Where Are All of the Gas-bearing Local Dwarf Galaxies? Quantifying Possible Impacts of Reionization

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Abstract

We present an approach for comparing the detections and non-detections of Local Group (LG) dwarf galaxies in large H I surveys to the predictions of a suite of n-body simulations of the LG. This approach depends primarily on a set of empirical scaling relations to connect the simulations to the observations, rather than making strong theoretical assumptions. We then apply this methodology to the Galactic Arecibo L-band Feed Array Hi (GALFA-HI) Compact Cloud Catalog (CCC), and compare it to the suite Exploring the Local Volume In Simulations (ELVIS) of simulations. This approach reveals a strong tension between the naive results of the model and the observations: while there are no LG dwarfs in the GALFA-HI CCC, the simulations predict ~10. Applying a simple model of reionization can resolve this tension by preventing low-mass halos from forming gas. However, and if this effect operates as expected, the observations provide a constraint on the mass scale of the dwarf galaxy that reionization impacts. Combined with the observed properties of Leo T, the halo virial mass scale at which reionization impacts dwarf galaxy gas content is constrained to be ~10^8.5 M_☉, independent of any assumptions about star formation.

Key words: dark ages, reionization, first stars – dark matter – galaxies: dwarf – Local Group

1. Introduction

Dwarf galaxies of the Local Group (LG) provide uniquely faint limits, yielding a similarly unique range of constraints on galaxy formation and cosmology. These constraints typically hinge on connecting simulations in an assumed cosmology (usually the concordance ΛCDM cosmology) to a particular model of galaxy formation, and comparing that in some manner to observations. This general approach has led to a number of unexpected findings (e.g., Klypin et al. 1999; Moore et al. 1999; Kravtsov 2010; Boylan-Kolchin et al. 2011; Brooks & Zolotov 2014). However, these approaches have tended to focus on the stellar component of LG dwarfs and their model equivalents. While this is a practical approach given that most dwarf galaxies of the LG are passive and lack gas (Greevich & Putman 2009; Spekkens et al. 2014), the dwarf galaxy Leo T demonstrates that even ultra-faint dwarfs can have gas even to the present day (Ryan-Weber et al. 2008). Hence, it is important to consider what additional constraints may be gained by investigating the presence or absence of gas-bearing galaxies.

Recent advancements have improved the prospects for such investigations, especially in tracking the diffuse gas traced by H I. With the installation of the Arecibo L-Band Feed Array (ALFA) at the William E. Gordon 305 m antenna at the Arecibo Observatory, the rate at which Arecibo can survey the 21 cm line of H I has increased nearly seven-fold. Arecibo provides the sensitivity of a single-dish instrument unavailable to radio interferometers with an angular resolution (∼1 kpc for objects 1 Mpc away) that is unavailable to smaller single-dish observatories. Therefore, the surveys conducted with ALFA provide the best available data sets for searching for these gas-rich dwarf galaxies in the LG. These surveys, tuned to compact H I clouds, have found interesting populations of Galactic disk clouds mixed in with dwarf galaxy candidates. Some of these have later been confirmed to be galaxies beyond the LG (Saul et al. 2012; Sand et al. 2015; Tollerud et al. 2015). This suggests that such H I surveys may be useful for improving the understanding of nearby dwarf galaxies.

A major uncertainty to any investigation of the gas (or stellar) content of low-mass galaxies is the impact of reionization. Theory and simulations strongly suggest that dwarf galaxies with dark matter halos of low enough mass are significantly affected by reionization, dramatically altering how the galaxies form (e.g., Barkana & Loeb 1999; Okamoto et al. 2008; Ricotti 2009). This can have major observational consequences, such as explaining the relatively small number of dwarf galaxies in the LG compared to the number of subhalos that are seen in ΛCDM simulations (e.g., Bullock et al. 2000). While it is strongly suspected that these impacts are important, the details of these effects, particularly when and at what mass scale the effects become important, are not at all clear. In this work, we investigate whether simply positing the presence of such an effect combined with the empirically observed H I content of LG dwarf galaxies can provide independent constraints on the impacts of reionization on dwarf galaxies and their dark matter halos.

