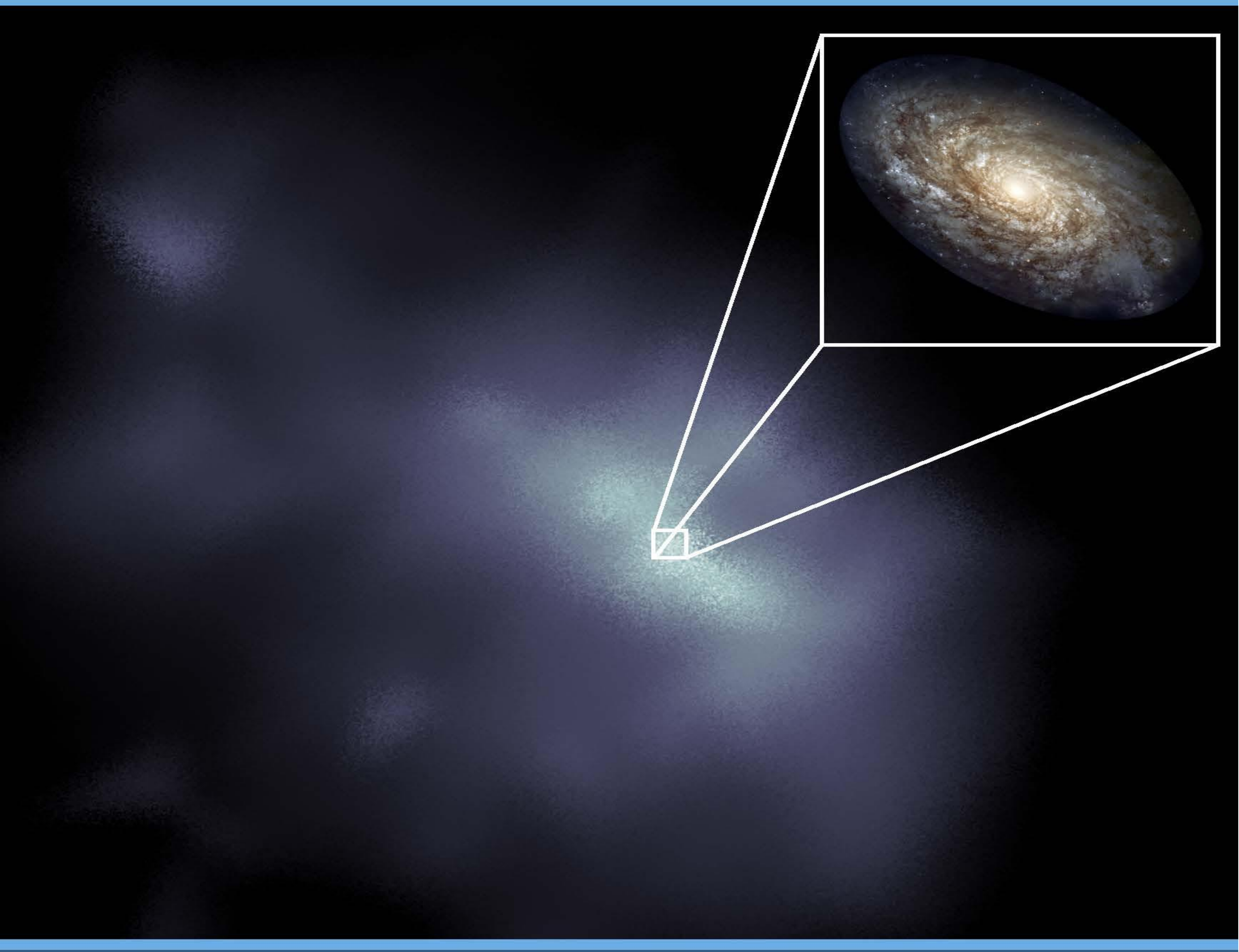
Basic Research Needs for

Dark Matter Small Projects New Initiatives



Summary of the High Energy Physics Workshop on Basic Research Needs for Dark Matter Small Projects New Initiatives

October 15 – 18, 2018

Cover image: Extraction from cosmological simulation of dark matter halo hosting a Milky Way-type galaxy. Image credits: Cosmological Physics and Advanced Computing Group, Argonne National Laboratory. Halo from the Outer Rim simulation, galaxy image (NGC 4414) from the Hubble Space Telescope Key Project. See also https://www.youtube.com/watch?v=I0D7_0Kus8g&t=193s.

Basic Research Needs for Dark-Matter Small Projects New Initiatives

Report of the Department of Energy's High Energy Physics Workshop on Dark Matter

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EXECUTIVE SUMMARY

Only one-sixth of the matter in our universe is made of the fundamental particles we understand. Understanding what the remaining “dark” matter is made of is one of the most important fundamental goals in modern science. It connects such disparate scientific areas as the formation of stars and galaxies, the earliest moments of our universe, and the constituents of matter at the smallest length scales. Astronomical evidence for dark matter has built steadily for eight decades, though the elementary particles or waves that constitute dark matter remain a mystery. Recent theoretical developments have highlighted the importance of searching for dark matter particles in the range from as heavy as a single hydrogen atom to the lightest mass consistent with galactic structure (30 orders of magnitude lighter). Remarkably, small projects at the $5M–$15M scale can explore key milestones throughout this range. By seizing these opportunities, we are now in a position to finally discover the nature of dark matter.

The Particle Physics Project Prioritization Panel (P5) identified the search for dark matter as one of the five priority science drivers for the High-Energy Physics Program. The 2014 P5 report further recommended a portfolio of small projects to enable an uninterrupted flow of high-priority results. This Basic Research Needs (BRN) Report presents a program of small projects to lead to the discovery of the nature of dark matter. The program makes use of Department of Energy (DOE) facilities and infrastructure and is complementary to the ongoing Generation-2 (G2) dark matter program.

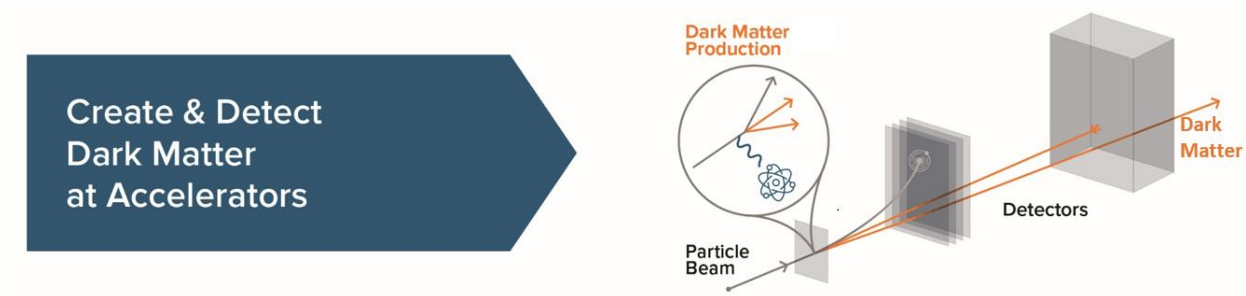
The G2 program has mostly focused on dark matter masses larger than the proton mass using nuclei as targets. The current program also explores wave-like dark matter in a narrow range of very low mass. Looking beyond the current G2 program, in this report we consider complementary searches for dark matter particles with mass less than the proton mass.

These goals motivate a discovery program along three Priority Research Directions (PRDs), reflecting complementary strategies that, taken together, address a Grand Science Challenge with the overarching goal of finally understanding the nature of the matter of the universe. The science priorities in this BRN report can be realized by a series of small projects that will produce high-priority results and are described by the three PRDs.

This program is achievable at modest cost because it leverages existing and planned large-scale DOE investments and expertise in accelerators, underground laboratories, detector R&D, novel quantum sensing, and theoretical physics.

The Priority Research Directions, in no particular order, are:

PRD 1: Create and detect dark matter particles below the proton mass and associated forces, leveraging DOE accelerators that produce beams of energetic particles.



Interactions of energetic particles recreate the conditions of dark matter production in the early universe. Small experiments using established technology can detect dark matter production with sufficient sensitivity to test compelling explanations for the origin of dark matter and explore the nature of its interactions with ordinary matter. These experiments draw on the unique capabilities of multiple DOE accelerators (Continuous Electron Beam Accelerator Facility, Linac Coherent Light Source-II, Spallation Neutron Source, Los Alamos Neutron Science Center, and the Fermilab complex) to enable transformative new science without disrupting their existing programs.

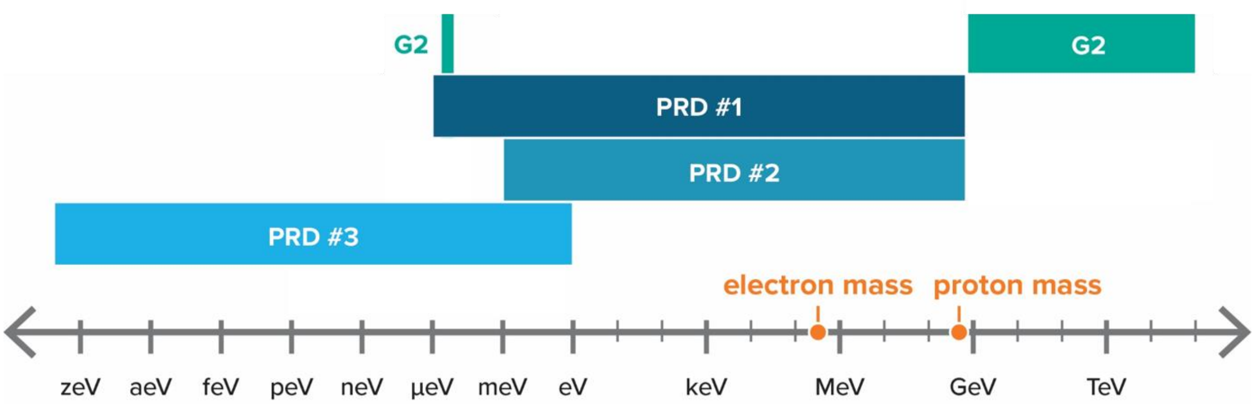
PRD 2: Detect individual galactic dark matter particles below the proton mass through interactions with advanced, ultra-sensitive detectors.

Galactic dark matter passes through the earth undetected every second. Recent advances in particle theory highlight new compelling paradigms for the origin of dark matter and its detection. Revolutionary technological advances now allow us to discover individual dark matter particles with a mass ranging from the proton mass to twelve orders of magnitude below, through their interactions with electrons and nucleons in advanced detectors. New small projects leveraging these theoretical and technological advances are needed and can be carried out by using DOE personnel, laboratories, and infrastructure, especially the underground infrastructure already built using DOE support.

PRD 3: Detect galactic dark matter waves using advanced, ultra-sensitive detectors with emphasis on the strongly motivated QCD axion. [1]

Recent technological and theoretical advances finally allow the detection of dark matter in wave form over the entire 20 orders of magnitude of the ultralight mass range, previously inaccessible to observation. Discovery of these dark matter waves with advanced quantum sensors would provide a glimpse into the earliest moments in the origin of the universe and the laws of nature at ultrahigh energies and temperatures, far above what can be created in terrestrial laboratories.

The three PRDs represent a comprehensive program of small projects to explore dark matter from below the mass of the proton down to the smallest possible mass for dark matter. Together, all three directions cover the key range of possibilities for dark matter across this mass range (G2 program range included for comparison). All three PRDs are needed to achieve broad sensitivity and, in particular, to reach different key milestones.



Successfully unravelling the nature of dark matter, its interactions, and its origin in the universe can only be achieved by combining results from projects spanning these new initiatives. In the event of a discovery, each provides a unique and essential piece of the puzzle.

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1 The QCD axion is a highly motivated dark matter candidate. It is a solution to the strong CP problem and arises in many frameworks of physics beyond the Standard Model of particle physics, including grand unified theories and string theory.

1. INTRODUCTION

Compelling new ideas for the origin and nature of dark matter, recent developments in detector and quantum sensors, and successful pathfinder experiments open an unexplored frontier for the exploration of dark matter.

Importance of Dark Matter

The universe visible to us is a rich tapestry of stars, galaxies, galaxy clusters, and galaxy filaments in a cosmic web of structure. But detailed study of the motions of visible objects reveals that there must be matter that we don't see, that is, dark matter. The gravitational force of dark matter is the glue that binds together galaxies and other structures. The evidence for dark matter has grown ever stronger in the more than 80 years since astronomers first discovered it. The importance of dark matter is not small. Modern precision cosmological measurements reveal that more than 80% of the matter of the universe is dark matter. Dark matter plays the dominant role in the evolution of structure in the universe starting from the initial conditions observed in the cosmic microwave background radiation, some 380,000 years after the big bang.

The existence of dark matter is compelling evidence that our otherwise remarkably successful Standard Model describing the fundamental particles and forces is incomplete since none of the known elementary particles can serve as dark matter. Dark matter signals a new piece of the fundamental laws of nature. We have searched for new fundamental laws beyond the Standard Model for decades, in experiments on tabletops to the most powerful particle accelerator in the world, the Large Hadron Collider. Discovery of a dark matter particles or waves would point the way forward beyond the Standard Model. Determining the properties of dark matter is crucial for a detailed understanding of the evolution of structure in the universe, and understanding its interactions would provide a glimpse into conditions of the very early universe.

The Current U.S. Program

The discovery of the basic properties of dark matter particles by a suite of dedicated experiments (much like the masses and interaction properties of neutrinos are currently being measured) would lead the way to a new understanding of physical principles beyond those embodied in the Standard Model. Several approaches to discover the non-gravitational interactions of dark matter have been and are part of DOE Office of High Energy Physics (HEP) programs, including the search for dark matter at particle colliders, indirect detection of dark matter through astronomical observations of the annihilation products of dark matter, and direct detection of dark matter. The hypothesis of the weakly interacting massive particle (WIMP) as the dark matter particle is well-motivated and has dominated experimental searches for the past few decades. For some time, the quantum chromodynamics (QCD) axion has also been recognized as another compelling dark matter candidate, although it has received less experimental attention. The search for these particles has resulted in three dedicated G2 direct detection experiments in the HEP program: the LZ (LUX-ZEPLIN) Dark Matter Experiment, Super

> Although the neutron has constituent charged particles (quarks), it has no net charge polarity (i.e., no electric dipole moment). A well-motivated solution is that the quark subcomponents of the neutron are forced into a charge-balanced configuration to minimize the potential energy of an associated field, *the axion*.

Cryogenic Dark Matter Search (SuperCDMS), and Axion Dark Matter Experiment (ADMX). Both LZ and SuperCDMS are primarily designed to detect nuclear recoils of dark matter particles with mass greater than the proton mass. While the ADMX was originally motivated to search for the QCD axion, in general, it searches for particles with mass of 2-40 μeV (2-40 x 10^{-6} eV).

The search for dark matter is a worldwide effort involving underground experiments, accelerator searches, laboratory investigations, ground-based and space-based astronomical searches, and computer simulations; all informed by an active and thriving theoretical community. The international dark-matter effort involves high-energy physicists, astrophysicists, cosmologists, and detector physicists. In this large international effort the diversity and depth of the U.S. effort is world leading. The U.S. effort is multidisciplinary and supported by several Federal agencies and well as private foundations. The anchor of the U.S. dark-matter search program is the Generation-2 (G2) experiments ADMX, LZ, and SuperCDMS. Completion of the G2 program is the highest priority of the dark-matter community. But like any active research area the frontier evolves, and in this report we identify new scientific opportunities beyond the reach of G2 that will maintain the U.S. dark-matter program at the forefront and offer real possibilities for discovery of the nature of dark matter. The scientific opportunities leverage significant DOE investments in the suite of particle accelerators, a program of development of quantum sensors, the expertise and facilities of national laboratories, and an active community of theorists and experimentalists.

New Directions, Why Now

New ideas for dark matter

Over the past decade, as initial searches for dark matter have shown no results, significant advances in dark matter theory have emphasized that, besides the QCD axion, there are many other compelling non-WIMP dark matter candidates. In particular, these candidates can be found anywhere in the mass range from 1 GeV (10^9 eV), which is roughly the lower sensitivity limit of G2 direct-detection experiments, down to 10^{-22} eV, which is the smallest possible dark matter mass consistent with structure formation.

A defining feature of these new candidates is that they do not interact directly with the known Standard Model forces. Instead, they are hypothesized to be part of a hidden sector and are connected to the Standard Model sector through a so-called "dark force," which means that the new force has very weak interactions with ordinary particles, such that it would have evaded detection so far. The hidden sector could also have a rich structure that leads to non-trivial dynamics in the dark sector. These dynamics allow the observed abundance of dark matter in the universe to be set in previously unanticipated ways. This has important implications for the evolution of our universe and the detection of such dark matter. The coupling of the dark forces to dark matter also allows for novel search strategies for the new forces. This compelling paradigm for dark matter is now ripe for experimental exploration using recently developed technologies and novel ideas for detection.

Technology and pathfinder experiments

In parallel with the extension of theoretical interest in the parameter space from 10^{-22} eV to 1 GeV (10^9 eV), new concepts for dark matter detection have been developed. These concepts are enabled by recent advances in detector and sensing technology and by state-of-the-art accelerator facilities. Recent pathfinder experiments have demonstrated the sensitivity of accelerator-based fixed target dark matter searches.[2] It is now clear that high-intensity proton beams and high-rate electron beams will enable dramatic sensitivity improvements. In addition, advances in low background detectors with a low energy threshold[3] make possible a new generation of dark-matter direct detection searches below the mass of the proton, with emerging technologies even enabling searches for dark matter below the electron mass.[4] Recent developments in quantum sensing technology (low-noise cryogenic and near quantum-limited amplifiers) have recently enabled the most powerful searches for the QCD axion in the ADMX,[5] albeit in a narrow mass range. New detection concepts and further advances in quantum sensing technology will enable sensitivity to dark matter over the entire wave-like mass range,[6] including the full QCD axion parameter space.

Provenance from the Particle Physics Project Prioritization Panel

The 2014 P5 report identified the search for dark matter particles as one of the five priority science drivers for the HEP program. To quote P5: "*It is imperative to search for dark matter along every feasible avenue*," and the breadth of "*well-motivated ideas for what dark matter could be, [which] include weakly interacting massive particles (WIMPs), gravitinos, axions, sterile neutrinos, asymmetric dark matter, and hidden sector dark matter.*"[7]

Some of these scenarios — including WIMP searches — are the purview of larger experiments, as described below. However, much of the well-motivated parameter space for dark matter can be explored by small experiments in the near future. This corresponds to another recommendation of P5, namely, that the HEP program should contain a portfolio of small projects to enable an uninterrupted flow of high-priority science results.

This Report

Recent experimental, technological, and theoretical advances have opened the potential for dark matter discovery in a mass range once thought inaccessible. The community's interest in realizing this opportunity led to a workshop, "US Cosmic Visions: New Ideas in Dark Matter," held on March 23-25, 2017, resulting in a whitepaper summarizing these new science opportunities.[8] Many of the new experimental approaches enabling this opportunity for discovery are expected to be realizable by small projects. In many cases, these are cost effective because they leverage substantial DOE investments in facilities, infrastructure, and technology development.

Building on the "US Cosmic Visions" whitepaper, HEP called for a BRN workshop on new initiatives in dark matter science. The focus of the workshop, held October 15-18, 2018, and of this report is identifying new opportunities for dark matter particle searches and high-impact PRDs to realize these science opportunities. A requirement was that the research should be pursued by small projects

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[2] A. A. Aguilar-Arevalo et al., Phys. Rev. D98 (2018) 112004; D. Banerjee et al., Phys, Rev. D97 (2018) 072002.
[3] See the discussion in the *Direct Detection Panel Report* in Chapter 4, pp. 54-66.
[4] See the discussion in the *Direct Detection Panel Report* in Chapter 4, pp. 54-66.
[5] https://depts.washington.edu/admx/
[6] See the discussion in the *Ultralight Dark Matter Panel Report* in Chapter 4, pp. 67-78.
[7] Particle Physics Project Prioritization Panel, *Building for Discovery: Strategic Plan for the U.S. Particle Physics Community in the Global Context*, https://science.energy.gov/~/media/hep/hepap/pdf/May-2014/FINAL_P5_Report_053014.pdf, p. 4 (2014).
[8] Marco Battaglieri, *US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report*, arXiv:1707.04591 [hep-ph] (2017).

(approximately $5M to $15M in total project cost) in which DOE's laboratory infrastructure and/or technology capabilities can be fully exploited. Small projects addressing much of this science are ready to start within the next few years, while others need further technology development before project initiation.
Leaders in the field invited to participate in the BRN workshop were divided into four panels, with panel topics organized around experimental approaches where significant theoretical and technology advances within the last 5 years will enable high-impact searches for dark matter over the next 5-10 years. The four panels covered the following topics:

1. Discovery of dark matter particles and related forces at accelerators
2. Detection of galactic dark matter particles through interactions with ordinary matter
3. Detection of dark matter as coherently oscillating waves
4. Cross-cutting science opportunities and technology development.

The findings of the BRN build on the "US Cosmic Visions" whitepaper as well as advances achieved in the intervening year and a half. The deliberations from these panels are documented in Chapter 3. The primary workshop goal was the identification of a short list of PRDs, which are summarized below and described in depth in Chapter 2.

The Priority Research Directions

The three PRDs in this report span an enormous range in mass for the dark matter particle, from 10^{-22} eV, to the proton mass, approximately 1 GeV (10^9 eV). The lower mass limit is set by the requirement that the de Broglie wavelength[9] of the dark matter particle must be smaller than the size of objects dominated by dark matter. The upper mass limit is set because the G2 program effectively covers the range above the proton mass. If dark matter is produced by thermal processes in the early universe (discussed later), its mass must be greater than the electron mass (0.5 x 10^6 eV) and less than about 100 TeV (10^{14} eV). The image below shows the dark matter range in this thermal period.

PRD 1: Create and detect dark matter particles below the proton mass and associated forces, leveraging DOE accelerators that produce beams of energetic particles.

Small experiments at accelerators can produce dark matter lighter than the proton, reproducing the conditions under which dark matter was created in the early universe. This capability offers broad sensitivity to this light dark matter and suggests a strong prospect to measure its physical properties. The role of accelerator production experiments is especially prominent in theories of *thermal dark*

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9 The de Broglie wavelength of a particle of mass *m* and velocity v is equal to h/mv, where *h* Is Planck's constant.

matter, where dark matter interactions with visible matter in the hot early universe explain its abundance today. Predictive realizations of this hypothesis require dark matter production rates within a factor of 1000 of current experiments' sensitivity, which is accessible to small experiments using existing technology over most of the electron-to-proton mass range. Searching for dark matter production in this range, by achieving a 10- to 1000-fold sensitivity gain over current experiments, represents an especially high-impact science opportunity. Moreover, thermal dark matter models below the proton mass imply the existence of new, unstable particles that are related to dark matter. These particles may decay into visible final states. Searching for these "dark sector" particles represents an additional avenue for both discovering dark matter and exploring how it is related to familiar matter.

Accelerators can produce many dark-sector particles, not only dark matter particles.

Two high-impact thrusts can be achieved by deploying proven technologies at DOE accelerators, as elaborated below. If successful, this PRD could entirely re-write our understanding of what dark matter is, and how it is related to familiar matter.

Thrust 1 (near term): Through 10- to 1000-fold improvements in sensitivity over current searches, use particle beams to explore interaction strengths singled out by thermal dark matter across the electron-to-proton mass range.

Two basic approaches can explore the parameter space of roughly 10^{-6} eV to 1 GeV (10^{9} eV), leveraging the unique capabilities of DOE accelerators.

- *Missing momentum experiments*, using modern detectors operating directly in a low-current lepton beam, identify dark matter production events based on the kinematics of visible particles recoiling from the production event. Such experiments in a continuous-wave electron beam offer a path to reach 1000-fold improvement in sensitivity over a broad mass range; missing momentum measurements in muon beams have significant potential sensitivity for detecting heavier dark matter masses and exploring a distinct coupling.

- *Beam dump scattering measurements* produce dark matter by stopping an intense electron or proton beam and detecting its scattering in a downstream detector. This approach offers a complementary and distinctive detection signal. Concepts exploiting existing electron and proton beams can achieve at least 10-fold sensitivity gains even when using conservative detectors. The capabilities of the DOE accelerator infrastructure provide unique opportunities for world-leading science, which in most cases can be done in parallel with these facilities' primary programs – in particular, multi-GeV continuous-wave electron beams and high-intensity proton beams such as those at the
    - Continuous Electron Beam Accelerator Facility (CEBAF), Jefferson Laboratory (JLab),
    - Linac Coherent Light Source-II (LCLS-II), SLAC National Accelerator Laboratory,
    - Spallation Neutron Source (SNS), Oak Ridge National Laboratory (ORNL),
    - Los Alamos Neutron Science Center (LANSCE), Los Alamos National Laboratory (LANL), and
    - the Fermilab complex at Fermi National Accelerator Laboratory (FNAL).

Thrust 2 (near and long term): Explore the structure of the dark sector by producing and detecting unstable dark particles.

A third approach, involving *spectrometer-based searches,* offers broad sensitivity to unstable dark sector particles and the capability to fully characterize their decays. Near-term proposals exploiting either continuous-wave electron beams or energetic proton beams are sensitive to dark force carriers and to a broad range of other unstable particles related to dark matter, as well as to physics beyond dark matter. In addition, many experiments primarily motivated by Thrust 1 also offer some complementary sensitivity to unstable dark sector particles.

Together, spectrometer-based, missing momentum, and beam dump experiments have powerful discovery potential for models of dark matter and associated forces. Some notable models are only partly explored by current accelerator-based experiments, and motivate future exploration of new concepts to extend this sensitivity.

PRD 2: Detect galactic dark matter particles below the proton mass through interactions with advanced, ultra-sensitive detectors.

Dark matter from the galaxy passes through the Earth undetected every second. Ultra-sensitive laboratory experiments seek to detect rare interactions of the dark matter depositing a small amount of energy in advanced detectors, which are typically placed deep underground to reduce interference from other known events, like cosmic rays. Up to now, "direct detection" experiments, i.e., experiments using this technique, have been primarily focused on detecting dark matter particles that are heavier than the proton. This PRD focuses on new experimental approaches to probe lower mass dark matter ranging from the proton mass to twelve orders of magnitude lighter. This will dramatically extend our sensitivity to dark matter into previously unexplored frontiers.

Direct detection would directly probe the galactic dark matter.

Many exciting new theoretical ideas have motivated searches in this wide mass range and have provided specific targets for experiments to explore. A mass range consisting of six orders of magnitude can be probed immediately with recently proven technology. An additional six orders of magnitude in mass can be probed after additional R&D of promising technologies. In each of these mass ranges, theory predicts dark matter candidates that could be discovered with just a gram of target material observed over one day. The experiments discussed in this PRD could be realized by DOE small projects, making critical use of DOE resources, such as national laboratories, expert personnel, infrastructure, and especially the underground infrastructure already built with DOE support.

Because theory targets exist in which the dark matter interacts only with nuclei, or only with electrons, this PRD consists of two thrusts of equal importance, which probe different possible interactions between dark matter and known matter. Each thrust contains small projects that are ready to be executed immediately based on proven technology, as well as longer-term R&D efforts that would allow an even wider range of masses and interaction strengths to be probed.

Thrust 1: Probe dark matter interactions with nuclei, as motivated by theoretical ideas for the nature of light dark matter, including its possible thermal and non-thermal origins.

Dark matter can interact with nuclei in various target materials, producing a signal that depends on the target material and detector setup. The type of interactions with the target includes dark matter scattering as well as dark matter absorption. Ultra-sensitive experiments in the near term can probe the scattering of dark matter with masses between 50 MeV (5 x 10^7 eV) and 1 GeV (10^9 eV), while medium-to-longer term experiments could probe the scattering of dark matter with masses down to about 1 keV (10^3 eV) and the absorption of dark matter as light as approximately 1 meV (10^{-3} eV).

Thrust 2: Probe dark matter interactions with electrons, as motivated by theoretical ideas for the nature of light dark matter, including its possible thermal and non-thermal origins.

This thrust is similar to Thrust 1, but here dark matter interacts with electrons in various target materials, and this in some cases requires the development of advanced materials. Ultra-sensitive experiments in the near term can probe the scattering of dark matter with masses between about 1 MeV (10^6 eV) and 1 GeV (10^9 eV) and the absorption of dark matter with masses between 1 eV and 1 keV (10^3 eV). Medium-to-longer term experiments can be sensitive to the scattering of dark matter with masses between 1 keV (10^3 eV) and 1 MeV (10^6 eV) and the absorption of dark matter down to masses of about 1 meV (10^{-3} eV).

PRD 3: Detect galactic dark matter waves using advanced, ultra-sensitive detectors with emphasis on the strongly motivated QCD axion.

Good candidates for the dark matter of the universe span the entire "ultralight" mass range from 10^{-22} eV to 1 eV. In this range, dark matter acts more like a wave than a particle. The frequency of this wave is set by the dark matter mass and ranges from 10^{-8} Hz to 10^{14} Hz. This range contains the strongly motivated dark matter candidate, the QCD axion. The QCD axion might also solve one of the deep mysteries in the fundamental laws of nature: understanding the differences between matter and antimatter inside the nucleus. The vast majority of this 22 order-of-magnitude range appears to be accessible with novel, small-scale, direct-detection experiments in the laboratory, leveraging advances in high-precision quantum technology.

Whether the dark matter is best described by a particle picture or a wave picture is determined by the occupation number of particles within a volume of radius equal to the de Broglie wavelength. If the occupation number is much larger than unity, the dark matter is best visualized as a wave. The crossover occurs at a dark-matter particle mass of about 1 eV, i.e., below this mass the wave description is better.

This ultralight dark matter, either in the form of axions or hidden photons, naturally arises from physics at ultrahigh energy scales. A detector in such an experiment thus probes fundamental physics at ultrahigh energies, far above what can be created in terrestrial laboratories. Such dark matter is naturally produced at the very earliest times in the universe, during the conjectured period of extraordinary inflation during the first 10^{-35} seconds after the big bang. Its abundance and properties are tied to the physics of inflation. Thus, a detection of such dark matter also provides information on the earliest times in the formation of the universe in ways highly complementary to cosmic microwave background experiments.

Discovery of dark matter waves would provide a glimpse into the earliest moments in the origin of the universe and the laws of nature at ultrahigh energies, beyond what can be probed in colliders.

Combining scientific motivation and technical readiness, the highest priority for small-scale DOE projects in ultralight dark matter is to search in the mass range of Thrust 1: 100 Hz to 10 GHz (roughly 10^{-12} eV to

10^{-4} eV), with the strongest emphasis on covering as much of the QCD axion line as possible. Thrust 2 will develop and extend new detector technologies to cover the entire ultralight mass range.

Thrust 1: Utilize new detector technologies to explore large parts of dark matter parameter space covering a broad range of mass from 100 Hz to 10 GHz (roughly 10^{-12} eV to 10^{-4} eV) and targeting sensitivity to the QCD axion where possible.

Excitingly, novel small-scale experiments to explore dark matter candidates in the mass range 10^{-12} eV to 10^{-4} eV are ready for conceptual development in the near future. A few complementary experiments could cover this entire mass range and, most importantly, could probe the QCD axion over the vast majority of this range. These complementary experimental approaches involve use of several techniques (magnetic resonance, lumped-element resonators, and microwave cavities), and leverage advances in high-precision quantum sensors.

Thrust 2: Develop or extend new detector technologies to enable experiments to cover the remaining parameter space for well-motivated dark matter models spanning roughly 20 orders of magnitude in mass and also targeting complete coverage of QCD axion models.

Farther into the future many promising approaches are poised to extend our coverage over the entire ultralight dark matter range. For example, new resonator and quantum sensing technologies are currently being developed to target higher frequency dark matter waves (above 10 GHz/10^{-4} eV) and also fill out coverage of the QCD axion at all frequencies. Other technologies (e.g., atomic interferometers and magnetometers and torsion pendulums) are being developed to extend the reach into the ultra-low mass frontier of dark matter wavelengths as large as the size of dwarf galaxies. To take advantage of the high impact of these approaches, further technology development is needed on all these directions.

Complementarity between PRDs and Cross-Cutting Opportunities

The three PRDs represent a comprehensive program of small projects to explore dark matter below the mass of the proton. This point is illustrated in Figures 1-1 and 1-2. Figure 1-1 shows the interaction strength for the mass range from keV (10^3 eV) to GeV (10^9 eV) for three hypotheses concerning the scaling of the dark matter scattering cross section with its velocity (v^{-4}, v^0, and v^2). Also displayed are the regions that are covered by PRDs 1 and 2 via searches for dark matter production at accelerators or by direct detection, respectively. Also indicated are regions of parameter space corresponding to near-term theoretical milestone scenarios which naturally explain the observed abundance of the dark matter in the universe. Together, the two PRDs provide an extremely powerful diagnostic tool for dark matter physics.

In Figure 1-2, the interaction strength is shown for the mass region from 10^{-22} eV (below which the dark matter would be unable to form observed galaxies) to 10^3 eV (above which the dark matter behaves as particles rather than waves), along with the regions that would be covered by PRD 2 and PRD 3. Also indicated is the theoretically motivated parameter space of the QCD axion.

