Gas distribution, metal enrichment and baryon fraction in Gaussian and non-Gaussian universes

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Abstract

We study the cosmological evolution of baryons in universes with and without primordial non-Gaussianities via $N$-body/hydrodynamical simulations, including gas cooling, star formation, stellar evolution, chemical enrichment from both population III and population II regimes, and feedback effects. We find that large $f_{\text{NL}}$ values for non-Gaussianities can alter the gas probability distribution functions, the metal pollution history, the halo baryon, gas and stellar fractions, mostly at early times. More precisely, (i) non-Gaussianities lead to an earlier evolution of primordial gas, structures and star formation; (ii) metal enrichment starts earlier (with respect to the Gaussian scenario) in non-Gaussian models with larger $f_{\text{NL}}$; (iii) gas fractions within the haloes are not significantly affected by the different values of $f_{\text{NL}}$, with deviations of $\sim 1$–10%; (iv) the stellar fraction is quite sensitive to non-Gaussianities at early times, with discrepancies reaching up to a factor of $\sim 10$ at very high $z$, and rapidly converging at low $z$; (v) the trends at low redshift are independent from $f_{\text{NL}}$: they are mostly led by the ongoing baryonic evolution and by the feedback mechanisms, which determine a $\sim 25$–30% discrepancy in the baryon fraction of galaxy groups/clusters with respect to the cosmic values; (vi) non-Gaussianity impacts on the cluster x-ray emission or on the Sunyaev–Zeldovic effect(s) are expected to be not very large and dominated by feedback mechanisms, whereas some effects on the 21 cm emission can be expected at early times; (vii) in order to address non-Gaussianities in the cosmological structure contest, high-redshift ($z \sim 10$) investigations are required: first stars, galaxies, quasars and gamma-ray bursts may be potential cosmological probes of non-Gaussianities.

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(Some figures may appear in colour only in the online journal)
1. Introduction

Any cosmological model has to face two main concerns: the first is to explain the spacetime evolution of the universe, and the second is to explain the formation and growth of the cosmic 'spacetime content', i.e. the cosmic structures.

Nowadays, it is possible to give good constraints on the first problem (Komatsu et al. 2011, and references therein): in particular, we know that the cosmological expansion is well described by the so-called ΛCDM model, in which the spacetime is flat and its expansion rate at the present is \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \) (\( h = 0.7 \) if \( H_0 \) is normalized to \( 100 \text{ km s}^{-1} \text{ Mpc}^{-1} \)). The density parameters describing the composition of the universe are (Komatsu et al. 2011) \( \Omega_{0,m} = 0.272 \) for matter and \( \Omega_{0,\Lambda} = 0.728 \) for the cosmological constant \( \Lambda \), often attributed to some kind of still unknown 'dark-energy' (Maio et al. 2006 first investigated its effects on gas hydrodynamics and cosmic chemical evolution via detailed numerical simulations and found some impacts on the early gas cloud distributions). According to the cited observational data, the resulting total-density parameter is unity, \( \Omega_{0,\text{tot}} = 1.0 \), but the only physically known fraction is very small, since baryons yields only \( \Omega_{0,b} = 0.0456 \).

The second problem is fundamentally related to the early 'seeds' from which cosmological structures will develop. More precisely, clusters and galaxies are supposed to evolve from primordial matter fluctuations that have a power-law primordial power spectrum, normalized via mass variance within 8 Mpc/\( h \)-radius sphere \( \sigma_8 = 0.8 \), and with a spectral index \( n = 0.96 \). Then, in order to make statistical predictions for the structure growth, such as mass functions or bias (Wagner et al. 2010, D’Amico et al. 2011, Fedeli et al. 2011, Hamaus et al. 2010, for example), one has to assume a probability distribution of primordial fluctuations, around the mean density \( \langle \rho \rangle \), as a function of the overdensity \( \delta \). According to the central-limit theorem, \( \delta \) is usually assumed to be Gaussian. However, the validity of this assumption has often been questioned over the years and non-Gaussian models have been considered for a long time (Peebles 1983, Grinstein and Wise 1986). Recent observational data do not rule out non-Gaussianities either (Komatsu et al. 2005, Komatsu 2011).

The most common way to parameterize non-Gaussian distributions (Desjacques and Seljak 2010, Verde 2010, and references therein) is by introducing a nonlinearity parameter, \( f_{\text{NL}} \), according to the following ansatz (Salopek and Bond 1990):

\[
\Phi = \Phi_L + f_{\text{NL}} [\Phi_L^2 - \langle \Phi_L^2 \rangle].
\]

In the previous equation (1), \( \Phi \) is the Bardeen gauge-invariant potential, \( \Phi_L \) is the 'linear' Gaussian part and the second term on the right-hand side is the nonlinear correction, whose contribution is regulated by the \( f_{\text{NL}} \) parameter. Since at any point the potential \( \Phi \) depends only on the value of \( \Phi_L \), non-Gaussianities of this form are also called 'local'. Observational constraints on primordial matter fluctuations suggest that the primordial distribution could present some departures from the Gaussian one, with \( f_{\text{NL}} \) in the range \( \sim 10–100 \) (Maio and Iannuzzi 2011, and their table 2 for a collection of constraints). The existence of a non-null \( f_{\text{NL}} \) would reflect on the growth of cosmological structures at any time and redshift (\( z \)). This means variations of the dark-matter halo mass function, mostly at large masses and/or at high redshift (Desjacques and Seljak 2010, Verde 2010, LoVerde and Smith 2011, Desjacques et al. 2011, and references therein). Non-Gaussian effects could also be visible in the baryon history of cosmic objects (Maio and Iannuzzi 2011, Maio and Khochfar 2011, Petkova and Maio 2011) and probably affect their gaseous and stellar components. The uncertainties on the baryonic evolution in non-Gaussian scenarios are mainly linked to the feedback effects which could strongly interfere with the original non-Gaussian signal. Besides the first attempt by Maio and Iannuzzi (2011) and Viel et al. (2009), there are, at the moment, no other investigations in this
field, and quite a large lack of knowledge of the hydrodynamical interplay of the cosmic gas with non-Gaussianities. The ignorance of the detailed gas properties and of feedback effects could be a strong limitation (Tescari et al 2011) when accounting for, e.g., metal abundances, Sunyaev–Zeldovich (SZ) signal (Sunyaev and Zeldovich 1969, 1970) or x-ray emission from galaxy clusters in non-Gaussian models. Additionally, it might also influence the gas emission at high redshift (like the 21 cm signal).

