Elements:
Improving tools based on data-description standards for gigabyte-scale data sets

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Project Summary

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Overview: The long-term goal of this work is to build and create community buy-in for a set of tools for the nuclear physics community to access binary data. The intent is to address one piece of a common software need in the community that is repeatedly solved in isolation and that costs the entire community unnecessary time and limits access to data and science. In pursuit of this goal, this proposal has four objectives: (1) Define a data-description language that allows scientists to describe any binary data format. (2) Improve existing software that automatically builds a convenient data-access library for any user-described data so that it works well with gigabyte-scale datasets. (3) Build community and support adoption of these community tools. (4) Increase access to analysis of original scientific data sets for undergraduate students, graduate students and postdocs, early career researchers, and scientists whose labs do not have access to dedicated software support. These objectives will be met as follows:

(1) Defining a data-description standard: The PI will use two already-existing standards that both have broad user support, DFDL and Kaitai-Struct. Kaitai-Struct will be used and where necessary further defined as the software created around this standard is better-suited to the needs of data analysis.

(2) Improving standards-based analysis software: Scientists who wish to generate a convenient library that allows them to read custom-format data can already do so using the existing Kaitai software. However, this software has poor performance in python for files larger than a gigabyte and this significantly limits the usefulness of this software to the nuclear physics community, particularly as data acquisition systems move to storing digitized pulses rather than pre-processed data. The PI proposes to create another Kaitai target that allows scientists to auto-generate a library that targets the awkward-array interface built and maintained by the IRIS-HEP collaboration. This data structure is designed to give rapid data-analysis access to the high energy physics community and is routinely tested on data sets that exceed several hundred gigabytes.

(3) Building community: The PI proposes to hold yearly workshops to bring together developers and scientists for training, user feedback, and software development. In addition, the PI has requested funds for graduate and undergraduate stipends and travel awards to foster community participation.

(4) Increasing Access: Many students who have the interest and ability to participate in science analysis are blocked by a lack of training in scientific computing. The often-complex scientific computing ecosystem is poorly represented in most physics curriculum and even computer science courses do not usually prepare students for the variety of systems they need to navigate to do typical data analysis. The PI requests funding for undergraduate students to develop and test documentation and training materials for fundamental scientific computing concepts and skills in addition to testing the documentation for the standards-based analysis tools.

Intellectual merit: This grant supports the science effort of a dark matter experiment, the SuperCDMS experiment, and the broader nuclear physics community that is in need of software support. At present this includes scientists working on the origin of the elements in the universe, fundamental symmetry testing, and detector testing for improved threat detection.

Broader impacts: The PI proposes this work because it would be immediately useful to her dark matter work and because software supported by an entire community that can provide easy

Project Summary

access to any data format would meet an increasingly-urgent need of communities dealing with gigabyte-scale data.

Focusing previously-isolated software efforts on a community solution offers the benefit of software that is well-tested and well-documented and with a community that can provide support for its users.

With materials available to help students and new researchers learn the basic skills required for science analysis, students can begin participating in true science research at much earlier stages, with less reliance on patient, local expertise being available at their institution. Right now, real science analysis is at best painfully accessible to a narrow set of students. With a small set of community standards and tools, we can broaden science access to a much wider group of individuals and increase the time expert scientists can spend on actual science.

Contents

1 Introduction (1 page)

[EFF: A lot of this text may not be needed as it mirrors the 1-page summary] The long-term goal of the SuperCDMS SNOLAB collaboration is to improve the understanding of dark matter by answering the following questions: what are its constituents, what are their particle and astrophysical properties, and how do they relate to the Standard Model? In pursuit of this goal, this proposal has four objectives: (1) Perform necessary calibration and performance measurements of SuperCDMS SNOLAB detectors to maximize the science return from the experiment. (2) Commission and operate the SuperCDMS SNOLAB experiment. (3) Measure a dark matter signal or place world-leading limits for the dark matter–nucleon cross section at masses below 10 GeV/c^2. (4) Train the next generation of scientists through research and outreach activities, and teach secondary students and the public about dark matter science. These objectives will be met as follows:

Experiment Characterization and Optimization: In order to maximize the science output of SuperCDMS SNOLAB, detailed understanding of the response of detectors to potential signals and backgrounds is required. Measurements at two underground facilities (NEXUS at Fermilab and CUTE at SNOLAB) will characterize and calibrate pre-production SuperCDMS SNOLAB detectors and the first production SuperCDMS SNOLAB towers, with supporting measurements from small devices at university test facilities. This data will allow energy scale calibration, measurements of background levels, understanding of the detailed phonon and electron physics of the detectors, and optimization of SuperCDMS SNOLAB operational parameters.

Commissioning and Operation of SuperCDMS SNOLAB: This proposal will fund the NSF-portion of commissioning the SuperCDMS SNOLAB experiment and the first year of science operations.

First SuperCDMS SNOLAB Science: This proposal will perform a dark matter search with world-leading sensitivity using data taken with one SuperCDMS SNOLAB Tower at CUTE and with the first data set from the full SuperCDMS SNOLAB experiment.

Training and Outreach: The activities in this proposal provide fertile ground for training of post-doctoral researchers and graduate students from the SuperCDMS collaboration, and opportunities to share the excitement of science with the general public.

Intellectual merit: This grant supports an experiment that will address one of the most fundamental problems of modern science, the nature of dark matter, in a way complementary to the Large Hadron Collider and indirect detection experiments. The SuperCDMS SNOLAB experiment will achieve world-leading sensitivity for dark matter masses less than 10 GeV/c^2.

Broader impacts: The SuperCDMS SNOLAB experiment will have a broad impact which extends beyond the search for dark matter. The experiment's phonon-mediated detectors have applications in cosmology, astronomy and industry. This effort will contribute opportunities for training of undergraduate and graduate students and postdoctoral researchers.

SuperCDMS will engage in education and outreach at local institutions and will coordinate our outreach at Soudan, SNOLAB, and SURF to increase the broader impact with focus on secondary education. The grant will support participating in SNOLAB-hosted Teacher Workshops, modifying and providing middle school dark matter education modules to U.S. educators, and maintaining SuperCDMS-related outreach materials for SNOLAB, Soudan, and SURF. Existing alliances will enable outreach to Sudbury First Nations communities. This effort will also support post-graduate education by providing speakers for Colegio de Física Fundamental e Interdiciplinaria de las Ámericas summer school in Puerto Rico.

This paragraph needs updating: The activities in this proposal are fully coordinated with the SuperCDMS collaboration in general, and its DOE and Canadian-supported institutions. This NSF proposals is tightly coordinated with two R&D proposals titled "SuperCDMS R&D Toward the Neutrino Floor" that have been awarded from the DOE KA23 and KA25 programs by Fermilab and SLAC respectively. This proposal is also coordinated with the DOE SuperCDMS SNOLAB Experimental Operations Plan.

This collaborative proposal subsumes most of the work done by the NSF institutions on SuperCDMS SNOLAB. This includes all calibration, characterization, commissioning, operation, analysis, and publication efforts. It also includes support for students, postdocs, and scientists that would have normally been funded through separate "base" proposals by each member institution. This support and expertise from university groups will be instrumental in turning the data products from the SuperCDMS SNOLAB experiment into fully vetted scientific results and publications. In addition, this proposal provides fertile ground for training graduate students and postdocs through their participation in the data taking and analysis.

This paragraph needs to be added after we do decide on the sections This project description is organized as follows. Sections 1.1–3 summarize the science and hardware of the SuperCDMS SNOLAB experiment. Section 6 describes the underground facilities to be used in the pre-operations portion of this proposal. Section 7 describes the plan of work of this effort, and Section 8 describes the schedule. Section 9 gives an overview of the management for this proposed grant, and Section 10 describes the broader impacts of the work. Finally, Section 11 summarizes the results from previous support.

1.1 Introduction

[EFF: This should be trimmed and incorporated into either the project overview or the science section] A critical research area in particle astrophysics is the search for the nature of dark matter. Dark matter, unlike ordinary matter, does not produce electromagnetic radiation and its only observed interaction with ordinary matter thus far has been gravitational. Its existence explains flat rotation curves of spiral galaxies, structure formation and galaxy cluster evolution, and the anisotropy of the cosmic microwave background. These astronomical observations indicate that approximately 85% of the matter in the universe must be dark matter, but they do not tell us much about its composition. A long-favored hypothesis is that a class of elementary particles generically labeled as WIMPs (Weakly Interacting Massive Particles) constitutes the dark matter. However, an absence of evidence for a heavy mass WIMP at the LHC and in direct detection dark matter experiments has motivated the development of a wide array of alternate theories which predict dark matter particles with masses between 1 MeV–10 GeV.

Determining the fundamental nature of dark matter is a high priority science objective for the National Science Foundation (NSF) and the DOE Office of High Energy Physics (OHEP). It is also a major focus for science in Canada, with support from the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Canada Foundation for Innovation (CFI).

The SuperCDMS collaboration has conducted a series of experiments designed to directly detect dark matter in underground laboratories, using ultra-pure germanium (Ge) and silicon (Si) crystals outfitted with ionization and phonon sensors and operated at cryogenic temperatures. For most of the last two decades, CDMS experiments at Stanford and Soudan have provided leading sensitivity to high-mass WIMPs. Recently SuperCDMS has focused on < 10 GeV/c^2 dark matter candidates, where our technology has unique advantages given the low energy thresholds provided by their athermal phonon sensor technology and Luke-Neganov phonon amplification techniques for ionization.

The NSF and DOE have jointly chosen SuperCDMS SNOLAB as the next-generation project to search for low-mass dark matter. The project is going through the DOE Critical Design (CD) review process and is expected to be complete in 2019. Canada is also supporting SuperCDMS SNOLAB via NSERC and CFI funding. The experiment will be located at SNOLAB, in Ontario, Canada, the deepest underground laboratory in North America.

2 Science (4 pages)

[EFF: Scrub this to be more focused on sub-10GeV dark matter] An abundant amount of evidence supports the existence of dark matter at all scales in the Universe [1]. Although its nature is still unknown, particle dark matter provides the clearest evidence for physics beyond the Standard Model of particle physics, and thus its detection and identification constitute one of the greatest challenges of modern physics. Phenomenology at the intersection of particle physics, cosmology, and astrophysics provides a wide spectrum of viable dark matter candidates that exhibit very different properties. For example, their mass can differ by many orders of magnitude, ranging from 10^{-15} eV/c^2 (in the case of hidden photons) to 10^{16} GeV/c^2 (for Wimpzillas). Also, their interaction with ordinary matter can be purely gravitational (as in the case of gravitinos) or involve a new interaction scale.

One long-standing favored candidate for particle dark matter is the Weakly Interacting Massive Particle (WIMP), a stable particle with weak-scale interactions that is naturally produced in supersymmetric extensions to the standard model that explain the light mass of the Higgs boson [2, 3, 4, 5, 6, 7] and that can be thermally produced in the early universe in the right amount to account for the observed dark matter relic abundance.

In response to the lack of experimental evidence for WIMPs at the LHC or in direct detection experiments, multiple alternative models have recently been developed that have dark matter candidates with masses within the MeV–10 GeV range [8, 9, 10, 11, 12, 13, 14]. Hidden sector super-symmetric dark matter models, for example, have an extremely small coupling to the visible sector, and thus their production in accelerators and their CMB annihilation signature would be suppressed. The lack of an annihilation signature in the CMB is also quite natural in a broad class of asymmetric dark matter theories where the measured relic density of dark matter is not due to annihilation freeze out, but rather due to an antimatter-matter asymmetry in dark matter production.

2.1 Direct Detection of Light-Mass Dark Matter

Under many of these theoretical models, dark matter within the local galactic halo can be directly probed via their elastic scattering off nuclei in a terrestrial detector [15, 16]. Even with the enhancement due to coherent scattering off a large number of nucleons when using high Z targets like germanium, the expected signal rate is quite low, less than 0.01 event/kg-day [17, 18]. As such, direct detection detectors must be housed deep underground for protection from cosmic rays and fabricated using radioactivity-free materials.

