Tracing the 6-D Orbital and Formation History of the Complete M31 Satellite System
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Scientific Justification

Our knowledge of low-mass galaxy evolution is anchored in the Milky Way (MW) halo. Within 300 kpc of the MW, HST observations of resolved stars have enabled the measurement of detailed star formation histories (SFHs) and precise proper motions (PMs) that complete the full 6-dimensional orbital phase space throughout the MW halo. These observations uniquely establish the relationship between dwarf galaxies and reionization (Brown et al. 2014; Weisz et al. 2014a; Boylan-Kolchin et al. 2015), provide stringent tests of CDM and the physics of galaxy formation (Boylan-Kolchin et al. 2012; Wetzel et al. 2016; Simon 2019), determine the 3-D orbits, infall times, and quenching timescales of several satellites (e.g., Kallivayalil et al. 2013; Sohn et al. 2013; Fritz et al. 2018; Simon 2018), and are sensitive to the internal motions and rotation of individual stellar orbits (van der Marel & Kallivayalil 2014). These results are fundamental to our understanding of all low-mass and satellite galaxies (e.g., Bullock & Boylan-Kolchin 2017).

However, there is growing evidence that the MW satellites may not be broadly representative. Compared to the MW, satellite systems throughout the local Universe show varying luminosity functions, stellar populations, quenching properties, and spatial configurations, often in excess of cosmic variance (e.g., McConnachie & Irwin 2006; Brasseur et al. 2011; Tollerud et al. 2012; Chiboucas et al. 2013; Geha et al. 2017; Greco et al. 2018; Müller et al. 2018; Pawlowski 2018; Smercina et al. 2018). Thus, it remains unclear whether the fundamental insights established in MW satellites are generally applicable to low-mass systems or stem from the specific accretion history of the MW. Unfortunately, direct comparisons between the lifetime evolution of MW satellites and systems outside the Local Group (LG) are not currently possible. Even in the nearest groups (e.g., M81, Cen A; $D \sim 3.5$ Mpc), severe crowding and multi-decade time baselines limit the measurement of accurate SFHs and prohibit PMs, even with HST (and/or JWST). Exploring such distant systems in detail similar to the MW satellites requires a 12-16m space telescope.

In contrast, the M31 system provides a unique, yet under-utilized, opportunity to study an entire galactic ecosystem outside the MW halo. Current data hint at important differences in the internal (e.g., kinematics, stellar content; Collins et al. 2014; Martin et al. 2017) and global (e.g., "plane of satellites"; Ibata et al. 2013; Pawlowski 2018) properties of M31 and MW satellites.

Observationally, HST can measure PMs and SFHs at the distance of M31 to a precision comparable to MW satellites (e.g., Sohn et al. 2012; Skillman et al. 2017). However, there has been comparatively little investment in HST observations of M31 satellites. To date, > 1000 orbits have been dedicated to MW satellites, while only ~ 200 have been spent on M31 satellites. HST has observed nearly all 51 known MW satellites, while of the 35 known dwarf galaxies within the virial radius (~ 300 kpc) of M31, only 12 (34%) have HST imaging that reaches the oldest main sequence turnoff (MSTO) and only the 2 (6%) with recent star formation have published PMs (e.g., Brunthaler et al. 2007; van der Marel et al. 2018).

Through this Treasury program, we propose a comprehensive ACS/WFC3 survey of the M31 satellite system. Our imaging will target all known satellites within ~ 300 kpc of M31, encompassing its full halo profile out to the virial radius. It will have the depth to measure robust SFHs, the cadence to provide secure RR Lyrae distances, and the astrometric precision for optimal first-epoch proper-motion measurements, all comparable in quality to current measurements of the entire MW

