

# The evolution of a pre-heated intergalactic medium

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## ABSTRACT

We analyse the evolution of the intergalactic medium by means of an extended set of large box size hydrodynamical simulations which include pre-heating. We focus on the properties of the  $z \sim 2$  Lyman  $\alpha$  forest and the population of clusters and groups of galaxies at  $z = 0$ . We investigate the distribution of voids in the Lyman  $\alpha$  flux and the entropy–temperature relation of galaxy groups, comparing the simulation results to recent data from high-resolution quasar spectra and X-ray observations. Pre-heating is included through a simple phenomenological prescription, in which at  $z = 4$  the entropy of all gas particles, whose overdensity exceeds a threshold value  $\delta_h$ , is increased to a minimum value  $K_{\text{fl}}$ . While the entropy level observed in the central regions of galaxy groups requires a fairly strong pre-heating, with  $K_{\text{fl}} > 100 \text{ keV cm}^2$ , the void statistics of the Lyman  $\alpha$  forest impose that this pre-heating should take place only in relatively high-density regions,  $\delta_h \gtrsim 30$ , in order not to destroy the cold filaments that give rise to the forest. We conclude that any injection of non-gravitational energy in the diffuse baryons should avoid low-density regions at high redshift and/or take place at relatively low redshift  $z \lesssim 1$ .

**Key words:** methods: numerical – intergalactic medium – cosmology: observations.

## 1 INTRODUCTION

Observations in the X-ray band of the hot intracluster and intragroup medium, along with observations of the absorption features in the spectra of distant quasars [quasi-stellar objects (QSOs)] from the intervening intergalactic medium (IGM) offer powerful means of tracing the evolution of diffuse cosmic baryons in different regimes. While X-ray observations of galaxy systems trace the high-density baryons in the low-redshift  $z \lesssim 1$  Universe (e.g. Voit, Kay & Bryan 2005), data on the Lyman  $\alpha$  forest convey information on baryons around the mean cosmic density at  $z \gtrsim 2$  (e.g. Meiksin 2007). As such, these different observational techniques complement each other in the reconstruction of the cosmic cycle of baryons.

One of the standard results from the X-ray observations of groups and clusters of galaxies is that the hot gas in the central regions of low-temperature systems has an entropy level higher than predicted by the gravitational process of accretion shocks (e.g. Tozzi & Norman 2001). The commonly accepted explanation for this is that the radiative cooling and heating from some feedback energy source should be the main mechanisms responsible for setting the hot intracluster medium on a relatively high adiabat, while preventing overcooling from converting into stars a unrealistically large fraction of baryons (Voit et al. 2005). In order to test these predictions,

hydrodynamical simulations including some form of extra gas heating have been analysed by a number of authors (Borgani et al. 2008, for a recent review). The general result from these simulations is that injecting  $\sim 1 \text{ keV}$  per gas particle is effective in increasing the central gas entropy to a level consistent with the observed one, while the question remains open as to what astrophysical mechanism should be responsible for this high-redshift heating. Clearly, any diffuse IGM heating at high redshift is expected to leave an imprint on its observational properties. For instance, increasing the gas temperature inside the filaments permeated by the IGM should significantly alter the statistical properties of the Lyman  $\alpha$  forest. Indeed, Shang, Crofts & Haiman (2007) recently suggested that the pre-heating required to reproduce X-ray cluster observations should leave the imprint of bubbles of ionized gas at high redshift. These authors analysed a sample of Sloan Digital Sky Survey QSO spectra searching for large voids in the Lyman  $\alpha$  forest associated to these bubbles. From the lack of detection of these voids, they concluded that any pre-heating should only involve IGM at a density higher than the mean one as traced by the Lyman  $\alpha$  forest.