Therefore, in this study we analyze the principal features of the gas behavior, during its condensation process within dark-matter haloes, and address the effect on the baryon fraction in the Gaussian and in different non-Gaussian scenarios. We will focus on the cosmic gas and its distribution at high and low redshift, down to $z = 0$, by stressing the consequences from star formation, and the impacts for metal spreading, gas fractions, stellar fractions and baryon evolution within the formed cosmological structures.

This work is organized as follows: in section 2, we summarize the main properties of the simulations and of the physical implementations; in section 3, we show our results on star formation (section 3.1), gas probability distribution functions (section 3.2), metal enrichment (section 3.3) and halo baryonic properties (section 3.4); we finally discuss our results and summarize our conclusions in section 4.

2. Simulations

We use the simulations presented by Maio and Iannuzzi (2011), who performed the first study of the effects of primordial non-Gaussianities on the cosmic star formation, via self-consistent $N$-body hydrodynamical chemistry simulations. Beyond gravity and hydrodynamics, the code includes radiative gas cooling at high (Sutherland and Dopita 1993) and low (Maio et al 2007) temperatures, a multi-phase model for star formation, UV background radiation and wind feedback (see Katz et al (1996), Springel and Hernquist (2003) for further details). It also follows chemical evolution, metal pollution from population III (popIII) and/or population II (popII) stellar generations, ruled by a critical metallicity threshold of $Z_{\text{crit}} = 10^{-4} Z_{\odot}$ (Tornatore et al 2007, Maio 2009, Maio et al 2009, 2010, 2011). The main agents of gas cooling (Sutherland and Dopita 1993, Maio et al 2007) are atomic resonant transitions of H and He excitations that can rapidly bring temperatures down to $\sim 10^4$ K, when molecules become the only relevant coolants in pristine environments. In metal-rich environments, atomic fine-structure transitions are additionally included (Maio et al 2007) and can further lower them, mostly at high redshift, since the formation of a UV background (Haardt and Madau 1996, Davel et al 1999, Gilmore et al 2009) at lower redshifts heats the IGM and hinders gas cooling. In dense environments, stochastic star formation is assumed, cold gas is gradually converted into stars (Kennicutt 1998), outflows take place and feedback effects inject entropy into the surrounding environment, leading to a self-regulated star-forming regime (see Springel and Hernquist (2003) for further details).

The simulations considered here assume a concordance ΛCDM model with total density parameter $\Omega_{\text{tot}} = 1.0$, matter density parameter $\Omega_{\text{m}} = 0.3$, cosmological density parameter $\Omega_{\Lambda} = 0.7$, baryon density parameter $\Omega_{b} = 0.04$, expansion rate at the present $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, power spectrum normalization via mass variance within $8$ Mpc/$h$-radius sphere $\sigma_8 = 0.9$ and spectral index $n = 1$. We consider the cases: $f_{\text{NL}} = 0$ (Gaussian), 100, 1000, in cosmological periodic boxes with 100 Mpc/$h$ aside, and with a gas mass resolution of $\sim 3 \times 10^8 M_\odot/h$.

The stellar initial mass function (IMF) is a key ingredient for stellar systems, because it determines the temporal evolution and the relative distribution of stars with different masses
and different metal yields. In the simplest approximation, it can be parameterized as a power law of the mass converted into stars $M_\star$ (Salpeter 1955)

$$\phi(M_\star) \propto M_\star^x$$  \quad (2)

and normalized via the relation

$$\int_{M_{\star,\inf}}^{M_{\star,\up}} \phi(M_\star) \, dM_\star = 1$$  \quad (3)

over the mass range $[M_{\star,\inf}, M_{\star,\up})$. Since the primordial IMF is quite uncertain, we bracket the possible scenarios by assuming both a top-heavy popIII IMF (normalized over the mass range $[100, 500]$ solar masses, and with metal yields for PISN), and a Salpeter (1955)-like (SL) IMF (normalized over the mass range $[0.1, 100]$ solar masses, and with metal yields for AGB, SNII, SNIa stars), as opposite limiting cases (Maio and Iannuzzi 2011). The slope is fixed to $x = -2.35$ (Salpeter 1955). For the popII-I stellar populations, we always adopt a common Salpeter IMF.

### 3. Results

In the following sections, we show the main results of our analysis, starting, for clarity, from the star formation rate densities in the simulated volumes (section 3.1) and considering the implications for the basic baryon properties, like probability distribution functions (section 3.2) and metal enrichment (section 3.3). Then, we will analyze the consequences on the cosmological structures (section 3.4), exploring the evolution of their gaseous and stellar components (sections 3.4.1, 3.4.2 and 3.4.3).

