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Chau, Alice ; Mayer, Lucio ; Governato, Fabio

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# Constraining the Nature of Dark Matter with the Star-formation History of the Faintest Local Group Dwarf Galaxy Satellites

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## Abstract

$\Lambda$  warm dark matter ( $\Lambda$ WDM), realized by collisionless particles of 1–3 keV, has been proposed as an alternative scenario to  $\Lambda$ -Cold-Dark Matter ( $\Lambda$ CDM) for the dwarf galaxy scale discrepancies. We present an approach to test the viability of such WDM models using star-formation histories (SFHs) of the dwarf spheroidal galaxies (dSphs) in the Local Group. We compare their high-time-resolution SFHs with the collapse redshift of their dark halos in CDM and WDM. Collapse redshift is inferred after determining the subhalo infall mass. This is based on the dwarf current mass inferred from stellar kinematics, combined with cosmological simulation results on subhalo evolution. WDM subhalos close to the filtering mass scale, forming significantly later than CDM, are the most difficult to reconcile with early truncation of star formation ( $z \geq 3$ ). The ultra-faint dwarfs (UFDs) provide the most stringent constraints. Using six UFDs and eight classical dSphs, we show that a 1 keV particle is strongly disfavored, consistently with other reported methods. Excluding other models is only hinted for a few UFDs. Other UFDs for which the lack of robust constraints on halo mass prevents us from carrying out our analysis rigorously, show a very early onset of star formation that will strengthen the constraints delivered by our method in the future. We discuss the various caveats, notably the low number of dwarfs with accurately determined SFHs and the uncertainties when determining the subhalo infall mass, most notably the baryonic physics. Our preliminary analysis may serve as a pathfinder for future investigations that will combine accurate SFHs for local dwarfs with direct analysis of WDM simulations with baryons.

*Key words:* dark matter – galaxies: dwarf – galaxies: star formation

## 1. Introduction

The nature of dark matter still remains a mystery. Most of the observational evidence points toward cold dark matter: the  $\Lambda$  cold dark matter ( $\Lambda$ CDM) cosmology model accurately describes the large-scale structure of the universe, naturally reproduces all the properties of the cosmic microwave background and produces a scenario for galaxy formation that is receiving increasing confirmations from various observational diagnostics. Indeed, small-scale problems that used to be vexing for two decades, such as the angular momentum problem in disk galaxies or the shape of the rotation curves of gas-rich dwarf galaxies, are largely solved by baryonic physics effects, most notably the effect of feedback processes that selectively eject low angular momentum baryons and produce cores in low-mass dark halos via impulsive heating of the dark matter cusps (Binney et al. 2001; Read & Gilmore 2003; Governato et al. 2004, 2010; Pontzen & Governato 2012). However, unsolved issues remain in the number counts of dwarf galaxies, both among satellite galaxies of large spirals, such in our Local Group, and in the field. Indeed, while the dearth of faint satellite galaxies, hosted by halos with  $V_{\text{vir}} < 20 \text{ km s}^{-1}$ , can be explained by the combined effect of reionization, stellar feedback and environmental processes (Bullock et al. 2001; Brooks & Zolotov 2014; Di Cintio et al. 2014), it has been pointed out that there is still a possible excess of massive satellite halos with  $V_{\text{vir}} > 20 \text{ km s}^{-1}$  relative to the number of observed bright dwarf galaxies (Boylan-Kolchin et al. 2011), which also appear to have lower central densities than predicted by CDM. Squelching by reionization cannot provide a simple solution in the latter case since gas will

be retained within hosts of this mass (Shen et al. 2014), which actually ought to be even more massive before infall (Mayer 2010). Cosmological hydrodynamical simulations, however, suggest that feedback before infall may modify the DM density profiles enough to reduce the central densities of satellites (Brooks & Zolotov 2014; Wheeler et al. 2015), while recent simulations embedding high-resolution models of satellites within cosmological MW-sized halos do show that tidal stripping and stirring of satellites with such previously modified central DM profiles may have a strong effect on the resulting satellite population, possibly eliminating the “massive failures” (Tomozeiu et al. 2016a, 2016b). Yet, also in the field, a dearth of dwarfs with  $V_{\text{vir}} \sim 40\text{--}60 \text{ km s}^{-1}$  has been noted relative to CDM prediction (Klypin et al. 2015), which is harder to explain since one cannot rely on the combination of feedback and environmental effects.

In order to seek alternative solutions to these small-scale problems, there has recently been revived interest in other dark-matter models such as the self-interacting dark matter (SIDM) and warm dark matter (WDM) models, and more importantly in models that give rise to a truncated power spectrum of density fluctuations at scales close to those of dwarf galaxies (Sommer-Larsen & Dolgov 2001; Lovell et al. 2014; Weinberg et al. 2015). Fry et al. (2015) have used cosmological hydrodynamical simulations to show that SIDM does not modify the central density of the dark halo in dwarfs with peak velocities of less than  $30 \text{ km s}^{-1}$ , a range where baryonic feedback effects are also inefficient, while, above that, baryonic feedback dominates and leads to results almost identical to CDM, at least for a fixed  $2 \text{ cm}^2 \text{ g}^{-1}$  SIDM cross-section. It

remains to be seen how SIDM models with a velocity-dependent cross-section would behave.

By construction WDM models reduce the abundance of dwarf galaxies, possibly up to the scale of the “massive failures” as long as the particle rest mass energy is high enough (above 1 keV). Here we consider WDM models in the 1–3 keV range. Compared to CDM, the WDM particle is much lighter, and therefore has more significant free-streaming. Popular candidates for WDM are the gravitino (Gorbunov et al. 2008) and the (right-handed) sterile neutrino (Drewes 2013), with a Fermi–Dirac-like momentum distribution, which can yield the desired cut-off of the power spectrum at small scales. These are models that follow in the category of thermal relics, and this is the category that we will always implicitly assume in this paper. Most stringent constraints on WDM mass are given by the Ly $\alpha$  forest with  $m \geq 3.3$  keV to a  $2\sigma$  confidence level (Viel et al. 2013). The number counts of dwarf galaxies yield also  $m \geq 2.3$  keV (Kennedy et al. 2014), at a  $2\sigma$  confidence level too, but with further uncertainties coming from the mapping between dark matter halos and baryons.

Lovell et al. (2014) performed WDM pure  $N$ -body zoom-in simulations of MW-sized halos assuming a sterile neutrino model in the range of 1.4–2.3 keV, finding that they can naturally avoid the “too-big-to-fail” problem highlighted by Boylan-Kolchin et al. (2011). However, in order to be a credible model for galaxy formation, WDM needs to pass a number of tests. Among these are the rate and timing of assembly of the baryons inside galaxies, which are reflected in their star-formation histories (SFHs) and final stellar masses. In other words, since in a WDM scenario low-mass halos tend to form later than they do in CDM, the timing of the assembly of their baryonic components will indeed be affected. However, to what extent and whether or not this is measurable with some clear diagnostic has not yet been determined. Governato et al. (2015) have begun to address these important aspects using a small set of zoom-in hydrodynamical simulations of field dwarfs. They have shown that the later formation time can leave an imprint on the SFHs of dwarfs and even more in the properties of the stellar populations traced with color–magnitude diagrams. Inspired by these recent numerical results, we attempt a novel test of WDM models in the context of galaxy formation. The test uses SFHs of dwarf galaxy satellites to infer a range of possible formation times and compares them with the formation time expected in different WDM scenarios as opposed to CDM. We use dwarf galaxies, which are known to be highly dark-matter-dominated, and hence are appropriate nearby objects to probe different dark matter models more directly. Moreover, most dwarf spheroidals show no currently active star-formation sites and all of them have a substantial, often highly predominant, population of very old stars (e.g., Gallart et al. 2015), allowing us to directly probe the early assembly history of such objects, which is the thrust of the method that we propose here.

We compare the formation time of the dwarf dark halo inferred in CDM and WDM models by our method and the time at which the galaxy has formed 90% of its stars, namely the bulk of its stellar component. This is a timely analysis owing to the improved accuracy of SF histories of local dwarfs by means of *HST*-based high-quality color–magnitude diagrams (Weisz et al. 2014a, 2014b and the papers of the LCID collaboration Bernard et al. 2008; Aparicio et al. 2016). We determine whether or not a dwarf SFH is to be consistent with a

certain WDM scenario by requiring that its WDM halo cannot form later than the bulk of its stars.

We note that Calura et al. (2014) have also used stellar ages to constrain WDM. However, they adopted a different approach, namely they used the ability to reproduce the luminosity function of low-mass galaxies as a way to discriminate between different dark matter models. By using stellar ages of Local Group dwarfs, we adopt a much smaller sample of objects but free ourselves to uncertainties in the completeness of samples, crucial for the luminosity function at the faint end. Also focusing on local galaxies for which any property, including stellar ages, is known with much better accuracy than anywhere else, which yields in principle more robust constraints.

