The epoch of structure formation in blue mixed dark matter models

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ABSTRACT
Recent data on the high-redshift abundance of damped Lyα systems are compared with theoretical predictions for 'blue' (i.e. $n > 1$) mixed dark matter (MDM) models. The results show that decreasing the hot component fraction $Q_h$ and/or increasing the primordial spectral index $n$ leads to an earlier epoch of cosmic structure formation. We also show, however, that varying $Q_h$ and $n$ in these ways makes the models barely consistent with the observed abundance of galaxy clusters. Therefore, requiring both the observational constraints on damped Lyα systems and the cluster abundance to be satisfied simultaneously represents a challenge for the MDM class of models.

Key words: galaxies: clusters: general – quasars: absorption lines – cosmology: observations – cosmology: theory – dark matter – large-scale structure of Universe.

1 INTRODUCTION
Observations of high-redshift objects have become a potentially powerful constraint for models of cosmic structure formation. The availability of statistically reliable samples of quasars provide a means of addressing this problem in a quantitative way in the framework of the cold dark matter (CDM) cosmogony (Efstathiou & Rees 1988; Haehnelt 1993). Moreover, the comparison between predictions and observations of quasar abundance at different redshifts has been used as a test for model reliability (e.g. Nusser & Silk 1993; Pogosyan & Starobinsky 1993).

Recently, damped Lyα systems (DLASs) have been recognized as a promising way of tracing the presence of high-redshift collapsed structures, thanks to the possibility of identifying them as protogalaxies and to their detectability at high $z$ (see Wolfe 1993 for a comprehensive review). DLASs are seen as wide absorption features in quasar spectra. The associated absorbing systems have a neutral hydrogen column density ($\sim 10^{20}$ cm$^{-2}$). The rather large abundance of DLASs makes it possible to compile reliable statistical samples (Lanzetta 1993; Lanzetta, Wolfe & Turnshek 1995; Storrie-Lombardi et al. 1995; Wolfe et al. 1995). Once the parameters of the Friedmann background are specified, observations of DLASs can be used to find the value of the cosmological density parameter $\Omega_h$ contributed by the neutral gas, which is associated with DLASs. It turns out that at $z \sim 3$ this quantity is comparable to the mass density of visible matter in nearby galaxies, thus suggesting that DLASs trace a population of galaxy progenitors.

Based on the APM QSO catalogue, Storrie-Lombardi et al. (1995) recently presented the most extended DLAS sample to date, covering the range 2.8 < z < 4.4. In this paper we will consider their highest redshift data as being the most constraining, and we will compare them with model predictions.

Several authors (Subramanian & Padmanabhan 1994; Mo & Miralda-Escudé 1994; Kauffmann & Charlot 1994; Ma & Bertschinger 1994) have recently claimed that the large value of $\Omega_h$ observed at $z \gtrsim 3$ is incompatible with predictions of the mixed (i.e. cold + hot) dark matter (MDM) model with spectral index $n = 1$ and hot component fraction $Q_h \approx 0.3$ contributed by one species of massive neutrinos and baryon fractional density $\Omega_b = 0.1$ (Klypin et al. 1993; Nolthenius, Klypin & Primack 1996). Klypin et al. (1995) reached essentially the same conclusions about this model, but emphasized two relevant points: (i) any theoretical prediction is very sensitive to the choice of the parameters of the model needed to obtain $\Omega_h$ observed at $z > 3$; (ii) a slight lowering of $\Omega_h$ to 0.20–0.25 keeps MDM in better agreement with DLAS data, independently of whether the hot component is given by one or by two massive neutrino species (see also Primack et al. 1995).

