DarkSide-20k: A Global Program for the Direct Detection of Dark Matter Using Low-Radioactivity Argon

<u>OVERVIEW:</u> Gravitational effects that cannot be explained by visible matter are well-documented, though their source remains unknown. A well-motivated leading candidate is as-yet undiscovered elementary Weakly Interacting Massive Particles (WIMPs). Motion of galactic halo WIMPs relative to a detector on Earth could result in WIMP-nucleus elastic collisions directly detectable by a low-background, low-threshold detector capable of unambiguously identifying a small number of nuclear recoils from a very large exposure.

This proposal is to support the NSF-funded DarkSide (DS) groups for the construction and operation of DarkSide-20k (DS-20k), a direct WIMP search using a Liquid Argon Time Projection Chamber (LAr TPC) with an active (fiducial) mass of 23 t (20 t). It also supports their participation in the Global Argon Dark Matter Collaboration (GADMC) that unites the DarkSide, DEAP-3600, MiniCLEAN, and ArDM collaborations into a single world-wide effort, centered around DS-20k as the first step towards the ultimate goal of detecting dark matter with LAr TPCs.

DS-20k was approved in April 2017 by INFN and LNGS, and by NSF in October 2017. DS-20k sub-projects were also approved and funded by the Italian Government, by Regione Abruzzo, and by Regione Autonoma della Sardegna. DS-20k is also an experiment officially supported by LNGS, LSC, and SNOLab.

DS-20k builds on the success of DarkSide-50 (DS-50), operating at LNGS since 2013, which produced two zero-background science results using atmospheric argon (AAr) and then underground argon (UAr) fills. DS-50 demonstrated an ^{39}Ar reduction of 1400 in the UAr. Electron recoil (ER) background was shown to be completely suppressed in the region of interest, with discrimination better than 1 part in 1.5×10^7. Results of the two combined DS-50 runs demonstrated the ability of large LAr TPCs to operate in an "instrumental background-free mode" – a mode in which less than <0.1 events (other than actual 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.

<u>INTELLECTUAL MERIT:</u> DS-20k will have ultra-low backgrounds, with the ability to measure its backgrounds *in situ*, and sensitivity to WIMP-nucleon cross sections of $1.2 \times 10^{-47}\,\mathrm{cm}^2$ ($1.1 \times 10^{-46}\,\mathrm{cm}^2$) for WIMPs of $1\,\mathrm{TeV}/c^2$ ($10\,\mathrm{TeV}/c^2$) mass, to be achieved during a 5 yr run with exposure of 100 t yr. This projected sensitivity is a factor of >50 better than currently-published results for spin-independent cross sections of WIMPs with $\geq 1\,\mathrm{TeV}/c^2$ mass, and covers a large fraction of the mass-cross section space currently preferred by supersymmetric models. 1.6 events resulting from atmospheric ν-induced nuclear recoils are expected in DS-20k, which could be the first direct dark matter detection experiment to reach this crucial milestone.

DS-20k will either detect WIMP dark matter or exclude a large fraction of the favored parameter space. It will also lay the groundwork for a future, multi-hundred tonne argon experiment designed to further explore dark matter and to measure low-energy solar neutrinos with high precision.

<u>BROADER IMPACT:</u> Scientific broader impacts of the DS UAr extraction program include: discovery of a novel, commercially viable helium source that today supplies 15 % of the National Helium Reserve feed; a proposed technology for ^{3}He extraction from ^{4}He production plants that could alleviate the ^{3}He shortage; production of hundreds of tonnes of low-radioactivity UAr for DS-20k, as well as for other technical uses requiring detection of ^{37}Ar for nuclear test ban verification, and ^{39}Ar, for radiometric dating. 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, used for various medical, industrial and energy generation applications. DS technology has also led to 3Dπ, an innovative patent-pending LAr-based TOF-PET with SiPM-based photosensors for enhanced cancer screening with a substantially lower patient radiation dose.

Specific E&O programs are planned with focus on educating K-12 teachers about basic physics and how it relates to dark matter detection, re-starting a summer school experience for high-school and undergraduate students, as well giving research opportunities to undergraduate students at participating underrepresented-minority serving institutions.

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I. INTRODUCTION

The idea of dark matter was conceived more than 80 years ago [1–3]. Since then, a wide range of observations has provided very strong evidence for its existence. These include rotation curves of galaxies and velocity dispersion in clusters of galaxies [4], discrepancies of mass distributions in galaxy clusters as estimated from gravitational lensing and X-ray surveys [5] (including the famous "Bullet cluster" [6, 7]), space-time distribution of large-scale structures [8], anisotropies of the cosmic microwave background [9], Big Bang nucleosynthesis [10, 11], and analysis of the Lyman-α forest [12]. All of these suggest the existence of non-luminous, non-baryonic, non-relativistic, stable matter, commonly known as dark matter. The ΛCDM Standard Cosmological Model, which emerged from the synthesis of all large-scale astophysical and cosmological observations, including the observed accelerating expansion rate of the Universe [13, 14], encapsulates the crucial importance of dark matter and dark energy in the history of the Universe. Although some alternative theories (modified Newtonian dynamics [15–17], emergent gravity [18]) explain some of these large-scale observations without dark matter, no theory can consistently explain all of the observations without dark matter and recent multi-messenger astronomy measurements of a binary neutron star merger, utilizing gravitational wave detection, rule out a large fraction of these [19]. The Standard Model of particle physics has no way of accommodating either dark matter or dark energy among its constituent fundamental particles and force carriers. Dark matter and dark energy represent, therefore, an incontestable piece of evidence for new physics beyond the Standard Model. The discovery of dark matter would be truly transformational, as it would compel a profound change in the representation of the Universe and its physical laws.

One of the most favored dark matter candidates is the hypothetical weakly interacting massive particle (WIMP) [20, 21], a heavy thermal relic of the Big Bang whose electroweak scale self-annihilation cross section provides a seamless mechanism for dark matter freeze out, so that the current abundance of dark matter is naturally and elegantly explained. Many extensions to the Standard Model feature natural WIMP candidates, including notably, but not exclusively, the family of supersymmetric theories [22–26].

WIMPs could be detected by observing the particles and radiation from WIMP-WIMP annihilation processes, as attempted in a large and expanding number of satellite- and ground-based experiments [27–34]. WIMPs can also be directly produced in high energy collisions at accelerators, notably the Large Hadron Collider (LHC). WIMP searches at colliders focus on the identification of vertex events with missing momentum and energy, and the two experiments ATLAS and CMS are making significant progress on ruling out regions of parameter space for WIMPs [35–38]. The recent LHC run at the center-of-mass energy of 13 TeV has raised the bar for the direct discovery of new physics, relegating much of the space for new particles to the multi-TeV/c^2 range.

Direct WIMP searches look for the nuclear recoils (NR) resulting from collisions of galactic WIMPs with ordinary matter in the laboratory. Since these WIMPs already exist in nature, direct searches do not suffer from the center-of-mass-energy limitation of the LHC and can therefore observe dark matter particles of very large masses, many tens, hundreds, or thousands of GeV/c^2. This is a new frontier for the exploration of physics at the high energy scale. The region of detector exposure left open before the onset of NR background from coherent electroweak scattering of atmospheric neutrinos (the so-called "neutrino floor"), extends from the current level of detection sensitivity, about 1 t yr, to several hundred t yr. Covering this vast space of opportunity with a background-free search is mandatory for a real discovery program given that the signal from dark matter lacks sharp spectral features.

Over the past ten years, improvement in sensitivity of direct dark matter searches has completely excluded a WIMP-nucleon cross section at the weak scale mediated by the Z boson and part of the cross section region for Higgs-boson-mediated couplings [39]. Also, in several classes of supersymmetric models, consideration of the measured mass of the Higgs boson results in dark matter particle masses at the scale of TeV/c^2 [40, 41]. Similarly, searches for rare flavor processes, such as $B_s \to \mu^+\mu^-$, also drive the expected masses of supersymmetric particles to the TeV/c^2 scale [41, 42]. The existing theories, constrained on one side by current limits from direct dark matter searches and on the other by null results of the LHC searches, predict a significant possibility for a discovery of dark matter in the mass-cross section parameter space right below current detection limits of direct dark matter searches [43]. The bulk of the region left open for discovery requires masses on the scale of TeV/c^2 and beyond, and this is exactly the region where argon-based dark matter searches will perform at their best. This is due to their unique ability to strongly reject background from minimum ionizing events over an exposure as large as several hundred t yr, as projected from the results of DarkSide-50 (DS-50) [44–46].

A number of direct detection experiments are currently underway using a variety of detector technologies, including cryogenic bolometers with ionization or scintillation detection (CDMS [47–50], SuperCDMS [51], EDELWEISS [52], CRESST [53]), sodium or cesium iodide scintillation detectors (DAMA/LIBRA [54–56], KIMS [57], SABRE [58]), bubble chambers (PICASSO [59], COUPP [60, 61], PICO [62, 63]), point contact germanium detectors (CoGeNT [64–67], MALBEK [68]), liquid argon (LAr) detectors (ArDM [69–71], MiniCLEAN [72], DEAP-3600 [73], WArP [74, 75], DS-50 [44, 45]), and liquid xenon detectors (ZEPLIN [76], XENON-100 [77–79], LUX [80–83], XMASS [84], PandaX-I [85], PandaX-II [86, 87], XENON1T [88, 89], LZ [90, 91], XENONnT [92]). Liquid xenon time projection chambers have led the field of direct detection over the last decade, beginning with ZEPLIN [76] and XENON-10 [93] and continuing with recent results from LUX [83], XENON1T [89], and PandaX-II [87].

The DarkSide (DS) Collaboration unites researchers from currently operating LAr direct dark matter searches to build the DS-20k detector [46, 94], designed to be experimental-background free and featuring the best sensitivity to high-mass WIMP dark matter among all experiments that are currently approved and foreseen to operate within the next 5-10 years (see Figure 1). The DS-20k detector is also complementary to the next generation xenon-based detectors, since a possible observation of WIMPs with two different targets could allow scientists to fully confirm the detection and to disentangle the correlation between mass and cross-section. The DS-20k experiment aims at a significant improvement in sensitivity, a factor of at least >50 with respect to the recent PandaX-II result [87], reaching $1.2 \times 10^{-47}\,\mathrm{cm}^2$ for WIMPs of $1\,\mathrm{TeV}/c^2$ mass. This goal will be achieved using a LAr time projection chamber (LAr TPC) with an active (fiducial) mass of 23 t(20 t), for a total exposure of 100 t yr to be accumulated in a run lasting 5 yr. Thanks to its exceptionally low instrumental background, DS-20k could extend its operations to a decade, increasing the exposure to 200 t yr and reaching a sensitivity of $7.4 \times 10^{-48}\,\mathrm{cm}^2$ for WIMPs of $1\,\mathrm{TeV}/c^2$ mass. These results are only possible due to the pulse shape discrimination (PSD) capabilities of argon, procurement of isotopically pure argon from an underground source, use of a liquid scintillator veto (LSV), and use of large photosensitive areas covered by silicon photomultipliers (SiPMs). A very strong discrimination of electron recoils (ERs) from nuclear NRs was demonstrated in DS-50 using PSD [44], and a supplementary analysis of Monte Carlo simulated data for DS-20k predicted an ultimate rejection factor $>3 \times 10^9$ [46]. This will allow us to completely discriminate the ERs, while the remaining neutron background will be tagged by the LSV neutron veto with very high efficiency. In addition, work to procure the target for DS-50 demonstrated that underground argon (UAr) can be obtained with an ^{39}Ar content that is suppressed by a factor of more than 1400, with respect to atmospheric argon (AAr), drastically reducing the expected number of ER events to be discriminated against. A complete description of the DS-20k program, goals, and detector is available online at Ref. [46].