The paper is organized as follows. In Section 2, we describe our methodology to determine the formation time (collapse redshift) of dwarf galaxy satellites, highlighting the assumptions on which it is based. In passing, we also discuss a self-consistency check on the infall mass assignment by means of the dynamical friction timescale. In Section 3, we present our main results concerning WDM models with particles having masses in the range of 2–3 keV, focusing on the MW ultra-faint dwarfs (UFDs), which we found to be the most constraining objects in our sample. In Section 4, we present our results to place constraints on the 1 keV particles, this time using both MW UFDs and the classical dwarf spheroidal galaxies (dSphs). In Section 5, we discuss the caveats of our methods and in Section 6 we provide concise conclusions. An appendix follows, which shows the constraints on 2–3 keV models coming from the SF histories of classical dSphs and a more thorough explanation of the dynamical friction argument that we use as a further check of the range of plausible infall masses for a given dwarf galaxy.

## 2. Methods

We aim to derive the collapse redshift of a dwarf satellite halo through the available kinematic data. In CDM, we may exploit the  $c$ – $z_c$  relation to infer the collapse redshift; however, this is excluded in WDM models since the relation is not monotonic anymore. We turn to an extended Press & Schechter (EPS) model, which yields  $z_c$ – $M$  curves. Wolf et al. (2010) showed that the mass of the dwarf halos can be inferred via their kinematic data, and their method was developed further by Boylan-Kolchin et al. (2012). We start by briefly reviewing their approaches before turning to EPS in WDM. We close this section with the Weisz et al. (2014a) reconstruction of star formation.

### 2.1. Infall Mass Assignment

Wolf et al. (2010) infer the mass of the host halo of the Milky Way satellites from the 3D deprojected half-light radius  $r_{1/2}$  and the mass enclosed within it  $M_{1/2} \equiv M(r_{1/2})$ , which can be solidly approximated by

$$M_{1/2} \simeq \frac{3}{G} \sigma_*^2 r_{1/2}, \quad (1)$$

where  $\sigma_*$  is the stellar velocity dispersion, which is assumed to be flat near the half-light radius. For most profiles,  $r_{1/2}$  can be approximated by  $r_h \simeq 3/4 r_{1/2}$ , where  $r_h$  is the (two-dimensional) projected half-light radius.  $r_h$  and  $\sigma_*$  are taken from McConnachie (2012). To a good extent,  $M_{1/2}$  owes the largest

**Table 1**

Mean Value of CDM Halo Concentrations for a Given  $M_{\text{infall}}$ , Assumed to be  $M_{200}$ , in the Wolf et al. Procedure

$M_{200} [M_{\odot}]$	$3 \cdot 10^7$	$3 \cdot 10^8$	$3 \cdot 10^9$	$3 \cdot 10^{10}$
$c_{200}$	18.2	14.5	11.6	9.2

**Note.** Values are taken from Macciò et al.’s (2008) fitting formula.

contribution to the dark matter mass enclosed within the half-light radius since dSphs are dark-matter dominated at all radii. Therefore, we neglect the stellar mass and determine the total mass of the dwarf by assuming that its total mass is that of an NFW halo (Navarro et al. 1997) whose enclosed mass  $M(r)$  for  $r = r_{1/2}$  matches the observationally determined value of  $M_{1/2}$ . In doing that, we have the freedom of choosing the concentration  $c$  of the NFW profile. Therefore, in practice, we first assume a possible  $M_{200}$  and then determine if there is a  $M_{200}-c$  pair that fits the constraints by using Macciò et al.’s (2008) fitting formula. We note that it has already been shown that the NFW model is also a good model to describe the dark matter distribution in the case of a WDM universe (see Lovell et al. 2014), therefore the same procedure can be repeated in both cases. The concentration values implied by the fitting procedures are different in the two cases though, as WDM concentrations are found to be lower both by analytical models and simulations (e.g., Colín et al. 2000; Bode et al. 2001; dropping below 10 Schneider 2015). Wolf et al. consider  $M_{200}$  as a good proxy for the mass of the subhalo hosting the dwarf before infall into the primary halo of the Milky Way or M31, which we will refer to as  $M_{\text{infall}}$ . Tables 1 and 2 report the  $M_{\text{infall}}, c$  pair of values adopted for the CDM subhalo models and various WDM subhalo models considered throughout the paper and discussed later on.

Note that the dark matter profile of dwarf galaxies is likely flattened away from the NFW profile due to baryonic feedback effects (Governato et al. 2010; Teyssier et al. 2013). We will discuss later, in Section 5, how this could affect our conclusions in light of recent work based on hydrodynamical simulations. We are also aware that dwarf galaxies lose mass due to tidal mass loss during the interaction with the primary halo. This does not simply reduce to tidal truncation of the halo inward to the nominal virial radius  $R_{200}$ , which can be described with a simple exponential cut-off (Kazantzidis et al. 2004) and would not affect the determination of  $M_{\text{infall}}$  but also includes the effect of repeated tidal shocks, which can strip the subhalo much further inside, depending on initial orbit and halo concentration (Taffoni et al. 2003; Zolotov et al. 2012). The latter effect can reduce the peak circular velocity, which essentially corresponds to a reduction of the enclosed mass at radii of the order of the scale radius of the NFW halo, which in turn is of the order of the size of the luminous component of dSphs (Kazantzidis et al. 2011). This reduction can be mild or quite strong depending on the orbit of the subhalo, but also depending on whether or not the inner profile of the subhalo develops a core-like distribution due to baryonic effects, an aspect that has only recently emerged from simulations (Kazantzidis et al. 2013). Recent cosmological simulations that can model the combined evolution of the stellar and the dark matter components of dwarf galaxy

**Table 2**

Typical Halo Concentrations in Warm Model Numerical Simulations (Schneider 2015), Where  $\text{WDM}_{\chi}$  Indicates a Warm Particle of  $m = \chi$  keV

$M_{\text{infall}} [M_{\odot}]$	$10^8$	$10^9$	$10^{10}$
$c$ in WDM2	8	10	12
$c$ in WDM3	12	14	14.5

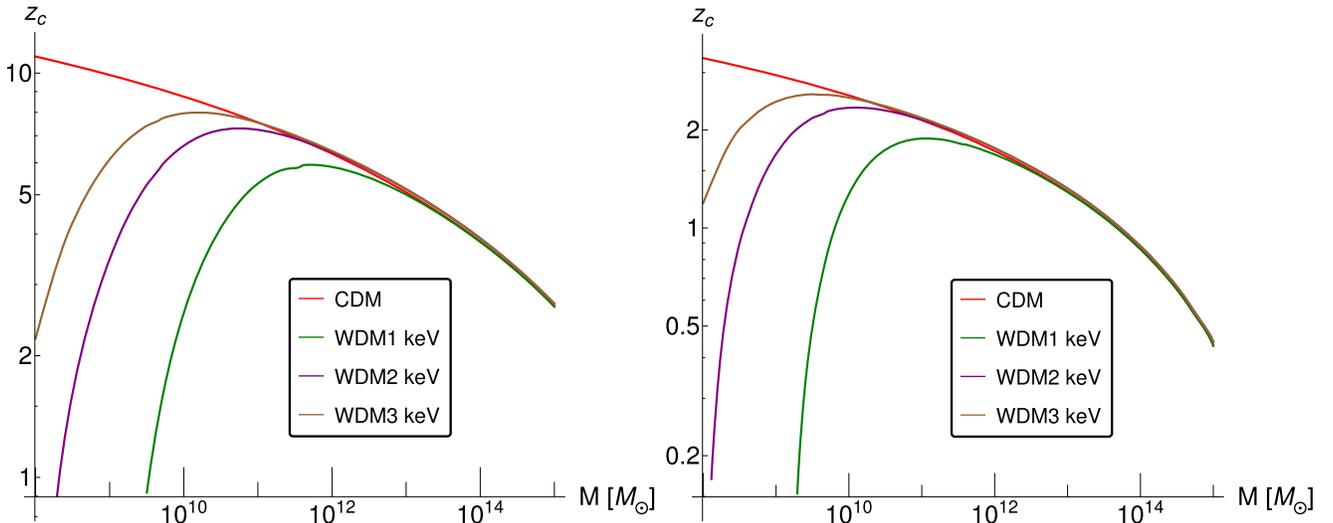
satellites of Milky-Way-sized halos, but only for a limited set of objects, show that in some cases  $M_{\text{infall}}$  can be underestimated by up to a factor of 10 with such a procedure. The largest offsets occur when the inner halo distribution is shallower than inferred from the NFW profile (Tomozeiu et al. 2016a).

