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Evolution of the baryon fraction in the Local Group: accretion versus feedback at low and high z

Sébastien Peirani^{1*}, Intae Jung^{1,2}, Joseph Silk^{1,3} and Christophe Pichon¹

¹ *Institut d'Astrophysique de Paris (UMR 7095: CNRS & UPMC), 98 bis Bd Arago, 75014 Paris, France*

² *Department of Astronomy, Yonsei University, Seoul 120-749, Korea*

³ *Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK*

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ABSTRACT

Using hydrodynamical zoom simulations in the standard Λ CDM cosmology, we investigate the evolution of the distribution of baryons (gas and stars) in a local group-type universe.

First, with standard star formation and supernova feedback prescriptions, we find that the mean baryonic fraction value estimated at the virial radius of the two main central objects (i.e. the Milky Way and Andromeda) is decreasing over time, and is 10-15% lower than the universal value, 0.166, at $z = 0$. This decrease is mainly due to the fact that the amount of accretion of dissipative gas onto the halo, especially at low redshift, is in general much lower than that of the dissipationless dark matter. Indeed, a significant part of the baryons does not collapse onto the haloes and remains in their outskirts, mainly in the form of warm-hot intergalactic medium (WHIM). Moreover, during the formation of each object, some dark matter and baryons are also expelled through merger events via tidal disruption. In contrast to baryons, expelled dark matter can be more efficiently re-accreted onto the halo, enhancing both the reduction of f_b inside R_v , and the increase of the mass of WHIM outside R_v . Varying the efficiency of supernovae feedback at low redshift does not seem to significantly affect these trends.

Alternatively, when a significant fraction of the initial gas in the main objects is released at high redshifts by more powerful sources of feedback, such as AGN from intermediate mass black holes in lower mass galaxies, the baryonic fraction at the virial radius can have a lower value ($f_b \sim 0.12$) at low redshift. Hence physical mechanisms able to slow down the accretion of gas at high redshifts will have a stronger impact on the deficit of baryons in the mass budget of Milky Way type-galaxies at present times than those that expel the gas in the longer, late phases of galaxy formation.

Key words: Galaxies: Local Group – Galaxies: haloes – Dark matter – Methods: N-body simulations

1 INTRODUCTION

The distribution of galaxies in the Universe on large scales, as revealed by sky surveys such as the CFA Redshift Survey (Geller & Huchra 1989), the 2DF Galaxy Redshift Survey (Colless et al. 2001) or the Sloan Digital Sky Survey (Gott et al. 2005) is structured into a filamentary web in which the intersections correspond

to the most massive objects (i.e. galaxy clusters, Bond et al. 1996). This specific distribution is now commonly and easily reproduced by cosmological hydrodynamical N-body simulations of the Λ CDM cosmology which also indicate that the distribution of dark matter, the dominant mass component of the Universe (Komatsu et al. 2011), follows the same trend. Indeed, since in the traditional picture of galaxy formation, galaxies are supposed to form when baryonic gas falls into the gravitational potential of their host dark matter halo, the distribution

* E-mail: peirani@iap.fr

of dark matter is therefore expected to faithfully trace that of the baryons. However on galactic scales, observations tend to suggest that the spatial distributions of dark matter and baryons (especially in the form of gas) may display some substantial differences. In particular, it has been shown that galaxies are missing most of their baryons, – most galaxies are severely baryons-depleted relative to the cosmological fraction (see for instance Bell et al. 2003; Hoekstra et al. 2005; McGaugh 2010).

This so-called “missing baryons problem” (see Bregman 2007 for a complete review), if *real*, calls for two alternative scenarios. Either a significant part of the gas never collapsed into the gravitational potential wells of protogalaxies in the first place, or some of the gas has been expelled by galaxy formation feedback processes such as supernova winds. Hence solving the missing baryon problem may prove to be central in order to constrain galaxy formation models.

Past studies based on hydrodynamical simulations indicate that most of the “missing” baryons might lie in a gaseous phase (the so-called warm-hot intergalactic medium, hereafter WHIM) in the temperature range $10^5 - 10^7$ K and at moderate over-density (Cen & Ostriker 1999; Davé et al. 2001; Cen & Ostriker 2006). According to these studies, the WHIM is primarily shock-heated during the formation of large-scale structures, while feedback mechanisms associated with star formation should also have an additional impact on this phase during galaxy formation. For instance, for low mass systems, the cosmological UV-background is supposed to reduce both the star formation and baryon content (Thoul & Weinberg 1996; Bullock, Kravtsov & Weinberg 2000; Gnedin 2000; Somerville 2002; Ricotti, Gnedin & Shull 2002; Benson et al. 2002; Read, Pontzen & Viel 2006; Hoeft et al. 2006; Okamoto, Gao & Theuns 2008; Peirani 2010; Nickerson et al. 2011, Hambrick et al. 2011a). Supernova feedback is also expected to expel some gas, especially for low mass systems, as suggested by various numerical investigations (Scannapieco et al. 2008, 2009; Faucher-Giguère, Kereš & Ma 2011 and references therein). Other mechanisms have been proposed, such as turbulence in the baryonic intergalactic medium (Zhu, Feng & Fang 2011) or pre-heating by pre-virialisation (Mo et al. 2005), although Crain et al. (2007) claimed that this process is unable to prevent the collapse of gas (instead, according to these authors, non-gravitational feedback is required in order to reduce the efficiency of gas cooling and star formation in dwarf galaxies). Another less investigated potential mechanism, which may also affect the evolution of the distribution of baryons on small scales, is the effect of accretion and merger events (and in particular their associated tidal disruption) that are expected to be frequent in the framework of the hierarchical model. For instance, in an early paper, Navarro & White (1993) have shown that during a merger involving dark matter and adiabatic gas, there is a transfer of energy between these two components that leads to a situation where the gas is less tightly bound. More recently, Sinha & Holley-Bockelmann (2010, 2011) found that a few percent of gas can be driven into the intergalactic medium (IGM) by galaxy mergers, using either merger trees cal-

culated from the Press-Schechter formalism or idealized simulations of mergers of galaxy clusters. Using hydrodynamical simulations, Nickerson et al. (2011) have also concluded that tidal forces may cause significant mass loss from satellites of all masses.

In the present work, we make use of cosmological “zoom” simulations with an extended treatment of the physics of baryons to study the formation of Milky Way-like galaxies. Our aim is to characterise the relative role of supernova feedback to accretion and mergers in the evolution of the distribution of baryons for objects of such masses. We will also test scenarios in which the accretion of the gas at high redshift is prevented by more powerful sources of feedback, such as AGN associated with massive black holes. This will allow us to quantify two distinct processes which may allow us to address the so-called missing baryon problem, should it persist.

This paper is organised as follows. In section 2, we summarize the numerical modelling, and section 3 presents our main results on the evolution of the distribution of baryons in our simulated local group universes. We give our main conclusions in the last section.

2 NUMERICAL MODELLING

2.1 Initial conditions and simulation

The numerical methodology used in the present paper is described in detail in Peirani (2010) to which we refer the reader for more information. For the sake of clarity, we summarize the main steps below.

