# 3

# Cosmic Probes of Dark Matter

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## 3.1 Executive Summary

The existence of dark matter represents direct evidence that the Standard Model of particle physics is incomplete. However, despite extensive empirical evidence for the existence of dark matter, its fundamental composition and microphysical properties have yet to be determined. The impact, importance, and interdisciplinarity of the dark matter problem make it one of the most exciting questions in science today. Over the next decade, cosmic probes of dark matter will continue to be a unique approach to study physics beyond the Standard Model of particle physics.

Cosmological and astrophysical observations currently provide the only robust, positive empirical measurements of dark matter. In particular, cosmic probes of dark matter are unique in that many do not rely on the assumption that dark matter has interactions with normal matter beyond gravity; thus they are the most "expansive" (and may be the only viable) approach to increasing our empirical understanding of dark matter. Furthermore, due to the extreme scales and environments studied by cosmic probes, they are sensitive to very rare interactions between dark matter and Standard Model particles. The sensitivity to both gravitational and particle interactions of dark matter makes cosmic probes of dark matter highly complementary to other experimental efforts in the Cosmic Frontier (i.e., CF1, CF2, CF7) and other HEP Frontiers (i.e., EF10, TF9, RF6, NF3). Furthermore, there are strong scientific and experimental synergies between cosmic probes of dark matter, dark energy, and the physics of the early universe (i.e., CF4, CF5, CF6, CF7).

Strong HEP support for cosmic probes is essential, not only for their independent capacity to provide insight into the fundamental properties of dark matter, but also for interpreting any future direct or indirect detections via a terrestrial experiment. Sustained collaboration between particle theorists, gravitational dynamicists, numerical simulators, observers, and experimentalists are required to fully realize the power of cosmic probes of dark matter. Such large collaborations are naturally matched to the HEP community, but new mechanisms are needed to support these emerging, interdisciplinary efforts. This report summarizes the ways in which cosmic probes are a key particle physics tool in the endeavor to fully characterize dark matter. First, we identify three core ways that cosmic probes of dark matter are a HEP community priority, in order to provide context for five major science opportunities described below:

- Current/near-future HEP cosmology experiments have direct sensitivity to dark matter particle physics [1–3]. **Cosmological studies of dark matter should be supported as a key component of the HEP Cosmic Frontier program due to their unique ability to constrain dark matter**

**microphysics and link the results of terrestrial dark matter experiments to cosmological measurements.**

- **The construction of future cosmology experiments is critical for expanding our understanding of dark matter physics.** Proposed facilities across the electromagnetic spectrum, as well as gravitational waves, can provide sensitivity to dark matter physics, as well as physics of dark energy and the early universe [4]. HEP involvement will be essential in constructing these facilities, and optimizing their sensitivity to dark matter physics should be a core consideration in their design.
- Cosmic probes provide robust sensitivity to the microphysical properties of dark matter due to enormous progress in theoretical modeling, numerical simulations, and astrophysical data. **Theory, simulation, and experiment must all be supported to maximize the efficacy of cosmic probes of dark matter physics.**

The allowed parameter space of dark matter models is large and requires a range of techniques for full exploration and testing. The experiments, observations, and interpretations of cosmic probes of dark matter are necessarily interdisciplinary. Emphasizing interdisciplinary coordination – both scientifically and bureaucratically – will enable strong scientific outcomes. However, because of the unique nature of the scientific problem that dark matter represents, a single figure of merit approach is not necessarily the best way to characterize progress. Instead, there are a plethora of clear opportunities that are sensitive to the particle nature of dark matter. Major scientific opportunities for cosmic probes of dark matter physics in the coming decade are summarized below, presented at length in the following document, and discussed in detail in a set of community white papers [1–11].

### Major Scientific Opportunities

1. The Standard Model of particle physics and cosmology can be tested at unprecedented levels of precision by measuring the cosmic distribution of dark matter. These measurements span an enormous range of scales from the observable universe to sub-stellar-mass systems [7, 12, 13]. **Measurements of the distribution of dark matter (e.g., the matter power spectrum, the mass spectrum of dark matter halos, dark matter halo density profiles, and abundances of compact objects) can constrain the fundamental properties of dark matter (e.g., particle mass, production mechanism, and interaction cross sections) and should be supported as a key element of the HEP Cosmic Frontier program.**
2. The ΛCDM model makes the strong, testable prediction that the mass spectrum of dark matter halos extends below the threshold at which galaxies form [5]. Sub-galactic dark matter halos are less influenced by baryonic processes making them especially clean probes of fundamental physics of dark matter. **The HEP community should pursue the detection of dark matter halos below the threshold of galaxy formation as an exceptional test of fundamental dark matter properties.**
3. Extreme astrophysical environments provide unique opportunities to explore dark matter couplings to the Standard Model that are inaccessible with terrestrial experiments [8]. **Instruments, observations, and theorists that study extreme astrophysical environments should be supported as an essential means to constrain the expanding landscape of dark matter models.**
4. Numerical simulations of structure formation and baryonic physics play a key role in addressing particle physics questions about the nature of dark matter. **HEP computational resources and expertise can be combined with astrophysical simulation expertise to rapidly advance numerical simulations of dark matter physics.**
5. **The interdisciplinary nature of dark matter research calls for interagency mechanisms that support a complete pursuit of scientific opportunities without regard to traditional disciplinary boundaries.**

When engaged together, these major opportunities provide a potential pathway for transforming our understanding of the basic constituents of matter in the universe. Though dark matter's existence has long been broadly accepted through community consensus, it remains the case that its fundamental properties remain a mystery. As we discuss later in this document, the possibility of successfully identifying the nature of dark matter using traditional and emerging cosmic probes arises from a variety of techniques embodied in the major opportunities above. This array of opportunities include using measurements of dark matter halos [5], observations of extreme astrophysical environments [8], searches for primordial black holes [7], and strengthening synergies between simulation and experiment [6]. These opportunities will be enabled by a suite of current and future facilities [4].

Dark matter is beyond Standard Model physics, but we know of its existence because of its impact, writ large, on our universe. Cosmic observations are a foundational tool for understanding the fundamental nature of dark matter. Furthermore, any terrestrial detection will need to explain and be informed by astrophysical observations. As new DOE- and NSF-supported facilities come online and plans for future facilities emerge, we find ourselves beginning a transformative decade in the effort to characterize dark matter, and in doing so, characterize dark energy, early universe inflation, and neutrinos. In this report, we present the possibilities created by a community commitment to a decade of dark matter.

## 3.2 Introduction

The existence of dark matter, which constitutes $\sim 85\%$ of the matter density and $\sim 26\%$ of the energy density of the universe, is a clear demonstration that we lack a complete understanding of fundamental physics. Over the past several decades, experimental searches for non-baryonic dark matter have proceeded along several complementary avenues. Collider experiments attempt to produce and detect the presence of dark matter particles, while direct detection experiments attempt to measure energy deposition from very rare interactions between dark matter and Standard Model particles. In parallel, indirect dark matter searches seek to detect the energetic Standard Model products from the annihilation or decay of dark matter particles *in situ* in astrophysical systems. Despite these extensive efforts, the only robust, positive empirical measurements of dark matter to date come from astrophysical and cosmological observations. This report summarizes the exciting scientific opportunities presented by cosmic probes of fundamental dark matter physics in the coming decade. The content of this report has been primarily guided by five solicited white papers [4–8] and six contributed white papers from the HEP community [1–3, 9–11].

Astrophysical and cosmological observations are a unique, powerful, and complementary technique to study the fundamental properties of dark matter. They probe dark matter directly through gravity, the only force to which dark matter is known to couple. On large cosmological scales, current observational data can be described by a simple cosmological model containing stable, non-relativistic, collisionless, cold dark matter (CDM). However, many viable theoretical models of dark matter predict observable deviations from CDM that are testable with current and future experimental programs. Fundamental physical 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.

In addition, astrophysical observations complement terrestrial dark matter searches by providing input to direct and indirect dark matter experiments, and by enabling alternative tests of any non-gravitational coupling(s) between dark matter and the Standard Model. For example, astrophysical observations are required to (*i*) measure the local density and velocity distribution of dark matter, an important input for designing and interpreting direct dark matter searches, (*ii*) identify and characterize regions of high dark matter density, an important input for targeting and interpreting indirect searches, and (*iii*) set strong constraints on the particle properties of dark matter, an important input for designing novel terrestrial dark matter experiments with viable discovery potential. In the event of a terrestrial dark matter detection—e.g., the detection of a weakly interacting massive particle (WIMP) or axion—cosmic observations will be crucial to interpret terrestrial measurements in the context of cosmic dark matter. Furthermore, cosmic probes provide critical information to direct future terrestrial searches for novel dark matter candidates. Finally, in many cases, astrophysical and cosmological observations provide *the only* robust, empirical constraints on the viable range of dark matter models.

There is also immense discovery potential at the intersection of particle physics, cosmology, and astrophysics. The detection of dark matter halos that are completely devoid of visible galaxies would provide an extremely sensitive probe of new dark matter physics. Measuring a deviation from the gravitational predictions of CDM in these halos would provide much-needed experimental guidance on dark matter properties that are not easily measured in particle physics experiments (e.g., dark matter self-interaction cross sections). Likewise, results from terrestrial particle physics experiments can suggest specific deviations from the CDM paradigm that can be tested with astrophysical observations. The expanding landscape of theoretical models for dark matter strongly motivates the exploration of dark matter parameter space beyond the current sensitivity of the HEP program.

In fact, cosmology has a long history of testing the fundamental properties of dark matter. For instance, neutrinos were long considered a viable candidate to make up all the dark matter [e.g., 14, 15]. The 30 eV neutrino dark matter candidate of the 1980s is an especially interesting case study of the interplay between particle physics experiments and astrophysical observations. In 1980, Lubimov et al. reported the discovery of a non-zero neutrino rest mass in the range $14\,\mathrm{eV} < m_\nu < 46\,\mathrm{eV}$ [16]. Neutrinos with this mass would provide a significant fraction of the critical energy density of the universe, but would be relativistic at the time of decoupling, thus manifesting as hot dark matter. Over the next decade, this "discovery" was aggressively tested by several other tritium $\beta$-decay experiments. During this same period, the first measurements of the stellar velocity dispersion of dwarf spheroidal galaxies showed that these galaxies are highly dark matter dominated. The inferred dark matter density within the central regions of dwarf galaxies was used to place lower limits on the neutrino rest mass that were incompatible with the 30 eV neutrino dark matter candidate [17, 18]. Furthermore, numerical simulations of structure formation were similarly found to be incompatible with a neutrino-dominated universe [19]. Similar stories can be told of stable heavy leptons [20–22] and other dark matter candidates that have been excluded by cosmological and astrophysical measurements. Cosmology has continually shown that the microscopic physics governing the fundamental nature of dark matter and the macroscopic distribution of dark matter are intimately intertwined.

