Missing Satellites Problem: Completeness Corrections to the Number of Satellite Galaxies in the Milky Way are Consistent with Cold Dark Matter Predictions

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There is No Missing Satellites Problem

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A critical challenge to the cold dark matter (CDM) paradigm is that there are fewer satellites observed around the Milky Way than found in simulations of dark matter substructure. We show that there is a match between the observed satellite counts corrected by the detection efficiency of the Sloan Digital Sky Survey (for luminosities $L \gtrsim 340$ L$_\odot$) and the number of luminous satellites predicted by CDM, assuming an empirical relation between stellar mass and halo mass. The "missing satellites problem", cast in terms of number counts, is thus solved. We also show that warm dark matter models with a thermal relic mass smaller than 4 keV are in tension with satellite counts, putting pressure on the sterile neutrino interpretation of recent X-ray observations. Importantly, the total number of Milky Way satellites depends sensitively on the spatial distribution of satellites, possibly leading to a "too many satellites" problem. Measurements of completely dark halos below 10^8 M$_\odot$, achievable with substructure lensing and stellar stream perturbations, are the next frontier for tests of CDM.

INTRODUCTION

One outstanding problem for the cold dark matter (CDM) paradigm is the missing satellites problem (MSP). When originally formulated, the MSP highlighted the discrepancy between the number of satellites predicted in CDM simulations, numbering in the 100s, and observed in the Milky Way (MW), numbering ∼10 [1–3]. Since then, increasingly sensitive surveys have pushed the observed satellite count to ∼50 (e.g., Ref. [4–6]). Simultaneously, however, improved resolution in numerical simulations has also increased the number of predicted satellites (e.g., [7]).

A crucial step towards resolving the MSP is to correct for those satellites that have not yet been detected. Only a fraction of the MW's virial volume has been surveyed [8]. The Sloan Digital Sky Survey (SDSS), by which ultra-faint dwarfs with luminosities as low as 340 L$_\odot$ (Segue I) were discovered, covered only about a third of the sky. For the faintest dwarfs, SDSS was complete to ∼10% of the MW's virial radius [9, 10]. The observed count is thus a lower bound on the luminous MW satellite population. Completeness corrections must be applied to derive the total number of luminous MW satellites.

Fully resolving the MSP requires that the completeness-corrected galaxy count match the predicted *luminous* satellite abundance. This depends on the physics of an additional key component: baryons. There is growing evidence that not all dark matter subhalos host an observable galaxy. Galaxy evolution models [11] and star-formation histories of ultra-faint dwarfs [12] indicate that feedback processes and reionization prevent star formation. In fact, subhalos below ∼10^9 M$_\odot$ are inefficient in forming a luminous component [13, 14]. In CDM, most MW subhalos are dark.

In this work, we compare completeness corrections of the observed MW luminous galaxy population to theoretical predictions for the luminous galaxy population. We use an analytic approach to highlight specific physics, and provide a roadmap for future MW-based DM constraints. Our completeness correction is inspired by Refs. [8, 15–17], which used simulations or Bayesian techniques to estimate that the MW hosts hundreds of luminous satellites. We calculate the total number of luminous galaxies down to 340 L$_\odot$ based on the satellites observed by SDSS. For comparison, we predict the number of luminous satellites expected in CDM based on empirical scaling relations between halos and galaxies.

Successful dark matter models cannot produce just enough dark matter subhalos to match the corrected galaxy count—they must produce enough *luminous* galaxies. This places stringent constraints on warm dark matter (WDM) and sterile neutrino models, competitive with Lyman-α forest constraints [18].

Successful galaxy formation models must produce enough luminous galaxies to match the corrected galaxy count. This has implications for the mass threshold for the subhalos that host the faintest galaxies, the redshift of reionization, and the tidal stripping of subhalos.

COMPLETENESS CORRECTIONS

The total number of luminous satellites within the MW virial radius ($R_{\rm vir} = 300$ kpc) can be extrapolated from the number of observed satellites by calculating the correction factor c that converts

$$N_{\rm tot} = c(\Phi) N_{\rm obs}, \quad (1)$$

where Φ represents the set of parameters the correction depends on. This includes the survey area, survey sensitivity, and the spatial distribution of satellites.

Recasting in luminosities L, and given either a continuous observed luminosity function $dN_{\rm obs}/dL$, or set of $N_{\rm obs}$ satellites we can express Eq. 1 as

$$N_{\rm tot} = \int c(L) \frac{dN_{\rm obs}}{dL} dL \;\approx\; \sum_{i=1}^{N_{\rm obs}} c(L_i), \quad (2)$$

i.e. we integrate over the luminosity function or sum together the correction for each observed satellite. The correction is

$$c(L) = \frac{\int_{V_{\rm vir}} n(\mathbf{r})\; d\mathbf{r}}{\int_{V_{\rm obs}(L)} n(\mathbf{r})\; d\mathbf{r}} \quad (3)$$

where $n(\mathbf{r})$ is the 3D satellite distribution, $V_{\rm vir}$ the MW virial volume, and $V_{\rm obs}(L)$ the volume over which a satellite of luminosity L has been surveyed. Note that the normalization to the spatial distribution cancels, and thus the correction depends only on the shape of the spatial distribution function—not the absolute number of satellites. Eq. 3 naturally accounts for anisotropies in the satellite distribution.