We analyse three cosmological zoom simulations for a Λ CDM universe using WMAP5 parameters (Komatsu et al. 2009), namely $\Omega_M = 0.274$, $\Omega_\Lambda = 0.726$, $\Omega_b = 0.0456$, $H_0 = 70.5$ km/s/Mpc, $n = 0.96$ and $\sigma_8 = 0.812$. Each simulation was performed in a periodic box of side $100 h^{-1}$ Mpc with 2×2048^3 effective dark matter and gas particles in the highest resolution region (a sphere of $7 h^{-1}$ Mpc of radius). In this region of interest, the mass resolution are $m_{DM} \approx 7.4 \times 10^6 h^{-1} M_\odot$ and $m_{gas} = m_{stars} \approx 1.5 \times 10^6 h^{-1} M_\odot$. The Plummer-equivalent force softening adopted for the high mass resolution particles were 1 and $0.5 h^{-1}$ kpc for dark matter and gas particles respectively and were kept constant in comoving units.

Initial conditions have been generated from the MPgrafic code (Prunet et al. 2008) and the simulations were performed using GADGET2 (Springel 2005), with added prescriptions for metal-dependent cooling, star formation (in this work we remind that the star formation efficiency is $c_*=0.02$), feedback from Type Ia and II supernovae (SN), UV background (starting at $z = 8.5$) and metal enrichment. The three simulations have common initial conditions whose phases are consistent with the local group but essentially differ in the quantity of energy released by SN derived from star particles i (E_i). As mentioned in Peirani (2010), we consider that a fraction γ of this energy is deposited in the j^{th} neighbour gas particle by applying a radial kick to its velocity with a magnitude $\Delta v_j = \sqrt{(2w_j\gamma E_i/m_j)}$, where w_j is the weighting based on the smoothing kernel and m_j is

Table 1. Fractions γ of the energy released by supernovae

	SIM1a	SIM1b	SIM2	
γ	0.1	1.0	50 ($8.1 \geq z \geq 7.7$)	0.1 elsewhere

the mass of gas particle j . The first simulation SIM1a uses the standard value of $\gamma = 0.1$ while in the second one, SIM1b, we have considered a higher efficiency $\gamma = 1.0$ in order to investigate how our results would be affected. In the third simulation (SIM2), our aim is to study the effects of earlier high energy ejection to the ISM induced either by intermediate mass black holes or other high energy processes such as hypernovae events. Intermediate mass black holes are the likely missing link between Population III and the supermassive black holes in quasars and plausibly as part of the hierarchy of structure formation. Hypernovae are likely to be more prevalent than normal supernovae in the earliest phases of star formation: for example, the Population III IMF is certainly top-heavy, and this may also be the norm for the precursors of spheroids, as evidenced for example by the radial distribution of SNe in disturbed (including recently merged) galaxies (Haberman, Anderson & James 2010) and the frequency of low mass x-ray binaries in ultracompact dwarf galaxies (Dabringhausen et al. 2012). A higher frequency of hypernovae could plausibly provide an order-of-magnitude higher feedback efficiency than supernovae. The case of AGN is intriguing, as even higher feedback is required in deep potential wells, where supernovae are relatively inefficient, in order to account for the correlation between black hole mass and spheroid velocity dispersion (Silk & Nusser 2010; Debuhr et al. 2012). Moreover, the recent detection of a massive gas outflow in a distant quasar ($z = 6.4$) strongly suggests that a strong quasar activity is already in place at very early times (Maiolino et al. 2012). For this purpose, a simple modelling was used in which a much higher efficiency ($\gamma = 50$) was considered during a very short ($\Delta t \sim 45$ Myr) at earlier times ($z \sim 8.0$) and $\gamma = 0.1$ otherwise. The feedback parameters are summarized in Table 1.

2.2 Physical properties of main galaxies

In each simulation, we analyse a pair of galaxies with physical characteristics similar to the Milky Way-Andromeda pair (MW-M31) and with similar galaxy environments up to $7 h^{-1}$ Mpc. Some relevant physical properties at the virial radius R_v at $z = 0$ of these two objects from each simulation are summarized in Table 2. Note that we keep the same definition of the virial radius R_V and virial mass M_V used in Peirani (2010) (see paragraph 2.3), namely R_V is the radius where the enclosed mean density $M_V/(4\pi R_V^3/3)$ is Δ_c times the critical density, and $\rho_c(z) = 3H(z)^2/8\pi G$, where $H(z) = H_0\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}$. In the cosmology adopted in the present study, $\Delta_c = 97.6$ at $z = 0$. Furthermore, the baryonic fraction is defined as follow:

$$f_b \equiv \frac{m_{\text{baryons}}}{m_{\text{baryons}} + m_{\text{DM}}}, \quad (1)$$

where m_{baryons} and m_{DM} refer to the masses of baryons (gas+stars) and dark matter respectively in the same specific region of the universe. When not specified in the text, we do not distinguish the cold and hot phases of the gas in the estimate of f_b . According to the adopted cosmology, the universal f_b value is:

$$\langle f_b \rangle \equiv \frac{\Omega_b}{\Omega_M} \approx 0.166. \quad (2)$$

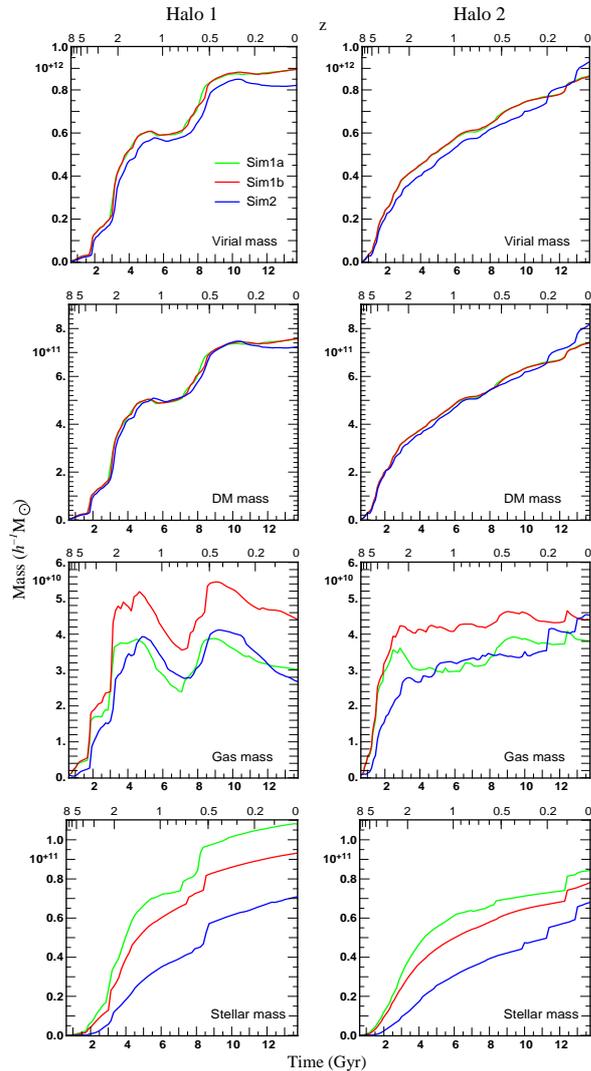
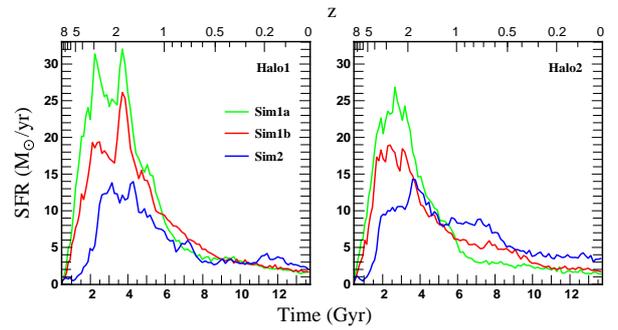
The time evolution of the virial, dark matter (DM), gas and stellar masses of each object at the virial radius and for the three simulations is shown in Figure 1. First, we notice that there is no particular difference between the evolution of dark matter halo masses (and hence virial masses) between SIM1a and SIM1b. However, the baryonic compositions are quite different. Indeed, stellar masses are significantly reduced in SIM1b due to higher amounts of energy released by the SN. The mass of the gas component is therefore higher in SIM1b, as expected. For SIM2, the stellar masses are even more reduced. This is mainly due to the fact that a significant fraction of the gas has been expelled at high redshifts.