The strong connection between cosmology, astrophysics, and particle physics serve as the motivation for the Dark Matter: Cosmic Probes Topical Group (CF3) within the Snowmass Cosmic Frontier. CF3 focuses on the use of cosmological techniques and astrophysical observations to study the fundamental nature of dark matter over the full range of allowed dark matter masses. While many experimental studies of dark matter search for a previously undetected interactions between dark matter and Standard Model particles, CF3 also seeks to measure the behavior of dark matter ever more precisely in order to compare against the predictions of ΛCDM. Thus, some of the scientific approaches and experimental facilities proposed by CF3 overlap significantly with cosmological studies of dark energy and the early universe. CF3 discussions took place between November 2020 and July 2022 through a series of meetings that occurred on a roughly bi-weekly cadence. CF3 received 75 letters of intent,[1] which resulted in the submission of 5 solicited white papers [4–8] and 6 contributed white papers [1–3, 9–11] from the HEP community. This report summarize nearly two years of community input, and its structure has been primarily guided by the five solicited community white papers.

- **WP1** - Dark matter physics from dark matter halo measurements [5].

[1] https://snowmass21.org/cosmic/dm_probes

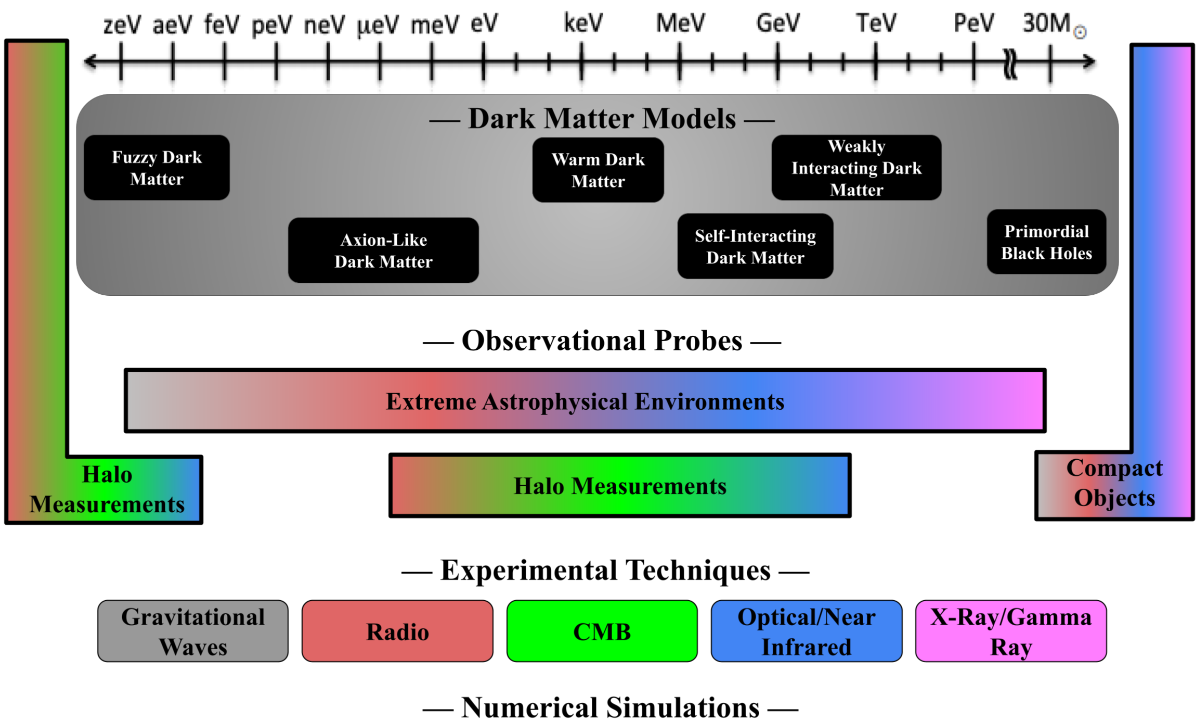


**Figure 3-1.** *Cosmic observations bound the available dark matter parameter space and probe dark matter physics over the entire allowed mass range. Cosmic probes explore the fundamental physics of dark matter both through gravity alone and through dark matter interactions with the Standard Model. Cosmic probes of dark matter physics are highly complementary to cosmological measurements of dark energy, inflation, and neutrinos. Furthermore, cosmic probes provide essential information for designing and interpreting terrestrial searches for dark matter. Inspired by similar figures in the literature [e.g., 23–25]*

- **WP2** - Cosmological simulations for dark matter physics [6].
- **WP3** - Primordial black hole dark matter [7].
- **WP4** - Dark matter in extreme astrophysical environments [8].
- **WP5** - Observational facilities to study dark matter physics [4].

## 3.3 Dark Matter Halo Measurements

In the standard model of cosmic structure formation, dark matter in the late-time universe is clustered into gravitationally bound over-densities called halos. These halos provide sites for baryons to cool, collapse and form galaxies. Astronomical observations show that dark matter halos are distributed according to a power-law mass spectrum extending from the scales of galaxy clusters ($\sim 10^{15} M_{\odot}$) to those of ultra-faint dwarf galaxies ($\sim 10^{8} M_{\odot}$). In the prevailing theory (CDM), dark matter is made of collisionless, cold particles or objects. The CDM theory does a good job of explaining the large-scale structure of the universe [35] and overall properties of galaxies [36, 37]. However, there are many reasons to believe that CDM is an approximation and that the dark sector is more complex and vibrant. From the theory perspective, CDM provides a parametric description of cosmic structure, but it is far from a complete theory. In CDM, the particle properties of dark matter, such as the mass, spin, interaction and production mechanism, remain

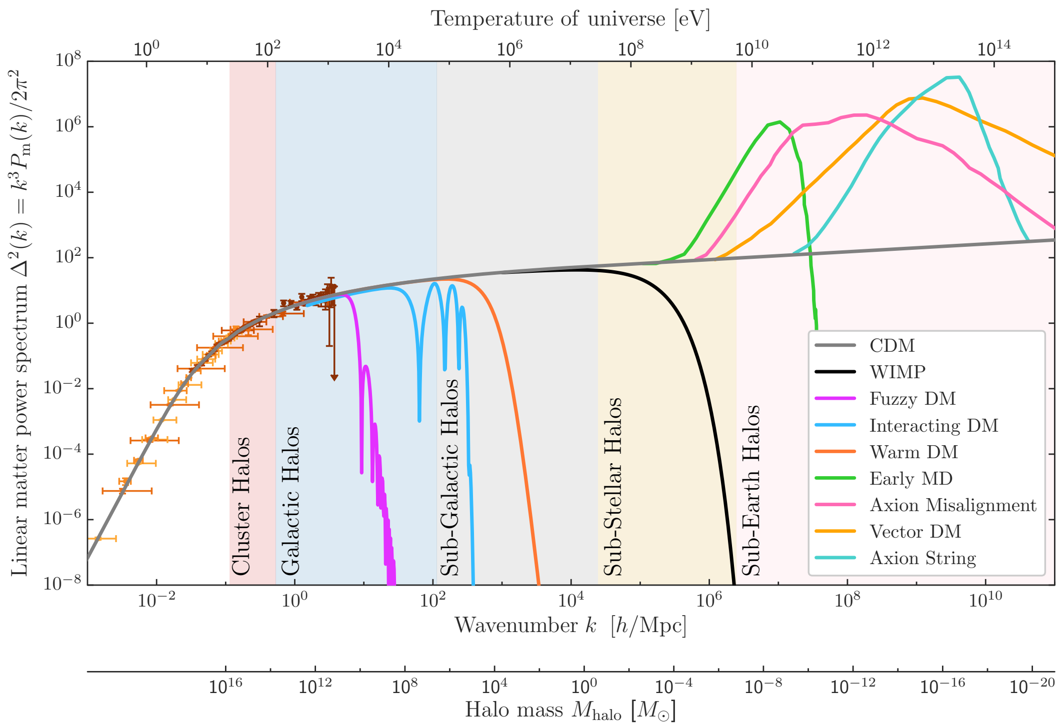


**Figure 3-2.** *The dimensionless linear matter power spectrum extrapolated linearly to $z = 0$. Theoretical predictions are plotted for four models that suppress power: (1) ultra-light axion "fuzzy" dark matter with a mass $m = 10^{-22}$ eV (magenta; [26]), (2) dark matter–baryon interactions with interaction cross section that scales with velocity as $\sigma_0 v^{-4}$ for $\sigma_0 = 10^{-22}\,\mathrm{cm}^2$ (blue; [27]), (3) thermal relic warm dark matter with a mass $m \sim 40$ keV (orange; [28]), (4) weakly interacting massive particle dark matter represented by a bino-like neutralino with a mass $m \sim 100$ GeV (black; [29]). Also shown are four models that enhance power on very small scales: (1) early matter domination assuming a reheat temperature of 10 MeV (green; [30]), (2) post-inflationary production of QCD axions dominated by the misalignment mechanism (pink; [31]), (3) vector dark matter produced during inflation assuming an inflationary scale of $10^{14}$ GeV and a DM mass of $10^{-6}$ eV (gold; [32]), and (4) post-inflationary production of axions dominated by strings (cyan; [33]). Note that the position of the power spectrum cutoff and/or enhancement depends on model parameters and is flexible for most cases shown here. Power spectrum measurements on large scales are compiled from [34]. Shaded vertical bands roughly indicate the characteristic kinds of halos formed on each scale, and the horizontal axes indicate wavenumber, halo mass, and the temperature of the Universe when that mode entered the horizon. Taken from [5].*

unspecified. In fact, many theoretical models describing the particle physics of dark matter predict that the simplest CDM model breaks down at small physical scales [5]. On the observational side, CDM has faced long-standing challenges to explain detailed measurements of dark matter distributions on galactic and sub-galactic scales [38, 39], where we are pushing the boundaries of both observations and numerical simulations. In the next decade, observations of dark matter halos over a wide range of mass scales will provide unique opportunities to test the vast landscape of dark matter theories and potentially discover deviations from the predictions of CDM.