#### 3.1. Star formation

We already mentioned that the $N$-body/hydrodynamical/chemistry simulations considered here have been presented for the first time in Maio and Iannuzzi (2011), who discussed the main effects of non-Gaussianities on the star formation history in the universe. In this work, we aim at a more detailed study of the cosmological evolution of cosmic structures, and in particular of their visible components, gas and stars, within Gaussian and non-Gaussian contexts. Therefore, we start from the star formation rate densities, which are re-proposed, for the sake of completeness, in figure 1, for both the top-heavy popIII IMF (left) and the SL popIII IMF (right). The star formation rate density, $\dot{\rho}_\star$, quantifies the mass converted into stars, $M_\star$, per unit time, $t$, and unit volume, $V$, and can be expressed as (Kennicutt 1998)

$$\dot{\rho}_\star = \frac{dM_\star}{dt dV} \propto \frac{\rho}{t_{ff}}$$  \quad (4)

where $\rho$ is the gas density and $t_{ff} \sim 1/\sqrt{G \rho}$ is the free-fall time. Therefore, the larger the gas density, the larger the star formation rate density. As clear from the plots in figure 1, the dependences on $f_{NL}$ are quite weak and it is not easy to distinguish among different cases, as long as $f_{NL} \leq 100$. Only an extremely high (and currently ruled-out) value of $f_{NL} = 1000$ would show appreciable differences with respect to the Gaussian case ($f_{NL} = 0$).

Moreover, the global trends show that the Gaussian models give a fair representation of the star formation history, also with respect to $f_{NL} = 100$ non-Gaussian corrections. The main difference is found for the $f_{NL} = 1000$ case, which predicts a significantly earlier onset of the star formation of almost $10^8$ yr, and thus a correspondingly earlier enrichment process from the first stars and galaxies (see the following sections).
Figure 1. Star formation rate densities as a function of redshift for $f_{\text{NL}} = 0$ (solid lines), $f_{\text{NL}} = 100$ (dotted lines) and $f_{\text{NL}} = 1000$ (dashed lines). Individual contributions from popIII regions (bottom lines) are also shown. In the left case, the assumed popIII IMF is top-heavy (TH) in the mass range $[100,500] M_\odot$, with a slope of $-1.35$ (Maio et al. 2010 have showed that the detailed value of the slope has little effects), while in the right case the assumed popIII IMF is SL (see Maio and Iannuzzi (2011) for further details).

The adopted primordial popIII IMF has consequences on the popIII star formation. It determines a popIII contribution to the total star formation rate varying between almost two orders of magnitudes. More in detail, in the top-heavy popIII IMF case, the popIII star formation rate densities reach at most $\sim 10^{-5} M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$ for any $f_{\text{NL}}$, and the relative contributions drop down below $\sim 10^{-5}$ at low redshift. In the SL popIII IMF case, instead, the star formation rate densities achieved are $\sim 10^{-3} M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$, with a popIII contribution of less than $\sim 10^{-3}$, even at low redshift, independently from $f_{\text{NL}}$.

We stress that the behavior of the total star formation rate density at low $z$ is practically unaffected by deviations from Gaussianity.

3.2. Gas distribution functions

Star formation is the main agent leading the whole evolution of cosmic gas. Indeed, at very early times, when the universe is younger than a few $10^8$ yr, there are no relevant star formation episodes, yet, and the gas has a purely pristine chemical composition. First, stars synthesize heavy elements in their cores and eventually spread them around, during the final stages of their lives, by exploding as SN or PISN. These explosive events lead metal pollution in the surrounding regions and inject large amounts of entropy into the medium. Obviously, this has severe impacts (feedback) on the following generations, since the gas will be in very different conditions, with respect to the primordial, pristine gas. In order to illustrate and summarize the behavior of cosmic gas during the cosmological evolution and its modifications due to non-Gaussianities, we consider the probability distributions, $P(n)$, as functions of the number density, $n$:

$$P(n) = \frac{df}{dn}. \quad (5)$$
Figure 2. Gas probability distribution function at different redshifts, $z$, as indicated by the labels for the boxes with 100 Mpc/h aside, and a top-heavy popII IMF.

with $df$ fraction of gas elements in the $dn$ density bin, and with normalization

$$\int_{-\infty}^{+\infty} P(n) \, dn = 1. \quad (6)$$

We display the gas probability distribution functions in figure 2, at different redshifts, for the runs having $f_{\text{NL}} = 0$, $f_{\text{NL}} = 100$ and $f_{\text{NL}} = 1000$. The assumed popIII IMF is top-heavy. From the plots, it is evident that at early times (e.g. at $z \sim 23–13$) the gas distributions are slightly affected by non-Gaussianities, the gas is mainly at the mean density, and the environments showing some deviations from the Gaussian behavior are only the ones with over-densities $\sim 10^1–10^2$ for $f_{\text{NL}} = 1000$. This basically reflects the features of the initial conditions, that, in the non-Gaussian cases, are biased toward higher densities. Within $\sim 1$ Gyr, a decrement in the differences of the high-density tails appears, with discrepancies going from $\sim 1$ order of magnitude at $z \sim 13$ down to a factor of $\sim 2–3$ at $z \sim 7.5$. Moreover, below $z \sim 7.5$, the ongoing star formation events and the related feedback effects efficiently push the material far away from the star forming sites: this causes a larger spread in the distributions of the underdense material that is fed by gas expelled by the dense star forming regions. The feedback mechanisms cause gas mixing among the cold and hot phases, and the interactions between the inflowing and outflowing material increase the turbulent state up to the Reynolds number of the order of $\sim 10^8–10^{10}$ (Maio et al 2011). These phenomena completely erase any imprints of non-Gaussianities (already by $z \sim 3$) for any $f_{\text{NL}}$. This is an important conclusion, since it clearly shows that low-$z$ baryon evolution is affected by gas and stellar feedback in a much more important way than by deviations from the Gaussian shape of the underlying matter distribution (see the further discussion in section 3.4.2), even when considering very large $f_{\text{NL}}$. Gas emission at high redshift (e.g. the hydrogen hyperfine-structure transition at 21 cm from early structures) is not supposed to change strongly for $f_{\text{NL}} = 0$ and $f_{\text{NL}} = 100$. For
$f_{\text{NL}} = 1000$, however, there would be an enhancement due to the slightly larger amounts of gas at higher densities, but only within the first Gyr.

