How cold is Dark Matter? Constraints from Milky Way Satellites

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ABSTRACT
We test the luminosity function of Milky Way satellites as a constrain for the nature of Dark Matter particles. We perform dissipationless high-resolution N-body simulations of the evolution of Galaxy-sized halo in the standard Cold Dark Matter (CDM) model and in four Warm Dark Matter (WDM) scenarios, with a different choice for the WDM particle mass ($m_w$). We then combine the results of the numerical simulations with semi-analytic models for galaxy formation, to infer the properties of the satellite population. Quite surprisingly we find that even WDM models with relatively low $m_w$ values (2-5 keV) are able to reproduce the observed abundance of ultra faint ($M_v < -9$) dwarf galaxies, as well as the observed relation between Luminosity and mass within 300 pc. Our results suggest a lower limit of 1 keV for thermal warm dark matter, in broad agreement with previous results from other astrophysical observations like Lyman-α forest and gravitational lensing.

Key words: galaxies: haloes – cosmology:theory, dark matter, gravitation – methods: numerical, N-body simulation

1 INTRODUCTION
The inflationary cold dark matter scenario gives a clear prediction for the initial fluctuation spectrum responsible for the formation of the Large Scale Structure in the Universe, with considerable power down to very small scales. As a consequence we expect the mass function of dark matter haloes to rise steeply towards low masses. N-body simulations have indeed revealed that in Cold Dark Matter (CDM) models, all Galaxy-sized haloes ($M_{DM} \sim 10^{12} M_\odot$) should contain a large number of embedded subhaloes that survive the collapse and virialization of the parent structure (e.g. Springel et al. 2008). Although the predicted number of substructures is in reasonable agreement with observed luminosity functions (LFs) in cluster sized haloes, in Milky Way (MW) sized haloes the number of predicted sub-haloes exceeds the number of observed satellites by at least an order of magnitude (Klypin et al. 1999, Moore et al. 1999). This tension between models and observations represents, together with the detailed reproduction of the star formation histories (e.g. Salvadori et al. 2008) and mass profiles of local dwarf galaxies (e.g. Walker et al. 2009), one of the most relevant questions for the present day theories of galaxy formation and evolution.

A possible cosmological solution to this discrepancy is to replace cold dark matter with a warm species (WDM, Bode, Ostriker & Turok 2001 and references therein). The warm component acts to reduce the small-scale power, resulting in fewer galactic subhaloes and lower halo central densities (Colín et al. 2000, 2008). One possible WDM candidate is a sterile neutrino which exhibit a significant primordial velocity distribution and thus damp primordial inhomogeneities on small scales (e.g. Hansen et al. 2002, Abazajian & Koushiappas 2006 Boyarsky, Ruchayskiy, Shaposhnikov 2009). Since ground based experiments may be far from directly studying in detail the nature and properties of the actual DM particle, it is of fundamental importance to determine astrophysical constraints on the maximum free streaming length of any warm candidate.

Limits on the mass of dark matter particles can be obtained from several astrophysical observations: theoretical phase space density studies combined with observations of stellar dynamics in Milky Way satellites (e.g. Boyanovsky, de Vega, Sanchez 2008; de Vega Sanchez & Sanchez 2009), luminosity function of high redshift QSOs (Song & Lee 2009), abundance of dwarf galaxies in the Local Volume (Zavala et al. 2009) and the size of (min)-voids around the Local Group (Tikhovov et al. 2009). Perhaps one of the most powerful tool for constraining the matter power spectrum are Lyman-α forest observations (neutral hydrogen absorption...
in the spectra of distant quasars, Narayanan et al. 2000, Viel et al. 2005). Lyman-α observations allows the possibility to studying the power spectrum down to small scales and over a large range of redshifts. Using HIRES data, a lower limit of \( m_w = 1.2 \) keV has been reported by Viel et al. (2008). Even tighter limits can be obtained combining Lyman-α observations with SDSS results (see Boyarsky et al. 2009a and references therein). These results have been recently confirmed by Miranda & Macciò (2007) in an independent estimation of lower limits for the mass of the WDM particle based on QSO lensing observations.

