Signature of cool core in Sunyaev–Zeldovich clusters: a multiwavelength approach

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ABSTRACT

We use the high quality pressure profiles of 239 galaxy clusters made available by the Archive of Chandra Cluster Entropy Profile Tables (ACCEPT) project in order to derive the expected Sunyaev–Zeldovich (SZ) signal in a variety of cases that hardly find a counterpart in the simulations. We made use of the Melin et al. cluster selection function for both the South Pole Telescope (SPT) and \textit{Planck} instruments. Prior knowledge of the entropy profiles of the same clusters allows us to study the impact of cool cores (CC) in cluster detection via SZ experiment and to test if this introduces a bias in inferred quantities as e.g. the mass function.

We infer a clear effect of the CC on the central Compton parameter $y_0$. We thus validate the suggestions by McCarthy et al., namely that at a given mass clusters with higher entropy levels show a lower $y_0$ than their low-entropy counterparts, on a much larger sample of clusters. For a high-resolution experiment like SPT, we expect that the fraction of detected clusters with respect to the total to decline at masses around $\sim 2 \times 10^{14} M_\odot$. For \textit{Planck} this happens at a somewhat higher mass. We find that the presence of CCs introduces a small bias in cluster detection, especially around the mass at which the performance of the survey begins to decrease. If the CC were removed, a lower overall fraction of detected clusters would be expected. In order to estimate the presence of such a bias by means of SZ-only surveys, we show that the ratio between $y_0$ and $y_{\text{int}}$ anticorrelates with the cluster central cooling time. If multiband optical cluster surveys are either available for a cross-match or a follow-up is planned, we suggest that likely CC clusters are those with a brightest cluster galaxy (BCG) at least 0.3 mag bluer than the average. A more robust estimate of the CC presence is given by UV–optical colours of the BCG, like the NUV-r, whose values can be 4 mag off the NUV-r equivalent of the red sequence, in clusters with low excess entropy. We also find correlation of the $y_0/y_{\text{int}}$ ratio with H$_\alpha$, IR and radio luminosities. We argue that the analysis of a combined SZ/optical/UV surveys can be also used to shed light on the suggested CC evolution with redshift.

Key words: galaxies: clusters: general – cooling flows – galaxies: elliptical and lenticular, cD – galaxies: evolution – X-rays: galaxies: clusters.

1 INTRODUCTION

There are great expectations for Sunyaev–Zeldovich (SZ) effect (Sunyaev & Zeldovich 1970; Carlstrom, Holder & Reese 2002) based clusters surveys. The ones already started (the South Pole Telescope (SPT), Ruhl et al. 2004, the Atacama Cosmology Telescope (ACT)) or up-coming (\textit{Planck}) will contribute to a dramatic increase in the number of galaxy clusters available for applications ranging from the hot intracluster medium physics to cosmological parameter determination (Barbosa et al. 1996; Benson, Reichardt & Kamionkowski 2002; Weller & Battye 2003).

Preliminary works explored the selection functions of different instruments as a function of instrumental characteristics (including noise) and of the adopted technique to actually detect clusters in the SZ signal. Several filtering methods like the matched filter approach (Melin, Bartlett & Delabrouille 2006), multifrequency Wiener filtering (Pierpaoli et al. 2005) and others (e.g. Diego et al. 2002; Pires et al. 2006; Schäfer et al. 2006; Vale & White 2006) have been studied in relation to one or more SZ experiments. We refer to Melin

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et al. (2006) and Pierpaoli et al. (2005) for a comprehensive discussion of (differing) cluster detection techniques and Leach et al. (2008) for the latest comparison of their performances on simulated Planck SZ maps. Most of these works adopted either analytic models or the results of \(N\)-body simulations (in which the gas follows the dark matter particles; e.g. Vale & White 2006) to mimic the SZ signal from the galaxy clusters. Indeed, these works were useful to better assess the capabilities of each instrument and plan its use. However, now that the first SZ detected clusters (Staniszewski et al. 2009) are available it is important to pay more attention to the intracluster medium (ICM) details. The fact that relation between cluster physical properties deviate from a self-similar scaling (Allen & Fabian 1998; Borgani et al. 2002) reminds us that the treatment of the gas physics must be very accurate. For instance, McCarthy et al. (2003a,b) showed that the presence of cool cores (CC) in cluster of galaxies may affect the SZ signal. McCarthy et al. studied the case in which the pre-heating is the cause of the high entropy floor seen in non-CC (NCC) clusters of galaxies and showed that the temperature of the gas near the centre of the cluster increases. At the same time, the density decreases. Since the effect is larger on the density rather than the temperature, the net result is that the gas pressure in the central regions of the clusters decreases. The SZ Compton parameter is the integral on the line of sight of the pressure profile (equation 3), hence we expect NCC clusters, namely objects in which the excess entropy is larger, to have a shallower pressure profile (lower SZ signal) than CC clusters of the same mass.

While differences in the SZ versus X-ray properties between CC and NCC clusters have been emphasized also by observational works (e.g. Morandi, Ettori & Moscardini 2007), previous estimates of both the cluster detection threshold and the completeness of SZ surveys, in terms of either the cluster mass or their SZ integrated signal, made use of mock cluster maps, did not pay attention to the presence of CCs or considered it negligible (Schäfer & Bartelmann 2007). In particular, the emission from clusters was often taken to trace the dark matter potential, without a detailed modelling of the ICM physics. The goal of the present paper is to be a first step in filling this gap.

Our approach is rather different in another aspect. In fact, we use the pressure profiles for 239 clusters obtained from high-quality Chandra data. We then recover their (expected) SZ signal by a direct integration of their pressure profiles and use it to infer which properties of the cluster (if any) make it detectable in a SZ survey. Our main aim is to test McCarthy et al.’s hypothesis on a more general (and larger) sample of clusters with respect to McCarthy et al. (2003b). We then focus on the bias on the recovered clusters mass and abundance in present on-going cluster surveys induced by the presence of CC. In particular we will ask ourselves the questions: are CC clusters more likely to be detected than NCC clusters of the same mass? What happens for clusters around the instrument limit\(^1\) mass for detection? At a given mass, is it easier for CC clusters to make such a threshold than NCC clusters? If so, should we expect a bias in the mass functions of the clusters derived by SZ-only surveys? Our sample is not complete in any sense. Therefore we cannot forecast e.g. the cluster mass function that can be constructed from SZ-only surveys. However, our clusters cover a large range in masses, redshift and entropy profiles. In practice we complement the modelling approach (Nagai 2006; Vale & White 2006; Nagai, Kravtsov & Vikhlinin 2007; Schäfer & Bartelmann 2007) presenting results that sample a large variety of conditions of the hot intracluster medium, with a spread that is fair representation of what happens in the local Universe. In this sense the goal is to make a first quantitative estimate of the CC bias around the instrument limit mass. The presence of the bias and its estimate are linked to the chosen method for cluster detection is SZ maps; however, our results can be read as a warning and possibly extended to other cluster selection criteria.

