The same with less: the cosmic web of warm versus cold dark matter dwarf galaxies

Darren S. Reed,[1]⋆ Aurel Schneider,[2,3] Robert E. Smith,[3] Doug Potter,[2] Joachim Stadel[2] and Ben Moore[2]

[1]*Institut de Ciències de l'Espai (IEEC-CSIC), E-08193 Bellaterra, Barcelona, Spain*
[2]*Insitute for Computational Science, Univ. of Zürich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland*
[3]*Astronomy Centre, Department of Physics and Astronomy, University of Sussex, Brighton BN1 9QH, UK*

ABSTRACT

We explore fundamental properties of the distribution of low-mass dark matter haloes within the cosmic web using warm dark matter (WDM) and cold dark matter (CDM) cosmological simulations. Using self-abundance-matched mock galaxy catalogues, we show that the distribution of dwarf galaxies in a WDM universe, wherein low-mass halo formation is heavily suppressed, is nearly indistinguishable to that of a CDM universe whose low-mass haloes are not seen because galaxy formation is suppressed below some threshold halo mass. However, if the scatter between dwarf galaxy luminosity and halo properties is large enough, low-mass CDM haloes would sometimes host relatively bright galaxies thereby populating CDM voids with the occasional isolated galaxy and reducing the numbers of completely empty voids. Otherwise, without high mass to light scatter, all mock galaxy clustering statistics that we consider – the auto-correlation function, the numbers and radial profiles of satellites, the numbers of isolated galaxies, and the probability distribution function of small voids – are nearly identical in CDM and WDM. WDM voids are neither larger nor emptier than CDM voids, when constructed from abundance-matched halo catalogues. It is thus a challenge to determine whether the CDM problem of the overabundance of small haloes with respect to the number density of observed dwarf galaxies has a cosmological solution or an astrophysical solution. However, some clues about the dark matter particle and the scatter between the properties of dwarf galaxies and their dark matter halo hosts might be found in the cosmic web of galaxies in future surveys of the local volume.

Key words: galaxies: haloes – cosmology: theory – dark matter.

1 INTRODUCTION

In warm dark matter (WDM) cosmological models, small-scale power is suppressed below the mass-scale of dwarf galaxy haloes due to relativistic free-streaming when particles freeze-out from the matter-radiation field. In contrast, cold dark matter (CDM) particles are 'cold' (non-relativistic) at freeze-out, so CDM small-scale structure is preserved down to 'micro-halo' scales, i.e. $10^{-6} \, h^{-1} \, M_\odot$ plus or minus several orders of magnitude (e.g. Hofmann, Schwarz & Stöcker 2001; Bertone, Hooper & Silk 2005; Diemand, Moore & Stadel 2005; Green, Hofmann & Schwarz 2005; Profumo, Sigurdson & Kamionkowski 2006; Bringmann 2009). CDM cosmology with a cosmological constant (ΛCDM) has been successful at reproducing a number of large-scale observations, including the cosmic microwave background (Planck Collaboration XVI

2014), the large-scale clustering of galaxies (Percival et al. 2010; Anderson et al. 2012), and the mass function of clusters of galaxies (Allen, Evrard & Mantz 2011; Mantz et al. 2015). However, none of these observations directly sample the matter power spectrum or halo mass function on mass-scales below that of bright ($\sim L_*$) galaxies, which means that CDM and WDM are both consistent with large-scale cosmological probes. Moreover, several measurements of structure on small scales are difficult to explain with CDM and have been cited as possible evidence for WDM. A number of possible physical mechanisms for producing WDM have been proposed (Colombi, Dodelson & Widrow 1996; Kawasaki, Sugiyama & Yanagida 1997; Boyarsky et al. 2009).

Among the observations that implicate a warm particle are the reduced number of satellite galaxies in the Milky Way and M31 relative to the number of CDM satellites from simulations (Moore et al. 1999b; Klypin et al. 1999). The overabundance of small haloes relative to galaxy numbers is not limited to the Local Group but extends to the flat-field optical and H I circular velocity functions

⋆ E-mail: reed@physik.uzh.ch

and the faint galaxy luminosity functions relative to the steep low mass halo mass function or circular velocity function (e.g. Blanton et al. 2001; Zavala et al. 2009; Trujillo-Gomez et al. 2011; Klypin et al. 2014; Schneider et al. 2014; Papastergis et al. 2015). A thermal relic of 2 keV is able reduce the numbers of WDM satellites to the number of observed satellites in cosmological simulations (e.g. Polisensky & Ricotti 2011). The lower concentrations of WDM haloes (Schneider et al. 2012; Schneider 2014) corresponds to lower densities in the inner regions (i.e. where there are stars), which brings the satellite halo circular velocities into better agreement with Local Group galaxy rotation curves (Lovell et al. 2012), pushing the 'missing satellite' issue to lower masses where star formation is more easily suppressed. Inefficient star and galaxy formation within low-mass haloes has also been proposed as a solution within CDM cosmology (e.g. Benson et al. 2003). Hence either a *cosmological* solution (WDM) or an *astrophysical* solution (baryon physics) have the potential to explain some of the small-scale CDM problems.

Both classes of proposed solutions have unsolved issues. Recent inferences of the matter power spectrum on small scales from Lyman α (Ly α) forest lines in quasar spectra disfavour a dark matter particle warm enough to reduce sufficiently the numbers of low-mass haloes for agreement with the numbers of dwarf galaxies (Viel et al. 2013). However, the astrophysical solution to the CDM small-scale structure problem also presents a challenge because it requires that star formation in the largest Milky Way satellites be quenched while still allowing some galaxies to form in much smaller haloes, as inferred from halo rotation curves and stellar kinematics – the 'too big to fail' problem (Boylan-Kolchin, Bullock & Kaplinghat 2011). This implies a need for large scatter in halo luminosity to mass if we have a CDM Universe.

Regardless of whether WDM is allowed by the Ly α forest to be warm enough to prevent the overproduction of small structures in CDM, or whether baryon physics is able to hide them, there remain no constraints against WDM that is a bit less warm. 'Lukewarm' DM particles of 4 keV or cooler remain viable candidates (Viel et al. 2013). Moreover, it is important to search for independent local constraints on the DM particle. For these reasons, we will explore whether a WDM particle might leave an imprint in the cosmic web of haloes beyond the main effect of suppressing low-mass halo numbers.

If one understood galaxy formation and associated baryonic effects on dark matter well enough to accurately map galaxy properties to halo mass, one could probe small-scale initial power by directly measuring the halo mass function at dwarf galaxy scales. However, the poorly understood effects of baryon physics on inner halo profiles combined with the mostly unknown scatter between halo mass and dwarf galaxy luminosities and other properties make this difficult. In particular, gravitational coupling of baryons to dark matter via gas cooling associated with star formation and gas ejection from stellar feedback has been shown in simulations to reduce central dark matter densities (Mashchenko, Couchman & Wadsley 2006; Governato et al. 2012; Pontzen & Governato 2012). This baryon feedback could perhaps transform CDM halo central density cusps into shallower cores, which would be a better apparent match to observed galaxies profiles (Moore et al. 1999a, and others). However, any such baryon gravitational coupling to the dark matter also makes it difficult to infer dark halo masses from galaxy kinematics, and the 'true' (i.e. unaltered by baryons) low-mass halo circular velocity function may be much steeper than inferred from observations. It is thus valuable to seek additional tests that might be able to distinguish between WDM and CDM cosmology.

Recent work has revealed subtle differences in the distribution of dwarf galaxies that might be exploited with galaxy surveys. The sizes of voids, defined by the distribution of haloes, have often been noted to be larger and emptier in WDM than CDM simulations because there are more low-mass haloes in CDM (Tikhonov & Klypin 2009; Tikhonov et al. 2009). The striking emptiness of voids in galaxy surveys has sometimes been cited as a problem for CDM (Peebles 2001). However, since voids are delineated by galaxies (lying in haloes), the sizes and emptiness of voids is highly sensitive to the number abundance of galaxies in a survey, and thus a comparison between observed and CDM voids requires knowledge of how galaxies populate haloes. A low efficiency of galaxy formation in low-mass haloes is able to create large and empty CDM voids, in agreement with those found in the local volume, by the effect on galaxy number density (Tinker & Conroy 2009), though it violates the 'too big to fail' test in that some very low V_c galaxies are observed below the galaxy formation cutoff (Tikhonov et al. 2009; Papastergis et al. 2015).

Other work has shown that haloes in a very warm DM cosmology should have somewhat stronger large-scale clustering (Dunstan et al. 2011; Smith & Markovic 2011; Schneider et al. 2012) because they are biased to lie in denser regions according to the peak-background split halo clustering model (Mo & White 1996; Sheth & Tormen 1999). Our work expands upon these studies by exploring some of the fundamental clustering properties of WDM haloes relative to CDM haloes. We focus on the dwarf galaxy halo mass range and include both field haloes and satellite haloes (subhaloes) within larger galaxy haloes.