In this Letter, we present a combined analysis of the void statistics in the Lyman  $\alpha$  forest at  $z = 2.2$  and the entropy level of the hot gas within galaxy groups at  $z = 0$ , from a set of pre-heated cosmological hydrodynamical simulations within a fairly large cosmological box. The analysis of the void statistics in the Lyman  $\alpha$  forest will be carried out by using the same procedure presented by Viel, Colberg & Kim (2008), where a description of the reference observational

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data set is also provided. As for the entropy of the intragroup gas, we will compare simulation predictions to the recently published results by Sun et al. (2008), who analysed *Chandra* data for an extended set of nearby groups. By changing both the strength of the pre-heating and the minimum overdensity at which such a pre-heating takes place, we aim at better exploiting the complementary information placed by the high-density hot gas in nearby groups/clusters and the lower density IGM associated to the high-redshift Lyman  $\alpha$  forest.

## 2 HYDRODYNAMICAL SIMULATIONS

We use simulations carried out with the TREE-SPH GADGET-2 code (Springel 2005). These simulations include radiative cooling and heating from a uniform evolving ultraviolet (UV) background (see Bolton et al. 2005 for details), for a primordial mix of hydrogen and helium. Since no self-consistent model for chemical enrichment is treated in these simulations, we decided not to include the effect of metals in the computation of the cooling function. The star formation criterion simply converts in collisionless stars all the gas particles whose temperature falls below  $10^5$  K and whose density contrast is larger than 1000. More details can be found in Viel, Haehnelt & Springel (2004). The cosmological model assumed for our simulations corresponds to a  $\Lambda$  cold dark matter ( $\Lambda$ CDM) Universe with  $\Omega_m = 0.26$ ,  $\Omega_\Lambda = 0.74$ ,  $\Omega_b = 0.0463$ ,  $n_s = 0.95$  and  $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $\sigma_8 = 0.85$ , in agreement with the latest results of cosmological parameters derived from cosmic microwave background and large-scale structure observables (Lesgourgues et al. 2007; Komatsu et al. 2008). We have used  $2 \times 400^3$  dark matter and gas particles in a  $120 h^{-1}$  comoving Mpc box for our purposes. The gravitational softening was set to  $15 h^{-1}$  kpc in comoving units for all the particles. Even if these simulations barely resolve the Jeans length, Viel et al. (2008) showed that the statistics of voids have numerically converged once the simulated spectra have been smoothed over a scale of  $1 h^{-1}$  Mpc comoving. With this mass resolution, the smallest groups in the observational data set by Sun et al. (2008) which have  $M_{500} \simeq 10^{13} h^{-1} \text{ Mpc}$ , are resolved with more than 5000 particles.

Non-gravitational heating is included following a standard purely phenomenological model of pre-heating, based on imposing a minimum entropy floor,  $K_{\text{fl}}$  to all the gas particles that, at a given heating redshift  $z_h$ , have density contrast above a given threshold  $\delta_h$ . We use the definition of entropy which is standard in the study of the intra-cluster medium, namely,  $K = n_e/T$ , where  $n_e$  is the electron number density and  $T$  is the gas temperature. Similar schemes to study the effect of pre-heating to the X-ray properties of galaxy clusters have been used by several authors (e.g. Bialek, Evrard & Mohr 2001; Muanwong et al. 2002; Tornatore et al. 2003; Borgani et al. 2005; Younger & Bryan 2007). The procedure adopted to pre-heat the gas is the following: at  $z_h = 4$ , we select from the reference run, which does not include any pre-heating, all the gas particles having  $\delta > \delta_h$  and entropy  $K < K_{\text{fl}}$ . The internal energy of these particles is then increased so that their entropy match the floor value. In this selection, we always exclude cold and dense star particles, with  $\delta > 500$  and  $T < 3 \times 10^4$  K, whose low-initial entropy would require an extremely strong and ad hoc heating. Such cold and dense gas is contained within galaxy-sized haloes, where star formation takes place (e.g. Kay et al. 2000). Therefore, imposing the above limits on density and temperature of the gas to be pre-heated amounts to protect the cold gas content of galaxies, which should be rather affected by some local feedback mechanisms [e.g. associated to supernova explosions]. We refer to Voit (2005) for an overview

of the role of pre-heating in modelling the thermodynamics of the intragroup medium.

