The inner structure of haloes in Cold+Warm dark matter models

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ABSTRACT

We analyze the properties of dark matter halos in the cold-plus-warm dark matter cosmologies (CWDM). We study their dependence on the fraction and velocity dispersion of the warm particle, keeping the free-streaming scale fixed. To this end we consider three models with the same free-streaming: (1) a mixture of 90\% of CDM and 10\% of WDM with the mass 1 keV; (2) a mixture of 50\% of CDM and 50\% of WDM with the mass 5 keV; and (3) pure WDM with the mass 10 keV. “Warm” particles have rescaled Fermi-Dirac spectrum of primordial velocities (as non-resonantly produced sterile neutrinos would have). We compare the properties of halos among these models and with a ΛCDM with the same cosmological parameters. We demonstrate, that although these models have the same free-streaming length and the suppression of matter spectra are similar at scales probed by the Lyman-α forest (comoving wave-numbers $k < 3 - 5 \, h$/Mpc), the resulting properties of halos with masses below $\sim 10^{11}\, M_\odot$ are different due to the different behaviour of matter power spectra at smaller scales. In particular, we find that while the number of galaxies remains the same as in ΛCDM case, their density profiles become much less concentrated, and hence in better agreement with current observational constraints. Our results imply that a single parameter (e.g. free streaming length) description of these models is not enough to fully capture their effects on the structure formation process.

Key words:

1 INTRODUCTION

It is usually said that cosmological data favour Cold Dark Matter. The cosmological “concordance model” is therefore often called ΛCDM. However, a more precise statement should be that hot dark matter particles (i.e. the particles that became non-relativistic only around recombination time, such as e.g. the ordinary neutrinos) are ruled out (Davis et al. 1985). The difference between cold and warm DM particles (the former being always non-relativistic and the latter becoming non-relativistic deeply in the radiation-dominated epoch) would show up at approximately galactic scales and it is only recently that such small scale effects are starting to be resolvable both theoretically (see e.g. Macciò & Fontanot 2010; Polisensky & Ricotti 2011; Semboloni et al. 2011; van Daalen et al. 2011) and experimentally (see e.g. Viel et al. 2005, 2006; Semboloni et al. 2011; van Daalen et al. 2011). Warm dark matter N-body simulations require significantly larger number of particles to resolve the same scales as compared with the CDM case (see e.g. Wang & White 2007; Lovell et al. 2012). Additionally, at sub-Mpc scales baryonic physics can hide (or mimic) the WDM suppression of power (see e.g. (Benson et al. 2002; Bullock et al. 2000; Semboloni et al. 2011), which makes the analysis of small-scale data challenging.

The tiny (from the cosmological point of view) difference between cold and warm dark matter is however of crucial importance for particle physics, as it means a huge difference in the properties of corresponding particles and may eventually provide a clue on the structure of a fundamental theory of particles and interactions.
Historically the first WDM models were thermal relics — particles that were in equilibrium in the early Universe and froze-out, being relativistic [Colin et al. 2004; Bode et al. 2001]. Such particles had thermal primordial velocity spectrum and strong cutoff-like suppression of the power spectra [Bode et al. 2001; Viel et al. 2002; Boyarsky et al. 2009a] at scales below few Mpc. Such models are characterized by only one scale — position of the cutoff in the power spectrum, related to their free-streaming horizon. One possible tool to probe the growth of structures of (sub)Mpc scales is the Lyman-α forest method — studies of statistics of absorption features in the spectra of distant quasars. The Lyman-α forest data [Hansen et al. 2002; Viel et al. 2003, 2006; Seljak et al. 2008; Viel et al. 2008; Boyarsky et al. 2009a] puts such strong constraints at their free-streaming length that “thermal relics” WDM models, compatible with Lyman-α bounds, produce essentially no observable changes in the Galactic structures (c.f. Strigari et al. 2006; Colin et al. 2008; Boyarsky et al. 2009a; de Naray et al. 2009; Schneider et al. 2012).