The SL popIII IMF cases present similar physical behaviors, with distributions which change accordingly to the different $f_{\text{NL}}$ values.

More differences will be found in the metallicity evolution, as we will discuss in the next section.

We note though (see also the discussion in section 4) that the difference at early times in both gas distributions and star formation rates already suggests that primordial ‘visible’ structures like first stars, galaxies, quasars and gamma-ray bursts (GRBs) could be affected by the initial (Gaussian or non-Gaussian) dark-matter distribution.

3.3. Metals

Metal spreading is one of the principal signatures of the evolution of baryonic matter, and it leads crucial changes to the formation process of cosmic objects.

To show the effects of different $f_{\text{NL}}$ values on metal evolution, in figure 3 we present the metal filling factor computed for the runs with $f_{\text{NL}} = 0$, 100 and 1000. This quantity represents the fraction of cosmic volume filled by metals and is computed from the outputs of our simulations, at each redshift, according to the equation

$$f_V \equiv \frac{\sum_i m_{Z,i} / \rho_{Z,i}}{\sum_j m_j / \rho_j} \sim \frac{\sum_i m_{Z,i} / \rho_{Z,i}}{V}$$

with $i$ and $j$ integers running over the number of the enriched particles and of all the SPH particles, respectively, $m_{Z,i}$ particle metal mass, $\rho_{Z,i}$ metal-mass density, $m$ total particle mass, $\rho$ total-mass density and $V$ simulation box volume. On the left panel, we show results from the simulations with a top-heavy popIII IMF, while on the right panel, we show results from the simulations with a SL popIII IMF. In the plots, we also distinguish by the metallicity regime to study the effects on the different stellar populations. The most evident feature is the convergence at low redshift of all the models. The most relevant differences are at high redshift, in correspondence of the different onsets of the first star forming events.
In the top-heavy popIII IMF case (left panel), the first enrichment patterns are found immediately after the first star formation events, due to the extremely short lifetimes of massive stars and PISN (\(\sim 2 \times 10^6\) yr). Indeed, in the runs with \(f_{\text{NL}} = 0\) and \(f_{\text{NL}} = 100\), the onset is at \(z \sim 16\), and in the run with \(f_{\text{NL}} = 1000\) it is at \(z \sim 22\) (see the left panel of figure 1). Correspondingly, first metals are spread in the universe at \(z \sim 15\) for \(f_{\text{NL}} = 0\) and \(f_{\text{NL}} = 100\), and at \(z \sim 21\) for \(f_{\text{NL}} = 1000\). Given the large metal yields (see Maio et al (2010) for further discussions), the popIII filling factors soon become sub-dominant of some orders of magnitudes for all the cases. We stress that the differences between the Gaussian case \((f_{\text{NL}} = 0)\) and the \(f_{\text{NL}} = 100\) case are negligible at any time. At lower redshift, when effects of non-Gaussianities are less relevant, all the models predict a total volume metal filling factor of \(\sim 10^{-3}\), and a popIII volume filling factor of \(\sim 10^{-7}\), four orders of magnitude smaller.

When a SL popIII IMF is adopted (right panel), the main changes are found at high redshift and are mainly due to the longer stellar lifetimes. In fact, they induce a larger delay of the pollution episodes, since the first metals are spread at \(z \sim 14\) for \(f_{\text{NL}} = 0\) and \(f_{\text{NL}} = 100\), and at \(z \sim 18\) for \(f_{\text{NL}} = 1000\), i.e. about \(\sim 5 \times 10^7\) yr, after the onset of star formation (consistently with the typical lifetimes of the first SNII explosions). Also, in these scenarios differences between \(f_{\text{NL}} = 0\) and \(f_{\text{NL}} = 100\) are not very appreciable and the asymptotic trends, led mostly by the popII-I regime, remain unaltered.

### 3.4. Baryon fraction in the cosmic haloes

After the general, global quantities previously studied, we investigate if and how the situation changes in the individual haloes found in the simulations, by paying more attention to their gaseous and stellar content. The formed structures are identified by a friends-of-friends (FoF) algorithm, with a linking length of 20% of the mean inter-particle separation. In this way, we can determine total masses \(M_{\text{tot}}\) and basic properties of all the cosmic objects and of their different dark-matter, gaseous and stellar components.

#### 3.4.1. Gas and stars in the haloes

In figure 4, the joint probability distributions \(P(f_b, M_{\text{tot}})\) and \(P(f_s, M_{\text{tot}})\) for the baryon fraction, \(f_b\) (upper panels), and for the stellar fraction, \(f_s\) (lower panels), respectively, as a function of the halo total mass, \(M_{\text{tot}}\), at redshift \(z = 0\), are displayed:

\[
P(f_b, M_{\text{tot}}) = \frac{1}{N_{b,\text{sample}}} \frac{dN_b}{dM_{\text{tot}} df_b}
\]

(8)

and

\[
P(f_s, M_{\text{tot}}) = \frac{1}{N_{s,\text{sample}}} \frac{dN_s}{dM_{\text{tot}} df_s}.
\]

(9)

In both these relations, \(N_{b,\text{sample}}\) is the total number of haloes sampled by the simulations, while \(dN_b\) is, in equation (8), the number of haloes within a given total-mass bin, \(dM_{\text{tot}}\), and within a given baryon-fraction bin, \(df_b\), and in equation (9), the number of haloes within a given total-mass bin, \(dM_{\text{tot}}\), and within a given stellar fraction bin, \(df_s\). With the previous definitions, the distributions are correctly normalized to 1.

