The low mass end of the neutral gas mass and velocity width functions of galaxies in $\Lambda$CDM

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ABSTRACT
We use the high-resolution Aquarius cosmological dark matter simulations coupled to the semi-analytic model by Starkenburg et al. (2013) to study the HI content and velocity width properties of field galaxies at the low mass end in the context of $\Lambda$CDM. We compare our predictions to the observed ALFALFA survey HI mass and velocity width functions, and find very good agreement without fine-tuning, when considering central galaxies. Furthermore, the properties of the dark matter halos hosting galaxies, characterised by their peak velocity and circular velocity at 2 radial disk scalelengths overlap perfectly with the inferred values from observations. This suggests that our galaxies are placed in the right dark matter halos, and consequently at face value, we do not find any discrepancy with the predictions from the $\Lambda$CDM model. Our analysis indicates that previous tensions, apparent when using abundance matching models, arise because this technique cannot be straightforwardly applied for objects with masses $M_{\text{vir}} < 10^{10} M_\odot$.

Key words: galaxies: luminosity function, mass function – galaxies: kinematics and dynamics – galaxies: dwarf – galaxies: halos

1 INTRODUCTION
The observed properties of our universe on large–scales are very well reproduced by the current standard $\Lambda$CDM cosmological model (Komatsu et al. 2011). However, on small scales the paradigm faces a number of challenges that could be related to inherent model flaws or due to our poor understanding and modelling of the physical processes that affect galaxies on these scales.

A well known problem is the excess of low–mass dark matter halos compared with the actual number of visible low–mass galaxies. This discrepancy is commonly known as the CDM overabundance problem or missing satellite problem (Moore et al. 1999; Klypin et al. 1999). One manifestation of this is evident in the faint–end of neutral hydrogen (HI) mass functions (Papastergis et al. 2011) and in galaxy luminosity functions (Klypin et al. 2014). For example, dark matter only simulations predict a slope for the mass–function of $\alpha \sim -1.8$, which is in contrast to the significantly shallower slope $\alpha \sim -1.3$ exhibited for example by the HI mass function of galaxies in the ALFALFA survey (Martin et al. 2010).

The mass and luminosity functions relate to properties of galaxies, but velocity functions are perhaps more revealing because they are connected to the internal properties of the host dark matter halos. Papastergis et al. (2014) and Klypin et al. (2014) have recently drawn attention to the fact that the velocity function of dark matter halos $dN/d \log V \sim V^{\alpha}$ has $\alpha \sim -3$, while observationally $\alpha \sim -1$ for galaxies with circular velocities smaller than ~60 km s$^{-1}$.

Furthermore, it has been pointed out that CDM halos hosting low mass galaxies would be too concentrated in comparison to what can be inferred from observations, such as from rotation curves (Ferrero et al. 2012) or velocity dispersions at the half–light radii of dwarf galaxies (Boylan-Kolchin et al. 2012). This is known as the “too big to fail problem” which has recently drawn a lot of attention in the literature.

We can classify the solutions to these problems in two types: those related to baryonic physics and those that propose changes in the nature of dark matter (see e.g. Kravtsov 2014, for a review). Among the many baryonic effects considered we can mention photoheating during the reionization epoch (e.g. Barkana & Loeb 1999, Bullock et al. 2001, Shapiro et al. 2004) which results in a lower baryon fraction in low mass halos, the inability (or inefficiency) of HI cooling for halos with virial temperature below $10^5 K$ (Haiman et al. 2004), and stellar feedback (e.g. Dekel & Silk 1986; Mac Low & Ferrara 1999). The latter not only acts to lower the baryon fraction in low mass galaxies, possibly preventing further star formation in the lowest mass systems, but may also modify the density profiles of dark matter halos, making them less concentrated (Governato et al. 2012). On the other hand, warm dark matter or self–interacting dark matter models, which effectively result in a suppression in the spectrum of fluctuations of the power on small scales, predict an important reduction in the number of small dark matter halos, and possibly systems with lower central
densities (e.g. Colin et al. 2000; Kamionkowski & Liddle 2000; Bode et al. 2001; Kennedy et al. 2014; Polisensky & Ricotti 2014; Vogelsberger et al. 2014).

Fully cosmological numerical hydrodynamical simulations are just beginning to model reliably these low mass scales, because of the difficulty in addressing simultaneously a large volume with high spatial resolution. Amongst the recent works that have discussed the issues highlighted above is Sawala et al. (2014) who have found that a combination of effects related to reionization and environment introduces strong biases in the halos that host dwarf galaxies, and those that remain dark.