However, particle physics motivated WDM candidates can be produced in the early Universe in non-thermal ways, may have significant non-zero primordial velocities in the radiation-dominated epoch and non-equilibrium velocity spectra (for review see e.g. Boyarsky et al. 2009a; Taoso et al. 2008; Feng 2010). In many models (e.g. sterile neutrinos, gravitino, axino) the same DM particles can be produced via two co-existing mechanisms and therefore generically primordial velocity spectra have “colder” and “warmer” components. Such models can be called mixed or “cold plus warm” dark matter models (CWDM) [Boyarsky et al. 2009a], see also Palazzo et al. 2008. Qualitatively, structures form in these models in a bottom-up fashion (similar to CDM). The way the scales are suppressed in CWDM models is more complicated (and in general less severe for the same masses of WDM particles), as comparable with pure warm DM models. The first results of Lovell et al. (2012) demonstrate that the resonantly produced sterile neutrino DM models, compatible with the Lyman-α bounds of Boyarsky et al. (2009a), do change the number of substructure of a Galaxy-size halo and their properties. The discrepancy between the number of observed substructures with small masses and those predicted by CDM models (first pointed out in Klypin et al. 1999; Moore et al. 1999) can simply mean that these substructures did not confine gas and are therefore completely dark (see e.g. Bullock et al. 2000; Benson et al. 2002; Somerville 2004; Macciò et al. 2010). This is not true for larger objects. In particular, CDM numerical simulations invariably predict several satellites “too big” to be masked by galaxy formation processes, in contradiction with observations (Boylan-Kolchin et al. 2011). Sterile neutrino DM of the minimal neutrino extension of the Standard Model (the νMSM) [Asaka & Shaposhnikov 2003; Boyarsky et al. 2009a], with its non-trivial velocity dispersion, turns out to be “warm enough” to amend these issues [Lovell et al. 2012] and “cold enough” to be in agreement with Lyman-α bounds (Boyarsky et al. 2009a).

In this paper we study the structures of halos in the CWDM models. To this end we pick two CWDM models, compatible with the Lyman-α data of Boyarsky et al. (2009a) and having the same free-streaming of the WDM particles. We demonstrate that the properties of halos differ in these models (and differ from both pure CDM and pure WDM model with the same free-streaming), meaning that they are not determined by the free-streaming alone.

The paper is organized as follows. We discuss the choice of parameters of our DM models and initial conditions for simulations in Section 2. The suite of simulations is discussed in Sec. 4 and the main results in Section 5. We discuss our results in Section 6.

2 MODEL SELECTION AND INITIAL CONDITIONS

For our simulations we selected two CWDM, one WDM and one reference ΛCDM model. Our first CWDM model (model $m1$ in what follows) is a mixture of 90% of cold dark matter and 10% warm dark matter with rescaled Fermi-Dirac spectrum and mass $m_{\text{wDM}} = 1$ keV, (model $m1$); the red solid line is a mixture 50% of cold and warm particles with the mass $m_{\text{wDM}} = 5$ keV (model $m5$) and the green dashed-dotted line (model $\text{wDM}$) is a 100% WDM model with the mass of DM particle $m_{\text{wDM}} = 10$ keV. All three models are compatible with the Lyman-α analysis of Boyarsky et al. (2009a).

Figure 1. Ratio of the power spectra of the three models used in this work to that of ΛCDM (for the same values of cosmological parameters). The blue short-dashed curve is a mixture of 90% of cold dark matter and 10% warm dark matter with rescaled Fermi-Dirac spectrum and mass $m_{\text{wDM}} = 1$ keV, (model $m1$); the red solid line is a mixture 50% of cold and warm particles with the mass $m_{\text{wDM}} = 5$ keV (model $m5$) and the green dashed-dotted line (model $\text{wDM}$) is a 100% WDM model with the mass of DM particle $m_{\text{wDM}} = 10$ keV. All three models are compatible with the Lyman-α analysis of Boyarsky et al. (2009a).