We further explore the connection between the presence of CC and the properties of the brightest cluster galaxies (BCGs). Indeed, recent studies in several bands have reported examples of ongoing star formation in the BCGs (Cardiel, Gorgas & Aragón-Salamanca 1998; Crawford et al. 1999; Edge 2001; Goto 2005; McNamara et al. 2006; Bildfell et al. 2008; Cavagnolo et al. 2008a; Edwards et al. 2007; O’Dea et al. 2008; Rafferty, McNamara & Nulsen 2008; Pipino et al. 2009a; Sanderson, Edge & Smith 2009); most of these BCGs reside in CC clusters and are located very close to the peak of the X-ray emission. In particular, it seems that up to the 25 percent of the BCGs are somehow active. Therefore, another goal of this paper is to extended the body of evidence for the CC–BCG connection. In particular, we will investigate if a correlation between star formation indicators like optical blue cores, UV excess, H\(\alpha\) emission, high IR and radio luminosities and the SZ effect from CC clusters exists. We will suggest a multiwavelength approach in order to complement SZ-only based surveys to assess the presence of a bias induced by CCs. The same technique can be applied to other science cases as e.g. the study of the evolution of the CC fraction in a larger sample of clusters than those provided by X-ray data only.

We will present our results for either a high-resolution experiment (SPT) and a lower resolution one (Planck). The plan of the paper is the following. The cluster sample and the SZ signal that we expect are characterized in Sections 2.1 and 2.2, respectively. We will present our results in Section 3, discuss their implications in Section 4 and draw our conclusions in Section 5.

2 MODELLING THE SZ SIGNAL

2.1 The cluster sample

We make use of the publicly available data made possible by the ACCEPT project (Cavagnolo et al. 2009). The catalogue comprises 239 galaxy clusters with accurate temperature, density, entropy and pressure profiles reduced in a homogeneous way from public Chandra data. The catalogue covers the temperature range 1–20 keV with redshifts ranging from 0.05 to 0.89 (see Fig. 1). We refer to Cavagnolo et al. (2009, and references therein) for details on the data reduction and further catalogue specifics. Here we note that this catalogue is neither flux limited nor volume limited. However, since ACCEPT clusters come from a large number of observing programs, it is quite unlikely that it is biased toward a particular class of clusters. Moreover, as noted by Cavagnolo et al. almost all (94 per cent) of the HIFLUGCS (Reiprich & Böhringer 2002) clusters are in ACCEPT. Therefore we will use HIFLUGCS clusters available in ACCEPT as a flux-limited subsample in order to make more quantitative estimates in the following.

\(^1\)See McCarthy et al. (2004, 2008) for a detailed discussion of the diversity in the cluster population, including the distinction between cool core versus non-cool core clusters.

\(^2\)The mass at which the detection rate falls below the 90 per cent. This is set by instrument properties, the noise, but also by the detection method.
where $R_{\Delta_c}$ is in units of $h^{-3}_{70}$, $\Delta_c$ is the assumed density contrast of the cluster at $R_{\Delta_c}$ and $\beta_7$ is a numerically determined normalization for the virial relation. The maximum radius ($R_{\text{max}}$) probed by X-ray observations is typically 1/2 of the virial radius (Fig. 2, top right-hand panel). Since clusters are at different redshifts and their projected angle $\theta_{\text{max}}$ on the sky matters, we converted the radii into angles after having calculated the distance of the clusters in a flat $\Lambda$ cold dark matter ($\Lambda$CDM) Universe with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$ and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (these are the value adopted in Cavagnolo et al. 2009 – we use them in order to be consistent with their estimates of e.g. luminosities). All clusters have properties measured out to (at least) 1 arcmin. Therefore all of them could in principle be resolved by an instrument like SPT (Bartlett 2006). Only few of them, instead, have dimension larger than 5 arcmin [namely the full width at half-maximum (FWHM) resolution of Planck in the 217-GHz channel].

We also fitted a single $\beta$ model (Cavaliere & Fusco-Femiano 1978) to our clusters in order to estimate the cluster core radius that we will employ to determine if a cluster can be detected (see Section 2.3). In order to be consistent with the assumption behind theoretical detection limit that we will use, we fixed $\beta = 0.66$. We did not attempt to fit double $\beta$ models in CC clusters where it seems to be required (Cavagnolo et al. 2009). Instead, in order to minimize the effect of the CC, we avoided the very central regions ($\log R/R_{\text{200}} < -2$) of the clusters. In practice, the SZ signal obtained by the integration of the $\beta$ model will give an estimate of the signal obtained for real clusters when the CC effect is removed. The core radius ($R_c$) distribution of our cluster sample is shown in the bottom right-hand panel of Fig. 2. Again, we show the angle on the sky rather than the radius in physical units. Most of the clusters have core size around 0.5 arcmin. Therefore, they must be treated as extended sources in order to properly evaluate the possibility to be detected by a given instrument. We note that the values for $R_c$ in CC clusters are marginally smaller than those for NCC. Such a trend is visible in the distribution of clusters core angles $\theta_c$ (the bottom right-hand panel of Fig. 2). This is a secondary bias linked to the presence of the CC, the primary being the increased Compton parameter, that the reader should be aware of. Note that the above discussion holds for the actual ACCEPT redshift distribution and will be used in the rest of the paper unless otherwise stated. As a matter of fact, we will also present a case (see Section 3.2) in which all the clusters are placed to higher redshift, while preserving their mass, to check our results in the case of a more typical redshift distribution. In that case, the resulting $\theta_c$ will be smaller – and with a different distribution – than the ones shown in Fig. 2.

From the bottom left-hand panel of Fig. 2, we note that there is a clear bimodality in the cluster entropy distribution defined as the entropy floor $K_0$ in units of keV cm$^2$, Cavagnolo et al. (2009, see also Rafferty et al. 2008) claim that this bimodality is not induced by a bias in the cluster selection. We have also to keep in mind that the fraction of CC clusters in ACCEPT is $\sim 40$ per cent, somewhat lower than the typical $\sim 50$–60 per cent reported in the literature (Peres et al. 1998), and that the ACCEPT lacks clusters with $K_0$ below 10 keV cm$^2$ at $z > 0.1$. We expect the latter to be less important. In fact, entropy levels below 10 keV cm$^2$ are typical of galaxy groups, namely systems not observed in SZ due to their very low signal. The distribution of clusters as a function of the central cooling time follows the one as a function of $K_0$ (see Cavagnolo et al. 2009). In the following we refer to CC clusters as those with entropy $K_0$ below 25 keV cm$^2$ or cooling time below 1 Gyr, being the differences between the two classification negligible in our results.

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**Figure 1.** Redshift distribution of the adopted sample of galaxy clusters. The dotted vertical line marks the median redshift ($\sim 0.13$) of the distribution.

**Figure 2.** Properties of the adopted sample of galaxy clusters. Top-left: $M_{500}$ distribution. Bottom-left: entropy distribution. Top-right: maximum radius probed by X-ray observation, namely the radius of the largest annulus available from ACCEPT for a direct integration of the pressure profile (projected in the sky). Bottom-right: core radius distribution inferred from a $\beta$-model fitting (see text). In this panel, CC clusters are displayed with a dotted line, NCC with a dashed line.