To at least partially overcome at these effects, we exploit the results of Boylan-Kolchin et al. (2012), which are based on cosmological dark-matter-only simulations. These simulations of course still miss the direct mapping between radii and masses of the luminous component of the dwarf and those of its halo, and neglect baryonic effects that can change the inner dark matter density slope. We will provide a discussion of the remaining caveats at the end of the paper. Using a numerical simulation from the Aquarius project, they compute properties, such as the infall mass, of DM subhalos that are consistent with the dynamics of the brightest dSphs. They assume that the simulated subhalos are a representative sample for  $\Lambda$ CDM simulations. Though they worked only with  $\Lambda$ CDM simulations to estimate the infall mass, studies of subhalo properties carried out in WDM models (Anderhalden et al. 2013) suggest that the only important difference in applying this matching procedure would be in the halo concentration parameter since for a given CDM halo, WDM produces a slightly smaller halo and subhalo concentration than in CDM.

Furthermore, the analysis of Boylan-Kolchin et al. (2012) is performed only for classical dSphs, which automatically select fairly high  $M_{\text{infall}}$ , often above the filtering mass of WDM models (and always well above the free-streaming mass). This means that such an analysis is not expected to be constraining for WDM models since statistically there will be enough subhalos to find  $M_{200}-c$  pairs that fit the observational constraints. Nevertheless, we carry out the matching and subsequent analysis of the SFH constraints for the WDM models using the infall masses determined by Boylan-Kolchin et al. (2012) and report this in Appendix B. For the two other sets of dwarfs, which are the Andromeda ones and the UFDs of the Milky Way, which are potentially much more constraining because they include objects with much lower present-day estimated stellar and dark-halo mass, the only available method is the Wolf et al. approach, which yields only an approximate estimate of the possible  $M_{\text{infall}}$ . The main analysis presented in this paper is based on the latter method.

## 2.2. Collapse Redshift via an Extended Press–Schechter Formalism

The Bullock model is unable to reproduce the turnover in the concentration–mass relation. Schneider (2015) showed that it can be improved with an extended Press–Schechter formalism and by requiring the average collapse redshift of halos that survive until today.  $z_c$  is defined as the time when the halo has accreted a fraction  $F$  of its final mass  $M$ .



**Figure 1.** Collapse redshift for a halo that accreted 4% (left panel) and 50% (right panel) of its mass  $M$  at redshift 0 in different scenarios, where  $\text{WDM}_\chi$  keV means WDM with a particle mass  $m = \chi$  keV. The curves are normalized to the Bolshoi simulations, which determine  $z_c$  for the upper mass range  $M = 10^{11} - 10^{15} M_\odot$ .

The average growth factor of all the progenitors can be straightforwardly derived:

$$D(z_c) = \left( 1 + \sqrt{\frac{\pi}{2}} \frac{1}{\delta_{c,0}} \sqrt{S_\chi(FM) - S_\chi(M)} \right)^{-1}, \quad (2)$$

where  $S_\chi$  is the variance for a given  $\chi$  DM scenario.  $D(z)$  can be inverted to find the collapse redshift. Schneider (2015) showed that the slope of the curves  $z_c - M$  fits results from CDM simulations up to a normalization. We use here the Bolshoi simulation results as quoted by van den Bosch et al. (2013), where two criteria are presented: the collapse redshift by when the halo accreted into 4% and half of its final mass. The curves are illustrated in Figure 1.

To derive the power spectrum and hence the variance  $S_\chi$ , we use the linear transfer functions computed with the CLASS code for a 2 and 3 keV WDM particle with a Fermi–Dirac-like angular momentum distribution and the fitting function of Viel et al. (2013) for the 1 keV model. For the cosmological parameters, we use the values obtained by the Planck collaboration, i.e.,  $H_0 = 68.14$ ,  $\Omega_m = 0.304$ ,  $n_s = 0.9$ , and  $\sigma_8 = 0.827$ .

Once the total mass  $M_{\text{infall}}$  of each galaxy dwarf is known, we derive the collapse redshift with the curves drawn in Figure 1 for the considered WDM model.

### 2.3. Dynamical Friction Constraints on Infall Mass

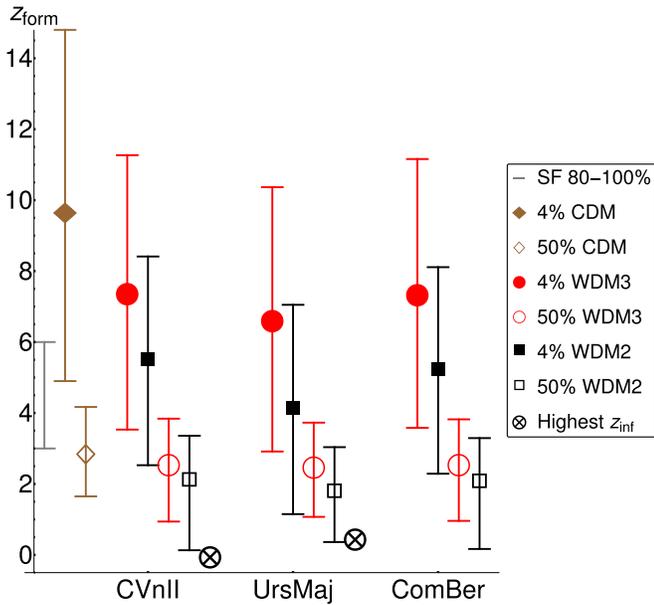
We also develop a separate argument that serves as a self-consistency check on the infall masses derived with the method just described. This is important since, as we discussed, the mass inference in WDM is uncertain by nature. We determine the highest subhalo infall masses that we could assign for WDM models from the Wolf et al.’s approach and still satisfy the natural constraint that the dynamical friction timescale at infall has to be (sufficiently) longer than the time elapsed between infall and the present time. This condition is quantitatively expressed by requiring that individual dwarf spheroidal or ultra-faint satellites have to end up at present-day galactocentric distances comparable to those at which they are found today relative to the MW or M31. Note that the

concentrations assigned in the standard procedures are on the high side of those expected in WDM models, so we can instead start by assigning a typical concentration measured in WDM simulations (Schneider 2015), which then yields halos that are 5–10 times heavier than in our default method. This choice also matches the extrapolation of the halo mass–stellar mass relation well (see Shen et al. 2014; Behroozi et al. 2013). By using a dynamical friction time estimate, we then computed the earliest infall time the galaxy could have, based on their current distance to the MW center. It turns out that from this analysis alone, it is not possible to exclude higher infall masses that would accommodate even a 1 keV model: only for an extreme parameter choice does the dynamical friction timescale become too short once one also takes into account the slowing effect of tidal mass loss on orbital decay. On the other hand, the infall masses that we obtain based on our default method are within the range of those admitted by the dynamical friction argument, so in this sense the self-consistency check is successful. The analysis is presented in Appendix C.

### 2.4. Star-formation History

Extended SFHs have only recently been determined, thanks to the high-quality color–magnitude diagrams (CMDs) produced by the *Hubble Space Telescope* (*HST*). Its instrumental uniformity has allowed Weisz et al. (2014a) to present the first consistent analysis for more than 40 dwarf galaxies of the Local Group. The SFHs are measured from CMDs using the maximum likelihood CMD fitting routine, MATCH. Not all the CMDs reach the oldest main-sequence turn-off (oMSTO) but Weisz et al. argue that only the first epoch(s) of star formation (SF) are unconstrained by their method. This property does not hamper our analysis since we are interested in the latest epochs of SF.

For the UFDs whose CMD analyses have been made, i.e., Ursa Major, Coma Berenice, Hercules, Leo IV, Bootes I, and Canes Venatici II, we use the Brown et al. (2014) conclusion: the dwarf galaxies formed 80% and 100% of their stars by  $z \sim 6$  (12.8 Gyr ago) and  $z \sim 3$  (11.6 Gyr ago), respectively. They have used ACS/*HST* CMDs reaching well below the oMSTO. We compare their result with our reference Weisz et al. (2014a) when results are available in Appendix D. The



**Figure 2.** Collapse redshift distribution for the three massive ultra-faint dwarfs of the MW indicated on the  $x$ -axis, for the different dark matter models and collapse redshift criteria indicated in the upper right corner. The redshift at which the galaxies formed 80% and all of their stars is depicted to the left in green and is valid for all dwarfs of the sample. We show both collapse redshifts at which 4% and 50% of the final mass were formed, in the different warm models, indicated by WDM $\chi$ , where  $m = \chi$  keV. We also show the highest infall redshift coming from the dynamical friction criterion discussed in Section 2.3 for Canes Venatici II and Ursa Major I; Coma Berenices, being closer to the galactic center, should have fallen at  $z > 10$ , which would be out of the frame and hence less relevant for our analysis. The error bars show the errors on the infall mass inference and the  $2\sigma$  scatter of  $z_c$  at a given mass. The shift in the  $x$ -axis has been arbitrarily chosen for the purpose of illustration.

