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The dark matter halos of dwarf galaxies: a challenge for the ΛCDM paradigm?

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ABSTRACT

The cold dark matter halo mass function is much steeper than the galaxy stellar mass function on galactic and subgalactic scales. This difference is usually reconciled by assuming that the galaxy formation efficiency drops sharply with decreasing halo mass, so that virtually no dwarf galaxies form in halos less massive than $\sim 10^{10}\, M_\odot$. In turn, this implies that, at any given radius, the dark mass enclosed by a galaxy must exceed a certain minimum. We use rotation curves of dwarf galaxies compiled from the literature to explore whether their enclosed mass is consistent with these constraints. We find that almost one half of the dwarfs in our sample with stellar mass in the range $10^6 < M_{\rm gal}/M_\odot < 10^7$ are at odds with this restriction: either they live in halos with masses substantially below $10^{10}\, M_\odot$ or there is a mechanism capable of reducing the dark mass enclosed by some of the faintest dwarfs. Neither possibility is easily accommodated within the standard ΛCDM scenario. Extending galaxy formation to halos well below $10^{10}\, M_\odot$ would lead to large numbers of dwarf galaxies in excess of current estimates; at the same time, the extremely low stellar mass of the systems involved makes it unlikely that baryonic effects can reduce their dark matter content. Resolving this challenge seems to require new insights into dwarf galaxy formation, or perhaps a radical revision of the prevailing paradigm.

Key words: Galaxy: formation – Galaxy: kinematics and dynamics – Galaxy: structure

1 INTRODUCTION

Cosmological N-body simulations and theoretical insight have led to clear predictions for the mass function of dark matter halos that form in the current ΛCDM paradigm (Press & Schechter, 1974; Sheth et al., 2001; Jenkins et al., 2001; Springel et al., 2005). On galactic and subgalactic scales, this halo mass function is much steeper than the galaxy stellar mass function, suggesting a complex non-linear relation between the mass of a galaxy and that of its surrounding halo.

The need for such non-linear correspondence was recognized in early attempts to model hierarchical galaxy formation (e.g., White & Rees, 1978), and has been traditionally thought to imply that the "efficiency" of galaxy formation (i.e., the fraction of baryons in a halo that gets turned into stars and assembled into a galaxy) decreases steadily with decreasing halo mass so that effectively few galaxies, if any, form in halos below a certain minimum mass. With slight variations, this assumption has been a cornerstone of semi-analytic galaxy formation models (e.g., Kauffmann et al., 1993; Cole et al., 1994; Somerville & Primack, 1999), and underpins most attempts to reconcile the shallow faint end of the galaxy luminosity function with the steep slope of the halo mass function.

The latest results from the Sloan Digital Sky Survey (SDSS) have extended the galaxy stellar mass function down to $\sim 10^7\, M_\odot$ (Baldry et al., 2008; Li & White, 2009), and have led to even stricter constraints on how galaxies populate low mass halos. For example, using either simple abundance-matching techniques or a full-blown semianalytic model applied to large cosmological N-body simulations, Guo et al. (2010, 2011) conclude that galaxies with stellar mass, $M_{\rm gal}$, exceeding $\sim 10^6\, M_\odot$ must inhabit halos with virial⋆ mass, M_{200}, typically exceeding $10^{10}\, M_\odot$.

The steep decline in the efficiency of galaxy formation near this minimum halo mass also implies that most faint galaxies must be surrounded by halos spanning a small mass range. In the model of Guo et al. (2010), for example, the halo mass of dwarfs in the stellar mass range $10^6 < M_{\rm gal}/M_\odot < 10^8$ differ by less than a factor of ~ 5. These results provide readily testable predictions that have elicited some tension in the theoretical interpretation of available data on dwarfs.

For example, since dwarf galaxies tend to be dark matter dominated then having similar halos means that their rotation velocity should approach a characteristic value of order 30 km/s, the virial velocity of a halo of mass $\sim 10^{10}\, M_\odot$. This would result in a large number of dwarfs with that characteristic velocity or, equivalently, in a very steep dependence of the number of galaxies on rotation speed at the faint end, an effect that can be searched for in blind HI surveys such as HIPASS (Barnes et al., 2001) or ALFALFA (Giovanelli et al., 2005). The "velocity width function" of galaxies reported by such surveys, however, is much shallower than expected in the scenario outlined above, and shows no sign of a characteristic velocity (Zwaan et al., 2010; Papastergis et al., 2011).

A related problem has recently been highlighted by Boylan-Kolchin et al. (2011) in the context of Milky-Way satellites. These authors note that the kinematics and structure of dwarf spheroidal (dSph) galaxies suggest that they inhabit halos with circular velocities well below 30 km/s. This represents a challenge not only because it would mean that galaxies *do* form in low-mass halos, but also because, according to the latest N-body simulations, Milky Way-sized halos should host several massive subhalos which, apparently, have failed to form visible satellites (see also Parry et al., 2012; Boylan-Kolchin et al., 2012; di Cintio et al., 2011; Vera-Ciro et al., 2012).

