The effects of baryons on the halo mass function

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ABSTRACT
We present an analysis of the effects of baryon physics on the halo mass function. The analysis is based on simulations of a cosmological volume having a comoving size of $410\,h^{-1}\,\text{Mpc}$, which have been carried out with the TREE-PM/smoothed particle hydrodynamics code GADGET-3, for a Wilkinson Microwave Anisotropy Probe-7 $\Lambda$ cold dark matter cosmological model. Besides a dark matter (DM)-only simulation, we also carry out two hydrodynamical simulations: the first one includes non-radiative physics, with gas heated only by gravitational processes; the second one includes radiative cooling, star formation and kinetic feedback in the form of galactic ejecta triggered by supernova explosions. All simulations follow the evolution of two populations of $1024^3$ particles each, with mass ratio such that to reproduce the assumed baryon density parameter, with the population of lighter particles assumed to be collisional in the hydrodynamical runs. We identified haloes using a spherical overdensity algorithm and their masses are computed at three different overdensities (with respect to the critical one), $\Delta_c = 200, 500$ and 1500.

We find the fractional difference between halo masses in the hydrodynamical and in the DM simulations to be almost constant, at least for haloes more massive than $\log(M/\Delta_c\,h^{-1}\,\text{M}_\odot) \geq 13.5$. In this range, mass increase in the hydrodynamical simulations is of about 4–5 per cent at $\Delta_c = 500$ and $\sim 1–2$ per cent at $\Delta_c = 200$. Quite interestingly, these differences are nearly the same for both radiative and non-radiative simulations. Mass variations depend on halo mass and physics included for higher overdensity, $\Delta_c = 1500$, and smaller masses. Such variations of halo masses induce corresponding variations of the halo mass function (HMF). At $z = 0$, the HMFs for gravitational heating and cooling and star formation simulations are close to the DM one, with differences of $\lesssim 3$ per cent at $\Delta_c = 200$, and $\lesssim 7$ per cent at $\Delta_c = 500$, with $\sim 10–20$ per cent differences reached at $\Delta_c = 1500$. At this higher overdensity, the increase of the HMF for the radiative case is larger by about a factor of 2 with respect to the non-radiative case. Assuming a constant mass shift to rescale the HMF from the hydrodynamic to the DM simulations, brings the HMF difference with respect to the DM case to be consistent with zero, with a scatter of $\lesssim 3$ per cent at $\Delta_c = 500$ and $\lesssim 2$ per cent at $\Delta_c = 200$.

Our results have interesting implications for assessing uncertainties in the mass function calibration associated with the uncertain baryon physics, in view of cosmological applications of future large surveys of galaxy clusters.

Key words: methods: numerical – methods: statistical – galaxies: abundances – galaxies: general – cosmology: theory – large-scale structure of Universe.

1 INTRODUCTION
An accurate calibration of the halo mass function (HMF hereafter) is at the hearth of a range of cosmic structure formation studies,
from the study of galaxy formation through semi-analytical models (e.g. Baugh 2006), to the cosmological application of galaxy clusters (Allen, Evrard & Mantz 2011). Under the standard hierarchical Λ cold dark matter (ΛCDM) model, haloes are formed from initial density peaks through gravitational instability. The HMF is directly connected to the primordial density field. Since the abundance of density peaks over a given mass scale \( M \) only depends on the rms value \( \sigma_M \) of the linear fluctuation field at that mass scale, the abundance of haloes is expected to be universal once expressed as a function of \( \sigma_M \), as assumed by the Press–Schechter approach based on the spherical collapse model (Press & Schechter 1974) and in the ellipsoidal collapse extension by Sheth & Tormen (1999).

Through the years, \( N \)-body simulations of large cosmological volumes have been used to calibrate fitting functions for a universal HMF (e.g. Jenkins et al. 2001; Springel et al. 2005; Warren et al. 2006; Lukić et al. 2007). Thanks to the progressive increase in the covered dynamic range of halo masses, simulation results have been shown to predict subtle but sizeable deviations from universality of the mass function (MF). For instance, Reed et al. (2003) found that the universal MF by Sheth & Tormen (1999) overpredicts the number of most massive haloes found at \( z > 10 \). This result was confirmed by the subsequent analysis by Reed et al. (2007), who pointed out that an even better fit for the MF can be obtained if it is allowed to depend not only on the linear rms overdensity, but also on the local slope of the linear power spectrum at the relevant mass scale. Using the spherical overdensity (SO) algorithm to measure cluster masses, Tinker et al. (2008) combined different simulations to calibrate the HMF, with masses measured at different overdensities. They found significant deviations from non-universality, with a monotonic decrease of halo abundance with increasing redshift, and provided fitting functions to such deviation. Besides confirming the non-universal behaviour of the high end of the HMF, Crocce et al. (2010) and Tinker et al. (2008) also pointed out that using more accurate second-order Lagrangian perturbation theory (2LPT) to set initial conditions could be relevant for an accurate HMF calibration. Bhattacharya et al. (2011) analysed the HMF for an extended suite of simulations also including quintessence models with \( w \neq -1 \) for the dark energy equation of state, and confirmed the violation of universality at the \( \sim 10 \) per cent level for the range of masses and redshift covered by their simulations.