\[
f(v) = \frac{\chi}{\exp\left(\frac{m_{\text{wDM}}}{T_{\nu}(z)}\right) + 1}
\]

where $m_{\text{wDM}}$ is the WDM mass, $T_{\nu}(z)$ is the temperature of cosmic neutrino background, evolving with redshift as $T_{\nu}(z) = T_{\nu0}(1 + z)$, $T_{\nu0} = 1.9$ K, and the constant $\chi$ is
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\begin{table}[h]
\centering
\begin{tabular}{lccc}
\hline
Name & Box size & N & force soft. \\
& $[h^{-1}\text{Mpc}]$ & & $[h^{-1}\text{M}_\odot]$ & $[h^{-1}\text{kpc}]$ \\
\hline
ACDM-20 & 20 & 350$^3$ & 1.31e7 & 1.42 \\
ACDM-45 & 45 & 350$^3$ & 1.49e8 & 3.21 \\
ACDM-90 & 90 & 400$^3$ & 7.99e8 & 5.62 \\
ACDM-180 & 180 & 400$^3$ & 6.39e9 & 11.25 \\
WDM-20 & 20 & 350$^3$ & 1.31e7 & 1.42 \\
WDM-45 & 45 & 350$^3$ & 1.49e8 & 3.21 \\
m1-20vel & 20 & 350$^3$ & 1.31e7 & 1.42 \\
m1-20 & 20 & 350$^3$ & 1.31e7 & 1.42 \\
m1-45 & 45 & 350$^3$ & 1.49e8 & 3.21 \\
m1-90 & 90 & 400$^3$ & 7.99e8 & 5.62 \\
m1-180 & 180 & 400$^3$ & 6.39e9 & 11.25 \\
m5-20vel & 20 & 350$^3$ & 1.31e7 & 1.42 \\
m5-20 & 20 & 350$^3$ & 1.31e7 & 1.42 \\
m5-45 & 45 & 350$^3$ & 1.49e8 & 3.21 \\
m5-90 & 90 & 400$^3$ & 7.99e8 & 5.62 \\
m5-180 & 180 & 400$^3$ & 6.39e9 & 11.25 \\
\hline
\end{tabular}
\caption{N-body simulation parameters}
\end{table}

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\begin{tabular}{lccc}
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Name & Box size & N & part. mass \\
& $[h^{-1}\text{Mpc}]$ & & $[h^{-1}\text{M}_\odot]$ \\
\hline
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ACDM-45 & 45 & 350$^3$ & 1.49e8 \\
ACDM-90 & 90 & 400$^3$ & 7.99e8 \\
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\hline
\end{tabular}
\caption{N-body simulation parameters}
\end{table}

\section{NUMERICAL SIMULATIONS}

All simulations have been performed with \texttt{PKDGRAV}, a tree code written by Joachim Stadel and Thomas Quinn (Stadel 2001). The code uses spline kernel softening, for which the forces become completely Newtonian at 2 softening lengths. Individual time steps for each particle are chosen proportional to the square root of the softening length, $\epsilon$, over the acceleration, $a$: $\Delta t_i = \eta \sqrt{\epsilon/a_i}$. Throughout, we set $\eta = 0.2$, and we keep the value of the softening length constant in comoving coordinates during each run. The physical values of $\epsilon$ at $z = 0$ are listed in Table \ref{tab:boxsize}. Forces are computed using terms up to hexadecapole order and a node-opening angle $\theta$ which we change from 0.55 initially to 0.7 at $z = 2$. This allows a higher force accuracy when the mass distribution is nearly smooth and the relative force errors can be large.

Table \ref{tab:boxsize} lists all of the simulations used in this work. We have run simulations for several different box sizes, which allows us to probe halo masses covering the entire range $10^{10} h^{-1} M_\odot \leq M \leq 10^{14} h^{-1} M_\odot$. For the small box simulations ($L = 20 \text{ Mpc/h}$) we have, for each CWDM model, two different runs, with and without thermal velocities.

Fig. \ref{fig:massfunction} shows the halo mass function for the \texttt{m5} model at $z = 0$. Only haloes with virial masses larger than $2 \times 10^{10} h^{-1} M_\odot$ are shown, and different symbols (and colors) refer to different box size simulations. The green line is
Figure 2. Halo mass function for all three models at \(z = 0\) follow predictions of ΛCDM with the same cosmological parameters (green dashed line is the Warren et al. (2006) predictions for ΛCDM). Shown are the points for \(m5\) model, the other two models (\(m1\) and WDM) give very similar results and are not shown.

