LSST Cadence Note: A resolved census of dwarf satellites around Local Volume galaxies

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In this Cadence Note, we present survey strategy recommendations for Vera C. Rubin Observatory (Ivezić et al., 2019) observations to maximize the discovery of dwarf galaxy satellites of host galaxies in the Local Volume ($1.3 < D \lesssim 6$ Mpc; beyond the Local Group). A complete census of satellites around hosts of a variety of masses, morphologies, and environments will provide an important dataset for constraining the nature of the dark matter that makes up most of the mass of faint dwarf galaxies, and studying the physical processes that govern the number and properties of dwarf galaxies that form in dark matter subhalos.

1 Science Case

The faintest dwarf galaxies are the most dark matter-dominated objects known in the universe. In order to elucidate the nature of the dark matter (DM) that provides the "seeds" (i.e., dark matter subhalos) in which dwarf galaxies form, we must also understand the processes governing galaxy formation and evolution in these subhalos. A key prediction of cosmological models is the total number and distribution of masses of DM subhalos that form alongside (and/or are later accreted by) more massive host galaxies. A census of the faintest dwarf galaxies and measurement of their properties (e.g., luminosity, size, shape, metallicity) in the Local Volume will provide a key method of studying DM, as well as the dependence of dwarf satellite populations and their properties on host galaxy mass and environment. Dozens of faint dwarfs are now known around the Milky Way (MW) and M31, where we can identify them relatively easily as stellar overdensities in surveys such as SDSS, PanSTARRS, DES, PAndAS, MagLiteS, and others (e.g., McConnachie, 2012; Martin et al., 2016; Simon, 2019; Drlica-Wagner et al., 2020). Because the MW's satellite population is the only relatively complete one we have, models are often fine tuned to match the properties of this single galaxy. Finding faint dwarfs via their resolved stars beyond the Local Group (i.e., at $D \gtrsim 1.3$ Mpc), however, requires observations deep enough to reach at least $\sim 1-2$ magnitudes below the RGB tip (TRGB), while also covering large enough areas of the sky to map the entire virial volumes of nearby galaxies (for example, the LMC's virial radius of ~ 150 kpc would subtend a diameter of $\sim 11.5^\circ$ at a distance of 1.5 Mpc, and $\sim 4.3^\circ$ at

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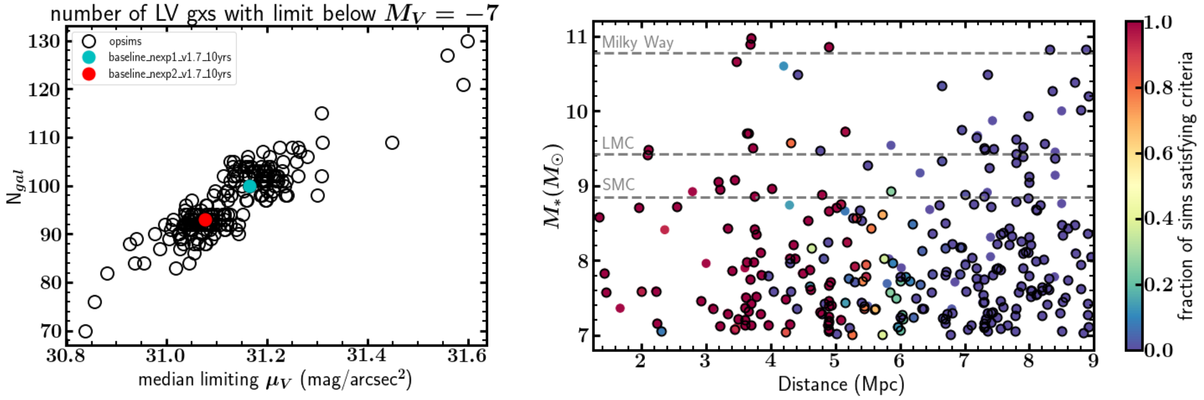