We use numerical simulations, described in Section 2, to address the potential of low-mass halo and mock galaxy clustering to differentiate between WDM and CDM cosmology. In Section 3, we show that WDM halo and galaxy clustering strength is very similar to that of CDM in our mock catalogues. We then demonstrate in Section 4 that other clustering measures such as the volume fraction occupied by voids and the probability distribution function (PDF) of nearest neighbour distances are also nearly the same in the two cosmologies. While this makes it difficult to use the cosmic web of galaxies to distinguish WDM and CDM, we discuss in Section 5 that some differences arise in small void statistics of cold and warm cosmology, if there is large scatter between galaxy luminosity and halo mass. Thus, there is the potential for observable signals of the dark matter particle type to be measured in the properties of small voids. Finally, in Appendix A, we discuss numerical issues that can affect WDM simulations and show evidence that any related systematic errors are not significant in our mock catalogues and do not affect our conclusions.

2 THE SIMULATIONS

The initial distribution of particles is created using relatively standard techniques as discussed in (e.g. Scoccimarro 1998; Crocce, Pueblas & Scoccimarro 2006; Prunet et al. 2008; Reed et al. 2013). We make use of a slightly modified version of the publicly available code 2LPT,[1] introduced by Crocce et al. (2006) to reduce early numerical errors, 'transients', caused by the fact that the simulation must be initialized at some finite redshift when the density field is no longer accurately described by linear perturbations. Simulations are initialized at $z_i = 100$, approximately 10 expansions before the formation of the first generations of haloes at $z \sim 10$. This start

---

[1] http://cosmo.nyu.edu/roman/2LPT

is early enough to model accurately the formation of early CDM haloes, and it should be late enough that initial cosmological power is sufficiently large such that real cosmological forces dominate over spurious forces. Moreover, because the WDM and CDM simulations use the same initialization epoch and identical simulation parameters, the effects of any potential numerical inaccuracies can be minimized in comparisons between the two cosmologies.

Two twin 25 Mpc volumes are simulated, one with a ΛCDM cosmology and one with a ΛWDM cosmology. We use the Eisenstein & Hu (1998) transfer function to set the CDM initial conditions power. The ΛWDM assumes a 2 keV thermal relic warm particle, and we include some results from warmer simulations of 0.1 and 0.5 keV from (Schneider, Smith & Reed 2013). By focusing on the 2 keV thermal relic, which as we discussed in the previous section, appears to be too warm for Ly α forest data (Viel et al. 2013), we maximize any differences between WDM and CDM – the goal of this work being to determine whether any such differences might be detectable. A small-scale power suppression using the prescription of Viel et al. (2005) is applied to the CDM transfer function to generate the WDM transfer function. The CDM and WDM particle distribution has been constructed with the same statistical realization to minimize the effects of finite sampling of large-scale waves when comparing the two simulations. Initial WDM thermal motions are neglected because they are expected to be insignificant relative to the halo kinematics by low redshift (Bode, Ostriker & Turok 2001). Each volume is a periodic cube of 1024^3 equal mass particles, for a particle mass of $3.9 \times 10^5 \, h^{-1} \, M_\odot$. A 'Hann filter', which reduces initial anisotropies in the density field (Bertschinger 2001) but also suppresses initial small-scale power (see discussion in Reed et al. 2013), is not used. While the simulation volume is small enough to suffer finite volume errors that suppress massive halo numbers, our focus on the scale of dwarf galaxies and the nature of our comparative study between WDM and CDM allow a relatively small box to be used, which saves computational resources.

Simulations are evolved using the particle gravity tree-code PKD-GRAV, an early version of which is described in Stadel (2001) and Wadsley, Stadel & Quinn (2004), with numerical accuracy parameters consistent with converged values in Reed et al. (2013). Force resolution is set by the comoving softening length of $\epsilon = 0.5$ kpc. The adaptive time-step length criterion, $\eta = \sqrt{(\epsilon/a)}$, where a is the acceleration acting on each particle, is set to $\eta = 0.2$. Medium- and long-range force accuracy is governed by the tree opening angle, $\Theta = 0.7$.

2.1 Warming the initial power spectrum

We briefly review the technique we use to transform the CDM initial fluctuation spectrum into a WDM spectrum, noting the important mass and length scales.

Several fitting formulas for the WDM density transfer function have been proposed (Bardeen et al. 1986; Bode et al. 2001); we adopt the formula in Viel et al. (2005):

$$T_{WDM}(k) = \left[\frac{P_{lin}^{WDM}}{P_{lin}^{CDM}} \right]^{1/2} = \left[1 + (\alpha k)^{2\mu} \right]^{-5/\mu}, \tag{1}$$

with $\mu = 1.12$, and the *effective* free-streaming length, below which initial density perturbations are insignificant, is

$$\alpha = 0.049 \left[\frac{m_{WDM}}{keV} \right]^{-1.11} \left[\frac{\Omega_{WDM}}{0.25} \right]^{0.11} \left[\frac{h}{0.7} \right]^{1.22} \text{Mpc} \, h^{-1}. \tag{2}$$

Here, we assume a fully thermalized WDM particle.

Another important scale is the 'half-mode' scale, the scale at which the amplitude of the WDM transfer function is reduced to 1/2 the CDM value. The half-mode length scale is given by

$$\lambda_{hm} = 2\pi \lambda_{fs}^{eff} \left(2^{\mu/5} - 1 \right)^{-1/2\mu} \approx 13.93\alpha. \tag{3}$$

(see e.g. Schneider et al. 2012). The corresponding half-mode mass scale is then

$$M_{hm} = \frac{4\pi}{3} \bar{\rho} \left(\frac{\lambda_{hm}}{2} \right)^3 \approx 2.7 \times 10^3 M_{fs}, \tag{4}$$

or $1.25 \times 10^9 \, h^{-1} \, h^{-1} \, M_\odot$ for our 2 keV relic. M_{hm} can be thought of as the approximate halo mass below which the WDM mass function diverges by a factor of a few or more from CDM.

2.2 Halos and simple mock galaxies

In order to identify haloes that can host galaxies, we use the Amiga Halo Finder (AHF Gill, Knebe & Gibson 2004; Knollmann & Knebe 2009). AHF finds self-bound field, central and satellite haloes (i.e. haloes and subhaloes). Field haloes are those that satisfy a spherical overdensity criterion corresponding to virialized objects and may contain multiple subhaloes defined by identifying local density maxima and the matter bound to them. We construct a simple mock galaxy catalogue by allowing every halo, field or satellite, to host one galaxy at its centre. Mock galaxies are selected by the circular velocity (V_c) at the peak of the rotation curve. Because V_c is less affected by tidal stripping than mass, it is likely a better indicator of pre-infall halo mass for the case of satellites, and thus is likely to better correlate to galaxy stellar mass, according to generally accepted models of galaxy formation. V_c-selected halo and subhalo catalogues have had success at matching the numbers and distribution of galaxies larger than $80 \, \text{km s}^{-1}$ (Trujillo-Gomez et al. 2011). Mass-selected AHF and Friends-of-friends (FoF; Davis et al. 1985) haloes, which correspond more closely to virialized haloes, are also considered separately in Appendix A.

Mock galaxy numbers in CDM and WDM are matched by abundance, initially with a one-to-one relation between galaxy luminosity and dark halo V_c. It is well known that absolute numbers of dwarf haloes are suppressed in WDM, and we should make the conservative assumption that stellar kinematics do not necessarily reflect halo mass. Thus, a fair comparison between the CDM and WDM cosmic web requires that the CDM and WDM mock galaxy catalogues be matched by galaxy number to reflect the possibility that we may live in a CDM universe whose low-mass haloes do not become galaxies. We also consider the effect of scatter between luminosity and V_c on our mock galaxy distribution.