At least in principle, calibrating the MF of dark matter (DM hereafter) haloes with great accuracy is just a technical problem to be tackled by extending the dynamic range of simulations and the parameter space of considered cosmological models. However, the back-reaction effects of baryons on DM haloes are known to impact on density profiles and, therefore, on their mass. In turn, these back-reaction effects are expected to depend on the detail of the physical processes, such as radiative cooling, star formation and energy feedback from astrophysical sources, which determine the distribution of baryons within DM haloes. Tinker et al. (2008) included a non-radiative hydrodynamical simulation of a large cosmological volume within the large set of simulations that they analysed, without however discussing in detail the effect of baryons on the HMF. Rudd, Zentner & Kravtsov (2008) compared the HMF computed for a DM-only simulation with those obtained from the corresponding hydrodynamical simulations, carried out with an adaptive mesh refinement (AMR) code both with non-radiative physics and including the effect of gas cooling and star formation (CSF). After computing masses at the virial radius, they found that the HMF for the non-radiative simulation is very close to the DM-only one, at least in the mass range numerically resolved by both simulations. On the other hand, the radiative simulation was found to produce a \( \geq 10 \) per cent higher MF, as a consequence of the higher halo concentration resulting from adiabatic contraction (e.g. Gnedin et al. 2004). A significant increase of halo concentration from adiabatic contraction is a well-known consequence of (over)efficient gas cooling (e.g. Pedrosa, Tissera & Scannapieco 2009; Duffy et al. 2010; Tissera et al. 2010). In line with this result on halo concentration, also the total matter power spectrum in radiative hydrodynamic simulations has been shown to have a higher amplitude than for DM-only \( N \)-body simulations, small non-linear scales \( k > 1 h \, \text{Mpc}^{-1} \) (Jing et al. 2006; Rudd et al. 2008; van Daalen et al. 2011; Casarini et al. 2012). However, also the simple case of non-radiative hydrodynamics has been suggested to increase halo concentration, as a consequence of a redistribution of energy between baryons and DM during halo collapse (Rasia, Tormen & Moscardini 2004; Lin et al. 2006). An increase of halo concentration leads to an increase of halo masses, hence increasing the HMF. Zentner, Rudd & Hu (2008) suggested that the main effects of baryons can be translated into a simple change of halo concentrations, thereby resulting in a uniform relative shift of halo masses. Stanek, Rudd & Evrard (2009) compared the cluster masses and mass functions for a set of simulations including only DM, non-radiative hydrodynamics, as well as radiative runs with and without pre-heating. They reported for the pre-heated run an average decrease of halo mass \( M_{500} \) by 15 per cent with respect to the non-radiative case, and 16 per cent halo mass enhancement for simulation with CSF with respect to the DM simulation. These mass variations result in differences of the HMF of up to \( \sim 30 \) per cent. Stanek et al. (2009) based their analysis on two different sets of simulations, based on smoothed particle hydrodynamics (SPH) and AMR codes, also using slightly different choices for the cosmological parameters. Furthermore, results for their CSF case were based only on resimulations of the 13 most massive haloes identified in the original simulation volume.

In order to improve on our current understanding of baryon effects on the HMF, we present in this paper the analysis of three cosmological simulations based on DM-only, non-radiative hydrodynamics and cooling, star formation and supernova (SN) feedback. These simulations are carried out starting from the same initial conditions and using the same TREE-PM/SPH code GADGET-3 (Springel 2005a). The resolution and box size of our simulations are adequate to cover the halo mass distribution over the range \( \log(M_{200}/h^{-1} M_{\odot}) \approx (12.5−15) \) at \( z = 0 \). Due to the inclusion of hydrodynamics, the dynamic range covered by our simulations is in general narrower than that accessible by \( N \)-body simulations used over the last few years for precision calibrations of the HMF. For this reason, the aim of this paper is not to provide one more of such calibrations; rather our goal is to assess in detail the impact of baryons on the HMF.

This paper is organized as follows. In Section 2, we describe the simulations. Section 3 is devoted to the presentation of the analysis method and results. After describing the halo identification method based on SO, we present the results of our analysis in terms of the mass variation of haloes and resulting effect on the HMF. Finally, we discuss our results and present the main conclusions in Section 4.