We choose four different values of the entropy floors:  $K_{\text{fl}} = 10, 50, 100$  and  $300 \text{ keV cm}^2$ ; and three overdensity thresholds:  $\delta_h = -1, 3$  and  $10$ . Only for the case with  $K_{\text{fl}} = 300 \text{ keV cm}^2$ , we also consider the case with a higher density threshold for heating,  $\delta_h = 30$ . While the lowest  $\delta_h$  corresponds to heating all the gas, the highest value is comparable to that expected at the boundary of a virialized structure. In this way, we run a total of 14 simulations (13 different pre-heated runs and the default run with no pre-heating). In the following, we will show results only for a subset of the whole simulation set. The different simulations will be labelled by the tuple of values of entropy floor (in  $\text{keV cm}^2$ ) and overdensity threshold for heating. The reference run will be indicated with the label REF. All the simulations are analysed at  $z = 2.2$  to compute the Lyman  $\alpha$  forest statistics and at  $z = 0$ , to compute the entropy–temperature relation of the galaxy groups.

The sample of high resolution, high signal-to-noise QSO spectra is described in Kim et al. (2007) and has already been used to compute several flux statistics (Viel et al. 2004; Bolton et al. 2008; Viel et al. 2008). Many systematic effects have been carefully addressed including metal lines contamination and continuum fitting errors. The median redshift of the sample is at  $z = 2.2$ . From this data set, we extracted the cumulative distribution of voids in the transmitted flux, i.e. connected regions with flux above the mean level, which at  $z \sim 2$  appear to trace reasonably well-underdense regions.

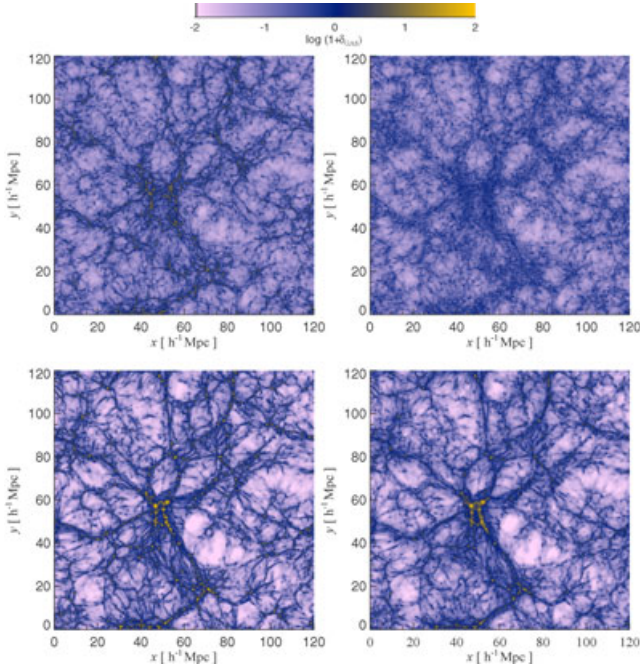
As for the *Chandra* sample of galaxy groups, it contains 40 objects selected by Sun et al. (2008) so that gas properties can be derived out to  $r_{2500}$  for all of them ( $r_\Delta$  is the radius encompassing an average density of  $\Delta \times \rho_c$ , being  $\rho_c$  the cosmic critical density). Sun et al. (2008) analysed this sample to derive the scaling relation between entropy and temperature at different overdensities and found an excess of entropy at  $r_{500}$ , with respect to the baseline value calibrated by Voit et al. (2005) from non-radiative hydrodynamical simulations of clusters, although this excess is smaller than suggested by previous analyses (e.g. Ponman, Sanderson & Finoguenov 2003; Piffaretti et al. 2005; Pratt & Arnaud 2005). Moreover, they also found that the excess entropy is larger at  $r_{2500}$ , thus confirming that any non-gravitational process has a larger effect in the central regions of groups.