Furthermore, the large mismatch in mass between GeV-scale dark matter and these preferred heavier nuclei dictates that four-momentum transfer to the nucleus is very inefficient in elastic recoils. As an example, the characteristic nuclear recoil energy scale for a 1 GeV/c^2 dark matter

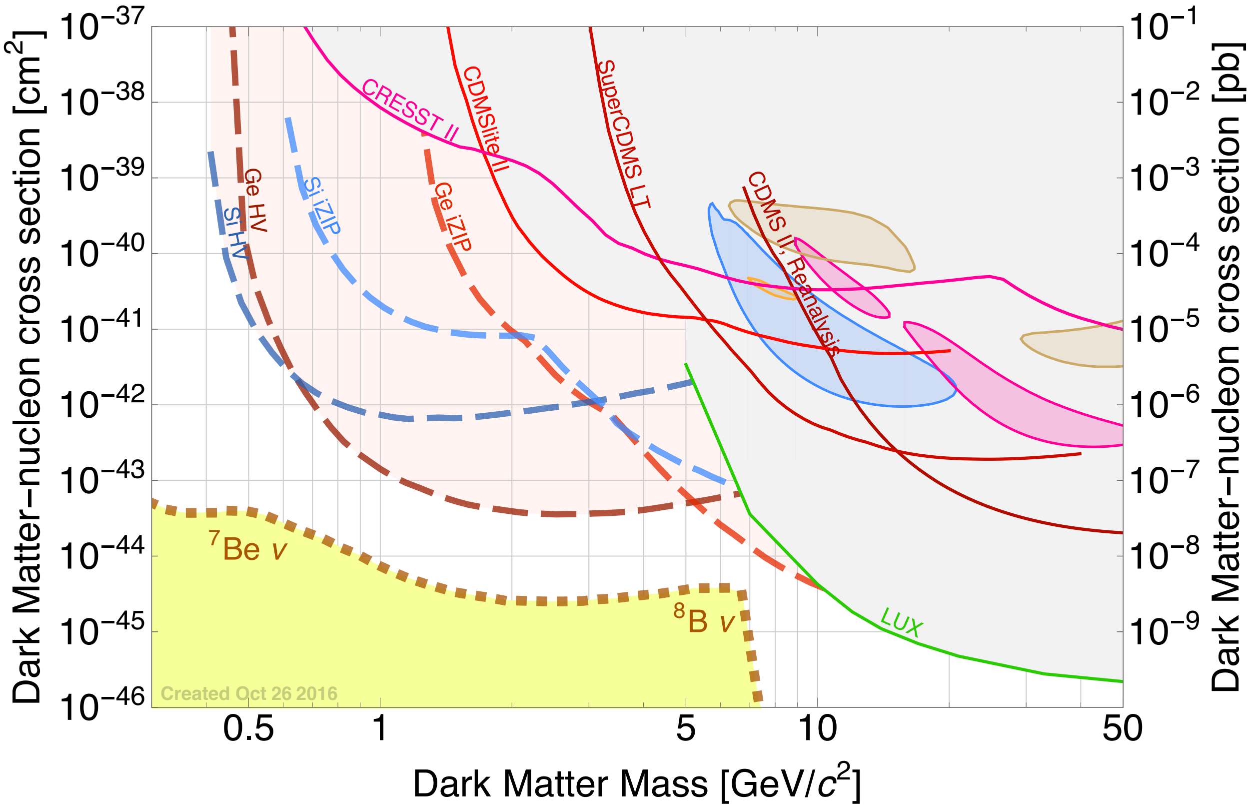

Figure 1: Projected exclusion sensitivity for the SuperCDMS SNOLAB direct detection dark matter experiment [19]. The vertical axis is the spin-independent dark matter-nucleon cross section under standard halo assumptions [18], and the horizontal axis is the dark matter mass, where dark matter is used to mean any low-mass particle dark matter candidate. The blue dashed curves represent the expected sensitivities for the Si HV and iZIP detectors and the red dashed curves the expected sensitivities of the Ge HV and iZIP detectors. These sensitivity limits are determined using the Optimum Interval method [20], which does not incorporate any knowledge of the specific disposition and source of background events observed during the experimental operation. The solid lines are the current experimental exclusion limits in the low-mass region, from the CRESST-II [21], SuperCDMS [22, 23] and LUX [24] experiments. The dotted orange line is the DM discovery limit from [25], which represents the cross-section at which the interaction rate from dark matter particles becomes comparable to the solar neutrino coherent elastic scattering rate.

particle interacting with Ge is ∼30 eV. Thus, the second experimental requirement for light-mass dark matter searches is the use detection technology with sensitivity to very small nuclear recoils.

2.2 Experimental Landscape in Direct Detection

Over the past two years, the SuperCDMS collaboration has lead the field in the search for low-mass matter (< 10 GeV/c^2). The most recent results from CDMSlite, a mode where the cryogenic germanium detectors are operated at a relatively high bias voltage to amplify the phonon signal reached an energy threshold for electron recoils as low as 56 eV. Based on 70 kg-days of exposure, these results excluded new parameter space for the dark matter-nucleon spin-independent cross section for dark matter masses between 1.6 and 5.5 GeV/c^2. In 2014 the collaboration released results from the first SuperCDMS analysis focused on searching for low mass dark matter using the iZIP detectors. At the time of publication, this result lead the field. These results are highlighted in Figure 1.

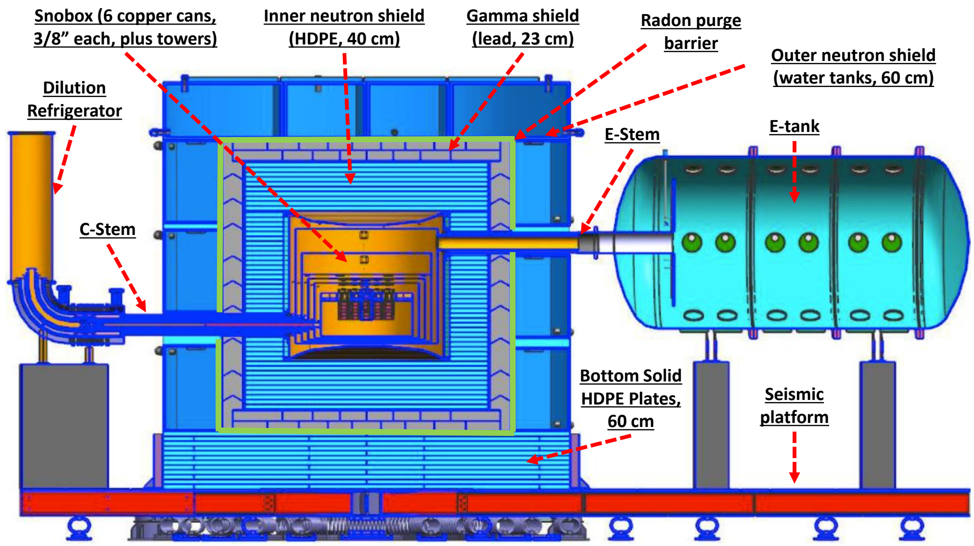

Figure 2: Schematic of the SuperCDMS SNOLAB experiment. The detectors reside within the inner can of the copper cryostat, and are shielded from the environment. A gamma shield protects from external gamma-rays and the inner polyethylene layers serve to absorb radiogenic neutrons emitted from the cryostat and gamma shield. The outer water tanks provide protection from external neutrons. The assembly rests on top of a seismic platform to provide isolation from seismic events.

Several collaborations (using different target materials and techniques) have reported potential signals of low-mass dark matter. In particular, an annual modulation in the detection rate was observed by the DAMA/LIBRA collaboration using NaI(Tl) [26, 27]. Also, CoGeNT [28, 29, 30] (using a germanium target) and CDMS II [31] (with data from the Si detectors) have excesses in their data that are compatible with light dark matter with a mass of the order of 10 GeV/c^2. These observations are challenged by the negative results obtained by other experimental collaborations. XENON10, XENON100, LUX [32, 33, 34] (based on Xe), the above mentioned germanium-based CDMS II, EDELWEISS [35], and SuperCDMS Soudan [36, 22], as well as KIMS (with CsI), CRESST [37] (with $CaWO_4$), PICASSO [38] (with C_4F_{10}), PICO 2L [39] (with C_3F_8), SIMPLE [40] (with C_2ClF_5) and COUPP [41] (with CF_3I) have obtained negative results, setting more stringent upper bounds on the dark matter-nucleon cross section. Figure 1 illustrates the experimental landscape for the dark matter-nucleus spin-independent scattering cross section as a function of the dark matter mass.

3 SuperCDMS SNOLAB (2 pages)

The SuperCDMS SNOLAB experiment will be a next-generation direct dark matter search specifically designed to explore the low mass (< 10 GeV/c^2) dark matter region, with ultimate sensitivity to dark matter-nucleon cross sections where solar neutrino-nucleus scattering becomes significant (the so-called neutrino floor). The SuperCDMS SNOLAB G2 Project is being designed to provide a shielded, ultra-low-background cryostat capable of housing up to 31 towers of solid state cryogenic detectors.The SuperCDMS SNOLAB Project baseline is outlined in Table 1. The experiment will include a mixture of detectors composed of cylindrical germanium (Ge) and silicon (Si) crystals, 100 mm in diameter and 33.3 mm thick. Each Ge(Si) crystal will have a mass of 1.39(0.61) kg. The detectors will be stacked into four towers of six detectors. Two towers of detectors will be

	iZIP		HV	
	Ge	Si	Ge	Si
Number of detectors	10	2	8	4
Total exposure (kg·yr)	56	4.8	44	9.6
Phonon resolution (eV)	50	25	10	5
Ionization resolution (eV)	100	110	–	–
Voltage Bias (V)	6	8	100	100

Table 1: The anticipated exposures and detector parameters for the SuperCDMS SNOLAB experiment. The exposures are based on 5 years of operation (from 2020–2024) with an 80% live time. The quoted phonon energy resolutions represent the r.m.s. values of the total measured quantity (*i.e.*, combining all active sensors). The quoted ionization resolution is derived from the readout electronics equivalent noise charge value of 33e and represents the r.m.s. energy resolution of a single channel for electron recoils.

operated in the ultra-low-energy threshold high-voltage mode (HV), providing the best sensitivity for dark matter masses below 5 GeV/c^2 [23]. An additional two towers of germanium and silicon detectors will be operated in standard (iZIP) mode. These detectors will provide better sensitivity in the 5–10 GeV/c^2 mass range due to their capability to discriminate between electron-recoil and nuclear-recoil interactions [22]. The anticipated exposure and detector parameters for SuperCDMS SNOLAB can be found in Table 1.

The detector towers will be cooled to 15–30 mK using a dilution refrigerator and cryocoolers. The cold region of the full experiment, referred to as the SNOBOX, consists of 6 cylindrical copper cans suspended by Kevlar ropes. In the design, the SNOBOX is surrounded by a 40 cm thick layer of polyethylene to moderate and absorb neutrons produced by radiogenic contamination, and to provide a shield from external neutrons. This inner polyethylene layer is surrounded by a 23 cm thick gamma shield made from low-activity lead. The lead shield layer is surrounded by a thin metal shield to block radon (Rn) diffusion into the inner shielding layers. This volume will be purged with boil-off nitrogen gas to reduce the overall Rn levels and the backgrounds caused by prompt Rn daughters. The outermost shield layer consists of polyethylene and water tanks that provide additional shielding from the cavern neutron flux. A schematic of the experiment shield and cryostat layers can be seen in Fig 2.

The large cryostat and passive shield provide the capability to expand the detector mass to the necessary level that would allow full exploration of the low-mass dark matter parameter space down to dark matter-nucleon cross sections where solar neutrino-nucleus scattering becomes significant. This could be accomplished through a combination of SuperCDMS detector tower upgrades and incorporation of similar detectors from the EURECA collaboration.

4 Plan of Work (10 pages)

4.1 Into (1.5 pages)

5 Experiment Performance, Calibration, and Optimization

5.0.1 Detector Performance (1.5 pages)

5.0.2 Detector Calibration (1.5 pages)

5.0.3 Detector Optimization (1.5 pages)

5.0.4 Background Studies (1 page)

6 Underground Test Facilities

A large part of this proposal is to perform critical measurements that require lower background environments than what has been available at our collaboration's surface test facilities. When operated at the surface, large cryogenic detectors can become swamped with cosmogenic background. Detailed detector performance properties, such as their discrimination power and behavior in the actual experimental environment, cannot be tested at surface facilities.

In this section we introduce two new underground sites that will be central to a large fraction of this work. The Cryogenic Underground TEst facility (CUTE) is being built by the SuperCDMS group at Queen's University and will be situated at SNOLAB. The Northwestern EXperimental Underground Site (NEXUS) is being built by the Northwestern University group and will be located in the MINOS near-detector hall at Fermilab.

At the core of each facility is a cryogen-free dilution refrigerator equipped with special provisions to minimize the level of vibrations that may be introduced by the pulse tube cooler that provides the cooling down to 4 K. Both refrigerators provide a large cold volume that can house a SuperCDMS tower with a full complement of 6 detectors, and both are surrounded by a passive shield to lower radiogenic backgrounds. The two facilities are complementary. With a target background rate of ∼2 events/keV/kg/day, CUTE will offer lower overall backgrounds and radon mitigation, allowing for production SuperCDMS SNOLAB towers to be installed and tested. It is a low-background facility fully capable of cutting edge science. With a target background rate of ∼100 events/keV/kg/day, NEXUS is better described as a prototyping and R&D facility, with less stringent background controls but more flexibility in its configuration and accessibility. Both still qualify as low-background environments when compared to surface facilities, which have a background rate of $\sim 10^4$/keV/kg/day. This is why a number of calibration and detector characterization studies can be performed at NEXUS and CUTE that would be difficult or impossible to perform at a surface installation.**[MP: There is no discussion of nuclear recoil backgrounds]**.