Figure 3. Density profiles for CWDM and WDM models. The plot shows the change in the inner slope of the halo density profile for one of the haloes in the simulation with the box size \(L = 20\) Mpc/h (as compared to the CDM – black line). Points and red line (the NFW fit) are for the \(m5\) model. For \(m1\) and WDM models we show only the NFW fit (to make the plot less crowded). Black line shows the predicted profile for ΛCDM using the fitting formula from Muñoz-Cuartas et al. (2011).

3.1 Halo parameters

In all of the simulations, dark matter haloes are identified using a spherical overdensity (SO) algorithm. We use a time varying virial density contrast determined using the fitting formula presented in Mainini et al. (2003). We include in the halo catalog all the haloes with more than 500 particles (see Macciò et al. (2008) for further details on our halo finding algorithm). For each SO halo in our sample we determine a set of parameters, including the virial mass and radius, the concentration parameter, the angular momentum, the spin parameter and axis ratios (shape). Below we briefly describe how these parameters are defined and determined. A more detailed discussion can be found in Macciò et al. (2003, 2008). Finally following Macciò et al. (2007), we split our halo sample into unrelaxed and relaxed haloes. In the rest of the paper we will only discuss the properties of relaxed haloes.

3.1.1 Concentration parameter

To compute the concentration of a halo we first determine its density profile. The halo centre is defined as the location of the most bound halo particle, and we compute the density \(\rho_i\) in 50 spherical shells, spaced equally in logarithmic radius. Errors on the density are computed from the Poisson noise due to the finite number of particles in each mass shell. The resulting density profile is fit with a NFW profile \(\rho(r) = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}\) (Navarro et al. 1997). During the fitting procedure we treat both \(r_s\) and \(\delta_c\) as free parameters. Their values, and associated uncertainties, are obtained via a \(\chi^2\) minimization procedure using the Levenberg & Marquardt method. We define the r.m.s. of the fit as:

\[
\rho_{\text{rms}} = \frac{1}{N} \sum_{i} \left( \ln \rho_i - \ln \rho_{\text{ms}} \right)^2
\]

where \(\rho_{\text{ms}}\) is the fitted NFW density distribution. Finally, we define the concentration of the halo, \(c_{\text{vir}} \equiv r_{\text{vir}}/r_s\), using the virial radius obtained from the SO algorithm, and we define the error on log \(c\) as \((\sigma_{r_s}/r_s)/\ln(10)\), where \(\sigma_{r_s}\) is the fitting uncertainty on \(r_s\).

3.1.2 Shape parameter

Determining the shape of a three-dimensional distribution of particles is a non-trivial task (e.g., Jing & Suto 2002). In this paper we do not resolve (due to resolution) and do not discuss the inner slope of DM density profiles, as for example in Macciò et al. (2012b). Therefore, possible deviations from the NFW profile due to WDM effects, even appearance of a core, are not considered.
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4 THE CONCENTRATION MASS RELATION

In Figure 4, we show the concentration mass relation for relaxed haloes in the ΛCDM model. In our mass range the $c_{\text{vir}} - M_{\text{vir}}$ relation is well fitted by a single power law at all redshifts, in agreement with several previous results (e.g. Klypin et al. (2011)), and references therein). The best fitting power law can be written as:

$$\log(c) = a(z) \log(M_{\text{vir}}/[h^{-1}M_\odot]) + b(z).$$  \hspace{1cm} (8)

The fitting parameter $a(z)$ and $b(z)$ are function of redshifts and are reported in table 2. These parameters are very not far from the ones suggested in Muñoz-Cuartas et al. (2011). From now on we will use these linear fits to compare (C)WDM models and the standard ΛCDM one.

Figure 5 (right) shows the mass and redshift dependence of the concentration parameter for the run model. Results for $z = 0$, $z = 0.5$ and $z = 1$ are shown from top to bottom. The error-bars on the points show the error in the mean concentration value (while the scatter is of the order of 0.3 dex independently on the mass scale) The three lines are the fits to the ΛCDM results from figure 4.