When constructing our mock galaxy catalogue, we set the minimum V_c to match the abundance of WDM haloes with more than 1000 particles ($5.5 \times 10^8 \, h^{-1} \, M_\odot$), approximately double the mass where spurious WDM haloes, which form from the artificial fragmentation of WDM filaments (Wang & White 2007), begin to become important; see further discussion of numerical issues related to WDM in particular in Appendix A. This conservative choice for minimum V_c results in approximately 10^4 mock galaxies with $V_c > 13.7 \, \text{km s}^{-1}$ (WDM) and $V_c > 22.9 \, \text{km s}^{-1}$ (CDM). In addition to the halo V_c resolution limit, we impose the restriction that the halo particles be formed from an initial Lagrangian volume that does not deviate significantly from spherical, an indicator of artificial structure (Lovell et al. 2014). Fig. 1 shows the halo catalogues and the effect of the removal of spurious haloes. Even with our conservative resolution limits, we sample well into the mass and V_c range where WDM halo numbers are reduced, so we are able to
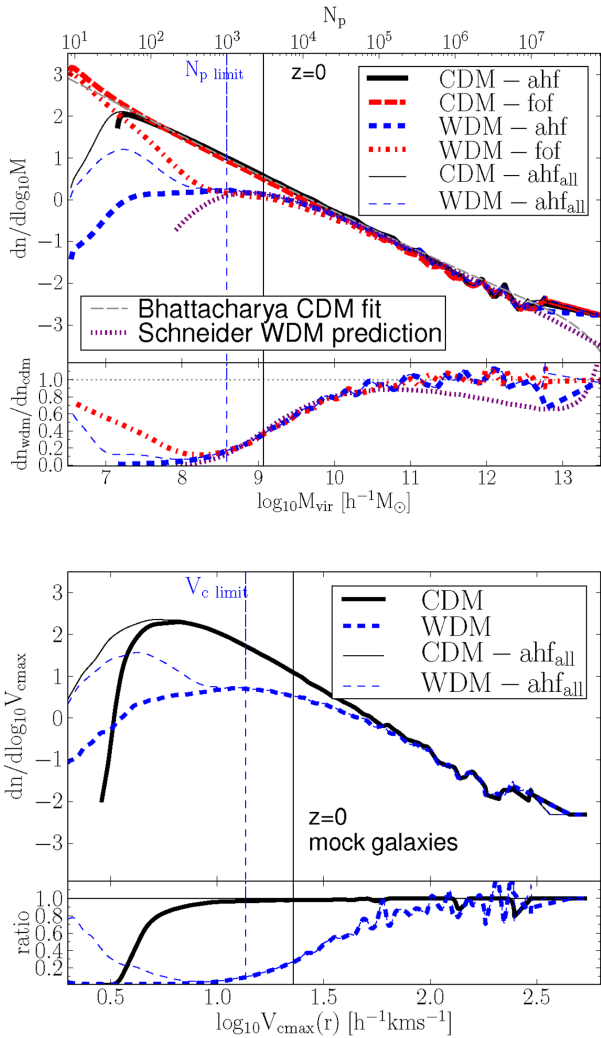
Figure 1. The halo mass function (top) and circular velocity function (bottom) for the WDM and the CDM runs for FoF and AHF haloes. Dashed vertical lines denote the minimum effective halo mass (or V_c) included in our mock galaxy catalogues, chosen to exclude the mass range of spurious WDM halo formation, indicated by the low-mass upturn. The WDM AHF haloes, which include satellites, have a similar mass function and a similar minimum resolved mass as FoF haloes. Thick AHF curves have been purged of spurious haloes based on the sphericity of the initial pre-collapse halo Lagrangian volume, based on Lovell et al. (2014); thin AHF curves include all AHF haloes.

examine any important differences caused by WDM-like suppression of structure formation. Our minimum halo V_c for inclusion in the catalogue is large enough that artificial halo numbers are insignificant. We thus believe that the amount of contamination from artificial structure is small and does not significantly impact our results.

3 THE SIMILARITY OF WDM AND CDM CLUSTERING

We first consider the pair autocorrelation function, ξ, as a measure of clustering strength. We estimate ξ via a histogram of halo pairs binned by radius:

$$\xi(r) = N_{pairs}(r)/N_{pairs,random}(r) - 1, \tag{5}$$
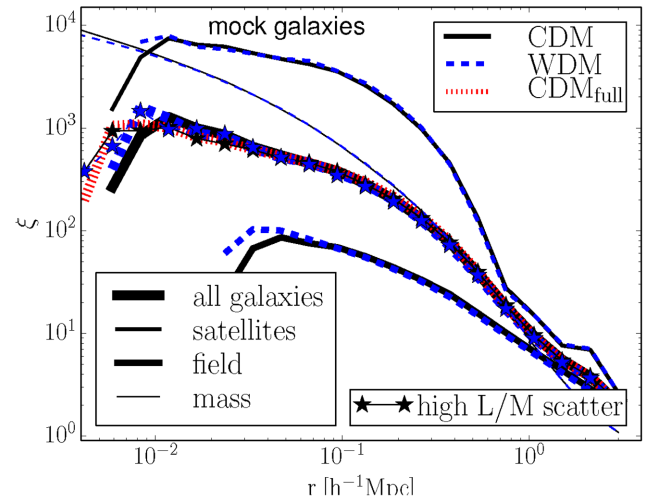
Figure 2. The correlation function of our mock galaxy catalogues selected by halo circular velocity ($V_c > 13.7\,km\,s^{-1}$ for WDM and $V_c > 22.9\,km\,s^{-1}$ for CDM) so that the abundance matches in the two cosmologies. The clustering in WDM and CDM is nearly indistinguishable. The CDM$_{full}$ sample uses the same V_c threshold as the WDM sample, showing that the selection criteria has little effect on CDM halo clustering. The stars show a mock galaxy catalogue that includes a large scatter in mass to light ratio, which could be present in the dwarf galaxy population, described in Section 4; this scatter has little effect on ξ.

where $N_{pairs,\,random}$ is estimated from the number density. Note that ξ is essentially the Fourier transform of the halo power spectrum (e.g. Peebles 1980). To determine ξ of the mass, we take a random subsample of 10^5 simulation particles, enough that statistical errors are much smaller than for halo pairs, and measure the same pair statistics as for haloes.

Fig. 2 compares the CDM and WDM mock galaxy catalogues, matched to each other by abundance. The differences in clustering between WDM and CDM mock galaxies are small, consistent with zero, given the uncertainties, and noting that shot noise is large at the smallest separations. One can estimate from the bin to bin scatter in the correlation function that the shot noise uncertainty is $\gtrsim 10$ per cent on small scales. The sample variance is larger than the shot noise because of our small boxes, but is not important for the CDM versus WDM comparison. Again, a V_c-selected halo sample serves as our simple mock galaxy catalogue. The CDM$_{full}$ curve uses the same minimum V_c threshold for catalogue inclusion as the WDM sample, so there are ~2.8 times more haloes in the CDM$_{full}$ sample. We include it here to show that the precise value of the minimum halo V_c does not much affect CDM clustering. The clustering of mass (particles) is nearly identical in the two cosmologies at scales larger than 10 kpc, though this is partly due to it being a mass-pair-weighted clustering measure, which is dominated by particle pairs in large haloes – WDM small-scale clustering has been shown to be suppressed in volume-weighted clustering measures such as the power spectrum (Schneider et al. 2012; Viel et al. 2012).

Satellites are much more strongly clustered than field objects as a result of being packed into the small virial volumes of their host haloes (the '1-halo' clustering component) combined with the high bias of massive hosts (the '2-halo' clustering component). Thus, small differences in low-mass structure suppression of satellites versus the field could have a large effect on overall halo clustering, which we examine next.
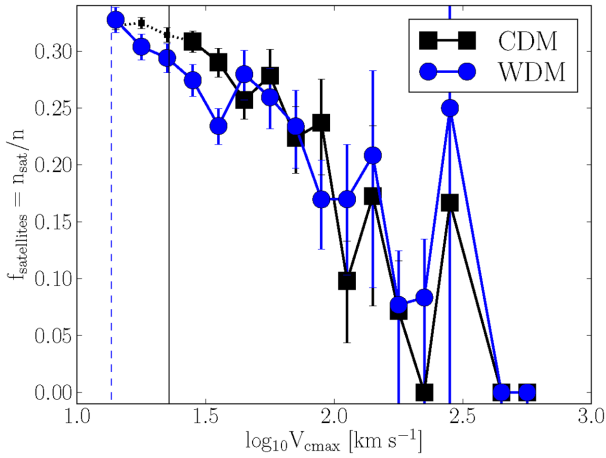
Figure 3. The probability that a mock galaxy in our catalogues is a satellite within a larger halo as a function of V_c. A low V_c mock galaxy is less likely to be a satellite in WDM cosmology than in CDM cosmology for the same V_c. Vertical lines denote the minimum values for inclusion in the self-abundance-matched pair of WDM and CDM mock galaxy catalogues.

3.1 Environments of WDM and CDM haloes

In this section, we examine whether the suppression of WDM haloes has any environmental dependence, in particular, whether it is the same for satellites versus field haloes. We consider first the probability that a halo is a satellite or a field member in WDM and CDM. A satellite in this case is taken to be any halo whose centre lies within the virial radius of a larger parent (field) halo.

Given their similar overall clustering strengths, we would expect to find similar satellite PDF (P_{sat}) in WDM and CDM in Fig. 3. However, the mock galaxy catalogue reveals that there is a higher probability to be a satellite for small CDM haloes than for WDM haloes of equal V_c, although this difference is only $\lesssim 10$ per cent. It is not obvious why a WDM galaxy should be preferentially more likely to lie in the field than to be a satellite compared to a CDM galaxy. It may be that WDM subhaloes are more heavily stripped due to their lower concentrations. In addition, even if the mass stripping is comparable for the two cosmologies, as suggested by (Elahi et al. 2014), it may cause a larger decrease in V_c for WDM haloes because their lower concentrations put their peak V_c at larger radii. The CDM enhancement of P_{sat} for this mock galaxy catalogue does *not* lead to enhancement in the CDM correlation function because once the different minimum V_c are considered, the WDM and CDM samples have a similar total fraction of satellites.

We now examine the host halo mass dependence of the radial profiles of CDM versus WDM satellites. The stacked radial number density profiles of satellites within their host dark matter haloes are shown in Fig. 4 for three host halo mass ranges; as a reminder, the abundance-matched construction CDM and WDM catalogue removes the zero-order effect that there are fewer WDM haloes. The main difference between the CDM and WDM satellite populations is that the central regions of the largest haloes, deficient of satellites in both cosmologies, are somewhat more deficient in WDM. This appears to confirm that the enhanced tendency for CDM haloes to be satellites in V_c-selected mock galaxies (Fig. 3) is due to preferentially reducing V_c by tidal stripping or destruction in the central regions of massive haloes, i.e. clusters and large groups.