This paper is organized as follows: In Section 2, we describe the Galactic Arecibo L-band Feed Array H I (GALFA-HI) survey and the compact high-velocity H I clouds it has identified as dwarf galaxy candidates. In Section 3, we describe optical searches for dwarf galaxies near the H I clouds described in Section 2. In Section 4, we describe a method for creating mock sets of GALFA-HI Compact Cloud Catalog (CCC) galaxies, using the Exploring the Local Volume In Simulations (ELVIS) suite of simulations. In Section 5, we describe how the combination of all of the above provides constraints on the scale at which reionization strips gas from dwarf galaxies, and in Section 6, we conclude. To allow reproducibility, the analysis software used for this paper is available at https://github.com/eteq/galvis.
2. GALFA-HI and Its Compact Clouds

The GALFA-HI survey comprises observations of neutral hydrogen with the 21 cm line taken with the 305 m William E. Gordon telescope located in Arecibo, Puerto Rico. These observations began in 2004 with the installation of ALFA, which provided an almost seven-fold increase in mapping speed over the L-band wide feed. GALFA-HI observations have an angular resolution of 4′ and a spectral resolution of 0.184 km s⁻¹, over the velocity range −650 to +650 km s⁻¹ LSR. This work relies on the observations compiled into the GALFA-HI Data Release 1 (DR1): 3046 hr of observations covering 7520 deg² of sky between decl. −1° and 38° (Peek et al. 2011).

Saul et al. (2012) used GALFA-HI DR1 to generate a catalog of 1964 compact H I clouds using a template-matching technique, the GALFA-HI CCC. The search was designed to be sensitive to clouds smaller than 20′ and with linewidths between 2.5 and 35 km s⁻¹. The sensitivity of the search was measured empirically through a signal injection approach (Section 3.3 of Saul et al. (2012)). Simulated clouds were injected with a range of positions, velocities, linewidths, sizes, aspect ratios, and brightnesses and the detection algorithm run. It was found that a rather simple function of these parameters was able to reliably predict whether the search algorithm could find a given cloud.

Saul et al. (2012) divided the 1964 clouds in the CCC into a number of categories based on their linewidth, position, and velocity. Among these categories, we are interested in two in particular, which contain all 719 the of the clouds with |v_LSR| > 90 km s⁻¹. All clouds that are close in position–velocity space to large high-velocity clouds (HVCs) known in the Wakker & van Woerden (1991) catalog are categorized as HVCs, while those far from these clouds are called “Galaxy Candidates.” This distinction was made under the assumption that small H I clouds near larger high-velocity clouds are much more likely to be HVCs than to be galaxies. Practically, this proximity is quantified using the parameter

\[ D = \sqrt{\Theta^2 + f^2 (\delta v)^2}, \]

where \( \Theta \) is the angular distance between two clouds, \( \delta v \) is the LSR velocity difference, and \( f \) is 0.5 km s⁻¹ s (Peek et al. 2009). For each cloud in Saul et al. (2012), this parameter is measured against all HVCs in the Wakker & van Woerden (1991) catalog, and those clouds with minimum \( D > 25° \) are classified as Galaxy Candidates. This procedure finds a total of 27 such candidates.

This method of distinguishing between likely HVCs and possible dwarf galaxies is supported by work by Donovan Meyer et al. (2015), who showed that including \( D < 25° \) clouds diluted an H I-based search for more distant UV-bright galaxies. Our goal in this work is to identify which of these candidates are actually LG dwarf galaxies (Section 3), and create a mock version of this survey using simulations in an appropriate cosmological context (Section 4).

3. Dwarf Galaxies in GALFA-HI

The set of Galaxy Candidates we describe in Section 2 require follow-up to determine which, if any, have optical galaxies within the GALFA-HI beam. It is precisely this that was the goal of the surveys described in Tollerud et al. (2015) and Sand et al. (2015). These samples, as described in greater detail in P. Bennet et al. (2018, in preparation), observed the GALFA-HI CCC Galaxy Candidate fields and resolve stars to a depth of ~2 mag deeper than Sloan Digital Sky Survey (SDSS). These surveys determined that five have optical counterparts that are likely nearby galaxies, but they are at 2−10 Mpc (Tollerud et al. 2016), placing them in the Local Volume (LV) rather than the LG.

