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CLUSTERS OF GALAXIES AT THE PLANCK TIME

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Abstract. Nodes of the filaments forming the cosmic web traced by the dark and baryonic matter, galaxy clusters are the place of many physical processes that shape a complex interaction between the formation and the evolution of galaxies, their environment and large scale structures. Their various components can be observed from X-ray to radio wavelengths. The ESA space mission Planck surveyor, lauched on May 14^{th} this year, is currently surveying the whole sky from sub-millimeter to centimeter wavelengths. Hundreds of new clusters are expected to be detected from the this survey. I review here various axis of research in the field of galaxy clusters studies, and I investigate the prospect of the detection of new distant clusters with the Planck satellite, which is expected to shed new light in the field of the formation and evoltution of large scale structures, and to provide cosmological constraints complementary to those derived from the CMB measurements.

1 Introduction

With the launch of the Planck Surveyor satellite this spring, a new window is opening for the study of galaxy clusters. Hundreds of new massive halos are expected to be detected by the Planck satellite via their Sunyaev-Zeldovich effect (SZE – Sunyaev & Zeldovich 1972). Their studies at the Planck frequencies and their follow-up at other wavelengths (such as in X-rays) will shed new light on our understanding of the formation and evolution of these large scale structures, and on their tight link to the overall matter and energy content of the Universe.

In the standard model of hierarchical structure formation, clusters form through gravitational collapse of dark matter (DM) around primordial over-densities (Bertschinger 1985). They are the largest auto-gravitating bound structures observed to date. They are located at the connecting nodes of the filamentary structures of the Universe. Clusters of galaxies form an homogeneous population of objects mainly constituted by DM (80% of their total mass), hot ionized gas (15% of their total mass) and galaxies (5% of their total mass). The population of clusters is a powerful tool in cosmology as well as in the study of the formation and evolution of structures. Their mass function, $N(M, z)$, their spatial distribution, their content in gas, are directly correlated with the (dark and baryonic) matter and energy content of the Universe, thus to the power spectrum of primordial density fluctuations, $P(k)$. Cosmological constraints from clusters are complementary to constraints from the Cosmic Microwave Background (CMB) or from supernovae. Also, clusters are especially fitted to probe the Universe bellow $z = 2$, where the effect of dark energy is predominant (Allen et al. 2004; Mantz et al. 2009). In the standard model, the collapse of structure is mainly driven by gravitation. However, we know that non-gravitational processes play an important role in the formation and in the evolution of structures: pre-heating of the gas by AGNs or supernovae, galactic winds, radiative cooling, metal enrichment... (e.g. Borgani et al. 2004; Voit 2005; Schindler & Diaferio 2008). The respective roles of all these processes have still to be understood and disentangled. They can be studied through their impact on the overall structural and scaling properties of clusters. (e.g. Croston et al. 2008; Pratt et al. 2009b,a; Arnaud et al. 2009). The inaccurate knowledge we currently have of these statistical properties limits our ability to properly understand the history of clusters formation, its coupling with the galaxy formation and evolution.

In the following I review three particular axis in clusters studies: (i) the importance of the measurement and use of clusters mass in halos studies (next section). (ii) the role of non-gravitational processes (Sec. 3) and the importance of mergers and dynamical activity in the formation of clusters (Sec. 4). I then briefly present the Planck cluster survey together with basics on the Sunyeav-Zel'dovich effect (Sec. 5). Finally I discuss the expectations for the Planck surveys in terms of cluster detection and follow-up plans (Sec. 6).

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2 The mass of clusters and cosmology

In the hierarchical model of structure formation, the population of clusters is homogeneous and self-similar, and characterised by structural and scaling properties: the matter distribution in clusters is universal, and well defined scaling laws link all the physical properties of clusters together (e.g. the X-ray luminosity-temperature relation is expected to be $L_X \propto T^2$) making the cluster population a two parameters population describe by its redshift z and its mass M: $Q(z, M) = A(z) \times M^{\alpha}$.

