



Publication Year	2019
Acceptance in OA @INAF	2021-01-25T10:48:41Z
Title	Dark Matter Science in the Era of LSST
Authors	Bechtol, Keith; Drlica-Wagner, Alex; Abazajian, Kevork N.; Abidi, Muntazir; Adhikari, Susmita; et al.
Handle	http://hdl.handle.net/20.500.12386/29961
Journal	BULLETIN OF THE AMERICAN ASTRONOMICAL SOCIETY
Number	51

Astro2020 Science White Paper

Dark Matter Science in the Era of LSST

Thematic Areas:

- Formation and Evolution of Compact Objects
- Planetary Systems
- Star and Planet Formation
- Stars and Stellar Evolution
- Resolved Stellar Populations and their Environments
- Galaxy Evolution
- Multi-Messenger Astronomy and Astrophysics
- Cosmology and Fundamental Physics

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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 white paper summarizes astrophysical observations that can constrain the fundamental physics of dark matter in the era of LSST. We describe how astrophysical observations will inform our understanding of the fundamental properties of dark matter, such as particle mass, 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 LSST to strengthen our understanding of the fundamental characteristics of dark matter.

Summary

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, the only direct, positive empirical measurements of dark matter come from astrophysical observations. Discovering the fundamental nature of dark matter will necessarily draw upon the tools particle physics, cosmology, and astronomy.

LSST will provide a unique and impressive platform to study dark sector physics in the 2020s. Originally envisioned as the “Dark Matter Telescope”¹, LSST will enable precision tests of the Λ CDM 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. In fact, some microscopic characteristics of dark matter are *only accessible* via astrophysics. Studies of dark matter, dark energy, massive neutrinos, and galaxy evolution are *extremely complementary* from both a technical and scientific standpoint. A robust dark matter program leveraging LSST data has the ability to test a broad range of well-motivated theoretical models of dark matter including self-interacting dark matter, warm dark matter, dark matter-baryon scattering, ultra-light dark matter, axion-like particles, and primordial black holes.

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 and thermal warm dark matter. 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 and dark photon 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. 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 astrophysical, direct detection, and other indirect searches for dark matter will help constrain dark matter-baryon scattering, dark matter self-annihilation, and dark matter decay.

Astrophysical dark matter studies 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 2010², during the Snowmass Cosmic Frontier planning process³⁻⁵, in the P5 Report⁶, and in a series of recent Cosmic Visions reports^{7:8}, including the “New Ideas in Dark Matter 2017: Community Report”⁹. 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 (~ 8 – 10 -meter class), deep spectroscopy on giant segmented mirror telescopes (~ 30 -m class), together with high-resolution optical and radio imaging. Further theoretical work is also needed to interpret those observations in terms of particle models, to combine results from multiple observational methods, and to develop novel probes of dark matter.

This whitepaper is a summary of Drlica-Wagner et al. (2019)¹⁰.

Model	Probe	Parameter	Value
Warm Dark Matter	Halo Mass	Particle Mass	$m \sim 18 \text{ keV}$
Self-Interacting Dark Matter	Halo Profile	Cross Section	$\sigma_{\text{SIDM}}/m_\chi \sim 0.1\text{--}10 \text{ cm}^2/\text{g}$
Baryon-Scattering Dark Matter	Halo Mass	Cross Section	$\sigma \sim 10^{-30} \text{ cm}^2$
Axion-Like Particles	Energy Loss	Coupling Strength	$g_{\phi e} \sim 10^{-13}$
Fuzzy Dark Matter	Halo Mass	Particle Mass	$m \sim 10^{-20} \text{ eV}$
Primordial Black Holes	Compact Objects	Object Mass	$M > 10^{-4} M_\odot$
WIMPs	Indirect Detection	Cross Section	$\langle\sigma v\rangle \sim 10^{-27} \text{ cm}^3/\text{s}$
Light Relics	Large-Scale Structure	Relativistic Species	$N_{\text{eff}} \sim 0.1$

Table 1: Probes of fundamental dark matter physics in the LSST era, organized by dark matter model and associated observables. Sensitivity forecasts appear in the rightmost column.