In principle, these difficulties can be explained away with plausible arguments. For example, the dwarf spheroidal companions of the Milky Way have likely been orbiting in the tidal field of the Galaxy for several Gyrs. Their dark matter content could therefore have been affected by tidal stripping, thus hindering the interpretation of their inferred halo masses. One should also keep in mind that the apparent conflict concerns a small number of objects, and is therefore subject to substantial uncertainty. Good mass estimates are only available for nine Milky Way dSphs, and the theoretical comparison is based on just seven ΛCDM halo realizations, six from the Aquarius Project (Springel et al., 2008) plus the Via Lactea simulation (Diemand et al., 2007). The possibility that the Milky Way is simply an outlier either in halo mass or in subhalo content thus remains (Wang et al., 2012).

Further, as discussed by Papastergis et al. (2011), the velocity-width function discrepancy could be explained if the gas rotation velocity systematically underestimates the circular velocity of the surrounding dark halo. This may occur if the size of the galaxy is small relative to the radius where a halo reaches its characteristic velocity (Stoehr et al., 2002). Indeed, the circular velocity of cold dark matter halos rises gradually with radius (Navarro et al., 1996, 1997, hereafter NFW): a $10^{10}\, M_\odot$ halo typically reaches its maximum velocity (~ 37 km/s) only at $r \sim$ 5-6 kpc, a radius larger than the size of the faintest dwarfs. The unexpectedly large number of galaxies with velocity widths below the expected characteristic velocity might then just reflect the fact that physically small galaxies trace the rising part of the halo circular velocity curve.

This hypothesis can be checked explicitly if spatially-resolved rotation curves are available, especially for galaxies where the inclination is well constrained by good photometry or by integral-field velocity data. Unfortunately, dwarf galaxies are typically unresolved in single-dish cm wavelength surveys such as ALFALFA, and the photometric data available are insufficient to estimate accurately the inclination information needed to turn velocity widths into circular velocity estimates.

We address these issues here by using a compilation of literature data for galaxies with spatially-resolved rotation curves and good photometric data. Since our interest lies in the scale of dwarfs, the dataset concerns mainly relatively isolated dwarf irregular galaxies drawn from eight recent studies. The data are heterogeneous, but they cover a wide range of galaxy stellar mass, from roughly 10^6 to $10^{10}\, M_\odot$, and should therefore provide insight into whether halo masses are in agreement with model predictions. This paper is organized as follows. We describe the data compilation in Sec. 2, present our results in Sec. 3, and summarize our main conclusions in Sec. 4.

2 THE DATASET

The main data used in our analysis are HI rotation curves and stellar masses (or absolute magnitudes) of galaxies compiled from the literature. The sample we use contains 7 galaxies from Côté et al. (2000), 69 from McGaugh (2005), 29 from Begum et al. (2008b)†, 5 from Oh et al. (2011), 70 from Swaters et al. (2009), 5 from Trachternach et al. (2009) and 25 from Wolf et al. (2010). We also include the 11 galaxies from Stark et al. (2009) not in the previous samples.

We are mainly interested in the total dark mass enclosed by a galaxy, so in practice we shall use the *outermost* point of the rotation curve, characterized by the radius, $r_{\rm out}$, and rotation velocity, $V_{\rm out} = V_{\rm rot}(r_{\rm out})$. In most cases, this is also the maximum rotation velocity measured for the galaxy, since rotation curves tend to be either rising or flat in the outer regions. In the rare cases of galaxies with peculiar rotation curves, such as a steeply-declining outer portion (suggestive of a warp), we choose instead the radius and velocity of the maximum of the rotation curve. As we shall see below, this is a conservative choice for the purpose of our analysis.

The galaxies from Wolf et al. (2010) lack rotation

⋆ We compute all virial quantities within spheres of mean density 200 times the critical density for closure.

† Complementary information for these galaxies was taken from the previous and more extended sample presented in Begum et al. (2008a).