2 THE SIMULATIONS

We carry out simulations of a flat ΛCDM cosmology with \( \Omega_m = 0.24 \) for the matter density parameter, \( \Omega_b = 0.0413 \) for the baryon

\[ 1 \] In the following, we will use the convention \( R_{\Delta} \) to indicate the halo radius encompassing an average overdensity of \( \Delta \) times the critical cosmic density \( \rho_c(\Delta) \). Accordingly, \( M_{\Delta} \) is the halo mass contained within \( R_{\Delta} \).

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component, \( \sigma_s = 0.8 \) 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 Zeldovich approximation for a periodic cosmological box with comoving size \( L = 410 \) h\(^{-1}\) Mpc. Initial density and velocity fields are sampled by displacing, at redshift \( z = 41 \), the positions of two sets of 1024\(^3\) particles each, according to the Zeldovich approximation, from unperturbed positions located on to two regular grids which are shifted by half grid size with respect to each other. Masses of the particles belonging to the two sets have ratio such that to reproduce the cosmic baryon fraction, with \( m_1 \simeq 3.54 \times 10^6 \) and \( m_2 \simeq 7.36 \times 10^6 \) h\(^{-1}\) M\(_\odot\). In the DM-only simulation both particle species are treated as collision-less, while in the hydrodynamical simulations \( m_2 \) provides the mass of gas particles. We emphasize that this prescription to set initial conditions for the DM simulation ensures that it starts exactly from the same sampling of density and velocity field as its hydrodynamical counterpart. The convergence of the MF against changing initial redshift and the effect of using 2LPT have been discussed by Tinker et al. (2008) and Crocce et al. (2010). Although small but sizeable effects have been detected in the high end of the MF, the general result is that the effect of 2LPT is rather small for the initial redshift and resolution relevant for our simulations. Furthermore, since our analysis is focused on the relative effect induced by the presence of baryons, we expect the main conclusions not to be affected by increasing the accuracy in the computation of displacements in the generation of initial conditions.

Simulations are carried out using the \textsc{tree-particle} code \textsc{gadget-3}, an improved version of the \textsc{gadget-2} code (Springel 2005b). In \textsc{gadget-3} domain decomposition is performed by allowing disjointed segments of the Peano–Hilbert curve to be assigned to the same computing unit, thus leading to a significant improvement of the work-load balance when run over a large number of processors. 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 a higher redshift.

Besides a DM-only simulation, we also carried out two hydrodynamical simulations. A non-radiative simulation only including gravitational heating of the gas (GH hereafter) used 64 neighbours for the computation of hydrodynamic forces, with the width of the B-spline smoothing kernel allowed to reach a minimum value equal to half of the gravitational softening. A second hydrodynamical simulation has been carried out by including the effect of CSF. In this simulation radiative cooling is computed for non-vanishing metallicity according to Sutherland & Dopita (1993), also including heating/cooling from a spatially uniform and evolving ultraviolet 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). In each multiphase gas particle, a cold and a hot phase coexist in pressure equilibrium, with the cold phase providing the reservoir of star formation. 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. The CSF simulation also includes a description of metal production from chemical enrichment contributed by Type II SN (SN-II), Type Ia SN and asymptotic giant branch stars, as described by Tornatore et al. (2007). Kinetic feedback is implemented by mimicking galactic ejecta powered by SN explosions. In these runs, galactic winds have a mass upload proportional to the local star formation rate. We use \( v_w = 500 \) 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 a Salpeter initial mass function. The feedback model included in the CSF simulation is known not to be able to regulate overcooling, especially in large cluster-sized haloes (e.g. Borgani et al. 2004). To show this, we implement a consistent comparison in Fig. 1, between observational results on the mass fraction in stars within \( R_{500} \) (from Gonzalez, Zaritsky & Zabludoff 2007; see also Gonzalez et al. 2007; Lagana et al. 2011) and results obtained from the analysis of the clusters and groups identified in the CSF simulation. Quite apparently, simulations predict a decline of the stellar mass fraction as a function of the cluster mass which is much milder than the observed one. As a result, massive systems in simulations are predicted to have an exceedingly high mass fraction in stars. Therefore, while none of the two hydrodynamical simulations provides a fully correct description of the evolution of baryons within DM haloes, considering both the GH and the CSF runs one should provide a useful indication of the impact of current uncertainties in the description of baryon physics.

