Merger-induced scatter and bias in the cluster mass–Sunyaev–Zel’dovich effect scaling relation

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ABSTRACT

We examine sources of scatter in scaling relations between galaxy cluster mass and thermal Sunyaev–Zel’dovich (SZ) effect using cluster samples extracted from cosmological hydrodynamical simulations. Overall, the scatter of the mass–SZ scaling relation is well correlated with the scatter in the mass–halo concentration relation with more concentrated haloes having stronger integrated SZ signals at fixed mass. Additional sources of intrinsic scatter are projection effects from correlated structures, which cause the distribution of scatter to deviate from lognormality and skew it towards higher inferred masses, and the dynamical state of clusters. We study the evolution of merging clusters based on simulations of 39 clusters and their cosmological environment with high time resolution. This sample enables us to study for the first time the detailed evolution of merging clusters around the scaling relation for a cosmologically representative distribution of merger parameters. Major mergers cause an asymmetric scatter such that the inferred mass of merging systems is biased low. We find mergers to be the dominant source of bias towards low inferred masses: over 50 per cent of outliers on this side of the scaling relation underwent a major merger within the last Gyr. As the fraction of dynamically disturbed clusters increases with redshift, our analysis indicates that mergers cause a redshift-dependent bias in scaling relations. Furthermore, we find the SZ morphology of massive clusters to be well correlated with the clusters’ dynamical state, suggesting that morphology may be used to constrain merger fractions and identify merger-induced outliers of the scaling relation.

Key words: large-scale structure of Universe – galaxies: clusters: general.

1 INTRODUCTION

Clusters of galaxies are the most massive gravitationally bound objects in the Universe, which makes them an important tool for cosmology: among other tests, their abundance provides information on the gravitational growth of structures and is regulated by the initial density field, gravity and the expansion history of the universe, which critically depend on the underlying cosmology. Thus, number counts of clusters, for which masses and redshifts are known, can be used to constrain cosmological parameters (see Allen, Evrard & Mantz 2011, for a recent review).

To relate observed number counts to theoretical predictions of the cluster mass function, these experiments need to infer cluster masses from observables. The thermal Sunyaev–Zel’dovich (SZ) effect, the signature of inverse-Compton scattering of cosmic microwave background photons with hot cluster electron, is thought to provide an excellent mass proxy as the SZ signal is proportional to the total thermal energy of a cluster and is thus less affected by physical processes in the cluster core which can largely affect the X-ray luminosity. This is confirmed by simulations (e.g. Nagai 2006; Shaw, Holder & Bode 2008; Battaglia et al. 2010; Sehgal et al. 2010) finding the scatter in the mass–SZ scaling relation to be of the order of 5–10 per cent. Furthermore, the SZ effect is not subject to surface brightness dimming and has a very weak redshift dependence, making it an ideal probe to study galaxy clusters at high redshift.

Currently, several large surveys are starting to detect hundreds of galaxy clusters through their SZ signal (Vanderlinde et al. 2010; Marriage et al. 2011; Planck Collaboration et al. 2011a) and...
derive cosmological constraint based on these samples (Andersson et al. 2011; Sehgal et al. 2011; Williamson et al. 2011). To exploit the statistical power of these upcoming cluster samples, the mapping between SZ signal and cluster mass needs to be well understood. Observations find normalization and slope of the scaling relations between SZ signal and lensing-derived masses (Marrone et al. 2011), or between SZ signal and X-ray properties (Planck Collaboration et al. 2011b,c) to be consistent with self-similar scaling and predictions from simulations.

Due to the steep slope of the cluster mass function, competitive cosmological constraints from these experiments require information about the distribution and redshift evolution of scatter in the mass scaling relation (e.g. Majumdar & Mohr 2004; Lima & Hu 2005; Shaw, Holder & Dudley 2010). As the true cluster mass and other physical cluster properties which may bias the mass proxy are unobservable, and as the noise and biases in the different mass estimators may be correlated, characterizing the intrinsic scatter in any of these scaling relation is difficult to obtain from observations. Hence, the sources and distribution of scatter in different mass estimators are mainly studied through simulations and mock observations (e.g. Rasia et al. 2006; Nagai, Vikhlinin & Kravtsov 2007b; Shaw et al. 2008; Yang, Bhattacharya & Ricker 2010; Becker & Kravtsov 2011; Fabjan et al. 2011).

In this work, we focus on the effect of merging events on the SZ signal of a galaxy cluster. As clusters form through merging of smaller objects, these are frequent and disruptive events, which may alter the physical state of the involved clusters significantly. Hence, merging clusters may deviate from the scaling relations observed in relaxed clusters and, as the fraction of morphologically disturbed clusters increases with redshift, cause a redshift-dependent scatter or bias in the mass scaling relation. Simulations of binary cluster mergers (Randall, Sarazin & Ricker 2002; Poole et al. 2006, 2007; Wik et al. 2008) find that the X-ray luminosities, temperatures, SZ central Compton parameters and integrated SZ fluxes increase rapidly during the first and second passage of the merging clusters. The clusters temporarily drift away from mass scaling relations and return to their initial scaling relation as the merging system virializes. These transient merger boosts found in binary mergers and some observations (Smith et al. 2003) can scatter the inferred masses towards higher values and thus bias the derived cosmology towards a higher normalization of the power spectrum, $\sigma_8$, and lower matter density (Randall et al. 2002; Smith et al. 2003; Wik et al. 2008; Angrick & Bartelmann 2011). On the other hand, mergers increase the non-thermal pressure support (Rasia et al. 2006; Lau, Kravtsov & Nagai 2009; Battaglia et al. 2010) found in cluster outskirts, and due to partial virialization merging clusters can appear cooler than relaxed clusters of the same mass (e.g. Mathiesen & Evrard 2001). For a cluster sample extracted from cosmological simulations, Kravtsov, Vikhlinin & Nagai (2006) find the X-ray temperatures of morphologically disturbed clusters to be biased, while the X-ray-derived SZ equivalent $Y_X$ shows no significant correlation with cluster structure. Comparing X-ray and SZ to weak-lensing-derived masses, Okabe et al. (2010) and Marrone et al. (2011) found undisturbed clusters to have of the order of ~40 per cent higher weak lensing masses than disturbed clusters at fixed $T$ and $Y_{SZ}$, and ~20 per cent higher weak lensing masses at fixed $Y_X$.