An alternative approach is to use semi-analytic (SA) models combined for example with a very high-resolution cosmological N-body simulation. For galaxies with neutral hydrogen mass \( M_{\text{HI}} \gtrsim 10^5 M_\odot \), Obreschkow et al. (2013) show good agreement between the properties of gas-rich galaxies in the HIPASS survey to the predictions from a SA model coupled to the Millennium dark matter simulation (Springel et al. 2005). For lower masses, and using a different technique, namely abundance matching, Papastergis et al. (2014) argue that the ALFALFA survey should be observing a much larger number of dwarf galaxies given the measured rotational velocities. Along similar lines, Garrison-Kimmel et al. (2014) predict there should be of the order of 1000 galaxies with stellar mass \( M_* > 10^9 M_\odot \) to be discovered within ~ 3 Mpc from the Milky Way (MW). Furthermore, assuming a one-to-one relation between \( M_* \) and \( M_{\text{HI}} \), these authors predict 50 undiscovered gas-rich dwarf galaxies with \( M_{\text{HI}} > 10^5 M_\odot \) within the local volume. However, care must be taken when applying abundance matching at the low mass end (i.e. virial mass \( M_{\text{vir}} < 10^8 M_\odot \)), because this is a regime of strong stochasticity where galaxy formation may or may not take place in halos of similar present-day mass depending on whether they were above or below a given threshold (e.g. for HI cooling) at higher redshift (see Fig. 16 of Li et al. 2010). As we shall see in this Paper (also in Sawala et al. 2014), for virial masses \( M_{\text{vir}} \sim 10^9 M_\odot \) only ~ 50% of the halos are expected to host a galaxy. A simple abundance matching like-technique that only ranks halos by mass around this mass scale will fail (Sawala et al. 2015).

Starkenburg et al. (2013) studied the properties of satellite galaxies around Milky Way-like halos combining a SA model with the Aquarius suite of cosmological simulations (Springel et al. 2008). This model reproduced well the luminosity functions as well as e.g. star formation histories of these systems, and it was found that the “too big to fail” problem could be solved by invoking a lower total mass for the Milky Way of \( \sim 8 \times 10^{11} M_\odot \) (Vera-Ciro et al. 2013). However, the model satellites had too high HI fractions, which was attributed to the lack of ram-pressure stripping of cold gas in the model once a galaxy becomes a satellite (see e.g. Fig. 11 of Li et al. 2010, who use the same SA model but applied to a different cosmological simulation).

Motivated by the recent HI surveys such as HIPASS and ALFALFA that probe the lowest mass ends, and by the relative success in solving a number of problems for low mass satellites, here we use the Starkenburg et al. (2013) model to focus on the faint galaxies in the field. Although the Aquarius simulation high-resolution box is small (~ 2.4 \( h^{-1} \) Mpc on a side), it is large enough to contain several hundred small galaxies whose properties can be contrasted to observations. By focusing on systems in the field, and specifically on central galaxies, we should also be able to establish if the gas content of our galaxies is modelled properly and whether the mismatch found for the satellites is only due to environmental effects.

This paper is organised as follows. We describe the most relevant characteristics of our SA method in Section 2. In Section 3 we compare the luminosity function (LF), HI mass function and the velocity function for the galaxies in the SA model to those in the ALFALFA sample from Papastergis et al. (2014). We explore in this section the reasons behind the success of this comparison, and on the failure of abundance matching methods on the lower mass end. In Section 4, we summarise our results and conclusions.

2 METHODOLOGY

Starkenburg et al. (2013) have used the Aquarius dark matter simulations in combination with a semi-analytic galaxy formation model that stems originally from De Lucia et al. (2004a); Croton et al. (2004b); De Lucia & Blaizot (2007b); De Lucia & Heimdahl (2008); Li et al. (2010). The Aquarius halos were identified in the Millennium-II Simulation (Boylan-Kolchin et al. 2009), a cosmological N-body simulation with the following parameters: \( \Omega_m = 0.25; \Omega_b = 0.75; \sigma_8 = 0.9 \), \( n_s = 1 \), \( h = 0.73 \) and \( H_0 = 100 km s^{-1} Mpc^{-1} \). A series of five zoom-in simulations with progressively higher resolution centered around 6 different Milky Way mass halos were performed, until a particle mass resolution of \( m_p \sim 1.7 \times 10^7 M_\odot \) and spatial resolution of ~ 20 pc were achieved (Springel et al. 2008). The SA model of Starkenburg et al. (2013) follows a number of important physical processes that affect the evolution of a galaxy, including star formation, feedback, cooling, heating, mergers, etc. We briefly describe here in more depth those processes that have an important effect on low-mass galaxies, and refer the reader to the papers mentioned earlier for more details. In summary:

- The feedback model corresponds to the De Lucia et al. (2004) prescription, in which the gas mass that is reheated by supernovae feedback is \( \propto E_{SN}/V_{vir}^2 \Delta M_* \), i.e. it is inversely proportional to the depth of the potential-well (as given by its virial velocity \( V_{vir} \)) and proportional to the amount of newly formed stars \( \Delta M_* \).
- Reionization is modelled following the simulations of Gnedin (2000), who quantified the effect of photoionization/photoevaporation on low-mass haloes. This effectively leads to a reduction in the baryon content in halos below a “filtering mass”, given by \( f_{\text{b,halo}}(z, M_{halo}) = f_b[1 + 0.26 M_{vir}(z)/M_{halo}]^3 \),

where \( f_b = 0.17 \) is the universal baryon fraction. For \( M_{halo} \) the analytical fitting function from Appendix B in Kravtsov et al. (2004) is used. Reionization is assumed to start at redshift \( z_{reion} = 15 \) and end at \( z_e = 11.5 \). Although this may be on the high redshift end of plausible values (Planck Collaboration et al. 2014), it is important to realize that the Aquarius simulations represent an overdense environment in which reionization may well have started earlier.
- Cooling depends on metallicity and temperature of the hot gas. Cooling via molecular hydrogen is assumed to be highly inefficient and prevented by photo-dissociation caused by UV radiation from the stars, especially at early times (Haiman et al. 2000), and in the model it is forbidden for halos below the atomic hydrogen cooling limit, \( T_{vir} = 10^4 K \), where \( T_{vir} = 35.9 (V_{vir}/km s^{-1})^2. \)

\(^1\) The 2nd line in Eq.(B2) of this paper contains a type-setting error, which has been fixed in the version on the arXiv.
• Star Formation in the quiescent mode (as opposed to in star-bursts) is assumed to take place in an exponential thin disc of radial scalelength $r_s$. The mass in cold gas of the disc that is in excess of critical threshold $M_{\text{crit}}$ is transformed into stars:

$$M_{\text{crit}} = 1.14 \times 10^7 (V_{\text{vir}}/20 \text{ km s}^{-1}) (r_s/1 \text{ kpc}) M_\odot,$$  

where this criterion effectively stems from the surface density critical threshold for star formation found by [Kennicutt (1998)]. The value of $r_s$ is calculated as in [De Lucia & Heliu (2008)], assuming conservation of specific angular momentum of the gas as it cools and settles into a rotationally supported disk (following [Mo et al (1998)]. However, it is recomputed at each time-step by taking the mass-weighted average profile of the gas disk already present and that of the new material being accreted.

The luminosities of our galaxies are computed from the stellar masses using stellar population synthesis models from [Bruzual & Charlot (2003), and assuming a Chabrier IMF (Chabrier 2003), as in [De Lucia & Blaizot (2007)].

In what follows we use the Aquarius series of halos resolution level–2 (hereafter, Aq-A-2, Aq-B-2, Aq-C-2, Aq-D-2, Aq-E-2 and Aq-F-2) coupled to our SA model to analyse different galaxy properties and compare them with observations. To assess the numerical convergence of the model we use four resolution levels of the Aq-A halo. Each of these simulations encompass a high–resolution region of radius $\sim 1.2 \text{ Mpc h}^{-1}$ that extends well outside the virial radius of the main Milky Way–like halo. The “field” or (central) halos (i.e. not satellites) located in this region are largely the focus of the current study.

The upper panel of Figure 1 shows the virial mass function of central halos within 1.2 Mpc $h^{-1}$ from the Milky Way–like galaxies for the different Aquarius level–2 halos (coloured lines). The lower panel shows the good convergence of the virial mass function of the Aq-A halo in the four different resolutions. The vertical lines show the different $M_{\text{vir}}$ thresholds above which the mass function has converged for each resolution level. The error bars in these plots, as well as similar figures in the rest of the paper, correspond to galaxies residing in the different Aquarius level–2 simulations. The inclusion of satellites in the models does not lead to a drastic change in the shape or normalisation of the luminosity function and satellite galaxies still embedded in their own subhalo, the average normalisation factor is, as expected, only slightly different, with $\log f = 0.8$. Depending on the systems shown, these normalisations are also applied in Figures 3 and 5. The black lines in the bottom panel of Figure 2 show how well the luminosity function has converged by comparing the results for the four different resolutions for central galaxies in the Aq-A series.