Although there are hints that the luminous satellite distribution is anisotropic [4, 8, 15, 19–23], we assume it is sufficiently isotropic to be separable. The correction factor is thus

$$c(L) = c_r(L)\; c_\Omega(L) \quad (4)$$

where c_r and c_Ω are the radial and angular corrections, respectively, and

$$c_r(L) = \frac{\int_0^{R_{\rm vir}} \frac{dN}{dr}\; dr}{\int_0^{r_c(L)} \frac{dN}{dr}\; dr} \quad \text{and} \quad c_\Omega = \frac{4\pi}{\int_0^{\Omega_c} d\Omega} \quad (5)$$

and $r_c(L)$ is the radius out to which a survey covering an area Ω_c of the sky is complete for a galaxy with luminosity L. To predict the number of satellites out to a given detection limit for other surveys based on counts from an earlier survey like SDSS, one can replace $R_{\rm vir}$ with the radius out to which those surveys are complete. For SDSS, we adopt the completeness radius derived by Ref. [10], for which

$$r_c(L) = 15.7 \text{ kpc} \left(\frac{L}{100\ {\rm L}_\odot}\right)^{0.51}. \quad (6)$$

The angular correction dominates for the brightest galaxies, while the radial correction dominates for the faintest galaxies. The turnover between the two occurs at roughly L = 500 - 2000 $L_\odot$ (depending on the satellite distribution), and rapidly becomes large at lower luminosities.

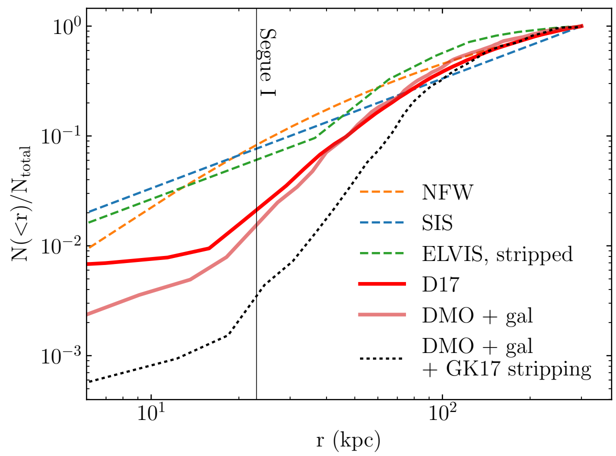

FIG. 1. Normalized radial distributions. The cumulative number of satellites within radius r, normalized to the total number of satellites at $R_{\rm vir} = 300$ kpc, is shown. Distributions marked by dashed lines are expected when satellites survive extreme tidal stripping. The solid red lines are our fiducial radial distributions, matching the MW classical satellites. The dotted black line depicts the latter distribution depleted by Ref. [24]'s tidal stripping model. See text for details.

The radial distribution of luminous satellites, which is highly uncertain, has a significant impact on the corrected galaxy count. Well-motivated radial profiles from the literature, spanning the range of uncertainty on tidal stripping and subhalo-galaxy identification, are shown in Fig. 1. The centrally concentrated NFW (with concentration $c_{-2} = 9$) [25] and SIS (singular isothermal sphere) [26] models correspond to the smooth dark matter distribution of the host. These profiles include satellites that are severely tidally stripped [8, 27], which may be considered destroyed in other contexts (or unresolved in numerical simulations). The light red line is representative of distributions generated from dark matter only (DMO) simulations, but with assumptions on which subhalos host galaxies [16, 28]. The black dotted line shows how tidal stripping by a baryonic disk reduces the number of satellites close to the center of the MW as in Ref. [24] (hereafter GK17; see also [29]). In contrast, the most severely stripped halos in Ref. [30] are shown in green. This corresponds to the hypothesis that the SDSS satellites are highly stripped remnants of larger galaxies. For our fiducial distribution, we adopt that derived in Ref. [28] (hereafter D17; shown by the dark red line), which matches the distribution of observed classical MW satellites.

We correct the number of galaxies observed through SDSS Data Release 8 (DR8) with these radial pro-

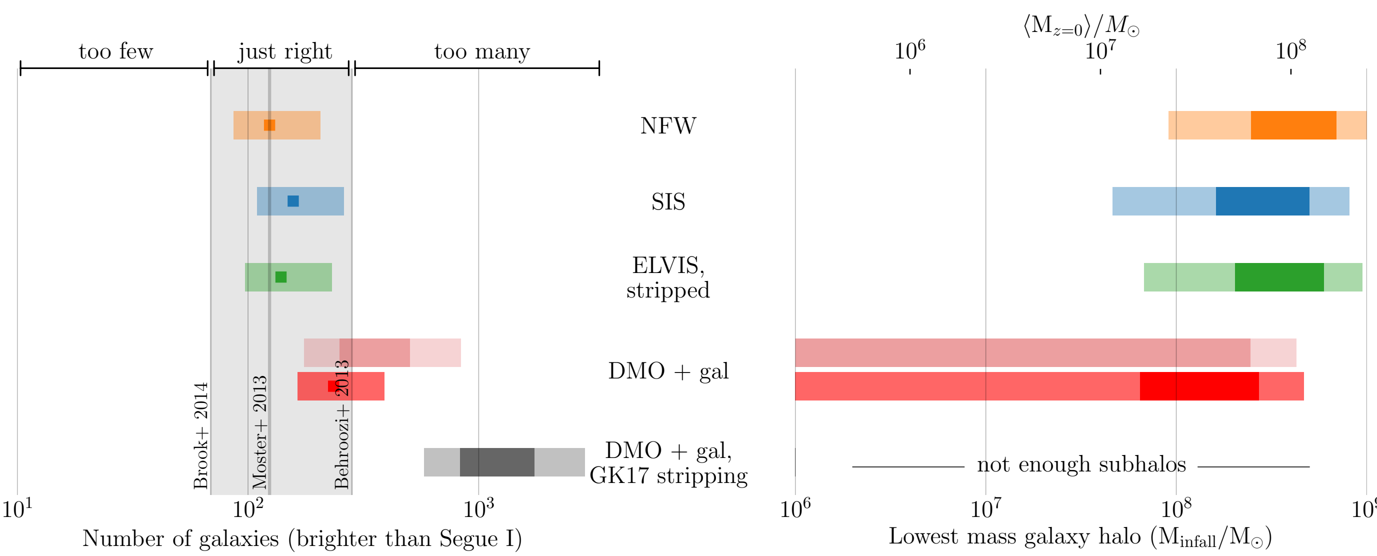

FIG. 2. The number of completeness corrected luminous satellites (left) and the infall mass of the lowest mass subhalo hosting a $L > 340L_\odot$ galaxy (right). Color match those in Fig. 1; the dark red denotes results based on D17. The light colored bands denote the uncertainty due to anisotropy (based on [15]). Left: The gray-shaded region shows the predicted number of luminous satellites expected for the MW based on the calculation described in Sec. . If the completeness-corrected count falls within these bounds, there is no MSP. Right: The width of the dark bands is set by the uncertainty on the MW mass, (1-2) $\times 10^{12}$ $M_\odot$. The light bands denote uncertainties due to anisotropy. The bottom axis shows the subhalo mass at infall, and the top axis shows the average corresponding subhalo mass today [31].