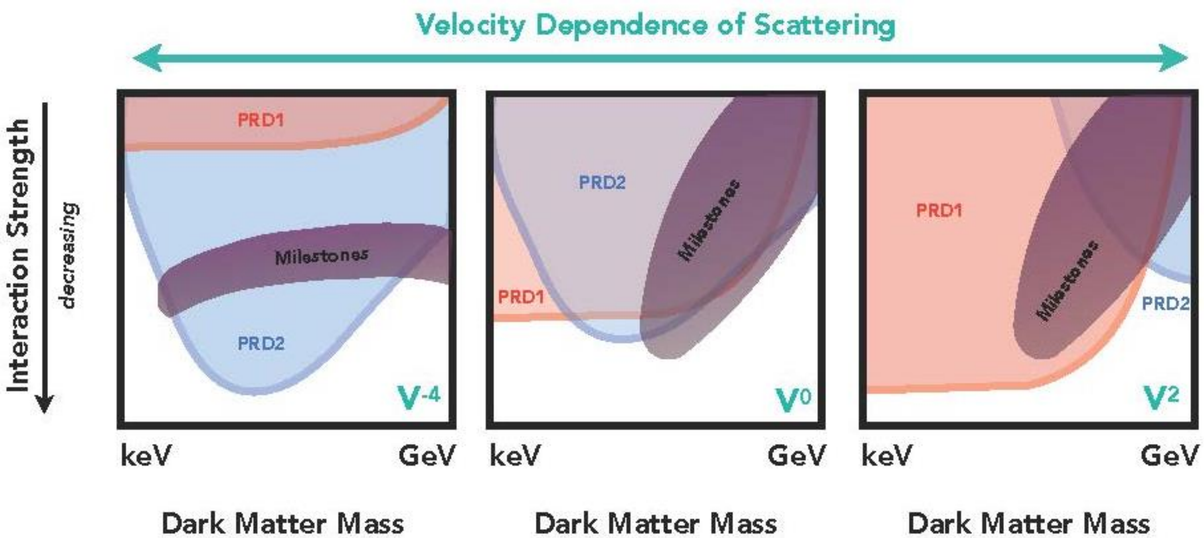


Figure 1-1: *Dependence of interaction strength and dark matter velocity for accelerator experiments and direct detection experiments in PRD 1 and PRD 2, respectively. The reach of the different techniques is indicated, as well as near-term theoretical milestone scenarios. Depending on the scaling of the dependence of the low-energy dark matter scattering with nuclei or electrons, direct detection or accelerator production could be most sensitive.*

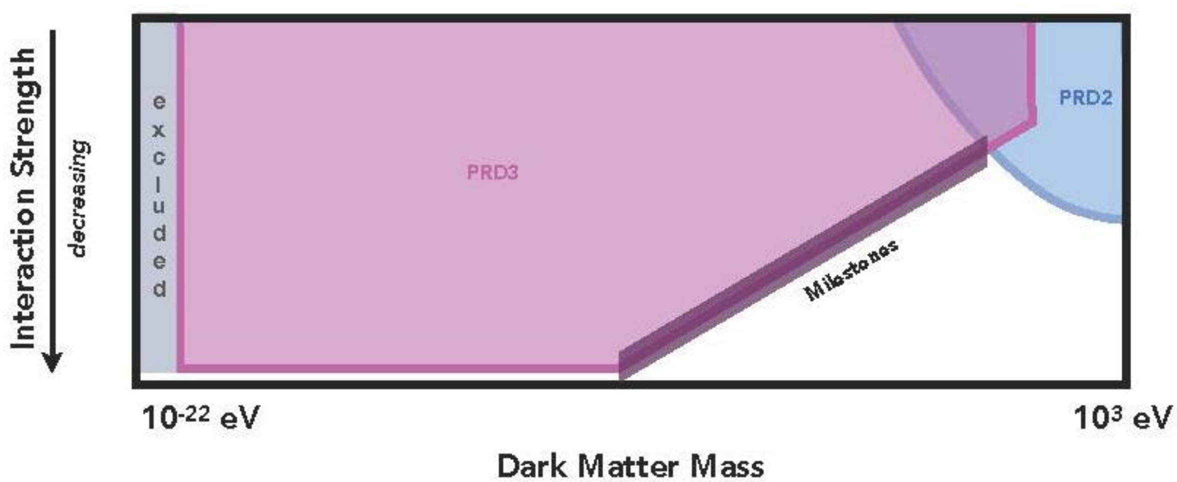


Figure 1-2: *Dependence of interaction strength parameter space for wave dark matter spanning many orders of magnitude. In the upper mass range, direct detection experiments (PRD 2) provide complementary information for PRD 3.*

2. PRIORITY RESEARCH DIRECTIONS

The workshop discussion identified three Priority Research Directions (PRDs) that define the basic research needs for the dark matter small projects initiative. Each PRD is discussed in depth with the associated research thrusts in this chapter. As background, Chapter 4 of the report provides an in-depth assessment of the current status of relevant research in the field of dark matter.

LIST OF PRIORITY RESEARCH DIRECTIONS AND ASSOCIATED RESEARCH THRUSTS

1. **Create and detect dark matter particles below the proton mass and associated forces, leveraging DOE accelerators that produce beams of energetic particles.**

   Thrust 1: Through 10- to 1000-fold improvements in sensitivity over current searches, use particle beams to explore interaction strengths singled out by thermal dark matter across the electron-to-proton mass range.

   Thrust 2: Explore the structure of the dark sector by producing and detecting unstable dark particles.

2. **Detect individual galactic dark matter particles below the proton mass through interactions with advanced, ultra-sensitive detectors.**

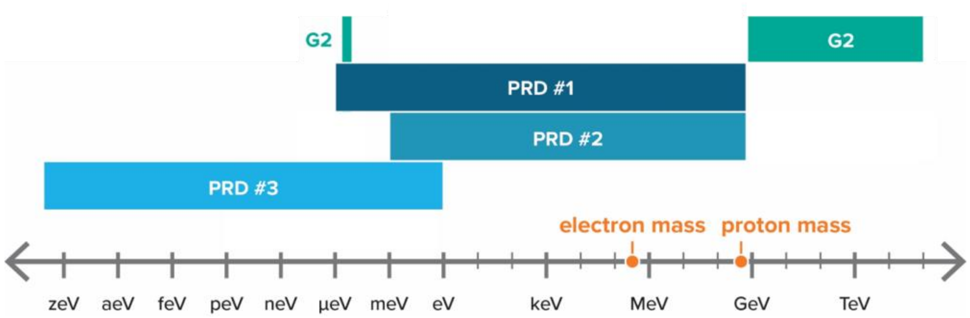
   Thrust 1: Probe dark matter interactions with nuclei, as motivated by theoretical ideas for the nature of light dark matter, including its possible thermal and non-thermal origins.

   Thrust 2: Probe dark matter interactions with electrons, as motivated by theoretical ideas for the nature of light dark matter, including its possible thermal and non-thermal origins.

3. **Detect galactic dark matter waves using advanced, ultra-sensitive detectors with emphasis on the strongly motivated QCD axion.**

   Thrust 1: Utilize new detector technologies to explore large parts of dark matter parameter space covering a broad range of mass from 100 Hz to 10 GHz (roughly 10^{-12} eV to 10^{-4} eV) and targeting sensitivity to the QCD axion where possible.

   Thrust 2: Develop or extend new detector technologies to enable experiments to cover the remaining parameter space for well-motivated dark matter models spanning roughly 20 orders of magnitude in mass and also targeting complete coverage of QCD axion models.



Mass range covered by PRDs and G2 program: O.1 zeV to 200 TeV (10^{-22} eV to 2 x 10^{14} eV). Early-universe thermal production of dark matter requires the dark matter particle mass to be less than about 200 TeV. For dark matter to be responsible for structure formation requires a mass larger than 10^{-22} eV. Although this is an enormous mass range, the PRDs in this report, together with the current G2 program, span the entire range. All three PRDs are needed to achieve broad sensitivity and, in particular, to reach different key milestones and targets.

PRD 1: Create and detect dark matter particles below the proton mass and associated forces, leveraging DOE accelerators that produce beams of energetic particles

Future experiments at existing DOE accelerator facilities using established detector technology offer a unique window on the physics of light dark matter at modest cost. These experiments use the collisions of electrons, protons, or muons on target atoms to produce and detect dark matter and associated unstable particles in the laboratory. The two thrusts of this PRD, described below, are each motivated by exploring different aspects of the thermal dark matter paradigm – a compelling paradigm in which dark matter originates from its interactions with ordinary matter in the hot early universe. Existing DOE High-Energy Physics, Nuclear Physics, Basic Energy Sciences, and National Nuclear Security Administration beams could be used to realize this program (Table 2-1). The multiple DOE beam facilities provide a variety of energies, particle types, and capabilities for this experimental program.

Table 2-1: *Summary of PRD 1. If realized, the possibility to produce and detect dark matter at DOE accelerators would create a tremendous opportunity to explore dark matter particles and associated forces below the proton mass. The techniques that realize this PRD are shown in the columns under the two thrusts and are defined later. The DOE accelerators/beamlines that have been studied and could enable these techniques are shown in the second column. Some combinations of technique and facility are conceived as "parasitic," i.e., designed to operate simultaneously with a primary physics program, while others are currently understood to require "dedicated" operations. Beams of different particle species (electron, proton, and muon) enable different concepts and probe different couplings to the dark sector. Beam dump and missing momentum experiments are primarily focused on Thrust 1, with additional applications to Thrust 2. Spectrometer-based experiments are primarily motivated by Thrust 2.*

		Thrust 1				Thrust 2
Lab	**Accelerator / Beamline**	**Proton Dump**	**Electron Dump**	**Electron Missing Momentum**	**Muon Missing Momentum**	**Spectrometer Based**
FNAL	BNB (8 GeV)	Dedicated				
	MI (120 GeV)	Dedicated				Dedicated
	2^{dary} muons				Dedicated	
ORNL	SNS	Parasitic				
LANL	LANSCE	Parasitic				
SLAC	LCLS-II		Parasitic	Parasitic		Parasitic
JLab	CEBAF		Parasitic	Dedicated		Dedicated

The science described in this PRD is motivating new efforts at laboratories around the world, including the European Organization for Nuclear Research (CERN), the High Energy Accelerator Research Organization (KEK), Mainz Energy-Recovering Superconducting Accelerator, and National Institute for Nuclear Physics (INFN). In this global landscape, the capabilities of the DOE accelerator infrastructure – in particular, multi-GeV continuous-wave electron beams and high-intensity proton beams – provide unique opportunities. By leveraging existing DOE accelerator infrastructure, U.S. small projects can provide world-leading contributions to this important and vibrant new science.

Science Opportunities

A compelling explanation for the origin of dark matter is that it was produced through interactions with the bath of familiar matter that filled the universe after the big bang. Producing this "thermal dark matter" in accelerator-based experiments is the only way to reproduce the kinematic conditions of these primordial interactions; therefore, such experiments offer an especially powerful window on the thermal dark matter paradigm.

The range of masses consistent with thermal dark matter is illustrated by the green band in Figure 2-1, while the light dark matter parameter space probed by this PRD is denoted by the blue shading. The new opportunities in this PRD complement existing collider, direct detection, and indirect detection efforts that search for WIMPs above the proton mass. Together, they can provide complete coverage of the viable mass range for thermal dark matter.

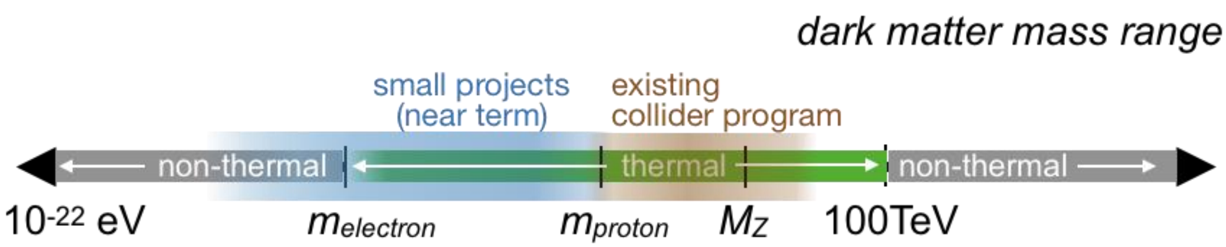


Figure 2-1: *Dark matter mass parameter space. The thermal dark matter mass range is shown in green, the mass range probed by accelerator-based small projects is shaded in blue, and the complementary mass range explored by the existing collider program is shaded in brown.*

A particularly simple, robust, and predictive realization of thermal dark matter is that dark matter and ordinary matter were once in thermal equilibrium, with the strength of interactions between them determining the abundance of dark matter seen today. Interaction strengths that could explain the origin of dark matter imply a minimum dark matter production rate at fixed-target experiments (illustrated by the green band in Figure 2-2). These predicted signals are within a factor of 1000 of current experiments' sensitivity. This strongly motivates a focus on experiments that achieve a 10- to 1000-fold sensitivity gain over current dark matter searches across the electron-to-proton mass range. A factor of 10 improvement would represent important progress, while a full factor of 1000 improvement would thoroughly explore this predictive scenario. Achieving these gains in sensitivity for dark matter production reactions is the goal of Thrust 1.

Thermal dark matter lighter than the proton implies the existence of light, unstable "dark sector" particles that interact with both the dark matter and ordinary matter. One example of such a state is the posited force carrier (discussed earlier) that mediates interactions between dark and familiar matter, which may decay into familiar matter. Moreover, many models of dark matter include excited states that may decay into visible particles or into a combination of visible and dark matter particles. Searching for these particles is an additional window on the physics of dark matter, with complementary discovery sensitivity. This motivates Thrust 2, focused on searching for new particles in a variety of visible final states. Accelerator experiments offer the only means of detecting this crucial part of the dark matter physics.

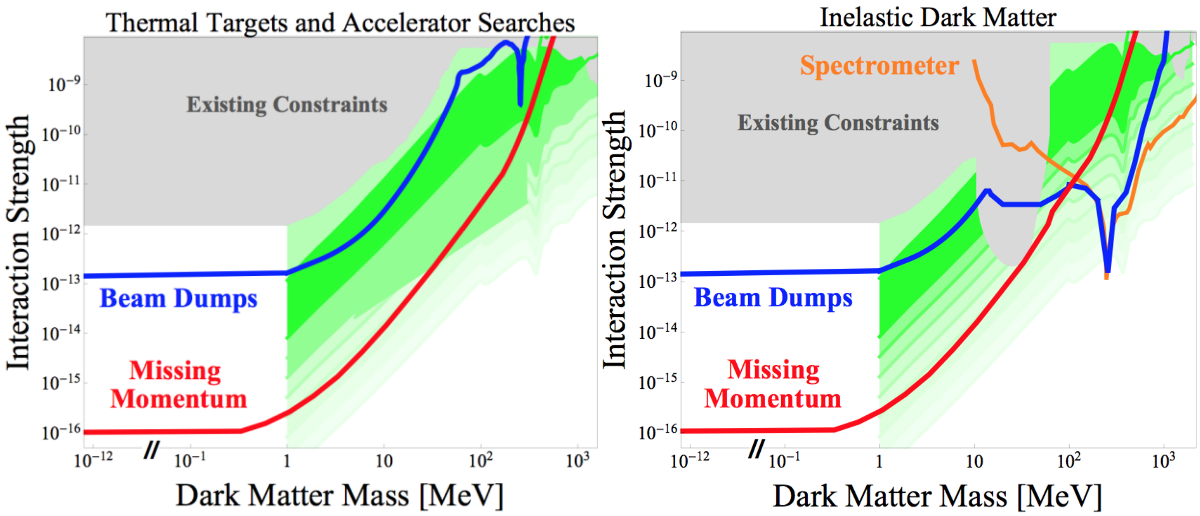


Figure 2-2: *Sensitivity of small accelerator-based experiments to two example benchmark models of dark matter. The interaction strength is* $(g_{DM}\, g_{SM}/4\pi)^2\, (m_{DM}/m_{MED})^4 / \alpha_{EM}$*, where the coupling of the mediator (MED) to dark matter (DM) is* g_{DM}*, and the coupling of the mediator to standard model particles is* g_{SM}*. For the figure,* $m_{MED} = 3m_{DM}$ *has been assumed. (Left) Sensitivity of proposed experimental techniques to minimal dark matter production signals, via kinematic or recoil signatures. (Right) Sensitivity of proposed experimental techniques to inelastic dark matter production, via kinematic or excited-state decay signatures. The width of the solid green bands reflects the range of possible velocity dependences of dark matter interactions (depending on the dark matter spin and mass structure) in each case, while the lighter green regions show the variation in interaction strength predictions in corners of parameter space or generalized thermal models.*

Research Thrusts

This section summarizes the kinds of physics measurements that have been considered to address the two scientific goals mentioned above, the accelerator infrastructure that they require, and the science potentially achievable by each kind of measurement. Assumed are the existing infrastructure, reasonable run times and detector scales, and efficient background rejection.

Thrust 1 (near term): Through 10- to 1000-fold improvements in sensitivity over current searches, use particle beams to explore interaction strengths singled out by thermal dark matter across the electron-to-proton mass range.

As described above, predictive milestones for thermal dark matter production motivate a factor of 10-1000 improvement in sensitivity beyond existing particle-beam measurements.

Small projects to achieve this goal fall into two categories: missing momentum experiments and beam dump experiments. Missing momentum experiments identify dark matter production events based on the kinematics of visible particles recoiling from the production event, while beam dump experiments rely on producing dark matter particles in the target and then detecting their scattering in a downstream detector. These techniques are illustrated in Figure 2-3. Recent experiments demonstrating the feasibility and power of both approaches are summarized in the *Current Status and Recent Theoretical and Technological Advances* section of the Accelerator Production Panel Report in Chapter 4. Near-term opportunities exist for transformational improvements over current sensitivity by using available detector technologies and existing DOE accelerator infrastructure.

As a byproduct of reaching the important milestones associated with predictive models for the origin of dark matter, these experiments will also broadly explore the parameter space for dark matter interactions with familiar matter, irrespective of its cosmological origin, including dark matter much lighter than the electron. In the following, we summarize the key capabilities of each technique and their general beam and detector requirements, with examples of DOE facilities that would enable them.

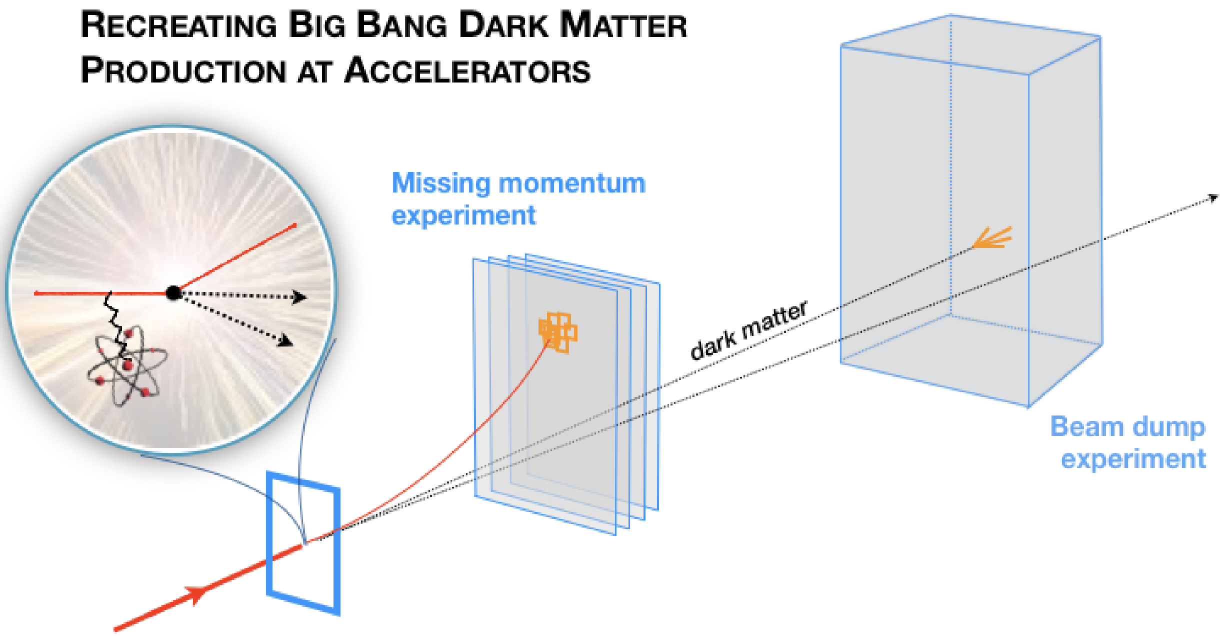


Figure 2-3: *A schematic of accelerator-based techniques which probe Big Bang dark matter production.*

Missing momentum experiments (see Figure 2-3, center) in a continuous-wave electron beam offer a path to achieving a full 1000-fold or better improvement compared with existing sensitivity over a broad range of dark matter masses. These high-rate, single-particle measurements capitalize on precise and modern fast-response and radiation-tolerant detector technologies. Moreover, they can use kinematic techniques to measure dark matter mass and interaction properties in the event of a discovery. Multi-GeV continuous-wave electron beams are necessary to enable electron missing-momentum experiments. DOE facilities providing such beams include SLAC (LCLS-II) and Jefferson Laboratory (CEBAF). Concepts for LCLS-II operation would parasitically extract a low-current electron beam in parallel with light source operation, while concepts for CEBAF operation would involve dedicated beam time in one of Jefferson Laboratory's experimental halls. A new dedicated detector operating on a muon beamline delivering O(10^7) muons per minute could be developed, for example, by upgrading a secondary muon beamline. With this beamline, FNAL could perform missing momentum searches similar to those utilizing electron beams, perhaps with the same type of detector. Although further studies are still needed, these experiments may reach 10-to-100-fold sensitivity gains over existing experiments for dark matter heavier than the muon and can also uniquely test the interaction between dark matter and muons.

Beam dump experiments (Figure 2-3, right) using existing electron or proton beams are capable of at least 10-fold sensitivity improvements over previous experiments. Additional measurements of the properties of dark matter can be performed in the event of a discovery. Electron beam-dump experiments rely on high-intensity electron beams. Parasitic use can be made of high-intensity electron beams, such as those delivered by CEBAF or LCLS-II, by placing a detector in a new experimental hall built downstream of their beam dumps. Proton beam dumps offer comparable reach, with unique sensitivity to nucleon couplings, and can be realized at several facilities. Existing infrastructure can be exploited in various ways: for example, by steering the FNAL Booster Neutrino Beam (BNB) proton beam into an upgraded beam dump and looking for dark matter scattering in existing neutrino detectors, or by operating new coherent neutrino-nucleus scattering detectors during routine operations of intense low-energy proton stopped pion sources, such as SNS or LANSCE. These approaches can expand the dark matter search sensitivity below the proton mass. Placing a new and improved detector on a high-energy proton beamline, such as the Fermilab's Main Injector 120 GeV (1.2 x 10^{11} eV) beamline, would extend sensitivity to higher mass.

Thrust 2 (near term and long term): Explore the structure of the dark sector by producing and detecting unstable dark particles.

Accelerator-based experiments are the only type of experiment capable of producing not only dark matter, but other related particles (the "dark sector"). The latter class of particles can be detected through their decays into ordinary matter. Two key examples are decays of (i) a new force carrier into two particles of visible matter and (ii) additional particles charged under these forces into a dark matter particle accompanied by familiar particles. The second signal is illustrated in Figure 2-4.

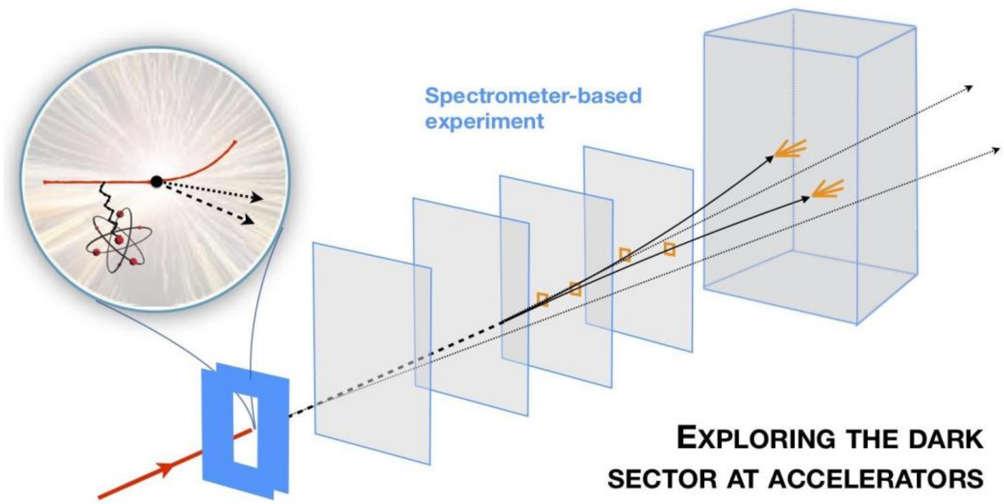


Figure 2-4: *Schematic of accelerator-based techniques that can explore the structure of the dark sector using spectrometer-based experiments.*

The decays of unstable dark sector particles may produce detectable signals in the beam dump or missing momentum experiments motivated by Thrust 1. For example, semi-visible excited states of dark matter may be sufficiently long-lived that their decays are seen in a beam dump experiment, while late decays of force carriers may occur in the detector volume of a missing momentum experiment. These dual capabilities underscore the inherently multi-purpose nature of these experimental concepts, the full capabilities of which are a subject of ongoing research.

In addition, the requirement of a dark sector motivates spectrometer-based experiments more directly tailored to searching for unstable dark sector particles. These experiments aim to identify and measure the visible products of a dark sector particle's decay – typically with much shorter baselines than beam dump experiments and with access to much more complete kinematic data. So far, spectrometer-based experiments have been performed with the CEBAF continuous-wave electron beam. A new opportunity in dark sector searches is the use of a spectrometer immediately behind a proton beam dump. High-energy proton beams can produce three to four orders of magnitude larger samples of dark particles than electron beams of comparable luminosity, and have unique kinematic access to heavier states. This concept for a proton beam dump spectrometer can be realized as an upgrade to the existing fixed-target program at Fermilab's Main Injector 120 GeV (1.2 x 10^{11} eV) beamline. This approach offers unique potential sensitivity to a range of well-motivated dark sector theories, including models of secluded, excited, and strongly interacting dark matter, which feature consistent and testable cosmological histories.

Most research to date has focused on dark matter coupled to electric charge, which offers both predictive milestones and a rich array of experimental opportunities. Dark matter that couples through neutrinos or Higgs particles presents a comparably exciting opportunity for future searches, which is presently less developed. Our best sensitivity to date to these models, in the sub-proton mass range, comes from past accelerator-based experiments that were not even motivated by dark matter. Given significant advances in accelerator and detector technology since these experiments were performed, there are likely inspiring opportunities for considerable improvement over these results. Continued R&D in both theory and experiment is essential to realize this potential.

Impact

The PRD described above capitalizes on the unique capabilities of the existing HEP accelerator dark matter program to simultaneously reach important milestones for thermal dark matter and perform a broad exploration of the dark sector. The power of the PRD to explore interaction strengths singled out by thermal dark matter is illustrated in Figure 2-2 (left). The green shaded area represents interaction strengths consistent with thermal dark-matter milestones. Missing momentum (red) and beam dump (blue) measurements can provide the sensitivity needed to discover or largely rule out the simple thermal dark-matter scenarios over the entire electron-to-proton mass range. Such techniques also provide powerful sensitivity to dark matter below the mass of the electron. In Figure 2-2 (right), we illustrate a scenario which explores the structure of the dark sector by producing and detecting unstable dark particles in missing momentum experiments (red), high-energy proton beam dump experiments (blue), or spectrometer-based experiments (orange). As discussed in a panel report (Chapter 3), spectrometer-based experiments play a key role in exploring this parameter space and unraveling the structure of the dark sector.

Beyond discovery, the controllable and tunable environment of accelerator-based experiments offers ample opportunities to corroborate a promising dark matter signal and understand its physical origin. A combination of measurements would enable determination of the dark matter mass, its spin, the physics of its interaction mediator, and the spectroscopy of the dark matter sector – launching an era of precision dark-matter particle science.

PRD 2: Detect galactic dark matter particles below the proton mass through interactions with advanced, ultra-sensitive detectors

Direct detection experiments search for galactic dark matter particles interacting with a target material, which is typically placed deep underground to avoid cosmic-ray background radiation. This interaction can lead to various types of small signals, including phonons, charge, and light (Figure 2-5), which can be detected with advanced sensors. Direct detection plays a unique and essential role in our quest to identify the dark matter since the discovery of a new particle at an underground direct detection experiment would be direct evidence that such a particle constitutes all (or at least part of) the dark matter.

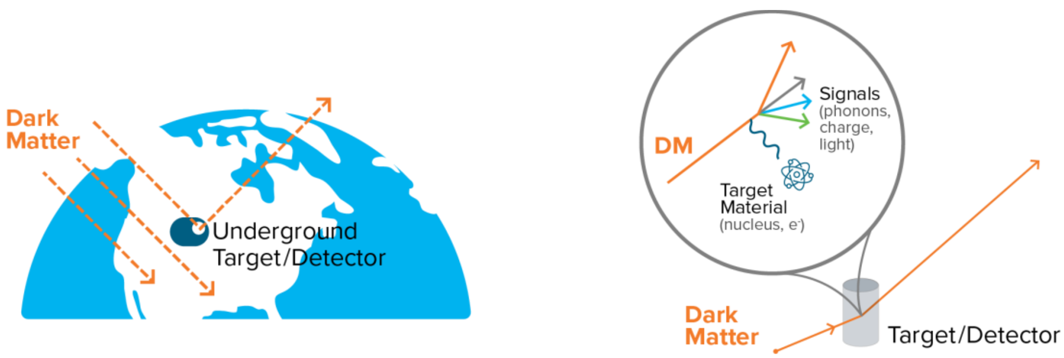


Figure 2-5: *Galactic dark matter particles interact with nuclei and electrons inside a target material. This produces small signals, including phonons, charge, and light, which are sensed with advanced detectors.*

Science Opportunities

Recent advances in theory and sensor technology allow new targeted investments to bring to fruition several recent direct detection ideas, developing them into small projects that utilize existing DOE laboratories, infrastructure, and personnel, including underground facilities. Six orders of magnitude in dark matter mass (three orders of magnitude -- MeV to GeV -- through scattering, and another three -- eV to keV -- in absorption) are immediately accessible over the next few years, with just a few small projects that probe different dark matter interactions with nuclei and electrons. Dark matter candidates in this mass range, well-motivated by theoretical and observational considerations, could be discovered with the first generation of experiments. In addition, R&D on promising technologies could lead to experiments that can probe an additional six orders of magnitude in even smaller dark matter mass (three orders of magnitude – 1 keV (10^3 eV) to 1 eV -- through scattering and another three – 1 meV (10^{-3} eV) to 1 eV -- in absorption). As shown in Figure 2-6, this PRD would allow theoretically motivated dark matter candidates to be probed across 12 orders of magnitude in mass --- between 1 meV (10^{-3} eV) and 1 GeV (10^9 eV) --- many orders of magnitude lower in mass than the G2 experiments (LZ and SuperCDMS).

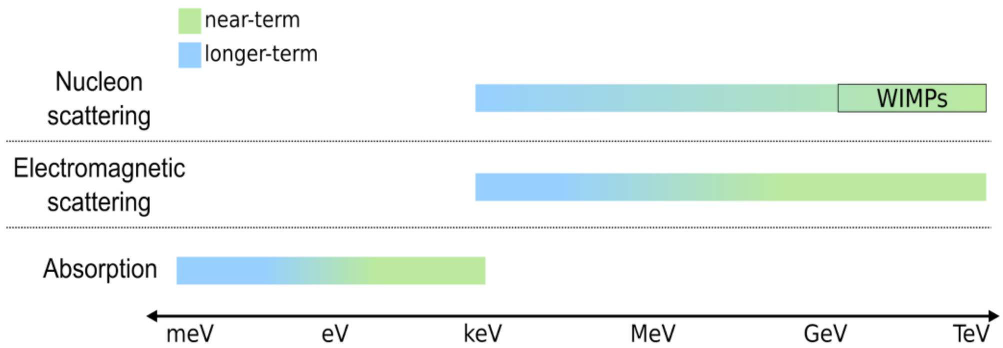


Figure 2-6: *Mass range probed for dark matter particles that scatter off nuclei, electrons, or collective excitations (1 keV to 1 GeV) and that are absorbed by nuclei, electrons, or collective excitations (1 meV to 1 keV). These masses are below those typically expected for WIMPs. Near-term experiments using existing advanced technologies can probe the mass range in green, while R&D on promising technologies can lead to experiments that can probe the extended mass range in blue.*

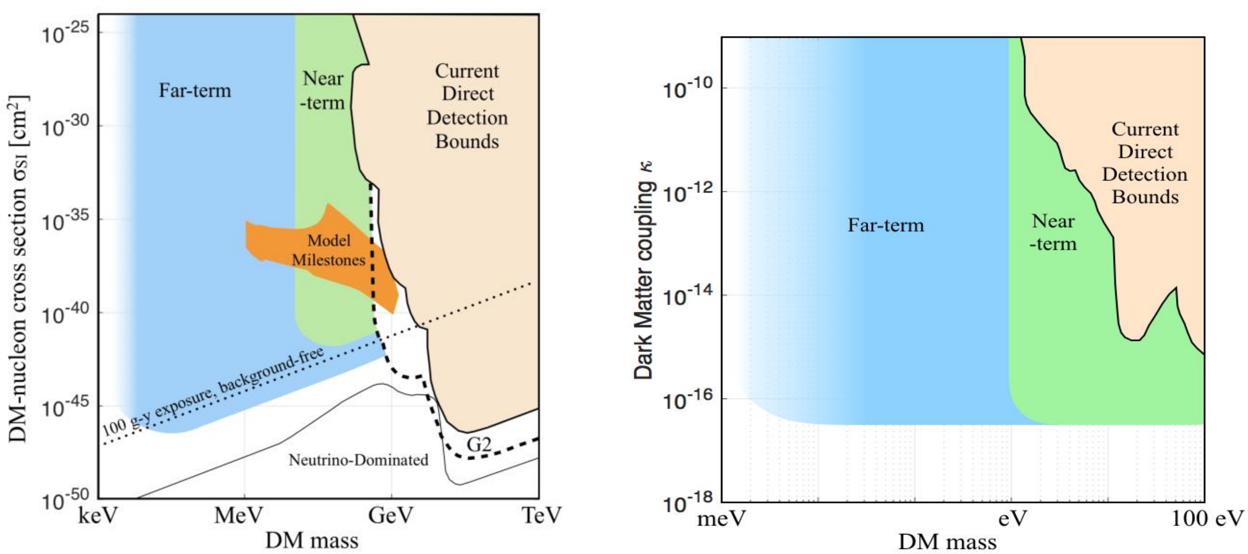


Figure 2-7: *Left: Parameter space for galactic dark matter (DM) scattering off nuclei that can be probed with advanced detectors with demonstrated technologies (green region) and additional R&D (blue region). The G2 direct detection program probes a complementary higher mass region (dashed line) that extends below the constraints of existing direct detection experiments (peach region). Neutrinos begin to dominate the rate below the solid black line. A modest exposure of 100 g per year can probe extremely low cross sections as long as the detector has the requisite energy sensitivity and sufficiently low backgrounds (dotted line). The orange region (labelled "Model Milestones") presents an example in which dark matter attains the observed relic abundance from its thermal contact with the Standard Model particles. Right: Parameter space for galactic dark-photon dark matter being absorbed by electrons or other excitations that can be probed with advanced detectors with demonstrated technologies (green region) and additional R&D (blue region). Existing constraints from past direct detection experiments are shown in peach.*

Direct detection also provides a unique opportunity, relative to higher energy probes, to explore dark matter candidates when the mass of the particle mediating the interaction is relatively light (lighter than the momentum transfer from the dark matter to the target particle). In this case, the scattering rate scales inversely as the fourth power of the momentum transfer, allowing for an enormous enhancement in the scattering rate for low-threshold probes like direct detection experiments.