The similar spatial clustering and satellite to field ratios of haloes in the WDM cosmology imply that WDM haloes should have sim-
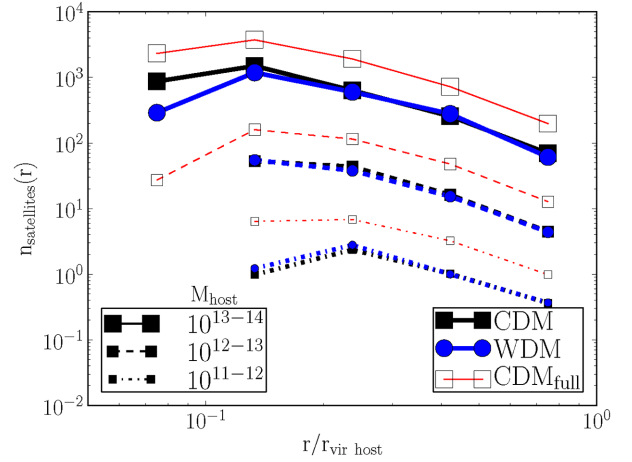
Figure 4. The stacked density profiles of the radial distribution of the population of V_c-selected satellites within their hosts. The only significant difference between CDM and WDM, once normalized by abundance, is that there are somewhat fewer WDM satellites near the centres of the most massive haloes, likely due to increased tidal stripping of the lower concentration WDM haloes. The CDM$_{full}$ curves use the same minimum V_c threshold as the WDM catalogue, illustrating the higher satellite numbers when CDM is not abundance-matched to WDM.
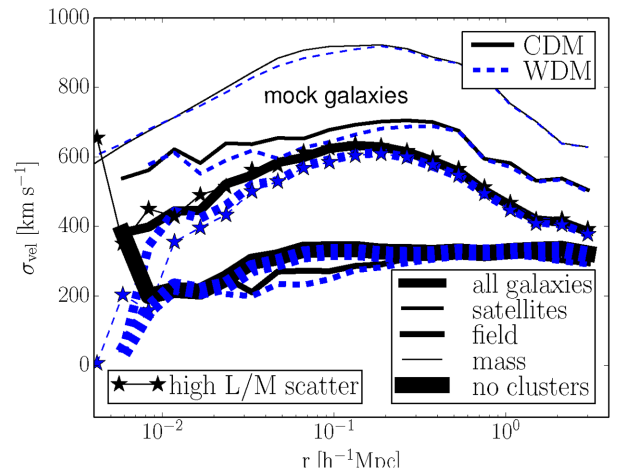

Figure 5. The pairwise velocity dispersion, $\sigma_{vel}(r)$, of our mock galaxy catalogue. The reduced WDM velocities in the full sample ('all galaxies') is mainly due to the central suppression of WDM satellites in the largest clusters ($> 10^{13} h^{-1} M_{\odot}$). Once those cluster members are excluded (thickest lines), the pairwise kinematics of WDM and CDM haloes and mock galaxies are indistinguishable.

ilar peculiar velocities. Indeed, we have examined the mock galaxy halo pairwise velocity dispersion, $\sigma_{vel}(r)$, defined as

$$\sigma_{vel}(r) = \sum V_{rel}^2 / N_{pairs},$$ (6)

and we find indistinguishable values (within our uncertainty levels) for CDM and WDM, once the satellites of the largest clusters are excluded (Fig. 5). The suppression of WDM satellites near cluster centres (Fig. 4) combined with the disproportionately large effect of clusters in the pair-weighted $\sigma_{vel}(r)$ causes some suppression of WDM kinematics in the complete sample. It is not obvious whether this effect could be detected given the other complex environmental effects that occur in clusters. Any effects of the reduced halo concentrations of WDM haloes on pairwise kinematics of their satellites
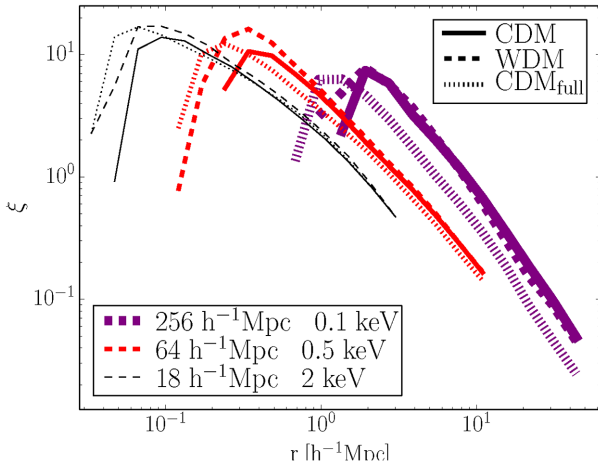
Figure 6. The correlation function of FoF haloes for several different simulations of different box sizes and different thermal relic particle masses, with catalogues selected by mass. When identical halo mass ranges are compared, as for 'CDM$_{full}$' and WDM, clustering is very different with cosmology, primarily because the WDM sample has a flatter mass function, and hence, a higher average halo mass. However, when samples are self-abundance-matched, as for 'CDM' and WDM, clustering is very similar. Legend lists box length and WDM particle mass. The 2 keV run is used for the mock galaxies throughout this paper.

are negligible because halo small enough to have altered concentrations (Schneider 2014) are also too small to host significant numbers of satellites.

3.2 Why is WDM clustering so similar?

We have shown that WDM haloes in the dwarf galaxy mass range are similarly clustered in WDM and CDM because the suppression of WDM haloes is largely independent of environment. Naively, it is perhaps surprising that suppressing small-scale structure in WDM has little effect on the clustering strength of small objects. One might expect WDM satellites to be much more easily tidally disrupted due to their lower concentrations, which would lower their clustering strength. One might also expect low-mass WDM haloes to be 'rare' objects whose formation might be enhanced by lying in a large-scale overdensity, having the opposing effect of increasing their clustering strength. Regarding the homogeneity of WDM halo formation, WDM suppression acts on low-mass haloes, which are relatively unbiased with respect to the matter density field in CDM (e.g. Bond et al. 1991; Sheth & Tormen 1999; Seljak & Warren 2004; Tinker et al. 2010) and also in WDM (Smith & Markovic 2011). Hence, halo formation in WDM is suppressed with nearly equal probability independent of larger scale environment, (reflected by Fig. 2). A thorough theoretical description of WDM versus CDM haloes bias is put forth by Smith & Markovic (2011) using a modified halo model of clustering that accounts for the suppression of low-mass WDM haloes and also includes the effects of WDM substructure suppression (Dunstan et al. 2011) on bias.

If we consider a more extreme (warmer) WDM cosmology with a free-streaming cutoff near or above M_*, defined as the mass of a 1σ overdensity, $\simeq 4.5 \times 10^{12} \, h^{-1} \, M_\odot$ for CDM, halo bias can be significantly affected. In Fig. 6, we show the bias of FoF haloes for some smaller WDM particle masses within larger simulation boxes (to capture the larger free-streaming halo masses) taken from Schneider et al. (2013) with the addition of a 0.1 keV WDM run, each assuming a WDM mass resolution limit given by equa-

tion (A1). If the WDM and CDM catalogue pair is constructed using identical minimum mass thresholds, the WDM sample is significantly biased with respect to CDM – the 'CDM$_{full}$' and 'WDM' lines – as predicted by (Smith & Markovic 2011) and shown in simulations by (Schneider et al. 2012). This effect is largest in the 0.1 keV run where the half-mode WDM suppression mass is $\sim 10 M_*$, and we sample to masses well below M_*. However, when samples are abundance-matched to each other – the CDM and WDM lines – there is little to no difference in clustering within our ~ 10 per cent uncertainties; we verified that this is also true for FoF haloes selected by V_c. Loosely, this similar clustering behaviour occurs because the integral of $N(m)b(m)dm$ is constant when the halo bias, $b(m) \simeq 1$. A minor difference between the warmer WDM models and their matching CDM catalogues is that the WDM halo pairs extend farther into the 'exclusion scale', approximately twice the radius of a halo, due to their lower mass selection criteria and corresponding smaller radii.

In summary, although WDM haloes with a very warm particle are expected to be more strongly biased than CDM haloes, for plausible WDM particle masses of 2 keV, this WDM bias is very weak. The weakness of WDM clustering enhancement is due to the fact that the WDM halo suppression scale is below M_*, and low-mass haloes are a reasonably good tracer of mass. Thus, suppressing halo formation at these scales, has little effect on halo clustering, in line with theoretical expectations. However, there are implications for the effects on clustering due to neutrinos and mixed dark matter models where the streaming mass scale of the warm or hot component is large.

4 WDM VOIDS AND NEIGHBOURS

We discussed in Section 1 that there is some controversy as to whether the distribution of void sizes and the void galaxy population are in agreement with CDM predictions. The emptiness of voids has been interpreted as a 'missing void dwarf galaxy problem' – essentially the 'missing satellite' problem in low-density regions. And there also is the appearance that observed voids are too large compared to CDM simulations when mock catalogues are matched to the same minimum V_c. These problems might be resolved if low-mass haloes do not form many stars, but that solution would seem to require large scatter between halo V_c and galaxy luminosity to avoid the 'too big to fail' problem in the field. In this section, we explore whether the 'warmth' of the dark matter power spectrum might be probed by the distribution of small voids delineated by dwarf galaxy haloes, including the effects of scatter in galaxy luminosity to halo mass. We focus on void size statistics and nearest neighbour statistics for mock dwarf galaxies.