While the description above focuses on new unknown galaxies, the GALFA-HI footprint also contains nearby dwarf galaxies that are not in the CCC simply because they were previously-known. Specifically, Sextans B, GR 8, and KKH 86 are in the GALFA-HI footprint. However, as with the confirmed galaxy candidates described above, and as discussed in more detail in McConnachie (2012, Figure 5), all three of these galaxies are clearly in the Hubble Flow (both by distance and velocity), and therefore not a part of the LG.

Hence, while there is a large set of GALFA-HI CCC Galaxy Candidates, no H I-bearing LG galaxies exist in the GALFA-HI footprint. This then raises the question of whether or not such galaxies might be expected by galaxy formation in an appropriate cosmological context. It is to this question that we turn in the following sections.

4. Constructing a Mock GALFA-HI Survey

We begin by asking how many dwarf galaxies we would expect in GALFA-HI given a simple set of galaxy formation and cosmological assumptions (i.e., ΛCDM). We start with the assumption that all dwarf galaxies are contained inside of dark matter halos (e.g., Willman & Strader 2012). This allows our starting point to be ΛCDM halo catalogs in an environment comparable to the LG.

The specific set of halo catalogs we use for this experiment are taken from the Exploring the Local Volume In Simulations (ELVIS) suite (Garrison-Kimmel et al. 2014). These simulations were designed to simulate environments similar to the LG in the sense of having two \( M_{\text{halo}} \sim 10^{12} \) halos at distances and relative velocities similar to the Milky Way (MW) and M31. We use this suite of simulations, because accounting for both \( \sim M_* \) galaxies of the LG is critical: a significant part of the GALFA-HI footprint is in the direction of the M31 halo on the sky. Garrison-Kimmel et al. (2014) demonstrated that the non-satellite dwarf galaxy halos in LG-like environments are significantly different than individual isolated \( \sim M_* \) halos. Hence, including both galaxies in their correct orientations relative to the simulated GALFA-HI footprint is important for generating a realistic estimate. The ELVIS suite provides just this, with 12 LG-like analogs (i.e., 24 total \( \sim M_* \) galaxies and their attendant dwarf halos).

The ELVIS suite comprises dark matter-only simulations. GALFA-HI is only sensitive to \( M_{\text{HI}} \) (and our optical observations detected \( M_* \)), so we must impose some model on the simulations to determine the observables for a given dark matter halo in ELVIS. Such models can span a wide range of complexity and assumptions, from full cosmological hydrodynamic simulations to basic semi-analytic approaches (e.g., Stewart et al. 2009; Benson 2012; Rodríguez-Puebla et al. 2012; Sawala et al. 2014; Snyder et al. 2015; Wheeler et al. 2015). Here, we consider a simple, primarily empirical model. While such a model is unlikely to capture the complex physics of galaxy formation in detail, our goal is a rough comparison with the GALFA-HI observables; a detailed
investigation of galaxy formation models is beyond the scope of this work. Our model is as follows: we begin with positions, velocities, and halo masses provided in the public data release of ELVIS.1 To obtain stellar masses for each halo, we apply the abundance-matching-based halo-to-stellar mass relation of Garrison-Kimmel et al. (2014) to obtain $M_{*,\text{halo}}$ for each halo. This has the specific advantage of being calibrated to both the LG and ELVIS, precisely the two data sets we are interested in here. For considerations of completeness of our optical follow-up, we convert to luminosity assuming a mass-to-light ratio of unity and a standard $r$-band bolometric correction.2 To determine $M_{\text{HI}}$, we then use the $M_{*,\text{halo}}$ in combination with the $M_{*,\text{halo}}$-$M_{\text{gas}}$ relation of Bradford et al. (2015). We convert this relation from $M_{\text{gas}}$ to $M_{\text{HI}}$ by inverting the procedure described in Bradford et al. (2015). This procedure is straightforward as the observations from that work are also $H_1$ observations. In Figure 1, we show this $M_\text{*,HI}$ relation (black lines), along with LG dwarf galaxies with $H_1$ from MacConnachie (2012)) and limits from Spekkens et al. (2014). This figure demonstrates that, even beyond where it is calibrated, the Bradford et al. (2015) is consistent with the LG dwarfs (although with scatter comparable to the Bradford et al. 2015 data set). While there may be a small bias in the relation relative to the LG, the MacConnachie (2012) compilation is inhomogeneous enough that we opt to stick with the Bradford et al. (2015) extrapolation with no corrections, as it is a much more homogeneous data set. We also see, from the Spekkens et al. (2014) data set, that satellites in the LG are clearly $H_1$ deficient relative to the Bradford et al. (2015) relation. This fact motivates our choice to remove satellites from the mock GALFA-HI CCC galaxies, described in greater detail below.

