Fermilab Cosmic Frontier Strategic Plan[1]

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I. Executive Summary: Fundamental Physics at the Cosmic Frontier

The 2014 Particle Physics Project Prioritization Panel (P5) report identified understanding cosmic acceleration (dark energy and inflation), pursuing the physics of neutrinos, and the new physics of dark matter as three of the primary science drivers in high-energy physics for the ensuing decade. Starting with the establishment of its Theoretical Astrophysics group exploring the early Universe in the early 1980's, through its leadership of the construction and operation of the Sloan Digital Sky Survey and Dark Energy Survey in the 1990's and 2000's, its critical roles in dark matter experiments from the late 1990's, and its more recent leadership in the Cosmic Microwave Background with the SPT-3G experiment, Fermilab has been in the vanguard of cosmic research aimed at addressing these P5 science drivers. Recently, the Fermilab-led Dark Energy Survey (DES) obtained world-leading constraints on dark energy and dark matter from its first year of data (see Fig. 9). The ADMX experiment, with Fermilab as lead lab, excluded theoretically predicted axion dark matter over a limited mass range for the first time (Fig. 5). SuperCDMS and SENSEI each achieved world-leading constraints on low-mass (sub-GeV) dark matter particles (Fig. 8), with the promise of much stronger constraints to come. The SPT-3G experiment at the South Pole, with major project contributions from and operations led by Fermilab, began the most sensitive, wide-area survey of the CMB. The Cosmic Frontier program at the lab has delivered these and other major science results even though it currently constitutes less than 4% of the Fermilab budget[2]. Moreover, the laboratory has developed a number of core capabilities that will enable it to play major roles in the next generation of Cosmic Frontier projects.

Cosmic Planning Process

In response to guidance received from the DOE Office of High Energy Physics (OHEP) in late 2017 as part of its Laboratory Optimization process, during CY 2018 Fermilab undertook a 3-phase strategic planning exercise:

- **Phase 1:** identify core capabilities (including infrastructure and expertise) that the laboratory provides to the OHEP Cosmic Frontier program;
- **Phase 2:** identify the major Cosmic Frontier activities that the lab should plan to pursue over the next 5 to 10 years, that exploit these capabilities, constitute critical contributions, align with OHEP and P5 priorities, deliver on the laboratory's commitments, and maximize its scientific impact;
- **Phase 3:** implement a focused Cosmic Frontier Strategic Plan by sensibly directing effort from activities not deemed essential in the first two phases of the process, to build our future program.

This planning process was proposed to OHEP as part of the annual lab budget briefing in March 2018, along with an initial inventory (Phase 1) of core capabilities, and the process was endorsed at that time. In the summer and Fall of 2018, the Fermilab Cosmic Frontier Strategic Plan Steering

[2] This fraction includes all sources, not just Cosmic Frontier Research.

Group (the authors of this document) met weekly to develop and draft the Plan. The members of the Group were selected to ensure that it had expertise in the major research thrusts of the Cosmic Microwave Background (CMB; Benson, Flaugher), Dark Matter Detection (Estrada, Hsu, Lippincott, and Sonnenschein, with input from Krnjaic), Cosmic Surveys (Drlica-Wagner, Frieman), and Astrophysics Theory (Hooper). The goals of the Group were to review the current cosmic portfolio of the lab and to lay out a focused, compelling, world-class program of cosmic R&D, project construction, operations, science analysis, and astrophysics theory that optimally exploits the lab's core capabilities and builds on its strengths, and to recommend relative priorities in different funding scenarios.

The Steering Group presented the elements of the draft Strategic Plan to the Fermilab astrophysics community in November 2018 and received and incorporated feedback from these colleagues into a revised Plan. The elements of the Plan were presented to OHEP senior management at the Fermilab-DOE retreat in early December and in more detail at a briefing at OHEP in Germantown on Dec. 19. The current document, which incorporates feedback received from OHEP in those two briefings and in Jan. 2019, provides more detail on the laboratory's Cosmic Frontier Strategic Plan. The Plan is designed to be flexible, and we expect it to continually evolve in response to changing priorities and opportunities. *This version of the written Plan is suitable for broad distribution*.

Elements of the Plan

Fermilab is a key partner in world-leading cosmic science experiments and is contributing innovative R&D efforts toward future dark energy, dark matter, and cosmic microwave background (CMB) experiments. Leveraging its capabilities that were applied to **SPT-3G**, the lab is helping to design, and is positioned to play major roles in building and operating the next-generation CMB experiment (**CMB-S4**) to constrain inflation, neutrino mass, and the dark sector. Fermilab scientists are advancing the search for dark matter, with major responsibilities in the construction and operation of each of the three, second-generation (G2) dark matter experiments. For the future, the dark matter detection program at the lab will focus on the scientifically exciting areas of **Axions** (leading ADMX) and **Sub-GeV dark matter** (**SuperCDMS/HVeV** and **Skipper CCDs**), while LZ activities will finish once those commitments are fulfilled. Building on its experience and expertise in constructing and operating SDSS and **DES**, Fermilab is partnering with other labs and universities to build and operate new cosmic surveys to explore dark energy (**DESI, LSST**), while beginning **R&D toward a future (Stage V) spectroscopic dark energy experiment**. Collectively, these activities comprise a focused program of research and development, project construction, operations, and analysis, supported and stimulated by a vibrant program in Astrophysics Theory and tied together with a Cosmic Physics Center. This program relies heavily upon many of the laboratory's core capabilities, which are highlighted in Section II, and synergizes with FNAL activities in Quantum, Neutrinos, and the Energy Frontier.

The current roster of Fermilab scientists (including postdocs) involved in the Cosmic Frontier program includes 21.6 FTEs supported on Cosmic Research, with an additional 12 FTE supported by a combination of LDRD, Early Career Awards, Detector R&D, experiment operations, the new DOE Quantum Initiative, Theoretical Astrophysics, plus private foundations and international sources. The Fermilab program also benefits from close connections with the Kavli Institute for Cosmological Physics (KICP) at the University of Chicago and from growing collaborations with nearby Argonne National Laboratory. The lab's Cosmic program is thus highly leveraged and serves a large user community, achieving a large bang for the buck.

The Cosmic Strategic Plan Steering Group considered priorities for the Fermilab cosmic program under three funding scenarios: growing, flat, or declining in terms of Cosmic Research-supported FTEs. In all scenarios, the Plan calls for the CMB scientific effort to grow substantially, in order to support major roles in CMB-S4 construction and operations that are well-matched to the lab's core capabilities. In all scenarios, the effort on axions is also slated to grow, with the ADMX experiment proposing to be upgraded in the near term and to be followed by a next-generation experiment sited at Fermilab enabled by advancing Quantum detector technology. With the upgrade and the Quantum-enabled experiment, we will discover or exclude dark matter axions over the majority of the theoretically preferred axion mass range. The other focus of the lab's dark matter detection activities will be to push down the sensitivity to sub-GeV dark matter particles by ~7 orders of magnitude through its contributions to SuperCDMS construction and operations and through R&D programs in both HVeV and Skipper-CCD technologies, with an anticipated technology down-select and merging of effort once a clearly winning technology emerges. The scale of the sub-GeV program will depend on available resources; in the declining scenario, the efforts will necessarily be merged earlier in time, and the lab's commitments to SuperCDMS operations will potentially be at risk. In the third research thrust, Cosmic Surveys, the current scientist effort on DES will transition over the next 3 years to support of LSST and LSST DESC operations, while the efforts on DESI construction will ramp down to small but critical roles in DESI operations. The effort-levels of these survey operations roles, which support technical operations roles requested by these two Stage-IV experiments, will depend on the resources available to the program. In addition, we plan to carry out a focused program of R&D on critical technologies for a next-generation (Stage V, post-DESI and post-LSST) spectroscopic dark energy experiment, initially with LDRD funds.

This document lays out the proposed Fermilab Cosmic Frontier Strategic Plan. Section II summarizes the core capabilities that the laboratory brings to the OHEP Cosmic Frontier program and that underpin its current and anticipated roles in cosmic experiments. Sections III, IV, and V describe the planned activities in the three thrusts of the Cosmic Microwave Background, Dark Matter Detection, and Cosmic Surveys in detail. Section VI describes the plan for Theoretical Astrophysics, and Sec. VII describes a proposed Cosmic Physics Center that would intellectually unify the activities at the laboratory and in the Chicagoland area, while serving a national cosmic user community. Sec. VIII presents a summary and conclusions.

II. Fermilab Core Capabilities for the Cosmic Frontier

Here we summarize Fermilab's core capabilities on the Cosmic Frontier and connect those capabilities to the roles that the lab is playing in current cosmic experiments. These capabilities form the basis for lab roles in future experiments; they synergize with and in many cases were developed to support activities on the Energy and Intensity Frontiers.

Infrastructure:

- Precision assembly, integration, R&D, and testing facilities at the Silicon Detector Facility (SiDet). This unique facility incorporates the most extensive experience of all the national labs in designing, assembling and testing precision detector modules (including CDF, D0, DECam, DESI, SPT-3G, DAMIC, SENSEI) and is a critical engine for detector upgrade projects at the LHC. It is central to the cosmic program, providing key detector activities and housing test facilities for ADMX and SuperCDMS, and enabling development of breakthrough cryogenic sensor technologies for low-mass dark matter detection and neutrino experiments. In the near future, it will be augmented by state-of-the-art cryogenic and engineering design and test facilities in the new Integrated Engineering Research Center (IERC, see Fig. 1).
- Low-background test facilities and materials expertise. NEXUS (Fig. 1) is a unique low-background cryogenic test facility that initially will be used for SuperCDMS but later will serve as a facility for many projects.
- Management and operations of underground facilities both on- and off-site, including NEXUS and the NUMI underground facility and extensive experience at SNOLAB, SOUDAN, LNGS, and SURF.
- Large-scale computing infrastructure and expertise for HEP experiments.

