SZ/X-ray scaling relations using X-ray data and Planck Nominal maps.

I. De Martino\textsuperscript{1}, F. Atrio-Barandela\textsuperscript{2}
\textsuperscript{1} Department of Theoretical Physics and History of Science, University of the Basque Country UPV/EHU, Faculty of Science and Technology, Barrio Sarriena s/n, 48940 Leioa, Spain; \textsuperscript{2} Física Teórica, Universidad de Salamanca, 37008 Salamanca, Spain; email: ivan.demartino1983@gmail.com; atrio@usal.es

Accepted xxx. Received yyy; in original form zzz

ABSTRACT

We determine the relation between the Comptonization parameter predicted using X-ray data $Y_{C,Xray}$ and the X-ray luminosity $L_X$, both magnitudes derived from ROSAT data, with the Comptonization parameter $Y_{C,SZ}$ measured on Planck 2013 foreground cleaned Nominal maps. The 560 clusters of our sample includes clusters with masses $M \geq 10^{13} M_\odot$, one order of magnitude smaller than those used by the Planck Collaboration in a similar analysis. It also contains eight times more clusters in the redshift interval $z \leq 0.3$. The prediction of the $\beta = 2/3$ model convolved with the Planck antenna beam agrees with the anisotropies measured in foreground cleaned Planck Nominal maps within the X-ray emitting region, confirming the results of an earlier analysis (Atrio-Barandela et al. 2008). The universal pressure profile overestimates the signal by a 15-21% depending on the angular aperture. We show that the discrepancy is not due to the presence of cool-core systems but it is an indication of a brake in the $L_X - M$ relation towards low mass systems. We show that relation of the Comptonization parameter averaged over the region that emits 99% of the X-ray flux and and the X-ray luminosity is consistent with the predictions of the self-similar model. We confirm previous findings that the scaling relations studied here do not evolve with redshift within the range probed by our catalog.

Key words: galaxies: clusters: general - X-rays: galaxies: clusters - cosmology: observations

1 INTRODUCTION.

Clusters of galaxies are the largest virialized structures in the Universe first observed as concentrations of optical galaxies. Compression and shock-heating processes raise the temperature of the Intra-Cluster Medium (ICM) to $T_X \sim 1 - 10\text{keV}$ and clusters can be observed through their X-ray emission and their thermal Sunyaev-Zeldovich (TSZ, Sunyaev & Zeldovich (1972)) distortion of the Cosmic Microwave Background (CMB). The self-similar model predicts simple scaling relations between cluster observables and their mass (Kaiser 1986). More specifically, hydrodynamical N-body simulations have shown that the TSZ signal integrated over the cluster volume scales with the cluster mass (White et al. 2002; da Silva et al. 2004; Motl et al. 2004; Nagai 2006; Wik et al. 2008; Aghanim et al. 2009). X-ray properties are also related to the cluster mass and gas temperature (Melin et al. 2011). Scaling relations have been determined observationally but their form does not necessarily coincide with the prediction of the self-similar model (Voit 2003; Arnaud et al. 2003, 2007; Pratt et al. 2009; Vikhlinin et al. 2009). Therefore, non-gravitational processes such as mergers, cooling and energy injection from Active Galactic Nuclei (AGN) have a significant contribution to the equilibrium state of clusters and scaling relations can be used to test the physics of clusters of galaxies (Bonamente et al. 2008; Marrone et al. 2009; Arnaud et al. 2010; Melin et al. 2011; Anderson et al. 2011; Comis et al. 2011). The redshift evolution of the scaling relations seems to follow the self-similar prediction (Bower 1997; Maughan et al. 2006), suggesting that cluster properties evolve with the density of the Universe. Large-scale surveys of the TSZ effect such as those carried out by the Atacama Cosmology Telescope (ACT, Kosowsky 2003) the South Pole Telescope (SPT, Carlstrom et al. 2011) and the Planck satellite (Planck Collaboration 2014b) have helped to constrain cosmological parameters using SZ clusters (Vanderlinde et al. 2010; Sehgal et al. 2011; Planck Collaboration 2014c) and to establish scaling relations between X-ray magnitudes and TSZ measurements (Pratt et al. 2009; Maughan et al. 2007; Pratt et al. 2009).
The effectiveness of clusters as cosmological probes depends on obtaining reliable mass estimates. In this respect, the scatter on the scaling relations needs to be understood in order to account for observational biases. The scatter includes statistical errors, systematic biases and the intrinsic differences between clusters. The intrinsic scatter is dominated by the cluster cores (O’Hara et al. 2006; Chen et al. 2007) since cool-core (CC) clusters deviate from self-similarity of the no cool-core (NCC) population. The difference in the cluster population have been thought to be responsible for discrepancies between numerical predictions and observations. Komatsu et al. (2011) found that the universal pressure profile (Arnaud et al. 2010) overestimated the TSZ amplitude by a 30%. Since the universal pressure profile agreed with TSZ data for CC but disagreed for the NCC clusters, it was thought that the excess was related to the dynamical state of the ICM. Nevertheless, subsequent analysis did not find any evidence of this discrepancy (Melin et al. 2013; Anderson et al. 2011; Rozo et al. 2012). This was further confirmed by the Planck Collaboration using a sample of ∼ 1600 clusters (Planck Collaboration 2011a,b). In this study, the TSZ anisotropy was individually measured for each object but, in order to maximize the statistical significance of the result, the signal was averaged in bins of X-ray luminosity. The Planck Collaboration also carried out an analysis of scaling relations using a sample of 62 clusters (later extended to 78) without binning their properties (Planck Collaboration 2011a, 2014). In this paper we extend this later analyses using a sample of 560 clusters with redshifts z ≤ 0.3 that includes systems with masses one order of magnitude smaller than the latter Planck sample. Briefly, in Sec. 2 we review cluster pressure profile models, in Sec. 3 we describe our cluster catalog and the CMB data used in this study and in Sec. 4 we discuss the scaling relations to be determined, the regression routines used and the associated errors. Finally, in Sec. 5 we present our results and in Sec. 6 we summarize our conclusions.