Cosmological numerical simulations in a standard framework have demonstrated these predictions (Navarro et al. 1997). XMM-Newton and Chandra have brought strong observational evidences for this universality in shape of the DM profile. Indeed, the study of local samples of relaxed objects have led to the precise measurements of their density and temperature profiles, thus to the determination of their dynamical mass profiles from the early type galaxy to the cluster scale (Pointecouteau et al. 2005; Vikhlinin 2006; Humphrey et al. 2006). Moreover, the scaling relations such as the mass-temperature relation, $M - T$ (Arnaud et al. 2005; Vikhlinin 2006), or the mass-integrated Comptonisation paramterer relation, $M - Y_X$ (i.e. derived from X-rays – Nagai et al. 2007; Arnaud et al. 2007, 2009), are now well calibrated for nearby relaxed clusters. Furthermore, together with the current constraints on the concentration-masse relation, $c - M$ (Pointecouteau et al. 2005; Vikhlinin 2006; Buote et al. 2007), these recent results demonstrate our qualitative and quantitative understanding of the physics of the DM collapse in the framework of the standard model down to the group regime in the local Universe. Henceforth, clusters (measurements in X-rays) have also been used for cosmological studies making use of the cluster (cosmic) baryonic fraction (Allen et al. 2004) and the cluster mass function (Vikhlinin et al. 2009). The same X-ray data have also helped to test MOND theories at the scale of groups and clusters (Pointecouteau et al. 2005; Angus et al. 2008).

However, problematic such as the mass distribution in the outskirts of clusters where virialisation is ongoing; the instrinsic dispersion of the $c - M$ relation (that links to epoch of cluster formation); the link between the dynamical state of clusters and their mass distribution and mass measurements; the proper quantification of the evoltution; detail of the non-gravtationnal physics... are still under deep investigation. In these studies the mass is a key ingredient in our understanding of the cluster population as it directly links to the matter and energy content of the Universe. However it is an "end-of-the-line" indirect observable for most observationnal methods (i.e. X-ray, velocity dispersion of galaxies, gravitationnal lensing, SZ), and its measurement (beside the gravitationnal lensing) relies on the observables of the baryonic components of clusters (i.e. galaxies and the intra-cluster medium (ICM) hot gas). Therefore, the characterisation of the properties of the baryonic content of clusters and of the physics driving its evoltution is a prerequisite to further use the cluster population as a cosmological probe.

3 Impact of non-gravitationnal physics in clusters

We know that non-gravitational processes at play in the ICM medium (e.g. radiative cooling, (pre)heating, feedback of galaxy formation on the ICM,...) play a fundamental role during the formation history of galaxy clusters (see reviews by Voit 2005; Arnaud et al. 2005). Their effect is deeply linked to the process involved in the formation history of member galaxies (galactic winds, ram-pressure stripping, AGN jets, SN rate...), thus to the star formation history within. This connection links physical processes spawning from scales of a few parsec to a few mega-parsecs. In the ICM, the baryons properties bear the signature of all these different processes. During the past decade, the high spatially resolved sectroscopy capabilities of the XMM-Newton and Chandra X-ray observatories have greatly help to improve our understanding of the formation and the evolution of halos, and thus the physics of the hot gas hosted by these halos from galactic to cluster scales. However, the observed departures to the predicted statistical properties for the hot gas component are important (see for instanc Pratt et al. 2009b,a) and reflect the impact of physical non-gravitational processes at play in IGM/ICM on the baryonic component of halos.

Current numerical simulations now implement most of these processes (Borgani et al. 2004; Kay et al. 2004) however they still fail to model them properly and to correctly explain the observed departures to similarity. From the observationnal side, huge progress has been made, especially via the systematic study of unbiased complete representative sample such as the REXCESS sample (Böhringer et al. 2007; Croston et al. 2008; Pratt et al. 2009b,a; Arnaud et al. 2009). We now have a quite clear picture of the structural and scaling properties of clusters and of the overall role of non-gravitationnal processes for local clusters. Quantifying the evolution