3 RESULTS

3.1 Halo identification

The two most common methods for halo identification simulations are the one based on the Friend-of-Friend (FoF) algorithm (e.g. Davis et al. 1985) and that based on the SO algorithm (Lacey & Cole 1994). The FoF halo finder has only one parameter, \( b \), which defines the linking length as \( hl = n^{-1/3} \) is the mean interparticle separation, with \( n \) being the mean particle number density. In the SO algorithm there is also only one free parameter, namely the mean density \( \Delta_c \). Contained within the sphere within which the halo mass is computed, with \( \rho_{\text{crit}} \) being 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 the difference of the halo mass and HMF defined by the two methods has been discussed in several analyses (e.g. White 2002; Reed et al. 2003, 2007; Cohn & White 2008; Tinker et al. 2008; More et al. 2011).
In our analysis we apply the SO method, with masses measured at four different overdensities corresponding to $\Delta_c = 200$, 500 and 1500, thus ranging from the overdensity which characterize the whole virialized region of haloes up to the typical overdensity which is accessible by Chandra and XMM–Newton X-ray observations. Our halo identification proceeds in two steps. In the first step, we run an FoF algorithm with linking length $b = 0.16$ over the distribution of DM particles (in the DM-only simulation the FoF is run over the distribution of more massive particles). Then, we identify in each FoF group the DM particle which corresponds to the minimum of the potential. The position of this particle is taken to be the centre of the cluster from where to grow spheres whose radius is increased until the mean density within it reaches the required overdensity $\Delta_c$. The mass $M_{\Delta_c}$ within this spherical region of radius $R_{\Delta_c}$ is

$$M_{\Delta_c} = \frac{4}{3} \pi R_{\Delta_c}^3 \Delta_c \rho_{\text{crit}}(z).$$

(1)

Since each halo is first identified starting from an FoF algorithm, it inherits some FoF disadvantages. A well-known potential problem with FoF is that there are situations in which two haloes are connected through a bridge of particles. Since this halo is counted only once, this could affect the number of SO haloes and the resulting MF. As discussed by Reed et al. (2007), this effect becomes more important at high redshift and for poorly resolved, low-mass haloes. Since we restrict our analysis to haloes having a minimum mass of $10^{13} h^{-1} M_\odot$, thus being resolved by at least $10^3$ particles, and redshift $z \leq 1$, and we use a linking length smaller than the usually adopted value $b = 0.2$, we expect that the bias induced by using FoF parent groups should be mitigated. Since the FoF grouping is carried out using DM particles as primary particles, we expect halo bridging to affect in the same way the $N$-body and the different hydrodynamical simulations. Therefore, our main conclusions on the relative effect of baryons on the MF should be left unchanged by the effect of using FoF groups as the starting point of the SO identification. Finally, since the groups identified by the FoF algorithm have by definition no overlapping, we do not include in our identification of SO haloes any restriction to prevent such overlapping (see Tinker et al. 2008 for a discussion on halo overlapping).

3.2 Effect on the halo mass and density profile

We first focus on the impact that baryons have on the mass of individual haloes. For this purpose, we show in Fig. 2 the distribution of the differences between haloes identified in the two hydrodynamical simulations and in the DM simulation, at different overdensities. This figure shows the results for all the haloes that in the DM simulation have $M_3 \geq 10^{14} h^{-1} M_\odot$. To compare halo masses, one has to identify a halo selected in the DM simulation with its counterpart in each of the hydrodynamical simulations. The easiest way to perform this identification is to look for the haloes having the closest coordinates. While this procedure provides a reliable identification of corresponding haloes in two different simulations for the most massive systems, it turns out not to be accurate for poorer systems. In fact, besides affecting the mass of haloes, the presence of baryons also slightly alters the overall dynamics and, therefore, the exact halo positions. In order to overcome this difficulty we decided to follow a different procedure to find in each of the hydrodynamical simulations the haloes corresponding to those identified in the DM run. For each halo in the DM simulation we identify the Lagrangian region from where particles following within its virial radius by $z = 0$ come from. We then look into each of the GH and CSF simulations for a halo that contains at least 60 per cent of the particles coming from the same Lagrangian region. We verified that the final results do not change significantly if we use a more restrictive requirement, which find instead 80 per cent of the particles from the same Lagrangian region.

From Fig. 2, we see that significant mass differences, of up to 20 per cent, are found for $\Delta_c = 1500$, with the distribution of such differences becoming narrower at $\Delta_c = 200$. Correspondingly, the mean value of the halo mass increase induced by the presence of baryons decreases from $\approx 6$–7 per cent at $\Delta_c = 1500$ to $\approx 3$–4 per cent at $\Delta_c = 500$, while being $\ll 1$ per cent at $\Delta_c = 200$. Furthermore, any differences between the two hydrodynamic runs are much smaller than the difference that each of them has with respect to the DM run. This result agrees roughly with the weak sensitivity of the baryon effects on the MF, as shown in Fig. 5. Even at the highest considered overdensity, $\Delta_c = 1500$, there are a small number of haloes whose mass in the hydrodynamical runs is