With the realization that the dark matter sector may be disconnected from the visible one, communicating only through new forces, the dark matter theory landscape has evolved in new directions in the last decade, emphasizing the need to probe non-WIMP dark matter candidates with a mass below about 1 GeV (10^9 eV). Several concrete benchmark models, created in the new theory panorama and shown in Figures 2-7 and 2-8, exist in which the dark matter abundance is related to its coupling to ordinary matter via this dark force. These models provide guidance and sharp targets in parameter space for direct detection experiments, which in some cases, can be probed by first-generation, low-cost experiments with target exposures of as little as 1 gram per day.

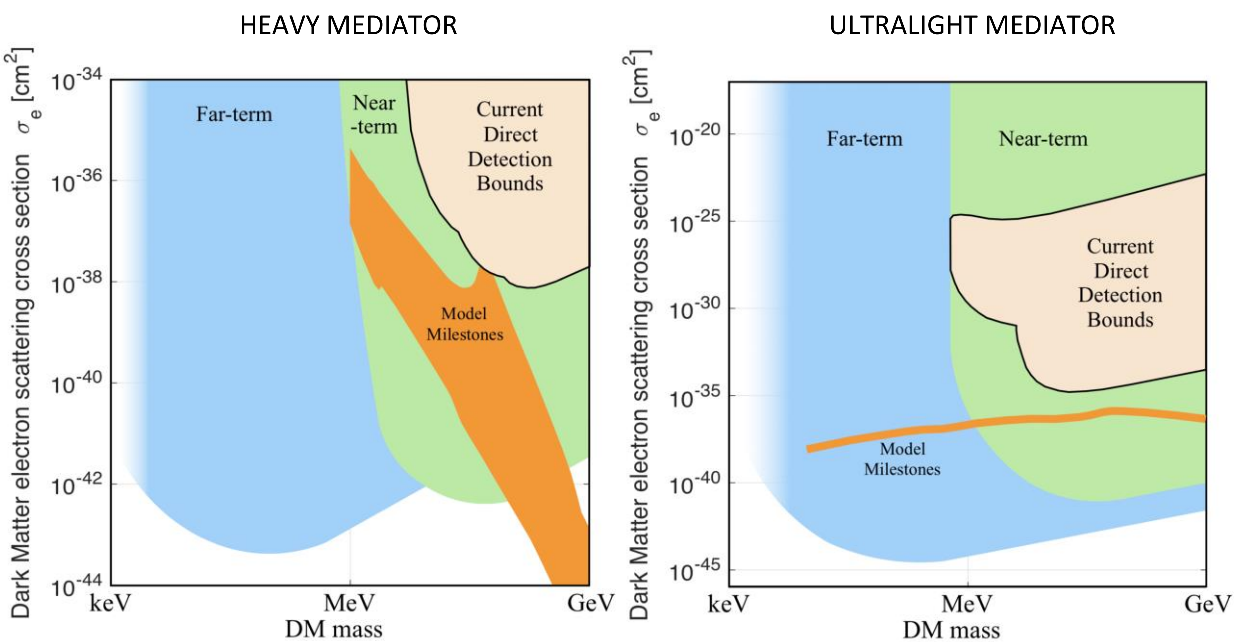


Figure 2-8: *Parameter space for galactic dark matter scattering off electrons, which can be probed by advanced detectors with demonstrated technologies (green region) and additional R&D (blue region), for a mediator with a mass that is heavy (left plot) or ultralight (right plot). Constraints of existing direct detection experiments are shown in peach. The orange regions (labelled "Model Milestones") present a range of model examples in which dark matter attains the observed relic abundance from its thermal contact with Standard Model particles (regions are as in the "US Cosmic Visions" report). In the right plot, the upper green region is currently unconstrained, assuming the dark matter is a subdominant component.*

Beyond the known sharp theory targets, new direct detection experiments can probe orders of magnitude of dark matter parameter space that is well-motivated but does not have a sharp target. This space includes the scenario in which dark matter attains its abundance by annihilating into a hidden sector. It includes proposed dark matter candidates that are force carriers analogous to the ordinary photon, such as axion-like particles and dark-photon dark matter. While there are many candidates proposed by theory, a given experiment often probes multiple candidates simultaneously, since many produce similar signals. Continued development of theory, both to propose and vet new models, as well as to develop novel detection concepts (in collaboration with different branches of physics, including condensed matter physics and atomic, molecular, and orbital physics), is essential for the healthy development of the field.

We emphasize that the range of possible models is large and encourage exploration of the parameter space to very low interaction strengths, at least to where solar neutrinos become a dominant background. In addition, sharp theory targets exist in which dark matter interacts only with baryons or only with leptons, emphasizing the need for experiments that probe dark matter couplings to electrons *and* experiments that probe dark matter couplings to nuclei. We now discuss the thrusts aligned with these goals.

Research Thrusts

Thrust 1: Probe dark matter interactions with nuclei, as motivated by theoretical ideas for the nature of light dark matter, including its possible thermal and non-thermal origins.

The current suite of direct detection experiments, collectively known as the G2 program, will radically advance our capabilities of searching for dark matter depositing small amounts of energy on nuclei in a large volume detector. These experiments, focused on high mass WIMPs, are complementary to the probes described here, which can search for much lighter dark matter. These new experiments, however, can leverage many of the techniques developed through existing direct detection experiments, such as improvements in backgrounds and calorimetry. They go beyond the G2 experiments by exploring new technologies, new target materials, and new ideas for detection. More precisely, dark matter in the few-MeV (10^6 eV) to GeV (10^9 eV) range, depending on the target nuclei, will interact with individual nuclei, while dark matter with mass as small as a keV (10^3 eV) can be detected by scattering from the coherent modes of multiple atoms. Suitable target materials include noble liquids, semiconductor or scintillating crystals, gaseous detectors, superfluid helium, superheated fluids, supercooled fluids, molecules, and others. Signals include charge, light, phonons, or sudden phase transitions. Several near-, medium-, and longer-term opportunities exist. Some technologies may see rapid improvements, so the time distinction below is only a best guess.

Near-term opportunities: 50 MeV to 1 GeV (scattering)

Recently demonstrated calorimeter technology can detect phonons or photons of total energy approximately 1 eV. This has resulted from ongoing efforts by the experimental community to reduce energy thresholds, and now enables the search for nuclear recoils from dark matter with mass as low as about 50 MeV (5 x 10^7 eV), with factors of 10^6 improvement in cross-section sensitivity. Possible target materials include semiconductors, superfluids, and scintillating crystals.

Nuclear recoils in noble-liquid and gaseous detectors can produce charge and light, and these technologies have also advanced significantly in recent years. Short-term R&D on reducing detector backgrounds and on improving understanding of the ionization efficiency from low-energy nuclear recoils could allow these detectors to be sensitive to sub-GeV (less than 10^9 eV) dark matter interacting with nuclei.

Dark matter interacting with superheated or supercooled fluids can induce sudden phase transitions. R&D is needed to determine the precise energy threshold — hence, mass threshold — but this method may allow searches for dark matter with 100 MeV (10^8 eV) to 1 GeV (10^9 eV) masses.

Medium-to-longer-term opportunities: 1 keV to 50 MeV (scattering), 1 meV to 20 eV (absorption)

Improving the sensitivity of phonon or photon detectors to sub-eV energy depositions will allow dark matter with mass below 50 MeV (5 x 10^7 eV) to be probed. This can be achieved by searching for novel signals that allow dark matter to deposit its *entire* kinetic energy into the material, which for low-mass dark matter is significantly larger than the energy transferred to a nucleus in an elastic collision: for example, 1 MeV (10^6 eV) dark matter has a kinetic energy of about 1 eV, but induces only a about a 1 meV (10^{-3} eV) nuclear recoil. Sub-MeV (less than 10^6 eV) dark matter, whose de Broglie wavelength is larger than the interparticle spacing in a solid or liquid, can create collective disturbances (phonons) in the target. Particularly promising is the creation of optical phonons in materials like sapphire, GaAs, or diamond, while another possibility is to create two nearly back-to-back zero-gap (acoustic) excitations, as occur in superfluid helium or crystals. In a molecular gas, dark matter with interactions that are spin independent or dependent can excite O(250 meV) vibrational modes, which de-excite by emitting photons. These various searches require phonon or photon detectors with sensitivity in the 0.1-0.25 eV scale (i.e., able to probe down to 10^4–10^5 eV dark matter masses or even better to lower masses). Improved phonon or photon detectors will also allow sensitivity to the absorption of dark matter below 20 eV, and in principle as low as about 1 meV (10^{-3} eV). Photons can be produced by dark matter absorption in an optical haloscope or a molecular gas, and phonons can be produced in crystals.

Thrust 2: Probe dark matter interactions with electrons, as motivated by theoretical ideas for the nature of light dark matter, including its possible thermal and non-thermal origins.

A promising technique to search for sub-GeV (less than 10^9 eV) dark matter particles is to look for their interactions with electrons. In particular, dark matter that scatters off electrons can deposit its entire kinetic energy and excite one or a few electrons from their ground state to an excited state. Depending on the material and detector setup, recent technological advances allow us to measure these excited electrons either directly or through the secondary signals they produce (such as light). Suitable target materials for electron recoils include noble liquids (e.g., xenon, argon), gases (e.g., neon, helium), semiconductors and scintillators (e.g., silicon, germanium, gallium-arsenide, sodium-iodide, and cesium-iodide), superconductors, two-dimensional materials (e.g., graphene), and Dirac or Weyl materials. As the case for Thrust 1, several near-, medium-, and longer-term opportunities exist, and the time distinction below is only a best guess.

Near-term opportunities: 1 MeV to 1 GeV (scattering), 1 eV to 1 keV (absorption)

Recently demonstrated technology can detect 1 eV energy depositions from an electron excitation. This now enables the search for dark matter-electron scattering down to about 1 MeV (10^6 eV) with factors of 10^6 improvement in cross-section sensitivity, as well as the absorption of dark matter by electrons down to 1 eV. Possible target materials include semiconductors and scintillators. Additionally, noble liquid and gaseous targets have single-electron sensitivity, but are currently limited by detector backgrounds. Ongoing R&D programs will substantially reduce these backgrounds and increase their current sensitivity by many orders of magnitude.

Longer-term opportunities: 1 keV to 1 MeV (scattering), 1 meV to 1 eV (absorption)

The typical band gap of semiconductors is above the kinetic energy and rest mass energy of dark matter with mass less than about 1 MeV (10^6 eV) and 1 eV, respectively, so that other materials need to be used. Dark matter scattering off electrons in superconductors can break their Cooper pairs into quasiparticles; the phonons generated from quasiparticle decay can then potentially be detected with ultrasensitive phonon detectors. The investigation of other small gap materials (like Dirac materials) offers another direction for R&D. Electromagnetic couplings to electrons also allow excitation of optical phonons, or multiple phonons, with potential sensitivity to dark matter scattering down to keV (10^3 eV) masses. Dark matter with sub-eV masses could be absorbed by an electron recoiling off a phonon (as in a superconductor) or multiple phonons (as in a semiconductor), or through an excitation of an optical phonon. Research and development is required in all cases to improve the energy resolution of sensors to the meV (10^{-3} eV) scale.

Impact

The current suite of experiments searching for the WIMP (collectively known as the G2 program) focuses on dark matter with mass above 1 GeV (10^9 eV). Because of the focus on the WIMP paradigm, dark matter hunters have had a blind spot to searching for lighter dark matter, even though theoretically light dark matter is a compelling paradigm arising naturally from theories with a hidden sector. This PRD addresses this issue by reaching twelve new orders of magnitude in mass – six reached through particle scattering and another six reached (without additional cost) through mass absorption. Half of this parameter space in mass can be accessed with existing technology, with the other half requiring R&D. Many different kinds of theories can be simultaneously constrained (because of similar signals), and compelling dark matter candidates can be observed with detectors a small fraction of the size of the current G2 detectors. Note that we are able to leverage the enormous progress in detector development, which has extended the sensitivity to small energy deposits. Extremely sensitive quantum sensors created through this process will also have application in other areas of physics, such as neutrino experiments and astronomy. These sensors include charge coupled devices with extremely low dark current, as well as calorimetric detectors with 100% quantum efficiency and excellent energy resolution for individual visible and infrared photons. If this program is carried out successfully over the next five or more years, we will have learned an enormous amount about the nature of the hidden sector comprising the dark matter, the start of a new field of physics.

PRD 3: Detect galactic dark matter waves using advanced, ultra-sensitive detectors with emphasis on the strongly motivated QCD axion.

The detection of wave-like dark matter offers unique opportunities to probe ultra-high energy physics and the cosmology of the early universe. Many of the theoretical structures that produce these particles emerge from physics at ultra-high energies such as the scales of grand unification and quantum gravity. Measurements of the interactions between the dark matter and the particles of the Standard Model could offer unique insights into these fundamental scales that cannot be directly accessed through other techniques.

Science Opportunities

Our knowledge of dark matter and its role in the evolution of the universe continues to grow. Recent theoretical developments indicate the possibility of very light dark matter particles that interact more like waves. These types of particles are produced in abundance in high level unification theories like string theory. Improvements in our understanding of cosmology, especially the period of inflation, show these very light particles to be excellent dark matter candidates. The techniques required to search for these very light particles are different from those for previous dark matter searches and rely heavily on advances in quantum sensing. The intersection of these theoretical and technical advances clears the path for great discoveries and motivates the need or a new program to search for these particles.

The QCD axion is one of the dark matter candidates whose existence is most highly motivated by theory. It is independently a possible solution to outstanding problems of particle physics, including the strong CP problem (related to symmetry breaking in QCD theory) and the hierarchy problem (related to the vast difference in the strength of gravity compared with the non-gravitational forces). It generically arises in many frameworks of physics theories beyond the Standard Model, such as grand unified and string theories. If the QCD axion exists, it is expected to be all or at least a significant fraction of the dark matter. Recent theoretical advances have significantly expanded the phenomenology of the QCD axion, resulting in the realization that QCD axion dark matter can exist over a wide range of masses from 100 Hz to 1 THz (roughly 10^{-12} eV to 10^{-3} eV).

The same frameworks that yield the QCD axion also generically lead to new ultralight particles, such as more general axions and hidden photons spanning an even broader mass range from 10 nHz to 1000 THz (roughly 10^{-24} eV to 1 eV), all of which is potentially accessible via wave detection techniques. Theoretical insights have also identified cosmological production mechanisms, naturally allowing such particles to be the dark matter of the universe. There is thus a compelling scientific case to probe dark matter in this mass range.

Since many of the simplest production mechanisms for wave-like dark matter involve cosmic inflation, their detection could also offer a unique window into this inflation, potentially even permitting a determination of the Hubble scale of inflation (its duration and spatial dimensions). This knowledge could be of substantial interest to subsequent measurements of the properties of the cosmic microwave background. In addition to the information gained by a discovery of wave-like dark matter, it is important to note that the lack of discoveries in this mass range also has important theoretical consequences. For example, since the QCD axion is independently motivated and is expected to be the dark matter in a number of cosmological scenarios, negative results from direct searches for it will be of significant consequence to both particle physics and cosmology.

At the same time as new theoretical breakthroughs have motivated new searches for wave-like dark matter, a revolution in the theory and tools of quantum information sciences has produced sensitive measurement techniques that will enable these searches. The signal from the dark matter waves can be coherently accumulated in various types of laboratory oscillators (atoms, cavities, and lumped-element circuits). In contrast to traditional HEP techniques to detect the impulse from scattering of individual dark matter particles, the wave detectors are driven by the collective force from macroscopic numbers of dark matter particles. Minimizing the backgrounds in this narrow-band detection then requires cryogenics and quantum sensor technologies to reduce readout noise to an unprecedented low level, quantum zero-point fluctuations or below. New quantum sensors, for the first time, allow measurements to be made near the intrinsic noise limits imposed by the Heisenberg uncertainty principle, thus accelerating searches for wave-like dark matter. This leverage works both ways: bringing the unique resources and expertise of the HEP community to bear on the development of quantum sensors will lead to rapid advances in this technology, which will surely benefit the quantum information science community.

The precision technologies developed to search for wave-like dark matter will advance several additional scientific goals, including the measurement of the properties of the dark energy that has been driving an accelerated expansion of the universe for the last roughly 5 billion years. These measurements are currently pursued through the gravitational effects of the dark energy on the expansion of the universe. If the dark energy is not simply a cosmological constant and instead evolves in time, it must be related to a particle with an ultra-low mass. Such a particle may interact with the Standard Model particles through non-gravitational interactions, leading to the exciting possibility that the dark energy could be detected through its non-gravitational effects in laboratory experiments. Experimental methods to search for ultra-light dark matter are ideally suited to probe these interactions. Precision technologies have already played a key role in the discovery of gravitational waves. Advancements made to search for wave-like dark matter could also allow fundamentally new gravitational wave detectors, enabling searches in frequency bands which are the most promising for observing gravitational waves from cosmic inflation. In addition to signals from the cosmos, these technologies can also significantly extend laboratory searches for new fundamental forces. Practical applications of these technologies include geological mapping, precision navigation, and the detection of electromagnetic and mass anomalies that are of interest to homeland security.

The QCD axion and the WIMP are the most promising dark matter candidates, so covering the QCD axion line is the most important scientific target in the ultralight mass range. Additionally, general axion-like particles (“general axions”) and hidden photons are well-motivated dark matter candidates, so it is important to broadly cover the mass range for ultralight dark matter.

Research Thrusts

The highest priority for near-term, small-scale DOE projects in ultralight dark matter is Thrust 1. Its aim is to search for ultralight dark matter in the mass range of 100 Hz to 10 GHz (roughly 10^{-12} eV to 10^{-4} eV), with the strongest emphasis on covering as much of the QCD axion line as possible (Figure 2-9). This priority arises from combining both scientific motivation and technical readiness. In Thrust 2, the mass range will be extended to span from 10 nHz to 1000 THz (roughly 10^{-24} eV to 1 eV), over 20 orders of magnitude.

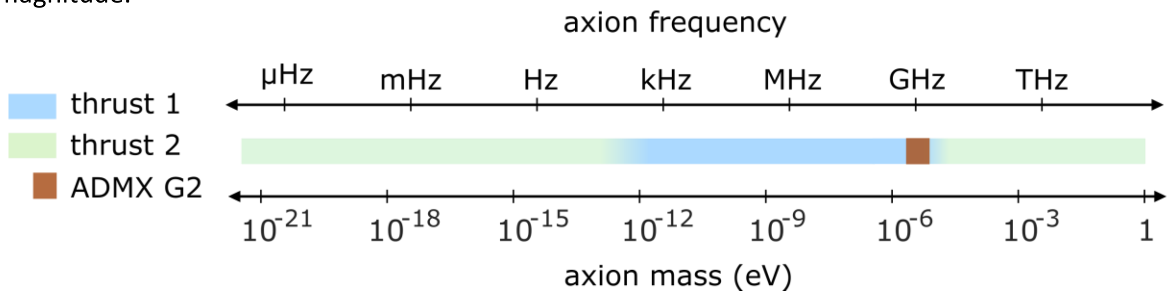


Figure 2-9: *General axion mass (frequency) parameter space showing (i) the region that has highest priority for this BRN (Thrust 1), because it combines the highest priority science of the QCD axion with techniques that are ready to scale up to full small-scale projects, and (ii) the full mass range that can be covered in the future after technology development (Thrust 2).*

Three techniques are currently capable of covering important amounts of the parameter space in Figure 2-9: magnetic resonance, lumped-element electromagnetic resonators, and microwave cavities. Figure 2-10 shows the axion coupling strength and mass for the three techniques relative to our science goals. As described in Thrust 2, it is also important to continue development of promising new technologies to access the remaining QCD axion parameter space as well as that of more general wave-like dark matter models. In particular, the QCD axion parameter space in Thrust 2 – QCD axion frequencies above 10 GHz (10^{-4} eV) – is scientifically as high a priority as the lower mass QCD axion parameter space; however, the experimental techniques for addressing this priority are not ready to be part of DOE small-scale projects as defined in this BRN, so projects in the Thrust 1 mass range are the higher priority for this report.

The three experimental techniques in Thrust 1 are sufficiently demonstrated to be ready to be turned into projects, that is, projects in which at least some demonstration detector has been built (or a full detector), data have been taken, and experimental limits on ultralight dark matter have already been demonstrated. For example, at the BRN Workshop, the ultralight dark matter limits were reported for

- the microwave cavity technique by collaborations from the ADMX (Axion Dark Matter Experiment)[10] and HAYSTAC (Haloscope At Yale Sensitive To Axion Cold dark matter) experiment,[11]

- the lumped-element electromagnetic resonator technique by collaborations from the ABRACADABRA (A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus)[12] and the Dark Matter Radio experiment, and

- the magnetic resonance technique by the CASPEr (The Cosmic Axion Spin Precession Experiment) collaboration.

All the techniques discussed for small-scale projects will rely crucially on DOE resources. Their overall size and scope means that they will necessarily need the infrastructure available at the national

[10] N. Du et al., Phys. Rev. Lett. 120 (2018) 15130.
[11] L. Zhong et al., Phys. Rev. D 97 (2018) 092001.
[12] J. L. Ouellet et al., arXiv:1810.12257 [hep-ex] (2018).

laboratories. These are experiments requiring extraordinary precision. As they grow in scale, achieving the substantial infrastructure without relaxing tolerances requires engineering and technical support available at the national laboratories. Additionally, DOE has the resources needed to manage projects of this scale, which are not generally resident in academic institutions.

In addition to general technical support in design, engineering, and integration on this scale, these experiments require the specific capabilities of the DOE laboratories in particular areas. One key example is the area of magnet design and development. QCD axion searches require large-volume, high-field superconducting magnets with unusual geometries (e.g., solenoidal toroids). This task is generally beyond capabilities in academia, but align well to DOE laboratories' expertise and infrastructure. The DOE also has unique expertise in the superconducting devices required to instrument these searches and in large-scale cryogenic infrastructure. Of particular note is the quantum sensor technology under development at DOE laboratories, which will allow measurement of signals better than the quantum limit. The DOE also has unique expertise in constructing large (approximately a kilometer) vacuum systems and access to deep vertical facilities at places such as Fermilab and the Sanford Underground Research Laboratory, which will be necessary for use of an atom interferometry-based detector. The integration of all these systems will push the bounds of what is achievable. The DOE laboratory resources make these experiments possible.

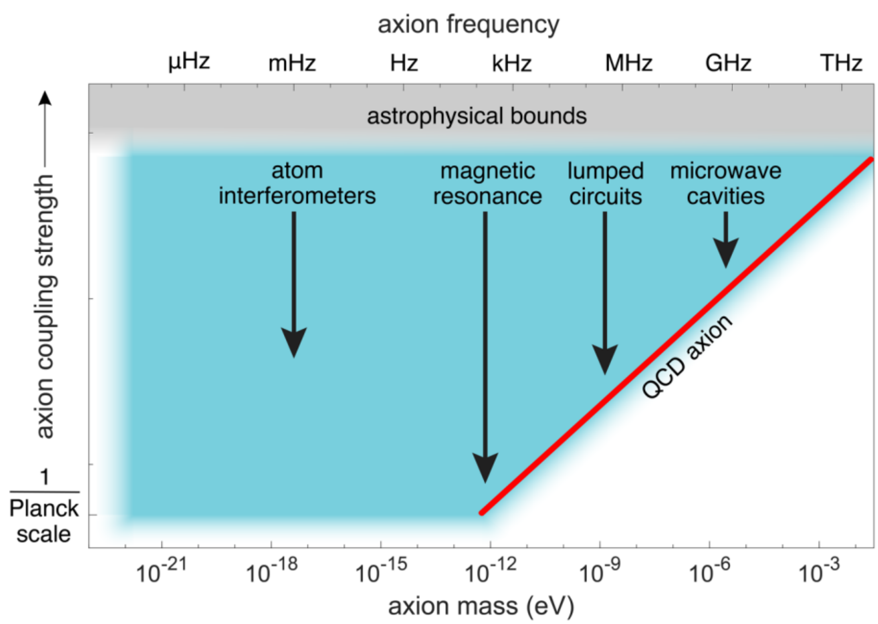


Figure 2-10: *Cartoon figure roughly representing the science goal for axion dark matter relative to various detection methods. The science goal for general axion dark matter is shown by region shaded in blue. The highest priority target line of the QCD axion is shown in red line. Current bounds set by astrophysical constraints are shown approximately by region in grey.*

Thrust 1: Utilize new detector technologies to explore large parts of dark matter parameter space covering a broad range of mass from 100 Hz to 10 GHz (roughly 10^{-12} eV to 10^{-4} eV) and targeting sensitivity to the QCD axion where possible.

Large amounts of parameter space for general axions and hidden photons can be covered over the frequency range 100 Hz to 10 GHz (roughly 10^{-12} eV to 10^{-4} eV). Importantly, this frequency range includes the QCD axion target. Most importantly, it is possible to reach all the way down to explore significant fractions of the QCD axion parameter space in this range.

The existing ADMX G2 experiment will cover the mass range 0.65 GHz to 2 GHz (2.7 x 10^{-6} eV to 8.3 x 10^{-6} eV) for general axions, hidden photons, and the QCD axion (Figure 2-11). The rest of the mass range, 100 Hz to 10 GHz (roughly 10^{-12} eV to 10^{-4} eV), is essentially unconstrained currently by any laboratory experiment. The only current bounds on couplings to known particles arise from astrophysics and are orders of magnitude above the QCD axion target.

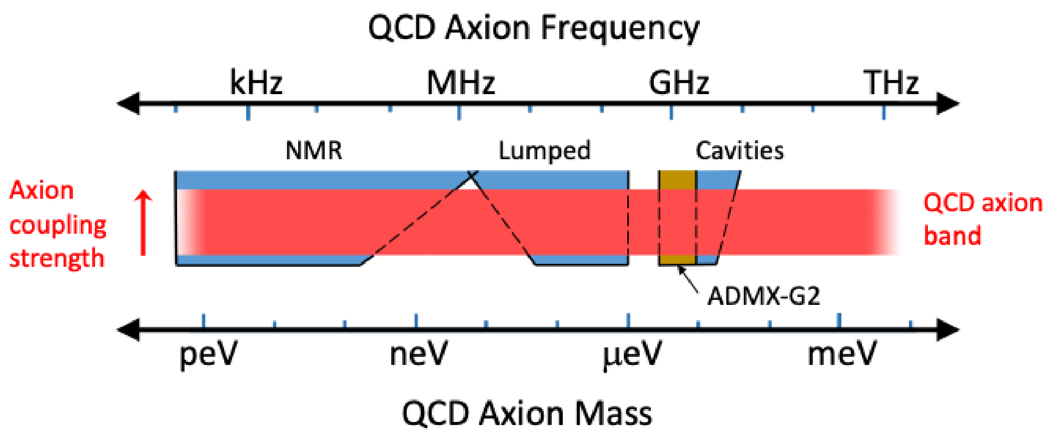


Figure 2-11: *Specific parameter space for the QCD axion band relative to three detection methods: nuclear magnetic resonance (NMR), lumped element, and microwave cavities (unlike Figure 2-10, which is for general ultralight dark matter and, therefore, has a significantly wider mass range).*

This frequency range can be probed using three separate couplings of the axion or hidden photon: QCD, electromagnetism, and spin, as shown in Table 2-2. Using these different couplings leads to complementary approaches and allows coverage of the maximal amount of this parameter space. For the QCD axion, using these couplings allows exploration of highly complementary mass ranges, as in Figure 2-10. The electromagnetic coupling allows exploration of the higher frequency QCD axions, while the QCD coupling allows exploration of the lower frequencies, as indicated in Table 2-2. Only by using both the QCD and electromagnetic couplings can we hope to cover most of the QCD axion parameter space.

Table 2-2: *Mass (frequency) ranges covered by Thrust 1 experimental techniques for both QCD axion and general ultralight dark matter. Also shown is the type of coupling of the dark matter to the detector that each technique relies on. Generally, the coupling to the nucleus via the strong force (QCD) or nuclear spin allows searches at lower frequencies while the coupling to electromagnetism allows searches at higher frequencies.*

Experimental Technique	QCD Axion Range accessible	General axion and hidden photon range	Coupling
Magnetic Resonance	100 Hz – 1 MHz (10^2 Hz – 10^6 Hz)	100 Hz – 100 MHz (10^2 Hz – 10^8 Hz)	QCD & spin
Lumped Element	3 MHz – 300 MHz ($3x10^6$ Hz – $3x10^8$ Hz)	100 Hz – 300 MHz (10^2 Hz – $3x10^8$ Hz)	Electromagnetism
Microwave Cavities	500 MHz – 4 GHz ($5x10^8$ Hz – $4x10^9$ Hz)	500 MHz – 10 GHz ($5x10^8$ Hz – 10^{10} Hz)	Electromagnetism

These three couplings combined with the three techniques are highly complementary for general axions and hidden photons in this frequency range as well. For general axions and hidden photons the accessible frequency ranges of the magnetic resonance and lumped-element approaches become significantly larger than they were for the QCD axion (see Table 2.2). In addition, there is a significant region of parameter space where magnetic resonance overlaps lumped element and where it overlaps microwave cavities. Further, magnetic resonance can measure the nuclear spin coupling of general axions and hidden photons in addition to the QCD coupling, providing another way to search for such dark matter, and also a complementary piece of information in the event of a discovery.

A candidate axion signal found with one coupling can be followed up by a search for another coupling, even if that second search would not have been sensitive enough to detect that axion candidate without a specific target frequency. For example, a QCD axion detected with an electromagnetic resonator at 10 MHz (10^{-8} eV) could be followed up and verified with a magnetic resonance experiment. This is true because these are both resonant experiments performed over a given frequency space. The time spent in any particular frequency band is quite small. However, given a candidate axion signal, any of these resonant experiments can sit at that particular frequency for a much longer time, greatly increasing their coupling sensitivity.

The ability to verify a discovery with two different techniques is important because these techniques have very different systematics. The ability to measure multiple different couplings of the axion or hidden photon in the event of a discovery is also important. For example, in order to know if one has seen an actual QCD axion instead of a general axion, it is necessary to measure the QCD coupling. By measuring multiple couplings (all of which are expected to exist for the axion) we will learn about the fundamental laws of nature at the extremely high energy scales from which the axion arises. For this frequency range, the QCD axion would arise from scales between roughly 10^{12} GeV and the Planck scale of 10^{19} GeV. These energy scales are far beyond what will ever be possible to probe in a collider, so measuring properties of the axion would be one of the very few ways to ever learn about the physics at such scales.

Thrust 2: Develop or extend new detector technologies to enable experiments to cover the remaining parameter space for well-motivated dark matter models spanning roughly 20 orders of magnitude in mass and also targeting complete coverage of QCD axion models.

Experiments over the entire nearly 20 orders of magnitude of mass (Figures 2-10 and 2-11) require further technology development to achieve maximum impact. The goal of the dark matter community is complete coverage of the entire mass range of possible dark matter candidates. No stone should be left unturned. As detailed in Thrust 1, recent technological advances already enable large improvements in experimental sensitivity over a broad range of well-motivated dark matter models, but the long-term goal of the community is to perform an exhaustive search for dark matter, which can only be achieved with continued R&D of even more sensitive detection strategies and techniques. This R&D would open up currently inaccessible but important science targets, such as higher mass axions and dark photons with frequencies greater than about 10 GHz (10^{-4} eV), which can arise in models of high-scale cosmic inflation currently being probed by cosmic microwave background experiments.