Indeed, while the DM masses are quite similar between the 3 runs, the virial masses for objects in SIM2 tend to be lower at high redshift, which indicate that a fraction of gas expelled at high z does not recollapse at some later stage. Interestingly, HALO2 undergoes a minor merger event at $z \simeq 0.1$, which corresponds for instance to a sudden variation in the evolution of its stellar mass. This same accretion event takes place at $z \simeq 0.2$ in SIM2. Moreover, we can also identify clearly in SIM2 another minor merger event at $z \simeq 0.05$ that has not occurred (yet?) in SIM1a and SIM1b. This explains why the virial mass of HALO2 is higher in SIM2 than SIM1a or SIM1b. This also suggests that small perturbations in the properties of halos at earlier times can have some significant impact on the whole accretion history (see for instance, Thiebaud et al. 2008). It is also worth mentioning that although the two main central objects have the same virial mass at $z = 0$, they have undergone different mass accretion histories. Indeed, while HALO2 grows regularly through smooth mass accretion, the evolution of the mass of HALO1 is more sporadic thanks to several major merger events. It is therefore instructive to see to which extent these two different mass evolutions could affect the evolution of the distribution of baryons in the vicinity of these two objects.

Finally, Figure 2 shows the evolution of the star formation rate (SFR) for each object and simulation. At $z = 0$, SFR values are around $[1-5] M_\odot/\text{yr}$ which is consistent with observational values derived by Robitaille & Whitney (2010) using SPITZER data. Note that these cosmic evolutions are similar for the two halos: at high redshifts ($z \geq 2$) the lower the SN efficiency the higher the stellar mass. And the higher the mass of formed stars at high redshift, the higher the subsequent SN feedback. This explains why, at low redshifts, a higher fraction of stars is produced in SIM2 relative to SIM1a and SIM1b.

Table 2. Physical properties of the 2 main central objects of each simulation derived at the virial radius R_v and $z = 0$.

	HALO1			HALO2		
	SIM1a ($\gamma = 0.1$)	SIM1b ($\gamma = 1.0$)	SIM2	SIM1a ($\gamma = 0.1$)	SIM1b ($\gamma = 1.0$)	SIM2
$m_{\text{DM}} (\times 10^{11} h^{-1} M_{\odot})$	7.58	7.58	7.23	7.43	7.40	8.17
$m_{\text{gas}} (\times 10^{11} h^{-1} M_{\odot})$	0.30	0.44	0.27	0.38	0.44	0.45
$m_{\text{stars}} (\times 10^{11} h^{-1} M_{\odot})$	1.08	0.93	0.71	0.84	0.78	0.68
$M_v (\times 10^{11} h^{-1} M_{\odot})$	8.96	8.95	8.21	8.65	8.62	9.30
R_v (Mpc)	0.282	0.282	0.274	0.279	0.279	0.286
f_b	0.154	0.153	0.119	0.141	0.141	0.121

**Figure 1.** The evolution of the virial dark matter (DM), gas and stellar mass for HALO1 (first column) and HALO2 (second column) as a function of the time or redshift. In each panel, green, red and blue curves represent evolutions derived from SIM1a, SIM1b and SIM2 respectively. Note that *Halo1* undergoes several major merger episodes while *Halo2* grows through smooth accretion. Moreover, different feedback process prescriptions lead to different baryon mass contents inside R_v .**Figure 2.** The evolution of the star formation rate (SFR) for HALO1 (left panel) and HALO2 (right panel) as labelled.

3 THE BARYON FRACTION IN THE LG

3.1 Spatial distribution in the simulated LG

Fig. 3 shows the projected distribution of baryons in our LG type universes derived from SIM1b and SIM2 and at four specific epochs (i.e. $z = 5, 2, 0.5$ and 0). We clearly see that the evolution of the distributions of baryons and dark matter do not follow the same trend. Indeed, the regions of the universe in red and dark blue correspond to regions where the baryonic fraction is lower than the universal value. And those specific regions are mainly located around the forming protogalaxies or galaxies at each redshift, while in the very inner part of dark matter haloes, f_b is higher. This is an expected result: due to cooling, the gas collapses to the center of haloes where stars can be formed. However, note that the size of these “red” cavities increases over time which suggests that the fraction of gas that has collapsed to the center of the halo is not immediately replaced by some fresh gas from its vicinity.

Note also, at high and low redshift, the existence of relative high baryon content regions which are located either in the filaments or beyond the virial radii. Such anisotropic distribution seems to be more pronounced in SIM2 relative to SIM1b. It is therefore crucial to characterise the mechanisms that drive such specific distributions.