R&D/Expertise:

- Front-end electronics and radio frequency engineering, which build upon the lab's accelerator expertise to provide critical components for all areas of the cosmic program, including ADMX, CMB-S4, DECam, DAMIC, Skipper-CCD, R&D for future Dark Energy projects (e.g., MKIDS).
- Cryogenic engineering and operations (Kelvin and sub-Kelvin). Expertise in applying these technologies to new and diverse experiments is unique within the national lab complex. Fermilab has/is leading these tasks for SuperCDMS, LZ, DECam, DAMIC, SENSEI, PICO, Darkside and others.
- Superconducting magnets and detectors.
- Liquid noble-gas detectors, which are central to the Intensity Frontier (neutrino) program.
- Quantum sensor development, quantum computing, and AI/Machine Learning (synergy with U. Chicago, ANL).

- Design, construction, and operation of cosmic surveys, including advanced data processing and handling – operations of SDSS and DES built upon the experience from the collider program and provide the foundation for future roles in LSST Survey and DESC operations.
- Project management for construction & operations.
- Theoretical Astrophysics and Cosmology theory – including Dark sector (dark matter and dark energy) phenomenology, cosmic surveys, CMB, and numerical cosmology.

Fig. 1: *Left panel:* Schematic of the NEXUS underground cryogenic detector test facility, a joint Fermilab-Northwestern University project now being commissioned at Fermilab. *Right panel:* Drawing of the planned IERC facility adjacent to Wilson Hall at Fermilab, set to begin construction in 2019, which will provide key engineering infrastructure for cosmic frontier activities.

These core capabilities have enabled the laboratory to take on major roles in a variety of experiments on the Cosmic Frontier. Fig. 2 provides a snapshot of the current program of Cosmic Frontier experimental and R&D activities at Fermilab, with a synopsis of the lab roles in each experiment and the corresponding core capabilities that have fed into those roles. In each case, the technical and management roles flow from one or more capabilities. In some cases, these capabilities have led Fermilab to take on leadership of projects (e.g., DES); in other cases, these capabilities have been recognized by the leadership of projects who have requested the lab to take on key roles as a result. These capabilities form the basis for the lab's future cosmic program, as outlined in the following four sections.

Dark Energy	FNAL critical roles	FNAL core capabilities
DES	Project management, detector test & integration, ops management, calibration, collaboration leadership, computing, data management & database	Detector testing, assembly & integration at SiDet; survey design & ops; data mgmt; project mgmt
DESI	Detectors, corrector, online database, fiber to target translation	Detector packaging, testing, assembly at SiDet; survey design & operations, active optics software, commissioning
LSST	Dark Energy Science framework, survey operations & strategy, data management	Survey operations, computing infrastructure, computing operations
Dark Matter	**FNAL critical roles**	**FNAL core capabilities**
SuperCDMS	cryogenics, electronics, operations, calibration, data analysis, project management	Precision assembly, testing; underground facility (NEXUS); cryo engineering; project management
LZ	TPC engineering, process control	Cryo and process control engineering
ADMX	RF cavity development, operations management, Quantum sensors	RF engineering; test & assembly at SiDet; Quantum sensors; magnets; ops management
Skipper CCD R&D	dark matter search (SENSEI), R&D for applications to dark matter/neutrino expt's & large scale surveys	Detector R&D expertise; SiDet facility
CMB	**FNAL critical roles**	**FNAL core capabilities**
SPT 3G	Cryostat, detector packaging and FP design, testing, integration, camera installation, operations lead	Detector test, assembly, integration at SiDet; operations management; detector electronics; project management
CMB S4	R&D, design, electronics, integration, management	

Fig. 2: Current program of Cosmic Frontier experimental activities at Fermilab in Dark Energy (red), Dark Matter Detection (blue), and the Cosmic Microwave Background (green). For each experiment or activity, we highlight the principal Fermilab roles and the corresponding core capabilities that enable them.

III. Cosmic Microwave Background

Given its unique ability to address fundamental questions about the physics of inflation and neutrinos, the next-generation CMB-S4 experiment was strongly endorsed by the P5 report as a high priority for the field; the report also noted that CMB-S4 will require the infrastructure and expertise of the national labs. **To help address this national priority, we have identified growth in CMB activity to enable major roles in CMB-S4 as the highest priority for the Cosmic Frontier program at Fermilab for the coming decade**. This activity builds upon the lab's long history of intellectual leadership in CMB theory, including the development of CMB measurements as precision cosmological probes, and more recently upon its major technical, management, and scientific contributions to the currently operating SPT-3G experiment. Building on the SPT-3G experience, Fermilab scientists are playing key roles in the design and planning for CMB-S4. As described below, many of the technical and scientific needs of CMB-S4 align well with Fermilab's core capabilities. The scale, complexity, and diversity of technical challenges of the CMB-S4 project will be best addressed by a multi-lab and university collaboration that can exploit the complementary capabilities of the different DOE labs. Fermilab has the infrastructure, technical expertise, necessary relationships and project management experience to play a leading role in such an effort.

SPT-3G

The SPT-3G instrument (PI John Carlstrom, U. Chicago) consists of 16,000 superconducting transition edge sensor (TES) detectors configured to measure the polarization of the CMB in three frequency bands. SPT-3G is the largest camera of its kind in the world and achieved first light on the South Pole Telescope (SPT) in January 2017. Fermilab played major roles in the camera construction and detector development (see Fig. 3), with responsibilities that included: leading the packaging of all the SPT-3G detector modules; co-development of the SQUID readout electronics for the TES detector arrays; leading the mechanical and cryogenic design and integration of the sub-Kelvin camera cryostat; and leading the SPT-3G camera integration and commissioning at the South Pole.

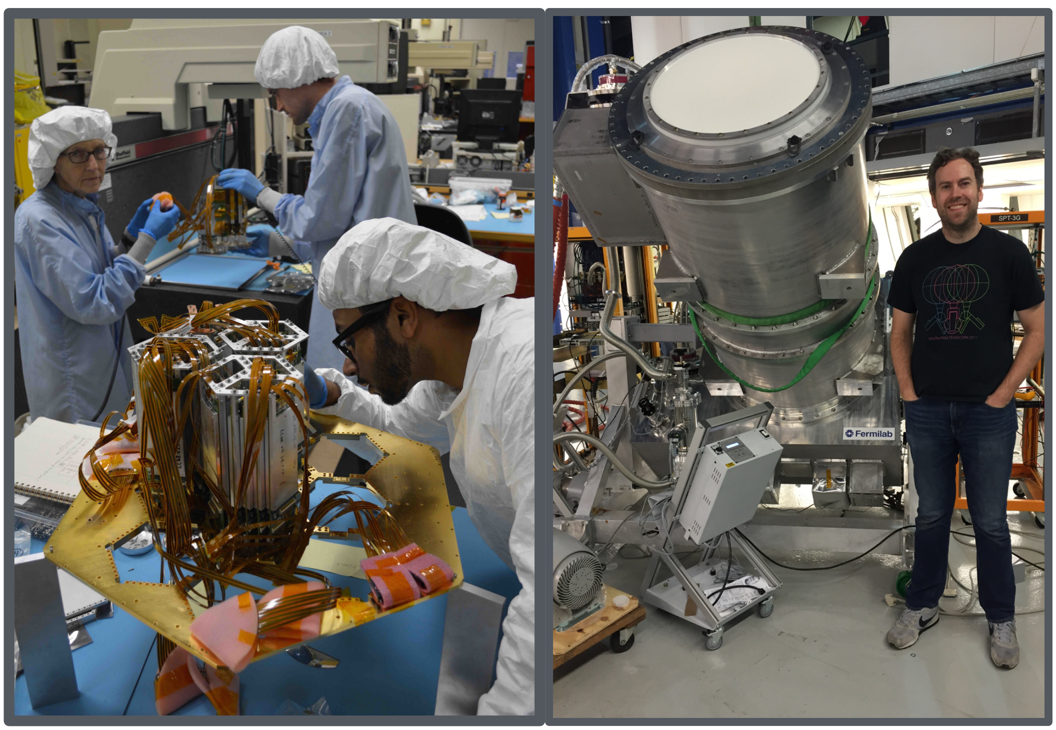


Fig. 3: *Left panel:* Assembly of the SPT-3G focal plane by Fermilab scientists and technicians at SiDet. *Right panel:* Fermilab Scientist Brad Benson with the SPT-3G cryostat at SiDet.

The Fermilab SPT-3G effort demonstrated the lab's core capabilities that enable it to play major roles in a major CMB construction project and highlighted its complementarity with the capabilities of ANL, U. Chicago, and other labs. ANL fabricated the SPT-3G detector arrays, based on an LBNL design, with Fermilab solely responsible for their packaging and wire-bonding (>100 total arrays from R&D through production). Fermilab also packaged and wire-bonded the majority of the SPT-3G cold-readout (<4K) components, including SQUID amplifiers made by NIST and superconducting LC resonators made by LBNL. Fermilab cryogenic engineering experience enabled it to lead the design and integration of the SPT-3G cryostat and the development of a fast-turnaround test-bed. This latter facility was integral to the larger SPT-3G detector and readout development effort, for which Fermilab was one of the primary institutions for testing components.

Currently, Fermilab is managing SPT-3G site and survey operations. In 2018, SPT-3G began a 5-year, 1500 sq. deg. survey that is poised to make important contributions to fundamental physics (see Fig. 4), including world-leading constraints on inflationary gravitational waves from a joint analysis of data from SPT-3G and BICEP/Keck, and two independent measurements of the sum of neutrino masses from CMB lensing and galaxy clusters, which will be further improved with joint analyses with DES. Fermilab postdocs are at the center of the scientific analysis in the collaboration, leading efforts to optimize the camera performance and write the CMB power spectrum analysis pipeline.

CMB-S4

CMB-S4 will consist of approximately 500,000 superconducting detectors, over an order of magnitude more than any previous CMB experiment, in multiple cameras on large- and small-aperture telescopes in Chile and at the South Pole. The baseline detector and readout technology uses superconducting TES detectors with a SQUID-based readout; the required scale of detector fabrication throughput and testing exceeds the capability of any single facility or institution. Similarly, the baseline camera design requires nine cryostats, each with its own dilution refrigerator, with the size of the three largest cryostats (for the large-aperture telescopes) significantly exceeding that built for any previous CMB experiment. The scale and complexity of CMB-S4 motivates participation of multiple DOE labs and shared responsibility between them, based on their complementary expertise and core capabilities.