Many studies have estimated the luminosity function in the field (e.g. [Norberg et al 2002; Bell et al 2003; Blanton et al 2005; Trujillo-Gomez et al 2011]). However, for the current study it is important to know its shape at the faint end. This is why we compare here to the luminosity function derived by [Klypin et al (2014)]. These authors have used the current version of Updated Nearby Catalog (Karachentsev et al 2013) which contains 869 galaxies with redshift-independent distances $D < 11 \text{ Mpc}$ and radial velocities with respect to centroid of the Local Group $V_{\text{LG}} < 600 \text{ km s}^{-1}$. We focus on the subsample with distances $D < 10 \text{ Mpc}$, which comprises 733 galaxies, of which 652 objects are brighter than $B$–band absolute magnitude $M_B = -10$ and 426 are brighter than $M_B = -13$. The grey filled circles in Figure 2 represent the resulting luminosity function, while the dotted grey curve presents a Schechter fit to this sample for galaxies with $M_B < -14$, with the following Schechter parameters: $\phi^* = 1.25 \times 10^{-3} h^2 \text{ Mpc}^{-3}$, $\alpha = 1.3$ and $M_{\text{lim}} = -20.0 + 5 \log(h)$ (Equation (2) of [Klypin et al (2014)].

This comparison shows that there is reasonable agreement between our model and the field luminosity function for $M_B < -14$. The inclusion of satellites in the models does not lead to a drastic change in the shape or normalisation of the luminosity function,
especially if we consider the important scatter from simulation to simulation. This is a consequence of the small volume (and hence relatively small number of objects) of the high–resolution region of the Aquarius halos. Coupled to possible incompleteness in the data for galaxies with $M_B > -12$, and the somewhat arbitrary normalisation, it is hard to argue that the modelling needs any improvement.

3 RESULTS ON THE HI MASS FUNCTION AND VELOCITY FUNCTION

3.1 Neutral hydrogen (HI) mass function

Figures 1 and 2 confirm that the virial mass function of halos and the luminosity function of galaxies have very different slopes at the low mass end. To further explore this difference we now focus on the HI mass function. This offers an independent test of the model because in low mass systems the baryonic budget is dominated by gas rather than by stars.

In the upper panel of Figure 3 we show the HI mass functions of central galaxies for all six Aquarius level–2 halos, for which $M_{HI} > 10^{5.5} M_\odot$ and located, as before, in the high–resolution box around the main Milky Way–like galaxies. Each colour corresponds to different resolutions and again indicate very good convergence.

Martin et al. (2010) have derived the HI mass function from a sample of $\sim 10^6$ extragalactic sources comprising the ALFALFA 40% survey (hereafter a-40), with $6.2 < \log(M_{HI}/M_\odot) < 11.0$. These are plotted as the grey filled circles in Figure 3. The grey dotted line is the Schechter function fit to this dataset with the parameters: $\phi^* = 0.0048$, $\log(M_*) = 9.96$ and $\alpha = -1.33$. The grey dotted line at the upper right–hand corner is the halo mass function. Lower panel: HI mass function of the Aq-A halo for four different resolutions for central galaxies within 1.2 Mpc $h^{-1}$ from the MW (black lines). We use different $M_{HI}$ thresholds for each resolution.

Figure 3. Upper panel: HI mass function of central galaxies for all six halos of Aq-2, with $M_{HI} > 10^{5.5} M_\odot$ and within 1.2 Mpc $h^{-1}$ from the MW (colour solid lines). The dashed curve shows the HI mass function for central galaxies containing both stars and gas, while the dot-dashed curve includes also satellite galaxies. Grey filled circles represent the HI mass function estimated while the grey dotted line is the Schechter function fit: $\phi^* = 0.0048$, $\log(M_*) = 9.96$ and $\alpha = -1.33$ (Martin et al. 2010). The grey dotted line at the upper right–hand corner is the halo mass function. Lower panel: HI mass function of the Aq-A halo for four different resolutions for central galaxies within 1.2 Mpc $h^{-1}$ from the MW (black lines). We use different $M_{HI}$ thresholds for each resolution.

of central galaxies for all six Aquarius level–2 halos, for which $M_{HI} > 10^{5.5} M_\odot$ and located, as before, in the high–resolution box around the main Milky Way–like galaxies. Each colour corresponds to a different halo. The black-dashed line shows the HI mass function for central systems that have both cold gas and stars, and is the average over all Aquarius level–2 halos. It evidences that many objects with cold gas (with $M_{HI} < 10^6 M_\odot$) have not been able to form any stars (see discussion below). The dot-dashed curve represents the corresponding HI mass function but now including both central and satellite galaxies, i.e. these are the counterparts of the objects shown in the top panel of Fig. 4. Note that the two curves follow each other relatively well, and are only offset by $\sim 0.2$ dex at $M_{HI} \sim 10^{6} M_\odot$. This difference, due to satellite galaxies baring HI, is relatively small in comparison to the scatter from simulation to simulation. The black lines in the bottom panel of this figure show the HI mass function of the Aq-A halo for the four different resolutions and again indicate very good convergence.