## 3 RESULTS

In Fig. 1, we show a projected slice whose thickness is 8 comoving  $h^{-1}$  Mpc of the gas distribution at  $z = 2.2$  and 0, for the default run and (300,10) run. Even by adding this strong pre-heating, at  $z = 2.2$ , the skeleton of the cosmic web at densities around the mean is still preserved. The main differences arise in dense structures, whose filling factor is small. At  $z = 0$ , the effect of pre-heating is quite visible as well: the mildly non-linear cosmic web evolves and gives rise to clusters of galaxies and galaxy groups. These very non-linear structures tend to be puffier and smoother compared to the reference case, with a suppression of the number of small haloes that trace the filaments.

### 3.1 Void statistics in the Lyman $\alpha$ forest

From the snapshots at  $z = 2.2$ , we extract a mock set of 1000 Lyman  $\alpha$  QSO spectra in random directions. Then, we smooth the spectra over a scale of 1 comoving  $h^{-1}$  Mpc, to be less sensitive to small structures at and around the Jeans length that might not be properly resolved by our simulations. We then compute the number of voids



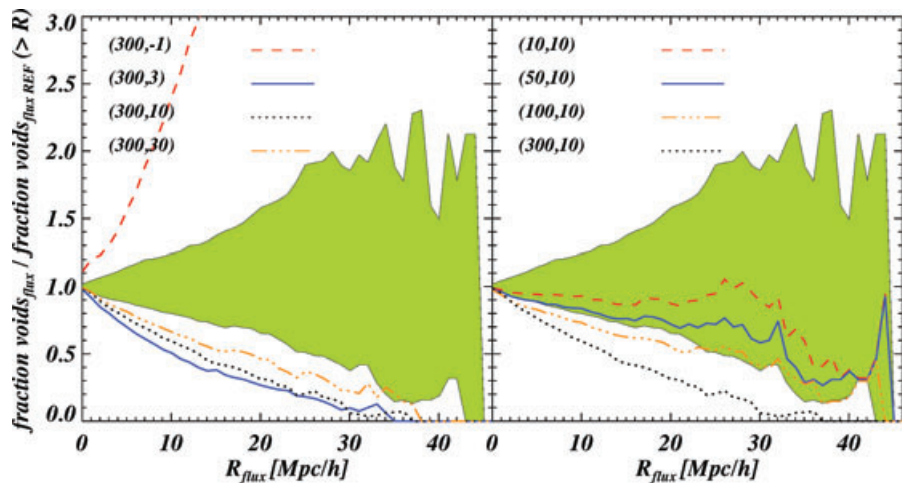
**Figure 1.** The different panels show the gas overdensity in a slice of 8 comoving  $h^{-1}$  Mpc for the reference simulation, with no pre-heating (left-hand panels) and for the (300,10) simulation (entropy floor of 300 keV  $\text{cm}^2$  for  $\delta_{\text{GAS}} > 10$ , right-hand panels). Top and bottom panels refer to the snapshots at  $z = 2.2$  and 0, respectively.

in the flux distribution, having size larger than a given value and compare the pre-heated runs with the default one. As shown by Viel et al. (2008), the reference run provides results in excellent agreement with the data. Results are presented in Fig. 2, where the shaded area indicates the uncertainty in the observed mean flux level, which sets the criterion for the selection of voids. Among all the possible uncertainties in the astrophysical and cosmological parameters, this error has the largest effect on the void statistics (see Viel et al. 2008 for more details). Therefore, we take it as a rough estimate of the error. We recall that the total error budget must also