Figure 2. The distribution of the mass ratios between the haloes identified in each of the two hydrodynamical simulations to the corresponding haloes in the DM simulation. The three panels from left to right show the results at $\Delta_c = 1500$, 500 and 200. The red and black continuous histograms show the results for $M_{\text{GH}/M_{\text{DM}}}$ and $M_{\text{CSF}/M_{\text{DM}}}$, respectively. In each panel, results are shown only for haloes with $M_3 \geq 10^{14} h^{-1} M_\odot$. The solid vertical lines correspond to no mass variation, while the dashed and dotted vertical lines show the mean values (which is shown on the right-top of each panel) of $M_{\text{GH}/M_{\text{DM}}}$ and $M_{\text{CSF}/M_{\text{DM}}}$, respectively.
The ratio between masses of haloes identified in the hydrodynamical simulations and the corresponding haloes from the DM simulation, as a function of the halo mass in the DM run, $M_{\text{DM}}$. The left- and right-hand panels show the results for the GH and CSF runs, respectively. In each panel different line styles, associated with different colours, correspond to different redshifts. Different symbols indicate instead different $\Delta_c$. For reference, the horizontal light long-dashed line corresponds to no mass variation.

smaller than that in the DM run. The reason for this is the different timing of merging of substructures in the different simulations. This occasionally causes some of these substructures to be found outside $R_{200}$ while located within this radius in the DM simulation.

In order to quantify a possible mass dependence of this halo mass difference, we show in Fig. 3 the mean value of such a difference for each mass bin where the MF is computed. Throughout our analysis, we use a fixed mass bin with width $\Delta \log M = 0.2$. With such a narrow bin, the MF suffers from a large sampling effect in the high mass end, due to the exponential dearth of the massive halo population. To overcome such a sampling effect, we merge mass bins containing less than 10 objects into the adjacent lower mass bin. Each mass bin is then weighted proportionally to the number of clusters it contains.

The increase of halo masses in both the GH and CSF simulations is to a good approximation independent of the halo mass, at least for $\log (M h^{-1} M_\odot) \gtrsim 13.5$, at overdensities $\Delta_c = 200$ and 500. Again, this shift in mass turns out to be similar in the two hydrodynamical runs. It amounts to about 1–2 per cent at $\Delta_c = 200$ and $\gtrsim$4 per cent at $\Delta_c = 500$, in line with the results shown in Fig. 2. The increasing star formation efficiency in lower mass haloes makes the mass increase in the CSF simulation larger than that for the GH case. This difference between GH and CSF halo masses further increases for $\Delta_c = 1500$. At this overdensity we cannot define a mass range over which the increase of halo masses due to baryons is nearly constant and independent of gas physics.

To better understand the origin of the mass difference between haloes identified in different simulations, we further show in Fig. 4 the radial profile of the mean total density for haloes identified in the three simulations. The four panels correspond to different mass ranges. Since density is normalized to $\rho_{200}$, i.e. the mean density within $R_{200}$, the profiles reach the unity value for $R/R_{200} = 1$. As for the haloes identified in the GH simulation (red dot–dashed curves), their profiles have small but sizable differences with respect to the DM case (solid black curves). At intermediate radii, $0.1 \lesssim R/R_{200} \lesssim 1$, the GH profiles lie above those of the DM simulation. This result, which holds independent of the halo mass, is consistent with that found by Rasia et al. (2004) in their comparison of halo profiles from DM-only and non-radiative hydrodynamical simulations. These authors argued that the more concentrated density profiles in non-radiative simulations, with respect to DM-only simulations, are the result of energy redistribution between the DM and the baryonic component during halo collapse (see also Lin et al. 2006). We postpone to a forthcoming paper a detailed comparison between concentrations for haloes identified in DM and hydrodynamic simulations (Rasia et al. in preparation). It is only at small radii, $R \lesssim 0.08 R_{200}$, that gas pressure support makes the total density profiles in the GH simulation slightly flattening with respect to the DM simulation.

As for the radiative CSF simulation (blue dashed curves), the sinking of cooled baryons, converted into stars, in the central halo regions causes the already known effect of adiabatic contraction, with the resulting steepening of the density profiles in these regions. A comparison of the resulting profiles for the different mass ranges indicates that this effect is more pronounced for haloes of smaller mass, consistent with the expectation that cooling is in fact more efficient in lower mass haloes, due to their higher concentration. The effect of gas cooling is rather pronounced for $R \lesssim 0.2 R_{200}$. We note that the vertical purple line in Fig. 4 marks the mean value of $R_{1500}$ for haloes of the DM simulation. The corresponding value of $R_{1500}$ for the CSF simulation is in fact slightly larger than in the DM case. This difference explains why halo masses in the CSF simulation are only slightly larger than those in the GH simulation already at $R_{1500}$.

