The MUSIC of Galaxy Clusters – III. Properties, evolution and $Y$–$M$ scaling relation of protoclusters of galaxies

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ABSTRACT

In this work, we study the properties of protoclusters of galaxies by employing the Multi-Dark SImulations of galaxy Clusters (MUSIC) set of hydrodynamical simulations, featuring a sample of 282 resimulated clusters with available merger trees up to $z = 4$. We study the characteristics and redshift evolution of the mass and the spatial distribution for all the protoclusters, which we define as the most massive progenitors of the clusters identified at $z = 0$. We extend the study of the baryon content to redshifts larger than 1 also in terms of gas and stars budgets: no remarkable variations with redshift are discovered. Furthermore, motivated by the proven potential of Sunyaev–Zel’dovich surveys to blindly search for faint distant objects, we compute the scaling relation between total object mass and integrated Compton $y$-parameter. We find that the slope of this scaling law is steeper than what expected for a self-similarity assumption among these objects, and it increases with redshift mainly when radiative processes are included. We use three different criteria to account for the dynamical state of the protoclusters, and find no significant dependence of the scaling parameters on the level of relaxation. We exclude the dynamical state as the cause of the observed deviations from self-similarity in protoclusters.

Key words: methods: numerical – galaxies: clusters: general – cosmology: miscellaneous – cosmology: theory.

1 INTRODUCTION

The formation of today’s large-scale structures, from massive clusters to smaller groups of galaxies, starts from high-redshift overdensities lying along the dark matter (DM) filamentary structure known as the cosmic web. In the early phases of their evolution, these objects are characterized by relatively smooth peaks in the spatial distribution of DM and galaxies, and grow into denser and larger concentrations of DM, gas and galaxies at later epochs. Therefore, by systematically searching for protoclusters, and studying their dynamics, evolution and abundance as a function of mass and redshift, it is possible to explore the high-$z$ stages of the assembly of present-day clusters, and possibly to shed light on the processes which affect the growth of structures on the tail of the halo mass function (MF) just as they shape from small overdensities, on the verge of virialization, into the largest, most massive bound objects in the Universe. The evolution of the halo MF puts constrain on $\Omega_m$ mass and redshift up to the very early stages of their assembly.

Currently, many observational and theoretical issues impose critical limitations to these kinds of studies: distance limits the quantity and accuracy of available observations of these objects. Several direct and indirect approaches have been tried to perform systematic searches of protoclusters in the high-$z$ universe, but none of them has been proved to be generally successful and therefore none has been employed for systematic protocluster searches up to now (see Section 2 for a review of current observing methods). A reliable observational proxy for their total mass, which assumes an insight of the structure assembly at high redshift and a proper validation of available proxies, as with low-$z$ clusters and groups, due to the necessity of exploring the mass distribution of protoclusters. Following the same approach of cluster studies performed up to redshift 1 (Sembolini et al. 2013), in this work we explore the possibility to observe protoclusters through the detection of their thermal Sunyaev–Zel’dovich (th-SZ, Sunyaev & Zeldovich 1970) imprint into the cosmic microwave background (CMB). Due to the lack of dimming of the scattered CMB photons off ionized gas in the high-$z$ haloes, and to the uniqueness of its spectral signature at mm/submm wavelengths, th-SZ effect appears as a viable tool for high-$z$ object-finding, as proved from the success of blind cluster surveys from

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the current generation of millimetre telescopes (Staniszewski et al. 2009; Marriage et al. 2011; Planck Collaboration et al. 2011, 2013a; Williamson et al. 2011; Reichardt et al. 2013). In principle, the high angular resolution and the sensitivity needed to provide reliable SZ detections of farther, fainter, less evolved objects should be at hand, thanks to the upcoming generation of instruments like Mustang2, ALMA, CCAT, SPT3G (among others) or satellite missions like Millimetron1 or the proposed PRISM2 (PRISM Collaboration et al. 2013).

Within a self-similar scenario of structure formation, a tight correlation between an aperture-integrated th-SZ signal (which is a measure of the total thermal energy of the hot gas in a large virialized structure) and the total mass $M$ of the object, is expected. For clusters and groups, this scaling law and its small deviations from self-similarity have been studied through semi-analytical approaches (e.g. Shaw, Holder & Bode 2008; Sun et al. 2011), simulations of cosmological volumes (Battaglia et al. 2012; Kay et al. 2012; Sembolini et al. 2013) and verified through observations (Bonamente et al. 2008; Marrone et al. 2012; Planck Collaboration et al. 2013a, 2013b; Sifón et al. 2013). In this paper, we verify for the first time the extension of the self-similarity assumption to the progenitors of today’s clusters. For this purpose, we use synthetic objects extracted from a large data set of hydrodynamical simulations of clusters of galaxies: MultiDark Simulations of galaxy Clusters (MUSIC). While the definition of a protocluster is in debate from an observational point of view (details are provided in Section 3), the availability of numerically simulated structures at all the ages up to $z = 4$ may allow us to trace the evolution of clusters back to the formation through the information of the merging tree for each object. This paper complements the analyses of MUSIC simulations started in Sembolini et al. (2013) and Biffi et al. (2014) and it is organized as follows. In Section 2, observational approaches of distant galaxies, assumed as possible progenitors of groups and clusters, are reported. The protoclusters extracted from simulation are described in Section 3, where also the baryons budget is explored in terms of gas and star fractions for different masses and protocluster redshifts. Considerations about the spatial distribution of the progenitors and useful criteria to quantify the virial state of these objects are also treated. The validity of the self-similarity approach, basics for the $Y - M$ scaling law, is verified in Section 4 for objects ranging from $z = 1$ up to $z = 4$. In Section 5, we summarize and discuss our main results.