For the three \(f_{\text{NL}}\) cases, we consider the runs with top-heavy popIII IMF.

In figure 4, both baryon and stellar fractions have similar behaviors and no big differences are found. The baryon fraction, \(f_b\), almost approaches the cosmic value at larger masses (a more quantitative analysis is performed in the next section) and exhibits some scatter (because of feedback mechanisms) in smaller structures, with peak values around \(f_b \sim 10^{-1}\). The stellar fraction, \(f_s\), has a much larger scatter around the peak values of \(f_s \sim 10^{-2}\), mostly in haloes
with masses lower than $\sim 10^{12} M_\odot/h$, and achieves asymptotic values of $\sim 10^{-1.5}$ in the larger objects. In all these trends, though, no crucial impacts from different $f_{NL}$ are visible.

The large scatter of $f_b$ and the even larger scatter of $f_s$ on galactic scales are strictly related to feedback effects that can strongly influence low-mass structures, because of their shallower potential wells. In fact, depending on the environment, gas heated by SN explosions in small haloes can be efficiently lost, and, on the other hand, more quiescent objects can be enriched by the gas expelled from nearby structures. Stellar scatter is probably connected to wind feedback, since each SPH particle undergoing star formation is eventually converted into a collisionless star-like particle with a typical velocity of $\sim 500$ km s$^{-1}$. Such velocities allow collisionless stellar particles to escape from small-halo potentials and to end up into different haloes.

As a comparison, in figure 5, we show the status at redshift $z \approx 7.3$. In this case too there are no significant changes among the $f_{NL}$ cases considered. Nevertheless, in the $f_{NL} = 1000$ case, there is slightly more baryonic (gaseous and stellar) mass in the larger objects at masses of $\sim 10^{12} M_\odot/h$: this reflects the growth enhancement at high redshift in models with large $f_{NL}$ values. The baryon fraction, $f_b$, peaks at $\sim 10^{-1}$, quite close to the cosmic value $f_b,\text{cosmic} = \Omega_b/\Omega_m \approx 0.1333$ for our choice of parameters. Since the star formation history at $z \sim 7.3$ has only started from just $\sim 0.5$ Gyr, the stellar fraction peaks at about one order of magnitude below the values at $z = 0$, i.e. at $f_s \sim 10^{-3}$–$10^{-2.5}$. These results are almost independent of $f_{NL}$, also in such high-$z$ regimes, and keep some non-Gaussian signatures only at large masses.

As a consequence, different $f_{NL}$ might slightly affect the masses of the haloes (see also section 3.4.2), but not significantly the gaseous and stellar fractions. In all the cases, the spread at low masses (at less than $\sim 10^{12} - 10^{13} M_\odot/h$) is independent of $f_{NL}$, since it is similarly large and it becomes smaller and smaller at masses corresponding to galaxy groups or clusters, with
the same trend for any $f_{NL}$. This is essentially due to the capability of feedback in heating or expelling the gas from lower potentials, and enriching the closeby satellites. In larger objects, the material is more easily trapped and minor losses take place. In support of this, we will see in the next section that substantial amounts of baryons are lost during the bulk of cosmic star formation episodes, when feedback mechanisms become very important.

3.4.2. Evolution of gaseous and stellar components. To better check evolutionary differences due to the assumed value for $f_{NL}$, we follow the gaseous and stellar components within the most massive haloes found in the simulations, where also most of the star formation activity takes place.

In figure 6, we plot masses (upper panels) and fractions (lower panels) of the baryonic (left), gaseous (center) and stellar (right) components for the runs with $f_{NL} = 0$, $f_{NL} = 100$, and $f_{NL} = 1000$. The dot-dot-dot-dashed line in the bottom-left panel is the cosmic baryon fraction expected from the simulations, $f_b,\text{cosmic} = \Omega_b/\Omega_m$. 

Figure 5. Same as figure 4 for redshift $z = 7.33$.

Figure 6. Redshift evolution of the masses (upper) and fractions (lower) of the baryonic (left), gaseous (center) and stellar (right) components in the most massive halo for $f_{NL} = 0$ (solid lines), $f_{NL} = 100$ (dotted lines) and $f_{NL} = 1000$ (dashed lines). Results refer to the top-heavy popIII IMF cases. The dot-dot-dot-dashed line in the bottom-left panel is the cosmic baryon fraction expected from the simulations, $f_b,\text{cosmic} = \Omega_b/\Omega_m$. 

$z = 7.33$
$f_{NL} = 1000$. The assumed popIII IMF is a top-heavy one, while the dot-dot-dot-dashed line in the bottom-left panel is the cosmic baryon fraction expected from the simulations. The baryon mass is about a few times $10^{10}$ $M_\odot$/h at $z \sim 10$ and $\sim 10^{14}$ $M_\odot$/h at $z = 0$; hence, this fairly represents the evolutionary path of a galaxy-cluster-like object. Also in this case, the mass evolution suggests that the model with the larger $f_{NL} = 1000$ predicts larger masses and earlier growth in all the components, while the models with $f_{NL} = 0$ (Gaussian) and $f_{NL} = 100$ do not have significant deviations. Looking at the temporal sequence, one sees that the major effects of non-Gaussianities are at high redshift (larger than $z \sim 3$), where differences reach up to a factor of $\sim 2$–$3$ ($\sim 10$ in the very early phase) for the stellar mass, as highlighted in the bottom panels. Gas masses, instead, are affected by just $\sim 1$–$10\%$ at most. The baryon fraction evolution shows that $f_b$ is roughly constant at $z > 5$ and traces the cosmic baryon fraction, $f_{b,}\,\text{cosmic}$, quite well at early times. However, there are evident deviations at $z$ below $\sim 5$ that reach the largest discrepancy between $z \sim 1$–$3$. The reason for that is immediately explained by figure 1. Indeed, at those $z$ the star formation rate has its peak, and feedback mechanisms become more and more effective in removing the material from the star forming sites, and in regulating the star formation activity (as visible e.g. from the gas and stellar fraction trends in the bottom-center and bottom-right panels).