DS-20k was jointly proposed to the US NSF, the Italian INFN, and the host laboratory, LNGS, 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 for NSF by statute NSF-14-1999 "Dear Colleague Letter - International Activities within the Physics Division - Potential International Co-Review" [96], following approval by the US State Department. Following the first joint review, the experiment has also been separately reviewed by the "Commissione Nazionale Seconda" of INFN, by the "Comitato Tecnico Scientifico" of INFN, by the "Comitato Scientifico" of LNGS, and by 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 is officially supported by three participating underground

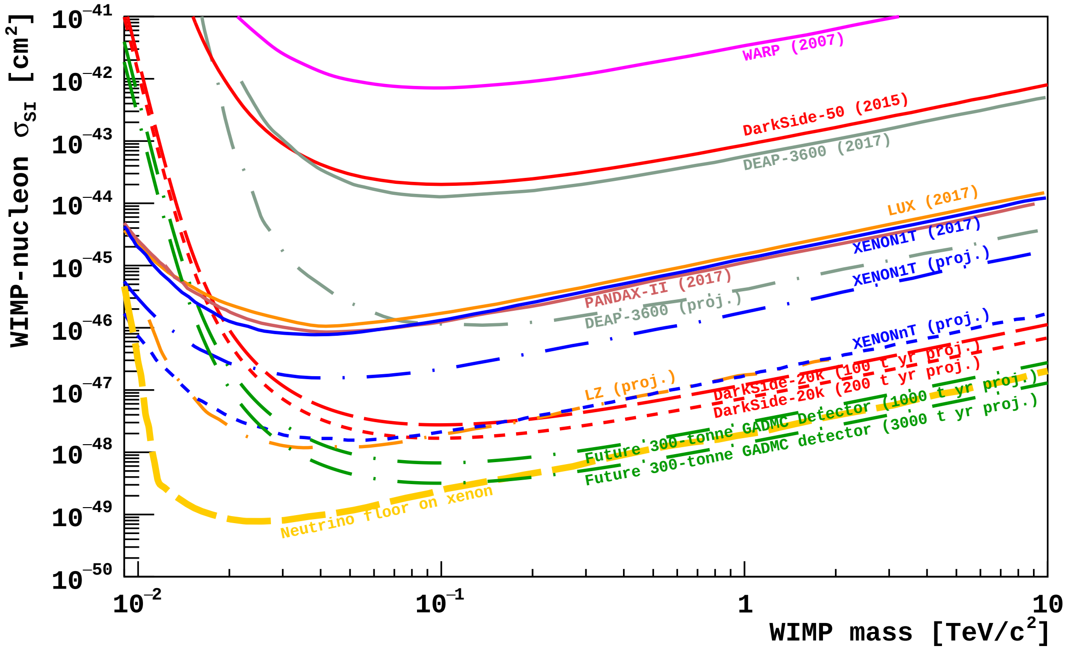


FIG. 1. WIMP spin-independent cross-section vs. mass limits and sensitivities from previous argon-based results, current best limits produced by xenon-based experiments, and expected future sensitivities (dashed and/or dotted lines). The "neutrino floor" curve follows the definition of Ref. [95].

laboratories: the host laboratory LNGS, Laboratorio Subterráneo de Canfranc (LSC), and SNOLab. Future reviews of the progress of the now approved experiment will involve the tight coordination of the Directorates of all three laboratories.

University groups from Poland, Russia, Spain, and Switzerland are already funded for work on DS-20k by their funding agencies. University groups from France, Germany, and UK are currently participating with the DS Collaboration through support from internal resources and are preparing proposals to each of their funding agencies.

Canadian groups have recently joined the DS Collaboration, in September 2017. Funding for large scale extraction of low-radioactivity argon is already available from CFI in Canada. Funding for R&D is available for DEAP-3600 from NSERC in Canada and a further request for development work on DS-20k and the future larger detector will be submitted at the end of 2017. An internal proposal for support to the DS-20k activities and for capital funds was submitted to TRIUMF in October 2017 and a decision is expected by the end of the 2017 calendar year. A proposal to the Canadian CFI for additional capital funds will be submitted to the next competition, expected in 2019.

The current list of Institutions and Collaborators is available on the front page of Ref. [46].

Scientists from the four world-leading LAr dark matter projects (ArDM at LSC, DS-50 at LNGS, DEAP-3600 and MiniCLEAN at SNOLab) have agreed to join forces to carry out DS-20k as a single next-generation LAr experiment at LNGS [46, 94]. The same inclusive group of scientists also signed a Letter of Intent signaling their interest to continue the collaboration beyond DS-20k to build a larger experiment, with a fiducial mass of a few hundred of tonnes, capable of collecting an exposure of 1000 t yr with the ability to remove (by discrimination, veto tagging, etc.) all backgrounds except NRs induced by atmospheric and diffuse supernova background neutrinos. The location and laboratory for this final experiment of our program are still to be debated within the collaboration. The same group of scientists also agreed to form the Global Argon Dark Matter Collaboration (GADMC), a consortium of all institutes active in the development of argon dark matter experiments. The GADMC will:

- Oversee the open access to currently operating LAr dark matter experiments (DS-50 and DEAP-3600) and their science data, to the benefit of all participating institutions,
- Coordinate the contributions to DS-20k at LNGS, the single, next generation LAr dark matter effort at the scale of a few tens of tonnes,
- Coordinate the contributions to the future LAr dark matter effort to build a detector at the scale of a few hundred of tonnes.

II. OVERVIEW

This proposal requests support for operations for the NSF-supported groups involved in the DS program to detect WIMP dark matter. The requested support would span the period of the DS-20k experiment construction, operations, and all necessary related activities, such as the extraction and purification of the low-^{39}Ar argon from underground sources (UAr) through the Urania and Aria projects [46].

The DS Collaboration currently comprises $\sim$350 scientists and engineers affiliated with $\sim$70 groups from 15 countries (Brazil, Canada, China, France, Germany, Greece, Italy, Mexico, Poland, Romania, Russia, Spain, Switzerland, UK, US). Historically, the DS Collaboration was founded in 2009 as a predominantly US collaboration, and to date, the US groups provide leading technological and intellectual contributions. NSF support has allowed the US groups to develop, through the DS-50 detector, the essential technologies enabling the DS-20k detector: the low background LAr TPC concept and design, the low-radon clean room system at Gran Sasso, the liquid scintillator neutron veto, the low-^{39}Ar UAr extracted from underground CO_2 wells, and the SiPM-based cryogenic photosensors.

The US groups lead many of the major efforts of the DS Collaboration. Currently, NSF-supported PI's include Drew Alton (Augustana), Cristiano Galbiati and Peter Meyers (Princeton), Ryan Haaland (Fort Lewis), Ed Hungerford and Andrew Renshaw (Houston), Amy Asunskis (Black Hills State), Jelena Maricic (Hawaii), Jeff Martoff and Jim Napolitano (Temple), Emilija Pantic (UC Davis), Andrea Pocar (UMass Amherst), Bruce Vogelaar (Virginia Tech), and Hanguo Wang (UCLA). These groups manage the DS-50 operations and lead the Urania and Aria projects. They are in charge of the design and realization of the DS-20k LAr TPC, of the design and development of the DS-20k cryogenics and point-of-use argon purification systems, and head the calibrations working group. US effort is also very substantial in the materials selection and screening, in the development of the SiPM 'tiles' and their packaging and integration, in the development of the readout electronics, in the DS-50 data analysis, and in the DS-20k Monte Carlo simulations. Furthermore, the NSF-funded US footprint has also been substantial in the recent ARIS calibration campaign of NRs response in LAr carried out in Paris. ARIS followed up on the success of SCENE [97], and produced calibration results with even higher precision.

Funding is requested for five years, May 2018 through April 2023, covering the following: operating costs related to installation and commissioning of DS-20k detectors and auxiliary infrastructure; the first two years of DS-20k running; and operations of the US PI's involved in the procurement and purification of the UAr for DS-20k. The main responsibilities of NSF-funded personnel as listed in the current DS-20k WBS and laid out within the separate construction proposal (accepted INFN and NSF in April and October of 2017, repsectively) include:

- **Project and technical management**: Princeton PI Cristiano Galbiati, and lead PI of this proposal, is the DS Collaboration Spokesperson who acts as the Project Director for DS-20k and Scientific Director for Aria. Princeton engineer Andrea Ianni is the DS-20k Technical Coordinator and Princeton PI Peter Meyers is one of three Project Scientists. Both Ianni and Meyers contribute to oversight of the entire project and its progress. Other PIs from the US groups are also involved in the project management and planning, at various levels, with details of the involvement given in IV 2.
- **UAr Procurement and Purification**: the US-NSF group (in particular Princeton who dis-

covered the UAr) has pioneered the extraction of low-^{39}Ar UAr from CO_2 wells, some of which is currently being used in DS-50. The required gas separation technology development was based on that developed for radon abatement in clean room air for the Borexino experiment, also supported by NSF. The scaled-up operations necessary for DS-20k are to be carried out under the Urania project and are led by the US groups, with substantial INFN investment for the UAr extraction plant itself. The purification of the UAr to detector grade will be carried out with the Aria plant, a novel 350 m tall cryogenic distillation column invented by Princeton PI Cristiano Galbiati and soon to be installed in Sardinia, which will also be used to study the feasibility of active isotopic separation of the argon isotopes.

- **Cryogenics and argon purification**: the design of the DS-20k cryogenics is based on that of the equivalent DS-50 systems that have been running successfully and without interruption for many years. The design is led by the US groups, with contributions from various institutions. In August 2017 the DS Collaboration and LNGS reached and finalized an agreement with the Accelerator & Technology Sector of CERN and its Technical Division to construct and commission the DS-20k cryogenics at CERN, with support from the Cryogenics Group and the Vacuum, Surfaces and Coatings Group (both groups are part of CERN's Technical Division).
- **LAr TPC design**: US groups lead the design, fabrication and construction of the various components of the LAr TPC, including the anode and cathode planes, wire extraction grid, detector reflector panels, field-cage and high voltage feedthrough. This work will also include work toward the construction, commissioning, and operation of the prototype detector (DS-Proto), which will test and certify all detector design choices for DS-20k.
- **SiPMs procurement and packaging**: this task, which already led to the successful first-time demonstration of final DS-20k SiPM 'tiles' [98], is led by the US groups, with contributions coming from various institutions. To date, SiPMs have been produced at FBK in Italy, while the focus of work on their integration has taken place in the US. As the project transitions from R&D to the large scale construction required for DS-20k, SiPMs production will shift to a silicon foundry selected by INFN, while their integration will shift to the new facility "Nuova Officina Assergi" (NOA) at LNGS, proposed by Princeton PI Cristiano Galbiati and funded by the Italian Government and Regione Abruzzo.
- **Materials screening**: US groups also substantially contribute to this effort, coordinating and carrying out various tests and measurements. The US groups heavily involved in the LAr TPC and SiPM work are closely coupled to this task.
- **Calibrations**: this task is led by the US groups, who are also responsible for coordination of the calibrations plan, as well as development, procurement and deployment/operations of various calibration subsystems.
- **DS-Proto Prototype**: a $\sim$1 t prototype is planned as a stepping stone towards DS-20k, under the leadership of INFN groups. The prototype will demonstrate most DS-20k subsystems, including cryogenics and fluid systems, LAr TPC design, SiPM tiles, readout electronics, and calibrations system. As such, the US NSF-supported groups will be some of the main participants in this effort, that will take place at CERN or LNGS.
- **Liquid scintillator neutron veto**: the US groups lead the scintillator purification operations, while the scintillator development and detector design are led by Italian and Canadian groups.
- **Water Cherenkov muon veto**: US groups lead the Monte Carlo simulations of the cosmogenic backgrounds, which are largely concentrated in the WCV, while the design and construction of the detector itself will be managed by the Italian and Canadian groups.
- **Construction, Operations and Data Analysis**: the US groups will be involved with the construction, start-up and commissioning of the detectors and subsystems, as well as data acquisition operations. The US groups plan to maintain a strong and leading role in the analysis of DS-20k. Within the newly formed GADMC, we are discussing the possibility of forming a joint DS-50/DEAP-3600 data analysis task force as part of the activities leading up to DS-20k, an effort which will also include detector Mote Carlo simulations, focused particularly on fully understanding and modeling the argon response and background discrimination.