Fermilab is helping to drive the design and development of CMB-S4. Since the inception of the CMB-S4 concept during the 2012 Snowmass process, Fermilab has been heavily involved in composing the Snowmass white papers for the Neutrinos and Inflation CMB-S4 science case (see Fig. 4), the 2015 CMB-S4 roadmap for the DOE CMB Cosmic Visions group, the 2016 CMB-S4 Science Book (CMB S-4 Collaboration, 2016), the 2018 CMB-S4 four-lab R&D plan, and the 2018-19 Decadal Survey Report. In addition, Fermilab scientists have had active roles in CMB-S4 planning through membership in the conceptual design team (CDT), the Interim Collaboration Coordination Committee, and the Governing Board.

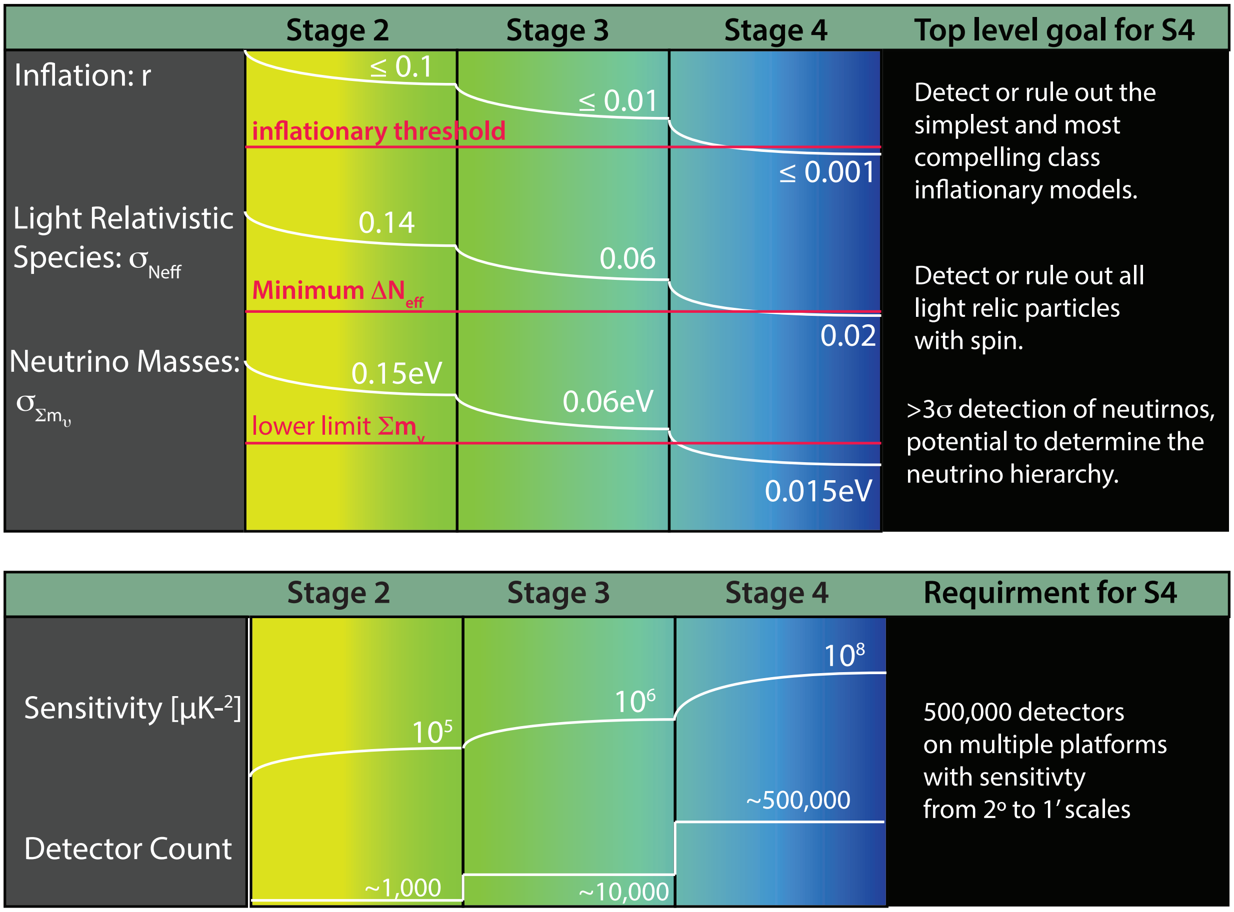


Fig. 4: Projected sensitivity to inflation gravitational waves (scalar-to-tensor ratio, *r*), light relativistic species (N_{eff}), and the sum of neutrino masses, for different stages of CMB experiment characterized by sensitivity and detector count; SPT-3G is a Stage 3 experiment, and CMB-S4 is the proposed Stage 4 experiment (CMB-S4 Collaboration 2016).

Based on its core capabilities, Fermilab is well-positioned to take on leading technical and management roles in the CMB-S4 project, outlined below. Fermilab brings project management expertise on large experiments across HEP, including DES within the Cosmic Frontier. Fermilab expertise and facilities infrastructure are well-aligned with the needs of the CMB-S4 project. This includes detector testing, integration, cryostat design and operations demonstrated for SPT-3G, cryogenic engineering expertise, the SiDet facility for wire-bonding, precision assembly, integration, and testing, and the new IERC facility that will include a cryogenic lab that can house more than 10 dilution refrigerators, a unique resource at the DOE labs. Fermilab has strong working relationships with the other DOE labs and has demonstrated ability to organize and coordinate the multi-lab efforts that will be required for CMB-S4. This includes close, synergistic relationships with the other Chicago-land institutions, ANL and the University of Chicago, with the latter providing scientific leadership and NSF connections for the CMB-S4 project. These institutions worked together well on SPT-3G and are providing integrated efforts to move the CMB-S4 project forward.

For CMB-S4, there are clear and complementary roles for several of the national labs. For example, ANL has significant expertise and infrastructure for cosmological simulations and detector fabrication. Fermilab collaborated closely with ANL in the development of the SPT-3G detectors, with Fermilab complementing the ANL efforts by providing detector packaging and testing. SLAC has significant expertise in small-aperture cryostats, data acquisition, detector fabrication and readout electronics, for which Fermilab has collaborated on the development of a GHz frequency domain readout. LBNL has significant infrastructure in data management, experience in wave-plate development, and long-standing expertise in detector design and readout. Fermilab has closely collaborated with LBNL on other cosmic frontier projects, such as DES, DESI, and low-mass dark matter CCD detectors.

Based on its core capabilities, we envision the following potential leadership roles for Fermilab on the CMB-S4 project:

- ***Project management***: Fermilab has demonstrated experience on other large HEP projects, ability to coordinate multi-lab efforts, and synergy with other Chicago-land institutions.
- ***Detector module packaging***: Large-scale detector packaging is a Fermilab core capability, enabled by the unique infrastructure at SiDet, developed and refined in numerous experiments, including CDF, D0, CMS, DES, DESI, and SPT-3G.
- ***Detector testing and characterization***: Fermilab has significant experience in this activity from DES, DESI, and SPT-3G. This activity will leverage new Fermilab infrastructure, including: two sub-Kelvin test-beds built for SPT-3G detector and readout development; cryogenic facilities in the planned IERC facility; and synergy with the Fermilab Quantum Initiative efforts, a new core capability, which shares similar technology and infrastructure.
- ***Cryostat Integration***: Fermilab was responsible for the integration of several cosmic frontier experiments, including DES, SuperCDMS, and SPT-3G. In the new IERC building, we will use one of the new 2500 sq. ft. project labs for integration of the largest CMB-S4 cryostats.
- ***Deployment, Integration, and Commissioning on-site***: This activity builds on experience with DES, DESI, and SPT-3G as well as expertise that will be developed during the project.

In addition to these leadership roles, Fermilab core capabilities in the following areas will enable it to provide critical oversight of project work at other labs and universities:

- ***Readout electronics***: Fermilab's accelerator physics program has a long history in RF electronics, one of its core capabilities. More recently, Fermilab scientists have been at the forefront of the development of the fMESSI electronics, an FPGA-based, GHz-bias readout for kinetic inductance detectors. Fermilab has begun a collaboration with SLAC to co-develop a similar GHz-bias system for CMB TES detectors.

- ***Cryostat design:*** This exploits Fermilab's core capability in cryo engineering, which enabled it to design the sub-Kelvin cryostats for SuperCDMS and SPT-3G.

The actual Fermilab scientist roles in the project will be determined in coordination with the CMB-S4 Project Office, which Fermilab is helping to establish, with a sensible match of scientist roles to the scope of engineering and technician roles on-project. For the latter, we note that engineering/technical support for the project is expected to become available as those efforts on Mu2e construction roll off in FY 2020. Joint positions with U. Chicago will provide cost-effective growth to lead this program.

IV. Dark Matter Detection

The 2014 P5 report identified determining the nature of dark matter as one of the high-priority science drivers in high energy physics. In recent years, the theoretical landscape for dark matter has broadened, requiring an experimental program with the capability to explore dark matter interactions over a wide range of masses and with a variety of experimental techniques. The current Generation-2 (G2) direct detection program comprises ADMX (axion search), SuperCDMS (low-mass, WIMP-like dark matter), and LZ (high-mass, WIMP-like dark matter). **Fermilab is committed to executing the G2 dark matter program** and is playing leading roles in each of these three experiments as requested by their proponents in recognition of the lab's core capabilities. Beyond G2, **Fermilab is making focused R&D investments in techniques to search for low-mass dark matter** primarily through the lab's LDRD program, DOE Early Career awards, and other external funding sources. **Fermilab plans to leverage this R&D –** and its core capabilities in low-background detector development, cryogenic engineering, superconducting and quantum sensors, and RF and magnet engineering **– to lead the next generation of direct searches for low-mass dark matter**, as described below. This program is strongly aligned with community priorities recently identified in the "Cosmic Visions: New Ideas in Dark Matter 2017" community report (Battaglieri, *et al.* 2017) and in the Dark Matter Basic Research Needs workshop. In FY19, the Dark Matter program, including associated R&D efforts, comprises about 5.9 FTE scientists and 3 FTE postdocs supported on Cosmic Research, with another 0.9 FTE assumed supported by Dark Matter operations and projects; this effort is further supplemented by 2.5 FTE supported by other funding sources.

