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.

The 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 2.4×10^8. 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: The 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 with a total exposure of 200 t yr. The projected $5\,\sigma$ discovery reach extends a factor of 5 below that of LZ. DS-20k will either detect WIMP dark matter or exclude a large fraction of the favored parameter space. It will be sensitive to a galactic supernova neutrino burst. It will also 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

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.

1. Scientific Justification

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 masses 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 initiated by particles recoiling from atomic electrons (ERs), the primary source of background in a WIMP direct detection experiment, has a time constant of approximately a microsecond. 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 of 2.4×10^8 [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 ionizaton 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.

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

The immediate objective of the GADMC is construction of the DS-20k two-phase LAr detector, which will operate in Hall-C of the Gran Sasso National Laboratory (LNGS). Fig. 2 shows a 3D schematic of the DS-20k detector. DS-20k detector consists of two nested detectors housed within a ProtoDUNE-style membrane cryostat [9, 10].

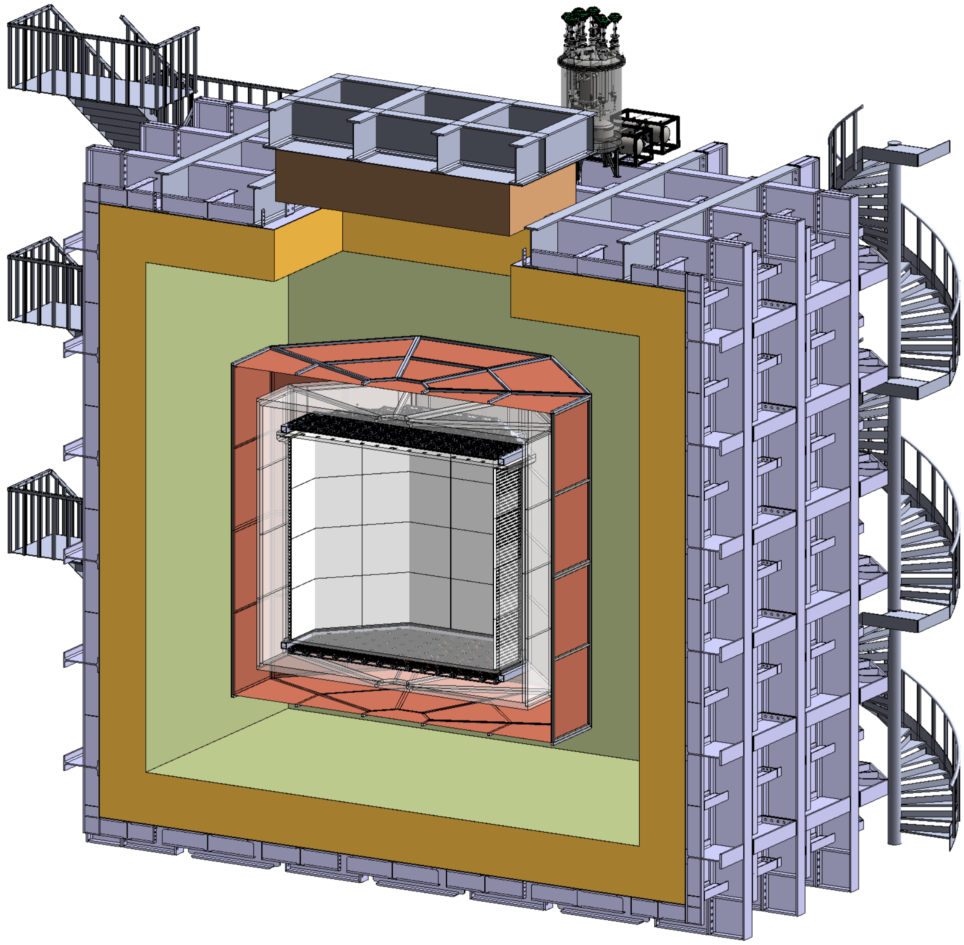

FIG. 1. Drawing of the DS-20k detector: the PMMA TPC filled with UAr surrounded by the veto detector made of a Gd-loaded PMMA shell between two AAr active layers, all contained within a membrane cryostat. The outer active argon layer is optically separated from the AAr by a membrane. For clarity, the mechanical supports holding the veto and TPC are not shown.