Using halo measurements to study dark matter physics has several advantages. First, they are sensitive to a broad range of dark matter models. To date, all positive experimental evidence for the existence and properties of dark matter comes from astrophysical observations. Measurements of the abundance, density profiles, and spatial distribution of dark matter halos offer sensitivity to an enormous range of dark matter models, and are complementary to both terrestrial experiments and indirect searches for dark matter annihilation and decay products. Second, our understanding of how the fundamental properties of dark matter at a microscopic scale impact structure formation throughout cosmic history is rapidly advancing. Recently, there has been tremendous progress in modeling the formation and evolution of dark matter halos for novel dark matter theories beyond CDM. There is enormous potential to further develop detailed phenomenology for a broader range of dark matter models, and to explore new regions of theory space with new and archival data. Third, there is a strong connection between dark matter halos and the physics of the early universe. The seeds of cosmological structure formation were established in the earliest moments after the Big Bang. As we measure the distribution of dark matter across a broader range of physical scales, we simultaneously learn about the initial conditions of the universe and probe periods of cosmic history that might be inaccessible by other means. Thus halo measurements provide a window on both dark matter physics and early universe cosmology. Fig. 3-2 illustrates these connections by showing the linear matter power spectrum predicted in several representative dark matter theories, together with relevant scales of the halo mass and temperature of the universe. In Fig. 3-3, we show the complementarity between constraints on the spin-independent dark matter–nucleon scattering cross section coming from measurements of the matter power spectrum and dark matter halos, and terrestrial direct detection searches.

To achieve the goal of leveraging halo measurements to extract fundamental dark matter particle physics, we set the following observational milestones. Firstly, precision measurements of galaxy-scale dark matter halos are critical. Current and near-future facilities will provide a detailed mapping between luminous galaxies and their invisible dark matter halos across 13 billion years of cosmic history and 7 orders of magnitude in dark matter halo mass. Detailed measurements of halo abundances and density profiles across cosmic time will provide a stringent test of the CDM paradigm. In addition, within the next decade, several observational techniques will become sensitive to dark matter halos at or below the minimum mass required to host stellar populations. Population studies of such completely dark halos offer unique advantages to constrain the microphysical properties of dark matter because their evolution is less affected by baryonic physics. Many theoretical models of dark matter predict conspicuous deviations from CDM in low-mass halos. Furthermore, a suite of innovative and ambitious observational techniques can be used to search for stellar- and planetary-mass-scale halos via their subtle gravitational effects. The discovery of such low-mass halos would immediately transform our understanding of both dark matter properties and the physics of the early universe. Numerical simulations are essential to connect dark matter models to halo observables and are the topic of the following section.

## 3.4 Dark Matter Simulations

Because dark matter research is uniquely situated at the intersection of particle physics, cosmology, astrophysics, and astronomy, it draws from the research toolkits of these different fields in a distinct way. Simulations are widely used across particle physics, but comprehensively understanding their particular utility in dark matter research requires careful attention to and expansion of techniques from astronomy and astrophysics. Astrophysical and cosmological measurements tell us *where* the dark matter is. Simulations tell us *how* to translate this measurement to the particle properties of dark matter. Using this combination of observational techniques and simulations, together particle physicists and astronomers can determine *what* type of particle dark matter is and how to confirm and further explore its properties in the lab [23]. As we look ahead to the second half of the 2020s and into the 2030s, there are a variety of exciting opportunities to advance this goal. Doing so requires a robust and well-supported approach to simulations. The time is *now* to build a novel simulation program to interpret observations so that we can robustly search for novel signatures of dark matter microphysics across a large dynamic range of length scales and cosmic time.

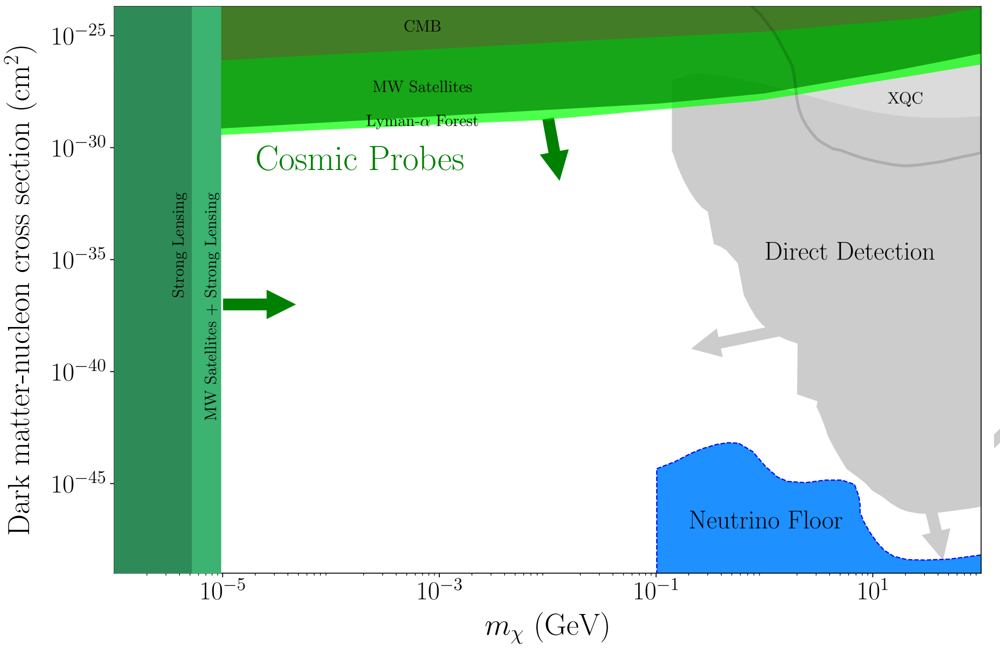


**Figure 3-3.** *Cosmic probes of the matter power spectrum and dark matter halos set strong constraints on the minimum thermal dark matter particle mass [e.g., 40, 41] and spin-independent dark matter–nucleon scattering cross section [e.g., 41–43] (green regions). These constraints are highly complementary to constraints from direct detection experiments [as collected by 44, 45] (gray regions). The neutrino fog for xenon direct detection experiments is shown in blue [46].*

Over the last 40 years, simulations have played an essential role in constraining dark matter particle properties. They have contributed to the development of the CDM paradigm as a dominant framework for interpreting data indicating the presence of dark matter and to eliminating neutrinos as a potential dominant component of the missing matter. The challenge and opportunity for this decade is to develop a robust and vibrant simulation program that connects the ground-breaking capabilities of observational facilities [1–4, 47, 48] to an expanding ecosystem of particle models for dark matter and tailored terrestrial experiments [23]. Because a well-synthesized theoretical, simulation, observational, and experimental program is critical to revealing the nature of dark matter, we identify six areas of focus for simulations that advance along key opportunities described in Sec. 3.1.

We identify the six key opportunities for numerical simulations to study the fundamental properties of dark matter with cosmic observations. The first valuable opportunity is an **emphasis on collaboration between simulators and particle theorists** in order to identify significant models and areas of parameter space for further study and successful implementation. As described in [6], cosmic probes are potentially the only arena in which certain tests of dark matter properties are possible. Model builders and observers both rely on simulations as a crucial link that draws their ideas and work together. This approach underpins the key opportunity of using cosmic probes to understand the microphysics of dark matter by enabling a mapping of dark matter microphysics to astrophysical structure formation and observables associated with it. For example, knowing the scale on which small structures are expected to be suppressed in a model can enable simulators to efficiently target well-motivated regions of parameter space. In turn, targeted parameter space searches can help theorists focus their efforts on realistic model-building efforts. A specific focus on theorists guiding correct initial conditions for simulations of different dark matter models will be of particular value.

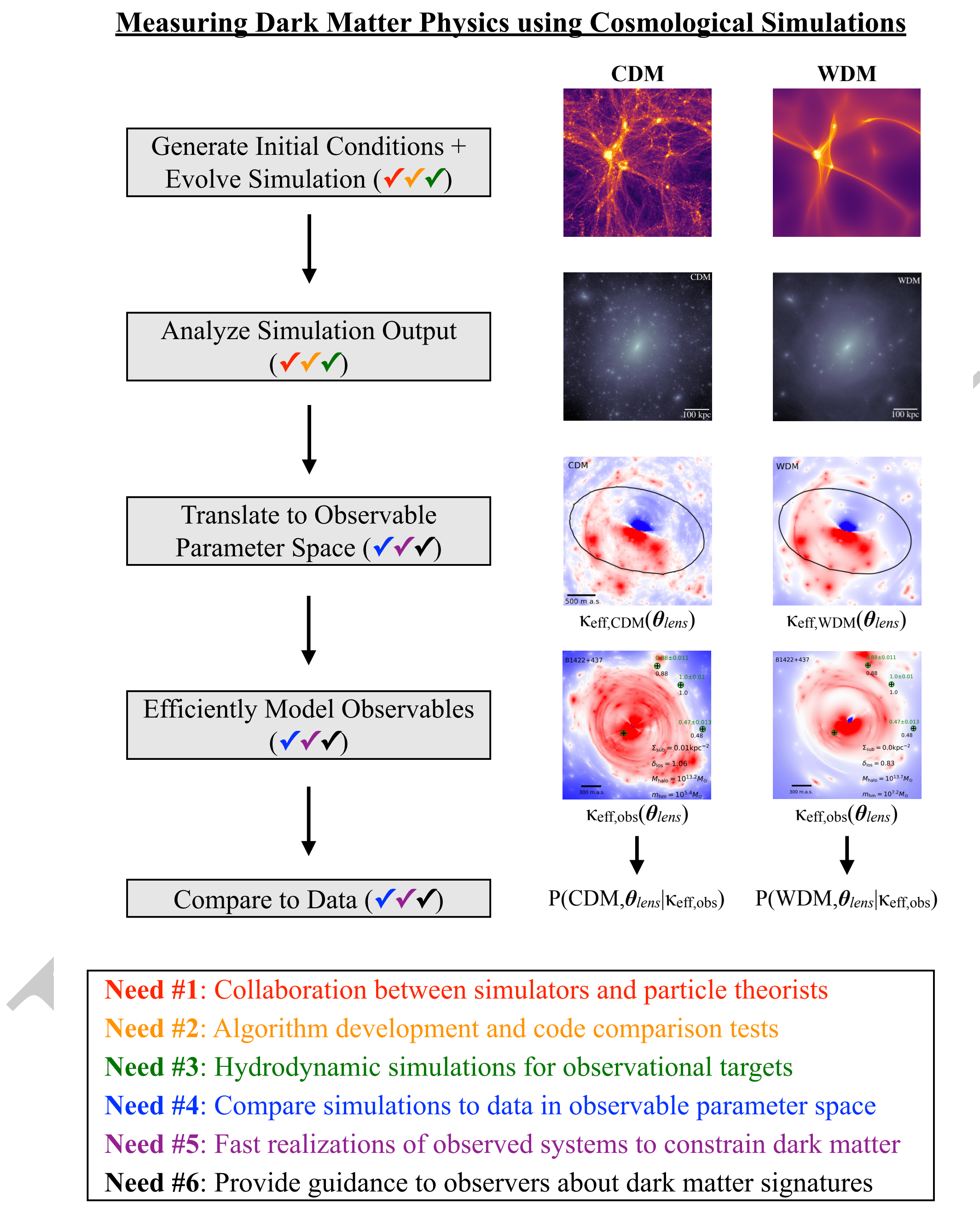


**Figure 3-4.** *An example flowchart for distinguishing predictions from cold and warm dark matter models in the context of dark matter halo substructure as observed in strong gravitational lens systems. This example highlights the need of collaborative efforts among particle physicists, simulation experts and observers, in order to harness the full power of new observational facilities in testing dark matter models quantitatively. The two right columns show images of simulations and lensing observables assuming cold and warm dark matter models. From top to bottom: large box numerical simulations of structure formation, simulated dark matter substructure within a galactic halo, a possible realization of dark matter structure generated under the model, and a particular realization of dark matter structure generated under the model consistent with HST observations of the strong lens system WGDJ0405-3308. Taken from [6].*

