The Future of US Particle Physics
Report of the 2021 Snowmass Community Study

Chapter 5: Cosmic Frontier

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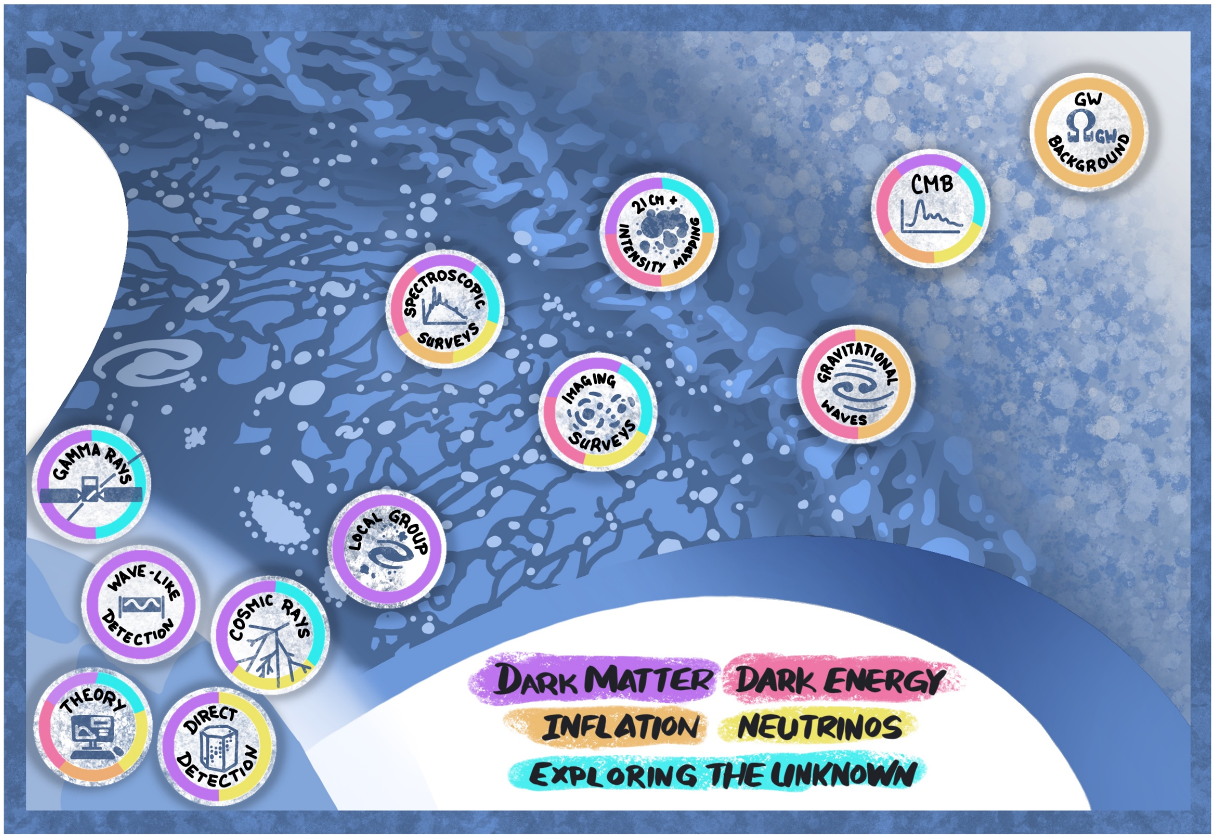

Abstract

We present the Snowmass 2021 strategy to delve deep, search wide, and aim high for new discoveries at the Cosmic Frontier of particle physics. The Cosmic Frontier is the bedrock of High Energy Physics in the twenty-first century, providing evidence for beyond the Standard Model physics that motivates much of the Snowmass 2021 program across all frontiers. The scientific scope of the Cosmic Frontier encompasses four of the five science drivers of the field: dark matter, dark energy and cosmic acceleration, neutrinos, and exploring the unknown in search of new particles, new fields, and new principles of Nature. Covering a time frame of 20 years, our plan features a portfolio of small, medium, and large projects which are ready to produce a continuous stream of groundbreaking science results within this decade along with pathfinders for the next generation of projects to come in the following decade. In this report, we articulate the fundamental questions to be addressed for each science driver and identify key measurements required to achieve well-defined scientific thresholds for discovery. We describe the ecosystem of experiments designed to obtain those measurements as well as the associated developments in theory and technology. We plan to delve deep in sensitivity and search wide across many orders of magnitude in mass to discover the particle nature of dark matter. Moreover, we aim high, through billions of light years of cosmic history, to discover the time-evolution of dark energy, make the first experimental observations of the physics of inflation, and search for new physics at the highest energy scales.

About Snowmass: Snowmass is the U.S. High Energy Physics (HEP) Community Planning Exercise organized by the Division of Particles and Fields (DPF) of the American Physical Society (APS). Through the Snowmass process, the community comes together to formulate a 10-year scientific vision for the field within a 20-year global context. The Particle Physics Project Prioritization Panel (P5) takes the scientific input from Snowmass and develops a strategic plan that will inform decisions by the funding agencies. The Cosmic Frontier is one of the major Snowmass sub-communities, focused on cosmic probes of fundamental physics. Cosmic Frontier key topics include: dark matter, dark energy, and inflation. During the Snowmass 2021 process period, from April 2020 to July 2022, the Cosmic Frontier community produced white papers, participated in town-hall meetings and workshops, and gathered input more broadly from all 10 Snowmass frontiers and several related fields. As a result, seven topical reports were produced. The community consensus is consolidated in this frontier-level report, led by the three Cosmic Frontier conveners and co-authored by the topical conveners.

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Cosmic Frontier

5.1 Executive Summary

The Cosmic Frontier realizes the High Energy Physics (HEP) community's goal of understanding the fundamental physics that governs the Universe and its constituents through a rich scientific research program designed to *delve deep, search wide, and aim high* towards discovery. Cosmic observations are exclusively responsible for our knowledge of the need to extend the Standard Model to describe dark matter, dark energy, and cosmic inflation. As a result, the Cosmic Frontier is uniquely positioned to shed light on these mysteries. The Cosmic Frontier research portfolio features large, medium, and small projects leveraging new developments in both technology and theory to produce a continuous stream of high-impact science over the coming decades.

Understanding the identity, nature, and origin of **dark matter** is one of the grandest challenges in physics and spans all Snowmass frontiers. Well-studied theoretical models provide a compelling scientific case to make broad and rapid inroads into unexplored dark matter parameter space via a *delve deep, search wide* strategy. The HEP community will delve deep to comprehensively explore the high priority science targets of weakly interacting massive particles and the QCD axion. Concurrently, they will also search wide to efficiently probe broad, logarithmic ranges of parameter space that includes hidden sectors and axion-like particles, deploying experimental tools incorporating cosmic probes and cutting edge technologies. Meeting the dark matter challenge will require a broad and coordinated program at multiple scales – including direct, indirect, and cosmic probe experiments – optimized for each decade in dark matter mass. This program of experiments will span many Snowmass frontiers. For example, while dark matter can only be concretely identified via direct observation of its presence in the cosmos, some of its properties can be best studied in controlled laboratory experiments with accelerator test beams or particle colliders. Given the importance of the science and the broad range of experimental opportunities, the overall investment in a coordinated dark matter program should be a priority and at a scale comparable to that of other large experimental programs.

Understanding cosmic acceleration, in both its present-day form of **dark energy** and in the early universe era of **inflation**, is a key science driver for our community. Cosmic surveys comprise experiments in the HEP program designed to study the physics of dark energy and inflation which would otherwise be inaccessible. Cosmic surveys *aim high* at observables spanning almost the entire 13.8 billion year history of our Universe. The current Golden Age of cosmic surveys includes optical/near-infrared survey projects that are under construction or recently commissioned, new cosmic microwave background projects that are actively underway, spectroscopy projects that are ready to be built this decade, as well as next-generation gravitational wave, line-intensity mapping, and cosmic microwave background projects for which pathfinders are now being carried out. Together, these experiments will make precision measurements of dark energy, determine the energy scale and dynamics of cosmic inflation, search for new light relics and other beyond-Standard-Model particles, and probe the physics of dark matter. Cosmic Frontier experiments are able to observe elements of the Standard Model at extreme energies and under extreme environmental conditions which are impossible to achieve in terrestrial laboratories. New messengers such as gravitational waves provide unobscured views of the Universe at its earliest moments, and could reveal new physics through dynamical processes such as early phase transitions which have never been probed to date.

5.2 Delve Deep, Search Wide, Aim High: the Cosmic Frontier Strategy for Discovery

The Cosmic Frontier (CF) comprises a broad set of activities aimed at understanding the fundamental physics which governs the evolution of the Universe and its constituents. For Snowmass 2021, the CF is organized into topical groups, each of which produced a report summarizing the open questions and scientific opportunities in its area:

- CF1 : particle-like dark matter [1];
- CF2 : wave-like dark matter [2];
- CF3 : cosmic probes of dark matter [3];
- CF4 : dark energy and cosmic acceleration in the modern universe [4];
- CF5 : dark energy and cosmic acceleration at and before cosmic dawn [5];
- CF6 : new facilities and complementarity in probes of dark energy and cosmic acceleration [6]; and
- CF7 : cosmic probes of fundamental physics [7].

Taken together, the topical working group reports present a broad program of inquiry that offers unique opportunities to understand the physics of dark matter, dark energy, and inflation, and to search for physics beyond the Standard Model (BSM) in a way that is highly complementary to the other Snowmass frontiers.

The Cosmic Frontier engages with all five of the 2014 P5 science drivers, with particular connections to: (i) identify the new physics of dark matter; (ii) understand cosmic acceleration: dark energy and inflation; and (iii) explore the unknown: new particles, interactions, and physical principles. Currently, the incontrovertible experimental evidence for physics beyond the Standard Model of particle physics consists of:

- dark matter;
- dark energy;
- cosmic inflation;
- the baryon asymmetry of the Universe; and
- neutrino masses and mixing.

With the exception of neutrino masses, all of these are the direct result of observational data from the Cosmic Frontier and neutrino masses involved solar neutrinos. Consequently, the techniques of the Cosmic Frontier are the only currently established handle to access several of these physics. The successful road map laid out by P5 in 2014 has resulted in a Golden Age of investigation into fundamental physics through CF projects, which have made great progress exploring the parameter space of dark matter models and pinning down the nature of dark energy. There is strong motivation to build and expand upon that vision to complete exploration of the physics of dark matter, dark energy and cosmic inflation, and to search for new physics that is too massive or too weakly-interacting to access terrestrially. A discovery in any of these areas would be transformational for particle physics, and would suggest new priorities for high energy physics (HEP) research across all the Snowmass frontiers in the future.

5.2.1 Fundamental Questions

CF projects engage with big fundamental questions at the core of the quest to extend/replace the Standard Model and aligned with the 2014 P5 science drivers. A non-exhaustive list of the central questions includes:

- What is the nature of dark matter? Is it a single particle or a set of multiple components? Does it belong to a dark sector?
- How does dark matter interact with the Standard Model? Does the Higgs serve as a portal between the two? Are there new bosonic mediators?
- Is the dark matter itself bosonic and does it exhibit macroscopic wave-like phenomena like oscillatory forces?
- What are the dynamics within the dark sector? Does dark matter have important self-interactions?
- How was the dark matter produced in the Early Universe?
- Does the nature of dark matter reveal further secrets informing physics beyond the Standard Model or cosmology?
- What is the nature of dark energy? Is the acceleration due to a new energy density component or does it demand a change in general relativity?
- If dark energy is an energy density, is it a cosmological constant, or a dynamical quantity changing with time?
- When did dark energy become important in the history of the universe?
- Why are there two eras of acceleration in the history of the universe?
- How is the inflationary paradigm realized in nature?
- What is the energy scale of inflation?
- Does inflation have dynamics that manifest themselves as an observable imprint on the primordial distribution of matter fluctuations?
- Did BSM degrees of freedom influence the thermal history of the universe?
- What is the scale of neutrino masses? Can cosmological observations sufficiently constrain it to distinguish between normal and inverted mass hierarchies?
- Can gravitational waves reveal new dynamics or early cosmological phase transitions?
- How can cosmic sources of high energy particles reveal their participation in new interactions or new physics?

5.2.2 State of the Cosmic Frontier

Since the previous Snowmass in 2013, the Cosmic Frontier has made great progress towards realizing the science goals prioritized by P5 in 2014. Searches for WIMP dark matter scattering with nuclei have advanced to generation two, and searches for axions have begun to probe the parameter space relevant to explain the strong CP problem. These searches 'delve deep' to study some of the high priority accessible targets in dark matter parameter space. At the same time, new techniques such as those sensitive to electron scattering are able to probe dark matter to sub-MeV masses and 'search wide', providing coverage for a wide parameter space consistent with dark matter production in the early universe.

The current U.S. priority on quantum information science has produced fruitful collaborations between HEP and researchers in other fields as ultra-weakly interacting dark matter is a natural science target for quantum sensing. Cross-disciplinary collaborations with the AMO and condensed matter fields have also produced novel dark matter search techniques to provide broad coverage of dark matter parameter space.

Indirect searches for dark matter using the Galactic center, Milky Way dwarf galaxies, and our local Galactic halo as observational targets have produced broad constraints on dark matter mass and self-annihilation cross section. However, despite a strong endorsement from the previous P5, indirect searches for dark matter with gamma-ray observatories have not been prioritized and the U.S. is ceding leadership in this area to other countries.

Investments in cosmological surveys are now coming to fruition – results from the Dark Energy Survey (DES) and BOSS/eBOSS surveys have cemented ΛCDM as a description of the expansion of the Universe, the Dark Energy Spectroscopic Instrument (DESI) is obtaining data at a phenomenal rate, and construction of the Vera C. Rubin Observatory is nearing completion. These experiments 'aim high', offering unprecedented opportunity to understand the nature of cosmic acceleration/dark energy as well as providing unique probes of the properties of dark matter such as self-interactions.

Major advances have also been made in Cosmic Microwave Background (CMB) science. The U.S. CMB community has coalesced around a single, large next-generation project, CMB-S4, which will observe the microwave sky with unprecedented statistical precision, targeting the physics of cosmic inflation, searches for BSM dark radiation, and measuring neutrino masses.

The detection of gravitational waves from merging binary neutron stars and black holes by the LIGO and Virgo Collaborations was a watershed moment for cosmic science. This new observational tool will be important for many areas of particle astrophysics and cosmology including measurements of cosmic acceleration at high redshift, searches for dark matter, and detection of relic gravitational wave radiation from early universe phase transitions.

5.2.3 Science Opportunities

We identify science opportunities across the broad themes of dark matter detection, identifying the correct model of cosmic inflation, precision cosmology for understanding both dark matter and dark energy, and the use of gravitational waves for these HEP science goals.

- **CMB probes of inflationary cosmology**: Completion of CMB-S4 will probe large classes of models of cosmic inflation and investigate the energy scale and dynamics of this ultra-high-energy sector. In a broad science program, it will also provide high-precision measurements of the matter power spectrum which can be used for a variety of cosmology studies, constrain the neutrino mass scale with possible sensitivity to the normal vs. inverted mass hierarchy, and will search for new physics in the form of cosmic relic particles.

- **Direct detection of WIMP dark matter**: The next generation of direct dark matter experiments will probe the WIMP paradigm down to and into the neutrino fog.
- **Direct detection of axion dark matter**: A portfolio of axion dark matter search experiments enabled by new quantum sensing technologies will "delve deep" in searches for the ultraweak QCD axion signal in most of its predicted band.
- **Cosmic probes of dark matter**: Cosmological and astrophysical observations, coupled with numerical simulations and theory, will widely probe and constrain the fundamental nature of dark matter over an expansive range of parameter space, some of which is inaccessible to terrestrial and laboratory searches. In the coming decade, the Rubin Observatory Legacy Survey of Space and Time (LSST) and DESI have the potential to revolutionize our understanding of microscopic properties of dark matter, such as mass, self-interactions, interactions with radiation, and quantum wave features. On a longer time horizon, the CMB-S4 and Spec-S5 projects have access to rich dark matter physics as well. The inclusion of dark matter physics in the research programs of these experiments alongside studies of dark energy and inflation should be strongly supported.
- **Indirect detection of dark matter via high energy astrophysics**: New $>$ 100 GeV gamma ray observatories including SWGO and CTA will study dark matter via its annihilations or decays in the galaxy, with sensitivity to the thermal-freezeout benchmark annihilation rate up to masses approaching the 100 TeV scale, where model-agnostic limits on the early-universe cross section come into play. Planned or proposed space missions will set stringent new bounds in the keV-GeV range, and new cosmic-ray detectors will perform the first dedicated searches for low-energy antinuclei as a background-free discovery channel. Planned and ongoing upgrades to existing observatories including IceCube and AugerPrime will provide unique probes of ultra-heavy dark matter.
- **Multi-pronged detection of thermal dark matter in dark portal scenarios**: A variety of new techniques including low-threshold microcalorimetry will be deployed to search for sub-GeV portal dark matter. Concurrently, accelerator-based experiments will search for new bosons which serve as the messengers between the dark and visible sectors.
- **Direct detection of ultralow mass dark matter using cross-disciplinary technologies**: Engagement with the fields of quantum information science and atomic, molecular, and optical physics has brought new ideas and technologies to bear on searching for ultra-low-mass wave-like dark matter, which produce periodic perturbations detectable via ultra-sensitive instruments such as atomic clocks and interferometers.
- **Precision cosmology with existing telescopes**: Cosmic surveys including DESI and LSST will provide strongly-constraining data sets for precision cosmology. One percent measurements of the dark energy density to $z \sim 1.5$ will provide crucial tests of dynamical dark energy models. Measurements of the overall matter power spectrum will enable tests for new dynamics in the early universe and for precision constraints on the total mass of neutrinos. By probing both the growth rate of density perturbations and the expansion history of the universe, these experiments will provide critical tests of whether cosmic acceleration is in fact due to a dark energy-like component of the Universe or if it instead requires a non-Einsteinian theory of gravity on cosmic scales. Increased statistics for Milky Way dwarf galaxies and studies of smaller dark halos will provide information on dark matter masses and self interactions and also provide new targets for indirect detection searches. For these surveys to reach their full potential, funding for innovative science analyses – including cross-survey measurements

– will be needed. New data from other facilities will be needed as a complement to unlock the full constraining power of LSST, including follow-up observations of supernovae and gravitational wave standard sirens as well as measurements of spectroscopic redshifts for deep training samples of objects to enable precision photometric redshift measurements.

- **Stage V spectroscopic probes of cosmic acceleration and inflationary cosmology:** The development of a powerful new Stage V spectroscopic facility will allow precision measurements of the cosmic expansion history to be extended to the limits of the modern universe ($z \lesssim 5$), simultaneously providing new constraints on the inflationary epoch of cosmic acceleration. Accessing high redshifts greatly expands the cosmic volume surveyed, enabling structures on the largest scales where inflationary signatures are expected to manifest to be explored. A Stage V spectroscopic facility also enables a search for new light relics and other beyond the Standard-Model particles including measurement of the sum of the masses of neutrinos, and probes of the physics of dark matter via a variety of precision studies of nearby galaxies and of stars in the Milky Way halo.

- **New pathfinder experiments for Stage VI precision cosmology**: Pathfinder experiments could enable progress on powerful new probes of cosmology such as line intensity mapping methods in 21 cm and millimiter wave molecular lines. Those new probes can extend matter power spectrum studies to still higher redshifts and greater volumes than Stage V spectroscopy can reach. For example, LuSEE-Night is a mission to the far side of the Moon being carried out in partnership between DOE and NASA as a pathfinder for a future Stage VI 21-cm experiment.

- **New experimental windows on fundamental physics**: Pathfinder experiments including multi-messenger cosmology with gravitational waves, new techniques for precision measurements in astrometry, spectroscopy and photometry, and new sky surveys from space at radio frequencies below Earth ionospheric cut-off have potential to unlock hiherto unused probes of fundamental physics through cosmological measurements.

- **Ultra-high-energy cosmic rays as a probe of new physics below the fermi distance**: The new level of precision achieved by AugerPrime, IceCube, and next-generation experiments will provide opportunities to study non-perturbative QCD and physics beyond the Standard Model using natural accelerators well beyond the reach of human-made ones. The already-established anomalous muon production in extensive air showers (which has eluded explanation in models tuned to LHC data) guarantees that discoveries will be made.

- **Gravitational waves as a new probe of particle physics and cosmology**: Gravitational waves have emerged as a new and unique probe of dark sector physics, which may only be minimally coupled to the standard model via gravity. In addition to searching for relic gravitational waves from early-universe phase transitions (including leptogenesis models or the QCD axion), current and future gravitational wave observatories can potentially perform precision measurements of cosmic acceleration through mergers of neutron stars and black holes, standard sirens, which are new standard distance indicators. These large interferometers also have a large effective collection area, enabling searches for heavy dark matter.

- **High-energy neutrinos as a new venue to study neutrino interaction and mixing**: The cosmic neutrinos detected by IceCube provide a new opportunity to learn neutrino physics at TeV-PeV energies. The upcoming IceCube Upgrade and future GeV cosmic neutrino experiments will measure the flavor composition and tau neutrino appearance with high precision. Future >100 PeV neutrino experiments may uncover cosmogenic neutrinos and probe BSM features at extreme energies.

5.2.4 The Experimental Program

The CF strategy detailed in this report encompasses a science-rich program with small, medium, and large experiments which are planned on both near-term and long-term timescales. The community consensus is that this coming decade must feature strong support for this program in full to ensure that HEP will enjoy the new era of discovery and groundbreaking precision measurements that have been promised for the next two decades, as well as building even more powerful experiments to reach key science thresholds. An overview of the CF program is provided in this section. Details about the projects and activities mentioned here are provided in later sections of this report.

Cosmic surveys: Figure 5-1 summarizes the cosmic survey projects and their discovery potential across multiple science areas of our program. For each fundamental question, we have identified a key measurement with a clear threshold for discovery. Together, the planned projects should deliver results spanning large swaths of cosmic frontier science, including studies of cosmic acceleration/dark energy, inflation, searches for indications of new particles (e.g., dark radiation), and exploration of dark matter properties. Cosmic surveys generally provide datasets that can be used for many purposes, addressing multiple HEP science drivers simultaneously. The figure shows a rough timeline for when each major project could come into play and gradually reach its full discovery power. The large CMB-S4 and Spec-S5 projects should play a key role in advances over the next decade and beyond. The figure also includes potential future surveys that will be enabled by R&D and small pathfinder initiatives; these projects would employ new technologies and techniques such as 21-cm and mm-wave Line Intensity Mapping (LIM), Gravitational Wave Observatories (GWO), and future broadband CMB imaging. This planned sequence of experiments ensures that CF will have a continuous stream of data to support scientific breakthroughs without gaps for construction of our largest facilities.

