Snowmass2021 - Letter of Interest

The Vera C. Rubin Observatory as a Dark Matter Experiment

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
■ (TF08) BSM Model Building
■ (TF09) Astro-particle physics & cosmology
■ (CompF2) Theoretical Calculations and Simulation

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Abstract:

Astrophysical observations currently provide the only robust, empirical measurements of dark matter. In the coming decade, astrophysical observations will guide other experimental efforts, while simultaneously probing unique regions of dark matter parameter space. This letter summarizes astrophysical observations that can constrain the fundamental physics of dark matter in the era of the Vera C. Rubin Observatory and associated 10-year Legacy Survey of Space and Time (LSST). We describe how astrophysical observations will inform our understanding of the fundamental properties of dark matter, such as particle mass, production mechanism, self-interaction strength, non-gravitational interactions with the Standard Model, and compact object abundances. Additionally, we highlight theoretical work and experimental/observational facilities that will complement Rubin Observatory to strengthen our understanding of the fundamental characteristics of dark matter.

More than 85 years after its astrophysical discovery, the fundamental nature of dark matter remains one of the foremost open questions in science. Over the last several decades, an extensive experimental program has sought to determine the cosmological origin, constituents, and interaction mechanisms of dark matter. To date, all direct evidence for the existence of dark matter and all positive empirical measurements of dark matter properties come from astrophysical and cosmological observations. Discovering the fundamental nature of dark matter will necessarily draw upon the tools of particle physics, cosmology, and astronomy.

The Vera C. Rubin Observatory and associated 10-year Legacy Survey of Space and Time (LSST) will provide a unique and powerful platform to study dark sector physics in the 2020s. Originally envisioned as the "Dark Matter Telescope",[1] Rubin Observatory will enable precision tests of the ΛCDM model and elucidate the connection between luminous galaxies and the cosmic web of dark matter. Cosmology has consistently shown that it is impossible to separate the *macroscopic distribution* of dark matter from the *microscopic physics* governing dark matter. Some microscopic characteristics of dark matter are *only accessible* via astrophysics. A robust dark matter program enabled by LSST data will test a broad range of well-motivated theoretical models of dark matter including supersymmetric particles, particles in hidden-sector theories, sterile neutrinos, QCD axions, axion-like particles (including ultra-light particles), and primordial black holes.[2]

As an unprecedentedly powerful multi-use survey, LSST has the potential to discover the identity of dark matter through diverse observational measurements.[2] LSST will enable studies of Milky Way satellite galaxies, stellar streams, and strong lens systems to detect and characterize the smallest dark matter halos, thereby probing the minimum mass of ultra-light dark matter, the free-streaming length of dark matter, and interactions between dark matter and Standard-Model particles. Precise measurements of the density and shapes of dark matter halos in dwarf galaxies and galaxy clusters will be sensitive to dark matter self-interactions probing hidden-sector models. Microlensing measurements will directly probe primordial black holes and the compact object fraction of dark matter at the sub-percent level over a wide range of masses, measuring the inflationary power spectrum as well as dark-matter physics. Precise measurements of stellar populations will be sensitive to anomalous energy-loss mechanisms and will constrain the coupling of axion-like particles to photons and electrons. Measurements of large-scale structure will spatially resolve the influence of both dark matter and dark energy, enabling searches for correlations between the two known components of the dark sector. In addition, complementarity between cosmological, direct detection, and other indirect searches for dark matter will help constrain dark matter-baryon scattering, dark matter self-annihilation, and dark matter decay.

Cosmological studies of dark matter with LSST will explore parameter space beyond the current sensitivity of the high energy physics program and will complement other experimental searches. This has been recognized in Astro 2010,[3] during the Snowmass Cosmic Frontier planning process,[4–6] in the 2014 P5 Report,[7] and in a series of recent Cosmic Visions reports,[8,9] including the "New Ideas in Dark Matter 2017: Community Report".[10] Analysis of LSST data will improve constraints on the dark matter free-streaming length, de Broglie wavelength, scattering cross section with baryons, photons, and neutrinos, self-interaction cross section, annihilation cross section, decay lifetime, and production time in the early Universe. LSST observations will help to robustly determine the mass threshold at which dark matter halos have negligible baryon content, and provide sensitivity to even lower mass halos that are completely dark, both within the Milky Way and on extragalactic scales via gravity-only techniques (e.g., stellar stream perturbations, gravitational lensing). The enormous sensitivity gains of LSST also open significant discovery potential, for instance, to measure a cutoff and other features in the matter-power spectrum and/or an excess population of compact objects. This, combined with terrestrial, lab-based probes of the non-gravitational interaction between dark matter and the Standard Model, will lead to a full microphysical description of dark matter.

In the 2020s, the impact of the LSST dark matter program will be enhanced by access to wide-field massively multiplexed spectroscopy on medium- to large-aperture telescopes ($\sim$ 8–10-meter class),[11] deep spectroscopy on giant segmented mirror telescopes ($\sim$ 30-m class),[12] together with high-resolution optical and radio imaging.[13] Further theoretical work is needed to interpret these observations in terms of particle models, to combine results from multiple observational methods, and to develop novel probes of dark matter.

Recommendations for Snowmass 2021

LSST is scheduled to begin a decade of science operation in 2023; however, dark matter research with LSST is not yet funded. Recognizing new opportunities created by LSST to constrain a broad range of dark matter models, we make the following recommendations to facilitate this science case:

- Support individual PIs and collaborative teams to study dark matter with LSST.
- Support associated theoretical and simulation-based research to investigate novel signatures of dark matter microphysics, perform joint analyses of cosmological probes, better understand the galaxy-halo connection, examine confounding baryonic effects, and strengthen ties with the particle physics community.
- Support complementary observational facilities to investigate dark matter, including spectroscopic follow-up and high-resolution imaging, as well as multiwavelength analyses.[14]
- Support cross-disciplinary, collaborative efforts to unite LSST dark matter analysis with particle theory and experiment.

A community of scientists is preparing for transformative studies of dark matter with the Rubin Observatory. The LSST Dark Energy Science Collaboration (DESC) has recently inaugurated a Dark Matter Working Group, which provides a forum for particle physicists, observational cosmologists, theorists, and data analysts to start developing the phenomenology of dark matter microphysics in LSST data. Importantly, the co-location of research efforts in dark matter, dark energy, neutrinos, and inflation within a single science collaboration provides the greatest opportunity to leverage technical and scientific overlap, and to capitalize on emerging scientific opportunities in the next decade.

We anticipate that LSST will enable new probes of dark-matter physics that have yet to be considered. New ideas are especially important as searches for the most popular dark matter candidates gain in sensitivity while lacking a positive detection. As the particle physics community diversifies the experimental effort to search for dark matter, a critical consideration is that astrophysical observations provide robust, empirical measurement of fundamental dark matter properties. Findings from astrophysical observations vastly exceed the sensitivity of terrestrial experiments for certain particle properties. In the coming decade, astrophysical observations will guide other experimental efforts, while simultaneously probing unique regions of dark matter parameter space.

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