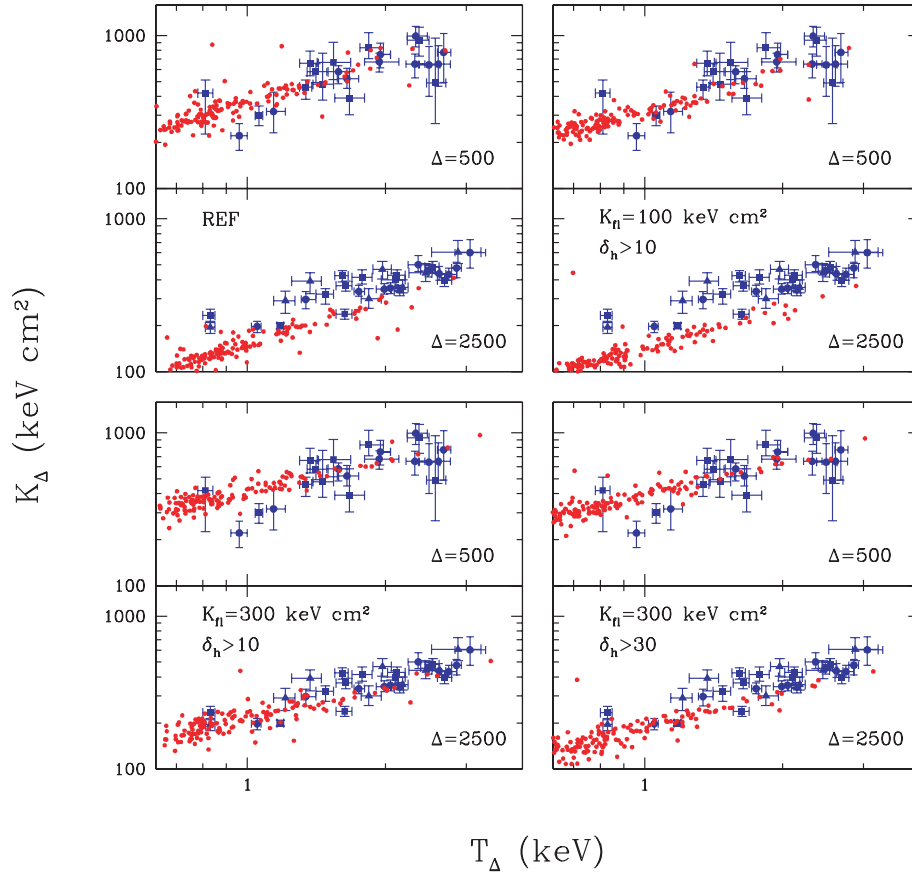
take into account the contributions from all the other parameters and it is larger than the one shown here. For example, an approximately three times higher temperature of the IGM at the mean density would boost the number of 30 comoving  $h^{-1}$  Mpc voids up to a factor of 1.5, bringing some of the models in better agreement with the observations. Basically, the error bars represented by the shaded area do not take into account the different thermal histories for the low-density IGM and/or different cosmological scenarios (warm dark matter or extra power at intermediate scales) that are more extensively discussed in Viel et al. (2008).

In the left-hand panel, we address the role of a different overdensity threshold for heating, keeping fixed the entropy floor at 300 keV  $\text{cm}^2$ . Clearly, heating up the whole IGM (i.e.  $\delta_h = -1$ ) substantially increases the number of voids since the neutral fraction will be reduced by the very large amount of heating. If we increase the overdensity threshold to  $\delta_h = 3$  and 10, then the void fraction is in better agreement with the default case, as expected, but there is a tendency to underpredict the number of large void regions. This result might seem counter-intuitive, since a heating of the IGM should reduce the hydrogen neutral fraction. However, we found that the gas in the relatively low-density environments of the pre-heated runs is denser compared to the default run and thereby carries with it a larger neutral hydrogen fraction. The opposite trend takes place in overdense regions where the default simulation is denser than the corresponding pre-heated ones. At low redshifts, the volume filling factor of underdense (overdense) regions gets larger (smaller) in all the models but the overall effect is a reduction of the size of large voids compared to the REF case since in the pre-heated runs the voids are less empty. The (300,30) is closer to the default case than the (300,10) owing to the decrease in the volume filling factor of the heated regions with increasing  $\delta_c$ .

In the right-hand panel of Fig. 2, we show the effect of changing the entropy floor, while keeping the overdensity threshold for heating fixed at  $\delta_h = 10$ . Increasing the entropy floor has the effect of lowering the fraction of large voids: at  $z = 4$ , the heating of dense gas particles at  $\delta > 10$  makes them leave quickly their haloes and reach the low-density IGM: these particles have usually a larger fraction of neutral hydrogen that can cause absorptions in the mock spectra that are extracted at  $z = 2.2$ .