Thus, star formation, also triggered by merger episodes, and the related feedback mechanisms are expected to be important sources of discrepancy between the cosmic baryon fraction and the one observationally estimated in galaxy groups and clusters (Giodini et al 2009). According to our findings, gas evacuation reduces $f_b$ by about 25–$30\%$, mostly during the cluster assembly history, at $z > 1$, when smaller objects can lose more easily the material heated by feedback. For example, an object with a baryon mass of $\sim 10^{14}$ $M_\odot$/h at redshift $z = 0$ (as the one in figure 6) is found to have a mass a few times smaller at redshift $\sim 1$ and more than ten times smaller at redshift $z \sim 3$, when its gas is being lost and the corresponding baryon fraction decreases. At $z < 1$, the gas results more tightly bound to the growing potential and some additional merging material, together with the decreasing star formation rate, sustains $f_b$.

The role of non-Gaussianities in these regimes has little relevance, since, due to feedback effects on hydrodynamics, the high-$z$ enhancements of $f_s$ (due to large $f_{NL}$ values) gradually disappear and are completely absent below $z \sim 3$. The final values are always around $f_b \sim 0.1$ and $f_s \sim 0.03$–$0.04$.

In figure 7, a similar analysis for the SL popIII IMF is done, but, besides the aforementioned differences at very early times ($z \sim 8$–$10$), the trends are still very similar and the physical interpretation does not change.
3.4.3. Profiles. Finally, in figure 8, the radial \((r)\) profiles at \(z = 0\) for the gas mass-weighted temperature \((T_{mw})\) and density \((\rho)\) of the most massive object are displayed in the three cases \(f_{NL} = 0, 100\) and 1000 (for a top-heavy popIII IMF). The \(x\)-axis is \(r/r_{200}\), with \(r_{200}\) the virial radius\(^1\) of each halo, equal to 1.064, 1.131 and 0.736 Mpc/\(h\) for \(f_{NL} = 0, 100\) and 1000, respectively. The gas distribution in the haloes reaches overdensities of the order of \(\sim 10^4–10^5\) (the critical density at \(z = 0\) is about \(277.4\, M_\odot\, kpc^{-3}\, h^2\)), so the baryons are essentially decoupled from the cosmological frame. The global behavior in the three cases is quite similar to a low-temperature environment \((T_{mw} \sim 10^5–10^6\, K)\) in the high-density regions (representing the cold innermost core) and an asymptotic behavior at larger radii (where \(T_{mw} \sim 10^7\, K\)). We note that apart from the denser core in the \(f_{NL} = 1000\) model, no other clear trends with \(f_{NL}\) are visible, and that the noisy inner part is more likely dominated by stochastic star formation feedback, gas cooling, non-thermal motions, etc (Sarazin 1988, Borgani and Kravtsov 2009, Fang et al 2009, Lau et al 2009, Biffi et al 2011). As a consequence, it seems that these structures have lost memory of the primordial initial non-Gaussianities and that their thermodynamical properties are mainly led by hydrodynamics and feedback mechanisms. These are typical examples of how the effects of different \(f_{NL}\) values can be strongly mitigated or even cancelled by the more powerful effects coming from gaseous and stellar evolution within the growing haloes.

We also point out that the drops in the temperature profiles at distances of a few percent \(r_{200}\) could be presumably alleviated by additional heating processes not explicitly considered here, such as thermal conduction, cosmic rays or AGN feedback, and that are still widely debated in the literature. An extensive study of all these different phenomena is beyond the aim of this work, but regarding non-Gaussianities we can safely state that they do not represent a crucial caveat, since they would add more degrees of stochasticity and would not affect our conclusions on the implications from different \(f_{NL}\) parameters.

\(^1\) The virial radius \(r_{200}\) is defined as the radius at which the matter density is 200 times the critical density.
4. Summary and conclusions

In this work, we have considered the first large-scale $N$-body/hydrodynamical numerical simulations, dealing with non-Gaussian initial conditions, and including gas cooling, star formation, stellar evolution, chemical enrichment (from both population III and population II regimes) and feedback effects (Maio and Iannuzzi 2011). We have studied in detail the basic properties and evolution of baryons in the different scenarios, by paying attention to the effects on star formation (section 3.1) on gas evolution (section 3.2), on metal pollution (section 3.3) and on the growth down to low redshift of the cosmological structures and their gaseous and stellar content (section 3.4).

The star formation (figure 1) in Gaussian ($f_{\text{NL}} = 0$) and non-Gaussian ($f_{\text{NL}} = 100, f_{\text{NL}} = 1000$) models presents different behaviors, mostly at high redshift and for larger $f_{\text{NL}}$, and, consistently with that, also the probability distribution functions (figure 2) show more overdense gas in the $f_{\text{NL}} = 1000$ case and less in the $f_{\text{NL}} = 100$ and 0 cases, to eventually converge at low redshift.