In the last five years our knowledge on the number and properties of satellite galaxies around our the MW has tremendously increased thanks to the results from the Sloan Digital Sky Survey (SDSS). The homogeneous sky coverage of the SDSS provided the first determination of the volume corrected MW satellite luminosity function down to luminosities as faint as 100 \( M_\odot \) (Koposov et al. 2008). Exploiting this advancement in the observational knowledge of our own Galaxy, several theoretical works have revised the problem of satellite number density, coming to the conclusion that it is possible to reconcile the observational evidences with the predictions of the standard (L)CDM scenario (e.g. Koposov et al. 2009, Macciò et al. 2009, Li et al. 2009a).

The aim of the present work is to expand the results presented in Macciò et al. 2010 (M10, hereafter), trying to use a combination of observational data and theoretical predictions to infer significant constraints on the allowed mass of any warm dark matter particle. We start from the findings of M10 and we re-simulate one of the DM haloes presented in that work, in a WDM scenario for different choices of \( m_w \).

We then combine the results with the best fit Semi Analytical Model (SAM) codes, as defined in M10, to compare the resulting prediction for the luminosity function of MW satellite in order to infer a lower limit on the WDM candidate mass.

2 SIMULATIONS AND SAMS

In this paper we combine merger trees extracted from very high resolution N-body simulations, describing the hierarchical assembly of a MW-like halo, with SAM techniques, to predict the relationship between the dark matter (sub)haloes and observable galaxy properties, allowing us to make a direct and detailed comparison with observational data from SDSS. We perform LCDM simulations and analyze them (including the definition of DM haloes and the reconstruction of their detailed merger tree) using the same tools described in full detail in M10 and we refer the reader to that paper for a more detailed discussion. In particular, for this work we select one specific halo (namely the G1 halo in M10) and we resimulate it for a suite of WDM models with particle masses \( m_w = 10, 5, 2, 1 \) keV. The dark matter particle mass is \( m_d = 4.16 \times 10^7 h^{-1} M_\odot \), and gravitational softening of 355 \( h^{-1} \) pc, with \( 3 \times 10^6 \) particles within the virial radius.

To generate initial conditions for WDM, we define a rescaled version of the CDM power spectrum using a fitting function that approximates the transfer function associated to the free streaming effect of WDM particles (Viel et al. 2005). We do not include the effect of a non zero primordial velocity dispersion for WDM particles in our simulations, this because even in our more extreme WDM model (1 keV) the rms of the random velocity component at the starting redshift of the simulations (\( z \approx 40 \)) is of the order of 2 km sec\(^{-1}\). This is much smaller than the typical velocities induced by the gravitational potential itself. Hence we do not expect that neglecting this random velocity component could alter our results. In the following, we will not show the results for the \( m_w = 10 \) keV model since it turned out to be indistinguishable from LCDM.

In order to predict the expected luminosities of satellite galaxies, we combine the results of the N-body simulations with two state-of-the-art SAMs, namely the Kang et al. (2005, 2006, see also Kang 2008) model and MORGANA (Monaco et al. 2007, updated in Lo Faro et al. 2009). In M10 we studied in full detail the effect of the various physical processes in shaping the luminosity function of MW satellites. We determined that suppression of gas infall by a photo-ionizing background, supernova feedback and tidal destruction are the most relevant processes responsible for the agreement between theoretical predictions and data. We characterize our best fit models as follows. (i) We regulate star formation efficiency in low mass haloes by shutting off gas cooling in structures with virial temperature below 10\(^4\) K (due to the inefficiency of H\(_2\) cooling). (ii) We suppress hot gas accretion in low mass haloes according to photo-ionization background, reionization and filtering mass arguments (Kravtsov et al. 2004). (iii) Stellar feedback is modeled as a function of halo circular velocity. For the purposes of this work we keep the parameters fixed at the same values in the best fit models of M10. The two SAMs provide consistent prediction with respect to the dependence of the LF on the WDM particle mass, and lead to similar conclusions. For a sake of simplicity, in the following of the paper we will focus and show only results referring to the Kang model.

3 RESULTS

The effects of WDM are clearly visible in figure 1 where we show the dark matter density map within 360 kpc for the 2 extreme models: LCDM (upper panel) and LWDM with \( m_w = 1 \) keV (lower panel). The difference in the number of substructures can be quantified by looking at the cumulative satellite mass function which is shown in figure 2. In order to identify bound subhaloes we use the AMIGA halo finder (Knollmann & Knebe 2009).