We estimate the mass of our clusters (not provided in ACCEPT) as

$$M_{500} = 3.02(kT/5\text{ keV})^{1.53}H_0/H(z)h^{-1}10^{14}M_\odot$$

(1)
given by Vikhlinin et al. (2009). This relation will set the baseline for our discussion. We note that our choice does not affect the results of the calculations shown in remainder of the paper. It is needed only to infer a mass for the objects we are dealing with. The mass distribution of our cluster sample is shown in the top left-hand panel of Fig. 2.

The radius of the clusters ($R_{\Delta_c}$) was calculated by Cavagnolo following Arnaud, Aghanim & Neumann (2002):

$$R_{\Delta_c} = 2.71 \text{ Mpc } \beta_7^{1/2} \Delta_c^{-1/2}(1+z)^{-3/2} \left(\frac{kT}{10\text{ keV}}\right)^{1/2},$$

(2)

$$\Delta_c = \frac{\Delta \Omega_m}{18\pi^2 \Omega_c},$$

$$\Omega_c = \frac{\Omega_m(1+z)^3}{\Omega_m[(1-\Omega_m-\Omega_\Lambda)1+z]^3+\Omega_\Lambda}.$$
2.2 SZ signal from our clusters

In the following we will express the SZ effect through the Compton $y$ parameter given by the following equation:

$$y(\theta) = \int \sigma_T n_e \frac{k_B T_e}{m_e c} \, d\ell,$$

(3)

where $\sigma_T$ is the Thomson cross-section, $k_B$ is the Boltzmann constant, $c$ is the speed of light in vacuum, $m_e$ is the electron mass, $T_e$ the electron temperature and the integration is along the line of sight. The central Compton parameter is $y_\theta = y(\theta = 0)$, whereas we recall that the integral effect within a given angle $\theta$ is

$$y_{\text{int}}(<\theta) = 2\pi \int_0^\theta y(\theta') \, d\theta'.$$

(4)

We obtain the Compton parameter $y$ by direct integration of the pressure profiles provided by ACCEPT. In Fig. 3 we show some examples of the Compton parameter radial profiles derived by us compared to the input temperature and density profiles. For the sake of clarity, we focus on clusters with mass $\sim 2.5 \times 10^{14} \, \text{M}_\odot$, as we will see in the following that this is roughly the mass at which the CC-induced bias is more relevant. Clearly, CC clusters exhibit steeper profiles in $y(\theta)$ than NCC clusters, due to the fact the CC, while decreasing the central temperature by a factor of a few, enormously enhances the central density. The pressure profile is thus steeper in CC clusters. However, in order to get $y(\theta)$ we have to further integrate the pressure profile along the line of sight (equation 3), leading to Compton parameter profiles less steep than the density profiles from which they arose. Note that the ACCEPT pressure profiles allow us a direct estimate of the SZ effect out to $R_{\text{max}}$.

Although $R_{\text{max}} \sim 0.5 R_{\text{200}}$ (Cavagnolo et al. 2009), this radius is not constant for all clusters. Moreover, clusters have differing redshifts, therefore, they will cover differing angles in the sky (see top right-hand panel of Fig. 2).

We will present also results out to $R_{\text{500}}$ ($R_{\text{200}}$) by adding the SZ signal at radii $R_{\text{max}} < R < R_{\text{500}}$ ($R_{\text{200}}$) estimated by the $\beta$-model fitted profile to the value for $y_{\text{int}}(<R_{\text{max}})$ obtained from direct integration of the ACCEPT pressure profiles. In this way we minimize the impact the $\beta$-model fitting procedure and maintain the effect of the CC. The comparison between these quantities is given in Fig. 4. In this figure, the dotted line is the 1:1 relation to guide the eye. The dashed line give the median offset from the 1:1 relation. In particular, the median offset between $y_{\text{int}}(<R_{\text{max}})$ and $y_{\text{int}}(<R_{\text{500}})$ is less than a factor of 2, since for many clusters $R_{\text{max}} \sim R_{\text{500}}$. In the case of the extrapolation of the Compton parameter out to $R_{\text{200}}$, the median difference is a factor of 2.8.

As for the SZ signal obtained through the integration of the $\beta$ model, we integrate out to both $R_{\text{max}}$ and $R_{\text{200}}$ the latter case being similar to the assumptions of Melin et al. (2006), who integrated out to $10 R_e$ (see below).

A comparison between $y_{\text{int}}(<R_{\text{max}})$ calculated in the above mentioned way and the SZ calculated from the $\beta$ model alone out to the $R_{\text{max}}$ will then highlight the role of CC in boosting the SZ signal.

2.3 Detection limit

The detection of a cluster in a SZ map not only depends on its flux, but also on its extension on the sky and the characteristics of competing signals. These quantities, then, should be coupled with the filtering method chosen to locate the cluster in a SZ map and for reconstruction of the signal. The selection function will be a product of all these factors. In this work we make use of the limits calculated by Melin et al. (2006) by means of their multifrequency matched filter applied on Monte Carlo simulated maps.

It suffices to say that Melin et al. assumed an isothermal $\beta = 0.66$ model profile out to $100 \, \rho_o$ as the filter template for the SZ signal, where only the core radius $\theta_c$ is free to vary, and tested the performances of several instruments. Here we make use of their results (c.f. their fig. 2) to quantify the fraction of our clusters that exceed a given sensitivity limit. In particular, Melin et al. (2006) show their...
filter noise in terms of integrated SZ flux as a function of the cluster core radius. The curves in their fig. 2, thus, show the minimum signal that a cluster must emit in order to achieve a signal-to-noise ratio (S/N) = 1, given its core radius, a chosen instrument and, of course, using the filtering scheme proposed by Melin et al. (2006). In the following we will always refer to the signal needed to attain S/N = 5. This is a conservative estimate of sensitivity limit for a detection of a given instrument. We note that lowering the S/N threshold to 1 will consequently increase the number of clusters that can be detected and reduce the minimum cluster mass that an instrument can probe. In real life, instead, things are much more complicated and other factors can decrease the performances of an instrument. For the Planck case, Leach et al. (2008) note that many of the recovered clusters are to be considered resolved, and thus emit on scales where the contamination from cosmic microwave background (CMB) is not negligible. Moreover, small-scale Galactic emission and the background of extragalactic sources further complicate the detection when included in the simulations. Therefore, it seems likely that previous estimates of the detection threshold (including Melin et al.’s one that we adopt) should be revised upward by a factor of 3–5 (Melin et al., private communication). It is important to note that, for a survey like Planck, the sensitivity is much less affected by the angular extension of the sky than for the high-resolution case (SPT). The ACCEPT cluster distribution is not representative of the number counts of clusters above a given mass (see e.g. Hallman et al. 2007). An accurate study should take into account that a larger number of relatively massive clusters is expected at redshifts higher than the typical ACCEPT redshift. In Section 3.2 we will present a case in which we randomly assign the ACCEPT clusters a higher redshift in order to assess this issue. Here we mention that, in this latter case, $\theta_c \ll$ instrument resolution and the cluster detection threshold decreases and tends to the point source case.\footnote{Defined in the Melin et al. (2006) case as the y-axis intercept of their selection functions, cf. their fig. 2.} According to Melin et al., such a detection limit is lower than the extended source case because of the lower noise associated to the smaller area covered by the cluster. Therefore, we will also present cases for the point-source detection limit with the aim of illustrating how the variation in the apparent dimension of the core changes the detectability of the clusters.\footnote{Note that we do not change the cluster redshifts here.}

### 3 RESULTS

#### 3.1 Overall results

We first compute how many clusters of our sample can be detected (given their mass, SZ signal and angular extension) by SPT and Planck. We wish to stress that an exact determination of the limit mass for cluster detection by different instrument is not the main scope of the paper, because of the adopted cluster sample characteristics and the fact that we make use of just one detection method (with its selection function) that may not be optimal. The values that we will discuss below, instead, should be taken as the mass at which we focus our study on the CC bias.