2 THE INTEGRATED COMPTONIZATION PARAMETER.

The TSZ effect is a distortion of the CMB black-body spectrum produced when CMB photons are scattered off by the free electrons of the ICM. The TSZ effect is independent of redshift and it is usually expressed in terms of the Comptonization parameter \( y_e = (k_B T_e/m_e c^2) \int T_X n_e dl \), where \( n_e, T_X \) are the electron density and temperature along the line of sight \( l \), \( \sigma_T \) the Thomson cross section, \( m_e \) the electron rest mass and \( c, \beta \) the speed of light. The temperature anisotropy \( \Delta T_{TSZ}(\hat{n}) = T_0 G(\nu) y_e \), with \( T_0 \) is the CMB black-body temperature and \( G(\nu) \) is the spectral dependence of the TSZ effect, that is different from that of any other known astrophysical foreground. In the non-relativistic limit \( G(\nu) = -\coth(\nu/2) - 4 \), where \( \nu = h \nu/k_B T_X \) is the reduced frequency and \( h, k_B \) are the Planck and Boltzmann constants, respectively. In this work we will include relativistic corrections up to fourth order in the electron temperature. Itoh et al. (1998); Nozawa et al. (1998, 2006). The SZ effect integrated over the solid angle subtended by the cluster is

\[
Y_C = \int y_e d\Omega = D_A^2(z) \int y_e dA
\]

where \( D_A(z) \) is the angular diameter distance, \( dA \) the projected area and \( dV = dldA \) the volume element. The integrated Comptonization parameter is dimensionless; i.e., it is measured in units of solid angle, generally in (arcmin)\(^2\). An alternative convention is to use \( D_A^3 Y_C \) and express this magnitude in units of Mpc\(^2\).

The pressure profile of the hot ICM was initially described by an spherically symmetric isothermal gas with the electron density profile given by the \( \beta \) model Cavaliere & Fusco-Femiano (1974)

\[
n_e(r) = n_{e,0} \left[ 1 + \left( \frac{r}{r_{cc}} \right)^2 \right]^{-\beta/2},
\]

where the cluster core radius \( r_{cc} \), central electron density \( n_{e,0} \) and slope \( \beta \) are determined from observations. By fitting the cluster X-ray surface brightness Jones & Forman (1984) estimated \( \beta = 0.6 \pm 0.8 \). The TSZ emission predicted for a cluster sample using the fiducial value \( \beta = 2/3 \), convolved with the WMAP antenna beam has been shown by Atrio-Barandela et al. (2008) to agree with the measured anisotropy in WMAP 3yr maps within the region emitting 99% of the X-ray flux.

Based on the Navarro-Frenk-White (NFW) dark matter profile Navarro et al. (1996) and using the the results of N-body simulations, Nagai et al. (2007) proposed the dimensionless pressure profile

\[
p(x) = \frac{P_0}{(c_{500})^\gamma (1 + (c_{500})^\alpha)^{(\beta -\gamma)/\alpha}},
\]

where \( x = r/r_{500} \) is the distance from the cluster center in units of the radius at which the mean overdensity of the cluster is 500 times the critical density, \( c_{500} \) is the gas concentration parameter at \( r_{500} \), \( (\gamma, \alpha, \beta) \) are the central, intermediate and outer slopes and \( P_0 \) is given in Table 1 Arnaud et al. (2010) assumed the profile of eq. (3) to be universal and used X-ray data from a sample of 33 clusters at redshift \( z < 0.2 \) to constrain the model parameters. The dimensionless electron

| Reference                  | \( P_0 \)         | \( c_{500} \) | \( \gamma \) | \( \alpha \) | \( \beta \) |
|----------------------------|-------------------|--------------|-------------|-------------|-------------|
| Arnaud et al. (2010)       | 4.291h^{-3/2}     | 1.177        | 6.03081     | 1.0510      | 5.4905      |
| Planck Collaboration, (2013)| 6.41             | 1.81         | 0.31        | 1.33        | 4.13        |

Table 1. The universal pressure profile parameters determined by Arnaud et al. (2010) and Planck Collaboration (2013).
SZ/X-ray scaling relations using X-ray data and Planck Nominal maps. 3

pressure profile derived from that data was
\[ P_n(x) = 3.36 \times 10^{-5} E^{8/3}(z) \times \]
\[ \times \left[ \frac{M_{500}}{2.1 \times 10^{14} h^{-1} M_{\odot}} \right]^{2/3+\alpha_p+\alpha'_p} p(x) \text{ [eV cm}^{-3}] \text{,} \] (4)

with \( \alpha_p = 0.12 \), and \( \alpha'_p(x) = 0.1(\alpha_p + 0.10)(x/0.5)^3(1.0 + (x/0.5)^3)^{-1} \). In this expression \( h = H_0/[100\text{km s}^{-1}\text{Mpc}^{-1}] \) is the reduced Hubble constant with \( H_0 \) its current value.

The parameters of eq. (4) have also been determined using the TSZ anisotropy of 62 nearby clusters, measured in the 2013 Planck CMB data (Planck Collaboration 2013). To test how well the model predictions agree with the measured anisotropy, in this article we will analyze if the amplitude of the TSZ effect predicted from the X-ray data convolved with the beam at each Planck frequency agrees with the measured anisotropy using the isothermal \( \beta \) model of eq. (3) and the pressure profile of eq. (4) with the two sets of parameters given in Table 1.

3 DATA.

We use a sample of 560 X-ray clusters and the Planck Nominal data released in 2014 to determine the X-ray/SZ scaling relation. Our work differs from previous studies in that all magnitudes used in our analyses have been derived from observations, except the X-ray temperature and \( r_{500} \) scale that were themselves obtained from scaling relations.

3.1 X-ray Cluster Catalog.

The cluster catalog was compiled from three ROSAT X-ray flux limited surveys: the ROSAT-ESO Flux Limited X-ray catalogs (REFLEX, Böhringer et al. 2004), the extended Brightest Cluster Sample (eBCS, Ebeling et al. 1998, 2000) and the Clusters in the Zone of Avoidance (CIZA, Ebeling et al. 2002). These three samples differ in selection techniques, flux measuring algorithms and are affected by different systematic effects. To construct a homogeneous all-sky sample, the different selection technique and the flux determination method employed have to be taken into account to guarantee that all three samples are complete to the same depth. A full discussion of the method used to combine the individual catalogs into a homogeneous all-sky sample is given in Kocevski & Ebeling (2003) and is briefly summarized here. First, the flux is recomputed using ROSAT All Sky Survey (RASS) data. The centroid of the cluster X-ray emission is determined and the X-ray count rate is computed taking into account the local RASS exposure time. The X-ray background is determined from an annulus of radius 1 and 1.5\( h^{-1} \text{Mpc} \) around the cluster centroid and subtracted from the measured counts. The resulting count rates are deconvolved from the telescope Point Spread Function (PSF) and converted to unabsorbed fluxes in the [0.1-2.4]keV band. For the RASS, the PSF is the weighted average of the PSF’s at all off-axis angles Ebeling et al. 1998. Clusters whose emission is dominated by a point source were removed and a cut of \( F_{\text{X}}[0.1-2.4\text{keV}] \geq 3 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1} \) was applied. The merged catalog contains 782 clusters with well measured positions, spectroscopic redshifts, X-ray fluxes in the [0.1-2.4]keV band and angular extents of the region emitting 99% of the X-ray flux, hereafter \( \theta_X \). Of those, only 623 clusters survive the point-source and the Planck galactic masks.

Foreground reduction converted the total number of clusters used in this study to \( N_{\text{cl}} = 560 \).