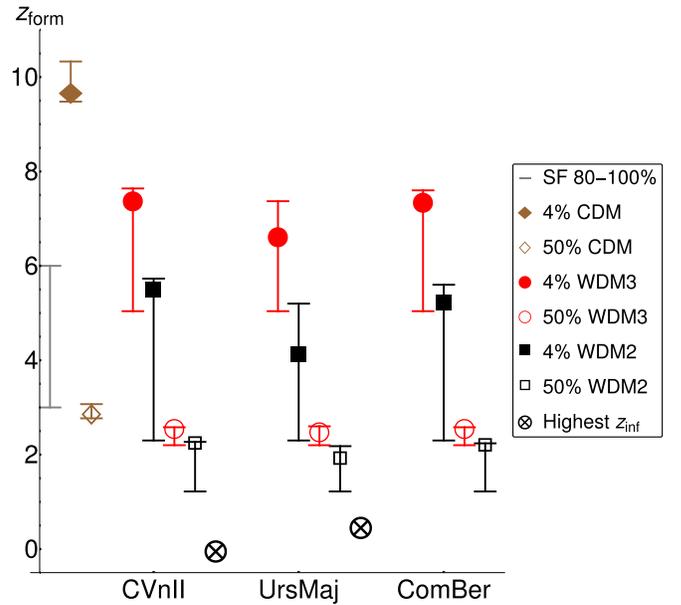
values in both methods are in favor of an early SF stopping except for CVnII. We use Brown et al. results because they are available for a more extensive sample of the UFDs.

For each dwarf galaxy for which respective data are available, we compare the collapse redshift with the redshift at which the galaxy formed 90% of its stars, except for the UFDs for which we use the time at which they have formed 80% to 100% of their stars because this is more consistent with the available stellar age resolution in the observations.

### 3. Constraining 2–3 keV WDM Models: The SF Histories of MW Ultra-faint Dwarfs

In this section, we report the main results of our work, which concern the interesting constraints on WDM scenarios obtained by using the SFHs and expected collapse times for the UFDs of the Milky Way. In Appendix B, we also show analogous results for eight bright MW dwarfs and a set of Andromeda satellites for which SF histories are available which, as we anticipated, are not providing strong constraints on WDM scenarios. The properties of the three sets of dwarf galaxies are summarized in Table 3 in Appendix A.

Our analysis is restricted to the UFDs, which have SF histories based on CMD diagrams; Ursa Major, Coma Berenice, Hercules, Leo IV, Bootes I, and Canes Venatici II. Results are shown in Figures 2–4 where, for each dwarf, we show the collapse redshift inferred from the infall mass assignment procedure of Wolf et al. and the expected time for the bulk of the star formation to have taken place, both with the (significant) error bars. The SFHs are taken from (Brown et al. 2014) and are



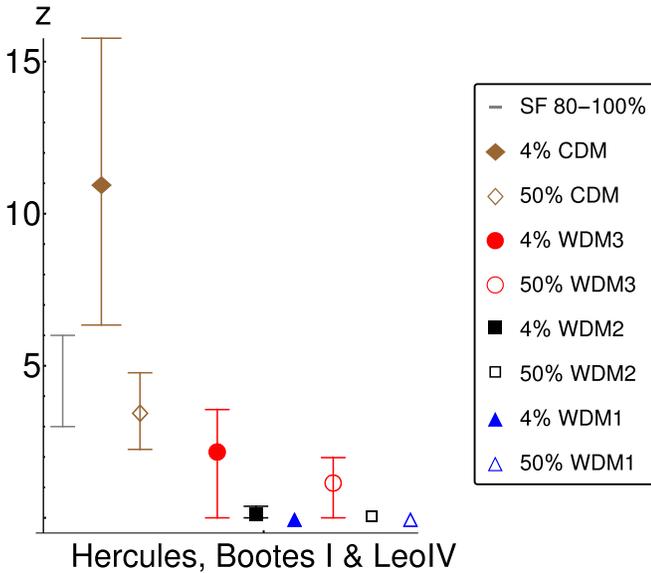
**Figure 3.** Collapse redshift distribution for the three massive ultra-faint dwarfs of the MW indicated on the  $x$ -axis, for the different dark matter models, indicated in the upper right corner. The results are reported from Figure 2. The error bars only show the errors on the infall mass inference, i.e., without the  $2\sigma$  scatter of  $z_c$  at a given mass.

valid for all dwarfs; we show it in green at the left side of the figure. Their CMDs are nearly indistinguishable, which implies that their SFHs are largely synchronized, with the agreement is estimated at the level of 1 Gyr.

For all of the dwarfs, we show the collapse redshift computed for the 2 and 3 keV WDM scenarios and for the CDM scenario. The 1 keV WDM scenario, which is already nearly ruled out by other types of constraints (e.g., the Lyman alpha forest), will be discussed separately in the next section. Note that we use two definitions of collapse redshifts, namely the redshift at which the subhalo has acquired, respectively, 4% and 50% of its final mass, both derived with the methodology described in Section 2, with the infall mass determined via Wolf et al.’s approach. The two cases are shown in Figure 1 for the various scenarios. While the 50% criterion might seem the most sensible and representative, we note that collapse redshift refers to the halo while the SFH refers to the baryons. Since it is conceivable that the baryonic component of the galaxy assembles in the inner region of the subhalo, and since even present-day field dwarf galaxies appear to reside within a few percent of the virial radius of the halo (e.g., Oh et al. 2015), it is equally reasonable to argue in favor of the 4% criterion as more representative because most of the halo mass can be gathered later than the assembly of the baryonic galaxy.

The error bars correspond to the raw  $1\sigma$  errors of the inferred  $M_{\text{infall}}$  (taken from Boylan-Kolchin et al. 2012 for the classical MW satellites, based on  $M_{1/2}$  for all other satellites) plus the  $2\sigma$  scatter of the collapse redshift at a given infall mass. The spread in concentration, which is what determines the error in the collapse redshift is that determined from CDM simulations,  $\Delta \log(c) = 0.14$ , as quoted by Wolf et al. (2010). We assume such scatter to also be relevant for the WDM scenarios, though this would require a systematic numerical study for verification.

For clarity, Figure 3 only shows the errors due to the uncertainties in the infall mass inference. In this plot, the error bars are larger for the 4% formation redshift, because the dependence



**Figure 4.** Collapse redshift distribution for the three light ultra-faint dwarfs of our sample, for the different dark matter models indicated in the upper right corner. We assume here a generic infall mass of  $10^8 M_\odot$  for the three dwarfs, following our argument of tidal loss. The redshift at which the galaxies formed 80% and all of their stars is depicted to the left in green. The errors correspond to the  $2\sigma$  confidence interval, which corresponds to the errors on the infall mass inference and the  $2\sigma$  scatter of  $z_c$  at a given mass. The constraints coming from the dynamical friction are weaker for light dwarfs,  $z > 10$ , and hence are less relevant and are not shown here. The shift in the  $x$ -axis has been arbitrarily chosen for the purpose of illustration.

of collapse redshift on mass turns out to be much steeper using the first definition relative to the second one (see Figure 1).

Among our six UFDs, our infall mass assignment procedure yields three that are hosted in very light subhalos at infall  $M_{\text{infall}} \sim 10^7$ . These are Hercules, Leo IV, and Bootes I. At that value, this would imply that the infall mass is already close to the free-streaming mass of the 2 keV model,  $4 \cdot 10^6 M_\odot$ , and hence would be strongly suppressed in such a case. The free-streaming mass of the 3 keV model is slightly lower  $\sim 10^6$ , but this model would still be marginally consistent. However, already excluding the two models at this stage would likely be erroneous since these dwarfs, if they are hosted in the smallest halos, are also the most likely to be strongly affected by tides. Using cosmological simulations augmented with high-resolution dwarf galaxy models, Tomozeiu et al. (2016a) have indeed shown that an object like Bootes I could originate from tidal stirring of a much more massive disk dwarf falling into the Milky Way halo at  $z > 2$ , especially if the halo profile was made core-like in the inner region due to baryonic effects. In those simulations, the progenitor of Bootes I could have had an infall mass  $M_{\text{infall}} > 10^8 M_\odot$ . Therefore, we decide to carry out the analysis using  $M_{\text{infall}} > 10^8 M_\odot$ . The results are shown in Figure 4 and are perhaps the strongest in this paper. While the interpretation of the results, as expected, are clearly different when using the 4% or the 50% criterion, the bottom line is that these three dwarfs alone appear to rule out the 2 keV model and render rather marginal also the 3 keV model (excluded at  $2\sigma$  for the 50% criterion, not ruled out with the 4% criterion).