files. Our results are shown in the left panel of Fig. 2 and are listed in Tab. I. The width of the bars denote the uncertainty due to anisotropy, as measured in [15] (see supplementary material for a detailed discussion of anisotropies). In agreement with Refs. [8, 16], we find that the correction is insensitive to the MW halo mass.

Radial distributions corresponding to the hypothesis that satellites survive extreme tidal stripping (NFW and SIS) are more centrally concentrated, resulting in smaller corrected counts. Accounting for the effects of tidal stripping due to the presence of a baryonic disk as predicted by [24] produce the largest corrections.

These results are a lower limit to the number of luminous satellites of the MW. We have not included the satellites of the Large Magellanic Cloud, dwarfs with surface brightnesses $\mu \leq 30$ mag arcsec^{-2} ("stealth galaxies", e.g. [32, 33]), which are below the detection limit of SDSS DR8, although they have been found by new surveys [4, 33], and dwarfs with luminosities below Segue I's. Segue I itself accounts for ∼40% of the correction; accounting for even fainter galaxies will increase the total number significantly. The inferred luminosity function of satellites is shown in the supplementary material.

TABLE I. Completeness corrected satellite counts

		Predictions	
distribution	all sky	DES	LSST Year 1
NFW	124	11	56
SIS	157	13	69
ELVIS, stripped	139	13	65
D17	235	18	102
DMO + gal	250-503	20-28	109-198
DMO + gal + GK17	830-1740	49-69	335-614

Predictions for DES, when complete after year 5, and sensitive down to apparent magnitudes $V = 24.7$; and for LSST after year 1, down to $V = 26$.

CONSTRAINTS ON GALAXY EVOLUTION AND DARK MATTER MODELS

The calculations above set only the total number of *luminous* MW satellites that we can infer exists based on the observed dwarfs. Do the corrected counts imply that the MSP is solved? We present our fiducial calculation here, and provide details on choices and variants in the supplementary material.

The number of dark matter subhalos hosted by the MW is derived by integrating the CDM mass function, which follows the form

$$\frac{dN}{dM} = K_0 \left(\frac{M}{M_\odot}\right)^{-\alpha} \frac{M_{\rm host}}{M_\odot}. \quad (7)$$

where M denotes the mass of a subhalo at infall. The mass function based on present day (e.g. $z = 0$) subhalo masses is lower due to tidal stripping ($M(z = 0) < M$). We adopt $K_0 = 1.88 \times 10^{-3}$ $\mathrm{M}_\odot^{-1}$ and $\alpha = 1.87$ as in D17. The total number of subhalos above a threshold $M_{\rm min}$ is thus

$$N_{\rm sub} = \int_{M_{\rm min}}^{M_{\rm host}} \frac{dN}{dM}\, dM. \tag{8}$$

Not all subhalos are believed to host galaxies [34–37]. Given the fraction of subhalos of a given mass that host a luminous galaxy, $f_{\rm lum}(M)$, we can derive the total number of luminous galaxies

$$N_{\rm gal} = \int_{M_{\rm min}}^{M_{\rm host}} \frac{dN}{dM} f_{\rm lum}(M) dM. \tag{9}$$

The luminous fraction is a strong function of reionization redshift. $z_{\rm re}$, and the survival criteria [38]. We adopt the relation by D17 (see their Fig. 3), which assumes $z_{\rm re} = 9.3$ and a generous baryon survival criterion, which requires $v_{\rm max} = 9.5$ km/s (the peak of the circular velocity curve) at $z < z_{\rm re}$ and $v_{\rm peak} = 23.5$ km/s at $z > z_{\rm re}$. Adopting a less generous criterion to match other work in the literature [39–41] drops the predicted number of luminous satellites by a factor 2—our results thus represent an upper bound.

For comparison with our completeness correction, which only includes galaxies brighter than Segue I, we adopt $M_{\rm min} = M_{\rm SegI}$. We derive its total stellar mass by assuming a stellar mass-to-light ratio of 2 (i.e. $M_*^{\rm SegI} = 680$ $\mathrm{M}_\odot$), expected for an ancient metal-poor stellar population with a Kroupa initial mass function [42, 43]. To derive Segue I's halo mass, we make use of the fact that a galaxy's stellar mass is empirically tightly correlated with halo mass [44, 45], a relation known as the stellar-mass–halo-mass (SMHM) relation. SMHM relations have only been calibrated for stellar masses greater than $M_* \sim 10^8 M_\odot$ [46, 47], but hydrodynamic simulations indicate that extrapolations to low masses are reasonable [48]. We adopt three SMHM relations that capture the diversity of SMHM relations and their scatter [46, 47, 49], which gives a large range for $M_{\rm SegI} = 8\times10^6$ to 7×10^8 $\mathrm{M}_\odot$. The SMHM of Moster et al. [47] best matches hydrodynamic simulations of isolated galaxies [48, 50].

The resultant number of subhalos and galaxies assuming a MW mass of 1.5×10^{12} $\mathrm{M}_\odot$ is shown in Fig. 3. The solid line denote the number of luminous satellites predicted by CDM; the dashed line shows the total number of subhalos. Down to $M_{\rm min} = 10^7$ $\mathrm{M}_\odot$, there exists ∼2600 total subhalos and 280 galaxies, implying that only ∼10% of such subhalos are luminous. The number of luminous satellites down to $M_{\rm SegI}$ for our range of SMHM relations is shown by the gray-shaded regions in Fig. 3 and the left-hand panel of Fig. 2. The SMHM relation of Moster et al. [47] predicts ∼120 galaxies.