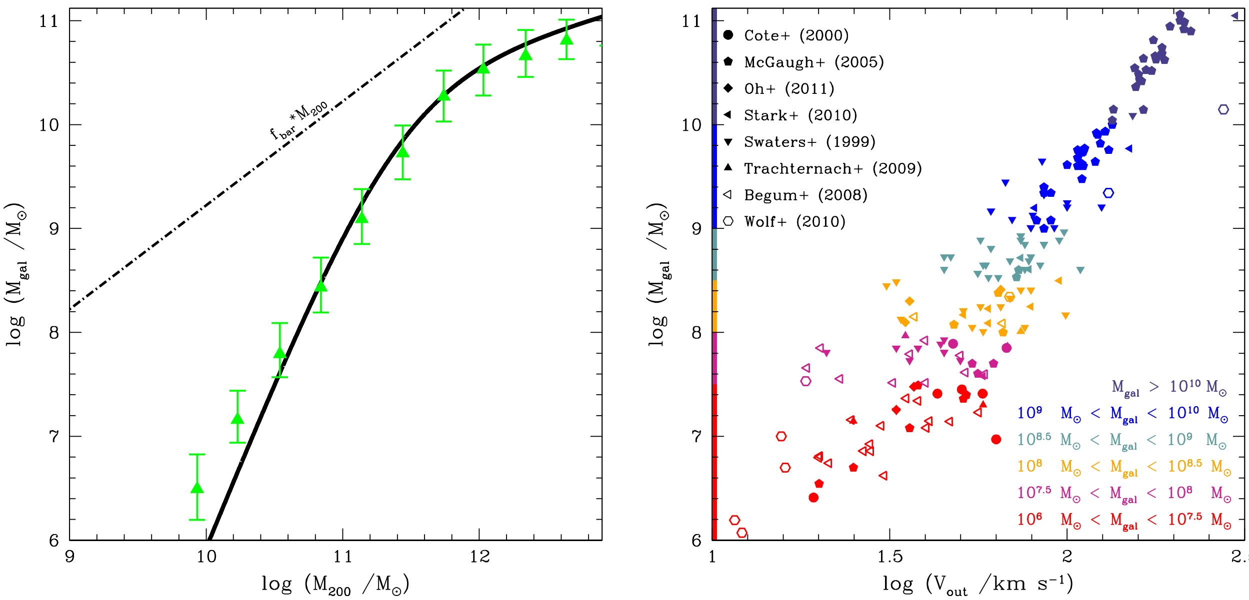

Figure 1. *Left:* The halo virial mass vs galaxy stellar mass relation derived by Guo et al. (2010) using abundance-matching techniques (solid line). Results from the semianalytic model of Guo et al. (2011) are shown by the solid triangles. Note how steep the relation becomes at the faint end, implying that essentially no galaxies with $M_{\rm gal} > 10^6\, M_\odot$ should form in halos with mass below $\sim 10^{10}\, M_\odot$. The dot-dashed line indicates the baryonic content of a halo according to the latest estimates of the universal baryon fraction, $f_{\rm bar} = 0.171$. *Right:* The "Tully-Fisher" relation for a sample of nearby galaxies. Data are compiled from the sources listed in the figure label. Stellar masses are taken from each paper, when given, or estimated from their absolute magnitudes and colors as described in the text. Rotation velocities correspond to the outermost point of the published rotation curve, except for the data of Wolf et al. (2010), which correspond to circular velocities at the stellar half-mass radius. Note that the relation between rotation velocity and stellar mass is well approximated by a single power-law despite the strongly non-linear $M_{\rm gal}$ vs M_{200} relation shown in the left panel.

curve data, but these authors provide the total mass, $M_{1/2}$, enclosed within the half-light radius, $r_{1/2}$: we shall adopt then those radii and corresponding velocities, $V_{1/2} = (GM_{1/2}/r_{1/2})^{1/2}$, as estimates of $r_{\rm out}$, and $V_{\rm out}$, respectively. The full rotation curves of galaxies taken from Begum et al. (2008a,b) are not yet published, but the authors list $r_{\rm out}$ and $V_{\rm out}$ in their papers.

Our analysis also makes use of the total stellar mass of the galaxies, $M_{\rm gal}$, for which we adopt the values quoted in the papers from which the data are taken. When these are not available, we estimate stellar masses from the B, R or V-band absolute magnitude, assuming Bell & de Jong (2001) mass-to-light ratios consistent with the average colors of galaxies in our sample: $\gamma_B = 0.5$, $\gamma_R = 1$ and $\gamma_V = 2$ in solar units. We emphasize that this is not critical for our analysis, since most dwarfs are heavily dark matter dominated: we have experimented with increasing and decreasing γ by a factor of two and none of our conclusions are affected by such changes.

3 ANALYSIS

The solid curve in the left panel of Fig. 1 shows the galaxy-halo mass relation derived by Guo et al. (2010) assuming that the abundance of dark halos ranked by virial mass, M_{200}, can be matched monotonically to the abundance of galaxies ranked by stellar mass, $M_{\rm gal}$. Despite the simplicity of this abundance-matching technique, more sophisticated semianalytic modeling (Guo et al., 2011) actually yields very similar results, as shown by the solid triangles in the same figure. A dot-dashed curve indicates the galaxy mass corresponding to all available baryons within the virial radius, assuming the universal baryon fraction, $f_{\rm bar} = \Omega_b/\Omega_M = 0.171$.

The $M_{\rm gal}$-M_{200} relation in Fig. 1 shows clearly the sharp decline in galaxy formation efficiency with decreasing halo mass alluded to in Sec.1: the baryonic mass of a $M_{200} = 10^{11}\, M_\odot$ halo is $f_{\rm bar}\, M_{200} = 1.7 \times 10^{10}\, M_\odot$ but it typically hosts a $10^9\, M_\odot$ galaxy containing $\sim 6\%$ of its baryons in the form of stars. On the other hand, a $10^6\, M_\odot$ galaxy inhabiting a $10^{10}\, M_\odot$ halo would contain just 0.06% of its available baryons.

Thus, most dwarf galaxies (understood here as those with $M_{\rm gal} \lesssim 10^9\, M_\odot$) should be surrounded by halos in a fairly narrow range of mass, spanning less than a decade in M_{200}, or just over a factor of 2 in circular velocity. Little sign of such characteristic scale is seen in the Tully-Fisher relation of galaxies in our sample. This is shown in the right-hand panel of Fig. 1, where we plot the outermost rotation velocity, $V_{\rm out}$, vs $M_{\rm gal}$ for galaxies in our sample. No obvious sign of convergence to a characteristic velocity is seen in these data, which span roughly 5 decades in galaxy mass (see also McGaugh & Wolf, 2010).