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The top panel of Figure 3 shows that there is good agreement between the observed HI mass function of galaxies with...
end our simulation box is too small and does not contain enough galaxies. There are, in fact, three comparisons to be made: i) with all central galaxies (including those without a stellar component, the coloured curves); ii) with central systems that host a luminous galaxy (dashed black curve); and iii) with centrals and satellites hosting a luminous galaxy (dot-dashed curve). One of the reasons to consider these three classes separately rests on our aim to establish if the HI contents of central galaxies (in the field) are consistent with observations, in particular in relation to gauging the impact of environmental effects such as ram pressure stripping on satellites. Note that in all cases, at the high–mass end our simulation box is too small and does not contain enough galaxies, as evidenced by the large error bars in this figure.

The first point to note is the relatively large scatter from simulation to simulation at intermediate masses for central galaxies, although all curves are consistent within 1σ of each other, and on average also consistent with the observed HI mass function. However, since most objects observed in the ALFALFA survey actually have an optical counterpart (see e.g. [Haynes et al. 2011]), a better comparison to make is to the dashed black curve, representing central luminous galaxies. We note the excellent agreement with the observations at these masses, although for masses \( M < 10^6 \, M_\odot \), the predicted HI mass function appears to decline to a point that may be in tension with the observations. On the other hand, it is possible that satellite galaxies are present in the observational sample. As expected, when these are included in the predicted HI mass function, there is an increase in the number of objects although the agreement with the observations is still very reasonable. This implies that ram pressure stripping, although it should be included when modelling the properties of satellite galaxies, will not result in dramatic changes that will break-down the good agreement between the models and the observations, at least for the range of masses probed by the latter.

More careful comparisons, especially regarding the low mass end of the HI mass function and the presence of systems without a stellar counterpart, are necessary. It will be important to have both deeper surveys in HI as well as in the optical, as these will allow us to establish whether the trends predicted are correct.

In the top panel of Figure 4, we have plotted the B–band absolute magnitude against the virial mass for all the 173 central galaxies in the high–resolution region of the Aquarius halos. The panel below shows the HI mass against the virial mass for all these galaxies as red circles, while the open circles denote objects that according to our SA model have not formed any stars (\( M_\ast = 0 \)) but do contain cold gas. There are 315 such objects with \( M_\text{crit} \geq 10^{5.5} M_\odot \). The reason such systems do not form stars is because their surface gas density is below the threshold for star formation imposed by our model.

An estimate of the dependence of the critical mass on the virial mass of objects can be obtained using Eq. (3). In that equation, we replace the disk radial scalelength by \( r_d = \lambda r_{\text{vir}} \sqrt{2} \) where \( \lambda \) is the dimensionless spin parameter (which we take to be \( \sim 0.035 \)) and \( r_{\text{vir}} \) the virial radius of the host halo. As explained earlier, this scale is obtained assuming conservation of specific angular momentum, and that when hot gas cools at the centre of dark matter halos, it settles in a rotationally supported disk (Mo et al. 1998). The value of \( r_d \) will typically be larger than \( r_{\text{vir}} \), because the latter is a mass-weighted average over the whole gas cooling history of the system. Therefore \( M_\text{crit} \) obtained in this way will be overestimated in general. Nonetheless, this rough zero order approximation of the critical mass is plotted as the line in the bottom panel. This comparison serves to tentatively support our claim that the density of cold gas in lower mass objects is too low to allow star formation taking place.

3.2 Velocity function

So far we have compared the observed global baryonic properties of galaxies to those in our models. An additional important complementary aspect concerns the internal dynamics of galaxies, which links the galaxies to their host dark matter halos. A fundamental question that potentially relates to the nature of dark matter, is whether the galaxies in the SA model are hosted by the right dark matter halos in the simulations.

