Galaxy clusters with the Square Kilometer Array

B. Ascaso[1], **Y. Ascasibar**[2], **J.M. Diego**[3], **and S. Planelles**[4,5]

[1] GEPI, Observatoire de Paris, CNRS, Université Paris Diderot, 61, Avenue de l'Observatoire 75014, Paris France
[2] Departamento de Física Teórica, Universidad Autónoma de Madrid, E-28049 Madrid, Spain
[3] Instituto de Física de Cantabria (CSIC-UC), Avenida de los Castros s/n, E-39005 Santander, Spain
[4] Astronomy Unit, Department of Physics, University of Trieste, via Tiepolo 11, I-34131 Trieste, Italy
[5] INAF, Osservatorio Astronomico di Trieste, via Tiepolo 11, I-34131 Trieste, Italy

Abstract

We review some science cases for galaxy clusters and the impact that the future SKA data will have in those analyses. We first describe how the search for galaxy clusters through radio-sources will be significantly improved through the detection of much fainter radio-sources in a big volume. Secondly, we bring out the benefits of using very sensitive radio data to study the thermal and non-thermal component of clusters and disentangle the main processes happening in the physics of their plasma. Moreover, we discuss the possibility of using the high frequencies of the SKA to separate the thermal Sunyaev-Zeldovich (SZ) effect from the radio halo emission and use the former as a mass proxy for galaxy clusters. Finally, we investigate how the very high sensitivity and spatial resolution of SKA will result into a great improvement in the lensing treatment, underlining the lensing distribution of the 21-cm intensity from the reionization period. As a whole, SKA will become an impressive window covering a significant wider range in redshift to look at an unknown radio universe and set constraints on different mechanisms happening in clusters.

1 Introduction

Within the standard model of cosmic structure formation, evolution proceeds in a hierarchical fashion. Clusters of galaxies, residing at the top of the cosmic hierarchy, are thought to be formed by mergers of smaller groups or clusters and the continuous accretion of matter and small galaxies ([33, 45] for recent reviews). Although dark matter is the main contributor to the mass in galaxy clusters ($\sim 70-80\%$), the cluster baryon content is shared between a hot and diffuse plasma ($T \sim 10^7 - 10^8$ K, $n_e \sim 10^{-4} - 10^{-2}$ cm^{-3}), called intra-cluster medium (ICM; $\sim 15-20\%$), and the stellar component ($\sim 3-5\%$). Cluster radio observations have also revealed the presence of a diffuse and extended synchrotron emission from the ICM ([25, 24, 9] and references therein) demonstrating that, besides the thermal plasma, there is also a contribution from non-thermal components, namely, magnetic fields ($\sim 0.1 - 10\,\mu$G) and cosmic rays (CR; in particular, relativistic electrons with $\sim$ GeV energies).

The SKA will become a superior instrument both in terms of sensitivity and resolution and therefore, will become very important at studying both the thermal and non-thermal component of the plasma. In this chapter, we aim to collect some of the interests regarding the understanding of physical properties of the clusters and illustrate the impact that the SKA data will signify for them. For a discussion of the potential of the SKA in the context of galactic evolution in dense environments, see Ascaso et al. (this proceeding).

The structure of the chapter is as follows. In §2, we focus on the expectations for SKA to detect galaxy clusters based on radio-sources and describe their selection functions. In §3, we summarize our current knowledge of the thermal and non-thermal components in clusters and describe their future significant improvement based on SKA data. We also focus on the benefits of using the high frequencies of SKA to measure the thermal SZ effect in clusters and calibrate their masses. Finally, section §4 is devoted to describe the new possibilities that the SKA data will offer for strong and weak lensing analysis, including the study of the lensing distribution of the 21-cm intensity from the reionization period.

2 Searching for galaxy clusters with SKA

Galaxy clusters, as structures consisting of dark matter, galaxies and ICM, can be traced by each of their components separately, providing different selection functions. Thousands of clusters have been found from systematic searches at different wavelengths, with a variety of techniques: modeling the properties of galaxies in the optical or infrared (IR) (e.g. [1, 2, 3] and references herein), using spectroscopic data to select the galactic population (e.g. [31, 32]), tracing the weak-lensing shear effect (e.g. [56]), detecting gas emission in X-rays (e.g. [49, 10]), analyzing the Sunyaev-Zeldovich (SZ; [53]) signature (e.g. [5, 52]), or searching for overdensities around different radio sources [6, 50, 30, 26, 15, 14, 8].