In Fig. 5 we present the number of clusters with mass larger than $M$ as a function of $M$ in the ACCEPT sample (solid black curve) and compare it with a similar curve made for all clusters whose SZ signal exceeds the detection threshold (dashed line). We also extract the number of NCC clusters that can be observed (dotted-dashed line). In particular we present two cases (point-source limit and extended source) for the two different surveys (high resolution – SPT and low resolution – Planck). In the bottom part of each panel – below the horizontal light solid curve – we show the ratio of detected cluster with mass above $M$ to the cumulative distribution for the entire ACCEPT sample as a dashed line. The corresponding fraction of NCC clusters is shown as a dashed-dotted line. The vertical dotted line marks the mass below which the detection loses more than the 10 per cent of cumulative distribution of the objects. Note, however, that we will define the limit mass for the detection when the fraction of clusters in a given mass bin falls below 90 per cent.

Similar plots can be obtained if we perform the integration of the pressure profile out to $R_{500}$ or when for integration of the $\beta$-model profile over $10\theta_c$ (as in Melin et al. 2006). In general, in the point-source approximation SPT recovers all the clusters above $\sim 2 \times 10^{13} M_\odot$, whereas when the dimensions of the clusters are considered the reconstruction can be considered more than 90 per cent complete over $10^{14} M_\odot$. Again, we stress that an exact determination of completeness levels of different surveys is beyond the scope of the paper. However, our findings are in line with expectations from a more thorough assessment of the instrument performances (e.g. Bartlett 2006) that took properly into account the number of cluster expected and recovered in a given volume of the universe.

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**Figure 4.** Comparison between the integrated Compton parameter at $R_{\text{max}}$ i.e. obtained by direct integration of the profiles coming from X-ray data and the extrapolated values at $R_{500}$ and $R_{200}$ (see text for details). The dotted line is the 1:1 relation to guide the eye. The dashed line gives the median offset from the 1:1 relation.
Figure 5. Number of clusters with mass larger than $M$ as a function of $M$ in the ACCEPT sample (solid black curve), compared to the number of clusters with mass larger than $M$ whose SZ signal exceeds the detection threshold (dashed line). We also extract the number of NCC clusters that can be observed (dotted–dashed line). In particular we present two cases (point-source limit and extended source) for two different surveys (high resolution – SPT and low resolution – Planck). In the bottom part of each panel – below the horizontal light solid curve – we show the ratio of detected cluster with mass above $M$ to the cumulative distribution for the entire ACCEPT sample as a dashed line. The corresponding fraction of detected NCC clusters with respect the total number of ACCEPT clusters is shown as a dashed–dotted line. The vertical dotted line marks the mass below which the detection loses more than the 10 per cent of objects with respect to the total sample.

The point-source limit emphasizes how the finite and non-negligible dimensions of the clusters impact the detection threshold.

In the case of Planck, instead, the performances are such that it will recover most of the clusters above $\sim 3 \times 10^{14} M_\odot$. This is not unexpected, since Planck is likely to miss a certain fraction of relatively massive clusters due to its resolution, as shown by e.g. Leach et al. (2008). In particular, we refer to this paper – and references therein – and Melin et al. (2006) for a more accurate description of the completeness of a cluster survey based on Planck’s results. We stress, however, that even if our sample is not complete and it is not representative of the volume of the universe that can be probed by a survey like Planck, the results that we get in our simple approach are consistent with more detailed calculations. Furthermore, we double-checked that the ACCEPT mass distribution (Fig. 2), that peaks at $\sim 5 \times 10^{14} M_\odot$, does not introduce some bias around this mass.

We present the analogous of Fig. 5 for the HIFLUGCS subsample (Fig. 6). The performance estimates given above are substantially unchanged. The fraction of recovered NCC clusters with respect to the (either ACCEPT or HIFLUGCS) total sample does not change, implying that the bias in the recovery of NCC clusters that we will discuss in the next section is not due to some feature of the ACCEPT sample nor to the fact that it is not a flux limited cluster sample. From the HIFLUGCS subsample we infer that the minimum mass of the clusters that can be detected (extended source case) for SPT is $\sim 0.8 \times 10^{14} M_\odot$, the minimum X-ray luminosity is $0.3 \times 10^{44} \text{erg s}^{-1}$ and the minimum temperature 2.1 keV. If we limit ourselves to the CC clusters the minimum X-ray luminosity is somewhat higher, being $0.6 \times 10^{44} \text{erg s}^{-1}$ and possibly corresponding to the fact the CC clusters are on average more luminous than NCC clusters at a given temperature. As far as Planck is concerned, instead, the minimum mass is $\sim 10^{14} M_\odot$, the minimum X-ray luminosity is $0.7 \times 10^{44} \text{erg s}^{-1}$ and the minimum temperature 2.8 keV. Again, if we limit ourselves to the CC clusters, the minimum X-ray luminosity is somewhat higher, being $0.8 \times 10^{44} \text{erg s}^{-1}$.

We wish to remind the reader that the ACCEPT catalogue is neither flux limited nor volume limited. According to Cavagnolo et al. (2009), since ACCEPT clusters come from a large number of observing programs, it is quite unlikely that it is biased toward a particular class of clusters. However, CC clusters are preferentially high surface brightness systems, so we cannot exclude that they are over-represented even when we limit us to the HIFLUGCS subsample. For instance, optical selection in groups (Rasmussen et al. 2006) hints toward a different picture than the X-ray selection, in that the fraction of high X-ray surface brightness systems diminishes. However, groups are below the detection limit of SZ surveys.
If this were the case also for clusters (Popesso et al. 2007), instead, we should expect that the effect of CCs in SZ cluster surveys is smaller than found here. A closer look at the X-ray underluminous optically selected clusters (Popesso et al. 2007; Dietrich et al. 2009) shows that either the mass derived from optical measurements has been overestimated, or suggests that these clusters may be still accreting mass and gas from filaments (Bower et al. 1997). In this latter case, the density and the temperature of the ICM are not high enough to lead to a detection in X-ray. Such a lack of detectability will be presumably similar (or even stronger, given the linear dependence of the density) in a SZ survey. While lensing surveys (e.g. Richard et al. 2010) may shed light on the mass distribution within the cluster and provide mass-limited catalogues, the combination of UV/optical with X-ray/SZ surveys will certainly allow us to make a more quantitative assessment of the incidence of CC/relaxed systems (see also Section 4.2.3).