The inner detector is a dual-phase argon time projection chamber (LAr TPC) contained within a vessel made from ultra-pure acrylic (PMMA) and filled with UAr. The central active volume of the TPC is defined by eight vertical reflector panels and the top and bottom windows of the acrylic vessel. Instead of the traditional copper field cage rings and Indium-Tin-Oxide (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$^{\mathrm{TM}}$ [11]). All the TPC surfaces in contact with the active argon volume will be coated with wavelength shifter tetraphenylbutadiene (TPB) to convert LAr scintillation light to a wavelength detectable by SiPMs. 8280 SiPM-based PhotoDetector Modules (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. 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 surrounding the inner detector and between 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

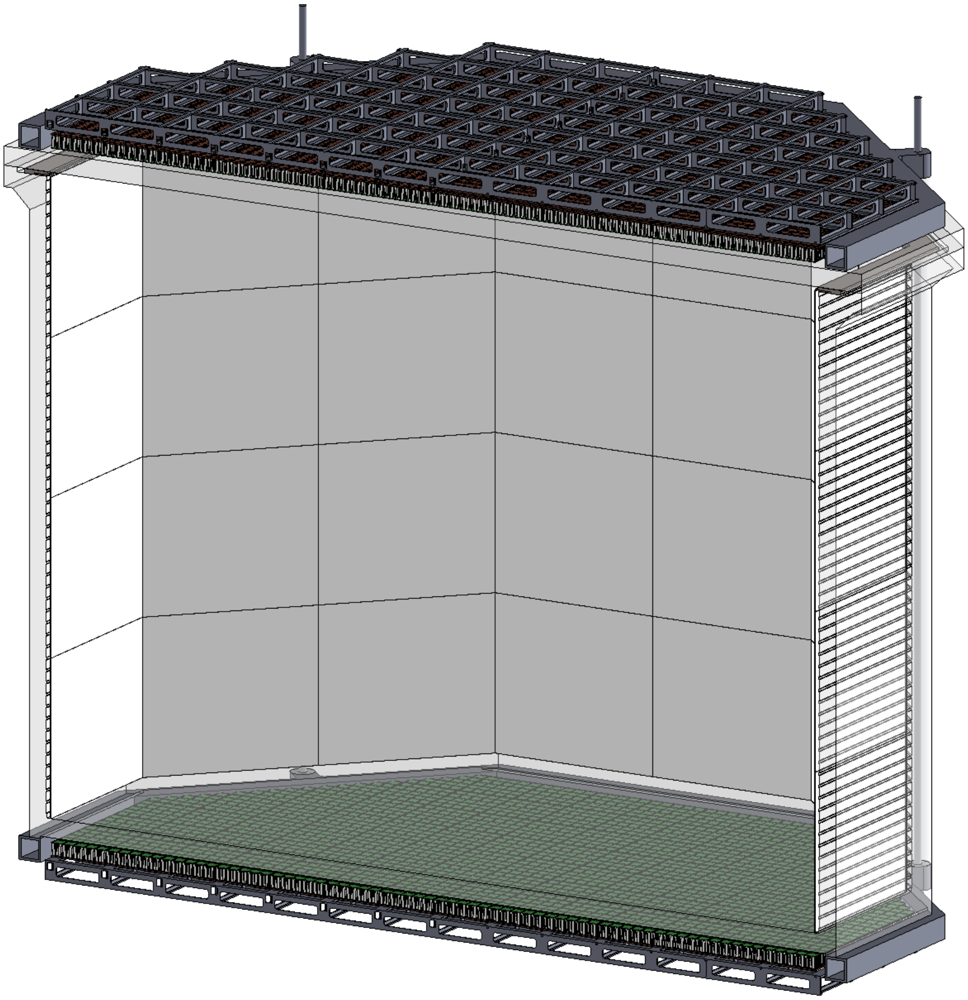

FIG. 2. Drawing of the DarkSide-20k LAr TPC, detailing the PMMA sealed vessel, TPC field cage, and PDMs support structure. For clarity, the mechanical supports holding the TPC and many other engineering details are not shown.

cosmogenic and radiogenic neutrons from the rocks surrounding Hall C.

The 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 five years run. 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.

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 ten years run with a 200 t yr exposure, see Fig. 3. During the 200 t yr exposure, 3.2 NRs 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 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.