Our goal is to isolate how mergers in a cosmological context affect the SZ signal of clusters, and if merging cluster can be detected as outliers of scaling relations. This extends previous work, as our analysis includes both multiple mergers with realistic distributions of orbits and mass ratios, and full smoothed particle hydrodynamics (SPH) treatment of gas physics with radiative cooling, star formation and supernova feedback. The simulations and the cluster sample are described in Section 2. We discuss the best-fitting scaling relations and their scatter in Section 3. The effect of merging events of the clusters SZ signal is quantified and the evolution of merging clusters with respect to the scaling relations is discussed in Section 4. In Section 5, we investigate if the dynamical state of clusters can be inferred from the morphology of the SZ signal. We summarize our results and conclude in Section 6.

2 SIMULATIONS

This analysis is based on two samples of galaxy clusters extracted from cosmological hydrodynamics simulations. In this section, we summarize the simulated physics and describe the derived quantities used in our analysis.

2.1 Cluster samples

Sample A. To study the time evolution of the cluster SZ signal, we use a sample of 39 galaxy groups and clusters with virial masses above $3 \times 10^{13} M_\odot h^{-1}$ from simulations presented in Dolag et al. (2006, 2009), 25 of these clusters are more massive than $10^{14} M_\odot h^{-1}$. These structures were identified as 10 different regions in a $(479 \text{ Mpc} h^{-1})$ dark-matter-only cosmological simulation (Yoshida et al. 2001), and resimulated at higher resolution using the zoomed initial conditions method (Tormen, Bouchet & White 1997). The resimulations, described in detail in Dolag et al. (2006), are carried out with GADGET-2 (Springel 2005), and include a uniform, evolving UV background and radiative cooling assuming an optically thin gas of primordial composition. Star formation is included using the two-phase model of the interstellar medium (ISM) by Springel & Hernquist (2003). In this subresolution model, the ISM is described as cold clouds, providing a reservoir for star formation, embedded in the hot phase of the ISM. Star formation is self-regulated through energy injection from supernovae evaporating the cold phase. Additional feedback is incorporated in the form of galactic winds triggered by supernovae that drive mass outflows (Springel & Hernquist 2003).

The simulation assumes a flat $\Lambda$ cold dark matter ($\Lambda$CDM) cosmology with $(\Omega_m, \Omega_b, \sigma_8, h) = (0.3, 0.04, 0.9, 0.7)$. It has a mass resolution of $m_{\text{res}} = 1.1 \times 10^5 M_\odot h^{-1}$ and $m_{\text{gas}} = 1.7 \times 10^8 M_\odot h^{-1}$, and the physical softening length is $\epsilon = 5 \text{ kpc} h^{-1}$ over the redshift range of interest. Our analysis is based on 52 snapshots covering the redshift range from $z = 1$ to $0$ and separated evenly in time with a spacing of 154 Myr between snapshots.

Sample B. The second cluster sample is a volume-limited sample of 117 clusters at $z = 0$ described in Borgani et al. (2004). These clusters are identified in a $(192 \text{ Mpc} h^{-1})^3$ cosmological SPH simulation carried out with GADGET-2 and using the same physics as described above. This simulation assumes a flat $\Lambda$CDM cosmology with $(\Omega_m, \Omega_b, \sigma_8, h) = (0.3, 0.04, 0.8, 0.7)$. The mass resolution is $m_{\text{res}} = 4.6 \times 10^6 M_\odot h^{-1}$ and $m_{\text{gas}} = 6.9 \times 10^9 M_\odot h^{-1}$, the physical softening length at $z = 0$ is $\epsilon = 7.5 \text{ kpc} h^{-1}$.

2.2 Masses and merging histories

Haloes are identified using a friends-of-friends algorithm and the cluster centre is defined by the particle in a halo with the minimum gravitational potential. Cluster radii $R_A$ and masses $M_A$ are defined
For equal-mass particles, an FOF group with linking length during mergers to be larger than the mean accretion rate $M_{\text{scatter}}$ formation redshift as a function of Distribution of formation redshifts $10^2 = \cdots$, $M$ and $M_{\text{scatter}}$ for haloes in the Millennium Run to more recent times. 0.7 $\cdots$ (see $M_M$ such that haloes accrete on average $\zeta$ $\zeta_\text{acc}$ such that accretion is bounded by $R_b/d_h = \cdots$ that requires the accretion rate $\geq \cdots > \cdots \geq \cdots \geq \langle \cdots z \rangle$ $\geq \cdots \geq \langle \cdots z \rangle$ $\geq \cdots \geq \langle \cdots z \rangle$. Motivated by the findings that the average mass accretion history of haloes is well described by exponential growth with redshift (Weschler et al. 2002; McBride, Fakhouri & Ma 2009) and that the average merger rate per halo per unit redshift is nearly constant for a wide range of halo masses and redshifts (Fakhouri & Ma 2008), we select merging events based on a threshold in fractional mass accretion rate per unit redshift $dM/dz/M > \xi_m$. We choose $\xi_m$ such that haloes accrete on average 30 per cent of the mass accreted since its formation redshift $z_f$, defined as the redshift at which a halo reaches half its present-day mass, during mergers. We checked that our results are insensitive to the exact choice of $\xi_m$: we find similar trends for any merger definition $\xi_M \geq \langle dM/dz/M \rangle_{\text{cluster}}$ that requires the accretion rate $dM/dz/M$ during mergers to be larger than the mean accretion rate (cf. discussion of Fig. 6).

Fig. 1 confirms that this merger definition does not strongly depend on cluster mass or redshift. The top panel shows the mean accretion rate as a function of scalefactor for all clusters (solid line) and massive clusters ($M \geq 10^{14} M_\odot h^{-1}$, dot–dashed line), and the overall mean accretion rate (dotted line). The lower panel shows the fraction of clusters that are merging as a function of scalefactor. There is a peak of merging activity around $a = 0.9$, but the accretion rate and merger fraction show no clear trends with cluster mass or redshift.

### 2.2.1 Comparison to the Millennium Run

The 39 cluster and group-scale-sized haloes in sample A are extracted from 10 resimulation regions selected from a large simulation box. One of the resimulated regions hosts a filamentary structure with four massive clusters ($M > 10^{15} M_\odot h^{-1}$), and three of the resimulation regions hosting other massive clusters contain several other smaller clusters. The resimulation technique allows us to analyse the evolution of these regions of interest in their cosmological context at a higher resolution. As a result of the resimulation strategy, the mass distribution of this sample does not follow the cluster mass function, and clusters which are not the most massive object in their resimulation region live in denser regions than an average cluster of the same mass in a volume-limited sample. In the following discussion, we refer to the most massive objects in their respective resimulation region as primary clusters, and all others as secondary clusters.