All the clusters in our sample were fitted to an isothermal \( \beta \) model (Cavaliere & Fusco-Femiano 1976). If \( S(r) \) is the projected surface brightness distribution, then \( S(r) = S_0 [1 + (r/r_c)^2]^{-\beta+1/2} \) where \( S_0 \), \( r_c \), and \( \beta \) are the central surface brightness, the core radius, and the \( \beta \) parameter characterizing the profile, respectively. Due to the low angular resolution of the RASS the surface brightness of our clusters is poorly sampled except for nearby clusters. The correlation between \( r_c \) and \( \beta \) introduces further uncertainties and makes the results for both parameters sensitive to the radius of the cluster chosen to fit the model. Due to these limitations, we take \( \beta = 2/3 \), the canonical value Jones & Forman 1984. Reassuringly, the values of \( r_c \) derived from the data agree with the values derived from the \( L_X - r_c \) relation determined by Reiprich & Böhringer 1999. Cluster luminosities and electron temperatures are used to determine central electron densities. The ICM temperature is derived from the bias corrected \( L_X = [0.1-2.4\text{keV}] - T_X \) relation of Lovisari, Reiprich & Schellenberger 2013.

From the RASS data, X-ray luminosities are measured within a radius of angular size \( \theta_X \), and k-corrected to rest frame [0.1-2.4] keV from the REFLEX/CIZA/eBCS surveys. Conversions between angular extents and physical dimensions are made using the \( \Lambda \)CDM model with Planck measured parameters (Planck Collaboration 2014c). Errors are due to Poisson noise in the number of the photons detected for each cluster and are, at most, 20%. By fitting a \( \beta = 2/3 \) model to the X-ray surface density, the core radii \( r_c \) and central electron density \( n_e(X) \) have been determined. To compare with previous analyses, we also evaluate our scaling relations at \( r_{500} \). We derive this scale from the \( r_{500} - L_X \) relation of Böhringer et al. 2007. From the latter, we define the angular size \( \theta_{500} = r_{500}/D_A(z) \) and mass scale \( M_{500} = 4\pi/3\rho_0(z)r_{500}^3 \), where \( \rho_0(z) \) is the critical density at the cluster redshift. These clusters are located within the redshift interval \( z = [0,0.3] \), have luminosities \( L_X = [0.3 - 22.5] \times 10^{44} \text{ erg/s} \) that correspond to \( T_X = [0.87 - 11.5] \text{ keV} \) and \( M_{500} = [0.2 - 14.7] \times 10^{14} M_{\odot} \). By comparison, the Planck Collaboration study used 78 individual clusters with \( z = [0,0.5] \), \( T_X = [3 - 14] \text{ keV} \) and \( M_{500} = [2 - 20] \times 10^{14} M_{\odot} \). The larger number of clusters and the wider mass range will allow us to test the accuracy with which the cluster pressure profiles of eqs. (2) and (4) fit the data and how well the average properties of the cluster population are described by the self-similar model.

3.2 Foreground cleaned Planck Nominal Maps.

Planck data were originally released in 2013 in a Healpix format with resolution \( N_{\text{side}} = 2048 \) Gorski et al. 2002. The

\footnote{Data downloaded from \url{http://www.cosmos.esa.int/web/planck}}

\footnote{H. Ebeling, private communication}
Nominal maps contained foreground emissions from galactic dust, CO lines, synchrotron, point sources and extended infrared sources. The angular resolution of the Low Frequency Instrument channels is $\theta_{FWHM} > 13^\prime$, larger than the angular extent of the clusters in our sample, so we will restrict our analysis to the High Frequency Instrument data. Prior to compute the TSZ anisotropies we clean the data from foreground and cosmological contributions as described in [De Martino et al. 2013]. First, we subtract the intrinsic CMB and kinematic SZ anisotropies using the LGMCA CMB template [Bobin et al. 2013, 2014]. Thermal dust emission is subtracted using the 857 GHz channel as a dust template [Planck Collaboration 2014d]. We clean this contribution on sky patches $P(\nu, i)$ centered on each cluster $i$ at each frequency $\nu$ following Diego et al. (2002). The CO emission at 100 and 217 GHz is removed using the Type 2 CMB template (Planck Collaboration 2014b,c). We use the PCCS-SZ-Union mask to excise point sources and mask the residual Galactic Plane emission (Planck Collaboration 2013a). The TSZ emission in each patch as $\hat{Y}(\nu)$ is measured using two different methods: (A) following Remazeilles et al. (2011), we can estimate the TSZ emission in each patch as $Y_C(\nu) = \nu \mathcal{P}(\nu, x)$. The weights $w(\nu)$ are obtained by minimizing $\chi^2 = N_{\text{pix}}^{-1} \sum_x (\hat{Y}_C(x) - \hat{Y}_C(x))^2$ where $N_{\text{pix}}$ is the number of pixels of each patch. The weights satisfy $\Sigma \nu w(\nu) \nu G_1(\nu) = \Sigma \nu w(\nu) B(\nu) = 0$ and are given by

$$w(\nu) = \left( B_k \hat{R}_k \hat{B}_k - \left( G_k \hat{R}_k \hat{B}_k \right) B_j \hat{R}_j \right) \left( G_k \hat{R}_k \hat{G}_1 \right) \left( B_m \hat{R}_m \hat{B}_m - \left( G_k \hat{R}_k \hat{B}_k \right) \right)^T.$$ (8)

Here $\hat{R}_i = N_{\text{pix}}^{-1} \sum_p T_i(p) (T_i(p) - (T_i))$ is the empirical covariance matrix computed on the foreground cleaned random patches and the indices $i, j, k$ run over the frequencies $\nu = \{100, 143, 217, 353\}$ GHz. Like before, the Comptonization parameter $\hat{Y}_C(\nu)$ is obtained by averaging on a disc of the radius $\theta$ the associated error is estimated using the ILC weights from 1,000 foreground cleaned patches placed randomly outside the known cluster positions. To demonstrate how efficiently our two pipelines remove foregrounds and the different effect on the low redshift and extended, the intermediate and the high redshift and compact clusters, in Fig. 4 we show the original Planck Nominal maps and the foreground cleaned patches in units of $T_0 G(\nu)$ for each frequency. In these units, the TSZ anisotropy does not change sign but the CMB residuals do. Patches subtend a solid angle of $1^\prime \times 1^\prime$. We selected three Planck clusters: A1656 (Coma) with redshift $z = 0.023$ and an angular extent of $\theta_{500} = 48.1^\prime$, PSZ1 G067.19+67.44 with $z = 0.1712$ and $\theta_{500} = 9.34^\prime$ and PSZ1 G081.01-50.92 with $z = 0.2998$ and $\theta_{500} = 5.45^\prime$. For each cluster, we also present the ILC reconstruction of the TSZ signal of the same data. While the TSZ emission is zero at 217 GHz, it dominates over the foreground residuals at all other frequencies except at 545 GHz, where dust residuals are still the dominant contribution. Therefore, this channel will not be used to avoid biasing the results.