A possible alternative, still in the framework of MDM, is to consider 'blue' ($n > 1$) primordial spectra of density fluctuations. The advantage of these models is that they antici-
pate the epoch of structure formation owing to the higher small-scale power. The choice of blue spectra was originally suggested by the analysis of cosmic microwave background (CMB) anisotropies on scales larger than $1^\circ$ (e.g. Devlin et al. 1994; Hancock et al. 1994; Bennett et al. 1994). Possible indications favouring blue spectra come from large bulk flows (Lauer & Postman 1994; see, however, Riess, Press & Kirshner 1995 and Branchini & Plionis 1996) and from large voids in the galaxy distribution (Pirani et al. 1993). In recent years many authors have pointed out that the inflationary dynamics can easily account for the origin of blue perturbation spectra (Liddle & Lyth 1993; Linde 1994; Matarrese, Matarrese & Lucchin 1994; Copeland et al. 1994), in particular in the framework of the so-called hybrid models. Recently Lucchin et al. (1996), using linear theory and N-body simulations, performed an extended analysis of the large-scale structure arising from blue MDM (BMDM) models: the most interesting advantage of these models is the increase in the galaxy formation redshift, for instance, taking $\Omega_v = 0.3$ one has, for the redshift of non-linearity on a galactic scale $(M = 10^{12} M_\odot)$, $z_n \approx 1.9$ if $n = 1.2$ and $z_n \approx 0.6$ if $n = 1$. The same class of models has been tested against observational data, using linear theory predictions, by Dvali, Shafl & Schaefer (1994) and Pogosyan & Starobinsky (1995a).

In this work we will compare BMDM model predictions, for different values of $\Omega_v$ and $n$ (for the sake of comparison we also consider the $0.9 \leq n \leq 1$ tilted models), with the observed DLAS abundance. We will furthermore, also discuss the implications of the observed abundance of galaxy clusters for BMDM models. In fact, increasing $n$ for a fixed $\Omega_v$ and fixed normalization to COBE raises the value of $\sigma_8$, the rms fluctuation within a top-hat sphere of $8 h^{-1}$ Mpc radius, which is constrained by the observed abundance of galaxy clusters to be $\sigma_8 \approx 0.6$ (White, Efstathiou & Frenk 1993).

2 METHOD

In order to connect our model predictions to DLAS observables, let us define $\Omega_{\text{coll}}(z)$ as the fractional matter density within collapsed structures at redshift $z$. Therefore,

$$\Omega_{\text{coll}}(z) = \frac{\Omega_v(z)}{\Omega_v f_h},$$

where $\Omega_v$ is the fractional baryon density (since $h = 0.5$ is assumed throughout the paper, we take $\Omega_v = 0.05$ according to standard primordial nucleosynthesis; see, e.g., Reeves 1994) and $f_h$ is the fraction of the H I gas, which is involved in DLASs. Although the observed decrease of $\Omega_v$ with redshift for $z \leq 3.5$ is usually considered as an indication of gas consumption inside stars (e.g. Lanzetta et al. 1995, Wolfe et al. 1995), the actual value of $f_h$ at the high redshift we are interested in is not clear. In any case, since $\Omega_v$ at such high redshifts is quite similar to the fractional density contributed by visible matter in present-day normal galaxies, we expect $f_h$ not to be a particularly small number. In the following we will show results based on $f_h = 0.5$ and 1.

Taking $h = 0.5$ and an Einstein–de Sitter universe, the data at $z = 4.25$ from Storrie–Lombardi et al. (1995) give $\Omega_{\text{coll}} = (8.8 \pm 2.0) \times 10^{-2}$ and $(4.4 \pm 1.0) \times 10^{-2}$ for $f_h = 0.5$ and 1, respectively.

From the theoretical side, the Press & Schechter (1974) approach gives a recipe for computing the contribution to the cosmic density owing to the matter within collapsed structures of mass $M$ at redshift $z$:

$$\Omega_{\text{coll}}(M, z) = \text{erfc} \left( \frac{\delta_c}{2 \sigma_m (z)} \right).$$

The above expression assumes Gaussian fluctuations and $\delta_c$ is the linearly extrapolated density contrast for the collapse of a perturbation; $\sigma_m$ is the rms fluctuation for the mass-scale $M$, where

$$M = (2\pi R^2)^{2/3} \rho$$

for the Gaussian window that we will assume in the following. Here, $\rho$ is the average matter density, which is taken to have the critical value.