As an example, one promising R&D direction is the development of quantum sensor technology to enable the search for dark matter waves. Future experiments will require larger scale deployment of quantum devices, including those which are able to measure better than the standard quantum limit using techniques such as squeezing, back-action evasion, photon counting, and the manipulation of entangled states. The appropriate quantum sensor technology depends on the frequency range and sensor technology. At lower frequencies, quantum sensors using atom interferometers can perform broadband searches for dark matter waves. Magnetic resonance techniques can be improved by using spin squeezing to improve sensitivity beyond the limit set by quantum spin-projection noise, and quantum sensors can improve on the superconducting quantum interference devices (SQUIDs) that are currently used to measure the spin signal. For lumped-element resonators below 300 MHz (10^{-8} eV), back-action evasion and squeezing can improve sensitivity and integration times beyond the standard quantum limit. Cavity searches in the few GHz range can be accelerated with squeezing, and the sensitivity of higher frequency cavities can be improved by using superconducting qubit-based photon sensors that count photons. Single-photon detectors based on Rydberg atoms and other devices can extend searches to higher frequencies. These and other sensor and detector R&D efforts have been funded by various sources, with recent grants awarded through the DOE Quantum Information Science Enabled Discovery program, Laboratory Directed R&D programs, the National Science Foundation, and private foundations. Synergies between the goals of the HEP and quantum information system fields are already yielding benefits for both.

Impact

This set of small-scale experiments for ultralight dark matter will lead to comprehensive coverage of the QCD axion (Figure 2-9), and even ultimately to experiments addressing the entire ultralight dark matter mass range, over 20 orders of magnitude in mass (Figures 2-10 and 2-11). The motivation for ultralight dark matter and the QCD axion in particular is so strong that even ruling out this possibility would have a significant impact on our understanding of fundamental physics. Of course, a discovery of ultralight dark matter would radically alter our picture of the universe by determining the nature of the dominant component of matter in the universe and adding a major missing piece to our knowledge of the fundamental laws of nature.

A series of successful tests has demonstrated that the technologies discussed above are ready to become full projects. Pushed by the strong motivation of discovering dark matter, these projects will also help drive the quantum technology for these sensors. Although developed for the search for dark matter, this quantum technology development will have important results for a wide variety of applications.

The detection of ultralight dark matter offers unique opportunities to probe ultra-high energy physics and the cosmology of the early universe. Many of the theoretical structures that produce these particles emerge from physics at ultra-high energies such as the scales of grand unification and quantum gravity (the Planck scale). Measurements of the interactions between the dark matter and the particles of the Standard Model could offer unique insights into these fundamental scales that cannot be directly accessed through any other techniques. A discovery in such an experiment thus teaches us about the physics of ultrahigh energy scales, far beyond those that can ever be created in a terrestrial experiment.

Additionally, a detection could also offer a unique window into cosmic inflation and the creation of the universe. Many of the simplest production mechanisms for axion and hidden photon dark matter involve cosmic inflation and are influenced by the physics of early universe cosmology. Thus, observing the abundance and properties of such dark matter will teach us about the earliest times in the universe, potentially even permitting a determination of the Hubble scale of inflation. This knowledge could also be of substantial interest to subsequent measurements of the cosmic microwave background.

3. CROSS-CUTTING SCIENCE AND SYNERGIES

Dark-Matter Discovery Case Studies

In this section, we explore three case studies which illustrate possible sets of observations which work together to elucidate the nature of dark matter. In each case, the point under study is built around positing a specific positive signal, though it should be understood that the specific chronology is not currently well-defined, and is laid out for illustrative purposes to simplify the narrative of how the three PRDs work together to form a coherent program. In many cases, these inputs would arise from experiments that may (and must) be performed simultaneously in order to uncover a full picture of the dark sector.

Case study #1

An experiment sensitive to dark-matter scattering with electrons observes a handful of events at eV recoil energies, consistent with a cross section for scattering or absorption of 10^{-37} *cm*^{2} [PRD 2].

From this observation, we learn that there is a component of the dark matter which interacts with electrons. Establishing that it makes up the bulk of the dark matter and determining its mass and its interactions with the rest of the Standard Model necessarily require input from additional experiments. Knowing that dark matter interacts with electrons, we expect to be able to produce it at electron-beam accelerator experiments. However, at this stage it is also possible that dark matter is a boson of mass about 1 eV being absorbed instead of scattering at the detector, which would result in a null result at electron beam experiments because the dark matter would not be expected to be produced at a sufficient rate.

- *Scenario 1A: a signal is seen at an electron-beam missing-momentum experiment consistent with production of an invisible particle of mass 30 MeV* [PRD 1].

  This result suggests that the invisible particle produced here is the same particle mediating dark-matter scattering in the electron-recoil experiment. The inferred mass is consistent with benchmark scenarios where dark matter obtains its abundance through thermal freeze-out. However, the missing-momentum signature does not guarantee that the mediator decays into the same dark-sector state(s) seen in the direct-detection experiment. To confirm this, a beam dump experiment with electron beams verifies that the electron scattering cross section at a downstream detector is consistent with both a 30 MeV mediator and a 10 MeV dark-matter particle [PRD 1], lending further support for the freeze-out hypothesis. The nature of the mediator is still unknown; does it have equal couplings to both protons and electrons, or does it preferentially couple to leptons? To determine the nature of the mediator, a beam dump experiment with proton beams [PRD 1] observes a signal consistent with the same mass values as the electron beam experiment, but with a coupling 3 times as large. This result is confirmed by a direct-detection experiment [PRD 2], which observes phonons of typical energy 10 meV from nuclear recoil, with a rate consistent with a dark-matter mass of 10 MeV. Simultaneously, a muon beam missing-momentum experiment [PRD 1] observes an event rate consistent with equal couplings to muons and electrons. Further work is now necessary to determine the nature of the mediator, as the hierarchy between lepton and nucleon couplings is inconsistent with mediator being a kinetically-mixed dark photon.

- *Scenario 1B: no signal is seen at an electron-beam missing-momentum experiment [PRD 1], with sufficient luminosity to cover the expected production cross section consistent with thermal freeze-out for dark-matter masses of 1-10 MeV.*

  This result disfavors the hypothesis of thermal freeze-out, and suggests that the interaction with electrons is enhanced at nonrelativistic velocities, such as in the case of scattering through an ultralight mediator with mass much less than 1 eV. The null result at electron beam experiments can be explained by highly suppressed couplings which strongly reduce the rate for producing relativistic dark matter; this scenario is consistent with the hypothesis of dark matter obtaining its present abundance through the freeze-in mechanism. To test the nature of the mediator, a direct-detection experiment with superconductors with 10 meV energy threshold is performed:

  * *Scenario 1B.1: approximately 100 events are seen with a wide spread of recoil energies between 10 meV and 1 eV* [PRD 2]. This suggests the mediator is a kinetically-mixed dark photon, where the mediator inherits suppressed in-medium couplings when scattering in a metal, and the cross section becomes effectively velocity-independent at low recoil.

  * *Scenario 1B.2: approximately 10,000 events are seen with a wide spread of recoil energies between 10 meV and 1 eV* [PRD 2]. The enormously increased rate compared to Scenario 1B.1 suggests that scattering continues to increase at low velocities down to very low recoil energies, which is inconsistent with the mediator being a kinetically-mixed dark photon. As in Scenario 1A, further work is necessary to determine the nature of the mediator, to measure its couplings to protons in both direct-detection experiments and proton beam dump experiments, and to reconcile its thermal history with its interactions with the Standard Model.

  * *Scenario 1B.3: approximately 100 events are seen, all of which have the same recoil energy of 1 eV to within experimental resolution* [PRD 2]. This result strongly favors the hypothesis of dark-matter absorption, where dark matter transfers its entire mass energy to the target electrons, with only a very small spread of 10^{-3} from the dark-matter velocity dispersion. The event rate is consistent with a spin-1 dark photon; the expected rate from absorption of a spin-0 axion-like particle is sufficiently low so as to predict 0 events at this particular experiment. The nature of the dark matter as a kinetically-mixed spin-1 particle of mass 1 eV can be confirmed by performing other experiments focused on ultralight particles, including optical haloscopes, light shining through walls, and short-range spin-dependent force searches [PRD 3].

Case study #2

A 4 GeV electron-beam, missing-momentum experiment sees 5 events with outgoing electron energies between 1 GeV and 1.5 GeV, with no other electromagnetic or hadronic activity in the downstream trackers and calorimeters [PRD 1].

From this observation, we learn that one or more invisible states exist, at least one of which couples to electrons, and for which the final-state invisible mass is less than about 2.5 GeV. One hypothesis is that a mediator of mass $m_{A'}$ is produced on-shell, which decays to two dark sector particles X_1 and X_2 with masses $m_1 + m_2 < m_{A'}$. Another possibility is that the mediator is lighter than $m_1 + m_2$ and is produced off-shell. Determining the nature of the mediator and the relationship of the invisible states to the galactic dark matter necessarily require input from additional experiments.

- *Scenario 2A: a 1 kg semiconductor experiment also sees an electron scattering signal consistent with a cross section of* 10^{-41} *cm²* [PRD 2].

  This result provides additional evidence for the hypothesis that one or more of the invisible states seen at the missing-momentum experiment are the same particle as the galactic dark matter. Furthermore, the observed cross section is too small to have been visible if dark matter were scattering through a light mediator, so this is additional evidence for the on-shell production of A' at the electron-beam experiment. Subsequently, a 1 GeV proton beam dump experiment observes no events [PRD 1], but an 8 GeV proton beam dump experiment observes electron scattering-like events consistent with 100 MeV dark matter scattering through a 300 MeV mediator [PRD 1], and an event rate consistent with equal couplings of the A' to protons and electrons. These results suggest that (a) A' couples to protons, and (b) its mass is greater than the pion mass, since mediator production from neutral pion decay is the dominant production process at the 1 GeV experiment. Finally, the observed cross section at the semiconductor experiment, combined with the equal couplings to matter, are consistent with one of the benchmarks for thermal production of 100 MeV dark matter through a dark photon. Further experiments (e.g., muon-beam missing momentum and direct detection through nuclear scattering) are necessary to confirm the identity of the A' as a kinetically-mixed dark photon.

- *Scenario 2B: a 1 kg semiconductor experiment sees no electron-scattering events. Further investigation with a longer exposure or a superconductor detector also fails to detect any events* [PRD 2].

  Null results at electron direct-detection experiments motivate the possibility that either the invisible states seen at the electron-beam experiment are stable on experimental but not cosmological time scales, or that the dark matter scatters inelastically and is kinematically forbidden from up-scattering in a direct detection experiment.

  * *Scenario 2B.1: a 4 GeV electron beam spectrometer-based experiment sees a significant excess of well-separated* e^+e^- *pairs with invariant mass of 30-40 MeV* [PRD 1]. This scenario corresponds to a benchmark pseudo-Dirac dark matter model mediated through a dark photon, where the dark matter states have a 40 MeV splitting and the signal in the detector is due to decay of the heavy state. Further investigation with proton beam production-and-detection experiments are warranted to confirm that the mediator also couples to protons.

  * *Scenario 2B.2: no events are seen at a 4 GeV electron beam production-and-detection experiment* [PRD 1]. Since the kinematics of the two electron beam (missing momentum and production-and-detection) experiments are so similar, stable particles produced in the former should also be produced by the latter. This scenario lends support to the hypothesis that the dark states are stable on the length scale of the electron beam experiment, but unstable on the length scale of the beam dump experiment, such that all have decayed before reaching the detector. Further investigation is warranted with different beam energies and baselines between beam stop and detector to determine the lifetime of the dark states. While an interpretation as galactic dark matter is disfavored, there are

numerous opportunities for conducting spectroscopy in the dark sector and determining the nature of the dark force, for example, by attempting to observe the decays of A' to e^+e^- at high-luminosity meson factories.

Case study #3

Two lumped-element electromagnetic experiments see narrow linewidth signals with lineshape matching the one expected from the velocity distribution of dark matter: the first experiment, using broadband readout with a 1 T magnet, sees a signal at f_1 = 1 MHz, and the second experiment, with no magnet, sees a signal at f_2 = 10 MHz [PRD 3].

From these observations, we learn that there are likely to be at least two species of ultralight dark matter: an axion-like particle which couples to external magnetic fields, with mass of 4 neV, and a dark photon-like particle which can source electromagnetic fields directly, with mass of 40 neV. Determining whether the axion-like particle is related to the QCD axion, and what the relative abundances of the two dark matter species are, requires input from additional experiments.

A follow-up magnet experiment [PRD 3] is performed with resonant readout tuned to 1 MHz, and after a day of data-taking, the lineshape of the signal is determined to high accuracy, and the axion-photon coupling is confirmed to lie above the one expected for the vanilla QCD axion of that mass. This measurement allows a precise extraction of the axion speed distribution $f_1(v)$. The mass of the axion implies that its coherence length is approximately 300 km. Repetitions of this experimental setup within and outside this coherence length will confirm the identity of this signal as arising from a coherent field and will allow determination of its 3-dimensional velocity distribution $f_1(\mathbf{v})$ from measurements of the field gradient.

The larger-than-expected coupling to photons may signal axion models with enhanced photon coupling compared to the QCD axion. To confirm this, an NMR experiment measuring the axion electric dipole coupling is performed [PRD 3]. No signal is found exactly at the expected QCD intensity, but additional data-taking reveals a signal slightly weaker than the expected QCD coupling. This result suggests that the axion-like signal is indeed the QCD axion, but with a relic abundance slightly below the local dark-matter abundance. This lends support to the dark photon-like signal arising from a dark-matter subcomponent. Further investigation of the QCD axion signal can be performed with experiments measuring the gradient "wind" couplings of the axion field, which could determine couplings to nucleons and electrons.

The results of the dark-photon experiment constrain the product of the dark-photon kinetic mixing and the dark-photon energy density. Under the hypothesis that the dark photon and axion together make up all of dark matter, the strength of the signal determines the kinetic mixing. Again, repetitions of the same experimental setup both within and outside the coherence length (here 30 km) allow determination of the dark-photon velocity distribution $f_2(\mathbf{v})$. At this point, a host of interesting astrophysical questions can be asked if $f_1(\mathbf{v})$ differs from $f_2(\mathbf{v})$, since the standard hypothesis of gravitational virialization would predict these two velocity distributions are exactly equal. Furthermore, both the axion and dark-photon measurements have strong implications for cosmology: an axion of the observed mass would typically suggest a relatively low scale of inflation, while the dark-photon abundance may in some models also be linked to the scale of inflation.

Finally, the existence of a kinetically-mixed dark photon in the particle spectrum allows the possibility of this new particle to act as a mediator to the dark sector. Further investigation is warranted in both direct detection and collider experiments to see if there are additional components of dark matter which couple to the mediator, or unstable dark states which may be produced at colliders and decay in downstream detectors through the dark-photon interaction.

For all the case studies above, we emphasize that confirming that a detected dark-matter candidate matches the observed cosmological abundance and determining the number of dark-matter species including any subcomponents necessarily require a cross-cutting approach involving many types of experiments which cover all PRDs in this report.

Synergies with Other Programs

The PRDs presented in this document have significant synergy with the rest of the scientific program for the DOE. In this section we discuss the main aspects of these synergies.

The role of theory

This document proposes a diverse and innovative set of experimental approaches, including potential game-changers, in the search for a broad set of motivated dark matter candidates. The ideas described in this document demonstrate the vibrancy of the dark-matter community in universities and labs in the U.S. Theorists have notably played important roles in all research thrusts, proposing the dark-matter models, identifying the theoretical targets for searches, and designing and proposing new technologies. Indeed, in many cases these proposals are the result of close collaboration between experimentalists and theorists. Furthermore, theorists play leadership roles in many of the collaborations pursuing this science. A thriving and supported theory program is thus vital for executing this program as well as to advance the field in the future and maintain the flow of new ideas.

More generally, a vibrant research program was and continues to be critical. Many of the new ideas presented here were spawned not by a programmatic approach to the dark-matter problem, but by small groups developing ideas and technologies to tackle a variety of fundamental questions. In many cases progress has been made by multi-disciplinary teams that include researchers from disciplines outside of traditional high energy physics, such as nuclear, atomic, and condensed matter physics.

Generic detector R&D

The development of new particle detectors has enabled the exploration of regions of the dark-matter parameter space previously unreachable due to technological limitations. This is especially true in the sub-GeV particle-like (PRD 2) and wave-like (PRD 3) dark-matter searches. The generic detector R&D program, supported by DOE HEP, has made several of these novel detector developments possible. The continuing leverage of the HEP generic detector R&D program to overcome the current limitations of dark-matter sensors will extend the reach of the proposed small projects dark-matter program.

Detector developments driven by DOE HEP projects have produced key technologies for exploration of the dark matter sector at accelerators (PRD 1). This is the case for the high granularity calorimeter developed for CMS[13] and DAQ systems from Mu2e,[14] which enables the missing momentum search at electron beams.[15]

Quantum information science

Recent years have seen groundbreaking advances in the field of quantum information science (QIS). The DOE has recently initiated a QIS program. Many of the research directions presented here make heavy use and, in fact, are enabled by quantum technologies. Quantum sensors play an important role in advancing the search for wave-like dark matter,[16] including the QCD axion as detailed in PRD 3.

The benefits, however, are bi-directional – some of the technologies developed for the next generation sub-GeV dark-matter detectors in PRD 2 (such as low threshold TES[17] or single-photon counting detectors[18]) may be used to enable and enhance the capabilities of quantum computers, and advance the field of quantum imaging. Cross fertilization between technologies in dark matter searches and QIS enhance the productivity of both fields, and adds value to both scientific programs.

Coherent neutrino-nucleus elastic scattering

The Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) scientific program has recently produced the first detection of CEvNS using a stopped pion beam.[19] This program is now pushing for CEvNS detection using lower energy neutrinos from nuclear reactors. The low threshold nuclear recoil detectors that were discussed here in the context of direct detection for dark matter particles lighter than the proton may also be sensitive to CEvNS, as discussed in Refs. 20 and 21. The development of the next generation of nuclear recoil sensors with a low threshold is vital for both efforts and greatly benefits from ongoing cooperation and collaboration, sharing resources and expertise.

The CEvNS process also provides a new window for physics in the low energy neutrino sector, and this phenomenology could provide the firsts hints of the dark sector.[22]

Liquid argon neutrino detectors

The DOE has an ambitious neutrino program based on powerful proton beams and large liquid argon detectors.[23] The experiments planned for this neutrino program are part of the accelerator-based probes for dark sector particles discussed in PRD 1.[24] In particular, the multi-purpose nature and the high capabilities of liquid argon detectors will present new opportunities for dark sector searches (see

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13 The CMS Collaboration, arXiv:1802.05987 (2018).

14 N. Atanov et al., arXiv:1802.06341 (2018).

15 T. Akesson et al., “arXiv:1808.05219 (2018).

16 Z. Ahmed, arXiv:1803.11306 (2018).

17 K. D. Irwin, *Appl. Phys. Lett.* 66 (1995) 1998.

18 J. Tiffenberg et al., Phys. Rev. Lett. 119 (2017).

19 D. Akimov et al., Science 357 (2017) 1123-1126.

20 J. Formaggio, E. Figueroa-Feliciano, and A. Anderson, Phys. Rev. D 85, no. 1 (2012) no. 1.

21 The CONNIE Collaboration, J. Instrumentation 11 (2016) no. 07, P07024 (2016).

22 R. Harnik, J. Kopp, and P.A.N. Machado, JCAP 07 (2012) 026.

23 http://www.dunescience.org; https://sbn.fnal.gov.

24 A. de Gouvêa, P. Fox, R. Harnik, K. Kelly, and Y. Zhang, arXiv:1809.06388 (2018); R. Essig, R. Harnik, J. Kaplan, and N. Toro, Phys. Rev. D82 (2010) 113008.

e.g., Ref. 25). The growing efforts in neutrino collaborations to search for dark sectors is allowing the infrastructure developed for the neutrino program to be leveraged in the search for dark matter.

Accelerator facilities outside the HEP program

The search for dark matter with accelerators (PRD 1) uses DOE facilities that in some cases are not part of the HEP-supported infrastructure as discussed in PRD 1. This constitutes an opportunity to diversify and broaden the science reach of those facilities.

Cryogenic facilities and expertise

The program described here relies heavily in the development of cryogenic detectors. These sensors play a very important role for the direct detection efforts (PRD 2), and in the search for wave-like dark matter (PRD 3). Cryogenic detectors are also a key technology for the development of the next generation of CMB survey instruments (CMB-S4)[26] and the current QIS initiative. The development and characterization of all these detectors require significant infrastructure and expertise in cryogenics engineering and cold electronics. These resources are currently available at DOE facilities and constitute a critical part of the success of this program.

Magnet technology development

As part of the development of the next generation of accelerators for HEP and BES, DOE has designed and fabricated advanced magnets with high field and large volumes.[27] This technology is part of the core technological capabilities at national laboratories. These novel high-performance magnets are expected to extend the reach of the experiments searching for wave-like dark matter (PRD 3). The transfer of the magnet technology to new dark matter searches is another very powerful synergy between the program described in this document and the rest of the DOE.

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[25] "Physics Opportunities in the Near DUNE Detector Hall Workshop," Fermilab 2018, https://indico.fnal.gov/event/18430/.

[26] https://cmb-s4.org.

[27] S. A. Gourlay et al., IEEE Trans. Appl. Superconductivity 16 (2006) no. 2.

4. PANEL REPORTS

The *High Energy Physics Workshop for Basic Research Needs for Dark Matter Small Projects New Initiatives* was structured around three panels:

Panel 1: Acceleration Production and Detection of Dark Matter

Panel 2: Direct Detection of Low-Mass Dark Matter

Panel 3: Ultra-low Mass Dark Matter

Each of the panels produced a report on the status of the field, scientific challenges and opportunities, and possible impact. These reports, presented in this chapter, formed the basis for identifying the three PRDs described in Chapter 2.

Accelerator Production Panel Report

Current Status and Recent Theoretical and Technological Advances

Theoretical motivation and progress

There is strong motivation to search for non-gravitational interactions of dark matter with normal matter: such interactions are allowed by known symmetries, arise in many compelling models for physics beyond the Standard Model (SM), and can explain the cosmological origin of dark matter.

These same interactions enable the production of dark matter particles at accelerator-based experiments, which can exploit either the collisions of two energetic beams of particles ("collider experiments") or the interactions of a single energetic beam in material ("fixed-target experiments"). Collider experiments generally achieve higher center-of-mass energy, allowing the production and detection of heavier particles. Fixed-target experiments achieve greater luminosities, giving them powerful sensitivity to the feeble interactions expected of light dark matter. Fixed target experiments at the $5-15M cost scale have compelling potential to discover and explore light dark matter, and are the focus of this panel report.

Fixed-target experiments are capable of searching for *any* light dark-matter particle with sufficient interaction strength, but are **particularly motivated by so-called "thermal dark matter" lighter than the proton,** a simple extension of the classic WIMP paradigm to these lower dark-matter masses.[28] Thermal dark matter offers a simple explanation for the creation of dark matter during the hot Big Bang, with a resulting sharp prediction for the strength of its interactions with familiar matter. The production and annihilation of dark matter from normal matter connect their abundances. As the universe cools and expands, these reactions "freeze-out," resulting in a final dark-matter abundance that scales inversely with the annihilation rate.

If the dark-matter abundance is set simply by its interactions with ordinary matter (rather than having a new, unstable intermediate state control its abundance), its observed density sets a characteristic "thermal target" for the interaction strength between dark and visible matter. Remarkably, the "thermal target" interaction strengths (Figure 4-1) coincide with the range of couplings arising from simple perturbative mechanisms, **and are accessible to next generation experiments**. The thermal target is sharper for accelerators than for other dark matter searches, because accelerator experiments produce dark matter relativistically -- similar to Big Bang production. Concretely, accelerators are especially powerful probes in models where scattering rates are suppressed by the dark matter velocity (e.g., Majorana fermion dark matter), or where tree-level scattering is kinematically forbidden at low velocities (inelastic scalar or fermion dark matter).[29]

Alternately, unstable particles related to dark matter may play a key role in its cosmological origin. For example, dark matter may annihilate into light mediators ("secluded dark matter"),[30] co-annihilate with slightly heavier particles ("exciting dark matter"),[31] or be part of a strongly interacting dark sector that

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[28] C. Boehm, T. A. Ensslin, and J. Silk, J. Phys. G30 (2004) 279.
[29] D. Tucker-Smith and N. Weiner, Phys. Rev. D64 (2001) 043502.
[30] M. Pospelov, A. Ritz, and M. B. Voloshin, Phys. Lett. B662 (2008) 53.
[31] E. Izaguirre, Y. Kahn, G. Krnjaic, and M. Moschella, Phys. Rev. D96 (2017) 055007.

includes unstable, visibly-decaying resonances.[32] Some of these models imply predictive milestones analogous to the thermal target, while others do not. In all cases, accelerator-based experiments play a crucial role: in addition to enabling discovery of the dark matter, they are also a unique and powerful avenue for the discovery of related unstable particles.

This report will summarize several different strategies for exploring the physics of dark matter at accelerators, and will summarize their sensitivity to a range of benchmark models. However, these experiments are not simply competing techniques to achieve the same physics. Indeed, each class of experiments measures related but distinct physical quantities — for example, (i) the dark matter production rate in missing-momentum experiments, (ii) dark-matter scattering rates (off electrons and/or nuclei) in beam-dump experiments, and (iii) the yields, lifetimes, and decay modes of related unstable particles at spectrometer-based experiments. A strength of the accelerator-based program, as a whole, is the ability to measure these various rates, as well as multiple kinematic observables. Together these measurements enable reconstruction of the spectrum and couplings of the dark sector. There is therefore substantial synergy among experimental approaches within the accelerator-based program, in addition to the powerful synergy with direct-detection experiments.

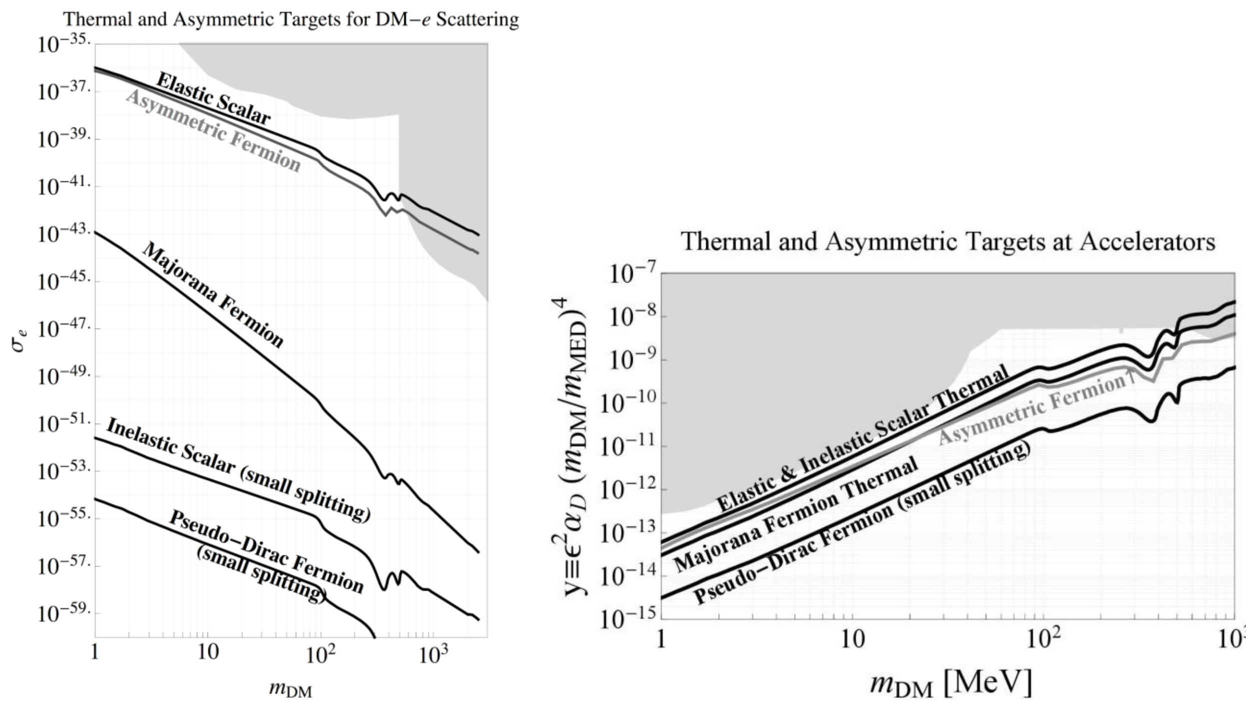

Figure 4-1: *Thermal freeze-out milestones in direct detection cross-section (left) and in the dimensionless interaction strength commonly used to characterize accelerator-based experiments' sensitivity (right). As discussed in the text, the relativistic nature of accelerator-based dark matter production leads to a fairly precise target, irrespective of detailed dark matter particle properties, while the rates of non-relativistic dark matter interactions vary dramatically depending on dark matter particle properties. See also Table 4-1.*

[32] Y. Hochberg, E. Kufilk, T. Volansky, and J. G. Wacker, Phys. Rev. Lett. 113 (2014) 171301.

Table 4-1: *Sensitivity of small accelerator-based experiments to the range of predictive thermal freeze-out milestones, including models where the rates of annihilation controlling freeze-out are velocity-suppressed (p-wave), velocity-independent (s-wave), or enhanced from the effective field theory expectation by a resonant or near-threshold mediator, as well as ELDER models of Ref. 70, where the freeze-out of DM* <u>*scattering*</u> *with familiar matter, together with additional dark-sector physics, controls its abundance. Check-marks (✓) indicate sensitivity of at least one representative concept to the benchmark over at least of order half of the electron-to-proton mass range, while question marks (?) indicate potential sensitivity, with future study needed. Where different approaches cover complementary mass ranges, this complementarity is indicated by (>) for high-mass coverage and (<) for low-mass coverage. In addition, visible mediator searches are often among the most sensitive probes of a new mediator relevant to secluded annihilation, though the sensitivity is model-dependent and these models are also consistent with invisibly small couplings. The above assumes models with approximately universal couplings to SM species.*

Sensitivity Milestones		Thrust 1				Thrust 2
		Proton beam dump	**Electron beam dump**	**Electron Missing Momentum**	**Muon Missing Momentum**	**Visible Searches**
Thermal freeze-out controlled by DM-SM coupling	p-wave	✓	✓	✓	✓	
	s-wave			✓	✓ (>)	
	large splitting excited	✓(>) decays	✓(>) decays	✓(<) production	~ production	✓(>) decays
	Resonant & near-threshold			✓	?	✓
	Elastic decoupling (ELDER)			✓	?	✓ decays
Secluded freeze-out						Some models

Experimental techniques and state of the art

We now summarize the main techniques for producing and detecting light dark matter at fixed-target experiments, and the current state of the art for each class of experiment (see also Tables 4-2 and 4-3).

Beam dump experiments: In a beam-dump experiment, dark matter is produced in collisions of an intense electron or proton beam with a target and detected through its scattering in a downstream detector.[33] Several dark-matter production mechanisms and scattering reactions are possible depending on the beam particle, beam energy, and detector type. Recent beam dump dark matter searches and reinterpretations of similar past experiments currently provide the strongest constraints over much of the light dark-matter mass range and serve as powerful proof-of-concept demonstrations for future experiments.

The MiniBooNE-DM collaboration recently performed the first dedicated light dark matter search with a proton beam, using 1.86 x 10^{20} protons from the Fermilab 8 GeV Booster steered into a steel dump to

[33] B. Batell, M. Pospelov, and A. Ritz, Phys. Rev. D80 (2009) 095025; E. Izaguirre, G. Krnjaic, P. Schuster, and N. Toro, Phys. Rev. D88 (2013) 114015.

mitigate beam-related neutrino backgrounds.[34] Several production channels, including neutral meson decay and proton bremsstrahlung, are relevant at these beam energies. Once produced, dark matter can be detected via scattering in the MiniBooNE detector, located 490 meters downstream of the dump. A search for dark matter-electron scattering sets the strongest limits on vector portal dark matter between 5 and 50 MeV. Searches for elastic and inelastic nucleon scattering were also performed.

The observation of coherent elastic neutrino-nucleus scattering by the COHERENT collaboration also opens the door to a new era of sensitive light dark matter searches using intense low-energy proton beams. A reinterpretation of this measurement has been used to set the best limits on light dark matter that couples dominantly to quarks.[35]

While the leading limits from proton beam dumps are derived from modern experiments, the state of the art in electron beam dumps is the SLAC E137 experiment carried out in the 1980s.[36] In this experiment approximately 30 C of 20 GeV electrons were dumped on an aluminum-water target. A sensitive electromagnetic calorimeter situated 400 meters downstream was capable of detecting forward energetic electrons that could have originated from the decay of a metastable particle or from the scattering of dark matter in the detector. A reinterpretation of a search for axion-like particles results in the strongest limits on light dark matter that couples dominantly to electrons or leptons.

Beam dump experiments can also probe unstable particles that are produced in the dump and decay in the downstream detector. Limits on such decays from past experiments have been considered (for example, Ref. 37); these can be further improved with dedicated new analyses of beam dump experimental data.