Simulations indicate a dependence of halo formation histories on environment with merger being more frequent in dense environments and late-forming massive clusters living in denser environments than earlier forming clusters of the same mass (Gao, Springel & White 2005; Wechsler et al. 2006; Fakhouri & Ma 2009). Hence, the merging histories of cluster sample A might not be representative of those of a volume-limited sample. To assess the impact of our sample selection on halo formation histories, we compare the formation redshifts of primary and secondary clusters in sample A and haloes in the Millennium Run simulation (Springel et al. 2005) in Fig. 2.

The symbols show the present-day masses and formation redshift $z_f$ for all clusters in sample A. Primary clusters are indicated by star symbols. The dashed and dotted lines are a fit to the mean formation time and its $1\sigma$ scatter for haloes in the Millennium Run from McBride et al. (2009). We convert the fitting formula from friends-of-friends halo mass with linking length $b = 0.2$ to $M_{200}$, assuming a constant conversion factor $M_{200} = 0.7M_{\text{FOF}}$. For the mass range of our sample, this conversion underestimates $M_{200}$ and biases the fit for $z_f$ to more recent times.

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1 For equal-mass particles, an FOF group with linking length $b$ is bounded by a surface of density $3 \Delta_{200} \rho_{\text{crit}}/(2 \pi b^3)$ (White 2002). Assuming that haloes follow NFW profiles with concentration $c = (4, 7, 10)$, the relation between $M_{200}$ and $M_{\text{FOF}}$ with $b = 0.2$ in the Millennium Run cosmology is given by $(0.71, 0.80, 0.85)$. In practice, however, the conversion between these mass definitions is complicated by deviations from the NFW profile and spherical symmetry.
2.3 SZ maps

The amplitude of the thermal SZ effect along a line of sight is proportional to the Compton y parameter:

\[ y = \frac{k_B \sigma_T}{m_e c^2} \int dl n_e T_e, \]

where \( n_e \) and \( T_e \) are the electron density and temperature, \( k_B \) the Boltzmann constant, \( \sigma_T \) the Thomson cross-section, \( m_e \) the electron rest mass and \( c \) the speed of light. For each cluster, we analyse Compton y parameter maps obtained from three orthogonal lines of sight. For sample A, the projection depth is 8 Mpc and maps are produced using the mapping tool SMAC (Dolag et al. 2005) and the JOBRUNNER web application. For sample B, we use projected maps which include all material with 6\( R_m \) described in Ameglio et al. (2007). From these maps, we measure integrated \( Y_\Delta \) parameters within different overdensity radii \( (R_{2500}, R_{500}, R_{200}, R_{vir}) \):

\[ Y_\Delta = \frac{k_B \sigma_T}{m_e c^2} \int \Delta n_e T_e, \]

where the integration volume is a cylinder of radius \( R_\Delta \) and height 8 Mpc (or 12 \( R_m \)) for sample A (or B). This definition of the integrated \( Y \) parameter includes projection effects due to halo triaxiality and nearby structures within the projection cylinder, but does not account for projection effects from uncorrelated large-scale structure along the line of sight.

3 MASS SCALING RELATIONS

Self-similar clusters models predict the gas temperature to scale as

\[ T \propto |M E(z)|^{2/3}. \]

Hence, the self-similar prediction for the relation between integrated Compton \( Y \) parameter and mass is

\[ Y_\Delta \propto M_{gal, \Delta} T \propto f_{gal} M_A^{1/3} E^{2/3}(z). \]

In this section, we determine the best-fitting scaling relations for the simulated clusters and discuss the scatter in these relations, focusing on the role of mergers.

3.1 Best-fitting scaling relations

We now determine the best-fitting \( M_A(Y_\Delta) \) scaling relation:

\[ M_A(Y_\Delta) = 10^4 \left( \frac{Y_\Delta}{\text{kpc}^2} \right)^\alpha E^\beta(z) 10^{14} M_{\odot} h^{-1}, \]

and \( Y_\Delta(D_\Delta) \) scaling relation:

\[ Y_\Delta(D_\Delta) = 10^\gamma \left( \frac{M_\Delta}{10^{14} M_{\odot} h^{-1}} \right)^\delta E^\gamma(z) \text{kpc}^2, \]

where the self-similar predictions are \((\alpha, \beta) = (3/5, -2/5)\) and \((\gamma, \delta) = (5/3, 2/5)\). Specifically, we first fit a line to the \( \text{lg}(Y_\Delta) - \text{lg}(M_A) \) distribution at each redshift, and then determine the redshift dependence by determining a linear fit in \( \text{lg}(E(z)) \) to the evolution of the normalization constant \( B(z) \). We find no significant indication for a redshift evolution of the slope \( \alpha \) or \( \gamma \).

The best-fitting parameters and the logarithmic scatter at fixed mass,

\[ \sigma_Y = \left\{ \sum_{i=1}^N [\text{lg}(Y_i/Y(M_i))]^2 \right\}^{1/2} / (N - 2), \]

where the sum runs over all \( Y \) measurements (three projections of each cluster at each redshift), are given in Tables 1 and 2.

The two scaling relations contain the same information. While the \( M(Y) \) scaling relation is the relation of more interest for cosmology and is the relation used in the rest of our analysis, the \( Y(M) \) relation is easier to interpret if one is more used to thinking about clusters properties at fixed mass rather than at fixed \( Y \), and we will focus the discussion of the fit results on this relation.

