The effect of active galactic nuclei feedback on the halo mass function

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ABSTRACT
We investigate baryon effects on the halo mass function (HMF), with emphasis on the role played by active galactic nuclei (AGN) feedback. Haloes are identified with both friends-of-friends (FoF) and spherical overdensity (SO) algorithms. We embed the standard SO algorithm into a memory-controlled frame program and present the Python spherical overdensity code – PIAO (Chinese character: 寥). For both FoF and SO haloes, the effect of AGN feedback is that of suppressing the HMFs to a level even below that of dark matter (DM) simulations. The ratio between the HMFs in the AGN and in the DM simulations is ~0.8 at overdensity \( \Delta_c = 500 \), a difference that increases at higher overdensity \( \Delta_c = 2500 \), with no significant redshift and mass dependence. A decrease of the halo masses ratio with respect to the DM case induces the decrease of the HMF in the AGN simulation. The shallower inner density profiles of haloes in the AGN simulation witnesses that mass reduction is induced by the sudden displacement of gas induced by thermal AGN feedback. We provide fitting functions to describe halo mass variations at different overdensities, which can recover the HMFs with a residual random scatter \( \lesssim 5 \) per cent for halo masses larger than \( 10^{13} \, h^{-1} \, M_\odot \).

Key words: galaxies: evolution – galaxies: formation – galaxies: general – galaxies: haloes – cosmology: theory – large-scale structure of Universe.

1 INTRODUCTION
The halo mass function (HMF) is a unique prediction of cosmological models of structure formation. The evolution of the HMF traced by galaxy clusters has been recognized since a long time as a powerful tool to trace the growth of cosmic structures and, therefore, to constrain cosmological parameters (see Rosati, Borgani & Norman 2002; Allen, Evrard & Mantz 2011, for reviews, and references therein). In particular, cosmological applications of the HMF require to know its shape and evolution to a high precision, in order to fully exploit its potential as a cosmological tool to be applied to ongoing and future large surveys of galaxy clusters (e.g. Wu, Zentner & Wechsler 2010; Murray, Power & Robotham 2013).

\( N \)-body simulations covering wide dynamic ranges are nowadays providing rather accurate calibration of the mass function of dark matter (DM) haloes (e.g. Jenkins et al. 2001; Reed et al. 2003, 2007, 2013; Lukić et al. 2007; Tinker et al. 2008; Crocce et al. 2010; Bhattacharya et al. 2011; Courbin et al. 2011; Angulo et al. 2012; Watson et al. 2013). Various extensions of the standard \( \Lambda \) cold dark matter (LCDM) cosmology model, such as coupled dark energy models (e.g. Baldi 2012; Cui, Baldi & Borgani 2012b), modified gravity models (e.g. Schmidt et al. 2009; Puchwein, Baldi & Springel 2013; Zhang et al. 2013), non-Gaussian initial conditions (e.g. Grossi et al. 2009; Pillepich, Porciani & Hahn 2010), massive neutrinos (e.g. Brandbyge et al. 2010; Ichiki & Takada 2012; Costanzi et al. 2013), warm DM (e.g. Angulo, Hahn & Abel 2013; Schneider, Smith & Reed 2013), have been studied using numerical simulations, and their effect on the HMF has been investigated.

A crucial aspect in the calibration of the HMF is related to the algorithm used to identify haloes, the two most widely used being the friends-of-friends (FoF) and the spherical overdensity (SO). The choice of a specific algorithm clearly impacts both the number of identified haloes and their mass (e.g. White 2001, 2002; Lukić et al. 2009; More et al. 2011; Watson et al. 2013, see also Knebe et al. 2011 for a detailed comparison between different halo finders).

All the above-mentioned HMF calibrations are based on \( N \)-body simulations that follow the evolution of a collisionless DM fluid. On the other hand, the presence of baryons is known to add subtle but sizeable effects on halo formation and internal structure, whose details also depend on the physical processes included in the numerical treatment of the baryonic component, such as gas cooling, star formation and energy feedback from supernovae (SNe) and active galactic nuclei (AGN; e.g. Kravtsov & Borgani 2012, and references therein).

A number of studies based on cosmological hydrodynamical simulations have been recently carried out to analyse in detail the
effect of baryonic processes on different properties of the total mass distribution, such as the power spectrum of matter density fluctuations (e.g. Rudd, Zentner & Kravtsov 2008; van Daalen et al. 2011; Casarini et al. 2012), the halo correlation functions (e.g. Zhu & Pan 2012; van Daalen et al. 2014), the halo density profiles (e.g. Lin et al. 2006; Duffy et al. 2010) and concentration (e.g. Bhattacharya et al. 2013; Rasia et al. 2013) and the HMF (e.g. Stanek, Rudd & Evrard 2009; Cui et al. 2012a; Balaguera-Antolín & Porciani 2013; Cusworth et al. 2014; Martizzi et al. 2014; Sawala et al. 2013; Wu & Huterer 2013).

As for the effect of non-radiative hydrodynamics, the presence of baryons has been shown to induce a slight increase of the HMF (Cui et al. 2012a, hereafter Paper I). When extra-heating is included, Stanek et al. (2009) found instead a decrease in the HMF. As for the effect of radiative cooling, star formation and SN feedback, different groups consistently found an increase of the HMF, an effect that is more evident in the high-mass end (Stanek et al. 2009; Paper I; Martizzi et al. 2014). On the other hand, Sawala et al. (2013) found that efficient SN feedback produces an opposite effect in low-mass haloes.

On the other hand, a number of analyses have shown in the last years that including AGN feedback in cosmological simulations provides populations of galaxy clusters in better keeping with observational results (e.g. Puchwein, Sijacki & Springel 2008; Fabjan et al. 2010; Short et al. 2010; McCarthy et al. 2011; Le Brun et al. 2013; Planelles et al. 2013). When the AGN feedback is included, different results were found by Martizzi et al. (2014) and Cusworth et al. (2014). The former showed that the HMF with AGN feedback is higher than the fitting function from Tinker et al. (2008), while the latter predicted a lower HMF compared to the same fitting function. However, their implementation of the AGN feedback differ. Martizzi et al. (2014) described AGN feedback by computing explicitly gas accretion rates on to supermassive black holes (SMBHs) included as sink particles in simulations that also include radiative cooling, star formation and SN feedback (e.g. Springel, Di Matteo & Hernquist 2005b; Booth & Schaye 2009). Cusworth et al. (2014) included AGN feedback by computing the associated feedback energy from the semi-analytic model of galaxy formation by Guo et al. (2011), without including radiative cooling and assuming zero mass for gas particles, so that no back-reaction of baryons on the DM distribution is allowed.

In this paper we extend our previous analysis of baryonic effects on the HMF, presented by Paper I, by also including in our simulations the effect of AGN feedback. We directly compare the HMF obtained from DM-only simulations to those produced by radiative hydrodynamical simulations both with and without AGN feedback, using exactly the same initial conditions, mass and force resolutions. The plan of the paper is as follows. In Section 2, we present the simulations analysed in this paper. Section 3 is devoted to the description of the halo identification methods. In Section 4 we present the results of our analysis and describe in detail the differences in the HMF induced by different feedback models. Our results are discussed and summarized in Section 5.

