

On the importance of high-redshift intergalactic voids

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Accepted 2008 February 19. Received 2008 February 7; in original form 2007 December 21

ABSTRACT

We investigate the properties of 1D flux ‘voids’ (connected regions in the flux distribution above the mean-flux level) by comparing hydrodynamical simulations of large cosmological volumes with a set of observed high-resolution spectra at $z \sim 2$. After addressing the effects of box size and resolution, we study how the void distribution changes when the most significant cosmological and astrophysical parameters are varied. We find that the void distribution in the flux is in excellent agreement with predictions of the standard Λ cold dark matter (Λ CDM) cosmology, which also fits other flux statistics remarkably well. We then model the relation between flux voids and the corresponding 1D gas-density field along the line of sight and make a preliminary attempt to connect the 1D properties of the gas-density field to the 3D dark matter distribution at the same redshift. This provides a framework that allows statistical interpretations of the void population at high redshift using observed quasar spectra, and eventually it will enable linking the void properties of the high-redshift universe with those at lower redshifts, which are better known.

Key words: quasars: absorption lines – cosmic microwave background – cosmological parameters – cosmology: observations – cosmology: theory.

1 INTRODUCTION

Over the past decade, properties of voids have been more widely investigated, using different observational probes and tracers (mainly in the local universe, see e.g. Hoyle & Vogeley 2004; Rojas et al. 2004; Goldberg et al. 2005; Hoyle et al. 2005; Rojas et al. 2005; Ceccarelli et al. 2006; Patiri et al. 2006a,b; Tikhonov & Karachentsev 2006), and theoretical – analytical or numerical – models in the framework of the Λ cold dark matter (Λ CDM) concordance cosmology (e.g. Peebles 2001; Arbabi-Bidgoli & Müller 2002; Mathis & White 2002; Benson et al. 2003; Gottlöber et al. 2003; Goldberg & Vogeley 2004; Sheth & van de Weygaert 2004; Bolejko, Krasiński & Hellaby 2005; Colberg et al. 2005; Padilla, Ceccarelli & Lambas 2005; Furlanetto & Piran 2006; Hoefl et al. 2006; Lee & Park 2006; Patiri, Betancort-Rijo & Prada 2006; Shandarin et al. 2006; Brunino et al. 2007; D’Aloisio & Furlanetto 2007; Neyrinck 2007; Park & Lee 2007; Peebles 2007; Tully 2007; van de Weygaert & Schaap 2007).

The emerging picture is encouraging. On the one hand, some results appear to be somewhat hard to understand, such as the fact that galaxies observed at the edges of and in voids appear to be

a fair sample of the whole galaxy population (the so-called ‘void phenomenon’, Peebles 2001), the fact that dwarf galaxies are not found in voids contrary to expectations from numerical simulations (e.g. Peebles 2007, or the cold spot observed in the cosmic microwave background (CMB) data (Naselsky et al. 2007; Rudnick, Brown & Williams 2007)). On the other hand, other observational results, such as those from the 2dF Galaxy Redshift Surveys or Sloan Digital Sky Survey (SDSS), from studies of voids in quasar spectra, or the CMB spectrum (Caldwell & Stebbins 2007), are in reasonably good agreement with theoretical predictions from numerical simulations of the standard Λ CDM cosmology. Linking the low-redshift properties of voids to those at higher redshifts offers the opportunity to constrain the void population over a significant fraction of cosmic time and to possibly find out more about voids, to ultimately understand their role in the context of cosmic structure formation.

Unfortunately, there are very few observables that constrain the population of voids at high redshift (see, however, D’Aloisio & Furlanetto 2007). Here, we will use the Lyman α forest as a tracer of voids in the high-redshift universe. The Lyman α forest (e.g. Bi & Davidsen 1997) has been shown to arise from the neutral hydrogen embedded in the mildly non-linear density fluctuations around mean density in the Intergalactic Medium (IGM), which faithfully traces the underlying dark matter distribution at scales above the

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Jeans length. It is a powerful cosmological tool in the sense that it probes the dark matter power spectrum in a range of scales (1 to $80 h^{-1}$ Mpc comoving) and redshifts ($z = 2\text{--}5.5$) not probed by other observables. However, the observable is not the matter distribution itself but the flux: a 1D quantity sensitive not only to cosmological but also to the astrophysical parameters that describe the IGM.

The so-called fluctuating Gunn–Peterson approximation (Gunn & Peterson 1965) relates the observed flux to the IGM overdensity in a simple manner once the effects of peculiar velocities, thermal broadening and noise properties are neglected:

$$F(\mathbf{x}, z) = \exp\{-A(z)[1 + \delta_{\text{IGM}}(\mathbf{x}, z)]^\beta\}, \quad (1)$$

with $\beta(z) \sim 2 - 0.7[\gamma(z) - 1]$, γ the parameter describing the power-law (‘equation of state’) relation of the IGM, $T = T_0(z)(1 + \delta_{\text{IGM}})^{\gamma-1}$, and $A(z)$ a constant of order unity which depends on the mean-flux level, on the ultra violet background (UVB) and on the IGM temperature at mean density. In practice, linking the flux to the density of the dark (or gaseous) matter requires the use of accurate hydrodynamical simulations that incorporate the relevant physical and dynamical processes. However, for approximate calculations equation (1), in conjunction with simple physical prescriptions of Lyman α clouds (e.g. Schaye 2001), can offer precious insights.

Provided the flux–density relation is accurately modelled, using the Lyman α forest to check the properties of the population of voids in the matter distribution would avoid having to know the bias between galaxies and dark matter, and would allow to sample over larger volumes the values of cosmological parameters that affect the void population. On the other hand, the fact that the flux information is 1D requires non-trivial efforts to relate it to the 3D (dark) matter-density field. Motivated by huge amounts of new data of exquisite quality, we here present a first attempt in this direction. Note that in the early 1990s, before the new paradigm of the Lyman α forest absorption was proposed, voids from the transmitted Lyman α flux of quasi-stellar object (QSO) spectra were analysed, using discrete statistics on the lines, by several groups (e.g. Crotts 1987; Ostriker, Bajtlik & Duncan 1988; Duncan, Ostriker & Bajtlik 1989; Dobrzycki & Bechtold 1991; Rauch et al. 1992). These attempts, however, did not reach conclusive results due to small number statistics. We defer to a future paper for a link between the observational properties outlined here and those at low redshift (e.g. Mathis & White 2002; Hoyle & Vogeley 2004) and for a careful investigation of the absorber–galaxy relation (e.g. Stocke et al. 1995; McLin et al. 2002).