Fig. 2 illustrates that the estimated Comptonization parameter is independent of our foreground cleaning technique and estimation method. In Fig. 2a, we plot the distribution of the Comptonization parameter measured on discs of angular radius $\theta_{500}$ at different frequencies, $Y_C(\nu) - 217 \mathrm{GHz}$ and its average over all channels. All measured values are very similar except those at 217 GHz (long-dashed green line) since dividing by $G(217 \mathrm{GHz}) \approx 0$ boosts the errors. Fig. 2a demonstrates that the Comptonization parameters derived using weighted frequency averages (method A) and the ILC map (method B) are fully compatible. To avoid overcrowding the plot, error bars are not shown. The red line represents
\[ \ln Y_{C,\nu,500} = A + B \ln Y_{C,\text{ILC},500} \]

whose best fit parameters are \( A = 0.001 \pm 0.007 \) and \( B = 0.97 \pm 0.03 \), consistent with the expected values of \( A = 0 \) and \( B = 1 \) at the 1\(\sigma\) confidence level (CL). In Fig. 2c we compare the error using each estimator to show that while the values of \( Y_{C,500} \) measured by both methods are comparable, the errors given by the ILC method (red histogram) are slightly smaller. This is logical since the 217 GHz channel is used to construct the ILC map while it is not used in the weighted average of eq. 6. Therefore, in our subsequent analysis we will quote the results using the ILC method.
4 SCALING RELATIONS.

To determine the scaling relation between the Comptonization parameter measured from the ILC map as described above and the value predicted using X-ray data \( Y_{C,X,ray} \), we will use the isothermal \( \beta = 2/3 \) profile and the universal pressure profile with the two set of parameters given in Table 1. We will compare the measured and the predicted values at two angular scales, \( \theta_{500} \) and \( \theta_{500} \). The luminosity \( L_X \), the gas temperature \( T_X \) and the Comptonization parameter \( Y_C \) are generally defined for clusters as: \( M_g \sim M, L_X \sim E(z)^{2/3}M^{2/3}, T_X \sim E(z)^{2/3}M^{2/3} \) \citep{Kaiser1986}.

In this expression, \( E(z) \) is the Hubble function in units of the Hubble constant today. In the Kaiser model, \( Y_C \propto E(z)^{9/4}L_X^{3/4} \) \citep{Maughan2007}. To facilitate the comparison with earlier results we will fit scaling relations of the form \( E(z) = (D_A Y_{C,SZ})^{\alpha} \),

\[
E(z) Y_{C,SZ}^{\alpha} = 10^{4/9} \left( D_A Y_{C,X,ray}^{10/4} E(z)^{\gamma} \right)^B,
\]

\[
E(z) Y_{C,SZ}^{\alpha} = 10^{4/9} \left( \frac{L_X}{7 \times 10^{42} \text{erg/s} E(z)^{\gamma}} \right)^B,
\]

where the luminosity is measured in the \([0.1 - 2.4 \text{keV}]\) band. The chosen normalizations are those of the Planck Collaboration \citep{Planck2011a}. In eq. (9), \( \gamma_y \) and \( \kappa_y \) parametrize any possible redshift dependence due to observational biases on the measured cluster X-ray and TSZ magnitudes. If there were no such systematics, \( (\kappa_y, \gamma_y) = (0, 0) \) and \( (A, B) = (-4, 1) \). In eq. (10), X-ray luminosity and Comptonization parameter depend on electron density and temperature differently. In the self-similar model \( (\kappa_L, \gamma_L) = (-7/3, -2/3) \) and \( B = 5/4 \) while \( A \) is determined observationally. In this equation, the X-ray luminosity normalization roughly corresponds to the mean X-ray luminosity of our sample. To simplify the analysis we will fix \( (\kappa, \gamma) \) to their self-similar values. To test the redshift evolution we will subdivide the sample in the redshift bins described above and we will compute \( (A, B) \) for each subsample.

4.1 Self-Similar Scaling Relations.

While the dynamical evolution of clusters is dominated by the collapse of the Dark Matter (DM) component, their observational properties are determined by the physical processes undergone by the baryon component. In the self-similar model all cluster observables scale with the cluster mass; in particular, the mass of the gas \( M_g \), the luminosity \( L_X \), the gas temperature \( T_X \) and the Comptonization parameter \( Y_C \) scale as:

\[
\begin{align*}
M_g &\sim M, \\
L_X &\sim E(z)^{2/3}M^{2/3}, \\
T_X &\sim E(z)^{2/3}M^{2/3}.
\end{align*}
\]

In this expression, \( E(z) \) is the Hubble function in units of the Hubble constant today. In the Kaiser model, \( Y_C \propto E(z)^{9/4}L_X^{3/4} \) \citep{Maughan2007}. To facilitate the comparison with earlier results we will fit scaling relations of the form \( E(z) = (D_A Y_{C,SZ})^{\alpha} \),

\[
E(z) Y_{C,SZ}^{\alpha} = 10^{4/9} \left( D_A Y_{C,X,ray}^{10/4} E(z)^{\gamma} \right)^B,
\]

\[
E(z) Y_{C,SZ}^{\alpha} = 10^{4/9} \left( \frac{L_X}{7 \times 10^{42} \text{erg/s} E(z)^{\gamma}} \right)^B,
\]

where the luminosity is measured in the \([0.1 - 2.4 \text{keV}]\) band. The chosen normalizations are those of the Planck Collaboration \citep{Planck2011a}. In eq. (9), \( \gamma_y \) and \( \kappa_y \) parametrize any possible redshift dependence due to observational biases on the measured cluster X-ray and TSZ magnitudes. If there were no such systematics, \( (\kappa_y, \gamma_y) = (0, 0) \) and \( (A, B) = (-4, 1) \). In eq. (10), X-ray luminosity and Comptonization parameter depend on electron density and temperature differently. In the self-similar model \( (\kappa_L, \gamma_L) = (-7/3, -2/3) \) and \( B = 5/4 \) while \( A \) is determined observationally. In this equation, the X-ray luminosity normalization roughly corresponds to the mean X-ray luminosity of our sample. To simplify the analysis we will fix \( (\kappa, \gamma) \) to their self-similar values. To test the redshift evolution we will subdivide the sample in the redshift bins described above and we will compute \( (A, B) \) for each subsample.
4.2 Fit methods.