Radio-sources in galaxy clusters can be split into those associated with the ICM and those associated with Active Galactic Nuclei (AGN) [29]. Among the first group, we differentiate three main sources: (1) the (giant) radio haloes (RH), which are morphologically regular and extended sources ($\gtrsim$1Mpc), at the center of the potential well of merging clusters, (2) the mini-halo, smaller ($\lesssim$0.5 Mpc) sources, usually associated to cool-core systems featuring a central brightest cluster galaxy (BCG) or AGN, and (3), the radio relics or radio *gischt*, large elongated and strongly polarized sources, typically located in the outskirts of the clusters and also associated to merging clusters and/or energy injection from the AGN [25].

The ability of detecting galaxy clusters using RHs as a tracer has been investigated for the SKA1-LOW survey [13]. Based on their predictions, the SKA1-LOW would be able to detect $\sim$ 2600 RHs up to z$\sim$0.6, being the detection peak at z$\sim$0.2. This is a factor 6 times larger than previous surveys as LOFAR. Using scaling relations between M_{500} and the minimum power of giant RH detectable in SKA1-LOW [12], the SKA cluster selection function as a function of halo mass was derived (see their Fig. 6), showing that SKA1-LOW will be able to detect galaxy clusters down to M $\approx 10^{14}\mathrm{M}_{\odot}$ at local redshifts and down to M$\approx 4 \times 10^{14}\mathrm{M}_{\odot}$ at $z \sim 1$. This selection function is comparable to the one obtained by Planck up to $z = 0.6$ or present X-ray surveys up to $z = 0.2$.

A similar analysis performed by [27] used instead the mini-haloes as galaxy cluster tracers. Assuming a given fraction of clusters with strong cool core clusters and deriving the observed radio-X-ray power correlation for mini-haloes, they estimated that around 600 and 2000 mini-haloes are waiting to be found with SKA1 and SKA2 respectively up to z$\sim$0.6. In addition, higher redshift mini-haloes might be detected with SKA.

Regarding radio relics, [41] derived the cluster halo mass function estimated from the radio relic number counts for different surveys, providing also a probability of discovery. As a tentative number depending on a variety of scaling relations based on a scarce sample of presently discovered radio relics and on the availably of complete galaxy cluster catalogues, SKA1 might be able to find up to $\sim$ 5000 radio relics

Additionally, AGN radio-galaxies are known to be found more likely in galaxy clusters than in the field (see Figure 13 in [20]). A variety of methods have been developed to search for overdensities around them (radio galaxy sources, [6, 50, 30, 26], FRI [15, 14], FRII, WAT [8], NAT and Bent-Tailed (BT) sources [17]. In particular, the latter method, based on a extrapolation from the results found in the ATLAS survey [17], has predicted to detect at least more than 1 million extended low-surface-brightness radio sources up to high-redshift ($\sim$ 2), out of which $\sim$ 80% will be BT sources. These number of detections are comparable to the number of clusters expected from next-generation survey such as LSST [35] and J-PAS [4] (Optical), Euclid [36] (Optical/IR), e-ROSITA [38] (X-Rays). Since many of these methods need deep IR data to search for overdensities around these radio sources, the data available from surveys such as Euclid will become an excellent tool to combine with the identification of such sources to detect galaxy clusters at high redshift ($z > 1.5 - 2$). Additionally, the combination with different datasets will also provide interesting scaling relations to calibrate the cluster mass and, therefore, to be usable for cosmological predictions.

Eventually, the SKA will be able to follow-up galaxy clusters using the SZ signature at $\sim$ 4 GHz frequencies (Band 5 of the SKA1-MID). In particular, this will be very useful to constrain the masses of the high-redshift ($z > 1$) clusters, since the SZ is redshift-independent. Indeed, [28] explored the ability for SKA1-MID to follow-up all the high-redshift clusters detected with e-ROSITA , finding that a 1000-hour program will be enough.