**2 THE SIMULATIONS**

Three large-volume simulations are analysed in this paper, namely two hydrodynamical simulations which include different description of feedback processes affecting the evolution of baryons and one N-body simulation including only DM particles. Initial conditions for these simulations are the same as described in Paper I and we refer to that paper for further details. The hydrodynamical simulations have the same number DM particles (1024³) and gas particles (1024³). A first hydrodynamical simulation includes radiative cooling, star formation and kinetic SN feedback (CSF hereafter), while the second one also includes the effect of AGN feedback (AGN hereafter). As for the DM simulation, it starts for the same initial conditions as the hydrodynamical simulations, with the gas particles replaced by collisionless particles, so as to have the same description of the initial density and velocity fields as in the hydrodynamical simulations.

The three simulations have been carried out using the TreePM-smoothed particle hydrodynamics (SPH) code GADGET-3, an improved version of the GADGET-2 code (Springel 2005). Gravitational forces have been computed using a Plummer-equivalent softening which is fixed to \( \epsilon_p = 7.5 \, h^{-1} \) physical kpc from \( z = 0 \) to 2, and fixed in comoving units at higher redshift. The simulations assume flat ΛCDM cosmology with \( \Omega_m = 0.24 \) for the matter density parameter, \( \Omega_b = 0.0413 \) for the baryon contribution, \( \sigma_8 \approx 0.8 \) for the power spectrum normalization, \( n_s = 0.96 \) for the primordial spectral index and \( h = 0.73 \) for the Hubble parameter in units of 100 km s⁻¹ Mpc⁻¹. Initial conditions have been generated at \( z = 49 \) using the Zel’dovich approximation for a periodic cosmological box with comoving size \( L = 410 \, h^{-1} \) Mpc. The masses of gas and DM particles have a ratio such that to reproduce the cosmic baryon fraction, with \( m_g \approx 3.73 \times 10^9 \, M_\odot \) and \( m_{DM} \approx 3.544 \times 10^{10} \, M_\odot \), respectively.

In the hydrodynamical simulations, radiative cooling is computed for non-zero metallicity using the cooling tables by Sutherland & Dopita (1993), also including heating/cooling from a spatially uniform and evolving ultraviolet (UV) background. Gas particles above a given threshold density are treated as multiphase, so as to provide a subresolution description of the interstellar medium, according to the model described by Springel & Hernquist (2003). Conversion of collisional gas particles into collisionless star particles proceeds in a stochastic way, with gas particles spawning a maximum of two generations of star particles. We also include a description of metal production from chemical enrichment contributed by Type II supernova (SN-II), Type Ia supernova (SN-Ia) and asymptotic giant branch (AGB) stars, as described by Tornatore et al. (2007). Kinetic feedback is implemented by mimicking galactic ejecta powered by SN explosions, with a wind mass upload proportional to the local star formation rate, \( M_w = \eta M_s \). In the CSF simulation we use \( \eta = 2 \) and \( v_w = 500 \, \text{km s}^{-1} \) for the wind velocity, which corresponds to assuming about unity efficiency for the conversion of energy released by SN-II into kinetic energy for the adopted Salpeter initial mass function (IMF).

As for the AGN simulation, it includes both the effect of galactic winds with \( v_w = 350 \, \text{km s}^{-1} \) and the same mass-load parameter \( \eta = 2 \), along with energy feedback resulting from gas accretion on to SMBHs. The model of AGN feedback used in this simulation is the same as that adopted by Fabjan et al. (2010) and is largely inspired to the model originally introduced by Springel, Di Matteo & Hernquist (2005a). SMBHs, seeded with an initial mass of \( 10^6 \, M_\odot \) in haloes resolved with at least 100 DM particles, subsequently grow by merging with other BHs and by gas accretion. The latter proceeds at the Bondi rate and is Eddington limited. A fraction \( \epsilon_f = 0.1 \) of accreted mass is converted into radiation, with a fraction \( \epsilon_r \) of this radiation thermally coupled to the surrounding gas. We assume \( \epsilon_r = 0.1 \) which increases by a factor of 4 whenever accretion takes place at a rate of at most 100th of the Eddington limit. We note that the main motivation for efficient SN feedback with \( v_w = 500 \, \text{km s}^{-1} \) in the CSF simulations lies in the need of reconciling simulation predictions on the cosmic star formation rate.
with observations, at least at redshift $z > 2$, a choice that still produces too efficient star formation at lower redshift (e.g. Tornatore et al. 2010). Although AGN feedback is motivated by the need of reducing the star formation rate at lower redshift, still its effect is quite significant already at $z \sim 2$. Therefore, in order to prevent too strong a reduction of star formation around this redshift when SN and AGN feedbacks are both included, we decided to reduce by a factor of 2 the kinetic energy associated with the former. This lowers the resulting wind velocity to $v_w = 350 \, \text{km s}^{-1}$.

3 HALO IDENTIFICATION

The two most common methods used for halo identification in simulations are the FoF algorithm (e.g. Davis et al. 1985) and the SO algorithm (Lacey & Cole 1994). The FoF algorithm has only one parameter, $b$, which defines the linking length as $bl$, where $l = n^{-1/3}$ is the mean interparticle separation, with $n$ the mean particle number density. In the SO algorithm, there is also only one free parameter, namely the overdensity $\Delta_c$. The overdensity determines the aperture of the sphere, within which the total mean density is $\Delta_c \rho_{\text{crit}}$. Here, $\rho_{\text{crit}}$ is the critical cosmic density. Each of the two halo finders has its own advantages and shortcomings (see more details in Jenkins et al. 2001; White 2001; Tinker et al. 2008, and references therein), and the differences between the two methods in terms of halo masses and HMFs have been discussed in several analysis (e.g. White 2002; Reed et al. 2003, 2007; Cohn & White 2008; Anderhalden & Diemand 2011; More et al. 2011; Knebe et al. 2013; Watson et al. 2013). We adopt both methods to identify haloes in this paper.

3.1 Friends-of-friends haloes

In our three simulations FoF haloes are identified by an on-the-fly FoF finder, with a slightly smaller linking length $b = 0.16$ compared to commonly used one, $b = 0.2$. DM particles are linked first. Then, each gas and star particle is linked to the nearest DM particle, whenever the linking criterion is satisfied.

3.2 Spherical overdensity haloes – PIAO

We carry out a SO halo search by using an efficient memory-controlled parallel Python spherical overdensity halo finding code – PIAO (Chinese character: .piāo). This code is based on the standard SO algorithm. Its aim is not to provide a new halo identification method, but to analyse large simulations on a small computer server or PC with limited memories. To overcome a memory deficiency problem, we adopt a simple strategy, which is based on splitting the whole simulation box into small mesh-boxes, and analysing them one-by-one. The details of this strategy and how to incorporate it within the SO method are discussed in Appendix A. PIAO is parallelized with a PYTHON MPI package (MPI4PY) to speed up the calculation by taking advantage of multicore CPUs.

We applied PIAO to the three simulations analysed in this paper. For all of them, SO haloes are identified at three different overdensity values, $\Delta_c = 2500, 500, 200$. As detailed in the appendix, local density maxima around which growing spheres encompassing a given overdensity are searched by assigning density at the positions of particles using 64 SPH neighbours and without allowing haloes to overlap with each other.

In the following, the overdensity value $\Delta_c$ is expressed in units of the cosmic critical density at a given redshift, $\rho_c(z) = 3H^2(z)/(8\pi G)$.