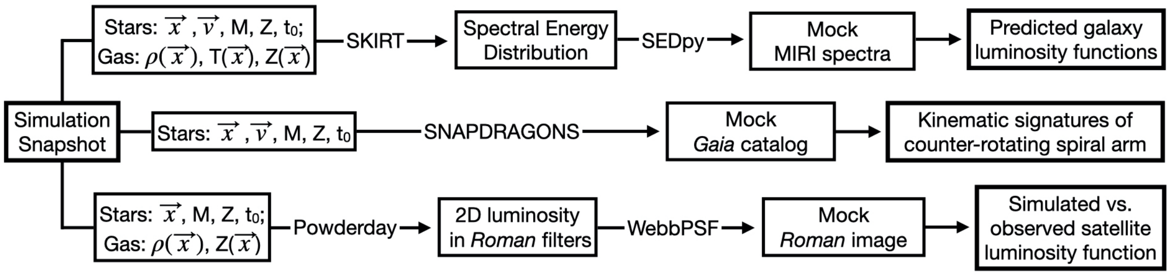


**Figure 3-5.** *An example of pipelines that can be used to convert outputs from numerical simulations into mock observations made with specific instruments. Taken from [6].*

Second, it is important to **sustain algorithm development and develop code benchmarks** to ensure that simulations meet the required precision targets set by the sensitivity of new facilities. Broadly speaking, we have four major classes of models/paradigms in dark matter that currently capture our attention: cold dark matter, fuzzy dark matter, self-interacting dark matter, and warm dark matter. Each of these presents distinct challenges in numerical implementation, requiring benchmarks for validating simulations and ensuring that they achieve the necessary precision to successfully support dark matter inference. Key predictions include measurements of (sub)halo mass functions; (sub)halo density profiles; and subhalo radial distributions, infall times and phase space distributions. There is also a great need to strengthen combined hydrodynamic and dark matter simulations, which necessitates evaluating and comparing different subgrid physics parameterizations for hydrodynamics.

Third, it is of key importance to **perform simulations with full hydrodynamics using validated subgrid models and numerical resolution at the relevant redshifts and cosmological scales.** Understanding the role of baryonic physics at small scales is critically important since key discrepancies between predictions of ΛCDM and alternative dark matter models occur at small scales where baryonic physics plays an important role [49]. Degeneracies between baryon physics and alternative dark matter models presents a challenge. Breaking these degeneracies requires full inclusion of baryonic physics in simulations and dedicated comparisons between validated simulations. Upcoming surveys from facilities such as the Vera C. Rubin Observatory, JWST, and the Nancy Grace Roman Space Telescope will usher in the discovery of many new types of systems with the potential to provide even sharper dark matter constraints, should support be provided for that specific scientific goal.

Fourth, we will benefit significantly from **analysis of simulation outputs in the realm of observations.** Forward modeling to the space of observables to enable apples-to-apples comparison between model and data is necessary to fully prepare for and utilize what will be unprecedented datasets from Rubin Observatory, JWST, and Roman Telescope. Proper theory-observation comparisons and tools that translate theoretical predictions to the land of observable quantities have been of great importance and are essential going forward. These kinds of comparisons can ensure that we are able to determine when a problem is in our numerical techniques and when it is a true physical problem. Fig. 3-5 gives an example of a pipeline that can be used to convert numerical simulations to mock observations from instruments of specific interest. As data analysis pipelines and simulations become more elaborate – and datasets become larger – strengthening our capacity to disentangle numerical effects from physical phenomena will be of critical importance. This will also enable evaluation of and planning for proposed new facilities.

Fifth, we need **fast realizations of observables for inference of dark matter properties** in order to constrain dark matter particle parameters from observation on feasible timescales. Cosmological simulations with full hydrodynamics are a critical tool to reveal how different physical properties of dark matter alter the abundance and internal structure of dark matter halos and subhalos, which can result in observable differences in astronomical objects and systems. These simulations produces "mock universes" that allow us to compare theoretical prediction with observations in the space of observable. As such, running these simulations will become the bottleneck of parameter inference and model comparison, because these tasks typically require generating a large sample of simulated datasets of different input parameters (dark matter properties in this case). Multiple methods have been identified [6] to address these challenges. They broadly fall into the categories of (1) reducing the computational cost of individual simulations by swapping some simulation components with models, and (2) reducing the number of simulations needed in our analyses. We will need to combine an array of approaches to cover vast space of unconstrained dark matter theories and the diversity of observational measurements. These efforts will benefit from the introduction of machine learning and artificial intelligence techniques that are described later in this chapter.

Finally, research synergies will be supported by **identifying novel signatures from simulations and providing guidance to observers** derived both from numerical simulations and fast realizations that point to signatures of dark matter physics. Simulations can play a major role in generating new observational strategies by revealing unforeseen and affirming analytic predictions of dark matter physics signatures. One example of this dynamic in operation is developing an understanding of the unique dark matter distribution in our home Milky Way galaxy. This example is particularly significant in a particle physics context because understanding how dark matter is locally distributed is key to proper design of terrestrial direct detection experiments. Moreover, other dark matter-related challenges sometimes only become visible on astrophysical scales, meaning that even with a direct detection, fully characterizing dark matter as a phenomenon requires understanding its behavior on cosmological scales. We face an additional challenge: we expect that not all dark matter (sub)halos will contain baryons. Simulations can help us gain insight into how to use observations to characterize phenomena that are potentially entirely non-luminous.

The next decade will be game-changing in the dark matter community's ability to learn about dark matter in the sky and in the lab. Simulations and the simulators who create them are the connectors between these two critical pathways to the discovery of the nature of dark matter. A close collaboration among simulators, particle physicists, and observational astronomers is essential to the success of simulations to serve as the connector. Only with a vibrant and cohesive cosmological simulation program will we be able to connect the lab to the sky to reveal the secrets of dark matter.

## 3.5 Primordial Black Holes, Dark Matter, and the Early Universe

As potentially the first density perturbations to collapse, primordial black holes may be our earliest window into the birth of the universe and energies between the QCD phase transition and the Planck scale. The corresponding length scales ($k = 10^7 - 10^{19}\ h\,\mathrm{Mpc}^{-1}$) are much smaller than those measured by other current and future cosmological probes, see Fig. 3-2. While earlier estimates suggested that primordial black holes were constrained to be a subdominant component of dark matter over much of the viable mass range, more recent analyses have relaxed many of these constraints, re-opening the possibility that, in certain mass ranges, primordial black holes may comprise a dominant component of dark matter, as shown in Fig. 3-6.

The detection of primordial black holes would change our understanding of the fundamental physics of the early universe and the composition of dark matter [7, 13]. Primordial black holes are a probe of primordial density fluctuations in a range that is inaccessible to other techniques. These curvature fluctuations are imprinted on space-time hypersurfaces during inflation, at extremely high energies, beyond those currently accessible by terrestrial and cosmic accelerators. Our understanding of the universe at these high energies ($\gtrsim 10^{15}\,\mathrm{GeV}$) comes predominantly from extrapolations of known physics at the electroweak scale. Measurements of the primordial density fluctuations via the abundance of primordial black holes would provide unique insights into physics at these very high energy scales.

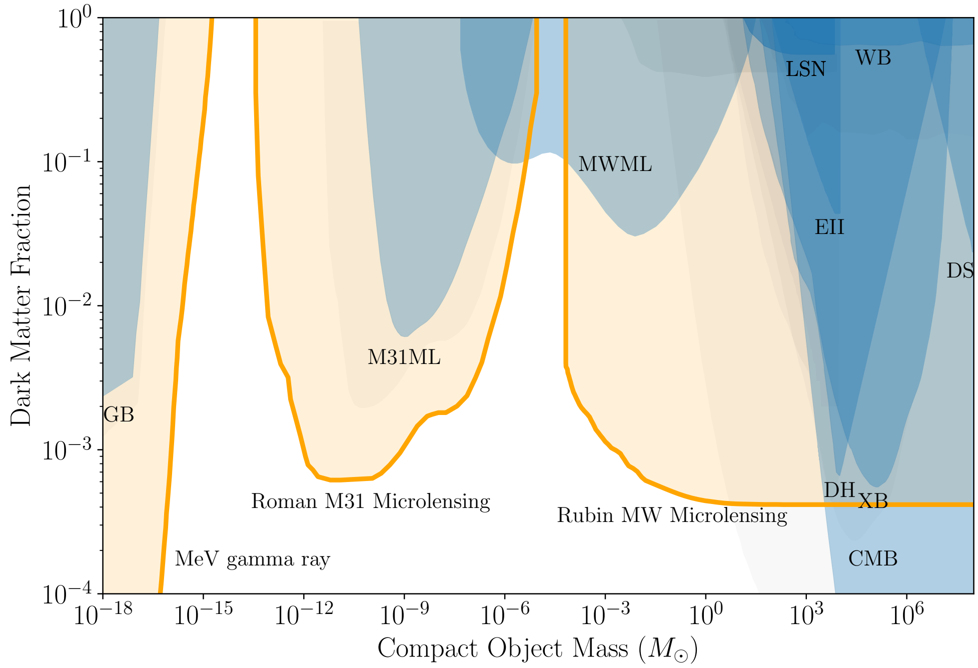


**Figure 3-6.** *Current constraints on the dark matter fraction composed of compact objects of a given mass (blue and gray) and selected projections for future gamma-ray and microlensing probes (gold). The blue and gray regions denote constraints based on more and less conservative assumptions, respectively. The existing constraints are from the gamma-ray background (GB) [50], M31 microlensing (M31ML) [51], MACHO/EROS microlensing (MWML) [52–54], supernovae lensing (LSN) [55], the Eridanus II dwarf galaxy (EII) [56, 57], wide binary stars (WB) [58, 59], dwarf galaxy dynamical heating (DH) [60–62], X-ray binaries (XB) [63], CMB distortions from accreting plasma by PBHs in early universe (CMB) [64, 65], and disk stability (DS) constraints [66]. Forecast projections for a Rubin microlensing survey of the Galactic Bulge [67], a dedicated Roman microlensing survey of M31, and for MeV gamma-ray facilities [68] are displayed. Note that recent work by [69] suggests that it is challenging to extend the Rubin microlensing probes beyond* $10^3 M_\odot$. *Taken from [7].*



This significant reward motivates the development of several complementary techniques that are sensitive to primordial black holes and subject to different astrophysical systematics, such as gravitational microlensing, gravitational wave detection, and gamma-ray signatures of black hole evaporation. In many cases, the science of primordial black holes can be performed by facilities that have well-motivated and multi-faceted scientific programs, e.g., optical/near-infrared time-domain imaging surveys, gravitational wave detectors, precision astrometry from radio interferometry, future MeV–TeV energy gamma-ray facilities. That said, realizing primordial black hole science from these facilities often requires specialized observing schemes, dedicated data analysis, and devoted theoretical studies. Therefore, it is important to closely integrate science efforts with enabling facilities across the scientific funding agencies (DOE, NASA, NSF).