At high masses the CWDM models basically agree with the pure cold dark matter predictions. The situation is different for masses below $10^{12}h^{-1}M_\odot$, where the CWDM model predicts lower concentrations with respect to the ΛCDM. For our lowest mass bin ($M \approx 10^{10}h^{-1}M_\odot$) the concentration is lower by 40% and there is a clear indication of flattening of the concentration mass relation, with an almost flat relation for log($M$) < 10.5. This flat tail of the cM relation at low masses is already in place at $z = 1$ and the difference between CDM and CWDM appears to be redshift independent.

This results is not surprising. In CWDM models the formation of small haloes is delayed with respect to CDM due to the lack of power on small scales. The concentration parameter is related to the density of the universe at the time of the halo formation (Wechsler et al. 2002); since the density of the universe decreases with time, a later formation time implies a lower value for the concentration.

The $m1$ model behaves similarly to $m5$ (left panel of figure 6), showing a lower values for the concentration parameter (with respect to ΛCDM) at small masses. In this case the difference with ΛCDM is less pronounced and at the lowest mass scales ($M \approx 10^{11}h^{-1}M_\odot$) it is less than 15%.

The difference between $m1$ and $m5$ is a direct consequence of the different power spectrum at small scales. As shown in Figure 1 the $m5$ model has less power at scales $k > 10$ h/Mpc, which correspond to mass scales of the order $8 \times 10^{10}h^{-1}M_\odot$. This lower power results in a later formation time for these halos and hence lower concentration. This is also confirmed by figure 6 where the concentration-mass relation for the WDM simulation is presented. Results for the pure WDM model are very similar to the $m5$ model, confirming the relation between initial power spectrum (fig 1) and halo concentration.

The difference between the two CWDM models shows that even models with the same free-streaming length (as $m1$ and $m5$) could lead to different halo internal structures. As a consequence the characterization of any models with a warm component only through its matter power spectrum suppression could lead to misleading results, since this single parameter is not capable to fully describe the effects of

| Name | $z = 0$ | $z = 0.5$ | $z = 1$ |
|------|---------|---------|---------|
| $a(z)$ | -0.0973 | -0.0928 | -0.0684 |
| $b(z)$ | 2.157 | 1.845 | 1.578 |
| $\alpha(z)$ | -4.78e-6 | -5.3095e-6 | -4.6561e-6 |
| $\beta(z)$ | 0.766 | 0.729 | 0.681 |

Table 2. Fitting parameter for the concentration and shape mass dependence

Following Allgood et al. (2006), we determine the shapes of our haloes starting from the inertia tensor. As a first step, we compute the halo’s 3 x 3 inertia tensor using all the particles within the virial radius. Next, we diagonalize the inertia tensor and rotate the particle distribution according to the eigenvectors. In this new frame (in which the moment of inertia tensor is diagonal) the ratios $s = a_3/a_1$ and $p = a_2/a_1$ (where $a_1 \geq a_2 \geq a_3$) are given by:

$$s \equiv \frac{a_3}{a_1} = \sqrt{\frac{\sum m_i z_i^2}{\sum m_i z_i^2}} \quad p \equiv \frac{a_2}{a_1} = \sqrt{\frac{\sum m_i y_i^2}{\sum m_i z_i^2}}. \hspace{1cm} (7)$$

Next we again compute the inertia tensor, but this time within the virial radius. Next, we diagonalize the inertia tensor (if it is not diagonal) the ratios $s \equiv a_3/a_1$ and $p \equiv a_2/a_1$ are computed. When deforming the ellipsoidal volume of the halo, we keep the longest axis ($a_1$) equal to the original radius of the spherical volume ($r_{\text{vir}}$). We iterate this procedure until we converge to a stable set of axis ratios.
a warm dark matter candidate on the structure formation process.

4.1 Effects of thermal velocities

For the small boxes (20 Mpc/h) we also run an additional simulation that included a thermal velocity component in the initial conditions. This thermal component is few percent of the initial velocity due to the potential field (according to the Zel’dovich approximation), nevertheless it is important to test its effects (if any) on the halo internal structure.