This is why we now focus on velocity function, namely the abundance of galaxies with a given circular velocity (Cole & Kaiser 1989; Shimazaki 1993; Gonzalez et al. 2000; Zavala et al. 2009; Trujillo-Gomez et al. 2011). To measure circular velocities for large numbers of galaxies is challenging, but wide-area single-dish 21 cm surveys are making this possible. Although ideally one would like to obtain full rotation curves for a large number of
systems spanning a large range in galaxy mass, this is too time-consuming to be currently feasible. Therefore, what is rather used is the peak of the spectral HI line profile \( w \). This is believed to be close to the peak rotational velocity of the system at approximately two radial scale-lengths.

Papastergis et al. (2011) have measured the velocity width function (WF) of HI-bearing galaxies down to \( w = 20 \text{ km s}^{-1} \) in the ALFALFA survey. This WF is based on 10,744 HI-selected galaxies from the \( \alpha \)-40 survey (a more than twofold increase over previous data sets), so it is the largest HI–selected sample to date.

For each dark matter halo in the Aquarius suite (Springel et al. 2008) has derived the peak circular velocity \( V_{\text{rot}} \) and the circular velocity at the virial radius \( V_{\text{vir}} \) as well as the location of the peak \( V_{\text{max}} \) and the virial radius \( r_{\text{vir}} \). With this information, and assuming an NFW shape, we may derive the full form of the rotation curve. Furthermore, we may derive \( V_{\text{rot}} \) i.e. \( v_r(2r_d) \) using the value of \( r_d \) as determined from our SA model.

To compare this data with the results of Papastergis et al. (2011), we convert rotational velocities into HI velocity widths by assuming the relationship given by Equation (4) of Papastergis et al. (2011):

\[
w = 2v_{\text{rot}} \sin i + w_{\text{eff}}
\]

This equation indicates that the galaxies are randomly oriented with respect to the line of sight (cos \( i \) is uniformly distributed in the [0, 1] interval), while \( w_{\text{eff}} \) is a small "effective" term used to reproduce the broadening effect of turbulence and non-circular motions on HI linewidths. Following Papastergis et al. (2011) we consider \( w_{\text{eff}} = 5 \text{ km s}^{-1} \) for the broadening term, which is added linearly for galaxies with \( v_{\text{rot}} > 50 \text{ km s}^{-1} \) and in quadrature for lower velocity galaxies.

Figure 5 shows the resulting velocity width function of the same central galaxies as in previous plots, with \( M_{\text{vir}} > 10^4 \text{ M}_\odot \) and with \( M_{\text{vir}} > 10^{5.5} \text{ M}_\odot \) for the all six halos of resolution level–2 (coloured lines). The dashed curve is the average over all size Aquarius halos taking into account only those systems hosting also stars. Grey filled circles represent the measured ALFALFA WF, and dotted grey curve represents the fit of the modified Schechter function: \( \phi = 0.011 h^3_{\text{in}} \text{Mpc}^{-3} \text{dex}^{-1} \), \( log w_r = 2.58 \), \( \alpha = -0.85 \) and \( \beta = 2.7 \) (Papastergis et al. 2011). The agreement between the predictions of the model and the observations is quite good. It shows that our model places galaxies of the right baryonic content (in stars and in HI gas) in the "right" dark matter halos. Contrary to previous work (see e.g. Papastergis et al. 2014, and references therein), our model does not present an excess of luminous galaxies with too low velocity widths compared to the observations. The resulting function has a similar slope as observed.

It is interesting to note that in our model, those systems with cold gas but lacking stars, lead to an excess above the Schechter function that fits so well the luminous galaxies in our model. This excess only appears for \( log w \sim 1.2 - 1.5 \), which is right around, and slightly below the limit of the ALFALFA survey.

### 3.3 Zooming into the properties of galaxies and their host halos

Our models do not appear to have a significant excess of halos hosting galaxies of a given velocity width \( w \) at the faint/low mass end. To understand further this result we now zoom into the properties of the halos hosting galaxies.

Papastergis et al. (2014) analysed the kinematics of a sample of gas–rich dwarf galaxies extracted from the literature. They derived \( V_{\text{rot}} \) by making inclination corrections using SDSS images, and estimated the value of \( V_{\text{max}} \) by considering the most massive halo that is consistent with the last measured point of the rotation curves available for these galaxies.

In Figure 5 we show the distribution of \( V_{\text{rot}} \) vs \( V_{\text{max}} \) for this dataset (grey solid points) as well as for the central dark matter halos hosting our model galaxies (red circles). With black open circles with indicate those systems in our model that have \( M_c = 0 \) but \( M_{\text{vir}} > 10^7 \text{ M}_\odot \), i.e. they are devoid of stars, and hence would not be in the observational compilation of Papastergis et al. (2014). The blue curve shows the relation predicted by abundance matching according to Papastergis et al. (2014).