Current and near-future observations can provide unprecedented sensitivity to the search of primordial black holes. However, it is necessary to ensure that these facilities acquire their data with a cadence and sky coverage that enables the searches [67, 70, 71]. In addition, the sensitivity of the searches will be maximized by combining data sets from multiple observational facilities. Development of joint processing and analyses of Rubin Observatory, Roman Space Telescope, and Euclid will maximize the opportunity to detect primordial black holes. Furthermore, current and future gravitational wave facilities will provide an

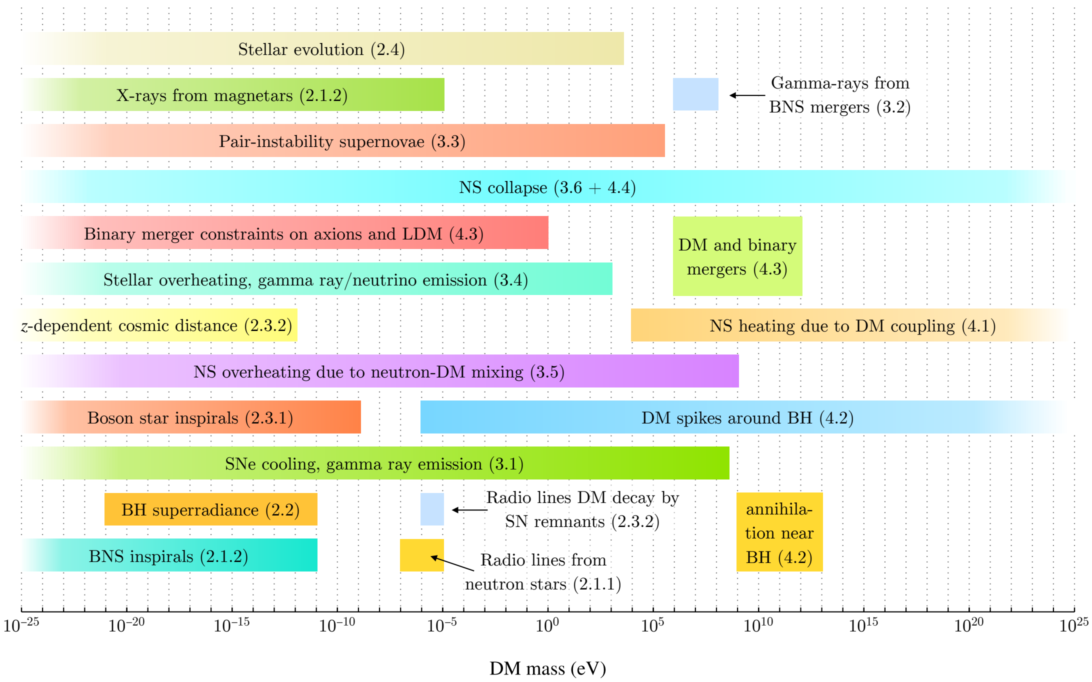


**Figure 3-7.** *A wide array of observations of extreme astrophysical environments have sensitivity to novel dark matter properties over $\sim 50$ orders of magnitude in dark matter particle mass. The parenthetical numbers refer to specific sub-sections in [8]. Taken from [8].*

unparalleled opportunity to detect primordial black holes directly through gravity. These facilities include both ground-based detectors, such as LIGO and Cosmic Explorer, and space-based detectors, such as LISA and AEDGE [e.g., 72].

The scale of current and near-future data sets and the complexity of analyses benefit from collaborative scientific teams. These teams will develop the tools to perform rigorous and sensitive searches for primordial black holes in current and near-future observational data. The computational challenges presented by these searches are well-matched to the capabilities of HEP scientists and facilities. In addition, theoretical studies will help us better understand the production mechanisms, clustering, and spin properties of primordial black holes. These characteristics will inform the expected abundance of black hole microlensing and gravitational-wave events and systematics with cosmic surveys, as well as the connections to primordial physics in the early universe. Furthermore, improved simulations of the merger rate of primordial black holes and of specific accretion rates will help inform observational constraints.

## 3.6 Dark Matter in Extreme Astrophysical Environments

Astro-particle searches for dark matter have historically focused on measuring the cosmic-ray or photon products from the annihilation or decay of a dark matter particle. However, dark matter interactions could also alter the physical processes occurring in the interiors of stars or stellar remnants, the dynamics of black holes, or the mergers of compact objects. These alterations would imprint characteristic signals in electromagnetic and gravitational wave observations. Exploring dark matter via observations of these extreme astrophysical environments—defined here as heavy compact objects such as white dwarfs, neutron stars, and black holes, as well as supernovae and compact object merger events—has been a major field of growth since the last Snowmass study. In the coming decade, observations of extreme astrophysical targets have the potential to open sensitivity to novel dark matter parameter space across a broad mass range (Fig. 3-7) [8]. Exploiting these opportunities relies on both advances in theoretical work and on current and near-future observatories, including both gravitational-wave instruments and instruments spanning the full electromagnetic spectrum, from radio to gamma-rays. We organize these searches by the dark matter mass range that is probed: ultralight dark matter ($< 1\,\mathrm{keV}$), light dark matter (keV–MeV), and heavy dark matter ($\gtrsim$ GeV). Despite this categorization, we emphasize that many of these probes overlap in mass range, as summarized in Fig. 3-7. In addition, we note that the parameter space of the dark matter that is probed does not always saturate the relic abundance; instead, dark matter is broadly defined as matter that does not interact appreciably with Standard Model matter.

Extreme astrophysical environments provide unique opportunities to probe ultralight dark matter. Ultralight particles can be produced in the hot, dense cores of stars and stellar remnants and affect their evolution. Ultralight dark matter—either ambient in the environment or produced in a neutron star—can convert in the high magnetic field environment of the neutron star into radio waves or X-rays that could be detected by telescopes. In the last decade, new ideas unique to bosonic dark matter have been developed. Specific models of ultralight dark matter can alter the shape of neutron star waveforms through their coupling to the dense neutron star matter. Black hole superradiance is a process that can extract energy and angular momentum from rotating black holes and place it into bound states of exponentially large numbers of ultralight bosons, as long as the Compton wavelength of the particle is comparable to the size of black holes. These systems yield signals of coherent gravitational waves as well as black hole spin down, which do not depend on particle interactions but only on gravity. Finally, ultralight dark matter can form collapsed structures like compact halos and boson stars that could be detected in gravitational waves or electromagnetic signals.

Opportunities to probe light dark matter exist from a variety of astrophysical situations: supernova explosions, the existence of neutron stars, neutron star temperatures, binary neutron star mergers, and black hole population statistics (made possible by gravitational waves from binary inspirals). Key observational targets for dark matter in this mass range include observation of gamma rays, neutrinos, and the populations of neutron stars and black holes as observed electromagnetically and via gravitational waves. Light dark matter produced in core collapse supernovae can be constrained from limits of their supernova cooling, or lead to visible signals in the X-ray or gamma-ray bands. Light dark matter produced during a binary neutron star merger can lead to a bright transient gamma-ray signal. Light dark matter produced in the cores of blue supergiants can affect stellar evolution, ultimately changing black hole population properties including the location of the black hole mass gap. Light dark matter scattering and annihilating in exoplanets, brown dwarfs, Population III stars, and stellar remnants can be probed through infrared and optical radiation, and through gamma rays. Neutron stars can be heated by light dark matter via the Auger effect, which is probed by telescopes in the ultraviolet, optical and infrared ranges of the electromagnetic spectrum. Lastly, accumulation of dark matter (in particular bosonic light dark matter) can lead to the collapse of astrophysical objects. Most of the signals arise from couplings to Standard Model photons and fermions. As an example,

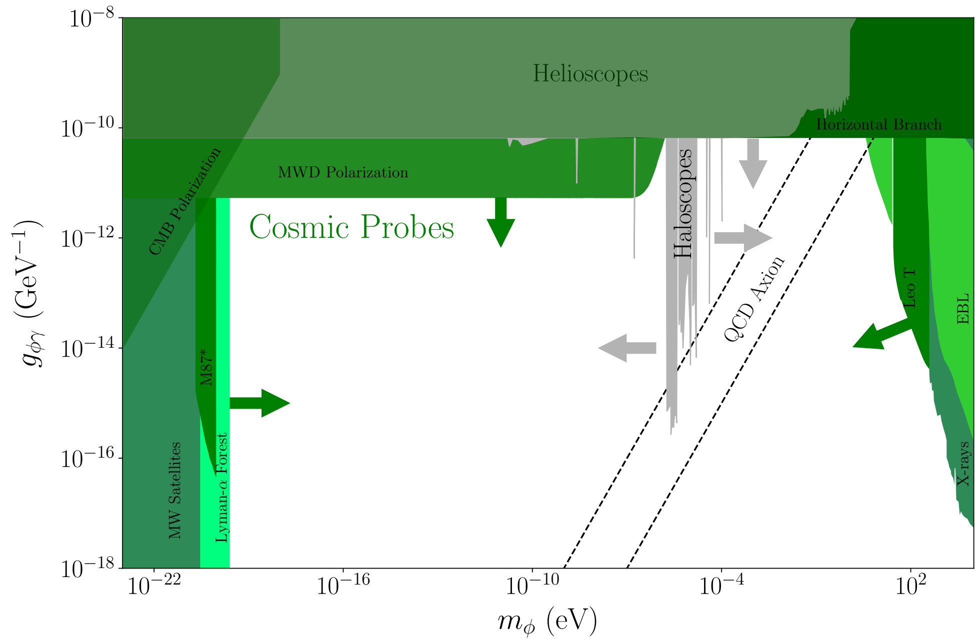


**Figure 3-8.** *Cosmic probes of extreme astrophysical environments [73–76] combined with measurements of dark matter halos [41, 77] and other cosmological observations [78–81] set strong constraints on the parameter space of axion-like particles (green regions). These constraints are highly complementary to other experimental searches with helioscopes and haloscopes [gray regions taken from 82]. This figure uses limit data available from [83].*

in Fig. 3-8 we show the complementarity between cosmic probes of light and ultra-light dark matter and terrestrial helioscope and haloscope in the context of searches for the signatures of axion-like particles.