Missing energy and momentum experiments: In missing energy[38] and missing momentum experiments,[39] dark matter is produced in the collisions of energetic particles with target nuclei, and is detected by the energy/momentum lost by the incoming beam particle in the reaction and the absence of any other detectable particles emerging from the collision. In comparison to beam dump experiments, missing energy/momentum experiments gain a significant advantage in event rate by not relying on downstream re-scattering. This approach thus requires significantly less intense beams to explore a given interaction strength, but creates other challenges. First, missing energy/momentum experiments must uniquely associate recoiling beam particles and other activity in the veto detectors with each individual incoming beam particle, requiring low-intensity continuous-wave beams with fast detectors. Second, vetoing backgrounds from Standard Model processes requires highly sensitive detectors to eliminate rare events arising from regular photon bremsstrahlung. Finally, pure lepton beams are the only way to ensure a sufficiently low level of irreducible backgrounds, which is only easily achievable with electron beams.

The NA64 experiment recently released first results[40] of a missing energy search for dark matter produced in fixed target collisions using 4.3 x 10^{10} electrons at 100 GeV from the CERN SPS. The

[34] MiniBooNE DM Collaboration, Phys. Rev. D98 (2018) no.11, 112004.
[35] S.-F. Ge and I. M. Shoemaker, JHEP 1811 (2018) 066.
[36] J. D. Bjorken et al., Phys. Rev. D38 (1988) 3375.
[37] R. Essig, R. Harnik, J. Kaplan, and N. Toro, Phys. Rev. D82 (2010) 113008.
[38] S. N. Gninenko, N.V. Krasnikov, M.M. Kirsanov, and D.V. Kirpichnikov, Phys. Rev. D94 (2016), 095025.
[39] E. Izaguirre, G. Krnjaic, P. Schuster, and N. Toro, Phys. Rev. D91 (2015) 094026.
[40] NA64 Collaboration, Phys. Rev. D97 (2018), 072002.

experiment precisely measures the energy of each incoming electron with a spectrometer and subsequently measures the final energy of the electron inside an active target consisting of electromagnetic and hadronic calorimeters. Having observed no events in the signal region, NA64 has demonstrated the sensitivity of electron missing energy experiments to light dark-matter signals.
To improve on missing-energy experiments like NA64, which only use the change in the scalar energy of the incoming particle across the target, missing-momentum experiments propose to use the change in the vector momentum as well. This additional kinematic handle is a powerful discriminator against rare backgrounds that are difficult to veto based on additional activity in the detector from the hard bremsstrahlung photon. In addition, the missing momentum distribution is sensitive to the mass of the recoiling dark matter, so missing momentum experiments can measure the dark matter mass.

Finally, missing energy and momentum experiments can also search for unstable dark sector particles that decay in their veto regions. The NA64 experiment at CERN has demonstrated the viability of this approach with a search for visibly decaying dark photons that has achieved new sensitivity.[41]

Spectrometer-based experiments: Spectrometer-based experiments can produce the full spectrum of dark sector particles and detect their visible decay products. Several production mechanisms are possible depending on the nature of the dark sector particle and on the beam type and energy. For example, visibly decaying dark photons can be radiated from electron and proton beams, or produced via meson decays and through the Drell-Yan process at proton beam experiments.

Unstable particles with meter-scale or shorter lab-frame lifetimes can be probed efficiently by spectrometer-based experiments that reconstruct ***all*** of the visible decay products of a dark-sector state. This approach is exemplified by the currently operating Heavy Photon Search (HPS)[42] and APEX[43] experiments at JLab, which collide intense electron beams in the 1-6 GeV energy range on a thin high-Z target. Dark particles below about 100 MeV that are displaced only mm from the target are most effectively probed by HPS and similar experiments. This sensitivity is quite complementary to that of beam dump experiments, such as SLAC E137,[44] the CHARM proton fixed-target beam dump at CERN,[45] and the LSND experiment,[46] which are only sensitive to much longer-lived dark particles (e.g., dark forces, axions, sterile neutrinos, and excited dark matter states) and do not fully reconstruct their decays.

Other accelerator experiments (collider and fixed-target missing mass): A third class of measurements is the missing mass search, which can be performed both at colliders and in suitable fixed-target experiments. By measuring all visible final states of a reaction, the total invariant mass of all invisible particles can be inferred. In the case that a mediator particle decays entirely into dark matter, searches for this signal offer a clean, self-calibrating signal of its production.

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41 NA64 Collaboration, Phys. Rev. Lett. 118 (2017) 011802.
42 HPS Collaboration, J. Phys. Conf. Ser. 556 (2014) 012064.
43 APEX: A Prime EXperiment at Jefferson Lab, http://arxiv.org/abs/arXiv:1301.2581.
44 B. Batell, R. Essig, and Z. Surujon, Phys. Rev. Lett. 113 (2014) 171802.
45 CHARM Collaboration, Phys. Lett. 157B (1985) 458-462.
46 LSND Collaboration, Phys. Rev. D63 (2001) 112001; P. de Niverville, M. Pospelov, and A. Ritz, Phys. Rev. D84 (2011) 075020.

Experiments at electron-positron colliders can perform missing mass searches for dark matter by reconstructing events with a single final-state photon. Such a search performed at BaBar[47] sets strong constraints on GeV-scale and heavier dark matter. The Belle II B-factory experiment at SuperKEKB, which plans to accumulate 50 ab^{-1} of data during the 2020s, will significantly improve on this sensitivity[48] (in our figures, we adopt the projection in Hearty[49] based on Monte Carlo studies at 20 fb^{-1}; the projection used in Ref. 50 was obtained by scaling this sensitivity to the expected luminosity of 50 ab^{-1}, but assuming zero background, which is likely too aggressive).

The missing mass method can also be applied to search for dark matter in fixed-target experiments, either using electron beams with the protons in hydrogen gas as targets (requiring reconstruction of the recoiling electron and proton, as in DarkLight[51]) or using positron beams with atomic electrons as targets (requiring reconstruction of a single forward photon). Several experiments using this technique have been proposed at Cornell University,[52] INFN-LNF,[53] Jlab,[54] and Novosibirsk.[55] Relative to beam dump and missing momentum experiments, these searches are more limited in mass and/or coupling sensitivity. In addition, they rely crucially on the production of an on-shell mediator. For both of these reasons, we will not further discuss fixed-target missing mass experiments in this report (more details can be found in section IV of Ref. 50). Nonetheless, missing mass experiments have two distinct strengths: they can precisely reconstruct the mass of a mediator, and are especially inclusive with respect to its decay products. These features make missing mass experiments an invaluable part of a broader search for dark sectors.

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[47] BaBar Collaboration, Phys. Rev. Lett. 119 (2017) 131804**.**
[48] Belle II Collaboration, arXiv:1808.10567.
[49] https://indico.fnal.gov/event/13702/session/9/contribution/123/material/slides/0.pdf.
[50] M. Battaglierei, et al., arXiv:1707.04591.
[51] J. Balewski, et al., arXiv:1412.4717.
[52] https://www.epj-conferences.org/articles/epjconf/pdf/2017/11/epjconf_admpp2017_01001.pdf.
[53] M. Raggi, V. Kozhuharov, and P. Valente, arXiv:1501.01867.
[54] L. Marsicano, AIP Conf. Proc. 1970 (2018) no.1, 020008.
[55] B. Wojtsekhowski, et al., JINST 13 (2018) no. 02, P02021.

Table 4-2: *Summary of status of detection approaches with proton, electron, and muon beams.*

	Beam Particle		
Detection Approach	**Proton**	**Electron**	**Muon**
Kinematics (Missing energy/momentum)	*No concepts developed – significant technical challenges expected*	Present results NA64, Ref. 41 New prospects: Higher beam current, faster detector, transverse momentum reconstruction	No demonstration, first proposed (2017)[56] Relative to electron beams, uses lower current on thicker target; good tracking for muon momentum resolution
Scattering of dark matter in downstream detector (beam dump)	Present results MiniBooNE-DM, Ref. 34 COHERENT, Ref. 35 New prospects: Larger and/or nearer detectors, higher current, lower neutrino backgrounds	Present results E 137, Ref. 36 New prospects: Higher beam current, closer and denser detector	*Insufficient luminosity*
Visible searches	Present results CHARM (80s), Ref. 45 LSND (00s), Ref. 46 New prospects: nearer detectors with higher acceptance and sensitivity to shorter lifetime	Present results: E137 (1988), Ref. 44 HPS (201X), Ref. 42	*Preconceptual study Ref. 57*

[56] Y. Kahn, G. Krnjaic, N. Tran, and A. Whitbeck, JHEP 1809 (2018) 153.
[57] C.-Y. Chen, M. Pospelov, and Y.-M. Zhong, Phys. Rev. D95 (2017) 115005.

Table 4-3: *A summary of concepts discussed under Thrusts 1 and 2 of PRD 1 and used as basis for the potential sensitivity curves in Figures 4-2 to 4-4 (discussed later). These can be classified into three distinct classes of measurements: beam dump, missing energy/momentum, and spectrometer-based searches.*

	Requirements		
Detection Approach and Concept Name	**Beam energy**	**Detector**	**Sensitivity Limitation**
Low-energy proton beam dump (e.g., COHERENT@SNS)	1 GeV p 3×10^{23} POT	1 tonne LAr/NaI @ 25m	Yield, Systematics
Low-energy proton beam dump (e.g., CCM@Lujan)	800 MeV 1.4×10^{22} POT	10 tonne liquid argon detector @15 to 40 m	Yield, Systematics
Mid-energy proton beam dump (e.g., SBN@BNB)	8 GeV 6×10^{20} POT	New dedicated beam dump, 112 tonne LAr-TPC @ 110 m	Yield
Electron beam dump (e.g., BDX @ CEBAF)	2-11 GeV 10^{22} EOT	1m^3 scale CsI(Tl) EM calorimeter	Yield
Missing momentum @ CW electron beam (e.g., LDMX)	8 GeV 10^{16} EOT	10% X_0 target, kinematics on recoil electron energy less than 0.25 * E_{beam}	Rate
Muon missing momentum @ muon beam (e.g., M^3)	15-25 GeV 10^{13} μOT	50 X_0 target, kinematics on recoil muon energy less than 0.6 * E_{beam}	Rate
Proton spectrometer (e.g., at the MI @ Fermilab)	120 GeV $10^{18}-10^{20}$ POT	Spectrometer, vertex resolution, EMCal	Yield

Experimental Opportunities and Challenges

As highlighted above, a variety of past accelerator-based experiments employing beam dump, missing energy, and spectrometer-based techniques place some of the strongest constraints on light dark matter and dark sectors. These results demonstrate the power of the various accelerator-based approaches to producing and detecting dark matter at or below the proton mass. New experiments leveraging the DOE accelerator portfolio could build on these results, with the objective of decisively testing motivated dark-matter thermal relic targets and broadly probing new forces and particles in the dark sector. This section describes the experimental opportunities and challenges of future proton/electron beam dump, lepton missing momentum, and spectrometer-based experiments.

This report necessarily focuses on DOE facilities, and we will use examples of beamlines and detector concepts to illustrate the opportunities available. A more comprehensive summary of proposals is provided in the 2017 “US Cosmic Visions” report, Ref. 8.

Beam dump experiments

Next-generation proton beam dump experiments could utilize existing DOE proton accelerator facilities at FNAL, ORNL, and LANL to produce and detect dark matter, and offer unique sensitivity to scenarios where dark matter interacts preferentially with nucleons. As with the successful MiniBooNE-DM search, concepts for future experiments utilize existing facilities and detectors developed for the U.S. neutrino program. A program of dark-matter searches can be advanced, in most cases, with parasitic running during currently scheduled beam delivery and with relatively modest investment in detectors and/or beam lines.

The short-baseline neutrino (SBN) program utilizes three LAr detectors of 112 tons (SBND), 89 tons (MicroBooNE), and 476 tons (ICARUST600) situated at 110 m, 470 m, and 600 m downstream of the target, respectively.[58] With capabilities in tracking, vertexing, calorimetry, and particle identification, these detectors offer the potential to discriminate dark matter scattering and other exotic dark-sector signals from ordinary neutrino-induced reactions. As in the MiniBooNE-DM run, the neutrino-induced background can be significantly reduced by steering the proton beam around the production target in dedicated dark matter running modes. A search for dark matter scattering in SBND is expected to yield the most sensitive results and could improve upon MiniBooNE-DM by more than one order of magnitude in sensitivity with 6×10^{20} POT.[59] Further improvement could be achieved by replacing the neutrino horn with an iron target or building a new target station to allow simultaneous neutrino and dark matter running modes [SBNRVW].

The recently discovered coherent elastic neutrino-nucleus scattering (CEvNS) process[60] introduces the opportunity to detect accelerator-produced dark matter via the analogous dark-matter-nucleus scattering process.[61] The COHERENT experiment currently running at the 1 GeV, 1.4 MW ORNL SNS is developing two technologies that may be scaled up in size to produce significant gains in search sensitivity. The COHERENT collaboration is planning to build a 1 ton liquid argon (LAr) detector and a 2 ton NaI detector. Light dark matter searches provide additional motivation for this program. In addition, the coherent CAPTAIN-Mills (CCM) program is investigating the feasibility of searching for sterile neutrinos and dark matter using the CEvNS process in a 10-ton LAr detector combined with the 100 kW proton beam at the LANL Lujan center.

Next-generation electron beam dump experiments could utilize existing DOE electron accelerator facilities at JLab and/or SLAC to produce and detect dark matter interaction with leptons and/or nucleons. Although the limits from E137 are still competitive over 30 years later, the experiment was not designed for dark matter discovery; its low luminosity (approximately 30 Coulombs) and poor acceptance (400 meter baseline) leave considerable room for improvement with future efforts.

New concepts for electron beam dump experiments leverage powerful, modern, existing DOE facilities such as CEBAF at JLab[62] and LCLS-II at SLAC, which deliver about 1 MW power (approximately 1000 Coulombs) to their dumps in order 1 yr of operation. Placing detectors behind the dumps of these machines allows for significant new dark matter search sensitivity from parasitic running. Detectors placed approximately 10 meters behind a beam dump have suitably low beam backgrounds and about a 100× improved geometrical acceptance relative to E137. Detectors are based on well-established calorimeter technologies, improved with modern photodetectors and streaming read-out data-acquisition techniques. Such experiments can improve over the sensitivity of previous experiments by a factor of 10-100, making electron beam dump experiments an attractive, established path forward towards exploring thermal dark matter milestones. Although sensitivity gains are modest compared to

[58] MicroBooNE and LAr1-ND and ICARUS-WA104 Collaborations, arXiv:1503.01520.
[59] P. deNiverville, C-Y. Chen, M. Pospelov, and A. Ritz, Phys. Rev. D95 (2017) 035006.
[60] COHERENT Collaboration, Science 357 (2017) no.6356, 1123.
[61] P. deNiverville, M. Pospelov, and A. Ritz, Phys. Rev. D92 (2015) 095005.
[62] C.W. Leemann, D.R. Douglas, and G.A. Krafft, Ann. Rev. Nucl. Part. Sci. 51 (2001) 413.

missing momentum techniques, beam dumps are based on proven technology and require no beamline modifications.

Missing momentum experiments

Missing momentum experiments utilize electron and muon beams produced at DOE accelerators at SLAC, JLab, and Fermilab to detect the production of dark matter in a fixed target. Improving upon missing energy searches like NA64 by measuring the change in vector momentum of incoming particles across a thin target, these experiments have the potential for up to 10000-fold improvement in sensitivity beyond current constraints. As previously discussed, these experiments offer significant sensitivity for visibly decaying dark sector particles, as well.

Prospects and requirements for ***next-generation electron missing momentum experiments*** have been explored in detail in Ref. 39. These experiments can explore dark matter couplings consistent with the thermal relic dark matter milestones with 10^{14} to 10^{16} electrons on target, attainable using a continuous wave beam with repetition rates of at least 40 MHz. These experiments utilize detector technologies with fast readout, including charged particle tracking and both electromagnetic and hadronic calorimetry. Technologies developed for other experiments, such as CMS and HPS, can be leveraged for these experiments.

Missing momentum experiments with muon beams [63] are complementary to electron beam experiments covering higher mass dark matter candidates due to a heaver beam particle and can utilize a similar detector. Because muons interact less in the target material, a thicker target can be used and the number of incoming beam particles can be significantly less than for electrons — 10^{13} muons on target. However, muon beams present additional challenges due to pion contamination and control of beam energy and trajectory. Detailed studies of performance using a secondary beamline at Fermilab are required to understand the capabilities of a muon missing momentum experiment.[56]

Spectrometer-based experiments

Next-generation spectrometer-based experiments utilize DOE accelerator facilities to search for other states in the dark sector, including the dark force carrier and excited states of dark matter. These particles can be detected through their visible decays to familiar matter such as electrons, muons, or hadrons. While decades-old experiments such as CHARM, E137, and LSND constrain some dark sector models, they were not designed to discover dark sectors, and many gaps in coverage remain. Particularly elusive are unstable dark particles that are relatively heavy (masses greater than about 100 MeV) with moderate lifetimes (decay lengths of order centimeters to meters) that arise in a variety of motivated thermal dark matter models. New accelerator-based experiments have the potential to extend current sensitivity to visibly decaying force carriers and other metastable dark particles by roughly one order of magnitude in certain cases.

These advances are made possible thanks to modern accelerator technology and optimized detector design. Current and future DOE accelerators can be harnessed to carry out fixed target experiments with significantly larger luminosities. Possibilities include the COHERENT experiment at SNS and the Fermilab-based experiments, especially in view of the Proton Improvement Plan-II (PIP-II) scheduled in the coming years.

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[63] S.N. Gninenko, N.V. Krasnikov, and V.A. Matveev, Phys. Rev. D91 (2015) 095015; Ref. 56.

As one example, an upgraded detector operated at the fixed target exit of the Fermilab Main Injector beamline could have a unique sensitivity to a broad array of visible dark sector particles. The potential of this setup arises from a combination of large production rates, high beam energy, and a compact detector geometry. This concept calls for a minimal infrastructure investment and no beamline modification, leveraging the existing SeaQuest spectrometer[64] with minimal improvements needed. The detector could be upgraded with electromagnetic and hadronic calorimeters, as well as additional very fine granularity trackers to efficiently differentiate high energy gamma, electron, and muon/charged hadron. With the high intensity expected of the Fermilab main injector, a spectrometer experiment using only 5-10% of the beam would be sufficient to completely probe several dark matter scenarios up to dark matter masses of a few times the mass of the proton. An example are models of strongly interacting dark matter[65] (see Figure 4-4, bottom right). In some other cases, as in models of excited dark matter, this experiment would be complementary to missing momentum experiments, covering higher masses and smaller displacements[66] (see Figure 4-4, top).

Future experimental R&D

Several directions in general detector R&D could enable improvements across the accelerator-based dark matter program outlined above. Some specific examples are:

- In proton beam dumps, time-of-flight reconstruction would allow for greater discrimination between neutrino backgrounds and dark matter signals.

- Lower energy thresholds for coherent recoil detection would also enable more sensitive beam-dump searches, particularly for experiments at stopped pion sources.

- Higher-rate readout electronics is needed to push electron missing momentum experiments beyond the 10^{16} electron level, to the 10^{18} electron scale neutrino trident floor.

All of these are, of course, widely applicable to other neutrino and/or high-energy experiments. In addition, R&D on megawatt-class beam dumps and beam studies could enable a low-background dark matter search using the 120 GeV Main Injector beam at Fermilab. This could offer unparalleled sensitivity to dark matter closer to a GeV in mass, at least for proton couplings and possibly more generally. It is advantageous to design this capability into the DUNE beamline up front, rather than attempting to retrofit it later.

[64] SeaQuest Collaboration, arXiv:1706.09990.
[65] A. Berlin, N. Blinov, S. Gori, P. Schuster, and N. Toro, Phys. Rev. D97 (2018) 055033.
[66] A. Berlin, S. Gori, P. Schuster, and N. Toro, Phys. Rev. D98 (2018) 035011.

Impact

The program of accelerator-based experiments outlined in this report would deeply influence our understanding of dark matter, regardless of outcome, because these experiments can comprehensively probe a wide range of thermal dark matter candidates below the proton mass.

The broad impact of a mature accelerator program designed around thrusts 1 and 2 in PRD 1 is presented in Figures 4-2 to 4-4. Figure 4-2 shows the parameter space for various dark matter candidates whose associated force carrier (a "dark photon") also exerts a force on known charged particles, with the left and right panel showing different slices through the multi-dimensional parameter space. In the left panel of this figure, the ratio of mediator to dark matter particle mass is fixed to 3, and a strong dark-matter-mediator coupling ($\alpha_D = 0.5$) is assumed. Both of these choices lead to conservative limits and projections (see Refs. 67 and 68) in the dimensionless interaction strength $y = \varepsilon^2 \alpha_D (m_{\mathrm{DM}}/m_{\mathrm{mediator}})^4$ plotted, where ε is the kinetic mixing parameter for a dark photon model, and α_D is the dark-force counterpart of the fine structure constant. In the left panel, the solid black curves represent the parameter space for which this force produces dark matter shortly after the Big Bang; each curve corresponds to a particular dark matter candidate (top to bottom: scalar, Majorana, Dirac). These key theoretical milestones are highlighted in a dark green band. In lighter shaded green regions outside this band, accelerator searches can test variations on this scenario in which the dark matter either has a particle/antiparticle asymmetry (above) or the force carrier's mass is nearly twice the dark matter mass (below). The right panel of Figure 4-2 shows an orthogonal slice of this same parameter space in which the dark matter mass is held fixed and the force carrier mass is varied, focusing on scalar dark matter.

The three panels in Figure 4-3 are similar to the left panel of 4-2, but show how the parameter space and future projections change for different kinds of dark force carriers. Unlike Figure 4-2, here the three panels depict scenarios in which the dark force preferentially interacts with electrons (top left), protons (top right), and muons (bottom left). Finally, Figure 4-4 shows the parameter space for various scenarios in which visible signatures are observed in beam dump, missing momentum, or spectrometer experiments; the top panel shows sensitivity for models of excited two-level dark matter in which the heaver state is unstable and decays semi-visibly; the bottom left shows the reach for dark force carriers that also interact with charged particles; the bottom right shows the reach for models of strongly self-interacting dark matter whose predictive cosmological abundance can arise in the shaded green region.

In addition to convincing discovery potential for thermal relic dark matter, accelerator experiments can unravel the nature of the dark sector in contrast with other experimental techniques, because they allow precise control over the conditions under which dark matter is produced. In the case of a discovery – with this program or via other approaches – accelerator experiments enable a variety of follow-up measurements to verify the existence of a signal and measure the mass, spin, and interactions of dark matter particles. A broad experimental program with multiple particle beams can understand the full theory of the dark sector – dark matter and potential new forces–- beyond merely establishing its existence. In a discovery scenario, this program would create a revolution in fundamental physics and our understanding of the universe.

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[67] E. Izaguirre, G. Krnjaic, P. Schuster, and N. Toro, Phys. Rev. Lett. 115 (2015) 251301.

[68] A. Berlin, N. Blinov, G Krnjaic, P. Schuster, and N. Toro, arXiv:1807.01730.

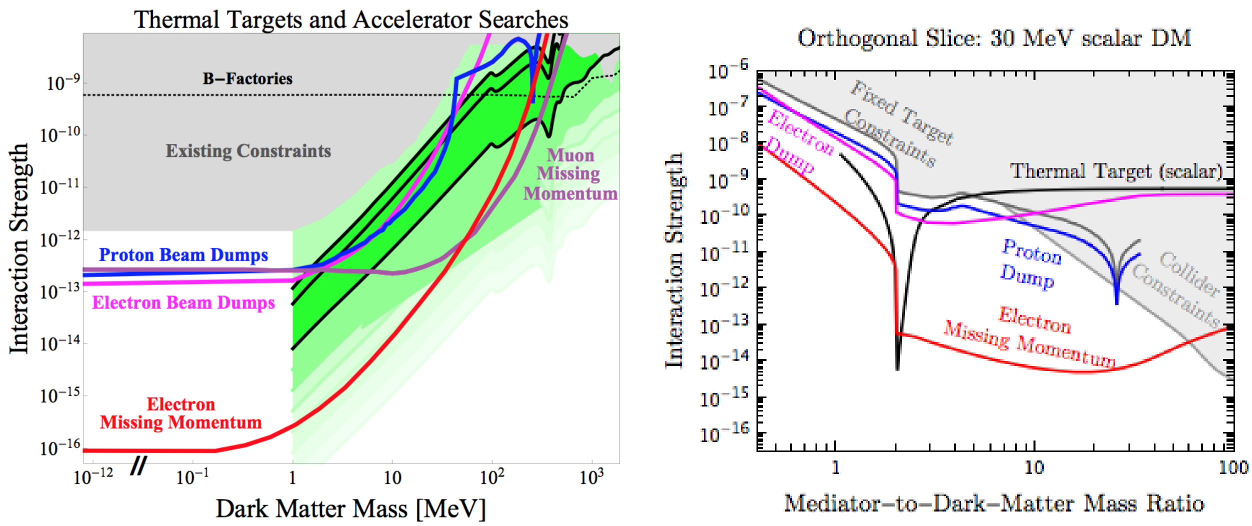

Figure 4-2: *Two plots illustrating the sensitivity of current searches (gray shading) to dark matter production (Thrust 1), and improvements achievable through the concepts presented in Table 4-2, which roughly characterize what can be feasibly achieved by each experimental approach. The left plot shows the sensitivity vs. dark matter mass for fixed DM-mediator mass ratio of 1/3. The vertical axis labeled "Interaction Strength" is defined as the product $y = \varepsilon^2 \alpha_D (m_{DM}/m_{mediator})^4$, where ε is the kinetic mixing parameter for a dark photon model, and α_D is the dark-force counterpart of the fine structure constant (Refs. 67 and 68). The green band represents the region favored by thermal dark matter production in the early universe; the black curves are predicted interaction strengths for thermal dark matter with specific dark matter spins. Lighter green regions above and below the bright green band represent the weaker predictions in special regions of parameter space, e.g. Ref. 69. The bottom gray curve is a production benchmark for elastically decoupling dark matter (ELDER) that acquires its abundance by scattering off visible matter instead of annihilating into it.[70] The right plot fixes the dark matter mass at 30 MeV and specializes to scalar dark matter, but varies the ratio of mediator to dark matter mass to exhibit the resonance structure in the thermal prediction and the mediator-mass-dependence of experimental sensitivity. Curves in right panel courtesy of Asher Berlin and Patrick deNiverville.*

However, even a series of null searches is extremely scientifically valuable. Since accelerator-based searches offer comprehensive sensitivity to thermal dark matter, they can exclude a broad class of models for dark matter with mass between the electron mass and few times the proton mass – roughly half of the (log) mass range compatible with a thermal production history. Together with established searches for thermal relics above the proton mass, they can test many of the most compelling thermal dark matter candidates, powerfully informing future searches for dark matter.

The techniques that comprise this program vary in how they address these possibilities. Missing-momentum experiments have the potential to cover the most parameter space for thermal dark-matter candidates. Beam-dump experiments cover less of the parameter space, but would enable a multi-faceted program of measurements to illuminate the nature of any new phenomena observed. Finally, spectrometer experiments offer a complementary set of measurements to explore the nature of the dark sector and are also sensitive to scenarios for thermal dark matter that would go undetected using the other two approaches.

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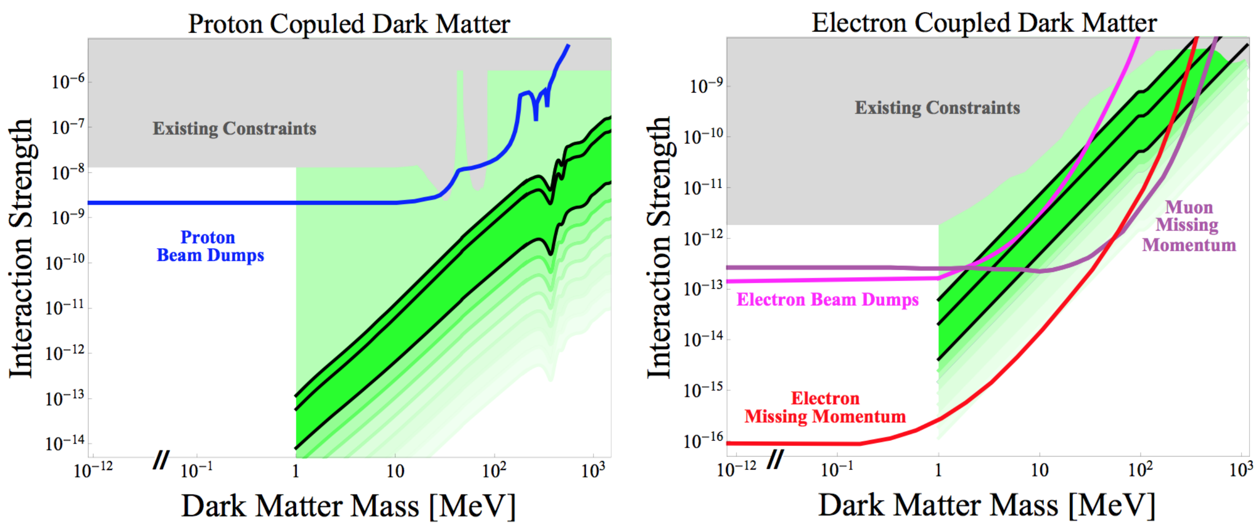
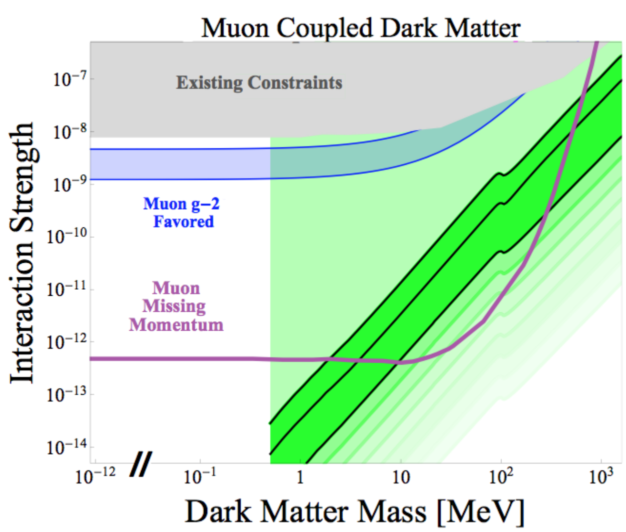
[69] J. L. Feng and J. Smolinsky, Phys. Rev. D96 (2017) 095022.

[70] E. Kuflik, M. Perelstein, N. Rey-Le Lorier, and Y.-D. Tsai, Phys. Rev. Lett. 116 (2016) 221302.





Interactions	Thrust 1				Thrust 2
	p BD	*e* BD	*e* MM	*μ* MM	Spectrom
Hadron couplings	X	m			varies
Electron couplings	m	X	X		varies
Muon couplings				X	varies

Figure 4-3: *Accelerator sensitivity for dark matter models with preferential couplings to protons (left) electrons (right), and muons (bottom left). These green regions and black curves follow the same conventions as Figure 4-2, but here the existing constraints and future accelerator projections differ on account of the model variation. The blue band in the bottom left plot represents parameter space for which a muon-specific interaction can resolve the anomaly between theoretical and measured value of muon $g\!-\!2$. In the bottom right is a table summarizing the couplings needed for discovery of dark matter in each class of experiment (X) and additional couplings that can be measured, if present (m).*

These scientific opportunities have initiated a growing international search program of experiments at multiple laboratories worldwide including CERN, KEK, INFN-LNF, and Mainz. However, the U.S. DOE accelerator infrastructure, which includes multi-GeV CW electron beams, multiple high-intensity proton beams, and dedicated muon beams, offers a unique opportunity to comprehensively explore thermal relic dark matter.

Thanks to their multi-purpose nature, these facilities will also be able to address additional open questions in particle physics, beyond the nature of dark matter: what is the origin of neutrino masses and oscillations? How to address the strong CP problem? What is the origin of the baryon-antibaryon asymmetry of the universe? How to address present anomalies in data like the one in muon (g–2) or the ones in B-physics? This ambitious program will be achieved by searching for a plethora of different visible signals as arising from sterile neutrinos, new force carriers, axion-like particles, and dark scalar models.