DS-20k is designed to operate with zero backgrounds, meaning that all sources of instrumental background are reduced to <0.1 events over a 200 t yr exposure. All background from minimum-ionizing radiation sources will be completely removed thanks to the combined action of PSD of the primary scintillation pulse and comparison of the primary and secondary scintillation (see Sec. I 1 4 for details on the suppression of background from *pp* scatters on electrons and Ref. [24] for that

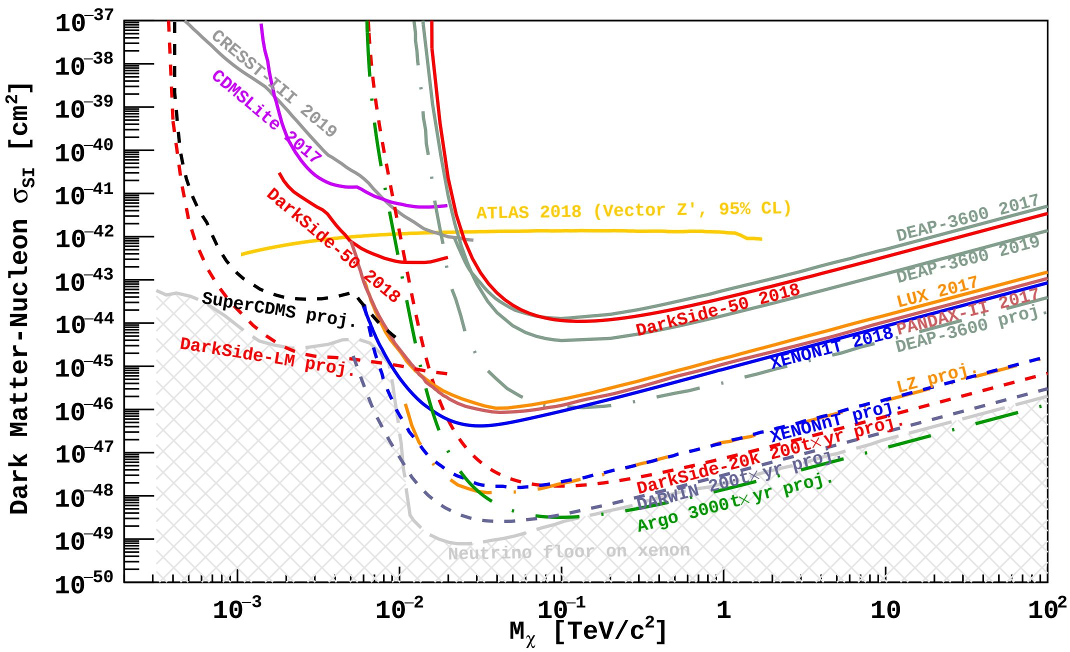

FIG. 3. 90 % C.L. exclusion limits showing leading results from direct (continuous lines, Ref. [6, 7, 12–15]) and accelerator-based dark matter searches (region above the yellow line [16]) compared with sensitivities of future germanium-, xenon-, and argon-based direct searches (dashed lines, Ref. [17–21] and this work). The "neutrino floor" curve follows the definition of Ref. [22]. 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 with coupling strengths to quarks, leptons and WIMPs of 0.25, 0.01, and 1, respectively [23].

from ^{222}Rn, ^{220}Rn, and progenies). Table I shows the expected radiogenic neutron background contributions of the various detector components following all TPC and veto cuts for the full DS-20k exposure. The only remaining background for WIMP searches will be the signal from the coherent scattering of atmospheric neutrinos on argon nuclei, with an expected 3.2 events over the 200 t yr exposure. DS-20k will thus be the first experiment in a position to detect this important signal.

This outstanding sensitivity to coherent nuclear recoils will 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.

