Dwarf Galaxies: From the Deep Universe to the Present
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The Future of Dwarf Galaxy Research: What Simulations will Predict?

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Abstract. We present a summary of the predictions from numerical simulations to our understanding of dwarf galaxies. It centers the discussion around the Λ Cold Dark Matter scenario (ΛCDM) but discusses also implications for alternative dark matter models. Four key predictions are identified: the abundance of dwarf galaxies, their dark matter content, their relation with environment and the existence of dwarf satellites orbiting dwarf field galaxies. We discuss tensions with observations and identify the most exciting predictions expected from simulations in the future, including *i*) the existence of "dark galaxies" (dark matter halos without stars), *ii*) the ability to resolve the structure (size, morphology, dark matter distribution) in dwarfs and *iii*) the number of ultra-faint satellites around dwarf galaxies. All of these predictions shall inform future observations, not only the faintest galaxies to be discovered within the Local Volume but also distant dwarfs driving galaxy formation in the early universe.

Keywords. galaxies: dwarf, galaxies: evolution, galaxies: formation, (cosmology:) dark matter, methods: numerical

1. Abundance of dwarf halos

The ΛCDM model makes strong predictions on the number of halos as a function of mass, or halo mass function. The hierarchy of structure formation in the CDM model implies that this function increases steeply as one moves towards the low mass end of the spectrum, with a power-law behavior close to M^{-2}. Volume-complete observations of galaxies in the Universe however find shallower slopes (Li & White 2009). This conundrum may still be reconciled within the ΛCDM framework by matching the abundances of halos of a given mass $M_{\rm halo}$ with that of galaxies of a given stellar mass M_* (or luminosity) and assuming a monotonous relation of halo-mass stellar-mass such that most luminous galaxies populate the most massive halos. The price to pay in such approach, known as *abundance matching*, is a strongly non-linear relation between the mass of the dark matter halo and the amount of stars that each halo harbors, with the characteristic that low mass halos (those hosting dwarf galaxies) become increasingly inefficient at forming stars the smallest the halo mass (Conroy & Wechsler 2009; Guo *et al.* 2010; Moster *et al.* 2013; Behroozi *et al.* 2013).

The halo-mass stellar-mass ($M_{\rm halo}$-M_*) relation has become a standard rule against which numerical simulations benchmark their results. And it has been encouraging to see that modeling of feedback and star formation in hydrodynamical simulations are currently in the position of "predicting" the needed trend of star formation efficiency with halo mass (e.g. Benítez-Llambay *et al.* 2015; Sales *et al.* 2017a; Munshi *et al.* 2017; Wang *et al.* 2017; Hopkins *et al.* 2018). For instance, Fig. 1 shows that a baryonic model for gas and star formation tuned to reproduce the properties of galaxies in cosmological

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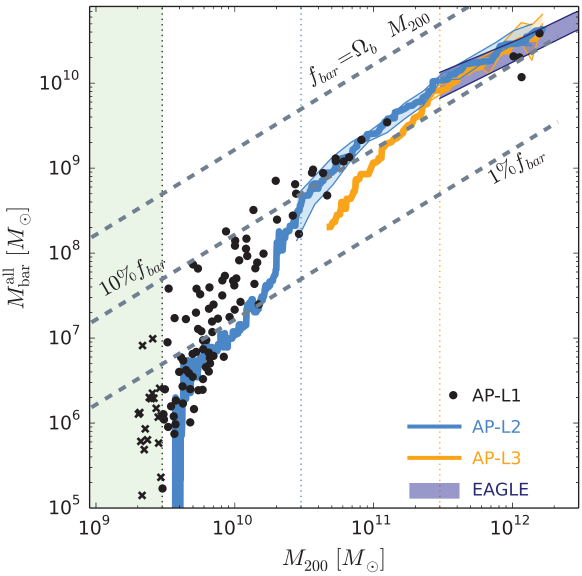