3.2 Search for a possible bias due to the presence of CC

From the results of the previous section, it is clear that each survey is capable of detecting almost all the clusters above a given limit. We now turn our attention to what happens near this limit and, in particular, if there is some bias induced by the presence of CCs. The effect that we expect is multifold: (i) the CC increases the SZ signal (see Introduction); (ii) CC clusters tend to have smaller core radii, therefore they are also favored if the cluster detection technique has a selection function whose threshold increases with the extension of the cluster core radius (measured in terms of multiples of the core radius as in Melin et al. 2006); (iii) if there is not an a priori knowledge of the cluster mass, this will be derived by the SZ. Therefore CC clusters with a mass below the nominal mass of the instrument can make it to be observed and they will be assigned a higher mass if their CC status is not recognized.

We limit our investigation on the first one. In Fig. 7 we show the relation between $y_0$ (or $y_{\text{int}}(R_{500})$) and the cluster mass in the entire ACCEPT sample. The horizontal lines give the S/N = 1 and 5 detection limits for both SPT and Planck. Diamonds correspond to CC clusters above the lowest of these thresholds. For the sake of simplicity we use the point-source detection threshold in order to emphasize only the effect that the CC has on the predicted SZ signal. From the bottom panel we infer a clear effect of the CC on $y_0$: at a given mass, the clusters that display the highest $y_0$ are CC. We thus validate the suggestions by McCarthy et al. (2003a) on a much larger sample of clusters than in the McCarthy et al. (2003b) paper. Were the detection based on $y_0$ we should expect a non-negligible bias due to the presence of CCs. On the other hand, the effect begins to be washed out already at 1 arcmin. Moreover, the scatter increases, simply because the clusters are at different redshifts, therefore the fixed aperture of 1 arcmin probes differing physical distances.

In Fig. 8 we plot the fraction of clusters in a given mass bin whose $y_{\text{int}}(R_{500})$ reached the S/N = 5 threshold for extended sources in both SPT (upper panel) and Planck (lower panel) survey as solid lines. Dot-dashed lines refer to the case in which we use the SZ signal from the $\beta$-model integration for all CC clusters in an effort to mimic the case in which all clusters were NCC. We focus on
the mass range at which the rate of detections from the two surveys under study begins to decline. One can clearly see that the exclusion of CC regions from clusters will lower the number of detected clusters. The effect is around the 20 per cent, for the SPT case getting larger and larger at lower masses, whereas it is lower and more or less constant with for Planck, probably because of the lower resolution of the latter instrument. A more precise estimate of the CC bias that does not rely on a fitted \( \beta \) model can be derived by counting the number of detected NCC clusters and comparing it to the expected one. In each panel, the dotted line refers to the ratio of NCC in a given mass bin to the number of clusters in ACCEPT in the same bin, namely the \textit{true} NCC fraction.\(^5\) The dashed line, instead, gives the same ratio, but for the NCC that exceed the sensitivity threshold with respect to the number of ACCEPT clusters \textit{observed} in that mass bin: this is the \textit{observed} NCC fraction. We note that the \textit{observed} fraction tracks the true one at high masses, for both experiments, and then is reduced when the overall performances of the instruments decrease and starts to be significant. We obtain a bias of 5–15 per cent, with a mass evolution that tracks the one given the dot–dashed versus solid curves. This confirms what we saw in Fig. 7 in the case of the point-source limit: at a given mass (near the \textit{limit} mass) CC clusters are more likely to be detected. A sample including more massive clusters than ours is probably needed to carefully assess the bias in this Planck case.

As noted in the previous section, the X-ray selection may yield artificially higher fractions of CC clusters. The fraction of CC clusters in ACCEPT is 40 per cent, somewhat lower than the typical \( \sim 50–60 \) per cent reported in the literature (Peres et al. 1998; Chen et al. 2007), and decreases at masses above \( 4 \times 10^{14} \, M_\odot \) down to the 26 per cent, in agreement with both numerical simulations (e.g. Burns et al. 2008) and observations (e.g. Chen et al. 2007). Therefore our results should be robust as far as the Planck case is concerned. At lower masses the fraction of CC clusters is more uncertain. Therefore, for the SPT case, we make the exercise of randomly replacing nearly half of CC clusters in the mass range \( 0.5–1.5 \times 10^{14} \, M_\odot \) with NCC, bringing the fraction of CC clusters in this mass range down to the 33 per cent. In particular, the randomly chosen CC clusters have been assigned a SZ signal calculated only from the \( \beta \)-model profile. We find that the bias is still present and has a mass dependence similar to what shown in Fig. 8 (upper panel). The amount is accordingly smaller, however, being around 5 per cent at \( \sim 1 \times 10^{14} \, M_\odot \).

Another potential concern is that our sample of clusters covers a range in redshift that is not representative of the expected massive cluster redshift distribution for the current cosmology (e.g. Halmann et al. 2007). We present in Fig. 9 (upper panel) the equivalent of Fig. 8 for the case in which all clusters are artificially set at \( z \sim 0.5 \). In particular, the clusters more massive than \( \sim 10^{14} \, M_\odot \) are distributed according to \( dN/dz \) calculated by Halmann et al. (2007) for the Wilkinson Microwave Anisotropy Probe (WMAP) 3 yr cosmological parameters. We show the new redshift distribution in the lower panel of Fig. 9. We did not change either the physical dimensions or the mass of these clusters. However, being the SZ effect integrated on the angle, if all the ACCEPT clusters were at much higher redshift than they really are their integrated signal over the solid angle will be lower. Therefore, a sharp decrease in the performances of the surveys is expected and the minimum recovered mass is higher than in the fiducial case. Moreover, their \( \theta_e \) are accordingly smaller. Since the Melin et al. detection threshold depends on \( \theta_e \), the net effect

\(^5\)The \textit{true} CC fraction is simply 1 – the \textit{true} NCC fraction.
Cool core clusters and SZ effect

4 DISCUSSION

In this section we first discuss some potential implications of the bias in SZ-only cluster detection induced by CC. We also suggest possible diagnostic tools to understand and pinpoint CC clusters in SZ surveys by means of a multiwavelength approach. Finally, we discuss the implicit assumption of a non-evolution of the CC cluster fraction with time that is behind the results presented in the previous section and argue that a multiwavelength approach can have a more general use, for instance to study the evolution of the CC fraction.

4.1 The bias in the mass estimate

Several cosmological applications in which SZ-only cluster surveys are employed need an accurate assessment of the cluster mass – SZ signal relation. Either this relation is calculated from locally calibrated relations (e.g. Morandi et al. 2007; Bonamente et al. 2008) or it is derived from the self-calibration approach (e.g. Majumdar & Mohr 2004), it is important to understand whether the presence of CCs could bias such an estimate. From the previous sections we understood that, especially around the limit mass of the instrument, CC clusters are more likely to be detected than NCC clusters. As an example, a linear fit to our calculated SZ signal for clusters at $z < 0.1$ and above $2 \times 10^{14} M_{\odot}$ would return $\log (y_{\text{int}}(< R_{500})) = 1.86 \log M_{500} - 29.4$ with a standard dispersion of 0.26, whereas if we use the limit the analysis to CC clusters we get $\log (y_{\text{int}}(< R_{500})) = 2.02 \log M_{500} - 31.9$ with a standard dispersion of 0.5, namely the presence of CC steepens the relation, lowers the normalization and induces a larger scatter. Observations (e.g. Morandi et al. 2007) have emphasized that a lower normalization is needed when the cluster sample comprises only CC clusters. We stress that this is due to the steeper relation obtained for CC clusters only. Our findings also hold at redshifts above 0.1.