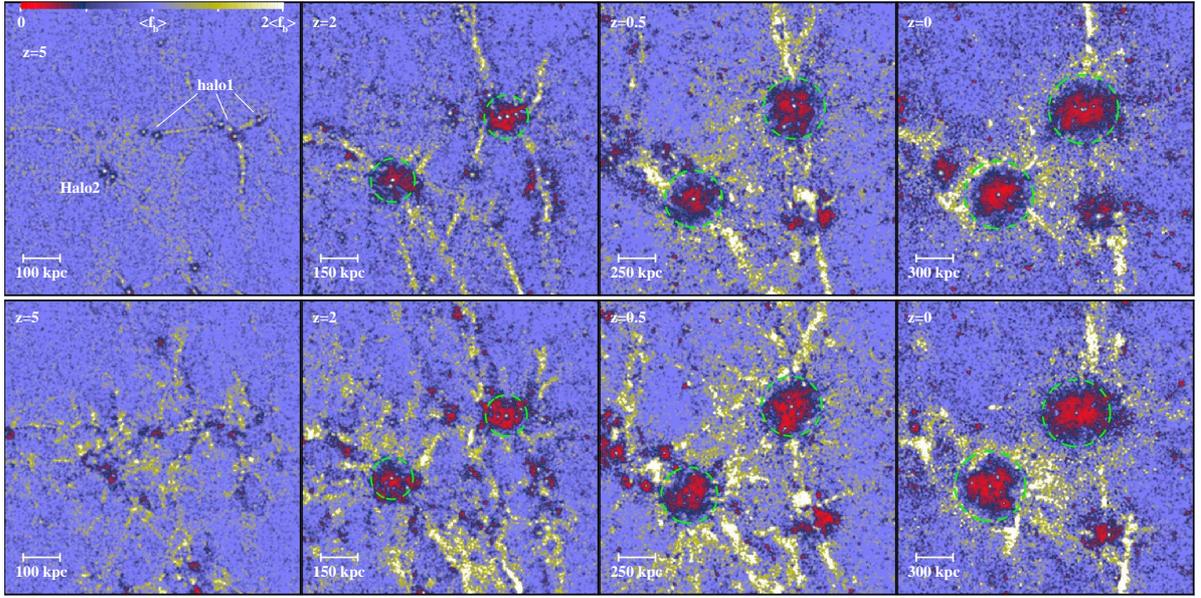


Figure 3. The projected baryonic fraction at $z = 5$ (first column) $z = 2$ (second column), $z = 0.5$ (third column) and $z = 0$ (fourth column) from SIM1b (first line) and SIM2 (second line). Dashed circles show virial radii. High f_b value regions are clearly visible around galaxies (or proto-galaxies) and in the filaments. This trend seems to be more pronounced in *Sim2* although the difference between the two simulations is vanishing at low redshift.

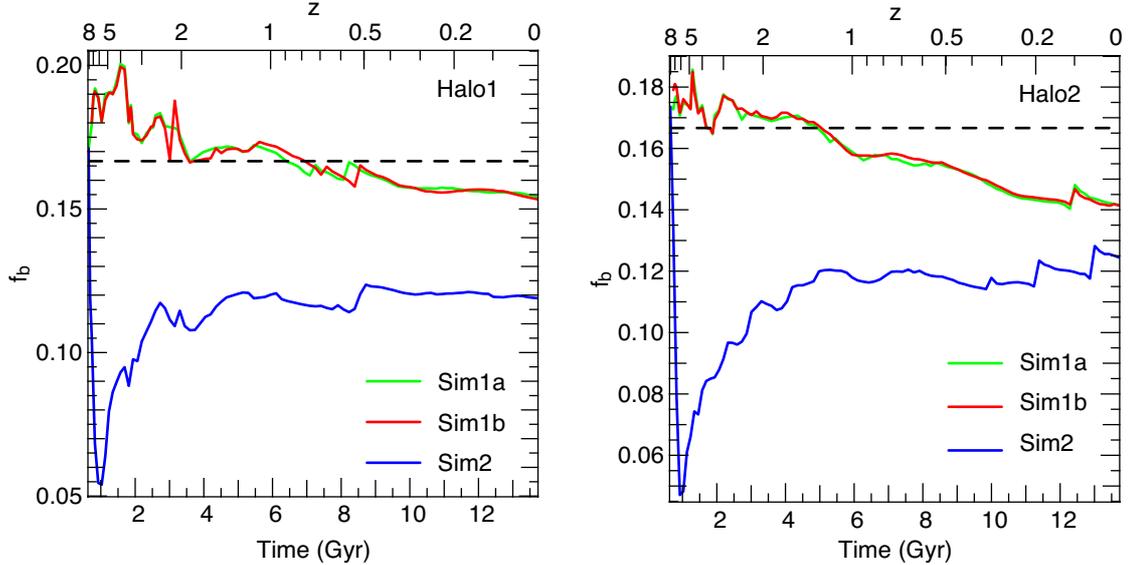


Figure 4. The evolution of the baryonic fraction f_b estimated at the virial radius for HALO1 (left panel) and HALO2 (right panel) as a function of cosmic time. In each panel, red, green and blue lines correspond to values derived from SIM1a, SIM1b and SIM2 respectively. The horizontal dashed line corresponds to the universal fraction. Note that the early feedback model induces a lower ($f_b \sim 0.12$) baryon fraction at present time.

3.2 Cosmic evolution of f_b

3.2.1 The effects of feedback at low redshift

Let us first only consider the role of supernovae feedback in the evolution of the mass budget of Milky Way-type galaxies. We therefore focus on both SIM1a and SIM1b in this sub-section.

The cosmic evolution of the baryonic fraction f_b

estimated at the virial radius for the two main halos is shown in Figure 4. In each of these two simulations, they follow the same trend. At high redshift, f_b is close to the universal value and sometimes is slightly higher. Cold flows provides gas to form stars. Note that the virial radius is estimated according to the local density, which is dominated by the newly formed stars. Since the resolution in these simulations is limited, especially for

low mass systems, the virial radius may be underestimated, and subsequently this baryonic fraction may be in fact overestimated at high redshifts.

From $z \sim 3$, f_b is decreasing with cosmic time until it reaches the values of ~ 0.15 and ~ 0.14 at $z = 0$ for HALO1 and HALO2 respectively. These values are in nice agreement with those obtained from other hydrodynamical simulations, for objects with a mass of $10^{12} h^{-1} M_\odot$ at $z = 0$ (Crain et al. 2007; Faucher-Giguère, Kereš & Ma 2011). Moreover, no particular differences are seen in the evolution of f_b between SIM1a and SIM1b. This suggests that higher SN feedback can reduce the star formation rate (and therefore the final stellar mass) but is rather inefficient in expelling the gas outside the virial radius at high and low redshifts for massive galaxies. These results are also consistent with Powell, Slyz and Devriendt (2011) who show from the NUT simulations, using different runs with and without SN feedback, that SN-induced winds carry out very little gas mass and that the cold gas rate inflow remains essentially unchanged.

We have also studied the distribution of the integral $f_b(< R)$ and differential $f_b(R)$ as respect to the radius R at three different redshifts $z = 4.7$, 0.8 and 0 in Figure 5. Only results from HALO2 are shown since similar trends are obtained for HALO1. At the center of each halo, f_b is high due to the presence of the galaxy. At larger radii, $R \gtrsim 3R_v$, $f_b(< R)$ tends towards the universal value as expected. Interestingly, for high redshifts ($z > 4.7$), $f_b(< R)$ converges to the universal value from above, while this is not the case at lower redshifts, which suggest, as mentioned above, that the gas infall is not recurrently replaced by some fresh gas from the outskirts of the haloes. Also, an excess of baryons at $(1.5 - 2.5)R_v$ can be clearly seen in the variations of the differential $f_b(R)$ for different cosmic times, which correspond to regions in yellow in Fig. 3 around haloes. Similar plots were recently derived from observations using Chandra and Suzaku facilities for an isolated elliptical galaxy with a \sim Milky way mass (Humphrey et al. 2011) and a fossil group (Humphrey et al. 2012).