The slope \( \gamma \) of the best-fitting relation in samples A and B is below the self-similar value, while other simulations including cooling and

\[ \text{Table 1. Best-fitting } M_A(Y_\Delta) \text{ scaling relation parameters (equation 6) and logarithmic scatter } \sigma_M \text{ at fixed } Y, \text{ defined analogously to equation (8)}. \text{ } A^*/B^* \text{ denote sample A/B restricted to clusters at } z = 0 \text{ with } M > 2 \times 10^{14} M_{\odot} h^{-1}. \]

| Sample | \( \Delta \) | \( A(z = 0) \) | \( \alpha \) | \( \beta \) | \( \sigma_m \) |
|--------|--------|--------|--------|--------|--------|
| A      | 200    | -0.348 \pm 0.007 | 0.639 \pm 0.010 | -0.57 \pm 0.08 | 0.063 |
| B      | 200    | -0.281 \pm 0.042 | 0.588 \pm 0.020 | -0.042 | 0.042 |
| B*     | 200    | -0.297 \pm 0.006 | 0.617 \pm 0.007 | -0.042 | 0.027 |
| A      | 500    | -0.466 \pm 0.001 | 0.641 \pm 0.007 | -0.74 \pm 0.10 | 0.089 |
| A*     | 500    | -0.406 \pm 0.036 | 0.607 \pm 0.020 | -0.042 | 0.037 |
| B      | 500    | -0.400 \pm 0.004 | 0.626 \pm 0.005 | -0.042 | 0.024 |
| B*     | 500    | -0.379 \pm 0.011 | 0.604 \pm 0.009 | -0.042 | 0.024 |

\[ \text{Table 2. Best-fitting } Y_\Delta(M_\Delta) \text{ scaling relation parameters (equation 7) and logarithmic scatter } \sigma_Y \text{ at fixed mass. } A^*/B^* \text{ denote sample A/B restricted to clusters at } z = 0 \text{ with } M > 2 \times 10^{14} M_{\odot} h^{-1}. \]

| Sample | \( \Delta \) | \( B(z = 0) \) | \( \gamma \) | \( \delta \) | \( \sigma_Y \) |
|--------|--------|--------|--------|--------|--------|
| A      | 200    | 0.547 \pm 0.003 | 1.560 \pm 0.014 | 0.85 \pm 0.10 | 0.103 |
| A*     | 200    | 0.489 \pm 0.052 | 1.648 \pm 0.056 | - | 0.070 |
| B      | 200    | 0.494 \pm 0.005 | 1.555 \pm 0.017 | - | 0.071 |
| B*     | 200    | 0.445 \pm 0.030 | 1.658 \pm 0.044 | - | 0.046 |
| A      | 500    | 0.714 \pm 0.003 | 1.553 \pm 0.017 | 1.03 \pm 0.14 | 0.136 |
| A*     | 500    | 0.697 \pm 0.038 | 1.601 \pm 0.051 | - | 0.068 |
| B      | 500    | 0.641 \pm 0.003 | 1.556 \pm 0.014 | - | 0.059 |
| B*     | 500    | 0.624 \pm 0.013 | 1.637 \pm 0.027 | - | 0.037 |
star formation find slopes comparable to or steeper than the self-similar predictions (Nagai 2006; Battaglia et al. 2010; Sehgal et al. 2010). We find a slope in agreement with previous results if we only consider massive clusters with $M_{200} > 2 \times 10^{14} M_\odot h^{-1}$ (‘Sample B’∗) which is identical to the mass threshold used in Sehgal et al. (2010). Projection effects may account for some of the difference from the results of Nagai (2006) and Battaglia et al. (2010): these authors use spherically averaged $Y$ measurements and do not include projection effects, which effectively boost the integrated $Y$ signal of lower mass clusters3 and hence lower the slope of the scaling relation.

After accounting for differences in the baryon fractions of different simulations, the normalization $B$ of the best-fitting scaling relation for sample B∗ is consistent with those obtained from other hydrodynamical simulations with similar physics [the cfs run in Nagai (2006) and the radiative run in Battaglia et al. (2010)].

The slope and normalization of the scaling relation for a sub-sample of massive clusters at $z = 0$ from sample A, denoted as A∗, are comparable to those found for the sample B∗. A direct comparison of these numbers is complicated by the fact that slope and scatter of the scaling relations are mass-dependent, and that the mass distribution within sample A does not follow the cluster mass function. Also, sample A∗ consists of only 11 clusters, five of these are the most massive objects in their respective resimulation region, and it is hard to assess at a precision cosmology level whether the non-representative environment of clusters in sample A affects the normalization of their scaling relation.

The redshift evolution of the scaling relation for sample A deviates significantly from self-similar expectations. This deviation may be caused by mergers: as we will discuss in detail in Section 4 the $Y$ signal of recently merged clusters is suppressed on time-scales of the order of a few Myr. As the merger rate per halo per unit time increases with redshift, the increasing fraction of recently merged clusters reduces the normalization of the scaling relation, causing $\delta$ to deviate from the self-similar value.

In the following, we will focus on scaling relations within $R_{200}$ as the $M_{200}$–$Y_{200}$ relation for sample A has less scatter than that within $R_{500}$. The accretion histories at $R_{500}$ are more erratic than at $R_{200}$ which complicates the identification of merging events and the interpretation of trajectories in the $M$–$Y$ plane. At the time resolution of the simulation snapshots, infalling substructures sometimes cross in and out of $R_{500}$ before coalescence, causing a series of mass jumps and mass losses in $M_{500}$. While it is not clear what the best mass definition is for a merging cluster, the scatter in the $M_{vir}$–$M_{\Delta}$ relation illustrates that masses within larger radii are less volatile: fitting $M_{\Delta}$ as a power law in $M_{vir}$ and $E(z)$, we find logarithmic scatter ($\sigma_{M_{200}}, \sigma_{M_{500}}, \sigma_{M_{2000}} = (0.046, 0.108, 0.326)$.

Fig. 3 shows the best-fitting $Y_{200}$–$M_{200}$ scaling relation for sample A and the distribution of the $z = 1$ and 0 clusters, which we plot in the form of the SZ signal scaled for redshift evolution:

$$\tilde{Y}_{200}(z) = Y_{200}(z)E^{\beta/\alpha}(z).$$

The right-hand panel shows the distribution of the scatter around the scaling relation,

$$\delta \log M = \log (M(Y)/M),$$

for the full sample and subsamples. This scatter definition gives the logarithmic error in the mass inferred from $Y$ measurements, positive scatter corresponds to clusters with $Y$ larger than expected for their actual mass. At all redshifts, the distribution deviates from lognormality with a tail at large $\delta \log M$, causing the distribution to have positive skewness and kurtosis.

The left-hand panel of Fig. 4 shows the $M_{200}$ and $Y_{200}$ data from sample B and the best-fitting scaling relation. We checked by visual inspection that the most extreme outliers, which are all in the direction of $Y$ higher than expected for the cluster mass, are indeed projection effects. These clusters have multiple peaks or appear

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3 Projection effects introduce an additive signal $Y_p \geq 0$ which scales as $Y_{p,A} \propto R_A^2 \propto M^{2/3}$, and thus the fractional error induced by projection effects decreases with cluster mass.
otherwise distorted in only one or two of the three orthogonal projections, indicating that these are not merging systems (yet).