Compact astrophysical objects such as neutron stars and black holes provide unique test beds for heavy ($>$ GeV) dark matter. Dark matter captured by neutron stars and their subsequent heating can be observed by upcoming infrared and radio telescopes. Dark matter can collect in high-density spikes around black holes causing enhanced annihilation rates. A black hole–compact object binary can form a dark matter spike that can be observed by future space-based gravitational wave observatories. Merging compact objects can also give insight into a wide variety of dark sector particles that modify the dynamics of the merger process. This includes fifth forces and modifications to gravity. Finally, sufficient accumulation of dark matter around a compact object can cause the dark matter particles themselves to collapse into a black hole. Upcoming pulsar searches and gravitational wave observatories will be sensitive to this kind of dark matter signature.

The key opportunities of the coming decade to maximize the sensitivity of these observations to novel dark matter phase space are summarized as follows. Observational and theoretical astrophysicists should collaborate to constrain the standard astrophysical properties of these extreme environments. We need coordination with the collaborations responsible for the upcoming major observatories: ground- and space-based gravitational wave interferometers, pulsar timing, radio, infrared, X-ray, and neutrino instruments. The goal is to ensure that the performance and capabilities of these future instruments are understood by particle theorists, and that observational campaigns and the resulting datasets are optimized as far as possible for the cutting-edge dark matter search strategies. Further theoretical development of dark matter signatures in extreme environments is needed, such as evaluating theoretical uncertainties related to the constraints and exploring interconnections among the observables.

## 3.7 Facilities for Cosmic Probes of Dark Matter

Over the next decade, observational facilities spanning the electromagnetic spectrum, as well as gravitational waves, offer the potential to significantly expand our understanding of dark matter physics. In this section, we briefly discuss current and near-future cosmology facilities that are aligned with the HEP portfolio and offer the opportunity to greatly enhance our understanding of dark matter physics. In many cases, these facilities have multi-faceted scientific portfolios that include sensitivity to dark energy, inflation, neutrino physics, and modifications to gravity. Furthermore, the technology used in these facilities leverages the core technical and scientific capabilities of the HEP community. Strong involvement from the HEP community will maximize the scientific output of these facilities. The capability to probe dark matter physics should be considered in the design phase of these new facilities.

The discussion in this section focuses on a series of facilities-oriented white papers submitted to CF3 as part of the Snowmass process [1–4, 11]. We note that the facilities described here complement other multi-messenger facilities [84], gamma-ray and X-ray experiments [85, 86], and gravitational wave facilities [72] submitted to the Snowmass process associated with other topical groups.

### 3.7.1 Current/Near-Future Facilities

**Dark Energy Spectroscopic Instrument**

The Dark Energy Spectroscopic Instrument (DESI) began regular operations in 2021 and is currently performing one of the most powerful wide-field spectroscopic surveys [57, 87]. The synergy between DESI and other current and near-future observing facilities will yield datasets of unprecedented size and quality, with sensitivity to dark matter physics over a wide range of scales and redshifts. DESI will measure the small-scale clustering of dark matter through observations of the Lyman-$\alpha$ (Ly-$\alpha$) forest out to $z \sim 5$ and radial velocities of $\sim$10 million stars around the Milky Way. DESI will detect four times as many Ly-$\alpha$ QSOs as were observed in the largest previous survey, yielding about 1 million spectra, which will put constraints on clustering of the low-density intergalactic gas. Radial velocities from DESI in conjunction with astrometry from *Gaia* (and eventually *Roman*) will enable us to constrain the global distribution of dark matter within the Milky Way, its dwarf satellites, and stellar streams. Large numerical simulations of non-CDM cosmologies are needed to interpret observations from DESI in the context of dark matter physics. Such simulations must be transformed into suites of queryable mock datasets which account for selection effects and survey volume. The creation of these mock data sets is a significant investment that could heavily leverage the infrastructure of the DESI Collaboration.

**Vera C. Rubin Observatory**

The Rubin Observatory Legacy Survey of Space and Time (LSST), which is scheduled to start in 2024, has the potential to become a flagship dark matter experiment [88]. LSST will probe dark matter through a wide suite of observations including measurements of Milky Way satellites, weak lensing halo measurements, galaxy clusters, microlensing searches for primordial black holes, and studies of stellar populations representing extreme environments [2, 12, 67] Due to the size and complexity of the Rubin LSST data set, a coordinated effort is required to perform rigorous dark matter analyses. A large collaborative team of scientists with the necessary organizational and funding support is needed to lead this effort. Studies of dark matter with Rubin LSST will also guide the design of, and confirm the results from, other dark matter experiments. Supporting a collaborative team to carry out a dark matter experiment with Rubin LSST is the key to achieving the dark matter science goals that have already been identified as high priority by the high-energy physics and astronomy communities.

**CMB-S4**

CMB-S4 is a ground-based experiment that will perform exquisite measurements of the CMB temperature and polarization anisotropies [24]. These measurements (on their own and in combination with other surveys) will provide new means to probe the nature of dark matter. These measurements will provide a snapshot of the universe as it was around the time of recombination, and they will also reveal the imprints of structure growth at much later times. Gravitational lensing of the CMB [89] leads to characteristic distortions of the primary CMB maps, allowing us to statistically reconstruct maps of the integrated line-of-sight density. Scattering of CMB photons in galaxy clusters (the Sunyaev-Zel'dovich effect) [90, 91] allows for the identification of the most massive bound structures in the universe out to very high redshifts. Cosmological measurements in general and CMB measurements in particular provide insights into dark matter physics that are complementary to direct, indirect, and collider searches for dark matter. Cosmological observables are impacted by the influence of dark matter on the entire cosmic history. Dark matter constraints derived from cosmology do not rely on assumptions about the dark matter density in the neighborhood of the Earth or of any astrophysical object. Furthermore, CMB observations are sensitive to regions of parameter space that are out of reach of current direct searches. Several aspects of the dark matter program are included among the CMB-S4 core science cases.

### 3.7.2 Future Facilities

Here we briefly discuss the landscape of proposed future facilities, starting with those probing the most energetic photons and moving to those with lower energies, and concluding with gravitational wave detectors. While these facilities are synergistic with a broad range of scientific objectives, strong support from the HEP community will be a key factor in getting these facilities built.

**X-ray/Gamma-ray Facilities**

Instruments operating at X-ray and gamma-ray energies have been indispensable for the indirect dark matter detection and multi-messenger communities [84–86]. While indirect detection is discussed elsewhere, these experiments also provide an important test of PBH evaporation and dark matter in extreme astrophysical environments. In particular MeV-scale $\gamma$-ray experiments like AMEGO [92] and GECCO [93] are important for probing PBH evaporation, while X-ray experiments like XRISM [94] and Athena [95] are important for probing the physics of extreme environments around neutron stars.

**Optical/Near-Infrared Facilities**

Optical/near-infrared telescopes have been the work-horse of dark matter studies on galactic scales. Proposed optical/near-infrared facilities include wide-field multi-object spectroscopic (WFMOS) surveys, such as DESI-II [96], MegaMapper [97], MSE [98], and SpecTel [99], and the US extremely large telescopes program [100], including the Giant Magellan Telescope (GMT) [101] and the Thirty Meter Telescope (TMT) [102]. Both classes of instruments plan to target stars in the Milky Way halo, stellar streams, and dwarf galaxies, as well as dark matter dominated galaxies in the local universe, and strong lens systems and galaxy clusters at higher redshift. The WFMOS survey instruments will provide medium- to high-resolution spectra of millions of stars, as well as providing information on a large number of higher redshift galaxies discovered by Rubin LSST. In contrast, the US ELTs will provide unprecedented sensitivity, image resolution, astrometry, and extreme precision radial velocity observations. In all cases, these facilities seek to extend measurements of the dark matter halo mass function below the threshold of galaxy formation ($10^6$–$10^8 M_\odot$) and to measure the density profiles of dark matter halos in the local universe (e.g., for our Milky Way, its satellites, and other local galaxies) and at higher redshifts (e.g., strong lens systems and galaxy clusters). Measurements of the dark matter halo mass function and density profiles can be translated into sensitivity to the dark matter particle mass and interaction cross-sections. Furthermore, these facilities provide multi-faceted fundamental physics programs that include measurements of dark energy and inflation. They would leverage HEP technology developed for Stage III and IV dark energy experiments (DECam and DESI) and advance technology toward a Stage V dark energy experiment. While these experiments have strong support from the astronomy community, it is likely that HEP support will be critical for their construction and to ensure that they maximize fundamental physics output.

**Microwave Facilities**

The proposed millimeter-wavelength facility CMB-HD [103] will extend the resolution of cosmic microwave background surveys by a factor of five and the sensitivity by a factor of three or more. These observations will open a new window of small-scale CMB observations and will uniquely enable measurements of the small-scale matter power spectrum (scales of $k \sim 10\,h\,\mathrm{Mpc}^{-1}$) from weak gravitational lensing using the CMB as a backlight. These observations will also enable measurements that rule out or detect any new light particle species ($N_{\mathrm{eff}}$) that were in thermal equilibrium with the Standard Model at any time in the early Universe, and enable probes of axion-like particles through CMB photon conversion, time-dependent CMB polarization rotation, cosmic birefringence, and ultra-high-resolution kinetic Sunyaev-Zel'dovich measurements. CMB-HD would leverage and extend the scientific and technical investment of HEP in CMB-S4.

**Radio Facilities**

Proposed centimeter-wavelength radio observatories, including the ngVLA [104] and DSA-2000 [105], can employ pulsar timing measurements to map the dark matter halo of the Milky Way and the substructures it contains. These experiments could complement other gravitational wave facilities at higher frequency. Proposed low-frequency radio experiments, such as LuSEE Night [11, 106], PUMA [107], and successors to HERA [108] can use the 21-cm line of hydrogen from the Dark Ages ($z \sim 50$) through cosmic dawn and reionization ($z \sim 6$) to probe dark matter physics via the thermal history of intergalactic gas and the timing of the formation of the first stars and galaxies. These facilities would have complementary programs to probe dark energy (measuring the expansion history and growth of the universe up to $z = 6$) and the physics of inflation (constraining primordial non-Gaussianity and primordial features).

**Gravitational Wave Facilities**

Proposed gravitational wave facilities, such as Cosmic Explorer and LIGO-Voyager, can probe dark matter directly through gravity [72]. These experiments are sensitive to channels including the detection of axion-like particles in binary neutron star mergers, ultralight bosons through superradiant instabilities of rotating black holes, the identification of boson stars in compact binaries, dark matter density spikes around black holes, and the existence of sub-solar-mass primordial black holes.