Linear fits are the most used regression algorithms; different statistical estimators can be used to determine the intercept $A$, the slope $B$ and their respective uncertainties. If $(X_i, Y_i)$ are the data points and $(\sigma_{X_i}, \sigma_{Y_i})$ their respective uncertainties, the commonly used least squares method is a biased estimator. As an alternative, Akritas & Bershady [1996] introduced the Bivariate Correlated Errors and intrinsic Scatter (BCES) that accounts for errors in both variables and their intrinsic scatter with respect to the regression line. If there are low-precision measurements that dominate over the other data points the method could be useless [Tremaine et al. 2002]. For comparison we use a Maximum Likelihood Estimator (MLE) introduced by [Kells 2007] that also accounts for correlated errors in both variables and their intrinsic scatter. We computed the regression coefficients using both methods and found the results to be in excellent agreement. The MLE performs marginally better than BCES when the measurement errors and the intrinsic scatter are large. Then, we will quote only the results computed as the error weighted residual

$$\sigma^2_{raw} = \frac{1}{N_{cl} - 2} \sum_{i=1}^{N_{cl}} \lambda_i (Y_i - B X_i - A)^2, \quad (11)$$

where $N_{cl}$ is the number of clusters and the weights are given by

$$\lambda_i = \frac{N_{cl} \sigma_{raw,i}^{-2}}{\sum_{i=1}^{N_{cl}} \sigma_{raw,i}^{-2}}, \quad \sigma^2_{int,i} = \sigma^2_{Y_i} + A \sigma^2_{X_i}, \quad (12)$$

while $\sigma^2_{int} = \sigma^2_{raw} - \sigma^2_{stat}$ is the difference between the ‘raw’ scatter and the statistical uncertainty ($\sigma^2_{stat} = N_{cl}^{-1} \sum_{i=1}^{N_{cl}} \sigma_{raw,i}^{-2}$) obtained by propagating the error on the measured quantities. A simple estimator of the intrinsic error is given by adding in quadrature uniform values to the measured uncertainties of each individual cluster and finding the value for which $\chi^2$ per degree of freedom is equal to unity, i.e., $\chi^2 = \sum_{i=1}^{N_{cl}} (d_i - Y_i - B X_i - A)^2 / (\sigma^2_{raw,i} + \sigma^2_{int}) \equiv N_{cl} - 2$

\[\text{Table 2. Average properties of full cluster sample and subsamples.}\]

| Subset | Ncl | $\varepsilon$ | $\theta_X$ (arcmin) | $\theta_{500}$ (arcmin) | $L_X$ ($10^{44}$ erg/s) | $M_{500}$ ($10^{14} M_\odot$) |
|--------|-----|---------------|---------------------|-----------------------|----------------------|----------------------|
| All Clusters | 560 | 0.11 | 6.93 | 12.02 | 2.45 | 3.20 |
| 0.0 < $z$ < 0.05 | 95 | 0.035 | 10.15 | 21.60 | 0.59 | 1.40 |
| 0.05 < $z$ < 0.10 | 217 | 0.074 | 7.30 | 12.60 | 1.37 | 2.45 |
| 0.10 < $z$ < 0.15 | 107 | 0.123 | 6.02 | 8.81 | 2.19 | 3.30 |
| 0.15 < $z$ < 0.20 | 79 | 0.169 | 5.06 | 7.65 | 4.14 | 4.80 |
| 0.20 < $z$ < 0.30 | 62 | 0.24 | 4.67 | 6.46 | 7.38 | 6.42 |

\[\text{(Maughan 2007); (Comis et al. 2011). An alternative estimator has been used in (Planck Collaboration 2011a) that differs from the one described previously on the fifth decimal place.}\]

4.3 Error bars.

For the $\beta$ model, the errors on $Y_{C,X\text{-ray}}$ are dominated by the uncertainties in $T_X$ and $n_{e,0}$, while for the universal pressure profile the dominant uncertainty is that of $r_{500}$ and, consequently, of $M_{500}$. The error on $n_{e,0}$ is negligible compared with the error on $T_X$, a magnitude derived from a scaling relation. In the case of the universal pressure profile, we propagated the error on $M_{500}$ and added in quadrature the uncertainty $\Delta_{par}$ due to the difference between the parameters of [Arnaud et al. 2010] and [Planck Collaboration 2013]. We estimated $Y_{C,X\text{-ray}}$ using both sets of parameters, denoted by subindices A and P, respectively, and we take this uncertainty to be the absolute value of their difference: $\Delta_{par} = |Y_{C,X\text{-ray}}^A - Y_{C,X\text{-ray}}^P|$. To estimate the errors on magnitudes derived from scaling relations we generated 10,000 realizations of $T_X$ and $r_{500}$ for each cluster, assuming that the errors on the parameters of their respective scaling relations were Gaussian distributed. On average, the relative error on $T_X$ was found to be $\sim 8\%$, while in $r_{500}$ was $\sim 12\%$. The corresponding error on $M_{500}$ is $\sim 35\%$. Since $\Delta_{par}$ contributes to the total relative error budget with less than $10\%$, the final error on the universal profiles was dominated by the uncertainty on the mass estimates.

4.4 Effect of selection biases.

Selection biases affect X-ray flux limited samples in two ways: Malmquist bias, due to higher luminosity clusters being preferentially selected out to higher redshifts and Eddington bias, due objects above the flux limit having above average luminosities for their mass as a result of the intrinsic or statistical scatter in their luminosity for any given mass. Scaling relations need to be corrected from these effects [Ikebe et al. 2002; Stanek et al. 2006; Pacaud et al. 2007; Pratt et al. 2004; Vikhlinin et al. 2009; Mantz et al. 2011; Mittal et al. 2011]. To determine the selection biases we follow the method outlined in [Czakon et al. 2013]. We generated a sample of $5 \times 10^4$ halo objects out to $z \leq 0.3$ by sampling the number density of halos of a given

\[\text{(Czakon et al. 2013). To determine the selection biases we follow the method outlined in (Czakon et al. 2013). We generated a sample of $5 \times 10^4$ halo objects out to $z \leq 0.3$ by sampling the number density of halos of a given}\]
mass given by [Tinker et al.] 2008). All relevant cosmological parameters were fixed to the Planck measured values (Planck Collaboration 2014). To each halo mass we assign two magnitudes $X = [Y_C, X_{\text{ray}}, L_X]$ using scaling relations; the Comptonization parameter comes from the relation $Y_C, X_{\text{ray},500} = M_{500}$ derived by [Arnaud et al.] 2014 and the X-ray luminosity from the $L_X - M_{500}$ relation given in [Lovisari, Reiprich & Schellenberger 2013]. Both these relations are corrected from statistical biases. The properties of individual clusters differ from one another according to the measured intrinsic dispersion. Then, we imposed the same flux cut than in the data and selected a sample of 560 clusters with the same redshift distribution than in the actual catalog. We repeat the process till three hundred samples have been selected.