This paper is organized as follows. In Section 2, we briefly describe the data set used. In Section 3, we present the hydrodynamical simulations. Section 4 contains the bulk of our analysis and the results, which are summarized in the conclusions in Section 5.

2 THE DATA SET

We use the set of 18 high signal-to-noise ratio (S/N) ($S/N > 30\text{--}50$), high-resolution ($R \sim 45000$) quasar spectra taken with the very large telescope (VLT)/UVES presented in (Kim et al. 2007). We regard these spectra as a state-of-the-art, high-resolution sample in the sense that many statistical properties of the transmitted flux (mean flux decrement, flux probability distribution function, and flux power and bispectrum) have been accurately investigated and interpreted by several authors from the same or from similar data sets (see e.g. McDonald et al. 2000; Kim et al. 2004; Viel et al. 2004b; Jena et al. 2005; Bolton et al. 2007). More importantly, systematics effects such as metal contamination, noise and resolution properties and continuum fitting errors have been extensively addressed. From

the data set, we discard the four highest redshift QSOs, in order to have a more homogenous sample at a median $\langle z \rangle = 2.2$ and with a total redshift path $\Delta z = 6.1$. The pixels contributing to the signal are in the wavelength range 3282–4643 Å while the wavelength ranges for each single QSO spectrum are reported in Kim et al. (2007). Both damped Lyman α systems and metal lines have been removed from this sample. The evolution of the effective optical depth derived from this data set, $\tau_{\text{eff}} = -\ln \langle F \rangle$, which – as we will see – is the main input needed to constrain and identify voids, has been widely discussed and compared with various other measurements (Kim et al. 2007).

3 THE SIMULATIONS

We use a set of simulations run with GADGET-2, a parallel tree smoothed particle hydrodynamics (SPH) code that is based on the conservative ‘entropy-formulation’ of SPH (Springel 2005). The simulations cover a cosmological volume (with periodic boundary conditions) filled with an equal number of dark matter and gas particles. Radiative cooling and heating processes were followed for a primordial mix of hydrogen and helium. We assume a mean UVB produced by quasars and galaxies as given by Haardt & Madau (1996), with helium heating rates multiplied by a factor of 3.3 in order to better fit the observational constraints on the temperature evolution of the IGM. This background naturally gives $\Gamma_{12} \sim 1$ at the redshifts of interest here (Bolton et al. 2005). The star formation criterion very simply converts all gas particles whose temperature falls below 10^5 K and whose density contrast is larger than 1000 into (collisionless) star particles (it has been shown that the star formation criterion has a negligible impact on flux statistics, see e.g. Viel, Haehnelt & Springel 2004a; Bolton et al. 2007). More details of the simulations can be found in (Viel et al. 2004a).

The cosmological model corresponds to the ‘fiducial’ Λ 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 $\sigma_8 = 0.85$ (the B2 series of Viel et al. 2004a). We use 2×400^3 dark matter and gas particles in a volume of size $120 h^{-1} \text{ Mpc}$ box. For cross-checks, we also analyse smaller boxes of size 60, 30 and $15 h^{-1} \text{ Mpc}$. The gravitational softening was set to $15 h^{-1} \text{ kpc}$ in comoving units for all particles for the largest-simulated volume and changes accordingly for the smaller volumes. In the following, the different simulations will be referred to by the tuple [comoving box size in $\text{Mpc } h^{-1}$, (number of gas particles) $^{1/3}$], so (120, 400) denotes our fiducial simulation etc. (all the sizes reported in the rest of the paper will be in comoving units). In Fig. 1, we show a 2D slice of thickness $10 \text{ comoving Mpc } h^{-1}$ of the gas density for our reference simulation at $z = 2.2$. Large regions whose gas density is below the mean are present and overdense regions separate them and give rise to the cosmic web. Occasionally, denser regions of overdensity ~ 100 reside in the inner regions of voids, however, their sizes are quite small and their impact parameter in the lines of sight to distant QSOs should be also relatively small. In Fig. 1, we also overplot the haloes whose total mass is above $2 \times 10^{11} M_\odot$ (white circles) and show some underdense regions of different sizes (filled triangles). Usually, the larger voids are surrounded by few and not very massive haloes that line up in filaments, while smaller voids, such as the one at $(x = 77, y = 73) \text{ Mpc } h^{-1}$ have more spherical shapes and have more massive haloes around them.

Note that some numerical efforts in order to simulate the intergalactic voids are required: on one side, large volumes need to be simulated in order to sample the void distribution at large sizes and on the other side, relatively high resolution is mandatory. In fact