A similar behaviour can be shown to hold when one considers the $y_{\text{0}}$–mass relation and the $y_{\text{int}}(<1 \text{ arcmin})$–mass relation (see Fig. 7). The above example means that it is likely to have CC clusters with a SZ signal a factor of $\sim 2$ higher than the mean value at their given true mass. If we tried to assign to such a cluster an observational mass by using the log ($y_{\text{int}}(< R_{\text{max}})) - \log M_{\text{500}}$ relation derived for the entire sample, we would obtain that $M_{\text{obs}}/M_{\text{true}} \sim 1.2$, namely we overestimate the mass by $\sim 20$ per cent. Therefore the presence of CC may induce a ‘leak’ of clusters with true masses around the limiting mass of the instrument towards higher masses and, at the same time, an inclusion in the observational sample of systems with a mass slightly lower than the cut-off mass that without CC would not be observed.

We recall the reader that a more thorough exploration of the consequences of the CC bias in the recovered mass function would require a starting sample that follows either a theoretical or an observational cluster mass function. As it can be seen from Fig. 2 this is not the case for our sample.

4.2 How to recognize the presence of the CC?

4.2.1 The case of SZ observations only

In the previous section we argued that the presence of CC clusters can bias the SZ-based cluster detection at masses near the limit mass of the instrument. It is, therefore, important to understand how to estimate if such a bias is present in blind SZ surveys. Interestingly, as

Figure 9. Upper panel: fraction of clusters in a given mass bin that reach the S/N $= 5$ threshold for extended sources in both SPT (upper panel) and Planck (lower panel) survey (solid lines) in the case in which all clusters are assumed to be at $z \sim 0.5$ (lower panel, see text). Symbols as in Fig. 8.
shown in Fig. 10 for clusters in the mass range $2-4 \times 10^{14} M_\odot$ (i.e. at nearly the limiting mass for a 90 per cent complete reconstruction of the cluster population), the ratio between $y_0$ and $y_{\text{int}}(<1\text{arcmin})$ anticorrelates with the central cooling time. In particular, for NCC clusters (i.e. those with central cooling time above 1 Gyr), this ratio is always below $-0.3$, whereas for most of CC clusters is larger than $-0.3$. The plot of Fig. 10 can thus be used as a rough diagnostic for the presence of CCs when only SZ observations are available. In particular, a value of $\log (y_0/y_{\text{int}}(<1\text{arcmin}))$ above $-0.3$ should warn the observer that that particular cluster might feature a CC and call for follow-up observations. A similar relation hold when considering the ratio between $y_0$ and $y_{\text{int}}(< R_{\text{max}})$, albeit with a larger scatter. Other observational works (e.g. Morandi et al. 2007) have noticed that the ratio $y_0/y_{\text{int}}$ tend to be higher in CC clusters but did not show any direct evidence of the link with the ICM thermal status. $y_0$, however, is not directly observed, because current SZ instruments have a much lower resolution. Therefore, we expect the CC effect to be blurred in the observed ratio $y_0/y_{\text{int}}(<1\text{arcmin})$. In fact, $y_0$ can only be reconstructed from the observed signal, often assuming a $\beta$ model, and the result might strongly depend on the assumed intracluster gas profile (e.g. Benson et al. 2004). Interestingly, our finding still holds when considering ratios at different radii. For instance, the presence of the CC is still evident at half the FWHM of current high-resolution instruments like SPT, i.e. at 0.5 arcmin, even if $y_0$ cannot be directly observed. Therefore, we suggest a ratio like $y_{\text{int}}(0.5\text{arcmin})/y_{\text{int}}(R_{\text{max}})$ as a proxy for the $y_0/y_{\text{int}}$ diagnostic of Fig. 10. In this sense, we require next generation instruments to have a minimum resolution of 0.5 arcmin in order to rely on SZ-only based surveys to understand whether their derived mass function have a bias induced by CCs.

4.2.2 X-ray follow-up

Dubious cases can then be assessed if one has either follow-up or archival X-ray observations. The cases of in which spectra are available – where a direct estimate of the cooling time is possible – will probably be just a handful. With X-ray imaging data only, the presence of the CC at high redshift can be the confirmed by using the ‘cuspiness’ of the gas density model fitted to the X-ray surface brightness (Vikhlinin et al. 2006, for a different definition see Santos et al. 2008). In particular, Santos et al. (2008) derive a power-law relation between the cooling time and an empirical surface brightness concentration index valid out to redshift $\sim 0.9$, which can be easily combined with the results of our Fig. 10. They do not find a correlation between the concentration index and the presence of a dominant galaxy. As we will see in the next section, there is indeed a relation, but observations at other wavelengths are needed to make it applicable to the investigation of the CC presence.

4.2.3 UV and optical follow-up

For SZ cluster surveys involving a large number of clusters, instead, a cross-correlation with optically selected clusters can be more beneficial and more effective than the X-ray follow-up. Several recent studies have reported examples of ongoing star formation in the BCGs (see Introduction). In particular, it seems that up to the 25 per cent of the BCGs had optical blue cores (Bildfell et al. 2008), that in many cases render the entire galactic light bluer than the observed red sequence (Bower, Lucey & Ellis 1992).

Therefore, if CCs make a cluster more visible in the SZ signal, the converse is true for the optical search based on the red sequence, likely to miss blue BCGs and, hence, CC clusters. We thus suggest that a way to enhance the presence of CC clusters is by cross-matching SZ-based cluster surveys with optical and UV ones in order to find clusters with a higher than average SZ signal that host unusually blue BCGs.

As an example, if the portion of the sky surveyed in SZ overlaps with the region observed by the SDSS, one can make use of existing optical cluster catalogues (Szabo et al., in preparation). In particular, Szabo et al. catalogue is based on a matched-ﬁlter technique applied to the Sloan Digital Sky Survey Data Release 6 (SDSS DR6). It comprises of approximately 74 000 cluster of galaxies with richness$^7$ above 20 and has been tested to include also blue BGGs. As shown by Pipino et al. (in preparation), this cluster/BCG catalogue is not affected by the colour bias and can potentially be coupled to SZ surveys to conﬁrm the presence of CCs. In such a catalogue, nearly the 15 per cent of BCGs in clusters with richness 30 is well below (i.e. bluer than) the red sequence at their given redshift, and likely to be missed by red galaxy search only. Remarkably this happens in the 10 per cent of the richest clusters (i.e. richness above 50), which will be surely observed in SZ survey. By using the richness-temperature relation derived by Szabo et al. (in preparation) and the mass–temperature adopted in this paper, a richness of 50 roughly corresponds to a mass of $\sim 10^{14} M_\odot$, namely where the CC bias seems to be most effective (see previous sections). We expect the clusters hosting very blue BCGs to harbour the strongest CC and thus to be the ones that deviate more from the $y_{\text{int}}$–mass relation. From the BCG analysis, we derive that the blue BCG fraction remains constant in the redshift range 0.1–0.4. In the same redshift range the CC fraction seems to stay constant as well around the value of 50 per cent (e.g. Bauer et al. 2005). Therefore, the cross-matching of SZ and optical surveys can emphasize 1/5 of the CC clusters, presumably the strongest ones.