In the Cosmic Frontier survey ecosystem each type of program brings unique strengths to the portfolio, including shape measurements that can only come from imaging, precise and robust redshift measurements that require spectroscopy, and multi-messenger data that exploits new gravitational wave detection capabilities; by also spanning a range in wavelength (e.g., Optical/IR vs. mm-wave vs. 21-cm), information from different redshift ranges can be accessed. While each survey will deliver groundbreaking results on its own, no single experiment can meet all of the discovery thresholds without complementary information from other programs.

As a result, the CF survey program is designed to leverage the strengths of multiple experiments simultaneously. One example of this complementarity is that going beyond discovery of the energy scale of inflation (which CMB-S4 could accomplish on its own) to conclusively probing its physics via precision measurements of the f_{NL} parameter, a combination of information from a Stage V Spectroscopic Facility (Spec-S5) with CMB-S4 would be needed. Other science goals such as studying the time evolution of dark energy, conclusively testing the cold dark mater hypothesis, searching for features in the primordial power spectrum, and discovering the cosmic gravitational wave background will require the next-generation of surveys for which pathfinders and R&D work should be supported in this decade. These and many other science opportunities realized by the CF's survey ecosystem have been discussed in detail in the topical group reports [3–6]. In any funding scenario to be considered by the next P5, the Snowmass community consensus is that support for the CF cosmic surveys program should be at a level that enables discovery across the entire scope of the science program.

Searching for dark matter: Figure 5-2 shows two snapshots of the key dark matter discovery parameter space, which has greatly expanded since the last Snowmass. They illustrate the broad coverage spanning many decades of dark matter parameters which will be achieved by the ambitious experimental program envisioned in this report, comprising both a broad portfolio of small/medium-scale direct and indirect

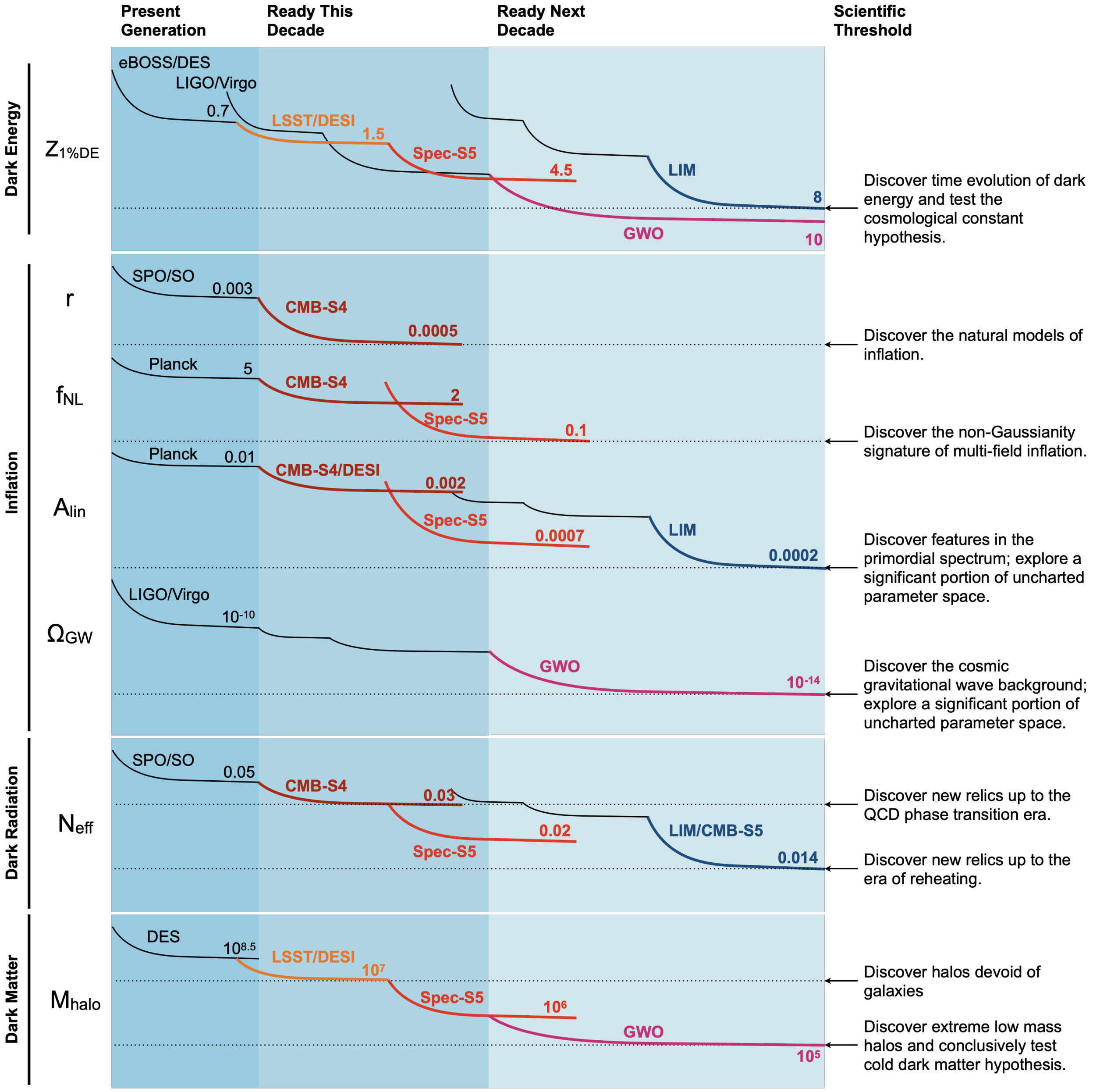

Figure 5-1. *The landscape of cosmic survey projects and their discovery potential. For each major science topic, we identified a key measurement threshold for discovery. Bold lines show medium and large projects ready to produce science in this decade or the next. In particular, CMB-S4 is a large project that is currently at CD-0 stage. Labeled thin lines represent the results from current surveys and unlabelled thin lines are pathfinders for the next generation of projects. Note that the bold line labels Spec-S5, GWO, LIM, and CMB-S5 do not represent specific projects. Instead, they represent categories of future experiments for which multiple proposed projects may currently exist in the community (namely, Stage V Spectroscopic Facility, next-generation gravitational wave observatory, 21cm/mm-wave line intensity mapping, and next-generation CMB, respectively). Please refer to the text for details about these projects and their key measurements.*

detection experiments optimized for each decade in dark matter mass, as well as an expanded cosmic probes program to identify the properties of dark matter via cosmic surveys, which is highly synergistic with the other science these surveys will undertake. The top panel shows current experimental limits via the grey shaded regions, while the bottom panel shows the projected sensitivity over the same parameter space after completion of our program. In many cases, utilizing new detector technologies will require cross-disciplinary collaborations to access the expertise, technology, and facilities of neighboring fields of study such as AMO, condensed matter physics, quantum information science, and gravitational physics. Similarly, for indirect probes of dark matter scattering, annihilation, or decay in galactic halos, HEP provides a critical role in developing instrumentation for astroparticle observatories. Understanding the astrophysical backgrounds will require collaboration with the broader non-HEP astronomy and astrophysics community.

Accomplishing the full scientific scope of the cosmic frontier program will require that robust support for ongoing, new, and future projects be well-matched by funding mechanisms for research groups to do science with data from those projects. This includes research support for teams within experimental collaborations and beyond (e.g., theory and simulation developments as well as detector R&D studies that may not be part of an existing experiment in our portfolio today, but that will enable the next generation of experiments). In particular, a strong feature of the CF program is that multi-project analyses can yield results of greater impact than the sum of their parts. Thus, new mechanisms in support of such multi-project initiatives have been identified as an important component of the CF strategy for discovery.

5.3 Dark Energy

The accelerating expansion of the modern universe over the last 5 billion years of cosmic history represents one of the most formidable scientific problems of our time. Its discovery was awarded the physics 2011 Nobel prize. Similar to what has happened after the discovery of the Higgs boson by our colleagues in the energy frontier, this discovery has launched our field into a new era of precision measurement studies aiming to understand the physics of cosmic acceleration — the explanation for which must clearly lie beyond the Standard Model.

Developing an understanding of the cause of cosmic acceleration in the modern universe should revolutionize our understanding of fundamental physics. Either we will discover a new form of energy whose source lies beyond the Standard Model of particle physics – some form of dark energy; or we will motivate a new theory of gravity beyond Einstein's general relativity. If dark energy is the solution, it then accounts for two-thirds of the total present mass-energy density of the universe and permeates the empty space between galaxies. It hinders the growth of density perturbations such as those which can form clusters of galaxies, and makes distant astrophysical sources appear dimmer than expected by increasing their distances. Detailed measurements of both the expansion history of the universe and of the rate at which cosmic structures grow are central to understanding the nature of cosmic acceleration; in combination, they allow us to distinguish explanations associated with dark energy from those which require modifications to theories of gravity.

Cosmology research in the twenty-first century is dominated by large cosmic survey experiments carried out by world-wide collaborations comprising hundreds of members from dozens of institutions. These large teams have developed specialized equipment and novel analysis tools which enable us to carry out observations of unprecedented scope and precision. For example, the Dark Energy Survey (DES) collaboration uses a 570-megapixel camera, the Dark Energy Camera (DECam), installed on a 4-meter telescope in Chile; the Dark Energy Spectroscopic Instrument (DESI) collaboration uses a system of 5000 robotic fiber positioners on a 4-meter telescope in Kitt Peak, Arizona; and the Legacy Survey of Space and Time (LSST) Dark Energy Science Collaboration (DESC) will use a 3.2 gigapixel camera on a 8.5-meter telescope at the Vera Rubin Observatory in Chile.

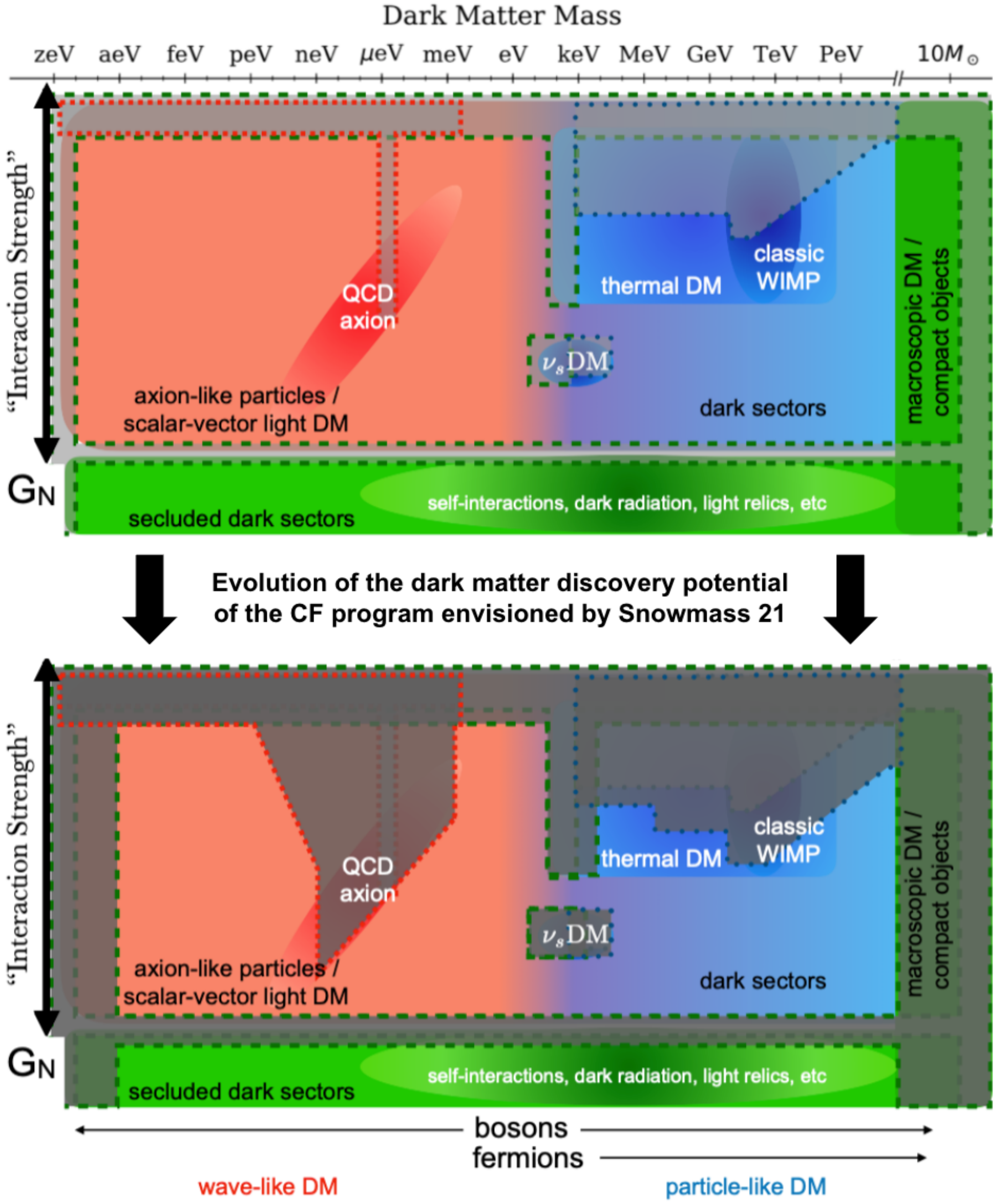

Figure 5-2. *Cartoon (not to scale) of the dark matter sensitivity of the Delve Deep, Search Wide strategy outlined in this report compared to current dark matter limits. The range of possible dark matter masses with well-studied origin stories now spans many orders of magnitude while the interaction strengths with standard model particles can range from electroweak scale down to purely gravitational strength. Broad, logarithmic coverage of this expanded dark matter parameter space is attainable with a range of new techniques which have been developed, but will require an ambitious and significantly expanded program of mid- and small-scale experiments as well as novel cosmic probes using existing and planned survey instruments. For details on each of the experimental projects and initiatives, please refer to the dark matter section of the report.*

As a result of this robust series of cosmic survey experiments, the community has advanced in leaps and bounds towards our goal of understanding cosmic acceleration via precision measurements of key cosmological parameters. These key parameters include:

- **The equation of state parameter of dark energy (w).** — If w is exactly equal to -1 and does not change throughout the cosmic history, then dark energy acts as a cosmological constant – the simplest, yet non-trivial, dark energy model. One of the key questions that our community wants to shed light upon is whether or not dark energy is consistent with this model. Determining the dark energy equation of state with percent-level precision over a wide redshift range is key for addressing many fundamental questions related to dark energy and cosmic acceleration. Over the past twenty years of CF research cosmic surveys have made huge progress in this area. We now can measure w well at $z < 0.7$; observations so far are consistent with a cosmological constant model, but the time evolution of the cosmic equation of state is only poorly constrained so far. Our next leap will be to study the signatures of dark energy to the limits of the modern universe ($z \lesssim 5$), which will provide novel insights into the earliest times when it began to become significant.

- **The rate of expansion of the universe today (H_0).** — This parameter is related to dark energy because it provides the low-redshift anchor to measurements of the cosmic expansion history. As a result, the value of H_0 has an impact on many constraints on w. H_0 has been determined with good precision by experiments relying on data from two vastly different eras of the universe. Early-universe measurements (using for example CMB observations) would be expected to agree with values derived from galaxies, supernovae and other observables in the dark energy-dominated modern universe. A discrepancy between the two regimes would indicate either that the model is incomplete or that there are systematic issues in the distance determinations used to anchor sets of H_0 measurements. At this point, measurements of H_0 with precision of 1-2% have been made with a variety of techniques; the tension between determinations tied to the low-redshift versus high-redshift distance scales is starting to exceed the 5-sigma level. Several new measurements that will help uncover the origins of this discrepancy over the next two decades are described in this report.

- **The amplitude of fluctuations in the density of matter in the universe (S_8).** — Precision measurements of the amplitude of density fluctuations in the universe and their growth over time are highly complementary to measurements of the cosmic expansion history (which should directly depend on the dark energy equation of state). For instance, if general relativity provides the correct description of gravity on large scales, the growth rate of density perturbations can be predicted directly from the expansion history; however, if cosmic acceleration occurs due to departures from Einsteinian gravity, this relationship is broken. Early and late-universe measurements of the amplitude of the matter power spectrum, as measured by the S_8 parameter, are currently in tension. The significance of this tension is lower than for H_0, but the ongoing CF experimental program is rapidly improving the precision of measurements in this area, and percent-level determinations of S_8 in both the modern and CMB eras will soon be possible.

5.3.1 The Next Stages of Dark Energy Experiments

The dark energy component of the CF program has long been planned to proceed via a series of cosmic survey *Stages*, each greater in scope and precision measurement capability than its predecessor, as defined in the Dark Energy Task Force (DETF) report [8]. The current state-of-the-art results are coming from DETF Stage III surveys (e.g., BOSS, eBOSS and DES); DETF Stage IV experiments are now underway (e.g., DESI) or soon to begin (LSST). These new experiments should provide percent-level constraints on w (for models where its value does not evolve with time), driven primarily by measurements at $z < 1.5$.

Since the last Snowmass report, CMB experiments have become a significant part of the CF program. The next-generation project, CMB-S4, was ranked highly by the previous Snowmass/P5 process and is currently at the CD-0 stage. The data obtained by CMB experiments plays a vital role in exploring the fundamental HEP questions of cosmic acceleration in both the modern universe (dark energy) and the early universe (inflation).

Looking forward, within the next two decades, our community seeks to build CMB-S4 as well as to develop new Stage V and Stage VI projects. This suite of experiments will make precision measurements of w, H_0, and S_8 and other cosmological parameters with data sets that probe not only the current era in which dark energy is firmly dominant, but also detailed measurements going well beyond the transition between the dark matter- and dark energy- dominated eras and new tests of consistency with early universe data.

In this report, we categorize the next stages of dark energy and cosmic acceleration experiments as follows:

- Stage IV – In this category we include those experiments which meet the DETF Stage IV definition (such as DESI and Rubin LSST), as well as fourth-generation CMB experiments. Both classes of experiment complement each other, as the science of early and late-time cosmic acceleration are strongly intertwined. A Stage IV CMB project (CMB-S4) is currently under development and should play a key role in cosmic frontier science. Stage IV cosmic survey experiments will provide precision constraints on dark energy, predominantly over the redshift range $z \sim 1.5$ (vs. $z \sim 0.7$ for Stage III). Novel analysis techniques that can take advantage of the leap in constraining power provided by Stage IV experiments, both when they are considered on their own and especially when analyzed in combination, should reduce systematic uncertainties and establish the true significance of the emerging tensions in H_0 and S_8.

- Stage V – In this category we include those experiments that would represent a substantial improvement ($3-4\times$ or better) in capabilities or cosmological constraining power over the equivalent Stage IV experiment. These projects will take the current precision cosmology program to the next level, providing percent-level constraints on the contribution of dark energy to the total density of the universe at redshifts up to $z \sim 5$; enabling new probes of the physics of inflation, with the potential to rule out broad swaths of models and to measure inflationary energy scales; and exploring in depth possible explanations for the origins of the current H_0 and S_8 tensions.

- Stage VI – This category encompasses a future generation of dark energy experiments which can further increase constraining power over Stage V and begin to test cosmology in the 'dark ages' of the Universe at $5 \lesssim z \lesssim 10$. Such projects will require smaller pathfinder efforts now to develop key technologies and methods, which should enable them to become ready to reach project status ~ 10 years from now. These ambitious experiments will incorporate novel technologies and take advantage of new opportunities, driving the field to its next leap in dark energy precision studies. Higher-redshift experiments should be able to explore even larger scales than Stage V, expanding the sensitivity to inflationary signatures, as well as providing sensitive tests for the presence of early dark energy.

5.3.2 A Stage V Spectroscopic Facility (Spec-S5)

The greatest near-term opportunity to revolutionize our understanding of cosmic acceleration both in the modern universe and the inflationary epoch will be provided by a new Stage V Spectroscopic Facility (Spec-

S5) which would combine a large telescope aperture, wide field of view, and high multiplexing. The technology for such a facility is at this point well-developed, building substantially on the legacy of DESI and Rubin Observatory. A Spec-S5 can simultaneously provide a dense sample of galaxies at lower redshifts to provide robust measurements of the growth of structure at small scales, as well as a sample at redshifts $2 < z < 5$ to measure cosmic structure at the largest scales, spanning a sufficient volume to probe primordial non-Gaussianity from inflation and to search for features in the inflationary power spectrum on a broad range of scales, while also testing dark energy models in poorly-explored regimes, determining the total neutrino mass, and strongly constraining the effective number of light relics. A Spec-S5 would also be able to probe the nature of dark matter using the kinematics of stars in the Milky Way halo and measurements of the matter power spectrum at small scales.

Multiple options for facilities that would qualify as a Spec-S5 have been proposed. These projects are described in the CF4 report [4], which also outlines the key factors to be considered when evaluating candidate facilities. The key requirement is that a Spec-S5 should represent a significant advance over what is possible with Stage IV facilities, should enable transformational progress on all of the Stage V science goals, and open up new discovery space, including:

- Measuring the contribution of dark energy to the total mass-energy density in the universe with uncertainties below 2% of $\Omega_{\rm total}$ out to $z = 5$, redshifts at which dark energy becomes dynamically negligible in w_0/w_a models, while simultaneously constraining modified gravity models over this range; cf. Figure 5-3. Spec-S5 measurements will also provide sensitive tests for early dark energy (at $500 < z < 50000$), as illustrated in Figure 5-4.
- Exploring the physical nature of the tensions in current measurements of H_0 (e.g., via BAO-based measurements spanning an unprecedented range of redshifts) and S_8 (with dense low-z samples providing many cross-checks for systematics by enabling measurements using many separate galaxy populations as well as multiple lensing methods).
- Testing for signatures of non-Gaussianity from inflation at a sufficient precision to be able to rule out all non fine-tuned multi-field models, while simultaneously searching for inflationary primordial features that signal the breaking of scale invariance and constraining contributions from dark radiation (sub-eV particles thermalized in the Universe). The Spec-S5 studies of inflation and dark radiation are points of synergy with CMB-S4 and will help the community to build a unified picture of the physics underlying both the early and late-time eras of cosmic acceleration.