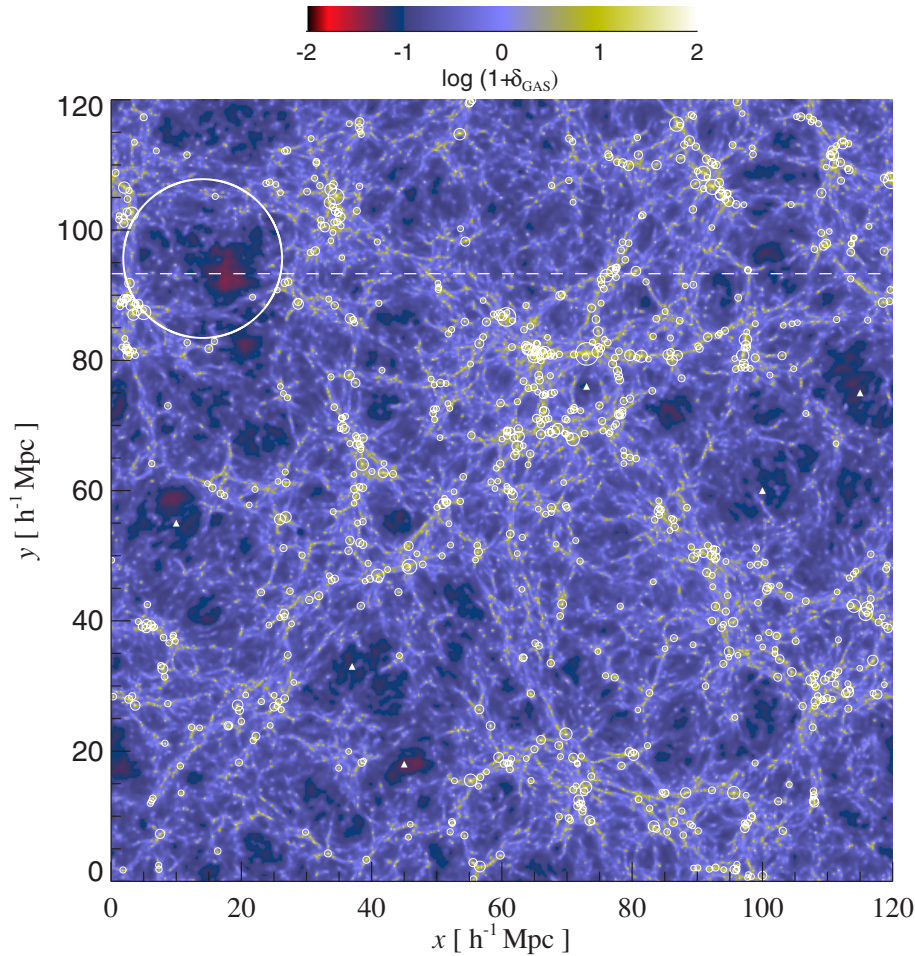


Figure 1. Slice of the projected gas density (thickness is $10 \text{ Mpc } h^{-1}$) from our reference Λ CDM hydrodynamical simulation at $z = 2.2$. The presence of roughly spherical regions below the mean density of sizes of the order of 10 of Mpc is clear, denser environments at $\delta \sim 100$ tend to line up in filaments or could be found (more rarely) inside underdense regions (voids). A large underdense region is shown as a white thick circles, while haloes with total masses above $2 \times 10^{11} M_{\odot}$, that trace the cosmic web, are represented by smaller white circles with radii proportional to their masses. The dashed line of sight will be analysed more closely in Section 4.4. Filled triangles indicate some underdense regions of different sizes: usually smaller voids are surrounded by many massive haloes, while larger ones have less haloes at their edges (with smaller masses).

with poor resolution, the denser regions at the edge of voids are not properly resolved and will result in a smaller amount of neutral hydrogen and thereby less absorption: this will cause an overestimate of the void sizes.

The parameters chosen here, including the thermal history of the IGM, are in reasonably good agreement with observational constraints and with recent results from CMB data, weak lensing and other data sets obtained from the Lyman α forest (e.g. Viel, Haehnelt & Lewis 2006; Lesgourgues et al. 2007). The mock QSO spectra extracted from the simulations have the same resolution and noise properties as the observed ones, even though this will not affect our results. Here, for two reasons, we consider only simulation snapshots at $z \sim 2$. First, the high-resolution data set has a median redshift (z) = 2.2. Secondly, at these redshifts the UVB should be uniform, and the IGM's equation of state is reasonably measured, leaving little room for ionization voids to be labelled as matter voids or for temperature fluctuations to strongly affect the Lyman α forest properties (Shang, Crots & Haiman 2007). However, we caution that: (i) recent results from Bolton et al. (2007), based on the flux probability distribution function, seem to suggest that the thermal state of the IGM at $z < 3$ could be more complex than expected; (ii)

patchy He II reionization at $z \sim 3.2$ could affect the uniformity of the UVB (e.g. Bolton et al. 2006; Faucher-Giguere et al. 2007) and some effects at smaller redshifts might influence Lyman α opacity.

4 RESULTS

4.1 The 1D flux void distribution

We search for flux voids in the simulated spectra in the following simple way: (i) we extract 1000 lines of sight from the simulated volume; (ii) we normalize the mock spectra to have the observed mean-flux value; (iii) we smooth the flux with a top-hat filter of size $1 h^{-1} \text{ Mpc}$, which roughly corresponds to the comoving Jeans length and (iv) we identify connected flux regions above the mean-flux level at the redshift of interest. The normalization is performed by multiplying the whole array of 1000 simulated optical depths arrays by a given constant (found iteratively after having extracted the spectra) in order to reproduce the wanted τ_{eff} value. The choice of a different mean flux will, of course, impact on the void selection criterion, since a smaller (larger) mean-flux level will increase (decrease) the number of pixels at high (low) transmissivity that

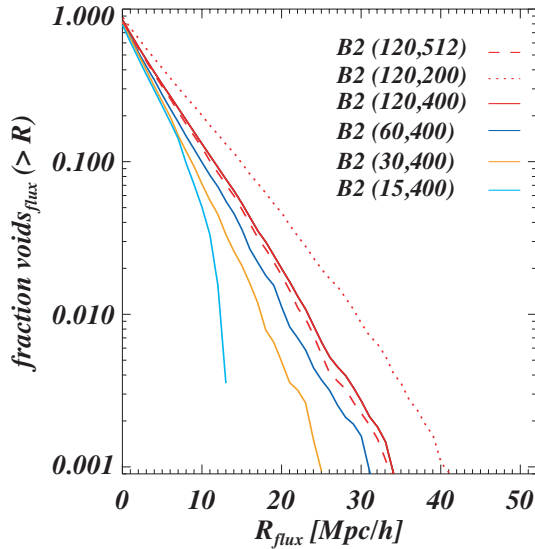


Figure 2. Box size and resolution effects at $z = 2$ on the fraction of 1D voids in the flux distribution (of size R or larger), extracted from four different simulation volumes (120 , 60 , 30 and $15 h^{-1}$ Mpc) and three different resolutions (200^3 , 400^3 and 512^3 gas particles). The flux has been smoothed with a 1D top-hat filter of size $1 h^{-1}$ Mpc, which roughly corresponds to the Jeans length at this redshift. Spectra have been normalized to the same effective optical depth.

are likely to correspond, in a non-trivial way, to under(over)dense regions.

As a first preliminary test, we check for the effects of resolution on the flux fractions of voids at $z = 2$. Results are shown in Fig. 2, which shows simulations with different box sizes and resolutions, but with the same initial conditions normalized to the same mean flux. Note that this analysis is performed in redshift space and peculiar velocities affect the flux properties. From the figure, it is clear that in order to sample the fraction of voids accurately a large enough volume and relatively high resolution are needed. For example, the $(120, 200)$ simulation differs dramatically from the $(120, 400)$ one, because in the latter relatively dense regions placed at the edge of void regions are better resolved. However, this discrepancy disappears once the flux is smoothed over a given scale (the Jeans length in our case). In a way, smoothing the flux degrades the resolution of the simulation making it less sensitive to the relevant physical processes causing absorption at and below the Jeans scale. Also note how increasing resolution beyond that in the $(120, 400)$ simulation – the $(120, 512)$ case – produce results that are well within the statistical errorbars that are observed and will be shown in Fig. 3. Because of this, $(120, 400)$ is now taken to represent our fiducial run that will be used to explore other physically meaningful parameters.