[MP: Shouldn't we say that wiring / readout / grounding schemes / DAQ for these underground facilities is identical to that of SuperCDMS. A huge part of our argument is that work at these 2 facilities minimizes commissioning time of SuperCDMS SNOLAB]

6.1 CUTE

The CUTE facility will be located in the Ladder Lab at SNOLAB, next to the SuperCDMS experiment. The cosmogenic background is therefore negligible, making the radiogenic backgrounds at CUTE dominant. The dilution refrigerator will be placed inside a dry-well in the center of a water tank with a diameter of about 3.7 m and a height of about 3.2 m. The water acts as shielding material against external gamma and neutron radiation **[MP: it's ultrapure water sourced from SNO right?]**. The water layer thickness is about 1 m on the bottom and 1.5 m on the sides. The dry-well and the refrigerator itself generate an opening in the shielding on the top of the setup. Early Monte Carlo simulations for such a setup indicate an external gamma rate of order of 100 events/keV/kg/day, strongly dominated by gammas entering directly from the top. In order to reduce the external gamma ray flux, and to protect the detectors from radiation that may originate from the dilution unit of the refrigerator, a 15 cm thick disk of lead is mounted inside the refrigerator, between the

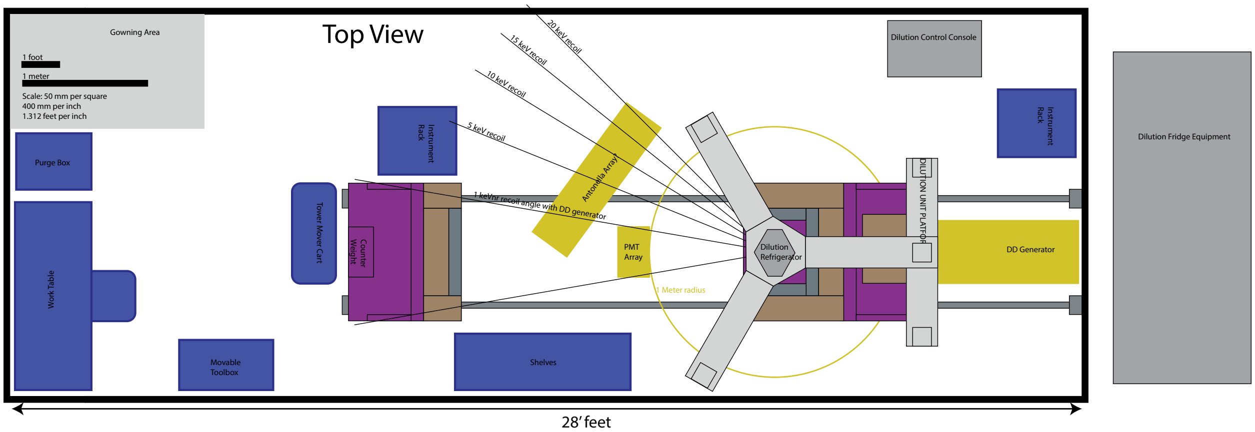

Figure 3: NEXUS layout schematic. The outer box delineates the clean room to be placed 100 m underground in the NuMI access tunnel. The blue boxes are support equipment, while the grey, brown, and purple structures are the passive shield, which is on rollers and half of it is moved out to the left to allow the neutron backing detectors to be placed. The D–D generator (described in Section 7.1.5) is shown as a yellow box on the right, with neutrons passing through a collimating hole in the shield toward the detectors. Neutrons hit the HV detectors in the dilution refrigerator and scatter into angles as labeled depending on the recoil energy. An existing array from Fermilab will cover the wider angles between up to 20 keV, while a purpose-made fine-grain neutron detector PMT array will cover the recoil energies below 1 keV.

cooling unit and the detectors. The residual background for this setup was estimated to be a few tens of events/keV/kg/day. The addition of an additional layer of lead inside the dry-well (15 cm at the bottom and 10 cm on the side walls, totaling $\sim$4 tons) is expected to reduce the external background by another order of magnitude. This background level of $\sim$2 events/keV/kg/day allows for the measurement of the intrinsic ^{32}Si background in SuperCDMS SNOLAB detectors and opens the possibility of dark matter science prior to the start of SuperCDMS SNOLAB.

The CUTE refrigerator has been ordered and is expected to be delivered to Queen's University for confirmation of performance in May 2017. The installation of the water tank and deck structure for access to the facility will begin in early 2017 so that the infrastructure is ready in summer 2017 when the refrigerator is expected to be delivered to SNOLAB. The commissioning phase of CUTE at SNOLAB is expected to begin in late summer or early fall 2017.

6.2 NEXUS

NEXUS is a testing facility planned for the MINOS near-detector hall at Fermilab (100 m underground). It will operate a dilution refrigerator surrounded by a 10 cm lead and 20 cm poly shield in a clean room environment. The rock overburden removes all muon-induced hadronic showers and lowers the muon flux to 0.5 muons/m^2/s. The lead shield (which includes a disk-shaped shield inside the refrigerator similar to CUTE) will reduce the background to less than 100 events/keV/kg/day. This facility is being built through a collaboration between Northwestern University and Fermilab. A schematic of the calibration setup described in Section 7.1.5 is shown in Figure 3. The design of the clean room facility, the structural support for the dilution refrigerator, and the passive shield mechanical design are all underway. Installation of the dilution refrigerator is expected in fall of 2017, and the facility will be operational by the end of that year.

6.3 Electronics and Shielding for SuperCDMS Detectors

Much of the SuperCDMS SNOLAB hardware required to perform the measurements and science outlined in this proposal, such as pre-production towers and detectors, will be made available after the items are no longer needed for the SuperCDMS SNOLAB project. There are several exceptions, which are budgeted in this proposal and described here. To complete the measurements in this proposal at NEXUS, the ability to read out two detectors is required. For CUTE, a full contingent of 6 detector readout channels is needed for the science measurement. Thus we request:

• Detector Control and Readout Cards (DCRCs). Two DCRC's are required to read out each HV detector, so we budget 4 for NEXUS and 4 for CUTE to test pre-production detectors. The HV tower will have its own DCRC's that will move to SuperCDMS SNOLAB with the tower.

• 300 K–4K wiring. The wiring to connect the DCRCs to the towers needs to be provided. Four are available for use at CUTE, so we budget 8 more (we need 12 to read out the tower) and 4 for NEXUS.

• Lead shield for CUTE. The order of magnitude background reduction provided by this shield will provide sensitivity to the ^{32}Si signal and the potential for early dark matter science. The shield for NEXUS is already part of the facility.

7 Pre-Operations and Commissioning Tasks

The SuperCDMS collaboration has had two decades of experience in operating underground dark matter experiments at Stanford and Soudan. The 'lessons learned' from this experience are being applied as we develop our pre-operations, commissioning, and operations models for the SuperCDMS SNOLAB experiment. In this section, we discuss the main activities that will be conducted during this three-year proposal. These follow from the objectives listed in Section 1, and are organized in a work breakdown structure as follows:

WBS	Descriptions
1.1	Calibration of Si and Ge SuperCDMS SNOLAB Detectors
1.2	Performance Optimization of SuperCDMS SNOLAB Detectors
1.3	Early SuperCDMS SNOLAB Science
1.4	SuperCDMS SNOLAB Commissioning
1.5	Education and Public Outreach

Table 2: Work Breakdown Structure for this proposal, based on the objectives laid out in Section 1.

The first two activities in the WBS are measurements essential to the scientific output of the SuperCDMS SNOLAB experiment. The third activity provides the potential for early world-leading low-mass dark matter results, which will not only have the potential for discovery, but provide training and publications for our young scientists in the collaboration. This proposal's fourth activity is the commissioning of the SuperCDMS SNOLAB experiment, clearing the final hurdle for operations to begin. The final activity is the education and public outreach component of the Broader Impacts of this proposal. The following sub-sections detail the work to be done in each of these activities.

7.1 Calibration of Si and Ge SuperCDMS SNOLAB Detectors (WBS 1.1)

[MP:

- **rename to measure the nuclear recoil ionization yield at very low energies**
- **I think we should add a section on testing the electronic recoil calibration signal using LEDs**
- **we need to write this section with the understanding that 0V operation has a natural nuclear recoil ionization scale.**

]

A major focus of the SuperCDMS pre-operations program is to measure the nuclear recoil energy response in both Ge and Si down to 100 eV and eventually down to ∼30 eV. This will match the energy thresholds we expect to achieve with the initial experiment and with upgraded detector towers. These measurements are crucial for optimizing the operational parameters of, as well as achieving science in the next three years with the first production HV SuperTower at the Cryogenic Underground TEst (CUTE) facility in SNOLAB. Thus it is important to perform these measurements as early as possible, ideally completing them before data taking with the HV tower at CUTE begins.

The signature of a WIMP-like dark matter interaction is a spectrum of low-energy nuclear recoils. [MP: **WIMP DM is excluded ¡ 10GeV ... we are looking largely for assymmetric dark matter models**] The nuclear recoils produce both ionization and phonons. The ionization yield (also know as quenching factor), which is the fraction of recoil energy that goes into the ionization, is recoil energy dependent. A calibration of the nuclear recoil energy scale requires a measurement of the ionization yield, both its mean and its distribution, for all recoil energies of interest.

Figure 4 shows current mean ionization yield measurements in germanium and silicon detectors made with a variety of detector technologies, along with the theoretical prediction from the Lindhard model [45]. Also shown (and discussed fully in the subsequent sections) are a set of simulated yield measurements demonstrating what would be possible with the proposed work, superimposed on the current state of knowledge of the low energy nuclear recoil yield in germanium [42] and silicon [43, 44, 46, 47]. Highlighting the importance of experimental data, a recent measurement, made by the DAMIC collaboration (top panel of Figure 4), indicates that the ionization yield in Si is significantly different from the theoretical predictions of Lindhard at and below 1 keV. Projecting the deviations down to 100 eV suggests even larger discrepancies.

For SuperCDMS, the interplay of ionization yield, trigger threshold and experimental sensitivity is complex. As the ionization signal is detected via its conversion to phonons by the Luke-Neganov effect, the total phonon signal measured includes both primary phonons from the recoil and Luke-Neganov phonons from primary ionization. In Figure 5, calculations for Si show how the sensitivity can vary with different ionization yield assumptions. Furthermore, systematic bias from uncertainty in the ionization yield can be reduced and sensitivity to the lowest masses regained by operating at reduced voltage at the cost of higher background in the signal region (as demonstrated by the extreme case of 0 V, which is used here to show the theoretical maximum effect). Both issues demonstrate the need to measure the ionization yield of SuperCDMS SNOLAB HV detectors by the time science runs at CUTE begin.

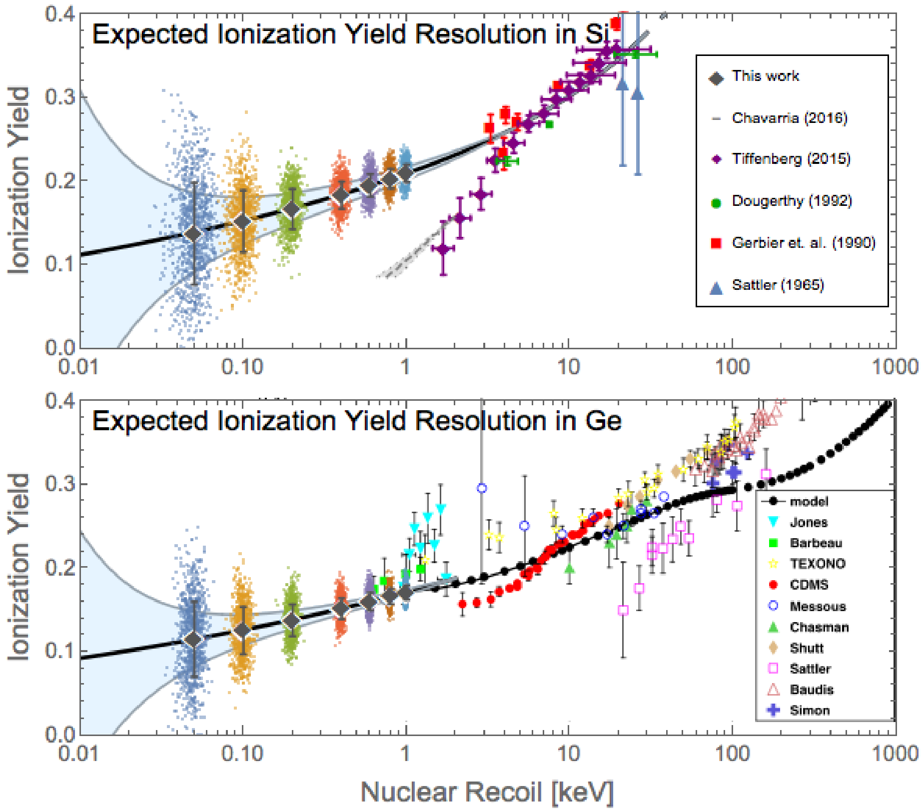

Figure 4: Comparison of a simulation of the proposed ionization yield measurement compared with existing measurements of the mean ionization yield from the literature. The proposed measurement, shown following a Lindhart ionization yield model, has the potential to provide essential data on the ionization yield mean and statistical fluctuations for dark matter rate calculations in the lowest energy ranges. The colored scatter points correspond to the simulated ionization yield as a function of recoil energy, superimposed on the $\pm 1\sigma$ statistical uncertainty band from Eq. 2 (note that the blue $\pm 1\sigma$ bands only account for the statistical uncertainty due to phonon energy resolution and neutron scattering angle, whereas the actual points also include the effect of electron-hole production statistics, i.e., the Fano Factor). The gray diamonds indicate the mean value of the calculated yield from the simulation, and the vertical bars are the square root of the variance. Figure adapted from [42, 43, 44].

7.1.1 Measurement Strategy

We propose to perform a precision measurement of the ionization yield in this energy range first at a neutron beam facility with small prototype detectors and subsequently using a D–D neutron generator with full-sized SuperCDMS SNOLAB detectors. In both these setups, the energy of the incoming neutron is known and the deposited nuclear recoil energy in the detector is determined kinematically by measuring the outgoing neutron angle. By directly measuring the ionization signal in the target/detector it is then possible to perform a direct measurement of the ionization yield.