A major strength of Spec-S5, in any of its proposed implementations, will be its ability to advance our understanding on multiple science fronts simultaneously, while also enhancing the science outcomes from other experiments in the CF portfolio. Cross-correlation measurements that combine Spec-S5 data with other surveys can be used to improve photometric redshifts for LSST as well as to unlock additional cosmological information (generally with reduced systematic uncertainties). Construction of the instrument for a Spec-S5 facility in collaboration with other partners could build upon HEP strengths and experience with DESI. Realizing Spec-S5 in any of the funding scenarios that P5 might consider would play a key role in advancing the scientific goals of the CF community.

5.3.3 New Opportunity: Gravitational Waves

The emergence of gravitational wave observatories (GWO) sensitive enough to detect sources at cosmic distances has revolutionized humanity's view of the universe. The HEP community, and the Cosmic Frontier

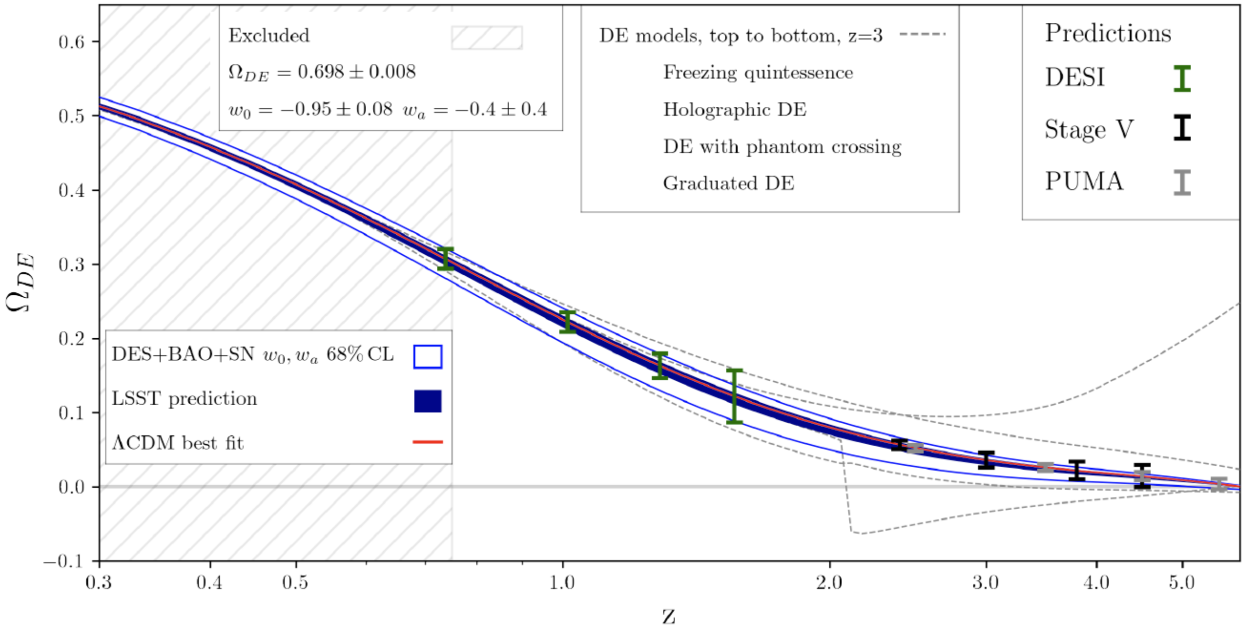

Figure 5-3. *Projected sensitivity to the fractional dark energy density relative to closure density as a function of redshift. Solid lines indicate extrapolations to high redshift of current conventional models fitted to data at low redshift* $0.1 < z < 0.75$*. Dashed lines indicate predictions of new models designed to address various tensions in the datasets. Data points with error bars indicate how the 2% level sensitivity obtained in ongoing and future high redshift surveys can directly constrain and discriminate between these models.*

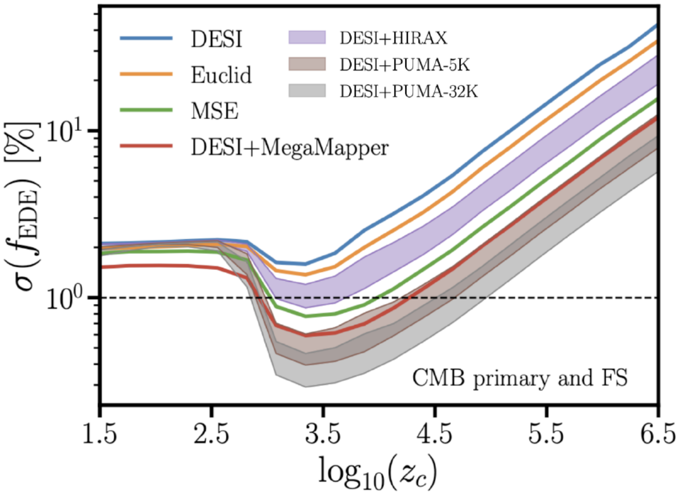

Figure 5-4. *Projected sensitivity of current and next-generation high redshift cosmic surveys to the fractional dark energy density relative to closure density near the CMB recombination epoch. The signal of early cosmic acceleration is an alteration to the growth of structure as measured via features in the matter power spectrum of the large scale structure. In particular, these probes will test models of early dark energy designed to explain the "Hubble tension," a discrepancy between high redshift CMB measurements and low redshift optical survey measurements of the Hubble expansion rate which is growing in statistical significance.*

sub-community in particular has been quick in realizing the implications of this new development and has been working towards incorporating GWO projects in our portfolio. Gravitational-wave standard sirens (merging compact object binary systems) allow measurement of the luminosity distance of the source and, together with redshift measurements, can be used to measure H_0 via the distance-redshift relation. Measurement of the Hubble parameter using standard sirens does not require a cosmic distance ladder and is model-independent: the absolute luminosity distance is directly calibrated by the theory of general relativity. Aiming to develop standard sirens into fully-fledged probes of dark energy, the DES collaboration launched a search and discovery program for the electromagnetic (EM) counterparts of events detected by the current GWO projects LIGO/Virgo. DES participated in the first multi-messenger discovery, of the binary neutron star merger GW170817, and contributed to the first standard siren-based measurements of H_0. Approximately fifty additional multi-messenger binary neutron star observations would be needed to reach the required precision to weigh in the Hubble tension debate [9]. The community is currently planning upgrades to the existing GWO network as well as a next-generation GWO network. One proposed next-generation project, currently being led by the US community, is known as Cosmic Explorer. The CF community plans to use standard sirens from a Cosmic Explorer-like GWO as a powerful sample of independent distance indicators going all the way up to $z = 10$. Combined with deep optical-to-near-infrared Stage IV and Stage V EM observatories, we can reach the required precision for Stage VI dark energy science.

Gravitational waves can probe dark energy and cosmic acceleration throughout the entire history of the universe with an observable that is novel and largely independent from the traditional observables employed thus far in the field. The next-generation GWO network will also have access to the binary black hole population when the universe was still in its infancy, to the equation of state of matter at neutron star cores at supranuclear densities and quark deconfinement phase transitions in hot merger remnants, and the ability to measure the properties of dark energy and dark matter, to stochastic gravitational-waves from early-universe phase transitions, and to the highly warped space-time in the strong-field and high-velocity limit of general relativity.

The CF community plans to incorporate GWO in its portfolio of tools for discovery with a long term strategic vision. We will pursue EM counterparts of events detected by the growing GWO network while launching new pathfinder (R&D) efforts to enable the HEP community to participate in the next-generation GWO project in a leading role. The new detector's sensitivity, roughly 10 times better than the planned LIGO upgrade, requires significantly larger facilities and a number of technological upgrades. Both are challenging requirements that the HEP community is well-equipped to meet, given our experience.

This is likely a once-in-a-century opportunity for the HEP community to make new breakthroughs in an entirely new class of experiments and utilize this new opportunity to advance on our scientific drivers at a much faster pace than previously anticipated.

5.3.4 Experimental Program & Facilities: Cross-Experiment Strategic Plan

In light of the opportunities for new breakthroughs in dark energy and cosmic acceleration over the next decades, the CF community has converged on a strategic plan with both near-term and longer-term action items, built upon a set of highly complementary projects/facilities and research initiatives. Figure 5-5 summarizes how cosmic surveys will advance over Stages IV-VI using a key statistic: the maximum redshift where we can measure the contribution of dark energy to the total mass-energy density of the universe with percent-level precision. Stage III has achieved this at $z < 0.7$, and Stage IV should reach this goal for $z \lesssim 1.5$. In contrast Stage V and VI experiments should extend our reach to $z \sim 5$ and $z \lesssim$ 8-10, respectively. These thresholds will allow us to definitively test whether simple cosmological constant or time-varying w_0/w_a models are sufficient descriptions of cosmic acceleration, or if instead more exotic explanations with more complicated time evolution (such as those invoked to explain existing tensions, such as the models illustrated in Figure 5-3) will be needed. In either scenario, Stages V and VI will lead to a breakthrough comparable to, if not surpassing, the discovery of dark energy itself.

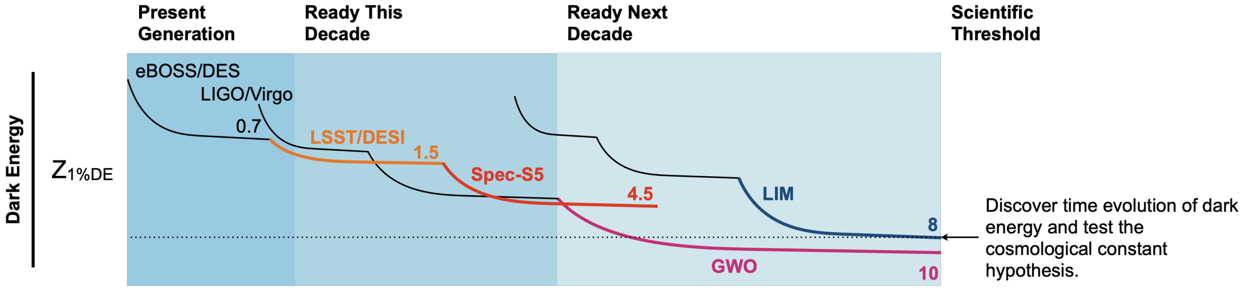

Figure 5-5. *Timeline illustrating the expected improvement in the redshift range over which the contribution of dark energy to the total mass-energy of the universe is strongly constrained. Their performance is quantified by $z_{1\%DE}$, the highest redshift at which the fraction of the critical density in dark energy, $\Omega_{\rm DE}$, can be measured with percent-level precision (uncertainties of 0.01 or less). We set the threshold for discovery at $z = 8$, which will allow us to rigorously test the cosmological constant hypothesis far beyond the dark energy-dominated era of the universe. Bold lines show medium and large projects ready to build this decade or the next; thin lines represent the current results and/or pathfinders for the next generation of projects.*

Figures 5-3 and 5-4 show projections for the sensitivity of example proposed Stage V and Stage VI surveys relative to current Stage IV surveys for two key parameters: the energy density of dark energy ($\Omega_{\rm DE}$), and the contribution of early dark energy to the overall cosmological model ($f_{\rm EDE}$). The program devised by the CF community will enable us to test a wide variety of dark energy models that have been proposed to explain the observed tensions in H_0 and S_8.

We summarize here the expected progression of projects and the key areas of support needed to address the questions of cosmic acceleration in both the modern and inflationary eras as described in the CF4 [4], CF5 [5], and CF6 [6] reports (noting that there is no significance to the ordering of items):

Near-future efforts: In the near term, it will be important to complete the Stage IV projects and fund the science efforts needed to take advantage of these powerful new facilities, including obtaining complementary data which will make them more powerful. Key needs to ensure the success of this program are to:

- Build and operate CMB-S4.
- Begin operation of Rubin LSST.
- Continue operation of DESI (via a new DESI-II program) to constrain dark energy in new domains and as a step towards a Stage V spectroscopic facility (Spec-S5).
- Fund science analyses of the Stage IV datasets.
- Establish funding mechanisms for small and medium scale projects to follow up transients discovered by LSST and standard sirens discovered by gravitational wave observatory (GWO) facilities, as well as to enable photometric redshift training spectroscopy for LSST.

Longer-term efforts: In order to enable longer-term progress, it will be vital to establish a flagship Spec-S5 program, as well as to explore new opportunities which can enable other Stage V and even Stage VI experiments. Key needs for this progress are to:

- Build and operate Spec-S5.
- Support R&D and pathfinder studies for a next-generation GWO.
- Support R&D and pathfinder studies for a next-generation CMB experiment (at the Stage V or VI level).
- Support R&D and small projects to develop technologies and methods that can enable a future surveys (e.g., LIM) and new precision probes of cosmology (e.g., redshift drift measurements).
- Support operations of Rubin Observatory beyond the initially planned 10 year LSST survey; the best future use of this facility should be evaluated later this decade after the first LSST analyses have been done.

Taking advantage of complementary experiments: The experiments in our program will probe dark energy physics in a variety of different ways, enabling cross-checks for and control of systematic uncertainties to obtain robust and rigorous results. For example, standard siren measurements based on sources from gravitational wave observatories will be subject to very different systematics from observables such as galaxy clustering or supernovae that have been commonly employed in precision cosmology studies to date. Furthermore, different experiments provide complementary information about the universe that yields more powerful constraints on cosmology when analyzed in combination.

However, such combined analyses present more challenges (particularly organizationally) than those which only involve one science collaboration. Key needs to ensure the success of multi-experiment analyses are to:

- Create funding streams and support for cross-survey analyses.
- Develop and support coordination between large facilities for optimized design, timely execution, and joint analyses.
- Create data archive centers for long term storage where data from cosmological surveys is replicated, continuously available, and easily accessible with software and computing resources for developing joint constraints on dark energy, inflation and dark matter.
- Create and support development of a diverse set of simulated data sets that could be used in joint analyses. Support should include common access to data and super-computing resources.

The CF strategy for medium and large cosmic survey facilities is designed to take advantage of the interconnected nature of the science questions we aim to approach. The same facilities which can provide compelling tests of the nature of cosmic acceleration can also probe the physics of inflation, neutrino masses, dark matter, and dark radiation, as described in other sections of this report. This is illustrated in Figure 5-6, taken from the CF6 report [6], which depicts the different areas of cosmic frontier science addressed by wide-field spectroscopic facilities (such as Spec-S5), CMB experiments (such as CMB-S4), line intensity mapping (which may play a key role in Stage VI), and gravitational wave observatories.

By incorporating both near-term and long-term projects at a range of scales, this experimental program should ensure that high-impact science results are continuously produced, avoiding lengthy gaps during project construction. In sum, the ecosystem of cosmic surveys proposed by the community to address the

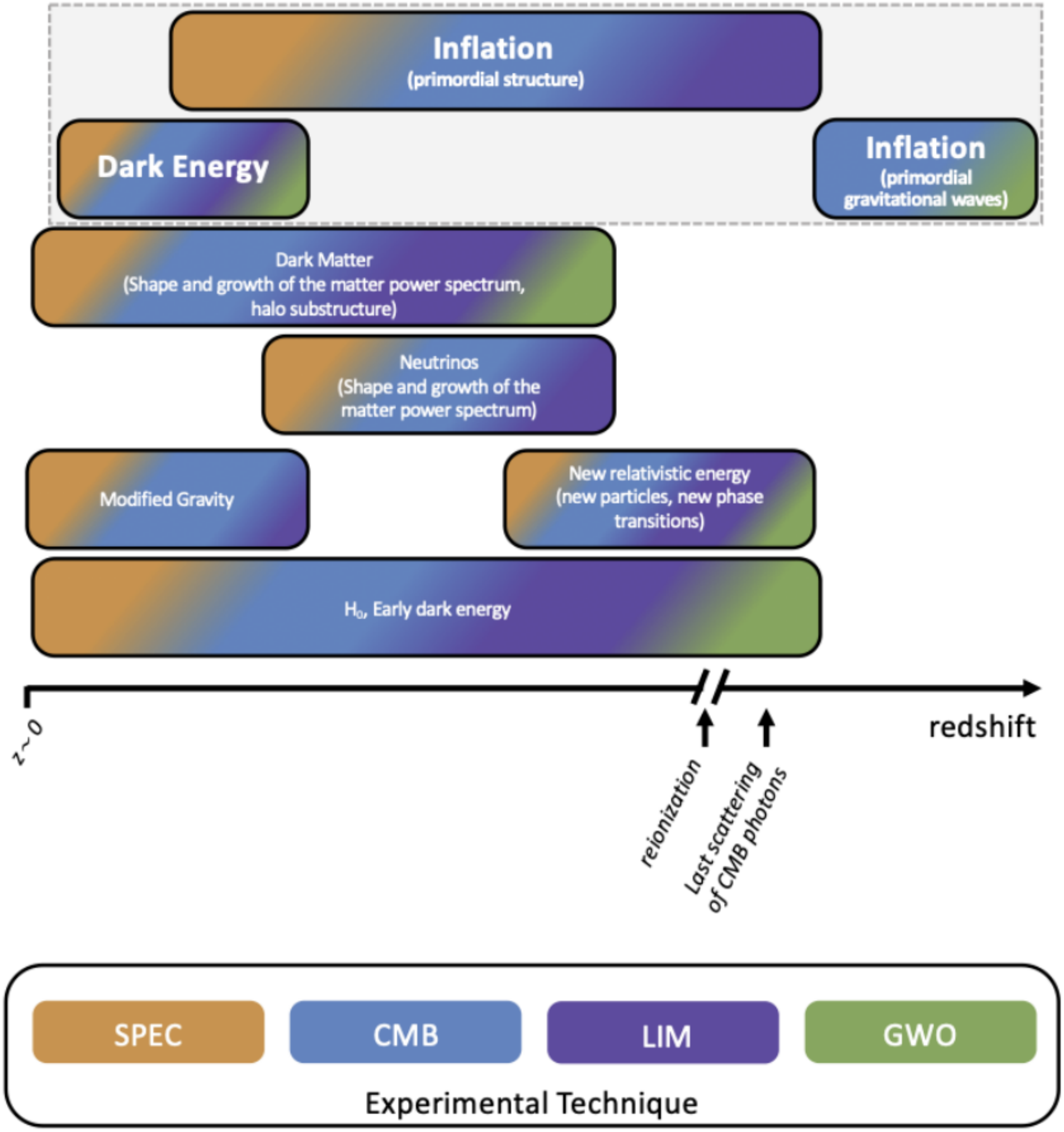

Figure 5-6. *A high-level summary of the key scientific opportunities. The horizontal extent of each box corresponds to the redshift-range of the tracer, while the coloring indicates the experimental technique used to measure the signal. The dashed grey box emphasizes dark energy and inflationary probes. Figure taken from the CF6 report [6].*

fundamental question of the source of cosmic acceleration is carefully thought out to efficiently address some of the greatest scientific questions of our time, extending across all areas of cosmology. Accomplishing this program in its entirety will ensure that the HEP community will continue its path of leadership in studies of the accelerating universe.

5.4 Inflation

There is strong evidence that the Universe went through a hyper-accelerated period of expansion during its earliest moments. This period of cosmic inflation reconciles a number of otherwise puzzling observations via the simple mechanism of an epoch in which cosmic evolution is dominated by a large quantity of vacuum energy. The consequences of inflation offer important clues to the necessary modification of the Standard Model of particle physics, in order to describe the dynamics at work. In addition, during this time the Universe effectively conducted the most extreme high energy physics experiment imaginable.

5.4.1 Determining the Energy Scale of Inflation

Future observations are poised to reveal the clues necessary to select among models of inflation. The amplitude of the associated gravitational waves (generally characterized by the tensor to scalar ratio, r), which can be inferred from the primordial B-modes of the CMB, encodes the absolute energy scale at which inflation takes place; projected sensitivity is shown in figure 5-7. CMB-S4 aims to improve sensitivity by more than an order of magnitude, covering much of the parameter space of natural models of inflation. The shape of the primordial power spectrum and its deviation from Gaussian statistics encodes inflaton interactions; a large-scale structure survey from a Stage-V spectroscopic survey and pathfinding missions based on radio and millimeter intensity mapping instruments would enable determinations of $f_{\rm NL}$ and A_{lin} and explore the range of dynamics. Inflationary physics may further imprint itself on the spectrum of the relic background of gravitational waves, Ω_{GW}. A cartoon summary of the potential for these advances is shown in Figure 5-8.

5.4.2 Reconstructing the Physics of Inflation

A large part of the future cosmic surveys program focuses on discovering new dynamics at ultra high energy scales using the inflaton beam as a cosmic collider. During the epoch of inflation, the cosmic particle horizon recedes with acceleration equal to the Hubble parameter $H_{\rm I} = \sqrt{\rho_{\rm I}}/M_{\rm Planck} \leq 10^{14}$ GeV. Interactions of quantum fluctuations with the accelerating horizon create a white spectrum of Hawking radiation in inflaton waves, gravitational waves, and possibly also waves of low mass dark matter particles such as axions or dark photons. While the gravitational waves propagate without rescattering to the present day and create B-mode polarization patterns in the CMB sky, and searches for ultralight dark matter are discussed elsewhere in this report, this section will focus on the hot fireball of inflaton waves which is traditionally measured in the temperature power spectrum of the CMB. These inflatons can scatter on each other via new dynamical interactions that could arise within the inflaton sector itself through its nonlinear potential, or could more generally be present in other high scale sectors that are accessible to this ultra high energy beam. Since, by the process of reheating, the inflaton waves eventually decay to produce the matter and radiation content of the universe, the spectrum of this primordial blackbody radiation is imprinted upon the large scale structure of the distribution of matter in the universe.