3.3 Matching haloes

Since all three simulations share the same initial conditions, DM particles have the same progressive identification number (ID). We exploit this information to match haloes identified in different simulations. Using a given halo identified in the DM simulation as the reference, a halo in the CSF or AGN simulation is defined to be the counterpart of the DM halo whenever it includes the largest number of DM particles belonging to the latter. We define the matching rate as the ratio of matched to total number of DM particles in the DM halo. Clearly, the larger this rate, the more accurate is the matching. In order to avoid mismatches, i.e. two haloes from CSF/AGN simulation matched to one halo in the DM one, only haloes with matching rate larger than 0.5 are selected. We verified that the fractions of matched SO haloes for $\Delta_c = 500$ are 97.5 per cent at $z = 0$, 98.3 per cent at $z = 0.6$, 98.6 per cent at $z = 1.0$ and 99.4 per cent at $z = 2.2$. Most of the mismatched haloes have smaller halo mass, e.g. 85 per cent of them have halo mass $M_{500} < 10^{13} \, h^{-1} M_\odot$ at $z = 0$.

At each overdensity $\Delta_c$, we only consider haloes with $M_{\Delta_c} \geq 10^{12.5} \, h^{-1} M_\odot$. With this choice, the smallest halo can still have $\sim 1000$ particles within the corresponding $R_{\Delta_c}$. However, to allow for a complete matching, we consider haloes as small as $M_{\Delta_c} = 10^{11.5} \, h^{-1} M_\odot$ in the AGN and CSF simulations to be matched to the haloes in the DM simulation. As shown by Reed et al. (2013), haloes resolved with fewer than $N \sim 1000$ particles are unlikely to be used for a high-accuracy HMF measurement. Furthermore, Watson et al. (2013) also pointed out that the correction for low number of particles sampling FoF haloes from Warren et al. (2006) is $\sim 2$ per cent for the FoF haloes containing 1000 particles. We used a fixed mass bin $\Delta \log M = 0.2$ for the calculation of the HMF, without further correction. As discussed by Lukić et al. (2007), the uncertainty in the HMF resulting from the choice of the binning is negligible as long as the bin width does not exceed $\Delta \log M = 0.5$.

4 RESULTS

Basic information on the number of haloes identified by the FoF and SO finders can be obtained from the cumulative HMF. We just mention here that over $10^4$ haloes are always found with both methods at $z = 0$ with halo mass $M \geq 10^{12.5} \, h^{-1} M_\odot$. This number can reach $\sim 70,000$ for FoF haloes and for SO haloes with $\Delta_c = 200$. At the highest considered redshift, $z = 2.2$, this number is still $\sim 10^4$ for FoF and for SO haloes with $M_{250} \geq 10^{12.5}$. However, at the same redshift we only have $\sim 10^3$ SO haloes with $M_{250} \geq 10^{12.5} \, h^{-1} M_\odot$. The CSF simulation has more both SO and FoF haloes than the DM one at all redshifts and halo masses, an increase that is less apparent for $\Delta_c = 200$. On the contrary, the AGN simulation produces fewer haloes of fixed mass than the DM one. Because of limited simulation box size, only a few haloes have mass $M \geq 10^{13} \, h^{-1} M_\odot$ for FoF and SO with $\Delta_c = 200$. Given the limited dynamical range accessible to our simulations, we attempt in the following to provide fitting expressions to the corrections to the HMF induced by baryon effects, while we avoid providing absolute fitting functions to the HMF.

4.1 The HMF from friends-of-friends

We compare in the upper panel of Fig. 1 the HMFs for the three different simulations, while the lower panel shows the relative difference between each of the two hydrodynamical simulations and the DM one. As for the effect of the baryon physics described by the CSF model, we note that the difference with respect to the DM case has a clear redshift evolution and halo mass dependence. As
redshift decreases from $z = 2.2$ to 0, the HMF ratio drops from $\sim 1.6$ to $\sim 1.1$, with a weak increasing trend of this ratio with halo mass, at all redshifts. Quite remarkably, including AGN feedback has the effect of reducing the difference with respect to the DM-only case: the HMF ratio drops to about unity for massive haloes with $M_{\text{FoF}} \gtrsim 10^{14} h^{-1} M_{\odot}$, while at smaller halo mass it decreases to $\sim 0.9$ for $M_{\text{FoF}} \approx 10^{12} h^{-1} M_{\odot}$. Unlike the CSF case, these differences do not show any evidence of redshift evolution from $z = 1$ to 0.0. At higher redshift, $z = 2.2$, the HMF ratio keeps fluctuating around 1, as a consequence of the limited statistics of haloes due to the finite box size.

4.2 The HMF from spherical overdensity

We compare in the upper panels of Fig. 2 the HMFs obtained from the SO halo finder at three overdensities, $\Delta_c = 2500, 500, 200$ (from left to right), along with the ratios of the HMFs from the CSF and AGN simulations with respect to the DM-only result (lower panels). As expected, baryons have a larger impact at the highest considered overdensity, $\Delta_c = 2500$. In this case, the ratio between CSF and DM HMFs shows a redshift evolution similar to the FoF results but with a higher amplitude, ranging from $\sim 1.4$ at $z = 0$ to $\sim 2.5$ at $z = 2.2$, but with no significant dependence on the halo mass. At lower overdensities, $\Delta_c = 200$ and 500, the redshift evolution becomes weaker and the differences with respect to the DM case are reduced, with only a $\lesssim 5$ per cent difference at $\Delta_c = 200$ (similar results for the CSF case were also found by Paper I).

When AGN feedback is included in the simulation, the corresponding HMF drops below the HMF from the DM simulation, by an amount that decreases for lower $\Delta_c$ values, with no evidence for redshift dependence of the HMF difference. At $\Delta_c = 2500$, this ratio has a weak halo mass dependence, ranging from $\sim 0.7$ at $10^{12.5} h^{-1} M_{\odot}$ to $\sim 0.5$ at $10^{14} h^{-1} M_{\odot}$. At $\Delta_c = 500$ and 200, the difference between AGN and DM HMFs reduces, with a mild dependence on halo mass: $dn/dn_{\text{DM}} \approx 0.7, \approx 0.8$ at $M \approx 10^{12} h^{-1} M_{\odot}$ to $dn/dn_{\text{DM}} \approx 0.9, \approx 1.0 (\Delta_c = 500, 200$, respectively) in the high-mass end.

In general, the effect of including baryons on the HMF goes in the same direction, independent of whether FoF or SO halo finders are used. While this holds at a qualitative level, as expected quantitative differences between FoF and SO results are found, especially for the CSF case. As we will discuss in the following, the effect of including AGN feedback is that of producing haloes that are less concentrated than in the CSF case. As a result, one expects that matching SO and FoF HMFs requires in the CSF simulation a higher $\Delta_c$ than in the AGN simulation. Many efforts are made to rematch the two halo mass functions by tuning $b$ and $\Delta_c$ (e.g. Lukić et al. 2009; Courtin et al. 2011; More et al. 2011). However, as shown in Watson et al. (2013), even in DM-only simulations, matching FoF HMFs to SO HMFs not only depends on the choice of $b$ and $\Delta_c$, but also on the concentration parameter, pseudo-mass evolution and the problems inside the two algorithms. These quantitative differences between FoF and SO results make this matching progress even more complex if baryon models are taken into account.