The above procedure results in a set of 12 halo catalogs of LG analogs, with halo, stellar, and $H_1$ masses for each. We now describe how we convert these catalogs into mock CCC galaxies that would be found in mock GALFA-HI surveys.

The first step is identification of the massive halos in the catalog with the MW and M31. While the LG total mass is relatively well constrained and the MW and M31 are clearly dominant, exactly how to apportion the mass between the two is relatively uncertain (e.g., Klypin et al. 2002; Watkins et al. 2010; Tollerud et al. 2012; González et al. 2014; Peñarrubia et al. 2014). Hence, to marginalize over this uncertainty and at the same time boost our count of mock surveys, we create a mock GALFA-HI footprint twice for each ELVIS pair, swapping which large halo hosts the MW and M31. While this does reuse some of the same halos twice, the details of detectability and different distances from the two hosts means that each mock survey is a different sample, and there is therefore a relatively weak covariance between the two mock surveys from the same ELVIS pair. While the presence of weak covariance means these are not 24 completely independent samples, the weakness of the covariance means there is substantially more power in using all of the halos individually instead of only one of each pair. Hence, the procedure described below is repeated for each of the 24 MW/ M31 pairs to produce our ensemble of mock surveys.

For each pair, we fix the orientation of the halos on the mock sky by placing the mock Earth in the unique position and orientation where the distance to the center of the MW halo is 8.5 kpc (IAU standard), the center of the MW halo is in the direction of the origin, and the center of the M31 halo is in the direction of $l = 121^\circ 17$, $b = -21^\circ 57$ (M31 in Galactic coordinates). In that orientation, we add a 220 km s$^{-1}$ velocity offset to each halo in the $l = 90^\circ$ direction to model the Sun’s motion around the Galactic center (IAU standard). This yields a mock survey footprint in Galactic coordinates with spatially variable depth and velocities and distances as would be observed from the real Earth.

To determine detectability of a galaxy in the Saul et al. (2012) CCC from the mock survey, we overlay the footprint (and spatially variable depth) of the real GALFA-HI, and identify the nearest pixel to each halo. Using the distance for that halo and its $M_{\text{HI}}$ from above, we compute its expected $H_1$ flux, and we accept it if it is higher than the detectability threshold of the CCC (described in Section 2). We further apply a $|v_{1,LSR}| > 90$ km s$^{-1}$ cut to match the galaxy candidate sample described in Section 2.

We also consider a final cut on optical detectability in the follow-up observations by assuming $M_{*,r}/L_r \sim 1$ and cutting on the $r$-band detection thresholds for follow-up observations. However, this cut is less stringent than the $M_{\text{HI}}$ sensitivity cut based on our thresholds from Section 3, and hence has no effect on the final count as described below. We leave this cut in as a parameter in the model, however, and investigate its effects further in Section 3.