### 3.3 Effect on the halo mass function

In order to compute the MF, we group SO haloes within mass bins having fixed width $\Delta \log M = 0.2$. Then, the mass assigned to each bin is computed as the mean over all the haloes belonging to that
mass bin. Whatever procedure one adopts to choose the mass to be assigned to a given bin, it is clear that the binning procedure introduces an uncertainty in the resulting MF. As discussed by Lukić et al. (2007), this uncertainty is negligible as long as the bin width does not exceed $\Delta \log M = 0.5$.

We show in Fig. 5 the HMF for our three simulations, computed for $\Delta_c = 200$, 500 and 1500 (from upper to lower groups of curves). To better emphasize the mass variation induced by the presence of baryons, we show in the lower panel the difference in the number of clusters within each mass bin, between each of the two hydrodynamical simulations and DM simulation. Due to the specific treatment of the last bin, its width can be different for different simulations. Therefore, when we compare the number of objects in such last bins, we rescale the cluster counts within each of them by scaling it to the bin width in units of $\Delta \log M = 0.2$.

In general, we find that the presence of baryons leads to an increase of the HMF by an amount increasing as we move to more internal regions at higher $\Delta_c$. In general, this variation is nearly independent of mass, except possibly in the high mass end, beyond $\log (M h^{-1} M_\odot) \simeq 14.5$. This is the regime where exponential tail takes place. Given the limited box size, the resulting limited statistics of massive haloes do not allow us to draw robust conclusions for such high masses, especially when considering $\Delta_c = 500$ and above. For the GH non-radiative simulation the HMF increase is negligible at $\Delta_c = 200$, and amounts to $\lesssim 3$ per cent at the largest sampled masses. This difference increases to $\lesssim 5$ per cent as we move to $\Delta_c = 500$, at least up to $\log (M h^{-1} M_\odot) \simeq 14.5$. We note that at such overdensities the effect of introducing baryons produces a variation of the HMF with respect to the DM simulation which is larger than the difference between the GH and the CSF run. This indicates that, while it is important to account for the presence of baryons in the HMF calibration for $\Delta_c \lesssim 500$, the details of the physical processes regulating their evolution have a minor impact. At a higher overdensity $\Delta_c = 1500$, the effect of radiative physics is the increase of the HMF by about 20 per cent for the CSF run and around 10 per cent for the GH run. This result agrees roughly with the expectation that a more concentrated density profile in the presence of gas cooling (Gnedin et al. 2004; Pedrosa et al. 2009; Duffy et al. 2010; Tissera et al. 2010).

In general, our results for an increase of the HMF for the GH simulation are in line with previous findings, also based on non-radiative simulations, for an increase of halo concentration induced by the presence of gas (Rasia et al. 2004; Jing et al. 2006; Lin et al. 2006; Rudd et al. 2008). The effect of the physics of baryons becomes more important at $\Delta_c = 1500$. In their analysis of the cumulative MF, Rudd et al. (2008) found that the presence of non-radiative gas induces a negligible HMF variation for masses estimated at the virial radius, corresponding to $\Delta_c \simeq 100$ for their simulated cosmology. While this result is in agreement with ours, Rudd et al. (2008) find that the HMF increases by about 10 per cent when radiative CSF is included. One possible reason for the different effect of radiative physics in our analysis and that of Rudd et al. (2008)
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Figure 5. The HMF for our simulations, with masses computed at different overdensities $\Delta_c$. Results for the DM simulations are shown with dotted curves, while results for the GH and CSF hydrodynamical simulations are shown with dashed and dot-dashed curves, respectively. The upper to lower curves correspond to the result for $\Delta_c = 200$, 500 and 1500 (green, red and black curves, respectively). The lower panel shows the ratio between the number of haloes found in each mass bin for each of the two hydrodynamical simulations and the DM simulation. We apply a linear interpolation of the mass functions to compute the difference in the halo number exactly for the same mass values.

Figure 6. The redshift evolution of the HMF for our simulations, with masses computed overdensity $\Delta_c = 500$. Results for the DM simulations are shown with dotted curves, while results for the GH and CSF hydrodynamical simulations are shown with dashed and dot-dashed curves, respectively. The upper to lower curves correspond to the result for $z = 0.0, 0.6$ and 1.00 (black, red and green curves, respectively). The lower panel shows the ratio between the number of haloes found in each mass bin for each of the two hydrodynamical simulations and the DM simulation.

could lie in the different efficiency of the feedback included in the simulations. In our case we include a rather efficient SN feedback that could mitigate the effects of adiabatic contraction. Stanek et al. (2009) compared results for a non-radiative simulation and for a pre-heated radiative simulations. They found that at $\Delta_c = 500$ the latter predicts an HMF which is lower than the former. Because the fairly strong pre-heating introduced in their simulation at $z = 4$ devoid haloes by a substantial amount of gas, the delayed re-acceleration of the gas cause the lower HMF.