The upcoming SKA data is opening a new window to an unexplored universe and will undoubtedly deliver exciting results. The main properties of the radio-sources and their relation with the environment will be constrained within a wider range of redshift and halo masses. Our current knowledge is mostly based on the analysis of a few thousands of objects in the local universe and the extrapolation of the observed scaling relations between their physical properties. The SKA data ahead are likely to bring us interesting and unexpected findings that may force us to modify our expectations.

3 Thermal and non-thermal gas emission in clusters

As described in §2, the radio sources associated to the ICM (so far detected in only a few tens of clusters) are generally classified in halos, mini-halos and relics [29, 9]. Robust correlations between some physical properties of radio halos and their hosting clusters have been reported by current observational studies ([9] and references therein). The spectrum of radio emission in galaxy clusters provides crucial information on the energetics and physics of the relativistic particles involved as well as on the strength and distribution of magnetic fields. However, the sensitivity needed to perform such studies ($\sim m$Jy $- \mu$Jy arcsec^{-2} with frequencies from MHz to GHz) represents a challenge for current facilities, making it difficult to combine multi-frequency observations with different radio telescopes on a large number of radio sources. The increased sensitivity of the SKA (by a factor of ~ 10) to radio emission on cluster scales, will allow a detailed analysis of the spectra, polarization and brightness distribution of radio halos and relics for an unprecedented number of clusters, enabling a deeper understanding of the connection between radio sources and the dynamical history of the hosting clusters. In this regard, it is expected that a large number of new radio halos, those with very steep spectra which are not detected by current radio telescopes, will be unambiguously identified and associated to minor merging systems. The combination of these radio observations with X-ray or SZ-selected samples will help to study separately the thermal and non-thermal ICM components, and the combination of multi-wavelength data sets will provide invaluable constraints on the underlying physics.

In particular, the origin and evolution of the non-thermal component in galaxy clusters is still not understood. The steep radio spectra of the cluster radio sources suggest short lifetimes for the emitting electrons, indicating that, to account for the observed radiation, these particles need to be locally accelerated or injected. To explain the acceleration of relativistic particles within the ICM, two different models have been proposed: primary or re-acceleration models, in which relativistic electrons are accelerated by shocks and/or turbulence mainly through the process of Diffusive Shock Acceleration (DSA; [7]), and secondary models, in which relativistic electrons and γ-rays are thought to be released from the decay of pions generated in interactions between thermal ions and non-thermal protons in the ICM.

Numerical simulations have shown that the merger of two massive clusters produces shock and compression waves, turbulence and mixing, and amplification of magnetic fields in the ICM, contributing to the non-thermal emission in clusters (e.g. [11, 23]). Additional sources of shocks and turbulence, such as SN remnants or high-velocity jets from AGNs, can also provide relativistic particles to the ICM. The SKA, in conjunction with future γ-ray observations, will make possible to set strong constraints on the contribution of cosmic-ray protons to the relativistic electron budget in galaxy clusters. These studies, together with a precise measurement of Faraday rotation of cluster radio sources, will also shed some light on the origin, distribution and intensity of magnetic fields. Besides, they will help in understanding the role that turbulence plays in the acceleration and transport of relativistic particles and its influence on the ICM plasma physics. In addition, it will be possible to distinguish between the radio emission from different sources, such as AGN jets or SN remnants, and the intrinsic radio emission from the ICM.

Moreover, to quantify the impact of the process of cosmic structure formation on the acceleration of relativistic particles, it is important to map the strength and distribution of both shock waves and magnetic fields within the ICM. In this respect, numerical simulations have also reported a complex distribution of external and internal shocks within the cosmic web (e.g. [47, 44]) but the efficiency in the acceleration of CRs is still unknown. As for the cosmic magnetic fields, simulations suggest that cluster dynamics can contribute significantly to amplify their strengths from primordial values to the observed levels [23, 51]. In this regard, thanks to the spectral and spatial resolutions of SKA, a detailed analysis of the distribution and strength of shocks and magnetic fields throughout the cluster volume is expected.