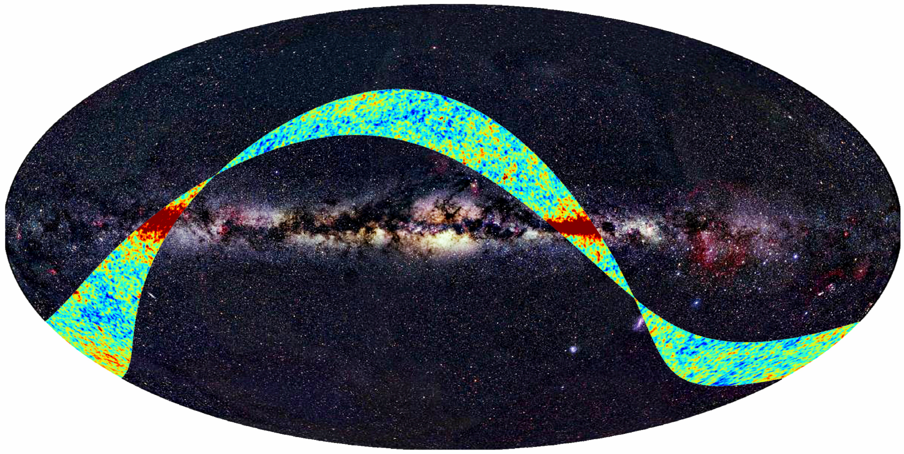

Fig. 1. The Planck first light survey overlaid on the digitalize sky survey (Credits: A. Mellinger) as published in the ESA press release of 17/09/2009 (see http://sci.esa.int/).

of the impact of these processed on the properties of clusters remains an observational challenge. Indeed the departure to purely gravitation driven self-similar evolution is small. Tentative works have tried to quantify these deviation (e.g. O'Hara et al. 2007), but systematic studies on well defined sample at high redshifts need to be carries out and compared with the local reference.

4 Hierarchical structure formation

In the past 10 years, a handful of new distant clusters have been detected up to very high redshift either via the X-ray emission of their hot ICM gas, e.g. RX J0848.9+4452 ($z = 1.26$, Rosati et al. 1999), XMMU J2235.3-2557 at ($z = 1.39$, Mullis et al. 2005), XMMXCS J2215.9-1738 ($z = 1.45$, Stanford et al. 2006); or via the study of their their near-infrared emitting members galaxies, e.g. ISCS J143809+341419 ($z = 1.41$, Stanford et al. 2005). Beyond this range of redshifts, overdensities of galaxies have been significantly detected and associated with proto-clusters candidates, e.g. Ly-α and Lyman break galaxies clustered near radio galaxies (Miley et al. 2004; Overzier et al. 2008).

From the first stage of galaxy clustering to the almost virialised massive halos, merger processes are the key of cluster assembly. The zoology of morphologies observed up to high z, as well as the increasing amount with redshift of sub-structures and dynamical activity in groups and clusters (Jeltema et al. 2005; Maughan et al. 2008), denotes the many dynamical states existing within massive halos, and are the signature of their merging history. Observed density and temperature rims and discontinuities, cold fronts and other shocks in hot gas halos are also the signature of the dynamical state of clusters and groups (Durret et al. 2005; Sauvageot et al. 2005; Markevitch & Vikhlinin 2007). XMM-Newton and Chandra data have been crucial to link the merger and accretion history of halos, as well as processes such as galaxy mergers and interactions, or ram pressure stripping to the evolution of member galaxies in dense environements (Rasmussen et al. 2008; Jeltema et al. 2008), and to the process of chemical enrichment traced via the observation of X-ray lines (Leccardi & Molendi 2008; Werner et al. 2008).

In this context, the interplay between the cluster dynamical activity, the mass accretion onto the SMBH hosted by the brightest cluster galaxies, the member galaxies SFR activities, the AGNs feedback energy injected within the ICM, the absence of cool gas in large amount at the groups and clusters centre is rather complex and emphasizes the difficulty to understand the physics of cluster mergers and massive halo assembly, which beyond the purely gravitational approach, remains probably one of the more delicate and complex problem in the study of large scale structures.

In this overall scientific framework the now ongoing Planck Surveyor survey if probably the best current way to look for and investigate this population of objects.

5 The Planck satellite and the SZ effect

The Planck Surveyor satellite was lauch on May 14^{th} 2009. This ESA space mission is designed to survey the whole sky in the frequency range 30-857 GHz with the primary scientific objective of mapping the temperature fluctuations of the Cosmic Microwave Background (CMB – Planck Collaboration 2006).