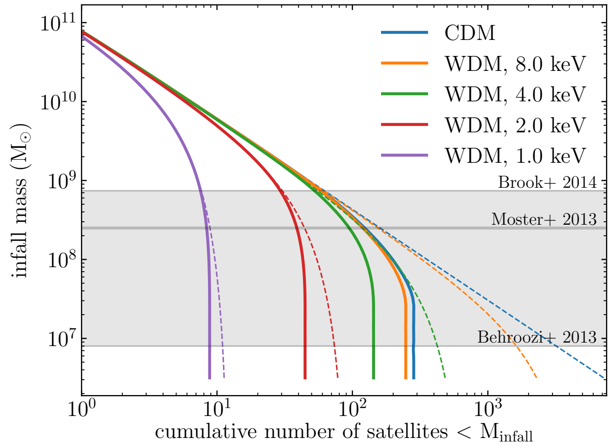

FIG. 3. The number of luminous (solid) and total (dashed) subhalos allowed by CDM and WDM mass functions for a given lower bound on the lowest mass subhalo, assuming a MW mass of 1.5×10^{12} $\mathrm{M}_\odot$. The number of luminous subhalos is modeled as in D17, assuming a reionization redshift $z_{\rm re} = 9.3$ [51]. The grey band shows SHMH predictions for the infall mass of Segue I.

We now have all the tools required to match the theoretical and completeness-corrected galaxy counts. Our key result is shown in the left-hand plot of Fig. 2. The number of galaxies more luminous than Segue I predicted in CDM matches the completeness-corrected observations for even the most conservative radial profile models (i.e. lies inside the gray-shaded region). Moreover, some radial profiles lead to corrected counts that exceed the predicted range. This is exacerbated if the reionization of the Local Group occurs earlier (see supplementary material). We call this the "too many satellites" problem.

These results have implications for galaxy formation theory and dark matter physics.

Subhalo minimum mass. Matching the corrected counts to CDM predictions gives a minimum subhalo mass for galaxies as faint as Segue I, as suggested by Ref. [17]. This is shown on the right panel of Fig. 2. The bars denote the uncertainty on the lowest mass galaxy halo due to uncertainties on the MW mass, which we allowed to range from $(1-2)\times$ 10^{12} $\mathrm{M}_\odot$. As the transition from mostly bright to mostly dark subhalos (e.g. $f_{\rm lum} = 0.5$) occurs at $\sim10^8$ $\mathrm{M}_\odot$ in our reionization model, the lowest mass galaxy is near that mass threshold. Counts accounting for tidal stripping as in GK17 predict even smaller masses. The tidal-stripping-induced uncertainty on the completeness correction is the single-biggest driver of uncertainty in the subhalo minimum mass.

Dark matter model. Dark matter models with suppressed matter power spectra [52–64], such as WDM, must reproduce *at a minimum* the completeness-corrected counts. We briefly sketch the constraints we can place on WDM models with our corrected counts. This calculation is not intended to be a rigorous derivation of WDM constraints, but an illustration of possible limits when corrected counts are taken into account.

The radial distribution of WDM satellites closely follows CDM [65], and thus the corrected counts derived above applies. To obtain the number of luminous satellites predicted by WDM, an identical analysis as in the previous section can be performed with the WDM mass function, which can be obtained from the CDM mass function by multiplying the factor

$$\frac{dn_{\rm WDM}}{dn_{\rm CDM}} = \left(1 + \frac{M_{\rm hm}}{M}\right)^{-\beta}, \qquad (10)$$

where $\beta = 1.16$, M is the infall mass, and $M_{\rm hm}$ is the half-mode mass quantifying the suppression scale of the matter power spectrum [66]. We again use D17's reionization cutoff to estimate the number of luminous galaxies. This is a conservative overestimate, as WDM halos tend to form, and form stars, later than in CDM [67], and because some of the satellites will be fainter than Segue I. In Fig. 3, we show the number of satellites predicted by WDM mass functions for thermal relic particle masses ranging from 1-8 keV. If the MW has 120-150 galaxies brighter than Segue I, thermal relics below ∼4 keV are ruled out, although this depends on the MW halo mass ([53], and see supplementary material). This implies that the 7 keV sterile neutrino is in tension with satellite counts. More robust limits require the machinery of Ref. [17], who find a 95% lower limit of 2.9 keV.

CONCLUSIONS

Since the MSP was first identified, several advances in our understanding of dwarf galaxy evolution have reduced the severity of the missing satellites problem. Star formation in low-mass halos has been demonstrated to be suppressed by reionization and feedback. The discovery of many new dwarfs below the luminosity limit of the classical dwarfs have also closed the gap, as has the understanding that completeness corrections for the new dwarfs are large. In this Letter, we show that such corrections imply that the number of satellite galaxies that inhabit the Milky Way is consistent with the number of luminous satellites predicted by CDM down to halo masses of $\sim 10^8$ $M_\odot$. There is thus no missing satellites problem. If anything, there may be a "too many satellites" problem. The major remaining uncertainty is the radial distribution of satellites, stemming from the uncertainty in tidal stripping. Our result pushes the scale for tests of CDM below $10^8 M_\odot$ in infall mass, or $\sim 10^7$ $M_\odot$ in present day subhalo mass. Methods that do not rely on baryonic tracers, like substructure lensing [68–70] or stellar stream gaps [71], are required to test the predictions of CDM below this scale. The implications for dark matter models are significant. WDM theories equivalent to having thermal relic particle masses below 4 keV are in tension with MW satellite counts.