Dark Matter Models

Astrophysical observations probe the physics of dark matter through its impact on structure formation throughout cosmic history. On large scales, current observational data are well described by a simple model of stable, non-relativistic, collisionless, cold dark matter (CDM). However, many viable theoretical models of dark matter predict deviations from CDM that are testable with current and future observations. Fundamental properties of dark matter—e.g., particle mass, self-interaction cross section, coupling to the Standard Model, and time evolution—can imprint themselves on the macroscopic distribution of dark matter in a detectable manner. With supporting theoretical efforts and follow-up observations, LSST will be sensitive to several distinct classes of dark matter models, including particle dark matter, field dark matter, and compact objects (Table 1).

Particle Dark Matter: LSST, in combination with other observations, will be able to probe microscopic characteristics of particle dark matter such as self-interaction cross section, particle mass, baryon-scattering cross section, self-annihilation rate, and decay rate. These measurements will complement and guide collider, direct, and indirect detection efforts to study particle dark matter.

Wave-like Dark Matter: Axion-like particles and other (ultra-)light dark matter candidates are a natural alternative to conventional particle dark matter. LSST will be uniquely sensitive to the minimum mass of ultra-light dark matter and to couplings between axion-like particles and the Standard Model.

Compact Objects: Compact object dark matter is fundamentally different from particle models; primordial black holes cannot be studied in an accelerator and can only be detected through their gravitational force. Primordial black holes (PBHs) formed directly from the primordial density fluctuations could make up some fraction of the dark matter, and a measurement of their abundance would directly constrain the amplitude of density fluctuations and provide unique insights into physics at ultra-high energies.

Dark Matter Probes

Minimum Halo Mass: The standard cosmological model predicts a nearly scale-invariant mass spectrum of dark matter halos down to Earth-mass scales (or below), e.g., in WIMP and non-thermal axion models^{11–13}. Modifications to the cold, collisionless dark matter paradigm can suppress the formation of dark matter halos on these small scales. Current observations provide a

robust measurement of the dark matter halo mass spectrum for halos with mass $> 10^{10} M_\odot$, and the smallest known galaxies provide an existence proof for halos of mass $\sim 10^8 M_\odot - 10^9 M_\odot$ ¹⁴⁻¹⁹. LSST will expand the census of ultra-faint satellite galaxies orbiting the Milky Way and enable statistical searches for extremely low-luminosity and low-surface brightness galaxies throughout the Local Volume. By measuring the galaxy luminosity function at the extreme low-mass threshold of galaxy formation, LSST will test the abundance of dark matter halos at $\sim 10^8 M_\odot$.

LSST will probe dark matter halos below the threshold of galaxy formation with stellar streams and strongly lensed systems. Galactic dark matter subhalos with masses as small as $10^5 - 10^6 M_\odot$ passing a stellar stream are capable of producing detectable gaps in the stellar density^{20;21}. By identifying additional stellar streams and increasing the density contrast of known streams against the smooth Milky Way halo, LSST will shift analysis from individual gaps into the regime of subhalo population statistics and (in)consistency with cold dark matter predictions. Importantly, LSST will allow studies of streams farther from the center of the Galaxy for which confounding baryonic effects are lessened. Meanwhile, strong gravitational lensing can be used to measure the abundance and masses of subhalos in massive galaxies and small isolated halos along the line of sight at cosmological distances, independent of their baryon content. LSST will increase the number of lensed systems from the current sample of hundreds to an expected sample of thousands of lensed quasars²² and tens of thousands of lensed galaxies²³.

Halo Profiles: Measurements of the radial density profiles and shapes of dark matter halos are sensitive to the microphysics governing non-gravitational dark matter self-interactions, which could produce flat density cores²⁴ and more spherical halo shapes²⁵. Through galaxy-galaxy weak lensing, LSST will be able to distinguish cored versus cuspy NFW density profiles for a sample of low-redshift dwarf galaxies with masses $M_{\text{halo}} = 3 \times 10^9 h^{-1} M_\odot$. Studies of the density profiles of massive galaxy clusters, as well as systems of merging galaxy clusters, will constrain the scattering cross section at the level $\sigma_{\text{SIDM}}/m_\chi \sim 0.1 - 1 \text{ cm}^2 \text{ g}^{-1}$. Measuring halo profiles over a range of mass scales will provide sensitivity to dark matter scattering with non-trivial velocity dependence.