In reality, the recent star formation creates blue cores which not necessarily affect the entire optical colour of the galaxy. None the less, it could be enough to make the galaxy blue in the UV–optical colours. Indeed, Pipino et al. (2009a) showed a one to one correspondence between blue cores and UV–optical colours for a limited number of BCGs. Here we assume that this link applies to the entire population of BCGs. Both ways to infer the presence of a CC hold true in the ACCEPT sample for the clusters which have a counterpart in the Szabo et al. catalogue (Pipino et al., in

$^7$Measured as the total luminosity in the $r$ band within $R_{200}$ in units of $L^*$. 

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Figure 10. Ratio between $y_0$ and $y_{\text{int}}(<1\text{arcmin})/\text{arcmin}^2$ versus central cooling time for clusters whose mass is in the range $2-4 \times 10^{14} M_\odot$. 

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In our specific case of the ACCEPT sample, a cross-match between the Szabo et al. catalogue returns 68 clusters in common. In Pipino et al. (in preparation) we show that optically blue BCGs are hosted by CC clusters. In particular, the NUV-r colour correlates with the excess entropy of these clusters: the smaller the NUV-r colour, the lower the entropy and the shorter the cooling time. In this way it will be possible to pick up CC clusters that cannot be detected or confirmed by means of the optical colours only. We refer the reader to Pipino et al. (2009a, in preparation) for a more detailed discussion on the colours of the BCGs in relation to the state of the intracluster medium of the host cluster. Here we show (Fig. 11) how the NUV-r colours of the BCGs can be a proxy for the ratio $\nu_0/\nu_{\text{int}}$. Unfortunately only a limited number of BCGs in clusters with mass above $\sim 2 \times 10^{14} M_\odot$ has both SDSS and Galaxy Evolution Explorer (GALEX) imaging. However, we can clearly see that UV–optical blue galaxies, namely those with NUV-r below 4 (asterisks encircled by a diamond), stand out in a region of relatively high values for the ratio $\nu_0/\nu_{\text{int}}$, whereas more normal galaxies tend to have a lower $\nu_0/\nu_{\text{int}}$. BCGs on the NUV-r red sequence (i.e. those with NUV-r above 6) display the lowest values for $\nu_0/\nu_{\text{int}}$. If BCGs undergo pure passive evolution at redshifts below $z = 1$, and taking into account the GALEX Medium Imaging Survey (MIS) magnitude limit (Martin et al. 2005), we expect to easily detect UV–blue BCGs out to $z \sim 0.6$ with current instruments. Moreover, if the GALEX MIS were continued and extended to have a larger overlap with, e.g. SDSS, we might be able to (i) confirm the findings of Fig. 11 on the basis of a larger number of BCGs and (ii) probe the region where recent observations suggest a strong decline of the CC fraction (see below).

### 4.2.4 Hα, IR and radio follow-up

The ACCEPT catalogue is complemented by Hα and radio luminosities associated to the BCGs in roughly half of the total sample. As for the former, they are derived from a number of sources (Crawford et al. 1999; Cavagnolo et al. 2008b, 2009 and references therein) and several apertures that do not reflect the actual full Hα flux from the galaxy. The latter measurements, instead, come from the NRAO VLA sky survey and the Sydney University Molonglo sky survey (refer to Cavagnolo et al. 2008 for further details and references). Indeed, Cavagnolo et al. (2008, see also Donahue et al. 2005) showed that below the entropy threshold of 30 keV cm$^2$, both the Hα and the radio emission suddenly switches on, whereas galaxies in clusters above that limit are quiescent and only upper limits are detected. In practice, such as emission can be either traced back to the recent star formation or to the active galactic nucleus (AGN) feedback (Edwards et al. 2009). Edwards et al. (2007) further showed that Hα emission, while present in 20 per cent of the entire population BCGs, systematically appears in BCGs bluer than expected. In this section we make use of the above findings and of the luminosities provided in the ACCEPT data base to suggest other diagnostic tools to infer the presence of a CC. In particular, in Fig. 12, we show the ratio between $\nu_0$ and $\nu_{\text{int}}$ versus the Hα luminosity as provided in the ACCEPT data base. The arrows are upper limit on the luminosity and typically they represent clusters with entropy above 30 keV cm$^2$. The solid line is a linear regression fit to the points (excluding the upper limits). We find that $\log (\nu_0/\nu_{\text{int}} < l \text{ arcmin})/\text{arcmin}^2 \sim 0.2 \log L (H\alpha)$. While a proper estimate of the slope of such relation would require a careful assessment of the aperture effects in the Hα measurements, our finding emphasizes the fact that Hα emission is a clear indicator of low $K_0$ and, hence, a strong CC status. Since Hα emission is detected in one quarter of the clusters (Crawford et al. 1999), as opposite to the 10 per cent of clusters hosting optically blue BCGs, such information is helpful to confirm the CC status in a wider range of cases than the cross matching process with optical surveys. The drawback of such proxy for the CC is that requires either spectral information or narrow-band imaging, whereas large surveys as the SDSS adopt larger bands for imaging and do not have spectral information for all the detected sources.

Interestingly, O’Dea et al. (2008) showed a correlation between IR emission measured by the Spitzer mission and literature Hα emission in BCGs, both being caused by star formation in most of the cases. Since O’Dea et al. (2008, see also Egami et al. 2006) show an anticorrelation between IR luminosities and cooling time, we do not repeat the exercise here and take their findings as corroborative to our argument.

Similar considerations apply to the radio luminosities (Fig. 13, see also Mittal et al. 2009). In this latter case the relation is flatter, being $\log (\nu_0/\nu_{\text{int}}) \sim 0.1 \log L (\text{radio})$, and exhibits a larger scatter than in the former. Incidentally, we note that radio sources associated with BCGs seem to have a steeper spectral index than sources.

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**Figure 11.** Ratio between $\nu_0$ and $\nu_{\text{int}}/\text{arcmin}^2$ versus the NUV-r colour for BCGs in clusters where combined SDSS and GALEX photometry is available (asterisks) above a mass of $\sim 2 \times 10^{14} M_\odot$. Blue galaxies hosted in CC clusters are emphasized with the diamond symbol. Note that UV–optical blue galaxies are those with NUV-r below 4.

**Figure 12.** Ratio between $\nu_0$ and $\nu_{\text{int}}/\text{arcmin}^2$ versus the Hα luminosity as provided in the ACCEPT data base. The arrows are upper limit on the luminosity and typically they represent clusters with entropy above 30 keV cm$^2$. The solid line is a linear regression fit to the points (excluding the upper limits).
associated with other cluster members (Lin & Mohr 2007), thus making the detection of the former more robust. However, in the radio case, the fact that the luminosity is presumably associated to the AGN – rather than to recent star formation – implies that the AGN duty cycle cannot be neglected. Moreover, a number of clusters with $K_0$ larger than 30 keV cm$^{-2}$ and an active AGN in the BCG are present in the ACCEP T sample. In a sense, a diagnostic based on the radio is less informative on the recent star formation and the CC status. Another drawback of the adopted radio surveys is that their current resolution is such that at redshift larger than 0.2 it is difficult to assess whether the radio emission is actually linked to the BCG. However, a multiwavelength approach involving UV, optical, IR and radio bands can put firm constraints on the CC status and make emission lines and unusual colours in BCGs unambiguously linked to either recent star formation episodes or AGN activity.