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[1] G. Kauffmann, S. D. M. White, and B. Guiderdoni, MNRAS **264**, 201 (1993).
[2] A. Klypin, A. V. Kravtsov, O. Valenzuela, and F. Prada, ApJ **522**, 82 (1999), astro-ph/9901240.
[3] B. Moore, S. Ghigna, F. Governato, G. Lake, T. Quinn, J. Stadel, and P. Tozzi, ApJ **524**, L19 (1999), astro-ph/9907411.
[4] A. Drlica-Wagner *et al.*, ApJ **813**, 109 (2015).
[5] K. Bechtol *et al.* (DES), Astrophys. J. **807**, 50 (2015), arXiv:1503.02584 [astro-ph.GA].
[6] S. E. Koposov, V. Belokurov, G. Torrealba, and N. W. Evans, Astrophys. J. **805**, 130 (2015), arXiv:1503.02079 [astro-ph.GA].
[7] V. Springel, J. Wang, M. Vogelsberger, A. Ludlow, A. Jenkins, A. Helmi, J. F. Navarro, C. S. Frenk, and S. D. M. White, MNRAS **391**, 1685 (2008), arXiv:0809.0898.
[8] O. Newton, M. Cautun, A. Jenkins, C. S. Frenk, and J. Helly, ArXiv e-prints (2017), arXiv:1708.04247.
[9] S. Koposov, V. Belokurov, N. W. Evans, P. C. Hewett, M. J. Irwin, G. Gilmore, D. B. Zucker, H. Rix, M. Fellhauer, E. F. Bell, and E. V. Glushkova, ApJ **686**, 279 (2008), arXiv:0706.2687.
[10] S. M. Walsh, B. Willman, and H. Jerjen, Astron. J. **137**, 450 (2009), arXiv:0807.3345.
[11] J. S. Bullock, A. V. Kravtsov, and D. H. Weinberg, ApJ **539**, 517 (2000), astro-ph/0002214.
[12] T. M. Brown, J. Tumlinson, M. Geha, J. D. Simon, L. C. Vargas, D. A. VandenBerg, E. N. Kirby, J. S. Kalirai, R. J. Avila, M. Gennaro, H. C. Ferguson, R. R. Muñoz, P. Guhathakurta, and A. Renzini, ApJ **796**, 91 (2014), arXiv:1410.0681.
[13] C. Wheeler, J. I. Phillips, M. C. Cooper, M. Boylan-Kolchin, and J. S. Bullock, MNRAS **442**, 1396 (2014), arXiv:1402.1498.
[14] S. Shen, P. Madau, C. Conroy, F. Governato, and L. Mayer, ApJ **792**, 99 (2014), arXiv:1308.4131.
[15] E. J. Tollerud, J. S. Bullock, L. E. Strigari, and B. Willman, ApJ **688**, 277 (2008), arXiv:0806.4381.
[16] J. R. Hargis, B. Willman, and A. H. G. Peter, ApJ **795**, L13 (2014), arXiv:1407.4470.

