

Snowmass2021 - Letter of Interest

Probing Dark Matter Physics with Maunakea Spectroscopic Explorer

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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Collaboration: Maunakea Spectroscopic Explorer Collaboration

Abstract: We discuss the potential to understand the nature of dark matter particles with the next generation spectroscopy program, determining the line-of-sight velocities of a large number of faint stars in the Milky Way's stellar streams and nearby dwarf spheroidal galaxies, obtaining the redshifts of low-mass galaxies in the local Universe ($z < 0.05$), and searching for strongly lensed galaxies at higher redshift. N-body and hydrodynamical simulations of cold, warm, fuzzy and self-interacting dark matter show that non-trivial dynamics in the dark sector will leave an imprint on structure formation, with much of this science having been developed in last few years. Sensitivity to these imprints will require extensive and unprecedented kinematic datasets for stars down to $r \sim 23$ mag and redshifts for galaxies down to $r \sim 24$ mag. We conclude that a 10m class wide-field, high-multiplex spectroscopic survey facility like Maunakea Spectroscopic Explorer is required in the next decade to provide a definitive search for deviations from the cold collisionless dark matter model.

Motivation. Dark matter has been detected through its gravitational influence on galaxies and clusters of galaxies, the large-scale distribution of galaxies, and the cosmic microwave background. But, the kinds of particles or fields that make up the dark matter have not been identified despite decades of dark matter searches deep underground, in particle colliders, and through multimessenger astronomy. At the same time, there has been a flowering of ideas for the nature of dark matter that have exciting signatures in astrophysical or terrestrial searches, and new production mechanisms¹.

Astrophysical observables are critical to constraining models of dark matter across a range of mass scales from 10^{-23} eV to $100 M_{\odot}$. We will soon enter a new era of high spatial resolution observations and fast sky imaging surveys with James Webb Space Telescope and the Legacy Survey of Space and Time (LSST) at the Vera C. Rubin Observatory, where these astrophysical observables have the potential to zero in on viable theory spaces. Recent progress in N-body and hydrodynamical simulations of cold collisionless dark matter (CDM), warm dark matter (WDM), fuzzy dark matter (FDM), and self-interacting dark matter (SIDM) have helped to bolster this case, while a wealth of new observations from dwarf galaxies to galaxy clusters have opened up the exciting possibility that non-trivial dynamics in the hidden sector could have left an imprint on structure formation. In particular, different dark matter models can impact the density and the abundance of dark matter halos, which could be measured via astronomical observations.

In addition to the imaging surveys, spectroscopic observations are essential to dark matter studies. In this letter, we discuss concrete ways in which astrophysical probes can elucidate the particle nature of dark matter with Maunakea Spectroscopic Explorer (MSE), which is a highly-multiplexed (4332 fibers), wide field of view (1.5 square deg), large aperture (11.25 m in diameter), optical/NIR (360–1300 nm) facility for obtaining spectroscopy with a spectral resolution resolution of $\sim 2500 - 4000$ in low-resolution mode and $\sim 20000 - 40000$ in high-resolution mode. We highlight several science cases in this letter, and group the science cases into the following four probes based on the distance of the objects being targeted – from nearby to the distant Universe. We note that a longer discussion is available on the arXiv review² from MSE Dark Matter Working Group, or Chapter 6 of the MSE Detailed Science Case document³.

Probes

Stellar streams are created by the tidal disruption of globular clusters and dwarf galaxies. The passage of a subhalo near or through a cold globular cluster stream can perturb the orbits of part of the stream stars and cause gaps and wiggles to form⁴⁻⁷. This is one of a small number of methods currently known that is sensitive to the subhalo mass function down to small masses ($M \lesssim 10^8 M_{\odot}$)⁸, the regime where dark matter halos are no longer able to form stars or a galaxy. Each subhalo flyby produces a unique signature on the stream density and orbit, which when combined with radial velocities of individual stream stars provides enough information to reconstruct the perturber properties, i.e. its mass, scale radius, relative velocity, and impact parameter⁹. In order to be able to probe subhalos down to $10^5 - 10^7 M_{\odot}$, a radial velocity precision of $100 - 300 \text{ m s}^{-1}$ is required. A large aperture telescope (to probe fainter stars) with high precision for velocity measurements ($\lesssim 1 \text{ km s}^{-1}$) is necessary for this science. To date, about 50 streams have been discovered in our Galaxy¹⁰⁻¹³ while less than one-third of them have had dedicated spectroscopic follow-up observations; the next generation of imaging surveys, such as LSST, are expected to find many more streams. A dedicated spectroscopic follow-up program for stellar streams requires both a wide field-of-view and large aperture.

