Mid-scale RI-1 (M1:IP): DarkSide

(Directorate for Mathematical and Physical Sciences/Division of Physics)

OVERVIEW: Gravitational effects that cannot be explained by visible matter are well-documented, though their source remains unknown. A well-motivated explanation for these observations is the existence of an as-yet-undiscovered elementary Weakly Interacting Massive Particle (WIMP). The motion of galactic halo WIMPs relative to a detector on Earth could result in WIMP-nucleus elastic collisions detectable by a low-background, low-threshold detector capable of unambiguously identifying a small number of nuclear recoils over the course of a very large exposure.

This proposal requests support for the DarkSide-20k (DS-20k) detector, a liquid argon time projection chamber (LAr TPC) designed to achieve leading sensitivity to high-mass (above $30\,\mathrm{GeV}/c^2$) WIMP dark matter, and Urania plant for the high volume extraction of low-radioactivity argon from an underground source (UAr). The DarkSide-20k project is being pursued by the Global Argon Dark Matter Collaboration (GADMC), a unification of the DarkSide, DEAP-3600, MiniCLEAN, and ArDM collaborations into a single, world-wide effort focused on argon dark matter searches. The project was approved in 2017 by the US NSF and the Italian INFN and is officially supported by LNGS, LSC, and SNOLAB. The DS-20k Project Execution Plan was approved by an international committee charged by INFN and NSF prior to the experiment's approval and a revised and updated version of the plan is included in this proposal. This proposal requests funding for pieces of infrastructure that are the direct responsibility of the US NSF-funded groups.

DS-20k experiment builds on the success of the DarkSide-50 (DS-50) and DEAP-3600 experiments, that have performed background-free searches for WIMP dark matter using large exposures of liquid argon. DS-50 has demonstrated that using UAr lowers the rate of ^{39}Ar events by a factor of 1400. DEAP-3600 has shown that electron recoil background events in the region of interest can be identified with discrimination better than 1 part in 10^9. Combined results from the two DS-50 runs demonstrate the ability of large LAr TPCs to operate in an "instrumental background-free mode," a mode in which fewer than <0.1 events (other than nuclear recoils from elastic scattering of atmospheric and diffuse supernova background neutrinos) are expected in the region of interest for the planned exposure of DS-20k detector.

INTELLECTUAL MERIT: DS-20k detector will have ultra-low background and the ability to measure its background rates *in situ*, resulting in an expected sensitivity to WIMP-nucleon cross sections of $7.4 \times 10^{-48}\,\mathrm{cm}^2$ ($6.9 \times 10^{-47}\,\mathrm{cm}^2$) for $1\,\mathrm{TeV}/c^2$ ($10\,\mathrm{TeV}/c^2$) WIMPs following a decade-long run with a total exposure of $200\,\mathrm{t\,yr}$. The projected $5\,\sigma$ discovery reach extends a factor of five below that of LZ. DS-20k will either detect WIMP dark matter or exclude a large fraction of the favored parameter space. It will also be sensitive to a galactic supernova neutrino burst, and will lay the groundwork for a future, multi-hundred tonne argon experiment, Argo, designed to complete the search for WIMPs through the so-called "neutrino floor" and measure low-energy solar and supernova neutrinos with high precision. The infrastructure of DarkSide-20k project will also enable DarkSide-LowMass, which, building upon the world-leading low-mass dark matter results of DS-50, is expected to dominate searches for WIMPs with masses below $10\,\mathrm{GeV}/c^2$.

BROADER IMPACT: Scientific broader impacts of the project include the discovery of a novel, commercially viable helium source that today supplies 15 % of the US production; the production of hundreds of tonnes of low-radioactivity UAr for DS-20k as well as for other technical uses including nuclear test ban verification and radiometric dating; and the development of low-background, large-area, single-photon, cryogenic photosensors. The planned Aria project for UAr purification may improve the worldwide availability of valuable stable rare isotopes such as ^{18}O, ^{15}N, and ^{13}C, which are used for various medical, industrial, and energy generation applications. LAr TPC technology has led to 3Dπ, an innovative, patent-pending LAr-based TOF-PET system that can enhance cancer screening sensitivity while dramatically lowering patient radiation dose.

Specific E&O programs are planned as part of the program with a focus on educating K-12 teachers about basic physics and its relation to dark matter detection, re-starting a summer school experience for high-school and undergraduate students, and giving education and training opportunities to undergraduate students at participating underrepresented-minority serving institutions.

I. INTELLECTUAL MERIT

1. Scientific Justification

This proposal is best categorized as an RI-1 Implementation Project (M1:IP). It seeks funding to support the development of infrastructure, the procurement of major equipment, and the construction and commissioning of the DarkSide-20k (DS-20k) detector and Urania plant. This funding will constitute the majority of the capital support for U.S. involvement in the project. The following will detail how the implementation of DarkSide-20k project will directly contribute to advances in fundamental science, engineering, technology, and other STEM related research and education.

There is strong evidence from astronomical and cosmological observations for the existence of dark matter in our Universe. Weakly Interacting Massive Particles (WIMPs) are a well-motivated dark matter candidate that may have been produced in the early Universe but are so massive and weakly interacting that they have yet to be observed in a terrestrial experiment. The observation of WIMPs with masses up to about 1 TeV/c^2 is a major objective of the experimental program at the High Luminosity Large Hadron Collider. Future high energy colliders like the FCC-*hh* (Future Circular Collider) will be able to extend these searches up to the $10\,\mathrm{TeV}/c^2$ mass range [1]. Direct and indirect dark matter detection techniques allow for a search program complementary to future colliders. For example, the direct detection of dark matter via elastic scattering of galactic WIMPs from a liquid argon target is a demonstrated technique capable of probing energies well above the reach of the LHC.

Liquid argon (LAr) is a particularly favorable target for the detection of WIMPs thanks to its excellent event discrimination capabilities. Scintillation light generated by particles recoiling from atomic electrons (ERs), the primary source of background in a WIMP direct detection experiment, has a time constant of several microseconds. This is in stark contrast to the nanosecond time constant of scintillation light emitted during an expected WIMP-nuclear recoil event (NR). The DEAP-3600 experiment has exploited this effect via pulse shape discrimination (PSD) to achieve ER background rejection in excess of 10^9 [2, 3]. Additional event discrimination in an argon-based detector was demonstrated by the DarkSide-50 (DS-50) experiment, which uses a two-phase time projection chamber to measure both the prompt argon scintillation light and the ionized electrons resulting from a particle interaction in the detector. This technique provides excellent position resolution and efficient detector fiducialization while maintaining PSD capabilities [4, 5]. DS-50 has performed a blind analysis of their data and observed no background events over a run period in excess of two years [6]. In addition to sensitivity to WIMPs with masses above $30\,\mathrm{GeV}/c^2$, the two-phase DS-50 detector has extended its reach to WIMP masses below $10\,\mathrm{GeV}/c^2$ by detecting single ionized electrons extracted from the liquid argon volume [7, 8]. With careful control of ER background from local radioactivity and a reduction of the ^{39}Ar background, a 1 t LAr detector has the potential to reach the “neutrino floor” of solar neutrinos in this low-mass parameter space.

Given the potential reach of an argon-based detector, scientists from all of the major groups currently using LAr to search for dark matter, including ArDM, DS-50, DEAP-3600, and MiniCLEAN, have joined to form the Global Argon Dark Matter Collaboration (GADMC) with a goal of building a series of future experiments that maximally exploit the advantages of LAr as a detector target. To this end, the GADMC is developing several novel facilities and techniques. The Urania plant will extract low-radioactivity argon from underground (UAr) that is naturally depleted in ^{39}Ar, the primary intrinsic background in argon extracted from the atmosphere. The Aria cryogenic distillation column will enable the high-throughput purification and active isotopic separation of argon, further reducing ^{39}Ar levels and other impurities. Light detection will be done using large-area, cryogenic photodetector modules (PDMs) made with silicon photomultipliers (SiPMs) optimized for use in LAr and assembled in a custom-built factory. A sealed radio-pure polymethyl methacrylate (PMMA) vessel will enclose the TPC, and the entire assembly will operate inside of a membrane cryostat, a technology developed at CERN for ProtoDUNE, filled with liquified atmospheric argon and operated as a veto detector.

The immediate objective of the GADMC is construction of the DS-20k two-phase LAr detector, which will operate at the Gran Sasso National Laboratory (LNGS). DS-20k detector will have ultra-low backgrounds and the ability to measure its backgrounds *in situ*, resulting in an expected sensitivity to WIMP-nucleon cross sections of $1.2 \times 10^{-47}\,\mathrm{cm}^2$ ($1.1 \times 10^{-46}\,\mathrm{cm}^2$) for $1\,\mathrm{TeV}/c^2$ ($10\,\mathrm{TeV}/c^2$) WIMPs following a 5 yr run with a total exposure of 100 t yr. This projected sensitivity is a factor of >50 better than currently-published results above $1\,\mathrm{TeV}/c^2$and covers a large fraction of the parameter space currently preferred by supersymmetric models. During the 100 t yr exposure, 1.6 NR events are expected from the coherent scattering of atmospheric neutrinos, making DS-20k the first ever direct dark matter detection experiment to reach this milestone. The sensitivity would further improve to $7.4 \times 10^{-48}\,\mathrm{cm}^2$ ($6.9 \times 10^{-47}\,\mathrm{cm}^2$) for $1\,\mathrm{TeV}/c^2$ ($10\,\mathrm{TeV}/c^2$) WIMPs for a decade-long run with a 200 t yr exposure, see Fig. 1. DS-20k experiment is foreseen to begin operating in 2022 and will either detect WIMP dark matter or exclude a large fraction of favored WIMP parameter space. As shown in Fig. 2, DS-20k experiment will have discovery sensitivity at the 5σ level for cross sections much below that probed by the LZ and Xenon-nT experiments and for dark matter masses above the reach of the LHC.