Figure 7 shows the one-to-one comparison of the median $c_{\text{vir}}$ at a given halo mass for the model $m1$, with and without primordial thermal velocities. As expected given the magnitude of the thermal velocity component, the effect is negligible. The model $m5$ presents the same behaviour. The thermal velocity component will play a role on smaller scales.

Figure 5. Mass and redshift dependence of the concentration parameter. Points with error-bars are CWDM simulation ($m1$ and $m5$ models at left and right panel correspondingly) results, the three straight lines are the fits to the CDM results from figure 4. From top to bottom: $z = 0$, $z = 0.5$, $z = 1$. One sees that $m1$ model is “colder” (closer to the CDM) than $m5$ at all redshifts.

Figure 6. Same as fig. 5 for the WDM simulation. Notice the similarity with Fig. 5, right panel.
4.2 Effects on halo shape

There is a well known relation between halo shape and mass with low mass haloes being less triaxial (higher value for the $s$ parameter) than high mass ones (Allgood et al. 2006; Macciò et al. 2008; Muñoz-Cuartas et al. 2011). This relation is usually explained by assuming that the halo “triaxiality” correlates with formation time, such that early halos have more time to virialize and hence reach a more equilibrated, less triaxial configuration. In this case we could possibly see a different trend between halo shape and mass in the CDM simulation with respect to the ΛCDM.

Figure 8 shows the redshift and mass dependence of the shape parameter $s$ for the ΛCDM model. In order to fit this relation we used the same equations as suggested by Muñoz-Cuartas et al. (2011):

$$s(z, M) = \alpha(z) (\log(M_{\text{vir}}/[h^{-1} M_\odot]))^4 + \beta(z).$$

The values of the fit parameters ($\alpha(z), \beta(z)$) are listed in Table 2.

Figure 9 shows the redshift evolution of the halo shape, quantified via the minor to major axis ratio: $s \equiv a_3/a_1$, for the m1 and m5 models (left and right panels in Fig. 9 correspondingly).

In this case the CDM model behaviour is very similar to ΛCDM and the two family models (ACDM and CDMWDM) seem to be consistent within the errors. Nevertheless there is a small hint for a lower values for the $s$ parameter (hence a larger triaxiality) at the very low mass bins ($\approx 10^{12} h^{-1} M_\odot$), as expected due to the later formation times at these mass scales.

5 SUMMARY AND DISCUSSION

Interest in warm dark matter models has increased in the last years, mainly motivated by the possible need for cored (or very low concentration) dark matter halo density profiles for dwarf galaxies in the local group (see e.g. Walker & Penarrubia 2011; Amorisco & Evans 2011), or by solution of various CDM “over-abundance problems” (Klypin et al. 1999; Moore et al. 1999, see e.g. Macciò & Fontanot 2010; Strigari et al. 2009).

While it is still under debate what is the effects of baryons on the dark matter distribution on such small scales (e.g., Pontzen & Governato 2012; Macciò et al. 2012b and references therein); it is worth studying through numerical simulations the effects of a warm component on the inner structure of DM haloes. It had been repeatedly argued that “pure warm” dark matter models (with a cutoff-like suppression of the matter power spectrum) could not be a solution to the core-cusp problem as the required free-streaming would be in a stark contradiction with Lyman-$\alpha$ bounds (see e.g. Strigari et al. 2008; de Naray et al. 2009).

In this paper we have performed the first N-body simulations for cold plus warm dark matter models (CWDM). In this class of models the dark matter particle candidate (e.g., sterile neutrinos, gravitino, axions) can be produced via two co-existing mechanisms and therefore the primordial spectrum is a superposition of a cold and a warm component, plus a complicated non-thermal velocity spectrum (e.g., Boyarsky et al. 2009).

We have mainly focused our attention on the inner structure of dark matter haloes in CWDM models, and its evolution with redshift. We have adopted the commonly used concentration parameter (e.g., Macciò et al. 2008) to parameterize the modification in CWDM models with respect to the standard Cold Dark Matter (CDM) model.