The metal enrichment process is consequently affected (figure 3), since metal pollution from dying stars starts earlier for $f_{\text{NL}} = 1000$ and later for $f_{\text{NL}} = 100$ and 0. Different choices for the popIII IMF have effects at early times, as metals are very sensitive to the typical lifetimes of the first stars, but do not alter the trends for different $f_{\text{NL}}$.

Baryon, gas and star fractions within cosmological structures are very little affected by non-Gaussianities at low redshift (figure 4), but might be quite affected at high redshift (figure 5). In all the cases, typical values have quite a large scatter at low masses ($< 10^{12} \, M_\odot/h$ at $z = 0$) and $f_b$ achieves almost the cosmic value at larger masses. More precisely, $f_b$ stabilizes a bit below the cosmic fraction with a weakly increasing trend for galaxy groups and clusters, while $f_s$ has a scatter of a few orders of magnitude below $\sim 10^{12} \, M_\odot/h$ and an almost constant or slightly decreasing trend at larger masses, where $f_s \sim 10^{-1.5}$ (see Giodini et al. 2009, Finoguenov et al. 2010, Leauthaud et al. 2011) for observational studies at $z < 1$, and references therein).

Some clear differences due to the assumed $f_{\text{NL}}$ are more readily evident when following individual objects. In the case of the most massive clusters, gas mass evolution is affected by only $\sim 1–10\%$ at most, and stellar masses by up to a factor of $\sim 2–3$ at $z > 4$, both in the top-heavy popIII IMF scenario (figure 6) and in the SL scenario (figure 7). These differences survive only at high redshift, though, since, the feedback mechanisms from gas and stellar evolution dominate the baryon behavior at later times (figure 8).

The baryon fraction is significantly correlated to star formation and feedback, since we find discrepancies from the cosmic values (of $\sim 25–30\%$) only when star formation becomes relevant ($z < 4$), independently from the primordial dark-matter distribution.

Thus, it is likely that feedback mechanisms are mainly responsible for washing out non-Gaussian signatures on the baryonic matter, by heating and mixing gas and by enhancing its turbulent state (Borgani et al. 2008). This would also mean that other gas properties, such as temperature, density and velocity, cannot keep vivid memory of the primordial $f_{\text{NL}}$ at lower redshift. The 21 cm emission from high-$z$ galaxies might still preserve some information, during the first Gyr, but the expected impact on, e.g., the x-ray emission from galaxy clusters or on the signal from the SZ effect(s) (Kitayama and Suto 1997, Borgani et al. 1999, Sartoris et al. 2010) should be as small as the ones on the baryons, since they involve quantities, such as electron fraction and temperature, that are strongly dominated by the feedback processes.

As already mentioned in the previous sections, what emerges from our analysis is the need for high-redshift research, in order to investigate purely non-Gaussian effects. Moreover, thanks
to available high-energy satellites (such as, e.g., Swift\(^2\), Fermi\(^3\), Integral\(^4\)), it is becoming possible to explore the \(z \sim 10\) universe also observationally (Cucchiara \textit{et al} 2011) and to impose constraints (based on observed data) on the GRB rate at high \(z\) (Campisi \textit{et al} 2011). Since the latter is strictly linked to the star formation history of the universe and to its underlying cosmological model, GRBs might be suitable cosmological probes of non-Gaussianities, independent of cosmic microwave background (CMB) determinations. Also high-\(z\) galaxies and quasars could represent interesting probes of non-Gaussianities. The former are observed up to \(z \sim 10\) and the latter are detected up to \(z > 6\) together with many young, star-forming galaxies (Fan \textit{et al} 2001, Yan and Windhorst 2004, Cool \textit{et al} 2006, Bouwens \textit{et al} 2007, Utsumi \textit{et al} 2010). Since these early structures are supposed to be tracers of high-density regions at high \(z\) (Djorgovski \textit{et al} 2003, Overzier \textit{et al} 2009), it is likely that their stellar content could be quite sensitive to non-Gaussianities too.

We conclude our discussion by summarizing as follows:

(i) non-Gaussianities lead to an earlier evolution of primordial gas, structures and star formation;
(ii) the consequent metal enrichment starts earlier (with respect to the Gaussian scenario) in non-Gaussian models with larger \(f_{\text{NL}}\);
(iii) gas fractions within the haloes are not significantly affected by the different values of \(f_{\text{NL}}\), with deviations of \(\sim 1\)–\(10\%\);
(iv) the stellar fraction is quite sensitive to non-Gaussianities at early times, with discrepancies reaching up to a factor of \(\sim 10\) at very high \(z\), and rapidly converging at low \(z\);
(v) the trends at low redshift are independent from \(f_{\text{NL}}\): they are mostly led by the ongoing baryonic evolution and by the feedback mechanisms, which determine a discrepancy in the baryon fraction of galaxy groups/clusters of \(\sim 25\)–\(30\%\) with respect to the cosmic values;
(vi) the impacts on the cluster x-ray emission or on the SZ effect(s) are expected to be not very large and dominated by feedback mechanisms, whereas 21 cm from high-redshift galaxies might preserve more information related to \(f_{\text{NL}}\);
(vii) in order to explore non-Gaussianities and baryonic structure formation, high-redshift \((z \sim 10)\) investigations are required, with first stars, galaxies, quasars and GRBs being optimal fields of study, and potential cosmological probes of non-Gaussianities.