In order to understand the origin of the baryonic effects on the HMFs predicted by our simulations, we further focus on the difference of masses of matched haloes at overdensity $\Delta_c = 500$ (see Section 3.3 for the description of the matching procedure). We show in Fig. 3 the ratio between masses of matched haloes in each one of the two hydrodynamical simulations and in the DM simulation (red and green points for the CSF and AGN case, respectively). In each panel, the thick lines show the mean value of these ratios computed within each mass bin (magenta for CSF and blue for AGN). As for the CSF case, the effect of baryons is that of increasing halo masses by an amount which is almost independent of redshift. At each redshift, the halo mass ratio weakly decreases with halo mass, from $\sim 1.1$ at $M_{500} = 10^{12.5} h^{-1} M_{\odot}$ to $\sim 1.05$ at $M_{500} \gtrsim 10^{13} h^{-1} M_{\odot}$, then becoming constant (see also Paper I). For the AGN simulation, the effect of baryons goes in the opposite direction of decreasing halo masses, thereby decreasing the corresponding HMF, as shown in Fig. 2. Also in this case, there is no evidence for a redshift evolution of the halo mass ratio, at least below $z = 1.0$. However, there is an obvious increase of this ratio with halo mass that ranges from $\sim 0.8$ at $M_{500} = 10^{12.5} h^{-1} M_{\odot}$ to $\gtrsim 1$ for the most massive haloes found in our simulation box. Similar trends are also found for the mass ratio with $\Delta_c = 2500, 200$, both of which also show no evidence of redshift dependence for both hydrodynamical simulations. We verified that using the median value of those data points gives almost identical lines to these mean lines. As discussed in Appendix C, this effect of reduction of halo masses in the presence of AGN feedback is quite robust against numerical resolution. We refer to this appendix for a more detailed discussion of the resolution test that we carried out.
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Figure 2. Effect of baryons on the HMF for SO haloes. Each panel is the same as in Fig. 1, but for the SO HMFs with halo masses computed for $\Delta_c = 2500$ (left-hand panel), 500 (middle panel) and 200 (right-hand panel).

Since the masses of SO haloes are computed by adding up all the particles within a sphere with radius $R_{\Delta_c}$, it is clear that a change of the halo density profiles induced by the presence of baryons would also change the corresponding values of $R_{\Delta_c}$. In order to quantify the effect of this variation, we also compute masses for each halo in the CSF/AGN simulations by using the value of $R_{\Delta_c}$ of the corresponding halo identified in the DM simulation. In Fig. 4, we show again the halo mass difference at $\Delta_c = 500$ after applying this re-tuning of the halo radii. A comparison with the $z = 0$ result from Fig. 3 demonstrates that these ratios are only slightly shifted towards unity, for both CSF and AGN models. This small change implies that the differences in halo masses are mostly contributed by the baryon effects on the halo density profiles, which cannot be recovered by simply changing the halo radius.

Including only SN feedback in the form of galactic ejecta is already known not to be able to regulate overcooling at the centre of relatively massive haloes, with $M > 10^{12.5} h^{-1} M_\odot$. Adiabatic contraction (e.g. Gnedin et al. 2004), associated with the condensation of an exceedingly large amount of cooled gas, leads then to an increase of density within a fixed halo aperture radius and, therefore, to an increase of the halo mass with respect to the DM case. The opposite effect is instead associated with the inclusion of AGN feedback. In this case, the sudden displacement of large amount of gas at epochs corresponding to the peak of AGN feedback efficiency, taking place at $z \sim 2-3$, causes sudden variations of the halo potential, which reacts with an expansion, thus decreasing halo masses (see discussion in section below).

4.3 Density profiles

Having quantified the variation of halo masses, we now discuss how this variation is associated with changes in the total density profiles of haloes induced by baryonic processes.

To this purpose, we show in Fig. 5 the stacked ratio between density profiles for haloes belonging to different mass intervals. We consider in this plot haloes that are matched in the CSF/AGN and in the DM simulations. Haloes are separated into five mass bins, according to the $M_{500}$ halo mass, measured in the DM simulation. For each matched halo, we first compute the ratio of cumulative density profiles, $\rho(<R)$. Then, we stack the density profile ratios for all haloes belonging to the same mass bin. The stacked density profile ratios for CSF and AGN haloes are shown with red and green curves, respectively, with error bars indicating the $1\sigma$ intrinsic scatter within each mass interval.

We note that density profiles for CSF haloes are always higher than those for the DM simulation for all mass bins. The effect is stronger towards the cluster centre, as a result of adiabatic contraction triggered by gas condensation from cooling. This result, which is in line with those found by several previous analyses (e.g. Gnedin et al. 2004; Puchwein et al. 2005), indicates that the feedback included in our CSF model is not efficient in counteracting the effect of radiative cooling in increasing total density in central halo regions. While the effect is quite small at $R_{200}$, it becomes sizeable at $R_{2500}$, where density increases by up to about 50 per cent for the smallest resolved haloes.
Figure 3. Mass dependence of the ratio of masses of matched SO haloes computed for $\Delta_c = 500$ at different redshifts, as reported in the upper right-hand corner of each panel. Each point represents a halo mass ratio between the matched CSF (red points) or AGN (green points) haloes to DM ones, as a function of the mass of the matched halo in the DM simulation. The thick magenta and green lines show the mean values of this ratio within each mass bin for the CSF and AGN simulations, respectively. The best-fitting relation for the mass correction of equation (1) is shown with the solid black lines. We note that the same relation provides a good fit at all redshifts, at least up to $z = 1$. See Table 1 for the values of the parameters defining this best-fitting relation.

Figure 4. The same as the bottom right-hand panel of Fig. 3, but for halo masses in the CSF/AGN simulations computed within the $R_{500}$ radius of the corresponding haloes from the DM simulation. The dashed thick lines are the previous results in Fig. 3 at $z = 0$.

It is quite interesting that a different behaviour is found when AGN feedback is included. In this case, an increase of total density associated with gas condensation is only found at small radii, below $(20–30) \, h^{-1}\text{kpc}$, which are however close the smallest scale that can be trusted at the resolution of our simulations. At larger radii, the effect of AGN feedback is that of decreasing the halo density profile, an effect that becomes negligible at large radii, approaching $R_{500}$, and for the most massive haloes found in our simulations. This result is in line with those from previous analyses of cluster simulations including AGN feedback (e.g. Dubois et al. 2010; Duffy et al. 2010; Mead et al. 2010; Killeen et al. 2012; Martizzi et al. 2014; Cui et al. 2014). The decrease of density profiles is caused by the effect of AGN feedback that, at redshifts corresponding to the peak of BH accretion $z \approx 2–3$, causes a sudden expulsion of gas from the potential wells of the cluster progenitor haloes (similar result is also found by Dubois et al. 2010). The expulsion of large amount of gas causes potential wells to react with some expansion, thereby causing a decrease of the density in central regions.