III. RESULTS FROM PRIOR NSF SUPPORT

Much of the collaboration's activity in recent years has been focused on the DS-50 experiment, see Figure 2. The DS-50 experiment is 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 4 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 the WIMP search results from our first physics run, an exposure of 47.1 live-days using AAr as the active material [44]. 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 [45]. Figure 3 (left) shows the distribution of events in f_{90} (ratio of S1 light in the first 90 ns relative to $S1_{Tot}$), the pulse shape discrimination (PSD) parameter in LAr, vs. S1, the number of measured scintillation photoelectrons that roughly scales with energy. The power of PSD in LAr combined with the high-efficiency neutron vetoing is apparent: the search box is empty. The resulting upper limit on the WIMP-nucleon cross section resulting from this null search is shown in Figure 1. The run with AAr further showed the robustness of the PSD technique to discriminate NRs from ERs, utilizing the large rate of ^{39}Ar in the AAr.

1. Intellectual Merit

Following the analysis of the 70.9 live-days data set, the WIMP search continues. Interspersed were 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 [99]. The detector is operated remotely, with no on-site shifts. Operations are generally smooth, and in the past 100 calendar days, with 4 days devoted to monthly PMT shutdowns, we have accumulated 89 days of WIMP-search livetime.

Our calibration campaigns have also enabled a rich set of detector-performance analyses.

^{83m}Kr: We regularly inject ^{83m}Kr into the recirculating argon to provide a monoenergetic, low-energy ER signal just above the WIMP search region. This is our primary light-yield monitor and energy calibration. As a secondary monitor of the light-yield we monitor the measured energy of certain γ-ray lines resulting from the decay of various isotopes in the detectors materials on a

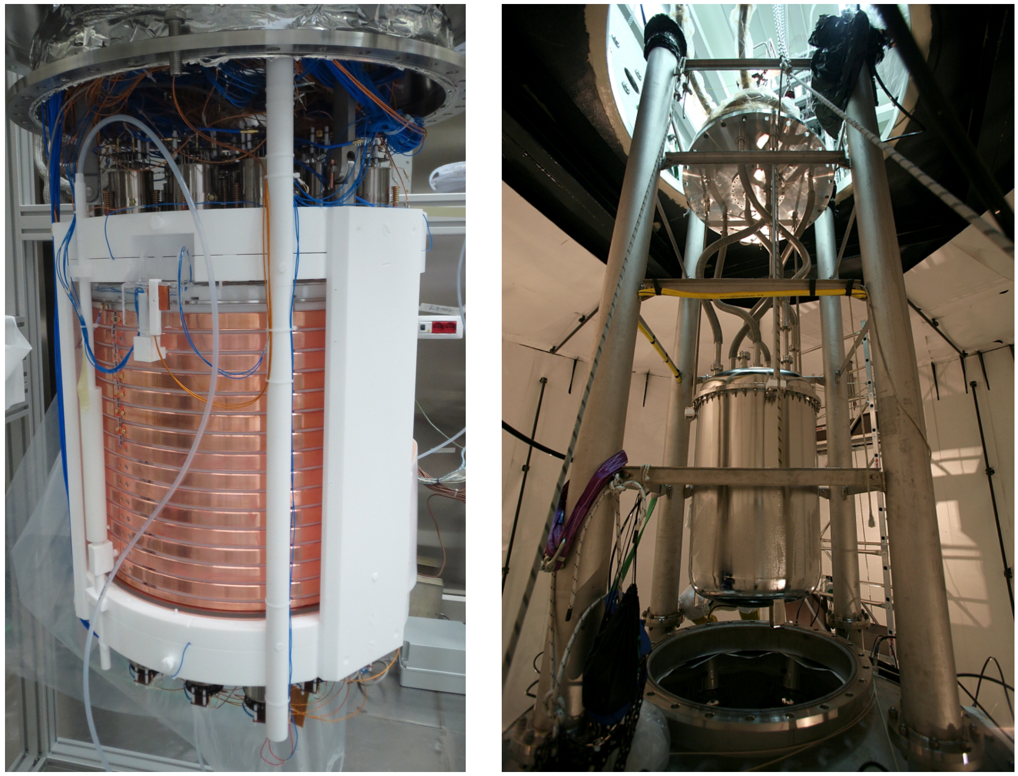


FIG. 2. **Left**: The DS-50 LAr TPC. **Right**: TPC cryostat being lowered into the liquid scintillator veto (LSV) (whose top entry point is visible at the bottom of the picture), which in turn sits inside the the water Cherenkov muon veto (WCV).

run-by-run basis and ensure that the light-yield dose not fluctuate by more than 1 %.

^{241}AmBe neutrons: 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 3 (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 [97], and that the two measurements are in good agreement with each other. Figure 4 shows the spectrum of ^{10}B captures in the neutron veto. The lower energy peak at around 28 PE shows our efficient detection of the heavily quenched α's from the capture to the ^{7}Li ground state (6.4 % branch, orange box), which is crucial to achieve the well over 99 % neutron veto efficiency [100].

^{241}Am^{13}C neutrons: The neutron veto also detects neutrons via elastic scatters from the hydrogen in the scintillator. The high rate of coincident γ-rays in ^{241}AmBe prevents detection of this signal. An americium alpha source irradiating a ^{13}C target through a thin gold foil yields neutrons without exciting the final-state ^{16}O. This gives neutrons with essentially no coincident high-energy γ-rays (only the 59.5 keV γ-rays from ^{241}Am that are stopped by a 2 mm thick lead shield). We produced such a source, and the ^{241}Am^{13}C data allowed us to study events in which a neutron produces a WIMP-like signature in the LAr TPC either before or after scattering and/or capturing in the LSV. We were therefore able to *measure* the veto efficiency for neutron-induced NRs in the LAr TPC. Using a Monte Carlo simulation to correct for the different origin and energy spectrum of neutrons from the source compared to radiogenic neutrons from detector materials, we estimated a data-driven neutron veto efficiency well above 99 %.

The DS external calibration campaigns have provided measurements crucial for optimizing the operation of the DS-50 detector and extraction of its scientific results. This effort will continue as described in Sec. IV 7. The two major efforts that the DS Collaboration has already undertaken

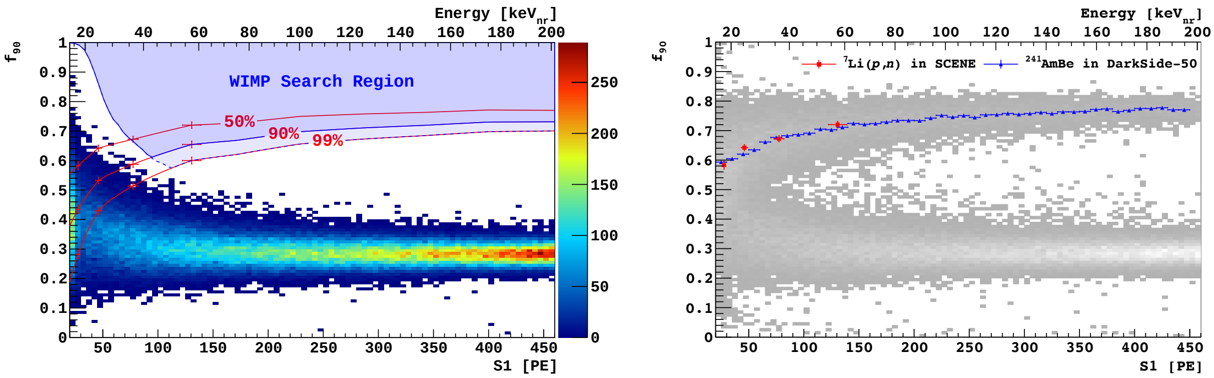


FIG. 3. **Left**: Results from a run of DarkSide-50 with a UAr fill for a 70.9 live-days livetime. The plot shows the distribution of events in the main pulse shape discriminant, f_{90} (the fraction of the primary scintillation pulse in its first 90 ns) vs. the total integral of the primary scintillation pulse, S1 (measured in photoelectrons, PE). The red 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 $n+\gamma$ 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.

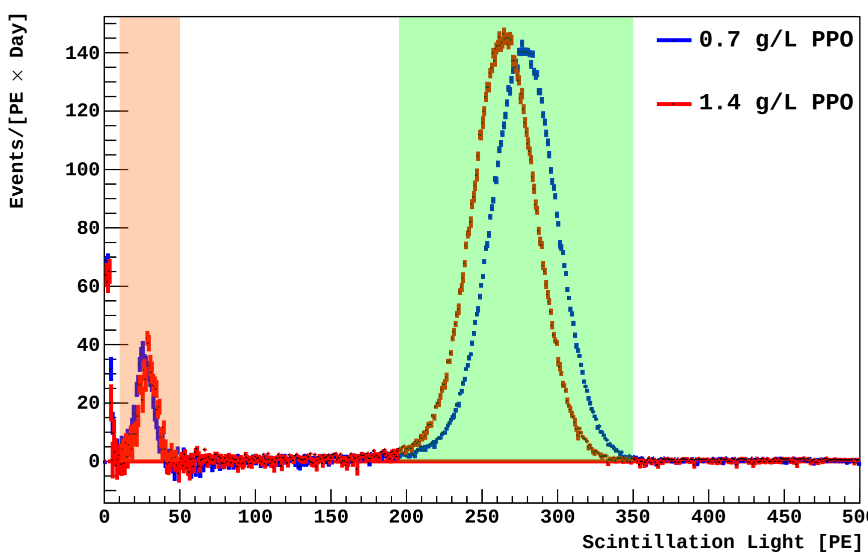


FIG. 4. Neutron-capture on ^{10}B in our borated-liquid-scintillator neutron veto with two versions of the scintillator cocktail. The orange (green) box indicates the signal from the α-only ($\alpha+\gamma$) final state.

are:

- **SCENE:** The first measurement of the low-energy light (10.3 keV$_{\mathrm{nr}}$ to 57.3 keV$_{\mathrm{nr}}$) and charge (16.9 keV$_{\mathrm{nr}}$ to 57.3 keV$_{\mathrm{nr}}$) yields for NRs as a function of drift field was performed in the SCENE experiment [97, 101], led by members of the DS collaboration. The choice of a standard drift field value of 200 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 [44, 45] were also determined using the SCENE data. Finally, the SCENE experiment gave a hint about the directional signature in

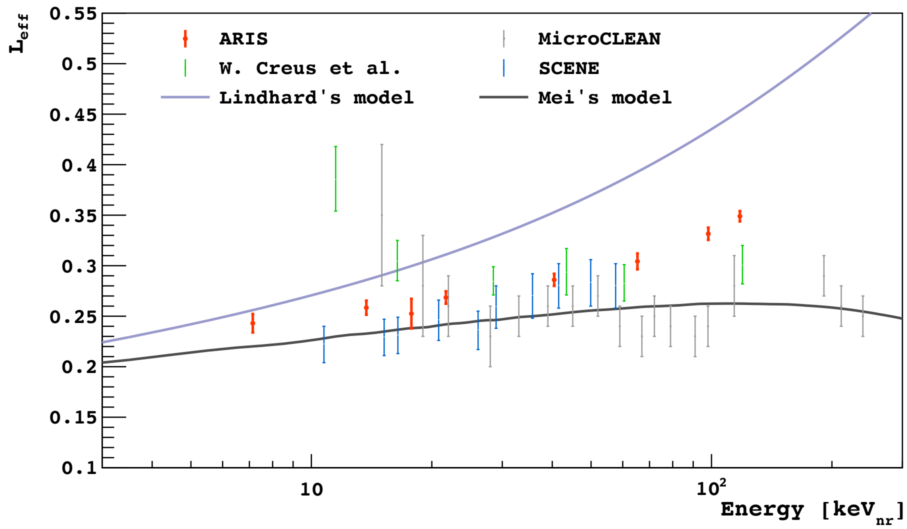


FIG. 5. ARIS results for quenching of NR light yield in LAr. The ratio of NR/ER light yield at zero field is shown vs. NR energy. This preliminary result is compared to previous measurements (see [97] and references therein). Publication of the ARIS results is expected during CY 2017.

the scintillation response of 57.3 $\mathrm{keV_{nr}}$ NRs.