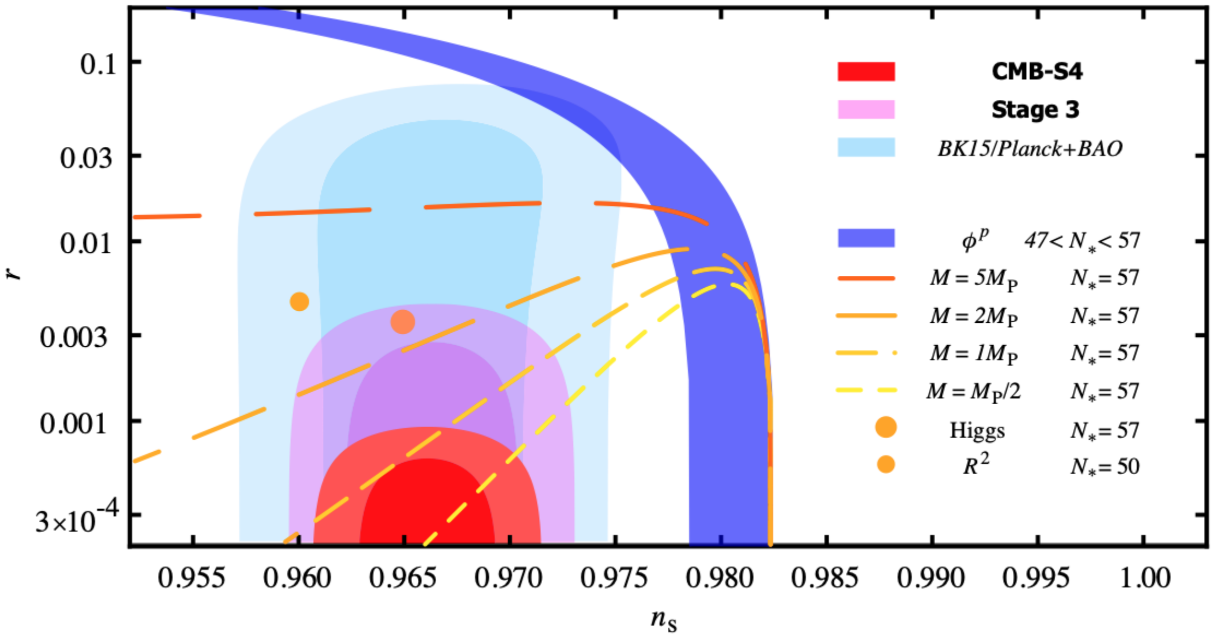

Figure 5-7. *The tensor-to-scalar ratio r plotted vs. the matter power spectral index n_s. r is observed from B-mode polarization patterns in the CMB sky, and is a measure of the absolute energy scale of cosmic inflation in the 10^{16} GeV range. The light blue region represents current constraints, the purple region the projected constraints from ongoing experiments including the South Pole Telescope and the Simons Observatory, and the red region the targeted sensitivity of CMB-S4. Dots and lines represent various models of inflation which will be tested.*

While new particle resonances in propagators are naturally spectroscopically measured via the 2-point correlation function, dynamical interaction terms in the Hamiltonian can be elucidated via 3-wave or 4-wave mixing measurements. In particular, the 3-point correlation function of the matter distribution can be measured in the fluctuations of the CMB sky, in redshift-resolved distributions of galaxies and clusters obtained via optical spectroscopic surveys, or even in redshift-resolved distributions of neutral hydrogen gas (or other species) obtained via the new technique of line intensity mapping. Just as the event topology and angular distribution of particles and jets in a collider experiment provide information about the underlying scattering event, the shape (local, equilateral, folded) of the 3-point triangle that is chosen for the analysis can be used to distinguish between different types of interaction terms in the ultrahigh energy Lagrangian. The strength of the interaction can be characterized by taking the Fourier transform of the 3-point function to form the power bispectrum and measuring its spectral amplitude f_{NL}. As inflaton wave energies in the originally Gaussian thermal spectrum are redistributed by repeated scattering events, primordial non-Gaussianities manifest as non-vanishing amplitudes for these higher order correlation functions.

Looking at the night sky, triangles formed at each distance scale probe scattering events at a different center-of-mass energy. The collection of such events in the sky forms a high statistics data set of independent scattering events at each energy. Higher angular or redshift resolution surveys will naturally provide higher statistics as typically characterized by the total number of resolved wave modes N_{modes}.

While CMB experiments including CMB-S4 will provide pristine measurements of the dynamical interaction amplitudes using data at a single slice in time or redshift, current optical spectroscopic surveys such as DESI also provide high resolution redshift information to measure the matter distribution in all 3 dimensions. Future instruments and facilities aim to increase the scattering statistics by a factor 10-100 relative to the

N_{modes} achieved by DESI, an improvement factor measured by the ”primordial figure-of-merit.” For example, the first factor of 10 would come from a Stage V Spectroscopic Facility targeting $2 < z < 5$ galaxies using the LSST dataset in order to reconstruct the full 3-d matter distribution. The statistics could be improved by a factor of 100 using a relatively inexpensive line intensity mapping (LIM) technique to probe the same physics and by using 21 cm observations to map the large scale distributions of neutral hydrogen in the universe via 21 cm emissions. An ambitious program, exemplified by the LuSEE-Night pathfinder, seeks to develop the LIM technique and understand the systematics to determine whether the full statistical power could in fact be attained.

A cartoon summary of the potential for these advances is shown in Figure 5-8.

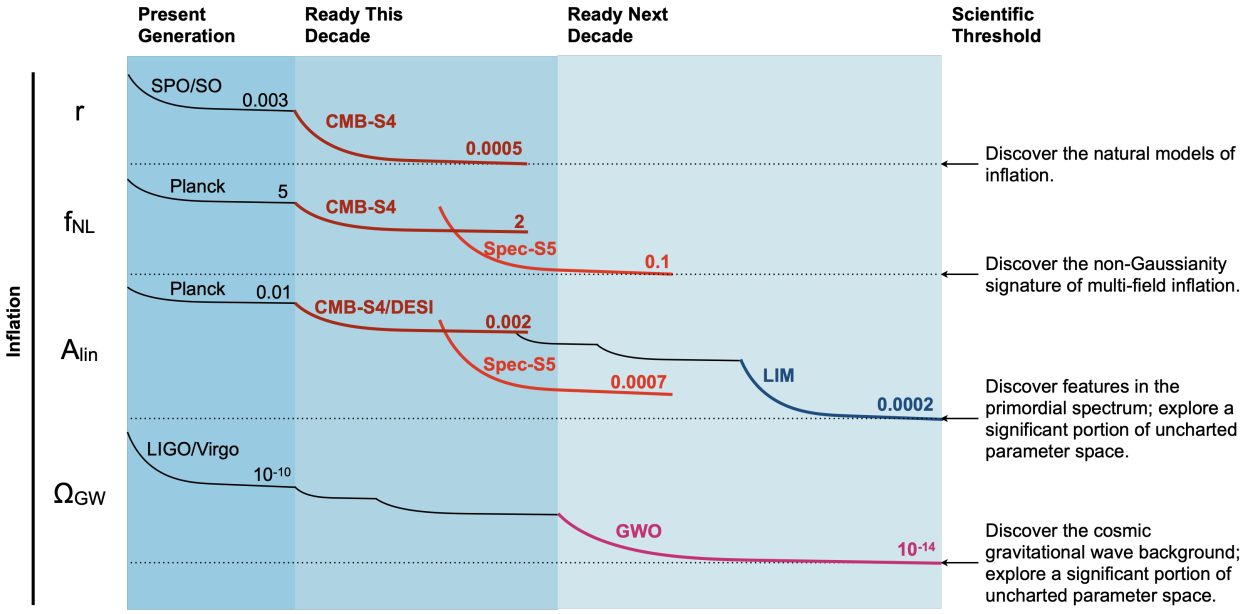

Figure 5-8. *Timeline of medium and large projects for inflation science.*

5.4.3 CMB-S4

CMB-S4 [10] is a Stage IV cosmic microwave background project that plans to field multiple telescopes at the South Pole and in the Atacama desert, Chile. See the Snowmass 2021 White Paper [11] for a discussion on the broader experimental context. CMB-S4 has an enormously broad science case with key science goals including searching for primordial gravitational waves through the B-mode signal in the CMB as predicted from inflation (detecting $r > 3 \times 10^{-3}$ at 5σ or limiting $r \leq 10^{-3}$ at 95% confidence if r is very small) and searching for the imprint of relic particles including neutrinos (measuring $\sigma_{N_{\mathrm{eff}}}$ with uncertainty ≤ 0.06 at 95% confidence). CMB-S4 will also offer unique insights into dark energy and tests of gravity on large scales, find large samples of high-redshift galaxy clusters, elucidate the role of baryonic feedback on galaxy formation and evolution, open a window onto the transient Universe at millimeter wavelengths, and explore objects in the outer Solar System, among other investigations.

The current CMB-S4 instrumental design calls for 500,000 polarization-sensitive bolometers that measure the sky at frequencies from 20–280 GHz. The superconducting detectors will be read out using time-domain multiplexed electronics and will be distributed between a set of telescopes at two sites: two 6-meter cross-Dragone reflecting telescopes in Chile, a 5-meter three-mirror-astigmatic reflecting telescope at the South Pole, and eighteen 0.5-meter refracting telescopes at the South Pole, grouped as triplets on six mounts, with each mount sharing a cryogenic system. This preliminary baseline design for CMB-S4 uses proven technology scaled up to much higher detector counts. The already-established integrated project office has addressed the technical challenges of the required scale-up with a detailed design and implementation plan that includes a full work-breakdown structure. The project office also maintains a register of risks and a detailed cost estimation plan. The preliminary, technology-limited project schedule contains nearly nine thousand milestones and catalogs the dependent relationships between them. A dedicated group within the project oversees the production of prototype detectors and leads the development of a unified detector fabrication plan that covers multiple fabrication sites.

5.5 Dark Matter

Astronomical and cosmological observations of the gravitational influence of dark matter provide one of the strongest indications of new physics beyond the Standard Model [12]. Ascertaining the nature of these mysterious new particles, their interactions both with Standard Model particles and with themselves, and their cosmological origin is perhaps the grand challenge of this generation. While the ambitious program to understand dark matter will require tools and techniques from across the HEP frontiers [13], the Cosmic Frontier is unique in that its experiments seek to detect and measure dark matter in its natural habitat – the halo of our Galaxy, the halos of distant galaxies, and the large-scale structure of the Universe. While other frontiers may hope to discover new particles that could play the role of dark matter, only the Cosmic Frontier can establish that a given discovery is, in fact, associated with the dark matter in the Universe.

Our understanding of the landscape of dark matter theories has evolved significantly in the past several years, as theoretical exploration has better defined the boundaries of what models are consistent with observations. As of Snowmass 2013 [14], the classification of dark matter candidates was largely based on the particle physics features of the underlying models (see Figure 5-9). Since then, focus has shifted toward exploring wide ranges of the possible phenomena in an effort to understand how well existing experimental searches cover the space of possibilities, and how new experimental opportunities provide sensitivity to regions of theory-space that are not captured by the current program [15]. There is great freedom to construct microphysical descriptions of dark matter, and a vast landscape of theoretical extensions of the Standard Model have been proposed. These models range from very simple extensions of the Standard Model containing a single new particle to complex dark sectors containing multiple dark matter states, composite dark matter blobs, or even towers of dark particles that could constitute several different components of dark matter simultaneously [16].

Cosmic observations set some of the strongest constraints on the properties of dark matter. Dark matter must interact gravitationally, must be produced sufficiently non-relativistically that it clusters to form galaxies, must be sufficiently long-lived that it is present in the Universe today, and must not interact frequently with the Standard Model or it would produce signals that would have been observed. Going forward, cosmic probes offer unique opportunities to learn about the properties of dark matter via the influence that it exerts on ordinary matter [3]. Measurements of the distribution of dark matter, including observables such as the matter power spectrum, the characteristics of dark matter halos (e.g., the mass spectrum, distribution, and density profiles), and the abundances of compact objects have become precise enough to place bounds on fundamental properties of dark matter such as particle mass and interaction strengths with itself and with the Standard Model. Since the last Snowmass study, there have been a series of breakthroughs in modeling cosmic structure formation in novel dark matter scenarios [17]. These studies set the basis for

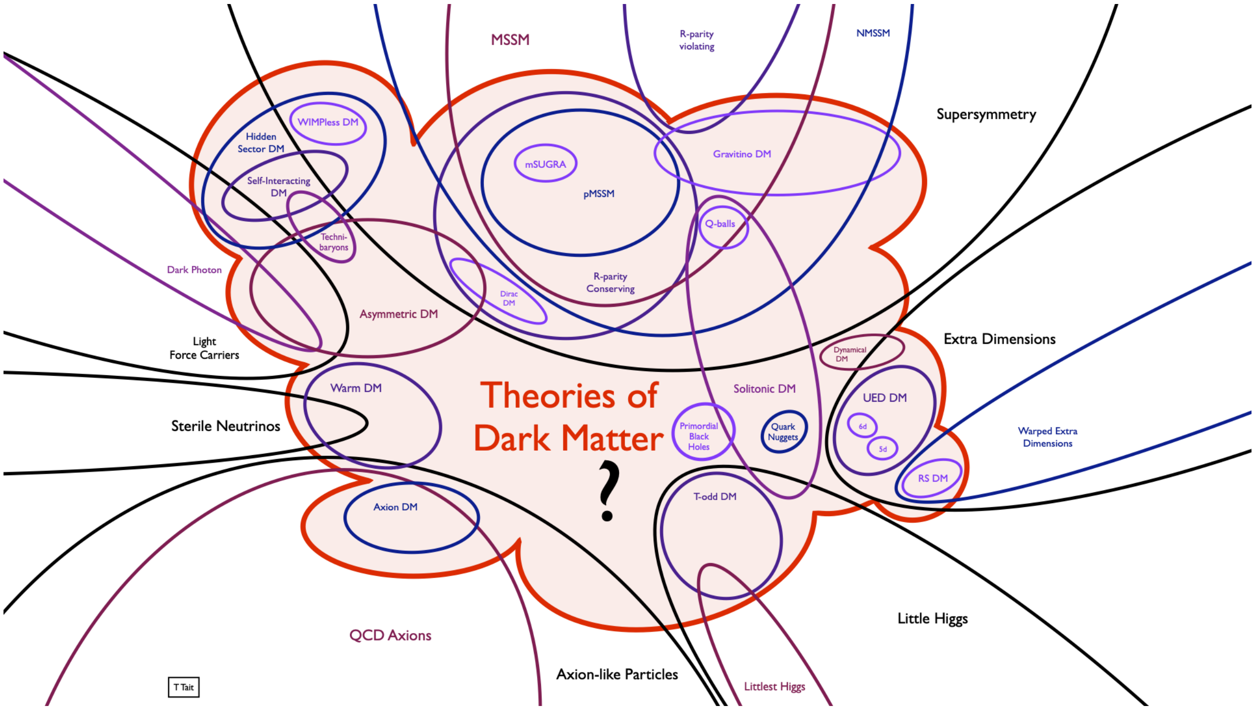

Figure 5-9. *Venn diagram of dark matter models from Snowmass 2013.*

quantifying astrophysical uncertainties and disentangling dark matter physics from baryon physics, a key step for extracting the Lagrangian parameters that describe a particular dark matter model from cosmic observations. We are at the threshold of definitively testing predictions of the cold dark matter paradigm on galactic and sub-galactic scales, and any observed deviation would revolutionize our understanding of the fundamental nature of dark matter. In many cases, cosmic measurements of dark matter can be achieved by the same facilities that are being constructed to measure cosmic expansion assuming sufficient resources are provided [18–22].

The primordial cosmic density of dark matter, which can be measured precisely from CMB data [23], sets an important backdrop for any viable theory of dark matter. Cosmic inflation typically erases any pre-existing density of dark matter, and so models must provide a physical ‘origin story’ to explain its presence in the Universe at the observed density. Two very plausible scenarios for how the dark matter could be produced include thermal freeze-out and misalignment production. In freeze-out, the dark matter has substantial interactions with the Standard Model which causes it to be thermally populated in the primordial plasma until freezing out of thermal equilibrium when the Hubble expansion catches up to the rate at which the dark matter and Standard Model interconvert. A dark matter mass and coupling of roughly weak scale sizes, assuming a standard cosmological history (e.g., no relevant additional physics beyond the Standard Model aside from the dark matter itself), results in approximately the correct relic abundance to match observations [24, 25]. In misalignment production, the bosonic dark matter field is initially displaced from the minimum of its potential. Rolling to the minimum releases the initial vacuum energy as cold dark matter, whose abundance depends on the physics of the dark matter potential as well as the initial displacement of the field. While both of these mechanisms in principle connect the observed dark matter abundance to specific regions of parameter space, it is worth bearing in mind that additional new physics beyond the dark matter itself can change the expectations for early cosmology, and thus the predicted abundance as a function of the model parameters [26–32].

Experimental efforts over the past two decades have focused on experiments to search for the weakly interacting massive particle (WIMP) and the QCD axion, both of which are strongly and independently motivated by other unsolved scientific mysteries. In vanilla models of GeV-TeV mass dark matter associated with solving the electroweak gauge hierarchy problem [33], WIMPs with electroweak couplings to Standard Model particles would be naturally populated at approximately the correct density by the freeze out mechanism described above. The QCD axion inevitably arises in Peccei-Quinn-type models in which the strong-CP problem (the otherwise inexplicable vanishing of the neutron electric dipole moment) is solved by promoting the strong CP-violating phase to a dynamical axion field [34]. The axion is produced via misalignment during the QCD phase transition, which causes the field roll to vanishing angle while releasing the original vacuum energy as axion dark matter. Much progress has been made in experimental searches on both fronts. Large second-generation WIMP detectors based on a variety of scattering targets, combined with indirect searches for high-energy annihilation products, have excluded Z-mediated couplings to standard model particles for WIMP masses up to $\sim$ TeV, and are now probing weaker couplings such as those mediated by Higgs boson exchange. Concurrently, axion experiments have finally achieved sensitivity to the predicted QCD axion coupling strengths by deploying various microwave quantum sensing technologies and have begun to slowly scan the axion mass parameter space using resonant cavity detectors. A cartoon encapsulating the current experimental situation is shown in Figure 5-10.

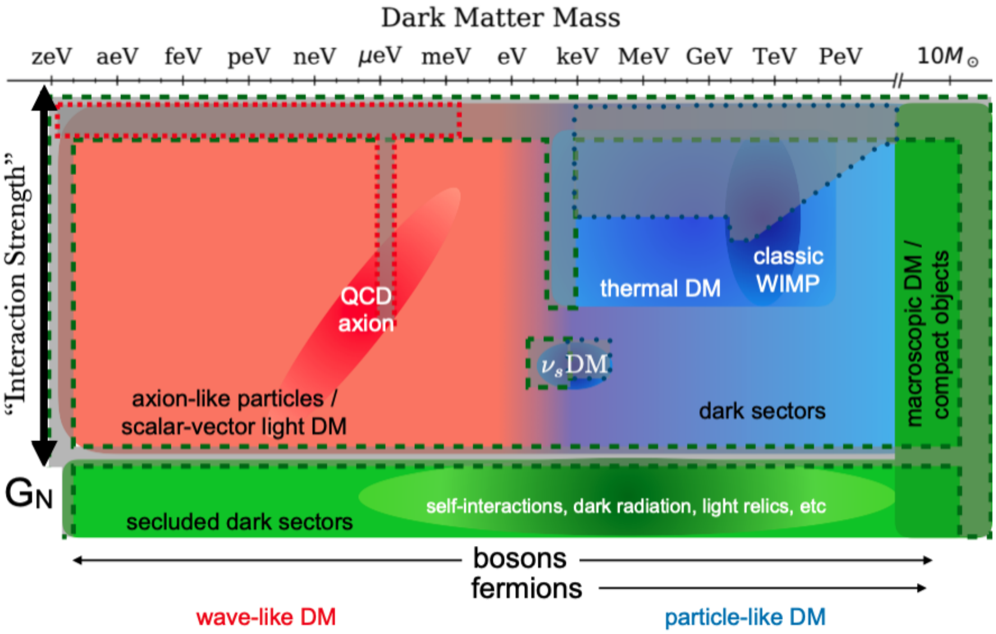

Figure 5-10. *Cartoon (not to scale) of current dark matter limits.*

While the WIMP and the QCD axion remain perhaps the most strongly motivated dark matter candidates, the breadth of dark matter searches has expanded enormously as new tools and sensing techniques have been identified that are able to probe large swaths of previously unexplored parameter space. Many of the new techniques have been proposed by theorists identifying and studying models beyond WIMPs and QCD axions, which are compatible with all experimental and observational data and furthermore have their own well-formed dark matter origin stories.

A particularly compelling class of new models are those of portal dark matter in which a hidden dark sector interacts weakly with the Standard Model sector through low dimension gauge singlet Standard Model operators coupled to messenger particles. For example, in the case where the messenger is a vector particle connected to the Standard Model via kinetic mixing with the hypercharge field strength portal, the result is a massive dark photon whose interactions are predominantly proportional to electric charge scaled down by the kinetic mixing parameter ε. Similarly, a dark Higgs can result from a scalar or pseudo-scalar messenger whose potential contains mixing with the Standard Model Higgs mass portal. Such theories offer natural scenarios in which the dark matter may have much smaller interactions with the Standard Model, realizing the correct freeze out relic density for masses in the eV to GeV range, far below the weak scale. Detecting the scattering of such low-mass dark matter requires much lower threshold calorimetric detectors sensitive to recoil energies in the range μeV – keV.

A generic prediction of hidden-sector dark matter is that dark matter carries its own forces, which may produce novel signals in direct and indirect detection experiments. Such a force may also change cosmic structure formation, leading to signatures beyond the prevailing cold dark matter paradigm. For example, a dark force could operate at the most fundamental level with a range of $\mathcal{O}(10^{-12})$ cm, but it would change the dark matter distribution within $\mathcal{O}(10^{22})$ cm in galactic halos, which could be detected in cosmic observations. In particular, dark matter self-interactions provide a compelling mechanism to produce diverse dark matter distributions ranging from tiny dwarf galaxies to huge galaxy clusters as inferred from observations [35, 36], which are a long-standing puzzle in cold dark matter [37]. In the next decade, Rubin LSST will measure the dark matter distribution at unprecedented small scales and hence it will provide a unique opportunity for probing interactions in the hidden sector [3, 38]. Furthermore, detection of additional relativistic degrees of freedom by CMB-S4 would immediately imply the existence of a hidden sector [10].

The range of possible dark matter masses spans at least 50 orders of magnitude from $\sim 10^{-22}$ to $\sim 10^{28}$ eV for individual particles with the lower end constrained by the smallest dwarf galaxies and the upper end constrained by the Planck mass. While composite baryonic matter (e.g., MACHOs) has been ruled out by measurements of the CMB and Big Bang Nucleosynthesis, exotic macroscopic compact objects, including primordial black holes, are still allowed to comprise some fraction of the dark matter up to mass scales greater than a Solar mass ($\sim 10^{57}$ GeV). For direct detection experiments, where the dark matter interacts directly with the detector, different detection techniques are needed to match the energy scale and overall detector size to the expected energy/momentum transfer and event rates for the traversing dark matter for each regime of dark matter mass. As such, the following broad classification of types of dark matter helps to distinguish between classes of experimental techniques that can be deployed as part of the“search wide” strategy to achieve comprehensive coverage of dark matter parameter space.