2 OBSERVATIONS AND SIMULATIONS OF PROTOCLUSTERS OF GALAXIES

In order to investigate when and how clusters are formed, it is necessary to obtain a sample of objects at $z > 1$. In the past decade, there has been a significant increase in the study of clusters at redshifts up to 1, while the difficulty of observing protoclusters of galaxies limits the amount and accuracy of the observations and surveys that are available. In fact, notwithstanding the development of a new generation of telescopes, many observational and theoretical issues impose critical limitations to these kinds of studies. The hindrances in observing protoclusters of galaxies are linked to the relative low angular resolution of the observation instruments used and consequently to the inability to investigate extended structures. Moreover, according to the cold dark matter ($\Lambda$CDM) model, it is extremely rare to find objects with $M > 3 \times 10^{14} M_{\odot}$ at $z > 1$ (Springel et al. 2005) and high-redshift galaxies do not dominate the number counts in surveys. In addition, X-ray emission becomes too faint to be measured since the surface brightness decreases as $(1 + z)^{4}$. Despite these limitations, observations made in the optical/IR wavelengths together with the $XMM–Newton$ have identified an overdensity of galaxies emitting at $z = 1.579$ in the X-ray band (Santos et al. 2011). Another finding in the survey XDCP ($XMM–Newton$ Distant Cluster Project) led to the identification of a low-mass (proto)cluster ($M = 10^{14} M_{\odot}$) at $z = 1.1$, thanks to the multiband observation with the GROUND imager (Pierini et al. 2012). X-ray observations thus make possible to observe groups and clusters at much earlier stages (i.e., $z \geq 1$). However, these surveys still remain subject to the selection effects.

The ability to perform systematic searches of protoclusters in the high-$z$ universe has long been sought after. Various methods have been applied in order to render this possible. High-redshift galaxies can be distinguished from the profuse nearby galaxies due to some peculiar spectral characteristics. Thanks to these features, it is possible to use other methods of detection in order to investigate the universe at high redshift. One of the methods most widely used is targeting high-$z$ radio galaxies (HzRGs). These are massive star-forming galaxies with enormous radio luminosities (Rocca-Volmerange et al. 2004; Seymour et al. 2007; Miley & De Breuck 2008). According to the model of hierarchical galaxy formation, it is possible to find galaxy overdensities around HzRGs (Stevens et al. 2003; Mayo et al. 2012), which should be likely surrounded by cluster progenitors (Venemans et al. 2007; Kuiper et al. 2010; Hatch et al. 2011; Wylezalek et al. 2013).

Recent results were obtained as part of the Herschel Galaxy Evolution (HerGEE) project. A study of the IR spectral energy distribution of the Spiderweb Galaxy at $z = 2.156$ showed that this protogalaxy is in a particular phase implying both of AGNs and starburst (Seymour et al. 2012). Moreover, by combining different studies of the environment of this galaxy, it was possible to identify several protocluster members surrounding the host galaxy, with an estimated mass $\geq 2 \times 10^{14} M_{\odot}$ within a region of 3 Mpc.

Another approach is based on the selection of the Lyman Break Galaxies (LBGs), which are star-forming galaxies at $2.5 < z < 5$ characterized by the Lyman break at 912 Å in the rest frame (Giavalisco 2002). Searching for Lyα emitters is another way to identify galaxy cluster progenitors (Steidel et al. 1998). Star-forming galaxies exhibit strong emissions of this particular line because Lyα photons are resonantly scattered in neutral hydrogen. Using narrow-band imaging, it is possible to search for overdensities of line emitting objects at a specific redshift. Many studies have been conducted using this particular method and have resulted in the discovery of cluster progenitors beyond $z = 3$ (Steidel et al. 2000; Matsuda et al. 2009; Capak et al. 2011; Yamada et al. 2012).

It is also possible to observe star-forming galaxies by detecting their sub-millimetre emission. In fact, the large and negative $k$-correction (Blain & Longair 1993), due to the steepness of the submm-spectra, makes the high-redshift galaxies more detectable than their low-redshift counterparts. It is possible to identify star-forming galaxy at FIR/submm wavelengths, through the detection of dust emission. Studies of radio galaxies have been concentrated on high-redshift objects since their submm luminosity increases with redshift and their emission is in correspondence with the peak of dust emission (Archibald et al. 2001). A population of almost 200 luminous galaxies at $z > 1$ has been revealed through deep surveys in the submm/mm waveband thanks to detectors such as SCUBA, MAMBO and BOLOCAM (Blain et al. 2002).
Thanks to the current ground-based projects (such as ACT, SPT), it is becoming increasingly possible to observe high-$z$ objects while steadily increasing the redshift through the SZ effect. Recently, it has been made possible to detect clusters at redshift greater than 1 via the SZ effect. The SPT-SZ survey allowed the identification of the highest redshift galaxy cluster that was seen via the SZ effect, which is at $z = 1.478$ (Bayliss et al. 2013).

In the last years, also simulations have been started to be used as a tool to study protoclusters. Most of the previous works on this topic applied semi-analytic models to DM-only cosmological simulations: mock catalogues of the Millennium simulation (Springel et al. 2005) have been used to study the abundances, redshift distribution, clustering and star formation rate of high-redshift objects (such as LBGs and distant red galaxies) up to redshift 6, in order to reproduce the observed star formation rates (Guo & White 2009; Overzier et al. 2009; Henriques et al. 2012; Merson et al. 2013). More recently, Chiang, Overzier & Gebhardt (2013) used again the Millennium Simulations to study the progenitor regions of about 3000 objects evolving into clusters at $z = 0$. On the other hand, the use of hydrodynamical simulations to study protoclusters is still not very common in the literature. Saro et al. (2009) used hydrodynamical simulations of two protocluster regions at $z = 2.1$ to compare them with the observational results of the Spiderweb Galaxy system, particularly focusing on the star formation rate and on the velocity distribution of the galaxies. Therefore, it is necessary the use of a large data set of simulated clusters, such as MUSIC, to enlarge the statistics of protoclusters.

3 PROTOCLUSTERS OF GALAXIES
IN THE MUSIC DATA SET

Since it is difficult to prove how and when today’s clusters of galaxies were formed, what is meant by the term ‘protocluster’ from an observational point of view is in debate. As a result, it is particularly important to be able to discriminate in this study all the high-$z$ objects related to present clusters. With this purpose, we define as progenitors all those objects which will merge during the cluster evolution to form and be part, with at least a consistent fraction of their mass (see Section 3.2), of the cluster observed at $z = 0$.