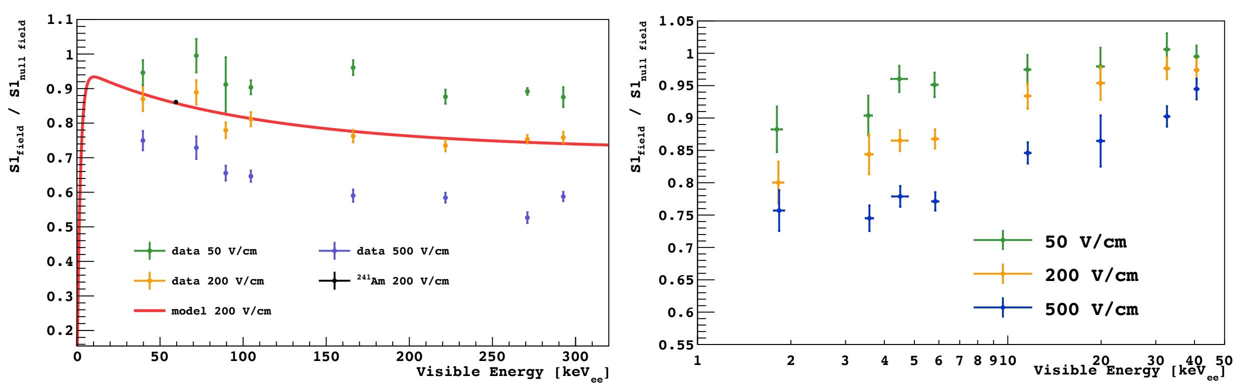


FIG. 6. **Left**: Preliminary ARIS results for quenching of ER light yield in LAr at different drift fields. The 200 V/cm dataset is compared to the PARIS model tuned on DarkSide-50 data [102]. **Right**: Preliminary ARIS results for quenching of NR light yield in LAr at different drift fields. Publication of the ARIS results is expected during CY 2017.

- **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, as shown for the zero drift field data in Figure 5. 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 (see Figure 6), 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 [102]. 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.

More recently, besides the publications referenced above, we published a technical paper detailing the electronics and data acquisition of the DS-50 veto detectors [103], a physics paper describing the effect of low electric fields on scintillation light yield from α's in LAr [104], and a technical paper describing our simulation of argon response and light detection in DS-50 [102]. The technical paper describing the calibration source deployment system was also published [99]. We have also very recently submitted several others papers for publication, including papers describing radiogenic neutron yield calculations for low-background experiments [105] and the details of the electronics, trigger and data acquisition system of the DS-50 LAr TPC [106].

We have accumulated over 500 live-days of WIMP search data since publication of the first search with 70.9 live-days of UAr. The new data is the subject of our first blind analysis. For the blind analysis, we have been developing predictions for the rates of all known backgrounds after existing and newly-developed cuts. Our goal is <0.1 events of predicted background from all sources in the WIMP search box, giving a reasonable likelihood of a background-free search. We are currently finalizing this analysis.

2. Broader Impact

Since inception in 2009, the NSF-funded DS program has had significant broader impacts in both the education and outreach areas, as well as in scientific developments affecting industry and broader fields of science.

Through 2012, the collaboration offered a unique multi-cultural summer program which 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 give 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 addresses 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 in total over the course of 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 the 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 DS 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 of course essential in many branches of science. It is a scarce, non-renewable resource which is rapidly getting scarcer and more expensive. Throughout the continuous (since 2008) 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 directly led to the start of the first ever commercial enterprise to extract helium from a CO_2 stream. The Air Products company built a helium production plant treating the entire Kinder Morgan Cortez CO_2 stream. This plant started production in July 2015 and presently supplies ^{4}He equivalent to 15 % of the declining production from the US National Helium Reservoir.

- 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 2018. Construction of the modules of the first Aria column is ongoing in Italy and Q&A tests are ongoing at CERN. 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 to be 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 DS collaboration to abandon the development of PMTs and to focus the DS R&D on SiPMs, and 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 [98].
- 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 LAr TPC concept, in conjunction with the use of SiPMs, has been proposed and is under development at Princeton to allow construction of higher-resolution PET scanners, using its 3D interaction resolution and fast timing.

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

IV. DARKSIDE-20K EXPERIMENTAL CONTRIBUTIONS

1. Research Plan

The DS-20k design is based on a scaled up version of its predecessor DS-50 but with several improvements and changes. A simplified 3D model of the DS-20k detector layout is shown in Figure 7. The detector system will be deployed at LNGS, in the underground Hall C. The following sections describe the main detector system components, focusing on the contributions from the US NSF-supported groups, while full details of the DS-20k experiment, as well as the procurement and purification of the UAr, can be found in [46]. It should be noted that the design of the LSV is undergoing a continuous improvement of design, taking into account the expertise that has been brought into the collaboration with the joining of the Canadian groups. They bring a high level of experience building large acrylic vessels for underground experiments like SNO and DEAP3600, and this has enabled the DS-20k veto group to propose an acrylic vessel instead of a stainless steel sphere. Having an acrylic vessel provides the advantage of bringing the LSV PMTs outside of the scintillator and placing a water buffer between them and the scintillator. This in turn reduces the event rate in the LSV and thus the accidental rate with the LAr TPC, allowing for maximal exposure to be collected. The design of the encapsulation of the PMTs would be much simpler

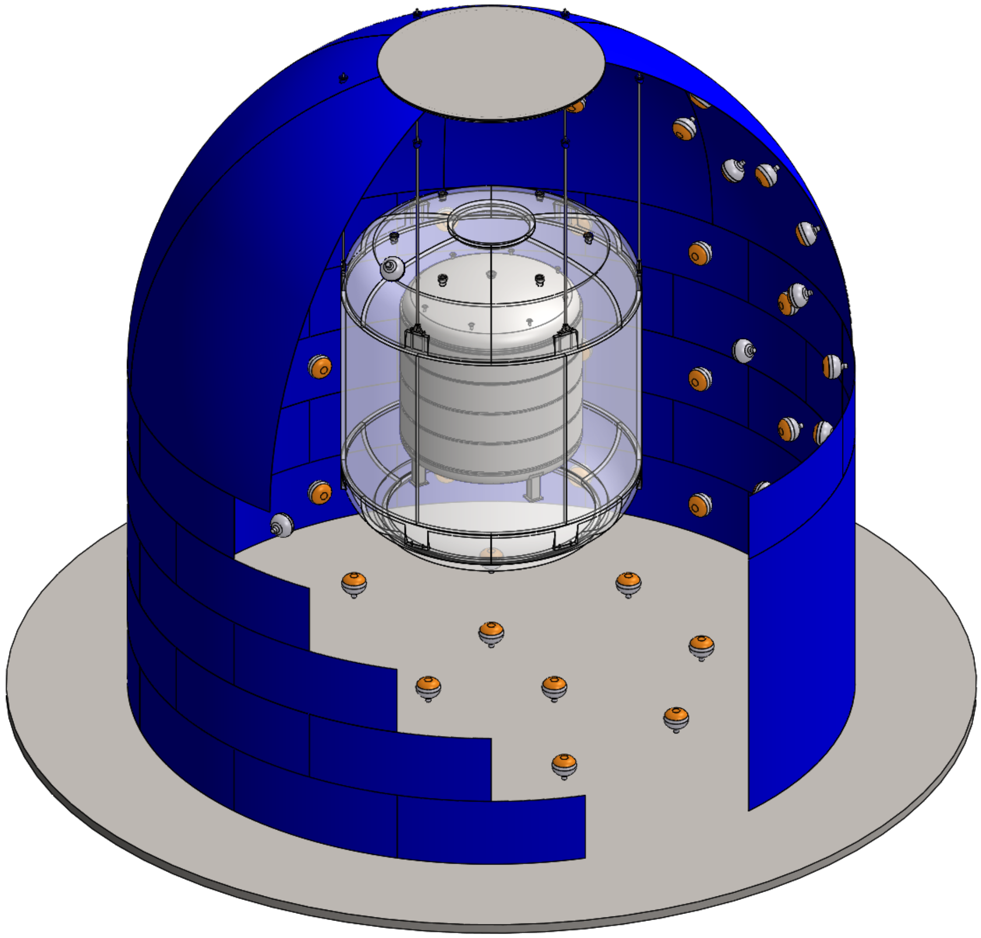


FIG. 7. Simplified 3D rendering of the DS-20k detector, showing the water tank making up the WCV detector, the acrylic vessel for the LSV detector, and the cryostat that contains the LAr TPC.

since they can mimic the design for the WCV PMTs. Changing the design of the LSV does not affect the distribution of responsibilities of the NSF-supported groups.

The group of PIs participating in this proposal have been instrumental in pushing the DS Collaboration to this point, from initiating the program for discovering and then extracting UAr to acting as leaders in the management and development of the DS-50 two-phase LAr TPC and it successful operations and data analysis. This effort will continue as the next detector in the DS family is built and operated. The work that will be carried out using the support requested in this proposal spans a broad range of the responsibilities that make up the entirety of the DS-20k project. The work will include:

- Project management and overall design of the DS-20k detectors and subsystems,
- Management of the UAr extraction and purification,
- Design, development, fabrication, construction, and commissioning of the cryogenics and gas handling system,
- Design, development, fabrication, construction and commissioning of the LAr TPC,
- Materials screening and selection,
- Calibration of the DS-20k detectors, including development and procurement of the required subsystems,
- Start-up, commissioning, and operations of DS-20k,
- Data analysis using both DS-50 and DS-20k data, as well as joint analysis of DEAP-3600 data.

An overview of the work breakdown structure (WBS) of DS-20k is given in Table I showing which

NSF-supported groups will be contributing to each task. While this section will only summarize the major efforts that the collective group of PIs will be working on, more details on specific responsibilities are given in the individual budget justification sections.

TABLE I. Overview of the DarkSide-20k WBS and NSF Group responsibilities.

Item	Work Package	NSF Groups Involved
1.1	Photo-Electronics	Princeton, Augustana, UMass
1.2	Inner Detector	Princeton, UCLA, UC Davis, Houston
1.3	Materials	Temple, BHSU
1.4	Calibrations	Princeton, Hawaii, Temple, Virginia Tech
1.5	Outer Detector	Houston
1.6	Electronics	Houston
1.7	Offline	All NSF groups
1.8	Site Management	Princeton
1.9	ReD	
1.10	ArDM	
1.11	DS-Proto	All NSF Groups
2.1	Urania Plant	
2.2	Urania Plant Installation	Houston, UMass, Temple, FLC
2.3	UAr extraction	Houston, UMass, Temple, FLC
3.1	Aria	Princeton

2. Project Management and Overall Experimental Design

The lead PI of this proposal, Cristiano Galbiati, is the Spokesperson for the DS Collaboration, and has been the all around driving force for the DS program, including the effort to extract and purify the low-^{39}Ar argon. Cristiano Galbiati is also the Scientific Director of Aria. Peter Meyers is a Project Scientist for DS-20k, a key role in the experiment and one of three people who will interface among all working groups to be sure that all components of the experiment will come together in the end to deliver the expected physics results. Princeton engineer Andrea Ianni is the Technical Coordinator of DS-20k and in charge of the coordination of all L1 managers. Hanguo Wang has played an essential role in the DS program since its inception, especially when it comes to technical challenges, and has been nominated L1 manager for the LAr TPC and cryogenics and gas handling system. He is responsible for the oversight of this comprehensive and crucial work package. Emilija Pantic has been nominated as the LAr TPC L2 manager and will be responsible for making sure all items falling under this work package are on track to deliver the core detector. Jelena Maricic has been nominated as the calibration working group L1 manager and will be coordinating this effort across several universities from around the world. Andrew Renshaw is the Technical Coordinator for the Urania project, as well as the L2 manager for the Urania site preparation, extraction plant installation, commissioning, and start-up. After completion of the plant fabrication in Italy, Renshaw will also be the Project Leader for siting and operations of the plant in the US. Livio Mapelli will act as the Project Leader for the Aria project, overseeing the construction and start-up of the first Aria column. Peter Meyers will continue to be the Project Leader of DS-50 as the detector continues to operate and data analyses are finalized and published. The work on the analyses for DS-50 will still be coordinated by Jeff Martoff, assisted by Emilija Pantic, and it is envisioned that this could potentially carry over to DS-20k as well.

The overall design of the experiment, including the placement of the major infrastructure items within Hall C at LNGS, has been carried out by collaborators at LNGS up to this point, acting under the guidance of the DS-20k Technical Coordinator Andrea Ianni. The DS-20k Technical Coordinator has been providing the main inputs to the team doing the experimental layout, taking into account all possible interferences within the experimental hall, inputs from the LNGS administration and safety team, as well as important inputs from the inner and outer detector designers and general physics measurements considerations. This work will continue into the future as the Technical Design Report document is being prepared for the DS-20k detectors and facilities, and will continue to be led by the DS-20k Technical Coordinator.