The SKA will provide unique high-resolution and high-sensitivity radio observations of cluster-scale emission over a wide range of frequencies, allowing for a thorough investigation of the connection between thermal and non-termal cluster emission and the formation and evolution of the large-scale structure in the Universe. Forthcoming cosmological simulations, with improved resolutions and with a more precise modeling of the physics of cosmic plasmas, will also play a crucial role. Therefore, a coordinated effort between future cosmological simulations and the next generation of observing facilities at different wavebands will be essential to improve our understanding of the complex physical phenomena shaping the observational properties of galaxies and galaxy clusters.

In addition to the synchrotron radiation emitted by the relativistic component, all free electrons in the cluster interact with the Cosmic Microwave Background (CMB) photons through inverse Compton scattering. Since most electrons are moving at non-relativistic speeds, the small amount of energy imparted to the photons results in a weak distortion of the CMB spectrum, known as the SZ effect, whose amplitude is proportional to the electron density along the line of sight, the gas temperature (thermal SZ effect) and/or the bulk radial velocity of the cluster (kinetic SZ effect).

At the high frequencies of SKA ($\approx$ 20 GHz), the distortion in the spectrum due to the thermal SZ effect is seen as a decrement in the temperature (typically of the order of ≈ 0.1 mK in the Rayleigh-Jeans regime) with respect to the surrounding CMB radiation. The distortion due to the kinetic SZ effect is normally weaker than the thermal SZ effect, and it can be either positive or negative depending on the sign of the cluster radial velocity. In this frequency range, the SZ effect is expected to dominate over the radio halo emission in most clusters; even when they are comparable, the very different frequency dependence allows to separate both components.

The SKA will probe the physical conditions (density and temperature) of the hot intracluster plasma through the thermal SZ effect (see [28] for a recent discussion). The thermal SZ effect also provides a direct measurement of the electron pressure in the ICM, which can be used as an excellent mass proxy for galaxy clusters and makes possible to constrain the cosmological parameters (see e.g. [43]). The combination of high and low spatial resolution SKA data is particularly interesting, since the latter greatly improves the subtraction of contamination by discrete radio sources in the cluster.

Although most of the SZ effect with SKA will require sort baselines, the use of the longer baselines of SKA are also interesting for high resolution studies of brighter features in the SZ effect. Two phenomena producing small scale bright SZ features are particularly interesting. Cluster mergers produce a sharp enhancement in the thermal SZ effect at the collision point where the pressure increases due to the ongoing collision. In certain scenarios, the combination of SZ and X-ray data can be used to constrain the geometry of the collision [22]. Cluster mergers involve also large relative pair-wise velocities that can be studied through the kinetic SZ effect [39]. On smaller scales, subsonic motions of the cluster cores have been found to be present on several clusters. The kinetic effect distortion from these small scale (< 1 arc min) bulk motions is expected to reach a few tens of μK (or of the order of 100 Jy/sr at 20 GHz [18]).

4 Gravitational lensing from clusters with the SKA

Gravitational lensing is arguably one of the most powerful techniques to study the distribution of dark matter. The gravitational lensing effect is particularly obvious in galaxy clusters where the deep gravitational potentials produce large deflection angles, and often multiple distorted images of the same background galaxy. Massive galaxy clusters can be studied through the strong gravitational lensing (SL) and the weak gravitational lensing (WL) [34]. Detailed studies of the SL effect in galaxy clusters can be done with experiments that combine both, good spatial resolution and great sensitivity such as e.g. the Hubble Frontier Fields, HFF, program [16, 37].

A similar treasury program could be carried out by SKA which combines both capabilities (sensitivity and spatial resolution) and hence offers a competitive way of studying the dark matter in galaxy clusters through the gravitational lensing effect. Deep SKA observations of strongly lensed galaxies behind galaxy clusters offers also the unique opportunity to reach fainter fluxes that could not be observed otherwise. Current progress on the understanding of the magnification power of gravitational lenses establishes that in around 0.3 arcmin^2 per cluster, the ultra-faint galaxies can be magnified about a factor 3 or more [57, 48] for well studied gravitational lenses. Several clusters can be added together offering the possibility to statistically study the population of very faint sources below the detection limit of SKA.