The functional form of the scalings given in eqs. (9, 10) is $\log(Y_{C, SZ}) = \log(Y_C) + A$. We assign a value of $\log(X)$ from the scaling relations taking into account the intrinsic scatter. The coefficients ($A, B$) are varied within predefined intervals. For the scaling relation of $Y_{C, X_{\text{ray}}}, M_{500}$, the normalization and slope were varied in the range $A = [-4.50, -3.50]$ and $B = [0.85, 1.45]$ while for the scaling of eq. (10) the range of variation was $A = [-4.50, -3.50]$ and $B = [1.00, 1.40]$, respectively. We fit the scaling relation to the 300 subsamples of simulated clusters for each pair of grid points ($A, B$) and we vary these coefficients in steps of 0.01. We use the same scaling relations to correct the selection biases determined at the $\theta_X$ aperture. This aperture is slightly larger than $\theta_{500}$. The scalings measured at the latter aperture are not very different from those at $\theta_{500}$ (Bonamente et al. 2008) and are well within the range defined above. In each realization, coefficients are measured using the MLE estimator. Like in Planck Collaboration (2011b), slopes and amplitudes are adjusted until the mock observed samples match those recovered from the actual data. Then, the unbiased scaling relation is that of the parent population.

5 RESULTS AND DISCUSSION.

We have used a sample of 560 X-ray selected clusters and the 2013 foreground cleaned Planck Nominal maps to determine two scaling relations, $Y_{C, SZ} - Y_{C, X_{\text{ray}}}$ and $Y_{C, SZ} - L_X$, using the BCES($Y|X$) and the MLE regression methods but the differences are below 1% and only the results from the latter method will be quoted. The uncertainties were determined by 10,000 bootstrap re-samplings (Akritas & Bershady 1996; Kelly 2007).

5.1 The SZ-XRay scalings from pressure profiles.

In Figs. 3 and 4 we represent the data and scaling parameters of the $Y_{C, SZ} - Y_{C, X_{\text{ray}}}$ relation. The Comptonization parameters were obtained by averaging the temperature anisotropies on discs on angular size $\theta_X$ (Fig. 3) and $\theta_{500}$ (Fig. 4). $Y_{C, SZ}$ was measured directly on the foreground cleaned Planck Nominal maps while $Y_{C, X_{\text{ray}}}$ was computed using the X-ray profiles described in Sec. 2: $\beta = 2/3$ model and universal profile with Arnaud et al. (2010) and Planck Collaboration (2013) parameters. In the top three panels we plot the full data and its error bars. The solid red line corresponds to the best fit and the dashed lines to scaling relation with the parameters modified by 1σ. The dotted line represents the scaling relation corrected of the statistical biases as described in Sec. 4.3. The cyan square shows the region of the parameter space occupied by the clusters used in Planck Collaboration (2011b).

In Table 3 we give the best fit parameters and the raw and intrinsic errors for the full catalog. The intrinsic scatter is always smaller but similar to the raw scatter, demonstrating that the uncertainties on the scaling relations are due to the physical differences within the cluster population and not to the statistical uncertainties on the measured magnitudes. For comparison we give the parameters of the scaling relation derived from the data and corrected from the statistical biases as indicated in Sec. 4.4. The raw and intrinsic errors are identical (differences are seen only at the fourth decimal place) since, by construction, the mock catalogs of simulated clusters used to correct for selection biases had the same dispersion than the data. At the $\theta_X$ aperture, the bias corrected relation shows that the intercept and slope of the $\beta = 2/3$ model are $A = -3.99 \pm 0.04$ and $B = 1.11 \pm 0.04$, deviating by about 2.5σ from the expected values of $A = -4$ and $B = 1$. The deviations are larger when the bias corrected relations of the universal profile are used. Evaluating magnitudes at the $\theta_{500}$ aperture, the intercept from the $\beta = 2/3$ model deviates by a 2.5σ but the slope is compatible with $B = -1$ while the universal profile predict slopes that deviate by more than 4σ but the intercepts are closer to the expected value. To quantify these deviations, we compute the mean Comptonization parameter weighted by the angular extent of each cluster, $\bar{Y}_C = \sum_i (Y_{C,i}\theta_i^2)/\sum_i \theta_i^2$. At $\theta_X$ and $\theta_{500}$, this average is $Y_{C, X_{\text{ray}}} = (1.04, 1.17) Y_{C, SZ}$ for the $\beta$ model and is $Y_{C, X_{\text{ray}}} = (1.15, 1.21) Y_{C, SZ}$ for the universal profile, respectively. Then, on average the $\beta = 2/3$ model correctly predicts the TSZ amplitude at $\theta_X$ (4% excess) but overpredicts it beyond this radius (17% excess) as already demonstrated by [Atto-Baradella et al.] 2008. The universal profile overpredicts the signal by a 21% at $\theta_{500}$, contrary to earlier findings by the Planck Collaboration Planck Collaboration (2011b). Similar results were obtained using a universal profile with the Planck Collaboration (2013) parameters.

We can verify if the discrepancy between the prediction of the universal pressure profile and the measured anisotropy is related to the cooling process of the ICM by dividing clusters into cool-core and non cool-core systems. We adopt the O’Hara et al. (2006) classification: CC clusters are those with central cooling times below the Hubble time ($t_H$). We used the central electron densities, X-ray temperatures listed in our catalog and the definition of cooling time $t_{\text{cool}} = 8.5 \times 10^{10} \text{yr} (n_e/10^{-3} \text{cm}^{-3})^{-1} (T_X/10^8 \text{K})^{1/2}$ by Sarazin (1988) to distinguish between CC and NCC clusters. The error on this cooling time was estimated by propagating the uncertainty of the X-ray temperature. In total, only 63 clusters in our sample were cool-core clusters. Reproducing the analysis, we found no significant difference with the results obtained using the full sample. When analyzing both subsamples separately, the results were similar in each subset; the only noticeable effect was the expected increment on the statistical uncertainty due to the smaller number of clusters, but the intrinsic scatter was still the largest compo-
Table 3. Scaling relations with MLE regression coefficients (eqs. [9][10] corrected and not corrected from statistical biases.