For the purpose of our work, two alternative and general definitions have been used. We assume as a protocluster (Fig. 1):

(i) the most massive halo at high redshift among all the progenitors;
(ii) the ensemble of all the progenitors with a mass larger than a selected value (which depends on limits on the observability or on the resolution of the simulation).

According to this, numerical simulations constitute the ideal tool to define and study protoclusters: in fact, using a merger tree, it is straightforward to trace back at high redshift the particles, and therefore the progenitors, which will end up into a virialized cluster at $z = 0$. This fundamental characteristic allows us to overcome the principal problem found in observations, where it is impossible at present day to be completely confident if a massive object observed at high redshift will actually evolve into a cluster during its history.

To the scope of this work, which is to study some integrated properties of protoclusters, we choose to adopt the first definition of the two aforementioned. Most of the analysis shown in this work is referred to protoclusters, though it is also interesting to make some considerations about all the progenitors in terms of their mass and spatial distributions.

Figure 1. Schematic representation of the two protocluster definitions. In the panels on the left, the red circle confines the protocluster at $z = 4$ according to the first definition (a) and the second (b). In the panel on the right, it is shown the representation of the present-day cluster, which is the main object at $z = 0$, formed during the evolution process of the protocluster (according to both definitions).

3.1 The simulations

The simulations used in this work are part of the MUSIC data set. A detailed description of the MUSIC data set can be found in Sembolini et al. (2013), so in this subsection, we will limit to recall some main characteristics of the simulations and to define the subset that we selected for our analysis. The protoclusters presented in this work have been taken from the MUSIC-2 data set, a mass-selected volume-limited sample of resimulated clusters extracted from the MultiDark (MD; Prada et al. 2012) simulation. From the MD simulation, a DM-only simulation of 2048$^3$ particles in a (1 $h^{-1}$ Gpc)$^3$ cube, all the objects with a total virial mass $M_{\text{vir}} > 10^{15} h^{-1} M_\odot$ at $z = 0$ in the low-resolution version of the simulation were selected and resimulated adding smoothed particle hydrodynamics (SPH) and star particles, plus various radiative processes (including radiative cooling, heating processes of the gas arisen from a UV background, star formation and supernovae feedback).

In total, 282 Lagrangian regions with a radius of 6 $h^{-1}$ Mpc surrounding a massive cluster were resimulated. All clusters were resimulated, with the same zooming techniques and resolution, both with radiative [cooling + star formation (CSF) subset, see Fig. 2] and non-radiative physics (NR subset). The mass resolution for these simulations corresponds to $m_{\text{DM}} = 9.01 \times 10^8 h^{-1} M_\odot$ and to $m_{\text{gas}} = 1.9 \times 10^8 h^{-1} M_\odot$. The parallel TreePM+SPH GADGET code (Springel 2005) was used to run all the resimulations. Among the 15 snapshots describing the evolution of each cluster in the redshift range $0 \leq z \leq 9$, we concentrate on those corresponding to $z = 1.5$, 2.3, 4.0, assuming that at $z \leq 1$ all objects have already evolved into clusters. The analysis shown hereafter is therefore focused on the protoclusters corresponding to the most massive progenitors of the most massive clusters of each of the 282 MUSIC-2 resimulated regions. Among all the massive clusters at $z = 0$, almost 50 per cent have $M_{\text{vir}} > 10^{15} h^{-1} M_\odot$ and almost all $M_{\text{vir}} > 5 \times 10^{14} h^{-1} M_\odot$.

$^3$ Initial conditions and snapshots of MUSIC clusters, plus many images, are publicly available at the webpage http://music.ft.uam.es.
3.2 Mass and spatial distributions of progenitors and protoclusters

As aforementioned, we can use a merger tree to track back in time the cluster history and individuate all the progenitors (including the protocluster) at high redshifts. We use the merger tree of the AMIGA Halo Finder (AHF; Knollmann & Knebe 2009) to select all the high-redshift objects containing particles which will be part of a massive cluster at $z = 0$, and, according to the definition given at the beginning of this section, we individuate as progenitors all those haloes whose at least the 80 per cent of their particles are found to be part of the cluster formed at $z = 0$. Considering that AHF is able to discern all haloes constituted by at least 20 particles, we can list all progenitors with $M > 1.2 \times 10^{10} h^{-1} M_{\odot}$.

It is interesting to study the mass distribution of protoclusters (calculated at the virial radius) to explore the mass evolution with redshift and to compare the mass of protoclusters with that of the other progenitors, in order to check at each redshift whether the protoclusters show already a mass sensitively bigger than the other progenitors. For each halo, the virial radius $R_{\text{vir}}$ is computed, defined as the radius at which the mean internal density is $\Delta_{\text{vir}}$ times the background density of the Universe at that redshift (the value of $\Delta_{\text{vir}}$ therefore depends on redshift too). According to this, the definition of virial mass is

$$M_{\text{vir}} = \frac{4\pi}{3} \Delta_{\text{vir}} \Omega_m \rho_{\text{crit}} R_{\text{vir}}^3.$$  

(1)

In Fig. 3, the distribution of $M_{\text{vir}}$, at the three considered redshifts, is compared with the mass distribution of the evolved clusters at $z = 0$. The mass distributions of protoclusters are almost completely separated among each other at the three different redshift considered (though showing a large dispersion, see Table 1); at $z = 4$ most of haloes have a mass of a few times $10^{12} h^{-1} M_{\odot}$, with only a small number of objects with $M > 10^{13} h^{-1} M_{\odot}$; at $z = 2.3$ almost all objects show masses in the range $10^{13} < M < 10^{14} h^{-1} M_{\odot}$; at $z = 1.5$ we find more than 100 haloes with $M > 10^{14} h^{-1} M_{\odot}$ and that therefore can be also considered as already evolved into clusters (if we define as cluster a virialized halo with $M > 10^{14} h^{-1} M_{\odot}$). In Fig. 4, we compare the MF of MUSIC progenitors (including for each MUSIC cluster the five most massive progenitors) with that of the parent DM-only MD simulation: at $z = 4$ we find that 25 per cent of MD objects with $M > 10^{13} h^{-1} M_{\odot}$ have been resimulated by MUSIC, at $z = 2.3$ we resimulated 50 per cent of MD objects with $M > 10^{13} h^{-1} M_{\odot}$ and at $z = 1.5$ we have identified in MUSIC more than 50 per cent of MD objects with $M > 2 \times 10^{14} h^{-1} M_{\odot}$ (at this redshift, MUSIC is also a mass-limited complete sample at $M > 4 \times 10^{14} h^{-1} M_{\odot}$). The averaged mass accretion history along the redshift of MUSIC protoclusters follows a simple exponential function, as in the following:

$$M(z) = M_0 e^{-\alpha z}.$$  

(2)