Compact Objects: LSST has the ability to directly detect signals of compact halo objects through precise, short- (~ 30 s) and long-duration (~ 1 yr) observations of classical and parallactic microlensing²⁶. If scheduled optimally, LSST could extend PBH sensitivity to $\sim 0.03\%$ of the dark matter fraction for masses $\gtrsim 10^{-1} M_\odot$. By supplementing the LSST survey with astrometric microlensing observations, it will be possible to break lensing mass-geometry degeneracies and make precise measurements of individual black hole masses. Thus, if PBHs make up a significant fraction of dark matter, LSST will effectively measure their “particle” properties and provide insight into the fundamental physics of the early universe.

Anomalous Energy Loss: Observations of stars provide a mechanism to probe temperatures, particle densities, and time scales that are inaccessible to laboratory experiments. Since conventional astrophysics allows us to quantitatively model the evolution of stars, detailed study of stellar populations can provide a powerful technique to probe new physics. In particular, if new light particles exist and are coupled to Standard Model fields, their emission would provide an additional channel for stellar energy loss. LSST will greatly improve our understanding of stellar evolution by providing unprecedented photometry, astrometry, and temporal sampling for a large sample of faint stars. In particular, measurements of the white dwarf luminosity function, giant branch stars, and core-collapse supernovae will provide sensitivity to the axion-electron coupling.

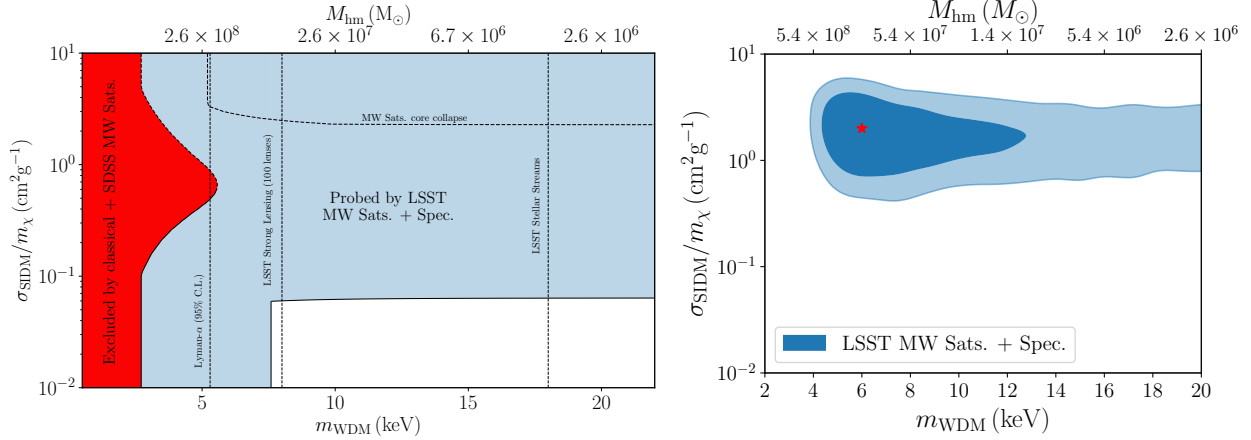


Figure 1: *Left*: Projected joint sensitivity to WDM particle mass and SIDM cross section from LSST observations of dark matter substructure. *Right*: Example of a measurement of particle properties for a dark matter model with a self-interaction cross section and matter power spectrum cut-off just beyond current constraints ($\sigma_{\text{SIDM}}/m_\chi = 2 \text{ cm}^2 \text{ g}^{-1}$ and $m_{\text{WDM}} = 6 \text{ keV}$, indicated by the red star)¹⁰. Complementary observations can break degeneracies among dark matter models that have the same approximate behavior on small scales but differ in detail.

Large-Scale Structure: LSST will produce the largest and most detailed map of the distribution of matter and the growth of cosmic structure over the past 10 Gyr. The large-scale clustering of matter and luminous tracers in the late-time universe is sensitive to the total amount of dark matter, the fraction of dark matter in light relics that behave as radiation at early times, and fundamental couplings between dark matter and dark energy. Measurements of large-scale structure with LSST will enhance constraints on massive neutrinos and other light relics from the early universe that could compose a fraction of the dark matter. Additionally, LSST will use supernovae and $3 \times 2\text{pt}$ statistics of galaxy clustering and weak lensing to measure dark energy in independent patches across the sky, allowing for spatial cross correlation between dark matter and dark energy²⁷.