The intrinsic scatter in the spherically integrated $Y$ parameter of large cluster samples has been found to be close to lognormal (Stanek et al. 2010; Fabjan et al. 2011). However, projection effects due to correlated structures and diffuse large-scale structure have been identified as a non-negligible source of scatter and bias in the mass scaling relation. The non-lognormal, positively skewed distribution of scatter in projected Compton $Y$ parameter in our cluster sample is in good agreement with the results of Hallman et al. (2007) and Yang et al. (2010), who analysed light cone/cylindrical projections of the SZ effect, respectively. Based on an Edgeworth expansion of the mass–observable distribution, Shaw et al. (2010) find that the higher order moments do not significantly impact the observed cluster mass function if the product of the scatter in the scaling relation, $\sigma_M$, and the slope of the mass function at the limiting mass of a survey is less than unity. Due to low scatter of the SZ scaling relation, this criterion is met by all upcoming SZ experiments, suggesting that projection effects will be insignificant for cosmological constrains (but see Shaw et al. 2008; Erickson, Cunha & Evrard 2011, for additional mitigation strategies).

### 3.2 Influence of halo concentration

The scatter in halo concentration at fixed cluster mass has been identified as an important source of scatter in X-ray temperature (Ameglio et al. 2009; Yang, Ricker & Sutter 2009) and SZ signal (Shaw et al. 2008; Yang et al. 2010) of simulated clusters. Understanding the role of halo concentration on these observables is especially important for understanding selection biases and for the comparison to lensing-derived cluster masses.

The right-hand panel of Fig. 4 shows the correlation between scatter in halo concentration at fixed mass and scatter in $\log Y_{200}$ at fixed mass for all clusters in sample B. We use the halo concentration measurements from Ameglio et al. (2009) derived from fitting Navarro–Frenk–White (NFW; Navarro, Frenk & White 1997) profiles to the integrated mass profile over the range $0.05 < r/R_{200} < 1$, and model concentration $c(M_{200})$ with a power law in mass. The scatter is positively correlated with more concentrated clusters having higher SZ signals at fixed mass, with a correlation coefficient of 0.30 for the full sample B and 0.68 for the massive subsample B$^*$. This result is in agreement with the positive correlation between scatter in concentration and spectroscopic-like temperature of these clusters reported in Ameglio et al. (2009). Similarly, Shaw et al. (2008) find a positive correlation between scatter in concentration and integrated $Y$ parameter in haloes from adiabatic SPH simulations and from N-body simulation in combination with semi-analytic gas models. On the other hand, Yang et al. (2009, 2010) find a negative correlation between scatter in concentration and scatter in temperature and integrated SZ signal. As discussed in Yang et al. (2010), the correlation between halo concentration and temperature at fixed mass depends on the assumed gas physics, and the inclusion of radiative cooling, star formation and feedback may change the sign of the correlation.

On the observational side, Comerford, Moustakas & Natarajan (2010) find $\Delta T$ anticorrelated with $\Delta c$. However, this analysis is based on a sample of eight strong lensing clusters and the authors note that this result vanishes if a different measurement for the concentration of one cluster (MS 2137.3$-2353$) is used. As strong lensing-selected cluster samples are strongly affected by projection effects and are biased towards higher halo concentrations and X-ray luminosities than average clusters (e.g. Meneghetti et al. 2010, 2011), larger, X-ray-selected data sets like the CLASH survey (Postman et al. 2011) will be needed to observationally constrain the correlation between scatter in temperature and halo concentration.
The scatter in halo concentration at fixed mass is linked to the formation epoch of a halo with more concentrated haloes forming earlier (Navarro, Frenk & White 1997), albeit with large scatter (e.g. Neto et al. 2007) which is likely due to environmental effects (see also Gao & White 2007). Hence, the positive correlation between scatter in concentration and SZ signal suggests that clusters with $Y$ biased low formed more recently.

4 SCATTER INDUCED BY MERGERS

We now turn to a detailed analysis of the evolution of merging clusters around the $M(Y)$ scaling relation fit to sample A. Fig. 5 shows the trajectory of six massive clusters around the best-fitting scaling relation in the $M_{200}-Y_{200}$ plane. Phases identified as mergers are shown in red. These examples suggest that the SZ signal lags behind the change in mass during extended merger events moving the merging clusters below the best-fitting scaling relation. This is similar to the findings of Rasia et al. (2011), who analysed the evolution of X-ray properties of two of these clusters (g8a and g1b) during mergers and find a time delay between mass increase and rise in temperature of the order of a few hundred mega years. We quantify the difference in evolution during mergers compared to the overall evolution of each cluster in the $M-Y$ plane in Fig. 6. The open symbols show the logarithmic increase in mass:

$$\Delta \lg M = \lg \left( \frac{M(z=0)}{M(z=1)} \right),$$

and $Y$ signal scaled for redshift evolution:

$$\Delta \lg Y = \lg \left( \frac{Y(z=0)}{Y(z=1)} \right).$$

As expected, the overall evolution from $z = 1$ to 0 as quantified by the slope of the best-fitting linear model with zero intercept is consistent with the slope of the best-fitting scaling relation.

The filled star symbols show the evolution of each cluster in the $M-Y$ plane during merger phases only (this corresponds to the sum of the red line segments for each cluster in Fig. 5, treating the different projections separately). The dashed red lines indicate the best-fitting slope for the relation between increase in mass and redshift scaled $Y$ during mergers. This shows that the $Y$ signal scaled for redshift evolution increases more slowly during mergers than expected from the overall scaling relation. The dashed lines show the best-fitting slope for the relation between increase in mass and redshift scaled $Y$ during mergers when relaxing the merger criterion to include all times at which the fractional accretion rate is above its mean value. This illustrates that the suppression of $Y$ during mergers is robust with respect to the definition of merger event. We further illustrate the connection between merging events and scatter in the $M_{200}(Y_{200})$ scaling relation in Fig. 7. The top left-hand panel shows how the clusters evolve around the scaling relation, giving the cumulative fraction of clusters evolving into outliers as a function of time, averaged over all clusters and all snapshots. Thick (thin) dot–dashed or dashed lines show the fraction of clusters which evolve at least 10 per cent (20 per cent) below or above the scaling relation within the next seven snapshots (corresponding to about 1 Gyr), about 30 per cent deviate at least 10 per cent above the scaling relation during that time period and about 35 per cent stay within 10 per cent scatter from the scaling relation. The asymmetry between these pairs of lines is due to the non-lognormal distribution of scatter; the thick lines correspond to the 24 per cent and 76 per cent quantile, the thin lines correspond to the 4 per cent and 96 per cent quantile. The top right-hand panel shows the same evolution around the scaling for clusters undergoing a merger at $t = 0$. Within 1 Gyr after a merger, 55 per cent of all clusters will go through a phase where the inferred mass is biased low by at least 10 per cent, while for only 30 per cent of these cluster the inferred mass will be