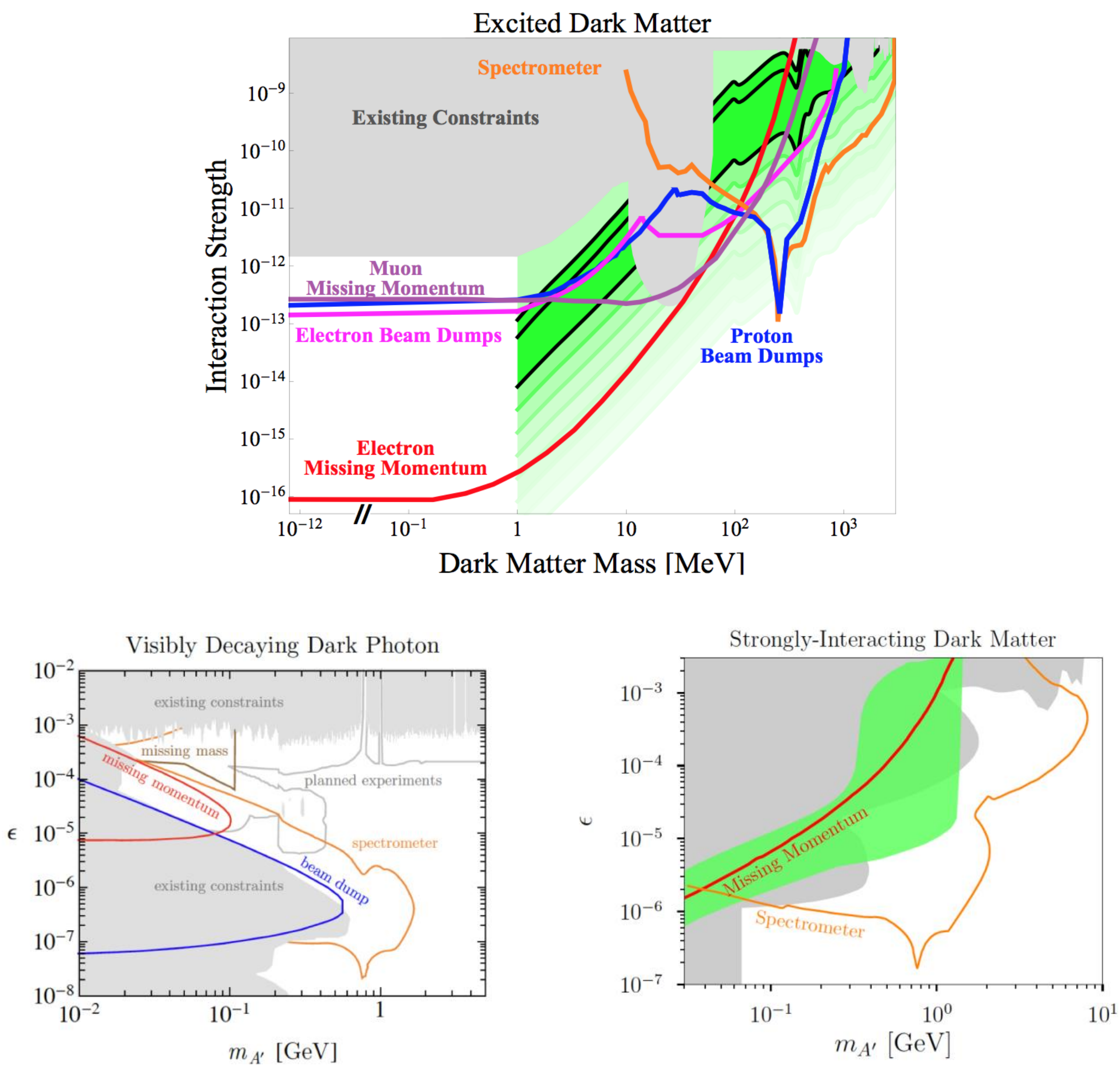


Figure 4-4: *Sensitivity plots for several models of unstable dark sector particles (Thrust 2). The top panel illustrates sensitivity to "exciting dark matter" models where dark matter is produced in combination with an excited state, both cosmologically and at accelerators, and the excited state decays semi-visibly. The illustrated thermal milestones are analogous to those in Figures 4-2 and 4-3. Spectrometer experiments are sensitive to the decay of the excited state, while beam dump experiments can search for both scattering and decay signals. The semi-visible signal opens up sensitivity for both classes of experiments to higher-mass parameter space. The bottom left panel illustrates the sensitivity to dark photon mediators decaying visibly. The gray non-shaded regions are the estimated sensitivities for planned experiments. The bottom right panel illustrates sensitivity to strongly-interacting dark sectors, with the cosmologically motivated band shown in green. Bottom two panels courtesy of Asher Berlin.*

Direct Detection Panel Report

Current Status and Recent Theoretical and Technological Advances

Direct detection experiments are essential tools for identification of dark matter. These experiments have traditionally focused on searching for nuclear recoils induced by WIMPs in the Milky Way dark-matter halo scattering off nuclei in various target materials, and are typically placed underground to reduce backgrounds generated by cosmic ray interactions. They employ sensitive equipment to measure recoils of order a keV and greater, and state-of-the-art target-material fabrication and purification to reduce contaminants that could mimic a dark matter signal. Great technological and theoretical advances have been made in the last few decades in searching for WIMP dark matter.

Current experimental landscape

The current experimental landscape for direct detection is focused on extending sensitivity to WIMPs with masses down to a GeV by looking for elastic scattering between WIMPs and nuclei. Leading this effort are the DOE G2 experiments LZ and SuperCDMS and competing international experiments. By 2025 these will have explored spin-independent WIMP-nucleon coupling to within an order of magnitude of the so-called neutrino floor, the irreducible background of nuclear scattering from solar, atmospheric, and astrophysical neutrinos. LZ will also have significant sensitivity to spin-dependent dark matter couplings as will PICO-500, a dedicated spin-dependent experiment in Canada. Unlike the spin-independent case, dedicated spin-dependent searches with light elements can continue to push several orders of magnitude in sensitivity beyond the current suite of experiments before reaching the irreducible neutrino background. There are also ongoing efforts to develop directional detection techniques to push beyond the neutrino floor, as well as dedicated investigations of the DAMA/LIBRA annual modulation. Continued exploration and experimental advances targeting high-mass WIMP parameter space remain an important component of the direct detection program, but are not discussed further in this document.

Current theory landscape

Current direct detection experiments are searching the preferred parameter space where weak-scale dark matter interacting with the standard model via the Higgs boson is expected to be observed. Theoretical advances in the last decade have shown, however, that a wider panorama of models gives rise to new signatures that would not be observed in the experiments designed to search for WIMPs having mass around the weak scale. In these theories, dark matter is part of a hidden sector, or hidden valley, with new forces that govern the dynamics, independent of the structure of the Standard Model (or its problems). The abundance of such hidden-sector dark matter may still be set by its interactions with the Standard Model. In this case, theory points to a new framework where dark matter, detectable in a new generation of direct detection experiments, has a mass in the meV to GeV mass range, having a wide range of interaction cross sections. A number of these models, such as freeze-in and asymmetric dark matter, predict interaction rates with electrons or nuclei that could be observed with much smaller exposures than the ton-scale WIMP experiments, but which are currently consistent with all known astrophysical and cosmological constraints. For a summary and an extensive list of references see Ref. 71.

[71] M. Battaglierei et al., arXiv:1707.04591.

Recent technological advances

Recent advances in technology have enabled the possibility to probe well-motivated dark matter candidates over twelve orders of magnitude using innovative detectors. As an example, athermal phonon calorimeters instrumented with transition edge sensors (TES) have demonstrated 3.5 eV sensitivities in very large area (46 cm^2) optical photon detectors as well as 72 meV in small prototype test structures. These achievements suggest that 1 cm^3 crystal and superfluid He volumes can currently be probed with 200 meV nuclear recoil energy sensitivity. Notably, even established experimental detection technologies have made substantial improvements in the past two years that have significantly improved their light mass dark matter search potential. Silicon CCDs, for example, have been instrumented with electronics that multiply measure a single pixel bringing their resolution down to 0.06 electrons from 2 electrons.[72] Likewise, the scintillation ionization yield for inorganic crystals (CsI, NaI, GaAs) has also been shown to increase substantially as the crystals are cooled; at 77 K, undoped CsI is nearly perfectly efficient at converting conduction band electrons into scintillation photons.[73]

Scientific Opportunities and Challenges

Figures 4-5 through 4-8 summarize near-, medium-, and longer-term efforts to probe dark matter twelve orders of magnitude below the proton mass.

Near term: Detector thresholds at the eV scale

Multiple detector technologies have now demonstrated eV-scale thresholds, potentially enabling both elastic nuclear recoil and inelastic electronic-recoil dark matter searches at lighter masses than previously possible.[74] These technologies include single-electron ionization counting in noble gases and liquids (Figure 4-9), single-photon scintillation counting in scintillating crystals, single-electron-hole-pair counting in semiconductors, low-threshold phonon observations in crystals and superfluids, and threshold detectors using superheated or supercooled fluids. Below we describe these technologies in some depth, summarizing their current status and highlighting the remaining R&D challenges.

Single-eV-scale electronic excitation sensitive detectors

In all detector technologies that measure the number of electronic excitations, the fundamental dark matter mass reach is set by the energy required to produce a single electronic signal quantum. For inelastic electronic dark-matter scattering, this ionization energy (1-10 eV depending on the material) corresponds to a mass reach 1 MeV-10 MeV. For elastic nuclear-recoil searches, the ultimate mass reach is suppressed by kinematics (a smaller fraction of energy can be transferred to the massive nucleus) and efficiency (the fraction of nuclear recoil energy that is converted into potential energy of electronic excitations is significantly smaller), corresponding to a mass reach of some hundreds of MeV.

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[72] SENSEI Collaboration, Phys. Rev. Lett. 119 (2017) 131802.

[73] S. Derenzo, E. Bourret, S. Hanrahan, and G. Bizarri, arXiv:1802.09171.

[74] R. Essig, J. Mardon, and T. Volansky, Phys. Rev. D85 (2012) 076007.

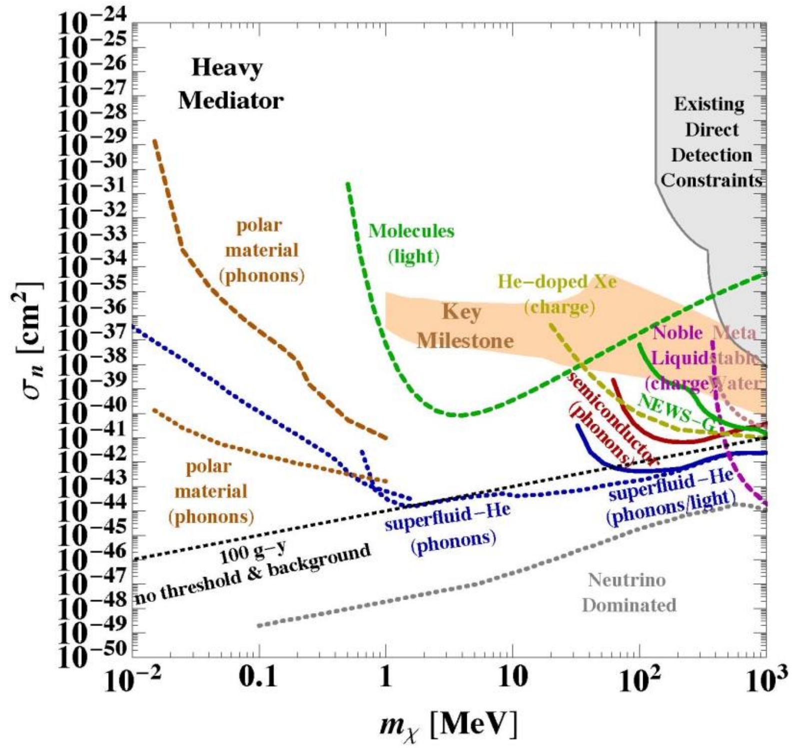

Figure 4-5: *Open parameter space for galactic dark matter scattering off nuclei (through a heavy mediator) that can be probed with advanced detectors with demonstrated or near-term technologies (solid lines) and with either medium-term (dashed lines) to longer-term (dotted lines) R&D. The readout technique is indicated in parentheses below the target material. Neutrinos begin to dominate the rate below the gray dotted line. A modest exposure of 100 g-years can probe extremely low cross sections as long as the detector has the requisite energy sensitivity and sufficiently low backgrounds (black dotted line).*

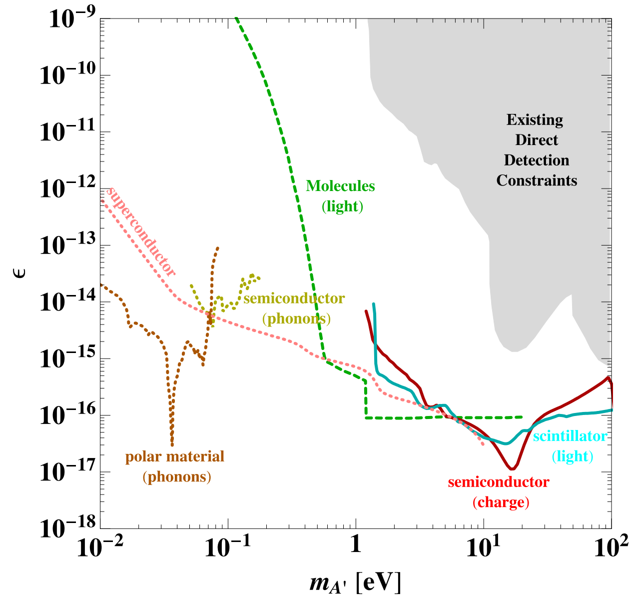

Figure 4-6: *Open parameter space for galactic dark photon dark matter being absorbed by electrons or other excitations that can be probed with advanced detectors. The parameter ε is the kinetic mixing parameter of the dark photon.*

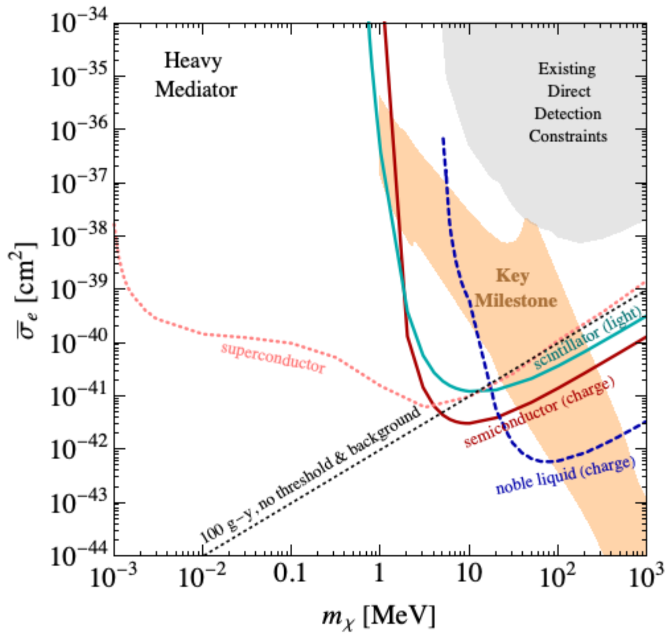

Figure 4-7: *Open parameter space for galactic dark matter* ***scattering*** *off* ***electrons*** *that can be probed with advanced detectors with demonstrated or near-term technologies (solid lines) and with either medium-term (dashed lines) to longer-term (dotted lines) R&D. The readout technique is indicated in parentheses below the target material. Dark matter interacting with electrons through a heavy mediator is assumed.*

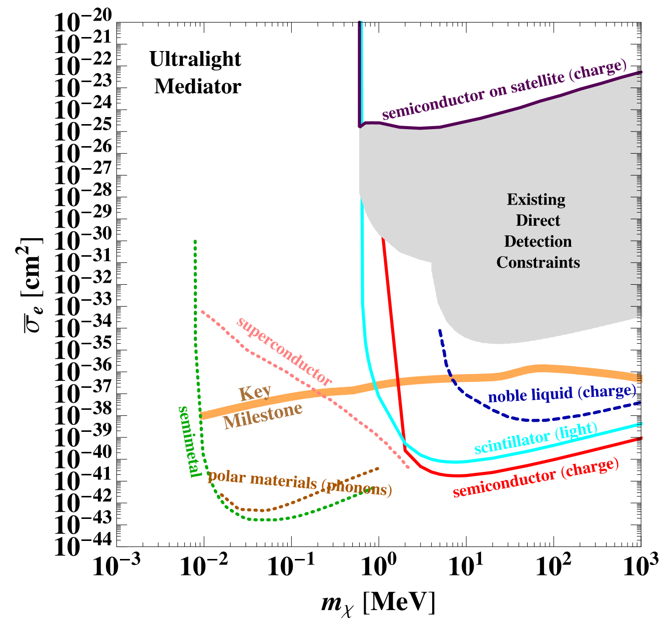

Figure 4-8: *Open parameter space for galactic dark matter* ***scattering*** *off* ***electrons*** *that can be probed with advanced detectors with demonstrated or near-term technologies (solid lines) and with either medium-term (dashed lines) to longer-term (dotted lines) R&D. The readout technique is indicated in parentheses below the target material. Dark matter interacting with electrons through either a heavy mediator an ultralight mediator is assumed. The orange regions (labelled "Key Milestone") present a range of model examples in which dark matter obtains the observed relic abundance from its thermal contact with Standard Model particles (regions are as in "US Cosmic Visions" report, Ref. 8.*

Though the electronic excitation measurement techniques discussed below are enormously varied, many of them share a common feature: they use large E-fields to either drift ionization and/or amplify the signal. Unfortunately, these same large E-fields can produce electronic excitations by enabling quantum tunneling processes (dark counts) that are indistinguishable from the dark matter interaction signals. The rate of these dark counts varies with the excitation type, material, and sensor technology, and should be used as a metric of readiness in the near term. Dark counts may arise from both surface and bulk effects. Understanding the sources of these excitations, along with eventually mitigating them to the extent possible, is a unifying short-term R&D theme that cuts across all technologies.

Detector response to nuclear recoils must be well calibrated in the dark-matter signal range in order for experiments to fully exploit their light-mass dark-matter nuclear recoil search capability. Currently, only germanium, silicon, and xenon have measured nuclear recoil ionization yields below 1 keV, and it is expected that low-energy silicon nuclear recoil ionization yields will be measured down to 50 eV within the next year. Due to the difficulty of these calibrations, the inelastic electronic recoil channel will probably be the preferred channel for early experiments. Once a nuclear recoil calibration is available, the existing data can then be used to immediately explore this valuable channel.

Electrons in gases and noble liquids: By taking advantage of ionization drift regions with large E-fields that can amplify the small charge signal produced by the interactions of light mass dark matter particles, gaseous drift chambers and dual-phase noble liquid time projection chambers (TPCs) have long had the capability to measure the single- or few-electron excitations produced by inelastic electronic dark matter interactions.[75] This sensitivity, in combination with the properties that have made noble liquid dual-phase TPCs the technology of choice for higher-mass dark matter searches (namely, excellent radiopurity and ease of scalability to large masses), have meant that nearly every argon and xenon high mass WIMP experiment of the last decade has attempted to search also for lighter mass dark matter.

Though these searches have been world-leading throughout the last decade, their sensitivity to light-mass dark matter has been limited by few-electron dark count rates that have proven hard to suppress. R&D into the causal mechanisms of these dark counts has been ongoing since the light mass dark matter search with XENON10. A dedicated small-mass experimental program may be advantageous in reducing these backgrounds. For example, a large fraction of the surface of the LZ time projection chamber is PTFE Teflon due to its very high reflectivity for xenon scintillation, which helps to maximize the collected scintillation signal for high energy nuclear recoils. However, this Teflon may also produce delayed scintillation that can ionize impurities in the noble liquid, producing few-excitation events that look identical to putative light dark matter signals. Also, higher electric fields may enable more efficient collection of electrons from high-energy events and help to limit delayed electron emission that can be a background for light dark matter. In summary, successful completion of short term R&D with small experimental test setups into the source of, and mitigation techniques for, few-electron dark count backgrounds would allow experimental concept development to begin.

The sub-GeV reach of liquid-xenon or liquid-argon detectors can be further extended by doping with lighter species (such as helium or hydrogen) since the light nuclei have favorable kinematic matching with low-mass dark matter and larger efficiency for generating electronic signals. Hydrogen doping also gives sensitivity to spin-dependent interactions, which are currently completely unexplored for dark

[75] XENON10 Collaboration, Phys. Rev. Lett. 107 (2011) 051301; Erratum: Phys. Rev. Lett. 110 (2013) 24990; R Essig, A. Manalaysay, J. Mardon, P. Sorensen, and T. Volansky, Phys. Rev. Lett. 109 (2012) 021301; DarkSide Collaboration, Phys. Rev. Lett. 121 (2018) 111303.

matter masses below a GeV. Doping a large liquid detector preserves the substantial self-shielding of external backgrounds by the heavier noble liquid and requires only sub-percent doping levels by mass. Gaseous detectors using light atoms as targets may also be sensitive to sub-GeV dark matter, provided a sufficiently low energy threshold is obtained.

Crystalline scintillators: These are attractive due to their simplicity of deployment and tunability of material properties, the key property being the electronic bandgap of the material; the smaller the bandgap, the larger the inelastic electronic recoil dark-matter rate. Secondary characteristics include the nuclear-recoil scintillation yield and the level and type of metastable sites that may produce dark counts via delayed emission. Within crystalline scintillators, sodium iodide and cesium iodide are long-standing technologies that have just recently been shown to have nearly double the scintillation yield when operated at 77 K instead of room temperature. For these larger bandgap materials with larger scintillation photon energies, photomultipliers tubes (PMTs, which are steadily improving in quantum efficiency) and silicon photomultipliers (SiPMs, a recent technology) are both possibilities to achieve the necessary single-photon sensitivity. Due to dark count rates inherent in both of these amplification technologies, multiple sensor coincidence would need to be employed to discriminate between dark counts and dark matter signals.

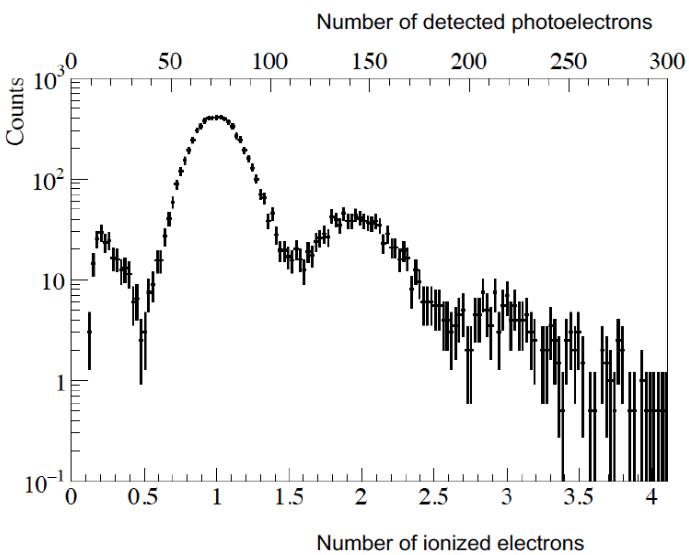

Figure 4-9: *Single-electron sensitivity as demonstrated in a kilogram-scale dual-phase xenon detector. The lower axis shows the number of ionized electrons in the liquid xenon. The upper x-axis shows the number of photoelectrons detected from the luminescence of the ionized electron as it moves through the gas phase.*

Due to its very small bandgap (1.55 eV), lack of measurable afterglow (few meta-stable excited electronic states), and large scintillation yields below 120K, gallium arsenide has excellent light-mass dark-matter potential.[76] Due to the small photon energies, however, readout options are more constrained, since currently available PMTs and SiPMs have poor quantum efficiency in the near IR. Potentially, specially designed SiPMs with much thicker drift regions for better photon collection efficiency or indium gallium arsenide-based avalanche detectors could achieve the necessary performance. Another promising readout option is the use of large area photon calorimeters. With measured performance of 3.5 eV in 45 cm^2 devices, it's expected that single-photon thresholds with near unity quantum efficiency and near zero dark count rates could be achieved in 1 cm^2 device geometries. Once the necessary calorimeter sensitivity is confirmed (expected to be on the 6 month

[76] S. Derenzo, R. Essig, A. Massari, A. Soto, and T.-T. Yu, Phys. Rev. D96 (2017) 016026; S. Derenzo, E. Bourret, S. Hanrahan, and G. Bizarri, arXiv:1802.09171.

time scale), concept development should be possible. Yet another option is to use superconducting nanowire single-photon detectors (SNSPD), assuming they can be scaled up in size.

Semiconductor technologies*:* Due to their small electronic bandgaps, semiconductor detector technologies have both large inelastic electronic recoil scattering rates (for a nominal free-electron dark-matter interaction cross section) and the ability to probe to very low dark matter masses; they have excellent light mass dark matter sensing potential.[77]

Only recently, however, have semiconducting technologies been able to achieve the necessary single electronic quanta sensitivity. Specifically, CCD readout electronics have been modified to independently measure a single pixel multiple times, thereby suppressing the low frequency measurement noise that dominates any single measurement. With this technique, measurement noise has been shown to be only 0.06 electrons.[78] Low-temperature semiconducting calorimeters have also recently shown sub-single excitation sensitivity.[79] In this measurement technique, an electronic excitation is drifted across a voltage, converting electrostatic potential energy into vibrational energy that is then sensed.

As with other single electronic excitation technologies, both CCDs and voltage-biased calorimeters exhibit an unwanted dark-count rate. Significant R&D on minimizing these backgrounds is ongoing. In CCDs, the dark count rate has been correlated to impurity densities, and thus next generation setups are being fabricated from highest available purity silicon. Furthermore, the small pixel volume minimizes the probability that multiple single dark counts occur within the same pixel during an individual readout period, minimizing multi-excitation dark matter signal contamination. For voltage-biased calorimeters, the majority of the dark counts have been determined to be autoionization of over-charged impurities in the bulk of the crystal, and R&D is currently focused on ionizing these states before commencing the dark matter search with very large E-fields or thermal excitation.

Experiments with 100 g and 1 kg of silicon CCD target material are already at the experimental concept development stage (Figure 4-10). Given their compact size, silicon CCD detectors are also ideal for balloon or space-based experiments that search for strongly interacting dark matter candidates that will not reach ground-based experiments due to interactions with the atmosphere. For calorimeters, successful completion of dark current mitigation R&D (ongoing now) would allow for concept development to commence.

Another approach to detecting single electrons is to amplify this ionization within the detector itself. Doped germanium detectors may be able to achieve single- or few-electron sensitivity in the future, though perhaps with increased dark current. R&D would be needed to test the performance of this method in comparison with CCD and voltage-based calorimeters.

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[77] R. Essig, J. Mardon, and T. Volansky, Phys. Rev. D85 (2012) 076007; P. Graham, D. Kaplan, S. Rajendran, and M. Walters, Phys. Dark Univ. 1 (2012) 32-49; S. Lee, M. Lisanti, S. Mishra-Sharma, B. Safdi, Phys. Rev. D92 (2015) 083517; R. Essig, M. Fernandez-Serra, J. Mardon, A. Soto, T. Volansky, and T.-T. Yu, JHEP 1605 (2016) 046; Y. Hochberg, T. Lin, and K. Zurek, Phys. Rev. D95 (2017) 023013; I. Bloch, R. Essig, K. Tobioka, T. Volansky, and T.-T. Yu, JHEP 1706 (2017) 08.

[78] SENSEI Collaboration, Phys. Rev. Lett. 119 (2017) 131802; Phys. Rev. Lett. 121 (2018) no.6, 061803.

[79] R. Romani et al., Appl. Phys. Lett. 112 (2018) 043501; SuperCDMS Collaboration, Phys. Rev. Lett. 121 (2018) 051301.

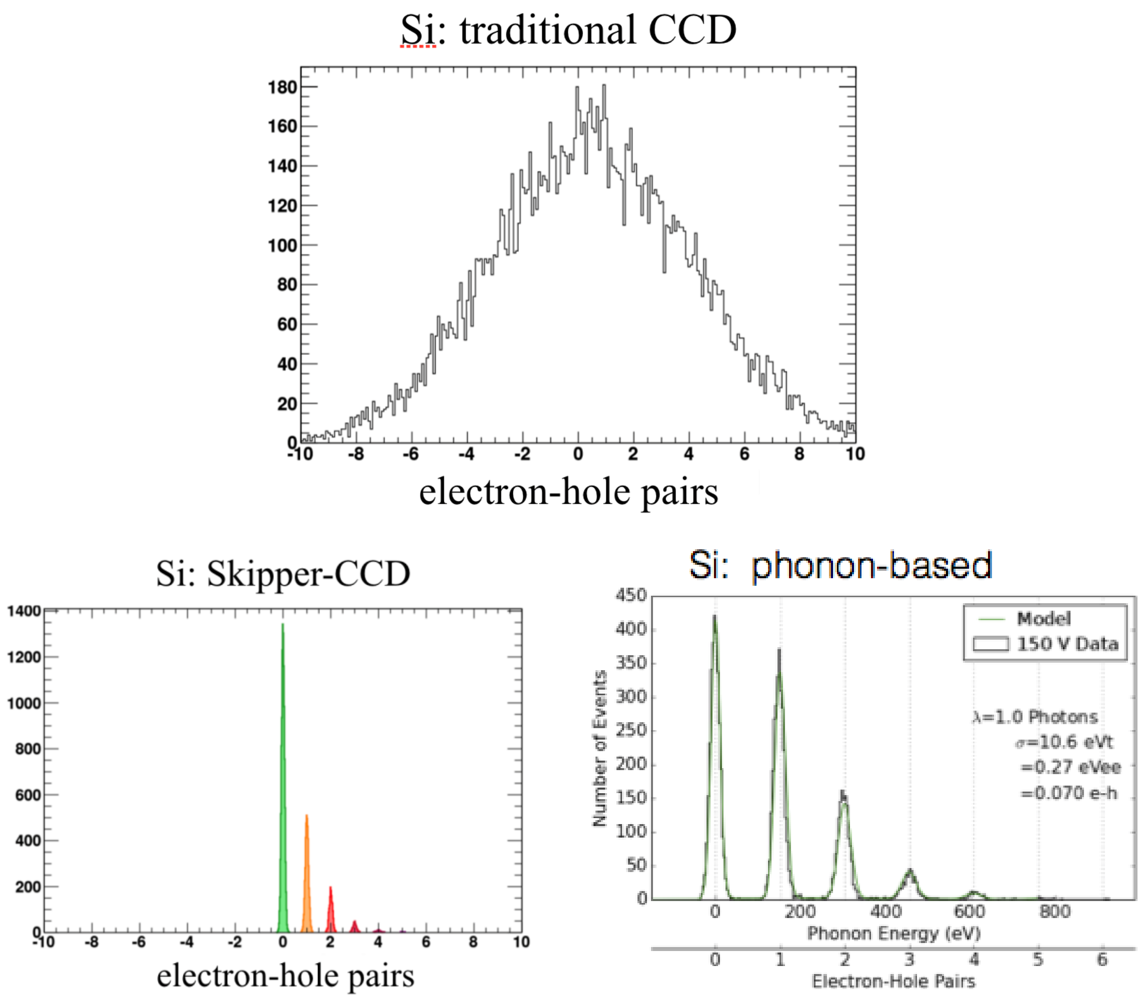

Figure 4-10: *Some example counting spectra, highlighting two parallel recent advances to counting single electron-hole pairs in a Si target.*

Sensing vibrations with eV scale sensitivity

All energy that is deposited in any detector material via interaction with dark matter will eventually be converted via thermalization processes into potential energy of long-lived electronic states, low-energy photons, and vibrations. Consequently, the measurement of vibrational energy is a complementary light mass dark matter search strategy to those searching for electronic excitations. One advantage of these vibrational sensing techniques is that the vibrational energy quanta are of the meV scale, and thus, in principle, these detectors can be sensitive to dark matter much lighter than an MeV. Secondly, in nuclear recoil interactions, the vast majority of the transferred energy is converted into vibrational energy, allowing low energy thresholds and straightforward calibrations. Finally, calorimeters do not typically use E-fields to drift electrons or amplify electronic charges; as such this set of techniques is naturally not susceptible to dark counts. Due to the minimal signal amplification, calorimetric techniques are susceptible to a variety of environmental noise sources that are not problematic for other measurement techniques. Most notably, mechanical vibrations due to refrigeration equipment and electromagnetic radiation from cell phones and experimental electronics can mimic dark matter signatures unless carefully shielded.

Over the last 2 years, large-mass, large-area calorimeters have made over an order-of-magnitude improvement in sensitivities. In particular, a 45 cm^2 silicon calorimeter that was designed for optical photon detection has achieved a sensitivity of 3.5 eV. To set the magnitude of this improvement, the large volume calorimeters used by SuperCDMS at Soudan had resolutions of 200 eV. Small sensor-only test structures have now also been measured with 40 meV resolution. The combination of these achievements suggests that eV-scale thresholds can be achieved in a variety of different experimental setups that use calorimeters.

Phonon sensors instrumenting crystals: The first phonon-based approach is to instrument a crystalline target mass with phonon sensors in direct contact with the target mass. This approach is conceptually similar to existing efforts at higher thresholds (such as SuperCDMS, EDELWEISS, and CRESST) except for two significant optimizations. First, the volume of an individual detector has been decreased by nearly three orders of magnitude to improve calorimeter sensitivity. Second, the fraction of the crystal surface that is instrumented with sensors has decreased by an order of magnitude, which sacrifices position information for energy sensitivity. With the recent technical achievements discussed, it is estimated that 1 cm^3 (2 g) silicon calorimeters will achieve 1.5 eV thresholds and can thus potentially search both for dark matter nuclear recoils and inelastic electronic recoil channels. Once demonstrated, this experiment would be immediately ready for conceptual development.

Phonon sensors instrumenting superfluid: The second phonon-based approach is to instrument a superfluid helium target mass with atomic sensors, likely calorimetry.[80] Phonons (and the phonon-like excitations known as "rotons") in superfluid helium diffuse in the target material as in a crystal, with the difference that at the top surface that interfaces with the vacuum, the phonon can liberate a ^4He atom in a 1-to-1 process termed "quantum evaporation". This conversion of a pulse of phonons to a pulse of ^4He atoms in vacuum enables an energy gain mechanism in which the evaporated atoms gain energy (10 to 40 times) in their adhesion to the sensor surface. As with the crystal-based techniques, this superfluid-based technique has been demonstrated (HERON) and now is ready to similarly benefit from recent advancements in calorimetry. This experiment is ready for conceptual development.