Figure 1: *Left:* Points represent our figure of merit as measured on 200 OpSims. We show the total number of Local Volume galaxies for which the simulation reached a limiting magnitude for dwarfs galaxies of $M_V > -7$, plotted against the average limiting surface brightness (within a 1 arcmin region) over all galaxies considered in each simulation. Baseline simulations are highlighted as colored points. *Right:* Color-coding denotes the fraction of the 200 simulations considered in which the galaxy met our limiting magnitude criterion of $M_V > -7$ for dwarf detection. This fraction is shown as a function of stellar mass (M_*) and distance. Many galaxies successfully meet our criteria out to distances of ~ 6 Mpc. Points without black circles around them are galaxies in high-extinction ($A_B > 1$) regions. Many (but not all) of the more nearby galaxies with low success fractions are at low Galactic latitudes, and thus not expected to have useful observations.

4 Mpc). It is vital for our understanding of DM and galaxy formation that LSST's survey strategy achieves the depth, data quality, and area needed to provide a surface brightness-limited census of dwarf satellites around Local Volume galaxies (similar to, e.g., Chiboucas et al. 2013; Merritt et al. 2014; Sand et al. 2014, 2015; Carlin et al. 2016; Smercina et al. 2018; Crnojević et al. 2019; Bennet et al. 2020).

The lowest stellar-mass galaxies we have considered (with $M_* \sim 10^7 M_\odot$) are expected to have 0-2 satellites of $M_* > 10^5 M_\odot$ each (Dooley et al., 2017b), while SMC/LMC mass systems should have as many as 8 such satellites (Dooley et al., 2017a). More massive, Milky Way-like galaxies (of which there are 5-6 available to the Rubin Observatory, should host > 20 such dwarf satellites. Thus a total of $\gtrsim 200$ dwarfs outside the LG can be expected to be discovered in LSST. More importantly, complete surveys around a large number of hosts will enable statistical comparison of satellite populations (e.g., their luminosity functions) to CDM models.

2 Cadence comparisons and recommendations

We use the latest tables from the Local Volume Galaxies Database[1] (based on Karachentsev et al. 2013), limiting our selection to Dec $< 35°$. We calculate the stellar mass of all galaxies using their total $K-$band luminosities, assuming mass-to-light of 1.0 in K. We then limit

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[1] `http://www.sao.ru/lv/lvgdb/`

the sample to galaxies with $M_* > 1 \times 10^7\ M_\odot$ (removing the faintest systems, which will not be expected to have significant dwarf satellite populations; e.g., Dooley et al. 2017b,a); this leaves a total of 302 galaxies between $1.3 < D < 9$ Mpc (of which 139 are within 6 Mpc).

To estimate the detectability of dwarf satellites, we begin by considering the unresolved background galaxies and foreground Milky Way stars that contaminate a CMD selection of candidate RGB stars. For each of the galaxies in our sample, we extract the expected number of galaxies per arcmin^2 using the `GalaxyCountsMetric`, and the expected stellar density from the `StarDensityMetric`. We apply a scaling factor to account for the sub-region of the CMD inhabited by our tracers (RGB stars) relative to the full-CMD area spanned by the simulations, and an additional scaling factor to account for unresolved galaxy contamination in a stellar sample selection at the faint end. Then, with an estimated number of contaminants, we calculate the number of stars required to be detected to reach a Poisson-limited S/N > 10. (This obviously varies by position, expected depth at that position, and relative depths due to different survey strategies.) For the region around each LV galaxy, we generate fake dwarf galaxies using a simulated luminosity function (in g and i bands) for an old (10 Gyr), metal-poor ([M/H] $= -1.5$) population for different values of total luminosity, continuing to fainter luminosities until we reach the S/N threshold. Our final figure of merit (FoM) is the number of LV galaxies for which the faintest detectable dwarf satellite galaxy is fainter than $M_V = -7$. The results for all 200 available OpSim surveys are seen in Figure 1; there are two "clouds" of points at $N_{\rm gal} \sim 95$ and ~ 105. This is a $\sim 10\%$ improvement relative to the baseline 2-snap OpSim (the red point) and is mostly due to the increased depth reaching more distant LV galaxies. There are three extreme outliers covering $121 \leq N_{\rm gal} \leq 130$ LV galaxies; in decreasing order, these correspond to `filterdist_indx3_v1.5_10yrs`, `footprint_bluer_footprintv1.5_10yrs`, and `filterdist_indx1_v1.5_10yrs`. Because the limiting factor in nearly all cases is the g-band depth, these three strategies greatly improve the survey grasp for LV galaxies by increasing the number of exposures in blue filters. Of the cadences in the `filter_dist`, only those that increase the number of g-band visits (`indx3, indx1`, and `indx7`) benefit our science case.