## 3.8 Tools for Comic Probes of Dark Matter Physics

**Collaborative Infrastructure**

Historically, many cosmic probes of dark matter physics have been pursued by small groups of scientists. However, as the scale and complexity of cosmic survey experiments increase, the need for numerical simulations to interpret data grow, and the range of possible dark matter models expands, it becomes difficult to find sufficient expertise within a small group of scientist. Similar challenges have been faced by the dark energy community, which has motivated the formation of large collaborative efforts to build and analyze data from new facilities. These collaborations bring together the efforts of university groups, international collaborators, and scientists at national laboratories to accomplish scientific tasks that are too large for any single investigator. Modern efforts to assemble collaborative teams to study cosmic probes of dark matter physics have already started in the context of LSST DESC [2]. In many cases, these teams can reside within existing collaborative infrastructure that has been established for other HEP mission goals. However, additional support must be provided to enable dark matter as a parallel branch of fundamental physics being pursued by these experiments.

**New Support Mechanisms**
Cosmic probes of dark matter provide a rich, diverse, and interdisciplinary area of research. While this leads to an exciting discovery space, it also leads to logistical difficulties in classifying the research within the existing research support structures (i.e., DOE HEP, NSF-PHYS, NSF-ASTR, NASA). In particular, support for cosmic probes of fundamental dark matter properties often resides in the cracks between these disciplines. This has been especially challenging for theoretical research in this domain, which has been increasingly challenged to find funding. We recommend that inter-agency coordination is required to assure that cosmic probes of dark matter physics are firmly supported. Multi-agency support extending across the spectrum of theory, simulation, and experiment will enable large gains in the coming decade.

**Artificial Intelligence/Machine Learning**
The interplay between models and observations is a cornerstone of the scientific method, aiming to inform which theoretical models are reflected in the observed data. Within cosmology, as both models and observations have substantially increased in complexity over time, the tools needed to enable a rigorous comparison have required updating as well. In the next decade, vast data volumes will be delivered by ongoing and upcoming cosmology experiments, as well as the ever-expanding theoretical search-space. We are now at a crucial juncture where we may be limited by the statistical and data-driven tools themselves rather than the quality or volume of the available data. Methods based on artificial intelligence (AI) and machine learning (ML) have recently emerged as promising tools for cosmological applications, demonstrating the ability to overcome some of the computational bottlenecks associated with traditional statistical techniques. Machine learning is starting to see increased adoption across different sub-fields of and for various applications within cosmology. At the same time, the nascent and emergent nature of practical artificial intelligence motivates careful continued development and significant care when it comes to their application in the sciences, as well as cognizance of their potential for broader societal impact [9].

**Cosmology Data Preservation**
Cosmology datasets and simulations have useful lifetimes that extend long beyond the operational period of individual projects. As datasets from facilities and simulations grow in size, the “take out” model of manual download followed by local computation will become insufficient and unwieldy. Future work needs to focus on co-locating data with computing, and automating the coordination between multiple data/compute centers. Furthermore, special attention should be paid toward facilitating the joint analysis of datasets beyond the lifetime of individual projects. Implementing a comprehensive data preservation system will require support not only for hardware, but also for personnel to develop and maintain the technologies to simplify cross-site data sharing and personnel to curate the relevant datasets. The authors of [109] recommend that the HEP community support a new cosmology data archive center to coordinate this work across multiple HEP computing facilities.

## 3.9 Roads to New Physics

So far, we have summarized major findings of the CF3 working group and highlighted key science opportunities in this emerging research area for the coming decade. In this section, we further consider three potential scenarios where astrophysical observations lead to the characterization of fundamental dark matter properties, and discuss their implications for revealing the particle nature of dark matter and understanding early-universe cosmology. In particular, we will highlight that uncertainties associated with astrophysical observations and theoretical modelling can be controlled and fundamental parameters of dark matter can be extracted.

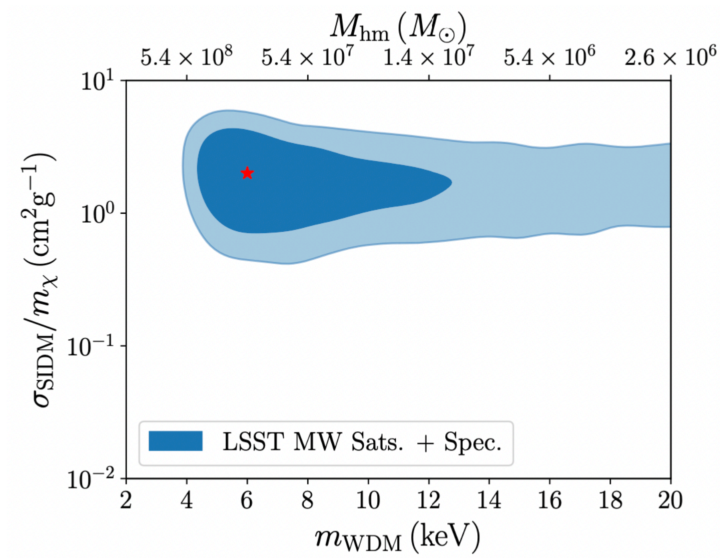


**Figure 3-9.** *Discovery example 1: potential measurements of the self-interacting cross section and warm dark matter mass from upcoming observations by the Rubin Observatory and a future spectroscopic survey. The projection assumes a dark matter model with a cross section of* $\sigma_{rmSIDM}/m_\chi = 2\ {\rm cm}^2/{\rm g}$ *and a suppressed matter power spectrum corresponding to a warm dark matter mass of* $m_{\rm WDM} = 6$ keV *(red asterisk). The uncertainties Contours are created by following a procedure similar to [110]*

### 3.9.1 Warm and Self-Interacting Dark Matter

We first consider a scenario where dark matter differs from the standard CDM model by having a warm thermal velocity distribution and an appreciable self-interaction cross section. The matter power spectrum of warm dark matter is suppressed compared to CDM, resulting in a reduction in the number of low-mass dark matter halos. For thermal warm dark matter, the power spectrum is completely determined by the dark matter particle mass, $m_{\rm WDM}$ [39]. The observed population of satellite dwarf galaxies of the Milky Way can be used to measure $m_{\rm WDM}$ if such a suppression is observed. Furthermore, dark matter self-interactions can thermalize the inner regions of dark matter halos and change the dark matter density profile. Thus, the self-interaction cross section per unit mass, $\sigma/m_\chi$, can be inferred from measurements of stellar velocities of galaxies, which are sensitive to the central dark matter content.

Fig. 3-9 demonstrates the ability of Rubin LSST combined with a future spectroscopic survey to measure the particle properties of dark matter from observations of Milky Way satellite galaxies. This projection assumes a thermally produced dark matter particle with a self-interaction cross section $\sigma/m_\chi = 2\ {\rm cm}^2/{\rm g}$ and a particle mass $m_{\rm WDM} = 6$ keV. We have used the galaxy-halo connection model from Nadler et al. (2019) [111] to generate mock observations of faint satellite galaxies, and use the method in Drlica-Wagner et al. (2019) [67] to model the impact of self-interaction and a cut-off in the mass function on the central densities of the satellites. We construct a binned likelihood in the space of stellar dispersion and luminosity and jointly fit for $\sigma/m_\chi$ and $m_{\rm WDM}$, marginalizing over galaxy-halo connection and Milky Way host halo nuisance parameters. Using a LSST detection threshold for Milky Way satellites of $M_V = 0$ mag and $\mu = 32\ {\rm mag/arcsec}^2$ and assuming that future spectroscopy will be able to measure velocity dispersions of $1\,{\rm km/s}$, we obtain the simultaneous measurement of $\sigma/m_\chi$ and $m_{\rm WDM}$.

The results shown in Fig. 3-9 should be regarded as an illustration of the capability of future facilities to *measure* fundamental dark matter particle properties using observations of the cosmic distribution of

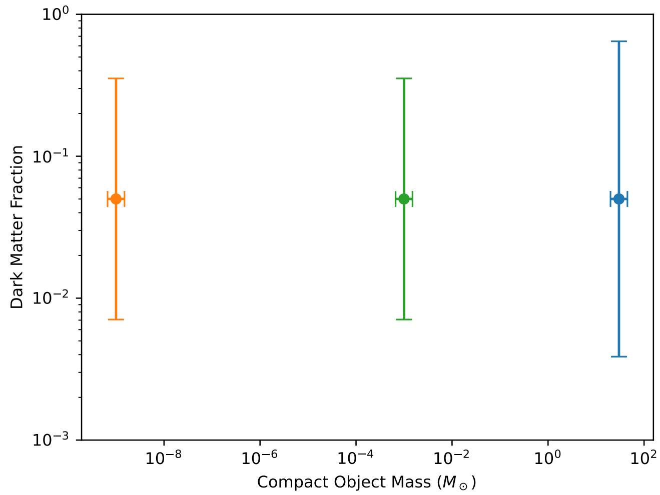


**Figure 3-10.** *Discovery example 2: potential measurements of the dark matter fraction and compact object mass. We assume three representative masses* $10^{-9}$ $M_\odot$ *(orange),* $10^{-3}$ $M_\odot$ *(green) and* 30 $M_\odot$ *(blue); a single mass makes up* 5% *of the dark matter. The errors indicate the measurement uncertainties, assuming Poisson uncertainties associated with the observational number counts expected from the relevant future microlensing experiment with the Rubin or Roman Observatories, and* 50% *uncertainties in mass.*



dark matter. It is important to note that *this measurement* ***does not*** *assume that dark matter couples to the Standard Model*. Furthermore, while degeneracies exist between dark matter particle properties and the physics of galaxy formation (e.g., the long tail towards large dark matter mass), these degeneracies can be broken by combining satellite galaxy measurements with a probe that is independent of subhalo luminosity, such as strong lensing and stellar streams, ultimately resulting in closed contours at high statistical significance. The discovery of a large self-interaction cross section and a cut-off in the matter power spectrum would have profound implications for constructing particle theories of dark matter and understanding its evolutionary history in the early universe, see [38] for relevant discussions.

Astrophysical observations can provide precision measurements of dark matter particle properties. To achieve this goal, a collaborative effort from different, but related areas is crucial. First, after LSST discovers new satellite galaxies, spectroscopic followup measurements of their stellar velocity dispersions are needed to constrain the dark matter density. Second, with the population of newly-discovered satellites, it will be possible to update models that capture the connection between invisible subhalos and visible galaxies to better control baryonic uncertainties. Third, dedicated N-body simulations are needed to make concrete predictions of self-interacting and warm dark matter models in terms of the properties of subhalos, such as their mass function, orbit and central density. Last but not the least, in order to implement the novel dark matter properties in the simulations and interpret the observational results, we need to use the methods of particle physics to calculate the self-interaction cross section and determine how it depends on the velocity and scattering angle, as well as the linear matter power spectrum that encodes the evolution of the dark matter candidate in the early universe. Thus, cosmic probes of dark matter are truly interdisciplinary.