Beside this primary goal Planck will allow for the first time, thanks to its full sky coverage, to observe and sample the population of massive clusters of galaxies up to high redshift. Indeed the inverse Compton scattering of CMB photons by the hot ICM electrons shifts the energy distribution of CMB photons towards higher temperature. This effect therefore produces a characteristic distortion of the CMB spectrum in the direction of galaxy clusters. The intensity of this so called thermal Sunyaev-Zel'dovich effect (SZE – Sunyaev & Zeldovich 1972) is directly proportional to the electron thermal pressure integrated along the line of sight (i.e. the ICM pressure). A companion effect is due to the intrinsic cluster velocity in a comobile volume. This Doppler effect, or kinetic SZE, is at least an order of magnitude smaller than the thermal SZE. The following equations gives the basics of SZ quantities.

The SZ monochromatic brightness is expressed as:

$$\left.\frac{\Delta I_\nu}{I_\nu}\right|_{th} = y\ f(x) \tag{5.1}$$

where $f(\nu, T_e)$ depicts the spectral shape of the SZE which has a second-order dependance to the hot gas temperature due to weakly relativistic electrons (Pointecouteau et al. 1998). e subscript refers to electron intra-cluster quantities. y is the Comptonisation parameter, which reads as:

$$y = \frac{k}{m_e c^2}\,\sigma_T \int_l T_g(r)\, n_e(r)\, dl' \tag{5.2}$$

The measure SZE flux can be expressed as:

$$F_{SZ} = \int_\Omega y' d\Omega' \int_\nu f(\nu', kT) d\nu' \tag{5.3}$$

where Y is the integrated Comptonisation parameter:

$$Y = \int_\Omega y(\Omega') d\Omega' = \frac{kT}{m_e c^2}\frac{\sigma_T}{d_A^2} N_e \propto f_{gas} kT \frac{M_{tot}}{d_A^2} \tag{5.4}$$

As shown by the equation above, the SZ flux is directly proportional to the ICM thermal pressure, i.e. $P_{gas} = M_{gas} \times T_{gas}$, thus to the cluster total mass (through the gas fraction, f_{gas}). If the SZE brightness is independant from redshift, the SZE flux sufers a classical $1/(1+z)^4$ diming due to its dependance in d_A^2.

6 Expectations from the Planck all sky survey

Assuming a ΛCDM comology, the current predictions for the Planck survey gives a range of ∼1500-2000 clusters to be detected (see Fig. 2 right). To date we know about 1000-1200 X-ray clusters, mainly from the ROSAT all sky survey cluster catalogues (NORAS and REFLEX, Böhringer et al. 2000, 2004) and from ROSAT serendipitous catalogues. Taking into account the Planck sensitivity, only massive hot clusters (i.e. $M > 3-6\times10^14$ M$_\odot$, $kT > 5-7$ keV) are expected to be detected. Due to the all sky nature of the Planck survey, this will provide us with a unique, all sky, mass limited, complete cluster sample that should be efficient up to high redshifts. It is worth to stress that massive and distant clusters are rare objects, thus the most constraining for cosmology and formation of structures in a Universe where evolution is driven by gravitation.

To date, we know only a handful of clusters above $z = 0.5$ and with $kT > 7$ keV (see Fig. 2 left). Above this redshift and temperature, we expect from 50 to 200 new detected clusters in the Planck survey. A considerable increase in number that will allow us to investigate in details the statistical properties of the high mass end of the distant cluster population. More specifically we will look at the ICM X-ray properties of this new SZ clusters (i.e. L_X, kT, M_{gas}); derive their (distributions in) dynamical mass (under the hypothesis of the HE and sphericity) and entropy; look at their content in gas (i.e. f_{gas}); calibrate the $Y_{SZ} - M$ relation and its evolution, mandatory to proceed with the full scientific exploitation of an catalogue of SZ clusters.