We show in Fig. 7 that the void volume fraction, f_{void}, is very similar in WDM and CDM in self-abundance-matched mock galaxy catalogues, assuming zero scatter between halo V_c and luminosity. f_{void} is defined as the fraction of randomly placed spheres that contain no mock galaxies – i.e. the fraction of the total volume occupied by empty (spherical) voids. Note that the sensitivity of f_{void} to the galaxy number density is removed since our CDM and WDM catalogues are self-abundance-matched. The PDF of nearest neighbour galaxies is also very similar for the CDM and WDM catalogue when no scatter in galaxy to halo properties is assumed, shown in Fig. 8. This indicates that the fraction of isolated galaxies and close pair galaxies does not depend on WDM versus CDM cosmology. In this sense, WDM voids are not larger or 'emptier' of haloes than CDM, as is sometimes loosely stated, but are nearly identical if one links galaxy properties to halo properties by simple abundance matching.
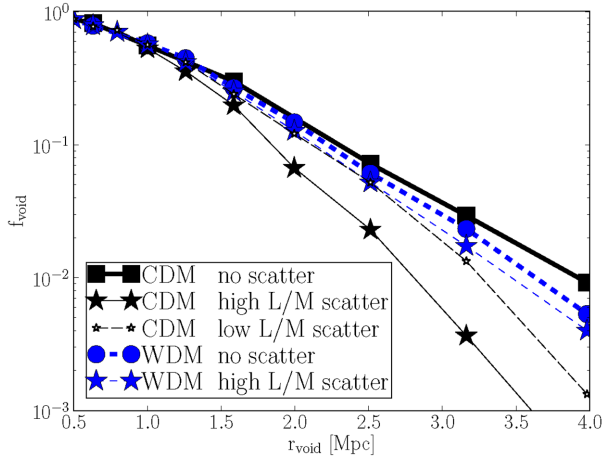
Figure 7. The void volume fraction for the WDM and CDM mock galaxy catalogues, determined by the fraction of randomly placed spheres that contain zero galaxies. Stars show the effect of a scatter between galaxy luminosity and halo V_c (described in text), which reduces the numbers of CDM voids.
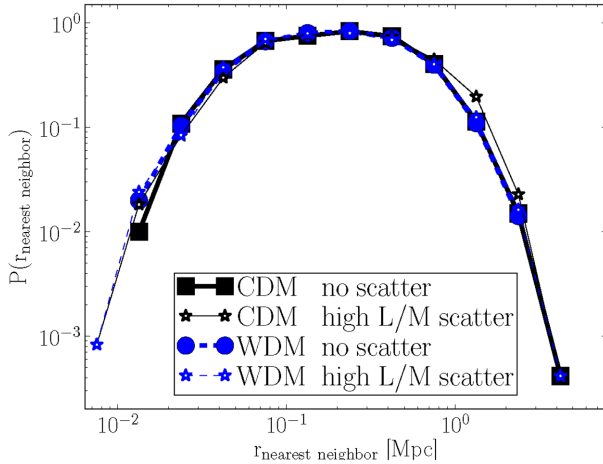
Figure 8. The PDF of nearest neighbour distances for the WDM and CDM mock catalogues are also very similar to each other. Symbols are identical to Fig. 7.

In contrast to this invariance of void properties when defined by galactic haloes, when defined by the mass distribution, small WDM voids are suppressed and WDM void profiles are flattened relative to CDM (e.g. Yang et al. 2015).

Imposing a scatter between galaxy luminosity and halo V_c can have a significant effect on void and neighbour statistics. Recent observations have shown that the scatter between luminosity and circular velocity grows with decreasing V_c for dwarf galaxies (e.g. Geha et al. 2006). We consider the potential qualitative effects of significant scatter between halo mass and luminosity on f_{void} and the nearest neighbour PDF. We allow luminosity to scatter by up to 2.5 mag (a factor of 10 scatter in mass to light ratio) for low-mass haloes and limit the scatter to 0.4 mag for haloes larger than 80 km s^{-1}, following this formula to describe the rms scatter in galaxy magnitude: $\sigma_{Mag}(V_c) = 0.4 + (V_c/80\,\mathrm{km\,s^{-1}})^{-2}$, where $\sigma_{Mag}(V_c) = 2.5$ for $V_c < 55$ km s^{-1}. This denotes our 'high L/M scatter' example. The somewhat arbitrary scatter is chosen to be large enough to demonstrate its effect; it is larger than that inferred from the stellar mass V_c relation for dwarf galaxies of (Geha et al.

2006). However, we note that the same study shows that luminosity-to-mass (L/M) scatter appears to increase for smaller galaxies. In addition, Local Group dwarfs show evidence of extremely large L/M scatter (Strigari et al. 2008). We also consider a 'low L/M scatter' example, which imposes a constant scatter of 1 mag below 80 km s^{-1}. We see in Fig. 2 that L/M scatter has little effect on halo correlation functions (stars). However, in Fig. 7, the void volume fraction (f_{void}) becomes significantly lower with increasing void size for CDM voids because some low-mass void haloes, of which CDM contains more, can be populated by relatively bright galaxies. Moreover, the shape of the $f_{void}(r)$ changes relative to the fiducial CDM catalogue, which has no scatter in L/M. The effect is much smaller for WDM due to the lower numbers of small haloes available to scatter up in luminosity and populate the voids. Fig. 8 shows that the effect of L/M scatter on nearest neighbour statistics is perhaps also important. There is an ∼50 per cent increase in isolated galaxies with nearest neighbours of ∼2 Mpc, corresponding to haloes in otherwise empty voids.

We chose to use a spherical void definition for its simplicity. Because spheres will not usually align well with the irregular boundaries of voids, our spherical voids likely are sensitive primarily to effects in the central regions of voids. Had we instead chosen a void definition that more accurately traces the shapes of individual voids, we might expect to be more sensitive to any effects near the edge of voids

To summarize this section, the void and neighbour statistics that we have considered would be unlikely to be useful as a means to distinguish WDM from CDM if the scatter between halo V_c and galaxy luminosity is small. However, if small haloes have a large scatter in galaxy to halo properties, completely empty CDM voids would occupy a lower total volume due to a small increase in isolated galaxies relative to WDM.

5 IMPLICATIONS FOR THE COSMOLOGICAL GALAXY POPULATION

The cosmic web of haloes is remarkably similar in a CDM and a WDM universe once the reduced number of WDM haloes is accounted for by halo abundance matching. The similar clustering properties of WDM and CDM haloes imply that it will be difficult to use dwarf galaxy clustering as a test of WDM versus CDM cosmology unless the scatter in halo to galaxy properties is rather large. In that case, some differences in the distribution of galaxies emerge. In particular, CDM voids would be less empty than WDM voids because some low-mass CDM haloes would scatter up to high luminosities. Curiously, Peebles & Nusser (2010) cite the existence of relatively bright but isolated galaxies in the local volume as a potential CDM problem because massive haloes strongly prefer to lie in the walls, filaments, and knots that bound void volumes. Our results imply, conversely, that within a CDM universe that also has large halo mass to luminosity scatter, there is the potential for a population of relatively isolated and bright galaxies, possibly alleviating any such problem.

If in fact we live in a CDM universe, a large scatter between galaxy luminosity and halo mass is suggested by observations. One example is the previously mentioned Tully–Fisher relation for dwarfs, which appears to have a scatter of order unity in luminosity and in stellar mass for haloes in the 20–50 km s^{-1} range (e.g. Geha et al. 2006). Considering luminosities even fainter than where the Tully–Fisher relation is well constrained, the common 300 pc dynamical mass scale of $10^7\,h^{-1}\,\mathrm{M_\odot}$ over approximately five orders of magnitude in luminosity for Milky Way satellites (Strigari et al.

2008) implies a very large scatter in dwarf galaxy luminosity to halo mass. CDM can remain viable if the proposed baryonic solutions to CDM problems can flatten the velocity function and the luminosity function in accord with the steep halo mass function, issues that are topics of numerous studies. It would not be surprising if these baryonic processes have some stochastic elements that lead to scatter between galaxy and halo properties. These issues suggest that the statistics of void sizes and isolated galaxies could be useful not just to indicate how warm our cosmology might be, but also to learn how galaxies populate haloes. Because the astrophysics of galaxy formation is very difficult to model directly, void statistics could thus provide useful clues about low-mass galaxy formation.