[17] P. Jethwa, D. Erkal, and V. Belokurov, MNRAS **473**, 2060 (2018), arXiv:1612.07834.
[18] V. Iri *et al.*, Phys. Rev. **D96**, 023522 (2017), arXiv:1702.01764 [astro-ph.CO].
[19] D. Lynden-Bell, The Observatory **102**, 202 (1982).
[20] S. R. Majewski, ApJ **431**, L17 (1994).
[21] N. I. Libeskind, C. S. Frenk, S. Cole, J. C. Helly, A. Jenkins, J. F. Navarro, and C. Power, MNRAS **363**, 146 (2005), astro-ph/0503400.
[22] K. Bechtol *et al.*, ApJ **807**, 50 (2015), arXiv:1503.02584.
[23] S. E. Koposov, V. Belokurov, G. Torrealba, and N. W. Evans, ApJ **805**, 130 (2015), arXiv:1503.02079.
[24] S. Garrison-Kimmel, A. Wetzel, J. S. Bullock, P. F. Hopkins, M. Boylan-Kolchin, C.-A. Faucher-Giguère, D. Kereš, E. Quataert, R. E. Sanderson, A. S. Graus, and T. Kelley, MNRAS **471**, 1709 (2017), arXiv:1701.03792.
[25] J. F. Navarro, C. S. Frenk, and S. D. M. White, ApJ **462**, 563 (1996), astro-ph/9508025.
[26] A. M. Nierenberg, M. W. Auger, T. Treu, P. J. Marshall, and C. D. Fassnacht, ApJ **731**, 44 (2011), arXiv:1102.1426 [astro-ph.GA].
[27] J. Han, S. Cole, C. S. Frenk, and Y. Jing, MNRAS **457**, 1208 (2016), arXiv:1509.02175.
[28] G. A. Dooley, A. H. G. Peter, T. Yang, B. Willman, B. F. Griffen, and A. Frebel, MNRAS **471**, 4894 (2017), arXiv:1610.00708.
[29] E. D'Onghia, V. Springel, L. Hernquist, and D. Keres, ApJ **709**, 1138 (2010), arXiv:0907.3482.
[30] S. Garrison-Kimmel, M. Boylan-Kolchin, J. S. Bullock, and K. Lee, MNRAS **438**, 2578 (2014), arXiv:1310.6746 [astro-ph.CO].
[31] F. C. van den Bosch, X. Yang, H. J. Mo, and P. Norberg, MNRAS **356**, 1233 (2005), astro-ph/0406246.
[32] J. S. Bullock, K. R. Stewart, M. Kaplinghat, E. J. Tollerud, and J. Wolf, ApJ **717**, 1043 (2010), arXiv:0912.1873.
[33] G. Torrealba, S. E. Koposov, V. Belokurov, and M. Irwin, MNRAS **459**, 2370 (2016), arXiv:1601.07178.
[34] T. Sawala, C. S. Frenk, A. Fattahi, J. F. Navarro, T. Theuns, R. G. Bower, R. A. Crain, M. Furlong, A. Jenkins, M. Schaller, and J. Schaye, MNRAS **456**, 85 (2016), arXiv:1406.6362.
[35] C. M. Simpson, R. J. J. Grand, F. A. Gómez, F. Marinacci, R. Pakmor, V. Springel, D. J. R. Campbell, and C. S. Frenk, ArXiv e-prints (2017), arXiv:1705.03018.
[36] A. J. Benson, C. S. Frenk, C. G. Lacey, C. M. Baugh, and S. Cole, MNRAS **333**, 177 (2002), astro-ph/0108218.
[37] R. S. Somerville, ApJ **572**, L23 (2002), astro-ph/0107507.
[38] N. Y. Gnedin, ApJ **542**, 535 (2000), astro-ph/0002151.
[39] C. M. Simpson, G. L. Bryan, K. V. Johnston, B. D. Smith, M.-M. Mac Low, S. Sharma, and J. Tumlinson, MNRAS **432**, 1989 (2013), arXiv:1211.1071 [astro-ph.GA].
[40] A. M. Brooks and A. Zolotov, ApJ **786**, 87 (2014), arXiv:1207.2468.
[41] B. W. O'Shea, J. H. Wise, H. Xu, and M. L. Norman, ApJ **807**, L12 (2015), arXiv:1503.01110.
[42] P. Kroupa, MNRAS **322**, 231 (2001), astro-ph/0009005.
[43] N. F. Martin, J. T. A. de Jong, and H.-W. Rix, ApJ **684**, 1075-1092 (2008), arXiv:0805.2945.
[44] A. Vale and J. P. Ostriker, MNRAS **353**, 189 (2004), astro-ph/0402500.
[45] A. V. Kravtsov, A. A. Berlind, R. H. Wechsler, A. A. Klypin, S. Gottlöber, B. Allgood, and J. R. Primack, ApJ **609**, 35 (2004), astro-ph/0308519.
[46] P. S. Behroozi, R. H. Wechsler, and C. Conroy, ApJ **770**, 57 (2013), arXiv:1207.6105 [astro-ph.CO].
[47] B. P. Moster, T. Naab, and S. D. M. White, MNRAS **428**, 3121 (2013), arXiv:1205.5807 [astro-ph.CO].
[48] F. Munshi, A. M. Brooks, E. Applebaum, D. R. Weisz, F. Governato, and T. R. Quinn, ArXiv e-prints (2017), arXiv:1705.06286.
[49] C. B. Brook, A. Di Cintio, A. Knebe, S. Gottlöber, Y. Hoffman, G. Yepes, and S. Garrison-Kimmel, ApJ **784**, L14 (2014), arXiv:1311.5492.
[50] P. F. Hopkins, D. Kereš, J. Oñorbe, C.-A. Faucher-Giguère, E. Quataert, N. Murray, and J. S. Bullock, MNRAS **445**, 581 (2014), arXiv:1311.2073.
[51] Planck Collaboration, A&A **596**, A108 (2016), arXiv:1605.03507.
[52] F.-Y. Cyr-Racine, K. Sigurdson, J. Zavala, T. Bringmann, M. Vogelsberger, and C. Pfrommer, Phys. Rev. D **93**, 123527 (2016), arXiv:1512.05344.
[53] R. Kennedy, C. Frenk, S. Cole, and A. Benson, MNRAS **442**, 2487 (2014), arXiv:1310.7739.
[54] J. F. Cherry and S. Horiuchi, Phys. Rev. D **95**, 083015 (2017), arXiv:1701.07874 [hep-ph].
[55] M. R. Lovell, S. Bose, A. Boyarsky, S. Cole, C. S. Frenk, V. Gonzalez-Perez, R. Kennedy, O. Ruchayskiy, and A. Smith, MNRAS **461**, 60 (2016), arXiv:1511.04078.
[56] M. R. Lovell, S. Bose, A. Boyarsky, R. A. Crain, C. S. Frenk, W. A. Hellwing, A. D. Ludlow, J. F. Navarro, O. Ruchayskiy, T. Sawala, M. Schaller, J. Schaye, and T. Theuns, MNRAS **468**, 4285 (2017), arXiv:1611.00010.
[57] S. Bose, C. S. Frenk, J. Hou, C. G. Lacey, and M. R. Lovell, MNRAS **463**, 3848 (2016), arXiv:1605.03179.
[58] S. Bose, W. A. Hellwing, C. S. Frenk, A. Jenkins, M. R. Lovell, J. C. Helly, B. Li, V. Gonzalez-Perez, and L. Gao, MNRAS **464**, 4520 (2017), arXiv:1604.07409.
[59] E. Polisensky and M. Ricotti, Phys. Rev. D **83**, 043506 (2011), arXiv:1004.1459 [astro-ph.CO].
[60] L. Hui, J. P. Ostriker, S. Tremaine, and E. Witten, Phys. Rev. D **95**, 043541 (2017), arXiv:1610.08297.
[61] H.-Y. Schive, T. Chiueh, and T. Broadhurst, Nature Physics **10**, 496 (2014), arXiv:1406.6586.
[62] B. Schwabe, J. C. Niemeyer, and J. F. Engels, Phys. Rev. D **94**, 043513 (2016), arXiv:1606.05151.
[63] P. Mocz, M. Vogelsberger, V. H. Robles, J. Zavala, M. Boylan-Kolchin, A. Fialkov, and L. Hernquist, MNRAS **471**, 4559 (2017), arXiv:1705.05845.
[64] M. Y. Khlopov, A. G. Mayorov, and E. Y. Soldatov, International Journal of Modern Physics D **19**, 1385 (2010), arXiv:1003.1144.
[65] M. R. Lovell, C. S. Frenk, V. R. Eke, A. Jenkins, L. Gao, and T. Theuns, MNRAS **439**, 300 (2014), arXiv:1308.1399.
[66] A. Schneider, R. E. Smith, A. V. Macciò, and B. Moore, MNRAS **424**, 684 (2012), arXiv:1112.0330.
[67] B. Bozek, A. Fitts, M. Boylan-Kolchin, S. Garrison-Kimmel, K. Abazajian, J. S. Bullock, D. Keres, C.-A. Faucher-Giguere, A. Wetzel, R. Feldmann, and P. F. Hopkins, ArXiv e-prints (2018), arXiv:1803.05424.