In parallel to DS-20k detector, the GADMC collaboration will pursue the development of an approximately 1 t detector specifically optimized for the detection of low-mass dark matter, DarkSide-LowMass (DS-LM). This detector will be developed at CERN and likely installed and operated at LNGS. DS-LM will achieve a lower energy threshold than DS-20k by triggering on the electroluminescence signal from ionized electrons, thereby adding sensitivity to WIMP masses below $10\,\mathrm{GeV}/c^2$ at the expense of the PSD power afforded by argon prompt scintillation light. Without PSD, contributors to the ER background in DS-LM must be reduced beyond the requirements of DS-20k through careful detector design and material selection. Based on the world-leading sensitivity for low-mass dark matter achieved with DS-50 coupled with the ^{39}Ar reduction by distillation available in Aria and the use of a massive AAr veto, this dedicated low-mass detector would have the ability to reach through the so-called "neutrino floor" in the low-mass search region, see Fig. 1. While DS-LM will be developed by the GADMC, the major funding for this effort will be

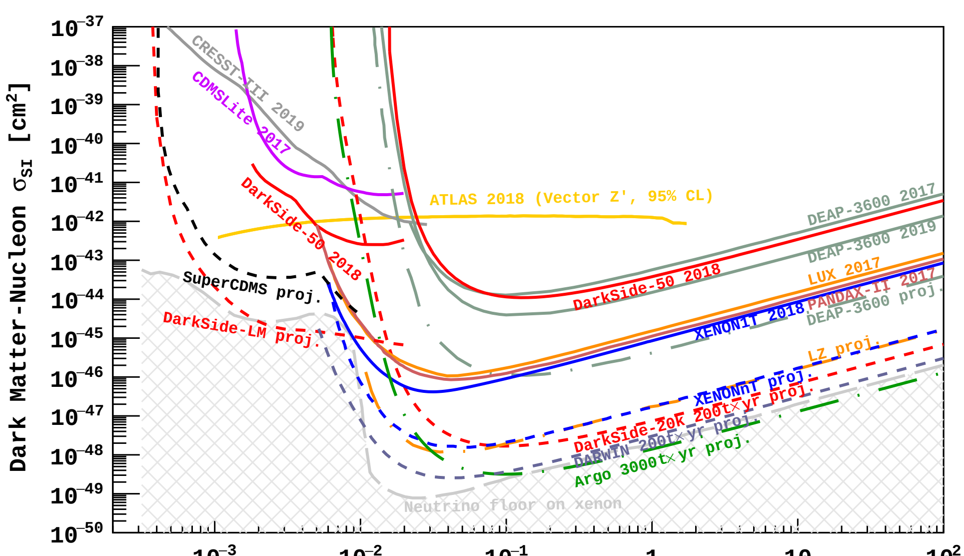

FIG. 1. 90 % C.L. exclusion limits showing leading results from direct (continuous lines, Ref. [6, 7, 9–12]) and accelerator-based dark matter searches (region above the yellow line [13]) compared with sensitivities of future germanium-, xenon-, and argon-based direct searches (dashed lines, Ref. [14–18] and this work). The "neutrino floor" curve follows the definition of Ref. [19]. The 95% C.L. limit from the ATLAS Experiment is shown for a benchmark model in which Dirac-fermion WIMPs interact with ordinary matter via a vector mediator[20] with coupling strengths to quarks, leptons and WIMPs of 0.25, 0.01, and 1, respectively.

requested via alternative funding programs.

The ultimate objective of the GADMC is the construction of the Argo detector, which will have a 300 t fiducial mass and will push the experimental sensitivity to the point at which the coherent scattering of atmospheric neutrinos becomes a limiting background. The excellent ER rejection possible in argon will eliminate backgrounds from solar neutrinos, which will extend the sensitivity of Argo beyond that of technologies with more limited ER discrimination. The throughput of the Urania plant and Aria facility will enable 400 t of UAr to be extracted and purified over a period of about 6 yr. At the depth of SNOLAB, Argo could perform a dark matter search and observe ultra-rare solar neutrino sources (CNO, *hep*) [21]. While the construction of Argo is not within the scope of this proposal, the implementation of DarkSide-20k project will pave the way for the development of Argo towards the end of the next decade. Combined DS-20k, DS-LM, and Argo, will completely cover the spin-independent WIMP hypothesis parameter space down to the neutrino floor for WIMP masses from $1\,\mathrm{GeV}/c^2$ to several hundreds of TeV/c^2.

1. Comparison with Xenon-Based Experiments and the "Neutrino Floor"

Next generation dark matter experiments will be sensitive to several sources of neutrinos via $\nu - e$ elastic scattering (ER) and coherent elastic neutrino scattering (CEνNS) on nuclei (NR). Atmospheric and diffuse supernovae neutrinos, which due to their high energies can produce NRs in excess of $20\,\mathrm{keV_{nr}}$, will be the dominant CEνNS background contributor for WIMP masses above $30\,\mathrm{GeV}/c^2$. Solar neutrinos are the main CEνNS background for dark matter masses below $10\,\mathrm{GeV}/c^2$. With argon's ability to discriminate ER from NR to better than a part in 10^9, CEνNS represents the only irreducible background for a large exposure argon dark matter search. The neutrino background is exacerbated in liquid xenon detectors, which, due to their limited ER rejection power, accept a non-negligible number of $\nu - e$ elastic scatters as signal.

When calculating the discovery sensitivity of a large dark matter search experiment, one must fully account for the presence of neutrino-induced backgrounds. We note that the position of the "neutrino floor", initially conceived as indicative of the maximum sensitivity attainable by an experiment in the presence of CEνNS background, is critically dependent on the target, experimental technique, statistical analysis, neutrino flux uncertainty and theoretical cross section uncertainty. We therefore include a detailed accounting of the CEνNS and $\nu - e$ backgrounds in the sensitivity and discovery potential curves shown in Fig. 1 and Fig. 2. We conservatively estimate a 20 % uncertainty on the neutrino background for high-mass ($30\,\mathrm{GeV}/c^2$) searches with Argo. This accounts for a 15 % uncertainty on the atmospheric neutrino flux at mid-latitude locations, such as SNOLAB or LNGS, based on the latest data-driven models of cosmic primaries [22] as well as models of solar cycle, seasonal, geographic, and geomagnetic dependence of the neutrino flux [23, 24]. Additionally, we account for a 5 % theoretical uncertainty on the Standard Model interaction cross-section, driven by uncertainties on the nuclear form factor and the expected constraints that the COHERENT collaboration will place on non-Standard Model contributions using a LAr target [25], which in turn is driven by their current 10 % uncertainty on neutrino flux [26] and a 6 % uncertainty on the LAr response as measured by SCENE [27, 28] and ARIS [29]. Planned improvements of COHERENT, including a sharper characterization of the neutrino flux and a measurement with a LAr target, would further reduce the uncertainty on the neutrino background below 10 %, strongly benefiting the DS-20k, and Argo experiments.

Within this framework, we calculate the 5σ discovery potential for DS-20k and Argo and compare it with that of the near-future LXe experiment LZ [30]. As seen from Fig. 2, DS-20k has significantly greater discovery potential than that of LZ.

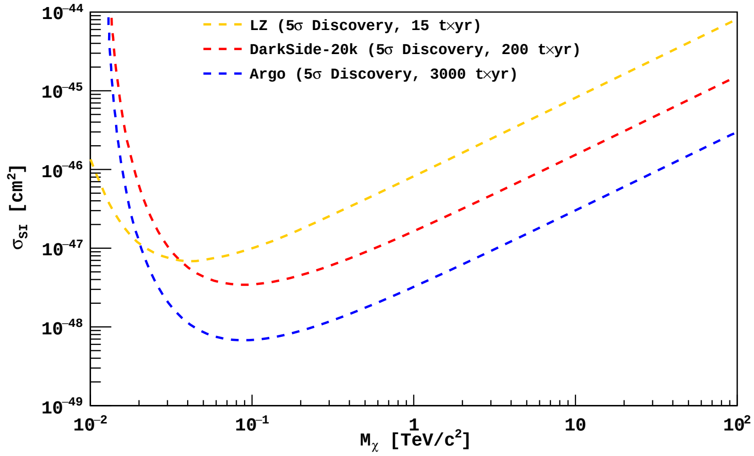

FIG. 2. 5σ discovery potential of the leading future noble liquid dark matter searches.

2. New Technologies

The following technologies are key to the success of DarkSide-20k project and the long term scientific goals of the GADMC. Their development will also have potentially wide-reaching effects within the physics community.

Low-radioactivity underground argon with Urania [31]: The DS-50 experiment established that UAr is depleted of ^{39}Ar by a factor of approximately 1400, a sufficiently low rate to be deployed in a detector the size of DS-20k. However, constructing DS-20k will require that large amounts of UAr be procured in a timely fashion. This will be accomplished by Urania, an argon extraction and purification plant capable of extracting 250 kg/d of UAr. The Urania plant is fully funded by the INFN and will be built by a contracted vendor following specifications established by the Urania Project team. The tender process for the plant's final design, construction, and shipment to the installation site in Cortez, Colorado, is underway and will conclude by the of end of July 2019 with the selection of a contractor. The preparation of the extraction site, as well as the installation and commissioning of the plant, falls under the responsibility of the U.S. NSF-supported groups. The Urania UAr extraction plant is projected to collect approximately 50 t of argon for use in DS-20k detector by 2022 and could continue to produce underground argon for Argo and other interested particle physics experiments that require UAr to achieve their scientific objectives.