As for the mass of the structures hosting DLASs, it has been argued that, since the high column density of the absorber is typical of large discs of luminous galaxies, DLASs should be located within massive structures of $\sim 10^{13} M_\odot$. However, it is not clear at all whether the properties of present-day galaxies can be extrapolated to their high-redshift progenitors. Therefore, we prefer to leave open the possibility that DLASs are hosted within smaller structures. It is clear that, when a model has trouble in accounting for the DLAS abundance if the hosting structure is a dwarf galaxy ($M \sim 10^{10} M_\odot$), this model would certainly be ruled out if more massive protogalaxies are required.

Linear theory for the top-hat spherical collapse predicts $\delta_c = 1.69$. However, effects of non-linearity as well as of asphericity of the collapse could cause significant deviations from this value. Klypin et al. (1995) estimated the halo abundance at different redshifts from high-mass-resolution N-body simulations. By using the Gaussian window, they found a good agreement with the Press–Schechter expression for values as low as $\delta_c = 1.3–1.4$ (see also Efstathiou & Rees 1988). On the other hand, Ma & Bertschinger (1994) found that for $\Omega_v = 0.3$ and a top-hat window $\delta_c \approx 1.8$ is always required, which corresponds to $\delta_c \approx 1.7$ for the Gaussian window. In the following we will prefer to show results based on $\delta_c = 1.5$ but, because of the previous uncertainties, we will discuss also the effect of different choices of $\delta_c$.

For the MDM transfer function we take the fit obtained by Pogosyan & Starobinsky (1995a), which provides a continuous dependence on the fractional density $\Omega_v$ contributed by one massive neutrino. As for the cold part of the transfer function, we use the CDM expression by Efstathiou, Bond & White (1992), with the shape parameter $\Gamma = \Omega_v h \exp (-2 \alpha_k)$, according to the prescription of Peacock & Dodds (1994), to account for the baryonic component. We varied $\Omega_v$ in the interval $0 \leq \Omega_v \leq 0.5$. We assume the primordial (post-inflationary) power spectrum to be $P(k) \propto k^\gamma$, with $0.9 \leq n \leq 1.4$. Each model is normalized to the 9th multipole component of the COBE DMR two-year data, $a_0 = 8.2$, which has been shown to be independent of the $n$ value to a good accuracy (Górski et al. 1994).
In Fig. 1 we plot the resulting $\sigma_8$ value. As for the $\Omega_c$ dependence, results are plotted in the left panel for $n = 0.9-1.4$ going from lower to upper curves with steps of 0.1. In a similar fashion, in the right panel we plot the $n$ dependence. Going from higher to lower curves, we plot results for $\Omega_c = 0-0.5$ with steps of 0.1. As expected, $\sigma_8$ is an increasing function of $n$, while it decreases with $\Omega_c$.

3 DISCUSSION

The results of our analysis on DLAs are summarized in Fig. 2, where we plot $\Omega_{\text{col}}$, estimated at $z = 4.25$, as a function of $\Omega_c$ (left panel) and of $n$ (right panel), after assuming $\delta_c = 1.5$ and $M = 10^{11} \, M_\odot$. In each panel, different curves are for the same choice of parameters as in Fig. 1. Upper and lower error bars show the effect of taking $M = 10^{10}$ and $10^{12} \, M_\odot$, respectively. The horizontal solid line is the observational result with the corresponding uncertainties (dotted lines), which is obtained by converting the $\Omega_c$ value, as reported by Storrie-Lombardi et al. (1995) at $z = 4.25$, to $\Omega_{\text{col}}$ according to equation (1) with $f_g = 1$.

Fig. 3 shows, in the $\Omega_c-n$ plane, the models which reproduce the observed $\Omega_{\text{col}}$, taking $f_g = 1$ (left panel) and $f_g = 0.5$ (right panel). The heavy solid curve corresponds to $\delta_c = 1.5$ and $M = 10^{11} \, M_\odot$, with the lighter curves delimiting the observational uncertainties. Upper and lower dashed lines show the effect of setting $\delta_c$ to 1.3 and 1.7, respectively. Upper and lower dotted curves refer to $M = 10^{10}$ and $10^{12} \, M_\odot$, respectively. The overall result that we obtain is that decreasing the hot component fraction $\Omega_c$ and/or increasing the primordial spectral index $n$ implies an earlier formation of cosmic structures.