[68] A. M. Nierenberg, T. Treu, S. A. Wright, C. D. Fassnacht, and M. W. Auger, MNRAS **442**, 2434 (2014), arXiv:1402.1496.
[69] Y. Hezaveh, N. Dalal, G. Holder, T. Kisner, M. Kuhlen, and L. Perreault Levasseur, J. Cosmology Astropart. Phys. **11**, 048 (2016), arXiv:1403.2720.
[70] S. Vegetti, G. Despali, M. R. Lovell, and W. Enzi, ArXiv e-prints (2018), arXiv:1801.01505.
[71] J. Bovy, D. Erkal, and J. L. Sanders, MNRAS **466**, 628 (2017), arXiv:1606.03470.
[72] See Supplemental Material for a detailed description of our analysis choices and variants, as well as completeness-corrected luminosity functions for the Milky Way, which includes Refs. [73-130].
[73] A. Kravtsov, Advances in Astronomy **2010**, 281913 (2010), arXiv:0906.3295.
[74] F. C. van den Bosch, Mon. Not. Roy. Astron. Soc. **468**, 885 (2017), arXiv:1611.02657 [astro-ph.GA].
[75] F. C. van den Bosch, G. Ogiya, O. Hahn, and A. Burkert, Mon. Not. Roy. Astron. Soc. **474**, 3043 (2018), arXiv:1711.05276 [astro-ph.GA].
[76] F. C. van den Bosch and G. Ogiya, Mon. Not. Roy. Astron. Soc. (2018), 10.1093/mnras/sty084, arXiv:1801.05427 [astro-ph.GA].
[77] V. Simha and S. Cole, Mon. Not. Roy. Astron. Soc. **472**, 1392 (2017), arXiv:1609.09520 [astro-ph.GA].
[78] A. M. Brooks, M. Kuhlen, A. Zolotov, and D. Hooper, Astrophys. J. **765**, 22 (2013), arXiv:1209.5394 [astro-ph.CO].
[79] R. Errani, J. Peñarrubia, C. F. P. Laporte, and F. A. Gómez, MNRAS **465**, L59 (2017), arXiv:1608.01849.
[80] J. Penarrubia, A. Pontzen, M. G. Walker, and S. E. Koposov, Astrophys. J. **759**, L42 (2012), arXiv:1207.2772 [astro-ph.GA].
[81] A. Fitts, M. Boylan-Kolchin, O. D. Elbert, J. S. Bullock, P. F. Hopkins, J. Oñorbe, A. Wetzel, C. Wheeler, C.-A. Faucher-Giguère, D. Kereš, E. D. Skillman, and D. R. Weisz, MNRAS **471**, 3547 (2017), arXiv:1611.02281.
[82] W. E. Kunkel and S. Demers, in *The Galaxy and the Local Group*, Royal Greenwich Observatory Bulletins, Vol. 182, edited by R. J. Dickens, J. E. Perry, F. G. Smith, and I. R. King (1976) p. 241.
[83] M. Metz, P. Kroupa, and H. Jerjen, MNRAS **374**, 1125 (2007), astro-ph/0610933.
[84] M. S. Pawlowski, Modern Physics Letters A **33**, 1830004 (2018), arXiv:1802.02579.
[85] A. R. Zentner, A. V. Kravtsov, O. Y. Gnedin, and A. A. Klypin, ApJ **629**, 219 (2005), astro-ph/0502496.
[86] X. Kang, S. Mao, L. Gao, and Y. P. Jing, A&A **437**, 383 (2005), astro-ph/0501333.
[87] J. D. Simon, ArXiv e-prints (2018), arXiv:1804.10230.
[88] T. K. Fritz, R. Carrera, and G. Battaglia, ArXiv e-prints (2018), arXiv:1805.07350.
[89] T. K. Fritz, G. Battaglia, M. S. Pawlowski, N. Kallivayalil, R. van der Marel, T. S. Sohn, C. Brook, and G. Besla, ArXiv e-prints (2018), arXiv:1805.00908.
[90] D. Massari and A. Helmi, ArXiv e-prints (2018), arXiv:1805.01839.
[91] N. Shipp *et al.*, ArXiv e-prints (2018), arXiv:1801.03097.
[92] T. S. Li *et al.*, ArXiv e-prints (2018), arXiv:1804.07761.
[93] P. Jethwa, D. Erkal, and V. Belokurov, MNRAS **461**, 2212 (2016), arXiv:1603.04420.
[94] B. F. Griffen, A. P. Ji, G. A. Dooley, F. A. Gmez, M. Vogelsberger, B. W. O'Shea, and A. Frebel, Astrophys. J. **818**, 10 (2016), arXiv:1509.01255 [astro-ph.GA].
[95] M. Boylan-Kolchin, V. Springel, S. D. M. White, and A. Jenkins, Mon. Not. Roy. Astron. Soc. **406**, 896 (2010), arXiv:0911.4484 [astro-ph.CO].
[96] G. A. Dooley, A. H. G. Peter, J. L. Carlin, A. Frebel, K. Bechtol, and B. Willman, MNRAS **472**, 1060 (2017), arXiv:1703.05321.
[97] E. J. Tollerud, M. Boylan-Kolchin, E. J. Barton, J. S. Bullock, and C. Q. Trinh, ApJ **738**, 102 (2011), arXiv:1103.1875.
[98] M. T. Busha, R. H. Wechsler, P. S. Behroozi, B. F. Gerke, A. A. Klypin, and J. R. Primack, ApJ **743**, 117 (2011), arXiv:1011.6373.
[99] A. A. Thoul and D. H. Weinberg, ApJ **465**, 608 (1996), astro-ph/9510154.
[100] M. Jeon, G. Besla, and V. Bromm, ApJ **848**, 85 (2017), arXiv:1702.07355.
[101] M. Ricotti, O. H. Parry, and N. Y. Gnedin, ApJ **831**, 204 (2016), arXiv:1607.04291.
[102] C. M. Simpson, G. L. Bryan, K. V. Johnston, B. D. Smith, M.-M. Mac Low, S. Sharma, and J. Tumlinson, Mon. Not. Roy. Astron. Soc. **432**, 1989 (2013), arXiv:1211.1071 [astro-ph.GA].
[103] J. H. Wise, V. G. Demchenko, M. T. Halicek, M. L. Norman, M. J. Turk, T. Abel, and B. D. Smith, MNRAS **442**, 2560 (2014), arXiv:1403.6123.
[104] J. Bland-Hawthorn, R. Sutherland, and D. Webster, ApJ **807**, 154 (2015), arXiv:1505.06209.
[105] H. Xu, J. H. Wise, M. L. Norman, K. Ahn, and B. W. O'Shea, ApJ **833**, 84 (2016), arXiv:1604.07842.
[106] R. Barkana and A. Loeb, ApJ **523**, 54 (1999), astro-ph/9901114.
[107] T. Okamoto, L. Gao, and T. Theuns, MNRAS **390**, 920 (2008), arXiv:0806.0378.
[108] T. Dawoodbhoy *et al.*, (2018), arXiv:1805.05358 [astro-ph.CO].
[109] A. J. Benson, C. G. Lacey, C. M. Baugh, S. Cole, and C. S. Frenk, MNRAS **333**, 156 (2002), astro-ph/0108217.
[110] C. Barber, E. Starkenburg, J. F. Navarro, A. W. McConnachie, and A. Fattahi, MNRAS **437**, 959 (2014), arXiv:1310.0466.
[111] R. Lunnan, M. Vogelsberger, A. Frebel, L. Hernquist, A. Lidz, and M. Boylan-Kolchin, Astrophys. J. **746**, 109 (2012), arXiv:1105.2293 [astro-ph.CO].
[112] S. Bose, A. J. Deason, and C. S. Frenk, (2018), arXiv:1802.10096 [astro-ph.GA].
[113] B. Diemer, S. More, and A. V. Kravtsov, ApJ **766**, 25 (2013), arXiv:1207.0816 [astro-ph.CO].
[114] K. L. Dixon, I. T. Iliev, S. Gottlöber, G. Yepes, A. Knebe, N. Libeskind, and Y. Hoffman, ArXiv e-prints (2017), arXiv:1703.06140.
[115] D. Aubert, N. Deparis, P. Ocvirk, P. R. Shapiro, I. T. Iliev, G. Yepes, S. Gottlober, Y. Hoffman, and R. Teyssier, Astrophys. J. **856**, L22 (2018), arXiv:1802.01613 [astro-ph.CO].
[116] J. Woo, S. Courteau, and A. Dekel, Mon. Not. Roy. Astron. Soc. **390**, 1453 (2008), arXiv:0807.1331 [astro-ph].
[117] M. Gennaro, K. Tchernyshyov, T. M. Brown, M. Geha, R. J. Avila, P. Guhathakurta, J. S. Kalirai, E. N. Kirby, A. Renzini, J. D. Simon, J. Tumlinson, and L. C. Var-