3. Underground Argon for DarkSide-20k

The tremendous effort to extract (156 ± 1) kg of UAr for use in DS-50, and the results showing the great reduction in ^{39}Ar, have paved the way for the construction of a detector such as DS-20k. Without a source of low-radioactivity argon, DS-20k would simply not be possible. It is imperative for the US groups to continue to extract the UAr from the same gas wells in Cortez, Colorado, USA, the only known source of low-radioactivity argon capable of large, sustained, and well understood UAr production. Princeton University and Kinder Morgan, the company operating the gas wells, have reached an agreement that allows the DS Collaboration to extract the argon in the gas stream for the purpose of research. However, the pilot-plant that was used to extract the UAr for DS-50 cannot provide the 50 t of UAr required for DS-20k on a suitable timescale. For this reason, the DS Collaboration is pursuing the Urania project, which will provide an industrial-scale argon extraction plant capable of delivering 100 kg/day of UAr at 99.9 % purity to satisfy the needs of DS-20k.

The plant will consist of modular units, built on skids for ease of delivery and assembly at the extraction site. The design of the plant is already at an advanced conceptual stage, and soon the final design will be completed. Upon completion of the final design, fabrication of the plant, funded by INFN, will begin in Italy, while at the same time site preparation work will be performed on location in Cortez. The plant will be shipped to Cortez upon completion for installation and commissioning on-site, followed by operations to extract the total mass required for DS-20k. The funding for the extraction plant is already in place through INFN, while the NSF-supported groups and Canadian groups are working on a final agreement to fund the remaining portion of the site preparations, plant installation and commissioning, and operations to extract the 50 t of UAr for DS-20k.

Final purification of UAr from the 99.9 % purity delivered by Urania into 99.999 % purity will be performed with Aria, a 350 m height cryogenic distillation column for high-throughput, high-resolution active isotopic separation. Aria was designed to test the ability to separate ^{39}Ar from ^{40}Ar by exploiting the tiny difference in the relative volatility of the two isotopes. The first Aria column, Seruci-I, is expected to perform isotopic separation of ^{39}Ar at the rate of 10 kg/day and with a depletion factor of 10 per pass in the column. It will also be capable of performing chemical purification of the UAr produced with Urania at the rate of O(1 t/day). The modules of Aria are currently being fabricated in Italy and undergoing stringent Q&A tests at CERN. Starting in early 2018, Aria will be installed inside a mine shaft in the last operating coal mine in Sardinia. UAr will be shipped to Sardinia in batches via industry-standard loss-less cryogenic containers. The demonstration of the isotopic separation with Seruci-I would then be a first step to a much larger production facility, since the Aria plan foresees the construction of Seruci-II, a larger column capable of a rate of 150 kg/day for the same depletion factor of 10 per pass in the column. Aria is funded by the Italian Government and Regione Autonoma della Sardegna through INFN.

More details about the Urania and Aria Projects can be found in Ref. [46].

The Princeton group led the original effort to discover the source, extract the UAr, and then purify it into (156 ± 1) kg delivered for use in the DS-50 detector. It has been their continued leadership in this area that has allowed the DS Collaboration to take the next step and make plans for the extraction of UAr at the increased rate required for DS-20k. This proposal seeks support for the collaborative effort for the extraction and purification of the argon target for DS-20k with Urania and Aria.

For Urania, the effort of the US NSF-supported groups (Houston, UMass, Temple, and FLC) will include participation in the review team that certifies the design of the argon extraction plant, as well as leading the preparation of specifications, requirements, and safety reviews that need to take place in the US at the Cortez extraction site. Reviews for site operations will include the Urania

Project management, personnel from the company operating the gas wells, and personnel from other contracting companies selected to perform work on site either for preparations, installation or commissioning. Upon successful completion of all reviews, the NSF-supported groups will be leading the site preparation work and installation, working closely with all contracting companies to ensure that the project is on schedule and all milestones and objectives are met. In addition, the NSF-supported groups will be heading the start-up and commissioning of the plant operations, fine tuning the plant operations in order to maximize extraction efficiency. The NSF-supported groups will also lead the extraction of UAr, with a special role envisaged for the Fort Lewis group, who will provide plant staff for full time operations, and for the Houston Group, who will assume the leading role in the US, throughout the duration of the Urania project.

The Aria project has already taken some large steps in the last year, with the top, bottom and a handful of central modules of the Seruci-I column already fabricated and qualified through stringent Q&A tests at CERN. The first of the central modules, along with the top (condenser) and bottom (reboiler), will be assembled into a test column called Seruci-0 that will serve to commission the hydraulic circuits and to understand in detail their performance. The Seruci-0 test will start in early 2018, while the remaining central modules are fabricated, tested, and installed inside the mine shaft to form the Seruci-I column. Upon completion of the Seruci-0 test, its three modules and accompanying external circuits will be separated and installed to complete the Seruci-I column. The future effort on Aria will include oversight of the construction and commissioning of Aria. The Princeton group will play the leading role, with PI Cristiano Galbiati, the inventor of Aria, serving as Scientific Director and overall coordinator, and Senior Researcher Livio Mapelli serving as the Leader of the Project team.

4. Cryogenics and Gas Handling System

The DS-20k cryogenics and gas handling system consists of several subsystems: 1) a cryostat hosting the LAr TPC, 2) a gas handling system including heat exchanger and argon condenser, 3) a purification system consisting of a hot getter and a cold synthetic charcoal radon trap, 4) a LAr handling system including the recovery units with their own gas handling systems and cold liquid transfer lines, 5) a LN_2 plant providing a cooling source on reserve, and 6) cryogenic shipping vessels for delivery of UAr (see Figure 8 for a complete overview). The key features of the DS-20k cryogenics and gas handling system are:

- Ability to efficiently cool down and purify 50 t of UAr at the <0.1 ppb purity level (O_2 content equivalent), which guarantees a $\geq$5 ms electron lifetime, while maintaining a stable pressure in the detector (within $\pm$0.1 psi);
- Ability to obtain a total gas recirculation flow equivalent to 1000 std L/min, which permits us to reach the desired purity of LAr during the course of about one month. This is driven by two custom made high-flow-rate gas pumps, mirroring the design principles and strategy of DS-50, with upgraded sizing of all components. The notable difference with respect to DS-50 is the addition of a fast liquid withdrawal loop, connected to the bottom of the cryostat through a custom designed bayonet assembly that also allows for fast draining of the detector in case of unexpected problems;
- Usage of new high efficiency heat exchangers to recover cooling power during fast purification circulation, exploiting a new custom-designed argon condenser with variable cooling power (from 0 kW to 5 kW). Heat exchangers boil off LAr that is drawn out of the bottom of the cryostat and at the same time cool the GAr coming from the hot getter as it heads towards the radon trap first, and then the condenser;
- Wide cooling power range to cover fast initial argon filling as well as normal operations, and TPC-off mode. With efficient thermal management, the total external cooling power needed to maintain the system in TPC-off mode is about 150 W;
- Incorporation of the robust safety features based on the experience with DS-50, including a feature that keeps the system immune from total failure of the main LNGS power line, by the

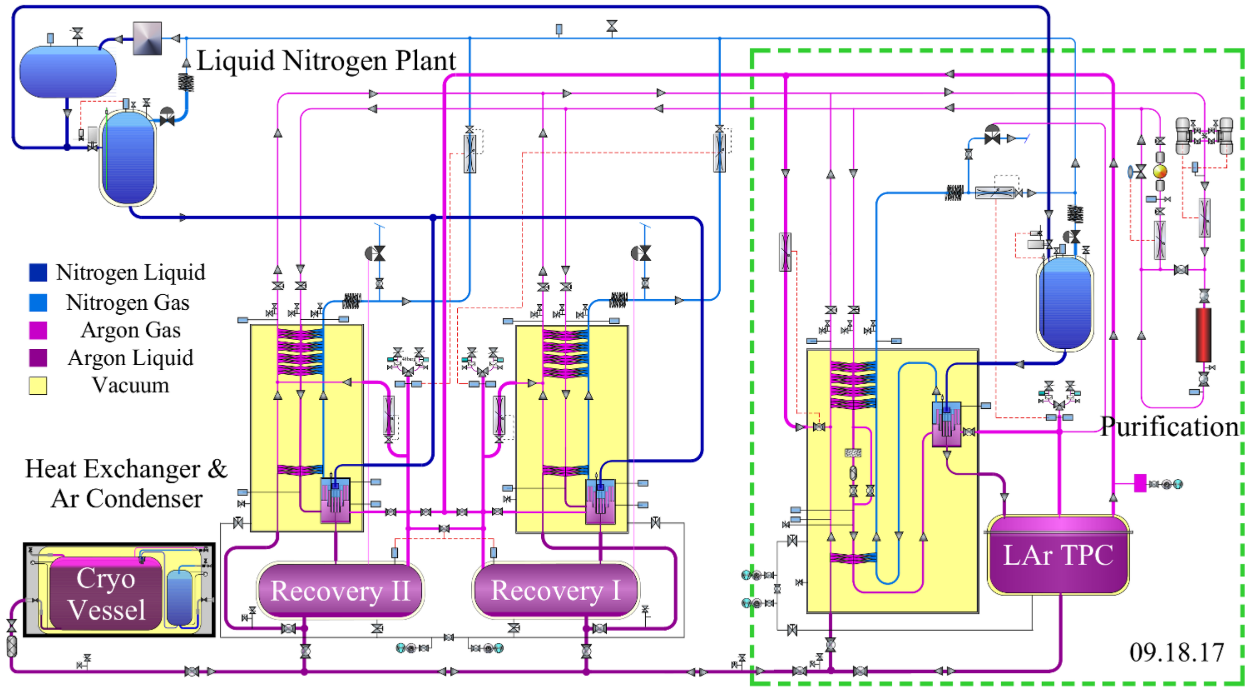


FIG. 8. Schematic of the DS-20k cryogenics and gas handling system. The green dashed box represents the main part of the DS-20k cryogenics system, and will be the focus of the cryogenics test planned at CERN during 2018.

use of a local UPS unit and a local LN_2 storage system. The backup system can work for 3 days off a small LN_2 reservoir located on the top of the condenser and for as long as >30 days off the central LN_2 storage.

The highly successful cryogenics and gas handling system for DS-50 was a US effort. The design of the DS-20k cryogenics builds upon the same design criteria, already successfully subjected to a stringent experimental test with DS-50. The UCLA group is responsible for the design and fabrication of the entire cryogenics system. This will include the design of every component in the system, modeling the system to understand the heat losses and efficiencies, and then fabricating and assembling the parts into the final system configuration. Construction and assembly of the DS-20k cryogenics will take place at CERN, during the first half of 2018, with support from CERN's Cryogenics Group and the Vacuum, Surfaces, & Coatings Group, as per an agreement executed in August 2017 between the DS Collaboration, LNGS, the Accelerator & Technology Sector of CERN, and its Technical Division. The DS-20k cryogenics will also be subjected to a stringent test with the operation of DS-Proto, possible at CERN or LNGS, starting in the second half of 2018.