**Figure 2.** The ratio between Lyman  $\alpha$  flux voids larger than  $R_{\text{flux}}$  (in comoving  $h^{-1}$  Mpc) of pre-heated and the no-heating (REF) case. In the left-hand panel, we show the effect of a different gas density threshold having fixed the entropy floor for the models (300,−1), (300,3), (300,10) and (300,30). In the right-hand panel, we show the effect of a different value for the entropy floor having fixed the density threshold for the models (10,10), (50,10), (100,10) and (300,10). The shaded area in both the panels could be considered as the  $1\sigma$  estimate of the observational statistical error (see the text).



**Figure 3.** The relation between entropy and temperature for simulated groups at  $z = 0$  (small circles) and for the *Chandra* observational of nearby groups analysed by (Sun et al. 2008) (points with error bars). The four panels correspond to the REF run (with no pre-heating; top left-hand panel), the (100,10) run (top right-hand panel), the (300,10) run (bottom left-hand panel) and the (300,30) run (bottom right-hand panel). The top and bottom parts of each panel refer to the  $K_{\Delta} - T_{\Delta}$  relation for  $\Delta = 500$  and  $2500$ , respectively.

### 3.2 The entropy–temperature relation of groups

At  $z = 0$ , we identify galaxy groups in our simulations by running a friends-of-friends algorithm with  $b = 0.15$  for the linking length in units of the mean dark matter (DM) interparticle separation. The centre of each group is then identified with the position of the DM particle having the minimum value of the gravitational potential. Following Sun et al. (2008), we compute for each group the temperature  $T_{\Delta}$  within  $r_{\Delta}$  (for  $\Delta = 500$  and  $2500$ ) by excluding the core region within  $0.15 r_{500}$ . Then, we measure the profiles of the electron number density,  $n_e(r)$ , and the gas temperature,  $T(r)$ . The values of entropy  $K_{\Delta}$  at  $r_{\Delta}$  are then computed as  $K_{\Delta} = T_{\Delta}/n_{e,\Delta}^{2/3}$ . X-ray temperatures are computed following the prescription by Vikhlinin (2006), which represents an extension to low-temperature systems ( $T_X < 3$  keV, relevant for our analysis) of the spectroscopic-like temperature, originally introduced by Mazzotta et al. (2004).

In Fig. 3, we compare the relation between entropy and temperature for our simulated groups to the observational data by Sun et al. (2008), for four of our simulated boxes. As for the case with no pre-heating (upper left-hand panel), a satisfactory agreement with data is obtained at  $r_{500}$ , while simulated groups have a too low level of entropy at  $r_{2500}$ . This result is in line with the comparison performed by Sun et al. (2008) between their observational results and the best-fitting relation from the hydrodynamical simulations by Nagai, Kravtsov & Vikhlinin (2007). These simulations include radiative cooling, star formation and a rather inefficient form of

feedback, and therefore are expected to provide similar results to the reference (non-pre-heated) run. Clearly, the entropy level at  $r_{2500}$  is not the only problem suffered by a radiative run without extra heating. Indeed, in this simulation overcooling causes about 40–50 per cent of the baryons within  $r_{500}$  to be converted in stars, with a decreasing trend with the system temperature. This fraction, which is a lower limit owing to the resolution dependence of the cooling efficiency (e.g. Balogh et al. 2001; Borgani et al. 2006), is in excess with respect to observational estimates (e.g. Gonzalez, Zaritsky & Zabludoff 2007). Therefore, while cooling plays the role of establishing the level of entropy (Voit & Bryan 2001), a form of non-gravitational heating is required to regulate the amount of lower entropy gas which is destined to cool and form stars.