Threshold detectors: Detectors based on superheated or supercooled liquids use a phase transition from a metastable state to amplify the vibrational energy deposited by a dark matter interaction. Recent advances indicate these detectors could have sensitivity to sub-GeV dark matter, either by reducing the threshold for the phase transition (superheated noble liquids) or by utilizing low-mass target nuclei (supercooled water). These approaches emphasize scalability and background rejection over threshold reduction, targeting dark matter masses in the 100 MeV to GeV range. R&D is needed to demonstrate requisite sensitivity to low-energy nuclear recoils.

Medium and longer term: Developing sensitivity to 1-100 meV excitations

***Extending the mass range*:** By achieving sensitivity to sub-eV excitations, we can extend the sensitivity to the scattering of dark matter particles with mass below 1 MeV and the absorption of dark matter particles with mass below 1 eV. Having single-quantum sensitivity to meV excitations extends the searchable dark matter mass range by 3 orders of magnitude for electronic scattering and absorption, and 5 orders of magnitude for nuclear scattering search channels relative to that expected from techniques that use eV-scale excitations. In some cases, the techniques and excitations are similar to

[80] H. Maris, G. Seidel, and D. Stein, Phys. Rev. Lett. 119 (2017); S. Hertel, A. Biekert, J. Lin, V. Velan, and D. McKinsey, e-Print: arXiv:1810.06283.

those discussed previously, but the dark matter interaction rates and kinematics are qualitatively different; for sub-eV excitations, the momentum transfers involved are typically so small, corresponding to length scales large compared to the atomic spacing in materials, that the dark matter interacts directly with many-body excitations rather than with a single nucleus or electron.

Quanta at the 1-100 meV scale: Once the dark matter mass drops below an MeV, the deBroglie wavelength of the dark matter exceeds the interparticle spacing. In this case, dark matter excitation, and subsequent detection, of coherent modes (phonons) can extend the dark matter mass search range significantly. In all crystals, dark matter scattering and absorption via nucleon and electromagnetic couplings can create acoustic or optical phonons with a wide energy spectrum up to hundreds of meV. In polar crystals, production of optical phonons (30-100 meV in sapphire) by dark matter scattering or absorption via electromagnetic couplings is enhanced by the unit cell's internal electric dipole.[81] Liquid helium offers its own unique quantum ground state, superfluidity. Its quantum excitations, phonons and rotons, can be created by interactions of dark matter with nuclei and electrons and can propagate large distances due to the intrinsic material purity.[82] Other quanta at the 100 meV energy scale include vibrational modes in molecules. Following a dark-matter scattering or absorption event, the excited molecule can spontaneously decay, producing one or more photons; in the case of absorption, the photons can be emitted coherently and focused in direction onto a tiny photodetector.[83] Finally, magnetic systems offer a distinct meV-scale quantum excitation corresponding to the flip of a magnetic dipole moment in an external field.[84]

Superconducting crystals offer, in addition to phonons, quasiparticles arising from the breaking of Cooper pairs.[85] These quasiparticles can be created directly by the dark matter interaction (via electromagnetic coupling), both via scattering or absorption, possibly with the emission of a phonon. Alternatively, a phonon directly produced by the dark matter interaction (both nuclear and electromagnetic couplings) can break Cooper pairs to create quasiparticles. In either case, the quasiparticles can propagate useful distances in high-quality crystals. Novel Dirac materials with smaller electronic bandgaps than standard semiconductors may have similar energy thresholds and dark matter mass reach as polar crystals and superconductors.[86]

***Transduction of meV-scale energy depositions*:** Since the coherent excitations produced by very light-mass dark-matter interactions have energies similar to the random vibrational kinetic energy of an atom at room temperature, the detector target material must necessarily be cooled to near absolute zero. Due to this temperature constraint, it is natural to consider using superconducting sensor technologies for transduction of these excitations into measurable electrical signals.

Superconducting transition edge sensors (TESs) and microwave kinetic inductance detectors (MKIDs) transduce these small energy excitations into a change of impedance. As noted above, TESs have demonstrated few-eV resolution and are expected to imminently demonstrate 250 meV energy resolution *integrated with a silicon target substrate*. Calculations imply that meV-scale resolution can be achieved by reducing the transition temperature of the superconductor (T_c) and the volume of the

[81] S. Knapen, T. Lin, M. Pyle, and K. Zurek, Phys. Lett. B785 (2018) 386.
[82] S. Hertel, A. Biekert, J. Lin, V. Velan, and D. McKinsey, arXiv:1810.06283.
[83] A. Arvanitaki, S. Dimopoulos, and K. Tilburg, Phys. Rev. X8 (2018) 041001.
[84] P. Bunting, G. Gratta, T. Melia, and S. Rajendran, Phys. Rev. D95 (2017) 095001.
[85] Y. Hochberg, M. Pyle, Y. Zhao, and K. Zurek, JHEP 1608 (2016) 057.
[86] Y. Hochberg et al., Phys. Rev. D97 (2018) 015004.

sensor. MKIDs have demonstrated resolution roughly at this level for individual sensors. For integration with a substrate, a roughly 100x gain is required to yield comparable performance (e.g., Ref. 87). Optimized MKIDs are expected to provide sub-eV-scale resolution soon, and reducing the T_c and volume and employing kinetic inductance parametric amplifiers for MKID readout should also provide meV-scale resolution.

Another possible readout path is to use magnetic materials whose magnetization changes due to the absorption of this excitation. This magnetization change could then be readout via SQUID, an extremely sensitive superconducting device that measures magnetic fields. Such devices can be run without amplification where the magnetization change is linearly related to the energy absorbed (e.g., Ref. 88). Alternatively, it has been proposed to operate these devices in "bubble chamber" mode, where the small initial signal would be enormously amplified: the detector can be initialized to be anti-aligned to an external magnetic field and thus have a large amount of magnetic potential energy. A small thermal energy deposition could then begin a spin avalanche, flipping the magnetic dipole of the detector and releasing additional energy.

While all these quantum excitations offer plausible options for extending the searchable dark matter mass range, R&D work is required to provide explicit demonstrations of the desired energy thresholds. Given the wide range of concepts that make use of TESs and MKIDs, we next discuss in more detail the current state and the R&D needed for a number of proposed detection techniques.

Phonon sensors instrumenting semiconducting and polar insulating crystals*:* While this topic has been discussed above in the context of eV-scale energy depositions, it is worth revisiting deposition energies below the characteristic vibrational energy scale for crystals (30-100 meV). At these scales, the deposition energy is too small to liberate a nucleus or electron from its site in the lattice, and also the wavelength associated with the momentum transfer is so large that the dark matter interacts with many lattice sites simultaneously. This interference modifies both the kinematics and the interaction rate. For crystals with very large acoustic sound speed like diamond and sapphire, acoustic phonons with energies greater than a meV can be generated via scattering by dark matter with mass greater than 10's of keV. Dark matter can be probed to even lower masses with back-to-back phonon excitation processes, where momentum conservation constraints are easy to satisfy and thus all of the kinetic energy (scattering) or total energy (absorption) of the dark matter can be converted into phonon excitation energy production.[89] The rates for these second-order processes are generally suppressed. In crystals with multiple atoms in the unit cell like GaAs, an optical phonon is a vibration where the Ga and As atoms have opposite directions of motions. These excitations are gapped (i.e., zero-momentum excitations have non-zero energy), and thus efficient energy transfer from light mass dark matter is possible even for single-phonon creation processes. Polar materials typically have excellent reach to dark photon/ electromagnetic couplings, where ions are naturally pushed in opposite directions.

Detection of single rotons and phonons in superfluid helium with meV-capable sensors**:** Since helium atoms are nearly non-interacting with each other, their vibrational states have a characteristic energy scale of meV rather than the 30-100 meV found in most crystals. This very low vibrational energy scale means that even 1 MeV dark matter can potentially scatter off each and every He atom individually;

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[87] D. Moore et al., Appl. Phys. Lett. 100 (2012) 232601; L. Cardani et al., Superconductor Sci. Technol., 31 (2018) 075002.

[88] L. Fleischmann et al., IEEE Trans. Appl. Superconduct. 19 (2009) 63.

[89] K. Schutz and K. Zurek, Phys. Rev. Lett. 117 (2016) 121302.

there is a large kinematic phase space for dark matter interactions, and thus rates remain high. On the other hand, the characteristic recoil energy of these interactions is small; sensitivity to single meV nuclear recoils is necessary to probe the MeV mass scale. Searches for dark matter with masses well below an MeV are also possible via offshell production of nearly back-to-back rotons.[90] The calorimetric strategy to sense these few superfluid helium vibrational quanta is identical to those proposed for the near-term eV nuclear recoil search that is ready for conceptual development; the only improvement that is required is enhanced calorimeter sensitivity. A second approach is proposed for detection of single helium atoms, namely, through field ionization. Since the resulting helium ions and electrons could then be accelerated by electric fields, they could be detected with higher signal strength, though perhaps at the expense of larger dark currents.

Phonon sensors instrumenting superconducting crystals: Superconducting crystals present the opportunity to search for nucleonic couplings via phonon production just like insulating crystals and for electromagnetic couplings via the breaking of a single Cooper pair with meV scale energies. In the latter case, liberated quasiparticles could then be sensed directly in very clean crystals with very long quasiparticle lifetimes, or they could be detected by sensing the athermal phonons produced during quasiparticle recombination. Detailed sensitivity calculations have been done for aluminum assuming a 1 meV energy deposition threshold, and the results indicate reach into unexplored parameter space down to keV dark matter masses and via absorption down to tens of meV for ultra-cold bosonic dark matter. In addition to the R&D required for phonon sensors to achieve the meV threshold, work must be done to measure the quasiparticle and phonon propagation properties of high-purity superconducting crystals.

***Photons from a molecular gas*:** Molecules have vibrational modes of order 100 meV, which can be excited by dark matter. A molecular gas can be used to search for the (spin-independent or spin-dependent) scattering off nuclei of 100 keV to 10 MeV dark matter, or for the absorption of a variety of bosonic dark matter candidates with 0.2 to 20 eV mass. In the case of dark matter scattering, which is an inelastic process, the entire dark matter kinetic energy can be transferred into the vibrational energy, allowing dark matter with mass as low as of order 100 keV to excite about a 250 meV vibrational mode. Depending on the dark matter mass, this can excite the first or higher vibrational modes, such that the subsequent one- or multi-step deexcitation process produces one or several photons. Photodetectors based on TESs, MKIDs, or superconducting nanowire single-photon-detector technology could be used to detect these photons.

***Dirac materials*:** A novel proposal makes use of Dirac materials.[91] In an ideal Dirac material, the electron band structure yields a linear, gapless electron dispersion relation and a vanishing density of states at the Fermi surface. With impurity doping, a very small bandgap can then be introduced in principle. Due to this bandgap, electron-phonon thermalization processes are impeded, and thus an athermal phonon signal could be read out using TES- or MKID-based technology. Another possible readout option for 2D Dirac materials, like graphene, is to have the excited electronic excitation overcome the material's work function and exit the material, where it can then be collected and measured.[92] This measurement technique would be limited to greater than MeV scale dark matter, but would have the benefit of directional sensitivity.

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[90] S. Knapen, T. Lin, and K. Zurek, Phys. Rev. D95 (2017) 056019.
[91] Y. Hochberg et al., Phys. Rev. D97 (2018) 015004.
[92] Y. Hochberg et al., Phys. Lett. B772 (2017) 239.

All of the above-discussed technologies (near, medium, and long term) are summarized in Table 4-4.

Table 4-4: *Technologies proposed for detection of sub-GeV dark matter. NR = dark matter coupling to nuclear recoil, ER = dark matter coupling to electron recoil, CE = dark matter coupling to collective excitations. These are grouped as short term (green), medium term (blue), and long term (magenta), with short term = 0-2 years, medium term = 2-4 years, and long term = > 4 years. We note that these time estimates are only approximate, and some medium-to-long-term efforts could see rapid technological improvement on a shorter timescale.*

Technology	Signals	Near-term dark matter masses	Medium-to-longer-term dark matter masses	Readiness
Cryogenic semiconductors	Phonons, charge	NR > 10 MeV ER > 1 MeV	NR > 1 MeV ER > 1 MeV	Ready for concept development
Cryogenic superfluid	Phonons, light	NR > 10 MeV	NR > 1 MeV CE > 1 keV	Ready for concept development
Cryogenic crystalline scintillators	Phonons, light	NR > 100 MeV ER > 1 MeV	NR > 10 MeV ER > 1 MeV	Ready for concept development
Charge-only semiconductors	Charge	ER > 1 MeV	ER > 1 MeV	Short-term R&D needed on readout, dark current
Charge-only noble liquids and gases	Charge	NR > 1 GeV ER > 1 MeV	NR > 100 MeV ER > 1 MeV	Short-term R&D needed on NR calibration, dark current
Superheated/cooled liquids	Heat, light	NR > 100 MeV	NR > 100 MeV	Short-term R&D on NR calibration
Polar materials	Phonons		NR > 1 MeV CE > 1 keV	Medium-term R&D needed on calorimetry
Diamond	Phonons		NR > 1 MeV	Medium-term R&D needed on calorimetry
Molecular gas	Light		NR > 100 keV	Medium-term R&D needed on readout
Superconductor	Charge, Phonons		PH > 1 keV	Long-term R&D on calorimetry
Graphene	Charge		ER > 1 MeV	Long-term R&D on readout
Dirac Material	Charge, light		CE > 1 keV	Long-term R&D on materials, calorimetry
Magnetic bubble	Magnetic flux		NR > 100 keV	Long-term R&D on materials, readout

Ultralight Dark Matter Panel Report

Current Status and Recent Theoretical and Technological Advances

In this section we discuss the direct detection of any dark matter in the mass range roughly 10^{-22} eV to 1 eV, the "ultralight" mass range. We are looking for this dark matter to interact with and excite a high-precision detector. The main feature that differentiates this section from the Direct Detection Panel Report is the mass range being looked at, and therefore, the detector technologies that are needed.

As discussed elsewhere, axions and hidden photons are strongly motivated dark-matter candidates. *Note that in this report we are always using the word "axion" to mean any new light scalar particle with suppressed couplings to the Standard Model and "hidden photon" to mean any new light vector particle with suppressed couplings to the Standard Model.* General axions and hidden photons can exist and be dark matter over the entire allowed mass range, down to masses as low as about 10^{-22} eV. There are well-known production mechanisms for axion dark matter, and some more recent theoretical work has revealed multiple production mechanisms for hidden photon dark matter as well.[93] There is even some motivation for considering ultralight dark matter at the lightest end of the range from the various astrophysical anomalies motivating fuzzy dark matter.

The QCD axion is one of the two dark matter candidates, along with the WIMP, with the strongest theoretical motivation. The QCD axion has a mass range from roughly 100 Hz to THz (10^{-12} eV to 10^{-2} eV). This entire QCD axion mass range was already known to be well-motivated for dark matter (see the "US Cosmic Visions" report[94]). However, recent theoretical work has pointed out new, natural production mechanisms for QCD axion dark matter, which motivate even more strongly the entire QCD axion mass range, in particular, all the way down to the lowest allowed mass of about 100 Hz.[95] In the post-inflation scenario, where Peccei–Quinn symmetry breaks after inflation, the QCD axion mass that gives the correct dark matter abundance is often around a few GHz. However, even in this scenario, this statement is dependent on the cosmological model; for example there has been much theoretical work demonstrating many models with significantly lighter masses that achieve the correct dark matter abundance (for a few recent examples, see Ref. 96.) Other recent theoretical work has pushed up the astrophysical upper limit on the QCD axion mass as well.[97] The QCD axion is thus strongly motivated as a good dark matter candidate all the way down to the lowest mass, about 100 Hz (10^{-12} eV).

To build detectors to search for ultralight dark matter, axions or hidden photons, we must know how it couples to the Standard Model. There are, in general, four allowed types of couplings, giving four different classes of experiments that can be used to search for any dark matter in the ultralight mass

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[93] P. Graham, J. Mardon, and S. Rajendran, Phys. Rev. D93 (2016) 103520; P. Agrawal, N. Kitajima, M. Reece, and F. Takahashi, e-Print: arXiv:1810.07188; R. Co, A. Pierce, Z. Zhang, and Y. Zhao, arXiv:1810.07196; J. Dror, K. Harigaya, and V. Narayan, e-Print: arXiv:1810.07195; M. Bastero-Gil, J. Santiago, L. Ubaldi, and R. Vega-Morales, e-Print: arXiv:1810.07208.

[94] M. Battaglierei et al., arXiv:1707.04591.

[95] P. Graham and A. Scherlis, Phys. Rev. D98 (2018) 035017; F. Takahashi, W. Yin, and A. Guth, Phys. Rev. D98 (2018) 015042.

[96] P. Agrawal, G. Marques-Tavares, and W. Xue, JHEP 1803 (2018) 049; A. Nelson and H. Xiao, Phys. Rev. D98 (2018) 063516; N. Kitajima, T. Sekiguchi, and F. Takahashi, Phys. Lett. B781 (2018) 684; M. Kawasaki, F. Takahashi, and M. Yamada, JHEP 1801 (2018) 053.

[97] J. Chang, R. Essig, and S. McDermott, JHEP 1809 (2018) 051.

range (see “US Cosmic Visions” report[8]). These couplings are: QCD, electromagnetism (E&M), spin, and scalar. This means the ultralight dark matter can couple directly to QCD, E&M, the spin of fermions, or Standard Model properties like fundamental fermion mass or charge. Dark matter with a scalar coupling both gives a new force on matter and also causes Standard Model properties (e.g., a fermion mass or charge) to oscillate in time. Either an axion or hidden photon may have any of these couplings. If CP is a good symmetry in the dark matter sector, then one generically expects the dark matter to have only a subset of these couplings, as shown in Table 4-5. For example, the QCD axion is generically a pseudo-scalar, and so would have QCD, E&M, and spin couplings, but it is also possible for it to have scalar couplings as well in some models (e.g., in relaxion models motivated by solving the hierarchy problem).

Figure 4-11 illustrates how the main technologies, discussed below, that can be used to search for ultralight dark matter in PRD 3.

Table 4-5: *Expected axion or hidden photon couplings.*

Particle type (spin)	**CP**	**Natural Leading Order Couplings**
“axion” (scalar)	pseudo-scalar (CP odd)	QCD, E&M, spin
“axion” (scalar)	scalar (CP even)	E&M, scalar
“hidden photon” (vector)	vector (CP even)	E&M, spin, scalar
“hidden photon” (vector)	axial vector (CP odd)	spin

Near-term technologies

The technologies discussed in Thrust 1 of PRD 3 address the highest priority science opportunities for the DOE charge for this BRN report. Namely, they address the highest impact science priorities which could be pursued by small projects (roughly $5M-$15M in total project cost) that could be ready to start within the next few years and would require DOE’s laboratory infrastructure and/or technology capabilities to be realized.

Magnetic resonance: This technology can be used to search for axion dark matter using spins as transducers in the frequency range between approximately 1 Hz and 100 MHz. Magnetic resonance technology must be used to search for the axion-gluon coupling g_d, which is the defining feature of the QCD axion.

Due to the axion-spin coupling, spins experience a torque that oscillates at the axion Compton frequency. When the external bias magnetic field is tuned to a value such that the spin sublevel splitting matches this frequency (magnetic resonance), the spins tilt and will precess. The resulting time-varying magnetization can be measured with a precision sensor. The search for the unknown axion Compton frequency is performed by sweeping the value of the bias magnetic field, i.e., by varying the current in a magnet. Therefore, the search can be done with minimal hardware changes. The approximately 1 Hz and 100 MHz frequency range corresponds to approximately 1 mG to 10 T bias magnetic field range.

The two pathfinder magnetic resonance experiments presently in operation are CASPEr-electric and CASPEr-wind, correspondingly searching for the axion-gluon coupling g_d and axion-wind coupling g_{aNN}. CASPEr-wind has so far been operating near 1 Hz frequency. CASPEr-electric pathfinder has demonstrated successful operation near 50 MHz, at design sensitivity. In addition to demonstrating magnetic resonance technology in the parameter regime relevant to axion dark matter searches, CASPEr-electric performed measurements of the spin relaxation parameters that confirm the feasibility of an experimental search with sensitivity down to the QCD axion level in the frequency range between 100 Hz and 1 MHz.

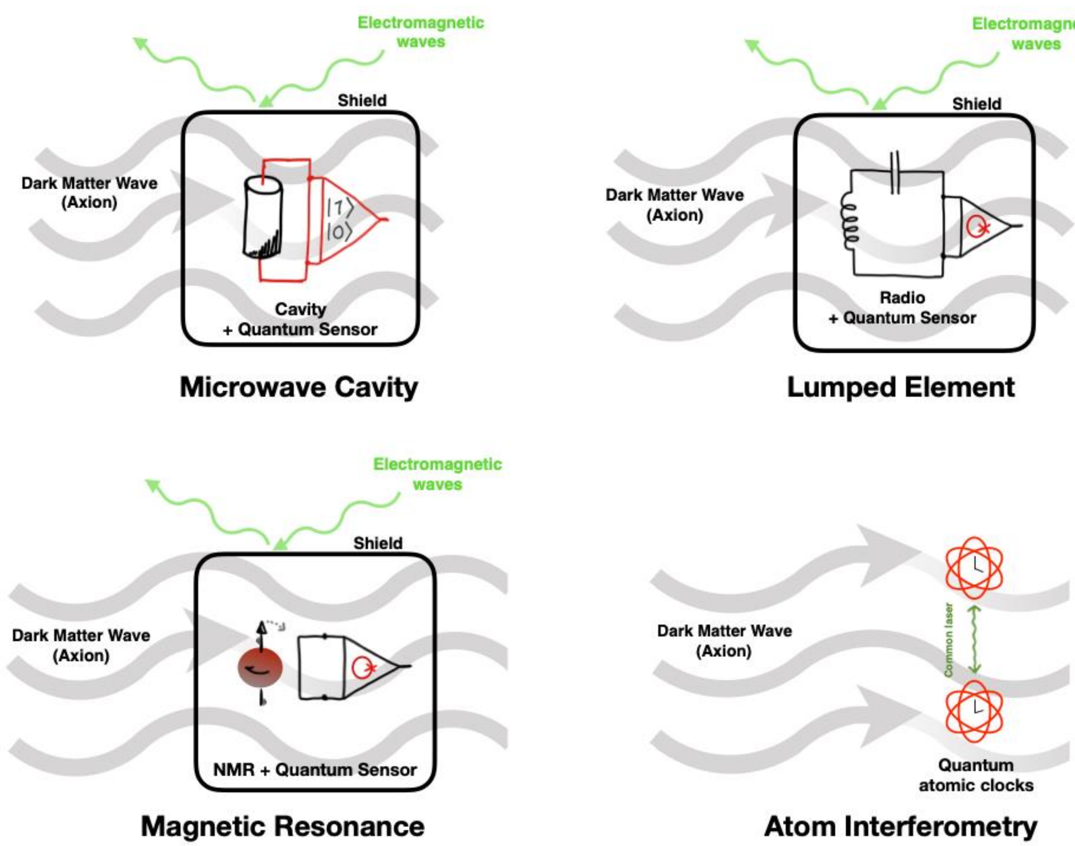

Figure 4-11: *Cartoons showing how the main technologies discussed can be used to search for ultralight dark matter.*

Lumped element: Lumped circuits (LCs) can be used to explore both axion and hidden-photon coupling to electromagnetism at frequencies between about 100 Hz and 300 MHz. In this frequency range, experimental dimensions are generally smaller than the wavelength of the photon being measured, so that lumped-element inductors and capacitors are used. Recent work has determined that the optimal lumped-element search uses single-pole LC resonators with high quality factor inside a superconducting shield, with inductive coupling to an electromagnetic signal induced by either axions or hidden photons.[98] Unlike cavity searches, which require the replacement of resonant cavities multiple times to cover large frequency ranges, lumped circuit searches can tune relatively quickly over a large mass

[98] S. Chaudhuri, K. Irwin, P. Graham, and J. Mardon, e-Print: arXiv:1803.01627.

range, with most of the same experimental hardware, by varying the values of lumped capacitors (with insertable dielectrics) and lumped inductors (by changing inductive coil windings).

Two pathfinder lumped circuit experiments are presently running: the Dark Matter Radio Pathfinder and ABRACADABRA-10cm. Dark Matter Radio Pathfinder has demonstrated successful operation with a high-Q superconducting LC resonator at low noise, with initial hidden-photon limits placed at several resonant frequencies and eventual frequency coverage between 100 kHz and 10 MHz. ABRACADABRA-10cm is presently operating in a broadband mode (rather than the optimal single-pole LC resonator) but has already incorporated a toroidal magnet for sensitivity to axions. The first data run for ABRACADABRA-10cm successfully covered the frequency range 100 kHz to 1 MHz with its noise limited by the commercially produced SQUIDs it uses.[99] Neither of these pathfinder experiment will, however, be sensitive to QCD axions.

Together, these two pathfinder experiments are demonstrating the technology components of a full-scale lumped-element search, including high-Q resonators, cryogenics, amplifiers, and data and science chains. The conceptual development of a full-scale experiment sensitive to QCD axions is appropriate in the near future. Engineering studies are needed for the optimization of the toroidal magnet design (including a tradeoff study of magnetic field and coupled volume), cryogenics, vibration damping, and sensor implementation. The implementation of quantum sensors enabling measurement below the Standard Quantum Limit (SQL) has the potential to significantly enhance the science reach of lumped resonator experiments, in particular, extending the QCD axion sensitivity to frequencies below 1 MHz. However, measurement below the SQL are not required for the conceptual development of a full-scale experiment.

Microwave cavity: Cavity resonators can be used to explore both axion and hidden-photon coupling to electromagnetism at frequencies above about 300 MHz. Cavity searches are the most mature technique to search for dark matter waves. ADMX G2 is a cavity resonator search that is one of the three G2 DOE dark matter projects. ADMX G2 explores the QCD axion at DFSZ coupling in the 650 MHz to 2 GHz range with a combination of traditional single- and multi-cavity resonator configurations, and has already released the first results with DFSZ axion sensitivity.[100]

The HAYSTAC experiment, which is NSF funded, has already operated with a cavity in the 4-6 GHz range,[101] and has invested R&D effort in optimizing a cavity geometry with a uniformly good form factor and a quality factor in the 6-12 GHz range. While the performance is good, the HAYSTAC cavity is small (1.5 liter, about 1% of the volume of the ADMX-G2 cavity) and does not presently reach the QCD axion. A primary R&D challenge will be to multiplex a larger number of cavities whose volume will enable probing as much of the axion model band as possible.

Future technologies

The technologies discussed in Thrust 2 of PRD 3 have generally not yet produced dark matter results, limits on axions or hidden photons. They are not yet ready to be DOE small-scale projects. These goals are lower priority under the definition given in the charge for this BRN. However, the approaches show promise, and more technology development is motivated in order to fully realize their potential and

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[99] J. Ouellet et al., e-Print: arXiv:1810.12257.
[100] N. Du et al., Phys. Rev. Lett. 120 (2018) 151301.
[101] L. Zhong et al., Phys. Rev. D97 (2018) 092001.

turn them into full dark matter experiments. These approaches will be discussed later in the subsection on Experimental Opportunities and Challenges.

Experimental Opportunities and Challenges

Near-term technologies

Here, we discuss the highest priority experimental opportunities that follow the charge from the DOE for this BRN report. Namely, these are demonstrated techniques that now appear ready to scale up to an official small project in the $5M-$15M range that rely on DOE resources. These three approaches are

1. magnetic resonance
2. lumped element
3. microwave cavities

See Figure 4-12 and discussion below for the rough frequency ranges that can be covered by these approaches, both for the QCD axion and for general ultralight dark matter, and the couplings being probed.

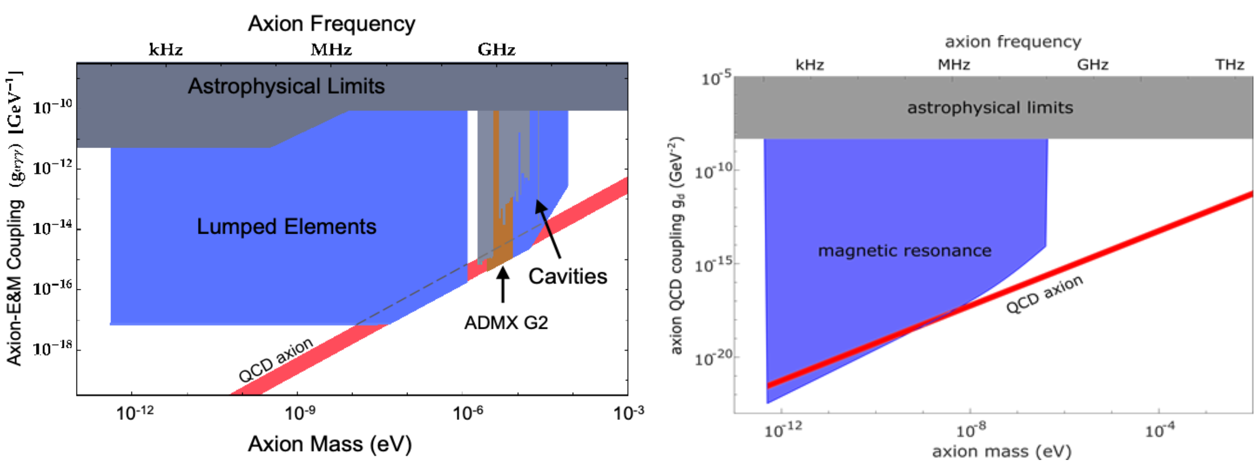

Figure 4-12: *Projected sensitivities for the three highest priority approaches: microwave cavities, lumped elements, and magnetic resonance.*

Microwave cavity: Extending on the success of the ADMX G2 project,[100] the resonant cavity technique can easily be envisioned exploring axion masses at DFSZ coupling up to 4 GHz in a small project by increasing the number of cavities. This requires no additional R&D. The DOE national lab infrastructure necessary to design and manufacture cryogenic cavities search exists and it is ready immediately. Beyond 4 GHz, a number of factors hamper existing technology: the standard quantum noise limit of the amplifiers increases, the cavity quality factor (Q) of traditional copper-coated cavities decreases, and the technical complexity of combining resonator array increases. To access frequencies above 4 GHz with current technology would possibly require larger magnets exceeding the scope of a small project. Alternately, R&D to mitigate the challenges faced by higher frequency cavities may bring higher frequencies within the scope of a small project.

Other important R&D topics include exploring the possibility of incorporating superconducting material into the cavity to improve Q and schemes to mitigate intruder or nuisance modes which occlude the electromagnetic mode of interest.

*Lumped **e**lement:* Building on the lumped circuit demonstration provided by the two pathfinder experiments, a small-scale project can be envisioned with QCD axion sensitivity reach that is entirely complementary to both magnetic resonance technology and electromagnetic cavities. A small-scale project can be envisioned with a sensitivity reach at the level of QCD axion dark matter for frequencies between 3 MHz and 300 MHz. The largest task for the conceptual development of such an experiment will be an engineering study of the required toroidal superconducting magnets, along with cryogenics, vibration and EMI control, sensor implementation, and systems integration.

The fundamental limit to the science reach of a lumped-element search for QCD axion dark matter is set by a combination of thermal noise and sensor noise.[102] A small-scale lumped-circuit project could potentially be enhanced by optional R&D to enable measurement below the SQL, allowing lumped circuits to potentially probe the QCD axion to below 1 MHz, closing the QCD axion sensitivity gap between lumped element and magnetic resonance experiments. However, with a small project limited by thermal noise and SQUID sensors with performance near the SQL, the projected sensitivity is that shown in Figure 4-12. In addition to the small project with science reach shown in Figure 4-13, R&D efforts could thus extend the QCD axion reach to lower frequencies and reduce cost and engineering risk for such a project.

Magnetic resonance: Building on the magnetic resonance technology demonstration provided by the pathfinder CASPEr experiment, a small-scale project can be envisioned with sensitivity reach at the level of the well-motivated QCD axion dark matter for frequencies between 100 Hz and 1 MHz. Conceptual development of such an experiment will require engineering studies of magnet design, cryogenics, vibration damping, sensor implementation, fabrication of the working sample, and systems integration.

The fundamental limit to the science reach of a magnetic resonance search for axion dark matter is the spin projection quantum noise. If an experiment attains this level of sensitivity, it will be able to search for QCD axion dark matter between 1 Hz and 100 MHz. However, at the present level of demonstrated technology, magnetic resonance-based searches for axion dark matter are limited by the thermal spin polarization, spin coherence time, and the sensitivity of the magnetic sensor used to detect spin magnetization precession. These factors limit the projected sensitivity shown in Figure 4-13. R&D efforts are necessary to mitigate these limitations and attain the quantum spin projection-limited sensitivity. Experimental opportunities include achieving near-unity spin polarization using dynamical polarization techniques from the field of solid-state nuclear magnetic resonance, extending spin coherence using dynamic driving of spins, and developing advanced magnetic sensors whose sensitivity and bandwidth is beyond the commercially-available SQUID magnetometers (see section on QIS-based technologies). Successful R&D efforts have the potential to significantly extend the frequency range over which a small project-scale experiment can be sensitive to QCD axion dark matter, and to mitigate the associated engineering challenges.

[102] S. Chaudhuri et al., arXiv:1803.01627.