This yields our sample of mock dwarf galaxies that could be found in the CCC under the assumption that all galaxies have their full allotment of $H_1$. However, Figure 1 demonstrates clearly that this is not the case: in the LG, most lower-mass satellite galaxies have orders-of-magnitude less $H_1$ than star-forming galaxy scaling relations imply. The exact process by which these satellites are quenched is not certain. Whether non-satellite dwarfs self-quench is an open question, but at least in the LG it seems likely to be quite rare given that nearly all dwarfs beyond the MW and M31 have gas (e.g., MacConnachie 2012; Wetzel et al. 2015). But it is clear that some mechanism removes gas and therefore quenches star formation in satellites (e.g., Spekkens et al. 2014; Fillingham et al. 2015; Wetzel et al. 2015; Simpson et al. 2017, and references therein).

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1 http://localgroup.ps.uci.edu/elvis/
2 http://mips.as.arizona.edu/~cnav/sun.html
Here, we consider two simple scenarios intended to bracket various host-driven quenching mechanisms and timescales. The two scenarios, as well as the approaches described in this section as a whole, are illustrated in Figure 2. In Scenario “Not-Now,” we assume any galaxy that is a subhalo of the MW or M31 at \( z = 0 \) has lost its gas, and all others are normal. In Scenario “Never,” we assert that galaxies immediately lose all of their HI gas the moment they become subhalos at any time. Note that this makes Scenario “Never” a strict subset of “Not-Now.” While neither of these scenarios are likely to be correct in detail, and do not allow for self-quenching, they bracket many scenarios based on direct physical effects between a host and its subhalos, and hence serve our current purpose of providing an estimate of what we would expect GALFA-HI to see.

In Figure 3, we show the counts of halos in each of the 24 mock CCCs (i.e., each of the ELVIS host halos as the MW). Each point represents an individual halo, and points inside a given circle are those that pass the corresponding cut. One clear point this figure demonstrates is the importance of the velocity and detectability cuts—together they remove \( \geq 50\% \) of the sample, underscoring the importance of correctly modeling the specific observational details of GALFA-HI and the CCC detection algorithm. Also important here is the recognition that there is quite a lot of variability in these samples, both in the total number of halos and the effects of the cuts. This represents a mix of true cosmic variance as well as uncertainty in the MW and M31’s properties, encoded in the spread of properties for the ELVIS host halos.

In Figure 4, we summarize the cumulative distribution functions for predicted dwarfs in the footprint over the 24 mock surveys. Unsurprisingly, for the scenario where satellites are included (green dotted–dashed), there are many satellites predicted. However, as discussed above, this case is already ruled out by the observation that most LG satellites lack observable HI. More striking are the lines for the Not-Now (red dashed) and Never (solid orange) scenarios. While the numbers are much reduced relative to the All scenario, the typical number counts are in the 5–20 range. In contrast, the observations (discussed in Section 3) show zero galaxies. In fact, none of the mock surveys in the scenarios outlined above are consistent with the observations.

The process outlined in this section demonstrates that, by constructing a mock GALFA-HI catalog from the ELVIS simulations, we determine that the GALFA-HI observation of no LG dwarfs is quite surprising at face value. Several caveats apply, however. First, because there are only 12 realizations of ELVIS simulations, we only have 24 mock catalogs. Hence, it is possible that the LG is simply a \( <1 \) in 24 (\( \sim 2\sigma \)) outlier. This

\[ \text{Subhalos are defined here following the ELVIS catalogs, based on the 6D friends-of-friends Rockstar halo finder (Behroozi et al. 2013).} \]
cannot be ruled out without more ELVIS-like simulations but is at least suggested against by the magnitude of the discrepancy outlined above. Second, this could be interpreted as evidence that ΛCDM (the underlying cosmology for ELVIS) is not an accurate description of small-scale structure, like some interpretations of the “missing satellites problem” (Götz & Sommer-Larsen 2003; Rocha et al. 2013), but here specific to gas-bearing dwarfs. Third, because ELVIS is a collisionless dark matter simulation, it does not contain any baryons effects. Hence, baryonic or hydrodynamic effects that might suppress the numbers of dwarf galaxies are not accounted for (e.g., Governato et al. 2012; Pontzen & Governato 2012; Brooks et al. 2013). Most work on this topic has focused on how this impacts the LG satellites, however, which we explicitly excise from the sample. It is unclear which, if any, of these mechanisms apply for non-satellites like those considered here, and investigating such effects is beyond the scope of this paper. Finally, it is possible that the $M_{\text{gas}}$-to-$M_*$ relation of Bradford et al. (2015) does not extend to below $M_*=10^6 M_\odot$ (i.e., the extrapolation in Figure 1). If there is a break in this relation, the number of dwarfs with gas would be suppressed, solving the aforementioned tension. It is precisely this possibility that is described in the next section, taking the causative mechanism to be reionization.