| Relation       | Angular Size | θ_X | θ_500 |
|----------------|--------------|-----|-------|
|                | A            | B   | σ_{raw} | σ_{logσ} | A   | B   | σ_{raw} | σ_{logσ} |
| Y_{C,SZ} - Y_{C,Xray} | -4.09 ± 0.04 | 1.07 ± 0.03 | 0.393 | 0.392 | -4.22 ± 0.04 | 0.95 ± 0.04 | 0.362 | 0.360 |
| Y_{C,SZ} - Y_{C,Xray} | -4.00 ± 0.03 | 1.22 ± 0.03 | 0.467 | 0.465 | -4.09 ± 0.03 | 1.16 ± 0.05 | 0.478 | 0.476 |
| Y_{C,SZ} - Y_{C,Xray} | -3.95 ± 0.03 | 1.21 ± 0.03 | 0.474 | 0.472 | -4.04 ± 0.03 | 1.16 ± 0.05 | 0.478 | 0.476 |
| Y_{C,SZ} - L_X [0.1-2.4]keV | -4.27 ± 0.04 | 1.19 ± 0.05 | 0.493 | 0.491 | - | - | - | - |
| Selection Bias Corrected Relations |
| Y_{C,SZ} - Y_{C,Xray} | -3.99 ± 0.04 | 1.11 ± 0.04 | 0.393 | 0.392 | -4.10 ± 0.04 | 0.97 ± 0.04 | 0.362 | 0.360 |
| Y_{C,SZ} - Y_{C,Xray} | -3.85 ± 0.03 | 1.27 ± 0.03 | 0.467 | 0.465 | -3.96 ± 0.03 | 1.20 ± 0.05 | 0.478 | 0.476 |
| Y_{C,SZ} - Y_{C,Xray} | -3.81 ± 0.03 | 1.25 ± 0.03 | 0.474 | 0.472 | -3.91 ± 0.03 | 1.21 ± 0.05 | 0.478 | 0.476 |
| Y_{C,SZ} - L_X [0.1-2.4]keV | -3.98 ± 0.05 | 1.25 ± 0.04 | 0.493 | 0.491 | - | - | - | - |

*: X-ray pressure profile from the β = 2/3-model.
**: X-ray pressure profile from Arnaud et al. (2010).
■: X-ray pressure profile from Planck Collaboration (2011b).
◇: We assumed an error of 10% on the X-ray luminosity.

The diamonds and error bars in the middle and bottom panels of Figs. 5 and 6 show the value of intercept and slope (A, B) in the five redshift bins described in Sec. 4 (not corrected from statistical biases). The solid dotted and dashed line show the mean, 68% and 99% CL of the full sample. There is no clear trend in either parameter for the three pressure profiles considered. The value of the coefficients A and B at each redshift is always compatible with the fit of the full sample, indicating that the scaling does not evolve with time and confirming the results of Planck Collaboration (2011b). Nevertheless, we cannot disregard the importance of statistical biasing effects since in the high redshift bins massive clusters are better represented compared with the low mass ones. Unfortunately, our redshift bins contain few clusters and the error bars on the measured values are consequently large so no statistical analysis could be made.

5.2 The Y_{C,SZ}-Xray luminosity relation.

Equally important is the scaling relation of the Comptonization parameter with X-ray luminosity since we can test the extensions of the self-similar model described in Sec. 1.1. In this case, we limit our study to θ_X, the aperture at which the X-ray magnitudes have been measured. In Fig. 5 we present the data, the best fit (solid line), the best corrected from statistical biases (dotted line) and the 1σ deviations from the best fit. We quote results assuming a 10% uncertainty in the X-ray luminosity of all clusters, but the results remain unchanged if we conservatively increase the relative errors to 20%. The slope and intercept are given in Table 3. The measured correlation parameter corrected from sta-
statistical biases is $B = 1.25 \pm 0.04$, fully compatible with the self-similar value $B = 5/4$. The deviations from self-similarity are compatible with zero: if we assume $\alpha_T = 0$ then $\alpha_g \simeq 0.0 \pm 0.03$ while if $\alpha_g = 0$ then $\alpha_T \simeq 0.0 \pm 0.15$. Our value is not directly comparable to $\alpha_g = 0.13 \pm 0.03$ found by Lin et al. (2012) using 94 clusters in the range $z = 0 - 0.6$ since magnitudes were evaluated at $\theta_{500}$. In Planck Collaboration (2011a) a similar analysis was carried out using a catalog of $\sim 1600$ clusters up to redshift $z \sim 1$. For this sample, the measured value was $B \simeq 1.095 \pm 0.025$. Again, the value is not directly comparable to ours since X-ray luminosities are measured at $\theta_{500}$ and the data was binned in luminosity to reduce errors.

In Fig. 3 also we present the parameters measured at different redshift using the same notation as in Figs. 3 and 4. Like before, we found no indication of redshift evolution. The deviations from self-similarity are compatible with zero: if we assume $\alpha_T = 0$ then $\alpha_g \simeq 0.0 \pm 0.03$ while if $\alpha_g = 0$ then $\alpha_T \simeq 0.0 \pm 0.15$. Our value is not directly comparable to $\alpha_g = 0.13 \pm 0.03$ found by Lin et al. (2012) using 94 clusters in the range $z = 0 - 0.6$ since magnitudes were evaluated at $\theta_{500}$. In Planck Collaboration (2011a) a similar analysis was carried out using a catalog of $\sim 1600$ clusters up to redshift $z \sim 1$. For this sample, the measured value was $B \simeq 1.095 \pm 0.025$. Again, the value is not directly comparable to ours since X-ray luminosities are measured at $\theta_{500}$ and the data was binned in luminosity to reduce errors.

Figure 3. Top panels: Scaling relation between the Comptonization parameter $Y_{C,X_{\text{ray}}}$ predicted using X-ray data, the $\beta = 2/3$-profile and the universal profiles with Arnaud et al. (2010) and Planck Collaboration (2013) parameters and the same magnitude $Y_{C,SZ}$ measured in the ILC map. The signal was estimated/measured on discs of radius $\theta_X$. The solid red line represents the best fit, the dashed lines the uncertainty at the 68% CL on the fit and the dotted line the fit corrected from the statistical biases as indicated in Sec. 4.4. The cyan square indicates the region occupied by the clusters used by the Planck Collaboration. Middle and bottom panels: intercepts and slopes of the scaling relation on the cluster redshift sub-samples. The solid, dotted and dashed red lines indicate the best fit, 68% and 99% CL of the best model represented in the top panels.

6 CONCLUSIONS.

We have fitted scaling relations between the Comptonization parameter predicted using X-ray data and the measured X-ray luminosity with the one measured from foreground cleaned Planck 2013 Nominal maps using a sample of 560 X-ray selected clusters. Prediction and measurement are compared at two angular scales, $\theta_X$ that correspond to the region that emits 99% of the X-ray flux and $\theta_{500}$, the scale at which the cluster density is 500 times the critical density. Our catalog contains cluster and rich groups with masses $M_{500} \gtrsim 10^{14}M_\odot$, one order of magnitude below the
mass range explored by the Planck Collaboration. We found that the Comptonization parameter $Y_{C,X-ray}$ predicted using the $\beta = 2/3$ model agrees with the measured value within $\theta_X$ but overestimates it at $\theta_{500}$ indicating that clusters are not isothermal. We also show that the Universal profile with either Arnaud et al. (2010) or Planck Collaboration (2013) parameters overestimates the SZ anisotropy. Averaged over our cluster sample, we find an excess ranging from 15% to 21% depending on the aperture and the set of parameters used. This is slightly lower than the 30% required to explain the TSZ power determined by WMAP (Komatsu et al. 2011). We verified that the discrepancy is not due to the presence of CC clusters. The discrepancy is greatly reduced if the analysis is restricted to clusters with $M_{500} > \sim 10^{14} M_\odot$, suggesting that the low and high mass systems are not well described by a universal pressure profile with the same set of parameters, an indication that the dynamical evolution of baryons in low and high mass systems was different. This conclusion supports the Lovisari, Reiprich & Schellenberger (2013) suggestion of a brake in the $L_X - M$ relation after correcting for selection biases. Then a simple power law cannot be used to describe both clusters and groups and to translate X-ray luminosities into masses. Finally, we have also shown that the relation of the Comptonization parameter averaged over the region that emits 99% of the X-ray flux and the X-ray luminosity are consistent with the prediction of the self-similar model.