gas, ApJ **855**, 20 (2018), arXiv:1801.06195.
[118] R. S. Bussmann *et al.*, ApJ **779**, 25 (2013), arXiv:1309.0836.
[119] R. M. Reddick, R. H. Wechsler, J. L. Tinker, and P. S. Behroozi, ApJ **771**, 30 (2013), arXiv:1207.2160 [astro-ph.CO].
[120] D. Campbell, F. C. van den Bosch, N. Padmanabhan, Y.-Y. Mao, A. R. Zentner, J. U. Lange, F. Jiang, and A. Villarreal, MNRAS **477**, 359 (2018), arXiv:1705.06347.
[121] P. F. Hopkins *et al.*, ArXiv e-prints (2017), arXiv:1702.06148.
[122] X. Ma, P. F. Hopkins, S. Garrison-Kimmel, C.-A. Faucher-Gigure, E. Quataert, M. Boylan-Kolchin, C. C. Hayward, R. Feldmann, and D. Kere, (2017), 10.1093/mnras/sty1024, arXiv:1706.06605 [astro-ph.GA].
[123] A. Fitts, M. Boylan-Kolchin, J. S. Bullock, D. R. Weisz, K. El-Badry, C. Wheeler, C.-A. Faucher-Giguère, E. Quataert, P. F. Hopkins, D. Kereš, A. Wetzel, and C. Hayward, ArXiv e-prints (2018), arXiv:1801.06187.
[124] S. Garrison-Kimmel, J. S. Bullock, M. Boylan-Kolchin, and E. Bardwell, MNRAS **464**, 3108 (2017), arXiv:1603.04855.
[125] P. Colín, V. Avila-Reese, A. González-Samaniego, and H. Velázquez, ApJ **803**, 28 (2015), arXiv:1412.1100.
[126] S. Bose, W. A. Hellwing, C. S. Frenk, A. Jenkins, M. R. Lovell, J. C. Helly, and B. Li, Mon. Not. Roy. Astron. Soc. **455**, 318 (2016), arXiv:1507.01998 [astro-ph.CO].
[127] A. V. Maccio, S. Paduroiu, D. Anderhalden, A. Schneider, and B. Moore, Mon. Not. Roy. Astron. Soc. **424**, 1105 (2012), arXiv:1202.1282 [astro-ph.CO].
[128] A. Schneider, Mon. Not. Roy. Astron. Soc. **451**, 3117 (2015), arXiv:1412.2133 [astro-ph.CO].
[129] M. Rocha, A. H. G. Peter, and J. S. Bullock, Mon. Not. Roy. Astron. Soc. **425**, 231 (2012), arXiv:1110.0464 [astro-ph.CO].
[130] F. Governato *et al.*, Mon. Not. Roy. Astron. Soc. **448**, 792 (2015), arXiv:1407.0022 [astro-ph.GA].