3.2.2 The effects of feedback at high redshift

In SIM2 however, due to earlier and important eviction of gas from other potential sources of feedback (AGN, hypernovae,...) f_b reaches its lowest value $f_b \sim 0.05$ at $z \sim 6$, then increases until $z \sim 1.5$ and becomes nearly constant ($f_b \sim 0.12$) until the present time. This strongly suggests that sources of feedback acting at high redshift, even for a very short period, can have a stronger impact on the final mass budget of massive galaxies than those acting in the later and longer phases of galaxy formation. One can also notice from Figure 2 that the gas outflow taking place at high redshift lead to the quenching of the star formation during a few million years ($5 \leq z \leq 8$). This is in nice agreement with conclusions of Valiante, Schneider & Maiolino (2012) using semi-analytical models of the formation and evolution of high-redshift quasars. Indeed, according to their model, the observed outflow of a distant quasar at $z = 6.4$ is dominated by quasar feedback which “has considerably

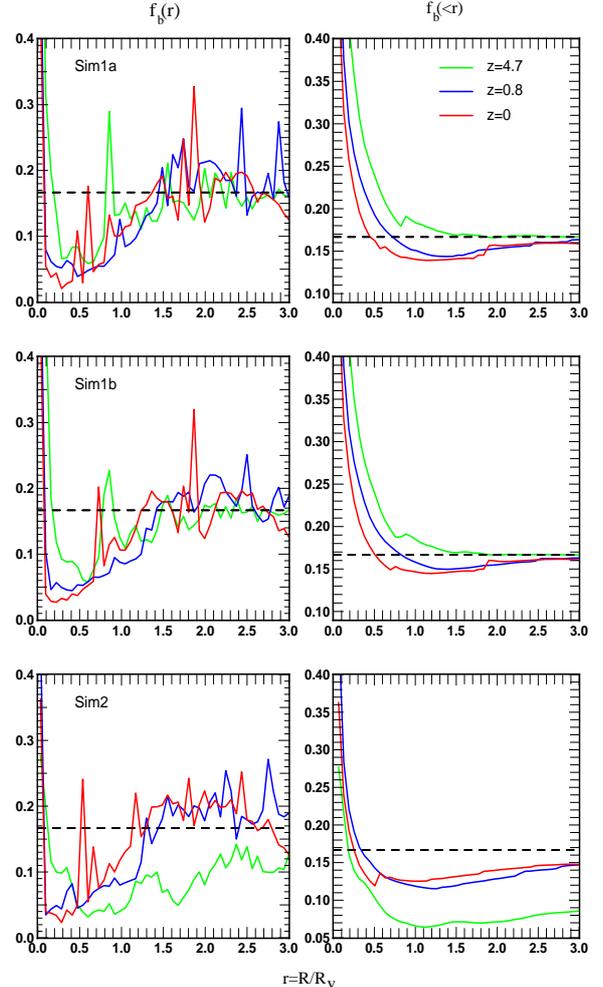


Figure 5. Distributions of the differential baryonic fraction, $f_b(R)$ (first column), and the integral baryonic fraction $f_b(< R)$ (second column) with respect to the radius, R , for HALO2 and for three different redshifts, namely $z = 4.7$ (green lines), $z = 0.8$ (blue lines) and $z = 0$ (red lines).

depleted the gas content of the host galaxy, leading to a down-turn in the star formation rate at $z < 7 - 8$ ”.

3.2.3 The role of accretion of matter

The time evolution of the baryonic fraction inside the virial radius depends on the competition between the evolution of the mass that arrives within R_v , and the mass that leaves R_v . It raises the following question: are the low values of f_b found at $z = 0$ due to the fact that more baryons have been expelled out of the virial radius or because more dark matter has been accreted inside R_v ? To answer this question, instead of studying the evolution of the mass that enter or leave the virial radius at each subsequent step, we focused on the location at a given redshift z of all particles that have been accreted up to this specific redshift. To do this, we have first identified all the particles that have been accreted at each snapshot of the simulation from $z \sim 8$ to “ z ”. Then, we have computed the fraction of those particles

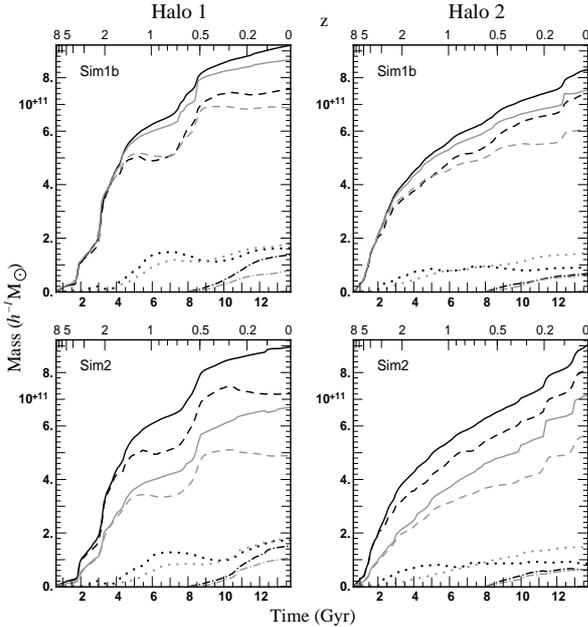


Figure 6. The evolutions of the total dark matter mass (solid black line) and baryon mass (solid grey line) that was accreted from $z \sim 8$ to a given redshift z (see the main text for more details) for HALO1 (first column) and HALO2 (column 2), derived from SIM1b (first line) and SIM2 (second line). In each panel, the corresponding fractions of mass of DM (black color) and baryons (grey color) that are inside R_v (dashed lines) or outside R_v (dotted line) is represented. The dotted-dashed black and grey lines represent respectively the fraction of DM and baryons outside R_v , corresponding to particles accreted from $z \sim 0.6$ to a given redshift z . Note that the baryon mass evolutions have been multiplied by $(\Omega_M - \Omega_b)/\Omega_b$ to facilitate a direct comparison with DM mass evolutions.

that are inside or outside R_v at the considered redshift. By doing this, the interpretation of our findings will be easier since each accreted particle contributes only once in the final result. Indeed, certain particles can be accreted, ejected and accreted again during the whole evolution of these halos.

Figure 6 shows the evolution of the total accreted DM and baryon mass from $z \sim 8$ to a given redshift, z , for both haloes, and for both SIM1b and SIM2 (results derived from SIM1a are not shown since they are similar to those from SIM1b). We also plot the fraction of these accreted particles that are located inside or outside R_v at this given redshift z . First, we look at the evolution relative to HALO1. One can see that a higher fraction of dark matter mass has been accreted from $z = 8$ to $z = 0$ relative to the baryon component (solid lines). Moreover, a similar fraction of dark matter and baryons are located outside the virial radius at $z = 0$. That means that the fraction of baryons released during the formation of HALO1 is not higher than that of dark matter, which demonstrate that the low value of f_b at $z = 0$ follows from the fact that more dark matter particles has been accreted over cosmic time. This can be understood given the difference in nature between the dissipative gas and the non-dissipative dark matter.