- 10^{-22} eV$\lesssim m_\chi \lesssim 1$ eV: “Ultralight” Dark Matter
- 1 eV$\lesssim m_\chi \lesssim 1$ GeV: “Light” particle Dark Matter
- 1 GeV$\lesssim m_\chi \lesssim 100$ TeV: “Heavy” particle Dark Matter
- $m_\chi \gtrsim 100$ TeV: “Ultra-Heavy” Dark Matter (UHDM)

In the following sections, the status and prospects for the detection of dark matter in each category will be discussed.

5.5.1 Waves of ultralight bosonic dark matter (10^{-22} eV to 1 eV)

Provided that gravitational clumping of a single dark matter species is responsible for the formation of all galaxies and galactic substructures, one may take from the kpc sizes of the dark matter halos hosting the smallest observed dwarf galaxies that the mode volume of this dark matter $(\Delta x)^3 = 1/(\Delta p)^3 \gtrsim (\mathrm{kpc})^3$. Estimating the momentum dispersion from the escape velocity from this local gravitational potential well, $\Delta p = m v_{\mathrm{escape}}$, a lower bound $m \gtrsim 10^{-22}$ eV can be derived. Dark matter with smaller masses than this "fuzzy dark matter" limit cannot be spatially localized within the volume of the smallest observed galaxies. In addition, for dark matter mass $m \leq 100$ eV, the mode occupation number must exceed unity in order for there to be enough dark matter to account for the local gravitational well that formed the dwarf galaxy. One may therefore infer from these cosmic probes that dark matter in the mass range 10^{-22} eV – 10^2 eV must be bosonic since the Pauli exclusion principle would prevent sufficient fermionic dark matter from fitting inside these small galaxies. At these low masses, the local Galactic dark matter takes the form of a gas of classical sine waves, each with large mode occupation number.

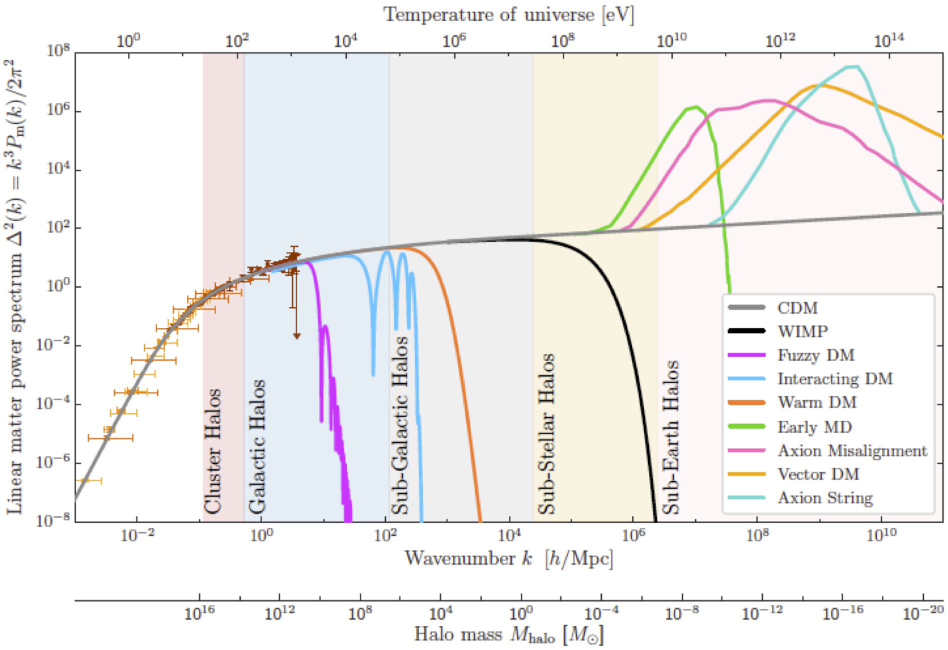

Figure 5-11. *Measurements of the sizes of Milky way dwarf galaxies and dark halos provide information about dark matter masses and interactions.*

In the near future, cosmic surveys will gain sensitivity to even smaller dark matter halos through measurements of dwarf galaxies, stellar streams, strong lensing, and the Lyman-α forest [39]. While the canonical collisionless cold dark matter model predicts that that the mass spectrum of dark matter halos extends far below the mass at which halos are known to form luminous galaxies (Figure 5-11), ultra-light bosonic dark matter that has a mass close to the fuzzy dark matter limit ($\sim 10^{-22}$ eV) or fermionic dark matter that is close to the Pauli exclusion limit ($\sim$100 eV) would suppress the formation and density profiles of these small halos. Thus, cosmic surveys such as Rubin LSST have an opportunity to discover signatures of these models through a measured absence of small halos, or further constrain the fundamental mass scale of dark matter if small dark matter halos are observed. These are just two examples of dark matter models where fundamental dark matter properties alter the distribution of dark matter in the universe in testable ways. Similar arguments apply for a large range of specific dark matter particle models, as shown in Figure 5-11.

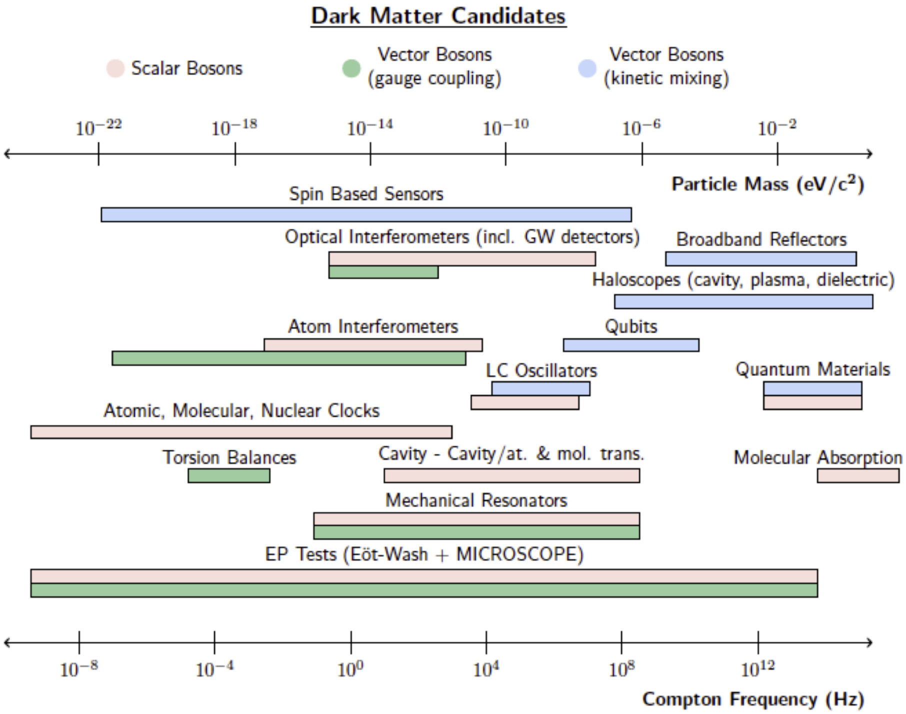

Figure 5-12. *Ultra low mass dark matter waves still have oscillation period less than 1 year. Direct detection of periodic forces exerted by these background waves utilizes various atomic, molecular, and optical techniques. These technologies can be transferred to HEP applications where sensitivities often must be further improved beyond state of the art in order to meet the dark matter challenge.*

Specialized terrestrial searches can also look for modulating signals due to the oscillation of the dark matter sine wave on experimentally accessible time scales, as shown in figure 5-12. For example, the lowest mass ($m \sim 10^{-22}$ eV) wave may produce a detectable time-dependent classical force on test masses over an oscillation period of approximately one year. Another class of theories couples scalar moduli dark matter (which are ubiquitous in string theory compactifications) to the sizes of the Standard Model parameters such that the oscillation of the dark matter wave mimics a modulation of the fundamental constants. Techniques from the field of atomic, molecular, and optical (AMO) physics can immediately be brought to bear on this new detection challenge, where instead of a slow drift of the fundamental constants, one optimizes the apparatus and analysis to search for narrow line, single frequency perturbations. Tools of choice include atomic clocks, atom interferometers, torsion balances, nuclear magnetic resonance, electric dipole moment experiments, and gravitational wave interferometers.

While much of this work remains in the domain of AMO physics, in some cases, capabilities of the HEP labs can greatly enhance the state of the art for these techniques beyond university-scale experiments in the process of adapting them to the dark matter challenge. For example, the MAGIS pathfinder experiment will utilize an access shaft of the NuMI beamline at Fermilab to achieve a world record 100 m vertical baseline for atom interferometry and probe dark matter interactions with period equal to the free-fall time. An upgraded km-scale interferometer is envisioned for the Sanford lab. Accelerator lab expertise in large scale experimental deployments of beam pipes, vacuum systems, etc. may also prove useful in construction and operations of future large optical interferometers.

5.5.1.1 A high priority target – the QCD axion (10^{-12} eV to 10^{-2} eV)

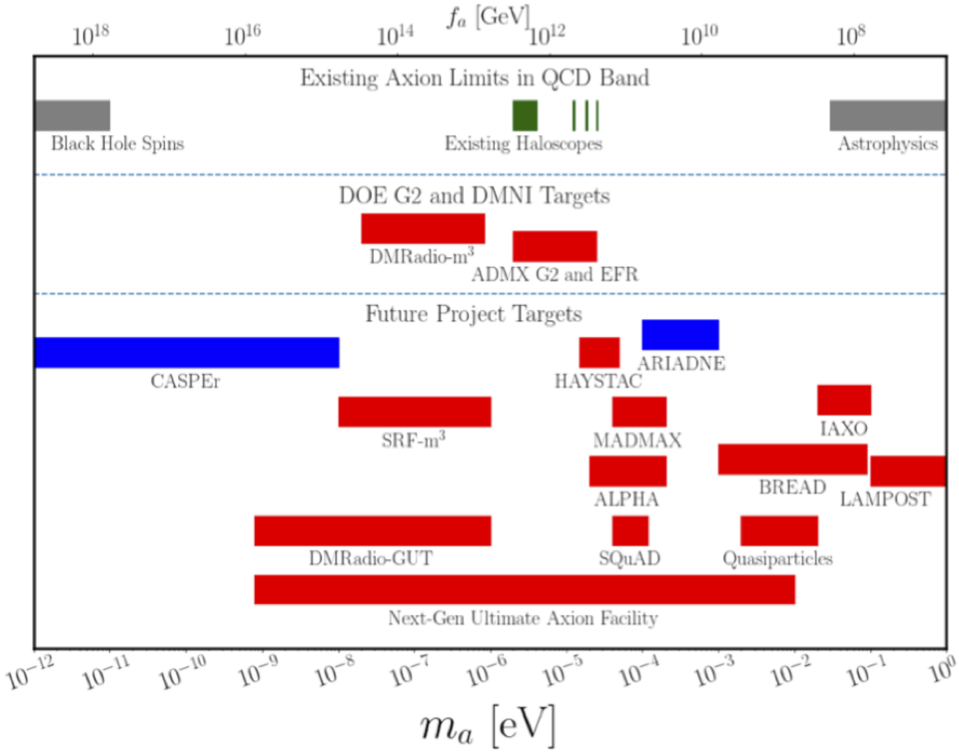

Figure 5-13. *A high priority target is the QCD axion which explains the observed vanishing of the neutron electric dipole moment as well as the origin of the dark matter from high temperature phase transitions. By virtue of a see-saw mechanism which generates the axion mass, the QCD axion model makes testable predictions for the interaction strengths as a function of mass, and a useful benchmark targets an dimensionless coupling strength of 1/3. This plot shows a suite of ongoing and future experiments which will test the QCD model by providing broad coverage of axion mass regions at the predicted coupling strengths.*

Perhaps the most significant technological development in the field of terrestrial dark matter searches since the last Snowmass is the demonstration by ADMX and HAYSTAC of experimental sensitivity to the invisible QCD axion. The large improvement in signal/noise ratio achieved by these experiments was made possible by the deployment of new quantum sensing technologies including dilution refrigerators, quantum-limited amplifiers, and squeezed state receivers. The ability to finally begin testing the QCD axion dark matter model has renewed both experimental and theoretical interest in the field of ultralight dark matter detection with several new techniques proposed to cover nearly the entire range of allowed QCD axion dark matter masses. These experiments would concurrently provide sensitivity to large areas of model-independent parameter space for more general axion-like particles and dark photons.

The QCD axion which emerges from the Peccei-Quinn (PQ) solution to the strong CP problem – the 70-year-old mystery of why the neutron has a vanishing electric dipole moment despite being made up of a

Fermi-sized collection of charged quarks. The PQ model begins with a standard wine-bottle phase transition in which a global U(1) symmetry is broken at some high energy scale f_a which results in a massive Higgs mode and a massless Goldstone mode called the axion. This axion field is coupled to the gluons of QCD and thus identified with a dynamical CP-violating angle. Later, during the QCD phase transition at energy $\Lambda_{\rm QCD}$, a gluon instanton condensate slightly tilts the wine-bottle potential, causing the axion vacuum expectation value to roll to its minimum potential energy. At this true minimum, the CP-violating angle vanishes and thus zeroes out the neutron electric dipole moment. The axion gains a tiny mass $m_a = \Lambda^2_{\rm QCD}/f_a$ via this see-saw mechanism between the QCD scale and the PQ scale. Furthermore, during this vacuum relaxation process, the potential energy associated with the original CP-violating value of the misaligned vacuum axion field is released as ultracold dark matter.

The QCD axion search program is simplified in that the coupling to SM fields is proportional to the axion mass, both being proportional to $1/f_a$ as a result of the see-saw mechanism. A couple of benchmark models (KSVZ and DFSZ) with order unity coupling coefficients determine a well-defined target region which cuts a diagonal band in a more general coupling vs. mass parameter space. As shown in figure 5-13, coverage of axion parameter space can therefore be represented via a single parameter, the axion mass, with a lower bound of $\sim 10^{-12}$ eV coming from the requirement that $f_a < M_{\rm Planck}$ for the validity of the effective field theory. Cosmic probes of astrophysics in extreme environments further constrain the allowed QCD axion mass range to lie between $\sim 10^{-12}$–10^{-2} eV [40]. For example, stronger axion-nucleon couplings predicted at larger axion masses would have caused supernova 1987a to cool more quickly than observed and would lead to anomalous cooling of neutron stars [41, 42], while stronger axion-photon or axion-electron couplings would be inconsistent with stellar evolution as observed in globular clusters [43–45]. Detections of black holes with non-vanishing spins also provide constraints on axions with masses near 10^{-12} eV, since axions would populate a gravitationally bound state around black holes extracting energy and angular momentum through superradiance [46]. Future observations of extreme astrophysical environments, along with improved theoretical understanding of the Standard Model physics at play in these environments, promise to further improve our sensitivity to axion physics.

The mass parameter space can further be split into pre-inflationary and post-inflationary axion production mechanisms. The mass determines the characteristic cosmological time scale at which the initial axion potential energy in the tilted potential can be released as dark matter. Because the photon and baryon densities are redshifting away, the dark matter production time determines its relative proportion of the overall cosmological energy density. At a mass of around 10^{-5} eV, the release of an initial potential energy density of order $\Lambda^4_{\rm QCD}$ would produce the observed dark matter energy fraction. At higher masses, the energy would be released too early while the baryon density is still too high, and so the dark matter would be underproduced. However, the potential energy could be bound to networks of topological defects which would also prevent early release. At lower masses, the dark matter is released too late and would be overproduced. A solution to this overproduction problem is to posit that the initial PQ phase transition happened prior to cosmic inflation. In this case, the earth could live in an inflated patch of the universe which had a downward statistical fluctuation in initial axionic potential energy density with correspondingly less energy released as dark matter.

5.5.1.2 Joint probes of axion and cosmic inflation parameter space

The interplay of axion production histories with cosmic inflation enables complementary probes of the joint parameter space using both axion experiments and inflation experiments. For example, if a low mass axion $m_a \leq 10^{-5}$ eV is discovered in a direct detection experiment, this implies that the PQ symmetry is broken at a high energy scale $f_a = \Lambda^2_{\rm QCD}/m_a \geq 10^{12}$ GeV. The requirement that this symmetry breaking happened prior to cosmic inflation then forces the energy scale of inflation to be quite low, $E_I \leq f_a$. Furthermore, even for very low axion masses for which $f_a \to M_{\text{Planck}}$, radiation of massless axions from the inflationary horizon would produce isocurvature perturbations in the CMB which are strongly constrained by the Planck experiment. In general, the detection of a low mass axion requires that $E_I \leq 10^{14}$ GeV to avoid overproducing axion isocurvature, but then concurrently, the Hawking radiation in gravitational waves from the horizon would also produce too little tensor mode power to be observed in the CMB B-mode spectrum. CMB experiments should then instead focus on improving precision on isocurvature measurements to study this low energy scale inflation. Conversely, if inflation occurs at a high energy scale $E_I \geq 10^{16}$ GeV, the higher amplitude gravitational waves may first be measured in CMB experiments via the B-mode polarization spectrum, and low mass axions would be excluded due to overproducing isocurvature. The axion direct detection program should then focus on higher mass axions in which the PQ symmetry is broken after inflation so that no massless isocurvature modes can be produced.

5.5.1.3 Wave dark matter status and strategies for direct detection

In the U.S., the DOE-supported ADMX-G2 resonant cavity experiment has excluded the QCD axion in the axion frequency range 645 MHz - 1.1 GHz (2.66-4.2 μeV) at even the more pessimistic DFSZ axion-photon coupling strength, and will continue to scan upward to 2 GHz using nearly quantum limited preamplifiers in their radio receiver. The NSF-supported HAYSTAC experiment has deployed a squeezed state quantum receiver and demonstrated KSVZ coupling sensitivity in a narrow band near 4.1 GHz (17 μeV).

Two new small-scale U.S. axion experiments are being developed within the DOE's Dark Matter New Initatives (DMNI) program for small projects. The first is ADMX-Extended Frequency Range (ADMX-EFR) which will increase the frequency scan rate by deploying and simultaneously operating multiple cavities within a single magnet bore, targeting higher frequencies 2-4 GHz. The other is DMRadio-m^3 which will search over a wide range of lower frequencies and lower axion masses $<$ 250 MHz (1 μeV) using a toroidal antenna incorporated into a lumped element LC circuit to couple to the axion waves. In each case, the total signal power will scale with the volume of the magnetized region which serves as the detector target for axion-photon conversion. Decisions on new starts within the DMNI program are expected to happen before the P5 report.

Meanwhile, private foundation-funded R&D continues on the CASPEr-Electric and CASPEr-Wind nuclear magnetic resonance experiments which aim to measure the dark matter-induced modulation of the nucleon electric dipole moment and the axion-nucleon spin coupling respectively. The ac effects on the spin energy levels can be resonantly detected by modulating an applied electric field for the ac EDM measurement or by tuning the spin precession frequency to match the axion wave frequency for the spin coupling measurement. Both experiments are currently targeting lower frequencies/masses below 1 MHz and have a longer term goal of reaching sensitivity to the tiny signals predicted for the QCD axion. This R&D is critical as only by observing the axion in multiple, predicted detection channels can it be distinguished from more general dark matter models.

Various quantum sensing technologies are being transferred to the dark matter axion search. For example, the low frequency experiments are limited by thermal noise. In this case, single quantum mixers used can be used to transduce signal photons to higher frequency ranges where quantum limited amplification is available. The low level of quantum noise relative to thermal noise then allows the resonant search to occur at constant ratio of signal to thermal noise over many Lorentzian linewidths to recover some of the speed advantage of a broadband search – the same strategy as was used in the Weber bar technique originally used to search for gravitational waves. Another strategy is to utilize an energized superconducting rf cavity (SRF) and use the ac magnetic field instead of a dc magnetic field to upconvert the low frequency axion wave into an rf signal photon.

At signal frequencies higher than those being probed by ADMX, the experimental challenge is that the size of the resonant cavities must shrink with increasing frequency to match the smaller wavelength of the signal photons, and so the signal power shrinks according to this rapidly decreasing target volume. While ADMX-EFR will pack many cavities into a single magnet to try to recover the lost volume, other ideas like ALPHA, the Axion Longitudinal Plasma Haloscope will try to create a large volume metallic metamaterial whose plasma frequency can be tuned into resonance with the dark matter wave. Alternatively, instead of attempting to maintain or increase the signal level, another strategy is to drastically reduce noise by using photon counting detectors which can have arbitrarily low dark count rates. The resulting noise from background count fluctuations can be far below the zero-point noise that is incurred by the currently employed frequency-resolved power readout techniques. New, ultra-low noise single microwave photon detection techniques based on superconducting qubits and on Rydberg atoms are being transferred from neighboring fields of quantum computing and AMO. The Superconducting Qubit Advantage for Dark Matter (SQuAD) prototype has demonstrated a factor of nearly 40 noise reduction relative to zero-point noise which, combined with high-Q dielectric cavities could enable QCD axion searches up to 20 GHz. R&D is also underway with the Rydberg Atoms at Yale (RAY) experiment to perform single photon counting at even higher microwave frequencies.

Finally, broadband techniques are also being developed which use large impedance mismatches at metallic or dielectric plates immersed in magnetic field to create axion to photon transition radiation. This radiation can be focused, even by the plate geometry itself, onto low noise single photon detectors. In Germany, a large R&D effort is underway to develop the MADMAX experiment which seeks to deploy a set of aligned plates to create multiple scattering targets within a large, high-field dipole magnet bore and read out signal power coherently using HEMT amplification. In the U.S., smaller-scale experiments such as BREAD and LAMPPOST are performing R&D funded by DOE-OHEP's QuantISED program to achieve high sensitivity to smaller signal levels via ultra low noise photon counting detectors such as quantum capacitance detectors, MKIDs, and SNSPDs. This new quantum photon counting technology covering 10 GHz - 100 THz may find use in various other areas of HEP outside of dark matter.