In the ΛCDM scenario, the nearly self-similar structure

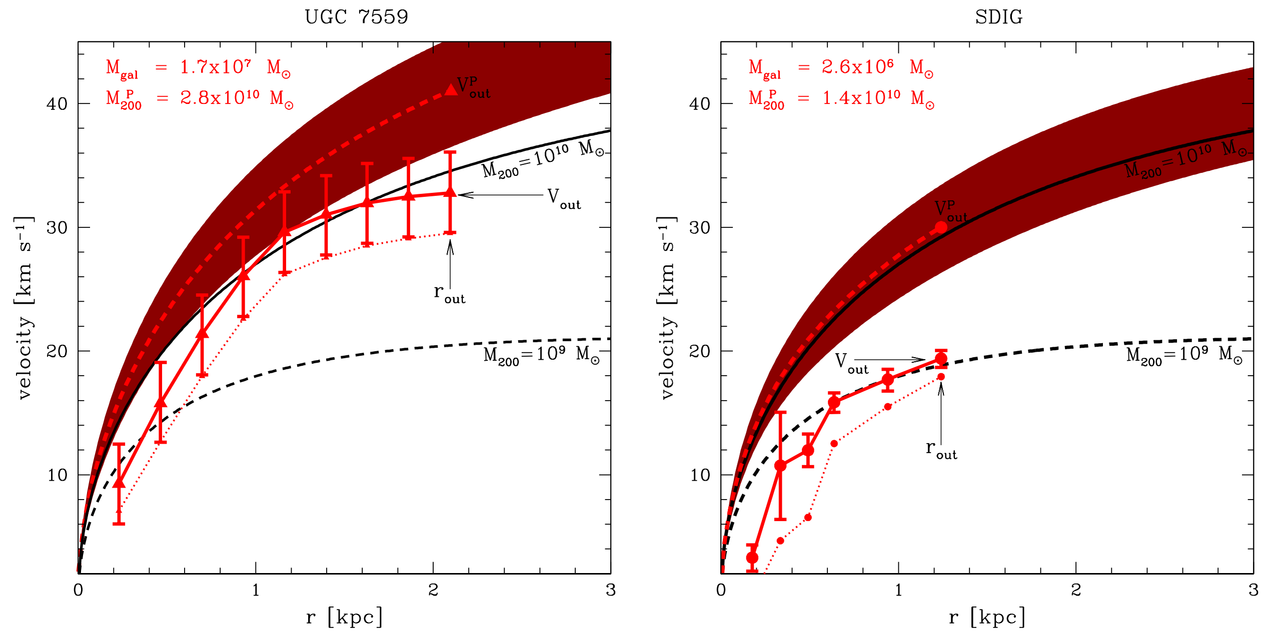

Figure 2. The rotation curve of two dwarf galaxies in our sample: UGC 7559 (Swaters, 1999) and the Sagittarius Dwarf Irregular (SDIG, Côté et al., 2000). Filled symbols with error bars reproduce the published rotation curve; a dotted line indicates the contribution of the dark halo, which dominates the enclosed mass at the outermost measured point, $r_{\rm out}$. The black lines indicate the circular velocity profile of a 10^{10} and a 10^{9} $M_{\odot}$ NFW halo of average concentration, $c = 10.8$ and $c = 13.4$, respectively. The red dashed curve in each panel shows the circular velocity profile expected if the NFW halo mass is chosen to match the $M_{\rm gal}$ vs M_{200} relation of Guo et al. (2010) given in the left panel of Fig. 1. The shaded area shows the result of varying by $\pm 1\sigma$ the concentration assumed for the halo. The abundance-matching model suggests that circular velocities should not lie below the black solid line. Within the uncertainties UGC 7559 seems to match this constraint, which is, on the other hand, clearly violated by SDIG.

of dark matter halos allows an independent probe of halo mass based on the rotation curve of a galaxy. We illustrate this in Fig. 2, where the thick solid and thick dashed black curves in each panel indicate the circular velocity profiles of two NFW halos with virial mass 10^{10} and 10^{9} $M_{\odot}$, respectively. The concentration parameter of each halo ($c = 10.8$ and 13.4, respectively) is chosen to be consistent with the results of Neto et al. (2007), corrected to the latest values of the cosmological parameters following Duffy et al. (2008). The point to note here is that the more massive a halo the higher its circular velocity is at *all* radii. The difference is small at small radii (all circular velocities approach zero at the origin) but it becomes more appreciable further out. Rotation curves that extend far enough out in radius are therefore telling probes of the virial mass of the halo.

Fig. 2 shows as well the rotation curves of two dwarf galaxies. The left panel shows UGC 7559, a galaxy with stellar mass $M_{\rm gal} \sim 1.7 \times 10^{7}\,M_{\odot}$ (Swaters, 1999); the panel on the right shows the $M_{\rm gal} \sim 2.6 \times 10^{6}\,M_{\odot}$ Sagittarius Dwarf Irregular (SDIG, Côté et al., 2000). The published rotation curves are shown by the solid symbols with error bars; the smaller symbols connected by a dotted line shows the circular velocity profile once the contribution of the baryons (gas+stars) has been discounted. These two galaxies, like most faint galaxies in our sample, are clearly dark matter dominated in the outer regions. The velocity at the outermost point of the rotation curve, $V_{\rm out}$, in particular, depends almost entirely on the enclosed dark mass within $r_{\rm out}$, with little contribution from the baryons.