In our data set, the best fit for this exponential $\alpha = 1.3 \pm 0.1$ is consistent with the accretion rate of massive objects ($M_0 > 2.8 \times 10^{13} h^{-1} M_{\odot}$) as reported in Wechsler et al. (2002), corresponding to a mean formation time for clusters of $\tau_z \sim 0.53$, consistent with the values presented by Krause et al. (2012).
Figure 4. Top panels: MF of the MD simulation (black) compared to the MF of MUSIC protoclusters (red) at $z = 4.0$ (left), $z = 2.3$ (centre), $z = 1.5$ (right), including the five most massive progenitors of each cluster. Bottom panels: ratio of number of MD objects resimulated with MUSIC (same redshifts than top panels).

The mean value of each mass distribution is reported in Table 1. It is interesting to measure the fraction of the total mass of the cluster at $z = 0$ which is contained in the progenitors at high redshift, $M_{\text{prog}}/M(z = 0)$ (Fig. 5): we find that at $z = 4$ only a very small fraction of the total mass (14 per cent, see Table 1) is hosted by the progenitors, showing how at this age of the Universe most of the matter which will collapse into clusters is still in the form of diffuse matter (i.e. filaments) or of structures under galaxy size; still at $z = 1.5$ only almost half of the total mass of clusters at $z = 0$ is still not detected in progenitors with $M > 1.2 \times 10^{10} h^{-1} M_{\odot}$. It is also worth mentioning that mass ratio between the second most massive progenitor and the protocluster itself is in mean about 70 per cent at $z = 4$ and still almost 60 per cent at $z = 1.5$, an evidence that during their formation history most of massive clusters go through a major merger at $z > 1$.

We also concentrate on studying the spatial distribution of progenitors at different redshifts; if we assume the centre of the region of the forming cluster as the centre-of-mass of the protocluster, we can define the root-mean-square distance as

$$R_{\text{rms}} = \sqrt{\frac{\sum_{i=1}^{N} r_i^2}{N}},$$

where $N$ is the total number of progenitors and $r_i$ the distance between the $i$th progenitor and the centre-of-mass of the protocluster. The distribution of the $R_{\text{rms}}$ at the three redshift analysed is shown in Fig. 6 and the mean values reported in Table 1: the initial cluster forming region shows in mean $R_{\text{rms}} \sim 11 h^{-1}$ Mpc at $z = 4$, contracted at $R_{\text{rms}} \sim 8 h^{-1}$ Mpc at $z = 1.5$. We remark that the typical virial radius at $z = 0$ of the clusters formed by these regions collapsing is about $2 h^{-1}$ Mpc and the mean virial radii of our data set at different redshifts are listed in Table 1. It is interesting to observe that even if we pull down from 80 to 50 or 20 per cent the threshold of particles of an object which have to be part of the cluster at $z = 0$ in order to define it as a progenitor, the mean values of the $R_{\text{rms}}$ do not change of more than 5 per cent; we find that the maximum radius (whose mean values are also reported in Table 1) of the cluster forming area is always $R_{\text{max}} \sim 2 R_{\text{rms}}$.

3.3 Baryon properties of protoclusters

It is interesting to explore the baryon content of protoclusters of galaxies, in order to follow the evolution of the baryon, gas and star fraction (respectively, $f_b$, $f_g$, $f_s$) of galaxy clusters in the range $0 \leq z \leq 4$; at the same time, we can check whether our data set is affected by cold flows or galaxy feedbacks, effects that usually affect the inner regions of clusters but that in the case of such small objects could affect also areas closer to the virial radius. This is important to verify if we want to study integrated properties of protoclusters, such as the integrate Compton parameter $Y$, directly depending on the gas content, which has therefore to be described correctly (see Section 4).
The baryon, gas and star fractions are defined by simply taking into account all the gas and star particles falling inside the virial radius

\[
 f_{b,g,s}(< R_{\text{vir}}) = \frac{M_{b,g,s}(< R_{\text{vir}})}{M(< R_{\text{vir}})},
\]

where \( M_b \) is the mass of the gas, \( M_s \) the mass of the star component, and the total baryon mass is defined as \( M_b = M_s + M_g \). Fig. 7 shows the behaviour of the mean baryon, gas and star fractions calculated at the virial radius in the redshift range \( 0 \leq z \leq 4 \) (results referring to \( z \leq 1 \) are taken from Sembolini et al. 2013), normalized to the critical cosmic ratio \( \Omega_m/\Omega_m \) (which according to the cosmology adopted by MUSIC is 0.174) in order to make a comparison with other works adopting different cosmological parameters (since now on we denote the normalized values of \( f_{b,g,s} \) using capital letters: \( F_{b,g,s} \)). The normalized \( F_b \) is around 95 per cent at all redshifts for both CSF and NR subsets, as expected slightly higher than what measured in simulations of clusters at \( z \leq 1 \) at \( \Delta_c = 500 \), \( F_{b,500} \sim 0.85 \) (Planelles et al. 2013; Sembolini et al. 2013). We remind that \( \Delta_c \) defines that the overdensity is calculated with respect to the mean critical overdensity of the Universe at the redshift analysed. This was easy to predict as the value of the baryon fraction is expected to approach the cosmic ratio going from inner to outer regions of (protoclusters) and does not vary with redshift.

