Snowmass2021 - Letter of Interest

The Merian[1] Survey: Characterizing Dark Matter in Star-Forming Dwarf Galaxies

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
□ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

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Abstract:

Extensive studies of dwarf galaxies, in the Local Group and beyond, have revealed a considerable scatter in many of their fundamental properties. In particular, galaxies with stellar mass of $10^8 - 10^9$ $M_\odot$ present a diversity of star formation rates and rotation-curve shapes which are in tension with theoretical models. Reliably characterizing the dark matter distribution and baryonic processes in these galaxies, such as feedback, is key to in order to establish a complete picture of dark matter on small scales and to understand the threshold of galaxy formation. We present a new methodology for studying dark matter in dwarf galaxies. Using two custom made filters, the Merian Survey will provide redshifts to a complete sample of 100,000 star forming dwarf galaxies (two orders of magnitude times larger than SDSS+GAMA) over an area of 867 deg^2. Combined with deep+high spatial resolution imaging from the Hyper-Suprime Camera, our program will result in the first high S/N weak lensing profile measurements for dwarf galaxies, probing their dark matter halos out to their virial radii. Comparisons with state-of-the-art, detailed, hydrodynamical simulations will help to fully capture the interplay between dark matter, feedback, and their roles in the formation and evolution of dwarf galaxies. This project is an important precursor to a much bigger program that can leverage the Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST).

[1] Honoring 17th century Maria Sibylla Merian (1647, 1717), the first female entomologist and naturalist. Her fascination with the world of tiny things combined with unique observational skills led to a number of important discoveries, including the previously unknown metamorphosis of caterpillars into butterflies.

Scientific Context:

Dwarf galaxies are a unique probe of the nature of dark matter and the interplay between dark matter and baryonic physics. For several decades, ΛCDM (cold dark matter) simulations failed to reproduce the properties of observed dwarf galaxies (the "cusp-core" controversy, e.g., Bullock & Boylan-Kolchin [5]). Recently, because of improvements in resolution and more realistic treatments of stellar and supernova feedback (e.g., Wetzel & Nagai [14]), simulations have produced more realistic dwarf galaxies. But, a number of challenges remain. First, it is unclear whether feedback prescriptions are realistic: reproducing the star formation rates and the observed range of dwarf rotation curves has proved difficult for ΛCDM simulations (the "diversity" problem, e.g., Santos-Santos et al. [13]). Non-CDM theories of dark matter (self-interacting, warm, and fuzzy dark matter) may be the solution to the diversity problem or stellar feedback sub-grid models may not yet be correct. Second, a key prediction of CDM is a power-law halo mass function down to sub-galactic scales – all non-CDM models of dark matter deviate from the CDM prediction at some scale. However, current estimates of the halo mass function and the stellar-to-halo mass relation (SHMR) from subhalo abundance matching and using galaxy kinematics strongly disagree[2 4 12]. Understanding the SHMR, currently poorly constrained on dwarf galaxy scales, is essential in order to use galaxy surveys as a proxy for a halo census. For this, understanding feedback processes in dwarfs is key.

These fundamental questions will only be resolved by contrasting high-quality data with predictions from both CDM simulations with more detailed feedback physics, and simulations of non-CDM models with feedback physics. A comprehensive, holistic, and multi-faceted program to better characterize dwarf galaxies is urgently needed. The mass range $\mathrm{M}_\star = 10^8 - 10^9\ \mathrm{M}_\odot$ is the "sweet spot" for detecting correlations between the properties of a dwarf's baryonic matter, the slope of its inner dark matter halo, and its overall dark matter halo mass (e.g., Di Cintio et al. [6],[7]). This program should: (1) measure the dark matter halo properties of dwarfs (not just the inner regions probed by rotation curves), (2) constrain feedback physics by mapping out the properties of dwarfs (mass-weighted size, shape, and star formation), (3) map the effects of AGN, merging, and stellar feedback, and (4) have a strong simulation based theoretical component in order to interpret results. Only with these components in place can we hope to disambiguate the roles that baryonic processes and dark matter physics play in sculpting dwarf galaxies.

This program has been historically challenging because SDSS is incomplete below $\mathrm{M}_\star < 10^9\ \mathrm{M}_\odot$, GAMA reaches $\mathrm{M}_\star < 10^8\ \mathrm{M}_\odot$ only at $z < 0.02$, and pencil beam surveys have limited gravitational lensing capabilities to probe the dark matter component. The Merian survey is a newly approved program that will use 65 nights (over three years) on the Blanco telescope starting in February 2021 to address these challenges. Merian will build the largest and most well-understood sample of dwarf galaxies by using: 1) the deep and wide imaging from the Hyper Suprime-Camera Subaru Strategic Program (HSC SSP), 2) DECam imaging using two custom built filters, and 3) spectroscopic follow up with Keck and Magellan. Merian will be uniquely positioned to study dark matter in dwarf galaxies, paving the way for an even bigger possible program with LSST. With a program like this, we can accomplish two important goals.