SuperCDMS detectors determine the properties of a particle interaction by measuring the energy deposited in two different physical channels: the phonon and ionization channels. When an interaction takes place in the detector the total recoil energy of an interaction is initially divided among a population of prompt athermal phonons and a population of charged excitations (*i.e.*, electrons and holes). A uniform electric field of a few V/cm causes the electrons and holes to drift to op-

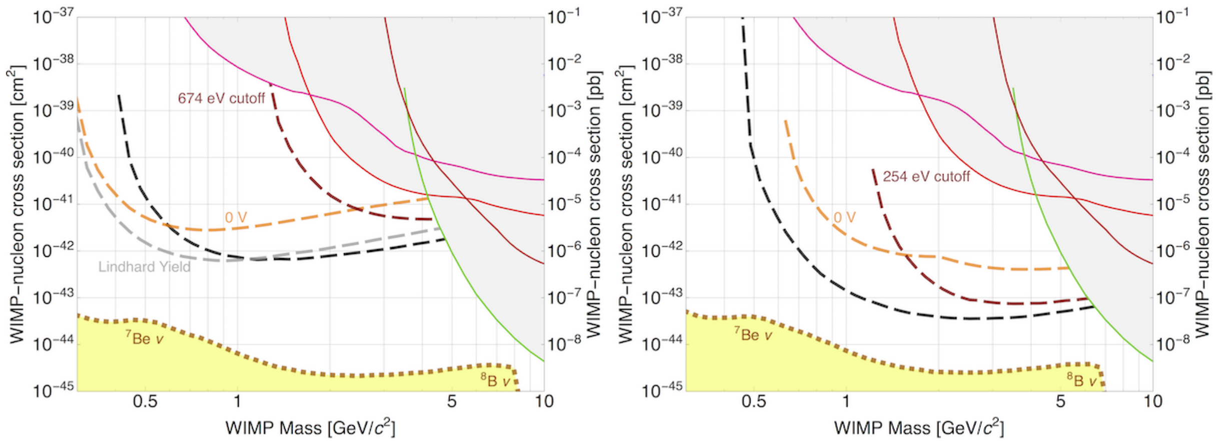

Figure 5: Left panel: Sensitivity scan of SuperCDMS SNOLAB Si HV detectors for different yield and analysis thresholds. Black is the nominal projected sensitivity, which uses the DAMIC yield function [47] and extrapolates the yield curve down to 40 eV [19]. Grey is Lindhard theory for comparison. Orange is the sensitivity projection for operation of the detector with zero voltage across the crystal. The red line shows the sensitivity from an analysis that sets the threshold at the lowest recoil energy for which data on ionization yield exists (675 eV). The region to the left of the red line highlights the WIMP parameter space that requires new experimental data for ionization-measuring detectors. Right panel: Same as Left but for Ge HV. The black line uses Lindhard theory, orange is zero-voltage operation, and red applies an analysis threshold of 254 eV.

posite surfaces where they are detected with a capacitively-coupled charge amplifier. The motion of the charged excitations in the crystal under the influence of the applied electric field creates a population of phonons known as Luke-Neganov phonons. These release to the phonon system an amount of energy equal to the work required to drift the charges through the field across the resistive crystal, i.e., $E_{Luke} = n_{eh}\, e\, V$, where n_{eh} is the number of electron hole pairs made in the recoil, and $e\, V$ is the electron charge times the voltage across the crystal. The total phonon energy E_{ph} measured in the detector for a given recoil energy E_r is,

$$E_{ph} = Er + E_{Luke} = E_r \left(1 + \frac{e\, V\, Y}{\mathcal{E}_{eh}}\right) \tag{1}$$

where $\mathcal{E}_{eh}$ is the average electron equivalent energy required to form an electron hole pair, Y is the ionization yield

Effective ionization resolutions on the order of few eV (corresponding to individual e-h pairs) can be achieved using the technique of voltage-assisted calorimetric ionization detection which was first used by the SuperCDMS experiment in a low-mass WIMP search using the current iZIP detectors [48, 23]. By applying a high voltage (HV) across the crystal the ionization signal can be effectively amplified and measured using the phonon sensors since the energy released into the Luke-Neganov phonon population will dwarf the intrinsic recoil phonons. The detector is then being effectively operated as a phonon-based charge amplifier in which the gain of the signal is proportional to the applied voltage, and the readout channel has a fixed resolution. The measurement uncertainty of the ionization yield, measured using Eq. 1 , the measured total phonon energy and an independent determination of the recoil energy (*e.g.*, from a neutron scattering angle measurement), is:

$$\sigma_y = \frac{\mathcal{E}_{eh}}{e\, V} \frac{\sqrt{E_{rec}^2 \sigma_{ph}^2 + E_{ph}^2 \sigma_{rec}^2}}{E_{rec}^2} \tag{2}$$

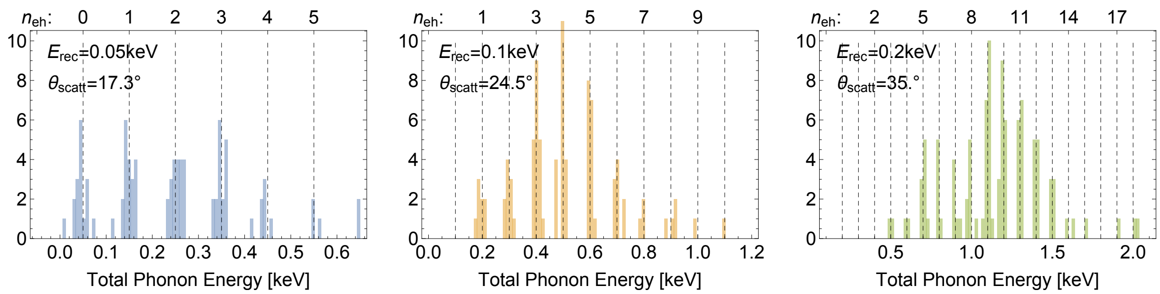

Figure 6: Demonstration of the ability to identify the number of discrete electron-hole pairs (indicated by the dashed vertical lines) created by a low energy nuclear recoil. The combination of high bias voltage and excellent energy resolution allows for the measurement of the Fano factor even with limited statistics.

Since the ionization yield uncertainty depends both on the phonon channel resolution and the bias voltage, a worse than expected phonon resolution can be compensated for with a higher voltage bias.

Figure 4 shows the result of a simulation with neutrons incident on a test detector with 50 eV resolution, superimposed on the current state of knowledge of the low energy nuclear recoil yield in germanium [42] and silicon [43, 44, 46, 47]. This simulation shows that this experiment will have the ability to reliably identify the mean value of the ionization yield down to ~ 50 eV. The horizontal spread in each population of events arises from a given neutron detector accepting a $\pm 1°$ range of scattering angles.

At the improved, but still conservative, energy resolution of 10 eV (this value is twice the expected 5 eV resolution of the SuperCDMS R&D devices that will be used for the measurement) it becomes possible to identify the number of electron-hole pairs produced by a given recoil as shown in Figure 6. This will provide an important piece of information regarding the statistical nature of ionization production and allow us to perform a direct measurement of the Fano factor down to the lowest recoil energies.

[MP: include quantization plot from Stanford. Switch plots to show quantized sensitivities]

7.1.2 Yield Calibration with a Neutron Beam at TUNL (WBS 1.1.1)

The Triangle Universities Nuclear Lab (TUNL) data taking campaign will occur in the first year of this grant (see schedule in Figure 8). TUNL operates a facility capable of delivering a mono-energetic neutron beam with energies in the range of 30 keV to a few MeV [49, 50]. A tandem Van de Graaff is used to accelerate protons and collide them with a ^{7}Li target. The resulting ^{7}Li(p,n)^{7}Be reaction produces a neutron that is primarily collinear with the proton beam. At a proton threshold energy of 1.88 MeV the reaction produces neutrons with 29.7 keV kinetic energy which are kinematically constrained to be in the forward direction. Increasing the proton energy allows for the production of neutrons with a range of kinetic energies and directions, however by selecting a particular direction (e.g. collinear with the proton beam) a unique neutron energy is obtained [51].

The neutron beam passes through a 2 foot high-density polyethylene (HDPE) block which collimates the beam and absorbs unwanted reaction products (such a γ-rays) and is directed to the target location. Backing detectors (5cm inch diameter plastic scintillator, with sensitivity to neutrons down to 6 keV) surround the interaction site and detect the scattered neutron providing knowledge of the scattering angle and timing of the event, and can be positioned around the interaction point as needed. The TUNL facility currently has 32 such detectors and is in the process of deploying 200 more to provide a solid angular coverage of almost 1π steradian. The additional neutron detectors are expected to become available in January of 2017. One of the most useful features of the facility is its ability of providing a pulsed beam, which in conjunction with the backing detectors' timing resolution of < 4 ns allows for an excellent rejection of events due to pileup, multiple scatter or radioactive backgrounds, and also provides a secondary measure of the neutron energy through its time-of-flight.

The details of the backing detector configuration will be investigated and optimized in the early stages of the proposed work plan in order to obtain an experimental setup that allows for making the measurement at the the desired level of accuracy in a minimum amount of beam time.

The Northwestern SuperCDMS group owns an Adiabatic Demagnetization Refrigerator (ADR) that can be transported to TUNL to perform such a measurement. The ADR can cool small, special-purpose Ge and Si HV detectors, each with mass of a few grams. Detectors of this size are produced as part of the SuperCDMS R&D program and are available for these measurements. Two such detectors (one made of Si, one of Ge) will be installed in the ADR so the TUNL measurements can be done without warming up or opening the cryostat.

The kinematics at a neutron beam result in an excellent recoil energy resolution: for a 1° uncertainty in the direction of the scattered neutron, the reconstructed energy resolution is on the order of 4 eV for a 100 eV recoil. This value is close the the expected 5 eV resolution of the SuperCDMS phonon sensors, and as seen in equation 2, is optimal for achieving excellent ionization yield resolution. The neutron beam measurements will be used to obtain the highest resolution ionization yield measurements at the lowest energies allowing us to study in detail the physics and statistics of electron-hole pair production via nuclear recoils at their creation threshold.

7.1.3 The TUNL Experimental Campaign

The simulation in Figure 4 assumed 10^3 events for each recoil energy. We investigated a feasable set of operational parameters necessary for obtaining such statistics in the actual data while minimizing the amount of multiple scatter, pileup and background events in the data. The two driving variables are the detector response time, and the interaction probability of a neutron with the detector.

Based on a conservative detector recovery time of $\tau = 1ms$ we wish to keep the interaction rate in the detector below 100 Hz to minimize pulse pileup. The mean free path of 30 keV neutrons in silicon (germanium) is $\sim 2cm$ ($\sim 2.3cm$), which gives a 18% (16%) probability for a single neutron to interact in the 4mm thick test detector. This can lead to a large number of simultaneous interactions in the detector from a single beam pulse contaminating the data. This effect can be mitigated by decreasing the average number of neutrons per beam bunch. A mean number of neutrons per bunch of $n_{mean} = 0.4$ results in less than 3% contamination from simultaneous interactions. The combination of $n_{mean} = 0.4$ and a bunch frequency of $\frac{1}{600\mu s}$ results in a net detector interaction rate of 100 Hz. Such an operating mode is well within the capabilities of the facility and given the < 4 ns timing resolution of the backing detectors there will be no difficulties distinguishing which beam bunch produced a particular interaction [52]. Assuming that each backing detector covers an angle of $(1^\circ)^2$, that they are positioned in groups of 10 at each of 20 angles, and that the

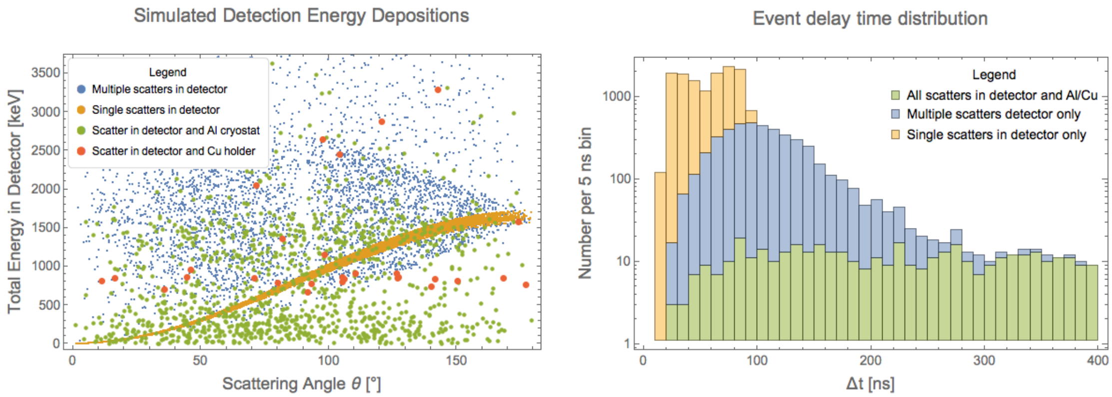

Figure 7: Left panel: Energy deposited in the detector as a function of neutron scattering angle. The orange band band represents events in which the neutron scattered only once within the detector without interacting with the surrounding material. Events which multiply scatter within the detector are shown in blue, and events which interact with the Al or Cu surrounding the detector are shown in green and red respectively. Right panel: Histogram of the event delay times, i.e. the time between the arrival of a beam bunch and the detection of a neutron in the backing detectors. The delay was defined such that $\Delta t = 0$ for a non-scattered neutron, and the backing detectors' timing resolution is < 4 ns.

net neutron interaction rate in the detector is 100 Hz, we can estimate the total active beam time required to obtain the necessary statistics to be around 12 hours. The data for the different recoil energies is collected simultaneously by the grid of > 200 backing detectors at 20 specific scattering angles. Assuming a net efficiency of five to six hours of beam time per calendar day, it is reasonable to expect that a data acquisition period of a few days is sufficient for a particular measurement. Data will be taken for both a prototype Si and Ge detector, at multiple bias voltages and operating conditions (such as crystal temperature) during a three week running window. An additional week before and after the data acquisition campaign for assembly/disassembly and verifying the operation of the detector at the TUNL facility will also be required.