It should be noted that realistic observational uncertainties should be larger than the error bars reported by Storrie-Lombardi et al. (1995), since they do not include any systematic observational bias. Recently, Bartelmann & Loeb (1996) emphasized the role of the amplification bias, caused by DLAS gravitational lensing of quasi-stellar objects (QSOs), in the DLAS detection. They pointed out that (a) lensing effects bias upwards the $\Omega_c(z)$ value by an amount depending on the parameters of the Friedmann background, as well as on the redshift; (b) the observed absorber sample may be biased towards larger values of their internal line-of-sight velocity dispersions leading to an overestimate of the total absorber mass. Therefore, both effects go in the direction of alleviating the galaxy formation redshift problem. On the other hand, Fall & Pei (1995) detailed the consequences of dust absorption in DLASs. They argued that dust obscuration causes incompleteness in the optically selected quasar samples and, therefore, in the DLAS samples as well. In this case, the resulting $\Omega_c(z)$ is biased downwards by an amount depending on the model for DLAS chemical evolution.

It is, however, clear that, even taking the observational results at face value with their small error bars, the rather poor knowledge of the parameters entered in the Press-Schechter prediction for $\Omega_c$ (i.e. $\delta_c$, $M$ and $f_g$) makes it difficult to put stringent constraints on $\Omega_c$ and $n$.

For instance, if one takes $1.3 \leq \delta_c \leq 1.5$, as suggested by several $N$-body simulations (e.g. Efstathiou & Rees 1988;
Klypin et al. (1995) and analytical considerations of the Press-Schechter approach (e.g. Jain & Bertschinger 1994), $\Omega_c \approx 0.2$ and $n = 1$ would be allowed for $M \sim 10^{10} - 10^{11} M_\odot$, unless $f_g$ is sensibly below unity. On the other hand, making the spectrum bluer to $n = 1.2$ increases the allowed hot fraction to $\Omega_c \gtrsim 0.4$, unless $\delta_c \approx 1.7$ or $M \sim 10^{13} M_\odot$ are taken. In order to constrain the models more tightly, a better understanding of galaxy formation through hydrodynamical simulations would be needed to clarify what DLASs actually are. This would provide more reliable values for $\delta_c$, $M$, and $f_g$.

It is, however, clear that those models which fit the data at $z \approx 4$ also need to be tested against present-day observables. One of these tests is represented by the abundance of galaxy clusters, which has been shown to represent a powerful constraint for dark matter models (e.g., White et al. 1993). In the Press & Schechter (1974) approach, the number of density of clusters with mass above $M$ is given by

$$n(M) \propto \frac{\sigma(R)}{\sigma(k)} \int_{M}^{\infty} \eta(R) \exp \left( - \frac{\delta_c^2}{2\sigma^2(R)} \right) \frac{dR}{R^2}$$

(5)

is the average cluster number density with mass in the range $[M, M + dM]$. In the above expression, the quantities

$$\sigma^2(R) = \frac{1}{2\pi^2} \int k^2 P(k) W^2(kR) \, dk,$$

$$\eta(R) = \frac{1}{2\pi^2 \sigma^2(R)} \int k^4 P(k) \frac{dW^2(kR)}{dr(kR)} \frac{dk}{kR}$$

(6)

convey the information about the power-spectrum. As before, we use a Gaussian window for $W(kR)$, so that $a = (2\pi)^{-2}$ in equation (5) and the mass $M$ is related to the scale $R$ according to equation (3). Klypin & Rhee (1994) found that $\delta_c \approx 1.5$ for their MDM cluster $N$-body simulations, with $\Omega_c = 0.3$ and a Gaussian filter (see Borgani et al. 1995, for the dependence of the cluster mass function on $\delta_c$ for different dark matter models).

As for observational data, White et al. (1993) estimated a cluster abundance of about $5 \times 10^{-7} \text{ Mpc}^{-3}$ for masses exceeding $M = 8.4 \times 10^{14} M_\odot$ using X-ray data. Biviano et al. (1993) based their analysis on observed cluster velocity dispersion and obtained an abundance of about $7.5 \times 10^{-7} \text{ Mpc}^{-3}$ for clusters exceeding the above mass limit.