Purification and active depletion with Aria [31]: The Aria plant is a 350 m tall cryogenic distillation column that was designed to explore the possibility of chemically separating argon isotopes. The construction of Aria is fully supported by INFN and the Regione Autonoma della Sardegna.

SiPM-based cryogenic photosensors [31–33]: The development of low-background, large-area, cryogenic silicon photomultiplier (SiPM) detectors capable of replacing conventional photomultiplier tubes is critically important for achieving the desired sensitivity of DS-20k and other large-scale LAr-based experiments, including DUNE, and LXe-based detectors, such as nEXO [34] and NEXT [35–37]. The DS-20k photodetector modules will be assembled at the Nuova Officina Assergi (NOA), a dedicated cleanroom packaging facility that will have future utility for any experiment needing large volume silicon detector production.

ProtoDUNE liquid argon cryostat [38, 39]: DS-20k detector will operate within a membrane cryostat filled with liquefied atmospheric argon, a technology initially developed at CERN for ProtoDUNE. Eliminating the organic liquid scintillator veto used in DS-50 for the AAr veto has several advantages. With the the DS-20k LAr TPC directly immersed in AAr, the massive stainless steel vacuum cryostat necessary for DS-50, and its correspondingly large contribution of background events, can be replaced with a transparent, radio-pure PMMA vessel. Photodetector modules can then be mounted outside of the PMMA vessel, reducing their contribution to the background rate and simplifying their assembly strategy. The ProtoDUNE cryostat has the added advantage that it is scalable, making it a technology appropriate for Argo.

Sealed acrylic TPC [2, 40, 41]: The DEAP-3600 collaboration has extensive experience developing large, radio-pure sealed PMMA vessels. This technology will be used to build the vessel for the DS-20k LAr TPC, eliminating the need for some of the most problematic radiogenic neutron contributors in DS-50, already mentioned stainless steel cryostat as well as the PTFE reflector. The PMMA vessel will also reduce the complexity of the TPC assembly.

2. Research Community Benefits

1. Relation to NSF's 10 Big Ideas

Growing Convergence Research: The GADMC was built to connect experts from a variety of disciplines to answer one of science's biggest questions: what is dark matter? The interdisciplinary collaboration consists of physicists from various sub-disciplines, engineers from a wide-range of specialties, chemists, and computer and data scientists. The GADMC has also built strong partnerships with a number of companies and foreign regional governments, which are either investing in the effort with funding or in-kind contributions. These connections bridge the gap between disparate professions and research groups operating at locations all over the world. This environment gives our students and young scientists broad exposure to an array of fields, professions, and cultures, helping them become experienced, versatile, and technically skilled researchers.

Harnessing the Data Revolution: As in many of today's large-scale particle physics experiments, many petabytes of physics, calibration, and monte carlo simulation data will be collected, analyzed, and stored over the course of the 5 year DS-20k operation. The collaboration is exploring new methods for storing and processing this data, including the use of machine learning algorithms for reconstruction, smart batch-data processing, and high-level physics analyses. The implementation of the DS-20k detector and its operation will expose a new generation of young researchers to big-data analysis.

Mid-scale Research Infrastructure: The DS-20k experiment falls under the definition of an NSF Mid-scale Research Infrastructure as outlined in NSF's "Bridging the Gap: Building a Sustained Approach to Mid-scale Research Infrastructure and Cyberinfrastructure at NSF." The 2015 DarkSide-20k proposal was approved by INFN and NSF in 2017 following a detailed review of the first version of the DarkSide-20k Project Execution Plan. LNGS also approved the experiment for installation in 2017. In 2018, DarkSide-20k project was approved as Recognized Experiment 37 (RE-37) at CERN. The DS-20k detector facility will be one of the most sensitive detectors in the world searching for WIMPs, enabling unique opportunities to train the next generation of the scientific workforce.

NSF INCLUDES: The U.S. DarkSide-20k effort will leverage the involvement of Fort Lewis College in Durango, Colorado, to increase inclusion of underrepresented groups. Since its founding in 1911, Fort Lewis College has demonstrated a unique commitment to the education of the local Native American population, in compliance with the deed that transferred the property of the former Fort Lewis from the Federal Government to the State of Colorado under condition that the land would be used for an educational institution, "to be maintained as an institution of learning to which Indian students will be admitted free of tuition and on an equality with white students" in perpetuity (Act of 61st Congress, 1911). With this proposal, we request support to re-establish the Princeton-Gran Sasso Summer School for Physics. In the US, we will target high-school seniors and college freshman students from the Cortez-Durango area, offering them a period of study at Princeton, followed by a research period spent either at the Colorado Urania facility, the Aria facility in Sardinia, at LNGS, or at CERN. This will expose them to otherwise unavailable on-site training and provide them with a network for pursuing job opportunities in the future, both through the project scientists and the companies partnered with the project. The participation of students from the Cortez-Durango area may be complemented with that of high-school students from the Italian regions of the argon trail, *i.e.* Sardegna and Abruzzo. Funds for the participation of the Italian students will be independently sought from Italian government sources.

Windows on the Universe: Recently, the Supernova Early Warning System (SNEWS) team submitted a proposal to the NSF Windows on the Universe solicitation for an upgrade to their system that enhance their capabilities. DS-20k was included in that proposal as a future partnering experiment that will work with the SNEWS network to detect galactic supernova neutrino bursts and provide an early warning of the incoming photon and gravitational wave signals. The DS-20k detector will have the unique ability to measure the supernova neutrinos in a flavor-blind way, meaning it will be able to constrain the total flux and the mean energy of the neutrinos over the duration of the burst. This measurement, coupled with the neutrino measurements of other experiments and the photon and gravitational wave measurements, will provide a multi-messenger probe of a galactic supernova capable of differentiating between explosion mechanisms, characterizing neutron stars, studying black hole formation, answering general questions in particle physics and astrophysics, and providing new insight into neutrino oscillations.

2. Community Recommendations

In the U.S., the 2014 report of the Particle Physics Project Prioritization Panel (P5) "Building for Discovery - Strategic Plan for U.S. Particle Physics in the Global Context" [42] acknowledges:

Technologies with major U.S. participation include: two-phase xenon; single- and two-phase argon; cryogenic germanium and silicon; bubble chambers; sodium iodide crystals; and directional time-projection chambers. The preeminent challenge in this field is the elimination of backgrounds, with approaches including the use of low background materials, self-shielding, particle identification, and astrophysical rate modulation.

It then states:

The experimental challenge of discovery and characterization of dark matter interactions with ordinary matter requires a multi-generational suite of progressively more sensitive and ambitious direct detection experiments. This is a highly competitive, rapidly evolving field with excellent potential for discovery. The second-generation direct detection experiments are ready to be designed and built, and should include the search for axions, and the search for low-mass (<10 GeV) and high-mass WIMPs. Several experiments are needed using multiple target materials to search the available spin-independent and spin-dependent parameter space. This suite of experiments should have substantial cross-section reach, as well as the ability to confirm or refute current anomalous results. Investment at a level substantially larger than that called for in the 2012 joint agency announcement of opportunity will be required for a program of this breadth.

And recommends:

Recommendation 19: Proceed immediately with a broad second-generation (G2) dark matter direct detection program with capabilities described in the text. Invest in this program at a level significantly above that called for in the 2012 joint agency announcement of opportunity.

It then states:

The results of G2 direct detection experiments and other contemporaneous dark matter searches will guide the technology and design of third-generation experiments. As the scale of these experiments grows to increase sensitivity, the experimental challenge of direct detection will still require complementary experimental techniques, and international cooperation will be warranted. The U.S. should host at least one of the third-generation experiments in this complementary global suite.

And also recommends:

Recommendation 20: Support one or more third-generation (G3) direct detection experiments, guided by the results of the preceding searches. Seek a globally complementary program and increased international partnership in G3 experiments.

In Europe, the “European Astroparticle Physics Strategy 2017-2026” [43] authored by the “Astroparticle Physics European Consortium” (APPEC) identifies the following as one of the key questions in Astroparticle Physics:

“The Dark Universe: What is the nature of Dark Matter and Dark Energy?”

In addition, it states:

Medium-scale Dark Matter and neutrino experiments: APPEC considers as its core assets the diverse, often ultra-precise and invariably ingenious suite of medium-scale laboratory experiments targeted at the discovery of extremely rare processes. These include experiments to detect the scattering of Dark Matter particles and neutrinoless double-beta decay, and direct measurement of neutrino mass using single-beta decay. Collectively, these searches must be pursued to the level of discovery, unless prevented by an irreducible background or an unrealistically high demand for capital investment.

It then adds:

Elucidating the nature of Dark Matter is a key priority at the leading tip of astroparticle physics. Among the plethora of subatomic particles proposed to explain the Dark Matter content of our Universe, one category stands out: the Weakly Interacting Massive Particle (WIMP). WIMPs arise naturally, for instance, in supersymmetric extensions of the Standard Model of particle physics. Many experiments located in deep-underground laboratories are searching for WIMP interactions. For masses in excess of a few GeV, the best sensitivity to WIMPs is reached with detectors that use ultra-pure liquid noble-gas targets; such detectors include XENON1T (using 3.5 tons of xenon) and DEAP (using 3.6 tons of argon), which both started operating in 2016. Their sensitivity can be further enhanced by increasing the target mass. A suite of smaller-scale experiments is exploring, in particular, low-mass WIMPs and other Dark Matter hypotheses such as those based on dark photons and axions.

