region. By imposing that $L_{\text{NT}} \ll P_{\text{CF}}$ we can constrain the intra-cluster magnetic field, finding a limit $B \gg 0.5 \mu\text{G}$. This value is in agreement with typical estimates of magnetic fields in cool cores and will further be tested with future surveys of Faraday rotation measures (e.g., Johnston-Hollitt et al. 2015). The scenario proposed in Bravi et al. (2016) of a common origin of radio mini-halos and gas heating by AGN-induced turbulence in cool cores can be validated by investigating whether all mini-halo clusters show evidence of AGN feedback. This will be possible with future surveys with the SKA, as discussed below in Sect. 5.

5. Future prospects with SKA radio surveys

The detection of radio mini-halos is complicated by the need of separating their faint, low surface brightness emission from the bright emission of the radio-loud BCG embedded in it, which is in fact very challenging with the current facilities. This may be the reason for the relatively low number of mini-halos known, although it has yet to be established. In fact, although a correspondence between radio mini-halos and cool cores is well recognized, it is still not clear whether these radio sources are intrinsically common or rare in cool core clusters.

Statistical studies of large cluster samples are necessary to reach a better understanding of these sources. In a chapter published in the SKA White Book (Gitti et al. 2015) we explored the prospects offered in this field by future observations with the SKA. Good cluster statistics in terms of X-ray properties are already currently available from *Chandra* and *XMM-Newton* and can be exploited to forecast future detection of radio mini-halos, provided that an intrinsic relation between the thermal and non-thermal cluster properties exists. For this purpose, we investigated the link between general X-ray and radio observables that can be easily obtained from (present and future) cluster surveys, such as the luminosities. By starting from a sample of 16 confirmed mini-halos, we derived a correlation between the 1.4 GHz radio power of mini-halos and the X-ray luminosity of the host clusters in the form: $\log P_{1.4} = 1.72(\pm 0.28) \log L_X - 2.20(\pm 0.46)$, where $P_{1.4}$ is in units of $10^{24} \text{ W Hz}^{-1}$ and L_X is in units of $10^{44} \text{ erg s}^{-1}$ (see right panel of Fig. 2).

5.1 The SKA view of cool core clusters: statistics of radio mini-halos and radio-loud BCGs

Since all known mini-halos are hosted by clusters with low central entropy ($K0 \lesssim 25 \text{ keV cm}^2$), which are defined as strong cool core clusters (Hudson et al. 2010), our basic assumption is that every strong cool core cluster hosts a radio mini-halo that follows the observed $P_{1.4}$ - L_X correlation. In the left panel of Fig. 3 we show the distribution in redshift of the strong cool core clusters in the X-ray ACCEPT³ sample, which is a collection of hundreds clusters with available entropy profiles derived from archival *Chandra* data (Cavagnolo et al. 2009). These are all candidates to host radio mini-halos. However, as it can be seen from the comparison with the clusters which are actually known to host mini-halos, highlighted in red, we are currently detecting only the tip of the iceberg.

³Archive of Chandra Cluster Entropy Profiles Tables.