The red dashed lines in Fig. 2 indicate the circular velocity profile[‡] expected if the halo mass of each galaxy were to coincide with the abundance-matching prediction shown in the left panel of Fig. 1. According to this model, the total mass of the halo inhabited by UGC 7559 ought to be $\sim 2.8 \times 10^{10}\,M_{\odot}$. The upper and lower limits of the shaded region corresponds to varying the concentration around the average by $\pm 20\%$, the rms scatter at fixed mass reported by Neto et al. (2007) in their analysis of thousands of halos in the Millennium Simulation. A similar procedure is followed in the right-hand panel to shade the region where the rotation curve of SDIG would be expected to lie if its surrounding halo mass is $\sim 1.4 \times 10^{10}\,M_{\odot}$, as suggested by the abundance-matching analysis.

As Fig. 2 makes clear, UGC 7559 is in rough agreement with the model expectation. Its rotation curve reaches a maximum of $V_{\rm out} \sim 32$ km/s, at $r_{\rm out} = 2.1$ kpc, only slightly below the $V^{P}_{\rm out} \sim 40$ km/s expected at that radius according to the model. The same is not the case for SDIG, whose paltry peak rotation speed is just $V_{\rm out} \sim 19$ km/s, well below the $V^{P}_{\rm out} \sim 30$ km/s expected at the outermost radius, $r_{\rm out} = 1.3$ kpc.

‡ The prediction assumes an NFW halo contracted to account for the effect of the baryonic component following Abadi et al. (2010). This correction is in practice negligible for dwarf galaxies since they are almost completely dark matter dominated.

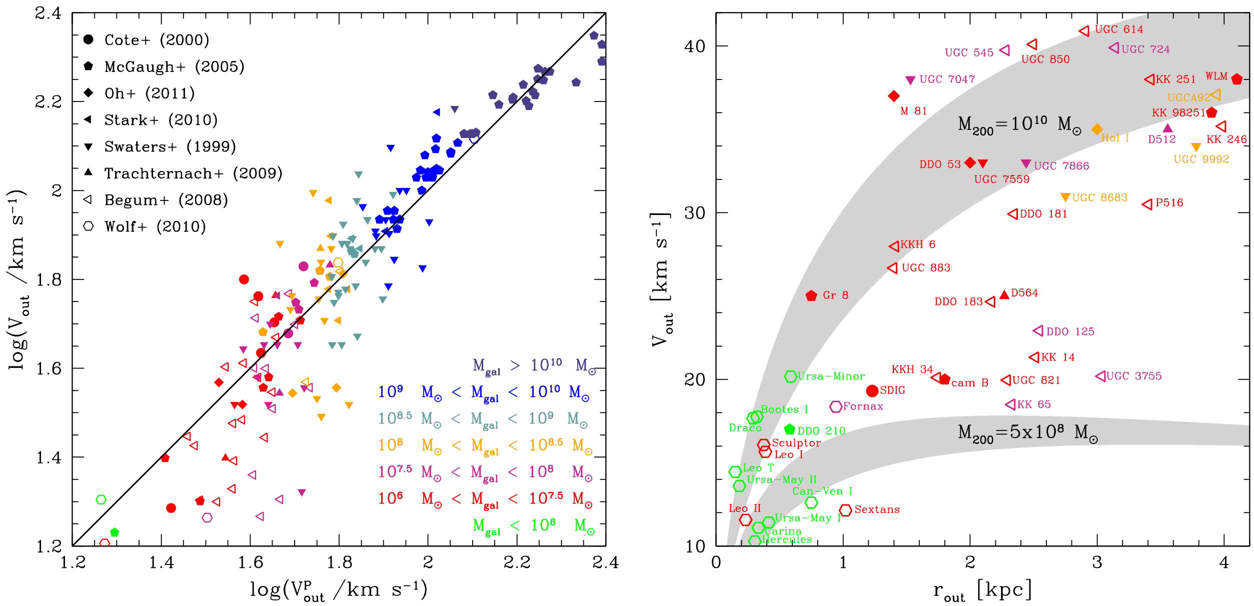

Figure 3. *Left panel:* Outermost rotation velocity, $V_{\rm out} = V_{\rm rot}(r_{\rm out})$, measured for each galaxy in our sample vs $V^P_{\rm out}$, its predicted value assuming that the halo mass is given by the $M_{\rm gal}$ vs M_{200} abundance-matching relation of Fig. 1. Note that the faintest dwarfs tend to have velocities well below those expected from the model, implying that they inhabit halos less massive than expected. *Right:* The outermost point of the rotation curve of a sample of dwarf galaxies compiled from the literature. Abundance-matching arguments suggest that all points should lie *on or above* the shaded area labeled $M_{200} = 10^{10}\,M_\odot$. This is clearly not the case. Instead, 17 out of the 44 galaxies with $V_{\rm outer} < 35$ km/s enclose masses within $r_{\rm out}$ more than a factor of 2 lower than predicted. The same is true for the faintest dwarfs in our sample: roughly 45% of all galaxies with $10^6 < M_{\rm gal} < 10^7\,M_\odot$ have masses that deviate by a similar amount from the expected values. If there is a minimum halo mass for dwarf galaxy formation, the data imply that it cannot be much higher than $\sim 5\times10^8\,M_\odot$.