We show that in our models the number of halos remains the same as in ΛCDM down to the smallest scales resolved in the simulations ($\approx 10^{10} M_\odot$). At the same time, keeping the free-streaming scale the same, the variation of WDM fraction is able to reduce the concentration parameter on mass scales as high as $M \approx 10^{12} h^{-1} M_\odot$, two/three order of magnitude above the free streaming mass of the model. On dwarf galaxies mass scale($ M \approx 10^{10} h^{-1} M_\odot$) the concentration parameter is almost half of the value predicted by ΛCDM and we see a clear sign of a strong flattening of the concentration mass relation. As a consequence we expect an even stronger concentration reduction on lower mass scales (below our resolution limits), mass scales directly explored by the Milky Way satellites. This decrease of the concentration of such large halos may explain why the “cuspy” matter distributions are not supported by observations of the rotation curves of spiral galaxies (see e.g., Salucci & Burkert 2000; Oh et al. 2003; Spano et al. 2008; de Naray et al. 2009), thus resolving one of the major challenges for the CDM cosmological model.

Another interesting result is the intrinsic difference in the concentration mass relation between the m1 and m5 models, that clearly shows that even models with the same free-streaming length could lead to different halo internal structures. As a consequence this calls for a detailed anal-
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In Macciò et al. (2012b) it was shown that the primordial velocities required to produce the cores of observable sizes in pure WDM cosmologies are so large that too few galaxies would be formed. This is because in pure warm dark matter models the phase-space density, defining the size of the core and suppression in the halo number density are defined by the same parameter – the average velocity of particles. Our results show that in the CWDM models the presence of the second parameter, $F_{\text{wdm}}$, allows to control the “warmness” of dark matter, separating the scales of modification of the matter power spectrum (halo number density) and that of modification of the density profile (size of the core).

We stress that unlike the recent work of Macciò et al. (2012b) this effect is not related to the finite phase-space density (the phase-space density of particles in our simulations is the same as in pure CDM ones). We ascribe the lower concentration at small masses to a shift in the halo formation time, that results in a delayed formation for CWDM models with respect to CDM, as already found in previous studies (Eke et al. 2001; Lovell et al. 2012). This delayed formation time could also be responsible of the lower ratio between the halo minor and major axis ($s$ parameter) that we saw at very low masses (even if the CWDM models are consistent with $\Lambda$CDM within the error-bars). We did not find any effect on the halo spin parameter distribution, which looks almost identical in all models.

We also tested the effect of explicitly including thermal velocities in the N-body initial conditions, We did not see any visible change in the concentration mass relation on the mass scales we are able to resolve. We plan to study in more details the importance of this thermal velocity component in a forthcoming paper, by employing “zoomed” high resolution simulations of single dark matter haloes.

Along with the Lyman-α forest method, the weak lensing surveys can be used to probe further clustering properties of dark matter particles as sub-galactic scales, as the next generation of these surveys (such as e.g. KiDS, LSST, WFIRST, Euclid) will be able to measure the matter power spectrum at scales down to $1 - 10 \, h/\text{Mpc}$ with a few percent accuracy. Markovic et al. (2011); Smith & Markovic (2011) argued that the next generation of lensing surveys can provide sensitivity, compatible with the existing Lyman-α bounds (Viel et al. 2006; Seljak et al. 2006; Boyarsky et al. 2009a). As in the case of the Lyman-α method the main challenge for the weak lensing is to properly take into account baryonic effects on matter power spectrum. The suppression of power spectrum due to primordial dark matter velocities can be extremely challenging to disentangle from the modification of the matter power spectrum due to baryonic feedback (Semboloni et al. 2011; van Daalen et al. 2011). Finally, the modified concentration mass relation can be probed with the weak lensing surveys (see e.g. Mandelbaum et al. 2008; King & Mead 2011) if their sensitivity can be pushed to halo masses below roughly $10^{12} M_\odot$.

While the observational difference between pure cold and mixed cosmologies is not drastic, clarifying this issue would have profound impact on the fundamental physics questions. Cold+Warm dark matter models are still in an infant state and an effort comparable with that, invested in theoretical investigation of structure formation of pure CDM may be needed before this question will be finally settled.

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