Material	Mass [tonne]	^{238}U [mBq/kg]	^{226}Ra [mBq/kg]	^{232}Th [mBq/kg]	Neutrons $[10\,\mathrm{yr}]^{-1}$	+TPC $[200\,\mathrm{t\,yr}]^{-1}$	+TPC+veto $[200\,\mathrm{t\,yr}]^{-1}$
TPC Vessel	2.7	1.2×10^{-2}	10	4.1×10^{-3}	5.7×10^{2}	0.17	1.7×10^{-2}
TPC SiPMs	0.12	-	-	-	5.4×10^{3}	0.16	1.6×10^{-2}
TPC Electronics	1.0	-	-	-	1.2×10^{4}	0.36	3.6×10^{-2}
TPC Mechanics	1.1	3.9	3.9	1.9	9.0×10^{2}	1.8×10^{-2}	2.0×10^{-3}
Veto SiPMs+elec.	0.40	-	-	-	6.4×10^{3}	0.10	1.0×10^{-2}
Veto Acrylic	13	1.2×10^{-2}	10	4.1×10^{-3}	2.6×10^{3}	4.2×10^{-2}	4.0×10^{-3}
Veto Reflectors	1.0	1.2×10^{-2}	1.0	4.1×10^{-3}	2.0×10^{2}	2.4×10^{-2}	2.0×10^{-3}
Veto Steel	1.1	3.9	3.9	1.9	9.0×10^{2}	1.4×10^{-2}	1.0×10^{-3}
$Gd_2(SO_4)_3$ α's on self	0.26	7.0	7.0	0.2	1.1×10^{2}	2.0×10^{-3}	$<1.0 \times 10^{-3}$
$Gd_2(SO_4)_3$ α's on PMMA	0.26	7.0	7.0	0.2	3.6×10^{2}	6.0×10^{-3}	1.0×10^{-3}
Copper Cage	1.0	0.30	0.30	2.0×10^{-2}	6.0	$<1.0 \times 10^{-3}$	$<1.0 \times 10^{-3}$
Cryostat Steel	250	50	1.0×10^{3}	3.9	1.0×10^{6}	-	$<1.0 \times 10^{-3}$
Cryostat Insulation	40	3×10^{3}	8.0×10^{3}	3.0×10^{3}	8.0×10^{7}	-	$<1.0 \times 10^{-3}$
Total						**0.9**	**0.09**

TABLE I. Radiogenic neutrons sourced by the LAr TPC construction materials, veto and cryostat materials, with details of expected contamination levels, background after TPC cuts, and residual background after combined TPC and veto cuts, all relative to the full 10 yr run time and the full fiducial 200 t yr exposure. The number of neutrons source is calculated from the expected contamination levels and material composition. Note that no specific activity is reported for the TPC SiPMs and associated electronics: in this case the predicted neutron yield is the results of an extremely detailed calculation, accounting for the cumulative contribution of several tens of components, individually assayed. The same consideration holds for the veto SiPMs and electronics, whose contribution is reported in combination. For neutrons due to (α,n) reactions from α's from impurities in $Gd_2(SO_4)_3$, the contribution is broken down between those due reactions on Gd sulfate itself and those due to reactions in the PMMA matrix containing the Gd sulfate; the mass fraction of Gd in the GdAS 1 %, for the anticipated 2 % concentration by mass of $Gd_2(SO_4)_3$. (For ease of conversion: 1 ppt(^{238}U) $\simeq 1.2 \times 10^{-2}$ mBq/kg; 1 ppt(^{232}Th) $\simeq 4.1 \times 10^{-3}$ mBq/kg.)

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

In parallel to DS-20k detector, the GADMC will pursue the development of an approximately 1 t detector specifically optimized for the detection of low-mass dark matter, DarkSide-LowMass (DS-LM). DS-LM will achieve a lower energy threshold than DS-20k by triggering on the electroluminescence signal from ionization 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. 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 $10\,\mathrm{GeV}/c^2$, see Fig. 3. Among these are the development of low-background PDMs [25, 26] 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. The development of DS-LM may exploit components of the DS-Proto detector under developed at CERN. Funding for the development, construction, commissioning, and operation of DS-LM will be separately requested via alternative funding programs.