7.1.4 Data Contamination

Environmental radiation background and neutron interactions with the material surrounding the detectors have the potential to contaminate the data. A proper understanding of these interactions requires a detailed Monte-Carlo simulation. The results from a basic `GEANT4` simulation done by our U. Florida collaborators and shown in Figure 7 are still quite informative. They simulated the interactions of a neutron beam with a detector surrounded by a 1mm thick copper housing, contained in a 1cm thick aluminum cylindrical shell (which represents the cryostats vacuum jacket). The figure's left panel shows the distribution of energy deposited in the detector as a function of neutron scattering angle. The thick orange band represents events in which the neutron scattered only once within the detector without interacting with the surrounding material. Multiple scatters within a detector, as well as events in which the neutron interacts with the surrounding material are also shown. The right panel shows the delay time distribution (the time between the arrival of a beam bunch and the detection of a neutron in the backing detectors). It can be seen that a time based acceptance cut can remove a large portion of multiply scattered events and interactions in the surrounding material. It is worth noting however, that even without applying any selection criteria, the simulation shows that contamination from such events is less than 5% for all recoil energies < 1 keV.

7.1.5 D-D Generator Measurements at NEXUS (WBS 1.1.2)

[MP: What about testing the concept of measuring nuclear recoil ionization yields with Cf by measuring 0V, 50V, 100V. This would give us the possibility of using Cf for insitu calibration of all detectors in SNOLAB (or at NEXUS) extremely easily]

There are several challenges associated with calibrating large cryogenic solid-state detectors in a fixed neutron beam. These massive detectors require a dilution refrigerator to operate at millikelvin temperatures, and such refrigerators are not portable. Adiabatic Demagnetization Refrigerators, although portable, lack the cooling capacity to effectively operate these detectors. Furthermore, underground calibrations are critical for large cryogenic detectors. When operated on the surface, the time between events from cosmic radiation can be less than the recovery time required for the phonon sensors to return to equilibrium. **[MP: this just isn't true. We have a compton background of 40Hz (25ms) and a falltime which is ¡100us ... we have 250 falltimes on average between comptons. The bigger problem is muons [perhaps what you were referring to] ... muons occur @1Hz and have a 200ms thermal falltime. We find that with a muon cut with 50% passage, we get rid of this to the point that it's subdominant to other noise sources ... it's definitely a penalty (50% livetime) ... but it's not a true deal breaker ... remember that the livetime of our old DAQ was only 15%. We still take more good data now with the muon cut then we ever took with the old DAQ at UCB)]**.

The portability of a D–D generator allows for neutron calibration at underground locations, such as NEXUS, described in Section 6.2.

Calibration with a D-D generator requires borated poly shielding to collimate the D-D neutrons into a beam and a moderate amount of lead shielding to block the capture gammas. Additionally, secondary neutron detectors are needed to measure the scattered neutrons at a given angle. The ANTONELLA collaboration has a neutron detector array, that was created exactly for this purpose and is currently available for use. This array covers relatively large angles of scatter (>10°). With this array, we can measure nuclear recoils down to a few keV with the D-D beam energies. Measurement down to 100 eV requires fabrication of a finer-grained neutron array. Design of such an array, with the reuse of 1.3 cm Hamamatsu photomultiplier tubes salvaged from the SELEX experiment, will be pursued by the U. Florida and Fermilab groups. The setup is schematically shown in Figure 3.

[MP: Has this array been procured? If not then you are just doing nuclear recoil ionization yield measurements @ a few keV]

In SuperCDMS detectors, there are energy-scale effects that are degenerate with measurement of the ionization yield and can vary with detector parameters such as the strength of the electric field, fabrication of the phonon sensors, and even the impurity levels in a given crystal. To understand these systematic effects, it is important to perform the calibration on detectors that will have the same electric field and style of phonon sensor. Furthermore, it is highly desirable to perform measurements on several different detectors of the same type, operated at several bias voltages. **[MP: explain]**

The primary challenge of the D–D calibration is the relatively high energy (2.5 MeV) of the neutrons compared to the recoil energies of interest (100 eV). For a 1° uncertainty in the direction of the scattered neutron the reconstructed energy resolution of a 100 eV recoil becomes $\sim$ 30 eV. This uncertainty becomes the limiting factor in the measured yield resolution. One way to compensate for this effect is to use a fine-grained neutron array to determine the neutrons' very small scattering angles. An angular resolution of $\sim 0.125°$ is needed to achieve the same recoil energy resolution as with the 30 keV TUNL neutron beam. The resulting scattering rates per secondary neutron channel will be approximately 60 times lower compared to the rates at a neutron beam facility. The lower detection rates, in turn, lead to longer data acquisition times and an increased sensitivity to environmental backgrounds. Studies will optimize the tradeoff between recoil energy resolution and the impact of data contamination sources such as background interactions in the neutron array and multiple scattering of the D–D neutrons both within the SuperCDMS detectors and the surrounding material of the dilution refrigerator.

The neutron beam and D–D setups will experience different experimental systematic effects. By taking data with the small calibration detectors at the D–D generator setup, we can correlate the neutron beam and D–D systematics, and use this understanding to extrapolate the high-resolution beam data to the kg-size detectors. Thus a cross-calibration would provide robustness to our understanding of the ionization yield and provide additional higher-resolution data points in the energy region where currently no data exists. The data with the small HV detectors at NEXUS will be taken in the latter part of Year 1 of this grant. Year 2 of the grant will be devoted to pre-production SuperCDMS SNOLAB detector calibration (see schedule in Figure 8).

The D–D calibration setup will enable a program of measurements that can explore the calibration differences that arise with different operating conditions and detector designs. This will lead to a full understanding of the systematic uncertainties associated with ionization production in SuperCDMS detectors.

In summary, the TUNL & NEXUS campaigns enable a program of measurements that can obtain high-resolution physics measurements of the ionization yield of Si and Ge at recoil energies down to 100 eV and below, explore and correct for systematics in the measurements, and perform direct measurements of the ionization yield of SuperCDMS SNOLAB detectors. This will enable a full understanding of the systematic uncertainties and provide essential inputs for the dark matter science analysis of SuperCDMS SNOLAB data.

7.2 Detector Performance Characterization and Background Studies (WBS 1.2)

[MP:

- **Nuclear Recoil Ionization Yield Measurement**
- **testing optical photon calibration techniques**
- **Charge Leakage Studies**
  - **optimize pre-bias voltage**
  - **optimize LED/blackbody frequency for A+,D-**
  - **optimize bias voltage**
- **Electronic Recoil / Nuclear Recoil Discrimination**
  - **Quantization / Statistical subtraction in HV**
  - **Standard ER/NR in iZIP**

- **Fiducialization Metrics**
- **(@ Berkeley) noise studies with small TES chips**

]

The **[MP: Nuclear Recoil / Electron Recoil?]** discrimination power and general behavior of SuperCDMS SNOLAB detectors under low-background conditions cannot be tested in regular detector test facilities due to the high rate of cosmic ray induced interactions in the detectors. A large focus of this proposal is to make such measurements at NEXUS and CUTE.

[MP: why not discuss charge leakage optimization specifically?]

7.2.1 Detector Characterization with NEXUS

Although the nuclear recoil energy calibration (described in detail in section 7.1) will be the main focus at NEXUS, having pre-production detectors at the site will also allow early detector characterization. The ability to kinematically reconstruct nuclear recoil energies, as well as the flexiblity to place and remove gamma sources, will faciliate studies that impact the analysis and interpretation of the SuperCDMS SNOLAB data.

[MP: these are all really important ... they should have similar size at the nuclear recoil ionization yield work if possible] These include position dependence and specific detector Monte-Carlo tuning studies (see Section 7.2.3), voltage bias scan studies, and other studies such as measuring single electron-hole pair production using optical fibers. The goal of the optical fiber studies will be to directly measure the separation between integer numbers of electron hole pairs near the threshold of HV detectors as a means to confirm the electron recoil energy scale near threshold. The optical fiber setup also allows for studies of charge collection, which could inform operating procedures for the main experiment. These measurements will take place during Year 2 of this proposal, at the end of each detector's calibration measurement.

7.2.2 Background Studies and Precommissioning with CUTE

A primary goal in the design of the CUTE facility is to test the capability of the SuperCDMS HV and iZIP detectors to distinguish surface from bulk events (fiducialization). The discrimination power between electron and nuclear recoils of the SuperCDMS iZIP detectors can also be studied in detail. Additionally, functionality and early commissioning checks of a tower can be performed before it is deployed within the main SuperCDMS cryostat. Functionality checks would verify that electrical and thermal connections in the tower are functioning properly after shipment to SNOLAB. Early commissioning checks include optimization of voltage bias and neutralization studies. These tests are best performed in a low-background installation such as CUTE because breakdown voltage and optimal neutralization conditions have previously been found to correlate with event rate.

Recent measurements of detectors used for SuperCDMSSoudan have shown that the noise in the signal region increases linearly with the applied bias voltage. Such behavior would limit the sensitivity of the new SuperCDMS HV detectors that are designed for operation with up to 100 V bias. The origin of this excess noise is not yet fully understood. Possible explanations include infrared leakage and injection of charges through the contacts. Low-angle Compton scattering has been identified as alternative explanation; this would also explain why the observed noise level appears to be the same in different test facilities with no, or only moderate, shielding.

[MP: where did this theory come from? ... why would there be a huge number (1e5Hz) of single e/h pair comptons?]

We will test this hypothesis and understand the behavior of the new SuperCDMS HV detectors in CUTE's low background environment.

As shown in the schedule (Figure 8) we expect to install in CUTE one of the two pre-production towers at the beginning of calendar 2018 after the tests planned by the SuperCDMS SNOLAB Project are finished. This tower is intended to have two pre-production HV detectors and one pre-production iZIP.

After 2 months of commissioning and basic checks of performance, we plan a 9-month testing program to study:

- Fiducialization and surface rejection in HV detectors.
- Nuclear recoil discrimination of iZIP detectors.

7.2.3 Detector Monte-Carlo Validation

The SuperCDMS collaboration is currently in the process of building a `GEANT4` based detector Monte-Carlo that incorporates low-temperature ionization and phonon physical processes governing the behavior of electrons, holes, and phonons in the SuperCDMS detectors. The physical processes being added to `GEANT4` include:

- A microscopic model of inter-valley scattering for charge charge carriers in the crystal.
- Luke-Neganov phonon emission based on the charge carrier mean free path in a varying electric field.
- A continuous process of phonon impurity scattering.
- The creation and tracking of quasiparticles in the the Al superconducting films that at part of the phonon sensors.
- Differential equation based models of the FET (ionization sensor readout) and TES (phonon sensor readout) responses.

Data from the TUNL and NEXUS campaigns will consist of a set of nuclear recoil events with well defined kinematics. Additionally, the data obtained from the precommissioning calibration at CUTE will provide a large set of events from gamma and neutron calibration sources taken in a low background environment. These data sets will provide a comprehensive collection of events for comparing against Monte-Carlo simulations. The data will be made available to members of the SuperCDMS collaboration who are working on detector Monte-Carlo and simulation activities and are validating the performance of the detector Monte-Carlo, and refining it in preparation for the SuperCDMS SNOLAB experiment.

7.3 Early SuperCDMS SNOLAB Science (WBS 1.3)

One of the attractive features of the plan we propose for CUTE is that it not only will give us the opportunity to exercise our detectors in a low background environment but that it might allow us to get early science results. While the characterization of the pre-production detectors described in 6.1 is taking place in calendar 2018, the SuperCDMS SNOLAB Project is scheduled to complete the first production HV tower. We are proposing to install this first tower in CUTE at the beginning of 2019 (Figure 8). This tower would have 6 HV detectors, with a mix of Germanium and Silicon. Our first goals will be to:

- Assess the performance of these detectors in a realistic environment (voltage limits, leakage current, background level)
- Develop biasing schemes for the HV detectors
- Learn what small detector or cold hardware modifications we could include in the second HV tower, being produced in 2019, to optimize its performance
- Exercise our data acquisition system, optimize our reconstruction software and begin to develop the algorithms for science analysis

Achievement of these goals would be very beneficial to the subsequent commissioning of the SuperCDMS SNOLAB experiment. If all goes well, there is a reasonable prospect for doing early science with the HV tower in CUTE, which is the main justification for installing the additional lead shield that we propose to acquire in this award. Current simulations indicate that we could decrease the gamma background from 30 events/kg/keV/day to about 2 events/kg/keV/day with the additional lead shielding. In that case, a six-month HV tower run at CUTE, with a baseline phonon resolution of 10 eV r.m.s. and 100 V bias (SuperCDMS SNOLAB goal) and the projected ^{3}H and ^{32}Si levels for SuperCDMS SNOLAB, might give a spin independent sensitivity as much as 4 orders of magnitude better than the current best limit [21] at a dark matter mass of 2 GeV/c^2 with Germanium, roughly a year before our first results from the SuperCDMS SNOLAB experiment will become available.