Figure 1. Relation between the baryonic mass (gas plus stars) in galaxies versus its virial mass for isolated galaxies in the APOSTLE hydrodynamical simulations. Current modeling of feedback and star formation naturally reproduces an efficiency of galaxy formation that declines rapidly with halo mass, such that dwarfs retain only a small fraction of their available baryons ($f \leqslant 5\%$). This is a necessary requirement to accommodate the number density of halos predicted in ΛCDM with the shallower mass function observed for faint galaxies. (*Figure taken from Sales et al. 2017a*).

boxes and masses $M_* \geqslant 10^{10}$ M$_\odot$ from the EAGLE project (Schaye *et al.* 2015) naturally leads to a significantly smaller baryonic mass content in dwarf galaxies when the *same* baryonic treatment is applied to higher resolution zoom-in simulations of Local Group analogs that are able to extend the resolved scales towards low mass halos (APOSTLE project, Sawala *et al.* 2016a). The most important physical mechanisms suppressing the formation of stars towards the low mass end of the galaxy luminosity function seem to be stellar feedback and reionization.

The increasing inefficiency to form stars and retain baryons in low mass halos has also an important consequence: below a certain scale dark matter halos should remain mostly dark. Indeed, several authors have found that the fraction of dark halos –dark matter halos that form no stars– increases steeply towards virial masses lower than 10^9 M$_\odot$ (Sawala *et al.* 2013; Sawala *et al.* 2016b; Fattahi *et al.* 2016; Fitts *et al.* 2017). This being perhaps one of the strongest predictions of our current understanding of galaxy formation within ΛCDM postulates an interesting challenge: How can we detect these dark galaxies free floating in space?

One possibility brought forward recently by results presented in Benítez-Llambay *et al.* (2017) postulates that dark halos might still contain significant amounts of HI gas, which should be in hydrostatic equilibrium with the dark matter halo potential and in thermal equilibrium with the ionizing UV background. These so-called RELHICs (REionization-Limited H I Clouds) would populate the virial mass range $\log(M_{200}/M_\odot) \sim [8.5\text{-}9.5]$ and would have a broad range of projected HI density (but no thermal broadening). Although the detectability of such objects is currently unclear, it would offer a unique probe to the small scale structure predicted by the ΛCDM model. An alternative probe for such population of dark halos might include strong gravitational lensing, as the chance alignment of halos along the line-of-sight of lensed images may significantly contribute (and even dominate!) the detected signal according to recent calculations (Despali *et al.* 2018).

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2. Structure of dwarf halos

If the cold dark matter scenario is correct, the mass distribution of collapsed objects is expected to have a well defined density profile, characterized by a central density cusp $\rho \propto r^{-1}$ and a transition towards a steeper fall off in the outskirts with $\rho \propto r^{-3}$ near the virial radius (commonly referred to as NFW profile, Navarro *et al.* 1996). This profile also has a characteristic maximum circular velocity $V_{\rm max}$ that is reached at about $r_{\rm max} \sim 2.1 r_s$, with r_s being the scale radius where the density profile slope is -2. This maximum circular velocity $V_{\rm max}$ scales with total virial mass in the halo, giving the opportunity to estimate halo mass by measuring circular velocities.

The mass distribution in galaxies have traditionally been measured by means of rotation curves, which allows one to infer the total gravitational potential (contributed by baryonic and dark matter) given the measured circular velocity of the gas. In particular, for L_* galaxies the outermost point of the rotation curve is a good indication of the $V_{\rm max}$ of the halo as the gas extends further out enough to trace the $r_{\rm max}$ region. Moreover, observationally, there is a well established relation between the baryonic content of galaxies and their rotation velocity, known as Tully-Fisher relation (Tully & Fisher 1977; Verheijen 2001; Stark *et al.* 2009). This relation has been found to have a steep scaling $M_{\rm bar} \propto V_{\rm rot}^4$ and tight scatter for objects with $M_{\rm bar} \geqslant 10^8\,{\rm M}_\odot$ or equivalently $V_{\rm rot} \geqslant 50$ km/s (McGaugh 2012; Lelli *et al.* 2016).