The gas fraction appears to be lower for protoclusters \( \Delta_c \geq 1.5, F_g \sim 0.65 \) than for clusters \( \Delta_c \leq 1 \), for which we find that \( F_g \) is around 75 per cent, values that can be treated as reasonable if we consider that CSF simulations show \( F_g \sim 0.65 \) at \( \Delta_c = 500 \). The mean value of the normalized star fraction rises from \( F_s \sim 0.2 \) at \( \Delta_c = 500, 0.3 \) at \( \Delta_c = 2500, 0.85 \) at \( \Delta_c = 500 \), and an amount still smaller than what is estimated in the inner regions of clusters (those which are more likely to be affected by cold flows) at \( \Delta_c = 2500 \). These results are conforming to the purpose of our analysis, as they allow us to state that there are no dramatic differences in the baryon content between clusters and protoclusters, and we can go on studying the integrated properties depending on gas content of the second ones.

### 3.4 Dynamical state of protoclusters

It is interesting to study the dynamical state of protoclusters in order to check if the morphology of these objects could have an impact on scaling relations. Three different criteria are commonly used to define the morphological state of clusters and protoclusters, aiming at distinguishing relaxed objects from disturbed ones (Shaw et al. 2006; Knebe & Power 2008):

(i) The presence of mergers, defining as major mergers those objects with a mass bigger than one half of the main object and as minor mergers those objects with a mass between 0.1 and 0.5 times the mass of the main object. Clusters experiencing or having experienced merger processes are more likely to be morphologically disturbed. All the events with accreted mass lower than 10 per cent are classified as smooth accretion.

(ii) The centre-of-mass offset, namely the spatial separation between centre-of-mass of the protocluster and the centre-of-density (maximum density peak), normalized to the virial radius (see equation 5). Objects showing a high value of \( \Delta r \) are considered as morphologically disturbed.

(iii) The degree of fulfillment of the virial theorem, calculating the virial ratio \( \eta = 2T/|U| \) (where \( T \) is the kinetic energy and \( U \) the potential energy). If the object is relaxed, \( \eta \sim 1 \) is expected.

The first criterion seems not to be successful when applied to protoclusters, as these show merger rate much lower than clusters at low redshift (35 per cent for clusters at \( z < 1 \)).

We have therefore to concentrate on the two other methods to fulfil our purpose of distinguishing relaxed protoclusters from disturbed ones. The centre-of-mass offset is quantified as

\[
\Delta r = \frac{|r_5 - r_{\text{cm}}|}{R_{\text{vir}}},
\]

where \( r_5 \) is the position of the centre-of-density of the halo, \( r_{\text{cm}} \) the centre-of-mass and \( R_{\text{vir}} \) the virial radius. \( \Delta r \) is used to quantify substructures statistics, providing an estimate of the halo’s deviations from smoothness and spherical symmetry. Different limit values of \( \Delta r \) are used in the literature in order to consider a halo as relaxed, ranging from \( \Delta r \leq 0.04 \) (Macciò et al. 2007) to \( \Delta r \leq 0.1 \) (D’Onghia & Navarro 2007). This method has been previously applied to hydrodynamical simulations to study the effect of the dynamical state on X-ray properties of clusters (Poole et al. 2006; Rasia et al. 2012; Biffi et al. 2014) or the mass–concentration relation (De Boni et al. 2013). Here, we will show that hydrodynamical simulations of clusters present higher values of \( \Delta r \) with respect to DM-only simulations, so we choose to adopt the largest value among those previously cited: \( \Delta r \leq 0.1 \) to define an object as relaxed.

The third and last requirement uses the virial theorem to determine which haloes are not dynamically relaxed. The standard definition for a dynamical system in equilibrium is usually represented by \( \eta \sim 1 \). Nevertheless, the effect of those particles located outside the virial radius but still gravitationally bound to the halo has to be taken into account and included in the estimate of the kinetic and potential energies, thus contributing to the virial ratio diagnostics. The additive term, to include this surface pressure energy at the boundary of the halo, can be quantified as (Chandrasekhar 1961)

\[
E_S = \int P_S(r) \cdot dS.
\]

Therefore, a modified definition of the virial parameter can be expressed as follows:

\[
\eta_1 = \frac{2T - E_S}{|U|}.
\]
The kinetic energy $T$ has been calculated taking into account the contributions of all the different kinds of particles (DM, gas and stars) bound to the object:

$$T = \frac{1}{2} \left( \sum_i m_{i,\text{DM}} v_{i,\text{DM}}^2 + \sum_i m_{i,\text{stars}} v_{i,\text{stars}}^2 + \sum_i m_{i,\text{gas}} v_{i,\text{gas}}^2 + \sum_i m_{i,\text{stars}} v_{i,\text{stars}}^2 \right),$$

where in the case of gas particles we also considered the thermal motion of particles (derived from the internal energy per gas particle, as provided by the simulation). The contribution of the thermal energy becomes less important for high redshifts (it ranges from 3 per cent at $z = 1.5$ to about 0.1 per cent of the total kinetic energy at $z = 4$.)

Assuming an ideal gas, the surface pressure can be calculated as (Shaw et al. 2006)

$$P_S = \frac{1}{3V} \sum_i \left( m_i v_i^2 \right),$$

where $V$ is the volume of the spherical shell between 0.8 and 1.0 $R_{\text{vir}}$ and $m_i$ and $v_i$ are the mass and velocity of the $i$th particle, respectively (where again, as in the case of the kinetic energy, all kinds of particles – DM, gas and stars – have been taken into account). Integrating $P_S$ over the bounding surface of the halo volume, it is found $E_S = 4\pi R_{\text{vir}}^2 P_S$, assuming $r_{\text{med}} \approx 0.9 R_{\text{vir}}$ (Knebe & Power 2008).

We apply this analysis, already performed for DM-only haloes by Knebe & Power (2008) and Power, Knebe & Knollmann (2012), to our hydrodynamically simulated protoclusters, in order to check any dependence between halo mass, virial ratio and centre-of-mass offset.

In the case of CSF objects, we find a mild dependence between the mass of the progenitor at different redshifts, $M_i$, and virial ratio $\eta_1$ (see Fig. 8)

$$\eta_5 \propto M_i^{0.04},$$

It is interesting to notice how this mass dependence is not fulfilled by NR clusters (Fig. 8, bottom panel). This trend is also evident in the upper panel of Fig. 8, where the low-mass population, being dominated by haloes in the high-$z$ snapshot, is concentrated around the lowest values of $\eta_1$.