Whether the scatter between galaxy luminosity and halo mass is large enough for galaxies bright enough to populate a sufficiently large volume that galaxy surveys may distinguish between WDM and CDM from void statistics is an open question. With sufficient statistics, one could determine whether the distribution of galaxies within voids and their boundaries is consistent with that expected from haloes in CDM simulations (e.g. Tinker & Conroy 2009; Hamaus et al. 2014; Ricciardelli, Quilis & Varela 2014). A potential difficulty to using small-scale void statistics as a probe of the matter power spectrum is that we have so far assumed that the L/M scatter depends only upon halo mass or V_c, i.e. that galaxy properties are independent of local environment. Environmental dependence of the galaxy–halo relation could be important. For example, voids may have a different UV heating history due to inhomogeneous reionization or other astrophysical processes (Sobacchi & Mesinger 2013), which could affect gas infall, star formation and galaxy–halo relations, perhaps washing away any effects on void statistics of the WDM versus CDM particle. In addition, later halo formation in voids makes them more prone to suppression of gas infall and star formation by UV photoheating (Hoeft et al. 2006). For success, it may be necessary to obtain constraints on the scatter between galaxy and halo properties in different environments. None the less, it is potentially significant and worthy of future exploration that the dark matter particle type may be imprinted on the cosmic web of galaxies. Forthcoming surveys results, the Large Synoptic Survey Telescope (LSST) in particular, will greatly improve our 3D positional mapping of dwarf galaxies and small voids in the local volume by allowing distance measures from stellar based techniques.

We briefly consider some possible implications that the different host halo mass ranges could have upon the galaxy populations of the two abundance-matched cosmologies. In our mock galaxy catalogue, without L/V_c scatter, galaxies populate all WDM haloes with $V_c > 13.7\,\mathrm{km\,s^{-1}}$, but the host halo population for CDM galaxies extends only to $V_c > 22.9\,\mathrm{km\,s^{-1}}$, corresponding to a factor of ∼3 in halo mass. Significant differences may thus be present in the properties of galaxies of similar luminosity due to the differing halo masses in the two cosmologies. Low-mass galaxies in the WDM cosmology would have significantly delayed star formation histories relative to CDM galaxies (Calura, Menci & Gallazzi 2014; Dayal, Mesinger & Pacucci 2015; Sitwell et al. 2014; Governato et al. 2015; Maio & Viel 2015). This delay in star formation is partly due to the delay in the formation of WDM haloes at fixed mass. In addition, CDM haloes, due to their higher masses, will more quickly surpass the mass threshold where baryon cooling by atomic transitions, and thus galaxy formation, is expected to be efficient (∼10 km s^{-1}, ∼10^4 K). However, if we instead live in a CDM universe with large L/V_c scatter, then some CDM galaxies should lie in lower mass haloes. This would imply a large scatter in star formation histories at fixed galaxy luminosities with respect to the

CDM low L/V_c scatter or WDM models. In this case, star formation may be delayed in some CDM galaxies with respect to the WDM case. These differences in galaxy properties might be detectable in local dwarfs or in the high-redshift galaxy population in the future as observations and our understanding of galaxy formation improve.

6 SUMMARY

We explore dwarf galaxy haloes in a pair of WDM and CDM cosmological simulations that differ only in that the WDM initial transfer function is suppressed on small scales to approximate the effects of a 2 keV thermal dark matter relic particle on the matter fluctuation spectrum. Abundance-matched CDM and WDM catalogues allow a fair comparison between a WDM cosmology and a CDM cosmology where low-mass galaxy formation is truncated below some halo mass (or virial velocity) threshold. In such abundance-matched CDM–WDM pairs of mock galaxy catalogues, if galaxy properties (e.g. luminosity) monotonically trace halo circular velocity, the features of the cosmic web that we consider – the pair correlation function, pair kinematics, the void volume fraction, and the isolated galaxy fraction – are very similar in WDM and CDM. This reflects the similar distributions of WDM and CDM haloes. However, in the case of a CDM universe with large scatter in the relation between galaxy and low-mass halo properties, a prospect that is well motivated to consider, CDM would contain an increased population of relatively isolated and bright galaxies. Such a population of void galaxies would be difficult to explain in a WDM universe.

REFERENCES

Allen S. W., Evrard A. E., Mantz A. B., 2011, ARA&A, 49, 409
Anderson L. et al., 2012, MNRAS, 427, 3435
Angulo R. E., Hahn O., Abel T., 2013, MNRAS, 434, 3337
Bardeen J. M., Bond J. R., Kaiser N., Szalay A. S., 1986, ApJ, 304, 15
Benson A. J., Bower R. G., Frenk C. S., Lacey C. G., Baugh C. M., Cole S., 2003, ApJ, 599, 38
Bertone G., Hooper D., Silk J., 2005, Phys. Rep., 405, 279
Bertschinger E., 2001, ApJS, 137, 1
Bhattacharya S., Heitmann K., White M., Lukić Z., Wagner C., Habib S., 2011, ApJ, 732, 122
Blanton M. R. et al., 2001, AJ, 121, 2358
Bode P., Ostriker J. P., Turok N., 2001, ApJ, 556, 93
Bond J. R., Cole S., Efstathiou G., Kaiser N., 1991, ApJ, 379, 440
Boyarsky A., Lesgourgues J., Ruchayskiy O., Viel M., 2009, Phys. Rev. Lett., 102, 201304
Boylan-Kolchin M., Bullock J. S., Kaplinghat M., 2011, MNRAS, 415, L40
Bringmann T., 2009, J. Phys., 11, 105027
Calura F., Menci N., Gallazzi A., 2014, MNRAS, 440, 2066
Colombi S., Dodelson S., Widrow L. M., 1996, ApJ, 458, 1
Conroy C., Wechsler R. H., Kravtsov A. V., 2006, ApJ, 647, 201

Crocce M., Pueblas S., Scoccimarro R., 2006, MNRAS, 373, 369
Davis M., Efstathiou G., Frenk C. S., White S. D. M., 1985, ApJ, 292, 371
Dayal P., Mesinger A., Pacucci F., 2015, ApJ, 806, 67
Diemand J., Moore B., Stadel J., 2005, Nature, 433, 389
Dunstan R. M., Abazajian K. N., Polisensky E., Ricotti M., 2011, preprint (arXiv:1109.6291)
Eisenstein D. J., Hu W., 1998, ApJ, 496, 605
Elahi P. J., Mahdi H. S., Power C., Lewis G. F., 2014, MNRAS, 444, 2333
Geha M., Blanton M. R., Masjedi M., West A. A., 2006, ApJ, 653, 240
Gill S. P. D., Knebe A., Gibson B. K., 2004, MNRAS, 351, 399
Governato F. et al., 2012, MNRAS, 422, 1231
Governato F. et al., 2015, MNRAS, 448, 792
Green A. M., Hofmann S., Schwarz D. J., 2005, J. Cosmol. Astropart. Phys., 8, 3
Hamaus N., Wandelt B. D., Sutter P. M., Lavaux G., Warren M. S., 2014, Phys. Rev. Lett., 112, 041304
Heitmann K., White M., Wagner C., Habib S., Higdon D., 2010, ApJ, 715, 104
Hoeft M., Yepes G., Gottlöber S., Springel V., 2006, MNRAS, 371, 401
Hofmann S., Schwarz D. J., Stöcker H., 2001, Phys. Rev. D, 64, 083507
Jenkins A., Frenk C. S., White S. D. M., Colberg J. M., Cole S., Evrard A. E., Couchman H. M. P., Yoshida N., 2001, MNRAS, 321, 372
Joyce M., Marcos B., 2007, Phys. Rev. D, 75, 063516
Joyce M., Marcos B., Baertschiger T., 2009, MNRAS, 394, 751
Kawasaki M., Sugiyama N., Yanagida T., 1997, Mod. Phys. Lett. A, 12, 1275
Klypin A., Kravtsov A. V., Valenzuela O., Prada F., 1999, ApJ, 522, 82
Klypin A., Karachentsev I., Makarov D., Nasonova O., 2014, preprint (arXiv:1405.4523)
Knollmann S. R., Knebe A., 2009, ApJS, 182, 608
Kravtsov A. V., Berlind A. A., Wechsler R. H., Klypin A. A., Gottlöber S., Allgood B., Primack J. R., 2004, ApJ, 609, 35
Lovell M. R. et al., 2012, MNRAS, 420, 2318
Lovell M. R., Frenk C. S., Eke V. R., Jenkins A., Gao L., Theuns T., 2014, MNRAS, 439, 300
Maio U., Viel M., 2015, MNRAS, 446, 2760
Mantz A. B. et al., 2015, MNRAS, 446, 2205
Mashchenko S., Couchman H. M. P., Wadsley J., 2006, Nature, 442, 539
Melott A. L., 1990, Comments Astrophys., 15, 1
Mo H. J., White S. D. M., 1996, MNRAS, 282, 347
Moore B., Quinn T., Governato F., Stadel J., Lake G., 1999a, MNRAS, 310, 1147
Moore B., Ghigna S., Governato F., Lake G., Quinn T., Stadel J., Tozzi P., 1999b, ApJ, 524, L19
Moster B. P., Somerville R. S., Maulbetsch C., van den Bosch F. C., Macciò A. V., Naab T., Oser L., 2010, ApJ, 710, 903
Papastergis E., Giovanelli R., Haynes M. P., Shankar F., 2015, A&A, 574, A113
Peebles P. J. E., 1980, in Treiman S. B., ed., The Large-scale Structure of the Universe. Princeton Univ. Press, Princeton, NJ, p. 435
Peebles P. J. E., 2001, ApJ, 557, 495
Peebles P. J. E., Nusser A., 2010, Nature, 465, 565
Percival W. J. et al., 2010, MNRAS, 401, 2148
Planck Collaboration XVI, 2014, A&A, 566, A54
Polisensky E., Ricotti M., 2011, Phys. Rev. D, 83, 043506
Pontzen A., Governato F., 2012, MNRAS, 421, 3464
Profumo S., Sigurdson K., Kamionkowski M., 2006, Phys. Rev. Lett., 97, 031301
Prunet S., Pichon C., Aubert D., Pogosyan D., Teyssier R., Gottloeber S., 2008, ApJS, 178, 179
Reddick R. M., Wechsler R. H., Tinker J. L., Behroozi P. S., 2013, ApJ, 771, 30
Reed D. S., Bower R., Frenk C. S., Jenkins A., Theuns T., 2007, MNRAS, 374, 2
Reed D. S., Smith R. E., Potter D., Schneider A., Stadel J., Moore B., 2013, MNRAS, 431, 1866
Ricciardelli E., Quilis V., Varela J., 2014, MNRAS, 440, 601