### 4.4 Correcting the halo mass function

Having traced the origin of the variation of halo masses induced by baryonic processes, we investigate now whether the application of a suitable correction to halo masses allows one to recover the HMF from a hydrodynamical simulation, starting from the DM-only HMF. In Paper I, we have already shown that the HMFs from non-radiative and CSF simulations can be corrected to the DM-only HMF one, up to a residual scatter of $\lesssim 3$ per cent, by adopting a constant halo mass shift. From Fig. 3, we note that the mean values of the halo mass difference between AGN and DM simulations...
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Figure 5. The stacked ratios of cumulative density profiles, \( \rho(< R) \), of matched haloes identified in each one of the hydrodynamical simulations and in the DM one. Different panels refer to different halo mass ranges, with the bottom right-hand panel showing the results for all haloes with mass \( M_{500} \geq 10^{12.5} h^{-1} M_\odot \). In each panel, the red and green solid lines are for the mean density ratios for the CSF and AGN case, respectively. Error bars indicate the 1\(\sigma\) scatter around the mean. Vertical dashed, dot-dashed and dotted lines indicate the median values of \( R_{200}, R_{500} \) and \( R_{2500} \) computed within each halo mass interval, with magenta and blue colours referring to the CSF and AGN simulations, respectively. We also show with continuous black lines the median values of \( R_{2500}, R_{500} \) and \( R_{200} \) for the DM simulation. The shadow regions show the limits of the gravitational softening.

(1) thick blue line) have a significant mass dependence that needs to be included in the correction.

As a convenient relation to describe the mass dependence of the mean mass ratio, we use these sigmoid functions

\[
\begin{align*}
&f(x) = \alpha/(1 + e^{-3(x-M_0)/2}) + 1 - \alpha, \quad \text{AGN,} \\
&f(x) = \alpha/(1 + e^{3(x-M_0)/2}) + 1, \quad \text{CSF,}
\end{align*}
\]

with \( M_0 \) and \( \alpha \) considered as fitting parameters. Here, \( f(x) \) is the halo mass ratio between AGN and DM sets, with \( x = \log M_{500,\text{DM}} \). Since the halo mass difference shows no evidence for redshift evolution, at least for \( z \leq 1.0 \), we do not attempt to fit a possible redshift dependence of the \( M_0 \) and \( \alpha \) parameters and exclude the results at \( z = 2.2 \) from the analysis. The values of \( M_0 \) and \( \alpha \) obtained in this way are reported in Table 1 for the three values of the overdensity \( \Delta_c \) at which SO haloes have been identified. The thin black line shown in Fig. 3 indicates this fitting to the correction for \( \Delta_c = 500 \). We verified that a redshift-independent mass correction also holds for the other \( \Delta_c \) values up to redshift \( z = 1 \). Further, we also checked that the fitted parameters show no significant difference, whether we choose to use median mass ratio or the mean mass ratio.

We show in Fig. 6 the ratio between the HMFs from the CSF, AGN and from the DM simulations, after correcting halo masses in the former according to equation (1). In each panel, different line types indicate results at different redshifts with different panels referring to different values of \( \Delta_c \). We note that the correction to halo masses allows one to recover the DM HMF to good accuracy, at least for masses larger than \( 10^{13} h^{-1} M_\odot \), the HMFs are matched to the DM one with no apparent systematic bias within random oscillations of \( \lesssim 5 \) per cent. We note that results become noisy whenever the sampling effects become important due to the limited halo statistics. This is the case for large masses and, especially, for the highest overdensity \( \Delta_c = 2500 \). At small masses, below \( 10^{13} h^{-1} M_\odot \), we note that the adopted mass correction systematically produces an overestimate of the corrected HMF for AGN set. For the smallest considered mass, \( M_{DM} \geq 10^{12.5} h^{-1} M_\odot \), this overestimate is as large as 10–15 per cent, the exact value depending on the overdensity \( \Delta_c \). The reason for this lies in the fact that this fitting of equation (1)

![Figure 5. The stacked ratios of cumulative density profiles, \( \rho(< R) \), of matched haloes identified in each one of the hydrodynamical simulations and in the DM one. Different panels refer to different halo mass ranges, with the bottom right-hand panel showing the results for all haloes with mass \( M_{500} \geq 10^{12.5} h^{-1} M_\odot \). In each panel, the red and green solid lines are for the mean density ratios for the CSF and AGN case, respectively. Error bars indicate the 1\(\sigma\) scatter around the mean. Vertical dashed, dot-dashed and dotted lines indicate the median values of \( R_{200}, R_{500} \) and \( R_{2500} \) computed within each halo mass interval, with magenta and blue colours referring to the CSF and AGN simulations, respectively. We also show with continuous black lines the median values of \( R_{2500}, R_{500} \) and \( R_{200} \) for the DM simulation. The shadow regions show the limits of the gravitational softening.](image)

Table 1. Values of the best-fitting parameters describing the variation of mass of matched haloes in the AGN, CSF and in the DM simulation, as described by equation (1).

| \( \Delta_c \) | \( \Delta_c = 2500 \) | \( \Delta_c = 500 \) | \( \Delta_c = 200 \) |
|----------------|-----------------|-----------------|-----------------|
| AGN            |                 |                 |                 |
| \( M_0 \)      | 13.952          | 13.471          | 13.334          |
| \( \alpha \)   | 0.322           | 0.288           | 0.274           |
| CSF            |                 |                 |                 |
| \( M_0 \)      | 13.629          | 14.305          | 14.182          |
| \( \alpha \)   | 0.295           | 0.085           | 0.045           |
does not provide an accurate description of the mass correction at small halo masses due to the halo mass cut at $10^{12.5} \, h^{-1} M_{\odot}$, as also shown in Fig. 3.

5 DISCUSSION AND CONCLUSIONS

Based on a set of large-scale $N$-body and hydrodynamical simulations, we presented an analysis of the baryon effects on the halo mass function, with emphasis on the role played by gas accretion on to SMBHs and the ensuing AGN feedback. As such, this analysis extends our previous one, presented in Paper I, to the case in which one accounts for a suitable model for AGN feedback that regulates star formation within massive haloes, thereby improving the degree of realism of the simulated galaxy clusters and groups. We compared three simulations: a first one including only collisionless DM; a second one including hydrodynamics with radiative physics and SN feedback; a third one which also includes AGN feedback. Based on these simulations, we analyse how the halo mass distribution reacts to overcooling and, in the presence of AGN feedback, to the sudden displacements and expulsion of large amount of gas.

We use both FoF and SO algorithms to identify haloes. FoF haloes are identified using a standard (on-the-fly) FoF finder with a linking length $b = 0.16$. As for SO haloes, they are identified using an efficient memory-controlled PYTHON code – PADO, in which haloes are not allowed to overlap. We focus on three overdensities $\Delta_c = 2500, 500, 200$ for the SO haloes.

The main results of our analysis are summarized as follows.

(1) Including AGN feedback in hydrodynamical simulations causes a reduction of the HMF with respect to the DM-only case, by an amount which depends on the overdensity within which halo mass is measured. This effect amounts to about 20 per cent for overdensity $\Delta_c = 500$, with no evidence of mass and redshift dependence, and increases at higher overdensity. Therefore, our model of AGN feedback reverses the effect of radiative physics with no efficient feedback, which instead leads to an increase of the HMF.