This is clear indication that the SDIG halo mass is well below the abundance-matching expectation: a naive fit of the rotation curve yields $M_{200} \sim 10^9\,M_\odot$, a factor of 10 below the mass expected from abundance-matching considerations. Unless the rotation curve measurements are grossly in error, which we deem unlikely, it is difficult to evade the conclusion that SDIG truly inhabits a halo of mass much lower than expected from the model. Note that having a spatially-resolved rotation curve that probes a large radial range is crucial to this conclusion. For example, if the data available were just a rotation velocity of 19 km/s from unresolved data, or if that velocity was reached within, say, 500 pc, it would be difficult to discount the possibility that SDIG might inhabit a much more massive halo.

Could SDIG be instead surrounded by a halo of unusually low concentration? Indeed, a $M_{200} = 10^{10}\,M_\odot$ halo with $c = 5$ (3σ below the average) would match the observed ($r_{\rm out}$,$V_{\rm out}$) for this galaxy. If this were true, it would mean that SDIG is a rare outlier, a possibility that may be checked by considering the remainder galaxies in our sample.

The results are displayed in Fig. 3, where we show, in the left panel, the measured outermost velocities versus the velocities predicted (at each value of $r_{\rm out}$) assuming halo masses derived from the abundance-matching $M_{\rm gal}$ vs M_{200} relation. Although massive galaxies seem to be in good agreement with the model, those with stellar masses below $\sim 3\times10^7\,M_\odot$ (and also a few more massive ones) have velocities that fall systematically below the expected ~ 30 km/s corresponding to a halo mass of $\sim 10^{10} M_\odot$.

About 17% of galaxies in our sample with $10^7 < M_{\rm gal}/M_\odot < 10^8$ have enclosed masses (within $r_{\rm out}$) more than a factor of 2 smaller than expected from the abundance-matching model. This fraction increases to 45% when considering galaxies with $10^6 < M_{\rm gal}/\,M_\odot < 10^7$, ruling out the possibility that galaxies like SDIG are just rare exceptions.

The right-hand panel of Fig. 3 illustrates the problem in a slightly different way. Here we show the outermost point of the rotation curves ($r_{\rm out}$,$V_{\rm out}$) of galaxies in our sample and compare them with the rotation curves expected for NFW halos of virial mass $10^{10}\,M_\odot$ and $5\times10^8\,M_\odot$, respectively. (Shaded regions correspond to varying the concentration by $\pm20\%$, as in Fig. 2.) There are clearly many dwarf galaxies, like SDIG, with rotation curves that fall well below the boundaries imposed by the circular velocity of a halo as massive as $10^{10}\,M_\odot$.

What could be going on? One possibility is that the interpretation of the data is incorrect. The rotation velocity of neutral gas in dwarf irregulars is not a direct measure of the circular velocity, and must be corrected for the partial support provided by gas pressure, by the presence of non-circular motions, and by the non-negligible velocity dispersion of the gas. These corrections are uncertain, and although they are attempted in most published studies, they may require revision when better data and more sophisticated modeling are available. Indeed, the data available in the literature on dwarf irregulars are highly heterogeneous and of varying quality. For example, many of the galaxies in our sample taken from Begum et al. (2008a,b) have no pub-