3. Argo

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

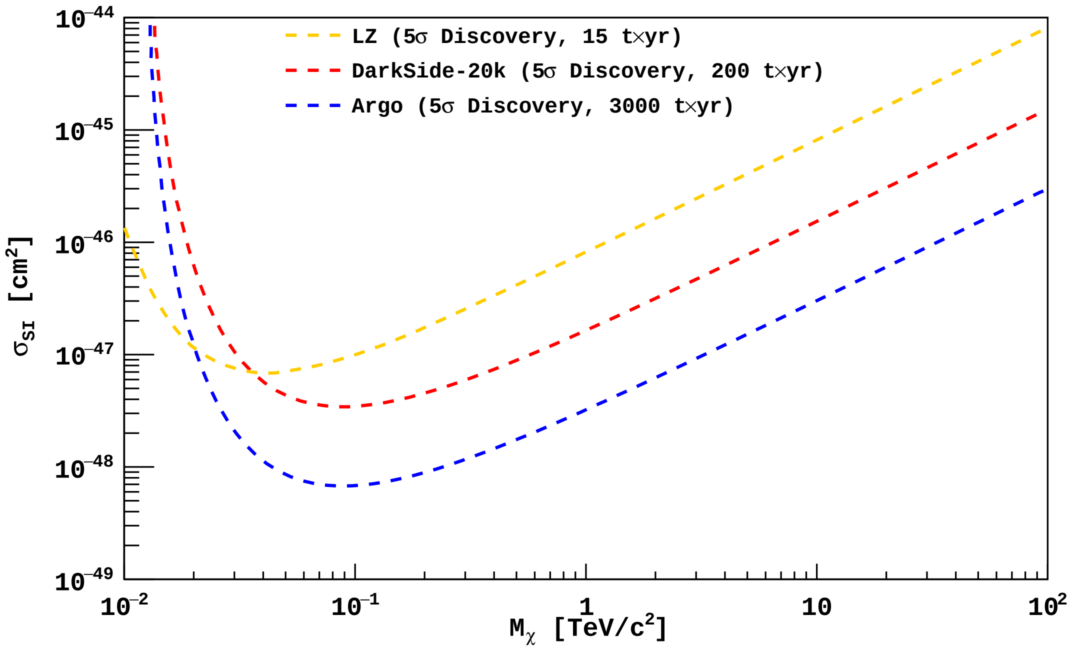

FIG. 4. 5σ discovery potential of the leading future noble liquid dark matter searches.

Urania plant and Aria facility will enable 400 t of UAr to be extracted and purified over a period of about 6 yr. 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 observe CNO neutrinos for the first time and solve the Solar Metallicity Problem [27]. 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.

4. 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 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 2.4×10^8, 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. 3 and Fig. 4. 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 [28] as well as models of solar cycle, seasonal, geographic, and geomagnetic dependence of the neutrino flux [29, 30]. 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 [31], which in turn is driven by their current 10 % uncertainty on neutrino flux [32] and a 6 % uncertainty on the LAr response as measured by SCENE [33, 34] and ARIS [35]. 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 [36]. As seen from Fig. 4, DS-20k has significantly greater discovery potential than that of LZ.

5. 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 [24]: 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 60 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 [24]: 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 Regione Autonoma della Sardegna.

SiPM-based Cryogenic Photosensors [24–26]: 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 [37] and NEXT [38–40]. 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 [9, 10]: 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 PMMA TPC [2, 41, 42]: 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, most notably the stainless steel cryostat. The PMMA vessel will also reduce the complexity of the TPC assembly.

6. 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" [43] 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.*

P5 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" [44] authored by the "Astroparticle Physics European Consortium" (APPEC) 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.*

APPEC then adds: *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.*

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.*

2. Research Community Benefits

The DS-20k project responds to two out of NSF's Six Research Big Ideas.

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.

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. In particular, the DS-20k data, due to the large number of expected ER background events, will have a massive class-imbalance. This creates an opportunity test new machine learning algorithms along with traditional analysis methods and compare their effectiveness. This is a common problem within the information technology community, and DS-20k will provide another opportunity to develop solutions in a basic research environment that will be broadly adaptable to other real-world problems.

Mid-scale Research Infrastructure: The DS-20k project meets the criteria of an NSF Mid-scale Research Infrastructure outlined in NSF's "Bridging the Gap: Building a Sustained Approach to Mid-scale Research Infrastructure and Cyberinfrastructure at NSF." It also benefits from the participation of and strong support of international partners.

DS-20k was jointly proposed to the US NSF, the Italian INFN, and LNGS, the host laboratory, in December 2015. The experiment was first reviewed by a joint panel charged by the Italian INFN and the US NSF. The joint review was made possible by NSF statute NSF-14-1999 "Dear Colleague Letter - International Activities within the Physics Division - Potential International Co-Review" [45] following approval by the US State Department. Following the first joint review, the experiment was also reviewed by the INFN *Commissione Nazionale Seconda* (CSN2), the INFN *Comitato Tecnico Scientifico* (CTS), the LNGS Scientific Committee, and the "Particle Astrophysics – Experiment" panel of NSF. Following all reviews, the experiment was approved by INFN and LNGS in April 2017 and by NSF in October 2017. Following a meeting of participating international funding agencies and laboratories held at the Embassy of Canada in Rome in September 2017, the experiment was officially supported by three participating underground laboratories: the host laboratory LNGS, Laboratorio Subterráneo de Canfranc (LSC), and SNOLAB.

The DS-20k experiment is hosted by LNGS. The LNGS Scientific Committee, which meets two times per year, has oversight of the experiment and has assigned two Committee members as reviewers of DS-20k. The reviewers evaluate technical developments, schedule compliance, and collaboration issues, and report their findings to the LNGS Scientific Committee.