Tinker et al. (2008) investigated the redshift evolution of the mass function computed at different values of $\Delta_c$ based on simulations including only DM. They found that at $\Delta_c = 500$ the latter predicts an HMF which is lower than the former. Because the fairly strong pre-heating introduced in their simulation at $z = 4$ devoid haloes by a substantial amount of gas, the delayed re-acceleration of the gas cause the lower HMF.

We show in Fig. 6 the evolution of the HMF at three different redshifts, $z = 0, 0.6$ and 1, for $\Delta_c = 500$. Similarly to Fig. 5 we also show in the bottom panel the ratio between the HMF from the DM simulation and that of the two hydrodynamical simulations. We apply a linear interpolation of the mass functions to compute the difference in the halo number exactly for the same mass values.

Due to the complexity and partial knowledge of the baryonic process taking place in galaxy formation, accurately calibrating the HMF from hydrodynamical simulation may appear a challenging task. However, owing to the results shown in Fig. 3, it turns out that the variation of halo masses in both GH and CSF simulations, with respect to the pure DM case, is to a good approximation independent of halo mass, at least within the mass range and for the $\Delta_c$ values for which the approximation is expected to hold. In Table 1 we report the average values of the mass ratio for haloes identified in the hydrodynamical and in the DM simulations, for different $\Delta_c$ and redshift values. These values, which are computed as an average over all haloes having mass $\log(M/\text{GeV}) \geq 13.5$, are then used to rescale the HMF from the hydrodynamical simulation.

In Fig. 7, we show the ratio between the number of haloes of different masses found in the hydrodynamical and in the DM
simulations, after applying the mass shifts reported in Table 1. A larger mass binning is used here, $\Delta \log M = 0.3$, to reduce fluctuations associated with sampling noise. From the left-hand panel of Fig. 7, the difference in the halo number is now consistent with zero, with fluctuations around this value of 3 per cent for $\Delta_c = 500$. This result holds independently of mass and redshift, at least for haloes with $\log (M_{halo} / h^{-1} M_\odot) \geq 13.5$. As expected, the correction is less effective for smaller masses, owing to the larger mass difference induced by baryonic effects in smaller haloes. Clearly, the correction is less pronounced at $\Delta_c = 200$, owing to the smaller impact of baryons at this overdensity. However, also in this case, correcting the HMF according to a unique mass shift further reduces the difference between hydrodynamical and DM simulations at the 1–2 per cent level. The number difference for the CSF run at $\Delta_c = 500$ is also suppressed to unity for all haloes with $\log (M_{halo} / h^{-1} M_\odot) \geq 13.5$.

In conclusion, the results obtained from our analysis indicate that the relative variation of halo masses due to baryon effects is always within 5 per cent, for both non-radiative and radiative simulations, also almost independent of redshift. This result holds for masses computed at overdensity $\Delta_c = 200$ and 500, and for haloes having mass at least comparable to that of a galaxy group. Correcting the MF with a constant mass shift in this mass range largely accounts for the differences between hydrodynamical and DM simulations.

In Table 1, mean values of the ratio between halo masses in the hydrodynamical and DM simulations, at different redshifts and $\Delta_c$ values, for both the non-radiative (GH) and radiative (CSF) simulations. Such values have been computed by including only haloes with $\log (M_{halo} / h^{-1} M_\odot) \geq 13.5$.

| Redshift | GH | CSF |
|----------|----|-----|
| $\Delta_c = 500$ | $\Delta_c = 200$ | $\Delta_c = 500$ |
| $z = 0.0$ | 1.037 | 1.012 | 1.049 | 1.016 |
| $z = 0.6$ | 1.028 | 1.000 | 1.044 | 1.005 |
| $z = 1.0$ | 1.028 | 0.997 | 1.040 | 0.999 |

4 DISCUSSION AND CONCLUSION

In this paper we presented an analysis of the effect of baryons on the calibration of the HMF. For this purpose, we carried out one DM-only simulation and two hydrodynamical simulations, a non-radiative one including only the effect of GH and a radiative one including the effect of star formation and SN feedback in the form of galactic ejecta. The three simulations, which are all based on the TREE-PMSPH code GADGET-3 (Springel 2005a), started from exactly the same initial conditions and followed the evolution of $2 \times 1024^3$ particles within a box having a comoving size of $410 h^{-1} \text{Mpc}$. Haloes have been identified using an SO algorithm, and results have been presented at three redshifts, $z = 0, 0.6$ and 1. Halo masses have been computed at different overdensities (with respect to the critical one), $\Delta_c = 200, 500$ and 1500. The main results of our analysis can be summarized as follows.