It continues:

The highest sensitivity for WIMPs in a mass range of around 5 GeV to 10 TeV is reached by experiments using, as a target, liquid xenon (notable examples include LUX in the US, PandaX in China and XENON100 in Italy) and liquid argon (e.g. DEAP in Canada, DarkSide-50 in Italy, pioneering the use of argon depleted in argon-39, and ArDM in Spain). A ton-scale xenon detector, XENON1T, is being commissioned and, after two years of continuous operation, can access cross-sections as low as 10^{-47} *per centimetre squared. For the near future, multi-ton-scale liquefied noble-gas detectors with strong European participation are already at an advanced planning stage: namely, XENONnT (8 tons of xenon), LZ (7 tons of xenon) and DarkSide-20k (20 tons of argon). For lower-mass WIMPs (below 6-7 GeV), the best performance is achieved using a combination of light and heat signals or ionisation and heat signals in cryogenic detectors cooled down almost to absolute zero: for example, CRESST (at LNGS in Italy) combines light and heat signals, while EDELWEISS (at LSM in France) combines ionisation and heat signals. In the U.S. and Canada, SuperCDMS and DAMIC are also pursuing low-mass dark matter.*

And it concludes:

APPEC encourages the continuation of a diverse and vibrant programme (including experiments as well as detector R&D) searching for WIMPs and non-WIMP Dark Matter. With its global partners, APPEC aims to converge around 2019 on a strategy aimed at realising worldwide at least one ‘ultimate’ Dark Matter detector based on xenon (in the order of 50 tons) and one based on argon (in the order of 300 tons), as advocated respectively by DARWIN and Argo.

3. DarkSide-20k: The High-Mass Search Program

DS-20k will be located in Hall-C of the Gran Sasso National Laboratory (LNGS) in Italy. It consists of two nested detectors housed within a ProtoDUNE-style membrane cryostat [38, 39].

The inner detector is a dual-phase argon time projection chamber (LAr TPC) contained within an acrylic vessel made from ultra-pure poly(methyl methacrylate) (PMMA) and filled with UAr. The central active volume of the TPC is defined by eight vertical reflector panels and the top and bottom

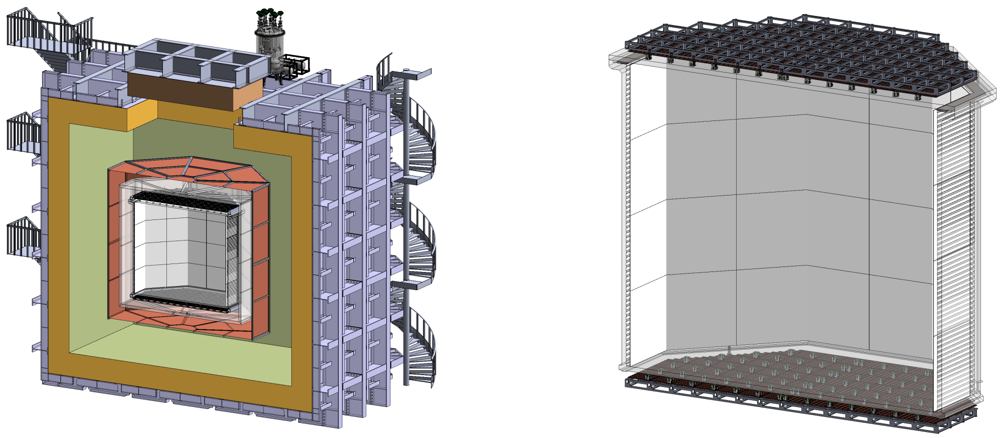

FIG. 3. The DS-20k detector. **Left**: The PMMA TPC filled with UAr, surrounded by the veto detector made of a Gd-loaded PMMA shell sandwiched between two AAr active layers, all contained within a membrane cryostat. The outer active argon layer is optically separated from the AAr by a membrane, whose characteristics are yet to be defined. **Right**: A detailed view of the TPC.

windows of the acrylic vessel. Instead of the traditional copper field cage rings and Indium-Tin-Oxyde (ITO) cathode and anode, DS-20k will use poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (also known as PEDOT:PSS and commercialized under the name Clevios^{TM} [44]). All the TPC surfaces in contact with the active argon volume will be coated with TPB wavelength shifter to convert LAr scintillation light to a wavelength detectable by SiPMs. 8280 SiPM-based PDM arrays will view the argon volume through the top and bottom windows of the acrylic vessel. The height of the TPC is 350 cm. With this design, the total mass of LAr in the active volume is 49.7 t.

The outer veto detector is made of a passive Gd-loaded PMMA shell, which surrounds the inner detector, sandwiched between two active AAr layers. The Gd-loaded PMMA shell moderates neutrons emitted from the LAr TPC until they capture on Gd, resulting in the emission of multiple γ-rays. The γ-rays interact in the AAr layers and cause scintillation light that is detected by photodetectors, thereby providing an efficient veto of radiogenic neutrons that could result in a NR in the TPC. The ProtoDUNE-like cryostat will be surrounded by layers of plastic to moderate cosmogenic and radiogenic neutrons from the rocks surrounding Hall C.

Fig. 3 shows a 3D schematic of the DS-20k detector. DS-20k is designed to operate with zero backgrounds, i.e., all sources of instrumental background reduced to <0.1 events over a 100 t yr exposure. The only remaining background will be that coming from the coherent scattering of neutrinos from argon nuclei. While coherent neutrino scattering is a background for the WIMP search, this sensitivity is a feature that enables DS-20k to detect a supernova neutrino burst coming from anywhere in the Milky Way Galaxy and, for a majority of the galaxy, clearly identify the neutronization burst. DS-20k would perform a flavor-blind measurement of the total neutrino flux and average energy, setting an overall normalization that is not affected by neutrino oscillations. When combined with a flavor-specific measurement from a detector like Super-Kamiokande or DUNE, this observation could have sensitivity to the neutrino mass hierarchy.

This proposal requests funds for the U.S. contribution to the construction and commissioning of the DS-20k detector at LNGS and the Urania UAr extraction facility, which will produce UAr for the inner detector. There are six major areas that the U.S. NSF-supported groups will contribute to: the Urania plant installation and commissioning, photoelectronics development and fabrication, cryogenics and gas handling system design and fabrication, inner detector design and component fabrication, and development of calibrations sources and systems. The responsibility of each NSF-supported group is outlined in the accompanying statements of work and other supplemental materials. These are critical components of the DarkSide-20k project that require the technical expertise and resources of the U.S. groups.

4. DarkSide-LowMass: The Low-Mass Search Program

While the DS-LM experiment is outside the scope of this proposal, the implementation of DarkSide-20k project will have direct impacts on the technological advancements required to enable DS-LM and the goal of reaching the neutrino floor for WIMP masses between $1\,\mathrm{GeV}/c^2$ and $10\,\mathrm{GeV}/c^2$. Among these are the development of low-background PDMs [32, 33] and the construction of the Aria cryogenic distillation column, which will completely remove ^{85}Kr and reduce ^{39}Ar levels to the level of 1 μBq/kg

5. Argo

The GADMC is planning a phased approach towards reaching the neutrino floor for high-mass WIMPs ($>10\,\mathrm{GeV}/c^2$). DS-20k, the objective of this proposal, with its planned 200 t yr exposure will reach a sensitivity approximately 60 times beyond that of DEAP-3600, which has a design exposure of 2.1 t yr. After DarkSide-20k project, the collaboration plans to construct the Argo detector for an ultimate dark matter search with an exposure of 3000 t yr, a factor of 15 improvment. Support for Argo is not requested as part of this proposal, but work on DarkSide-20k project will enable this future program. We anticipate a detector with a fiducial mass of approximately 300 t, with the experiment starting around 2028. In addition to dark matter detection, such a large detector would also have excellent sensitivity to a neutrino burst associated with a galactic supernova. If located at SNOLAB or at similar depth, Argo will also have the potential to detect CNO neutrinos for the first time and solve the Solar Metallicity Problem [21].

II. RESULTS FROM PRIOR NSF SUPPORT

1. Intellectual Merit

Much of the collaboration's activity in recent years has been focused on the DS-50 experiment, a direct search for WIMPs using a two-phase LAr TPC with an active mass of (46.4 ± 0.7) kg of LAr. The LAr TPC is surrounded by a 4.0 m-diameter borated-liquid-scintillator neutron veto (LSV), which is in turn surrounded by a 1-kton water Cherenkov muon veto (WCV). The experiment has been running since 2013 at LNGS, the underground lab in central Italy operated by INFN.

The US groups have been the backbone of this effort, and while supported by NSF Grants PHY-0919363, PHY-1004054, PHY-1004072, PHY-1242585, PHY-1242611, PHY-1314483, PHY-1314507, associated collaborative NSF Grants PHY-1211308, PHY-1314501, PHY-1455351 and PHY-1606912, as well as Major Research Instrumentation Grant MRI-1429544, they have provided:

- the scientific leadership of the experiment,
- the design of the LAr TPC, the fabrication of its parts, and its assembly in Italy,
- the conceptual design of the LSV,
- the cryogenic and argon purification system for the TPC, which has operated continuously and stably for over 5 years,
- the deployment system for calibration sources, including specially made sources such as ^{241}Am^{13}C and a low-rate, tagged ^{2}D-^{2}D neutron generator,
- a dedicated low-background HPGe assay facility,
- a high-precision radon monitoring system for the DS clean rooms, and
- the extraction and purification of (156 ± 1) kg of UAr from underground sources for use as a low-^{39}Ar target.