We now perform the same search for the observed QSO spectra. The results are shown in Fig. 3, which shows the distribution of the flux void population extracted from the observations (points with Poissonian errorbars) and from our largest volume simulation. From the figure, it is clear that the fiducial $(120, 400)$ run is in excellent agreement with observations and that flux voids of sizes $> 35 h^{-1}$ Mpc are about 1000 times less common than voids of sizes larger than few h^{-1} Mpc. We also note a bump at around $20 h^{-1}$ Mpc in the voids fraction, but one would need a larger sample of QSOs in order to better test its statistical significance. The continuous lines show how the void fraction changes when the effective optical depth is varied at a $\pm 3\sigma$ level around the observed value. In particular,

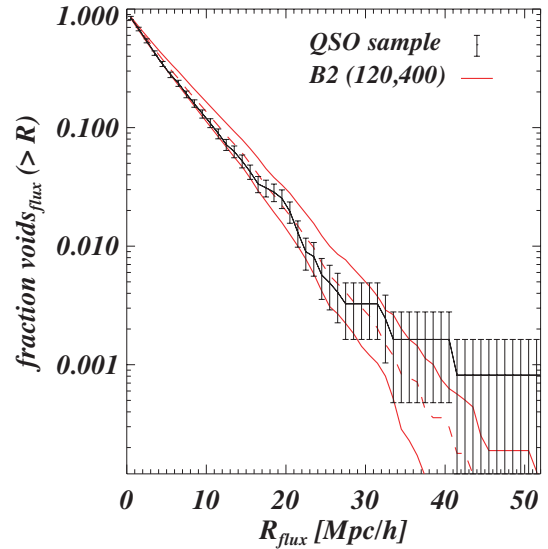


Figure 3. Fraction of 1D voids in the flux distribution at $z = 2.2$ of size larger than R as extracted from the observed sample (1σ Poissonian errorbars). Continuous lines represent the reference hydrodynamical simulation ($120 \text{ Mpc } h^{-1}$) with voids identified taking $\pm 3\sigma$ values around the observed effective optical depth value (dashed line). The flux has been smoothed with a 1D top-hat filter of size $1 \text{ Mpc } h^{-1}$.

the lower and the higher τ_{eff} values ($\tau_{\text{eff}} = 0.136$ and 0.19 , respectively) have been chosen in such a way to conservatively embrace at a confidence level of 3σ the values obtained in Viel et al. (2004a), where the measured value for the effective optical depth was $\tau_{\text{eff}} = 0.163 \pm 0.009$. The recently determined power-law fit of Kim et al. (2007) $\tau_{\text{eff}} = (0.0023 \pm 0.0007) (1+z)^{3.65 \pm 0.21}$ by using QSO spectra in the range $1.7 < z < 4$ is influenced by the scatter coming from QSO spectra over a large range of redshift, and would, in principle, allow for a larger range of effective optical depths. However, by selecting only a subsample at a given redshift, smaller statistical errors on the effective optical depth can be obtained.

We stress that the definition of void used here is based on the transmitted flux and thus is very different from studies based on the distribution of voids as inferred from the galaxy distribution.

4.2 Exploring the parameter space

We now discuss the main cosmological and astrophysical parameters that can affect the population of voids in the flux distribution. In Fig. 4, we plot the ratios of the flux void fractions in the fiducial and in other simulations, where we changed τ_{eff} at $z = 2.2$ within the observational bounds and the value of σ_8 . As could be expected, the fraction of voids changes dramatically with a change in τ_{eff} : at $z \sim 2$, the flux probability distribution function (pdf) is a steep function around the mean-flux level. Thus, adopting a different void selection criterion has a large impact on the void distribution. In the following, we normalize the mock QSO sample to reproduce the same effective optical depth. Changing σ_8 appears to have a smaller effect. A simulation with $\sigma_8 = 1$ results in a faster evolution of cosmic structures and in a 50 per cent increase of the void population of size $R = 20\text{--}35 h^{-1}$ Mpc, compared with the reference $\sigma_8 = 0.85$ case. In the simulation with a lower value of σ_8 , the void sizes are more evenly distributed. Note, however, that the trend at the largest sizes ($45 \text{ Mpc } h^{-1}$) is somewhat different: here, the low σ_8 simulation predicts more voids than the higher σ_8 , since

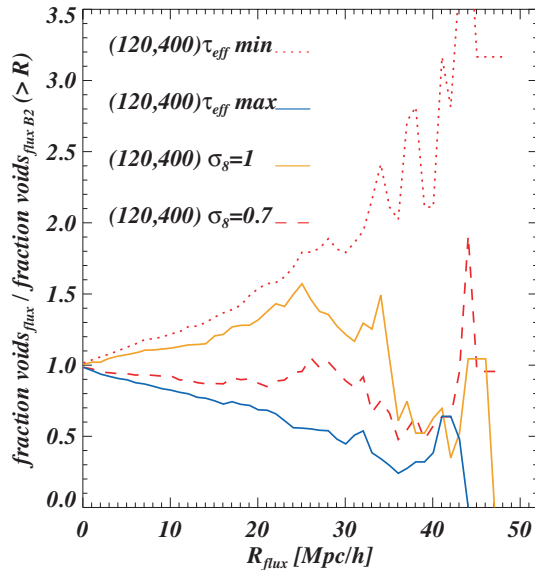


Figure 4. Ratio of the flux void fraction of the (120, 400) simulation ($\sigma_8 = 0.85$) with runs that use a different value of the power spectrum amplitude ($\sigma_8 = 0.7$ and 1, represented by the dashed and continuous lines, respectively). Also shown are the ratios when the effective optical depth (which is used as a threshold to define voids in the flux distribution) of the reference run is conservatively varied between the observational bounds ($\pm 3\sigma$ values represented by the dot-dashed and dotted lines). Spectra have been normalized to the same effective optical depth.