Generation 2 Dark Matter Program

The QCD axion is one of the most theoretically compelling particle dark matter candidates. In 2018, the ADMX-G2 experiment sited at U. Washington achieved a leap in sensitivity sufficient to probe the DFSZ axion dark matter model for the first time, a long-standing goal of the field (see Fig. 5). Fermilab is currently the lead lab for ADMX-G2, which will search for the QCD axion over the mass range 2.5 – 8.3 μeV (0.6 – 2 GHz in frequency) in FY18 – 21. During this phase of the ADMX program, Fermilab is playing critical roles in project and operations management, cryogenic and mechanical engineering, data management, quantum electronics packaging, and coordination of the science analysis. Exploiting its cryogenic expertise, Fermilab is also building a facility for comprehensive testing of ADMX resonator arrays at 4 K and will perform a system test for the 1.5 – 2 GHz resonator array in FY19. In FY19, the Cosmic Frontier Research program supports 1.8 scientist FTEs and 0.5 postdoc FTE for ADMX operations, with approximately 2 additional FTEs on R&D projects supported by other grants (mentioned below).

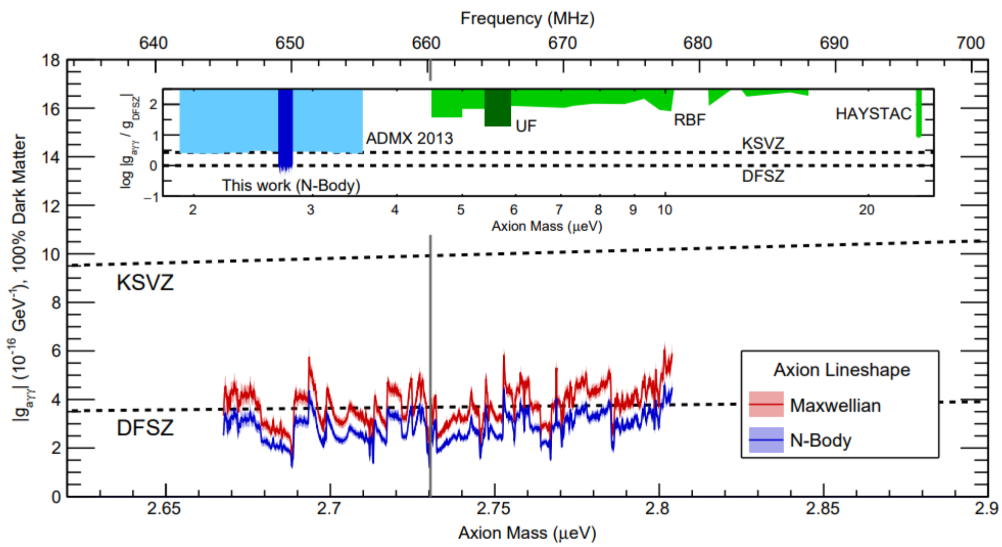
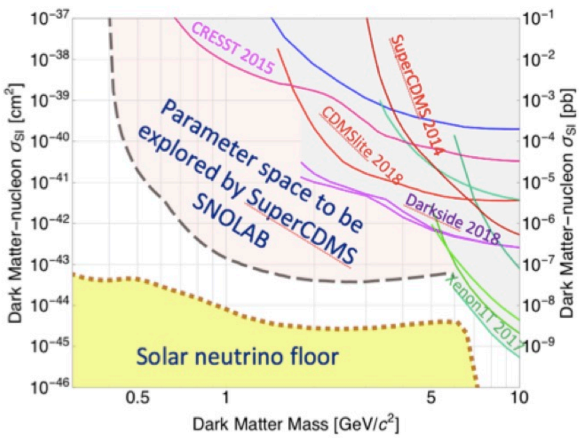


Fig. 5: ADMX-G2 constraints on axion-photon coupling over the axion mass range 2.66 – 2.81 μeV, showing exclusion of DFSZ axion dark matter over this range (Du, et al. 2018); red and purple shading show results for two different models for the axion velocity distribution function in the Milky way halo.

For much of the past two decades, Fermilab has led the search for the other major dark matter candidate, the Weakly Interacting Massive Particle or WIMP. Fermilab's G2 role in the search for WIMPs and WIMP-like dark matter includes the construction of major components for SuperCDMS SNOLAB, which will improve sensitivity to dark matter-nucleon couplings by several orders of magnitude for particles with mass between 1 and 10 GeV. Fermilab is responsible for the design and engineering of half of the Project Level-2 sub-systems, including the cryogenic system, warm electronics, calibration systems, shielding, and on-site installation; These systems, which will be commissioned by Fermilab personnel in 2019 – 2020, make extensive use of the lab's expertise in sub-Kelvin cryogenic engineering, readout electronics, and controls systems. Fermilab roles include the Deputy Project Manager and the former Spokesperson, highlighting the importance of the lab to the project. Beyond construction, the Fermilab group's unique expertise will be necessary for successful operation of the experiment and any future upgrades, and Fermilab will support the sub-systems it has built during the operations phase. First results from

SuperCDMS SNOLAB are expected in 2021, with the expectation that the experiment will run through at least 2025 (see Fig. 6).



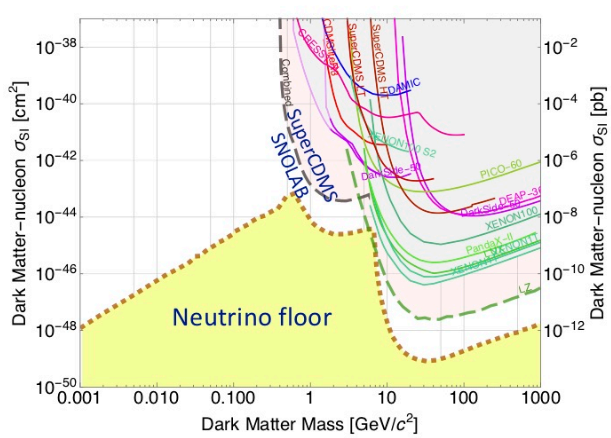


Fig. 6: *Left Panel:* Projected sensitivity for SuperCDMS SNOLAB to low-mass, spin-independent WIMP-nucleon scattering. *Right Panel:* Zoom-out of left panel, showing potential of unexplored regions above the neutrino floor, for dark matter masses below 1 GeV. R&D toward future SuperCDMS-style detectors is targeting this parameter space (SuperCDMS Collaboration 2017; T. Saab, private communication).

In conjunction with the SuperCDMS project, Fermilab is leading a major component of the early SuperCDMS operations program, the nuclear recoil calibration of the detectors. To support this effort, Fermilab has built the NEXUS underground test facility in partnership with Northwestern University. Located in the MINOS near-detector hall, NEXUS provides an ideal low-background environment to test cryogenic dark matter detectors. A neutron scattering setup with a low-energy neutron beam will be installed alongside NEXUS to perform the calibration measurements. In FY19, the Cosmic Frontier research program at Fermilab supports 2.8 FTE scientists and 0.5 FTE postdoc for both the SuperCDMS project and early operations.

Fermilab is playing significant roles in the third G2 project, LZ, delivering key cryogenic apparatus and process control for the experiment, among other engineering resources. Fermilab scientists have served as the LZ Instrument Scientist, with responsibility for requirements and verification since 2015. Fermilab scientists have also served as Physics and Simulations Coordinators for the collaboration, leading Mock Data Challenges and the writing of the LZ sensitivity paper. In the near future, Fermilab intends to provide operations support for the process control and cryogenic systems that it built and delivered to the project, but in order to focus the program we have decided that our scientific role will come to an end once the project is completed. In FY19, the Cosmic Frontier research program at the lab supports 1.0 FTE scientists and 1.0 FTE postdoc for LZ.

Dark Matter beyond Generation 2 program

While WIMPs remain a viable solution to the dark matter problem, the absence of a discovery after decades of remarkable progress in sensitivity is driving the community to reconsider the nominal WIMP paradigm that dark matter is an O(100 GeV)-mass particle. Moreover, emerging technologies now offer exciting opportunities to search for a broader range of dark matter candidates. The recent "Cosmic Visions: New Ideas for Dark Matter" (Mar. 2017) and Dark Matter Basic Research Needs (Oct. 2018) Workshops highlighted three promising avenues to pursue at high priority: (1) axions or other "wave-like" dark matter; (2) sub-GeV dark sector particles interacting with nucleons or electrons; and (3) accelerator-based experiments to probe dark sector particles. In these 3 areas, novel theoretical ideas and impressive experimental advances are enabling the design of experiments that can improve sensitivity to dark matter by orders of magnitude in previously underexplored regions of parameter space. Fermilab is driving both the novel theoretical ideas and the cutting-edge experimental techniques that will enable the search for dark matter beyond conventional WIMPs.

(1) Axions Beyond ADMX-G2

The currently approved ADMX program will end in FY21. We plan to propose a seamless, 3 to 4-year extension of this program, continuing to use the solenoid magnet, cryogenic system, and other infrastructure currently operating at U. Washington. This is a cost-effective option in the near term for expanding mass-range coverage in an important region of parameter space for QCD axions, up to 17 μeV (corresponding to 4 GHz in frequency).