In the WDM scenario not only the total number but also the formation history of dark matter structures is expected to be different with respect to LCDM. Due to the lack of power on small scales (sub)haloes will both form and be accreted onto the main halo at different times. This effect could leave a footprint on the luminosity of the satellites hosted by the subhaloes. Subhaloes will have a different mass at the time of reionization and this will affect the extent of gas suppression. Moreover, their accretion redshift onto the main halo will be different, with relevant implications for the luminosities.

1 A more detailed and critic discussion of how the variation in SAM parameters may affect the final luminosity function can be found in M10.

2 The Amiga Halo finder (AMIGA) can be freely downloaded from http://www.popia.ft.uam.es/AMIGA
Figure 1. Dark matter density map within a sphere of radius $R = 360$ kpc. LCDM and LWDM results ($m_w = 1$ keV) are shown in the upper and lower panel respectively.

Figure 2. Subhaloes mass function in LCDM and LWDM models. Solid, (gray) dotted, (red) dot-dashed and (blue) dashed lines refer to LCDM and LWDM ($m_w = 5, 2$ and $1$ keV) respectively.

Figure 3. Shows the distribution of accretion ($z_{acc}$) and formation ($z_{form}$) redshifts, where this latter quantity is defined at the time when the halo virial temperature exceeds $10^4$ K (allowing gas cooling), for the LCDM and LWDM ($m_w = 2$ keV) models. As expected, gas cooling and star formation start later in the WDM scenario, with almost no haloes with $z_{form} = 11$ (upper panel). At the same time, they seem to have (on average) a later accretion time in WDM models with respect to LCDM (lower panel). Those two effects act on opposite ways in shaping the stellar content of the galaxy hosted by the dark matter (sub)halo, and, as we will see next, the net effect on the satellite luminosity function is almost negligible.

Our main results on the MW satellite luminosity function are presented in figure 4. In each panel, we compare the original results for the G1 halo in the LCDM cosmology (shown as a solid line) with the predictions corresponding to the different LWDM cosmologies (dotted lines). We decide to show only G1 in this work since, among the four haloes presented in M10, it was the one giving the best agreement with the observed satellite luminosity function. This makes the comparison between the observed and simulated LF in WDM models more straightforward. It is evident from the figure that the number density of satellites of different luminosity is reproduced for a WDM particle $m_w > 2$ keV as well as for the standard cosmology. Only when considering $m_w = 1$ keV we detect a significant discrepancy with the observational data, with only nine predicted satellites fainter than $M_V = -9$. This result can be used to set a lower limit on the warm dark matter particle mass ($m_w > 1$ keV), in broad agreement with the results coming from the analysis of the galaxy power spectrum.

It is worth noting the peculiar behavior of the bright end of the luminosity function. There is no satellite brighter than $M_V = -12$ in the $m_w = 5$ keV and $m_w = 2$ keV realizations, while the predictions for the $m_w = 1$ keV model are in broad agreement with the observational data. We checked that this peculiar behavior is not related to the modeling of the dynamical friction or tidal stripping in the SAMs, but it is related to the different properties of G1 merger tree in the various LWDM cosmologies. As an effect of the reduced small-scale power, the statistical properties of DM haloes change: haloes are on average less concentrated (Eke et al. 2001) and both the accretion time and the mass of a dark matter halo at that time are modified with respect to LCDM. Given the small number statistics associated to the bright end of the satellite LF for a galaxy-sized halo (less than 4 objects in total), this result is not totally unexpected. For this reason we stress that the stronger constraints come from the comparison of the faint end, where the number statistics are high enough to reveal any significant modification of the LF with respect to the LCDM result.
Figure 3. Lower panel: Distribution of accretion redshifts $z_{\text{acc}}$ for subhaloes with $M(z_{\text{acc}}) \geq 10^9 M_\odot$. Solid (black) line shows results for the LCDM model, while the dot-dashed (red) line is for the LWDM with $m_w = 2$ keV. Upper panel same as lower panel but for the formation redshift $z_{\text{form}}$, defined as the redshift at which the halo virial temperature exceeds $10^4$ K. 

Mateo et al. (1993) and Strigari et al. (2008, see also Walker et al. 2009) have noted that all satellites with luminosity between $10^3$ and $10^7 L_\odot$ have a common mass of $\sim 10^7 M_\odot$ within a radius of 300pc ($M_{0.3}$). Moreover, within this inner region, all objects result to be dark matter dominated. Macciò, Kang & Moore (2009, see also Li et al. 2009b, Okamoto & Frenk 2009) showed that this relation is not totally unexpected in a LCDM Universe. Given the expected modification in the properties of DM haloes as a function of redshift in a WDM model, it is interesting to check if our simulated satellites are still able to reproduce the observed normalization and small scatter of the $M_{0.3} - L$ relation.