[Q1] WFD footprint and [Q2] Use of additional time: Of the simulations in the "cloud" of points at $N_{\rm gal} \sim 105$ in Figure 1, 16 are from the `wfd_depth` family. Thus, it is clear that allocating additional time to the WFD footprint is beneficial. `footprint_no_gp_northv1.5_10yrs`, `footprint_gp_smoothv1.5_10yrs`, and `footprint_add_mag_cloudsv1.5_10yrs` are all within that cloud ($N_{\rm gal} >= 102$), and many of the other `footprints` family simulations yield 98-105 well-mapped galaxies, so there are improvements gained by increasing or altering the footprint. Additionally, `goodseeing_gri_v1.5_10yrs` also performs well. The improved seeing increases the limiting magnitude at which we reach the required S/N, thereby increasing the survey depth. This both optimizes the dwarf satellite search and general science studies of the host galaxies themselves.

[Q3] u-band and [Q4] Changes in time allocation: Many of the lowest yields in terms of $N_{\rm gal}$ were simulations from the `u_long` family. We thus conclude that the longer u-band exposures have a rather detrimental effect on the Local Volume census of dwarf satellites. The `var_expt` (variable exposure time) families also result in less total exposure in g and i, which adversely affects our science case.

As noted above, `footprint_bluer_footprintv1.5_10yrs` and simulations `indx3, indx1`, and `indx7` from the `filterdist` family far outperform the other simulated cadences for our science goals. This is because the primary limiting factor in our search is the g-band limiting magnitude; increasing the number of visits in g is beneficial for this science.

[Q5] Visit pairs/triplets, [Q6] rolling cadence/season length, [Q7] dithering patterns: The choice of filters in pairs/triplets has little effect on our figure of merit. The rolling cadence simulations had a wide variety of outcomes, but in general seem to yield slightly worse performance for dwarf satellite detection. While dithering patterns are not necessarily vital to the detection of dwarf satellites, both rotational and somewhat large translational dithers may improve the science output near the bright inner regions of the galaxies considered in this Note.

In this Cadence Note we did not consider the many additional science cases to be made for deep, high-quality imaging of Local Volume galaxies. Studies in the main bodies of nearby galaxies will require excellent seeing to enable quality crowded-field photometry, and in less crowded regions will benefit from depth in at least 2-3 bands to enable disentangling stars from the more numerous unresolved background galaxies at faint magnitudes. We also note that while we have focused on detecting satellites with resolved stars, the surface brightness sensitivity that LSST will achieve will uncover unresolved dwarf galaxies well beyond 6 Mpc (see, e.g., the Cadence Note from the LSST Galaxies Science Collaboration).

Finally, while we have focused on a census of faint dwarf galaxies that accompany *known* massive galaxies in the Local Volume, we note that the depth and large area covered by LSST will enable discovery of *isolated* dwarf galaxies in the Local Volume. We have found that the g-band depth is important for searches around known systems, but the total sky area covered is an equally important concern for finding nearby isolated dwarfs.

In conclusion, the main drivers of success for the Local Volume dwarf satellite census proposed here are (1) the exposure length (1x30s is superior to 2x15s), (2) depth in the g filter, and, to a lesser extent, (3) the total area observed.

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