As many of these direct detection technologies are nearing maturity and are already or will be shovel-ready in the next decade, there is a key opportunity to cover most of the remaining $\sim$10 orders of magnitude in the QCD axion mass parameter space while concurrently exploring much of dark photon parameter space. The detector and sensor component of most of the experimental techniques falls firmly in the small experiment category and so a portfolio of small experiments could be strategically devised to divide and conquer the remaining axion parameter space. However, a critical path and long lead time item for most experiments is the large bore, high field magnet needed to induce the interaction between axion waves and signal photons. While resonant cavity experiments are viable in the frequency range 1-30 GHz and have been operated with commercial research solenoids or MRI magnets, the frequency scan speed has been in practice limited by the availability of magnet space. For example, if ADMX could operate two magnets instead of one, then nearly identical radios deployed in each magnet could be tasked to scan through independent frequency ranges to cover twice as much mass range in the same amount of time. Unlike most other techniques, these frequency scanning experiments enjoy linear scaling of science return with project cost which is usually dominated by magnet cost.

While the resonant experiments are constrained in size to the wavelength scale of the signal, lumped element experiments targeting lower frequencies and broadband antenna targeting higher frequencies each rely on using larger, customized magnets to intercept enough of the dark matter flow to achieve sensitivity to the QCD axion. A serious effort to comprehensively cover the many decades in allowed axion mass parameter space in finite operations time will thus require a significant investment in magnet facilities both in large, custom magnets for signal-limited experiments and a fleet of smaller commercial magnets for the resonant cavity experiments. Given that a Mu2e or CMS-scale solenoid may take a decade to construct, and even smaller superconducting magnets take several years to fabricate, a possible path forward is for the magnets to be planned, constructed, and operated as user facilities in which multiple experiments could be concurrently or sequentially deployed. A HEP magnet facility would focus on large bore magnets for longer term tenants, in contrast to the current portfolio of small bore, ultra high-field magnets that provided for shorter term condensed matter experiments by the NSF's National High Magnetic Field Facility.

5.5.1.4 Complementarity with gravitational wave searches for low-mass cosmic bosons

Gravitational waves have been recently shown to be an excellent new cosmic probes of ultralight bosonic matter. For example, if the Peccei-Quinn phase transition is sufficiently strongly first order, then a stochastic background of gravitational waves could be created by the boiling of the vacuum during this phase transition. Measuring the spectrum of this stochastic background with LIGO or with future GW observatories would determine the energy scale of the PQ transition and then via the axion model, uniquely determine the mass of the axion dark matter. The axion direct detection program could then be focused on a narrow mass window rather than needing multiple experiments with different technologies to cover each of the ∼10 decades the currently allowed mass window.

Searches for narrow line gravitational wave signals also constrain ultralight bosons of any type due to the prediction of the formation of gravitational atoms around spinning black holes. Just as in the hydrogen atom, particles bound to a black hole are confined to orbits of quantized angular momentum. Since bosons do not have a Pauli exclusion principle, these orbits become classically occupied with boson condensates which are created from the gravitational superradiance effect when the boson Compton wavelength is comparable to the black hole size. Transitions of bosons between different orbitals then results in narrow line gravitational wave radiation. A range of current and planned GW observatories can conduct model-independent searches for low-mass bosons from 10^{-21}–10^{-11} eV.

5.5.2 Light particle dark matter (1 eV to 1 GeV)

Above the ∼eV scale, the dark matter typically manifests as individual quanta. A priority target is the sterile neutrino, whose existence is suggested by the need to incorporate neutrino masses in the Standard Model, and which typically becomes sufficiently long-lived to play the role of dark matter at masses below around 10 keV. If sufficiently mixed with the active neutrinos, sterile neutrinos with masses below a few keV would thermalize as warm dark matter, and would suppress structure formation due to free-streaming to a degree that is inconsistent with cosmic observations. Evading this cosmological bound requires a mechanism to produce the dark matter in a very cold state, and appropriately weak coupling to the Standard Model such that it does not kinetically thermalize. The power of these constraints from structure formation highlight the key role that cosmic probes play in defining the viable parameter space for dark matter models.

5.5.2.1 Direct Searches

For sub-GeV-mass dark matter, direct detection technologies generally rely on individual dark matter particles scattering or being absorbed on various target media in detectors with low energy and momentum threshold. In scattering processes, the signal energy is at most the initial dark matter kinetic energy and the momentum transfer must be less than twice the initial dark matter momentum. For typical Galactic dark matter velocities of $v = 10^{-3}c$, $E_{\rm max} \approx 10^{-6}M_{\rm dm}$, and $p_{\rm max} \approx 10^{-3}M_{\rm dm}$, detectors with energy thresholds in the meV–keV range are needed to search for scattering of dark matter in the mass range keV–GeV. At these lower dark matter masses, kinematic matching for efficient billiard-ball scattering requires using lower mass nuclei, electrons, or collective modes such as phonons or magnons as scattering targets.

The universe itself provides an exceptional calorimeter in the form of the primordial baryon–photon plasma prior to recombination. Scattering between light dark matter and nucleons and/or electrons would transfer heat and momentum between the Standard Model and dark matter. This would have the effect of heating the dark matter and resulting in a suppression of the matter power spectrum similar to that seen in warm dark matter, which would be observable in the CMB, Lyman-α forest, and dwarf galaxies [47–51]. These cosmic probes provide access to the full range of light dark matter masses at large scattering cross sections that inaccessible to terrestrial experiments due to shielding by the Earth's atmosphere. Expected improvements will come from current and near-future cosmic survey experiments like DESI, Rubin LSST, CMB-S4, and Spec-S5 [3, 18].

In terrestrial experiments, noble liquid detectors have achieved signal thresholds of 20 eV when detecting electrons in the ionization channel, demonstrating the lowest background rate per unit target mass in this signal energy range. Various ways of doping the target medium are being explored in order to increase scintillation and ionization yield and to improve kinematic response to lower mass particles with low-A nuclei. Odd-A nuclei also provide sensitivity to spin-dependent interactions.

Semiconductor-based detectors have a threshold near the typical band gap energies of 1 eV in the electron scattering channel, providing sensitivity to dark matter masses near 1 MeV, approximately an order of magnitude below that of the noble liquid detectors. A recent significant development has been the demonstration of sub-electron charge resolution using skipper CCDs which perform repeated, non-destructive measurements of the charge in individual pixels to average away the readout noise. The ongoing SENSEI and DAMIC-M experiments are planning a factor of 10–100 scale-up in silicon CCD target mass in a jointly proposed experiment Oscura, part of the the DOE's DMNI program. Meanwhile, semiconductor crystal detectors such as SuperCDMS HVeV and EDELWEISS are also reaching single electron sensitivity using voltage bias across the semiconductor diode to increase the single electron signal energy.

To further lower thresholds for the electron scattering channel, novel target materials with collective electronic excitations with meV scale bandgaps are being investigated. For example, superconducting nanowire single photon detectors can also be used to detect energy deposited from dark matter scattering events with trigger thresholds near 250 meV for localized energy deposits which quench the bias supercurrent. Dark matter can also have electric couplings to the oscillating dipoles exhibited by optical phonon modes in polar crystals. The 10-100 meV scale bandgap of optical phonons provides both a low detection threshold and a large phase velocity for good kinematic matching to the relatively fast 300 km/s speeds of the galactic dark matter distribution. Engineered semiconductor materials with small Dirac cone band gaps such as heavy fermion materials are also being developed. A key challenge is scaling up these 2-d materials to sufficiently large target masses to provide deep coverage of dark matter parameter space. Collective plasmon modes including those in new heavy fermion materials may also be better kinematically matched to low mass dark matter scattering.

In the phonon channel, the semiconductor and crystalline detectors such as CRESST, EDELWEISS, SuperCDMS, and MINER are targeting eV or sub-eV resolution by reducing the readout noise in transition edge sensors. To achieve strong phonon response for lower mass dark matter scattering, SPICE, part of the TESSERACT program also funded through DOE DMNI is exploring targets made of polar crystals which have strong optical phonon response to dark matter interactions mediated by dark photons. The optical phonon band gap of around 10–100 meV provides the low detection threshold when paired with a sufficiently low noise readout. Beyond the NTDs and TESs traditionally used to read out microcalorimeters, new sensor technologies being explored include kinetic inductance detectors, magnetic microcalorimeters, SNSPDs, and superconducting qubits, with some of this next-generation technology being funded through various DOE quantum programs. While development of ultra-low-threshold quantum sensors may justifiably be funded through dedicated quantum programs, the deployment of these sensors and the studies of dark matter detector response including both measurements and simulations, and the characterization of new low energy backgrounds are uniquely HEP activities that could best be carried out in small, pathfinder experiments. As in the case of the axion searches described above, the DOE DMNI program currently provides funding to develop a limited number of proposed techniques. Given the variety of new sensing technologies, an opportunity exists to cover broad swaths of unexplored sub-GeV dark matter parameter space by expanding the portfolio of small experiments.

In addition to sensors designed to measure excitations of internal bulk phonon modes, a complementary approach is to monitor the center-of-mass motion of a composite object [52]. Optical or electrical readout of such mechanical sensors, in either the classical or quantum regime, offers a novel approach to detecting particle dark matter on a wide range of mass scales, including both heavy [53] and light [54] candidates. These sensors are naturally directionally dependent because they monitor changes to three-momentum of the mechanical system, and can reach energy thresholds well below the eV scale [54].

Beyond the technical capabilities of any particular detector, the distribution of deposited energies is also sensitive to the microphysics, being largely determined by nature of the mediator connecting the dark matter to the Standard Model. Heavy mediators manifest as non-renormalizable interactions which favor larger energy transfer (up to the kinematic limit), whereas light mediators enhance lower transferred energy. Figure 5-14, shows four cases of mediators, corresponding to heavy mediators with preferred coupling to electrons or nuclei, and light mediators coupled to electrons or in the form of dark photons. In each panel, existing bounds are shaded in tan, potential advances in the the probed parameter space of dark matter mass versus coupling/cross section in the near term (~ 5 years) based on existing research investments are shaded green, whereas those achievable in the far term (longer time scales) are shaded blue. Each shaded region represents the combined footprint of several experiments.

5.5.2.2 Indirect Searches

Low-mass particle dark matter can be detected through its decay or annihilation into Standard Model messengers. Below a GeV, the available Standard Model channels include photons, neutrinos, electrons, muons, and the lightest hadrons. Because of poorly understood astrophysical backgrounds and confounding factors such as Galactic magnetic fields (which scramble the incident direction of charged particles), photons with energies $\gtrsim$ keV are typically considered among the most promising messengers.

Indirect searches are uniquely powerful for probing the dark matter lifetime. A compilation of constraints based on the searches for X-ray and gamma-ray signals across many decades of mass is shown in Figure 5-15. It is striking that such constraints require the dark matter to live many orders of magnitude longer than the current age of the Universe.

In thermal freeze-out scenarios, indirect detection probes the same interactions that fix the dark matter abundance in the early universe. In the sub-GeV mass range, current limits already generically rule out the simple thermal freeze-out scenario for s-wave annihilation, unless the dark matter annihilation products are almost exclusively neutrinos, significantly constraining the space of viable dark matter candidates that were once in thermal contact with the Standard Model (e.g., [55]). In particular, constraints from measurements of the CMB [23] have a key role in establishing the viable portals by which dark sectors could communicate with the Standard Model.

At the low end of this energy range, X-ray telescopes have placed stringent constraints on sterile neutrinos, complementary to cosmic probes of warm dark matter [56]. Upcoming X-ray telescopes (XRISM [57, 58],

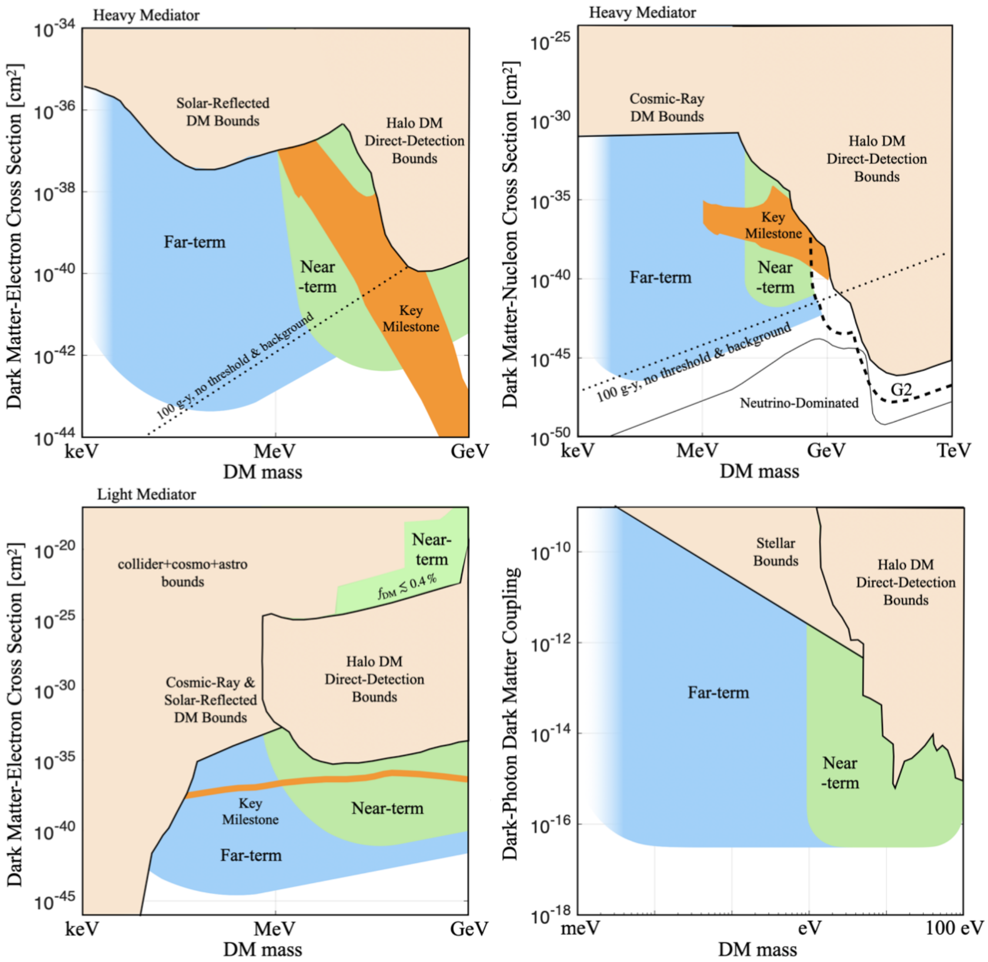

Figure 5-14. *Predicted near-term and far-term sensitivities to dark matter with mass in the range 1 eV–1 GeV through different types of mediators connecting to the Standard Model. Key milestones indicate representative target regions in which the dark matter is thermally produced for each scenario. Near-term projections are based on demonstrated sensitivities to electron recoil and nuclear recoil in the 1 eV and 10 eV range respectively. As the maximum energy deposit in scattering is the initial kinetic energy of the dark matter of order* $10^{-6} M_{\rm dm}$*, far term projects with lower energy thresholds will be anabled with ongoing R&D in novel target materials with band gap below the 1 eV scale of semiconductors and of chemistry. Examples include optical phonons in polar materials with band gap 10-100 meV and superconductors and other quantum materials with sub-meV gap. Concurrently, demonstration of low threshold sensor technology, including those based on quantum sensors will be required.*

Micro-X [59], Athena [60], HEXP-P [61]) will further improve constraints on decaying/annihilating light DM in general, and sterile neutrinos in particular; some will have sufficient energy resolution to seek to resolve DM-sourced spectral lines.

At higher energies, there is currently a sensitivity gap in the MeV–GeV gamma-ray band. The last major experiment was NASA's Imaging Compton Telescope (COMPTEL)[62], which operated from 1991–2000. Several proposed future experiments aim to address this gap: the Compton Spectrometer and Imager (COSI) [63] has a planned launch date in 2025, and will survey the gamma-ray sky at energies of 0.2–5 MeV; AMEGO-

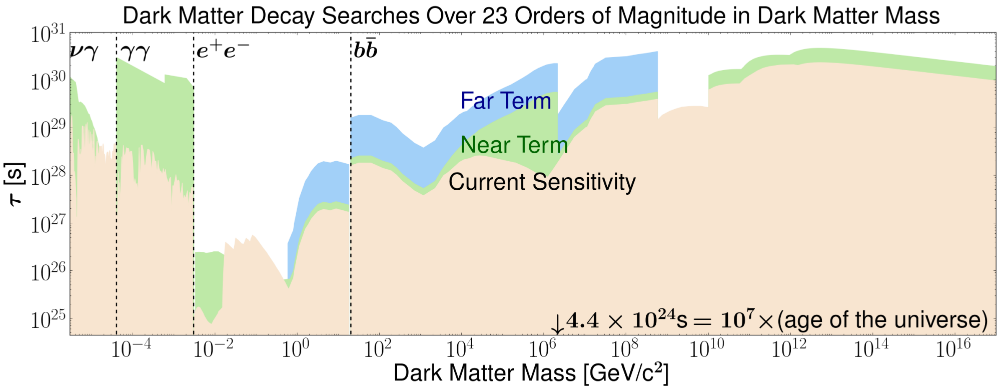

Figure 5-15. *Constraints on the lifetime of dark matter based on null searches for produced X-rays and gamma rays, as well as planned improvements in the near term (green) and far term (blue). The sharp boundaries are artifacts of analysis, rather than instrumental thresholds.*

X [64] has a planned satellite launch date in the late 2020s and will probe energies from 25 keV-–1 GeV using a silicon pixel tracker, CsI calorimeter, and plastic anti-coincidence detector; and e-ASTROGAM [65] would target the 0.3 MeV–3 GeV energy range using a similar approach. Other proposals focused on the MeV band include SMILE [66–69], GRAMS [70], and GammaTPC, which rely on gaseous or liquid time projection chambers (TPCs), and GECCO [71] (based on a novel CdZnTe imaging calorimeter with a deployable coded aperture mask).

Investment in such experiments would enable both data-driven studies of backgrounds relevant for lower and higher energy indirect searches, as well as providing greater sensitivity to decaying and/or annihilating light dark matter in the MeV–GeV mass range. They have the potential for sufficient sensitivity to probe thermal freeze-out even when the dominant annihilation is *p*-wave [56, 72] (which is suppressed at non-relativistic velocities and thus challenging to observe via indirect detection), further complementing terrestrial experiments focusing on this mass range.

5.5.3 Classic WIMPs (1 GeV to ∼100 TeV)

Dark matter masses between ∼ GeV and hundreds of TeV populate the classic WIMP parameter space, where theories aimed at explaining the electroweak hierarchy typically reside. Such theories have been the subject of extensive theoretical exploration [73–78], driven both by the connection to electroweak physics as well as the fact that roughly electroweak-sized couplings naturally lead to a relic abundance close to the one required by cosmological observations through freeze-out. As a result, searches for WIMPs remain extremely well-motivated, with many interesting models inhabiting viable and testable parameter space [79, 80].

5.5.3.1 Direct Searches

For these masses, the most efficient scattering is with nuclei, which can be described as an expansion in the dark matter velocity by terms in an effective field theory [81–84] Two classes of interactions dominate in the non-relativistic limit: spin-dependent (SD) scattering, which requires a nuclear target with non-zero spin, and spin-independent (SI) scattering, which is coherently enhanced in many models for large-A targets.

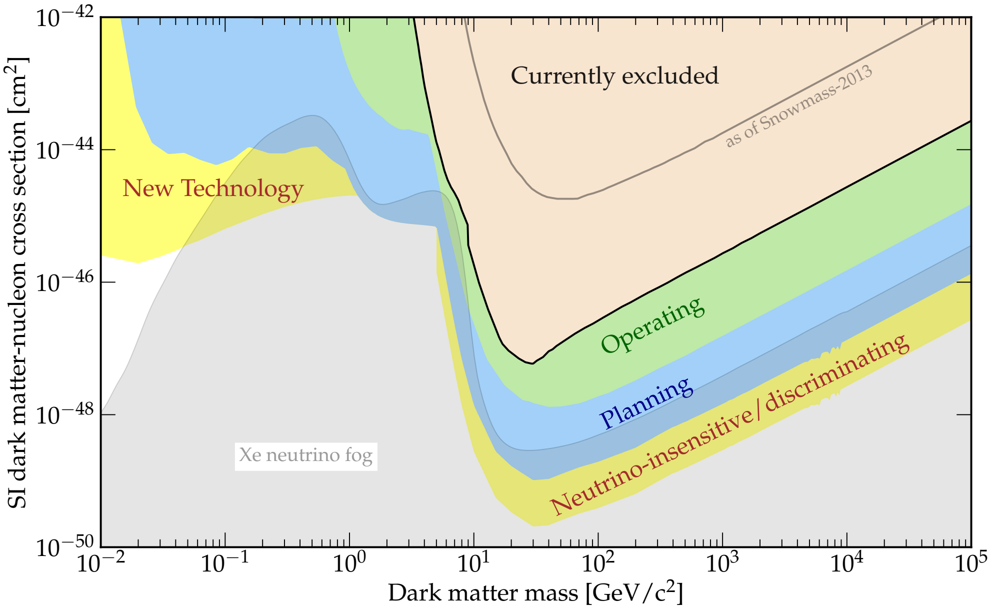

Figure 5-16. *Combined Spin-independent dark-matter nucleon scattering cross section space. Current 90% c.l. constraints are shaded beige, while the reach of currently operating experiments are shown in green (LZ, XENONnT, PandaX-4T, SuperCDMS SNOLAB, SBC). Future experiments are shown in blue (SuperCDMS, DarkSide-LowMass, SBC, XLZD, ARGO) and yellow (Snowball and Planned× 5). The neutrino fog for a xenon target is shaded light grey. (Reproduced from Ref. [87]).*

Detectors employing heavy nuclei to target SI scattering have seen rapid advance in their size and control of backgrounds, achieving many decades of improved sensitivity over the past twenty years. Such experiments are now within an order of magnitude of sensitivity to the expected background neutrinos produced in the atmosphere, Sun and supernovae. This 'neutrino fog' is interesting to measure in its own right, but will require new technologies and analysis techniques to be distinguished a dark matter signal, such as the expected annual modulation of the DM rate [85] and directional detectors (see *e.g.* the review found in [86]). Directional DM detectors would further open up the tantalizing potential to map out the local DM structure of the Galaxy.