Figure 5. Evolution of six massive clusters in mass and $Y_{200}$, the redshift evolution scaled $Y_{200}$. Offsets are added to show all clusters in one plot. We show three orthogonal projections for each cluster to illustrate the magnitude of projection effects. Phases identified as merging events are shown in red. The dashed and dotted lines show the best-fitting scaling relation for sample A and its 1σ error.
Merger-induced scatter in the $M-Y$ relation

Figure 6. Logarithmic mass growth and increase in SZ signal scaled for cosmological evolution for all clusters in sample A. The left-hand panel shows the evolution within $\Delta = 200$, the right-hand panel for $\Delta = 500$. The black open symbols show the overall evolution of individual clusters between $z = 1$ and 0, the black solid lines are the best linear fit with zero intercept to these points, yielding a slope of $1.62 \pm 0.19$ at $\Delta = 200$ ($1.62 \pm 0.29$ at $\Delta = 500$), consistent with the slope of the best-fitting scaling relation. Filled, red stars show the evolution of each cluster during merger phases, the dashed lines are the best linear fit with zero intercept to the evolution during mergers with slope $0.94 \pm 0.15$ ($0.95 \pm 0.22$). The dotted lines show the best-fitting slope for the evolution during mergers when the merger criterion is relaxed to times when the fractional accretion rate per unit redshift is larger than the mean fractional accretion rate per unit redshift.

In summary, our analysis shows that the SZ signal changes more slowly than cluster mass during mergers. This indicates that for a cosmological distribution of merger orbits and mass ratios the delay between mass accretion and heating of the intracluster medium (ICM) by shocks and partial virialization are more important than merger boosts. Hence, the inferred mass of recently merged clusters tends to be biased low and we find that a large fraction of negative outliers are associated with recent mergers.

Note that throughout this section we have analysed deviations from a scaling relation determined from a fit to sample A. Since the merger histories of this environment-selected sample are not necessarily representative of a volume-limited sample, the calibration of this relation may be biased. However, the results in this section and the correlation between scatter in halo concentration and SZ signal of the volume-limited sample discussed in Section 3.2 suggest that this bias would increase the normalization $B$ and slope $\gamma$ at fixed $Y$. Hence, such a calibration bias would downplay the asymmetric scatter induced by mergers that we reported in this section. This suggests that in a volume-limited sample merging clusters may be less frequent, but their inferred masses could be more biased.

5 SZ MORPHOLOGIES

Since we found the dynamical state of clusters to be correlated with scatter in the $M(Y)$ scaling relation, we now test if the morphological appearance of SZ maps can be used to identify clusters that deviate from the scaling relation. Quantitative measures of the X-ray surface brightness morphology are commonly used to identify disturbed clusters; observations (e.g. Böhringer et al. 2010; Okabe et al. 2010; Marrone et al. 2011) and simulations (Jeltema et al. 2008; Ventimiglia et al. 2008; Böhringer et al. 2010) find the inferred masses of morphologically disturbed clusters to be biased low. Ventimiglia et al. (2008) analysed the morphology of clusters from the simulation of Borgani et al. (2004), which is our sample B, and find significant correlations between the centroid shift, axial ratio and power ratios of the X-ray surface brightness distribution of these clusters and scatter in the $T_X(M)$ relation. Böhringer et al. (2010) compared the morphology of these simulated clusters to observed morphologies in the REXCESS sample, and show that the simulated X-ray morphologies show a larger dynamic range and appear more disturbed during mergers. They trace this...
Figure 7. Top left: cumulative probability for a cluster to deviate from the scaling relation by $\delta \lg M$ as a function of time. Thick (thin) dot-dashed blue lines show the fraction of clusters deviating at least 0.04 (0.08) below the scaling relation, corresponding to a bias of 10 per cent (20 per cent) in the inferred mass. Thick (thin) dashed lines show the fraction of clusters deviating at least 0.04 (0.08) above the scaling relation. The black solid lines show the fraction of clusters which deviate less than 10 per cent from the scaling relation within a given time. In all panels, error bars indicate statistical errors estimated from 100 bootstrap realizations. Top right: the same for merging clusters. Note that extended merging events are counted as multiple mergers, effectively giving more weight to major mergers. Bottom left: ratio of the above panels, highlighting the enhanced probability for mergers to evolve below the scaling relation compared to an average cluster. Bottom right: cumulative fraction of clusters which have undergone a merger as a function of look-back time and their current deviation from the scaling relation.

difference to the fact that cool cores are more pronounced in this simulation.

Here we test the effectiveness of a number of morphological parameters, which are typically used to measure X-ray morphology of clusters or optical morphology of galaxies, at quantifying substructure in projected $y$ maps. Within a circular aperture of radius $R_{200}$ we compute the following quantities.

(i) **Asymmetry $A$** measures substructures and differences from circular symmetry; it is defined as the normalized difference between an image $I$ and a copy $R$ of the image rotated by 180°, $A = \sum |I_i - R_i|/\sum I_i$, where sum runs over all pixels in the aperture, and the centre of the aperture is chosen to minimize $A$ (Conselice 2003).

(ii) **Centroid shift $w$** (Mohr et al. 1995) is another measure of the distribution of bright substructures based on the change of the centroid of different isophotal (iso-$y$) contours. Specifically, we follow the implementation of Ventimiglia et al. (2008) and compute the variance of the centroid for 10 iso-$y$ contours spaced evenly in $\lg y$ between the maximum and minimum of $y$ within the aperture.

(iii) **Concentration $C$**. We quantify the apparent concentration of the $y$ distribution by the fraction of integrated $Y$ contained within $0.3 \times R_{200}$, $C = Y_{0.3 R_{200}}/Y_{200}$. 
(iv) **Ellipticity** $\epsilon = 1 - B/A$ is defined as the ratio of semimajor (A) to semiminor axis (B) and is calculated directly from the second-order moments of the $y$ distribution (Hashimoto et al. 2007).