Of course, SuperCDMS SNOLAB will then go on to produce much better sensitivity and reach to even lower mass. The two iZIP towers that will be included in the first SuperCDMS SNOLAB payload will provide an independent measurement of the background, which should yield an additional factor of 5 in sensitivity over the no-background-subtraction projections in [19]. Moreover, the second HV tower planned for the first SuperCDMS SNOLAB payload will have benefited from the experience of the first tower at CUTE and is likely to perform better. In the long run, the SuperCDMS SNOLAB set up is designed to allow us to reach the neutrino floor, well beyond what will ever be possible at CUTE. Still, the potential sensitivity of a run of the first HV tower at CUTE is an exciting science opportunity and will provide theses for our graduate students and interesting publications to further the career of our younger scientists.

7.4 SuperCDMS SNOLAB Commissioning (WBS 1.4)

The SuperCDMS SNOLAB Project will include acceptance tests of all parts of the experimental apparatus at the surface. The Project objective is to complete the installation of all equipment underground at SNOLAB, although the Project threshold does not require this. SuperCDMS SNOLAB Operations will pick up any remaining installation tasks, then commission the experiment and transition to operations. We expect this period to occupy approximately the last six months of this proposal's performance period.

The commissioning period will be a mix of installation and testing of subsystems, followed by system testing and data runs that exercise the full experiment. System experts will be responsible for testing and documenting their equipment, with work coordinated by an on-site commissioning czar. The initial focus will be on the cryogenics system, since a successful cool down of the experiment to base temperature is required before detector tower commissioning is possible. In parallel, the readout electronics, data acquisition/trigger and software chain can be exercised. Once base temperature has been established, the focus will shift to commissioning the detector towers, using gamma and neutron sources for calibration. iZIP and HV detector towers will be studied in parallel, and the electronic noise and vibration environment will be characterized.

As system commissioning matures, the operations manager and operations team will begin to take overnight data runs and examine the data along with the commissioning czar and system experts, to find any subtle problems. The data quality monitoring system will be commissioned, as well as the data pipeline and processing systems. Towards the end of commissioning period, we will be running most of the time, with scheduled down times to fix any problems that have been identified. During this period, the operations documentation needs to be finalized.

NSF-funded scientists will play key roles in commissioning, with a special focus on areas covered by this proposal, especially detector performance and calibration. Data from pre-operations studies will be extremely useful in making sure that commissioning is smooth and that the experiment can begin taking dark matter search data as quickly as possible.

8 Schedule

Figure 8 gives a broad view of the activities of the SuperCDMS collaboration centered on the SuperCDMS SNOLAB experiment, including the DOE/NSF G2 Project, the pre-operations and commissioning period covered by this proposal, the actual operation of SuperCDMS SNOLAB (also detailed in the Experimental Operations Plan), and the R&D program that will naturally lead to upgrades for SuperCDMS SNOLAB that allow it to probe the low-mass dark matter region down to the neutrino floor.

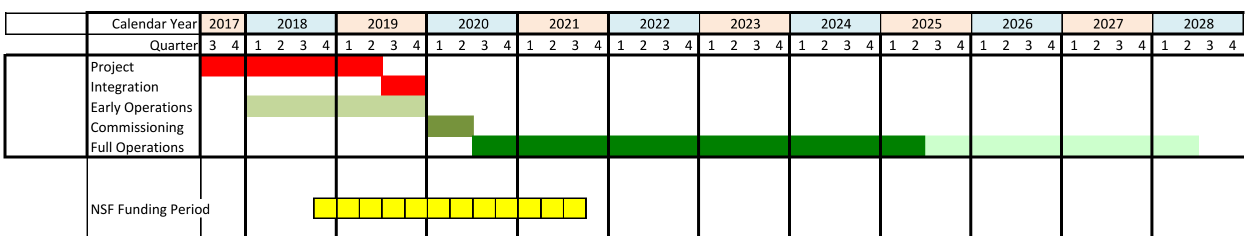

Figure 8: Schedule for the SuperCDMS SNOLAB Experiment.

Year 1: 7/2018–6/2019
During the first year the focus will be on calibration of the small HV test detectors from Stanford University with the Northwestern ADR at TUNL. These detectors will then be taken to NEXUS, to perform cross-calibration measurements in preparation for the large detector calibrations. The first pre-production detectors arrive at CUTE in January 2018, and the performance and background measurement campaign begins soon after.

Year 2: 7/2019–6/2020
The second year is dominated by runs of pre-production detectors at NEXUS for calibration and at CUTE for performance testing and background measurements. The first production SuperCDMS SNOLAB HV tower arrives at CUTE in 12/2018, with testing commencing in 1/2019. Performance and run optimization of all six detectors of the HV tower will continue until 6/2020.

Year 3: 7/2020–6/2021
There is no activity planned for NEXUS on this grant in the third year. At CUTE, the SuperCDMS SNOLAB HV tower science run will be taking data until 11/2019, when the tower will be taken out of CUTE to prepare it for installation in the SuperCDMS SNOLAB experiment. Commissioning activities for SuperCDMS SNOLAB will be the main focus of this grant in the last six months of the award, along with the collaboration-wide effort in analysis and publication of all the data products

from this work.

9 Management

The management team of this NSF collaborative proposal will be chaired by the Northwestern PI and consist of all the PI's and Co-PI's of the proposal. They will interact with the NEXUS, CUTE, and SNOLAB facility managers to coordinate all the activities delineated in this proposal, as well as with the SuperCDMS Collaboration for science analyses and training of students and postdocs.

The work funded by this proposal is part of the full set of SuperCDMS SNOLAB operations and commissioning activities, some of which are outside the scope of this proposal and are funded by DOE or Canadian funds. The management team for this proposal will be in close coordination with all parties involved in the SuperCDMS SNOLAB Project and Operations, as well as R&D, and other SuperCDMS Collaboration activities. These multi-agency collaboration-wide activities will be coordinated by a team consisting of the SuperCDMS SNOLAB Project and Operations Managers, the SuperCDMS Spokesperson, and the NSF Operations PI. This team will meet regularly to coordinate activities.

The early operations phase of the SuperCDMS SNOLAB experiment covered by this proposal is when it is both necessary and appropriate to ramp up the operations management and support functions for SuperCDMS SNOLAB, which should all be in place for the commissioning phase of the experiment in order to ensure a smooth transition to the operations phase as quickly as possible.

The detailed planning for commissioning of SuperCDMS SNOLAB will be led by a scientist identified to be the SuperCDMS SNOLAB Commissioner, with this role naturally evolving into that of a Run Coordinator during the operations phase. Details of the operations phase functions and management (which are outside the scope and period of performance of this project) are given in the SuperCDMS SNOLAB Experimental Operations Plan.

9.1 Facilities Management

Since much of the work in this proposal occurs in dedicated underground facilities, we outline here the management of these facilities and their relationship to this grant's management.

9.1.1 NEXUS

The NEXUS facility will receive primary management oversight from the Northwestern PI. In addition, SuperCDMS collaborators at Fermilab will provide support to interface with Fermilab as needed. A fraction of an FTE will be provided by this grant for an operations manager, to oversee the activities delineated in this proposal.

9.1.2 CUTE

The CUTE facility will receive primary management oversight from our collaborators at Queen's University. This grant's management team will coordinate with Queen's to oversee the CUTE activities delineated in this proposal.

9.1.3 SNOLAB

As mentioned above, the commissioning of SuperCDMS SNOLAB is an activity coordinated at the collaboration level. The PI of this grant will be part of the Operations Management team and will work closely with the SuperCDMS SNOLAB Operations Manager to coordinate and integrate the NSF-sponsored commissioning work with the overall multi-agency commissioning effort. SNOLAB conducts a Gateway review process for projects which includes pre-operations activities, operation of the experiment, and decommissioning. For Gateway 1 and 2, the Project Director is the primary contact for review of the design and fabrication of the SuperCDMS SNOLAB experiment. For Gateway 3 and 4, the Operations Manager is the primary contact for review of the experiment pre-operations and operations. The Collaboration Canadian PI is involved in all interfaces between SuperCDMS SNOLAB project and operations and SNOLAB management. This grant's PI will be in close coordination with the Project Director, the Operations Manager and the Canadian PI to oversee the commissioning activities supported by this proposal.

10 Broader Impacts

The SuperCDMS collaboration continues to deliver on its potential for broader impact including strong technical development, education at all levels, and engaging public outreach.

Technical Development CDMS and SuperCDMS have developed, and continue to advance detector technologies that have significant impact both inside and outside of the dark matter community. These technologies include electrothermal feedback, transition-edge sensors (TESs); detection and utilization of athermal phonons; large, kilogram-scale phonon-mediated germanium and silicon-based detectors; arrays of large-scale, low-noise SQUIDs; and usage of LPN HEMPTs for ionization readout.

The field of direct detection of dark matter has benefited from these advances. The EDELWEISS and CRESST collaborations have both implemented some of these concepts. In addition, SuperCDMS pioneering of very-low-mass WIMP detection has had a strong impact on the field. There are now many R&D efforts focused on very-low-mass WIMP detection. Multiple of these programs are run by PIs who were primarily engaged in liquid noble direct detection. The concepts developed by SuperCDMS have had far reaching impacts benefiting even direct detection experiments using the liquid nobles.

The broader, basic-science community has benefited from SuperCDMS technology advances. The TES technology is now a core technology for multiple cosmic microwave background experiments including APEX, South Pole Telescope, and PolarBear. It is being rapidly adapted for far-infrared instruments including Super-SCUBA, single-photon spectroscopy, and large X-ray calorimetry experiments at NIST and NASA GSFC including the forthcoming Micro-X, which will launch the first TES into space. In addition, the TES technology is beginning to impact industry as TESs are being adapted for use in electron microscope sensitive surface element analysis and are being investigated for use in quantum coherence and computing.

The direct impact of SuperCDMS research is underscored by the number of graduate students impacted and the number and quality of the SuperCDMS publications. In the past three years, SuperCDMS has produced 12 Ph.D. theses and 11 science publications not including conference proceedings. The impact of these publications is underscored by their many citations (over 3,000 since 2011).

Undergraduate, Graduate, and Postgraduate Education Direct detection of dark matter is multidisciplinary and therefore creates a broad spectrum of opportunities for students to explore and advance in many fields. From year to year, numerous undergraduates, graduate students and postdoctoral researchers from the SuperCDMS NSF-funded institutions have benefited from these collaborative opportunities and have been guided to develop precise simulations of semiconductor-based detectors, sensitive analysis techniques, statistical applications, and application of advanced software techniques. These opportunities combined with regular mentoring have afforded many high-visibility talks for students and postdocs.

As a collaboration, SuperCDMS strives to ensure that graduate students and postdoctoral researchers receive proper exposure to the wider dark matter and particle physics communities to support their scientific development and establish the basis for future career and collaborative opportunities. To that end, a committee within the collaboration, headed by a senior member, identifies and advocates for high profile talk opportunities within the dark matter field. PIs from institutions on this proposal have provided strong representation on this committee. Interactions between university-based scientists and technical experts in industry, particularly in the areas of cryogenics and electronics continue to provide long-term benefits to the physics community at large, and are likely to lead to excellent job opportunities for some of our students.

Over the past seven years, SuperCDMS grad students have attained postdoctoral appointments at Caltech, Stanford, MIT, UC Santa Barbara, Texas A&M, Northwestern, NASA GSFC, MIT, Berkeley, Lincoln Labs, LBNL and Fermilab, and others are pursuing careers in industry and tech. Also in this period, grad students and postdoctoral researchers from SuperCDMS NSF-funded institutions have obtained faculty appointments at Caltech, UC Berkeley, U. Illinois at Urbana-Champaign, San Diego State U., U. Massachusetts-Amherst, and three are senior researchers at NIST, SNOLAB and PNNL. The current SuperCDMS analysis coordinator is from an NSF-funded institution.

Broad engagement of undergraduates in the research continues to be a strong focus. Currently, there are more than 25 undergraduates involved in SuperCDMS research, gaining the direct lab experience that is increasingly a discriminator in graduate school admission and an important complement to the undergraduate, mostly theoretical, education. At Northwestern University, the PI participates in the Summer Research Opportunities Program, which brings students from other US institutions to Northwestern and other universities in the Big Ten Alliance. Of the 34 undergraduates he has supervised, 15 were female and 10 were members of an underrepresented minority.

Colegio de Fsica Fundamental e Interdiciplinaria de las mericas (COFI) is a physics research institute in San Juan, Puerto Rico, which hosts summer schools in different topics in physics, for graduate and undergraduate students, as well as talks for public audiences. In Summer 2016, the topic was high-energy physics instrumentation, in which Northwestern University PI Figueroa-Feliciano participated. The Institute is interested in partnering with SuperCDMS to bring theorists and experimentalists to their summer schools to give talks on dark matter and related topics. COFI opens its summer schools to all students (undergraduate and graduate students), but has a particular mission of bridging the span between North America and South America, bringing students and researchers from South America to interact with US researchers in San Juan. Given its unique character as a Spanish-speaking location in the US, this is a natural bridge between the communities. COFI is also interested in reaching students from underrepresented groups and bringing them to their summer schools. In year 2, SuperCDMS will provide two speakers on dark matter-related topics at a COFI summer school.