Currently, the most stringent SI bounds for $\gtrsim$ 10 GeV dark matter masses are from liquid xenon (LXe) and liquid argon (LAr) detectors employing time projection chamber (TPC) technology. Charge and phonon detectors are able to reach lower DM masses and are expected to reach sensitivity for dark matter masses between 0.5–5 GeV to within a decade of the neutrino fog, limited by cosmogenically activated isotopes including ^{3}H and ^{32}Si, ^{210}Pb, and by dark counts. Phase change detectors such as bubble chambers can provide powerful background-discriminating technology and the combination of scalability, low threshold, and background discrimination *at low threshold* could allow noble-liquid bubble chambers to explore the neutrino fog in the 1–10 GeV WIMP mass range [88].

Figure 5-16 shows the current, operating, and future projected 90% CL constraints for WIMP DM interacting spin-independently [87]. The beige regions show the current best exclusion for each mass, combining previously reported limits [89–104], as collected by Ref [105]. A measure of the incredible progress of the past decade is provided by the comparison with the grey line from Snowmass 2013 [106]. The projected

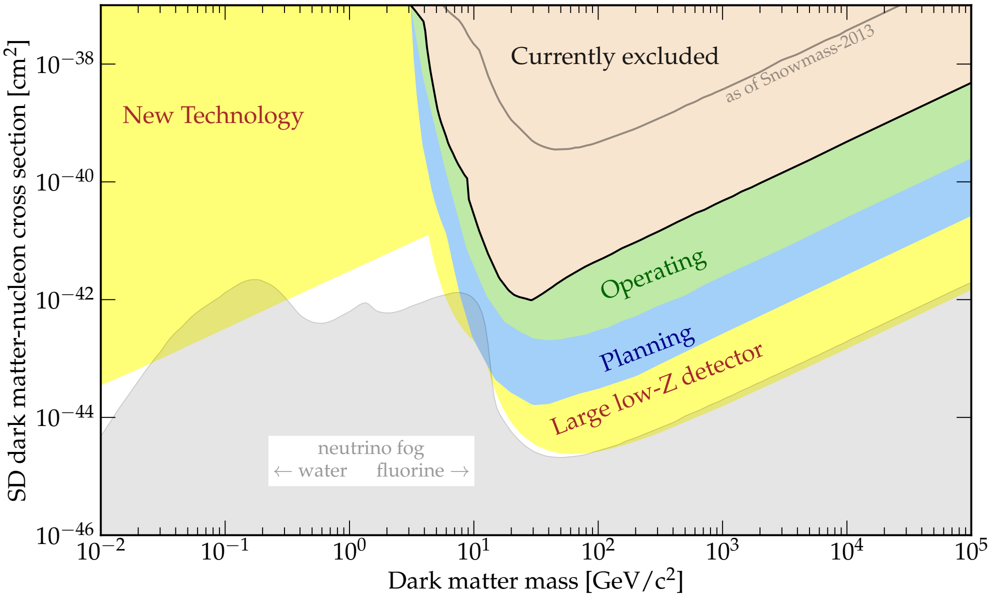

Figure 5-17. *Combined Spin-dependent dark-matter nucleon scattering cross section space for scattering with neutrons or protons. Current 90% c.l. constraints are shaded beige, whereas the reach of currently operating experiments are shown in green (LZ, XENONnT). Future experiments are shown in blue (PICO-500, XLZD) and yellow (Snowball, PICO-100 ton). The neutrino fog for a water or fluorine target is shaded light grey. (Reproduced from Ref. [87]).*

reach of currently operating experiments is shaded in green, whereas proposed upgrades are shown in blue (including SuperCDMS, DarkSide-LowMass, SBC, XLZD, and ARGO) and the reach of proposals based on new technologies are shaded in yellow (Snowball and Planned$\times$ 5). The region corresponding to the neutrino fog for a xenon target is shaded light grey.

Similarly, Figure 5-17 shows the current, operating, and future projected 90% CL constraints for WIMP DM interacting spin-dependently [87]. Shaded in beige is the union of the currently excluded parameter space, led by LXe TPCs and freon-based bubble chambers [92, 107–109, 109–117], as collected by Ref [105]. The expected reach of currently operating experiments is shaded green, and future proposed experiments are shaded blue (including PICO-500 and XLZD) and yellow (Snowball and PICO-100 ton). The region corresponding to the neutrino fog for a water or fluorine target is shaded light grey.

Taken together, Figures 5-16 and 5-17 illustrate the exciting prospects for direct searches in the WIMP regime, with a suite of experiments based on different technologies capable of probing WIMP dark matter all the way down and into the neutrino fog.

5.5.3.2 Indirect Searches

Indirect searches for dark matter play a very important role in covering the parameter space. At lower masses, as discussed above, measurements of the CMB have a key role in constraining the viable portals to communicate with the SM. At the highest masses, indirect detection achieves sensitivity to WIMP parameter

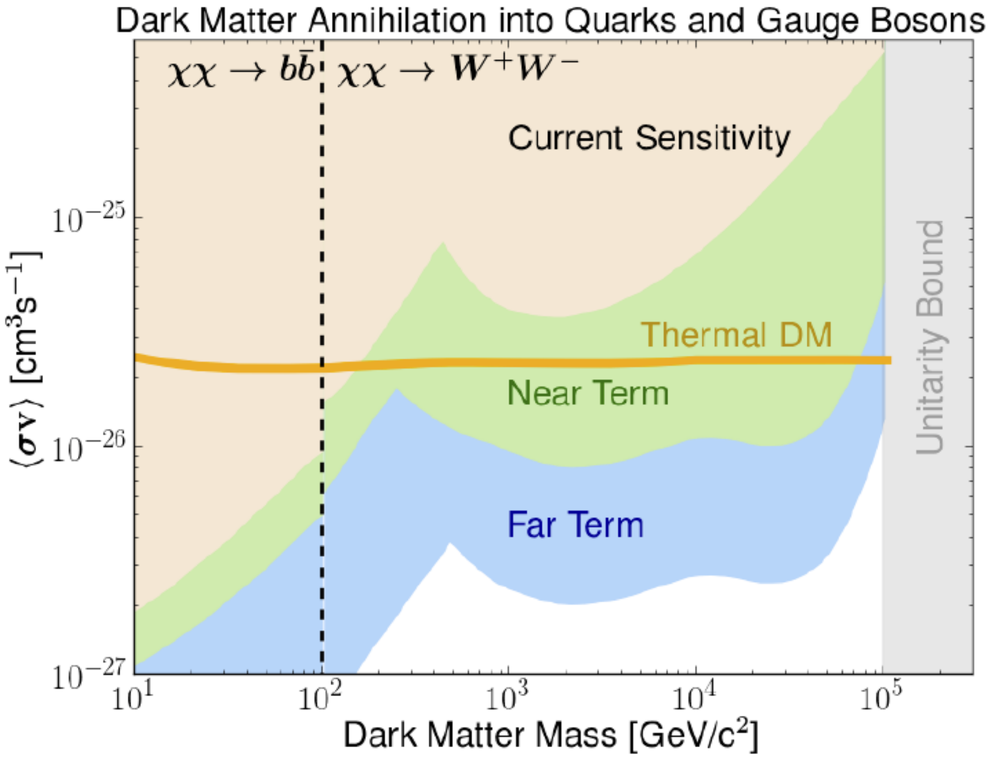

Figure 5-18. *Limits on WIMP annihilations into pairs of bottom quarks (for masses below* ~ 100 *GeV and* W *bosons (for larger masses) based on null searches by gamma-ray observatories. The beige regions indicate the current limits for each mass, whereas the green shaded region indicates near future gains based on planned missions, and the blue shading indicates the reach that would be enabled by long term investments in ground- and space-based observatories.*

space that is inaccessible to direct or collider searches, and in general provides a broadly model-agnostic probe of thermal freezeout scenarios. The most effective messengers of WIMP annihilation are gamma rays (which point back to their origin, giving an additional analysis handle) and energetic anti-matter signals in cosmic rays. Especially for higher DM masses, where abundant energy is available to produce the full range of SM particles, indirect signals are generically expected to be multi-messenger and multi-scale [118].

The rate of annihilation depends on the underlying microphysics, which determines both the rate into each specific annihilation channel as well as its dependence on the relative velocity between the annihilating dark matter particles. Dark matter making up the halos of galactic structures is typically highly non-relativistic ($v \sim 10^{-4} - 10^{-3}$, and thus s-wave annihilations (for which $\langle\sigma v\rangle$ is v-independent) typically dominate over annihilations at higher partial wave. Additional challenges involve determining the dark matter distribution along the line of sight of an indirect search, which strongly impacts the rate of annihilation, since $\langle\sigma v\rangle \propto \rho_\chi^2$. This systematic uncertainty benefits strongly from advances in simulation of galaxy formation. Modeling of astrophysical backgrounds with sufficient precision as to be able to distinguish a subtle signal of dark matter annihilation or decay from more prosaic astrophysical processes is also a key ingredient (see Refs. [1, 119, 120] for further discussion); this is already manifest in a number of puzzling excesses in indirect searches [119].

Gamma rays may be detected both by space- and ground-based telescopes. The space-based Fermi-LAT is optimized to reconstruct gamma rays from $1 - 100$ GeV and is effectively able to observe the entire sky as it orbits, whereas ground-based air and water Cherenkov telescopes are effective at energies above ~ 100 GeV. Most current Cherenkov telescopes are located in the Northern Hemisphere, but Southern Hemisphere locations are advantageous for observing both the Galactic Center and the central dense region of the Milky Way's dark matter halo. For s-wave annihilation, Fermi-LAT has already strongly constrained the thermal freeze-out cross section for masses up to ~ 100 GeV based on observations of the Milky Way's dwarf spheroidal galaxies (e.g. [121, 122]), which are (as measured by stellar dynamics) dark matter rich and baryon poor, limiting the expected sources of background. These limits are expected to improve in the near future, as surveys such as Vera Rubin discover (about a factor of two) more dwarf spheroidal galaxies [123].

In the near future, the SWGO [124] (water Cherenkov) and CTA [125] (air Cherenkov) telescopes, successors using similar technology to the successful HAWC and VERITAS Cherenkov telescopes but with larger installations and Southern Hemisphere sites, have the potential to probe the thermal freeze-out scenario up to 10s of TeV masses (depending on the annihilation channel) [126, 127], approaching the 100 TeV scale where we can begin to set unitarity-based limits on the capacity for freeze-out to generate the correct relic abundance. Further in the future, APT [128] is a concept for a space-based successor instrument to the Fermi-LAT (with a demonstrator suborbital mission scheduled for 2025), which aims to improve sensitivity at lower masses by an order of magnitude. Figure 5-18 shows the limits on WIMP annihilations into pairs of bottom quarks (for masses below ~ 100 GeV) and W bosons (for larger masses) based on null searches by gamma-ray observatories. The beige regions indicate the current limits for each mass, whereas the green shaded region shows improvements expected in the near future based on planned Cherenkov observatories and including new populations of dwarf spheroidal galaxies expected to be discovered by Rubin / LSST. The blue shading indicates parameter space that could be probed by longer term investment into future large Cherenkov arrays and new space-based missions. The orange band indicates the benchmark cross section corresponding to the correct relic abundance from freeze-out. The gray "unitarity bound" region corresponds to the general mass range (the exact bound is model-dependent and depends on assumptions about long-range forces, compositeness of the dark matter, etc.) in which obtaining the correct dark matter abundance via freeze-out becomes inconsistent with unitarity in the early universe, under standard assumptions for the cosmological history.

Cosmic-ray experiments (primarily AMS-02) currently set competitive constraints on heavy annihilating or decaying DM, with systematic uncertainties independent from gamma-ray probes. In the near future, GAPS [129] will provide the first dedicated search for low-energy anti-deuterons, which are expected to have only tiny astrophysical backgrounds and could serve as a very clean discovery channel, and HELIX [130] will provide new constraints on cosmic-ray propagation. Far-future proposals ALADInO [131, 132] & AMS-100 [133] involving superconducting magnetic spectrometers seek greatly improved sensitivity to anti-deuterons and anti-helium; GRAMS [70] would employ a liquid-argon TPC to search for both gamma rays and charged cosmic rays, and ADHD [56] is a proposal to pursue a novel delayed-annihilation signal from anti-nuclei in a helium detector. Fixed-target accelerator experiments including NA61/SHINE [134], ALICE [135], LHCb [136], and AMBER [137] can also provide complementary measurements to constrain cosmic-ray production and propagation, helping to reduce systematic uncertainties in both signals and backgrounds.

5.5.4 Ultra-Heavy Dark Matter (> 1 PeV to 100 $M_\odot$)

Measurements of baryon acoustic oscillations and the cosmic microwave background set some of the strongest limits on the total baryonic fraction of matter in the universe. The sound waves of the primordial plasma have compressions due to gravitational attraction and the restoring force due to plasma pressure causes the following rarefactions. The higher amplitude in the odd-numbered power spectrum peaks indicate that most

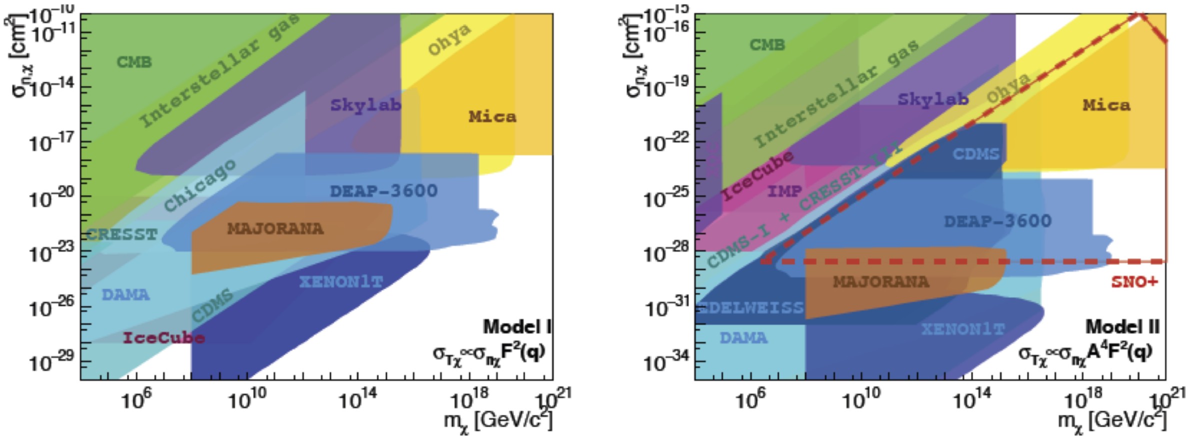

Figure 5-19. *Because the kinematics of nuclear recoil asymptotes to fixed recoil energy for large dark matter masses, direct detection experiments also have sensitivity to ultra heavy dark matter where sensitivity is primarily limited by the cross-sectional area of the detector.*

of the gravitating matter does not exhibit pressure when compressed and is hence not electromagnetically charged like protons or electrons. So even if dark matter took the form of non-luminous, cold baseballs (a model that is difficult to constrain observationally), these baseballs would still have to be made of some non-standard exotic particles.

For masses beyond the unitarity limit, it becomes a challenge to produce dark matter via freeze-out. One interesting set of models produces dark matter in this mass range as composite blobs of more fundamental particles, held together by new dark forces. Cosmic observation of the CMB and interstellar gas set robust constraints at large cross sections, while observations of extreme astrophysical environments can also constrain the presence of UHDM. Both the searches for WIMPs described in the previous subsection as well as more specialized searches have sensitivity to this UHDM regime, depending on the strength and nature of its interactions with the SM (see Ref. [118] for a more in-depth discussion). For strongly interacting blobs, a typical event in a terrestrial experiment could involve multiple scattering, necessitating new analysis techniques and implying that the area of the detector is the most relevant factor rather than its volume. For indirect searches, high energy neutrinos and cosmic rays become especially important at high masses. Cascades of secondary particles from high-energy primaries often lead to observable indirect signatures at much lower energies than the DM mass, such that the gamma-ray telescopes described above have sensitivity to DM masses much higher than their target energy ranges. This situation represents an ongoing theoretical challenge, requiring new techniques for accurate predictions to take advantage of the opportunity to observe rich and complementary multi-wavelength and multi-messenger signals [118]. For DM masses of order GUT-scale, however, the secondary photons *en route* to Earth travel unscathed. Accordingly, AugerPrime and next-generation cosmic ray observatories anchor unique DM indirect detection experiments which are free of astrophysical background: a clear detection of an extreme energy photon would be a momentous discovery [138]. Fig. 5-19 shows the current and projected experimental regions of ultra-heavy parameter space.

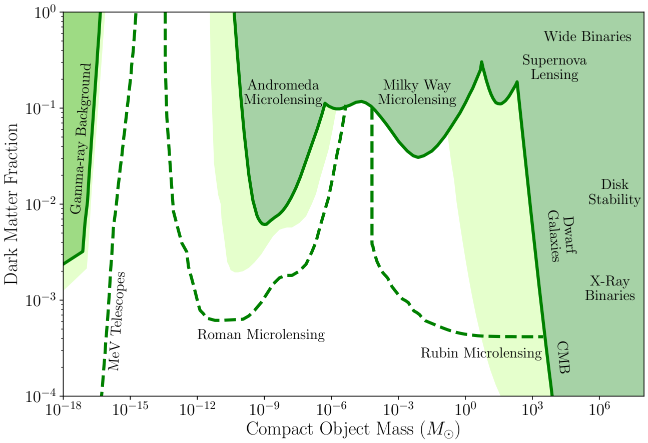

Figure 5-20. *At even higher masses, some fraction of the dark matter could take the form of macroscopic, compact objects such as primordial black holes. Upcoming microlensing and gamma-ray searches will provide greater sensitivity in this regime (dashed lines).*

5.5.4.1 Dark Matter Beyond the Planck Scale

Dark matter at the Planck mass ($\sim 10^{-5}$ g) and above is very difficult to detect directly due to its extremely low flux. Detection techniques rely on scattering to be mediated via long range forces so that effects can be seen in sparsely instrumented detectors with large collecting area. For example, if dark matter had a long range Yukawa force 10^3 times greater than gravity, then interactions of 10 kg mass dark matter with the 10 kg scale mirrors of the LIGO gravitational wave observatory could potentially be detected as the clumps traversed within the near field of the 4 km long interferometers [139]. Proposed larger observatories such as the 40 km long Cosmic Explorer or laser ranging between astroids would provide a larger collection area [140].

Heavier compact constituents of dark matter including primordial black holes (PBHs), can be detected through cosmic probes (Figure 5-20). PBHs with masses of $\sim 10^{-18}\,M_\odot$ ($\sim 10^{15}$ g) should be evaporating today, creating short bursts of Hawking radiation in the GeV-TeV range that could be observed with space-based and ground-based gamma-ray telescopes, as well as neutrino observatories. For higher masses, gravitational micro-lensing provides the most sensitive probe of the abundances of PBHs. Near-future observatories such as Rubin LSST have the potential to radically increase the sensitivity of micro-lensing searches if scheduled optimally [141]. Sub-solar mass PBHs may be detected through microlensing with Rubin LSST and other observatories or through mergers with next-generation gravitational wave detectors including LISA and pulsar timing arrays. High redshift searches with optical or gravitational wave probes may also reveal the existence of primordial black holes.

5.5.5 Delve Deep, Search Wide

The parameter space of dark matter models is vast, yet experiments which will provide significant inroads into this space are relatively inexpensive. The Cosmic Frontier plans to explore dark matter parameter space over the next decade through targeted searches to make deep progress on high-priority science targets, and an expanded portfolio of cosmic probes and small pathfinder experiments implementing new detector technologies to search wide and provide broad coverage of the range of possibilities. This strategy will cover large regions of model-space, and could easily lead to a transformational discovery within the next decade (see Figure 5-21).

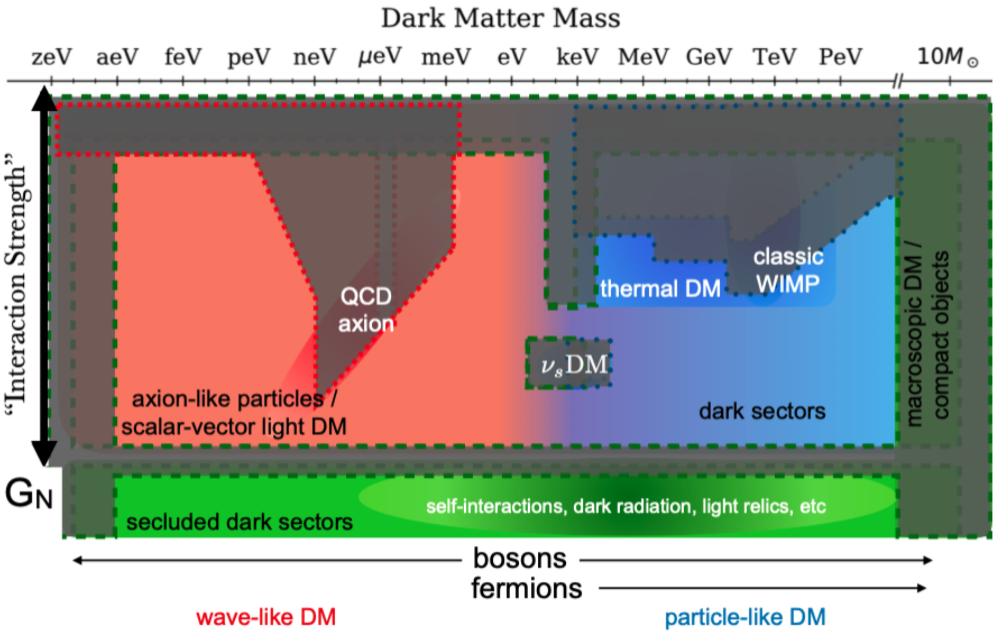

Figure 5-21. *Cartoon (not to scale) of future dark matter sensitivity which could be obtained by implementing the Delve Deep, Search Wide strategy outlined in this report.*

The WIMP and the QCD axion remain highly motivated and clear experimental targets. Tremendous progress has been made in the past two decades in liquid noble detectors and a multi-national collaborative project would continue this momentum to push sensitivity down to the solar neutrino background. Concurrently, indirect searches with proposed TeV gamma-ray observatories would conclusively test the self-annihilation cross section which defines the WIMP model, up to the scale where unitarity bounds become relevant. In the axion field, a portfolio of complementary techniques including NMR, lumped element resonators, cavity resonators, quantum sensors, and novel scattering targets would cover most of the remaining parameter space of the QCD models that solve the strong-CP problem. Axion-like particles are also well-motivated with a parameter space that can be targeted over the next ten years and beyond. Similarly, a portfolio of new technologies including CCDs, novel condensed matter scattering targets, and ultra-low-noise readouts (specifically reducing the size and thus heat capacity of transition edge sensors to match them to the smaller phonon signal strengths expected in sub-eV band gap target materials) is being assembled to test a broad range of portal dark matter models. Pathfinder experiments using AMO techniques including atomic clocks, atom interferometers, and opto-mechanical oscillators are also being developed. Cosmic and indirect probes will complement and inform all of these searches, while broadly exploring parameter space and phenomena that are currently inaccessible to terrestrial experiments. With the exception of the medium-scale multi-national WIMP experiments (and of the large-scale cosmic survey experiments), all of the other terrestrial dark matter experiments would be best characterized as "small."