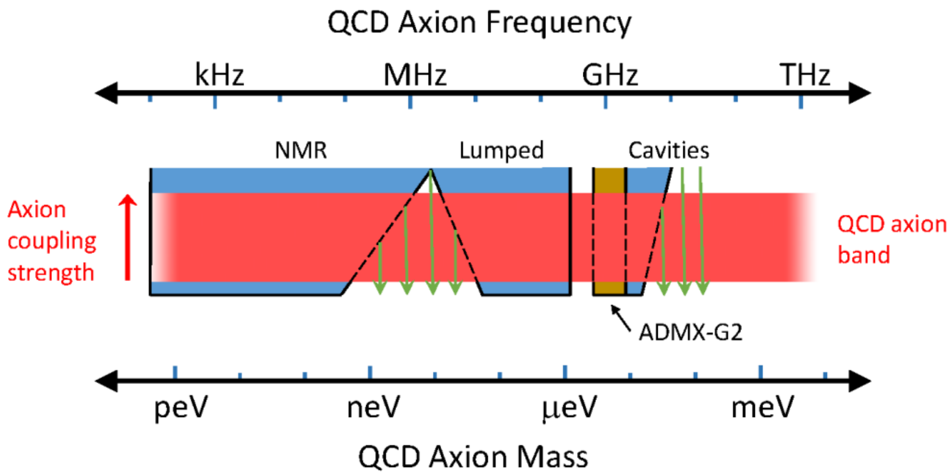

Figure 4-13: *Cartoon showing the approximate science reach into the QCD axion band for NMR, lumped element, and cavity-based experiments, similar to Figure 4-12. Quantum sensing below the Standard Quantum Limit can increase the science reach of small projects searching for QCD axions in both the MHz and GHz range, as shown by the green arrows. The implementation of microwave squeezing and photon-counting can increase the high-frequency reach of cavity experiments to the QCD axion band in the 4-30 GHz range. The implementation of backaction evasion and squeezing has the potential to enable lumped element and NMR experiments to completely cover the QCD axion frequency range between 100 kHz and 10 MHz, so that axions in the full axion band below 1 μeV (300 MHz) can be excluded or detected.*

Enhancing small wave dark matter projects with quantum sensing R&D

Research and development in quantum sensing has the potential to increase the discovery potential for small projects searching for QCD axions and other wave-dark-matter candidates. Small projects that are ready for conceptual development can provide impressive partial coverage of the QCD axion band below 40 μeV (10 GHz), but the coverage is projected to be incomplete from 500 peV to 40 neV, and in the entire region above 16 μeV (see Figure 4-13). Quantum sensing techniques have the potential to fill the gap left between NMR and lumped searches, and to extend cavity searches up to approximately 100 μeV (see green arrows in Figure 4-13). These techniques will also broadly enhance searches for wave-dark-matter candidates, including axions and hidden photons over a large mass range. Relevant quantum sensors research is already being funded by the DOE HEP QuantISED program and by various sources outside of DOE-HEP, including private foundations. Once the technology comes to fruition, wave-dark-matter searches will be immediately enhanced for expanded coverage of the well-motivated QCD axion model parameter space both in mass and coupling sensitivity and for the broader search for both axion and hidden-photon wave dark matter.

In particular, new quantum metrology technologies will enable future direct detection experiments to search for higher mass axions motivated by cosmological scenarios of high scale cosmic inflation. At these higher masses, greater than about 20 μeV, the current technique of signal power readout is no longer viable in simple haloscope experiments due to the poor scaling of the signal-to-noise ratio with increasing frequency. While the signal rate could in principle be improved with expensive high-field magnets and intricate, large volume cavity structures, a less technically challenging strategy is to instead reduce noise using backaction-evading techniques imported from the field of quantum metrology.

Further, new quantum metrology techniques will also enable future experiments to search for lower mass axions which are motivated by both high-scale and low-scale inflation. In this lower mass range of 500 peV to 40 neV (two orders of magnitude in mass), readout with even the best SQUID amplifiers operating near the SQL are not sufficient to probe the full QCD axion band within an achievable integration time. While the signal rate could in principle be improved by extremely expensive high-field, high-volume magnets, quantum sensors using backaction-evading techniques can allow full coverage of this band within a reasonable program scale.

***Squeezing for masses larger than 10 μeV dark matter*:** The first implementation of quantum sensing below the SQL for axion searches uses squeezed vacuum states. Squeezing evades the SQL by pushing as much of the noise as possible into one part of the signal (a "quadrature", or sine-like component), while measuring the signal in the other "quadrature" (the cosine-like component). Squeezing is currently being implemented in HAYSTAC and should result in a factor of 2 increase in the mass scan rate; a modest R&D program could produce significant gains, for example, a factor of 10 improvement, which would have a major impact on axion experiments in the ranger larger than 10 μeV.

***Photon counting for masses larger than 20 μeV dark matter*:** A more ambitious goal is to achieve completely background-free operation in which the readout noise has been reduced to vanishing levels. This limit is achievable at sufficiently high frequencies where the cavity has low thermal occupation, and where the occasional signal photon can be read out with high quantum efficiency, low dark rate, single-photon resolving sensors. These sensors, including Rydberg atoms and artificial atoms based on superconducting qubits, can evade the SQL noise by measuring only the signal photon's wave amplitude while being agnostic about the conjugate phase observable. Furthermore, as demonstrated by Haroche (2012 Nobel Prize), repeated quantum non-demolition measurements of the signal photon can improve the measurement fidelity to such an extent that the "false positive" background rate vanishes. Early adaptations of this technology with designs optimized for HEP dark matter have already demonstrated background rates 100 times smaller than the SQL, with dark count rates being limited by technical challenges rather than by fundamental physics.[103]

The establishment of both microwave cavity squeezing and photon counting has the potential to extend the science reach for QCD axions up to about 0.1 meV, as is schematically shown by the green arrows on the right side of Figure 4-13.

***Photon upconversion for neV dark matter in lumped circuits*:** A similar challenge faces experiments searching for lower mass axions where the signal is suppressed due to the mismatch of the axion Compton wavelength with the meter-scale size of cost-effective magnets. Again, quantum metrology techniques can be used to achieve large reductions in readout noise to enable these low-mass axion searches in the challenging mass range 500 peV to 40 neV.

At lower masses (less than 1 μeV) superconducting circuits using Josephson junctions can enhance the science reach of Lumped searches by enabling sensitivity below the SQL, even though the resonators are generally in a thermal state.[1022] Superconducting circuits can couple LC resonators tuned to near the axion frequency to a superconducting resonator operating at GHz frequencies.[104] These circuits can upconvert photons generated by dark matter in the MHz frequency range to GHz frequency range. Early adaptation of this technology is being implemented with designs optimized for HEP dark matter

[103] A. Dixit, A. Chou, and D. Schuster, Springer Proc. Phys. 211 (2018) 97.
[104] J. Mates, G. Hilton, K. Irwin, and L. Vale, Appl. Phys. Lett. 92 (2008) 023514.

searches, enabling the implementation of quantum protocols such as backaction evasion and squeezing. These devices can enhance the science reach of lumped searches for the QCD axion, helping to enable full coverage of QCD axions in the 500 peV to 40 neV range (shown by green arrows in the middle of Figure 4-13).

Squeezing for neV dark matter in NMR searches: NMR-based searches are presently limited by the noise of the available SQUID amplifiers, rather than spin-projection noise. Similar devices to the photon upconverters that are being developed for backaction evasion and squeezing of lumped searches can be designed to provide lower noise for the sensing of the NMR spins in NMR-based searches through squeezing the electromagnetic resonator. The successful development of these devices, combined with those for lumped circuits, will enable full coverage of QCD axions in the 500 peV to 40 neV range (shown by green arrows in the middle of Figure 4-13). The quantum spin projection noise itself can also be evaded by techniques including spin squeezing, further extending the sensitivity of these experiments.

Longer-term technologies

The technologies discussed in Thrust 2 of PRD 3 are important but answer the part of the DOE charge for this BRN report that asks about experimental approaches that are not ready to be small-scale projects but for which technology development is motivated and important.

Atom interferometry: Atom interferometers are intrinsically quantum mechanical sensors that use laser pulses to interfere the wavefunctions of atoms for precision sensing applications.[105] Recent theoretical work has identified three different signatures of dark matter in the 10^{-22} eV to 10^{-11} eV mass range that can be measured by atom interferometers: dark matter can exert time-dependent, equivalence-principle (EP) violating accelerations on the atoms,[106] induce time-variation in atomic transition frequencies,[107] and cause precession of nuclear spins.[108] In parallel, the key technology has been developed and demonstrated in the laboratory. Important recent demonstrations include atom interferometers with macroscopic wavefunction delocalization yielding dramatically increased sensitivity;[109] a gradiometer configuration for noise cancellation;[110] single-photon atom interferometry;[111] atomic cooling to reach effective temperatures as low as 50 pK;[112] and dual species interferometers.[113] Given these developments, atom interferometry technology is sufficiently mature for a pilot dark matter experiment to be performed. As discussed below, additional R&D is important to enhance the scientific reach of atom interferometric dark matter detectors.

Several experimental R&D thrusts could dramatically improve the sensitivity of atom interferometers to dark matter, including improved atomic beam splitters, higher flux atom sources, atomic levitation, and

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[105] G. Tino and M. Kasevich, Proceedings of the International School of Physics Enrico Fermi, Course CLXXXVIII, Varenna (2013).
[106] P. Graham et al., Phys. Rev. D 93 (2016) 075029.
[107] A. Arvanitaki et al., Phys. Rev. D 97 (2018) 075020.
[108] P. Graham et al., Phys. Rev. D 97 (2018) 055006.
[109] T. Kovachy et al., Nature 528 (2015) 530; P. Asenbaum et al., Phys. Rev. Lett. 118 (2017) 183602.
[110] P. Asenbaum et al., Phys. Rev. Lett. 118 (2017) 183602.
[111] L. Hu et al., Phys. Rev. Lett. 119 (2017) 263601.
[112] T. Kovachy et al., Phys. Rev. Lett. 144 (2015) 143004.
[113] C. Overstreet et al., Phys. Rev. Lett. 120 (2018) 183604.

resonant methods.[114] Finally, the integration of entangled states[115] could push the interferometer phase resolution beyond the SQL. Beyond dark matter applications, such an R&D program would broadly advance quantum sensing technology.

DOE infrastructure and capabilities would be essential to an atom interferometric dark matter detector. For such a detector to reach its potential, a tall vacuum tube (100 m scale or longer) is required to boost sensitivity via increased gradiometer baseline, atom free fall time, and wavefunction delocalization. DOE facilities such as FNAL and SURF contain deep shafts that could accommodate such an apparatus. Additionally, DOE could provide critical infrastructure and engineering support, including vacuum system and magnetic shield design and construction as well as systems integration expertise. For these reasons, DOE facilities, infrastructure, and expertise would be required for a pilot experiment.

Nb superconducting cavity resonators: Extremely high-quality factor superconducting niobium cavities greatly extend the sensitivity of hidden photon dark-matter experiments. These cavities, operating in the 1-10 GHz band, have recently demonstrated $Q_{cav} > 10^{10}$ at 20 mK temperature,[116] where surface processing techniques developed by the superconducting RF accelerator community have resulted in significant reduction in losses due to residual two-level system contaminants. While the lifetime of the photon modes of these cavities greatly exceeds the expected coherence time of the dark matter waves, the cavities can still be used to incoherently accumulate signal power over long periods of time while simultaneously reducing the detection bandwidth to efficiently reject background noise. Quantum-limited dark matter experiments based on these cavities can, therefore, achieve nearly background-free operation for reasonable integration times of around 10 seconds per radio tuning. New experiments of this type could achieve sensitivity to the kinetic mixing angle orders of magnitude beyond current experimental bounds and directly test models of vector dark matter production associated with high scale cosmic inflation.[117]

Multiwavelength resonators: Above 4 GHz, the combination of many cavity resonators to achieve sufficient volume for QCD sensitivity becomes cumbersome. Another solution is to use sophisticated resonators that have an active volume many times the naive volume of a single wavelength cubed. The R&D challenges associated with the resonators center around insuring that the mode of interest couples well with the axion field and making the mode of interest tunable over a range of frequencies. A number of approaches to this are in active development, and in many cases also have a higher Q than achievable in a single-cavity resonator. Some examples are photonic-bandgap inspired resonators,[118] which confine modes within a forest of dielectrics. Periodically spaced dielectrics in an open resonator benefit from both enhanced Q's and much larger volumes than cavities and are already being used in several prototypes such as Orpheus[119] and MADMAX[120] (a non-U.S. project). Future R&D will determine whether these ideas are candidates to be scaled up to a small project scale.

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[114] P. Graham et al., Phys. Rev. D 94 (2016) 104022.
[115] O. Hosten et al., Nature 529 (2016) 505; K. Cox et al., Phys. Rev. Lett. 116 (2017) 093602.
[116] A. Romanenko et al., eprint arXiv:1810.03703 (2018).
[117] P. Graham, J. Mardon, and S. Rajendran, Phys. Rev. D93 (2016) 103520.
[118] Proceedings of the Axion Cavity Workshop 3.
[119] G. Rybka et al., Phys. Rev. D 91 (2015) 011701.
[120] MADMAX Working Group, e-print: arXiv:1611.04549.

Atomic magnetometers: High-precision atomic magnetometers can be used to search directly for spin precession of nuclei or electrons caused by axions or hidden photons.[121] Initial demonstrations of this technique are currently ongoing at Princeton in the Romalis group and at PTB Berlin. This technique appears promising to search for ultralight dark matter at the lightest masses, roughly 10^{-8} to 10^{2} Hz, several orders of magnitude past current limits.

Torsion pendulums: Torsion pendulums can function as sensitive detectors searching for the direct force/torque of ultralight dark matter on the proof masses. This can be done in two ways. The torsion pendulums made to test the principle of equivalence can search for a new force from ultralight dark matter with a scalar coupling. Spin-polarized torsion balances can search for the spin torque from the ultralight dark matter with a spin coupling.[121] The Eot-Wash group is currently testing these techniques with demonstration experiments using current pendulums. This technique appears promising to search for ultralight dark matter at the lightest masses, roughly 10^{-8} to 10^{2} Hz, several orders of magnitude past current limits.

New forces and light through walls: Although not a direct dark-matter detection experiment, ultralight particles can be seen by searching for a new force between test masses in the lab mediated by exchange of the dark matter particle. Such a force can be either spin-dependent (spin-spin or dipole-dipole) or scalar (monopole-monopole) or spin-scalar (monopole-dipole). For example, such new force searches have been carried out by the Eot-Wash collaboration using torsion pendulums or by the Romalis group using atomic spins.

Another example is the proposed ARIADNE experiment, which aims to reach all the way down to the QCD axion at the highest end of the frequency (mass) range. This experiment aims to search for spin-scalar (monopole-dipole) forces, in particular, as would be mediated by the QCD axion. This uses a spinning rotor as source mass and nuclei controlled through nuclear magnetic resonance as the proof mass. It is thus sensitive to a product of the scalar and spin couplings of the axion. A first phase of this experiment could cover significant unexplored parameter space for new forces from general axions. An ultimate version of the experiment would aim to cover a significant piece of the QCD axion band at the higher QCD axion masses (above roughly 10^{-4} eV). This approach appears promising and an initial demonstrator experiment is in preparation now.

Light through walls experiments aim to detect axions and hidden photons generated by an electromagnetic field on one side of a shield (e.g., either in a resonant optical or microwave cavity) using a similar electromagnetic detector (e.g., optical or microwave cavity) on the other side of the shield. This is a promising approach and, for example, the ALPS experiment is attempting this. This technique could possibly reach down to at least part of the band for the QCD axion at the highest masses (frequencies).

In a similar vein, IAXO aims to detect axions produced in the sun that reconvert to a photon in the detector. Although a much larger project than the DOE small-scale projects being discussed in this report, it could potentially pick up some parameter space for general axions at high coupling, and even possibly some of the QCD axion band at the highest masses allowed.

See the “US Cosmic Visions” report[8] for more information on all technologies discussed.

[121] P. Graham et al., Phys. Rev. D97 (2018) 055006.

Impact

This program will hopefully lead to the discovery of dark matter, the dominant component of the matter in our universe. The set of small-scale experiments discussed should lead to comprehensive coverage of the QCD axion, and even ultimately to experiments addressing the entire ultralight dark matter mass range, over 20 orders of magnitude in mass. The motivation for ultralight dark matter, and the QCD axion in particular, is so strong that even just ruling out this possibility would be a major piece of knowledge gained for physics. Even this would have strong impacts on our theories of fundamental physics. Of course, a discovery of ultralight dark matter would significantly affect our understanding of the fundamental laws of nature.

The detection of ultralight dark matter offers unique opportunities to probe ultra-high energy physics and the cosmology of the early universe. Many of the theoretical structures that produce these particles emerge from physics at ultra-high energies such as the scales of grand unification and quantum gravity (the Planck scale). Measurements of the interactions between the dark matter and the particles of the Standard Model could offer unique insights into these fundamental scales that cannot be directly accessed through any other techniques. A discovery in such an experiment thus teaches us about the physics of ultrahigh energy scales, far beyond those that will ever be accessible in a collider.

Additionally, a detection could also offer a unique window into inflation and the creation of the universe. Many of the simplest production mechanisms for axion and hidden photon dark matter involve cosmic inflation and are influenced by the physics of early universe cosmology. Thus, observing the abundance and properties of such dark matter will teach us about the earliest times in the universe, potentially even permitting a determination of the Hubble scale of inflation. This knowledge could also be of substantial interest to subsequent measurements of the cosmic microwave background.

5. CONCLUSIONS

For every gram of normal matter in the universe there are over 5 grams of dark matter. Although evidence for dark matter is overwhelming, understanding the nature and properties of dark matter has proved elusive.

Recent theoretical proposals and developments in technology have pointed to new directions for the detection of dark matter. This report describes new approaches for the science grand challenge of identifying the nature of dark matter in the universe.

The Basic Research Needs Workshop identified three science opportunities that can be pursued by small projects (approximately $5M to $15M in total project cost) that could be ready to start within the next few years and are capable of reaching high-value milestone targets. To be realized, the science opportunities require DOE's laboratory infrastructure and/or technology capabilities. This report also suggests opportunities that could be pursued by future small projects, which also require DOE capabilities, but need further technology development before project initiation.

The science opportunities are addressed by three Priority Research Directions (PRDs). The three PRDs are complementary to each other and to the Generation-2 experiments currently underway and supported by DOE HEP. The mass-range coverage of the three PRDs span an enormous range from the proton mass down to the smallest mass possible for dark matter.

The three PRDs each have two thrusts. They are (in alphabetical order)

PRD 1: Create and detect dark-matter particles below the proton mass along with associated forces, leveraging DOE accelerators that produce beams of energetic particles.

- <u>Thrust 1:</u> (near-term): Use particle beams to explore interaction strengths singled out by thermal dark matter through 10- to 1000-fold improvements in sensitivity over current searches, across the electron-to-proton mass range.
- <u>Thrust 2:</u> (near- and long-term): Explore the structure of the dark sector by producing and detecting unstable dark particles.

PRD 2: Detect individual galactic dark-matter particles below the proton mass through interactions with advanced, ultra-sensitive detectors.

- <u>Thrust 1:</u> Probe dark matter interactions with <u>nuclei</u>, as motivated by theoretical ideas for the nature of light dark matter, including its possible thermal and non-thermal origins.
- <u>Thrust 2:</u> Probe dark matter interactions with <u>electrons</u>, as motivated by theoretical ideas for the nature of light dark matter, including its possible thermal and non-thermal origins.

PRD 3: Detect galactic dark-matter waves using advanced, ultra-sensitive detectors with emphasis on the strongly-motivated QCD axion.

- <u>Thrust 1:</u> Utilize new detector technologies to explore large parts of dark-matter parameter space covering a broad range of mass from roughly 10^{-12} to 10^{-4} eV (100 Hz to 10 GHz), and targeting sensitivity to the QCD axion where possible.

- Thrust 2: Develop or extend new detector technologies to enable experiments to cover the remaining parameter space for well-motivated dark matter models spanning the entire roughly 20 orders of magnitude in mass and also targeting complete coverage of QCD axion models.

This is an exciting time in dark matter detection experiments. Together, the three PRDs greatly extend the discovery space for dark matter into very interesting regions with real promise of finally solving one of the greatest mysteries in astronomy and particle physics, the nature of dark matter.

APPENDIX A: Cosmic Visions

Community input to this report was largely through the "US Cosmic Visions: New Ideas in Dark Matter" workshop and the published report of that workshop. The Cosmic Visions Workshop focused "… on the science case for additional new small-scale projects in dark-matter science that complement the G2 program …"

The workshop was held 23-25 March 2017 at the University of Maryland with over 150 registered participants and over 100 presentations. The scientific advisory committee consisted of:

- Marco Battaglieri (co-chair), INFN (battaglieri@ge.infn.it)
- Roni Harnik, Fermilab (roni.harnik@gmail.com)
- Matt Pyle, UC Berkeley (mpyle1@berkeley.edu)
- Gray Rybka, U. Washington (grybka@uw.edu)
- Pierre Sikivie, Florida (sikivie@phys.ufl.edu)
- Tim Tait, UC Irvine (ttait@uci.edu)
- Natalia Toro (co-chair), SLAC (ntoro@slac.stanford.edu)
- Richard Van De Water, Los Alamos National Lab (vdwater@lanl.gov)
- Neal Weiner, NYU (neal.weiner.nyu@gmail.com)
- Kathryn Zurek, Lawrence Berkeley National Lab (kmzurek@lbl.gov)

There were four working groups at the workshop:

1. **New avenues in direct detection: e.g., sub-GeV, electron recoil.** Conveners:
    - Rouven Essig, Stony Brook (rouven.essig@stonybrook.edu).
    - Juan Estrada, Fermilab (estrada@fnal.gov).
    - Dan Mckinsey, UC Berkeley (daniel.mckinsey@berkeley.edu).
2. **Ultra-low mass (sub-eV) dark matter detection.** Conveners:
    - Aaron Chou, Fermilab (achou@fnal.gov).
    - Peter Graham, Stanford (pwgraham@stanford.edu).
3. **Dark matter production at fixed target and collider experiments.** Conveners:
    - Bertrand Echenard, Caltech (echenard@caltech.edu).
    - Eder Izaguirre, Brookhaven (eder@bnl.gov).
4. **New Candidates, Targets, and Complementarity.** Conveners:
    - Jonathan Feng, UC Irvine (jlf@uci.edu).
    - Patrick Fox, Fermilab (pjfox@fnal.gov).

The results of the Workshop were summarized in a whitepaper posted to the archive on 14 July 2017 (arXiv:1707.04591). The whitepaper is comprehensive: 113 pages and 254 signatories from 112 Institutions in the US, Australia, Austria, Canada, Denmark, Germany, Israel, Italy, Japan, Korea, Russia, Switzerland, Taiwan, and the UK.

The large number of participants and contributions is indicative of the high level of community interest in the area.

APPENDIX B: Basic Research Needs (BRN) Study for Dark-Matter Small Projects Participants

Ten Panel Leads, 27 Panel Members, and 2 Co-Chairs participated in the Basic Research Needs Workshop.

Co-chairs:
- Rocky Kolb (Chicago)
- Harry Weerts (Argonne)

Accelerator Panel Leads:
- Natalia Toro (SLAC)
- Richard Van de Water (LANL)

Direct Detection Panel Leads:
- Rouven Essig (Stony Brook)
- Dan McKinsey (Berkeley)
- Kathryn Zurek (LBNL)

Ultralight Panel Leads:
- Aaron Chou (FNAL)
- Peter Graham (Stanford)

Cross Cut Panel Leads:
- Juan Estrada (FNAL)
- Joe Incandela (Santa Barbara)
- Tim Tait (Irvine)

DOE Attendees:
- Christie Ashton
- Karen Byrum
- Lali Chatterjee
- Michael Cooke
- Glen Crawford
- William Kilgore
- Theodore Lavine
- Helmut Marsiske
- Jim Siegrist
- Kathy Turner

NSF Attendees:
- Jean Cottam
- Jim Whitmore

Accelerator Panel Members:
- Marco Battaglieri (INFN)
- Brian Batell (Pitt)
- Stefania Gori (Santa Cruz)
- Gordon Krnjaic (FNAL)
- Tim Nelson (SLAC)
- Adam Ritz (Victoria)
- Philip Schuster (SLAC)
- Rex Tayloe (Indiana)
- Nhan Tran (FNAL)

Direct Detection Panel Members:
- Adam Bernstein (LLNL)
- Jodi Cooley (SMU)
- Eric Dahl (Northwestern)
- Sunil Golwala (Caltech)
- Scott Hertel (U Mass)
- Reina Marayama (Yale)
- Matt Pyle (Berkeley)
- Javier Tiffenberg (FNAL)

Ultralight Panel Members:
- Karl van Bibber (Berkeley)
- Kent Irwin (SLAC)
- Tim Kovachy (Northwestern)
- Surjeet Rajendran (Berkeley)
- Gray Rybka (U Washington)
- Alex Sushkov (Boston U)
- Lindley Winslow (MIT)

Cross Cut Panel Members:
- Roni Harnik (FNAL)
- Yoni Kahn (Chicago)
- Mariangela Lisanti (Princeton)

APPENDIX C: Workshop Agenda

The BRN Workshop was held October 15 – 18, 2018 in Gaithersburg, Maryland. The Workshop Agenda is given below.

Day 1, Monday 10/15

9:00am – 10:45am PLENARY

- 15 minutes: Logistics, purpose and organization of the BRN – DOE and Chairs
- 25 minute each reports from Direct + Accelerator+ Ultralight panels
    - Brief review of CV workshop filtered through our charge
    - What's new since CV
    - Report on pre-workshop phonecons
        - Where there is agreement
        - Key questions and areas of contention

15 minutes: Discussion all

11:00am – 1:00pm

- WG breakout sessions

1:00pm – 2:00pm (working lunch for core group members)

2:00pm – 5:00pm

- WG breakout sessions

Day 2, Tuesday 10/16

9:00am – 11:00am PLENARY

- 30 minute each reports from Direct + Accelerator + Ultralight panels
    - 15min report on previous day's work
    - 15min all participant discussion
- 30 minute presentation and discussion of cross-cut opportunities

11:15am – 1:00pm

- WG breakout sessions

1:00pm – 2:00pm (working lunch for core group members)

2:00pm – 5:00pm

- WG breakout sessions

Day 3, Wednesday 10/17:

9:00am – 11:00am PLENARY

- 30 minute each reports from Direct + Accelerator + Ultralight panels
    - Present draft PRD for discussion
    - 15min all participant discussion
- 30 minute participation and discussion of cross-cut opportunities

11:15am – 1:00pm

- WG breakout sessions

1:00pm – 2:00pm

- Core group meeting

2:00pm – 3:00pm

- Final WG wrap up breakout sessions

3:00pm – 6:00pm PLENARY

- 30 minute each reports from Ultralight+Direct+Accelerator WG's
    - Outline final WG findings and discuss final science opportunities
    - Discuss technology roadmaps
- 30 minute report and discussion of cross-cut opportunities
- 60 minute group discussion about Priority Research Directions

Day 4, Thursday 10/18:

Morning Core Group

- Incorporate workshop initial conclusions for final document

APPENDIX D: Charge Letter

Department of Energy
Office of Science
Washington, DC 20585

AUG 20, 2018

MEMORANDUM FOR	KATHLEEN TURNER and KAREN BYRUM OFFICE OF HIGH ENERGY PHYSICS (HEP)
FROM:	GLEN CRAWFORD (signed 8/20/18) DIRECTOR, RESEARCH AND TECHNOLOGY DIVISION FOR HIGH ENERGY PHYSICS (HEP)
SUBJECT:	Basic Research Needs Study for Dark Matter New Initiatives

I request that you organize and carry out a Basic Research Needs (BRN) study to assess the science landscape and new opportunities for dark matter (DM) particle searches and to identify which areas would be suitable to be pursued with small projects in the HEP program. This request is in response to the 2014 P5 recommendations that the search for dark matter particles is high priority science and that a diversity of project scales in the program should be maintained.

You should select co-chairs to lead the study and work with them to select the core group to carry it out. A focal point of the study should include a workshop, with wider attendance, expected to be held in October 2018. The study participants are to serve by invitation only.

The current global program of experiments using particle physics detectors, accelerators and other techniques has yet to discover DM particles or shed any light on its nature, although large regions of possible dark matter parameters have been ruled out. The HEP program currently has a suite of complementary direct-detection experiments using multiple technologies that were approved following the P5 recommendation to develop a robust “Generation-2” suite of projects. One of these experiments is currently taking data and the others are expected to begin operations in the next few years. Searches for dark matter particles using accelerator-based experiments are also being carried out in the program.

Recent new theoretical ideas have underscored that both major candidates for DM that are the subject of current searches, axions and WIMPs, are special cases of a broader theoretical framework. Other varieties of particle dark matter have many of the same attractive features as the “traditional” search candidates, and provide strong motivation to explore DM parameter space beyond the HEP program’s current sensitivity.

In March 2017, the Cosmic Visions Dark Matter community group sponsored a workshop focused on the current DM landscape and identified new directions in DM not yet explored in the current HEP program. Four science areas, along with technologies that could address them, were identified in the workshop and described in the resulting white paper report, "US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report", available at arXiv:1707.04591v1.

The 2017 white paper should provide the primary input for considering the science landscape for the BRN study, with recent theoretical and experimental studies also incorporated.

Development of metrics to aid in comparisons may prove helpful in carrying out the study. In carrying out the assessment, the BRN study should address the following specific items:

- Identify science opportunities for new directions and areas of parameter space that will provide high impact science return and advancement for DM particle detection.
- Determine the high impact science opportunities which could be pursued by small projects (approximately $5M to $15M in Total Project Cost) that could be ready to start within the next few years, and in which DOE's laboratory infrastructure and/or technology capabilities are required to be realized.
- Determine high impact science opportunities which could be pursued by future small projects that require use of DOE infrastructure and capabilities but need further technology development before project initiation.

Note that the priority opportunities should not include significant upgrades of current large projects or development of new large projects in the HEP program, nor small contributions to large projects supported by other sources. While not the focus of the study, it may be useful to summarize the parameter space and science reach of existing or planned experiments in the program and globally, as well as relevant future directions that may be addressed by significant upgrades or next steps for the large projects. If applicable, the study can also develop a technology R&D roadmap, along with a notional timeline and schedule, identifying key technical milestones relevant to enabling future DM searches.

The study results should be described in a report delivered within two months following the completion of the workshop. DOE will use the study results to inform program planning. The next steps may include a call for proposals to support small project concept and technology development that satisfy the study priorities.

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Extraction from cosmological simulation of dark matter halo hosting a Milky Way-type galaxy.

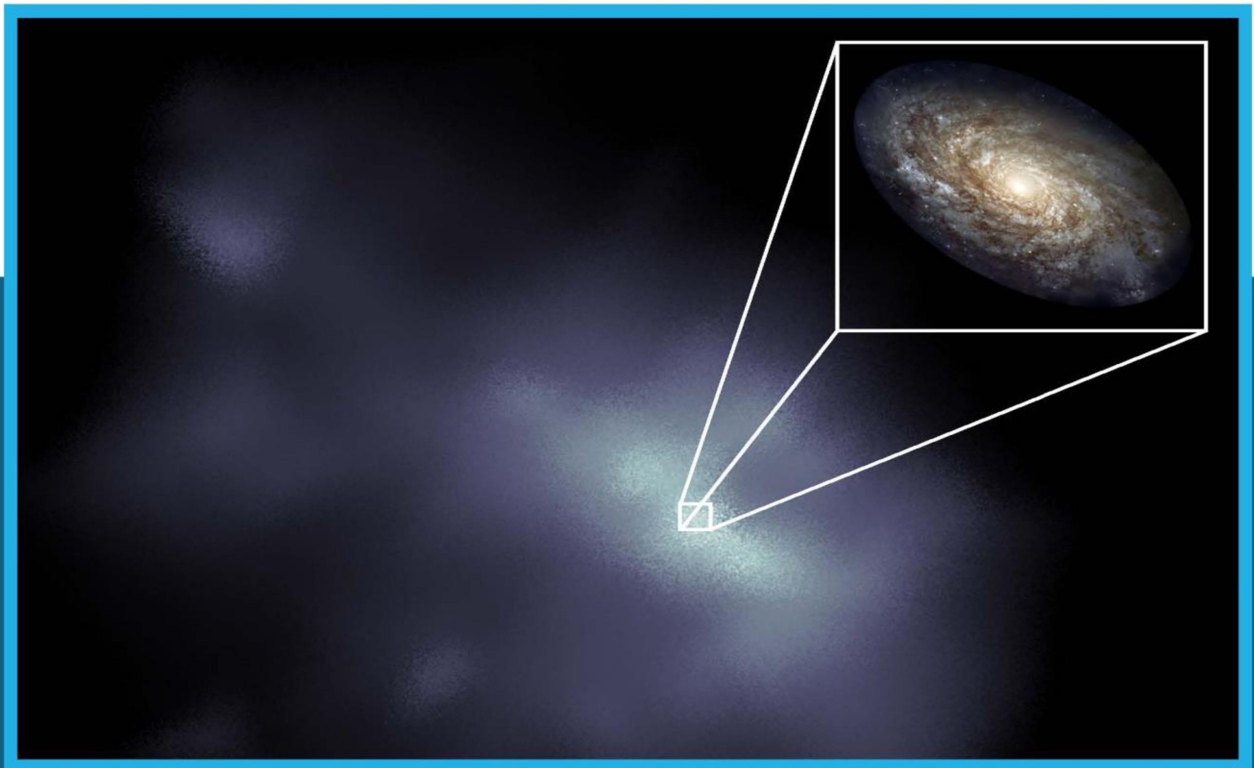

Image credits: Cosmological Physics and Advanced Computing Group, Argonne National Laboratory.
Halo from the Outer Rim simulation, galaxy image (NGC 4414) from the Hubble Space Telescope Key Project.

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