As for heating with  $K_{\text{fl}} = 100$  keV cm<sup>2</sup> (upper right-hand panel of Fig. 3), it has a rather small effect on the gas entropy, while it does have a significant effect on the fraction of stellar mass, which drops to 10–20 per cent. This result implies that, with this level of  $K_{\text{fl}}$ , radiative cooling is still main responsible for setting the entropy level, while extra heating regulates the amount of cooled gas. A further increase in  $K_{\text{fl}}$  is then required to alleviate the tension between the observed and measured levels of entropy in galaxy groups. Indeed, using  $K_{\text{fl}} = 300$  keV cm<sup>2</sup> (bottom panels of Fig. 3) brings the entropy level in the simulated groups to better match the observed one. However, as discussed in the previous section, imposing an entropy floor generates too large voids in the Lyman  $\alpha$  forest, an effect that can be compensated by increasing the heating

overdensity threshold,  $\delta_h$ . However, increasing the latter from  $\delta_h = 10$  (bottom left-hand panel) to 30 (bottom right-hand panel) induces a slight but sizable decrease in  $K_\Delta$ , especially for  $\Delta = 2500$ , as a consequence of the smaller number of gas particles heated at  $z = 4$ . Therefore, while heating at relatively high overdensity is required by the void statistics of the Lyman  $\alpha$  forest, it goes in the wrong direction to reproduce the thermodynamical properties of intragroup medium at small radii. This demonstrates how effective is combining observations of the high- $z$  IGM and low- $z$  intragroup medium to constrain the thermal history of the cosmic baryons.

#### 4 CONCLUSIONS

We presented an analysis of cosmological hydrodynamical simulations, including radiative cooling and pre-heating, aimed at characterizing both the properties of the high-redshift Lyman  $\alpha$  forest and the thermodynamical properties of the diffuse gas within nearby galaxy groups. We use a simple phenomenological recipe for pre-heating, in which at  $z = 4$  all the gas particles lying at an overdensity above  $\delta_h$  are brought to a minimum entropy level of  $K_\parallel$ . At  $z = 2.2$ , mock QSO spectra were extracted and their properties compared to the observed distribution of voids in the Lyman  $\alpha$  flux (Viel et al. 2008), while at  $z = 0$ , the entropy–temperature relation of galaxy groups is compared with recent results from X-ray *Chandra* observations (Sun et al. 2008). The main results of our analysis can be summarized as follows: (i) pre-heating all the gas, irrespective of its density, produces voids in the Lyman  $\alpha$  forest, which is too large if compared to observations; (ii) imposing a modest overdensity threshold for heating,  $\delta_h = 3$ , suddenly reduces the size of the voids to values which are even too small; (iii) further increasing  $\delta_h$  makes the void sizes approaching those of the non-pre-heated run, owing to the progressively smaller amount of heated gas which ends up in the Lyman  $\alpha$  forest; (iv) the entropy level within galaxy groups at  $r_{500}$  can already be matched in non-pre-heated simulations, which however fail at accounting for this level at  $r_{2500}$  and (v) a fairly strong entropy injection, with  $K_\parallel > 100 \text{ keV cm}^2$ , is required to match the entropy–temperature relation of poor systems at  $r_{2500}$ .

The need of reproducing the entropy structure of the low-redshift intragroup medium and the void statistics of the high-redshift Lyman  $\alpha$  forest leads us to conclude that for a mechanism of non-gravitational heating to work, it must provide a fairly large amount of extra entropy at relatively high overdensities, comparable to those characteristic of virialized haloes. Our conclusion, in agreement with the argument by Shang et al. (2007), is that the amount of pre-heating required by low-redshift galaxy clusters and groups should avoid low-density regions for it not to produce too large voids in the Lyman  $\alpha$  forest or should act at lower redshift,  $z \lesssim 1$ . Admittedly, our scheme of non-gravitational heating is an oversimplified one. For this reason, our aim is not to look for the best values of  $K_\parallel$  and  $\delta_h$ , which are able to fit at the same time the observed intragroup entropy and void statistics of the Lyman  $\alpha$  forest. Rather, the main goal of our analysis is to provide an indication of the general properties that a plausible mechanism of non-gravitational heating should have. We defer to a forthcoming analysis a detailed study of the combined constraints of the low- and high- $z$  IGM properties using

physically motivated models of heating from astrophysical sources, such as supernovae, active galactic nuclei and DM annihilation.

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