Cosmological numerical simulations able to predict a reasonable $M_{\rm halo}$-M_* relation plus a M_*-size relation have shown remarkable success at also reproducing the Tully Fisher scaling in such regime (Sales *et al.* 2017a; Ferrero *et al.* 2017). However, if the mapping between stellar mass and halo mass is non-linear as needed to reproduce the right abundances of galaxies in the low mass end of the spectrum (see Section above), it is then expected that the Tully Fisher relation presents strong deviations from a single power-law, specially for $M_{\rm halo} \leqslant 10^{11}\,{\rm M}_\odot$ or equivalently $V_{\rm circ} \leqslant 60$ km/s.

In Fig. 2 (taken from Sales *et al.* 2017a) we have compiled from the literature information for all resolved rotation curves of galaxies observed with baryonic masses $M_{\rm bar} \sim 10^{9.5}\,{\rm M}_\odot$ and below and found that such trend is not present. Here we have used the outermost measured point in the rotation curve as representative of the circular velocity (see gray points). We highlight that the scatter of the BTF for dwarf galaxies increases significantly, but still shows no signs of a steepening expected for the $M_{\rm bar}$ - $V_{\rm max}$ relation in simulations (see green line).

The apparent disagreement between theory and observation can be solved though by taking into account the sizes of dwarf galaxies. Indeed, low mass galaxies are small in size, meaning that their baryons trace only the innermost parts of their dark halos. Circular velocities for low mass objects might therefore not reach $r_{\rm max}$, meaning that the circular velocity measured is not a good indication of $V_{\rm max}$. Taking such effect into account and measuring in simulations the circular velocity at the right radius (and not $r_{\rm max}$) tends to "straighten up" the predicted BTF relation, bringing it in better agreement with observations (see red symbols in Fig. 2). In fact, similar conclusions have been reached by other teams using different simulations as well as employing line widths instead of resolved rotation curves (see e.g., Brook *et al.* 2016; Brooks *et al.* 2017).

Perhaps a more challenging discrepancy between observations and simulations regarding rotation curves is their observed *diversity* in shapes, put recently forward by Oman *et al.* (2015). At a fixed outer circular velocity, observed galaxies show a large variation in shapes of rotation curves for the inner regions, ranging from slowly rising constant density cores to some that rise even more steeply than the predicted NFW profiles. Current theoretical solutions to this problem include a combination of feedback-induced cores combined with non-circular motions in dwarf galaxies (e.g., Santos-Santos *et al.* 2018) to invoking the need for dark matter self-interactions (which creates cores at the

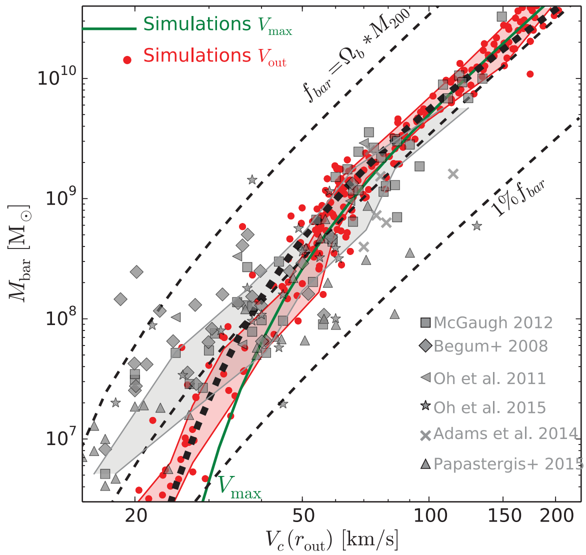

Figure 2. The baryonic Tully Fisher relation (baryonic mass versus rotation velocity) for galaxies with observed resolved rotation curves taken from the literature (gray dots). The relation is consistent with a single and steep power-law, with a scatter that increases towards low mass objects. On the other hand, theoretical model predict a significant steepening towards low mass halos ($V_{\max} < 40$ km/s, green solid line). However, one must take into account the sizes of small dwarfs in observations, where baryons trace the potential in radii much smaller than $r_{\max}$. Considering realistic sizes for dwarf galaxies and measuring the rotation velocity at the scales comparable to observations the relation "straightens up" (see red symbols) bringing predictions in better agreement with observations. *Figure taken from Sales et al. 2017a*