(2) The baryonic effects on the HMF can be traced to the effect that different feedback models have on the halo density profiles and total masses. In the absence of AGN feedback, we confirm that halo density profiles steepen as a consequence of adiabatic contraction associated with overcooling, thus causing an increase of halo masses. AGN feedback generates shallower density profiles and a corresponding decrease of halo masses. This effect is caused by the improved regulation of overcooling associated with AGN feedback and to the sudden displacement of large amount of gas, which makes the gravitational potential responding with an expansion. The relative decrease of halo masses is larger in smaller objects, where AGN feedback is relatively more efficient, and at higher overdensities; for $\Delta_c = 500$, it amount to ~20 per cent at $\log M_{2500} = 12.5$, while becoming negligible for the largest haloes found in our simulation box, with $\log M_{2500} \simeq 15$. Interestingly, this effect is independent of redshift, at least up to $z = 1$ where we have a large enough statistics of massive haloes.

(3) We provide a mass-dependent fit to the halo mass variations induced by baryonic effects. After applying this model for the mass correction to the HMF obtained from the DM-only simulation, we recover the HMF from hydrodynamical simulations, up to a random scatter of $\lesssim 5$ per cent for haloes more massive than $10^{12.5} \, h^{-1} M_{\odot}$, with no significant bias and independently of redshift.

Our analysis demonstrates that baryon effects can cause sizeable variations of the HMF and, therefore, affects the measurement of cosmological parameters from redshift number counts of galaxy clusters. For instance, recent results from the Planck Collaboration (Planck Collaboration et al. 2013, cf. also Spergel, Flauger & Hlozek 2013) highlight that the cosmological model preferred by cosmic microwave background (CMB) analysis overpredicts the number of clusters expected in the Sunyaev–Zel’dovich (SZ) Planck Cluster Survey by about 50 per cent. Interestingly, this tension would be relaxed, although by a small amount, if the HMF calibrated with our AGN simulation is used to predict SZ cluster number counts.

In a recent paper, Khandai et al. (2014) also investigated the effect of including AGN feedback on the HMF. Since they considered simulation boxes smaller than ours, with size of $100 \, h^{-1} M_{\odot}$, they better probed the low-mass end of the HMF, while having a worse sampling of the high-mass end. As a result of their analysis, they found that the FoF halo mass function can be described with a
universal form to a reasonable accuracy, even after accounting for baryon effects.\footnote{After the submission of our paper, a paper by Velliscig et al. (2014) appeared on the arXiv, which also included an analysis of baryon effects on halo masses and HMF, when AGN feedback is also included. Using box size and resolution quite similar to those of our simulations, they confirmed our results on the effect of AGN feedback on the HMF.}

Numerical convergence in the calibration of the HMF from purely collisionless simulations could in principle be reached by ‘brute force’ (i.e. increasing the dynamic range accessible and the gravitational force integration accuracy). The same may not be true when the effects of baryons are included. In fact, our analysis shows that baryons can generate variations of the HMF with respect to the DM case which goes in different directions, depending on the nature and, possibly, on the numerical implementation of feedback.

In this respect, confidence in the calibration of baryon effects in the HMF is strictly related to the level of agreement between observational results and model predictions for a variety of properties of galaxy clusters. Current implementations of AGN feedback in cosmological simulations produce cluster populations with an increased degree of realism (e.g. Puchwein et al. 2008; Dubois et al. 2012; Le Brun et al. 2013; Planelles et al. 2013, 2014, and references therein). As an example, we compare in Appendix B two basic properties involving baryons in clusters, namely the stellar mass fraction and the total baryon mass fraction, with observational results. The good agreement between the AGN simulation and observational results is quite encouraging. Still, it is fair to admit that important tensions still exist between a number of observed and simulated cluster properties, such as the thermal structure of cool cores and the properties of the brightest cluster galaxies (e.g. Dubois et al. 2011; Ragone-Figueroa et al. 2013; Planelles et al. 2014, cf. Kravtsov, Vikhlinin & Mészáros 2014). There is no doubt that providing an HMF, that accounts for the inclusion of the baryon physics at the per cent level of accuracy required by the next generation of large-scale cluster surveys, still requires substantial work and, ultimately, a precise numerical description of galaxy formation in a cosmological framework.

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We apply such a strategy to the SO method, and for this purpose we wrote a `PYTHON` code – `PIAO`. `PIAO` makes extensive use of the `NUMPY` library. We also made a modification of the `CKDTREE` package in the `SCIPY` library, adding the SPH density calculation in it. We adopt the same SPH kernel as the `SPATIAL` package in the `Cython` library. `PIAO` also made a modification of the `MPI` strategy in a standard SO halo finder algorithm and describe our `PIAO`.\footnote{\textit{PIAO} is publicly available at https://github.com/ilaudy/PIAO} We check the consistency of `PIAO` and tackle the problem of halo overlapping in SO methods in Section A2. Finally, we also show that `PIAO` is very efficient in memory control.

### A1 Methodology and program

With the rapid growth of supercomputing power, cosmological simulations increase not only in resolution, but also in sheer volume. Thus, the output dimension of these simulations increases enormously, up to several Terabytes, or even Petabytes. Analysing such a huge amount of data on a relatively small server, easily meets a memory shortage problem. Limited memory forbids reading all the simulation information at one time.

We use a simple strategy to overcome this problem: splitting the whole simulation box into small mesh-boxes, then analysing them one-by-one. We apply this strategy in two steps. Step one: the whole box is meshed into small ones. Each mesh-box is written into separated files which only contain only the needed information. Step two: each file is iteratively read in and analysed. Although this strategy inevitably wastes time on I/O processes and hard disk space, we show below that this meshing/I/O time is usually very short compared to the time spent in actually performing the analysis.

We apply such a strategy to the SO method, and for this purpose we wrote a `PYTHON` code – `PIAO`. `PIAO` makes extensive use of the `NUMPY` library. We also made a modification of the `CKDTREE` package in the `SCIPY` library, adding the SPH density calculation in it. We adopt the same SPH kernel as the `GADGET` code. To achieve high performance, `CKDTREE` implements the algorithm described in Maneewongvata et al. (1999) in `Cython`. `PIAO` is also parallel with a `PYTHON` MPI package (`MPI4PY`) to speed up the calculation by taking advantage of multicore CPUs. In its first step, `PIAO` reads in particles’ positions from simulation snapshots part by part, and meshes them into small boxes according to mesh size. Only particles’ ID, position and mass are saved into mesh files. In a second step, `PIAO` reads in one mesh file at a time, and builds a buffer region around this mesh-box by reading in information from all nearby mesh-boxes. All the particles’ densities within the mesh-box and its buffer region are calculated using the nearest neighbours $N_{\text{enm}}$ of each particle and applying the selected SPH kernel over them.

`PIAO` uses the following simple loop to identify SO haloes.

\begin{enumerate}
\item The particle with the highest SPH density is chosen as the centre of a SO halo.
\end{enumerate}
(2) The code iteratively finds a radius $R_3$, centred on the above particle, and enclosing a fixed overdensity $\Delta = M(<R_3)/(4\pi R_3^3)/\rho_{crit}$. If the centre was within the current mesh-box, all properties of this halo are computed, and the halo is then saved.

(3) All particles within the radius $R_3$ are flagged and excluded from being new centres by themselves. If we do not allow halo overlapping, those particles are also excluded from belonging to further haloes.

(4) If the current halo contains less than a chosen number of particles $N_{\text{cut}}$, the cycle ends. All of the remaining particles will not belong to any halo.

(5) Next particle with highest SPH density is selected, and the loop continues from step (2).