Complementarity

LSST will enable complementary studies of dark matter with spectroscopy, high-resolution imaging, indirect detection experiments, and direct detection experiments. While LSST can substantially improve our understanding of dark matter in isolation, the combination of experiments is essential to confirm future discoveries and provide a holistic picture of dark matter physics.

Spectroscopy: Wide field-of-view, massively multiplexed spectroscopy on 8–10-meter-class telescopes as well as deep spectroscopy with 30-meter-class telescopes will complement studies of minimum halo mass and halo profiles.

High-Resolution Imaging: High-resolution follow-up imaging at the milliarcsecond-scale from space and with ground-based adaptive optics are needed to maximize strong lensing, microlensing, and galaxy cluster studies with LSST.

Indirect Detection: By precisely mapping the distribution of dark matter on Galactic and extragalactic scales, LSST will enable more sensitive searches for energetic particles created by dark

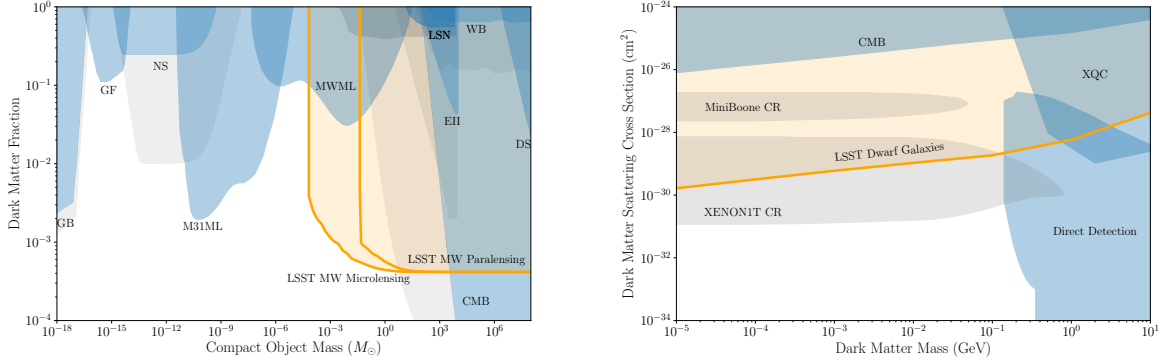


Figure 2: *Left:* Constraints on the maximal fraction of dark matter in compact objects from existing probes (blue and gray) and projected sensitivity for LSST microlensing measurements (gold). *Right:* Constraints on dark matter-baryon scattering through a velocity-independent, spin-independent contact interaction with protons from existing constraints (blue and gray) and projections for LSST observations of Milky Way satellite galaxies (gold)^{10;32}.

matter annihilation and/or decay, e.g., using gamma-ray or neutrino telescopes^{28–30}. LSST will also provide sensitivity to axion-like particles via monitoring extreme events in the transient sky³¹.

Direct Detection: LSST will complement direct detection experiments by improving measurements of the local phase-space density of dark matter using precision astrometry of Milky Way stars. For dark matter-baryon scattering, small-scale structure measurements with LSST can probe dark matter masses and cross sections outside the range accessible to direct detection experiments.

Recommendations for Astro 2020

LSST is scheduled to begin a decade of science operation in 2022; however, dark matter research with LSST is not yet funded. Recognizing new opportunities created by LSST to constrain a range of dark matter models, we make the following recommendations to facilitate this science case:

- Support individual PIs and collaborative teams to analyze LSST data for dark matter science.
- Support associated theoretical research to better understand the galaxy-halo connection, examine confounding baryonic effects, perform joint analyses of cosmological probes, investigate novel signatures of dark matter microphysics, 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.

We anticipate that the multi-faceted LSST data will allow further 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 seeks to diversify the experimental effort to search for dark matter, it is important to remember that astrophysical observations provide robust, empirical measurement of fundamental dark matter 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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