the smaller amount of power in the former can occasionally produce large regions devoid of matter and absorption. We also checked the impact of varying other parameters such as Ω_m , H_0 and a change in the shape of the linear dark matter power spectrum in the initial conditions to account for a presence of warm dark matter (WDM) and adding some extra power (EP) at intermediate (from Mpc to tens of Mpc) scales that results in an effect opposite to that of WDM. The mass chosen for the WDM particle is 0.15 keV. A mass that is already ruled out from the flux power spectrum of the Lyman α forest (see Viel et al. (2008)) and that produces a suppression of power at scales around $0.4 \text{ Mpc } h^{-1}$, which are marginally sampled in the initial conditions of our (120, 400) simulation. However, for the qualitative purposes of this paper this simulation should show the impact of a WDM particle on the distribution of the largest voids in the flux. At the scale of $2.5 \text{ Mpc } h^{-1}$, the power is 100 times higher (smaller) in the EP (WDM) simulation than the corresponding (120, 400). The results are plotted in Fig. 5, where all the simulations have the same value of $\sigma_8 = 0.85$: it is clear that the WDM and EP runs have opposite effects. WDM significantly enhance by a factor larger than of 3 the fraction of largest voids, by erasing substructures below a given scale, while the EP simulation presents more collapsed structures that suppress the number of the largest voids. The effect of a larger value of $\Omega_m = 0.4$ is similar to that of the EP simulation and determines a 90 per cent reduction in the fraction voids whose sizes are larger than $30 \text{ Mpc } h^{-1}$. Finally, we checked for the effect of a smaller value of $H_0 = 45 \text{ km s}^{-1} \text{ Mpc}^{-1}$, a value proposed recently by Alexander et al. (2007) to be the true value of the Hubble constant outside a local underdense region of very similar density to those explored here. Having a smaller value for the Hubble constant produces effects that are very similar to those of a smaller value of $\sigma_8 = 0.7$ (see Fig. 4): the evolution of the cosmic web is less pronounced and can occasionally produce large regions devoid of ab-

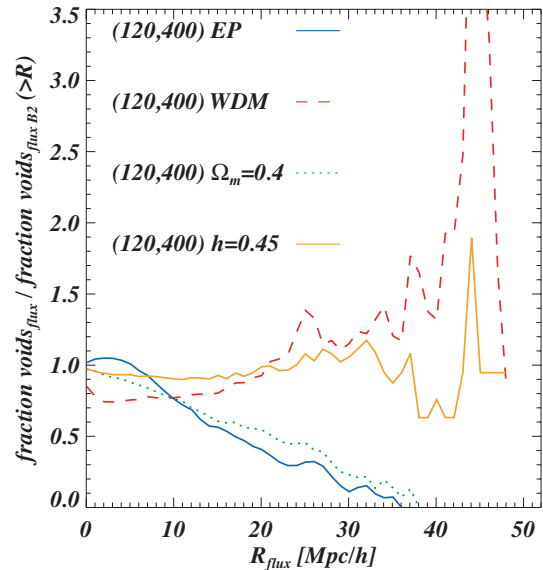


Figure 5. Ratio of the flux void fraction of the (120, 400) simulation ($\sigma_8 = 0.85$) with runs that have some extra power (EP, continuous line) and less power (WDM, dashed line) at Mpc scales. Also shown are the ratios when the Hubble constant is set to a smaller $h = 0.45$ value (dot-dashed line) and a simulation with a larger value of $\Omega_m = 0.4$ (dotted line). The reference B2 (120, 400) run has $h = 0.72$ and $\Omega_m = 0.26$. Spectra have been normalized to the same effective optical depth.

sorption, even if on average the effects are quite mild. We also varied the spectral index n_s but found small differences to the reference case. As can be appreciated from Fig. 3, the statistical errors on the observed void fraction are somewhat large and thereby distinguishing between different cosmological model is still very difficult and none of the models presented here could be convincingly ruled out.

Several other parameters could have an impact on the void distribution, in particular the two parameters that are poorly constrained and that describe the thermal state of the IGM: T_0 and γ . We investigate the effect of a different value of T_0 in Fig. 6. A colder (hotter) IGM will result in a higher (lower) density of neutral hydrogen and thereby in more absorptions, which, in turn, will decrease (increase) the fraction of large voids. In Fig. 6, we also overplot the effect of changing γ from the reference value $\gamma = 1.6$ to 1.1 (represented by the dotted line in the figure), which is a better fit to the data at this redshift (Bolton et al. 2007). A flatter equation of state will not only make underdense regions hotter, but also make the slightly overdense regions colder. The overall effect is a slight decrease in the fraction of flux voids, since cold regions embed on average more neutral hydrogen than hot ones. This result shows that by selecting mean-flux level regions, we are sampling regions around mean density (for which the power-law ‘equation of state’ could be a poor fit to the actual distribution).

Note that the effect of changing γ was addressed by running a new simulation that self-consistently results in a low γ at $z = 2$ (using a modified version of the GADGET-2 code kindly provided by J. Bolton) and not by rescaling the gas–temperature relation a posteriori as is sometimes done. Another important input parameter is the overall amplitude of the UVB, parametrized by Γ_{-12} , for which we have some observational constraints (Bolton et al. 2005). However, this quantity is degenerate with the value of τ_{eff} , so changing Γ_{-12} will result in the same change as changing τ_{eff} .

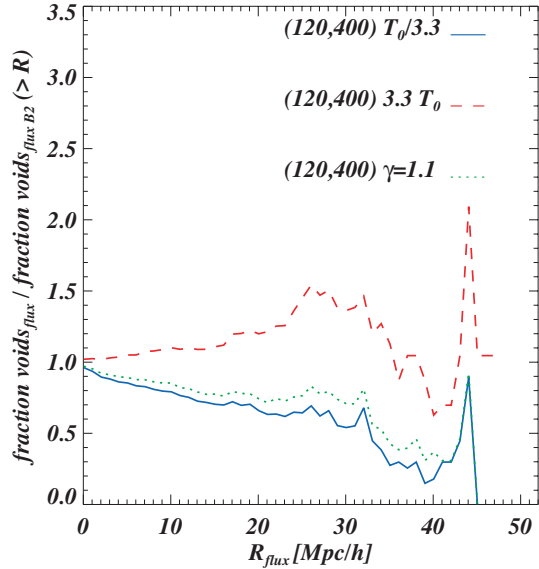


Figure 6. Ratio of the flux void fraction for the (120, 400) runs, comparing the fiducial run ($\gamma = 1.6$ and $T = T_0$) with runs that have a different value of the IGM temperature at mean density ($2T_0$ and T_0 are represented by dashed and continuous lines, respectively) and with a run that has a different value of γ (dotted line). Spectra have been normalized to the same effective optical depth.