### 3.9.2 Primordial Black Holes

The second example we consider is the discovery of primordial black holes, a modern realization of compact object dark matter. Primordial black holes are fundamentally different from particle dark matter candidates as the former cannot be produced in particle accelerators and can only be detected observationally. Much of the parameter space has been constrained by existing probes, but a large window remains where primordial black holes with masses comparable to asteroids ($10^{-15}$–$10^{-10}$ $M_\odot$) could make up the entirety of dark matter, see Fig. 3-6.

Rubin LSST provides an exciting opportunity to directly measure the mass function of compact objects through microlensing observations. Existing microlensing surveys lose sensitivity for the mass $\gtrsim 1$ $M_\odot$ due to the 10-year duration of these surveys. If scheduled optimally, LSST will provide sensitivity to microlensing event rates corresponding to $10^{-4}$ of the dark matter density in compact objects with masses $\gtrsim 0.1$ $M_\odot$, a factor $10^2$–$10^3$ improvement compared to the existing limits, see Fig. 3-6. In addition, the *Nancy Grace Roman Space Telescope* also provides microlensing opportunities in the search for primordial black holes in the next decade. As a high resolution space-based imaging system, *Roman* has the potential to detect or constrain primordial black holes through various types of lensing.

Fig. 3-10 shows discovery potential for three representative compact object masses. The error bars indicate that the expected uncertainty for a population of compact objects of a single mass making up 5% of the dark matter. We assume Poisson uncertainties with the observational number counts expected from the relevant future microlensing experiment (Rubin or Roman). True compact object masses are assumed to be $10^{-9}M_\odot$ (orange), $10^{-3}M_\odot$ (green), $30M_\odot$ (blue). Uncertainty in the final mass is shown as 50%, conservatively using the uncertainty in the recent detection of a microlensing event reported in [112].

The detection of primordial black holes by Rubin LSST and/or *Roman* will provide insights into early universe cosmology. Primordial black holes could form at early times from the direct gravitational collapse of large density perturbations that originated during inflation. The same fluctuations that initialize seeds of galaxies, if boosted on small scales, can lead to some small areas having a Schwarzschild mass within the horizon, which collapse to form black holes. Thus the detection of primordial black holes would directly constrain the amplitude of density fluctuations. These constraints probe small scales between $k = 10^7$–$10^{19}$ h/Mpc, much smaller than those measured by other current and future probes.

### 3.9.3 Axion-like Dark Matter in Extreme Environments

In this example, we demonstrate the potential to measure properties of axion-like dark matter using observations of supermassive black holes. Near a spinning black hole, axion-like particles can form a dense cloud [113], analogous to the formation of a hydrogen atom. The presence of such a cloud of axion-like particles can lead to oscillations in the electric vector position angle (EVPA) of linearly polarized radiation emitted near the black hole, due to the axion-induced birefringence effect [114, 115]. Ref. [75] used polarimetric measurements of the emission near the supermassive black hole in M87 from the Event Horizon Telescope (EHT) collaboration [116] and derived the strongest constraint on the axion-photon coupling in the mass range $\sim 10^{-21}$–$10^{-20}$ eV.

We consider an example of a potential axion-induced birefringence signal that can be discovered by future EHT observations. In order to characterize the discovery potential, we perform a mock data study with an injected axion signal using `IPOLE` [117, 118]. We take the supermassive black hole of M87 as a case study, which can be well modeled by the analytic Radiative Inefficient Accretion Flows [119], and choose

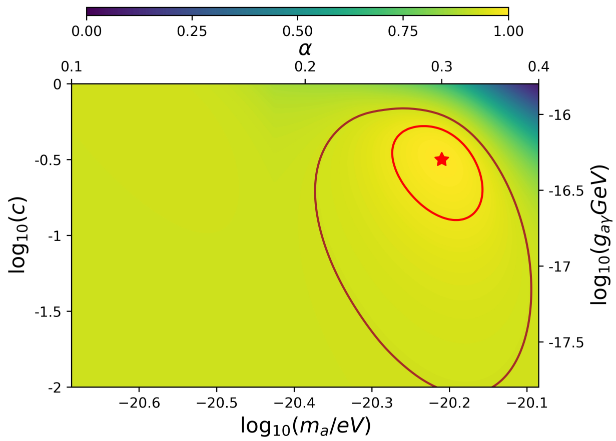


**Figure 3-11.** *Discovery example 3: potential measurements of of the axion-photon coupling and axion mass using the Event Horizon Telescope. We assume the axion particle parameters as* $c \equiv 2\pi g_{a\gamma} f_a = 10^{-0.5}$ *and* $\alpha \equiv m_a M_{\rm BH} = 0.3$ *(asterisk), and show* $1\sigma$ *and* $2\sigma$ *contours in the* $c$*–*$m_a$ *plane after taking into account both measurement uncertainties and those from modeling accretion flows. We convert* $c$ *to* $g_{a\gamma}$ *by assuming* $f_a = 10^{15}$ GeV*. The color in the plot represents the value of likelihood.*

the axion parameters as $c \equiv 2\pi g_{a\gamma} f_a = 10^{-0.5}$ and $\alpha \equiv m_a M_{\rm BH} = 0.3$. The black hole mass is taken to be $M_{\rm BH} = 6.5 \times 10^9$ $M_\odot$.

Fig. 3-11 shows $1\sigma$ and $2\sigma$ contours in the $c$–$m_a$ plane, including both measurement uncertainties and those in modeling the accretion flow. The duration of the observations is assumed to be 10 times longer than the four-day EHT measurement in 2017 [116]. We further assume the measurements at five different radii between $5.5 r_g$ and $9.5 r_g$, equally separated by one $r_g$, where $r_g$ is the gravitational radius of the black hole. In the future, the EVPA variations are expected to be measurable at larger radii from the black hole center. Three different radiation frequencies are considered as well. When measuring the differential EVPA introduced in [75], many details in accretion flow modeling become less important in the axion search. The dominant astrophysical uncertainty comes from the washout effects to the axion signal, which are caused by both the non-negligible radiation length and the contribution of the lensed photons. The lensed photons can be highly suppressed once we focus on the observation at larger radii and low frequencies, such as 86 GHZ. The non-negligible radiation length is mostly affected by the thickness of the accretion flow. To take account of this uncertainty, we vary the dimensionless thickness parameter [119] from 0.05 to 0.3.

## 3.10 Summary and Outlook

More than 80 years after the first astrophysical discovery of dark matter, its fundamental nature remains an open question. Over the last several decades, the HEP community has designed and carried out extensive searches for dark matter signals in a wide variety of terrestrial experiments. Despite these heroic efforts, the only positive empirical measurements of dark matter continue to come from cosmic and astrophysical observations. Importantly, scientific advances over the last 80 years have made it possible to use precision measurements of macroscopic astrophysical systems to probe the microscopic particle properties of dark matter. This Snowmass study presents the critical opportunity for the community to fully realize both the importance and potential of cosmic probes and broaden the approach to the dark matter problem accordingly.

In this report, we have laid out ways for probing and measuring fundamental properties of dark matter that are valid in the scenario where the coupling between dark matter and normal matter is extremely weak, even as weak as gravity. Cosmic and astrophysical measurements of the distribution of dark matter, including the matter power spectrum, the mass spectrum and abundance of dark matter halos and compact objects, can constrain particle properties of dark matter, such as the mass, interaction cross section and production mechanism. Moreover, if dark matter has feeble non-gravitational interactions with normal matter, extreme astrophysical environments, such as neutron stars and black holes, provide unique opportunities to explore dark matter physics over 50 orders of magnitude in the mass; much of this model space is inaccessible with terrestrial experiments. In addition, precision astrophysical measurements of dark matter with current and near-future observational facilities are critical for interpreting results from conventional dark matter searches.

We have further demonstrated that with the unprecedented coverage and sensitivity of current and near-future observational facilities, the rapidly improving scale and accuracy of numerical simulations, and better theoretical modelling, astrophysical uncertainties can be controlled and the fundamental parameters of dark matter can be extracted. This makes it possible to map Lagrangian parameters describing a particular dark matter model to astrophysical observables, and vice versa. Thus cosmic probes can provide precision measurements of particle physics properties of dark matter in a similar way that HEP experiments have enabled the construction of the Standard Model of particle physics.

Cosmic probes of particle properties of dark matter have emerged as a new research field, largely due to tremendous progress in broadened investigations of novel dark matter scenarios, theoretical modelling and N-body simulations of structure formation, as well as astrophysical observations of dark matter distributions, since the last Snowmass community study. There is a new and exciting trend in the HEP community that more and more particle physics theorists have begun working on astrophysical aspects of dark matter. At the same time, astrophysicists working on N-body simulations have started to develop simulation algorithms that can model novel dark matter scenarios beyond CDM. We must encourage and support this promising and evolving trend from both communities.

Furthermore, we must develop new mechanisms to further support synergistic efforts among theorists, simulators, dynamicists, observers, and experimentalists/instrumentalists, who are traditionally supported by different agencies and/or programs. Cosmic probes of dark matter are fundamentally multidisciplinary and interdisciplinary, and traditional disciplinary divisions limit scientific outcomes. New support mechanisms can be pursued from small to large scales. On small scales, a program like the DOE Dark Matter New Initiatives (DMNI) is well suited to support a small-scale collaborative effort from particle physicists and astrophysicists with a well-defined scientific goal. Cosmic probes of dark matter were not included in the current DMNI program. If the program continues, we strongly urge that DOE integrates cosmic probes into its portfolio. Alternatively, a similar program could be established to make rapid progress in this emerging field.

Dark matter physics associated with current and near-future facilities, such as DESI, Rubin, and CMB-S4, is extremely rich. Dark matter science should be supported within these projects on intermediate scales in parallel to studies of dark energy and inflation. Such a program will fully leverage the unprecedented capabilities of these facilities. On large scales, the construction of future cosmology experiments is critical for expanding our understanding of dark matter physics. HEP involvement will be essential for the design and construction of these facilities, and dark matter physics should be a core component of their scientific mission.

Cosmic probes of dark matter are unique and important, because they have sensitivity to microscopic physics of dark matter and provide precision measurements, regardless of whether dark matter has sizable interactions with normal matter. It is the time for the HEP community to appreciate the power of this approach and maximize its full potential. The support for comic probes, which may be the **only** viable way to measure dark matter properties, is essential for the decade of dark matter to come.

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