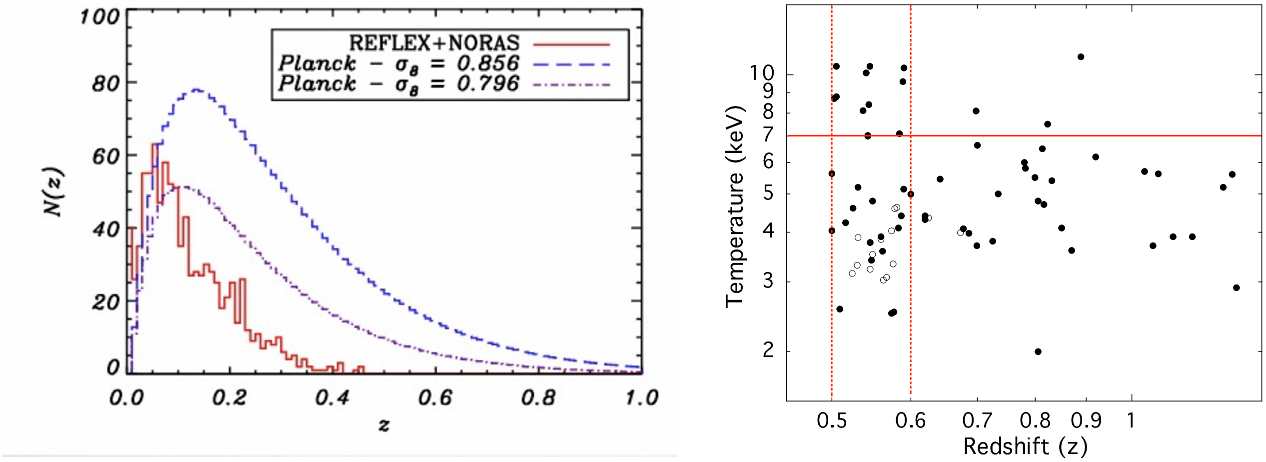

Fig. 2. Left : Comparison between the redshift number counts of the NORAS+REFLEX RASS catalogues and the expectation for the Planck all sky survey (courtesy of A. Chamballu, Chamballu et al 2009, in prep). **Right**: Known clusters above $z = 0.5$ (Courtesy of M. Arnaud).

These objectives obviously require for each cluster candidate: (i) an optical identification and redshift estimation, (ii) a cross-combination of Planck SZ data with X-ray observations of these clusters. Therefore, we will undertake an systematic optical and X-ray follow-ups of a well defined and selected sampe of new detected Planck clusters. If the fisrt and primary goal of an optical follow-up will be the identification of the Planck cluster candidates and the estimation of their photometric redshift, the scientification implications of an X-ray follow-up are deeper. As these clusters are massive, they are expected to be X-ray luminous even at hight redshift (i.e. $0.8 < z < 1.0$): $f_X[0.5\text{–}2\ \text{keV}] > 10^{13}$ erg/s/cm^2). Such fluxes are encouraging for the perspective of an X-ray follow-up program with XMM-Newton. We can compare to similar existing X-ray observation of high redshift clusters. For instance, the temperature of MS 1054-0321 ($z = 0.83$, $f_X[0.5\text{-}2\ \text{keV}] = 2.5 \times 10^{13}$ erg/s/cm^2) was derived with a 10% precision with an exposure time of 25ks (Gioia et al. 2004). So based on the aforementioned expected number of high redshift clusters and considering an exposure time of 25-50ks per target, as an indication of what could be done with XMM-Newton, we would need a very large program of 5-10Ms to follow-up 100-200 Planck clusters candidates (see also Bartlett et al. 2008).

7 Conclusion

The Planck satellite is currently surveying the sky and is expected to provide us with the detection of about 2000 clusters. From this unique all sky survey, we will draw a sub-sample of SZ selected distant clusters. From the Planck SZ measurements together with multi-wavelength follow-ups of this sample we will scrutinize their physical properties. In the framework of the study of galaxy clusters, Planck should allow us to derive constraints to address questions among which: (i) How do non-gravitatinnal processes produce departure from the simplest gravitational model. (ii) How does the ICM history depends on each of these physical individual processes. (iii) How do cluster of galaxies evolve. (iv) How do the first large scale structures form. (iv) What comsmological constraints can we draw from Planck clusters study.

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References

Allen, S. W., Schmidt, R. W., Ebeling, H., Fabian, A. C., & van Speybroeck, L. 2004, MNRAS, 353, 457
Angus, G. W., Famaey, B., & Buote, D. A. 2008, MNRAS, 387, 1470
Arnaud, M., Pratt, G. W., Piffaretti, R., et al. 2009, eprint arXiv:0910.1234