This comparison is extremely satisfactory and confirms again that model galaxies are placed in the right host dark matter halos. No discrepancies are found, and there is no evidence from this plot that the dark matter halos in the simulations would be too massive or too dense to host the observed galaxies.

However, this is in tension with the naive conclusion that one would have drawn from comparing the observations to the predictions of abundance matching. It is important therefore to understand why the galaxies in our model do not follow the predictions of abundance matching. Equally important it is to understand why only halos with \( V_{\text{max}} > 20 \text{ km s}^{-1} \) host luminous galaxies.

The reason that abundance matching does not work at the low mass end of the halo spectrum is that the ability of a halo to host a galaxy depends on its capacity to i) retain the baryons; ii) cool gas from the hot phase; and iii) have enough cold gas at high density for...
star formation. These conditions are redshift dependent, and hence the virial mass or velocity at the present–day are not sufficient to establish whether a halo will host a galaxy (unless this mass is significantly different from the various thresholds). Of the halos that are near the thresholds for these physical processes to take place, some fraction will satisfy these requirement, and this fraction is not fully random, and is not mass ranked (as in abundance matching) but depends on the specific history of the halo.

This point is made clear by considering the fraction of central halos that host galaxies as a function of virial mass. This is plotted in Figure 7 where the fraction of galaxies with \( M_\ast > 10^9 M_\odot \) at a given \( M_{\text{vir}} \) is indicated by the solid line, and the fraction of systems with \( M_{\text{HI}} > 10^9 M_\odot \) is given by the dashed line. From this figure we see that all halos with \( M_{\text{vir}} > 10^{10} M_\odot \) host luminous galaxies, while only 50% of those with \( M_{\text{vir}} \approx 10^9 M_\odot \) do. On the other hand, this function is shifted to lower masses if we consider the systems with cold gas: 50% of the halos with \( M_{\text{vir}} = 10^9 M_\odot \) contain HI. This shift is present because, not only must a halo be able to cool gas but in order to form stars, this gas must be above the threshold for star formation. It is also interesting that these functions are not exactly steps, and this is a manifestation of the various processes at work which have different thresholds, as discussed above.

Figure 8 shows the \( V_{\text{vir}} \) vs \( V_{\text{max}} \) for the central model galaxies as red circles, the systems with no stars but with \( M_{\text{HI}} > 10^9 M_\odot \) as open black circles, and the dark matter halos without baryons as grey crosses. This demonstrates clearly that virial velocity today \( V_{\text{vir}} \) is not enough to predict if a halo will host a luminous galaxy. It also shows that at a given \( V_{\text{vir}} \), luminous galaxies are hosted in halos with higher \( V_{\text{max}} \). This implies that for a given \( V_{\text{vir}} \) these are the most concentrated halos since for a NFW halo:

\[
V_{\text{max}} = 0.465V_{\text{vir}} \left( \frac{c}{f(c)} \right)^{1/2}
\]

and

\[
f(c) = \ln(1 + c) - c/(1 + c)
\]

Figure 6. Distribution of \( V_{\text{rot}} \) vs \( V_{\text{max}} \) for the dataset from Papastergis et al. (2014) (grey solid points), for the dark matter halos hosting our model galaxies (red circles), and for systems in our model that have \( M_\ast = 0 \) but \( M_{\text{HI}} > 10^9 M_\odot \) (black circles). The blue curve shows the relation predicted by abundance matching given by Papastergis et al. (2014). The luminous central galaxies in our model occupy the same region as the observations. Note that for \( V_{\text{max}} > 100 \) \( \text{km s}^{-1} \), the rotational velocities of the observed galaxies are systematically higher. This merely reflects that the baryon contribution (which is not taken into account for the model galaxies), is non-negligible for these systems.

Figure 7. Fraction of halos hosting a luminous galaxy with \( M_\ast > 10^9 M_\odot \) (solid) and halos with more than \( 10^9 M_\odot \) HI gas (dashed) as function of \( M_{\text{vir}} \).

Figure 8. Distribution of \( V_{\text{rot}} \) vs \( V_{\text{max}} \) for the central dark matter halos hosting our model galaxies (red circles), for systems in our model that have \( M_\ast = 0 \) but \( M_{\text{HI}} > 10^9 M_\odot \) (black open circles) and for completely dark halos (grey crosses).

where \( c = r_{\text{vir}}/r_s \) is the concentration, with \( r_s \) the scale radius of the halo.