The numerical values of $E_S$ are generally almost one order of magnitude smaller than the kinetic energy. The correction due to the surface pressure makes therefore the value of the virial ratio lower, but in most cases not enough to reach the expected value of 1.

In Fig. 9, we represent the relation between the two definitions of virial ratio, $\eta$ and $\eta_1$, computed both for CSF (top panel) and NR (bottom panel) subsets, for the same redshift bins we previously considered. We note that the $\eta_1 - \eta_1$ relation is independent on redshift. Therefore, the surface pressure correction is also independent on $z$. On the other hand, the $\eta_1$ values for the $z = 4$ CSF protoclusters are the only ones that reach values of unity. This feature hints to a higher probability to find virialized objects in high-$z$ snapshots. At $z = 4$, the extent of the range covered by the virial ratio for CSF protoclusters is much larger than in the NR case, having clusters with values closer to $\eta_1 = 1$, that is expected for relaxed objects. On the contrary, NR clusters at all redshifts present a behaviour of the virial ratios with no dependence on redshift, none of them having values smaller than 1.2, regardless of whether the pressure term is considered or not. At lower redshifts ($z = 1.5$) higher mean values of $\eta$ and $\eta_1$ are found, which are similar for both CSF and NR objects. Therefore, we conclude that the effect of the effective pressure term computed as mentioned above, underestimate the contribution of bound particles outside our definition of virial radius.\(^5\) Nevertheless, it is interesting to see that there are some high-$z$ protoclusters in CSF simulations that follow the virial theorem, even without correction for pressure terms.

We finally explore the relation between the two criteria adopted here to define the dynamical state of haloes, virial ratios ($\eta$, $\eta_1$) and centre-of-mass offset ($\Delta r$). In Fig. 10, we show the relation between the average values of $\eta_1$ (and $\eta$) CSF and NR protoclusters at different redshift bins $\Delta r$. There is a clear relation between the two dynamical state estimators. The virial ratios flatten off for values of $\Delta r \leq 0.1$ and they begin to increase when $\Delta r \geq 0.1$. Therefore, this confirms the validity of both criteria to study the dynamical state of simulated haloes. According to these results, we simply

\(^5\)In the AHF halo finder, the _virial_ radius of the haloes is defined as the radius that encompasses a mean density that fulfills the numerical solution of the spherical top-hat model at that redshift.
Figure 9. $\eta$ vs $\eta_1$ relation for CSF protoclusters (top panel) and NR protoclusters (bottom panel): $z = 1.5$ is red, $z = 2.3$ is yellow and $z = 4$ is blue. In the CSF relation, there is a linear dependence between the two parameters; objects at redshift $z = 1.5$ show lower values of $\eta_1$, $\eta_1$; NR protoclusters exhibits the same linear dependence than CSF objects, but the values of $\eta_1$ are distributed on a narrower range at high values.

As we already pointed out before, it is also clear from Fig. 10 that CSF protoclusters present values of $\eta_1$ much closer to 1 than NR protoclusters, while at lower redshift this difference is much less evident. This is better seen in Fig. 11 where we compare the $\eta_1$ as a function of $\Delta r$ for CSF and NR for high (upper panel) and low redshifts (lower panel). This behaviour is reflecting the different ways of mass growth of haloes at different redshifts. At high redshift, the major accretion of matter to haloes is by smooth mass inflow along filaments (Kereš et al. 2005; Madau, Diemand & Kuhlen 2008). In the case of CSF haloes, the infalling cooled gas is able to overcome the accretion shocks and makes its way towards the centre of protoclusters, forming stars efficiently (Birnboim & Dekel 2003; Dekel et al. 2009), deepening the potential well. Since most of the accretion is smooth, no significant amounts of non-thermal kinetic energy are injected to the protoclusters. Thus, the matter rapidly virialize in the deeper potentials of CSF clusters as compared with the shallower potentials of NR clusters. At later epochs, the mass growth of protoclusters is dominated by merging activity rather than by smooth matter accretion, with the consequence of a more substantial injection of kinetic energy in the haloes. As a result, the deepening in the potential wells caused by cooled baryons is less efficient in ensuring virialization over short time-scales. Therefore, low-$z$ objects are more likely to exhibit significant deviations from $\eta_1 = 1$. This effect, as expected, is present only in the CSF simulations, whereas the NR runs exhibit a departure from the virialization state at all times.

4 THE EXTENSION OF THE $Y-M$ SCALING TO PROTOCLUSTERS

The applicability to protoclusters of scaling relations connecting integrated properties of clusters, such as X-ray luminosity and SZ effect, has never been investigated. One of the main caveats on this analysis would be the problematics related to the observability of objects at high redshifts (as also discussed in the previous sections of this work).

Here, we try for the first time to explore the evolution of the $Y-M$ scaling relation at $z > 1$, with the purpose of checking whether the
hypothesis of self-similarity, already well studied for clusters of galaxies, can be applied also to protoclusters.

It has been shown that the integrated th-SZ effect, $Y$, whose definition is recalled here as$^6$

$$Y \equiv \int \Omega y \, d\Omega = D^2 \left( \frac{k_B \sigma_T}{m_e c^2} \right) \int_0^\infty dl \int \Delta n_e T_e \, dA$$

(11)

is a robust proxy of the total mass of the cluster, more stable than other proxies in the X-ray band (such as bolometric luminosity and temperature), as it is less affected by the physical processes taking place in the central regions of clusters. Previous works (Bonaldi et al. 2007; Aghanim, da Silva & Nunes 2009; Kay et al. 2012; Sembolini et al. 2013) have demonstrated that the $Y-M$ scaling relation, which connects the integrated SZ effect directly to the total mass of the cluster, confirms with good accuracy the hypothesis of self-similarity, showing values extremely close to the self-similar prediction, $A = 5/3$.

$^6$ $\Omega$ is the solid angle subtended by the cluster, $D_A$ is the diameter angular distance, $k_B$ is the Boltzmann constant, $\sigma_T$ is the Thomson cross-section, $m_e$ is the electron rest mass, $T_e$ is the electronic temperature and $n_e$ is the numerical density of electrons.