In 2015, we published WIMP search results from our first physics run, an exposure of 47.1 live-days using AAr as the active target material [4]. In April 2015, we began a second physics run, this one with a fill of UAr. The discovery, extraction, and measurement of this UAr was the result of a long-tem NSF-supported effort. The first goal of the new run was to determine the activity of

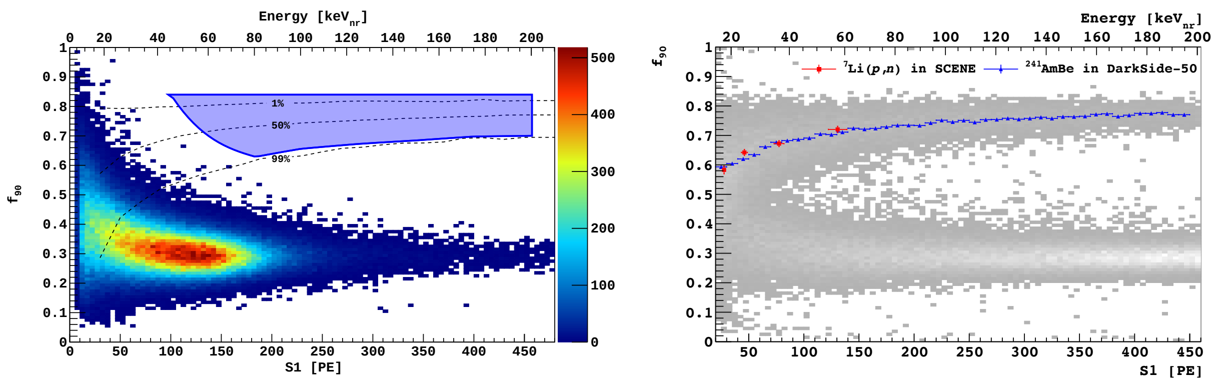

FIG. 4. **Left**: Results from a run of DarkSide-50 with a UAr fill for a 532.4 live-days livetime. The plot shows the distribution of events in the main pulse shape discriminant, f_{90} (the fraction of the primary scintillation pulse in its first 90 ns) vs. the total integral of the primary scintillation pulse, S1 (measured in photoelectrons, PE). The dashed lines identify the lower boundaries of nuclear-recoil signal regions having the indicated acceptances. The shaded blue region above the blue line is the WIMP search box. The NR energy scale relevant for WIMP scattering is shown across the top axis. **Right**: f_{90} vs. S1 distribution for NRs (WIMP-like) and ERs (background) from ^{241}AmBe calibration data. The scatter of events between the bands is due to n+γ mixed events from the source. Our measurements of the median of the NR band are compared to those from SCENE, which cover only the low energy range.

the UAr, only upper limits on which were possible with smaller, higher-background detectors. We found that the level of ^{39}Ar in the UAr was a factor of 1400 ± 200 lower than that in AAr. We published our initial WIMP search with UAr using 70.9 live-days of data [5].

Following the analysis of the 70.9 live-days data set, DS-50 collected an additional 532.4 live-days of blind UAr data. Before unblinding the high-mass WIMP region of interest, we embarked on an exhaustive simulation and analysis campaign to make reliable predictions of all backgrounds and design analysis cuts that reduced the total predicted background below <0.1 events in the full exposure. The outcome of this high-mass WIMP dark matter search is a null result (see Fig. 4), delivering on the promise of zero-background and producing the best limit with an argon target at the time of publication [6] (later improved by DEAP-3600 [2]).

The extremely low background, high stability, and the ability to trigger on the S2 signal from single electrons also allowed us to extend the analysis threshold to 100 eV$_{\mathrm{ee}}$ (600 eV$_{\mathrm{nr}}$). Two dark matter searches were performed using this technique. The first, an S2-only nuclear-recoil dark matter search, is published in Physical Review Letters [7] and was chosen as an "Editors Suggestion." It remains the world's most sensitive limit in the mass range between 1.8 GeV/c^2 and 6.0 GeV/c^2. The second used the S2 signal to constrain the rate of dark matter scattering from electrons and was also published in Physical Review Letters [8]. It also remains the most sensitive limit in the range from 30 MeV/c^2 to 50 MeV/c^2 for dark matter scattering from electrons via a heavy mediator.

Critical for the blind analysis of 532.4 live-days of UAr data was the completion of several calibration campaigns, performed either by injecting sources directly into the LAr via the cryogenics and gas handling system, or by positioning sources against the LAr TPC cryostat with a deployment device reaching through the water tank and neutron veto [45]. These calibration campaigns have also enabled a rich set of detector-performance analyses. For instance, an americium-beryllium neutron source was deployed for several campaigns. ^{241}AmBe neutrons gave us our first direct look at WIMP-like NRs in the LAr TPC and neutron capture signals in the neutron veto. Figure 4 (right) shows the f_{90} response in the LAr TPC for NRs and ERs induced by neutrons and γ-rays, respectively, from the ^{241}AmBe source. It also shows the median f_{90} response of NRs as extrapolated from our independent calibration experiment, SCENE [27], and that the two measurements are in good agreement with each other.

The DS external calibration campaigns have provided measurements crucial for optimizing the operation of the DS-50 detector and extraction of its scientific results. The two major efforts that the GADMC Collaboration has already undertaken are:

- **SCENE:** The first measurement of the low-energy light ($10.3\,\mathrm{keV_{nr}}$ to $57.3\,\mathrm{keV_{nr}}$) and charge ($16.9\,\mathrm{keV_{nr}}$ to $57.3\,\mathrm{keV_{nr}}$) yields for NRs as a function of drift field was performed in the SCENE experiment [27, 28], led by members of the DarkSide-50 collaboration. The choice of a standard drift field value of $200\,\mathrm{V/cm}$for DS-50 was based on the SCENE results, and motivated by the need to minimize the loss of scintillation light for NRs due to higher drift fields. The NR energy scale and NR acceptance curves used in the DS-50 science papers [4, 5] were also determined using the SCENE data. Finally, the SCENE experiment gave a hint about the directional signature in the scintillation response of $57.3\,\mathrm{keV_{nr}}$ NRs.
- **ARIS:** The ARIS experiment also provided light yield measurements for NRs as a function of the drift field, and did so with much higher precision and spanning a larger energy range ($7.9\,\mathrm{keV_{nr}}$ to $119.4\,\mathrm{keV_{nr}}$) than SCENE. Additional ARIS results include measurements of the recombination probability of electron-ion pairs as a function of energy and applied electric field for both ERs and NRs, and the confirmation of the light yield linearity of the LAr ER response. These results are important in the construction and calibration of models which predict the behavior of LAr to recoiling electrons and nuclei. The Precision Argon Response Ionization and Scintillation (PARIS) model has been developed to describe the LAr response inside the DarkSide LAr TPC detectors [46]. We plan to use ARIS data to further improve the PARIS model, a crucial tool for predicting the sensitivity of future large LAr detectors in the search for dark matter.

In addition to the publications referenced above, we have published a technical paper detailing the electronics and data acquisition of the DS-50 veto detectors [47], a physics paper describing the effect of low electric fields on scintillation light yield from α's in LAr [48], a technical paper describing our simulation of argon response and light detection in DS-50 [46], a technical paper describing the calibration source deployment system [45], a physics paper describing radiogenic neutron yield calculations for low-background experiments [49], a technical paper detailing the electronics, trigger and data acquisition system of the DS-50 LAr TPC [50], and a physics paper describing the electroluminescence pulse shape and electron diffusion in liquid argon [51].

2. Broader Impact

Since its inception in 2009, the NSF-funded DS program has had significant broader impacts in the areas of education and outreach, and the program's scientific developments have impacted industry and a variety of basic research fields.

Through 2012, the collaboration offered a unique multi-cultural summer program that brought together high-school students from Italy and South Dakota for underground-physics-related instruction and activities at Princeton, LNGS, and Sanford Lab. The program, the Gran Sasso-Princeton-South Dakota Summer School, benefited several hundred students.

Most groups in the collaboration have given undergraduate students the opportunity to contribute to the research effort in various ways. These include formal education (junior and senior theses at Princeton, Houston, Augustana, Hawaii, UCLA, Temple, and elsewhere; TURF-CREWS projects at Temple, etc.) as well as informal activities, such as lectures to large General Physics classes (UCLA, others), Physics Clubs (Temple, others), undergraduate seminars, and the like. The Augustana PI regularly visits high school physics classes in South Dakota to talk about underground physics, contacting around 300 students each year. The Hawaii PI and students act annually as section leaders in the "Expanding your horizons" science workshop for middle school girls. The Temple PI has given invited informal talks to local astronomy clubs and to a local retirement community. The UC Davis PI and group members annually contribute to a hands-on summer school for undergraduate and graduate students from various disciplines. Princeton PI Cristiano Galbiati visited over twenty schools in the Sulcis-Iglesiente district of Italy, near the site of the Aria cryogenic distillation plant discussed below. These visits presented the research program of the GADMC collaboration and the plans for the Aria project to more than 1000 students.