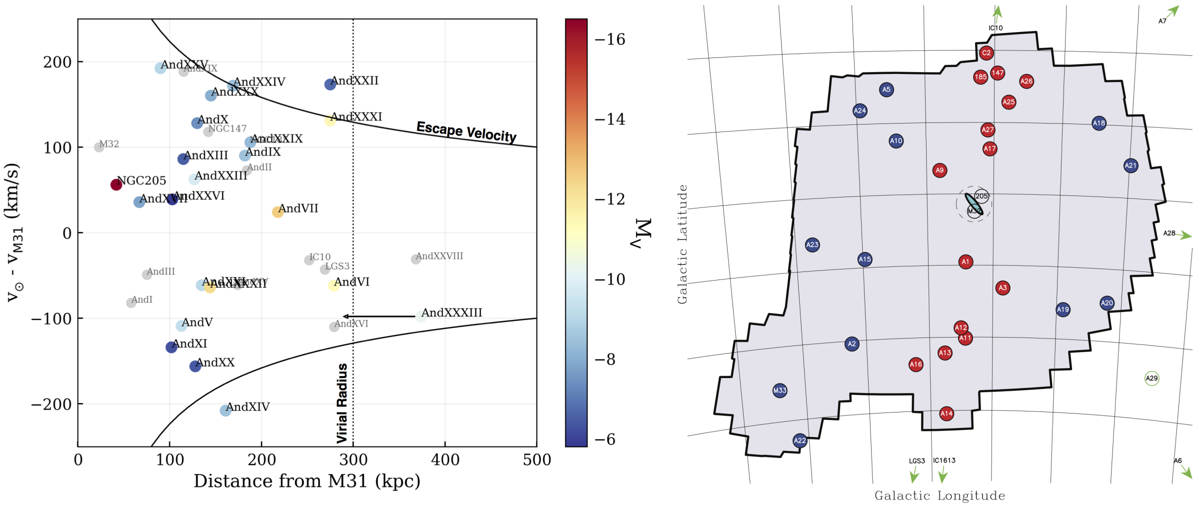

FIGURE 1: *M31 dwarf galaxies in context:* ***Left–*** *Distances and LOS velocities of M31 satellites relative to M31. Our proposed sample is color-coded by luminosity. Current distances are generally highly uncertain (e.g., Conn et al. 2012), highlighted by uncertainty in And XXXIII's location inside/outside M31's virial radius. Virtually all of these satellites are gas-poor, underlining the importance of the M31 halo environment in dwarf galaxy evolution.* ***Right–*** *The spatial distribution of all known M31 satellites as of 2013 (Ibata et al. 2013), with putative members of the thin plane in red and nominal non-plane members in blue. We will observe 23 systems that do not have existing deep HST imaging. Full phase-space information, detailed SFHs, and RR Lyrae-based distances provided by our observations will allow us to investigate the membership, coherence, and origin of the plane, as well as rewind the clock on each galaxy and study the effects of reionization and environment on its evolution.*

system. We will target the 23 known M31 dwarf galaxies that do not have adequately deep HST imaging. Our immediate science goals include (1) measuring SFHs of all M31 satellites; (2) quantifying putative differences between the MW and M31 systems to better understand variations in low-mass systems between galactic ecosystems; and (3) investigating properties of on- and off-plane M31 satellites (Figure 1; Ibata et al. 2013) using homogeneous variable star distances;. Over the next decade we will use HST and JWST to obtain second-epoch imaging to measure PMs and provide full 6-D phase space information for these dwarfs, which are too faint for Gaia. Our program will reconstruct the dynamical and star formation history of the M31 satellite system.

Given the nature of the observations involved, it is "now or never" to start this survey. Making PM measurements with precisions similar to MW satellites ($\sim$ 40 km/s) at the typical distance of M31 ($\sim$ 800 kpc) requires an 8 - 12 year baseline with HST and JWST. It is thus imperative to establish first-epoch imaging *now* to leverage JWST's full lifetime for optimal PM measurements. As we argue below, this enables unique and transformative HST science including critical issues in galaxy formation, cosmic reionization, and the nature of dark matter. Our M31 program is the *only* way to explore another galactic ecosystem at a similar level of detail as the MW. We now describe the four most critical science goals enabled by our program.

(1) The effect of environment on low-mass galaxy evolution. Outside of the MW, M31 represents our best opportunity to study environmental effects on galaxy formation in exquisite detail.