At lower fluxes, the population of radio sources is largely undetermined with current estimates reaching approximately the 10 μJy level at 1.4 GHz. In this regime, the density of radio sources is estimated to be $S^{2.5}dN/dS \approx 5\text{Jy}^{1.5}/sr$, with S being the flux density [55, 40], resulting in a density of $N \approx 1$ source per arcminute^2 in the range $10 < S < 11$ μJy for instance. Using these approximate densities and assuming the fraction at $z \geq 1$ to be about 30% of the total [42], it is possible to estimate the lensing effect for a realistic cluster. For this purpose we have used the deflection field derived by [21] and corresponding to the cluster MACSJ0717.5+3745 that was observed as part of the HFF program. After setting a typical deep SKA threshold of 1 μJy at 1.4 GHz and assuming a beam of 1 arcsecond, we lensed the simulated background of sources above $z = 1$ by the cluster. A typical result is shown in Fig. 1 where several arcs and multiply lensed images can be appreciated above the limiting threshold of SKA. Even though this simulation did not account for magnification effects in the flux, it shows the power of SKA as a tool for gravitational lensing studies.

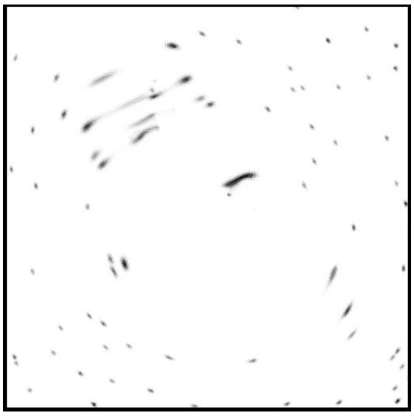

Figure 1: Simulated SKA observation through the lens MACSJ0717.5+3745. The field of view is 4 arcminutes on a side and all the radio sources have demagnified fluxes above 1 μJy at 1.4 GHz. The density of sources is derived from the law $S^{2.5}dN/dS \approx 5\mathrm{Jy}^{1.5}/sr$ above 5 μJy. Below 5 μJy we adopt the law $S^{2.5}dN/dS \approx 1.0S_{\mu\mathrm{Jy}}\mathrm{Jy}^{1.5}/sr$ that follows the predictions. Both laws merge at S=5 μJy. The lens model is taken from [21]

.

Since SKA can reach 1 μJy fluxes (1.4 GHz), we should expect at least one strongly (or multiply) lensed galaxy per massive cluster ($M > 5 \times 10^{14}$ $\mathrm{M}_\odot$) allowing to estimate the masses of clusters from the SL data. The identification of the redshift of the background lensed galaxy through the 21-cm line will also eliminate one of the main sources of uncertainty in SL studies where redshifts are usually photometric. This will result in an improvement in the lensing reconstruction. A deep program carried out by SKA (below the 1 μJy level at 1.4 GHz) on selected galaxy clusters could unveil a wealth of multiply lensed galaxies that would compete in quality with the optical data. This level of sensitivity is already planned for the SKA [40] and could easily be improved with a dedicated treasury program.

Furthermore, SKA data can be used to study the WL effect beyond the regime of the SL. The magnification bias does not rely on difficult shape measurements and it has been proven to provide useful information to constrain the cluster mass [54]. Studies of the magnification bias together with the classical WL analysis can be carried out with the SKA complementing the SL constraints. Radio data from SKA will be less affected than optical data by instrumental and astrophysical systematic effects. Radio telescopes have stable and well-understood point spread functions that simplify the corrections needed in optical-based data. This fact, together with the possibility of measuring redshifts for a significant fraction of the lensed galaxies through the HI emission lines, makes the SKA an attractive instrument for WL studies around galaxy clusters.

However, the unique contribution that SKA will do is on the lensing distribution of the 21-cm intensity from the reionization period. Anisotropies in the intensity due to the reionization are expected to produce a continuous background at high redshift. Lensing of this background can be studied with the SKA opening the door to novel techniques for mass reconstruction, some of which have been already implemented in the lensing of the CMB. In particular, lensing of a continuous background introduces correlations between the Fourier modes that can be used to reconstruct the mass distribution responsible for the lensing effect. However, while the CMB probes a particular redshift range, the 21-cm line probes a much wider redshift range that can be used to do tomographic studies of the universe by simply shifting to lower frequencies in SKA corresponding to higher redshifts. [58] shows that a large radio array such as SKA could measure the lensing convergence power spectrum and constrain the cosmological parameters. More recently, [46] focuses on the particular case of the low frequency of SKA and concludes that the SKA low frequency instrument could be used to study the lensing signal using the epoch of reionization as a background. With the mid-frequency instrument, SKA will survey a wider region of the sky and although not appropriate for studies of the epoch of reionization, fluctuations in the intensity from galaxies will form also a background of sources that can be used for lensing studies as described above. In the particular case of clusters, when a cluster is known to lie along the line of sight, spatial filters can be used to isolate the lensing signal as shown by [19] although it is difficult the evaluate the feasibility of such direct studies as the signal depends on the amount of anisotropy in the background signal which is controlled by the type of reionization (patchy, or instantaneous).