Technologies developed for the DS program have had or may develop significant impacts on industry and other branches of science. A non-exhaustive list includes:

- In the course of our UAr extraction from natural gas wells, significant amounts of ^{4}He were discovered in the gas stream. ^{4}He is essential in many branches of science. It is a scarce, non-renewable resource which is rapidly growing in cost and scarcity. Throughout the operation of the DS-50 UAr extraction plant at the Kinder Morgan Doe Canyon CO_2 facility near Cortez in southwestern Colorado, we measured and kept records of the content of ^{4}He. We demonstrated to Kinder Morgan the presence of a sustained and commercially exploitable fraction of helium in their gas stream. This result led to the start of the first ever commercial enterprise to extract helium from a CO_2 stream. Air Products built a helium production plant treating the entire Kinder Morgan Cortez CO_2 stream, which started production in July 2015 and presently supplies ^{4}He equivalent to 15 % of the declining production from the US National Helium Reservoir. The discovery of helium in Cortez performed by the GADMC Collaboration enabled the provision of major quantities of this crucial resource, which is regularly shipped to serve research laboratories and industries across the US.
- The UAr itself is finding applications in ultra-low-level counting applications such as nonproliferation and clandestine nuclear test detection, groundwater aging studies, and other areas.
- Princeton PI Cristiano Galbiati invented the cryogenic distillation plant "Aria" for active isotopic purification of UAr for DS-20k and larger projects. Aria was further developed by DS-50 collaborators. Funded by the Italian Government and Regione Autonoma della Sardegna, the first Aria column will be the tallest plant in the world at 350 m in height. Installation inside a mine shaft in Sardinia will start in 2019. Thanks to its high mass resolution and throughput, Aria will have the ability to increase the world-wide availability (and lower the cost) of rare stable isotopes important to industry, science, and medicine, including ^{18}O, ^{13}C, ^{15}N, and others.
- Princeton PI Cristiano Galbiati proposed and founded the Nuova Officina Assergi (NOA), a modern clean-room facility for the assembly of silicon devices that will be located at LNGS and first used to build the SiPM-based cryogenic photodetectors of DS-20k. NOA is funded by Regione Abruzzo and the Italian Government. This development was made possible by the early (2014) decision of the GADMC collaboration to abandon the development of PMTs and to focus the DS R&D on SiPMsand the ensuing success obtained by the Collaboration in that development. As a direct result of this early focus, DS researchers produced many leading results on the utilization of SiPMs as cryogenic photosensors. In particular, we demonstrated the operation of large (tens of cm^2) single-channel cryogenic photosensors with single photoelectron sensitivity, defeating the noise induced by the very large capacitance of SiPMs arrays. Today, these large photosensors allow us not only to replace PMTs for DS-20k, but also to surpass their technical performance in every metric. Our SiPM-based cryogenic photosensors maintain the excellent photon detection efficiency and resolution of SiPMs, superior to those of PMTs, and also possess, at cryogenic temperature, a dark noise rate lower than PMTs [32].
- Other ultra-clean technical methods developed for DS-50 extend the reach of important existing industrial processes (*e.g.*, precision cleaning) or offer new possibilities for industrial processing (radon-suppressed clean rooms).
- The application of the LAr TPC concept, in conjunction with the use of SiPMs, to build higher-resolution PET scanners has been proposed and is under development at Princeton.

The maintenance and further development of all these techniques will continue to be essential for the GADMC effort in the DS-20k era and beyond.

III. PRELIMINARY ACTIVITIES ACCOMPLISHED

1. LAr TPC and ProtoDUNE Cryostat Design

The conceptual design of the DS-20k LAr TPC has been finalized. Verification of the design will proceed through a staged effort at CERN, first using a small prototype, DarkSide-ProtoZero

(DS-ProtoZero), and then the $\sim$1 t scale DarkSide-Proto (DS-Proto). The fabrication and construction of DS-ProtoZero is nearly complete, and the detector will be operated at CERN in the summer of 2019. It will test the first 50 PDMs produced by the collaboration and will study the effect of the TPC geometry on the S2 signal generation and detection. The DS-Proto detector will be equipped with 400 PDMs and will be a scaled-down version of DS-20k LAr TPC, serving as its proof of principle prototype. Work is ongoing at CERN and at collaborating U.S. and Canadian Institutions to complete the final design of the detector.

A team of engineers and researchers, with members from the GADMC Collaboration and from CERN, is currently co-located at CERN and making rapid progress on the design of the ProtoDUNE cryostat and the integration of the LAr TPC and the veto detector into the cryostat.

2. Cryogenics and Gas Handling System

The design of the cryogenics and gas handling system for DS-20k is complete. Fabrication has already started at CERN, with various major components already completed and tested. The documents necessary for certifying the equipment and completing the CERN final safety review are moving in parallel with construction. The final safety review performed by CERN will be satisfactory for LNGS.

3. Photoelectronics

The production of the first set of 25 PDMs is complete and will be used in the upcoming DS-ProtoZero test. The first opto-link system, which combines an optical driver and an optical receiver board for routing PDM signals out of the TPC, has also been produced and tested. Production of the second set of 25 PDMs and the second opto-link system is ongoing, with half of the SiPM tiles already mounted and successfully tested at cryogenic temperature.

In order to accommodate the large volume of SiPM wafers necessary for DS-20k, FBK, who produced all of the SiPMs used for the development of the DarkSide PDMs has transferred their SiPM technology to a large silicon foundry, LFoundry. LFoundry completed their first engineering run in September of 2018, demonstrating the successful implementation of FBK's SiPM technology. A second engineering run devoted to the implementation of Through Silicon Vias (TSVs) is currently ongoing at LFoundry. Production of the SiPMs that will equip the 400 PDMs for DS-Proto will also be carried out at LFoundry, with the first batch expected by the end of June 2019.

The construction of DS-20k will require the production of more than 8280 PDMs in 2.5 years. This can only be accomplished using NOA, a dedicated silicon packaging facility outfitted with cutting edge equipment and highly trained personnel. Assembly of the NOA facility is underway. The INFN has completed tenders for two major pieces of equipment, a cryogenic wafer prober and a flip-chip bonder, and their delivery is expected in the fall of 2019. The Collaboration has begun training students and dedicated personnel in a temporary clean-room facility at LNGS until the 700 m^2 clean-room space at the Tecnopolo dell'Aquila, which will eventually host NOA, becomes available.

4. Underground Argon Extraction and Purification: Urania

INFN opened a tender for the construction of the Urania underground argon extraction plant in 2018. The adjudication is expected by July 2019. All bidders have received the detailed technical specifications provided by INFN in accordance with the GADMC Collaboration requirements, including the extraction rate of 250 kg/d, and are developing their final bids. Until the tender process is closed, we cannot provide any details of the technology choices of the potential contractors.

A successful meeting between the Collaboration and the Kinder Morgan Company team took place in Cortez, Colorado, on March 5, 2019, at which time Kinder Morgan's commitment to the project was reconfirmed. The current plan is to install and commission the plant between the end of 2020 and the fourth quarter of the 2021 calendar year, allowing for extraction of the 50 t of UAr by the middle of the 2022 calendar year. The required preparation work for the installation of the plant is well understood, and the extraction site is ready for work to begin as soon as the local approvals are made for the land development permit and the remaining required funding is secured.

5. Final Argon Purification: Aria

Purification of UAr will be carried out with the 350 m tall Seruci-I cryogenic distillation column, which is composed of a bottom reboiler module, a top condenser module, and 28 central modules. All modules have been built, certified leak-free following tests at CERN, and received at the "Monte Sinni" mine of Carbosulcis in Sardinia. The last authorization required for the installation in the Seruci mine shaft was received in April 2019. Installation of the platforms necessary for supporting the column starts in June 2019. The first batch of UAr will arrive in Sardinia during the beginning of 2022.

Construction of the 24 m Seruci-0 pilot plant, which consists of a bottom reboiler, a top condenser, and a single central module, at the "Laveria" above ground site in Nuraxi Figus is complete. A leak test of the three modules was successfully completed in May 2019. Seruci-0 will start operations in June 2019. This prototype column will test all of the components of the full Seruci-I column. The Seruci-I plant is estimated to be able to process UAr at a rate of 10 kg/d, obtaining a ^{39}Ar depletion factor of 10 per pass and enabling further suppression of ^{39}Ar by two or three orders of magnitude. This will play a crucial role in the science reach of DS-LM. Commissioning of Seruci-0 will begin in June 2019 following completion of the pressure test and final plant certification of compliance with the European Directive on Pressure devices (PED).

6. Argon radioactivity assessment: DArT

Existing infrastructure from the ArDM experiment at LSC, Spain, will be reused to host DArT, a detector that will measure the purity of underground argon. DArT will consist of a small 1 L scintillation detector equipped with SiPMs and inserted at the core of the ArDM detector, which will serve as a veto detector. DArT will be able to test small batches of argon with a sensitivity to ^{39}Ar better than 1 part in 10 000. The DArT Technical Design Report has been completed, approved by the GADMC Collaboration, and submitted to LSC. Fabrication of the detector components is under way and will be completed by July 2019.

7. Offsite Neutron Calibrations: ReD

The ReD LAr TPC was developed to continue the kind of precision neutron calibrations successfully carried out by SCENE [27, 28, 52] and ARIS [29]. The characterization of the ReD light yield and S1 and S2 response is now complete, and we are planning to request beam time for the ReD LAr TPC test at LNS following the completion of a neutron beam characterization measurement that will be completed by the end of May 2019.