In particular, the gas component can be shock-heated at the virial radius which considerably affects and slows down its further accretion on to the halo. In contrast, especially after an important episode of accretion or merger event, the dark matter component can “damp out” its orbital motion until it completely relaxes. For HALO2 the same trends are observed but the mass of baryons outside the virial radius turns out to be higher than that of dark matter. However this does not necessarily mean that a higher fraction of baryons has been expelled through physical mechanisms such as feedback or merger events. Indeed, if we represent the fraction of baryons and DM released from $z \sim 0.6$ to $z = 0$ (see Figure 6), one can see that same amounts of mass have been expelled at $z = 0$ by the two components. It implies in fact that a significant fraction of dark matter which has been expelled between $z = 8$ and $z \sim 0.6$ has been re-accreted between $z \sim 0.6$ and $z = 0$. This is not the case for baryons which are generally heated through the expelling process and therefore remain outside the virial radius afterwards. In order to illustrate this, Figure 7 presents the evolution of the distribution of baryons and dark matter for HALO1. From $z = 2.6$, the main progenitor undergoes two mergers with mass ratios of 1:1.8 and 1:5. Here, we have selected all particles inside the virial radius of each of the 3 objects. Note that the orbits of the two mergers are quite radial. After the two merger events, the spatial distributions of baryons and dark matter are quite different. Most of the dark matter particles are located inside the virial radius, though a small part has been expelled in the same orbital direction. The baryons tends to either collapse toward the center or are expelled all around. This phenomenon is observed at $z = 0$ where a non-negligible part of baryons have been expelled and remain outside the virial radius. Figure 7 also shows the evolution of the mass of DM and baryons located outside the virial radius. In the case of the dark matter component, there are 3 distinct phases. First, from the beginning of the experiment until $t = 3$ Gyr, both satellites are accreted inside R_v . Then in the second phase (from $t = 3$ to $t \sim 4.5$ Gyr) some of the dark matter is expelled via tidal disruption. Finally from $t \sim 4.5$ Gyr some of the dark matter particles are re-accreted. Note that evolution from $t \sim 10$ Gyr is probably due to the effect of another merger event. However, the baryon component follows the two first phases but not the third one: once baryons are expelled, most of them remain outside the virial radius. In this specific example, we found that 2.1% and 5.8% of dark matter and baryon masses respectively are released at $z = 0$ from the three main objects. This is in good agreement with results obtained from idealized simulations (Sinha & Holley-Bockelmann 2009). It is also interesting to see that due to mergers, unbound gas diffuses far away from the galaxy; thus mergers represent a potential mechanism for enriching the IGM with metals. Note that this enrichment must occur early, as in our model, to avoid disruption of the cold and weakly enriched Lyman alpha forest.

Finally, it is interesting to point out that HALO1 undergoes major merger events between $z \sim 0.8$ and $z \sim 0.5$, leading to important mass outflows from $z \sim$

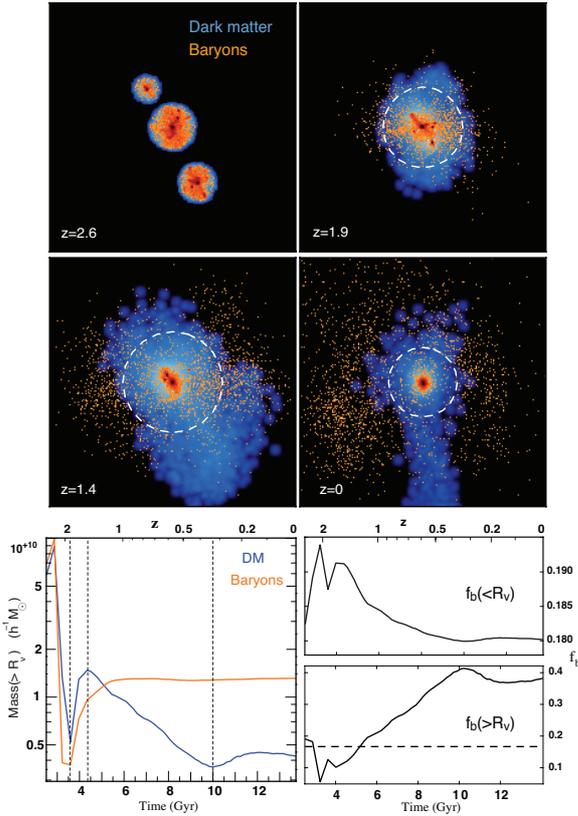


Figure 7. An illustration of the evolution of the distribution of baryons and dark matter during and after given merger events. Panels at $z = 0$ is 1×1 Mpc across while the other ones are 0.3×0.3 Mpc across. The white dashed lines represent the virial radii. In the lower panels, we show the evolution of the mass of baryons and DM outside the virial radius of the host halo (left panel) and the evolution of the baryonic fraction estimated from these 3 haloes inside and outside the virial radius (right panel). One can see that a non negligible number of DM particles are re-accreted inside R_v (from $t \sim 4.5$ to $t \sim 10$ Gyr) which is not the case for baryons. As a result, the final values of $f_b(<R_v)$ and $f_b(>R_v)$ are respectively lower and higher than initial ones.

0.5 and $z = 0$. In particular, Figure 6 indicates that more dark matter particles are released than baryons after the merger events. Most of this dark matter is not yet re-accreted, which explains why HALO1 tends to have values of f_b higher than HALO2 at $z = 0$. This also explains why in Figure 3 the high f_b value regions around HALO1 seem to be less pronounced in comparison to those around HALO2.

Thus, the evolution of the mean baryonic fraction value f_b at the virial radius is essentially governed by the relative efficiency at which the dark matter and baryons are accreted. Indeed, the evolution of the accreted mass of both dark matter and baryons follows two different regimes: a rapid growth at high redshifts ($z \geq 1.5$) and a slower one at lower redshifts. These evolutions are directly related to the total mass evolutions in Figure 6 which also presents these two regimes. This behaviour compares well to the evolution of individual dark matter halos (see for instance Wechsler et al. 2002; Vitvitska et

al. 2002, Peirani, Mohayaee & Pacheco 2004, McBride et al. 2009 and Tillson, Miller & Devriendt 2011), indicating a fast growth of the mass for $z > 1.5 - 2.0$, followed by a phase where the accretion rate is slower. Hydrodynamical simulations have also suggested that galaxy formation presents two phases: a rapid early phase ($z \geq 1.5$) during which stars mainly form within the galaxy from infalling cold gas (Katz et al. 2003; Kereš et al. 2005; Ocvirk, Pichon & Teyssier 2008; Dekel et al. 2009) and a second one ($z \leq 1.5$) during which stars are accreted (Oser et al. 2010; Hirschmann et al. 2012). This latter phase is dominated by the accretion of diffuse matter and small satellites (Fakhouri & Ma 2010; Genel et al. 2010; Wang et al. 2011; van de Voort et al. 2011). Hence the high f_b values at high redshift derived from SIM1a and SIM1b can be explained by the accretion of high gas-to-dark matter ratio from dense region such as filament via cold flows. But at lower redshift, f_b is decreasing due to the accretion of low gas-to-dark matter ratio material, in particular from the diffuse region. Indeed, we found that the baryonic fraction of the diffuse accreted matter (namely $f_b \sim 0.11 - 0.14$) is on the average much lower than the universal value: as the haloes become more massive, the temperature at the virial radius increases and the gas is shock-heated and this process slows down its accretion onto the halo. For SIM2, f_b reaches its lowest value ($f_b \sim 0.05$) at $z \sim 5$ right after some significant expulsion of gas. After that, there is a short phase where f_b increases because the accreted matter has a higher baryonic content (but not necessarily higher than the universal value). Then, in the late phase of evolution of each halo, f_b tends to be constant ($f_b \sim 0.12$) because the average accreted matter tends to have the same baryonic fraction value as the mean value inside virial radii.