In Fig. 4 we plot the $\Omega_c - \sigma$ relations for different values of $N(>M)$ (see caption), taking $M = 8.4 \times 10^{14} M_\odot$. Quite remarkably, for $\delta_c = 1.5$ (left panel) no values of $\Omega_c$ and $\sigma$ in the considered ranges give a cluster abundance as low as the observational ones. For instance, assuming $(\Omega_c, n) = (0.2, 1)$ we have $N(>M) \approx 3.3 \times 10^{-7} \text{ Mpc}^{-3}$, while $N(>M) \approx 7.1 \times 10^{-6} \text{ Mpc}^{-3}$ is obtained for $(\Omega_c, n) = (0.3, 1.2)$. In general, lowering $\Omega_c$ and/or increasing $n$, as suggested by the DLAS analysis, makes the disagreement even worse. This result agrees with the expectation that $\sigma_c \approx 0.6$ (White et al. 1993) in order to reproduce the observed cluster abundance, while in general larger normalizations are required by our models (cf. Fig. 1). Increasing $\delta_c$ to 1.7 alleviates the disagreement to some extent. Even in this case, however, in order to reproduce the observational $N(>M)$ one should have $\Omega_c \gtrsim 0.2$ and $n \lesssim 0.95$, with the limiting values $(\Omega_c, n) = (0.2, 0.9)$ being only marginally consistent with the DLAS constraints corresponding to the...
most optimistic choice of the parameters (cf. the upper dotted curve in the left panel of Fig. 2). This general problem of the models in reproducing the cluster abundance was also recognized by Pogosyan & Starobinsky (1995a). The point is also discussed by Lucchin et al. (1996).

Although systematic observational uncertainties could well affect the determination of cluster masses from both X-ray and velocity dispersion data, it is not clear whether or not they can justify the order of magnitude (or even more) discrepancy between the data and those models which would have been preferred on the grounds of DLAS constraints.

A first possibility for alleviating this problem would be to increase the baryon fraction $\Omega_b$. This has the effect of lowering the small-scale fluctuation amplitude and, therefore, $\sigma_8$; however, this fluctuation suppression should not damage too seriously DLAS predictions on $\Omega_b$, since this effect is partly compensated by a larger denominator in equation (1). For instance, taking $\delta = 1.5$ for the $(\Omega_b, n) = (0.2, 0.9)$ model the cluster abundance changes from $N(>M) \approx 1.4 \times 10^{-4}$ to $\approx 8.2 \times 10^{-4}$ Mpc$^{-3}$ when passing from 5 to 10 per cent of baryonic fraction. However, such an effect turns out to be ineffective in reconciling with observational data those models which largely overproduce clusters. Indeed, even for $\delta = 1.7$, $N(>M)$ for $(\Omega_b, n) = (0.3, 1.2)$ drops only from $7.1 \times 10^{-4}$ to $2.5 \times 10^{-4}$ Mpc$^{-3}$ when passing from 5 to 20 per cent of baryonic fraction, the second value already being largely inconsistent with the primordial nucleosynthesis predictions.

A further possibility is sharing the hot component between more than one massive neutrino species (Primack et al. 1995; Pogosyan & Starobinsky 1995b; Babu, Schaefer & Shafi 1995). The subsequent variation of the neutrino free-streaming has been shown to decrease $\sigma_8$ to an adequate level, without significantly affecting results at the galactic scale, which is relevant for DLAs.

As a general conclusion we would stress the effectiveness of putting together different kinds of observational constraints to restrict the range of allowed models. As we have shown, the effect of making the primordial perturbation spectrum more blue goes in the direction of increasing the redshift of structure formation. However, this also increases the rms fluctuation on the cluster mass-scale to a dangerous level. Deciding whether the narrowing of the allowed region of the $\Omega_b$–$n$ plane points towards the selection of the best model or towards ruling out the entire class of models requires a clarification of both the observational situation and of how models have to be compared to data.

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