4.3 From flux to 1D gas density

Having identified voids at $z \sim 2$, using the mean flux as a threshold, we are now interested in linking the flux properties to the underlying physical properties of the gas-density field. The main problem we have to deal with is that the flux is observed in redshift space, while we want to recover gas properties in real space. The role of peculiar velocities in determining the properties of the transmitted flux has been investigated by several authors (e.g. Weinberg et al. 1998), however for the purpose of the analysis performed here it produces a shift of the absorption feature from the real-space overdensity to the redshift space observed flux. This increases the scatter since redshift space pixels are not related in a simple manner to the underlying real-space density field.

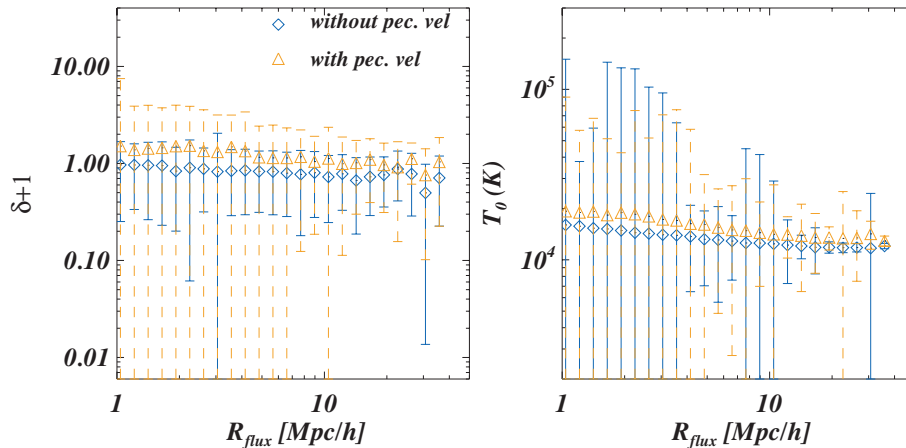


Figure 7. 1D gas density and temperature in void regions along lines of sight extracted from the fiducial simulation at $z = 2.2$. Voids have been identified from the flux distribution as regions above the mean-flux level. Results are shown with (triangles) and without (diamonds) peculiar velocities, and errorbars represent the scatter.

Occasionally, peculiar velocities could be of the order of a few hundred km s^{-1} , so the correspondence is non-trivial (see e.g. Rauch et al. 2005). However, we can rely on hydrodynamical simulations in order to infer, at least on a statistical basis, the physical properties of the gas. In Fig. 7, we show the mean values and scatter (rms values) in the real-space gas overdensity and temperature fields, corresponding to the flux voids of the previous sections. We show the fields both without (diamond symbols) and with (triangles) peculiar velocities, which alter the flux distribution observed in velocity space. From the plot, it is clear that selecting regions above mean flux at $z \sim 2$, as we did in the previous sections, allows us to identify and measure (with a large errorbar) the density in 1D gas voids with sizes larger than $\sim 10 h^{-1} \text{Mpc}$ in the case with peculiar velocities. If peculiar velocities are neglected the scatter is much smaller (as expected), and the density can be measured for somewhat smaller voids (sizes larger than $\sim 7 h^{-1} \text{Mpc}$). For even smaller voids only upper limits of the order a few times mean density can be set, and very little can be inferred about their temperature. The gas temperature inside the largest flux voids is of the order of 10^4K . These regions are thus cold and, as expected from the nature of Lyman α forest absorptions, sample the IGM ‘equation of state’ around mean density. Therefore, even when peculiar velocities are taken into account, the physical properties of the largest voids can be reliably studied. Furthermore, note that the effect of the peculiar velocities for the recovered mean density and temperature inside voids is systematically slightly higher than the corresponding values for the case when peculiar velocities are neglected. As before, this effect is expected since the peculiar velocity shift can move some denser clumps of gas into voids regions that increase their overall mean density. We stress that the ‘gas voids’ defined in this section, as identified from the transmitted flux, do not correspond to underdense regions in the gas distribution but to regions around the mean density.

In Fig. 8, we plot the voids’ densities for voids whose sizes are larger than $7 h^{-1} \text{Mpc}$, with and without peculiar velocities and with a varying flux threshold. The scatter is large, but for voids regions above the mean-flux level in 68 per cent of all cases these regions have overdensities in the range $\delta = [-0.8, 0.8]$. If the flux threshold is lowered, large voids regions start to sample environments at higher overdensities. The dashed line represents a linear fit to the points (with peculiar velocities): $\delta + 1 \equiv \rho / \langle \rho \rangle =$

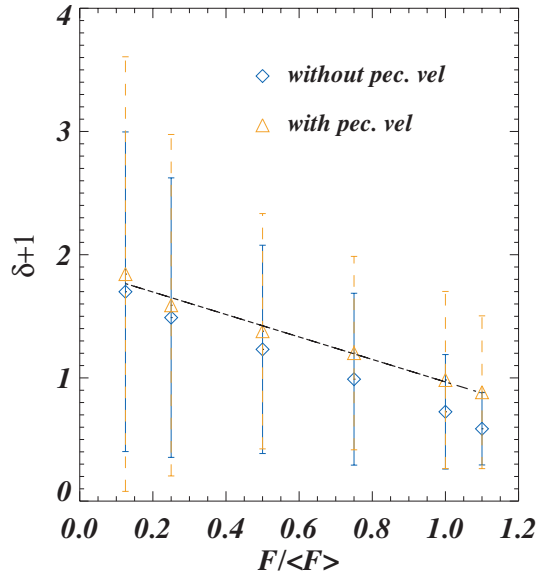


Figure 8. Densities of voids (larger than $7 h^{-1}$ Mpc) as a function of flux threshold level at $z = 2.2$. Results are shown with (triangles) and without (diamonds) peculiar velocities, and errorbars represent the scatter. The dashed line shows a linear fit to the case with peculiar velocities.

$-0.9 F/\langle F \rangle + 1.9$. This relation should describe the mean 1D density of large (>7 comoving $\text{Mpc } h^{-1}$) voids identified in the flux distribution at $z \sim 2$, as derived from high-resolution Lyman α forest QSOs spectra. We note that a systematic trend is present and the recovered gas density is larger in the case with peculiar velocities: we attribute this to the fact that with peculiar velocities the corresponding gas absorptions are shifted and a void region identified in the flux is not simply related to an underdense region but can incorporate regions at higher density that will increase the recovered global density.