Figure 11. $\eta_1-\Delta r$ relation at $z = 4$ (top panel) and $z = 1.5$ (bottom panel). CSF protoclusters (red diamonds) show lower values of $\eta_1$ than NR protoclusters (blue triangles) at high redshift.

To estimate the integrated $Y$ of our data set of protoclusters, we use the same approach already shown in Sembolini et al. (2013), where a detailed analysis of the $Y-M$ scaling relation for massive clusters of galaxies has been performed in the redshift range $0 \leq z \leq 1$. As in the case of massive clusters, we build synthetic maps of the Compton $y$-parameter for each protocluster at the different redshifts analysed, and we estimate the $Y$ value integrated inside the virial radius. The choice of the integration up to the virial radius is motivated by the limited angular resolution of the expected observations towards so far objects.

The $Y-M$ scaling relation at a fixed overdensity is studied performing a best fit of

$$Y_\Delta = 10^9 \left( \frac{M_\Delta}{h^{-1} \text{M}_\odot} \right)^{A} E(z)^{2/3} [h^{-2} \text{Mpc}^2],$$

(12)

where $M_\Delta$ is the total mass calculated inside the sphere of radius $r_\Delta$ that we are considering: in our case $\Delta = \Delta_{\text{vir}}$, so that $M_\Delta$ corresponds to the total virial mass of the protoclusters. The normalization $B$ is defined as:

$$B = \log \left[ \frac{\sigma_T}{m_e c^2} \frac{\mu}{\mu_e} \left( \frac{\sqrt{\Delta G H_0}}{4} \right)^{2/3} \right] + \log f_\beta,$$

(13)

and contains all the constant terms and the gas fraction (where $\mu$ and $\mu_e$ are the mean molecular weights, respectively, of gas and electrons, see section 4.2 of Sembolini et al. 2013 for more details).

As in the previous section, in the analysis of the $Y-M$ relation, we consider three redshifts: 1.5, 2.3 and 4. We find contrasting results. At $z = 1.5$ (Fig. 12) we find a situation comparable to what already observed at $z \leq 1$: a slope very close to the self-similar value ($A = 1.69 \pm 0.01$), with no substantial differences between NR and CSF subsets, even if objects simulated with NR physics show higher values of $Y$ and lower slope, as in massive clusters at low redshifts. At $z = 2.3$, we observe an intermediate situation, with CSF clusters still close to self-similarity ($A = 1.70 \pm 0.01$) but with a normalization which starts to depart from those of NR objects and of the same objects analysed at $z < 1$. At $z = 4$ (Fig. 13) we find that CSF objects show a much stronger deviation from self-similarity ($A = 1.79 \pm 0.01$) and values of $Y$ (and of the normalization) much smaller than NR protoclusters, whose scaling relation do not exhibit any significant change from $z = 0$ even at this high redshift. This deviation from self-similarity is confirmed also when we include

Figure 12. $Y-M$ relation for MUSIC protoclusters at $z = 1.5$: CSF protoclusters are represented by red diamonds (the best fit is the black line) and NR protoclusters by blue triangles (the best fit is the orange line).
The five most massive progenitors of each cluster in our analysis. Various hypothesis can be made to explain this apparently non-self-similar behaviour of protoclusters at high redshift. Among these we can remind: the effect of disturbed objects on the scaling relation, an incorrect description of the physical processes taking place in the protoclusters or an effect due to the resolution of the simulation.

Aiming at studying the impact of unrelaxed haloes on the $Y-M$ relation, we build two different scaling relations separating relaxed protoclusters from disturbed ones. The results, shown in Fig. 14, demonstrate that, as it happens for clusters, the dynamical state of the haloes does not affect the $Y-M$ scaling relation: both relations exhibit a very similar slope well far from the self-similar value. Moreover, it could be observed that neither the fraction of disturbed objects at high redshift does not differ significantly from the one at low redshifts, nor NR protoclusters analysed at the same redshifts show any deviation from self-similarity even having the same number of particles, not to be affected by the same effects of resolution.

The effect of the resolution of the simulation could constitute a non-physical explanation of the deviation from self-similarity: in fact, if we consider the mass resolution of MUSIC simulation this allows us to describe massive clusters (with $M_{v} > 5 \times 10^{14} h^{-1} M_{\odot}$) by using several millions of particles. On the contrary, when we move to analyse protoclusters the mass range taken into account is about three order of magnitudes smaller (the mean virial mass of our sample at $z = 4$ is $5 \times 10^{12} h^{-1} M_{\odot}$), resulting into haloes described by only a few ten thousands particles, which may be not enough to describe with sufficient precision the integrated properties of protoclusters, such as the integrated $Y$. At the same time, NR protoclusters seem, even if constituted by approximately the same number of particles, to be not affected by the same effects of resolution.

Finally, Fig. 15 shows the evolution of the slope $A$ of the $Y-M$ scaling relation from $z = 0$ to 4: values referring to CSF subset are identified by the red diamonds, the NR subset is represented using blue diamonds. The similarity observed at $z = 4$: in fact, the processes taking place in the protoclusters can be different than those used to model clusters at low redshifts. Moreover, MUSIC simulations do not include AGN feedback, which could play a prominent role on gas physics at high redshifts. On the other hand, we have to consider that the effect of AGNs on clusters is usually that of deviating from self-similar conditions and not to get closer to them: therefore, it looks quite unlikely that the presence of AGNs could move the scaling relation of protoclusters towards more self-similar values.

The study of the progenitors of clusters of galaxies can give a fundamental contribution to better understand how the massive objects that we observe at present time have evolved. The biggest issue related to the analysis of these objects is related to the difficulties of observing them using present experiments and to the rarity of massive objects at $z > 1$ predicted by the standard $\Lambda$CDM model. The use of simulations is therefore crucial to limit this problem, making very easy to individuate the high-redshift haloes which will evolve into clusters. For the purpose of this work, we adopt the definition

5 SUMMARY AND CONCLUSIONS

The study of the progenitors of clusters of galaxies can give a fundamental contribution to better understand how the massive objects that we observe at present time have evolved. The biggest issue related to the analysis of these objects is related to the difficulties of observing them using present experiments and to the rarity of massive objects at $z > 1$ predicted by the standard $\Lambda$CDM model. The use of simulations is therefore crucial to limit this problem, making very easy to individuate the high-redshift haloes which will evolve into clusters. For the purpose of this work, we adopt the definition
of a protocluster as the most massive high-redshift progenitor of a galaxy cluster observed at \( z = 0 \) and for progenitors as all those high redshift object whose a considerable fraction of mass will be part of the cluster.