For the longer term, we plan to carry out R&D leading toward a next-generation experiment that will cover an even larger axion mass range. The recent leap in sensitivity for ADMX (Fig. 5) was due to the use of a new superconducting (Josephson Parametric) amplifier technology developed initially for quantum information applications, including quantum computing. We see this as the beginning of an important trend in high energy physics, with new types of rare event and precision measurement experiments enabled by the dramatic progress occurring in quantum technologies. We intend to grow this aspect of the program to take advantage of these new opportunities to push detector noise below the standard quantum limit. The lab has invested significant LDRD funding ($2.3M in FY17-19) for development of superconducting quantum devices for axion detection and has recently won a DOE Early Career Award (PI: D. Bowring), a QuantISED award (PI: A. Chou), and an award for graduate student support from the Heising-Simons Foundation (PI: A. Chou) for these efforts. These funds are being used in part to create a state-of-the-art facility for testing Qubits and other quantum devices useful for future axion detection projects. This effort is a collaboration with U. Chicago, NIST/U. Colorado, and Yale.

Once R&D on quantum sensors has reached sufficient maturity, we will propose a next-generation axion experiment to be sited at Fermilab (see Fig. 7). This project will build upon core lab capabilities for the engineering of quantum sensors, high-field superconducting magnets, and RF resonator structures. Construction of this experiment could begin as early as FY23. Given the importance of such a flagship experiment, we expect to apply a larger fraction of Cosmic Frontier Research support to axion searches over time, with a doubling (to approximately 4 scientist FTEs) over the next 5 years.

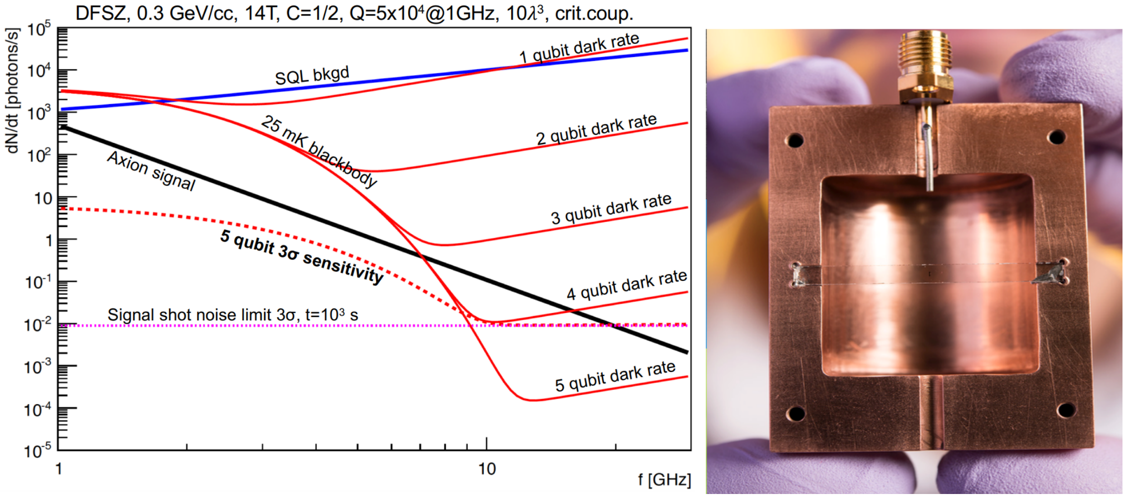


Fig. 7: *Left panel:* Sensitivity plot showing that a 5-qubit system can in principle probe DFSZ axion dark matter at frequencies up to 10 GHz or more (corresponding to axion masses up to ~50 μeV; A. Chou, private communication). *Right panel:* Superconducting aluminum qubit designed by Fermilab and U. Chicago to test axion detector concepts. The qubit is fabricated on a sapphire substrate and mounted inside a copper resonant cavity. A single photon stored in the cavity produces a measurable qubit frequency shift.

(2) Sub-GeV Dark Matter

Over the last 30 years, substantial improvements have been made in constraining dark matter WIMPs above 1 – 10 GeV, but there is a large swath of parameter space ripe for exploration and of growing theoretical interest in the sub-GeV range (Fig. 6, right panel). Over the next few years (2019-2021), SuperCDMS will deploy a series of prototype devices with world-leading sensitivity to sub-GeV dark matter that interacts via either nuclear or electron recoils (Essig, *et al.* 2016, Kurinsky, *et al.* 2019). SuperCDMS already generated a world-leading limit with such a device, which can measure single electron-hole pairs (Fig. 8, SuperCDMS Collaboration 2018). Fermilab, in partnership with Northwestern University, will lead these efforts through use of the NEXUS test facility described above; prototype detectors will be calibrated at this facility and then used to search for dark matter.

Longer-term plans for SuperCDMS R&D include the development of ultra-high-resolution phonon detectors for sub-GeV dark matter searches. Such detectors will be designed and packaged at Fermilab and tested underground at NEXUS. Taken together, the family of SuperCDMS detectors will competitively probe dark matter interactions for particles with masses from 1 MeV to 10 GeV (Fig. 8, right panel). In FY19, the SuperCDMS R&D effort consists of 0.5 FTE postdoc supported by the Cosmic Frontier Research program.

Fermilab is leading the development of a novel detector technology for multiple high-energy physics applications, including the search for sub-GeV dark matter. Skipper CCDs, developed in close collaboration with the Micro Systems Lab (MSL) at LBNL, eliminate the readout noise of conventional scientific CCDs by allowing multiple, non-destructive measurements of the charge in each pixel. With Skipper CCDs, we have demonstrated the capability of detecting low-energy ionization events generating a single electron (Tiffenberg et al. 2017). In early 2018, we demonstrated the remarkable potential of this technology for dark sector searches by achieving the then-world's best limit on light dark matter (mass less than a few MeV) scattering on electrons, using a prototype detector with less than 1 gram of active mass during a surface run (SENSEI Collaboration 2018). While this limit was soon overtaken by the SuperCDMS result mentioned above, very recently we achieved another world-leading result from a prototype device at the shallow MINOS hall at Fermilab, as shown in Fig. 8 (SENSEI Collaboration 2019).

Fermilab is the technical driver and leader of this effort; based on its core capabilities, the lab has developed the cryogenic system, the sensor packaging, the readout electronics and is leading the data analysis for these prototype experiments. These new sensors also have applications in quantum information science (QIS), coherent neutrino-nucleus scattering, nuclear treaty verification, and astronomical instrumentation (see Sec. V). The current development effort for Skipper CCDs is supported with more than $5M by ongoing LDRDs at Fermilab, private funding from the Heising-Simons Foundation, a DOE Early Career Award (Tiffenberg), and a Quantum Information Science grant, highly leveraging the 1.3 FTE of Cosmic Frontier Research support for R&D. This effort has also been recognized by the IEEE best paper award 2017 (Sofo-Haro), the Physical Society of Argentina Thesis Award 2018 (Sofo-Haro), and a CPAD Instrumentation Award 2018 (Tiffenberg).

As part of the ongoing Skipper-CCD program, Fermilab is leading an international collaboration developing a 10-gram detector to be operational in 2019 at the MINOS site, with a 100-gram detector to operate at SNOLAB in 2020. Following these R&D demonstrations, we plan to develop the engineering solutions to scale this technology up to a 10-kg experiment, to be proposed in a couple of years.

The Skipper CCDs and the SuperCDMS HVeV detectors are two of the most promising, rapidly maturing, and best-developed techniques for exploring dark matter masses of order 1 GeV and below, particularly using electron recoils. With 1 kg-year of background-free exposure at SNOLAB, they have the potential for a remarkable factor of $\sim 10^7$ improvement in sensitivity to low-mass dark matter over current limits (Fig. 8). Given its capabilities, which will be significantly enhanced by the unique IERC facility in the near future, Fermilab is in excellent position to lead the next phase of these efforts and to coordinate with OHEP and the dark matter community to determine which technology will provide the most effective investment for a next-generation sub-GeV dark matter experiment.

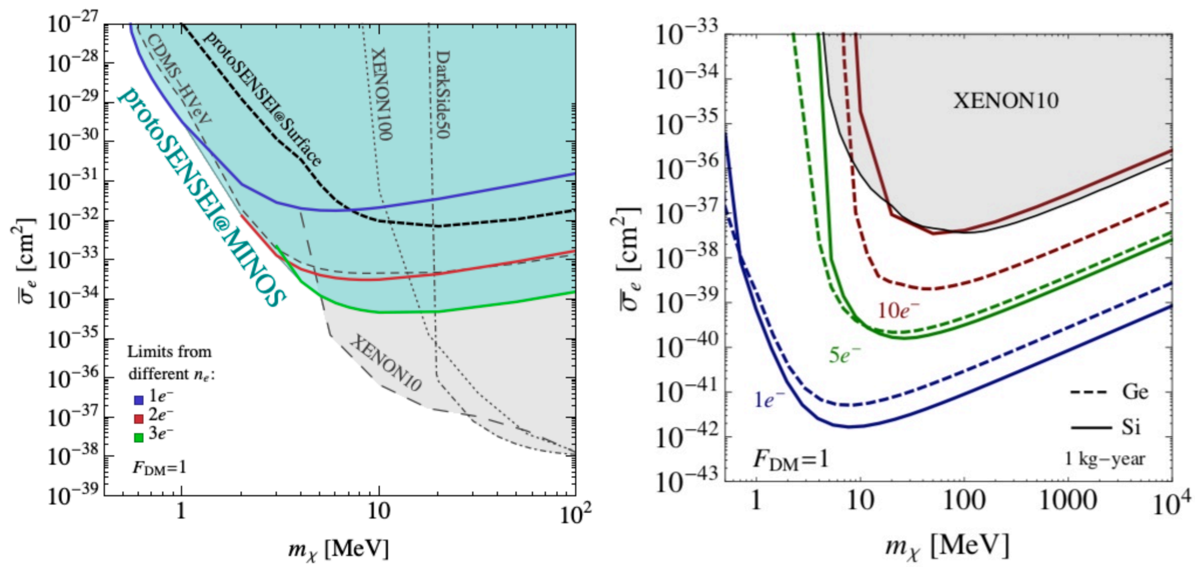


Fig. 8: *Left panel*: A series of recent, world-leading constraints on low-mass dark matter particles from electron-recoil experiments: protoSENSEI Surface (SENSEI Collaboration 2018), SuperCDMS-HVeV Surface (SuperCDMS Collaboration 2018), and protoSENSEI MINOS (SENSEI Collaboration 2019), demonstrating the power of these rapidly maturing techniques to detect sub-GeV dark matter. *Right panel:* Projected reach of solid-state detectors with indicated thresholds, for 1 kg-year of background-free running.