INFN has already provided most of the capital funds needed to support the DS-20k project. R&D and laboratory set-up costs have been covered by INFN CSN2. Additional funding in Italy, including support for the Urania, Aria, and NOA facilities, comes from special and regional funds, the Ministero dello Sviluppo Economico (MISE), the Ministero dell'Istruzione, from the Universita e Ricerca (MIUR), the Regione Abruzzo, and the Regione Autonoma della Sardegna. The Regione Autonoma della Sardegna and INFN instituted a Comitato di Indirizzo to manage the Aria project. The Regione Autonoma della Sardegna and INFN instituted a *Comitato di Indirizzo* to oversee and monitor the Aria project. Within INFN, the experiment is regularly reviewed by the CSN2, which oversees technical developments and budget, collaboration, and schedule issues. CSN2 appoints six permanent referees charged with the review and monitoring of DS-20k.

Several groups from Canada joined the DS Collaboration in September 2017. They have secured funding for the large scale extraction of low-radioactivity argon from CFI in Canada and funding for DEAP-3600 R&D from NSERC. An internal proposal for capital funds to support DS-20k activities was submitted to TRIUMF in October 2017 and was approved for funding. A proposal to the Canadian CFI for additional capital funds will be submitted in October 2019. Recently, an agreement between INFN and The Institute of High Energy Physics of the Chinese Academy of Sciences (CAS-IHEP) reached an agreement to produce the acrylic material for both the TPC and the veto detectors in China. The GADMC collaboration is currently composed of 59 institutions and 371 scientists from 15 nations: Brazil, Canada, China, France, Germany, Greece, Italy, Mexico, Poland, Romania, Russia, Spain, Switzerland, the United Kingdom, and the U.S.

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.

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 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 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 blinded 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. 5 and Fig. 6), 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, and the ability to trigger on the S2 signal from single electrons, allowed us to extend the analysis threshold to $100\,\mathrm{eV_{ee}}$ ($600\,\mathrm{eV_{nr}}$). 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 from $1.8\,\mathrm{GeV}/c^2$ to $6.0\,\mathrm{GeV}/c^2$. The second search 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 $30\,\mathrm{MeV}/c^2$ to $50\,\mathrm{MeV}/c^2$ 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 [46]. 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 5 (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 [33], and that the two measurements are in good agreement with each other.

The 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 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 [33, 34], 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 [47]. 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 [48], a physics paper describing

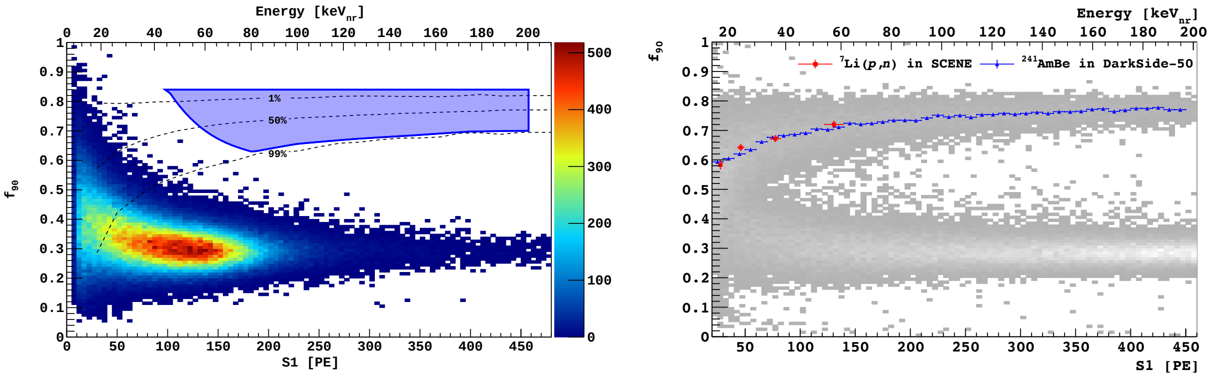

FIG. 5. **Left**: Results from a run of DarkSide-50 with a UAr fill for a 532.4 live-days livetime. The plot shows the distribution of events in the main pulse shape discriminant, f_{90} (the fraction of the primary scintillation pulse in its first 90 ns) vs. the total integral of the primary scintillation pulse, S1 (measured in photoelectrons, PE), after application of the standard analysis cuts that maximize the DS-50 sensitivity. 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. In both plots, the NR energy scale relevant for WIMP scattering is shown on the top axis.