IV. IMPLEMENTATION PLAN

The tasks and technical activities for the implementation of DS-20k have been distributed among the GADMC collaborating institutions and organized into three sub-projects: the DS-20k detector, Urania, and Aria. The list of specific tasks that must be accomplished for the timely completion of the detector is detailed in the work breakdown structure (WBS). The organization of the GADMC management and the list of Level 1 WBS items are summarized in Tab. I. A detailed schematic of the GADMC management structure can be found in the accompanying Project Execution Plan.

The collaborating U.S. institutions will play critical roles in the construction and commissioning of the DS-20k detector and the Urania facility, with a focus on the Urania plant installation and commissioning, photoelectronics development and fabrication, the cryogenics and gas handling system design and fabrication, the inner detector design and component fabrication, and the development of calibration sources and systems. A summary or the individual contributions of each institution follows.

University of California Davis: The UC Davis group is responsible for delivering the high voltage systems, field cages, and reflector cages for the DS-Proto and DS-20k TPCs. They will oversee the fabrication and testing of parts for these subsystems, manage their integration into the TPC, and participate in the assembly and commissioning of the detector.

University of California Los Angeles: The UCLA group leads the DS-20k TPC and cryogenic task. In this role, they will coordinate the design, fabrication, and testing of the DS-Proto and DS-20k TPC and cryogenic system at CERN and the installation of the DS-20k systems as LNGS. They will design many of the cryogenic and gas-handling subsystems, including the argon condenser and the argon purification loop.

Fort Lewis College: Fort Lewis will assist with the installation and commissioning of the Urania facility on-site in Colorado. They will also spearhead the revitalization of the Princeton-Gran Sasso Summer School of Physics.

University of Hawaii: The Hawaii group leads the calibrations task. Within this role they will develop a liquid argon camera system for detector monitoring and procure, build, and upgrade the radioactive sources required for detector calibration. This effort includes the design and fabrication of systems for deploying these sources within DS-Proto and DS-20k.

University of Houston: UH is responsible for the technical coordination of the Urania project, including the preparation and installation of infrastructure at the plant site and the receipt, installation, and commissioning of the plant. UH is also designing and fabricating the support frames and wire grids for the DS-Proto and DS-20k TPCs.

University of Massachusetts, Amherst: UMass will lead the integration of the photodetector modules with the TPC assembly and oversee the development of SiPMs at LFoundry with integrated through silicon vias (TSVs). They are also responsible for ensuring the Urania plant is fully integrated with the Kinder Morgan facility prior to the start of underground argon extraction.

Princeton University: The Princeton PI is the spokesperson for DarkSide and as such will oversee the DS-20k experiment, coordinating the resources of the international scientific and industrial team. Princeton is also responsible for the procurement of several large components of the gas-handling and cryogenics system, the continued development of low-background, SIPM-based photodetector tiles, and the on-site construction of the DS-20k experiment.

The GADMC is organized so that global directives, approvals, and monitoring are handled by a central body, which ensures that the physics performance goals are met, milestones are completed within the determined time schedule, systems are integrated, and hardware and software is of uniform quality between the projects. The Institutional Board (IB) decides on all appointments and terminations of the DarkSide management roles and approves of any major design changes of the experiment. Each institution within the GADMC is represented on the IB and decisions are taken by consensus or vote. The Resources Review Board (RRB) is responsible for the overall resource planning, ensuring that resource needs are consistent with the various local and national funding sources.

Whenever appropriate, decision making is handled at the sub-project level. Project management is delegated to a Project Leader (PL) and to a Technical Coordinator (TC) for each of the three sub-projects; DS-20k, Urania, and Aria. The PL is the scientist responsible for the project direction and for coordinating L1 sub-projects. He or she ensures that the design and construction of the

TABLE I. Organization chart according to the Work Breakdown Structure at Level 1.

WBS	Activity	Key Personnel	Key Personnel Role	Lead Institutions (alphabetic)
	GADMC	C. Galbiati (Princeton) G. Fiorillo (Napoli) G. Batignani (Pisa)	Spokesperson Deputy Spokesperson Collaboration Board Chair	All
1	**DS-20k**	A. Ianni (Princeton)	Technical Coordinator	All
1.01	Photo Electronics	E. Scapparone (Bologna)	Level 1 Manager	BNL, Bologna, Cagliari, LNGS, Milano, Napoli, Pisa, Princeton, TIFPA, Torino, UMass
1.02	Inner Detector & Cryogenics	H. Wang (UCLA)	Level 1 Manager	Alberta, BNL, Carleton, CIEMAT, Davis, FNAL, Napoli, Roma 1, UCLA
1.03	Materials	R. Santorelli (CIEMAT)	Level 1 Manager	CIEMAT, Krakow, Princeton
1.04	Calibrations	J. Maricic (Hawaii)	Level 1 Manager	BNRU, Hawaii, Krakow, MSU, Princeton, Temple Virginia Tech
1.05	Outer Detector	G. Testera (Genova)	Level 1 Manager	Alberta, Carleton, CIEMAT, Genova, IHEP
1.06	Electronics	M. Rescigno (Roma 1)	Level 1 Manager	Roma 1, TRIUMF, Virginia Tech
1.07	Offline	D. Franco (APC)	Level 1 Manager	APC, Roma 1, Roma 3
1.08	ReD	L. Pandola (LNS)	Level 1 Manager	BNL, Bologna, Cagliari, Genova, LNGS, LNS, Napoli, Pisa, Roma 1, APC, UCLA, Roma 3
1.09	Prototype	G. Fiorillo (Napoli)	Level 1 Manager	UCLA, Napoli, Princeton, Roma 1
1.10	Outer Cryostat	M. Nessi (CERN)	Level 1 Manager	CERN, UCLA, INFN, LNGS
2	**Urania**	A.Renshaw (Houston) M. Simeone (Napoli)	Technical Coordinator Project Leader	BNL, Carleton, Houston, Napoli, PNNL
2.01	Project Manager Oversight	B. Walsh (BNL)	Level 1 Manager	BNL
2.02	Plant Fabrication and Delivery	M. Simeone (Napoli)	Level 1 Manager	Carleton, Napoli, PNNL
2.03	Site Prep. & Installation	A.Renshaw (Houston)	Level 1 Manager	Carleton, Houston, PNNL, Princeton, UMass, Temple
2.04	Extraction	H. Back (PNNL)	Level 1 Manager	BNL, Canada, Carleton, Fort Lewis, Houston, PNNL, Princeton
2.05	Storage and Shipping	M. Boulay (Carleton)	Level 1 Manager	Carleton
2.06	Shutdown	A.Renshaw (Houston)	Level 1 Manager	Houston
3	**Aria**	R. Tartaglia (LNGS) L. Mapelli (Princeton)	Technical Coordinator Project Leader	Cagliari, LNGS, Princeton, Napoli
3.01	Seruci-0 and Seruci-I	F. Gabriele (LNGS)	Level 1 Manager	Cagliari, Fermilab, LNGS, Napoli, Virginia Tech
3.02	DArT in ArDM	W. Bonivento (Cagliari)	Level 1 Manager	Cagliari, CIEMAT, LNGS, ETHZ
4	**Infrastructures**	A. Ianni (Princeton)	Level 1 Manager	Carleton, LNGS, Princeton
5	**NOA**	E. Scapparone (Bologna)	Level 1 Manager	Bologna, LNGS, Princeton Temple

project is carried out on schedule, within the cost ceiling, and in a way that meets the performance and reliability requirements determined within the framework of GADMC resource planning. The TC is responsible for the project construction and the technical integration of all its components. The TC ensures the implementation of engineering standards and procedures, monitors the overall construction of detectors and infrastructure, and is responsible for the sub-projects' integration and safety.

The Technical Board (TB) is the main body for directing the execution of the GADMC projects and for direct communication between the GADMC management and the sub-projects. The TB is composed of Management (SP, Deputy(ies) SP, IB Chair, RC, PL's, TC's), all L1 sub-project coordinators, the Group Leader In Matters Of Safety (GLIMOS), and the environmental contact for the experiment (RAE).

V. FOREIGN COLLABORATOR CONTRIBUTION

The DarkSide program has been characterized by a strong international contribution since its inception, most notably with the siting of DS-50 at the Gran Sasso National laboratory in Italy and the significant participation and funding contribution from the INFN. The increasing role of INFN in DarkSide activities led to the submission of a joint DS-20k proposal to INFN and the NSF. In addition to the strong collaboration with Italy, early DarkSide collaborators included groups from China, Poland, Russia, and Ukraine, and eventually expanded to groups from France, Brazil, Canada, Greece, Mexico, Germany, Romania, Spain, Switzerland, and the UK. This expansion coincided with the formation of the GADMC during which DarkSide joined forces with the miniCLEAN program at SNOLAB, Canada, and the ArDM program at Canfranc, Spain. The GADMC as it exists today was cemented with the merging of the DEAP program in 2017, with the participation of three national underground laboratories (Gran Sasso, SNOLAB, and Canfranc), and a partnership with the LAr neutrino program at CERN. The current DarkSide-20k collaboration counts 374 scientists and engineers from 77 institutions and laboratories from 16 countries as members. The responsibilities of foreign institutions include:

- Italy (INFN): DS-20k (laboratory logistics, argon veto, PDMs, DAQ, computing, mechanical integration, simulations, material screening), ReD, Aria, Urania (plant design and delivery), and DART
- Italy (Regione Sardegna): Aria
- Italy (Regione Abruzzo and Italian Government): Nuova Officina Assergi (NOA)
- Canada: DarkSide-20k (acrylic vessel, TPB coating, conductive film development, electronics and DAQ) and Urania (underground argon transportation and storage)
- Poland: DarkSide-20k (material screening and radon control)
- Spain: DarkSide-20k (TPC fabrication, material screening) and DART
- France: DarkSide-20k (simulations, veto), ARIS, and ReD
- Russia: DarkSide-20k (background simulations, veto development, ultra low radioactive material development and screening, calibration systems development, development of machine learning algorithms for particle identifications, monte-carlo and offline software)
- China: DarkSide-20k (acrylic procurement)

VI. OPERATIONS AND UTILIZATION PLAN

The organizations proposing this work, including the sub-award recipients, are all part of two existing collaborative NSF awards that have Princeton as the lead-institution. The award numbers for the Princeton component are PHY-1812540 and PHY-1622415, but all associated collaborative awards fall within the same scope. These grants run through 2022 and 2023, respectively, and therefore cover any operations and maintenance costs that fall outside of the scope of this Mid-scale RI-1 Program request but within the same time period. The first award provides personnel support and operations costs for DarkSide-20k and the second provides some initial capital construction costs for DarkSide-20k. The proposers hope that the level of support provided to the groups with the collaborative awards will be extended beyond the 2022 end date in order to ensure successful operation of the DarkSide-20k experiment for the entirety of the planned runtime.