We found that the scaling relation $Y_{C,SZ} - L_X$ is consistent with the self-similar model described in Sec. 4.1. If the temperature scales with mass as in the self-similar model ($\alpha_T = 0$) then deviations of the scaling of the gas mass with the total mass are compatible with zero ($\alpha_g = 0.0 \pm 0.03$) and is in tension with the value of $\alpha_g = 0.13 \pm 0.03$ measured by Lin et al. (2012), although the two results are not directly comparable since $\alpha_g$ was determined from scaling relations measured at different apertures.

We tested the redshift evolution by dividing the catalog in five redshift subsamples. We found no evidence of evolution within $z < 0.3$ in the two scaling relations analyzed. A comparison with the earlier results of Maughan (2007) is not straightforward since this author did not obtain $Y_{C,SZ}$ from CMB data but used scaling relations. His sample of 115 clusters includes systems with $z = 0.1 - 1.3$ and he finds the exponent to be $B \leq 1.1$, depending on the angular scale used. The difference is significant enough to suggest that the scaling relations could be evolving in time but our sample is not deep enough to be sensitive to the effect. This question will require a separate study.

ACKNOWLEDGMENTS

We warmly thank H. Ebeling and D. Kocevski for sharing with us their cluster X-ray data and the referee for helping us to improve the paper. IDM acknowledges financial support from the University of the Basque Country UPV/EHU under the program "Convocatoria de contratación para la especialización de personal investigador doctor en la UPV/EHU..."
Figure 5. The $Y_{\text{C,SZ}} - L_X$ scaling relation at $\theta_X$. Panels and lines follow the same conventions as in Fig. 3.
2006, MNRAS, 365, 509
Maughan, B. J. 2007, ApJ, 668, 772
Melin, J., Bartlett, J. G., Delabrouille, J., et al. 2011, A&A, 525, A139
Mittal, R., Hicks, A., Reiprich, T. H., & Jaritz, V. 2011, A&A, 532, A133
Motl, P. M., Hallman, E. J., Burns, J. O., & Norman, M. L. 2005, ApJ, 623, L63
Nagai, D. 2006, ApJ, 650, 538
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
Nozawa, S., Itoh, N. & Kohyama, Y. 1998, ApJ, 508, 17
Nozawa, S., Itoh, N., Suda, Y. & Ohhata, Y. 2006, Nuovo Cimento, 121, 487
O’Hara, T.B., Mohr, J.J., Bialek, J.J., & Evrard, A.E. 2006, ApJ, 639, 64
Pacaud, F., Pierre, M., Adami, C., et al. 2007, MNRAS, 382, 1289
Planck Collaboration, 2011a, "Planck Early Results: Statistical analysis of Sunyaev-Zeldovich scaling relations for X-ray galaxy clusters", A&A, 536, A10.
Planck Collaboration, 2011b, "Planck Early Results. XI. Calibration of the local galaxy cluster Sunyaev-Zeldovich scaling relations", A&A, 536, A11
Planck Collaboration, 2013, "Planck Intermediate Results V: Pressure profiles of galaxy clusters from the Planck Survey", A&A, 550, 131
Planck Collaboration, 2014a, "Planck 2013 results. I. Overview of products and scientific results", A&A, 571, I
Planck Collaboration, 2014b, "Planck 2013 results. XI. All-sky model of thermal dust emission", A&A, 571A, A11
Planck Collaboration, 2014c, "Planck 2013 results. XII. Component separation", A&A, 571, 12
Planck Collaboration, 2014d, "Planck 2013 results. XIII. Galactic CO emission", A&A, 571, 13
Planck Collaboration, 2014e, "Planck 2013 results. XVI. Cosmological Parameters", A&A, 571, 16
Planck Collaboration, 2014f, "Planck 2013 results. XX. Cosmology from Sunyaev-Zeldovich cluster counts", A&A, 571, 20
Planck Collaboration, 2014g, "Planck 2013 results. XXVIII. The Planck Catalogue of Compact Sources", A&A, 571, 28
Planck Collaboration, 2014h, "Planck 2013 results. XXIX. The Planck catalogue of Sunyaev-Zeldovich sources", A&A, 571, 29
Planck Collaboration, 2015, "Planck 2015 results. XXIV. Cosmology from Sunyaev-Zeldovich cluster counts", arXiv:1502.01597
Pratt, G.W., Arnaud, M. & Pointecouteau, E. 2006, A&A 446, 429-438
Pratt, G.W., Croston, J.H., Arnaud, M. & Bhringer, H. 2009, A&A, 498, 361
Reiprich, T. H., & Böhringer, H. 1999, Astron. Nachr., 320, 296
Remazeilles, M., Delabrouille, J., & Cardoso, J.-F. 2011, MNRAS, 410, 2481
Rozo, E., Vikhlinin, A. & More, S. 2012, ApJ, 760, 67
Sarazin, C. L. 1988, "X-ray Emission from Clusters of Galaxies", Cambridge Astrophysics Series, Cambridge University Press.
Sehgal, N., Trac, H., Acquaviva, V., Ade, P. A. R., Aguirre, P., Amiri, M., Appel, J. W., Barrientos, L. F., Battistelli, E. S., Bond, J. R., et al. 2011, ApJ, 732, 44
Stanek, R., Evrard, A.E., Böhringer, H., Schuecker, P. & Nord, B. 2006, ApJ, 648, 956
Sunyaev, R. A., & Zeldovich, Y. B. 1972, Comments on Astrophys. Space Phys., 4, 173
Tinker, J., Kravtsov, A. V., Klypin, A., et al. 2008, ApJ, 688, 709
Tremaine S., Gebhardt, K., Bender, R., et al. 2002, ApJ, 574, 740-753
Vanderlinde, K., Crawford, T. M., de Haan, T., et al. 2010, ApJ, 722, 1180
Vikhlinin, A., Burenin, R. A., Ebeling, H., et al. 2009, ApJ, 692, 1033
Vikhlinin, Forman & Jones 1999, ApJ, 525, 47
Voit, G. M. 2005, Rev. Mod. Phys., 77, 207
White, M., Hernquist, L., & Springel, V. 2002, ApJ, 579, 16
Wik, D. R., Sarazin, C. L., Ricker, P. M., & Randall, S. W. 2008, ApJ, 680, 17