The roles for Fermilab in low-mass dark matter searches described here – both sub-GeV WIMPs and axions – fit well with existing and planned infrastructure and laboratory capabilities. The NEXUS user facility will host a dilution refrigerator in a low-background environment for the development of cryogenic detectors and will provide an excellent testing ground for cryogenic detectors for sub-GeV dark matter. Fermilab is also building the Integrated Engineering Research Center (IERC), with a very significant area dedicated to detector technologies that are key for light dark matter searches, including a 2,500 sq-ft CCD laboratory and a cryogenic lab housing multiple sub-Kelvin cryostats. This multi-project facility will provide infrastructure for the development of next-generation experiments, and there is no similar facility at any other national laboratory. Fermilab is also developing a QIS program to use quantum science technology in HEP and to transfer HEP technology into QIS applications. The Skipper-CCD sensors and much of the planned axion R&D are part of this new quantum initiative, which also includes the development of cryogenic detectors. With these investments in new, state-of-the-art facilities and in quantum sensors, Fermilab's infrastructure and expertise will enable the laboratory to be the leader in future light dark matter searches. The planned program also constitutes a continuing focusing of the dark matter efforts, from four currently (ADMX, LZ, SuperCDMS, Skipper-CCD) to three in FY2020 (when LZ involvement ends) to two by 2025 (axions plus down-select for sub-GeV program).

(3) Accelerator-based experiments and other synergies

As highlighted in the recent Dark Matter Basic Research Needs workshop, fixed-target accelerator experiments offer a potential new approach to probing dark sector particles below the proton mass.

The MiniBooNE-DM collaboration reported the first results from a dedicated search for such particles (MiniBooNE-DM Collaboration 2018), and Fermilab theorists have studied the prospects for parasitic, complementary searches at neutrino experiments such as MicroBooNE, SBN, and DUNE. Fermilab scientists are also playing leading roles in developing the theoretical motivation for and conceptual design of new accelerator-based experiments, an area of rapidly growing interest that is poised to grow in prominence over the coming decade. In particular, they are leading efforts to develop concepts for new electron-beam, fixed-target experiments such as LDMX at SLAC and BDX at Jefferson Lab, as well as a new muon-beam experiment, M^3 at Fermilab, to comprehensively probe models of light dark matter. Other synergistic efforts include MAGIS-100, R&D toward dark photon and axion-like detection with Superconducting RF cavities, and a proposed parasitic dark sector search at the Fermilab SeaQuest Experiment (Berlin, *et al.* 2018). All of this exploratory work is completely supported outside of Cosmic Frontier Research but is included here for completeness and as examples of programs that would exploit the lab's core capabilities.

Collider searches for dark matter are a major focus of the CMS research group at Fermilab, providing a key synergy between the Cosmic and Energy Frontiers. Recently, a working group has been developed with membership from Fermilab's collider, direct detection, and indirect detection communities to discuss how the various techniques can work together to develop optimal sensitivity to dark matter, whatever its nature. This working group plans to organize a workshop later in 2019 on this topic, and such cross-cutting efforts will continue going forward.

There are other interesting opportunities in direct detection dark matter searches that fit well with Fermilab's core capabilities but are not currently part of the lab's focused, long-term plan. An example is a third-generation noble-liquid experiment. A large liquid-Argon detector, such as the one proposed by the Argo Collaboration, would have many technological similarities to the detectors being built for Fermilab's neutrino program, and such a large-scale project would require strong leadership from a national laboratory. Currently, Fermilab is providing modest engineering support for the liquid-argon DarkSide experiment, but this effort is no longer supported by Cosmic Frontier Research. Another example is a recent proposal to use a liquid-Helium detector for low-mass dark matter searches, which would mesh well with Fermilab's sub-Kelvin cryogenic capability. The MINOS facility, which currently hosts NEXUS and SENSEI, would be a natural venue for early physics running and cryogenic R&D for a Helium experiment.

V. Cosmic Surveys

Dark energy and dark matter together make up 95% of the Universe but have yet to be detected in the laboratory. Astrophysical data from cosmic surveys and the CMB currently provide the only empirical evidence for and information about these dominant components of the Universe. Fermilab plays critical roles in three large, DOE-sponsored cosmic surveys targeted at understanding the fundamental physics of the dark sector: the Fermilab-led Dark Energy Survey

(DES), the LBNL-led Dark Energy Spectroscopic Instrument (DESI), and the SLAC-led Large Synoptic Survey Telescope (LSST). Fermilab's technical roles in these surveys stem from several of its core capabilities: (1) precision detector assembly, integration, and testing, (2) development and support of critical operational software infrastructure, and (3) large-scale data processing, handling, and distribution. Fermilab's scientific involvement in cosmic surveys stems from its expertise in probing cosmology with galaxy clusters, gravitational lensing, large-scale galaxy clustering, supernovae, and the structure of near-field systems such as the Milky Way, as well as in photometric redshifts upon which these methods depend. Fermilab's involvement in the next generation of cosmic surveys is guided by the lab's scientific interests in dark energy and dark matter and builds upon the lab's core capabilities. The scientific impact of the cosmic survey program will be significantly enhanced by combining data from different experiments (including future CMB experiments), an area in which the lab has built significant expertise. **Over the next five years, the primary thrust of the Fermilab cosmic surveys program will be to ensure the timely production of world-leading dark energy measurements with DES, while transitioning into core operational and scientific roles in LSST**. Support for DESI will continue into operations but will be scaled back to enable support of other Cosmic Frontier programs. Over a longer timeline, Fermilab will exploit its critical expertise in **R&D to perform pathfinding research for future "Stage V" dark energy experiments.** The Cosmic Surveys effort currently comprises ~6.5 FTE scientists and 3.5 FTE postdocs supported on Cosmic Research in FY19, with another 1 FTE assumed supported by operations.

Dark Energy Survey (DES)

The **Dark Energy Survey (DES)** is currently the world-leading dark energy experiment. As founding and lead lab, Fermilab fulfills leadership roles in the collaboration, operations, and science. The first year of DES data, in combination with CMB data, yielded world-leading constraints on the dark energy equation of state parameter and the cosmological dark matter density through a combination of weak lensing and galaxy clustering measurements (DES Collaboration, 2018a). Early results from the DES supernova program (Fig. 9) provided the best-calibrated supernova cosmology sample to date (DES Collaboration, 2018b), and we have demonstrated the power of combining weak lensing and supernova results from the same experiment (DES Collaboration 2018c). In CY 2019, the collaboration expects to produce cosmology results from the first 3 years of survey data, with final results from the 6-year survey by FY21-22.

During DES operations, which finished in early 2019, Fermilab maintained the DECam instrument; led the design, optimization, and implementation of the DES observing strategy; set priorities for the data management system; led the calibration of the data; and produced high-level science data products used for cosmology. As DES mountain-top operations drew to a close, Fermilab transitioned to providing the resources, infrastructure, and organizational leadership to enable world-leading scientific results on dark energy and dark matter. Fermilab's core capabilities in computing and data management allowed the lab to uniquely tackle the critical infrastructure task of producing large, image-level simulations that are essential to characterize the sensitivity of the survey. Some of the key roles held by Fermilab scientists include DES director, deputy director, data management project scientist, and working group convenor positions in photometric calibration, strong lensing, photometric redshifts, and Milky Way science. The Cosmic Research program at Fermilab currently (FY18) supports 4.7 FTEs scientist and 3.5 FTE postdoc effort on DES, with another ~1 FTE on operations. We expect this effort to ramp down over the next 3 years as the effort on LSST ramps up.

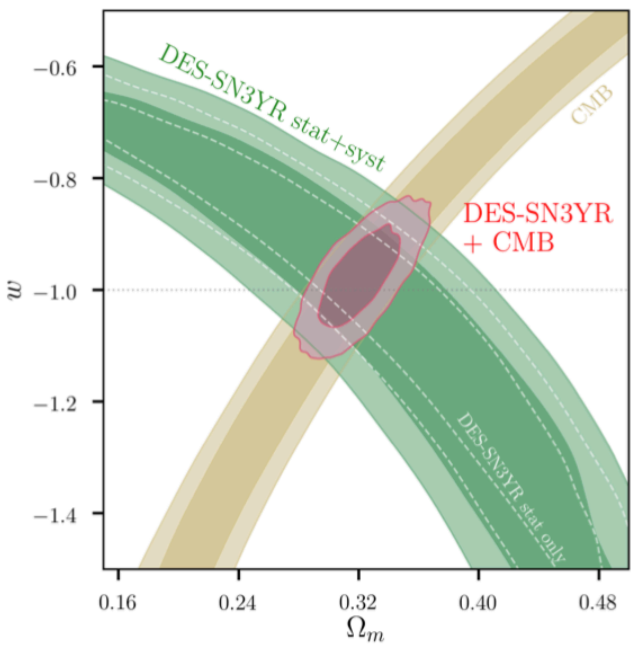


Fig. 9: Constraints on the dark energy equation of state parameter, *w*, and on the matter density of the Universe from the DES 3-year *spectroscopic* supernova data (green) and in combination with Planck CMB data (grey/red) (DES Collaboration, 2018b). Results from the 5-year *photometric* supernova data set (an order of magnitude larger) will deliver substantially tighter constraints, especially in combination with other DES measurements.