VII. BROADER IMPACTS

1. Advances in Technology

INFN and Princeton University recently filed patent P137IT00 for an innovative, LAr-based, high-definition 3D positron annihilation vertex imager called 3Dπ. The 3Dπ project uses LAr-TPC technology to overcome existing limitations of Positron Emission Tomography (PET) and Time-Of-Flight PET (TOF-PET). These nuclear imaging techniques are used in the fight against cancer, neurological-imaging, and cardio-imaging.

The development of SiPMs for DS will drive substantial improvements to this technology. SiPMs could replace PMTs in many particle physics experiments, especially those needing to detect photons at cryogenic temperatures, in magnetic environments, and in the presence of strong electric fields. SiPMs could also be used in future generations of detectors for national security purposes. Finally, the functional unit of SiPMs, the SPAD, finds application in fast light detectors, such as LiDaR distance sensors in cars.

The GADMC Collaboration will advance techniques for isotopic separation and the collection of rare isotope gases that are important to industry, scientific advancement, and national security. Examples include ^{4}He (and ^{3}He) extracted from underground CO_2 wells at the Cortez facility in southwestern Colorado. These helium isotopes are essential, non-renewable resources for university research the and high-tech industry. Helium isotopes play an indispensable role in national defense projects and the space exploration industry. The GADMC collaboration has already played a major role in improving the US availability of ^{4}He. In conjunction with the Urania project, DS researchers are investigating methods for separating ^{3}He from massive streams of helium, *e.g.* the one at Cortez. If successful, this effort could help solve possible future shortages of ^{3}He [53], a very rare isotope that has application in nuclear fusion and neutron detection.

The ^{37}Ar radioisotope is of great interest for the detection of underground nuclear tests. The production of ^{37}Ar via the reaction ^{40}Ca$(n,\alpha)^{37}$Ar has a relatively high cross section and is a signature of a large flux of neutrons interacting with soil [54]. Being a noble gas, ^{37}Ar is expected to migrate to the surface following an underground nuclear test where it can be studied. The chemistry of argon recovery and purification is important for preparing the soil-gas samples for this type of measurement and has significant overlap with the challenge of recovering and purifying geologic argon for use in a dark matter detector.

Internal-source argon gas-proportional counters are used to detect environmental radio-tracer isotopes. One of the most sensitive methods for age dating water relies on assaying challenging radionuclides like tritium [55] and ^{39}Ar [56]. As with dark matter detection, the ^{39}Ar background in atmospherically-sourced argon becomes an important limit to sensitivity. The availability of low-radioactivity geologic argon from methods developed for DS will extend the reach of these measurements. Geologic argon samples from the GADMC Collaboration R&D effort have been recently used at Pacific Northwest National Laboratory to characterize ultra-low-background proportional counter backgrounds [57, 58]. The UAr development that is central to the physics reach of DS will significantly enhance the ability of researchers worldwide to employ ^{39}Ar as an environmental radio-tracer for hydrologic transport.

The Aria project may help improve availability and lower the costs of rare stable isotopes such as ^{18}O, ^{13}C, and ^{15}N. ^{18}O and ^{13}C are widely used as precursors of tracer isotopes for tumor therapy, clinical studies, and the development of new drugs. ^{18}O is a precursor of the positron emitter ^{18}F, the core ingredient of ^{18}F-FluoroDeoxyGlucose (^{18}F-FDG) [59], a glucose analog with a hydroxil group replaced with ^{18}F. This is the most common radiopharmaceutical used in medical imaging by PET, TOF-PET, and PET/CT [60, 61]. ^{18}F-FDG also plays an important role in neuroscience [62]. ^{13}C is a marker used in thousands of stable-isotope-labeled, custom-synthesized organic compounds with numerous applications. Its traceability by nuclear magnetic resonance allows applications such as the ^{13}C-Urea breath test, which can replace gastroscopy for identifying infections from Helicobacter pylori [63], and the ^{13}C-Spirulina platensis gastric emptying breath test [64]. It is also used in fundamental studies in proteomics, carbon fixation, and many other applications.

Uranium nitride loaded with ^{15}N, $U_n{}^{15}N_m$, is among the best candidates for fueling IV Generation nuclear reactors due to its superior thermal and mechanical properties [65–67]. The main drawback is that uranium nitride must be synthesized from ^{15}N that is more than 99 % pure to avoid neutron absorption on ^{14}N. The advantage of uranium nitride fuels is that they require fewer refueling shutdowns, larger up-times, and greater economy. The higher density, higher melting temperature, better thermal conductivity, and lower heat capacity [68, 69] of uranium nitride compared with other oxides helps improve the safety margin in reactor design [70]. The adoption of uranium nitride as the fuel of choice for IV Generation nuclear reactors would create a new market for ^{15}N valued in the hundreds of millions of dollars per year.

2. STEM Education and Outreach

The GADMC collaboration is composed of a diverse group of scientists with significant collective STEM outreach experience. Together, we will continue to advance public understanding of particle astrophysics and dark matter science, taking advantage of the scale and excitement surrounding the DS-20k experiment to provide STEM educational opportunities that reach underrepresented students.

As a central outreach portion of this project, the collaboration plans to run a program for the education and training of students from the argon trail: the Cortez-Durango area, Abruzzo, Italy, and Sardinia, Italy. For this purpose, we plan to re-establish the Princeton-Gran Sasso Summer School of Physics with help from the entire GADMC Collaboration and in cooperation with the Gran Sasso Science Institute (GSSI). This Summer School will give rising high-school seniors and rising freshman undergraduate students the opportunity to spend a week each at Princeton and at least one other DarkSide-collaborating institution in Italy where they will participate in educational and research activities related to the DS program.

The focus of the U.S. portion of the collaboration will be the recruitment of students from the Cortez-Durango area, where the Urania plant will operate. This initiative will be led by faculty members at Fort Lewis College, which, by statute, is maintained as an institution of learning to which Native American students will be admitted free of tuition in perpetuity (Act of 61st Congress, 1911). We are requesting funds to support up to five students per year from the Cortez-Durango area to participate in the Princeton-Gran Sasso Summer School of Physics, and we expect significant participation of Native American students. The students will attend a week at Princeton where they will receive classroom instruction in particle astrophysics and get hands-on experience with scientific instrumentation followed by a research experience at the Urania facility in Colorado, the Aria facility in Sardinia, or LNGS. Each student will gain an appreciation for the skills one needs to work in these types of environments and the experience will spur their interest in dark matter physics, engineering, and STEM-related topics in general. In addition to an educational experience, participants will have the opportunity to meet researchers and professionals in industry, establishing a professional network that can assist them with future career opportunities. This program will be evaluated on a yearly basis with a survey of the students that gauges their perceived benefits from the program as well as long term follow-ups with past participants to determine any career benefits from their participation. The participation of students from the argon trail in Italy, Sardinia and Abruzzo, will be enabled through separate funds raised from governmental and private sources in Italy.

The DarkSide collaborating institutions serve a diverse group of undergraduate students. Fort Lewis College is a Native American Serving institution and is regionally connected to populations of rural, first-generation immigrants and low-income students. This complements the diverse, urban populations served by our team members from larger institutions, several of which are minority serving (Houston for example is a Hispanic and Asian serving institution). We will engage these students in undergraduate research and, through partnerships within the collaboration, give them access to an interdisciplinary, cutting-edge research program operating at a global scale.

The DarkSide team has experience building compelling narratives around the DarkSide project and the science and engineering challenges involved therein. These narratives form the basis of a curriculum that will be used by the DarkSide team to conduct outreach to our regional communities. This curriculum may also be shared with K-12 educators as a resource to add locally relevant context to the science they are learning in the classroom. For example, science teachers in the Montezuma-Cortez, Colorado, school district will be encouraged to use DS-supplied materials based on the argon extraction happening in the region. Similar activities may take place in the Sulcis-Iglesiente district of Sardinia in the context of the Aria project.

To date, the GADMC Collaboration has conducted educational outreach to local public schools (K-12) and engaged high school and undergraduate students in meaningful research related to DarkSide science. The scale of the DS-20k project gives us the opportunity to expand upon, integrate, and formalize these efforts so that we can reach a larger, more diverse population of students. In doing so, we promote the science of DarkSide to a broader audience and build a cadre of scientists and engineers prepared to enter the STEM workforce.

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