These more concentrated halos will have typically collapsed earlier, implying that they reach a higher mass at earlier times which therefore increases their likelihood of being above e.g. the HI cooling limit at which point they can start forming stars if they have retained enough baryons (after photoevaporation).

This also explains why the hosts of luminous galaxies are to the left of the abundance matching curves, since

\[
\frac{V_{\text{rot}}^2}{V_{\text{max}}^2} = 4.63 \frac{f(x)}{x}
\]

where \( f(x) \) is given by Eq. 6 with \( x = 2r_{\text{vir}}/r_s \). In general, we can assume that \( x \approx 2 \) (i.e. \( r_{\text{vir}} < r_s \)), in which case \( f(x)/x \) increases with increasing \( x \). This implies that for fixed \( r_s \), galaxies with smaller \( r_{\text{vir}} \) (i.e. in more concentrated halos), have larger \( V_{\text{rot}}/V_{\text{max}} \). In other words \( V_{\text{max}} \) at fixed \( V_{\text{vir}} \) is lower for more concentrated halos. This highlights that for abundance matching to work, it is important to select halos that are most concentrated amongst those that are near the thresholds.

Figure 6 shows that dark halos (grey crosses) have \( V_{\text{vir}} > 20 \) \( \text{km s}^{-1} \), which is consistent with the fact that the HI cooling limit is \( V_{\text{vir}} \approx 16.7 \) \( \text{km s}^{-1} \). Eq. 6 explains why basically all objects with \( V_{\text{max}} \approx 20 \) \( \text{km s}^{-1} \) are dark, as the function \( \sqrt{c/f(c)} \) is
weakly dependent on c. Since halos hosting luminous galaxies are on average in more concentrated halos as discussed above, their $V_{\text{max}}$ is higher as seen in this figure.

### 4 CONCLUSIONS

We have used the high-resolution Aquarius cosmological dark matter simulations in combination with the semi-analytic model by Starkenburg et al. (2013) to study the HI content and dynamical properties of galaxies at the low mass end in the context of the cold dark matter paradigm. We have compared our predictions to the observed ALFALFA survey, and found excellent agreement with the HI mass and velocity width functions measured by this survey for central galaxies, down to the lowest mass scales probed. Implicit in this conclusion, is our assumption that luminous satellite galaxies do not contribute significantly to these HI distribution functions. This is based on the fact that even if these systems are considered when computing the model HI mass function, we still find good agreement with observations, and the same is true for the luminosity function. Therefore, even if we do not include the effect of ram pressure stripping in our models explicitly, we argue that its effect will not lead to dramatic changes in the properties of galaxies. This is because the gas that is present in these systems is too diffuse to contribute to star formation, and hence have an impact on the evolution of these objects.

We have also studied the relation between two global parameters of the circular velocity curves of the galaxies in our models and in the ALFALFA survey, namely between their peak velocity and circular velocity at 2 radial disk scalelengths. The distribution found in our models overlaps perfectly with that inferred from observations. This suggests that our galaxies are placed in the right dark matter halos, and consequently and at face value we do not seem to find any discrepancy with the predictions from the ΛCDM model.

Our model predicts the existence of a population of HI halos that do not have a stellar counterpart (e.g. Salvadori & Ferrara 2012). The exact abundance of these objects is likely to depend rather strongly on the implementation of star formation in the models, including whether cooling below $10^4 K$ is allowed (via $H_2$) and on the critical density floor for star formation. Although these objects are relatively gas-rich, their cold gas is too diffuse. Furthermore, their baryon fraction is well below universal, since typically $f_b < 0.01$, reflecting the fact that they lost an important fraction of baryons because of photoevaporation during reionization.

We are grateful to Manolis Papastergis and Simon White for interesting discussions and the Aquarius project members, especially toVolker Springel. We are also indebted to Gabriella De Lucia and Yang-Shyang Li for the numerous contributions in the development of the semi-analytic code used here. The referee, Darren Croton, is acknowledged for a very positive and constructive report that has helped improve the manuscript. This work has been partially supported by the Consejo de Investigaciones Científicas y Técnicas de la República Argentina (CONICET), by the Secretaría de Ciencia y Técnica de la Universidad Nacional de Córdoba (SeCyT) and by the European Commissions Framework Programme 7, through the International Research Staff Ex-change Scheme LACEGAL. AH acknowledges financial support from the European Research Council under ERC-StG grant GALACTICA-240271. AH and MA acknowledge grant PICT1137 from FONCYT Argentina. ES acknowledges partial funding from the Canadian Institute for Advanced Research (CIFAR).

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