centers of halos) combined with the gravitational effects of baryons (Kamada *et al.* 2017; Creasey *et al.* 2017).

Uncertainties in the interpretation of dwarf galaxies rotation curves as circular velocity profiles are currently preventing a further assessment of this problem. In fact, uncertainties on inclinations, non circular motions and pressure support are believed to prevent a straightforward interpretation of observational results. This highlights the need for one-to-one comparisons between observations and simulations of dwarf galaxies, for example by creating mocked velocity fields, that may allow a more direct comparison of theory and observations. Steps towards this direction are currently being taken (Oman *et al.* 2017; Santos-Santos *et al.* 2018).

3. Environment of dwarf halos

Dwarf galaxies can be found in the field but also as satellites of larger systems. One example is our own Local Group, where more than 100 dwarf galaxies can be found orbiting within the gravitational potential of the Milky Way and Andromeda galaxy. Satellite dwarfs are also found in abundance in larger systems such as groups and clusters, such as Virgo, Coma and Perseus, where catalogs of several hundred to thousands dwarfs are starting to become available (e.g., Ferrarese *et al.* 2016; Venhola *et al.* 2018). The properties of field and satellite dwarf galaxies are markedly different. For instance, whereas field dwarfs are mostly dwarf irregulars (gas rich, star forming and blue), satellite dwarfs are more abundant in the form of early types dwarf spheroidals and dwarf ellipticals (gas poor, not currently forming stars and old stellar populations). Moreover, for dwarf galaxies with $M* \sim 10^9$ $M_\odot$ all isolated dwarfs seem to be star-forming today (Geha *et al.* 2012), whereas such population in clusters like Virgo and Coma are mostly quiescent (e.g.

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Binggeli *et al.* 1990). A challenge of current and future numerical simulations will be to reproduce this richness of dwarf types as a function of environment.

Encouragingly, cosmological hydrodynamical simulations are starting to resolve both, the structure of dwarf galaxies together with cosmological boxes large enough to include a variety of different environments. At the scales of clusters of galaxies comparable to Virgo, Mistani *et al.* (2016) have shown that dwarf galaxies in simulated clusters from the Illustris simulation (Vogelsberger *et al.* 2014a,b) have significantly redder colors than counterparts in the field, a property for which the simulations have not been tuned and therefore constitute a genuine prediction of the theoretical models (Sales *et al.* 2015; Trayford *et al.* 2016). Moreover, following the individual star formation histories of infalling dwarfs in clusters Mistani et al. find that starburst events are rather common on satellite dwarfs but not in field dwarfs. Such starburst events are associated with infall and the first pericenter passages in dwarfs around the cluster potential, likely as a result of compression of gas triggered by tidal effects and the encounter with the hot intracluster medium. Interestingly, such starburst events tend to rapidly terminate star formation in dwarfs, with typical timescales of 0.5-1 Gyr. But Mistani *et al.* (2016) also find a large spread on the typical times between infall and the stopping of star formation, with lower ends of 0.5 Gyr associated to starbursts, but upper ends as large as 8 Gyrs. This large spread indicates that the mechanisms that regulate star formation in dwarf galaxies within clusters are varied, ranging from gas consumption + feedback (starburst) for the shortest timescales, to ram pressure stripping (intermediate timescales) to the slow consumption of the internal gas brought in at infall –often referred as starvation– most common on dwarfs that become quiescent over long timescales.