All combined, a coordinated U.S. experimental program to delve deep and search wide for dark matter might reasonably be expected to cost as much as a single large experiment. Such a comprehensive and coordinated program would be very reasonably justified by its broad science reach in addition to its broader impacts in technology development, contributing to the quantum ecosystem, and training the next generation of experimental hardware specialists.

Development of new experimental techniques for both low-mass portal dark matter, axions, and more general bosonic waves has been slow to ramp up as most DOE/NSF dark matter funding has been invested in the larger dark matter experiments as per the recommendations of the previous P5 report. Identifying this gap in the U.S. dark matter strategy, private foundations including the Simons Foundation, the Heising-Simons Foundation, and the Moore Foundation have begun to invest in university programs to fund dark matter instrumentation R&D including pathfinder experiments at the $10M level. Some of the technology development and instrumentation work has also been enabled by leveraging various quantum programs, given that ultraweak dark matter interactions are a natural target for new quantum sensor technology. Cross-disciplinary engagement with neighboring scientific communities including atomic, molecular, and optical physics, condensed matter physics, and quantum information science have been facilitated by DOE-OHEP's QuantISED program and by the National Quantum Initiative Science Research Centers. This collaborative research enables the direct transfer of novel detection concepts as well as mature detector technologies from neighboring fields to HEP applications as well as the direct engagement of hardware experts who are able offer fresh perspectives on the detection challenges.

A positive development has been two DOE Basic Research Needs workshops, the first creating the Dark Matter New Initiatives (DMNI) program to fund small dark matter experiments of a scale smaller than the medium-size LZ and SuperCDMS experiments, and the second aimed at identifying instrumentation R&D needs including quantum sensing for fundamental physics. The DMNI program has funded the technical design studies of a limited portfolio of small experiments as recommended in the previous P5 report. These include the axion experiments ADMX-Extended-Frequency-Range and DM-Radio, the 1 eV threshold Oscura silicon CCD experiment, the sub-eV threshold TESSERACT program that utilizes novel condensed matter targets, as well as beam dump experiments LDMX and CCM that probe portal dark matter models via light mediators. While these experimental concepts have not yet proceeded to project status, the DMNI program provides a prototype for implementing a broad and coordinated dark matter program with a portfolio of complementary experiments to target different regions of unprobed parameter space.

Similar support could significantly strengthen cosmic and indirect probes of dark matter. These approaches have the potential to yield large scientific dividends by searching wide ranges of dark matter parameter space. For example, Rubin LSST has enormous potential to discover new physics beyond the prevailing cold dark matter paradigm [20, 38]. Rubin LSST can measure the distribution of dark matter on unprecedentedly small scales, thereby probing microscopic properties of dark matter, including thermal particle mass, self-interactions, interactions with radiation, and quantum wave features. Microlensing measurements will directly probe primordial black holes as a component of dark matter. The planned CMB-S4 [10] and Spec-S5 [22] projects will extend access to rich dark matter particle physics. For instance, detection of additional relativistic degrees of freedom by CMB-S4 would imply the existence of a dark sector. However, building the infrastructure to perform dark matter analyses with these experimental facilities requires devoted support for experimental collaborations, theorist, and large numerical simulations (which are crucial to distinguish novel dark matter physics from baryonic astrophysics). Rubin LSST and other cosmology facilities should be explicitly identified as a dark matter facilities to enable what promises to be an exciting decade of dark matter research.

5.6 Neutrinos

Cosmic probes can provide crucial information about the neutrino sector and exhibit a high degree of complementarity to terrestrial probes [142]. Cosmology is sensitive to the number and masses of the neutrinos through their impact on the evolution of the Universe, providing information that is currently inaccessible through other means.

5.6.1 Cosmic Measurements of Neutrino Masses

The current cosmological limits on the sum of the neutrino masses is $\sum m_\nu < 0.12$ eV as obtained using cosmic microwave background, baryon acoustic oscillations, supernova Ia, and large scale structure measurements. Additional information on impact of cosmological neutrinos on the growth of structure both will be obtained from high redshift galaxy surveys. CMB-S4 will reach sensitivity $\sigma(\sum m_\nu) < 0.02$ eV and if the data indicate a mass sum < 0.1 eV, this would rule out the inverted neutrino mass hierarchy which predicts higher mass sum. A Stage V Spectroscopic Facility would reach similar constraints from an independent experiment at $2 < z < 5$. Further gains in accuracy on $\sigma(m_\nu)$ beyond what CMB-S4 and Spec-S5 each will achieve will be limited by the currrent τ prior, unless that parameter is constrained better. Proposals to achieve such improvements are described in the CF4 report [4]. Higher statistics observations of the matter distribution at high redshifts could be measured by line intensity mapping surveys (in 21-cm and mm-wave) and other probes, such as future high resolution CMB imaging, and would reach resolution $\sigma(\sum m_\nu) < 0.01$ eV.

5.6.2 New Opportunity: High-energy neutrinos

The discovery of TeV-PeV astrophysical neutrinos opens up unique opportunities to probe the neutrino sector at energy scales not accessible with laboratory neutrino beams. High-energy neutrinos from IceCube were used to discover the Glashow resonance and high-energy neutrino-nucleon cross section. Future statistics will allow further tests of the Standard Model neutrino physics between 1 TeV and 10 PeV. In addition, ultrahigh energy neutrinos (UHE; $\gtrsim 100$ PeV neutrinos) have been long-predicted but remain undetected. They provide a path to probe weak-scale physics at center-of-mass energies above 50 TeV. Next-generation UHE neutrino experiments have the potential to detect these neutrinos and push the forefront of neutrino physics [143].

Observations of neutrino flavors and neutrino-antineutrino ratios may probe BSM physics [144]. The search for BSM neutrino interactions with other neutrinos or with dark matter may shed light on the UV theory of neutrinos and the origins of their low mass. Such new interactions could be observed for example via spectral distortions in the cosmic neutrino flux in the PeV-EeV range as they scatter on the cosmic neutrino background. Deviations from equal admixtures of the 3 neutrino species might occur at various energy thresholds when new interactions turn on. Neutrino production measurements from CERN's Forward Physics Facility will provide important information to calibrate the atmospheric neutrino background produced by cosmic rays scattering on nuclei in the atmosphere and thus allow cleaner detection of cosmic neutrinos [145, 146]. Finally, at GeV energies, the upcoming IceCube Upgrade and other future cosmic neutrino experiments will provide neutrino oscillation sensitivity complementary to long baseline experiments.

5.7 Exploring the Unknown: New Particles, New Fields, New Principles of Nature

5.7.1 Dark Radiation

Dark radiation can be observed in various cosmological epochs while it is still relativistic, before its kinetic energy redshifts away. Within the Standard Model (SM), neutrinos form an important component of dark radiation, and constraints from their impact on the cosmic evolution at the epochs of Big Bang Nucleosynthesis and the CMB provide powerful constraints on the number of neutrino species, typically reported as N_{eff}, the "effective number of neutrinos". In addition, determinations of the dark radiation content of the Universe provide unique opportunities to search for particles produced in the early universe, even when such particles are extremely weakly interacting with the SM. A few well-motivated examples include light particles invoked by models that aim to explain the physics of a dark sector, address the strong CP problem, solve the weak hierarchy problem, account for short baseline neutrino anomalies, and/or models of warm inflation.

Figure 5-22 shows the current measurement of ΔN_{eff}, and future prospects from operation of the Simons Observatory and CMB-S4. The projections indicate the contribution to ΔN_{eff} from a single species of one of three different types of relic particles (Goldstone or vector bosons and Weyl fermions) for a particle which was initially in chemical equilibrium with the SM plasma, but whose interactions decoupled at freeze out temperature T_F. CMB-S4, by reaching a precision of $\Delta N_{\text{eff}} \lesssim 0.05$ will be able to rule out or establish the existence of such weakly-interacting particles which have frozen out back to the temperature of the QCD phase transition (~ 0.5 GeV). A Stage V Spectroscopic Facility would reach similar constraints from an independent experiment at $2 < z < 5$ which could be combined to probe higher precision. A future measurement reaching a precision of 0.027 would be sensitive to such particles freezing out all the way back to the electroweak scale.

Quintessence models promote the dark energy from a cosmological constant to a dynamically evolving field which is slowly rolling in a scalar potential, triggering a new epoch of cosmic inflation. A natural question is then whether this quintessence field is slowly rolling in a flat potential, or if it is rolling in a steeper potential but slowed down by dynamical friction. In this warm dark energy scenario, the ongoing interactions during the slow roll in the present day universe would populate the universe with dark radiation in the form of relativistic, low mass particles with temperature and energy density typically characterized by the milli-eV scale (10 K) of the dark energy density [147]. This late injection of entropy is not constrained by bounds on CMB distortion at earlier times. Searches for this 10 K bath of exotic particles would nicely complement the cosmic surveys studies of the evolution of cosmic acceleration. Wave dark matter detectors and quantum sensors could provide the required low energy threshold of 10^{-3} eV to see absorption of this dark radiation.

5.7.2 The Highest Energy Particles

Cosmic particles above 100 TeV provide a unique window into into fundamental particle physics at energy scales beyond those reachable by terrestrial accelerators. In addition to providing indirect probes of dark matter in various annihilation or decay channels and the measurements of the neutrino sector described elsewhere in this report, observatories of cosmic rays, neutrinos, gamma rays, and gravitational waves together constitute a rich, multi-messenger program to explore the unknown through the study of the highest energy particle astrophysical phenomena in the universe.

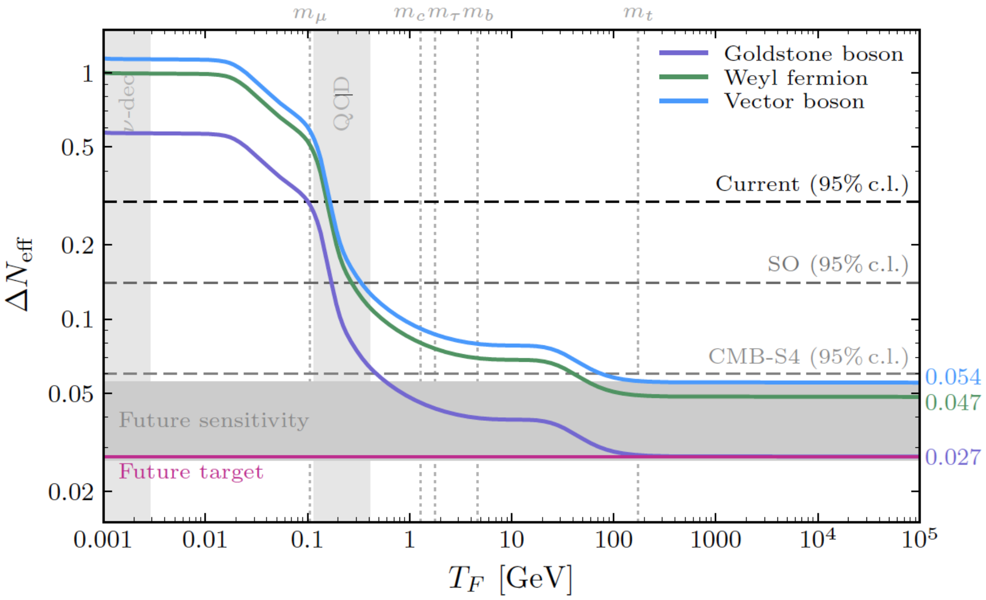

Figure 5-22. *The presence of additional relativistic BSM particles beyond the three known neutrino species increases the Hubble expansion rate and thus the power spectrum of acoustic oscillations in the primordial plasma. Measurements of the CMB can be used to discern the presence or absence of these exotic degrees of freedom, as parameterized as* $N_{\rm eff}$*, the effective number of relativistic species active during this epoch. Some representative models are shown in this plot along with the current constraints on additional particles and projections for the Simons Observatory and CMB-S4.*

In the area of hadronic shower physics, a long standing puzzle is the mysterious excess of muons in UHE cosmic ray ($> 10^{18}$ eV cosmic-ray) air showers beyond what is expected from extrapolations of hadronization models calibrated with LHC and other collider data [148]. Ongoing upgrades of the Pierre Auger Observatory and IceCube will provide greater resolution of the electromagnetic and muonic flux in air showers as well as measurements of the depth of shower maximum which provides complementary information on the initial particle species. The proposed Forward Physics Facility at the LHC [145, 146] would also provide muon and electron neutrino shower data which could be used to calibrate kaon production in high energy hadronic showers. Higher than expected kaon production rates would enhance the muon production by reducing the production of neutral pions which siphon energy into the electromagnetic portion of the shower. Whether the puzzle is resolved by a better understanding of the fragmentation process or potentially by BSM physics at high center-of-mass energies, these data will better inform the modeling and design of future high energy colliders. The high boosts and large, cosmological propagation scales of UHE cosmic particles allow powerful tests of Lorentz and CPT symmetries by searches for spectral distortions in the flux of UHE cosmic rays, very-high-energy gamma-rays ($0.1 - 100$ TeV photons), UHE gamma-rays (> 100 TeV photons), and cosmic neutrinos [149].

High energy gamma rays and neutrinos additionally offer probes of new physics including the decays of super-heavy relics left behind from the Big Bang, cosmic strings, and axion-photon conversion in large-scale magnetic fields. Next-generation gamma-ray telescopes such as the Southern Wide-field Gamma-ray Observatory (SWGO), the Cherenkov Telescope Array (CTA), and the All-sky Medium-Energy Gamma-ray Observatory (AMEGO) will open up the access to new sky regions and energy ranges, and advance fundamental physics studies with significantly improved sensitivities. Next-generation UHE neutrino ($>$ 100 PeV neutrino) observatories led by the U.S. community such as the IceCube-Gen2, The Radio Neutrino

Observatory in Greenland (RNO-G), Probe of Extreme Multi-Messenger Astrophysics (POEMMA), Beam forming Elevated Array for COsmic Neutrinos (BEACON), the Payload for Ultrahigh Energy Observations (PUEO), and the Extreme Neutrino Observatory (Trinity), have the potential to discover UHE neutrinos and use them to probe fundamental physics.

The concept of multi-messenger astronomy is finally being realized with co-detection of gamma rays and gravitational waves in a binary neutron star merger and the co-detection of neutrinos and gamma rays in a blazar flare [150]. Studies of these violently energetic astrophysical events may reveal new physics including the nature of quark matter in neutron stars, the possible accumulation or scattering of dark matter on these objects, and the production of exotic particles in large astrophysical large magnetic fields. Various tests of Einstein gravity may lead to discoveries of relevance to cosmology including modifications to the understanding of cosmic acceleration and the distribution of matter. As remarked in the dark matter section of this report, while a 20-year strategic plan is being developed for most cosmic particle channels across broad ranges in energy, an ongoing concern is the lack of coverage for MeV-GeV gamma rays beyond that provided by the aging Fermi telescope.

5.7.3 Probes of Fundamental Physics with Gravitational Waves

One of the most significant scientific developments of the past decade is the emergence of gravitational wave detection as a powerful new tool to study fundamental physics. In addition to the extensive menu of gravitational physics that will be studied by current and future gravitational wave observatories, the new GW probes will also provide unique and independent information in a number of areas of interest to the high energy physics community. For example, neutron star binary mergers will probe the neutron star equation of state and may also be sensitive to accumulations of various types of dark matter within the neutron stars. Once the neutron star physics is understood, the binary mergers may provide a new standard candle for measurements of cosmic acceleration with systematics independent of those of the currently used optical probes. Alternatively, the neutron star merger's gravitational wave luminosity distance may be combined with redshift information from the host galaxy to provide new measurements of the Hubble parameter at large redshifts.

Gravitational wave observatories will also provide unique probes of early universe phase transitions which may have happened at times prior to big bang nucleosynthesis – a period about which not much information is currently available. These phase transitions may produce a stochastic background of gravitational waves from boiling of the vacuum during strongly first order phase transitions or from the oscillations and decay of cosmic strings and other topological defects which may form during these phase transitions. The resulting gravitational wave power spectrum will provide information about these new fundamental energy scales which, once discovered will provide concrete new information for BSM model building.

The signal will be visible even through the cosmic microwave background which obscures photon probes of earlier cosmological epochs. Even phase transitions which might happen in secluded dark sectors which have no BSM couplings to standard model particles can still be probed due to the universal coupling of gravity to all matter and energy. As example, figure 5-23 shows how a broad program of new gravitational observatories targeting different frequency ranges can probe deeply into the predicted power spectrum of phase transitions at energy scales from $10^{10} - 10^{15}$ GeV for various models of thermal leptogenesis. The observatories range from pulsar timing arrays at the lowest frequencies to space-based experiments at sub-Hz frequencies to next generation ground-based interferometers at the highest frequencies.

New physics of early universe phase transitions may even be observed with the current generation of gravitational wave observatories. As a case study, LIGO may already be sensitive to the stochastic power

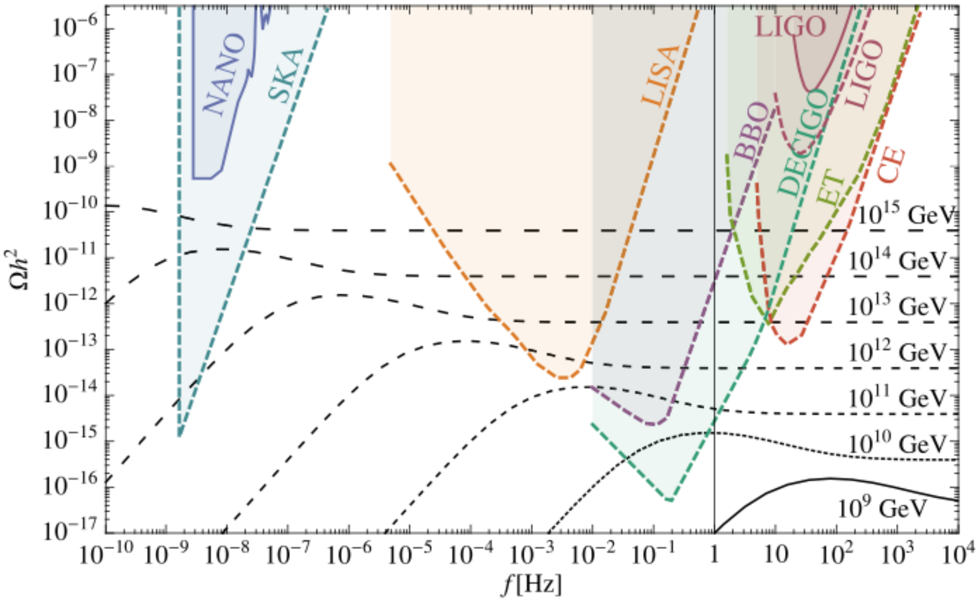

Figure 5-23. *Future gravitational wave observatories will be sensitive to the stochastic spectrum of GWs created by cosmic string decay or by boiling of the vacuum in first order phase transitions. This plot shows an example of the high energy symmetry breaking scales that can be probed in a particular model of thermal leptogenesis. In other models, the predicted spectrum may be peaked at certain frequencies, in which case observatories optimized for specific frequency ranges may have greater sensitivity. Figure shown in the Seattle meeting by H. Murayama and reproduced from reference [151].*

spectrum from Peccei-Quinn phase transition in QCD axion models if a particularly violent phase transition occurs at relatively low energies around 10^8 GeV where the red-shifted frequency spectrum of the GW emission becomes matched to the LIGO band. If the energy scale of the phase transition can be determined in this way, then the axion model gives a firm prediction for the mass of the dark matter axion and will narrow the search window for the direct detection experiments from 10 decades in mass down to a single decade. A confirmation of an dark matter signal would then provide corroborating evidence for the axion solution to the strong-CP problem. Alternatively, if the dark matter signal is discovered first in the post-inflationary scenario with mass between $10^{-5} - 10^{-2}$ eV, then this provides a firm target for the sensitivity and frequency range needed for future gravitational wave observatories to observe the phase transition. Similar strategies may be employed to search for new fundamental energy scales and test see-saw models in other contexts.

The collection of currently operating gravitational wave observatories include the LIGO facilities in Livingston, Louisiana and Hanford, Washington, along with the Virgo facility in Italy and the recently constructed, underground KAGRA observatory in Japan. LIGO-India will also be online at the end of the decade, and the space-based LISA observatory is planned for the next decade. Pulsar timing arrays operating at lower frequencies include NANOGrav in North America, the Parkes Pulsar Timing Array in Australia, and the European Pulsar Timing Array, while plans are being made for a future Square Kilometer Array. Near term plans for the U.S. gravitational wave community include the LIGO Voyager upgrade in which the existing fused silica mirrors may be replaced with crystalline silicon mirrors which can be more easily thermalized to avoid geometric distortions from heating, and the Cosmic Explorer proposal which would increase the interferometer arm length and hence antenna size from 4 km to 40 km. The AMO community is also developing long baseline atom interferometry as a potential new technique targeting lower frequency gravitational waves as well as oscillatory forces from dark matter in the 1 Hz band. The MAGIS-100 pathfinder experiment will utilize a 100 m vertical beamline access shaft at Fermilab with possible future expansion to a 2 km drop at SURF and eventually a space mission to avoid terrestrial Newtonian noise.

Participation of the HEP community may be key to the success of these ambitious projects and to ensure that optimizations for HEP science can be integrated into the designs, data pipelines, and operations plans. As an example, searches for stochastic gravitational wave power can be performed within a narrow band to reject noise as opposed to measurements of time domain waveforms which intrinsically require broader bandwidth template searches. Similarly, searches for kg-mass dark matter passing within an antenna length of the interferometers will need dedicated data pipelines and analyses. More direct engagement by national laboratories may also be critical for the construction of future large scale GWO projects.

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