5. Two-Phase Liquid Argon TPC

The low-background cryostat (built from highly screened stainless steel or ultra-low radioactivity titanium) holds ~35 t of LAr in total, with 23 t inside the instrumented LAr TPC. See Figure 7 for an overview of the DS-20k detector system and Ref [46] for detailed information about its design, with the exception of the modification of the LSV vessel material from stainless steel to acrylic. The active LAr volume is defined by a transparent conductive indium-tin-oxide (ITO) cathode on an acrylic window at the bottom (−52 kV), a 50 µm thick stainless steel wire grid (−3.8 kV) just below the liquid surface, and a reflecting surface with an octagonal footprint (roughly 290 cm width) on the sides. The reflecting octagon is made of sixteen flat, highly-reflective 2.5 cm thick PTFE panels (each 119 cm tall and 120 cm wide). A 3D drawing of the LAr TPC is shown in Figure 9. The high voltages will be delivered by a custom-made high voltage feedthrough (HVFT), similar in design

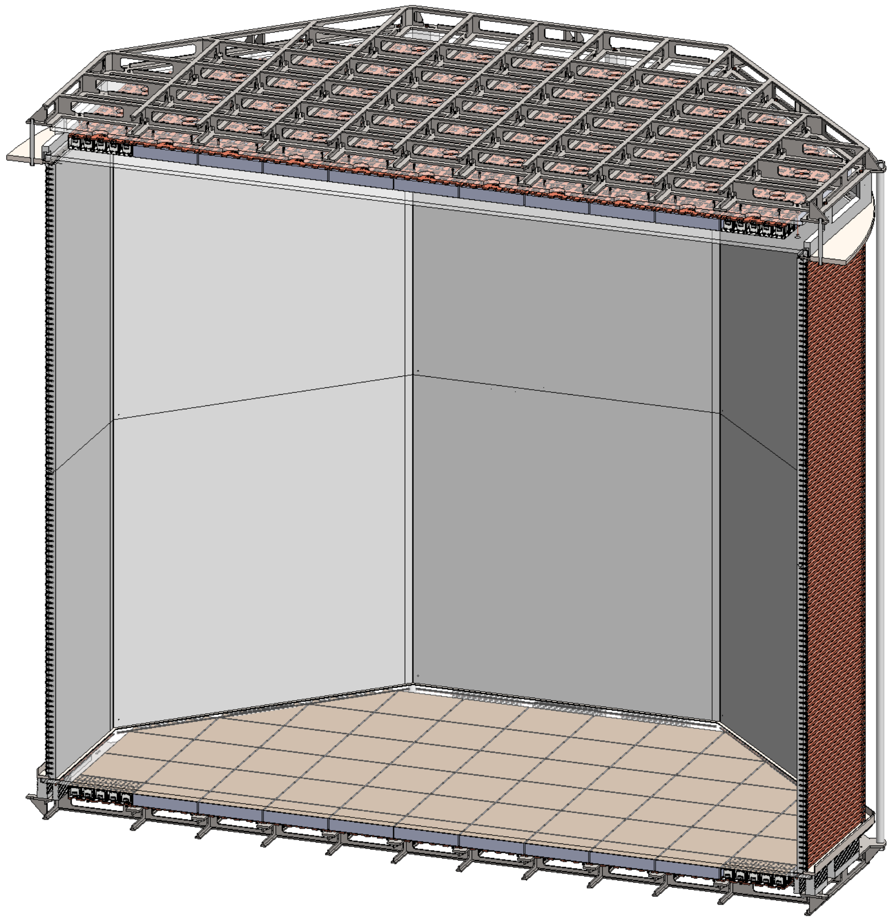


FIG. 9. 3D rendering of the DS-20k LAr TPC.

to that used in DS-50. A uniform electric drift field is provided by a field cage consisting of a set of 119 octagonal field shaping rings, equally spaced along the z-axis and biased with a uniform voltage gradient.

The thin argon gas electroluminescence region (7 mm thick argon gas pocket with 4.2 kV/cm electroluminescence field) above the liquid surface is bounded at the top by a flat acrylic diving bell shaped window coated with an ITO anode electrode (at ground). The grid separates the electron drift (200 V/cm uniform drift field) and extraction (2.8 kV/cm extraction field) regions.

All inner surfaces delimiting the active volume are coated with the high efficiency [107] wavelength shifter tetraphenylbutadiene (TPB), converting the 128 nm argon scintillation photons into photons with optical wavelength, which can be reflected with high efficiency by the PTFE surfaces and detected with high efficiency by the SiPM-based cryogenic photosensors. A possible modification to the baseline design of the reflector cage is under consideration and would instead use 3M VikuitiTM specular interference reflector, already successfully utilized in the DarkSide-10 detector [108]. This approach would help further mitigate several background sources (radiogenic neutrons and others), but in turn requires a dedicated R&D program, which has already started.

Interactions in the active LAr volume generate prompt scintillation light (the S1 signal). The ionization electrons surviving recombination are drifted upward and extracted into the gas, where they are accelerated to create secondary scintillation via electroluminescence (the S2 signal). Both the S1 and S2 signals are detected by top and bottom densely packed arrays of SiPM-based photosensors which view the active LAr volume through the large 15 mm thick flat acrylic windows.

Each array consists of 2605 photon detection channels. A single readout channel, called a photodetector module (PDM), is defined as a $50 \times 50\,\mathrm{mm}^2$ SiPM tile assembly with summing and amplification electronics. The S1 signal is distributed roughly evenly over both arrays, while the S2 signal, emitted in the gas pocket under the anode window, is concentrated in the top array and within a few SiPM tiles around the transverse position of the ionization drift, thus yielding a precise x-y location. The drift time (the time between the S1 and S2 signals) determines the z-location of the event in the LAr TPC. Precise 3D reconstruction of interaction points with resolution of 10 mm in x-y and 1 mm in z is expected to be achieved.

The joint effort between Fondazione Bruno Kessler (FBK) and LNGS allowed the custom development and precise characterization of the best SiPM technology satisfying the complex DS-20k requirements. The development of SiPMs was pursued under the guidance of a detailed list of stringent specifications for their use in DS-20k, which feature high photon detection efficiency (PDE, >40 % at 420 nm), low power dissipation ($100\,\mu\mathrm{W/mm}^2$, corresponding to a total dissipated power of 250 mW per PDM), and low noise ($0.1\,\mathrm{Hz/mm}^2$ at 87 K). The DS Collaboration has developed and optimized a custom-built cryogenic transimpedance amplifier (TIA) in order to overcome the unique challenge of SiPM readout given their capacitance ($50\,\mathrm{pF/mm}^2$). Following very intense R&D, the TIA is capable of stable cryogenic operations and it amplifies and shapes the signal in the immediate proximity of the sensor, all while making use of ultra-high purity components: a complete description of results can be found in Ref. [109]. With this unique development, the DS Collaboration achieved the first operation of large area, first $20 \times 20\,\mathrm{mm}^2$ and then $50 \times 50\,\mathrm{mm}^2$, SiPM assemblies as a single channel photodetector, while retaining very high PDE and sensitivity to single scintillation photons.

The whole LAr TPC is supported from the bottom of the top flange (stainless steel or titanium) of the croystat. The design allows for the field and reflector cages, as well as cathode/anode windows and SiPMs arrays, to co-shrink together when cooled, and for the anode window to maintain flatness under buoyancy of the gas pocket.

The LAr TPC is being designed and developed almost entirely by the US NSF-supported groups, with a balanced sharing of tasks and loads. The US NSF-supported groups will be responsible for the design and testing of all components for the LAr TPC: reflector panels and field cage, anode and cathode planes, wire extraction grid, high voltage feedthrough, as well as for the overall mechanical integrity and support of the assembled detector. The tasks of the NSF-supported groups will include the initial materials and components testing, followed by mock-up tests of the various components and finally a full scale prototype of each part. The UCLA group will lead the overall design of the LAr TPC and will serve as the main point of contact for integration of any design changes into the official baseline design. The work to develop and fabricate the reflector panels, high voltage feedthrough, and field cage will be the responsibility of the UC Davis group, while the Houston group will be in charge of the anode and cathode planes and the wire extraction grid, and will play a part in the development, procurement, installation, testing, and commissioning of the front-end electronics and data acquisition system. The effort on the LAr TPC will take place in close coordination with the outer detector working group and the photoelectronics working group, such that each subsystem can be integrated seamlessly. Final development of the SiPM tiles for the PDMs, along with initial testing and characterization of the devices, will be carried out by the Princeton, Augustana, and UMass groups, although the final production and testing of the tiles and PDMs will occur at LNGS at the new NOA facility.

In order to test and vet all of the mechanical choices of the LAr TPC before committing to the construction of the full scale detector, the DS Collaboration will construct DS-Proto, a prototype detector on the scale of ∼1 t. DS-Proto will not be a physics-capable detector. On the other hand, DS-Proto will be an important test bench for the DS-20k PDMs. Construction of DS-Proto is expected in 2018. A first test operation with a reduced number of photosensors is expected in the second half of 2018, followed by a second operation with a full complement of PDMs in 2019. It is expected that all NSF-supported groups will participate in the DS-Proto effort, either through materials screening and selection, provision of detector components, contributions to the calibrations efforts, or participation in the commissioning and operations of the detector.

6. Materials Selection and Screening

Because it is important to have all experimental backgrounds under control when attempting to directly detect WIMP dark matter, it is crucial to make sure all materials that will go into the LAr TPC cryostat have been screened for their radioactivity content, including the steel or titanium required to produce the cryostat. This work has already started, with the screening of various materials underway so that final materials selections can be made for items that have more than one choice available [46]. The US NSF-supported groups will be contributing to this effort through the use of the Temple and BHSU high purity germanium γ-ray counting facilities, as well as the ability to carry out ICP-MS analysis at BSHU. They will coordinate with the leaders of the materials working group to receive samples of various materials throughout the duration of the development phase of the project and assay them in their detectors. This will play a major role in not only determining the proper materials to use, but also selecting the right vendors able to consistently provide the material batches with the low-activity levels.

7. DS-20k Calibrations

We will carry out a comprehensive calibration plan for DS-20k that includes calibration of all three detectors individually: LAr TPC, LSV, and WCV. The low level calibrations include charge and timing calibration of the PMTs in the vetoes and of the SiPM-based PDMs in the LAr TPC. These calibrations will be performed periodically using a combination of laser and LED pulses, provisions for which are already included in the the TPC and veto designs. High level calibrations based on experience with DS-50 will use various radioactive sources (γ-ray, (α,n), $\beta^{\pm}$) to monitor the spatial uniformity and temporal variations of detector response, as well as to calibrate the detector response in terms of light yield, energy, and particle identification. Additionally, high level calibrations will measure efficiency in detecting and selecting WIMP-like scatters, as well as checking the sensitivity to several classes of expected background events. More importantly, redundancy and flexibility built in to the system will allow calibration and investigation of unexpected event categories which may appear during the 5 yr course of DS-20k operations. As such, calibrations will effectively complement and cross-check the level of active background suppression in DS-20k contributing to the goals of a background-free run in search for a convincing claim of dark matter detection.

A key detector response is the LAr TPC light yield in the $30\,\mathrm{keV_{nr}}$ to $200\,\mathrm{keV_{nr}}$ energy range of interest for WIMP scatters. A distributed exposure of low energy ERs will be obtained by periodically introducing ^{83m}Kr (τ=2.64 h, with near-coincident conversion electrons summing to 41.5 keV) from within the cryogenics system into the active argon volume [110–113]. This isotope is obtained by milking an external ^{83}Rb (τ=124.4 day, EC) source into the argon return line of the recirculation system. A suitable ^{83}Rb source holding system, capable of supporting periodic refurbishments of the source, to compensate for its natural decay, has been permanently installed in the cooling tower of DS-50 by the Princeton group. This will be duplicated and installed for DS-20k. Another planned distributed source is the short-lived ^{220}Rn whose decay chain produces several γ-rays, β's, and α's, often in easily tagged time-correlated coincidences, which promises to be very useful to study calibration of the low-energy ERs response. The ^{220}Rn source will be developed by the collaborators from Jagiellonian University in Poland.

Calibrations of DS-20k will include the deployment of external neutron generators through a dedicated insertion system designed by the Hawaii group, with support from the Virginia Tech group, as well as the possibility of inserting miniature γ-ray and neutron sources through a permanently installed guide-tube system reaching along the cryostat wall. The guide-tube system provides efficient, risk-free deployment of miniature γ-ray and neutron sources close to the LAr TPC and inside the LSV, allowing a study of the LSV neutron detection efficiency, calibration of the NR and ER energy scale, and Monte Carlo tuning. In particular, the Hawaii group plans to use ^{57}Co, ^{133}Ba, and ^{137}Cs sources in the guide tubes, to calibrate the detector ER response in S1, S2, f_{90}, and energy scale, as well as to tune the Monte Carlo. This strategy is similar to what was done for

DS-50. The Virginia Tech group will also be contributing various γ-ray sources for calibrations. Use of higher-activity sources than in DS-50 is foreseen for better penetration inside the LAr TPC volume. However, edge events naturally provide calibration in the locations where most spatial non-uniformities are expected, and where a good fraction of the detector volume resides.