At Berkeley, undergraduates will be largely drawn from subsidized campus programs, including the Undergraduate Research Apprenticeship Program (URAP) and CalTeach, a program that enables science majors to concurrently complete their BS degree and a California teaching credential. The Compass Project, an initiative developed by Berkeley physics graduate students and launched in August 2007, aims to increase the percentage of minority and women students that matriculate with a bachelors degree in one of the physical sciences by engaging students who express an interest in such fields as early as possible. As the programs faculty advisor, Bernard Sadoulet has facilitated their efforts to ensure the sustainability of this proven recruitment and retention program, by helping them secure a long-term, institutionalized base of support. Compass received the 2012 Award for Improving Undergraduate Physics Education, by the American Physical Society. Compass offers an intensive summer program for incoming freshmen from underserved schools, fall and spring term retention courses (including a course for transfer students to support their transition to Berkeley), mentoring, a research lecture series, and other social and academic support.

Sadoulet is the director of Berkeley Connect in Physics, a mentoring program within the physics department that accepts undergraduate students at all levels. The course is a small seminar class led by a physics graduate student, under the guidance of the director. The goals of the program are to help students develop understanding, community, and career preparedness that go beyond what traditional courses provide. Interactions with graduate students and faculty play a large role throughout the semester. Under Sadoulets leadership, this course has significantly gained in enrollment with every succeeding semester since its launch in Spring 2014.

The Physics Department at CU Denver maintains an undergraduate-only program committed to providing students with hands-on research experience at this urban campus. The Department operates in close collaboration with the Physics Department at Metropolitan State University of Denver, and students from both institutions participate in the CU Denver groups activities, broadening the reach of the research program beyond a single institution. Underrepresented groups and first-generation college students are well represented in the PIs group, and many of his mentees have proceeded to graduate school in physics and other disciplines, or embarked on careers in industry at companies such as Northrop Grumman. Currently, there are eight undergraduates in the CU Denver group majoring in Physics, Electrical Engineering, and Mechanical Engineering.

At the U. Florida, the PI has been the Education Outreach contact person for the Physics Department. His group hosts three (non UF) undergraduates for summer research internships as part of the REU program.

Southern Methodist U. typically funds one to three undergraduate students to work with the Cooley group each year. In the past five years, the eight undergraduates who have participated in the groups research have either entered graduate programs in physics or engineering or embarked on careers in industry at companies such as Texas Instruments and AT&T.

The PI at the U. South Dakota serves as the Chair of the SuperCDMS Outreach Committee, and is a member of the Education and Outreach committee at USD. He increases the opportunities for undergraduates at USD and other institutions by mentoring non-physics and physics undergraduates in their honors thesis. The PI has been instrumental in bringing new, popular physics demonstrations to life including a Rubens tube and a cloud chamber that are now used in introductory physics classes. He has recruited four undergraduates who have contributed to the PIs research program in the past two years, and he has guided two undergraduates through the process of writing a proposal for a NASA Research Stipend. A major issue confronting many undergraduate physics majors from colleges and smaller universities is the lack of exposure to the many fields of physics research. To address this issue, the PI presents colloquia and seminars at local colleges and universities, helping to spread the word about the new USD PhD program. All domestic students accepted into the USD Fall 2015 graduate class were a direct result of the PIs talks. The PI is attempting to strengthen undergraduate research opportunities at USD through partnership on two USD NSF REU proposals. The PI was an organizer of the 2015 NSF sponsored USD Germanium Workshop and actively sought to increase minority and female participation at the workshop. As a result, 23% of the participants were women, 80% of whom were presenters. The PI personally invited one third of the minority attendees and arranged for all of them to give plenary talks. In addition to engaging undergraduates on campus, SuperCDMS will support an 8-week undergraduate summer research internship at SNOLAB, in years 2 and 3.

K-12 Education SuperCDMS institutions provide strong support for K-12 education through programs for both teachers and students. Too numerous to describe in detail in this proposal, these programs take place in local schools, on campus and directly in the lab. At the core of many of the programs is engagement of students from disadvantaged backgrounds and underrepresented groups, including women.

CU Denver, U. Florida, SMU, and USD engage middle school students in physics learning through lab tours, classroom visits and science camp. Northwestern U., UC Berkeley, U. Florida, TAMU, SMU, and SD School of Mines and Technology support a range of high school programs, including summer research internships for students and teachers, hands-on research projects for underserved high school students of color, mini-courses to prepare Native American students for postsecondary education in science and engineering, interviews with physicists conducted by high school students, and structured physics courses for high school teachers.

Local Public Outreach SuperCDMS groups are actively engaged in efforts to share SuperCDMS science with the public. PIs and group members at Northwestern, UC Berkeley, and CU Denver present public lectures on dark matter, on campus, at community events and civic organizations, and at science cafes. The PI at Northwestern has presented two talks in the past year in San Juan, Puerto Rico.

UC Berkeley, U. Florida, SMU, SD School of Mines and Technology, and TAMU participate in outreach events on campus, at community festivals, local farmers markets, science fairs and science camps. Activities include lab tours and hands-on physics demonstrations. SuperCDMS scientists have been featured in the media, including NPRs Science Friday and in the popular press.

Site-Based SuperCDMS Education & Outreach In recent years, SuperCDMS has taken advantage of the Soudan Underground Laboratorys (SUL) location in a state park to impact thousands of tourists and dozens of school groups each year through laboratory science tours. These tours have taken students and tourists 2,341ft below the surface to the underground laboratory to view the SuperCDMS and MINOS experiments. At a SuperCDMS interactive table on the tours, tourists and students had the opportunity to not just see and hear about the SuperCDMS experiment but also physically interact with experimental elements including a sample detector. In addition, SuperCDMS scientists would speak directly with the public at a full-day science Open House, which attracted around 600 people annually. At the surface, a touch-screen kiosk continues to provide videos and descriptions of the SuperCDMS (and MINOS) experiments.

With the departure of SuperCDMS from SUL and the completion of MINOS, underground outreach activities have ceased. However, the Ash River SUL group, under the leadership of Prof. Richard Gran (U. Minnesota-Duluth) is continuing outreach activities at a nearby NOvA site, with plans for a NOvA-centric summer program. The SUL Outreach Education Coordinator reports that public audiences and science educators are intensely interested in SuperCDMS science, and staying current with SuperCDMS SNOLAB is a priority. SuperCDMS will team with the Ash River SUL group (see the attached letter of collaboration) as a perfect conduit to continue our SUL Minnesota outreach. We will provide the Ash River SUL group SuperCDMS support and materials including posters, and virtual tours focused on the history of dark matter and neutrino physics. SuperCDMS will also enable the NOvA SUL group to effectively speak about dark matter by continuing to develop answers to commonly asked dark matter questions.

SuperCDMS is already reaching out to the public at the future experimental site, SNOLAB, and envisions growing that outreach during the timescale of this proposal to a level similar to the Soudan outreach. SuperCDMS is currently engaging SNOLAB tour groups by displaying a poster at a regular tour stop in the underground lab. In addition, SuperCDMS is highlighted in the SNOLAB NewEyes on the Universe, an interactive, mobile exhibit, which debuted in London, England, in July 2016.

SuperCDMSs SNOLAB education and outreach will ramp up on a timescale parallel to its operational ramp. SuperCDMS will increase the impact on underground tours by developing an interactive display that enables tour members to explore the question of dark matter and the SuperCDMS experiment. SNOLAB has developed an online virtual tour that enables the general public to tour the SNOLAB underground lab remotely, be it from home, school, museum or community center.

The Ladder Labs area, which will house SuperCDMS, is already featured in the virtual tour. SuperCDMS will explore ways to strengthen its engagement with virtual tourists including virtual science treasure hunts. These hunts will be designed to tell the science stories behind SuperCDMSs search for dark matter. For example, one hunt will follow the life story of a dark matter detector as it is built at TAMU, tested at Berkeley, and installed at SNOLAB. Another will tell the story of the importance of eliminating radioactive backgrounds and how the SMU and SDM&T groups are helping to solve this problem for SNOLAB. These virtual tours will be augmented by a web presence and social media platforms, making the science compelling and accessible to teachers, students and the general public.

We will coordinate our outreach efforts with the SNOLAB education and outreach team to leverage resources. For example, each year, high school students enroll in the International Summer School for Young Physicists. The students spend part of their time on underground science tours at SNOLAB. SuperCDMS graduate students and postdocs will serve as science guides for these students during the time underground. Each summer, the Tri-Institute Summer School on Elementary Particles (TRISEP) is held at Laurentian University in Sudbury. We will participate by sending graduate students to TRISEP and offering SuperCDMS faculty to serve as TRISEP educators.

The 2017 TAUP conference will be held in Sudbury, and we anticipate using TAUP as a launching point for faculty and student involvement at SNOLAB. In addition, we will participate in SNOLAB education and outreach programs as opportunities arise and will provide outreach materials to SNOLAB.

SuperCDMS will broaden its scope of outreach to also include the Sanford Underground Research Facility (SURF). At SURF, the USD and SDSM&T PIs are working with the SURF E&O team to coordinate an outreach program beginning with a presence at SURF Neutrino Day. Neutrino

Day is an annual outreach event at SURF that has live science demonstrations and talks that directly reaches about 1,000 people and indirectly reaches tens of thousands through resulting media coverage including a live South Dakota Public Radio broadcast.

In addition, we will develop six dark matter education modules for integration of SuperCDMS science into the SURF Search for Dark Matter middle school curriculum. These units are designed to aid teachers in the classroom and fill a South Dakota educational requirement. It is part of SURFs strategic plan to expand these beyond South Dakota. The Berkeley group will look into how three of these modules can be modified to accommodate California educational standards, and the Northwestern U. group is willing to host three of these modules for use by educators in the Chicagoland area. We will support a SURF education person to travel to Sudbury to provide teachers with a 2 to 3 day professional development workshop on the implementation of the curriculum materials.

Another priority is to establish an alliance with Sudbury's First Nations communities for the sharing of science education. This is of interest to the outreach division at SNOLAB, and SuperCDMS has already expressed interest in working with them on development. CDMS at Berkeley has experience in this area through an established association with the founder and leadership team of the Native American Science Academy. Through this alliance, SuperCDMS will also develop channels to integrate SuperCDMS science with indigenous science education in the US.

11 Results from Prior NSF Support

In this section we describe the results from prior NSF support, divided by institution. Note that Co-PI J. Sander has not recieved NSF Funding in the last 5 years, and that Co-PI M. Pyle was funded through a Berkeley award as a postdoctoral researcher.

11.1 Northwestern University, PI E. Figueroa-Feliciano

PHY-1408089, PHY-1550658
Dark Matter and Neutrino Physics with Cryogenic Detectors
Period of Support: 7/2014–8/2017, transferred from MIT to Northwestern as PHY-1550658 when Figueroa-Feliciano moved to Northwestern. Amount of Support: $330,535
Publications: [19, 23, 53, 54, 55, 56, 57, 58, 59, 25, 22]
Data products from this work are available at the SuperCDMS collaboration's publications website [60] and the Figueroa group's website [61].

11.1.1 Intellectual merit

This grant supports students and scientists working on an experiment that will address one of the most fundamental problems of modern science, the nature of dark matter. The SuperCDMS SNOLAB experiment will achieve world-leading sensitivity for dark matter searches in the 1–10 GeV/c^2 mass range.

Analyses of CDMS II data demonstrated the power of improved analysis techniques [57, 54], and provided limits for alternate dark matter models [58]. It also revealed a possible signal on Si [31], the analysis and publication of which was lead by the Figueroa Group, then at MIT. Operation of 15 SuperCDMS "iZIP" detectors at Soudan since 2012 demonstrated the detectors' rejection capabilities [62] and yielded world-leading sensitivity to low-mass DM [36, 22, 23]. Our group designed the masks used to fabricate the detectors in SuperCDMS Soudan, had major roles in the rejection capability analysis, and led the low-treshold analysis [22] from SuperCDMS Soudan. The first operation of a single ("CDMSlite") detector with a high voltage bias provided the world's most constraining limits for DM masses below 6 GeV/c^2 by achieving an extremely low energy threshold of 170 eV electron-recoil energy [36]. A second run of the detector reached an energy threshold for electron recoils as low as 56 eV and demonstrated the power of a fiducialization cut [23]. The Figueroa Group developed key data quality cuts for the first two CDMSlite run analyses, and is currently involved in the analysis of the third run.

The Figueroa Group made the first map of the so-called "neutrino floor" in the WIMP-nucleon cross section vs WIMP mass plane [63]. As part of this grant the group has expanded this work to study complementarity and the effect of target on the neutrino floor [25], and contributed to a study on moving beyond the neutrino floor with directional detection [53]. We also looked at the prospects of neutrino physics with dark matter searches [59].

On the R&D effort, the Figueroa Group has continued studying the active veto concept. As part of this grant, they developed a GEANT4 Monte Carlo of both a bucket scintillator and Ge ring veto concepts. They also made a design of a CDMS holder that will enable a test of a ring veto in a standard CDMS II tower. Another R&D effort has focused on the preparation of the ADR cryogenic system that will be made available for use for the TUNL calibration campaign described in Section 7.1.2. In addition, the Northwestern group has collaborated with the UF and Fermilab groups in the studies and simulations leading to the optimization and design of the calibration campaign described in this proposal.