For the other three UFDs, the resulting constraints are less stringent and strongly depend on whether one considers the 4% or the 50% of the infall mass as the collapse redshift criterion. The results are shown in Figures 2 and 3. For the 50% criterion, the formation time inferred in the 2, and even in the 3 keV

models is very difficult to reconcile with their SF history even when accounting for errors. We conclude that the UFDs almost exclude the 2 and 3 keV models if we use the 50% criterion. Instead, if we use the 4% criterion as an upper limit, we observe that the formation time inferred from the SF history and the collapse redshifts can overlap within the errors. We conclude that, while the 4% criterion might not exclude the 2 keV model, it still favors  $m \geq 2$  keV.

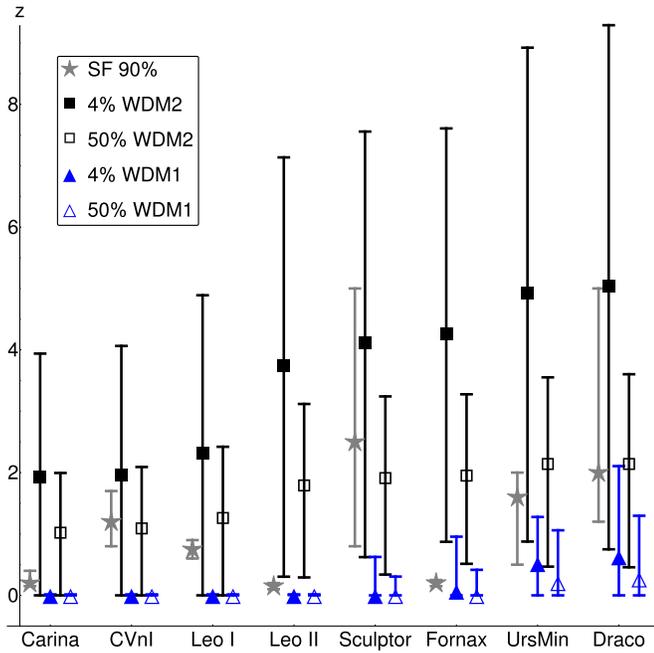
In order to highlight the quantitative difference between possible collapse redshifts for these three dwarfs in CDM and WDM scenarios, we show the results for these three dwarfs for the two scenarios in Figure 3, without the scatter due to the infall redshift uncertainty caused by the error on the concentration (this is by construction the same in WDM and CDM scenarios). As a comparison, the mean collapse time in the CDM scenario is shown on the left in brown. This value is always in agreement with the star-formation criterion, but arguably at the borderline. However, we expect this to depend on the value of the concentration adopted as a reference. Since, in CDM, there is no intrinsic limit on how early a subhalo could collapse, in principle, one is allowed to postulate that UFDs are simply a population of objects biased to form very early, and hence with concentrations that are systematically higher than average.

Therefore, we argue that in the CDM scenario there always exists a combination of parameters that fit the SFH of the galaxy. Let us assume the dwarf halo to be much lighter at infall, for example,  $10^7 M_\odot$ . This would still match the constraints from the Wolf et al. procedure and would have  $c \sim 25$  based on simulations (Schneider 2015), which would then yield a collapse redshift  $z = 10$  for the 4% criterion (Zhao et al. 2009). This is clearly early enough to accommodate any of the SF histories of UFDs.

The constraint on infall redshift coming from the dynamical friction timescale is shown in Figures 2 and 3 for the case in which the UFDs were hosted in heavy subhalos before infall, namely  $M_{\text{infall}} = 10^{10} M_\odot$ . Indeed, at such high infall masses, the collapse redshift would be at the upper end of the error bars shown in the same figures, making the WDM models marginally consistent with the timing of star formation for the 4% criterion. The resulting infall redshift in this case is  $z < 1$ . This reveals a potential tension with the fact that the same UFDs appear to have stopped forming stars at  $z > 2$ . Due to such low infall redshift, it is impossible to explain the truncation of star formation via environmental mechanisms such as ram pressure stripping and tidal mass loss (Mayer et al. 2006). One cannot invoke reionization either to stop star formation at  $z > 2$  because that would be only for  $M_{\text{vir}} < 10^8 M_\odot$  (e.g., Susa & Umemura 2004; Kaurov et al. 2015), namely below the masses considered here. Hence the SFH of such galaxies would be puzzling in a WDM scenario if they have relatively large masses, unless some non-conventional explanation is required, such as a possible assembly bias effect aided by the local ionizing background of the primary galaxy (see, e.g., Gallart et al. 2015). This suggests that they are difficult to fit with WDM without violating some constraints.

#### 4. Constraints on the 1 keV WDM Model from Star-formation Histories of LG dSphs

In order to estimate how strong the constraining power of our method is compared to other more conventional ones, we repeat the analysis of the classical and UFDs of the Milky Way with the 1 keV model. This is a WDM model that is indeed already nearly excluded by the Ly $\alpha$  forest (e.g., Viel et al. 2013). Figures 5 and 6



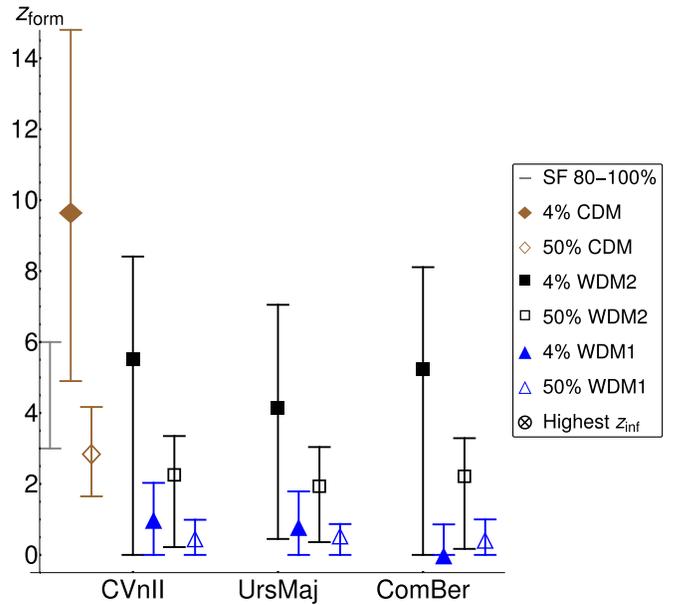
**Figure 5.** Collapse redshift distribution for the bright classical dwarfs of the MW, for the different dark matter models indicated in the upper left corner. For each dwarf, we also show the redshift at which the galaxy formed 90% of its stars to the left in green. The error bars show the  $2\sigma$  confidence interval, which corresponds to the errors on the infall mass inference and the  $2\sigma$  scatter of  $z_c$  at a given mass. The shift in the  $x$ -axis has been arbitrarily chosen for the purpose of illustration.

compare the time needed for 90% and 80%–100%, respectively, of the stars to be formed, with the collapse redshift in a WDM cosmology with a mass of 1 keV. The figures also show the expected collapse redshift in a  $2\text{ keV}$  model, allowing for the comparison of the achieved accuracy of the two cosmogonies. Here the error bars show the uncertainties on the mass inference plus the  $2\sigma$  scatter of  $z_c$  at fixed mass.

For all dwarfs of the sample, the 1 keV model is clearly excluded at  $2\sigma$ , if based on the 50% criterion. For the 4% criterion, Fornax, Ursa Minor, and Draco do not contradict the star-formation time, but the errors are too large to exclude the 1 keV model at  $2\sigma$ . However, in our whole sample of 11 dwarf galaxies, only the 3 dSphs Fornax, Ursa Minor, and Draco exhibit significant uncertainties. We deduce that the 1 keV model is excluded by our approach. This joins other, independent, constraints on WDM, such as those given by the  $\text{Ly}\alpha$  forest and the count of satellites.

## 5. Caveats

One of the main weaknesses of our approach is its high sensitivity to the infall mass, which is due to the abrupt turnover in the formation redshift–mass relation in the WDM scenario (Figure 1). Our method is thus as accurate as the determination of the infall mass. Some of the errors associated with the latter have been taken into account in our analysis, such as the variation due to variation in the assumed subhalo concentration. We have also considered to some extent the fact that the concentration itself might have been reduced by tidal shocks, making values at the lowest end of those expected based on the mass–concentration relation found in numerical simulations absolutely plausible, a notion that we have implicitly exploited when we assumed a higher infall mass for the three faintest UFDs. However, there are more caveats.