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References

Biffi V, Dolag K and Böhringer H 2011 \textit{Mon. Not. R. Astron. Soc.} \textbf{413} 573–84
Borgani S, Diaferio A, Dolag K and Schindler S 2008 \textit{Space Sci. Rev.} \textbf{134} 269–93
Borgani S and Kravtsov A 2009 unpublished
Borgani S, Plionis M and Kolokotronis V 1999 \textit{Mon. Not. R. Astron. Soc.} \textbf{305} 866–74
\(^2\) http://heasarc.nasa.gov/docs/swift/swiftsc.html
\(^3\) http://fermi.gsfc.nasa.gov/
\(^4\) http://science1.nasa.gov/missions/integral/
Bouwens R J, Illingworth G D, Franx M and Ford H 2007 Astrophys. J. 670 928–8
Campisi M A, Maio U, Salvaterra R and Ciardi B 2011 Mon. Not. R. Astron. Soc. 416 2760–7
Cool R J et al 2006 Astron. J. 132 823–30
Cucchiara A et al 2011 Astrophys. J. 736 7
D’Amico G, Musso M, Noreña J and Paranjape A 2011 Phys. Rev. D 83 023521
Davé R, Hernquist L, Katz N and Weinberg D H 1999 Astrophys. J. 511 521–45
Desjacques V, Jeong D and Schmidt F 2011 Phys. Rev. D 84 063512
Desjacques V and Seljak U 2010 Class. Quantum Grav. 27 124011
Djorgovski S G, Stern D, Mahabal A A and Brunner R 2003 Astrophys. J. 596 67–71
Fan X et al 2001 Astron. J. 122 2833–49
Fang T, Humphrey P and Buote D 2009 Astrophys. J. 691 1648–59
Fedeli C, Carbone C, Moscardini L and Cimatti A 2011 Mon. Not. R. Astron. Soc. 414 1545–59
Finoguenov A et al 2010 Mon. Not. R. Astron. Soc. 403 2063–76
Gilmore R C, Madau P, Primack J R, Somerville R S and Haardt F 2009 Mon. Not. R. Astron. Soc. 399 1694–708
Giodini S 2009 Astrophys. J. 703 982–93
Grinstein B and Wise M B 1986 Astrophys. J. 310 19–22
Haardt F and Madau P 1996 Astrophys. J. 461 20
Hamaus N, Seljak U, Desjacques V, Smith R E and Baldauf T 2010 Phys. Rev. D 82 043515
Katz N, Weinberg D H and Hernquist L 1996 Astrophys. J. Suppl. 105 19
Kennicutt R C Jr 1998 Annu. Rev. Astron. Astrophys. 36 189–232
Kitayama T and Suto Y 1997 Astrophys. J. 490 557
Komatsu E 2010 Class. Quantum Grav. 27 124010
Komatsu E et al 2011 Astrophys. J. Suppl. 192 18
Komatsu E, Spergel D N and Wands D 2005 Astrophys. J. 634 14–9
Lau E T, Kravtsov A V and Nagai D 2009 Astrophys. J. 705 1129–38
Leauthaud et al 2011 arXiv:1109.0010
LoVerde M and Smith K M 2011 J. Cosmol. Astropart. Phys. JCAP08(2011)003
Maio U 2009 Switching on the first light in the Universe PhD Thesis Ludwig Maximilian University
Maio U, Ciardi B, Dolag K, Tornatore L and Khochfar S 2010 Mon. Not. R. Astron. Soc. 407 1003–15
Maio U, Ciardi B, Yoshida N, Dolag K and Tornatore L 2009 Astron. Astrophys. 503 25–34
Maio U, Dolag K, Ciardi B and Tornatore L 2007 Mon. Not. R. Astron. Soc. 379 963–73
Maio U, Dolag K, Meneghetti M, Moscardini L, Yoshida N, Baccigalupi C, Bartelmann M and Prerotta F 2006 Mon. Not. R. Astron. Soc. 373 869–78
Maio U and Iannuzzi F 2011 Mon. Not. R. Astron. Soc. 415 3021–32
Maio U and Kochfar S 2011 arXiv:1110.0493
Maio U, Kochfar S, Johnson J L and Ciardi B 2011 Mon. Not. R. Astron. Soc. 414 397
Overzier R A, Guo Q, Kauffmann G, De Lucia G, Bouwens R and Lemson G 2009 Mon. Not. R. Astron. Soc. 394 577–94
Peebles P J E 1983 Astrophys. J. 274 1–6
Petkova M and Maio U 2011 arXiv:1110.0492
Salopek D S and Bond J R 1990 Phys. Rev. D 42 3936–62
Salpeter E E 1955 Astrophys. J. 121 161
Sarazin C L 1988 X-ray Emission from Clusters of Galaxies (Cambridge: Cambridge University Press)
Sartoris B, Borgani S, Fedeli C, Matarrese S, Moscardini L, Rosati P and Weller J 2010 Mon. Not. R. Astron. Soc. 407 2339–54
Springel V and Hernquist L 2003 Mon. Not. R. Astron. Soc. 339 289–311
Sunyaev R A and Zeldovich Y B 1969 Nature 223 721–2
Sunyaev R A and Zeldovich Y B 1970 Astrophys. Space Sci. 7 3–19
Sutherland R S and Dopita M A 1993 Astrophys. J. Suppl. 88 253–327
Tescari E, Viel M, D’Odorico V, Cristiani S, Calura F, Borgani S and Tornatore L 2011 Mon. Not. R. Astron. Soc. 411 826–48
Tornatore L, Ferrara A and Schneider R 2007 Mon. Not. R. Astron. Soc. 382 945–50
Utsumi Y, Goto T, Kashikawa N, Miyazaki S, Komiyama Y, Furusawa H and Overzier R 2010 Astrophys. J. 721 1680–8
Viel et al 2009 Mon. Not. R. Astron. Soc. 393 774
Verde L 2010 Adv. Astron. 2010 768675
Wagner C, Verde L and Boubekre L 2010 J. Cosmol. Astropart. Phys. JCAP10(2010)022
Yan H and Windhorst R A 2004 Astrophys. J. 612 L93–6