3.3 Properties of the IGM

The WHIM has proven to be difficult to detect and represents a serious candidate for the missing baryons. It is therefore instructive to estimate the fraction of the WHIM in our simulated local universes. For this purpose, we have divided the Inter-Galactic Medium (IGM) into four components: (1) galaxies and stars, (2) cold gas ($T < 10^5$ K), (3) WHIM (10^5 K $< T < 10^7$ K) and hot gas ($T > 10^7$ K). Figure 8 shows the time evolution of these four baryon components within a sphere centred on the local Universe-type halos and of comoving radius 1.5 Mpc/h. It shows that the WHIM represents $\sim 30\%$ of the baryon budget at $z = 0$, in good agreement with past work based on hydrodynamical simulations (Cen & Ostriker 1999; Davé et al. 2001; Cen & Ostriker 2006; Rasera & Teyssier 2006; Tornatore et al. 2010) when AGN feedback is not taken into account. Note that the evolution of the hot gas ($T \geq 10^7$ K) is not shown in Figure 8 since this component represents less than 1% of the total baryon mass budget in our selected region, as expected since we are not in a cluster environment. We also found that the warm and hot gas becomes the dominant baryonic component at large radii ($R > 150$ kpc) from each main halo, in good agreement with previous observational analysis of massive galaxies (Humphrey

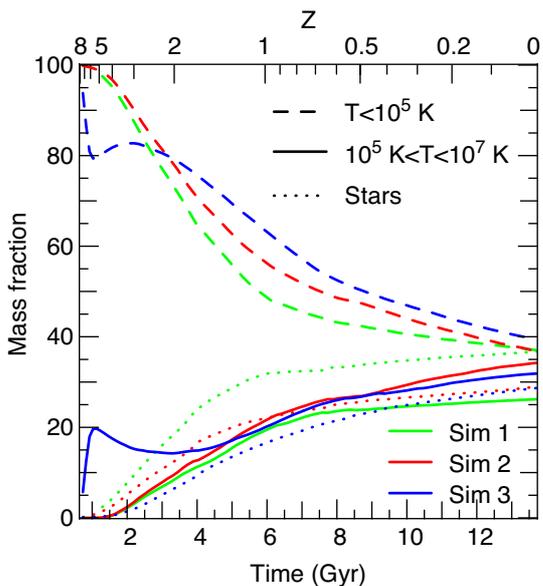


Figure 8. The evolution of the IGM components within a sphere centred on the local Universe type halos and of comoving radius 1.5 Mpc/h: cold gas ($T < 10^5$ K, dashed lines), WHIM (10^5 K $< T < 10^7$ K, solid lines) and stars (dotted lines). Green, red and blue lines correspond to SIM1a, SIM1b and SIM2 respectively.

et al. 2011, 2012) or with previous numerical simulations (van de Voort et al. 2011; van de Voort & Schaye 2012). However, when the contribution of the WHIM is not taken into account in the estimation of the baryonic fraction at the virial radius, namely when only the cold gas ($T \leq 10^5$ K) and stars are considered, f_b values obtained at $z = 0$ only decrease by $\sim 15\%$. This follows from the fact that stellar masses obtained in our experiments have a large contribution in the final f_b values and thus we probably need the additional effect of AGN feedback to regulate the SFR and also increase the mass of WHIM inside the virial radius. Nevertheless, the distribution of baryonic fraction seen in Figure 3 is significantly affected when the WHIM is not taken into account. Indeed, Figure 9 shows that in this latter case, the baryonic fraction is lower than $0.5\langle F_b \rangle$ in the direct vicinity of the virial radius.

Outside the virial radii, our analysis in the previous section has suggested that the IGM is composed of gas that either never collapses onto haloes or is released by mechanisms such as feedback or merger events. But what are the relative proportions? From Figure 6 we can estimate that $\gtrsim 20\%$ of the total accreted baryons is expelled from $z = 8$ to $z = 0$ for HALO1 and HALO2, which is quite significant. These results are also in good agreement with Sinha & Holley-Bockelmann (2010) who found from semi-analytic techniques that up to $\sim 25\%$ of gas can be unbind over the course of galaxy assembly. From our analysis, we found that the gas that has been released after being accreted on to haloes is mainly located between R_v and $2R_v$ at $z = 0$. If we focus on HALO1 which is quite isolated, we found that the gas component between R_v and $2R_v$ consists of 55.9%,

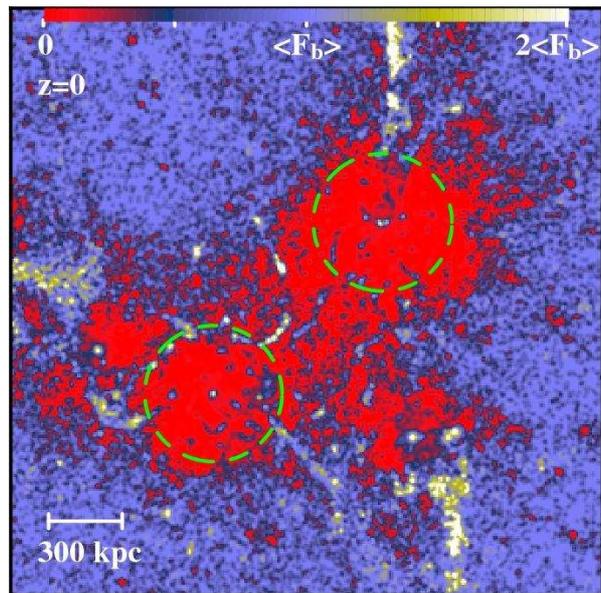


Figure 9. The projected baryonic fraction at $z = 0$ derived from SIM1a when the WHIM is not taken into account in the estimation of f_b .

58.6% and 60.5% of gas that has been expelled from HALO1 from SIM1a, SIM1b and SIM2 respectively. In other words $\sim 40\%$ of this gas has never collapsed onto HALO1. It is also worth mentioning that $\gtrsim 95\%$ of the gas that has been released through merger events or feedback is in the form of WHIM at $z = 0$ but only $\sim 65\%$ in the case the gas that has never collapsed into the halo. Hence, the gas that has been ejected through different mechanisms during the galaxy formation and evolution significantly increases the mass of the WHIM.

4 DISCUSSION AND CONCLUSIONS

In this paper, we have analysed hydrodynamical simulations with an extensive treatment of the physics of baryons in order to study the evolution of the distribution of baryons in a local group-type object. In particular, we have investigated the impact of i) supernova feedback, ii) more powerful sources of feedback at high redshift such as AGN from intermediate mass black holes or hypernovae and iii) accretion/ejection and merger events in the evolution of the mass content of Milky-Way type galaxies.