Probing The Dark Matter Halos of Dwarfs

• *Direct Measurements of Halo Mass*. Rotation curves of dwarf galaxies only constrain the inner regions of dark matter halos (typically a factor of ∼10-20 smaller than the actual halo radius). Any "halo mass" estimate from rotation curves is in fact an extrapolation that relies on assumptions about the shape of the dark matter profile (e.g., Buckley & Peter [4]). One of the most powerful ways to directly probe total halo masses out to the halo radius is "galaxy-galaxy lensing." This is the average weak lensing signal from background "source" galaxies around a sample of foreground "lens" galaxies. Existing weak lensing measurements have been limited to $\mathrm{M}_\star > 10^9\ \mathrm{M}_\odot$. However, Leauthaud et al. [11] recently showed that new generation lensing surveys can measure the lensing signal of dwarfs with high significance. *The Merian survey will yield the first lensing measurement for dwarf galaxies*. The HSC DR1 lensing source catalog is publicly available.

With 100,000 dwarfs, we will measure the lensing signal around dwarfs with $S/N = 36$ out to $R = 0.5$ Mpc ($S/N = 100$ to 1 Mpc). This will allow us to study both the SHMR at the dwarf scale and also the scatter around this relation. It will be the first direct measurement of the SHMR relation and of the halo mass function on these small scales.

• *Connecting Inner and Outer Halo Properties*. The ongoing LVHIS [10] and WALLABY [9] 21-cm surveys on the ATCA and ASKAP radio telescope arrays will measure HI velocity profiles for dwarfs. LVHIS produces rotation curves at ~ 1 kpc resolution for Local Volume dwarfs. We will identify analogs of the dwarfs in our survey in the Local Volume, and use the rotation curves to anchor the gravitational potential in the inner regions of galaxies while using the gravitational lensing to pin down the halo mass and the larger scale dark matter environment). Furthermore, WALLABY's footprint and redshift range overlaps ours, so we will be able to directly identify gas rich dwarfs in our survey (however, Merian will be more complete at these mass scales). Galaxies will not be resolved in HI but we can use the gas mass and velocity profile to compare against simulations. The velocity profile will also be used to measure a maximum rotation velocity of the HI gas which, combined with a high signal-to-noise ratio, will probe further into the halo. Forward modeling will be used to compare these observations with our theoretical models (e.g., Brooks et al. [3]).

• *Weak Lensing Profiles*: Banerjee et al. [1] showed that the shape of the one-halo term of dark matter halos is sensitive to the strength of self-interactions of dark matter. This effect extends out to near the edge of the virialized region, and is therefore more robust to baryonic effects compared to the inner halo. The change in shape is directly probed in galaxy-galaxy lensing. The Merian survey will provide the ideal data set to constrain dark matter interactions at the dwarf scale.

Decoupling Feedback from Dark Matter

• *Mass-Size Relation*: Dwarf galaxies sit in a shallow potential well and accrete relatively few stars, so the quantitative details of dwarf size and structure should provide powerful constraints on the star formation feedback prescriptions employed by simulations at all scales, from (sub-)galactic to cosmological. Constraining these details requires a sample that is large, mass-complete, and has imaging of sufficient resolution and depth to characterize dwarf structure on an individual level. The effective surface brightness limits of current spectroscopic samples preferentially select compact dwarfs in the ROMULUS25 cosmological simulation [15], providing a biased view of the dwarf population. The medium band imaging approach employed by the Merian survey, when combined with sizes measured from HSC imaging data will yield a complete view of the star forming dwarf population. When coupled with the direct halo measurements and focused simulations, this effort will be able to comprehensively disentangle the contributions of feedback and dark matter to the diversity of dwarf galaxies.

• *Connection between feedback and gas fractions*: The amount of HI and its distribution in galaxies is extremely sensitive to feedback. WALLABY will provide HI masses for the most gas rich dwarfs in our sample (top $\sim 10\%$). The comparison of Merian+WALLABY using a forward modeling approach based on our simulations will provide another important constraint on feedback models and will further inform models of the gas+stellar+halo connection.

Merian is a novel and ambitious program that will expand known complete samples of dwarf galaxies in the mass range $8 < \log(M*/M_\odot) < 9$ but more than a factor of one hundred and will provide gravitational lensing measurements of the abundance and shape of their dark matter halos in order to test the nature of dark matter. The lessons learned from Merian can be used to extend the study of dwarf galaxies down to the stellar mass range $6 < \log(M*/M_\odot) < 8$ with LSST [8].

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