Using hydrodynamical simulations of galaxy clusters, here we studied some general properties of protoclusters: the mass and spatial distribution and their redshift evolution, the criteria to distinguish relaxed haloes from disturbed ones and the baryon content. We also applied for the first time the study of the \( Y-M \) scaling relation to objects at redshifts higher than 1, comparing the results with those referring to clusters at \( z \leq 1 \) reported in Sembolini et al. (2013). Our analysis was performed using MUSIC, the largest data set of hydrodynamically simulated clusters of galaxies at present available. We concentrated on MUSIC-2, an ensemble of 282 Lagrangian regions surrounding massive clusters (usually with \( M_{\text{vir}} > 5 \times 10^{12} \text{h}^{-1} \text{M}_{\odot} \)) extracted from a big DM only cosmological simulations and resimulated with radiative (CSF subset) and non-radiative (NR subset) physics. We analysed protoclusters and progenitors of MUSIC clusters at three different redshifts, \( z = 1.5, 2.3 \) and \( 4.0 \). The main results of our work can be summarized as follows:

(i) At \( z = 4 \), only a few protoclusters have \( M > 10^{13} \text{h}^{-1} \text{M}_{\odot} \), while at \( z = 1.5 \) we already find more than 100 haloes with \( M > 10^{14} \text{h}^{-1} \text{M}_{\odot} \). At high redshifts, only a fraction (slightly more than 50 per cent at \( z = 1.5 \), less than 15 per cent at \( z = 4 \)) of the mass of the present-day cluster is hosted by the progenitors, as most of the mass belongs to diffuse matter or to structure with \( M > 1.2 \times 10^{10} \text{h}^{-1} \text{M}_{\odot} \). The study of the spatial distribution of protoclusters shows that the cluster forming region, whose centre is individuated by the protocluster, has a mean \( R_{\text{rms}} \) that decreases from about \( 11 \text{h}^{-1} \text{Mpc} \) at \( z = 4 \) to \( 8 \text{h}^{-1} \text{Mpc} \) at \( z = 1.5 \).

(ii) The analysis of the baryon content of protoclusters does not show any crucial difference with the results inferred from simulations of galaxy clusters at \( z < 1 \). The baryon fraction, normalized to the cosmic ratio and calculated inside the virial radius is \( F_b \sim 0.95 \) with no redshift evolution. The normalized gas fraction \( F_g \) is ranges from 60 (high redshifts) to 70 per cent (low redshifts) and the star fraction \( F_s \) increases with redshift but always with values lower than 40 per cent: the effects of cold flows in MUSIC are therefore limited also at \( z > 1 \).

(iii) We considered different criteria in order to study the dynamical state of protoclusters and to distinguish the relaxed haloes from the disturbed ones. Excluding the effect of mergers, which seems to have a smaller impact on high-redshift objects, we concentrated on the virial ratio \( \eta_1 \), corrected including the effect of surface pressure term, and on the spatial shift between the centre-of-mass and the centre-of-density, \( \Delta r \). There is a linear relation between the total mass and the virial ratio, observed only in the CSF subset, and objects at \( z = 4 \) show values of \( \eta_1 \) closer to 1. The two different methods seem to be correlated, as to higher value of \( \Delta r \) correspond higher values of \( \eta_1 \) differently from what observed in DM only simulations, there is a linear dependence between the two parameters. Moreover, the effect of the surface pressure seems to have an impact smaller than in haloes simulated only with DM particles. We chose to define as disturbed the ones with \( \Delta r \geq 0.1 \).

(iv) We extended for the first time the analysis of the \( Y-M \) scaling relation to objects redshifts higher than 1. While NR protoclusters seem to be in good agreement with the self-similar model up to \( z = 4 \), on the other hand CSF objects seem to show a deviation from self-similarity at \( z > 2 \). The \( Y-M \) relation of CSF clusters at \( z = 4 \) has a slope \( \alpha = 1.79 \), well different from the self-similar expected value \( \alpha = 5/3 \) and \( Y \) values lower than NR haloes. In order to check a possible effect of the dynamical state of objects, we studied the \( Y-M \) relation discerning relaxed protoclusters and disturbed ones. No differences have been found between the two subsets. We also made the hypothesis that the deviation from self-similarity may be due to the mass resolution of the simulation, as protoclusters at \( z = 4 \) have masses up to three order of magnitudes smaller than clusters at \( z = 0 \): anyway NR haloes, simulated with the same number of particles, do not show any deviation from self-similarity. Another factor which may contribute to this effect could be an incomplete description of the physical processes taking place inside the protoclusters (i.e. MUSIC simulations do not include AGN feedback): by the way, these factors are expected to have an opposite effect on scaling relations, moving them away from self-similarity.

To summarize, the use of hydrodynamical simulations to study protoclusters of galaxies seems very promising to better understand the evolution of present-day clusters of galaxies and to approach problems that are challenging with the resolution of present observational instruments. The proposed large-class satellite mission, PRISM (PRISM Collaboration et al. 2013), thanks to the large spectral coverage, angular resolution and sensitivity is expected to deeply explore the universe beyond \( z = 2 \) planning to detect thousands of objects with \( M > 5 \times 10^{13} \text{M}_{\odot} \). The analysis of many interesting protoclusters’ properties, such as the dynamical state, the baryon content or the scaling relations, can be considerably improved when using simulations including gas and star particles with respect to DM only simulations.

In order to double check whether the deviation from self-similarity observed in CSF protoclusters at \( z = 4 \) is due to real physical effects or it is just a consequence of the resolution of the simulation, we plan to resimulate MUSIC protoclusters in the range \( 1 \leq z \leq 4 \), improving the mass resolution of at least a factor of eight and eventually adding more physical processes, such as AGN feedback, and using a binning in redshift narrower than the one adopted in this work.

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