We found that the evolution of the mean baryonic fraction value f_b estimated at the virial radius of the two main central objects is essentially governed by the relative efficiency at which dark matter and baryons are accreted. Indeed, in the first and early phase of galaxy formation (the cold mode of accretion $z \geq 1.5$) during which stars mainly form within the galaxy from infalling cold gas (Katz et al. 2003; Kereš et al. 2005; Ocvirk, Pichon & Teyssier 2008; Dekel et al. 2009) f_b is in general higher than the universal value. But in the second phase (the hot mode of accretion), dominated by the accretion of diffuse matter or small satellites, f_b tends to

decrease and is 10-15% lower than the universal value, 0.166, at $z = 0$. This decrease is not due to the fact that more baryons (relative to DM) are expelled beyond the virial radius by physical mechanisms such as feedback or merger events. Rather this essentially follows from the relative nature of dissipative gas and non-dissipative dark matter. Specifically, the gas component can be shock-heated at the virial radius, which considerably slows down its further accretion into the halo. Additionally, we found that accretion and particularly merger events can release a fraction of both dark matter and baryons. But again, dark matter that has been expelled can be re-accreted more efficiently than the corresponding baryons, hereby enhancing the decrease of f_b inside the virial radius. Consequently, our simulations suggest that the gas located beyond the virial radius is mainly in the form of WHIM that comes from either gas that never collapsed prior to the formation of the proto-galaxy ($\sim 40\%$) or gas expelled by feedback and merger processes ($\sim 60\%$).

Our comparison of SIM1a and SIM1b also suggest that globally increasing somewhat the efficiency of supernovae does not significantly affect the evolution of f_b inside the virial radius. In other words, standard SN feedback is not powerful enough to expel the baryons out of the gravitational potential of dark matter haloes of such mass scales. But at high redshift the situation is quite different since haloes are less massive and thus feedback mechanisms have a more effective contribution. Indeed for our other scenario (for which a higher fraction of gas is expelled at high redshift ($z \sim 8$) by more powerful source of feedback such as AGN from intermediate mass black holes or hypernovae implemented in SIM2) the accretion of gas is strongly affected at high redshift, and drives the mean baryonic value inside the virial radius a lower values at $z = 0$. This is one important conclusion of this paper: to get a low value of f_b at present time, physical mechanisms able to slow down the accretion of gas *at high redshift* will have a stronger impact on the deficit of baryons in the mass budget of Milky Way type-galaxy today than those that expel the gas in the longer, late phases of galaxy formation.

However, it is worth mentioning that the effective contribution of non-gravitational heating such as galactic winds from supernovae in the evolution of f_b within the virial radius of Milky Way type galaxy is still controversial and a debated topic in the recent literature. From our modelling and experiments, we found that increasing the efficiency of supernova feedback leads to the reduction of the stellar mass but has no particular impact on the evolution of $f_b(< R_v)$ for system of such mass scales (cf Powell, Slyz & Devriendt 2011). Such statements were also advocated by Anderson & Bregman (2010) from observational constraints on the density of hot gas around the Milky Way. Moreover, using cosmological simulations, Faucher-Giguère, Kereš & Ma (2011) have investigated the net baryonic accretion rates through R_V . Although the net baryonic accretion rates is sensitive to galactic outflows, especially for low mass systems, the baryon mass fractions at $z = 0$ for objects with a mass higher than $10^{12} M_\odot$ and for different SN feedback prescriptions have similar values to those de-

rived in the present study. However, other hydrodynamical simulations from Scannapieco et al. (2008, 2009) using higher SFR efficiency ($c_* = 0.1$) found that at $z = 0$, the baryon fractions inside the virial radius are ≤ 0.10 within the virial radius “*indicating that a significant amount of baryons has been lost through winds*”.

AGN feedback is supposed to play an important role in the formation of massive objects such as giant ellipticals in galaxy groups (Tabor & Binney 1993; Ciotti & Ostriker 1997; Silk & Rees 1998). From previous numerical studies, the inclusion of AGN is expected to reduce the stellar mass (see for instance Sijacki et al. 2007; Dubois et al. 2010, 2012; Hambrick et al. 2011b) and also increase the mass of WHIM (Cen & Ostriker 2005; Tornatore et al. 2010; Durier & Pacheco 2011; Roncarelli et al. 2012). Our study does not include the effect of AGN feedback at low redshift, but we think that such sporadic events will not have a major contribution in the baryonic fraction value inside the virial radius at present time. Indeed, from observationally motivated constraints, AGN and SN at low to moderate redshift seem not to produce the expected correlations with the baryonic Tully-Fisher relationship (Anderson & Bregman 2010). Moreover, as mentioned above, observations of massive objects reported by Humphrey et al. (2011, 2012) seem to suggest that AGN feedback has no particular impact on the baryonic fraction values within the virial radius. Also, recent hydrodynamical simulations show that AGN and SN feedback may mutually weaken one another’s effect by up to an order of magnitude in haloes in the mass range of $10^{11.25} - 10^{12.5} M_\odot$ (Booth & Schaye 2012). At high redshift, the effects of galactic winds on the IGM are also controversial. In the present paper, our simple minded modelling indicates that galactic winds can expel some gas outside the virial radius and affect significantly the evolution of the baryon content of massive galaxies. Similar conclusions have been recently drawn by Roncarelli et al. (2012) from hydrodynamical simulations suggesting that galactic winds acting at earlier epochs can prevent the IGM to collapse in dense structures. Also, as mentioned above, semi-analytical model from Valiante, Schneider & Maiolino (2012) indicates that the observed outflow of a distant quasar at $z = 6.4$ (Maiolino et al. 2012) is expected to have considerably depleted the gas content of the host galaxy. However, simulations conducted by Di Matteo et al. (2011) or Shen et al. (2012) found that galactic outflows at high redshift may not be very effective at stopping the cold gas from penetrating the central regions.

In summary, our study indicates that in order to reach lower f_b values at $z = 0$ for Milky Way type galaxies, preventing the accretion of cold gas during the first phase of galaxy formation at high redshifts proves to be crucial. Moreover, efficient high redshift feedback processes seem also to be required in order to slow down the growth of galaxies at high redshift and thus to reproduce the observed number density evolution as recently pointed out by Weinmann et al. (2012). If such statements are correct, numerical and observational efforts have to be focused towards characterising the respective role of each feedback process at high redshift on the IGM. In particular, are the baryons expelled from

protogalaxies or do they never collapse into the gravitational potential well of these objects? In the present paper, we only focus on the first mechanism, but it is not excluded that processes such as photoionization play a major role especially at high redshifts for low mass systems. In this regard, it is interesting to compare our results with those of Guedes et al. (2011) who have studied the formation of late-type spirals from the ERIS simulation. Specifically, they claimed that the collapse of baryons is heavily suppressed at high redshift by the UV background. And it is particularly instructive to see that from their highest mass resolution simulation, the evolution of the baryonic fraction (see their Figure 6 in Guedes et al. 2011) is very similar to those we obtained from SIM2. They also found a similar value at $z = 0$ namely $f_b \sim 0.7 < f_b >$. Our simulations do include UV background but our mass resolution may be too small to account for this process properly.

More detailed and well-resolved hydrodynamical simulations are required to investigate the evolution of the mass content of galaxies and high and low redshifts. But in order to achieve this goal, one must first improve the constraints of the expected energy injection to the IGM from SN, AGN, UV background (etc...) via observations.

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