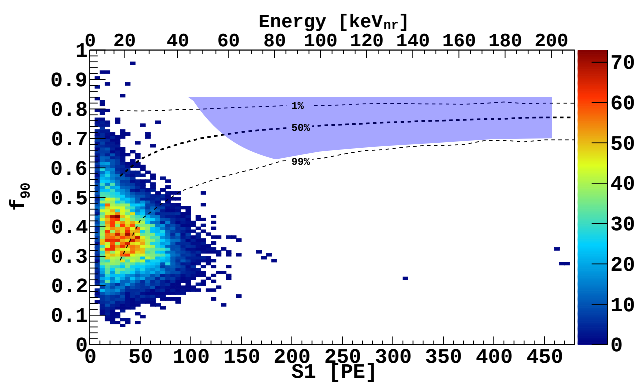

FIG. 6. Event distribution of a 532.4 live-days UAr exposure from DarkSide-50. The plot shows the main pulse shape discriminant, f_{90} (the fraction of the primary scintillation light collected in the first 90 ns) vs. the total integral of the primary scintillation pulse, S1 (measured in photoelectrons, PE), after the application of the standard analysis cuts and additional radial and S2/S1 cuts similar to those that will be applied in DS-20k. The dashed lines identify the lower boundaries of nuclear-recoil signal regions at the indicated acceptances. The shaded blue region is the WIMP search box. The NR energy scale relevant for WIMP scattering is shown across the top axis.

the effect of low electric fields on scintillation light yield from α's in LAr [49], a technical paper describing our simulation of argon response and light detection in DS-50 [47], a technical paper describing the calibration source deployment system [46], a physics paper describing radiogenic neutron yield calculations for low-background experiments [50], a technical paper detailing the electronics, trigger and data acquisition system of the DS-50 LAr TPC [51], and a physics paper describing the electroluminescence pulse shape and electron diffusion in liquid argon [52].

2. Broader Impact

Since its inception in 2009, the NSF-funded DS program has had 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, connecting with 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 co-organize a hands-on Nuclear Analytic Techniques 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 and industry. 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 the *Tecnopolo dell'Aquila* 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 collaboration to abandon the development of PMTs and to

focus the DS R&D on SiPMs. As a direct result of this early focus, many leading results on the utilization of SiPMs as cryogenic photosensors were achieved. 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 [26].

- 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 $\sim$10 kg 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 U.S. and other collaborating 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 experiment, FBK, who produced all of the SiPMs used for the development of the DarkSide2k PDMs, has transferred their SiPM technology to a large silicon foundry, LFoundry. LFoundry completed their first engineering run in September 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 July 2019.

The construction of DS-20k detector will require the production of more than 8280 PDMs in 2.5 yr. 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 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 in March 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 60 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 Canfranc Underground Laboratory (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, 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 [33, 34, 53] and ARIS [35]. The characterization of the ReD light yield and S1 and S2 response is now complete and a neutron beam characterization measurement is planned for June 2019 at the INFN Laboratori Nazionali del Sud (LNS) in Catania, Italy. Upon completion of the neutron beam characterization, a run with the ReD LAr TPC on the neutron beam will be scheduled. A request for beam time was approved by the Scientific Committee of LNS, resulting in the allocation of five weeks of beam time in 2019.

IV. IMPLEMENTATION PLAN

The tasks and technical activities for the implementation of DarkSide-20k project have been distributed among the GADMC 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 project and the GADMC management structure is detailed in the accompanying Project Execution Plan (PEP).

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 of 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.

Virginia Tech: Virginia Tech is responsible for the design and implementation of a detector performance monitoring system that will integrate the major sub-system slow controls. They will work with the veto group on improving veto light collection and the calibration group on camera and gamma source components.

A detailed overview of the GADMC management structure can be found in the PEP. The collaboration 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 decides on all appointments and terminations of the GADMC 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 made by consensus or vote. Each of the three sub-projects is managed by a Project Leader and a Technical Coordinator. The management of each sub-project is divided between Level-1 and Level-2 managers, who are responsible for the direction of various sub-tasks. The execution of the project is responsibility of the Technical Board. The Resources Review Board is responsible for the overall resource planning, ensuring that resource needs are consistent with the various local and national funding sources.