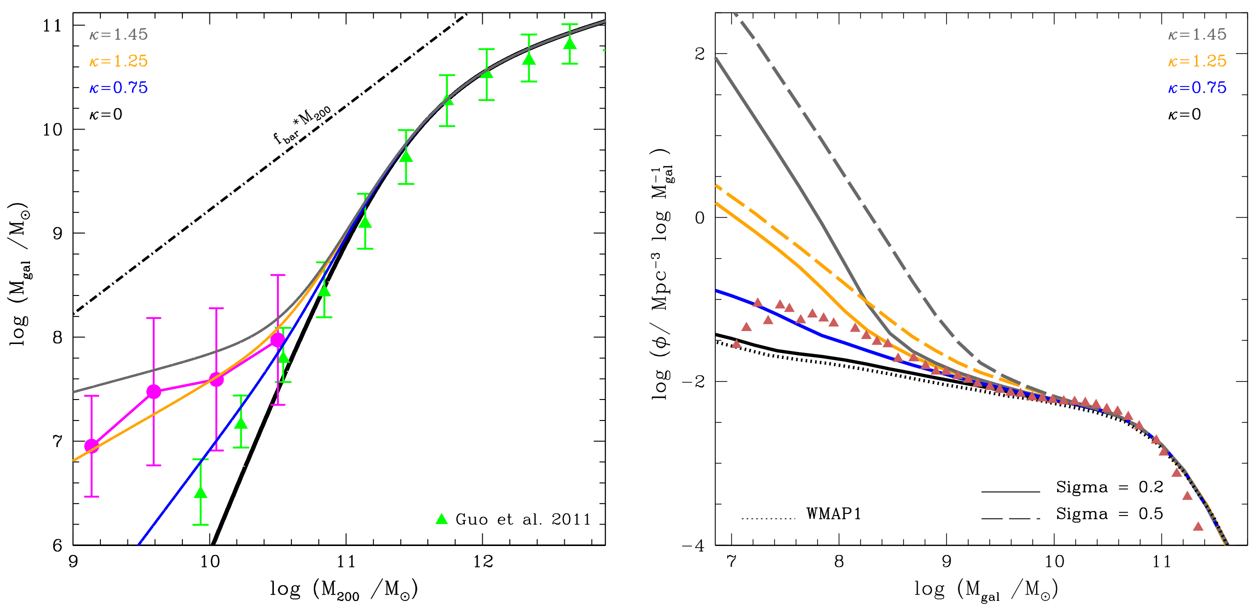

Figure 4. *Left:* Galaxy stellar mass-halo virial mass relation. The black solid line indicates the abundance-matching model of Guo et al. (2010); solid triangles correspond to the semianalytic model of Guo et al. (2011). The dot-dashed line indicates the total baryon mass of a halo according to latest estimates of the universal baryon fraction, $f_{\rm bar} = \Omega_{\rm bar}/\Omega_{\rm M}$. The magenta curve shows the average galaxy mass-halo mass relation derived from dwarf galaxies in our sample. Halo masses of individual galaxies are computed by fitting NFW halos to the kinematic data shown in the right-hand panel of Fig. 3. Circles indicate the average in each halo mass bin; the error bar indicates the dispersion, computed after 3σ clipping a few outliers. Colored solid curves correspond to various values of the parameter κ introduced in eq. 1; $\kappa = 0$ corresponds to the abundance-matching relation, higher values correspond to shallower halo mass dependence of galaxy mass. *Right:* Galaxy stellar mass function corresponding to the various $M_{\rm gal}$-M_{200} relations shown in the left-hand panel, contrasted with the observational estimates of Baldry et al. (2008) (points with error bars). Solid curves are computed assuming a uniform scatter of 0.2 dex in the galaxy mass-halo mass relation; dashed curves assume 0.5 dex scatter. We assume the halo mass function of Jenkins et al. (2001), corrected to cosmological parameters consistent with the latest WMAP measurements. For reference, we also show with a dotted line the result of adopting cosmological parameters from the 1st-year WMAP data analysis. Note the large excess of dwarf galaxies expected if the galaxy-halo mass relation is as shallow as that suggested by the dwarf kinematic data.

lished rotation curves (our analysis uses only their tabulated values of $V_{\rm out}$ and $r_{\rm out}$), so it is difficult to assess their reliability. We have labeled individually each galaxy in the right panel of Fig. 3 in an attempt to encourage further observational scrutiny of the systems responsible for the challenge we highlight here.

A second possibility is that baryonic effects such as supernova-driven gas blowouts (e.g., Navarro et al., 1996), or gravitational fluctuations created by star-forming regions (see, e.g., Pontzen & Governato, 2012, and references therein) might reduce the dark matter content of dwarf galaxies and alleviate the problem. It is unclear, however, how baryons in galaxies with stellar masses as small as those of globular clusters could affect the central regions of a $10^{10}\,M_\odot$ halo. Although this possibility should be explored more thoroughly, the outlook does not seem promising (see, e.g., Boylan-Kolchin et al., 2012; Governato et al., 2012).

Finally, the simplest interpretation is that many dwarf galaxies inhabit halos of much lower mass than posited by abundance-matching or semianalytic models. This, however, is inconsistent with a shallow faint end of the galaxy stellar mass function, as shown in Fig. 4. The magenta circles in the left-hand panel of this figure show the average galaxy-halo mass relation derived by assigning to each dwarf galaxy in our sample a halo mass, M_{200}, consistent with its value of $r_{\rm out}$ and $V_{\rm out}$.

We estimate M_{200} for all $10^6 < M_{\rm gal}/M_\odot < 10^9$ galaxies in our sample by finding the NFW halo (contracted to account for the effects of the baryons) whose circular velocity curve passes through ($r_{\rm out}$,$V_{\rm out}$) after accounting for the contribution of the gas and stars in the galaxy. We assume that halos follow the mean mass-concentration relation expected for ΛCDM halos (see discussion of Fig. 2 above). Further, we remove from the analysis the satellites of the Milky Way and M31 since their mass profiles may have been affected by tides.

The magenta circles in the left-hand panel of Fig. 4 show the resulting average galaxy mass as a function of halo mass, together with error bars denoting the dispersion in each bin computed after 3σ clipping a few outliers. The $M_{\rm halo}$ dependence of galaxy mass is clearly shallower than either the abundance-matching model results of Guo et al. (2010) (extrapolated to low halo masses, solid line) or the semianalytic model results of Guo et al. (2011), shown with filled triangles. We can parameterize this deviation by introducing a correction to the functional dependence advocated by Guo et al. (2010); i.e.,

$$\frac{M_{\rm gal}}{M_{\rm halo}} = C\left[1+\left(\frac{M_{\rm halo}}{M_1}\right)^{-2}\right]^{\kappa}\left[\left(\frac{M_{\rm halo}}{M_0}\right)^{-\alpha}+\left(\frac{M_{\rm halo}}{M_0}\right)^{\beta}\right]^{-\gamma}, \quad (1)$$

with $C = 0.129$, $M_0 = 10^{11.4}M_\odot$, $M_1 = 10^{10.65}M_\odot$, $\alpha =$

0.926, $\beta = 0.261$, and $\gamma = 2.440$. The M_1 term in eq. 1 is our only modification to the relation of Guo et al. (2010). The larger the exponent κ the shallower the galaxy-halo mass function is in low mass halos; $\kappa = 0$ corresponds to the original abundance-matching relation (solid line in Fig. 4). We show results for four different values of κ in Fig. 4: $\kappa = 0$, 0.75, 1.25, and 1.45, respectively.