We paralleled PIAO using the MP4P4 package to take advantage of multiple core architectures. Since the analysis of each mesh-box is independent, this part is completely parallel and does not need any communication nor barrier. One processor is used for controlling and assigning tasks, i.e. mesh-cubes to free processes. This makes PIAO very flexible and balanced. In principle, it can run on any number of processors.

A2 Consistency check

In this subsection, we test PIAO on a simulation, having 256$^3$ DM ($M_{\text{DM}} = 1.93 \times 10^8 h^{-1} M_\odot$) and 256$^3$ gas particles ($M_{\text{gas}} = 3.86 \times 10^7 h^{-1} M_\odot$) in a periodic box of comoving size 18$h^{-1}$ Mpc. This simulation includes metal-dependent cooling, star formation and SN thermal and kinetic feedback (see more details about the model for star formation and energy feedback in Murante et al. 2010). Also this simulation has been run using the TreePM-SPH GADGET-3 code with the same cosmological parameters of the simulations presented in the main text of the present work. We used this simulation instead of those described in Section 2 just because it contains a lower number of particles, and the analysis is thus quicker. Results on properties of galaxies and of diffuse baryons in that simulation will be presented elsewhere. Here we mainly focus on our halo finder performance, and in particular on two PIAO parameters: mesh-box size and SPH neighbour. We fix the overdensity parameter to $\Delta = 500$, and minimum number of particles per halo to $N_{\text{cut}} = 64$.

A2.1 Mesh-box size

Since PIAO employs a mesh to split the whole simulation into small boxes, we first need to check that such a splitting does not influence the halo identification procedure. We used two mesh-box sizes ($3.6 h^{-1}$ Mpc) and checked our results against those obtained when the whole test simulation is analysed without any splitting.

Given that the mesh-box size should not affect the results, we expect to find the same halo masses for the three different mesh-box sizes. Since we use the same SPH neighbours $N_{\text{lbs}} = 64$ for those tests, particles at the centres of identical haloes are expected to have the same SPH density.

We decided that haloes found in different analyses are the same one if their centre particles have the same particle ID. All haloes above mass $M_{\text{lbs}} = 1.5 \times 10^9 h^{-1} M_\odot$ are well matched between different mesh-box sizes. We confirm that all the matched haloes have the same mass. Thus, mesh size does not change the properties of all identified haloes. We found the same result both allowing and not allowing haloes to overlap.

A2.2 SPH neighbours

SPH density depends upon the number of neighbours $N_{\text{lbs}}$. Changing the SPH density of particles can change the identification of the most dense particle, i.e. the centre of halo. If the centre changes, all halo properties can also vary. We check the convergence of this parameter by using three SPH neighbours numbers $N_{\text{lbs}} = 32, 64, 128$ on our test simulation, keeping fixed the mesh-box size to $6 h^{-1}$ Mpc.

In Fig. A1, we show halo mass functions from test simulation with different SPH neighbours. The meaning of the colour and line style is shown in the top right-hand legend. We show ratios of the halo mass functions with respect to that obtained using $N_{\text{lbs}} = 128$ in the lower panel. At the high-mass end of the mass functions, $M_{\text{lbs}} \gtrsim 10^{12} h^{-1} M_\odot$, there are no differences between the results for any value of $N_{\text{lbs}}$. This means that this SPH neighbour parameter has no effect on massive haloes. This SPH parameter makes the HMF ratio fluctuate below a halo mass of $\sim 10^{11.5} h^{-1} M_\odot$. While at smaller halo mass, these scatters are basically reduced within ~1 per cent. Above all, we expect that the SPH density accuracy will have a $\lesssim 3$ per cent effect on halo mass function. If we do not allow haloes to overlap, the discrepancies are even smaller.

We also matched all the individual haloes having mass $M_{\text{lbs}} > 1.5 \times 10^9 h^{-1} M_\odot$ and found using $N_{\text{lbs}} = 128$ neighbours, with those identified using $N_{\text{lbs}} = 32$ and 64 neighbours. First, we matched haloes with the central particle having the same ID. Then, for all unmatched haloes from our $N_{\text{lbs}} = 128$ analysis we calculated the minimum distances from the centres of unmatched haloes in the $N_{\text{lbs}} = 32, 64$ analyses. If such a distance is smaller than both the $N_{\text{lbs}} = 128$ and the $N_{\text{lbs}} = 32, 64$ halo radius, we decided that the corresponding haloes matches. After this one-by-one matching procedure, we are left with 7 (0.15 per cent) unmatched haloes in our $N_{\text{lbs}} = 32$ analysis and 1 (0.02 per cent) with the $N_{\text{lbs}} = 64$ one when we allow overlapping. In the case of non-overlapping haloes, we have 5 (0.11 per cent) unmatched objects for our $N_{\text{lbs}} = 32$ analysis and 2 (0.04 per cent) for the $N_{\text{lbs}} = 64$ one. Most of the unmatched haloes have $M_{\text{lbs}} < 10^{10} h^{-1} M_\odot$. We show the halo mass ratios in Fig. A2 for all matched haloes.
Even if the halo number, at a given mass scale, changes less than 3 per cent (as discussed above), inaccuracies in the SPH density evaluation can lead to large halo mass difference for particular objects (see magenta triangles in Fig. A2). Therefore, when halo-by-halo matching is needed, we recommend a higher number of neighbours to be used in the density evaluation.

A2.3 Overlapping problem

In X-ray or SZ observations, clusters are usually allowed to overlap, and overlapping objects count as separate objects. However, usually such observations only focus on most massive clusters, with masses larger than $10^{14.5} \, M_\odot$. Overlapping between these clusters is rare. Even if two haloes with such a mass overlap, at worst one halo will have its mass increased by less than 50 per cent with the other one suffering an equivalent mass decrease. Simulations span a wider mass range, currently five or more orders of magnitudes, and reach lower masses. We need to have an accurate halo mass function at per cent level over the whole covered mass range. Thus, the difference between overlapping and non-overlapping halo identification must be carefully examined.

To answer the question of how halo overlapping can change the halo mass function, we used PIAO to analyse our DM-only simulation described in Section 2 at three overdensities $\Delta = 2500, 500, 200$, both allowing overlapping and not allowing it. Since SPH neighbours should not affect halo mass function too much (see the discussion in Section A2.2), we fixed the number of SPH neighbours to $N_{\text{neigh}} = 64$. The minimum halo particle number parameter is set at $N_{\text{min}} = 64$. Resulting halo mass functions are shown in Fig. A3. In the lower panel of this figure, we show the ratios of mass functions obtained at the various overdensities when we allow overlapping with respect to the non-overlapping case. The effect on the halo mass function is within 3 per cent over the whole halo mass range, with the overlapping case systematically overpredicting the mass function. This result does not strongly depend on the chosen overdensity nor on the mass scale, apart from the higher masses ($M > 10^{14.5} \, h^{-1} M_\odot$, where the two analyses give identical results).

A3 Summary

We used a simple meshing strategy to overcome the problem that analysing large simulations on a small server or PC can be difficult due to memory limitation, and present a simple parallel PYTHON SO halo finding code – PIAO.