Comparison with observational data indicates that less extreme environments such as that of the Milky Way or the Local Group, although more benign than the dense and hot intracluster medium, are still able to imprint fundamental differences on the properties of the dwarf population (Wheeler *et al.* 2014; Fillingham *et al.* 2015, 2016). Numerical simulations are starting to be able to resolve such differences in cosmological zoom-in simulations. The signature is more evident when looking at the star formation histories of field and satellite dwarfs of Milky-Way like systems. Environmental effects driven by the host halos of galaxies comparable to the Milky Way seem to have a sizable effect on suppressing intermediate and young stellar populations, an effect that is stronger the smaller the satellite mass (Digby et al.*in -prep*, Simpson *et al.* 2018).

Cosmological hydrodynamical simulations have also been instrumental at revealing that environmental effects can also occur outside the very non-linear regions of host halos and as part of the interaction with the network of filaments (referred to as "cosmic web") that is expected naturally within the ΛCDM model. Although the average gas density in filaments is low, this *cosmic web stripping* may still occur for galaxies with a relatively high peculiar motion with respect to a nearby sheet or filament (see Benítez-Llambay *et al.* 2013) for which the ram pressure force induced by the filament is enough to overcome the restoring force of their (small) dark matter halos. Such mechanism is predicted to act before a dwarf galaxy is accreted as a satellite, giving rise to a population of galaxies with suppressed star formation seemingly in the field. Some examples in the Local Volume exist (Cetus or Tucana), and simulations predict that should not be uncommon (e.g. Bahé *et al.* 2012; Benítez-Llambay *et al.* 2013).

4. Hierarchical assembly of dwarf halos

Structure formation within the ΛCDM scenario proceeds bottom-up or *hierarchically*, in a way that small structures collapse first and then aggregate to form even more massive structures. A natural prediction of such model is that the dark matter halo surrounding galaxies is full of *substructure*, or smaller agglomeration of mass that remains self-bound

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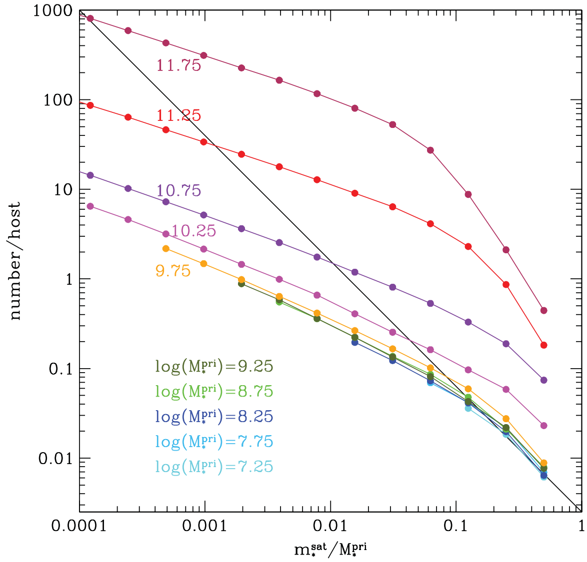

Figure 3. Cumulative stellar mass function of satellites for isolated central galaxies of different stellar mass (as labeled by different colors) in the Millennium II simulations. This confirms an important prediction of the ΛCDM model: satellite galaxies are expected around hosts of any stellar mass, including faint satellites around dwarf galaxies. Notice that once the x-axis is normalized to the stellar mass of the host, the satellite mass function becomes independent of primary stellar mass for dwarf galaxy centrals/primaries with $M_*^{\rm pri} \sim 10^{9.5}\,{\rm M}_\odot$ and below. *Figure taken from Sales et al. 2013.*