Rodríguez-Puebla A., Drory N., Avila-Reese V., 2012, ApJ, 756, 2
Schneider A., 2014, preprint (arXiv:1412.2133)
Schneider A., Smith R. E., Macciò A. V., Moore B., 2012, MNRAS, 424, 684
Schneider A., Smith R. E., Reed D., 2013, MNRAS, 433, 1573
Schneider A., Anderhalden D., Macciò A. V., Diemand J., 2014, MNRAS, 441, L6
Scoccimarro R., 1998, MNRAS, 299, 1097
Seljak U., Warren M. S., 2004, MNRAS, 355, 129
Sheth R. K., Tormen G., 1999, MNRAS, 308, 119
Sitwell M., Mesinger A., Ma Y.-Z., Sigurdson K., 2014, MNRAS, 438, 2664
Smith R. E., Markovic K., 2011, Phys. Rev. D, 84, 063507
Sobacchi E., Mesinger A., 2013, MNRAS, 432, L51
Stadel J. G., 2001, PhD thesis, Univ. Washington
Strigari L. E., Bullock J. S., Kaplinghat M., Simon J. D., Geha M., Willman B., Walker M. G., 2008, Nature, 454, 1096
Tikhonov A. V., Klypin A., 2009, MNRAS, 395, 1915
Tikhonov A. V., Gottlöber S., Yepes G., Hoffman Y., 2009, MNRAS, 399, 1611
Tinker J. L., Conroy C., 2009, ApJ, 691, 633
Tinker J. L., Robertson B. E., Kravtsov A. V., Klypin A., Warren M. S., Yepes G., Gottlöber S., 2010, ApJ, 724, 878
Trenti M., Smith B. D., Hallman E. J., Skillman S. W., Shull J. M., 2010, ApJ, 711, 1198
Trujillo-Gomez S., Klypin A., Primack J., Romanowsky A. J., 2011, ApJ, 742, 16
Vale A., Ostriker J. P., 2004, MNRAS, 353, 189
Vale A., Ostriker J. P., 2006, MNRAS, 371, 1173
Viel M., Lesgourgues J., Haehnelt M. G., Matarrese S., Riotto A., 2005, Phys. Rev. D, 71, 063534
Viel M., Markovivc K., Baldi M., Weller J., 2012, MNRAS, 421, 50
Viel M., Becker G. D., Bolton J. S., Haehnelt M. G., 2013, Phys. Rev. D, 88, 043502
Wadsley J. W., Stadel J., Quinn T., 2004, New Astron., 9, 137
Wang J., White S. D. M., 2007, MNRAS, 380, 93
Warren M. S., Abazajian K., Holz D. E., Teodoro L., 2006, ApJ, 646, 881
Yang L. F., Neyrinck M. C., Aragon-Calvo M. A., Falck B., Silk J., 2015, MNRAS, preprint (arXiv:1411.5029)
Zavala J., Jing Y. P., Faltenbacher A., Yepes G., Hoffman Y., Gottlöber S., Catinella B., 2009, ApJ, 700, 1779

APPENDIX A: NUMERICAL ISSUES OR HOW I LEARNED TO STOP WORRYING AND LOVE THE SIMULATION

This section addresses some of the caveats to this necessarily imperfect numerical simulation. It is possible, with sufficient computational power, to achieve per cent level accuracy for many properties of gravity-only simulations due to their relative simplicity (e.g. Heitmann et al. 2010; Reed et al. 2013). Our conservative effective halo resolution limit of 1000 particles avoids the sensitivity of low-mass haloes to numerical problems such as mass discreteness effects (e.g. Melott 1990; Joyce & Marcos 2007; Joyce, Marcos & Baertschiger 2009), time-stepping or force accuracy (e.g. Reed et al. 2013). However, WDM simulations present a particular challenge at the dwarf-galaxy scales in which we are most interested. The low amplitude of small-scale cosmological density perturbations means that artificial perturbations due to mass-discreteness or force errors are relatively larger with respect to the real perturbations.

Wang & White (2007), and later, Schneider et al. (2012), Angulo, Hahn & Abel (2013) and Lovell et al. (2014), showed that below some halo mass scale, the mass function of WDM simulations becomes dominated by spurious structure, noting that filaments fragment into small pieces separated uniformly by the mean particle separation. This results in a striking 'beads on a string'

visual effect and is clearly a numerical artefact, as confirmed by mass resolution convergence tests. By comparing the mass function in simulations with varying mass resolution, they determined that the resolved WDM mass scale increases very slowly with finer resolution, $M_{halo,min} \propto M_{particle}^{1/3}$. This convergence showed that WDM mass function is relatively robust provided that one ignores all haloes below the resolved scale. The resolved halo mass scale of CDM simulations, conversely, appears to scale much better, and generally appears to be proportional to particle mass (e.g. Jenkins et al. 2001; Warren et al. 2006; Reed et al. 2007; Trenti et al. 2010; Bhattacharya et al. 2011).

To mitigate the WDM resolution problem, we apply a spurious halo removal that requires the initial condition Lagrangian regions of particles that will end up in AHF haloes be approximately spherical, a test shown by Lovell et al. (2014) to significantly reduce artificial WDM haloes. The method consists of computing the shape parameters ($c <= b <= a$) of every proto-halo patch in the initial conditions. Haloes with unusually elongated initial patches, $c/a < 0.2$, are marked as artificial and omitted from the sample. See Lovell et al. (2014) for a detailed explanation of the method. For technical reasons, we measure the initial conditions shape of the material present in each halo at $z = 0$ rather than measuring the halo material at the epoch where the halo has reached half its maximum mass, as advocated by Lovell et al. (2014) – this would allow satellite halo initial shapes to be captured before accretion into larger haloes and subsequent stripping, which could erase the signal of spurious halo formation. We note that our spurious halo removal identifies more field objects than satellites as spurious, which may reflect that spurious haloes are formed from fragmentation of filaments in the field. We note, however, that our implementation may be less effective at detecting spurious satellite haloes that have been stripped of their outer layers, which might be expected to contribute the most to asphericity of the initial patch. Our minimum halo V_c threshold is high enough that this spurious halo removal does not impact our results, but instead confirms that we are free from significant contamination.

Fig. 1 shows the FoF and AHF mass functions, which are relatively similar to each other. The spurious halo correction to our AHF catalogue has little effect on the mass function above our mass and V_c resolution limits. Ignoring haloes below our effective sample V_c resolution limit of one thousand particles, the FoF mass function is consistent with the 'WDM prediction' mass function of (Schneider et al. 2013), based on excursion set theory. Our minimum halo mass for inclusion in the catalogue is chosen to be above the mass where artificial haloes dominate this model. Our corrected AHF mass function diverges from the WDM mass function fit approximately at our fiducial 10^3 particle minimum halo V_c and mass. This implies that haloes below our resolution limit are heavily contaminated by spurious structures whereas haloes more massive than our resolution limit are relatively uncontaminated. Importantly, the mass scale below which the mass function upturns, indicating spurious haloes, is approximately equal for AHF haloes (including subhaloes) and FoF haloes. In only one case, where high scatter between luminosity and halo V_c is assumed, do we allow haloes below threshold resolution to scatter into the catalogue. This does not pose an issue because if some of the WDM haloes are spurious in Figs 7 and 8, the differences between CDM and WDM would decrease. Instead, the WDM high scatter sample is very similar to the WDM zero scatter sample.

The halo shape exclusion criteria detects significant artificial structure beginning at approximately 200 particles. The departure from the Schneider et al. (2013) prediction, however, occurs beginning at approximately 1000 particles. This could indicate that the

halo shape test is incomplete at identifying artificial structure or that this WDM mass function prediction is too low.

We note that the spurious upturn is also apparent in the uncorrected circular velocity function of haloes (bottom panel of Fig. 1). Our conservative minimum V_c is matched to the abundance of the mass-selected catalogue, yielding a selection criteria well above the spurious upturn in the circular velocity function. We have checked the effect of removing unbound particles from FoF haloes (i.e. 'unbinding') based on each halo potential – most FoF haloes with more than ~100 particles are self-bound collections of particles, whether spurious or not.