11.1.2 Broader impacts

This grant strongly contributes to the training of undergraduate and graduate students and post-doctoral researchers, continuing the group's strong involvement in mentoring undergraduates from underrepresented groups by participating in the Summer Research Opportunities Program (SROP), which brings undergraduates from across the U.S. to do a summer of research at Northwestern. The group is also working to develop summer schools for training graduate students and postdocs at the "Colegio de Física Fundamental e Interdiciplinaria de las Americas" (COFI), located in San Juan, Puerto Rico.

11.2 UC Berkeley, PI B. Sadoulet

We summarize here the scientific and broader impact results obtained with NSF support at Berkeley over the past five years. Our group has been supported by awards PHY-1102841 (Jul 1, 2011-Jun 30, 2014, $1,260,000, Experimental Particle Cosmology), and PHY-1408597 (Aug 15, 2014- Jul 31 2017, $1,177,400, Experimental Particle Cosmology). SuperCDMS Soudan has been supported by the NSF project award PHY-0902182 (Jul 1, 2010-Jun 30, 2013, SuperCDMS Soudan, $1,833,707) and operation award PHY-1004714 (Oct 2011-Sept 2013, SuperCDMS Operation at Soudan, $1,154,213) with UC Berkeley as the lead institution (PI B. Sadoulet) and subcontracts to MIT, Santa Clara U., Syracuse U., U. Colorado-Denver, U. Florida, and U. Minnesota-Duluth. In addition, Berkeley (PI B. Sadoulet) has been the lead NSF institution for the R&D toward SuperCDMS at SNOLAB (PHY-1242645, Sep 1, 2012- Aug 31, 2014, R&D toward SuperCDMS at SNOLAB, $2,912,376) with subcontracts to MIT, Santa Clara U., and U. Colorado-Denver. Currently, Berkeley (PI B. Sadoulet) is the NSF lead institution of the SuperCDMS SNOLAB project (PHY-1415388, May 1, 2015-Apr 30, 2019, SuperCDMS SNOLAB, $12,000,000) with subcontracts to Santa Clara U., U.

Colorado-Denver, Stanford and SLAC, Texas A&M, and U. of Minnesota-Twin Cities.

11.2.1 Intellectual Merit

SuperCDMS Soudan Science

Over the past five years, SuperCDMS Soudan has led the field in the search for low mass DM (<10 GeV/c^2) [23, 22, 36]. Berkeley's contributions to this science output are delineated below:

- All prototype testing of the SuperCDMS Soudan iZIP for performance as well as the functional testing of every iZIP detector operated at Soudan was done in the Berkeley test facility.
- Matt Pyle personally designed, tested, and optimized the SuperCDMS iZIP and 3 earlier generation prototype devices as part of his dissertation work [64]. Fiducialization cuts used in [23, 22] were largely based on this work.
- Bruno Serfass led the analysis effort during detector commissioning at Soudan and coordinates the collaboration wide software and computing group.
- Berkeley graduate student Todd Doughty led the underground ER/NR discrimination studies [62] as well as the SuperCDMS Soudan high mass dark matter analysis (to be published soon).
- Berkeley led the optimization of the hardware trigger bandwidth for slower athermal phonon collection of the iZIP that decreased the energy threshold in our low energy analysis [23].

11.2.2 SuperCDMS SNOLAB Detector and Electronics R&D

- Berkeley developed complex impedance based techniques to distinguish the coupling mechanisms of the cryocooler noise at Soudan. Furthermore, via active measurement of the vibrational sensitivity of current athermal phonon detector technology, it has developed a vibrational specification for the SuperCDMS SNOLAB facility.
- Dark current as a function of voltage bias has been measured for 5 test detectors at the Berkeley test facility. With this data, IR production and surface tunneling hypotheses have been disfavored.
- The Berkeley group developed analytical detector modeling and sensitivity code for both the SuperCDMS iZIP and HV detectors that was used throughout the SuperCDMS design process (Fig. 1) and which has recently been submitted for publication [?]. A major upgrade to these sensitivity estimates, which is complete and soon to be published, models the quantization of ionization production which could potentially be used for ER/NR discrimination.
- In CDMS-II and SuperCDMS Soudan, the labor associated with manual testing of a detector was substantial. As such, the SuperCDMS project has highlighted full automation of detector testing as a priority. The Berkeley group has written semi-automated SQUID biasing and TES tuning routines and a fully automated version should be operational in FY17.
- The SuperCDMS SNOLAB iZIP low mass sensitivity is largely determined by electronic noise in the ionization signal readout amplifier. In recent years, our collaborators at CNRS/LPN have developed low-noise, low-power high electron mobility transistors (HEMTs) with better low frequency noise performance than can be achieved with Si based JFETs. Berkeley has designed and built a HEMT-based charge amplifier located entirely at 4K to minimize the susceptibility to environmental noise pickup. HEMT switches have also been implemented to allow for the removal of the feedback resistor. We obtained a r.m.s. of 91 eV_{ee} which exceeds the SuperCDMS SNOLAB goal requirement. The HEMT switch is currently under study for possible inclusion in the project baseline.

11.2.3 Broader Impacts

Since 2004, the Berkeley group has partnered with the Level Playing Field Institute to support the Summer Math and Science Honors (SMASH) Academy, an enrichment program for high-achieving students of color from underserved Bay Area communities. The group hosts a course for the incoming SMASH cohort, which engages them in research projects with STEM grad students, many of whom are from underrepresented groups. The Berkeley group participates regularly in campus and community-based outreach activities, described in more detail in Section 6.3 and is involved in the collaboration based outreach at Soudan.

11.3 CU Denver, PI M. Huber

The direct awards to CU Denver are NSF/PHY-1102795, "SQUID-based Readout Systems for Cryogenic Dark Matter Detectors" ($163,711, July 1, 2011-June 30, 2015), and NSF/PHY-1408414, "Readout Systems for Cryogenic Dark Matter Detectors" ($148,893, September 15, 2014-August 31, 2017). This work has resulted in publications [31, 62, 36, 22, 58, 57, 23, 54].

11.3.1 Intellectual Merit

The CU Denver group has played a prominent role in all aspects of the phonon readout system, utilizing the PI's extensive experience in SQUID design, characterization, and room-temperature electronics. The group supported operation of the SuperCDMS Soudan facility through it's decomissioning, conducted research and development toward the SuperCDMS SNOLAB experiment, and pursued R&D avenues with a view of improving detector readout for future CDMS programs. The group supports undergraduate education through extensive participation by Physics and Electrical Engineering majors in its various activities.

A primary activity of CU Denver has been the evaluation of Superconducting Quantum Interference Device (SQUID) series array preamplifiers. The microfabricated SQUIDs are a key component of the phonon readout system. The CU Denver group has advanced understanding of the requirements for phonon readout systems for the iZIP and HV detectors. In collaboration with NIST-Boulder, work by the CU Denver team contributed to the design of the next-generation SQUID array amplifier readout prototype. Intensive study of these prototypes, including measurement of the input self-inductance, dynamic resistance, equivalent input current noise, and closed-loop circuit bandwidth, allowed for a selection of the final design for the engineering detector tower. Precision measurement of the self inductances of the input and feedback coils, the mutual inductance between input and feedback coils, and the mutual inductance of each coil to the SQUID fed into a model of the equivalent circuit of the TES + SQUID system. Knowledge of these inductances informed design of the cold electronics striplines and connectors, by way of determining allowable levels of parasitic inductances on the input circuit. The resulting model and transfer function enabled simulation of the warm and cold electronics phonon readout system, which was essential in design of the warm-electronics circuit. These prototype tests also resulted in statistics for quantitative characteristics, qualitative metrics, and fabrication yield information. This process led to a standardized reporting format for characterizing the engineering-grade devices. To date, CU Denver has tested all of the ∼100 devices required for the Detector Tower engineering model and associated work at collaboration test facilities. The characterization has included the dc transfer function, ac (noise) performance, and measurement of other parameters of the SQUID arrays.

CU Denver has participated in the continued development of room-temperature electronics for

SQUID and TES readout. This participation has included measurements on the bench and with cold SQUIDs of the performance of the warm electronics. These tests contributed to further development by FNAL of the Detector Control and Readout Card (DCRC) for SuperCDMS SNOLAB. From the testing of the prototype DCRCs, the CU Denver group found that the noise levels and bandwidth are acceptable only if used with passive filtering. This and other testing informed the design of further generations of the warm electronics. With the FNAL and SLAC staff, the UC Denver group evaluated the schematics and design for the next-generation DCRC, which was expanded to operate 12 phonon channels (compared to the four previously), requiring a significant redesign of the circuit. The proposed circuit was evaluated to ensure it meets the technical requirements of the experiment. As a part of this evaluation, a member of the UC Denver team traveled to UC Berkeley to assist in testing the noise performance of the DCRC.

CU Denver began studies of compatibility of the SuperCDMS SNOLAB SQUIDs for planned SuperCDMS high-voltage operation, which could require voltages that are internal to the SQUID circuit for which the devices were not designed. These studies included testing and development of instrumentation for high-voltage tests, and measurement of the voltage limit beyond which breakdown in the SQUID chip occurs. These tests contributed to the decision by the collaboration to set these high voltages by floating all of the warm electronics associated with a given detector side, so that there would be no large potential differences on an individual SQUID chip.

The CU Denver group conducted extensive tests on the performance of the SuperCDMS SNOLAB SQUID arrays in various shielding environments. This testing included use of a large external high-permeability shield, close-in nested cryoperm cans, a close-in aluminum can, and a Faraday cage around the test probe. Additionally tests were done on the effects of certain metals (nickel and copper) in the vicinity of the SQUIDs, to provide information on the use of these materials in the cold-hardware design. From the tests on magnetic shielding and SQUID sensitivity, at Soudan and in Denver, the CU Denver group found that the SQUIDs used in Soudan are sensitive to ac magnetic fields with an amplitude ($\sim$0.7 mG) similar to ambient fields found at the experiment site. The SNOLAB SQUIDs, which have a different design, were found to be less sensitive ($\sim$1.9 mG) to magnetic noise pickup. The CU Denver group also measured the stability at cryogenic temperatures of candidate shunt resistors to be used for the TES circuit in the detector towers.

The CU Denver group investigated the feasibility of a SQUID-based charge-pulse readout for CDMS. The resonant frequencies of the coils of a superconducting transformer, which was fabricated by the group, were measured using a vector network analyzer. The work was concluded when the use of HEMTs for charge readout, rather than SQUIDs, was chosen.

CU Denver supported operation of SuperCDMS Soudan through regular shifts at the experimental site in the Soudan Underground Laboratory. The PI and the Senior Engineer both served multiple on-site shifts at Soudan.

11.3.2 Broader impacts

The CU Denver Physics Department maintains an undergraduate-only program committed to providing students with hands-on research experience at this urban campus. Electrical Engineering and Mechanical Engineering students have also participated in internships in the CU Denver lab. Minorities and first-generation college students have been well represented in these internships, and many of the PI's mentees have proceeded to graduate school in physics and other disciplines, or embarked on careers in industry at companies such as Northrop Grumman and the Lockheed Martin

Corporation. In the preceding five years, there have continually been six to eight undergraduates in the Huber group.

At CU Denver, the PI has participated with a local magnet school, the Logan School for Creative Learning, in their field trip program. Students in grades 5 - 8 have participated in small group discussions with him on topics of interest to them in the field of physics, followed by a tour of the laboratory. Their conversations with Huber and their tours of the lab are key components of presentations they give to their classmates and other visitors during the school's annual EXPO event. Students from other local middle schools and high schools have also participated in the lab's activities.

The CU Denver PI has presented public talks on dark matter and the CDMS experiment at institutional and other local venues, which have included the CU Denver Mini-STEM School and the Denver Cafe Scientifique. He has a standing invitation to return for future talks at Cafe Scientifique. The CU Denver senior engineer gave a talk to a local Rotary Club about the search for dark matter and CU Denver's involvement, addressing about 100 business and cultural leaders of the communitiy.

11.4 SuperCDMS Collaboration Broader Impacts

The SuperCDMS experimental and R&D efforts advance phonon-mediated detectors and new active veto concepts, which have already found many applications in cosmology, astronomy and industry. Collaboration wide, a priority is the education of the groups' undergraduate and graduate students and postdoctoral scholars, providing them with opportunities to explore and advance in many fields. The success of this emphasis is evidenced in the high level of professional advancement of these students and postdocs, to careers as faculty, research scientists and technology experts in industry. SuperCDMS PIs participate in programs to support K-12 students and teachers in their local schools, on campus and directly in the lab. At the core of many of the programs is engagement of students from disadvantaged backgrounds and underrepresented groups, including women. These programs include summer research internships, a program engaging underserved high school students of color in research projects, mini-courses to prepare Native American students for postsecondary education in science and engineering, and structured courses in physics for high school teachers. SuperCDMS groups have actively engaged in efforts to share SuperCDMS science with the public, through lectures on dark matter at diverse venues, including campus lecture halls, science cafes and civic organizations. The groups regularly participate in outreach events on campus, at community festivals, science fairs and science camps. Activities include lab tours and hands-on physics demonstrations. SuperCDMS scientists have been featured in the media, including NPR's Science Friday and in the popular press.

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