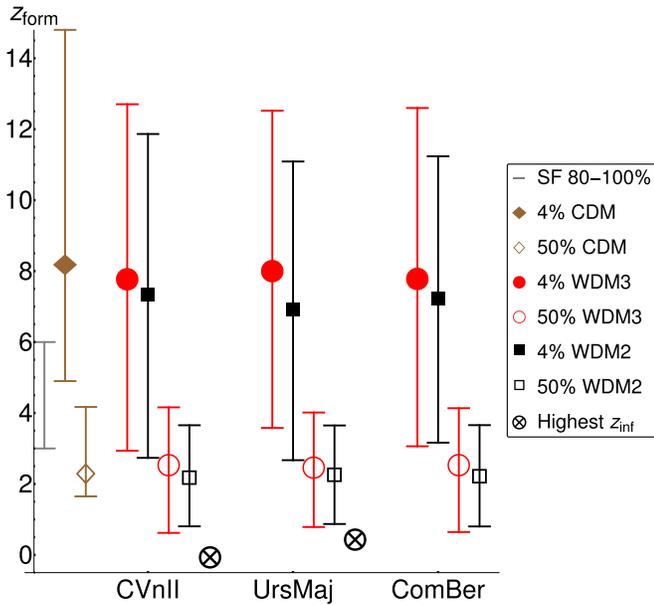
**Figure 6.** Collapse redshift distribution for the three massive UFDs of the MW, for the different dark-matter models indicated in the upper-right corner. The redshift at which the galaxies formed 80% and all of their stars is depicted to the left in green and is valid for all dwarfs of the sample. The error bars show the  $2\sigma$  confidence interval, which corresponds to the errors on the infall mass inference and the  $2\sigma$  scatter of  $z_c$  at a given mass. The shift in the  $x$ -axis has been arbitrarily chosen for the purpose of illustration.

Baryonic effects, completely neglected in our mapping of the infall mass from present-day dwarf properties, may affect the way we associate an infall mass to each galaxy when we follow the Wolf et al. procedure.

Brook & Di Cintio (2014) quantified this by adding an individual ratio  $M_*/M_{\text{halo}}$  to the NFW profile and asking how that would modify the mass distribution taking into account the effect of feedback associated with a given  $M_*$  assembled in the halo, calibrated with a set of numerical hydrodynamical simulations of dwarf galaxy formation.

Their correct profile generally associates galaxies to higher infall masses than the standard NFW profile owing to the same effect that we have considered for the tidal shock argument—the central density is reduced, which corresponds effectively to lowering the concentration of the halo and therefore increasing the value of  $M_{\text{infall}}$  that can be assigned. We estimate that on average the assigned infall mass would increase by a factor of 10, though large fluctuations can be expected on a case-by-case basis because there is not a simple linear relation between the flattening of the profile and other properties of the dwarfs such as the present-day stellar-to-halo mass. In any case, the effect goes in the direction of allowing an earlier collapse redshift in the WDM models. As an example, we analyze the borderline cases of some MW classical dSphs: Sculptor would be hosted by a subhalo having an infall mass of  $1.5 \cdot 10^{10}$  and Ursa Minor by a subhalo of  $10^{10}$ . Even the formation redshift for the 50% criterion is now not problematic, becoming 2.39 in the  $2\text{ keV}$  model, which is early enough, compared to the redshift when the galaxy formed 90% of its stars, which is just below 2.

For the UFDs, we expect the results of the 50% criterion to not change since the difference with the time of the onset of SF,  $z \geq 3$ , is too large anyway (Figure 1). On the contrary, if we choose the 4% criterion, the  $2\text{ keV}$  model easily admits now  $z > 3$  for a subhalo infall mass of  $10^{10} M_{\odot}$ . However, considering



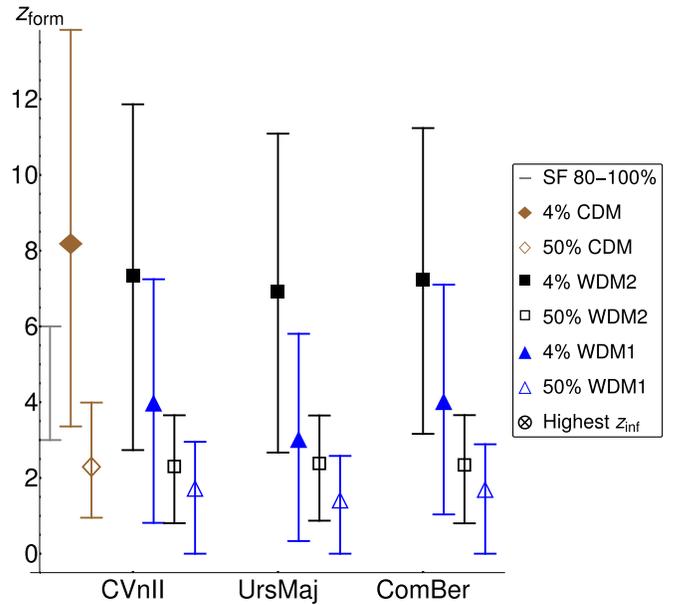
**Figure 7.** Collapse redshift distribution for the three massive UFDs of the MW if their inferred mass was 10 times heavier ( $10^{10} M_{\odot}$ , for the different dark matter models indicated in the upper right corner). The redshift at which the galaxies formed 80% and all of their stars is depicted to the left in green and is valid for all dwarfs of the sample. The error bars show the  $2\sigma$  confidence interval, which corresponds to the errors on the infall mass inference and the  $2\sigma$  scatter of  $z_c$  at a given mass. The shift in the  $x$ -axis has been arbitrarily chosen for the purpose of illustration.

that the scatter in  $z_c$  is large even in the case of halos of  $10^9 M_{\odot}$ , the results of Brook & Di Cintio do not actually weaken our analysis much for the three UFDs with the largest inferred infall masses, Ursa Major, Coma Berenice, and Canes Venatici II, see Figure 7, which is similar to Figure 2. These results do not change our previous conclusions. However, this argument only holds for the 2 and 3 keV models. For the 1 keV model, the errors that used to be small because of the low collapse value also become important for the three UFDs with large inferred infall masses (here  $10^{10} M_{\odot}$ ), see Figure 8. The 1 keV model is then not necessarily excluded as strongly, the 4% criterion thus also has large uncertainties. Generally, for heavy halos, all the models will become indistinguishable in the power spectrum, as shown by the 2 keV results, which are close to CDM. Heavy halos fit the SFHs more easily and hence make the CDM and WDM scenarios less distinguishable by our method.

However, we do not expect the UFDs to have such a high-mass halo, even before tidal stripping. Such a mass is similar to that of halos of classical dSphs, for which mass modeling is much better established, so it would be surprising if the star-formation efficiency was so much lower in UFDs (which have much fewer stars). On the other hand, tidal stripping could have reduced the mass of both dark matter and stars, but Tomozeiu et al. (2016a) showed that in extreme stripping events an object with the luminosity of Bootes can be obtained but not the many other UFDs, like ComBer, that are even fainter.

Baryonic effects could potentially weaken the conclusions for the three UFDs with the lowest infall mass  $10^8 M_{\odot}$ , Hercules, Leo IV, and Bootes I. However, for these, we have already assumed an infall mass that is 10 times higher than the standard procedure that Wolf et al. would have suggested, so our conclusions for the light UFDs do not change.

Since there are currently no high-resolution, self-consistent simulations with baryonic physics, the former remains one of the



**Figure 8.** Collapse redshift distribution for the three massive UFDs of the MW if their inferred mass was 10 times heavier ( $10^{10} M_{\odot}$ , for the different dark matter models indicated in the upper right corner). The redshift at which the galaxies formed 80% and all of their stars is depicted to the left in green and is valid for all dwarfs of the sample. The error bars show the  $2\sigma$  confidence interval, which corresponds to the errors on the infall mass inference and the  $2\sigma$  scatter of  $z_c$  at a given mass. The shift in the  $x$ -axis has been arbitrarily chosen for the purpose of illustration.

largest unknowns in any cosmological simulation and hence is probably responsible for most of the systematic errors in our model as well. Thus it is difficult to estimate an absolute error for the infall mass procedure, while we discussed how some physical processes, such as tidal stirring, dynamical friction, and galaxy formation paradigm, rather favor low infall mass.

The extended Press–Schechter approach assumes the linear perturbation growth, which is thought to be able to reproduce the statistical properties of structure formation. The full nonlinear regime would, however, add to the scatter between  $z_c$  and  $M_{\text{infall}}$ . One could opt to derive the average growth factor from the Press & Schechter theory. More WDM numerical simulations are ultimately needed. Macciò & Fontanot (2010), using zoom-in DM-only simulations, concluded that the formation and accretion times for a 2 keV WDM model do not differ significantly from CDM, though the WDM subhalos form, on average, slightly later than in CDM. How large the difference is will depend on which subhalo mass one chooses, however. Note that in their Figure 3 the difference in the number of subhalos as a function of formation time between WDM (2 keV) and CDM appears at  $z > 9-10$ , but this is done for subhalos with infall masses  $M(z_{\text{acc}}) > 10^9 M_{\odot}$ , which is high compared to what we adopt in our paper for the faintest and most constraining dwarfs (some of the UFDs). Of course, at higher mass scales, it becomes more difficult to discriminate between WDM models at a few keV and CDM. Their choice to focus on relatively large subhalos is likely forced by resolution limits in their simulations. Therefore, we believe they do not provide enough systematic information across a wide range of sun-halo masses at infall to provide a thorough comparison with our EPS calculations. Pure dark matter simulations will not be conclusive, as they are not in the CDM case (and a trivial rescaling of the baryonic effects based on the CDM simulations with hydrodynamics is also potentially flawed

since small halos grow differently and would not only have a different timing for the onset of star formation but would also possibly have a different amount and pattern of star formation over time, see, e.g., Governato et al. 2015).