Large Synoptic Survey Telescope (LSST)

A primary goal of Fermilab's cosmic surveys program is to transfer critical, hands-on expertise in survey operations, data processing, and scientific validation from DES to **LSST**. Expertise accrued over the last 3 decades of leadership in SDSS and DES will be indispensable for the smooth and successful operation of the dark energy science program with LSST. Fermilab personnel are slated for major roles in the DOE-supported operations plan for LSST as Production Scientists, Computational Facilities Scientists, Observatory Support Scientists, Data Release Systematics Scientist, Scheduler Scientist, and Community Support Scientist. These roles will be primarily supported by the Cosmic Research program. In addition, Fermilab is slated for technical support roles (~8 FTE), primarily in database and systems administration, supported by operations. In addition to the project, the DOE-funded LSST Dark Energy Science Collaboration (DESC) is actively preparing and analyzing simulated scientific data challenges. In support of this DESC effort, Fermilab scientists have accepted roles as Science Pipeline Workflow Architect and co-convener of the Survey Simulations working group, and they have been leading the development of the CosmoSIS analysis framework software. We expect Fermilab's scientific roles in LSST

DESC to grow over the next few years, with matching between the efforts that Fermilab scientists currently lead in DES and those that are evolving in LSST DESC, i.e., galaxy cluster cosmology, strong lensing, photometric redshifts, and photometric calibration. Fermilab scientists are also actively working to extend astrophysical probes of the nature of dark matter from DES to LSST (Drlica-Wagner et al. 2019). These probes provide novel tests of the ΛCDM cosmological model, complementing traditional dark energy probes, and therefore form a key component of LSST DESC's comprehensive 'dark sector' physics program

Dark Energy Spectroscopic Instrument (DESI)

Fermilab has played critical roles in construction of **DESI**, capitalizing on expertise from DECam construction to take on critical roles in packaging and testing the red and near-infrared CCDs for the DESI spectrographs, leadership roles in project construction (co-Project Scientist), and assembly of the mechanical support and alignment of the lenses and the redesign and construction of large mechanical structures on the top end of the telescope (see Fig. 10). Building on SDSS, Fermilab developed software to map fiber positions onto the locations of astronomical targets. Building on expertise from DECam, Fermilab scientists led construction of the DESI instrument control system and online telemetry database. During DESI commissioning and operations, Fermilab will support the fiber-positioning and instrument-control software and build a framework to validate the DESI focus and alignment system. As DESI moves into operations, Fermilab's role will decrease to the support of critical operations at the level requested by the experiment, while maintaining scientific involvement that allows us to capitalize on the lab's position at the nexus of DES, DESI, LSST, SPT-3G and CMB-S4. Continued involvement in DESI will enable better photometric redshift calibration for LSST and the most competitive neutrino mass measurements with CMB-S4. Fermilab currently commits 2.1 FTEs scientist effort and 0.5 FTE postdoc effort to DESI (roughly 2 FTE on Cosmic Research).

Fig. 10: Based on core capabilities and expertise developed in the DECam project, Fermilab played major roles in construction of the outer ring, barrel, cage, hexapod, and ADC rotator for the DESI project (at left), including testing with a state-of-the-art, large-scale coordinate-measuring machine at SiDet.

R&D for Future Cosmic Surveys

Shedding light on the dark sector requires precise tests of the ΛCDM paradigm at increasing levels of precision. Experimentally, this means performing precise measurements of larger samples of fainter and/or more distant astronomical systems. The dark energy community has recognized a pressing need for a large, massively multiplexed spectroscopic instrument to complement and extend the science reach of upcoming photometric surveys such as LSST (Dodelson *et al.,* 2016a; Dodelson *et al.* 2016b; Dawson *et al.* 2018). These next-generation redshift surveys could take on a wide variety of scopes, from a small-scale upgrade of an existing instrument to full-scale construction of a massively-multiplexed instrument on a large-aperture telescope. The roadmap of spectroscopic surveys could include an upgrade of DESI, participation in a spectroscopic instrument led by the astronomical community (e.g., the Maunakea Spectroscopic Explorer; Hill et al. 2018), and ultimately a newly constructed instrument in the southern hemisphere that would constitute a "Stage V" dark energy experiment (e.g., the Southern Spectroscopic Survey Instrument). Whatever form or forms such a future takes, Fermilab anticipates making major technical contributions to the project management, design, and construction of the instrument and is actively pursuing R&D efforts to develop the technology for the associated instruments. On-going work on Microwave Kinetic Inductance Detectors (MKIDs) aims to enable real-time, low-resolution spectroscopic imaging surveys, while the development of ultra-low noise skipper-CCDs could improve the efficiency of low-signal, low-noise spectroscopic observations by a factor of two (see Fig. 11). The lab's mechanical engineering expertise also forms the basis of an R&D program to tackle challenging engineering problems, such as increasing the packing of spectroscopic fibers to enable massively multiplexed instruments. We anticipate that the lab's active R&D program, in part supported by LDRD, will enable Fermilab to continue to lead future cosmic survey programs.

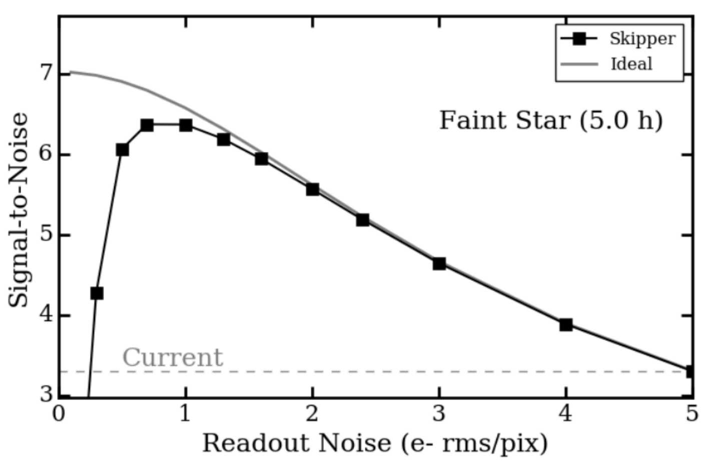


Fig. 11: Projected gain in signal-to-noise enabled by low-read-noise Skipper-CCD technology for a long spectroscopic exposure of a faint source, as expected for a Stage-V spectroscopic dark energy survey.

VI. Theoretical Astrophysics

The Cosmic program at Fermilab began in the early 1980's with the establishment of the Theoretical Astrophysics Group, which focused on using the early Universe as a laboratory to constrain models of particle physics beyond the Standard Model in a way that complements the laboratory's accelerator-based program. The group seeded and then supported and helped guide the lab's experimental astrophysics program, starting with the Sloan Digital Sky Survey (SDSS) and expanding into subsequent cosmic surveys, dark matter detection experiments, the Pierre Auger Cosmic Ray array, and most recently CMB experiment. Members of the Theoretical Astrophysics Group work closely with their observational and experimental colleagues, helping to guide and stimulate the cosmic efforts and playing major roles in motivating, analyzing, and in some cases leading the experiments. The Theoretical Astrophysics Group is integrated within the Fermilab Astrophysics Department, interacts and coordinates closely with the Theoretical Physics Department, and plays important roles in connecting the Cosmic Frontier efforts at the lab to Intensity and Energy Frontier activities. The Theoretical Astrophysics Group is supported by the Theoretical Physics B&R, not by Cosmic Frontier Research; it currently includes 4 FTE scientists and 2.5 FTE postdocs.

Current and recent research activities of the group include dark matter model-building (informed by direct, indirect, collider, and fixed-target experiments); numerical cosmology (which supports probes of dark matter and analysis of surveys); neutrino astronomy (e.g., models for sources of high-energy neutrino flux); and the early universe (inflation, baryogenesis, neutrino decoupling, dark matter production). Anticipated areas for near-future investigation also include motivation and conceptual design of dark matter searches in accelerator experiments (see Sec. IV); analysis of cosmic surveys (DES, LSST, DESI, plus the CMB) to constrain models of dark matter, dark energy, and neutrinos; the impact of dark matter interactions on the early Universe, recombination, and the dark ages; and neutrino cosmology and phenomenology (the impact of neutrino mass on structure formation, interactions with dark matter, constraints on sterile neutrinos, etc).

In the latter vein, Fermilab's major experimental investment in neutrino physics has created the need for and opportunity to strengthen connections between Theoretical Astrophysics, Cosmic experiments, and Intensity Frontier research. With this in mind, we are developing plans to launch a Cosmic Neutrino Initiative, which will bring together members of Fermilab's Theoretical Astrophysics, Theoretical Physics, Cosmic, and experimental neutrino physics communities to develop and exploit the synergies between these efforts. Of particular importance are measurements of cosmic large-scale structure (with DES, DESI, and LSST) and the cosmic microwave background (SPT-3G, CMB-S4), which will provide powerful probes of the sum of the masses of the three Standard Model neutrinos (see Fig. 4), as well as tests for other (sterile) neutrino species that may have been present in the period leading up to recombination. This information is both highly informative and complementary to the laboratory-based neutrino program being carried out at Fermilab. To kickstart this activity, we plan to host a Cosmic Neutrino Workshop in late 2019 aimed at bringing these communities together.

With the recent departure of Scott Dodelson (now Head of the Physics Department at Carnegie Mellon) and promotion of Josh Frieman (to Head of the Fermilab Particle Physics Division), the Fermilab Theoretical Astrophysics Group is now significantly smaller than it has been historically. As recognized in the 2018 DOE Laboratory Theory Program Comparative Review and in the subsequent Fermilab PAC report, these changes provide an opportunity to reinvigorate the group and to align the activities in Theoretical Astrophysics with the experimental and observational cosmic efforts being carried out at the lab, as well as with Fermilab's broader experimental program. An Associate Scientist hire was recently made (Gordan Krnjaic) who strengthens the connections with the dark matter, neutrino, and Theoretical Physics efforts at the lab. A second hire is anticipated, with preference for a junior or senior scientist who can strengthen the connections between the astrophysics and neutrino efforts.

VII. Cosmic Physics Center

In the Cosmic Plan laid out here, the future program is increasingly focused around fewer core activities within the three major thrusts: CMB, Dark Matter, and Cosmic Surveys. While the Theoretical Astrophysics efforts provide important connective tissue between these *within* the lab, we believe that a **Cosmic Physics Center** (CPC) will enable and energize connective activities for the broader, DOE-supported *cosmic user community,* enhancing the productivity of the U.S. cosmic program. Following the successful Fermilab models of the LHC Physics Center and the Neutrino Physics Center, the Cosmic Physics Center will serve the growing cosmic user community – which currently comprises roughly 100 annual on-site users, with over 700 cosmic users of Fermilab computing facilities – by hosting visiting scientists and graduate students in a range of activities.