(v) **Gini coefficient** $G$ measures the uniformness of pixel values regardless of their spatial distribution (Lotz, Primack & Madau 2004). It is based on the Lorentz curve, the rank-ordered cumulative distribution of pixel values. It is defined as

$$G = \frac{1}{2\bar{y}n(n-1)} \sum_{i=1}^{n} \sum_{j=1}^{n} |y_i - y_j|,$$  

(13)

where $n$ is the number of pixels inside the aperture, $y_i$ the value of the $i$th pixel, and $\bar{y}$ is the mean pixel value. The Gini coefficient of a uniform distribution is zero, and it is 1 if one pixel contains all the signal. It increases with the fraction of $y$ in compact components.

(vi) **Second-order brightness moment** $M_2$ (Lotz et al. 2004). The total second-order moment $M$ is the signal in each pixel $y_i$ weighted by the squared distance to the centre of the galaxy cluster $(x_{1c}, x_{2c})$, summed over all pixels inside the aperture:

$$M = \sum_{i} M_i = \sum_{i} y_i \left[ (x_{1c} - x_i)^2 + (x_{2c} - y_i)^2 \right].$$  

(14)

Again, the centre is determined by finding $(x_{1c}, x_{2c})$ that minimizes $M$. The second-order moment of the brightest regions measures the spatial distribution of bright subclumps. $M_{20}$ is defined as the normalized second-order moment of the brightest 20 per cent of the cluster’s flux. $M_{20}$ is computed from the pixels ranked ordered by $y$:

$$M_{20} = \log \left( \frac{\sum M_i}{M} \right) \quad \text{while} \quad \sum_{i} y_i < 0.2Y_{200}.$$  

(15)

$M_{20}$ is similar to $C$, but it is more sensitive to the spatial distribution of luminous regions and is not based on any symmetry assumptions.

(vii) **Multiplicity** $\Psi$ (Law et al. 2007) is another measure of the amount (multiplicity) of bright substructures. Using the observed $y$ distribution as a tracer of the cluster’s projected mass, one can calculate a ‘potential energy’ of the $y$ distribution:

$$\Psi_{\text{actual}} = \sum_{i=1}^{n} \sum_{j=1,j\neq i}^{n} \frac{y_i y_j}{r_{ij}},$$  

(16)

where $r_{ij}$ is the distance between pixels $i$ and $j$. This value is normalized by the most compact possible rearrangement of the pixel values, i.e. a circular configuration with pixel values decreasing with radius. The ‘potential energy’ of this most compact light distribution is

$$\Psi_{\text{compact}} = \sum_{i=1}^{n} \sum_{j=1,j\neq i}^{n} \frac{y_i y_j}{r_{ij}}.$$  

(17)

where $r_{ij}$ is the distance between pixels $i$ and $j$ in the most compact configuration.

The multiplicity coefficient is defined as

$$\Psi = 100 \times \log \left( \frac{\Psi_{\text{compact}}}{\Psi_{\text{actual}}} \right).$$  

(18)

It is similar to $A$ and $M_{20}$, but has a larger dynamical range than $M_{20}$ and requires no centre or symmetry assumption.

(viii) **Power ratio** $P_a/P_0$ (Buote & Tsai 1995) corresponds to a multipole expansion of the $y$ map inside an aperture centred on the $y$ centroid. We measure the power ratio $P_a/P_0$ which is related to the projected cluster ellipticity.

We measure morphology at a fixed physical resolution of $17.6$ kpc pixel$^{-1}$ and do not include any noise or observational effects.

Fig. 8 shows the morphology as measured by $C$, $A$ and $\Psi$ of four massive clusters from simulation A during their evolution since $a = 0.5$. The evolution of these clusters around the $M(Y)$ scaling relation is shown in Fig. 5. Vertical lines indicate the onset of mergers. Clusters g696a, g696c and g1lb illustrate the expected course of a merger: as a merging object enters the aperture within which morphologies are computed, the clusters appear less symmetric (higher $A$), less concentrated (lower $C$) and shows more substructure (higher $\Psi$). As the infalling clump sinks towards the cluster centre and dissolves, the cluster appears less disturbed again. However, linking accretion history to morphology is complicated by extended merger phases (g696c, g1lb at $a > 0.8$) with multiple infalling clumps. It is also apparent from these examples that fluctuation in morphology is not always linked to major accretion events (e.g. g8a, late-time evolution of g696a).

For a more representative distribution of dynamical states and morphologies, we show the distribution of scatter in the $M(Y)$ relation and morphological parameters for all clusters in sample B in Fig. 9. Shaded regions contain the 25 per cent most disturbed/most elongated/least concentrated clusters. Overall, the inferred mass $M(Y)$ has larger scatter for clusters with disturbed morphologies, but it is nearly unbiased. Splitting the cluster sample by mass shows

**Figure 8.** Evolution of morphological parameters $G$, $A$, $\Psi$ for four massive clusters from sample A; different lines in each panel show the three orthogonal projections. The bottom panel shows the fractional accretion rate on a logarithmic scale, the dotted and dashed lines indicate the mean accretion and the accretion rate threshold used to define mergers throughout this analysis. Vertical lines mark the onset of mergers, i.e. the time when the fractional accretion rate first crosses the threshold used to define mergers. At the onset of a merger, clusters appear less concentrated, more asymmetric and show more substructure.

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Figure 9. Relation between scatter in the $M_{200}(Y_{200})$ relation δlg $M_{200}$ and morphological parameters for all clusters from sample B measured within an aperture of size $R_{200}$. Open star symbols show clusters with $M < 10^{14} M_\odot h^{-1}$, filled circles show clusters with $10^{14} M_\odot h^{-1} < M < 2 \times 10^{14} M_\odot h^{-1}$, and filled triangles show massive clusters with $M > 2 \times 10^{14} M_\odot h^{-1}$. Dashed vertical lines indicate the 25 and 75 per cent quantiles of the morphology distribution. Shaded regions contain the 25 per cent of the data points which are classified as most disturbed by that morphological parameter. Numbers in the upper left or right corner give the Spearman rank correlation coefficient between the morphological parameter and scatter in the $M(Y)$ relation. From top to bottom, these numbers are for mass samples $M > 2 \times 10^{14} M_\odot h^{-1}$, $M > 10^{14} M_\odot h^{-1}$, $M < 10^{14} M_\odot h^{-1}$. If a correlation is not significant (significance level >0.01), we do not list the correlation coefficient.