Acknowledgments

This work has been supported by a grant funded by the “Consorzio per la Fisica di Trieste”. SP also acknowledges support by the PRIN-INAF09 project “Towards an Italian Network for Computational Cosmology”, by the PRIN-MIUR09 “Tracing the growth of structures in the Universe”, and by the PD51 INFN grant. Partial support is also provided by *Spanish Ministerio de Ciencia e Innovación* (AYA2010-21322-C03-02). JD acknowledges support from the Spanish Ministry of Economy and Competitiveness (MINECO) through grants AYA2010-21766-C03-02, AYA2012-30789, and the Consolider-Ingenio project CSD2010-00064 (EPI: Exploring the Physics of Inflation). YA is financially supported by the Spanish Ramn y Cajal programme (RyC-2011-09461) and grant AYA2013-47742-C4-3-P (MINECO), as well as the ‘Study of Emission-Line Galaxies with Integral-Field Spectroscopy’ (SELGIFS) exchange programme, funded by the EU through the IRSES scheme (FP7-PEOPLE-2013-IRSES-612701). BA acknowledges financial support for a postdoctoral fellowship from the Observatory of Paris.

References

[1] Ascaso, B., Wittman, D., & Benítez, N. 2012, MNRAS, 420, 1167

[2] Ascaso, B. 2013, Highlights of Spanish Astrophysics VII, 115

[3] Ascaso, B., Wittman, D., & Dawson, W. 2014, MNRAS, 439, 1980

[4] Benitez, N., Dupke, R., Moles, M., et al. 2014, arXiv:1403.5237

[5] Bartlett, J. G. 2004, Astrophysics and Space Science, 290, 105

[6] Best, P. N., Lehnert, M. D., Miley, G. K., Rottgering, H. J. A. 2003, MNRAS, 343, 1

[7] Blandford R. D., Ostriker J. P., 1978, ApJL, 221, L29

[8] Blanton, E. L., Paterno-Mahler, R., Wing, J. D., et al. 2014, arXiv:1411.6025

[9] Brunetti G., Jones T. W. 2014, International Journal of Modern Physics D, 23, 30007

[10] Burenin, R. A., Vikhlinin, A., Hornstrup, A., et al. 2007, ApJS, 172, 561

[11] Bykov A. M., Dolag K., Durret F., 2008, Space Science Reviews, 134, 119

[12] Cassano, R., Ettori, S., Brunetti, G., et al. 2013, ApJ, 777, 141

[13] Cassano, R., Bernardi, G., Brunetti, G., et al. 2014, arXiv:1412.5940

[14] Castignani, G., Chiaberge, M., Celotti, A., Norman, C., & De Zotti, G. 2014, ApJ, 792, 114

[15] Chiaberge, M., Capetti, A., Macchetto, F. D., et al. 2010, ApJL, 710, L107

[16] Coe, D., Bradley, L., & Zitrin, A. 2014, arXiv:1405.0011

[17] Dehghan, S., Johnston-Hollitt, M., Franzen, T. M. O., Norris, R. P., & Miller, N. A. 2014, AJ, 148, 75

[18] Diego, J. M., Mazzotta, P., & Silk, J. 2003, ApJL, 597, L1

[19] Diego, J. M., & Herranz, D. 2008, MNRAS, 383, 791

[20] Diego, J. M., & Partridge, B. 2010, MNRAS, 402, 1179

[21] Diego, J. M., Broadhurst, T., Zitrin, A., et al. 2014, arXiv:1410.7019

[22] Diego, J. M., Broadhurst, T., Molnar, S. M., Lam, D., & Lim, J. 2015, MNRAS, 447, 3130