5. Implications for Reionization

To estimate the effects of reionization, we now consider a minimal toy model of the effect of reionization on dwarf
galaxies, inspired in part by the approach of Boylan-Kolchin et al. (2014). Of course, there is a wide range of models for reionization and its effect on dwarf galaxies, which are far more thorough than that used here (e.g., Barkana & Loeb 1999; Gnedin 2000; Okamoto et al. 2008; Bovill & Ricotti 2011; FITTS et al. 2017). We use the model described here primarily because it is both simple and can provide a direct probabilistic mapping between ELVIS and the GALFA-HI observations.

5.1. Lower Limits from GALFA-HI and ELVIS

Our model assumes there exists a characteristic halo virial mass ($M_c$) at a particular redshift ($z_{\text{reionization}}$). Halos with a virial mass below $M_c$ at $z_{\text{reionization}}$ have their gas entirely removed (by $z = 0$), and those above have their gas content unaffected by reionization. While such a sharp break in the $M_{\text{HI}}$ -to-$M_{\text{halo}}$ relation is unphysical, the subsequent evolution in $M_{\text{halo}}$ from $z_{\text{reionization}}$ to $z = 0$ has the effect of smearing the break over $\sim$1 dex in $M_\ast$ at $z = 0$, where our comparison to observations is performed (see Section 5.2). This model is implemented in the context of the formalism of Section 4 by identifying the main-branch progenitors of the $z = 0$ halos at a particular $z_{\text{reionization}}$. Those with a virial mass below $M_c$ are flagged as undetectable in GALFA-HI due to the removal of their gas.

This model is flexible enough to immediately solve the problem posted at the end of Section 4: if $M_c$ is high enough, no LG dwarf galaxies will have gas at $z = 0$, thereby solving the apparent tension between the ELVIS model and the observations. With that in mind, we now turn to asking the probabilistic question of what $M_c$ is, given the observation that there are no LG dwarfs in the GALFA-HI CCC. To obtain this probability distribution, we start from the process of Section 4 applied to each of the ELVIS hosts for both the “Never” and “Not-Now” scenarios, for a range of optical $r$-band follow-up detection limits. We apply the reionization model described above over a grid of $M_c$ and $z_{\text{reionization}}$ values of $z \sim 6.3, 7.1, 8.1, 9.3$ (set by available ELVIS timesteps). We then ask what fraction of the 24 hosts yield galaxy number counts consistent with the observations (zero), and consider this to be proportional to the probability density $P(M_c, r_{\text{lim}}, z_{\text{reionization}})$. We then marginalize the probabilities over the available $z_{\text{reionization}}$ values to provide estimates of $M_c$ (and the $r$ limit).

To perform the marginalization, we assume a (discrete) uniform distribution of the $z_{\text{reionization}}$'s available, because our goal is to provide estimates relatively agnostic to assumptions about $z_{\text{reionization}}$. However, a more specific reionization model would likely provide a more peaked $z_{\text{reionization}}$ distribution, and therefore provide tighter constraints than we obtain here. Relatedly, we note in passing that a different choice of marginalization (and stronger assumptions) could yield a different inference: marginalizing over $M_c$ to instead estimate $z_{\text{reionization}}$. For the purposes of this paper, we opt not to do this because we are more interested in $M_c$, and our $z_{\text{reionization}}$ grid is quite coarse, but this methodology could be straightforwardly applied to a more specific galaxy formation model's $M_c$ prediction, yielding a probability distribution over $z_{\text{reionization}}$.