V. FOREIGN COLLABORATOR CONTRIBUTION

The GADMC has been characterized by a strong international contribution since its inception in 2017. The current collaboration counts 371 scientists and engineers from 59 institutions and laboratories from 15 countries as members. The responsibilities of foreign institutions include:

- Italy (INFN): DS-20k detector (laboratory logistics, argon veto, photoelectronics, 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): NOA.
- Canada: DS-20k detector (acrylic vessel, TPB coating, conductive film development, electronics and DAQ) and Urania (underground argon transportation and storage).
- Poland: DS-20k detector (material screening and radon control).
- Spain: DS-20k detector (TPC fabrication, material screening) and DArT.
- France: DS-20k detector (simulations, veto), ARIS, and ReD.
- Russia: DS-20k detector (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: DS-20k detector (acrylic procurement).
- U.K.: DS-20k detector (veto, photoelectronics).

Further information can be found in the Project Execution Plan.

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. Princeton's awards are PHY-1812540 and PHY-1622415, with all associated collaborative awards falling within the same purpose. 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 detector and the second provides some initial capital construction costs for DarkSide-20k project. 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

The technologies developed by GADMC benefit society at large in a variety of ways, ranging from medical diagnostics, advances in photon detectors, and isotope separation.

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 treatment of cancer, neurological-imaging, and cardio-imaging.

The development of SiPMs for DarkSide-20k project will drive substantial improvements in 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.

GADMC 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. GADMC has already played a major role in improving the US availability of ^{4}He. In conjunction with the Urania project, GADMC 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 [54], a very rare isotope that has applications 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 $^{40}\mathrm{Ca}(n,\alpha)^{37}\mathrm{Ar}$ has a relatively high cross section and is a signature of a large flux of neutrons interacting with soil [55]. 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 [56] and ^{39}Ar [57]. 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 DarkSide-20k project will extend the reach of these measurements. Geologic argon samples from the GADMC R&D effort have been recently used at Pacific Northwest National Laboratory to characterize ultra-low-background proportional counter backgrounds [58, 59]. The UAr development that is central to the physics reach of DS-20k experiment 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) [60], 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 [61, 62]. ^{18}F-FDG also plays an important role in neuroscience [63]. ^{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 [64], and the ^{13}C-Spirulina platensis gastric emptying breath test [65]. 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 [66–68]. 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, have larger up-times, and possess a greater fuel economy. The higher density, higher melting temperature, better thermal conductivity, and lower heat capacity [69, 70] of uranium nitride compared with other oxides helps improve the safety margin in reactor design [71]. 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 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, while 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 collaborating institution in Italy where they will participate in educational and research activities related to the DarkSide-20k project.

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 GADMC 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 GADMC has experience building compelling narratives around the DarkSide-20k 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 educational 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 has conducted educational outreach to local public schools (K-12) and engaged high school and undergraduate students in meaningful research related to DarkSide-20k science. We plan 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 GADMC to a broader audience and build a cadre of scientists and engineers prepared to enter the STEM workforce.

VIII. SUPPLEMENTARY DOCUMENTS

The first of the "Supplementary Documents" attached to this proposal is the "Project Execution Plan" requested in the solicitation.

A "Preliminary Design Report" was prepared in 2016 and later published as Ref. [24]. However, following the approval of the experiment in 2017, LNGS requested that the GADMC reconsider its original approved plan, an organic liquid scintillator veto detector nested inside a water Cherenkov veto detector, in order to minimize any possible environmental impacts of underground LNGS operations. Following this recommendation, the GADMC abandoned its original plan and developed a new solution based on the ProtoDUNE membrane cryostats developed at CERN. The LAr TPC of DS-20k is placed at the center of the ProtoDUNE cryostat, which will be filled with 700 t of liquefied AAr. Part of this volume will be instrumented and serve as a scintillation (and Cherenkov) anti-coincidence veto detector. The new design basis is captured in an "Intermediate Design Report", also appended as a Supplementary Document. A detailed "Technical Design Report" is in preparation and its completion is expected by the spring of 2020.

Other Supplementary Documents include a letter from the INFN President F. Ferroni, detailing INFN's approval and LNGS's commitment to host the experiment; a letter from the Vice President for Source & Transportation of the Kinder Morgan CO2 Company K. Havens, approving the Urania specifications and detailing their commitment to hosting the Urania facility; an excerpt from the authorization for the installation and commissioning of Seruci-I (and its translation into English); and the most significant quotations provided in support of the Basis of Estimate.

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