[23] Dolag, K., Bykov, A. M., Diaferio, A., 2008, Space Science Reviews, 134, 311

[24] Feretti L., Giovannini G., Govoni F., Murgia, M. 2012, Astronomy & Astrophysics Rev., 20, 54

[25] Ferrari, C., Govoni, F., Schindler, S., Bykov A. M., Rephaeli Y. 2008, Space Science Reviews, 134, 93

[26] Galametz, A., De Breuck, C., Vernet, J., et al. 2009, A&A, 507, 131

[27] Gitti, M., Tozzi, P., Brunetti, G., et al. 2014, arXiv:1412.5664

[28] Grainge, K., Borgani, S., Colafrancesco, S., et al. 2014, arXiv:1412.5868

[29] Kempner, J. C., Blanton, E. L., Clarke, T. E., et al. 2004, The Riddle of Cooling Flows in Galaxies and Clusters of galaxies, 335

[30] Kodama, T., Tanaka, I., Kajisawa, M., et al. 2007, MNRAS, 377, 1717

[31] Knobel, C., Lilly, S. J., Iovino, A., et al. 2009, ApJ, 697, 1842

[32] Knobel, C., Lilly, S. J., Iovino, A., et al. 2012, ApJ, 753, 121

[33] Kravtsov A. V. & Borgani S. 2012, ARA&A, 50, 353

[34] Hamana, T., Takada, M., & Yoshida, N. 2004, MNRAS, 350, 893

[35] Ivezic, Z., Tyson, J. A., Abel, B., et al. 2008, arXiv:0805.2366

[36] Laureijs, R., Amiaux, J., Arduini, S., et al. 2011, arXiv:1110.3193

[37] Lotz, J., Mountain, M., Grogin, N. A., et al. 2014, American Astronomical Society Meeting Abstracts #223, 223, #254.01

[38] Merloni, A., Predehl, P., Becker, W., et al. 2012, arXiv:1209.3114

[39] Mroczkowski, T., Dicker, S., Sayers, J., et al. 2012, ApJ, 761, 47

[40] Norris, R. P., Afonso, J., Bacon, D., et al. 2013, Publications of the Astronomical Society of Australia, 30, e020

[41] Nuza, S. E., Hoeft, M., van Weeren, R. J., Gottlöber, S., & Yepes, G. 2012, MNRAS, 420, 2006

[42] Oh, S. P. 1999, ApJ, 527, 16

[43] Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2014, A&A, 571, AA20

[44] Planelles S. & Quilis V. 2013, MNRAS 428, 1643

[45] Planelles S., Schleicher D.R.G., & Bykov A.M. 2014, Space Sci Rev, DOI 10.1007/s11214-014-0045-7

[46] Pourtsidou, A., & Metcalf, R. B. 2014, arXiv:1410.2533

[47] Quilis V., Ibá*ñ*ez J.M. & Sáez D. 1998, ApJ, 502, 518

[48] Richard, J., Jauzac, M., Limousin, M., et al. 2014, MNRAS, 444, 268

[49] Rosati, P., Borgani, S., & Norman, C. 2002, Annual Review of Astronomy and Astrophysics, 40, 539

[50] Seymour, N., Stern, D., De Breuck, C., et al. 2007, ApJS, 171, 353

[51] Skillman S. W., Xu H., Hallman E. J., O'Shea B. W., Burns J. O., Li H., Collins D. C., Norman M. L., 2013, ApJ, 765, 21

[52] Staniszewski, Z., Ade, P. A. R., Aird, K. A., et al. 2009, ApJ, 701, 32

[53] Sunyaev R. A., Zeldovich Y. B. 1972, Comments on Astrophysics and Space Physics, 4, 173

[54] Umetsu, K. 2013, ApJ, 769, 13

[55] Vernstrom, T., Scott, D., & Wall, J. V. 2011, MNRAS, 415, 3641

[56] Wittman, D., Dell'Antonio, I. P., Hughes, J. P., et al. 2006, ApJ, 643, 128

[57] Wong, K. C., Ammons, S. M., Keeton, C. R., & Zabludoff, A. I. 2012, ApJ, 752, 104

[58] Zahn, O., & Zaldarriaga, M. 2006, ApJ, 653, 922