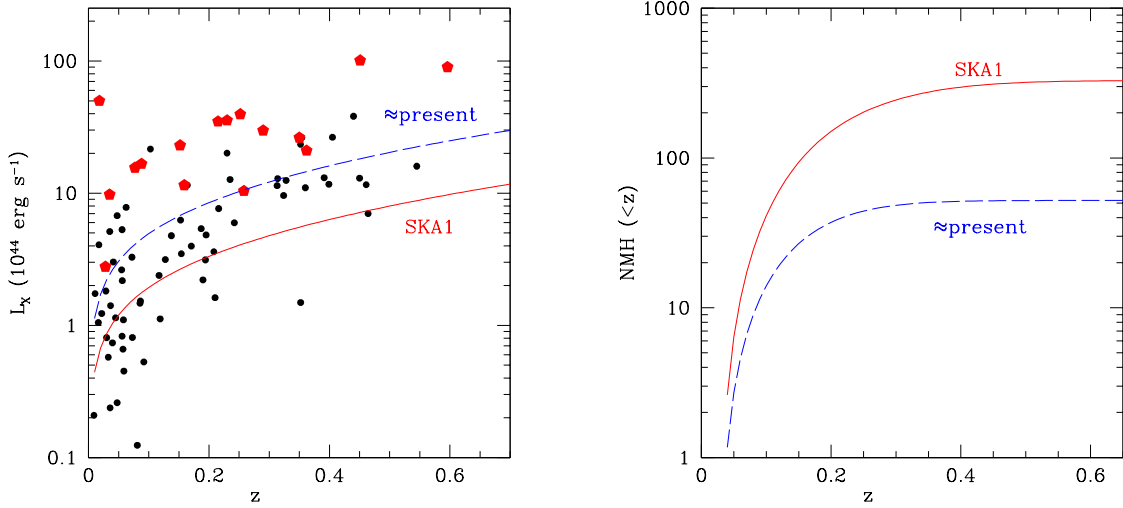


Figure 3: *Left panel:* X-ray luminosity, L_X , versus redshift for the strong cool core clusters in the ACCEPT sample (Cavagnolo et al. 2009). The clusters known to host radio mini-halos are highlighted in red. The blue dashed line is indicative of the current mini-halo detection limit, whereas the red solid line represents the detection limit reachable by SKA1 surveys at confusion limit ($4 \mu\text{Jy rms}$). *Right panel:* Integrated number of radio mini-halos detectable at 1.4 GHz out to z , $N_{MH}(<z)$, as a function of redshift. The predictions for All Sky surveys with SKA1 and for a hypothetical survey conducted with current telescopes are shown with the red solid line and the blue dashed line, respectively. Both panels are updated from Gitti et al. (2015) after the rebaseline of the SKA.

We estimated that all-sky surveys with rms of $4 \mu\text{Jy/beam}$ at $2''$ resolution (then tapered to confusion limit $\sim 8''$) planned with the SKA1, which is predicted to start operating in 2020, will be able to follow-up $> 70\%$ of the ACCEPT sample (see left panel of Fig. 3). On the other hand, when full operational (in phase 2, around 2030), the SKA will be able to complete the follow-up of the full ACCEPT sample, and most likely also of the future X-ray cluster surveys that will be available by then, for example with eROSITA and Athena (Gitti et al. 2015).

At the same time, the SKA will be able to trace the radio-mode feedback in clusters by performing a complete census of the radio-loud BCGs down to a total 1.4 GHz power of $10^{22} \text{ W Hz}^{-1}$ and resolving the radio emission in the radio lobes filling the X-ray cavities. In particular, the ICM X-ray characterization of the cluster cores achievable with the Athena mission (expected launch in 2028) will allow a direct combination with the radio data to search for cavities, although an efficient synergy with the SKA will rely on the achievement of $\approx 1''$ angular resolution of the X-ray telescope. On the radio side, the detection of typical cavities in medium or large mass clusters is within the reach of SKA surveys at any relevant redshift (see Sect. 4 of Gitti et al. 2015).

5.2 How many radio mini-halos await discovery with the SKA?

We estimated the number counts of radio mini-halos that can potentially be discovered by the SKA as a function of redshift by integrating the radio luminosity function of mini-halos over radio luminosity and redshift, where the radio luminosity function of mini-halos is obtained from the X-ray luminosity function of clusters by considering the observed $P_{1.4}-L_X$ correlation and the fraction of clusters with strong cool cores (~ 0.4 , Hudson et al. 2010). Our predictions are shown in the right panel of Fig. 3. In particular, we estimated that all-sky surveys with SKA1 will be able to detect up to ~ 330 new mini-halos out to redshift $z \sim 0.6$, thus producing a breakthrough in the

study of these sources (Gitti et al. 2015).

6. Summary and Conclusions

The non-thermal emission from cool core clusters is in the form of radio-loud AGN and diffuse radio mini-halos. In this contribution we summarized the results of a homogeneous *Chandra* analysis of the largest collection of mini-halo clusters. The inferred correlation between the radio power and the cooling flow power can be explained in the context of a turbulent re-acceleration scenario which envisions a common origin for radio mini-halos and gas heating in cool cores, while constraining at the same time the intra-cluster magnetic field (Bravi et al. 2016). We further discussed the potentialities of future SKA survey for assembling large mini-halo samples that will allow us to establish the mini-halo origin and connection with the cluster thermodynamical properties, especially in synergy with future X-ray characterization of the cluster cores (Gitti et al. 2015).

References

- Bravi, L. et al.. 2016, MNRAS, 455, L41
- Brunetti, G. & Jones, T. W. 2014, International Journal of Modern Physics D, 23, 30007
- Burns, J. O. 1990, Astronomical Journal, 99, 14
- Cavagnolo, K. W. et al.. 2009, ApJ Supplement Series, 182, 12
- Fabian, A. C. et al.. 1994, ApJ, 425, 40
- Feretti, L. et al.. 2012, Astronomy & Astrophysics Rev., 20, 54
- Giacintucci, S. et al.. 2014, ApJ, 781, 9
- Gitti, M. et al.. 2012, Advances in Astronomy, 2012
- . 2004, A&A, 417, 1
- . 2002, A&A, 386, 456
- . 2007, A&A, 470, L25
- . 2013, A&A, 557, L14
- . 2015, Advancing Astrophysics with the Square Kilometre Array (AASKA14), 76
- Hudson, D. S. et al.. 2010, A&A, 513, A37
- Johnston-Hollitt, M. et al.. 2015, Advancing Astrophysics with the Square Kilometre Array (AASKA14), 92
- McNamara, B. R. & Nulsen, P. E. J. 2007, Annual Rev. of Astronomy & Astrophysics, 45, 117
- . 2012, New Journal of Physics, 14, 055023
- Peterson, J. R. & Fabian, A. C. 2006, Physics Reports, 427, 1
- Zhuravleva, I. et al.. 2014, Nature, 515, 85