Figure 5 shows the result of the above procedure for the “Not-Now” scenario. The $M_c$ values are converted to virial temperatures in this figure for comparison with literature values that are often reported as $T_{\text{vir}}$. It is immediately apparent that the probability density goes to $\sim$1 at high $T_{\text{vir}}/M_c$ values. This is a result of the effect described above, that an arbitrarily large $M_c$ will always be consistent with the observational result of no dwarf galaxies, as all of the candidates are removed by reionization. Figure 5 also shows horizontal lines for two optical detection thresholds: the upper one corresponds to our estimated follow-up limits (Section 3), and the lower one is a highly conservative estimate based on the actual detected non-LG dwarfs from Tollerud et al. (2015) and Sand et al. (2015). The corresponding probabilities for $T_{\text{vir}}$ along those limits are essentially identical, showing that even if our follow-up detection limits are overly-optimistic, the key results of this work still hold. Figure 5 also shows that the cutoff $T_{\text{vir}}$ has a $\sim$50% of being at least $10^{5.6} M_\odot$, or $M_c \gtrsim 10^6 M_\odot$, consistent with simulation predictions of $M_c$ (e.g., Okamoto et al. 2008).

5.2. Upper Limits from Leo T

The procedure above provides only a lower limit on $M_c$, because the GALFA-HI observation here is the lack of any detected H I-bearing galaxies. From these observations alone, $M_c$ could be arbitrarily high, as this would still yield no observable H I-bearing galaxies. But of course, observations of the wider universe, indeed even other observations in the LG, provide evidence of the existence of galaxies with H I. Applying the Copernican principle, it is reasonable to then use the existence of such galaxies in the LG as a joint constraint with the GALFA-HI observation to achieve an actual estimate of $M_c$. Leo T provides the ideal constraint: it is both a dwarf galaxy in the LG (at $\sim$400 kpc from the MW, not a satellite as we have defined it here) and the lowest-mass known H I-bearing galaxy (Ryan-Weber et al. 2008; Weisz et al. 2012). It therefore provides the best source for an upper limit on $M_c$. Combining this constraint with the GALFA-HI observations can then provide an estimate of $M_c$ (rather than just a limit).

Creating an upper limit on $M_c$ based on the existence of Leo T requires an estimate for the virial mass of the halo hosting Leo T at the time of reionization. To make such an estimate, we start from the present-day luminosity of Leo T from de Jong et al. (2008), converted to a stellar mass ($1.4 \times 10^5 M_\odot$). We
then find all the $z = 0$ halos from the model outlined in Section 4 that have stellar masses within $\pm 20\%$ of our Leo T estimate. For those halos, we then identified the main progenitor at $z_{\text{reionization}}$ and adopt that as a possible $M_{\star}$ limit. This procedure provides an estimate of the scatter in the possible virial mass at $z_{\text{reionization}}$ of Leo T due only to uncertainty in its merger history. Other sources of scatter may contribute to the effects of reionization on Leo T-mass galaxies, possibly quite significantly (e.g., Fitts et al. 2017). However, we find that relatively large changes in the stellar mass assumed here yield negligible changes to the width of the distribution of $z_{\text{reionization}}$ halo masses. This implies that the primary impact on the $z_{\text{reionization}}$ virial mass of Leo T itself is driven by uncertainty in mapping any individual present-day halo back to $z_{\text{reionization}}$. We therefore adopt this merger-history driven scatter as the sole source of scatter for the purposes of this $M_{\star}$ estimate.

### 5.3. Combined Limits

With an upper limit on the $z_{\text{reionization}}$ $M_{\star}$ set by the above procedure for Leo T and a lower limit set by the above GALFA-HI observation comparison, the joint probability of the two together provides an estimate of $M_{\star}$. Precisely this exercise is demonstrated in Figure 6. We show this for both the “Not-Now” (top, red) and the “Never” (bottom, orange) scenarios. While the latter scenario has a notably wider distribution due to the more conservative assumptions built into it, both provide a constraint on the halo mass of reionization around $3 \times 10^8 M_{\odot}$, although potentially from $10^8$ to $10^9 M_{\odot}$. But unlike other estimates for $M_{\star}$, this estimate depends on no assumptions about the effects of reionization on star formation—rather this estimate derives (solely) from observations of the H I content of the $z = 0$ LG galaxies.