Because the spurious halo mass range extends to masses well above the inflection point of the FoF spurious halo upturn (Angulo et al. 2013; Schneider et al. 2013; Lovell et al. 2014), it is not practical to choose a mass large enough to definitively avoid all contamination. At present, we cannot rule out the possibility that some effects of spurious WDM haloes persist at several times higher masses than our 1000 particle spurious mass threshold. Since artificial haloes live preferentially in denser regions (Schneider et al. 2013), there is a possibility for our WDM sample to have systematic biases in clustering properties. However, reassuringly, convergence occurs well below the mass scale where WDM numbers are suppressed, implying that we have captured the important physical effects of WDM above our resolution limits. Moreover, catalogues selected by minimum circular velocity, such as our mock galaxy catalogues, converge more quickly than catalogues selected by mass. Our results are converged to the ~10 per cent level for different choices of WDM minimum V_c thresholds in our catalogue, which indicates that the mass-dependent WDM spurious halo fraction is not important.

Finally, we note that for this study we have available only the present-day V_c for our haloes. Results of the SubHalo Abundance Matching technique of mapping galaxy luminosity to halo masses (e.g. Kravtsov et al. 2004; Vale & Ostriker 2004; Conroy, Wechsler & Kravtsov 2006), suggest that the peak halo mass, or its mass prior to infall before becoming a satellite, is more closely related to its present-day luminosity (e.g. Conroy, Wechsler & Kravtsov 2006; Vale & Ostriker 2006; Moster et al. 2010; Rodríguez-Puebla, Drory & Avila-Reese 2012; Reddick et al. 2013).

The issues discussed here provide some confidence that the halo mass range we have chosen is sound with regards to the relative CDM versus WDM clustering measures that we consider. Further improvement in WDM simulations may be possible with a new simulation technique by Angulo et al. (2013) that is able to largely avoid forming spurious WDM structure.

A1 Why do artificial haloes form – a toy model

We now describe a simple intuitive toy model for spurious halo formation. If one assumes that the WDM resolution scale is determined entirely by filament fragmentation, one can reproduce the empirical scaling resolution for the minimum resolved halo mass. A filament whose Lagrangian (pre-collapse) radius is equal to the free-streaming scale will have little to no cosmological power on transverse scales below this free-streaming scale. However, the formation of the filament by radial collapse of discrete masses will result in clumps of particles. If the filament is aligned with a grid axis, particles will be in clumps along the filament with spacing equal to the initial grid spacing; this is simply due to the initial grid geometry (though with noise if a 'glass-like' instead of a grid initial particle distribution is used). For filaments at other angles, the densities of these filament particles will still be highly inhomogeneous,

implying that they will readily collapse to form haloes. In CDM, this spurious fragmentation does not seem to occur because there is sufficient small-scale power that particles clump together from real cosmological perturbations.

One can estimate the mass scale at which this effect becomes strong, substituting the half-mode mass scale for the free-streaming scale (see equation 4):

$$M_{\text{fragment}} = \kappa \overline{\rho} \pi \lambda_{\text{hm}}^2 l_{\text{grid}}, \tag{A1}$$

where $l_{\text{grid}} = L_{\text{box}} N_{\text{part}}^{-1/3}$ is the initial inter-particle spacing. The empirical mass-scaling factor, $\kappa \approx 0.5$, is required to calibrate the spurious pre-collapse Lagrangian radius, which is of order λ_{hm}. Our estimate of κ is determined by the mass at which the WDM mass function begins to deviate upward from the Schneider et al. (2013) fit, $M_{\text{fragment}} \approx 500$. It would not be surprising if κ depends weakly on cosmology or mass-resolution.

This intuitive toy model recovers the empirically determined scaling of the effective WDM halo mass resolution

$$M_{\text{fragment}} \propto M_{\text{part}}^{1/3} \tag{A2}$$

below which the WDM mass function becomes a steep power due to spurious fragmentation (Wang & White 2007). Our toy model for M_{fragment} is a good match (within $\sim 2 \times$) to the artificial structure upturn for several simulations in the literature (e.g. Zavala et al. 2009; Angulo et al. 2013; Schneider et al. 2013; Lovell et al. 2014). At scales significantly larger than M_{fragment}, there should be sufficient power to promote genuine longitudinal filament fragmentation. Our one thousand particle effective halo mass resolution threshold is conservative, well above $M_{\text{fragment}} \approx 500$. M_{fragment} is generally consistent with M_{lim} of (Wang & White 2007) though the relative difference varies somewhat with free-streaming scale because we use the transfer function suppression scale (λ_{hm}) whereas they use the power spectrum peak wavenumber to estimate a fragmentation scale.

APPENDIX B: MASS-SELECTED HALOES

Throughout the paper, we select haloes by V_c because it is less vulnerable to the effects of tidal stripping and so should better correlate with galaxy properties. When one instead considers mass-selected haloes, some differences arise. Mass selection is more appropriate for studies that consider the effects of lensing substructure.

Fig. B1 (top panel) compares a mass-selected CDM and WDM halo catalogue, matched to each other by abundance, which is set by including all WDM haloes with more than 1000 particles, or $5.5 \times 10^8 \, h^{-1} \, \text{M}_\odot$, leading to a CDM abundance-matched mass limit to $1.7 \times 10^8 \, h^{-1} \, \text{M}_\odot$. The mass-selected WDM haloes have a weak ($\sim$50 per cent) clustering enhancement on scales below a few hundred h^{-1} kpc – approximately the virial radius of M_* haloes. By contrast, when V_c-selection is used for the catalogues, clustering was nearly identical (Fig. 2). We see in Fig. B2 that low-mass WDM haloes are more likely than CDM haloes to be satellites inside larger haloes, which should account for the overall clustering difference. One possible explanation for the enhancement of WDM mass-clustering is that because of the large amount of mass stripping satellites undergo, many satellites were much more massive in the past in both cosmologies. The low-mass satellite WDM population then consists of both relatively unstripped low-mass haloes that
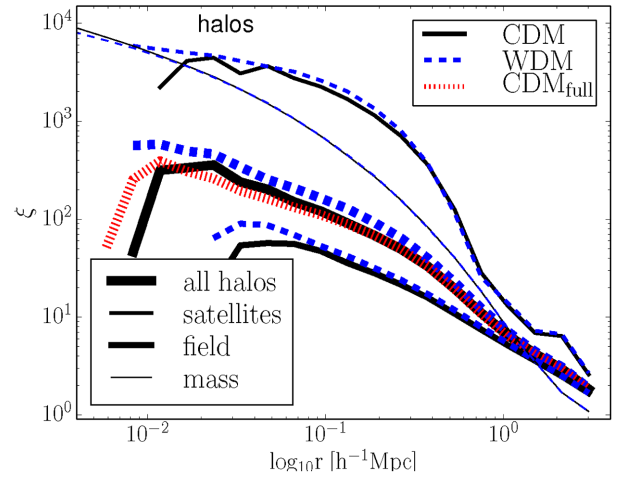
Figure B1. The correlation function of mass-selected haloes more massive than $5.5 \times 10^8 \, h^{-1} \, \text{M}_\odot$ for WDM (1000 particles) and $1.7 \times 10^9 \, h^{-1} \, \text{M}_\odot$ for CDM, self-abundance-matched. WDM mass-selected are by a small significant amount, as opposed to V_c-selected haloes wherein WDM and CDM clustering is approximately equal. CDM$_{\text{full}}$ uses the same mass threshold as the WDM sample, showing that the selection criteria has little effect on CDM halo clustering.
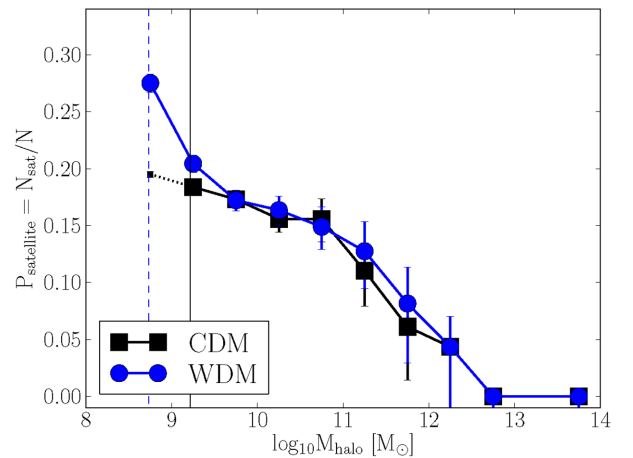
Figure B2. The probability that a mock galaxy is a satellite of a larger halo as a function of mock galaxy halo mass. A low-mass halo is more likely to be a satellite in WDM cosmology than a CDM halo of the same mass, contrary to the case for V_c-selected haloes (Fig. 3). Vertical lines denote the minimum values for inclusion for the self-abundance-matched pair of WDM and CDM mock galaxy catalogues. The likely explanation is that many low-mass WDM satellites are stripped higher mass objects (see text).

have been accreted and heavily stripped haloes that were more massive upon accretion. The stripped massive halo population is proportionally much larger in WDM than CDM because the WDM mass function is relatively flat. This does not imply more small substructures in absolute terms for WDM; low-mass halo numbers are reduced in all environments, but more so in the field.

This paper has been typeset from a TEX/LATEX file prepared by the author.