Dwarf galaxies in the Milky Way and Andromeda Galaxy (M31) can be used as an incisive test of dark matter physics, as various viable dark matter models provides different predictions on the abundance of dwarf galaxies as well as the dark matter distribution within them, especially on the faintest galaxies – so called ultra faint dwarf galaxies – where the effects from baryonic (feedback) processes is minimal. A dedicated spectroscopic survey program with a limiting magnitude of $r \sim 23$ will enable characterization of the

new discoveries, for example the roughly 200 Milky Way’s satellite dwarf galaxies^{14;15} LSST is supposed to find, and it will significantly increase the stellar sample sizes in known dwarf galaxies. Furthermore, for searches of dark matter annihilation or decay into high energy Standard Model particles (e.g. X-ray or γ -ray), dwarf galaxies are the ideal target since they are nearby, dark matter dominated, and background free. Spectroscopic follow-up observations are essential to determine the dark matter density at the center of the galaxies to constrain the dark matter self-annihilation cross sections or decay lifetimes.

Low-redshift ($z < 0.05$) dwarf galaxy beyond the Milky Way also make inferences about the nature of dark matter. A spectroscopic survey down to $r \sim 24$, combined with efficient target selection, can produce a near-complete dwarf galaxy sample for Leo I like dwarf galaxies ($M_r \sim -12$) at $z < 0.05$. This allows us to obtain the satellite luminosity function at the faint end beyond the Milky Way and M31, which is a critical discriminant of the too-big-to-fail problem and its proposed solutions^{16;17}. In addition, weak gravitational lensing in low mass dwarf galaxies ($M_h < 10^{11} M_\odot$) provides a direct unbiased measurement of the total mass, and this is critical for an accurate assessment of the implications of the too-big-to-fail problem. Since these low mass galaxies are only detectable at low redshift ($z < 0.2$), contamination of high-redshift galaxies in the lens sample could either smear out the lensing signal or produce catastrophic photo- z outliers, resulting in a bias in the inferred mass profile. A spectroscopic survey alleviates both these issues.

Strong gravitational lensing by galaxies provides powerful ways to constrain the mass function of low-mass dark halos and subhalos, since lensing is sensitive to all the mass along the line of sight. For unresolved sources such as lensed quasars, the presence of substructure is manifested in the flux-ratio anomalies: differences between the relative magnifications of lensed images as compared to the predictions of smooth mass models¹⁸. Surveys with the next generation spectroscopic facilities will be essential for confirming quasar lenses from a vast amount of lensing systems found by LSST, and selecting ideal candidates for high spatial resolution imaging with Adaptive Optics or space-based telescopes. These systems can then be used to infer the presence of dark matter substructure within or along the line of sight to the lens, or place constraints when they are not found. For resolved sources (galaxies), measurements of the surface-brightness perturbations of the lensed images (e.g. arcs) can reveal the presence of unseen mass and this provides stringent constraints on the subhalo mass function¹⁹. Galaxy redshift surveys (using SDSS) have proven to be an excellent source for the discovery of new galaxy-galaxy strong lensing systems^{20–24}. A wide field-of-view spectrograph on a 10m class telescope, combined with dedicated survey operations mission, can enable flux-limited galaxy surveys ten times larger than the original SDSS, delivering a sample of thousands of strong galaxy-galaxy lenses, from which we may expect dozens of substructure detections. The redshifts obtained for these systems via the spectroscopy survey will be an essential component in the lens modeling.

Recommendations for Snowmass 2021

While there are many planned spectroscopic surveys with 4-m class telescopes (e.g. WEAVE, 4MOST, DESI), there are no current plans for a spectroscopic survey with a 10-m class telescope. Considering the large sky area that needs to be covered and the relatively small FOV of 10m class telescopes compared to 4-m class telescopes, a dedicated survey telescope is necessary to conduct the proposed programs for Dark Matter and other science. There is *no* capability on existing 10m class telescopes to conduct such a survey. Among the fourteen 8-10m telescopes (Keck, LBT, VLT, HET, Gemini, Subaru, GTC, SALT), only Subaru Telescope has a relatively large FOV, which is, however, a facility telescope with limited spectroscopic survey time. *Therefore, a 10m class wide-field, high-multiplex spectroscopic survey facility like Maunakea Spectroscopic Explorer is required in the next decade to provide a definitive search for deviations from the cold collisionless dark matter model.*

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