and orbiting the larger potential well of the host. Some of these subhalos –those massive enough to retain cold gas and form stars on their own– will light up and form their own, although faint, satellite galaxies orbiting around larger companions. From this perspective, the presence of faint satellite galaxies around the Milky Way or Andromeda and within groups and clusters of galaxies is somehow a natural prediction of this cosmological model. Because structure in ΛCDM is self-similar, we expect the halos of dwarf galaxies to be scaled-down models of more massive halos and, therefore, also be swarming with a spectrum of smaller subhalos. This is exciting since, in the same way than for larger host galaxies, some of these substructures present within dwarf halos may also be massive enough to contain their own (although rather faint!) dwarf galaxy itself, providing the testable prediction that dwarf galaxies should also contain a population of fainter companions. Such prediction has been confirmed with N-body only simulations for the dark matter case (Springel *et al.* 2008; Deason *et al.* 2015) as well as in semi-analytic and hydrodynamical models (Sales *et al.* 2013; Wheeler *et al.* 2015).

The exact number and luminosity of the satellite companions will result from the combination of the subhalo mass function (which is universal in ΛCDM once the satellite mass is expressed in terms of the host mass, Yang *et al.* 2011) and the halo-mass vs. stellar-mass relation discussed in Sec. 1. Fig. 3 shows this prediction taken from Sales *et al.* (2013), which was computed using the Millennium-II simulations (Boylan-Kolchin *et al.* 2009) plus the semi-analytical model from Guo *et al.* (2011). Different lines show the expected number of satellites as a function of stellar mass (normalized to the stellar mass of the host), and shows that for host galaxies $\sim L_*$ and above, the number of satellites scales with the host. However, below this scale the stellar mass function is predicted to become scale-free or, in other words, independent of the mass of the host. This scalability can be understood as a consequence of the combination of two power-laws:

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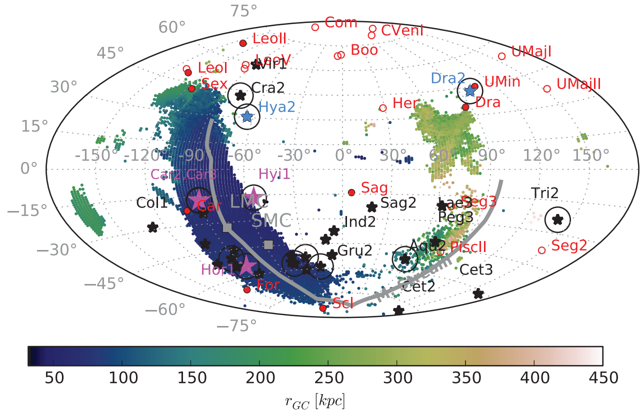

Figure 4. All sky distribution of ultra-faint dwarf galaxies in the Milky Way (stars) together with the predicted footprint of the LMC debris on the sky. Encircled symbols are among the dwarfs with full 6D information from the Gaia DR2 data. Taking into account position on the sky, distance and 3D velocities at least 4 of these dwarfs are consistent with having been accreted as part of the LMC system (magenta): Hor1, Hyi1, Car2, Car3. We also highlight in blue Hya2 and Dra2 which are marginally consistent. This hierarchy of assembly is a natural prediction of the model that is encouragingly being confirmed by observations of the Milky Way satellites. (*Figure taken from Kallivayalil et al. 2018*)

one coming from the substructure function and the other one from the $M_{\rm halo}$-M_* relation, which occurs only for low mass galaxies (those with stellar mass below the knee of star formation efficiency at $M_* \sim 10^{10}\,{\rm M}_\odot$). Tentative evidence of this has been confirmed using a large sample of isolated host galaxies in a wide range of masses from the SDSS catalog (see Sales *et al.* 2013), but deeper observations are needed to push the stellar mass function towards fainter satellites.