We envision the Cosmic Physics Center program as encompassing several classes of activities:

1) Targeted workshops to accelerate the pace of research, bringing key researchers together to stimulate new developments. Fermilab has a tradition and the capability of rapidly organizing and hosting small workshops in fast-moving areas; a key feature of the cosmic workshops will be to involve users in organizational leadership and to enable users to propose workshop topics that are aligned with our program.
2) Host and modestly support visiting scientists and students to enable cross-cutting analyses of cosmic experiments. As noted above, an increasingly important feature of cosmic research is exploiting synergies between different experiments and probes to optimally extract maximum fundamental physics information from them. The CPC will bring together small groups of users and Fermilab scientists to enable joint analysis and cross-correlation of cosmic experiments, e.g., combining SPT-3G or CMB-S4 with DES, LSST,

or DESI data to extract more precise, robust dark energy constraints from galaxy clusters and from weak gravitational lensing. As another example (see Sec. IV), the CPC will bring together community researchers to develop a consistent framework for combining multiple probes of dark matter from colliders, direct detection, indirect detection, and astrophysics measurements. Such a coherent approach will help to optimize the future dark matter detection program.

3) The Cosmic Neutrino Initiative (see Sec. VI), a cross-cutting activity that will bring together cosmic and neutrino experimentalists with theoretical astrophysicists and particle physicists to similarly develop a coherent framework for constraining neutrino physics through multiple probes, is also envisioned as a broader community effort nucleated at the lab, and therefore will naturally live in the CPC. Activities in classes (2) and (3) will rely critically on Fermilab's core capabilities in computing to enable large-scale data analysis by the user community across the Cosmic, Intensity, and Energy frontiers.
4) Exploiting the lab's core capabilities in detector development, the CPC will develop programs that bring early career scientists to the lab, either individually, in small groups, or in summer schools, for hands-on training in hardware and detector development. To date, the lab has developed the capability for such training through informal programs, primarily bringing students from South America for extended traineeships who come with their own fellowships. The CPC will enable the lab to extend this highly successful model to a broader community of cosmic students and postdocs.

In addition to serving the national community, the CPC will serve as a mechanism to develop and strengthen the cosmic synergies and connections between Fermilab and key local institutions, particularly ANL, the University of Chicago, and Northwestern, and thereby realize the tremendous potential of the Chicagoland cosmic community. Several Fermilab cosmic scientists have joint, part-time, or primary appointments at U. Chicago or Northwestern, and there are strong collaborative efforts among these institutions in CMB, dark matter, cosmic surveys, and theory. Going forward, the new CASE program at U. Chicago will enhance professional ties between Fermilab scientists and the University, the University and the lab are discussing pursuing joint positions in strategic areas, and they are committed to fostering greater support for U. Chicago graduate students to carry out research at the lab. As noted in Sec. III, we anticipate that the CMB-S4 project will involve close collaboration between Fermilab, ANL, and U. Chicago, building on the successful coordination developed for SPT-3G. More broadly, the CPC will foster collaboration with the other national labs and with other efforts in Quantum, Intensity, and Energy.

VIII. Summary and Conclusions

Over 35 years, Fermilab has developed a vibrant Cosmic program that has yielded key advances in cosmological theory, dark matter, and dark energy. These advances have been made possible by a remarkable array of core technical capabilities, a number of which are unique or world-leading within the national laboratory system. As the laboratory's Intensity Frontier program enters an exciting new period of growth, and the Energy Frontier program supports the CMS high-luminosity upgrades at the LHC, we have undertaken an in-depth look at the Cosmic Frontier program and defined priorities for its future.

The resulting Cosmic Strategic Plan builds on Fermilab's core capabilities, delivers on the lab's commitments to on-going experiments and projects, is well-aligned with DOE OHEP and community (P5) science priorities, is designed to serve a growing cosmic user community, and aims to foster synergies with research on the Intensity and Energy Frontiers and in Quantum HEP science through cross-cutting efforts, particularly in dark matter and neutrinos. The Plan aims at major/leadership roles in CMB and axion experiments as the highest priorities, efforts that are slated for growth in all scenarios. The other elements of the plan are support for SuperCDMS and LSST operations and R&D toward a next-generation sub-GeV dark matter experiment and spectroscopic dark energy survey. The levels of effort on these other elements will depend on available resources; flat or declining scenarios require trade-offs among them, with associated risks to those parts of the program. The program will be strengthened by the Theoretical Astrophysics group, with a growing focus on cosmic neutrinos, and by the Cosmic Physics Center, which will serve the cosmic user community through workshops, hands-on detector training, and community exploitation of the lab's computing facilities. Fig. 15 provides a schematic timeline for Fermilab activities within the 3 thrusts of CMB, dark matter, and cosmic surveys.

An important goal of this planning exercise was to define a *focused* set of activities that make optimal use of the lab's capabilities and in which the lab can make critical contributions. Indeed, the Cosmic program is already more focused than it was just two years ago, as the lab is no longer scientifically involved in DAMIC, PICO, DarkSide, or the Holometer, and the efforts on LZ and DESI are in the process of ramping down. Moreover, to maintain a focused program, we have decided not to pursue other potentially exciting avenues, such as 21cm surveys, in the foreseeable future. At the same time, we believe it is important for the program and this Plan to remain flexible, so that we can respond in a timely manner to new opportunities and a changing landscape. A hallmark of the Fermilab program, which helps enable such flexibility, is the strong and growing leverage of Cosmic Research support by other programs, including R&D, LDRD, Early Career Awards, Theoretical Physics Research, and private foundation support. We will continue to vigorously pursue these opportunities and develop partnerships with other institutions to strengthen the program.

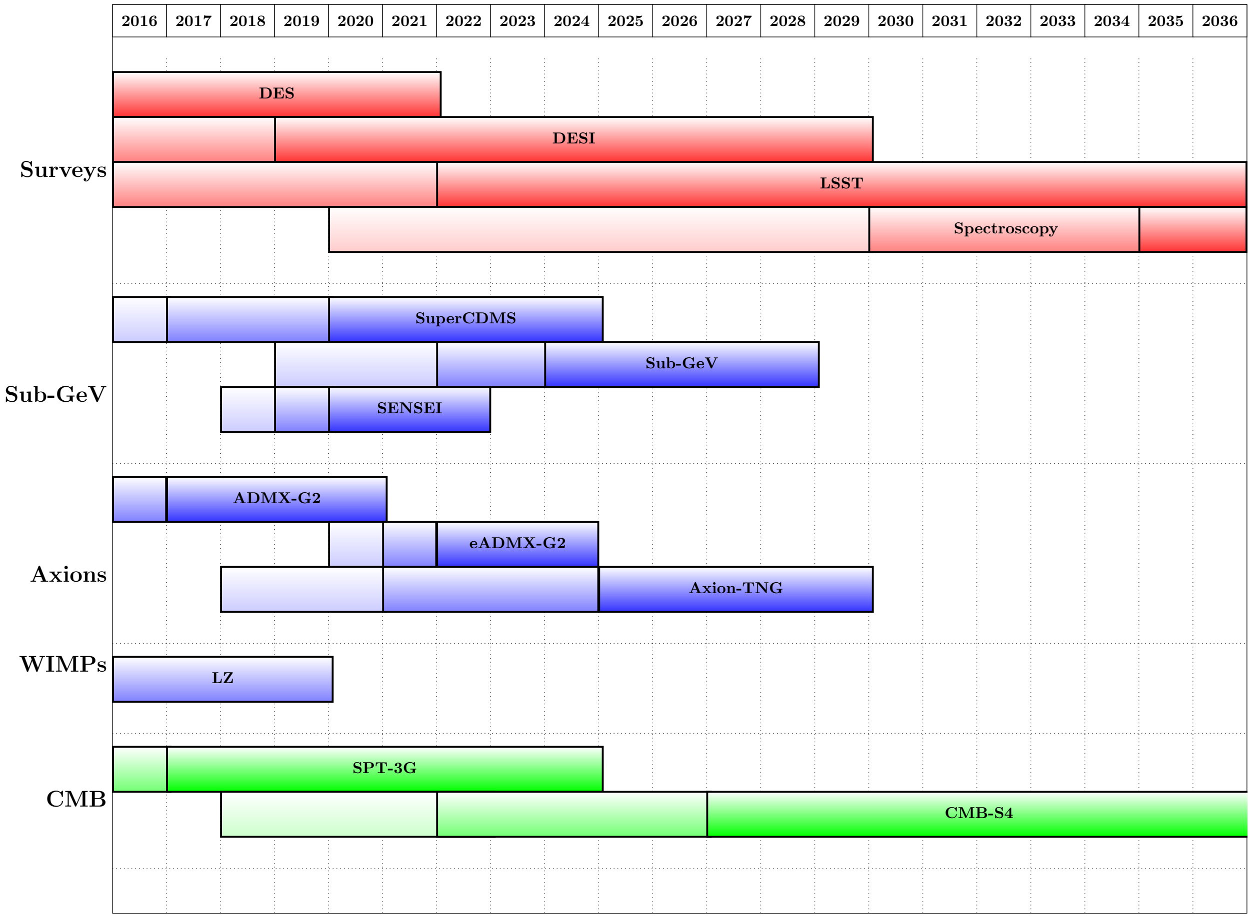


Fig. 15: Approximate timeline for Fermilab activities in cosmic surveys (red), dark matter detection (blue), and CMB (green). For each activity, light shading corresponds to the R&D phase, medium shading to the construction phase, and dark shading to data-taking and analysis. "Sub-GeV" denotes a next-generation dark matter experiment based on either the SuperCDMS/HVeV or Skipper-CCD technology. "eADMX-G2" corresponds to an upgrade of ADMX to reach 4 GHz frequency, and "Axion-TNG" is a next-generation axion experiment based on quantum detector technology. The LZ effort at Fermilab stops when its deliverables for the construction project are completed.

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