4.4 From 1D gas density to the 3D dark matter distribution

In this section, we link the 1D properties of flux voids to the 3D dark matter properties. We use a void-finding algorithm for the dark matter distribution of the reference simulation. The algorithm is described in more detail in Colberg et al. (2005). Its main features can be summarized as follows. The starting point for the void finder is the adaptively smoothed distribution of the matter distribution in the simulation. Protovoids are constructed as spheres whose average overdensity is below a threshold value δ_t , which is a free parameter. These protovoids are centred on local minima in the density field. Protovoids are then merged according to a set of criteria, which allow for the construction of voids that can have any shape, as long as two large regions are not connected by a thin tunnel (which would make the final void look like a dumbbell). The voids thus can have arbitrary shapes, but they typically look like lumpy potatoes. For each void, we compute the radius R_{DM} of a sphere whose volume equals that of the void. While strictly speaking R_{DM} is not the actual radius of the void, it provides a useful measure of the size of the void. In this work here, we adopt a value of $\delta_t = -0.5$ (for a justification of this choice see below). As a first preliminary check, we compared the void size distribution of the fiducial simulation with earlier results by Colberg et al. (2005) and found good agreement. Note that the size of the grid used for the density field limits the sizes of the smallest voids that can be found with this void finder – in our case $1 h^{-1}$ Mpc. However, as discussed above, peculiar velocities make studies of voids smaller than $7 h^{-1}$ Mpc very hard, so we need not be concerned about the smallest voids at all.

As a qualitative example, in Fig. 9, we show one line of sight through the simulated volume. We plot the 1D gas-density field in real space (top panel), the simulated flux (middle panel) in redshift space and the gas peculiar velocity field in km s^{-1} (bottom panel) in real space. The x -axis indicates the comoving (real space) coordinate along the line of sight. Flux absorption is usually produced by gas overdensities shifted by the peculiar velocity associated to the same gas element. For example, the absorption in the flux at $70 \text{ Mpc } h^{-1}$ is produced by the gas-density peak at around $68 \text{ Mpc } h^{-1}$, shifted by $\sim 200 \text{ km s}^{-1}$ – which corresponds to roughly $2 h^{-1}$ Mpc.

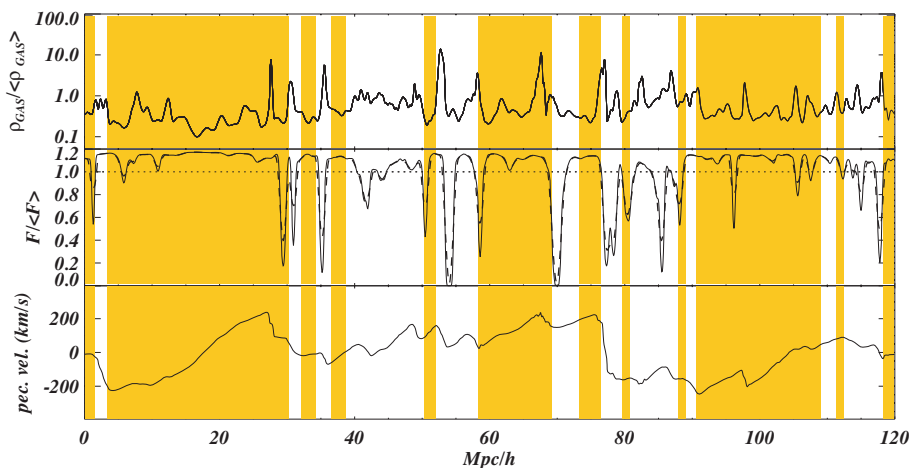


Figure 9. Relation between 3D dark matter voids and physical quantities along the line of sight to distant QSOs. The intersections of 3D real-space voids in the dark matter distribution along the line of sight are represented by shaded rectangles. The top panel shows the 1D real-space gas overdensity, the middle one the simulated Lyman α flux in redshift space, the bottom panel the peculiar velocity field in km s^{-1} . Absorption features in the flux distribution correspond to overdensity peaks shifted by the peculiar velocity of the bottom panel (100 km s^{-1} roughly corresponds to $1 h^{-1}$ Mpc comoving). The dotted line in the flux distribution sets the criterion for the void definition, while the dashed one represents the flux smoothed over $1 h^{-1}$ Mpc. This particular line of sight is taken along the x -axis and at a y -coordinate of $93 \text{ Mpc } h^{-1}$ in the slice of Fig. 1.

The shaded regions show the intersections with the line of sight of 3D voids in the dark matter distribution identified with the void finder algorithm described above. In the middle panel, we overplot the mean-flux level as a dotted line, with the flux smoothed on a scale of $1 h^{-1} \text{ Mpc}$, as in Section 4.1. We find that the choice of threshold overdensity $\delta_t = -0.5$ for the 3D void finder results in a good correspondence of the resulting voids with voids defined in the flux distribution. From the bottom panel of Fig. 9, it is clear that the void regions are expanding, and the gas velocity fields for the largest voids are of the order of $\pm 200 \text{ km s}^{-1}$ (see the void centred on around $20 \text{ Mpc } h^{-1}$). These high-redshift voids in the IGM will keep growing, get emptier of matter and could be the progenitors of lower redshifts voids of sizes similar to the Tully void (Tully 2007). The peculiar velocities along the line of sight rise smoothly from negative values to positive ones and are sandwiched by regions in which the peculiar velocity shows a negative gradient, which could be the signature of a moderate shock. It is worth emphasizing that these velocity profiles are not always completely symmetric because the line of sight does not necessarily pierce the 3D voids in their centres. Moreover, from the top panel it is clear that the 1D density profile inside the void is quite complex, showing small density peaks, which correspond to small haloes that most likely host the observed void galaxy population.