1. The fractional difference between halo masses in the hydrodynamical and in the DM simulations is found to be almost constant, at least for haloes more massive than $\log (M_{halo} / h^{-1} M_\odot) \geq 13.5$. In this range, the mass increase in the hydrodynamical simulations is of about 4–5 per cent at $\Delta_c = 500$ and 1–2 per cent at $\Delta_c = 200$. Quite interestingly, these differences are nearly the same for the GH and CSF simulations (see Fig. 3 and Table 1). Such relative mass variations cannot be considered any more as constant at higher overdensity, $\Delta_c = 1500$, and smaller masses. In these cases, the mass difference markedly increases for smaller haloes in the CSF simulation, while it decreases in the non-radiative GH simulation.

2. These variations of halo masses induce corresponding variations of the HMF (see Fig. 5). At $z = 0$, the HMFs for the GH and CSF simulations are close to the DM one, with differences of $\lesssim 3$ per cent at $\Delta_c = 200$, in line with the small correction in halo masses. Such a difference increases to $\lesssim 7$ per cent at $\Delta_c = 500$ and reaches $\sim 10–20$ per cent at $\Delta_c = 1500$. At the latter overdensity, the increase in the HMF for the CSF run is larger by about a factor of 2 with respect to the GH run. This result is in line with the expectation that baryonic processes have a stronger impact in the central halo regions. At higher redshift, differences with respect to the DM HMF tend to increase, especially for $\Delta_c = 1500$ (see Fig. 6) and for

Figure 7. The number difference after halo mass calibration. Different colourful lines show the redshift, while the two line styles, solid and dotted, represent $\Delta_c = 500$ and 200, respectively. The left-hand panel shows the corrected results for the GH run and the right is for the CSF run.

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the CSF case. Again, this result agrees with the increase of cooling efficiency within haloes at higher redshift.

(3) Based on the above results, we showed that assuming a constant mass variation to rescale the HMF from the hydrodynamic simulations reduces the difference with respect to the DM case. We apply a uniform mass shift, calibrated for halo masses log (M h⁻¹ M⊙) ≥ 13.5 for Δc = 200 and 500. We verified that the difference between hydrodynamical and DM HMFs becomes negligible, with fluctuations around null of ≤3 per cent at Δc = 500. Even though mass variations are smaller at Δc = 200, we still find that a uniform mass rescaling gives a small but sizable reduction of the HMF difference also at this overdensity.

The future generation of large surveys of galaxy clusters, from X-ray, optical and Sunyaev–Zeldovich observations, could provide stringent constraints of cosmological parameters through the study of the evolution of the MF. However, a necessary condition to fully exploit the cosmological information content of such surveys is that the theoretical MF needs to be calibrated to a precision better than 10 per cent (e.g. Wu, Zentner & Wechsler 2010). In this respect, the results of our analysis have interesting implications to gauge the uncertainty in the MF calibration associated with the uncertain baryon physics.

First of all, the HMF turns out to be less prone to such effects if computed at Δc = 500, while they become more important and likely difficult to model in detail at higher overdensities. Furthermore, adopting a constant mass shift provides a rather accurate correction to the HMF calibrated from DM simulations, at least for haloes having size of galaxy groups or larger. This result holds for both the non-radiative (GH) and the radiative (CSF) simulations, which have rather similar mass corrections at Δc = 500. Since the CSF run only include SN feedback, but no active galactic nucleus (AGN) feedback, clusters in these simulations still suffer from overcooling. Therefore, the GH and CSF simulations should in principle bracket the case in which the correct amount of baryons cool within DM haloes. However, we note that Stanek et al. (2009) found a slight decrease, rather than an increase of the HMF in simulations including an impulsive pre-heating. Since a phenomenological pre-heating only provides an approximate description of the astrophysical mechanisms regulating star formation, it would be interesting to repeat our analysis also in the presence of a mechanism for AGN feedback that regulates cooling in groups and clusters to the observed level (e.g. Puchwein, Sijacki & Springel 2008; Fabjan et al. 2010; McCarthy et al. 2010).

Another direction in which our analysis should be improved concerns the size of simulation box, so as to better sample the population of massive haloes. Although our results indicate that a mass-independent mass shift should be applied to account for baryonic effects, one may wonder whether this prescription can be extrapolated to the most massive haloes, whose population is mostly sensitive to the choice of the cosmological model. Future development in supercomputing capabilities will soon open the possibility to carry out hydrodynamical simulations which will cover dynamic ranges comparable to those accessible by the N-body simulations currently used to calibrate the HMF.

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