There are also some uncertainties due to the fact that our method is using an inhomogeneous set of data with different intrinsic errors and systematics, while, ideally, a consistent way of deducing the star formation should be used for the whole sample.

Finally, there are uncertainties about the nature of the warm particle itself, which ultimately implies that the simple-minded notion according to which WDM is just CDM with a truncation of the power at some small enough scale is only one of the many possible realizations. The problem indeed is that bounds from structure formation actually constrain the free-streaming length, rather than the “raw” mass of the particle. Most numerical simulations of structure formation are based on the assumption that warm DM particles are produced via a mechanism that gives them a thermal spectrum. If this assumption does not hold anymore, it might become difficult to draw general conclusions. One example is the resonant thermal mechanism, which can be seen as a superposition of a WDM component and a non-thermal cold component. In the latter case, the particle could have a lower rest-mass energy than in the standard thermal relic WDM scenario, while still being consistent with the Ly $\alpha$  forest constraints (Drewes 2013). Only recent numerical simulations have thoroughly studied the structure formation with resonantly produced sterile neutrinos (Bozek et al. 2016).

## 6. Conclusion

We have introduced a new, simple method for possibly excluding WDM scenarios via the timing of the onset of star formation in the oldest dSph and ultra-faint galaxy satellites in the LG. Most of the galaxies of our sample, e.g., for which the inferred infall mass does not exceed a few  $10^9 M_\odot$ , could disfavor at  $2\sigma$  statistical level a particle of 1 keV, consistently with other results. In the 2 and 3 keV models, large uncertainties weaken our results but three UFDs could still disfavor the 2 keV model at that level. With their early SFHs and low mass, they are indeed the objects less affected by our various caveats. The simplicity of our method suggests that, with better SF data and more robust theoretical predictions of collapse times in WDM directly coming from simulations, it can potentially be critical in excluding or admitting WDM models in the critical range of a few keVs. It offers clues of what to look for in future numerical hydro-simulations of satellite galaxy formation in the WDM scenario. Improving the time resolution in the SFHs of LG dSphs, as well as increasing the number of UFDs with SF histories measured at least at the same level of time resolution of the six used in this paper, will allow us to increase the constraining power of our analysis by reducing the errors. We note that there are other dwarfs, such as Andromeda XIII (Weisz et al. 2014a), with strong evidence in favor of a very early mass assembly but which do not have available kinematics and therefore were not included in our sample. These objects can potentially strengthen the case for excluding the 2 and 3 keV models. In passing, we note that we have not included in our samples the distant dSphs Cetus and Tucana or the transition dwarfs, such as Phoenix and LGS3, for which accurate determinations of the SF histories exist (e.g., Gallart et al. 2015). This is because these are all bright dwarfs that would yield weak constraints as the classical dSphs, as their infall masses will inevitably be predicted to be in the high end of the distribution.

As we discussed, biases, and not just errors, might be hidden behind our determination of the infall mass as presented in this paper. In order to gain accuracy in the infall mass determination, the analysis could be repeated adopting dark matter density profiles that take into account the effects of baryonic physics, such as those proposed by Brook & Di Cintio (2014). However, this requires that such new profile models be calibrated with a variety of baryonic feedback recipes rather than with only specific recipes, which will eventually be accomplished. In the meantime, we believe our analysis based on NFW profiles for dark matter subhalos is able to produce a simple proof-of-concept description of the new constraining method proposed in this paper.

We thank Aurel Schneider for extensive help on the calculation of the collapse redshift based on extended Press–Schechter theory, and for providing feedback on early results of our work. We also thank Alexandre Refregier and his group members at ETH Zürich for useful comments during the development of the master’s thesis on which this paper is based. We thank the referee for the useful questions raised that improved the presentation of this work.

## Appendix A Dwarf Galaxy Properties

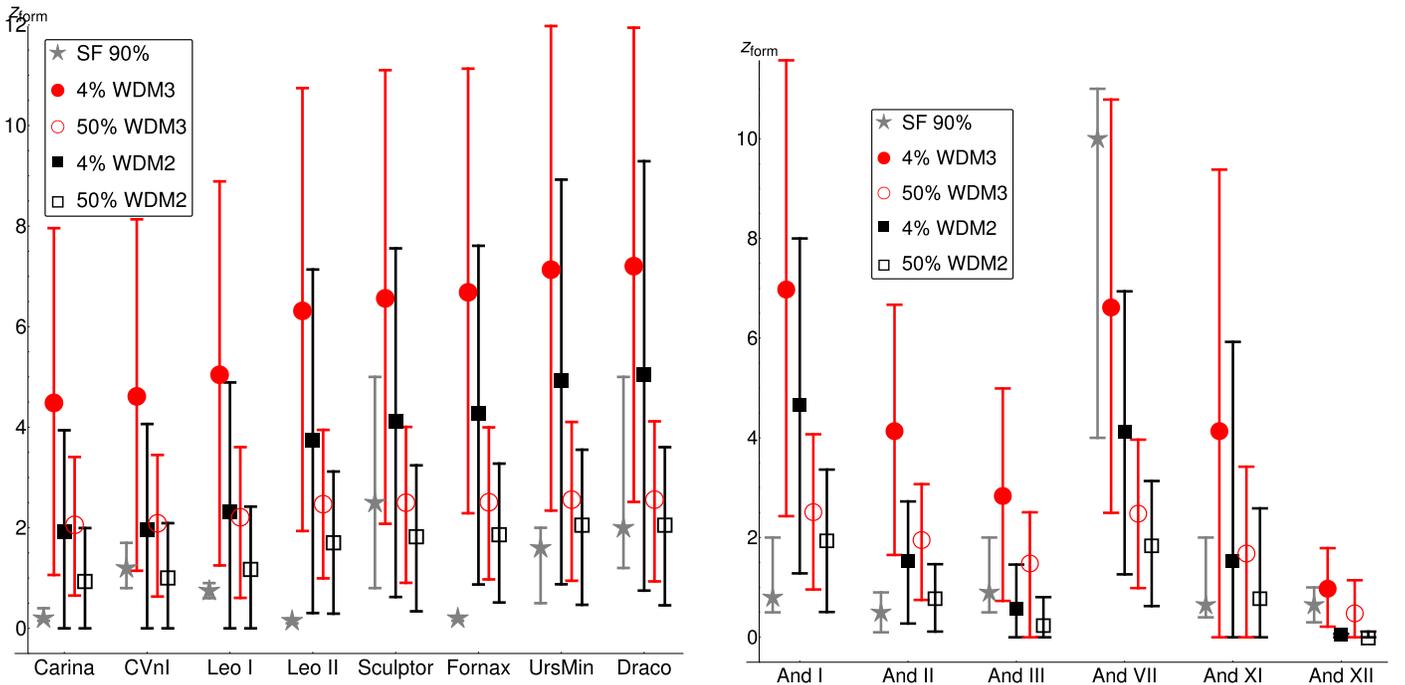
Table 3 lists several properties of the studied dwarf galaxies, such as their stellar mass, velocity dispersion, half-light radius, and dynamical mass. We used the review by McConnachie (2012).

**Table 3**

Summary of General Dwarf Galaxy Properties, Regrouped in Our Three Sets: the Milky Way Bright Classical dSphs, the MW Ultra-faint Dwarfs, and the Andromeda Satellites

Galaxy	$M_\star$ ( $10^6 M_\odot$ )	$\sigma_*$ (km s $^{-1}$ )	$r_h$ (pc)	$M_{\text{dyn}}$ ( $10^6 M_\odot$ )
Carina	0.037	6.6	250	6.3
Canes Venatici I	0.23	7.6	564	19
Leo I	5.5	9.2	251	12
Leo II	0.74	6.6	176	4.6
Sculptor	2.3	9.2	283	14
Fornax	20	11.7	710	56
Ursa Minor	0.29	9.5	181	9.5
Draco	0.29	9.1	221	11
Bootes I	0.029	2.4	242	0.81
Canes Venatici II	0.0079	4.6	74	0.91
Coma Berenices	0.0037	4.6	77	0.27
Hercules	0.037	3.7	330	2.6
Leo IV	0.019	3.3	206	1.3
Ursa Major	0.014	7.6	319	11
Andromeda I	3.9	10.6	672	44
Andromeda II	7.6	7.3	36	105
Andromeda III	0.83	4.7	479	6.1
Andromeda VII	9.5	9.7	776	42
Andromeda XI	0.049	$\leq 4.6$	157	1.9
Andromeda XII	0.031	2.6	304	1.2

**Note.** Column 1: galaxy Name. Column 2: stellar mass  $M_\star$  of the dwarf, assuming a light-to-mass ratio of 1. Column 3: observed velocity dispersion  $\sigma_*$  of the stellar component. Column 4: half-light radius  $r_h$ , corresponding to the radius that encloses half of the total density of the stars. Column 5: dynamical mass  $M_{\text{dyn}}$  of the dwarfs, corresponding to the mass enclosed within the half-light radius following Walker et al. (2009) with  $M_{\text{dyn}} = 580 r_h \sigma_*^2$ . Reference: McConnachie (2012).