In order to provide a more quantitative picture, in Fig. 10, we plot the underlying mean values of 1D quantities obtained once the 3D voids have been identified (using $\delta_t = -0.5$). The top panel represents the probability distribution function of the sizes of such 1D flux voids, while in the other three panels each point shows, from top to bottom panel, the mean gas overdensity, flux and peculiar velocity field for a given 3D DM void. Note that while in Section 4.1, we were interested in measuring the properties of voids once the mean-flux threshold was set as a criterion to define voids, here we use

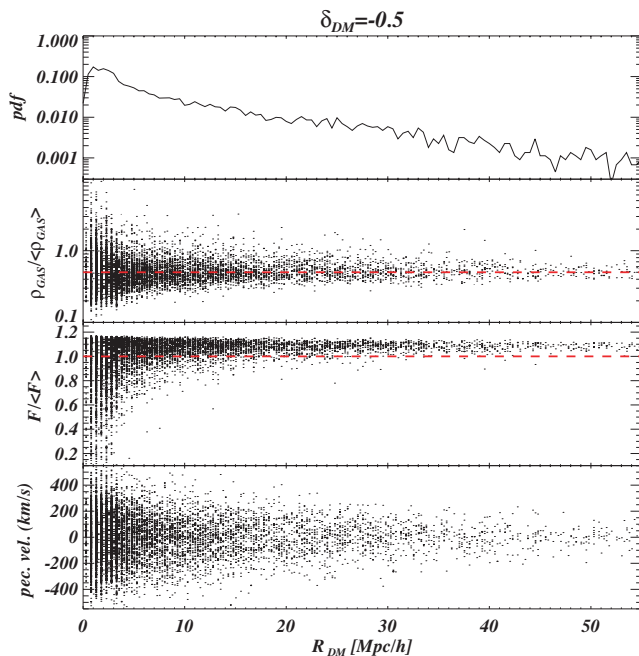


Figure 10. Voids in the 3D dark matter distribution have been identified with the algorithm described in the text using a density threshold of $\delta_{\text{DM}} = -0.5$. Here, we plot the 1D void flux pdf, the 1D gas median overdensity along the line of sight for each identified void in the 3D dark matter distribution, the median $F/\langle F \rangle$ value in the void and the median peculiar velocity for the same void region (from top to bottom panel).

the 3D DM distribution to look for the corresponding 1D (Lyman α forest) flux-related quantities.

The overall picture suggests that large voids ($> 7\text{--}10 \text{ Mpc } h^{-1}$) are usually related to flux values above the mean, and the corresponding mean values of gas-density and peculiar velocities have less scatter than smaller voids. The corresponding mean value for the gas overdensity is $\delta_{\text{GAS}} = -0.43$, so the 3D void region is slightly denser in gas than in dark matter, something that can be expected since baryons feel pressure and are thus more diffused than the collisionless dark matter (e.g. Viel et al. 2002). The different value of δ_{GAS} than the one found in Section 4.3 does not contradict our earlier findings, since now the requirement to define a void is *less* stringent. Now, the actual void has to be a quasi-spherical 3D region in the DM distribution and not a connected 1D region with flux above the mean flux. This means that in 1D one is more sensitive to clumps of matter producing absorptions, while the same clump will have a smaller impact on the mean density of the 3D region surrounding it. Cases for which the flux voids correspond to actual DM voids are averaged out statistically by small lumps of gas around the mean density along the line of sight, that cause absorption and do not alter the global 3D DM density of the void region

For this population of large voids, the typical scatter in the peculiar velocity field is 170 km s^{-1} . We thus have shown that the population of 1D large flux voids, i.e. regions above the mean-flux level, as estimated from a set of mock high-resolution spectra at $z \sim 2$, traces reasonably faithfully a population of 3D dark matter voids of similar sizes, with a typical $\delta_t = -0.5$.

We have also checked that the scatter plots of Fig. 10 are not very sensitive to the cosmological model (i.e. different values of σ_8), which means that the voids physical properties are the same for different values of the power spectrum amplitude.

5 CONCLUSIONS AND PERSPECTIVES

We used Lyman α forest QSO spectra to constrain the void population at $z \sim 2$ at a range of scales and redshifts, which cannot be probed by other observables. The main conclusions can be summarized as follows:

- (i) the properties (sizes) of voids identified in simulations from the flux distribution as connected regions above the mean-flux level are in good agreement with observed ones;
- (ii) using a set of hydrodynamical simulations and varying all the astrophysical and cosmological parameters, along with checking box size and resolution effects, we find that the flux void size distribution is a robust statistics that depends primarily on the flux threshold chosen to define the voids;
- (iii) the flux seems to be a reliable tracer of the underlying dark matter distribution, altering the statistical properties of the dark matter density field (changing amplitude, shape, adding or suppressing power in a wavenumber-dependent manner) changes the properties of the void population although at present is difficult to give constraints on cosmological parameters using these statistics;
- (iv) flux voids, i.e. connected regions above the mean-flux levels, correspond to gas densities around the mean density, regardless of the role of peculiar velocities, which contribute to a scatter in this relation, but do not alter significantly the mean values;
- (v) linking 1D voids to the corresponding 3D dark matter voids is more difficult, and we used a void-finding algorithm for that: we find that 3D DM voids with a mean overdensity of $\delta_t = -0.5$ correspond to the flux voids that we have defined from the QSO

spectra. However, the correspondence is good only for voids with sizes larger than about $7\text{--}10\text{ Mpc } h^{-1}$.

In this paper, we made a preliminary attempt to link the population of voids in the transmitted Lyman α flux to the underlying 1D gas density and temperature and 3D dark matter density. The use of Lyman α high-resolution spectra is important in the sense that it explores a new regime in scales, redshifts and densities which is currently not probed by other observables: the scales are of order few to tens of Mpc, the redshift range is between $z = 2$ and 4, while the densities are around the mean density. Further studies that could possibly rely on wider data sets such as the low-resolution SDSS data (Shang et al. 2007), other future observables at higher redshifts (D'Aloisio & Furlanetto 2007) or tomographic studies involving QSO pairs or multiple line of sights (D'Odorico et al. 2006; Saitta et al. 2008) would be important in understanding the dynamical, thermal and chemical evolution of the void population and the interplay between galaxy and the IGM over a large fraction of the Hubble time.

ACKNOWLEDGMENTS

Numerical computations were done on the COSMOS supercomputer at DAMTP and at High-Performance Computer Cluster (HPCF) in Cambridge (UK). COSMOS is a UK-CCC facility which is supported by HEFCE, PPARC and Silicon Graphics/Cray Research. The authors thank the Virgo Consortium and the Lorentz Centre in Leiden for their hospitality during the Virgo Workshop in early 2007, where this work was begun. We thank the anonymous referee for his/her very careful reading of the paper and the comments made.

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