4.3 The effect of the evolution of CC and BCG properties at $z > 0.5$

An important caveat that the reader should bear in mind is that, until this point, we implicitly assumed that the CC fraction does not evolve with time. Indeed, Bauer et al. (2005) presented a comparative study of cool cores at low and intermediate redshift and found no signs of evolution of the cool core fraction in the redshift range 0.15–0.4 to the present time. This corroborates our assumption and makes the method for detecting CC clusters via UV/optical colours presented in the previous sections robust in the redshift range 0.1–0.4. At higher redshifts, where high-resolution SZ surveys are expected to deliver a fraction of clusters, it seems that strong CCs disappear (e.g. Vikhlinin et al. 2007; Santos et al. 2008), therefore the CC-induced bias might quickly vanish accordingly. In particular, while Vikhlinin et al. suggest that the CC disappear at $z > 0.5$, the analysis by Santos et al. indicates a significant fraction of distant clusters harbouring a moderate CC out to $z = 1.4$, similar to the local fraction, and a decrease in strong CC at $z > 0.7$. Both works argue that the absence of strong cooling is likely linked to the higher merger rate expected at these redshifts, and should also be related to the shorter age of distant clusters, implying less time to develop a cool core. The role of mergers in destroying cool cores has long been debated (Fabian et al. 1994), both from observational results and from simulations. Currently, observations seem to favour CC destruction through cluster mergers (Allen, Ettori & Fabian 2001; Sanderson, Ponman & O’Sullivan 2006). Simulations, however, yield ambivalent results: CC can be destroyed by early major mergers according to Burns et al. (2008), whereas Poole et al. (2006) argue that, in the CDM scenario, the merger rate is too small to account for the local abundance of NCC clusters whose disruptions occur on short time-scales. Interestingly, the simulations by Burns et al. (2008) do not show the decrease of CC clusters at $z > 0.7$. Therefore, a quantitative study of the CC evolution in the redshift range 0.5–0.7 is crucial for these studies as well as for understanding the properties of SZ-only selected clusters.

In a sense, we can turn the argument around and suggest that the CC evolution might be independently confirmed by cross-matching SZ-based cluster catalogues with UV/optically/IR selected ones, especially at the high richness end, namely clusters that are detectable out to the highest redshifts. In the previous section we have seen that the fraction of rich CC clusters hosting a blue BCG is around 10 per cent in the redshift range 0.1–0.4. Observational studies (e.g. Stanford, Eisenhardt & Dickinson 1998) suggest that the red-sequence evolution out to redshift 1 is consistent with a pure passively evolution (i.e. no major star formation episodes) and does not depend from the cluster richness or its X-ray properties, especially at the high-mass end (e.g. Bundy, Ellis & Conselice 2005). No evolution in the number density of massive early type galaxies is detected in the same redshift range (e.g. Scarlata et al. 2007). On the theoretical side remarkably either models based on monolithic collapse (e.g. Pipino & Matteucci 2004) or those based on the hierarchical growth of structure (De Lucia & Blaizot 2007; Pipino et al. 2009b) predict basically no major star formation episodes involving BCGs at $z < 1$ and a very mild evolution of the colours. If there is any residual star formation, this must be associated with some ‘cooling flow’ not entirely offset by the heating sources. On example might be the cluster XMMU J1229+0151 (Santos et al. 2009) at $z \sim 1$, where some residual star formation is inferred from emission lines in an otherwise normal (optically red) BCG. Therefore, in the simplest scenario in which BCGs do not undergo mergers at redshift $z < 1$, a complete UV/optical + SZ cluster survey would exhibit a fraction of rich clusters featuring an excess in the SZ signal and a (UV/optical) blue BCG gradually decreasing from the 10 per cent to zero if a CC evolution were in place at $z = 0.5$–1. More accurate predictions, however, require a careful treatment of the colour classification of the BCGs at $z > 0.5$, with a detailed consideration of all evolutionary effects and the errors in the photometry, that are beyond the scope of this paper. Here we just note that the Butcher & Oemler (1978) effect, i.e. the increase with redshift of the fraction of blue cluster galaxies, seems strictly connected to the decrease of the fraction of cluster S0 galaxies with redshift (Dressler et al. 1997; Poggianti et al. 1999; Fasano et al. 2000; van Dokkum et al. 2000; Tran et al. 2005), whereas the fraction of elliptical galaxies – which dominate the central regions of galaxy clusters – does not change. This effect is therefore likely to affect only a minor fraction of the ‘early type’ galaxies as a whole. More important, it seems that the transformation of late-type galaxies into S0 is not restricted to, and possibly even avoids, the cores (see Wilman et al. 2009 in the case of optically selected groups). This seems to be the case of higher redshift clusters, e.g. MS 2053–04 at $z \sim 0.6$ (Tran et al. 2005), in that the properties of the blue cluster members in both the main cluster and infalling structures indicate that they will evolve into low-mass $L < L_{\ast}$ galaxies with extended star formation histories like that of low-mass S0 galaxies in Coma, making us confident that the properties of the BCG will not be affected.
5 CONCLUSIONS

We used the high-quality pressure profiles of 239 galaxy cluster made available by the ACCEPT project (Cavagnolo et al. 2009) in order to derive the expected SZ signal in a variety of cases that hardly find a counterpart in the simulations. We made use of the Melin et al. (2006) estimates for the detection threshold in the cases of point-like and extended sources for the SPT and the Planck instruments. Prior knowledge of the entropy profiles of the same clusters allows us to study the impact of CC in cluster detection via SZ experiment and to test if this might introduce a bias in inferred quantities as e.g. the cluster mass function.

We infer a clear effect of the CC on $y_0$. We thus validate the suggestions by McCarthy et al. (2003) on a much larger sample of clusters. For a high-resolution experiment like SPT, we expect that the fraction of detected clusters with respect to the total to decline at masses around $\sim 2 \times 10^{14} \, M_\odot$. For Planck this happens at a somewhat higher mass. We found that the presence of CC introduces a small bias in cluster detection, especially around the mass at which the performances of the survey begins to significantly decrease. If the CC were removed, a lower overall fraction of detected clusters would be expected. In order to estimate the presence of such a bias by means of SZ and X-ray observations, we show that the ratio $y_0/y_{\text{X-ray}}$ anti-correlates with the central cooling time. If multiband optical cluster surveys are either available for a cross-match or a follow-up is planned, we suggest that likely CC clusters are those with a BCG at least 0.3 mag bluer than the average. Using the Szabo et al. (in preparation) SDSS DR6 cluster catalogue, we estimate that this should happen in at least the 15 per cent of rich clusters. A more robust estimate of the CC presence is given by UV–optical colours, like the NUV-r, whose values can be 4 mag off the NUV-r equivalent of the red sequence, in clusters with low excess entropy. We argue that the analysis of a combined SZ/optical/UV survey can be also used to shed light on the suggested CC evolution with redshift.

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