A shallow $M_{\rm halo}$-dependence of galaxy mass translates into large numbers of faint galaxies and, consequently, a steep faint end of the luminosity function. This is shown in the right-hand panel of Fig. 4, which shows the galaxy stellar mass function corresponding to each of the choices of κ and contrasts them with the data from Baldry et al. (2008). Extrapolating the abundance-matching relation to low-mass galaxies (i.e., adopting $\kappa = 0$; thick solid black curves in Fig. 4) actually yields fewer low-mass galaxies than reported by Baldry et al. (2008). Increasing κ to 0.75 fits better the semianalytic model results of Guo et al. (2011) (solid triangles) and yields a galaxy stellar mass function in better agreement with observation down to the smallest galaxy mass probed.

Increasing κ further, as required in order to match the shallower dependence suggested by our analysis (solid circles), results in a pronounced excess of low-mass galaxies over the Baldry et al data. For $\kappa = 1.25$ the model predicts almost one order of magnitude more $M_{\rm gal} = 10^7\, M_\odot$ galaxies than observed, an excess that increases to more than two decades for $\kappa = 1.45$. These numbers assume that the $M_{\rm gal}$ vs M_{200} relation has an intrinsic scatter of 0.2 dex, which is actually smaller than we find for our dwarf sample (the average dispersion is 0.6 dex). An increase in scatter would of course exacerbate the excess of low-mass galaxies, given the steepness of the halo mass function. We illustrate this in the right-hand panel of Fig. 4, where the dashed lines assume a scatter of 0.5 dex.

Unless the abundance of dwarfs with $M_{\rm gal} < 10^{8.5}\, M_\odot$ has been dramatically underestimated in optical surveys (a distinct possibility given the difficulty of identifying low-surface brightness, faint objects), we are led to the conclusion that it is not possible to reconcile the low halo masses suggested by the kinematic data with the faint end of the galaxy stellar mass function. One solution would be to postulate a mechanism to single out a small fraction of low mass halos to be galaxy hosts while leaving dark the vast majority of systems of comparable (or even higher) mass. The most obvious mechanisms, such as feedback from stellar evolution and the effects of photoionization, are already included in the semi-analytic models (see, e.g., Fig. 1). A novel mechanism seems required to explain such "stochasticity" in the way dwarf galaxies populate dark matter halos, but has yet to be identified (Boylan-Kolchin et al., 2012).

4 SUMMARY

We have analyzed literature data for a sample of galaxies with spatially-resolved HI rotation curves and good photometry in order to place constraints on their halo masses. Our sample spans 5 decades in galaxy stellar mass, $10^6 < M_{\rm gal}/M_\odot < 10^{11}$, with emphasis on galaxies at the faint end. We focus the analysis on comparing the (mainly dark) total mass enclosed by dwarf galaxies with expectations based on galaxy formation models and cosmological N-body simulations.

Contrary to the general prediction of abundance-matching or semianalytic models of galaxy formation, we find no evidence that dwarfs of widely differing stellar mass are surrounded by halos that span a narrow range in mass. Further, many of the galaxies in our sample have enclosed masses much lower than expected from halos as massive as $10^{10}\, M_\odot$, the characteristic halo mass below which galaxy formation must become extremely inefficient in order to reconcile a shallow faint end of the galaxy luminosity function with the steep dark halo mass function on galactic scales.

If the formation of dwarf galaxies with stellar masses exceeding $10^6\, M_\odot$ extends to halos with masses as low as a few times $10^8\, M_\odot$ then this would lead to a very steep faint end of the galaxy stellar mass function unless a mechanism is found to populate halos with galaxies almost stochastically and with extremely low efficiency. To our knowledge, no obvious candidate exists for such mechanism.

The difficulties could be alleviated if the measured rotation curves underestimate substantially the circular velocity of dwarf galaxies. The magnitude of the correction needed to bring observed velocities into agreement with the models appears too large for this to be a viable alternative. Resorting to baryonic processes to reduce the dark mass enclosed by dwarfs is similarly unappealing, especially considering that the discrepancy is clearest in the least massive systems, some of which contain as few stars as a massive globular cluster. There are simply too few baryons to drive the transfer of energy needed to push substantial amounts of matter out of the center of a massive halo.

A more prosaic alternative is that current observations have missed a large number of faint galaxies, and that the galaxy stellar mass function does indeed have a sharp upturn on mass scales below $10^{8.5}\, M_\odot$. Should future observations fail to uphold this, however, our finding that many dwarf galaxies inhabit halos with virial masses well below $10^{10}\, M_\odot$ would add to the list of concerns brought about by the surprisingly low halo masses inferred for the dwarf spheroidal companions of the Milky Way (Boylan-Kolchin et al., 2011, 2012; Parry et al., 2012) and by the unexpectedly shallow velocity-width function found in blind HI surveys (Zwaan et al., 2010; Papastergis et al., 2011).

A radical view would take the puzzle we note here as indicative of the need to revise some of the basic tenets of the ΛCDM scenario. Models where low mass halos are substantially less concentrated or less abundant, such as in a universe dominated by warm dark matter, for example, might help to resolve the discrepancy. Alternatively, we must concede that our understanding of how dwarf galaxies form in ΛCDM halos is primitive at best, and perhaps flawed. Neither alternative at this point seems particularly palatable.

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