Satellite luminosities are direct outputs of the SAM, while for computing $M_{0.3}$ we used the same approach detailed in Macciò, Kang & Moore (2009). At time of accretion of each satellite we compute the parameters ($r_s$ and $\delta_c$) that describe its density profile assumed to be NFW (Navarro et al. 1997, see Macciò et al. 2008 for more details). The present value of $M_{0.3}$ is then computed by integrating the density profile, under the assumption that $r_s$ and $\delta_c$ do not evolve with time. Figure 4 shows the distribution of the the mass within 300 pc as a function of the satellite luminosity. The upper panel presents results for a WDM with $m_w = 5$ keV (blue open squares), which turn out to be indistinguishable from the LCDM ones (red points) and hence in good agreement with the observational findings of Strigari et al. 2008. The lower panel shows results for our most extreme WDM model ($m_w = 1$ keV); in this case simulated satellites suggest a stronger correlation between their inner mass and luminosity which is in (slight) disagreement with the flat distribution of the observational data. Nevertheless, this discrepancy is not as strong as that seen for the luminosity function and it does not allow us to reject the $m_w = 1$ keV model. We should also point out that our determination of $M_{0.3}$ can be partially affected by neglecting primordial thermal velocities that would create a core in the density profile (Strigari et al. 2006). The expected size of the core is 100 and 8 pc for the $m_w = 1$, $m_w = 5$ keV models respectively (Strigari et al. 2006), thus for $m_w = 5$ keV our approach for computing $M_{0.3}$ could be not fully self-consistent.

4 DISCUSSION AND CONCLUSIONS

In this paper we compare the most recent observational data on the luminosity function of MW satellites with a suite of $N$-body simulations combined with SAM techniques, with the aim of constraining a possible “warm” nature for DM particle. In particular, we want to make use of the new tight observational constraints on the faint-end, which have already been proved to be of fundamental importance to test SAMs in the light of the problem of MW missing satellites (see M10).

We perform a series of $N$-body simulations with different choices for the mass of the warm dark matter particle ($m_w$), and we combine them with Semi-Analytical Models (SAMs) for galaxy formation, using the best fit solution found in M10 for the parameters describing the SAMs. We then compare the resulting statistics of MW satellites with
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Figure 5. Mass within 300 pc versus luminosity. Red dots show results from LCDM numerical simulations. The (blue) squares show results for WDM satellites for a $m_\nu$ mass of 5 keV and 1 keV in the upper and lower panel respectively. Black points with error bars are the observational results from Strigari et al. (2008).

Both the predictions for a LCDM Universe and observational data.

Our results show that we are indeed able to put a lower limit on $m_\nu$ (1 keV), which is in agreement with previous determinations based on the galaxy power spectrum and Lyman-\alpha forest observations (Viel et al. 2008, Boyarsky et al. 2009a). It is worth noting that our limits are less tight with respect to the previous determinations, as a number of caveats have to be taken into account. First, only the $m_\nu = 1$ keV realization really fails on reproducing the MW satellites luminosity function (with our “standard” choice of SAM parameters). Using a $m_\nu$ value as small as 2 keV, we still predict a luminosity function which is almost indistinguishable from the concordance LCDM cosmology. This is due to the fact that the for $m_\nu > 1$ keV, the small-scale power modifications do not affect considerably the substructures responsible for the formation of the bulk of visible MW satellites, showing an intrinsic limit of this approach with the current observational data. Moreover, the faint-end of the LF, which provides us the strongest statistical constraints, is sensitive to the details of the description of baryonic physics included in the SAMs, and in particular to the strength of stellar feedback in low-mass halo (see M10). Therefore only models that drastically failed in reproducing the data (as $m_\nu = 1$ keV) can be realistically ruled out. In the present work we only considered a very simple WDM model; it is worth notice that there are more complex and more physically motivated models discussed in the literature (e.g. warm+cold dark matter, Boyarsky et al. 2009b or composite dark matter Khlopov 2006, Khlopov & Kouvaris 2008). These scenarios deserve special studies and can provide new, interesting hints on the nature of dark matter.

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