We also note a possibly surprising feature of Figure 6. In both scenarios, the relative overlap of the probability distributions from the Leo T upper bound and the GALFA-HI lower bound is quite limited. That is, the absolute probability of both being correct is relatively low. While the joint probability shown in Figure 6 has been normalized to unity for clarity, the absolute values are quite low. This implies that, fundamentally, there is a tension between the GALFA-HI observations and the very existence of Leo T’s H I (particularly for the “never” scenario). This tension persists even if we compare Leo T to only the lowest mass H I-bearing galaxy surviving through the models described in Section 4; this experiment is illustrated in Figure 7. While these model Leo T analogs have, on average, lower masses than the Never/Not-Now distributions shown in Figure 6, they are still in tension with the Leo T distribution. While this could be due to inadequacies in the assumptions underlying the models used to infer $M_{\star}$, it may also imply that Leo T truly is at the edge of the stochastic regime suggested by Fitts et al. (2017) and therefore is at a mass where reionization can have a major impact on galaxy formation.

### 6. Conclusions

In this paper, we:

1. Described a process that takes dark matter simulations analogous to the LG and, using scaling laws and well-characterized sensitivity functions, generates mock H I galaxy catalogs;
2. Applied this transformation to the ELVIS suite of simulations removing dwarf galaxies likely to have been stripped by interaction with the host. We find more H I observable gas-rich dwarf galaxies in all simulations than we see in GALFA-HI CCC. At face value, this suggests a significant tension between the observations and the simulations;
3. Found that this non-detection of gas-rich dwarf galaxies expected by simulations can be interpreted as a lower limit of the mass scale of reionization ($\sim 10^{8.5} M_{\odot}$), independent of any assumption about the impact of reionization on star formation; and
4. Infer the mass scale at which reionization significantly affects dwarf galaxy formation by combining the above limit with the limit inferred from the very existence of the gas-rich dwarf galaxy Leo T. This scale is consistent with those inferred by theoretical estimates.

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*6 This specific percentage was chosen as the needed minimum to include enough halos to adequately sample the probability distribution. A slightly wider or narrower range in stellar mass showed no signs of systematic bias in the center or width of the distribution.
Figure 7. Probability distributions (over the ELVIS simulations) of virial mass at reionization for halos that end up at \(z = 0\) as the lowest-mass HI-bearing galaxies in the simulation, for the “Not-Now” and “Never” scenarios (red and orange, respectively). Both are computed assuming \(M_\text{vir}\) is the median from the joint distributions of Figure 6. These halos can be interpreted as Leo T analogs under the assumption that Leo T truly is the lowest-mass gas-bearing galaxy in the LG. The green line represents the at-reionization virial mass distribution for Leo T (identical to the green line in Figure 6). It is clear that these distributions only weakly overlap, highlighting the tension between Leo T’s existence and the GALFA-HI observations (see the text in Section 5.3 for more details).

The final point also serves to explain the relative paucity of new discoveries of gas-rich LG dwarf galaxies despite extensive HI surveys. While here it is cast as a limit on reionization, reversing the conclusion yields the result that if reionization becomes significant at roughly the Leo T-mass scale, reionization has suppressed these galaxies’ gas content. This explains their absence in the HI surveys.

While these results are at the limits of what is achievable with current HI and optical surveys, new prospects are on the horizon. The Five Hundred Meter Spherical Telescope (FAST) with its higher resolution, larger field of regard, and larger multiplexing factor, will allow us to conduct an order-of-magnitude more powerful study and further constrain the history of reionization. It will also provide a way to test the predictions of the simple model posed here, as new gas-bearing dwarf galaxy detections (or lack thereof) will provide cross-checks on the results presented here. FAST is beginning its science surveys next year and should support experiments similar to the GALFA-HI analysis presented here. Further afield, combined with focused observations or large, deep optical surveys like the Large Synoptic Survey Telescope (LSST), the techniques laid out in this paper will provide an excellent opportunity to improve the constraints on dwarf galaxy formation and reionization.

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8