The Local Volume offers the best opportunity to assemble a volume-complete census of dwarf galaxies. And because faint dwarfs become increasingly difficult to observe with distance, the Milky Way is perhaps our best shot at quantifying this predicted hierarchical assembly of dwarfs. The Large Magellanic Cloud (LMC) is the largest satellite of the Milky Way, it is currently only 50 kpc away and it is expected to be on its first infall onto our Galaxy (Kallivayalil *et al.* 2006, 2013). The combination of these factors place the LMC as the ideal test-bed for this prediction and suggests that several of the dwarf galaxies around the Milky Way today should have been accreted as part of the LMC system. Although the impact of environment is minimized because of the recent infall onto the Milky Way potential, the tidal disruption of the LMC halo –and with it of its system of satellites– should have already set in, which means that the satellites associated to the LMC pre-infall should today be found around the Milky Way not randomly oriented but along the tidal stream of the system (Sales *et al.* 2011, 2017b).

This tidal stream uniquely characterizes the combination of position on the sky, distance and velocities that a dwarf galaxy must have in order to be consistent with a companionship with the LMC. Using cosmological simulations of an LMC analog, Sales *et al.* (2011) determined that no classical dwarf –except for the SMC– was consistent with being associated to the LMC before infall. This however changed when looking at the full 6D kinematics from proper motions of several ultra-faint dwarfs available thanks to the GAIA DR2 data. Encouragingly Kallivayalil *et al.* (2018) finds that between 4 to 6 dwarf ultra-faint galaxies are consistent with the position and kinematics expected for satellites of the LMC (see Fig. 4), which may confirm one of the most important predictions of the ΛCDM model: the hierarchy of structure assembly.

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As we push the detection limits to fainter galaxies in external systems, a final confirmation of this prediction will come from associations of bound dwarf galaxies in the field. Numerical simulations are now reaching the resolution needed to predict luminous companions around faint field dwarfs (e.g. Wheeler *et al.* 2015 Jahn *et al.*, *in-prep*). And new observational efforts are starting to detect such dwarf associations as pairs and also more populated groups of dwarfs (Stierwalt *et al.* 2017; Besla *et al.* 2018).

5. Summary & Future Prospects

We have discussed four aspects of dwarf galaxy formation from a theoretical perspective: *i*) abundance, *ii*) scaling relations and their dark matter content, *iii*) effects of environment and impact on stellar populations and *iv*) hierarchical assembly of dwarfs. We have emphasized predictions that can be contrasted with observations and identified a few tensions that arise with the data. As we look forward to the future challenges of the model, we can summarize a few key aspects of what numerical simulations will be able to predict in the near future, including:

• The existence of "dark galaxies". If the ΛCDM model is correct most low-mass dark matter halos should exist but not contain stars. Numerical simulations have already found them, but the effects of numerical resolution and details of the star formation and feedback model have not been studied extensively. In the future cosmological hydrodynamical simulations will improve in resolution allowing a proper assessment whether the already found "dark galaxies" remain without stars when higher resolution is achieved.

• Dark Galaxies and reionization. At the threshold of galaxy formation, determining which halos light-up versus those that will remain dark seem strongly connected to reionization and the assembly history of each halo (Sawala *et al.* 2016b; Fitts *et al.* 2017). As more and higher resolution numerical simulations become available models will be able to make robust predictions on the number of "reionization fossils" (dwarf galaxies that stop their star formation due to reionization) expected in the vicinity of the Milky Way, providing a testable prediction with upcoming observations.

• Structure and Morphology of Dwarfs. Although the progress on the modeling of dwarf galaxies has been huge, current simulations lack the resolution to study the internal structure of dwarf galaxies. Sizes, rotation support and even the inner distribution of dark matter seems today strongly coupled to numerical limitations or uncertainties on the baryonic modeling. In the future improved resolution and better sub-grid models for the treatment of key processes such as star formation and feedback will allow predictions on the size and morphology of dwarf galaxies that might be directly comparable to observations.

• Dwarfs around dwarfs. Hydrodynamical simulations of isolated dwarf galaxies will make predictions for the numbers and distribution of faint dwarfs orbiting isolated dwarfs, providing a theoretical framework to interpret new upcoming data from large telescopes surveying the Local Universe (e.g. LSST, WFIRST) and also missions targeting the formation of dwarf galaxies in the early universe (e.g. JWST).

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