Calibrations with neutron sources are essential to determine and monitor the neutron detection efficiency in the LSV and the NR responses (S1, S2, f_{90}, and energy scale) of the LAr TPC. As in DS-50, we will deploy a conventional ^{241}AmBe neutron source (custom made miniature version fabricated by the Hawaii group) to calibrate LAr TPC response to NRs: we will trigger on the 4.4 MeV γ-rays detected in the LSV, then search for coincident NRs in the LAr TPC with a very low level of γ-ray-induced, ER contamination expected. In addition, an ^{241}Am^{13}C source with the α's slightly degraded in energy by a thing gold foil before entering the ^{13}C converter produces quasi-monoenergetic 4 MeV neutrons with no coincident hard γ-rays, only the 59.5 keV nuclear γ-rays from the decay of ^{241}Am into ^{237}Np [114], stopped by a small amount of lead shielding. With such a source, producing about 10 n/s, we can use the LAr TPC to tag nuclear scatters, then select coincident captures of ^{241}Am^{13}C neutrons in the veto. This method was used successfully in DS-50 and allowed a very realistic calibration of the LSV efficiency for neutrons interacting in the LAr TPC. Additionally, we will rely upon an already-procured and constructed, customized ^{2}D-^{2}D tagged neutron generator based on the Thermoscientific API-120, prepared by the Temple group. This ^{2}D-^{2}D generator has been modified to have low, controllable intensity of 10^4 n/s which will provide single neutron scattering events in the LAr TPC. The neutron recoil response (light and charge yields and absolute efficiency) of the LAr TPC can be measured by deploying the ^{2}D-^{2}D generator close to the cryostat in order to bring a fraction of neutrons into the LAr TPC without scattering and at their initial energy of 2.45 MeV. A similar technique has been successfully employed by the LUX experiment, which eventually allowed them to greatly reduce their energy threshold and also allowed verification of the nuclear model and NR tagging efficiency [115]. Given the large size of the DS-20k LAr TPC, single and multiple scatters should be clearly visible and easily identifiable.

The DS Collaboration plans to continue its external calibration campaign with the Recoil Directionality (ReD) experiment. The ReD detector is a small LAr TPC equipped with the same SiPM tiles planned for use in DS-20k (though possibly read-out with smaller voxels), details of which are found in Ref [46]. Improvements compared to the SCENE and ARIS experiments will include very high light yield for improved photoelectron statistics, 3D position reconstruction, and improved LAr TPC design. The customized ^{2}D-^{2}D tagged neutron generator, mentioned above, is currently installed at University of Naples Federico II, where it will be used for long-term operation for increased data statistics and to extend the recoil nucleus energy range up to about 200 keV. The ReD detector will also study the possibility of a variation of the NR signals as a function of their directions relative to the applied electric field, following up on the initial hint from SCENE [97]. The groups of Cagliari, Genoa, Naples and Rome cover most of the ReD activities. The US NSF-supported groups will be contributing to the ReD effort via the ^{2}D-^{2}D tagged neutron generator, development of the customized LAr TPC to reduce the rate of neutrons scattering in detector material, and participation in detector operations and data analysis.

8. DS-20k Commissioning and Operations

1. *Commissioning*

We define the start of commissioning of the LAr TPC as the point when the detector is installed in its cryostat, and the cryostat is sealed. At this point the final signal, HV, and monitoring cables will have been attached and the cryostat will be mounted inside the sealed acrylic vessel of the LSV. The commissioning of each veto detector starts from the time that its PMTs are installed and all the cables connected, even before being filled.

Electronics, DAQ and slow controls: Commissioning of the electronics and DAQ will start at university labs even before the whole electronics and DAQ system is received at LNGS. Once the system is installed on-site at LNGS, commissioning will proceed and be finalized once the detector is ready for start-up. The slow controls will also be commissioned along with the electronics and DAQ system.

LAr TPC: The LAr cryogenic system will be tested at CERN during 2018 and 2019. Installation in the final position at LNGS and integration with the slow controls will proceed immediately after the DS-Proto test has been completed. There are 6 phases between the closing of the LAr TPC cryostat and data collection: inspection in the clean room of all SiPMs; low voltage check of field cage; leak-check; insertion of cryostat into the LSV; pump and purge of LAr TPC cryostat; cooldown and fill with LAr; inspection (lasers, krypton) and leveling of the liquid surface; and initial evaluation of performance (electron drift life-time, light yield and S2/S1). Physics data taking starts at the end of LAr TPC commissioning.

Outer Detector: The outer detector PMTs will be installed and then commissioned in a dry nitrogen atmosphere. The LSV should be mechanically stable independent of the presence of water in the water tank and could then be filled before the water tank. The liquid scintillator will pass through newly constructed storage and mixing plants and benefits from the extensive experience of the DS Collaboration in operating similar systems. The system will have been tested by circulating liquid through the buffer tank; commissioning of the final loop will start as the first liquid is circulated through the LSV. The water will be treated by the Borexino water treatment plant; there is no recirculation. It would be optimal if the water is not loaded until the LSV has been commissioned with scintillator to avoid the need to drain the tank in case of a problem with the LSV. However, if it is determined that the water must be filled at the same level as the scintillator in order to help balance the internal pressure on the LSV vessel, the water tank and acrylic vessel will be filled simultaneously keeping the height of the liquid in both vessel equal for the duration of the filling procedure.

2. Operations

We will use the DS-50 and DS-Proto experiences to estimate the operational requirements associated with the DS-20k LAr TPC and to estimate the operations requirements associated with the neutron and muon vetoes.

LAr TPC: Two essential support systems associated with the LAr TPC- the argon purification system and the argon condensing and circulation system used to maintain the argon in a stable and liquid state - will operate continuously throughout the life of the experiment and will need constant monitoring. The monitoring will be eased by the development of a sophisticated control system designed to produce alerts and alarms at the onset of critical condition. Experience with DS-50 has shown that a cryogenics system with a similar design is capable of very precise detector environment control, even with the loss of all power.

Outer Detector: Once the LSV has been filled with scintillator of adequate performance, the recirculation and online re-purification will continue until the design purity and light yield are reached. At that stage, recirculation and purification can be stopped, and restarted only when the monitoring indicates the onset of any significant degradation. The WCV uses the Borexino water processing system and we do not anticipate any costs associated with the operation of the system or the procurement of the water. With the switch to an acrylic container for the liquid scintillator, we anticipate the ability to discharge the water directly into the sewage pipes while monitoring the total carbon content of the waste water, similar to what was done for DS-50.

3. Data Collection

Data collection will start at the end of the commissioning of the LAr TPC, and will foresee a couple of different modes of data taking:

Initial Calibrations: When the detector is filled with UAr, we will perform a series of calibration runs with gamma and neutron sources to qualify the performance of the detector and identify the regions of interest for nuclear and electron recoils. We will use a ^{83m}Kr source to calibrate the low energy scale and study the spatial variation of the detector response within the LAr TPC sensitive volume. A neutron source/generator will serve to study the argon recoil population and the veto performance. The initial calibration campaign will inform the selection of a region of interest for the initial WIMP search.

Routine Calibrations: Along with the WIMP data collection, to be started right after the first calibration campaign, we are planning to perform regular energy calibrations and neutron calibration runs. SiPM gain and stability will be monitored daily by means of brief dedicated laser runs.

WIMP Search: Standard operations of the DS-20k detector will include full-time system monitoring via software and at least one person at all times. Initially, the shifts will be on-site at LNGS so that sudden problems can be handled immediately. Once detector operations have gone smooth for an extended period of time, on-site shifting will evolve to fully-remote data taking operations, as is currently done for DS-50. All groups supported by the proposal will take on-site shifts during commissioning and calibrations, as well as participate in remote shift operations once the time comes.

9. Physics Reach and Data Analysis

The design goal of DS-20k is to search for particle dark matter in the form of WIMPs while producing a background-free exposure of 100 t yr with a 23 t (20 t) active (fiducial) LAr mass. In order to carry out a successful discovery program it is crucial to maintain the zero-background condition: to claim a detection with the same statistical significance, the number of required detected events increases up to a factor of 3 when the expected number of background events increases from 0 to 1.

We aim to limit the instrumental background to <0.1 events for the full exposure in the WIMP search ROI. A WIMP interacting in the active volume is detected through the induced NR – Figure 10 (left) shows the NR energy spectra induced in the LAr target for different WIMP masses. The WIMP search ROI is chosen to maximize both the background rejection and the WIMP acceptance. The largest source of background is the internal contamination of ^{39}Ar: assuming the same contamination of the UAr measured in DS-50, we expect 1.8×10^8 ER in the $30\,\mathrm{keV_{nr}}$ to $200\,\mathrm{keV_{nr}}$ ROI ($7\,\mathrm{keV}_{ee}$ to $50\,\mathrm{keV}_{ee}$ equivalent). The DS-50 experiment demonstrated that the pulse shape discrimination (PSD) guarantees a rejection factor $>1.5 \times 10^7$, also supported by recent measurements with DEAP-3600 [116]. With a dedicated Monte Carlo simulation we have extrapolated the distribution of the PSD parameter to the expected large statistics in DS-20k, in order to set the lower boundary of the minimal WIMP search region required to maintain the background to <0.1 events, and see an expected rejection factor $>3 \times 10^9$. It has to be noted that the expected improvement in light collection, made possible by the use of SiPM-based photosensors instead of traditional PMTs, is beneficial as it permits to lower the energy threshold at which the required PSD rejection is achieved. The expected rates from other ER background sources, such as radioactivity from the detector materials, ^{222}Rn emanation, and solar neutrino electron scatters, are only a small fraction compared to the internal ^{39}Ar and their leakage probability into the WIMP search region is negligible. In addition to PSD, the ratio between ionization and scintillation can be used, on an event-by-event basis, to further discriminate ER events which are not rejected by PSD.

The final NR acceptance curve, shown in Figure 10 (right), ranges from $30\,\mathrm{keV_{nr}}$ to $200\,\mathrm{keV_{nr}}$.

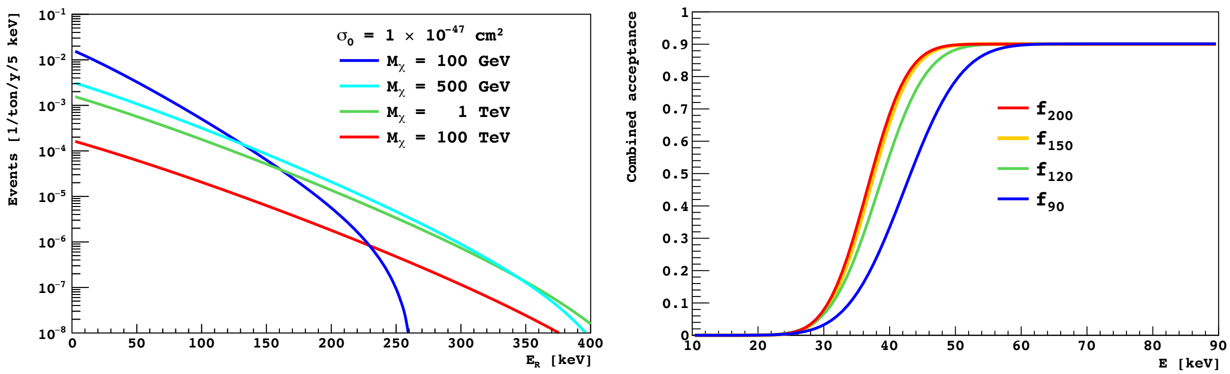


FIG. 10. **Left**: Predicted WIMP NR spectra in LAr. **Right**: The NR acceptance for different values of the PSD parameter, assuming the performance of the DS-20k detector that is described in Ref. [46].

The energy spectra fall exponentially with increasing recoil energy, but the low-energy threshold of the detector limits the experimental sensitivity for WIMP masses below 50 GeV/c^2, as depicted in Figure 1.