**Figure 9.** Collapse redshift distribution for the Milky Way classical satellites and seven Andromeda satellites, for the different dark matter models indicated in the upper left corner. For each dwarf, we also show the redshift at which the galaxies formed 90% of their stars, depicted left in green. The shift in the x-axis has been arbitrarily chosen for the purpose of illustration.

## Appendix B

### MW Bright Satellites and Andromeda Satellites

Figure 9 shows the results for the bright satellites of the Milky Way in the left panel. The galaxies are reported in order of increasing halo mass from left to right, namely from Carina at the left corner to Draco at the right corner. In the right panel, we show the Andromeda satellites for which SFHs have been determined, here reported in order of numerical suffix from left to right. For each galaxy, the redshift at which 90% of stars are formed is plotted in green, and the collapse redshifts, i.e., the redshifts at which the halo had accreted 4% and 50% of the material, respectively, in the 2 and 3 keV models, are plotted in red and blue colors. The redshifts are deduced from the infall mass of each individual galaxy by applying the method explained in 2 and using the curves in Figure 1.

We note that, while the constraints from SFHs are not as stringent as those for the UFDs described in the main text, Draco, Sculptor, and CVnI are only marginally consistent with collapse redshifts expected in the 2 and 3 keV models. Clearly, more accurate SF histories would be beneficial. Among Andromeda satellites, And VII and And XII, only for the 3 keV model, pose a stronger constraint since at least the 50% collapse redshift criterion is inconsistent with their SFH. The population of And dwarfs is large and we only have SF histories for a subset, suggesting a potentially significant room for improvement for the predictive power of our analysis.

## Appendix C

### Dynamical Friction

A dwarf galaxy of mass  $M$  orbiting in the Milky Way typically traverses a distribution of stars and dark matter, the

latter being the dominant component. The individual stars and the dark matter distribution are deflected by the gravitating mass  $M$ , hence the density of matter behind the satellite galaxy is greater than in front of it. The wake provokes a gravitational attraction on  $M$ , which decelerates its motion. As a final consequence, the satellite is slowly falling toward the center of the galaxy host. The phenomenon is called dynamical friction.

Typically, to reach the center, the satellite needs

$$t_{\text{fric}} = \frac{19 \text{ Gyr}}{\ln \Lambda} \left( \frac{r_i}{5 \text{ kpc}} \right)^2 \frac{\sigma}{200 \text{ km s}^{-1}} \frac{10^8 M_{\odot}}{M}. \quad (3)$$

To reach a distance  $r_f \neq 0$ , the satellite needs

$$t_{\text{fric}} = \frac{19}{\ln \Lambda} \left( \frac{r_i^2 - r_f^2}{25 \text{ kpc}} \right) \frac{\sigma}{200 \text{ km s}^{-1}} \frac{10^8 M_{\odot}}{M} [\text{Gyr}]. \quad (4)$$

For an initial orbit radius with typical values of  $r_i \sim 100 \text{ kpc}$ ,  $\sigma \sim 200 \text{ km s}^{-1}$  for the MW, and  $M \sim 10^9 M_{\odot}$  for the satellite, we get  $t_{\text{fric}} \sim 110 \text{ Gyr}$ . For a satellite of that mass, the dynamical friction is not efficient since the mass does not reach the center of the MW in a time comparable to the age of the universe. However, with a heavy halo infall mass (see the discussion in the main text 2.3), the satellite experiences more friction and only needs 17 Gyr to fall into the center. Furthermore, the dispersion velocity of the MW is known to be  $\sim 200 \text{ km s}^{-1}$  at  $z = 0$  but lower at higher redshifts, typically at  $z \sim 2$ , based on simulations but also on scaling arguments in extended Press–Schechter theory. Indeed, the Milky Way had a

**Table 4**  
The Frictional Time  $t_{\text{fric}}$  for Different  $M$ ,  $\sigma$ , and  $r_f$

$\sigma = 200 \text{ km s}^{-1}$	$10^9 M_\odot$	$10^{10} M_\odot$	with $e$	$10^9 M_\odot$	$10^{10} M_\odot$
$t_{\text{fric}} \rightarrow 0 \text{ kpc}$	111 Gyr	17 Gyr		329 Gyr	50 Gyr
$t_{\text{fric}} \rightarrow 50 \text{ kpc}$	83 Gyr	12 Gyr		247 Gyr	37 Gyr
$\sigma = 100 \text{ km s}^{-1}$					
$t_{\text{fric}} \rightarrow 0 \text{ kpc}$	69 Gyr	12 Gyr		164 Gyr	24 Gyr
$t_{\text{fric}} \rightarrow 50 \text{ kpc}$	52 Gyr	9 Gyr		123 Gyr	18 Gyr
$\sigma = 50 \text{ km s}^{-1}$					
$t_{\text{fric}} \rightarrow 0 \text{ kpc}$	47 Gyr	11 Gyr		82 Gyr	12 Gyr
$t_{\text{fric}} \rightarrow 50 \text{ kpc}$	52 Gyr	8 Gyr		62 Gyr	9 Gyr

**Note.** The right part of the table displays the merging time with the tidal stripping effect, this is why the values are higher, except for very low  $\sigma \sim 50 \text{ km s}^{-1}$ , where these differences are lessened.

lower mass at earlier epochs, and hence a lower dispersion velocity.

In addition to the pure dynamical friction, the MW satellites also experience tidal stripping. As they orbit, they lose mass. As a result, their progression to the center is delayed. Colpi et al. (1999) showed that the mass decays exponentially, hence the frictional time is about a factor  $e$  higher:

$$\tau_m = 1.2 \frac{J_{\text{cir}} r_{\text{cir}}}{[GM/e] \ln(M_{\text{MW}}/M)} \epsilon^{0.4} \text{ [Gyr]}, \quad (5)$$

where  $J_{\text{cir}}$  is the angular momentum per unit mass,  $r_{\text{cir}}$  is the radius of the circular orbit, and  $\epsilon$  is an eccentricity factor, which is typically  $\sim 0.7$  for dwarfs thus  $\epsilon^{0.4} \sim 1$ . Table 4 shows  $t_{\text{fric}}$  for different  $M$ ,  $\sigma$ , and  $r_f$  and with or without the tidal stripping effect.

We infer from Table 4 that only the heavy infall masses in a young Milky Way (so that its velocity dispersion  $\sigma$  is small) experience a significant dynamical friction. For the purpose of our analysis, we look at the current distance to the center of the MW of the heaviest dwarfs and use Equation (4) to compute the time they needed to orbit from a typical infall distance of  $100 \text{ km s}^{-1}$  to their current orbital distance. Most of the dwarfs are known to be not too close to the MW center (except Sagittarius and Coma Berenices), hence the dynamical friction they experienced so far gives a shorter time than the characteristic values listed in the table above. The timescale for two of the UFDs, Canes Venatici II and Ursa Major, drops even more since their galactic-centric distances are  $\sim 100 \text{ kpc}$ , or greater. Once we computed the time, we converted it to a redshift via the standard time-redshift relation and the lookback time definition. We take the distances listed in Wolf et al. (2010) and use  $\sigma \sim 100 \text{ km s}^{-1}$ .

## Appendix D Comparison of the SFH Methods

We compare the results of Brown et al. (2014) with our reference Weisz et al. (2014a) when results are available in Table 5. In both methods the values are in favor of an early SF stopping, except for CVnII, though the set of available data is limited.

**Table 5**  
Comparison of the Two Methods of SFHs

dSph	$z_{\text{SFH}=0.9}$ (Weisz et al.)	$z_{\text{SFH}=0.8-1}$ (Brown et al.)		
CVnII	1.1	4.5	+0.6	+1.5
			-0.8	-1.5
Hercules	7.5	4.5	+0.5	+1.5
			-7.0	-1.5
LeoIV	4	4.5	+1.0	+1.5
			-3.4	-1.5

**Note.** The table shows the time at which the galaxy formed 90% of its stars, with the total uncertainties.

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