that morphologically disturbed clusters with low mass ($M_{200} < 10^{14} M_\odot h^{-1}$, open star symbols) tend to be biased towards larger inferred masses, while massive clusters ($M_{200} > 2 \times 10^{14} M_\odot h^{-1}$, filled red triangles) with disturbed morphologies are preferentially biased low in inferred mass. We quantify this trend using the Spearman rank order correlation coefficient for different mass samples and show the correlation coefficients in Fig. 9. If the significance level of a correlation between a morphology parameter and mass bias is low ($r > 0.01$), we do not list a correlation coefficient. We find a significant correlation between morphology and mass bias in all three mass bins ($M > 2 \times 10^{14} M_\odot h^{-1}$, $M > 10^{14} M_\odot h^{-1}$, $M < 10^{14} M_\odot h^{-1}$) for the multiplicity, concentration, $M_{200}$ and asymmetry parameter. These different morphology parameters consistently show that the correlation between disturbed morphology and negative mass bias increases with mass threshold, and the correlation coefficient changes sign for the low-mass clusters. For centroid shifts and the Gini coefficient, we only find significant correlations with scatter in the $M(Y)$ relation in two mass bins, which follow the same pattern as just described. Power ratio $P_{y}/P_{x}$ and ellipticity are correlated with mass bias only for the most massive clusters, such that less circular clusters tend to be biased low in mass.

This segregation in mass, which is consistent among all morphological parameters, suggests that a large fraction of morphologically disturbed clusters which are biased high in inferred mass is caused by projection effects. The more massive clusters, which are less affected by projection effects, show correlations with disturbed morphology corresponding to a negative bias in inferred mass as expected from X-ray results. We expect cool cores to have a smaller influence on the SZ morphology than is found in X-ray, as the SZ signal is linear in density and less sensitive to physics in the cluster core. Projection effects due to uncorrelated large-scale structure along the line of sight are on average more diffuse than the projection effects from nearby structure that is included in our analysis. Hence, we do not expect the morphology of massive clusters to be dominated by projection effects for line-of-sight projections which include all intervening structure.

As a first step towards including resolution effects, we convolve all projected $y$ maps with a circular Gaussian beam with full width at half-maximum (FWHM) of 150 kpc, and sample the maps at a resolution of 4 pixel per FWHM. For a telescope with a 1-arcmin beam, this physical resolution is reached for a source at $z \sim 0.15$; for an experiment with beamwidth of about 20 arcsec, this corresponds to $z \sim 0.8$. Fig. 10 shows the correlation between mass bias and cluster morphology as measured from these blurred maps for all massive clusters with $M > 2 \times 10^{14} M_\odot h^{-1}$ from sample B. For this choice of beam and pixel scale, cluster morphology and bias in inferred mass are well correlated and resolution effects are small. However, since this analysis is based on noise-
background-free y maps and a simplistic mapmaking procedure, more realistic simulations are required to assess whether SZ-based morphology can in practice be used as a proxy for the dynamical state of a cluster.

6 SUMMARY AND DISCUSSION

Using projected Compton y maps of galaxy clusters extracted from cosmological hydrodynamical simulations, we analyse the clusters’ thermal SZ signal and its scaling relation with cluster mass. We study the detailed time evolution of a sample of 39 clusters around the scaling relation using simulations with outputs closely spaced in time. Compared to previous studies, which focused either on the evolution of isolated, idealized mergers or on large samples of clusters at widely spaced redshifts, this sample enables us to isolate the effect of merging events for a cosmologically representative distribution of merger orbits, mass ratios and impact parameters. Our main results can be summarized as follows.

(i) The best-fitting scaling relations to the integrated $Y_{200}$ signal of these clusters are close to self-similar predictions and agree well with other simulations that include comparable gas physics.

(ii) The scatter around these scaling relations is small (of the order of 10 per cent scatter in mass at fixed $Y_{200}$) and it is overall well correlated with the scatter in halo concentration, such that more concentrated haloes have larger Y signal at fixed mass.

(iii) The scatter in the scaling relation deviates from a lognormal distribution and is skewed towards clusters with Y signals larger than expected from their mass. We find projection effects due to nearby structures to be an important source of this upward scatter. However, due to the small magnitude of the scatter in the mass scaling, projection effects are not expected to be a significant contamination for cosmological constraints from SZ cluster surveys.

(iv) Merging clusters fall below the scaling relation, such that their inferred masses are biased low. More quantitatively, we find that within a Gyr following a merger, clusters are twice as likely as the average cluster to undergo a phase during which their inferred mass is biased low by more than 10 per cent.

(v) We identify merging events to be a major source of downward scatter in the scaling relation: a large fraction of clusters whose inferred masses are biased low recently underwent a merger (cf. Fig. 7).

(vi) For massive clusters, we find the morphology of SZ maps to be well correlated with deviations from the scaling relation. While the robustness of this result with respect to noise and imaging artefacts requires further analysis, it suggests that SZ morphology may be useful to reduce the scatter of mass estimates, and to infer merger rates of massive haloes and hence test theories of halo formation.

Our analysis of the time evolution of merging events is in agreement with the conclusions drawn from earlier studies comparing morphologically disturbed and undisturbed clusters in cosmological simulations at fixed redshifts (e.g. Mathiesen & Evrard 2001; Kravtsov et al. 2006; Nagai 2006; Jeltema et al. 2008; Ventimiglia et al. 2008). Specifically, it supports the hypothesis that for a cosmological distribution of merger parameters partial virialization and non-thermal pressure support due to mergers are more important than merger boosts found in simulations of direct collisions between mergers. For simulated clusters, the intrinsic scatter in the scaling relation and the mass segregation between morphologically relaxed and disturbed clusters are significantly smaller than recent observational results based on SZ measurements, X-ray morphology and weak-lensing-inferred masses (Marrone et al. 2011). However, as these authors note, the observed scatter is in agreement with the scatter expected in weak lensing mass measurements (Becker & Kravtsov 2011). Similarly, the mass segregation is enhanced by the sensitivity of weak lensing mass estimates to cluster triaxiality, and these observational constraints on the intrinsic scatter and bias in SZ mass estimates are limited by the accuracy of weak lensing mass reconstruction.

Further complications arise when inferring cluster masses from SZ observations as most Y measurements are derived from fitting parametric profiles (e.g. Nagai, Kravtsov & Vikhlinin 2007a;
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