PIAO employs two additional parameters besides the overdensity $\Delta$: the mesh-box size, which splits the whole simulation box into smaller ones, and the SPH neighbours number, which is used for the SPH density calculation. In Section A2, we showed that the mesh-box size parameter does not influence the identification of haloes nor their properties. Since SPH density is used to locate halo density peaks, we further investigated the impact of the SPH neighbours number parameter on halo properties. The halo mass function is not strongly affected by it (at most at the $\lesssim 3$ per cent level). On the other hand, one-by-one halo comparison suggests that an inaccurate density estimate may lead to large disagreements for individual haloes. At last, we investigated the halo overlapping problem in Section A2.3, and showed that the halo mass function is $\sim$1–3 per cent higher for overlapping haloes for three different overdensities, independently from the value of the overdensity.

We notice here, that all these tests in this appendix are done on a desktop PC, with a 4 core 2.67 GHz CPU and total memory $\sim 3.4$ GB. For test simulation with mesh-box size $6 \, h^{-1}$ Mpc buffer region, peak using memory is $\lesssim 0.9$ GB for one processor. The meshing time is about 2 per cent of the analysing time. For the DM simulation, we used mesh-box size $41$ and $4.5 \, h^{-1}$ Mpc buffer region. Although the DM simulation has about eight times more particles than the test simulation, the allocated memory for one CPU is only $\sim 10$ per cent of the total memory, because the DM simulation was separated into 1000 mesh boxes. However, using the same number of CPUs, the analysing time for the DM simulation is about eight times more than for the test simulation.
APPENDIX B: THE STELLAR AND BARYON MASS FRACTION

For better understanding and calibrating the effects of baryons on the HMF, the baryon and stellar fraction can provide a key element. We define the total baryon mass fraction as the ratio between the gas + stars mass and the total mass within \( R_{500} \):

\[
f_b = \frac{(M_{\text{gas}} + M_{\text{stars}})}{M_{\text{tot}}},
\]

while the stellar fraction is

\[
f_s = \frac{M_{\text{stars}}}{M_{\text{tot}}}.
\]

The two fractions have been investigated in many works (from observation e.g. Lin, Mohr & Stanford 2003; Gonzalez, Zaritsky & Zabludoff 2007; Giodini et al. 2009; Andreon 2010; Lagana et al. 2011, 2013; Zhang et al. 2011; Lin et al. 2012; Gonzalez et al. 2013), (or from theory e.g. Borgani et al. 2006; Ettori et al. 2006; Fabjan et al. 2010; Puchwein et al. 2010; McCarthy et al. 2011; Le Brun et al. 2013; Planelles et al. 2013). The total baryon fraction is commonly found to increase with the mass of the halo, while the stellar fraction seems to increase when going from clusters of galaxies mass scale to groups ones.

In Fig. B1, we show the baryon fraction \( f_b \) and stellar fraction \( f_s \) from CSF and AGN simulations, described in Section 2. The four panels show results from redshift \( z = 2.2 \) to 0. Different colour points show the fractions \( f_b \) and \( f_s \) computed for the two simulations, for each halo, while the solid colour lines are the mean of the points. Comparing the results from CSF and AGN sets, we can see that without AGN feedback, continuous star-forming processes produce both higher stellar fraction \( f_s \) and baryon fraction \( f_b \) inside \( R_{500} \) compared to the AGN set at all redshifts. Similar to the finding of Planelles et al. (2013), both fractions, for the two simulations, show almost no redshift evolution for the most massive haloes. However, at smaller halo mass, \( f_b \) computed on our CSF simulation shows a smaller decrease in time, when compared to the result from AGN simulation (\( \sim 0.13 \) at \( z = 2.2 \) to \( \sim 0.07 \) at \( z = 0 \)). The stellar fraction \( f_s \) computed on our CSF set increases with time, while there is a slightly decreasing trend for the same fraction calculated on our AGN simulation.

In the lower right-hand panel of Fig. B1, we compare our results with observations from recent works of Gonzalez et al. (2013) and Lagana et al. (2013) at redshift \( z = 0 \). Both papers use a 7-year Wilkinson Microwave Anisotropy Probe (WMAP7) cosmology, and we corrected our results to account for that. Clearly, both fractions computed on our AGN simulation show a better match to the observations than our CSF simulation results. The trend of the fraction \( f_b \) with mass, in our AGN simulation, is also in good agreement with observations. However, the fraction \( f_s \) computed on the same AGN...
simulation is flatter than the observation results at the high-mass end. This indicates that AGN feedback in our simulation is still not efficient enough to quench star formation at the observed levels in the most massive haloes.

APPENDIX C: RESOLUTION TEST

In this section we discuss the convergence against numerical resolution of the results on the mass correction induced by the baryonic effects included in the AGN simulations. While we did not carry our simulations of cosmological boxes at higher resolution, we analysed zoomed-in simulations of galaxy clusters and groups carried out at different resolutions. These simulations include all the baryonic effects as the AGN large-box simulation analysed in this paper. More in detail, we used four of the 29 Lagrangian regions surrounding massive clusters, presented by Bonafede et al. (2011). Ragone-Figueroa et al. (2013) and Planelles et al. (2014), and presented results from hydrodynamical simulations of these Lagrangian regions which include the effect as SN and AGN feedback, as in the simulation considered in this paper. DM and baryonic particles in these simulations have masses of $8.47 \times 10^8$ and $1.53 \times 10^8 h^{-1} M_\odot$, respectively. As such they have mass resolution which is a factor of about 4 better than the cosmological simulations presented in this paper. Four of these Lagrangian regions have been resimulated by further increasing mass resolution by a factor of 10. We identified seven haloes in these four simulations, all having masses of at least $10^{13} h^{-1} M_\odot$, whose counterparts in the low-resolution (LR) and high-resolution (HR) versions are both free of contaminant DM particles coming from outside the zoomed-in Lagrangian regions. The $M_{500}$ values for these haloes have been compared to the corresponding masses measured in DM-only version of the same simulations. The results on the mass variation induced by the baryonic effects included in the AGN simulations are shown in Fig. C1, both for the LR and HR versions. Therefore, this figure illustrates how baryonic effects impact on halo masses when mass resolution is increased by a factor of about 40.

Clearly, the relatively small number of objects prevents us from drawing any robust statistical conclusion from this test. Still, we confirm the decrease of halo masses when AGN feedback is included. This decrease is also confirmed to be more pronounced in smaller haloes, with a trend that shows no evidence of resolution dependence. This result is in line with the resolution test presented by Velliscig et al. (2014). More in detail, we note that the absolute value of halo masses in the DM-only simulations (as reported on the abscissa) can have small, but sizeable, variations with resolution, again with no obvious trend. The reason for these variations lies in the fact that, when mass resolution is increased, higher frequency modes from the linear power spectrum are also added when computing the displacement and velocity fields in the initial conditions. This effectively causing small variations in the timing of halo formations and mergers, which result in variations of halo masses at a fixed redshift.

Figure C1. Resolution test at $z = 0$ for the values of the $M_{500}$ halo masses. Small green dots are for the haloes identified in the simulations analysed in this paper (see also bottom right-hand panel of Fig. 3). Overplotted are the results from zoomed-in simulation of galaxy clusters carried out for the DM and AGN cases, at two different resolutions. The lower resolution (LR; blue triangles) simulations have a mass resolution which is a factor of about 4 better than for the reference cosmological boxes, while the higher resolution (HR; red squares) have a mass resolution 10 times better than the LR ones. Cluster counterparts identified in the two simulations sets are connected by black solid lines.

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