Arnaud, M., Pointecouteau, E., & Pratt, G. W. 2005, A&A, 441, 893
Arnaud, M., Pointecouteau, E., & Pratt, G. W. 2007, A&A, 474, L37
Bartlett, J. G., Chamballu, A., Melin, J.-B., Arnaud, M., & of the Planck Working Group 5, M. 2008, Astronomische Nachrichten, 329, 147
Bertschinger, E. 1985, ApJ Suppl., 58, 39
Böhringer, H., Schuecker, P., Guzzo, L., et al. 2004, A&A, 425, 367
Böhringer, H., Schuecker, P., Pratt, G. W., et al. 2007, A&A, 469, 363
Böhringer, H., Voges, W., Huchra, J. P., et al. 2000, ApJ Suppl., 129, 435
Borgani, S., Murante, G., Springel, V., et al. 2004, MNRAS, 348, 1078
Buote, D. A., Gastaldello, F., Humphrey, P. J., et al. 2007, ApJ, 664, 123
Croston, J. H., Pratt, G. W., Böhringer, H., et al. 2008, A&A, 487, 431
Durret, F., Neto, G. B. L., & Forman, W. 2005, A&A, 432, 809
Gioia, I. M., Braito, V., Branchesi, M., et al. 2004, A&A, 419, 517
Humphrey, P. J., Buote, D. A., Gastaldello, F., et al. 2006, ApJ, 646, 899
Jeltema, T. E., Binder, B., & Mulchaey, J. S. 2008, ApJ, 679, 1162
Jeltema, T. E., Canizares, C. R., Bautz, M. W., & Buote, D. A. 2005, ApJ, 624, 606
Kay, S. T., Thomas, P. A., Jenkins, A., & Pearce, F. R. 2004, MNRAS, 355, 1091
Leccardi, A. & Molendi, S. 2008, A&A, 487, 461
Mantz, A., Allen, S. W., Rapetti, D., & Ebeling, H. 2009, eprint arXiv:0909.3098
Markevitch, M. & Vikhlinin, A. 2007, Physics Reports, 443, 1
Maughan, B. J., Jones, C., Forman, W., & Speybroeck, L. V. 2008, ApJ Suppl., 174, 117
Miley, G., Overzier, R., Tsvetanov, Z., et al. 2004, Nature, 427, 47
Mullis, C. R., Rosati, P., Lamer, G., et al. 2005, ApJ, 623, L85
Nagai, D., Kravtsov, A. V., & Vikhlinin, A. 2007, ApJ, 668, 1
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
O'Hara, T. B., Mohr, J. J., & Sanderson, A. J. R. 2007, eprint arXiv:0710.5782; Submitted to ApJ
Overzier, R. A., Bouwens, R. J., Cross, N. J. G., et al. 2008, ApJ, 673, 143
The Planck Collaboration, 2006, "The Scientific Programme of Planck",eprint arXiv:astro-ph/0604069
Pointecouteau, E., Arnaud, M., & Pratt, G. W. 2005, A&A, 435, 1
Pointecouteau, E., Giard, M., & Barret, D. 1998, A&A, 336, 44
Pratt, G. W., Arnaud, M., Piffaretti, R., et al. 2009a, eprint arXiv:0909.3776, submitted to A&A
Pratt, G. W., Croston, J. H., Arnaud, M., & Böhringer, H. 2009b, A&A, 498, 361
Rasmussen, J., Ponman, T. J., Verdes-Montenegro, L., Yun, M. S., & Borthakur, S. 2008, MNRAS, 388, 1245
Rosati, P., Stanford, S. A., Eisenhardt, P. R., et al. 1999, Astron. J., 118, 76
Sauvageot, J. L., Belsole, E., & Pratt, G. W. 2005, A&A, 444, 673
Schindler, S. & Diaferio, A. 2008, Space Science Reviews, 134, 363
Stanford, S. A., Eisenhardt, P. R., Brodwin, M., et al. 2005, ApJ, 634, L129
Stanford, S. A., Romer, A. K., Sabirli, K., et al. 2006, ApJ, 646, L13
Sunyaev, R. A. & Zeldovich, Y. B. 1972, Comments on Astrophysics and Space Physics, 4, 173
Vikhlinin, A. 2006, ApJ, 640, 710
Vikhlinin, A., Kravtsov, A. V., Burenin, R. A., et al. 2009, ApJ, 692, 1060
Voit, G. M. 2005, Reviews of Modern Physics, 77, 207
Werner, N., Durret, F., Ohashi, T., Schindler, S., & Wiersma, R. P. C. 2008, Space Science Reviews, 134, 337