The most pernicious backgrounds are those producing NRs that can not be rejected by means of the PSD, such as radiogenic and cosmogenic neutrons. For the latter class, we simulated 34 yr of cosmic ray irradiation at the depth of the LNGS laboratory and found no events interacting in the LAr TPC and being unnoticed by the two veto systems. Radiogenic neutrons, on the other hand, originate by spontaneous fission or (α,n) reactions from the detector components and propagate inside the sensitive volume. Since the interaction length of radiogenic neutrons in LAr is of the order of 10 cm, we expect to be able to reject many of these events based on their topology (multi-sited events with multiple S2 signals) and fiducialization. Still, the probability for a neutron to interact only once in the fiducial volume is non negligible. The LSV is designed to efficiently capture and detect these neutrons. After identifying the major sources of radiogenic neutrons (the cryostat and the PTFE reflectors), we performed a detailed set of Monte Carlo simulations, varying the LSV size and composition. We found that an adequate choice of radiopure materials and a fiducial volume cut of a few cm are required in order to suppress this background.

The only irreducible background is represented by neutrino-nucleon scattering, producing low energy NR uniformly distributed in the sensitive volume. The expected number of background events is 1.6 for the full 100 t yr exposure. Taking this into account, as well as the NR acceptance discussed above, one can draw the sensitivity curves of Figure 1, where it is seen that DS-20k will have sensitivity to WIMP-nucleon cross sections of 1.2×10^{-47} cm^2 (1.1×10^{-46} cm^2) for WIMPs of 1 TeV/c^2 (10 TeV/c^2) mass, to be achieved during a 5 yr run with exposure of 100 t yr. This projected sensitivity is a factor of >50 better than currently-published results for spin-independent cross sections of WIMPs with $\geq$1 TeV/c^2 mass, and covers a large fraction of the mass-cross section space currently preferred by supersymmetric models. 1.6 events atmospheric ν-induced nuclear recoils are expected in DS-20k, which could be the first experiment to reach this crucial milestone.

The foreseen design of the experimental setup makes it suitable for a coincident observation of neutrino signals in the three detectors in the event of a supernova explosion, inside or around the Milky Way. The expected number of interactions for a 10 kpc baseline is of the order of 10^2 in both the water tank and the LSV [117], most of them expected in a short time window of 10 ms. Due to the relatively high CNNS cross-section, the number of interactions in a 20 t LAr target is several orders of magnitude larger. Still, due to the small amount of deposited energy and the relative quenching of NRs, only a small fraction of them, depending on the detection threshold, are accessible. Many of these events will eventually result in an S2-only topology. Operating the detector with a special low trigger threshold will allow to lower the detection threshold down to a fraction of a keV, while the expected background in the time window would be negligible compared to the signal rate. The unprecedented measurement of the spectral shape and time profile of the supernova neutrino emission would allow DS-20k to contribute to better constraining the current model for core-collapse supernovae. Moreover, a recorded neutrino burst will serve as a trigger for observations in the optical regime and would be complimentary to currently running and future planned experiments that will detect supernova neutrinos.

Additionally, other hypotheses can be tested by focusing on the low energy side of the ER spectrum, if an excellent understanding of the detector response and backgrounds is achieved. Magnetic inelastic Dark Matter (MiDM) should scatter inelastically off an argon nucleus, causing a very small NR while exciting the nucleus [118]. The nucleus then de-excites after a short time (µs's), producing a coincident signal between the low-energy NR and the low-energy de-excitation ER, a nice signature in a detector with very good energy resolution. In the case that the low-energy NR is below detector threshold, these events would show up in the detector as single ER events in the low-energy part of the spectrum. Similar to this MiDM channel, a leptophilic or axion-like dark matter particle would produce very low-energy ERs in the LAr, and so a search for these type of particles would focus on low-energy ERs with specific spectral shapes [119, 120].

A successful DS-20k experiment would represent a fundamental milestone toward the realization of an even larger detector, conceived to reach a background-free exposure of 1000 t yr, with a fiducial mass of a few hundred tonnes. Such a detector would be sensitive to WIMP-nucleon cross-sections well below the neutrino floor. In addition to the dark matter search, a future multi-hundred tonne detector could carry on a competitive solar neutrino physics program, as detailed in [121]. Monte Carlo simulations show that, if the internal contamination of ^{222}Rn is successfully kept low, this future detector could improve the current precision on the ^{7}Be and *pep* solar neutrino fluxes by a factor of 2, reaching 2 % for ^{7}Be and 10 % for CNO neutrinos. In addition, it could potentially make the first measurement of the CNO solar neutrinos, reaching a 15 % accuracy.

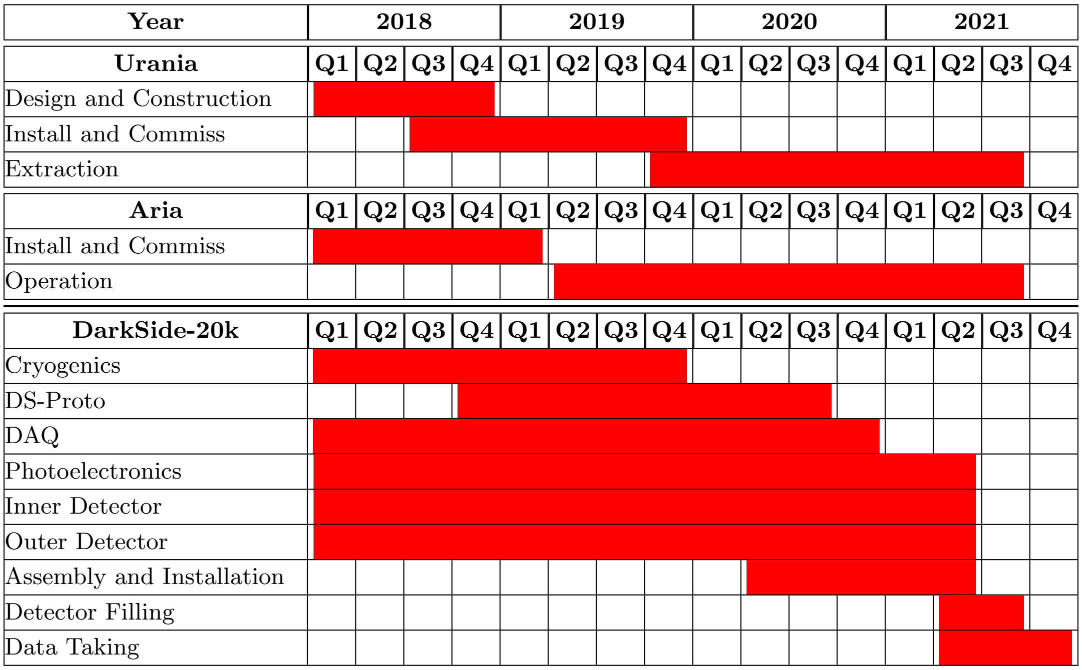
Data analysis will continue on the DS-50 data sets for some time to come, including finalization of the blind analysis for the detection of WIMP dark matter, and all groups included in this proposal will be involved in these efforts at varying levels. Currently, the Princeton group is leading the DS-50 operations and the Temple Group is leading the physics analysis effort with help from the UC Davis group. It could be a natural transition for these responsibilities to continue on with DS-20k. The physics goals of DS-20k are now being coordinated by the Project Scientists, with Princeton PI Peter Meyers playing an important role. Houston postdoc Paolo Agnes is leading the science simulation effort using the Geant4-based Monte Carlo simulation package G4DS, especially developed for the DS family of detectors and similar geometries. All groups included in this proposal currently take part in the DS-50 analysis and will continue in this effort as tools and analyses are brought online for DS-20k. Eventually this will transition into playing a large role in the data collection/analysis effort for DS-20k. This effort will include regular shift taking, performing analysis work on commissioning and science data, participating in calibrations, as well as performing physics and development studies for future larger LAr TPCs.

V. TIMELINE FOR RESEARCH

The timeline for DS-20k is driven by the schedule that foresees start of data taking during 2021, at which time we expect DS-20k to quickly take over the lead in sensitivity for the direct detection of high-mass WIMP dark matter. The work-plan outlined in this proposal follows the general timeline of the experiment given in Table II:

- **Year 1:** One of the major focal points for the first year of activity will be the fabrication of the Urania argon extraction plant, the preparation of its site, and its installation and commissioning, with the latter two activities led by the Houston Group. By the end of the first year, it is expected that the argon extraction plant will be ready for full time operations, with UAr extraction ready to start at the beginning of the second year. The construction and testing of the Seruci-0 column of Aria is also set to take place during this first year, under the leadership of the Princeton group. Construction of the Seruci-I column is also set to begin within the first year of activity. The first year of the activity will also include fabrication and testing of the cryogenics system

TABLE II. Timeline of the DarkSide-20k Project.



(UCLA), prototyping of components for the DS-20k LAr TPC that can then be used in DS-Proto (UCLA, Houston, UC Davis), and finalization of the design of the calibration systems in time for their possible testing in DS-Proto (Hawaii, Temple, Virginia Tech). DS-Proto may collect data during the last part of 2018 and for sure in 2019. During this time BHSU and Temple will also carry out materials screening to aid in the selection process, and Princeton, Augustana and UMass will help to finalize the SiPM-based PDMs and begin to test and characterize them as they become available. All groups will shift the focus of their effort to DS-20k. In particular, effort on DS-50 data analysis will rapidly transition towards preparation of the software that is required for a prompt bootstrap of the physics program with DS-20k. The large data set acquired with DS-50 will offer a sandbox for testing of the software and analysis tools developed for DS-20k. We envisage that this effort will proceed continuously throughout the entire period of construction and commissioning of DS-20k. Construction of the facilities (water tank, scintillator vessel, scintillator plants) in Hall C of LNGS will also start in the first year of activity under the lead of the INFN groups and managed by the Technical Coordinator Andrea Ianni.

- **Year 2:** UAr extraction will start in the second year of activity, providing a portion of the full inventory of UAr required. The NSF-supported groups will continue to provide major contributions to maintenance and operations of the plant, and will coordinate shipments of UAr between Colorado and Sardinia. Construction of the Seruci-I column is set to be completed within the second year of activity. Following installation and commissioning of Seruci-I, UAr purification will start. DS-Proto data collection will continue during the first part of the second year, but early results from the first phase of running will have already provided the insight necessary to proceed with the fabrication of the major components of the DS-20k LAr TPC, cryogenics system, and calibrations systems. Materials screening and selection will continue throughout the second year of activity.
- **Year 3:** The extraction of the UAr will continue during the third year, producing a large fraction of the required total mass. The bulk of the purification of the UAr by Seruci-I will also take place during this year. All of the components for the LAr TPC and cryogenics system will be fabricated by the end of the third year of activity. Construction of the facilities in Hall C of LNGS will also be complete by the end of the third year of activity. The NSF-supported groups will start leading the assembly and installation of the LAr TPC.

- **Year 4:** The fourth year of the activity will see the final delivery of the remaining UAr from Urania, the bulk of assembly and installation of the LAr TPC, and the start of commissioning of DS-20k, followed by transition to long-term operations for data taking. Data taking operations will include routine shift assignments, scheduled calibration work, and on-the-fly data analysis, activities participated by all NSF-supported groups. Responsibilities for everyday operations will be shared among all groups in the DS Collaboration, with the leadership roles defined in Sec. IV 2 expected to remain in place.
- **Year 5:** The final year of the proposal will be the first full year of detector operations and data analysis. Once again, all NSF-supported groups will participate in these activities at every level.

VI. BROADER IMPACT

This collaboration offers a unique set of broader impacts that benefit society in measurable ways. These benefits include technological advances and specific educational opportunities for underrepresented populations that can increase the diversity of a STEM-competent work force. We believe the diversity of the partner institutions creates opportunity and enhances the overall success of the program.

1. Advances in Technology

The technologies developed by the DS Collaboration programs benefit society at large in a variety of ways. Broadly, these technologies fall into categories of medical diagnostics, advances in photon detectors, and isotope separation.

In the realm of medical diagnostics, 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 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 focus on development of SiPMs for DS will drive substantial improvement in this recent and very promising technology. SiPMs could replace PMTs in many particle physics experiments, especially those with the option of operating SiPMs 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 those of the LiDaR distance sensors in cars.

The DS Collaboration will also advance techniques for isotope 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 and high-tech industry. Helium isotopes play a strategic role, indispensable for national defense projects and the space exploration industry. As outlined in Sec. III 2, the DS collaboration already played a major role in improving the US availability of ^{4}He. In conjunction with the Urania project, DS researchers are investigating methods to separate ^{3}He from massive streams of helium, *e.g.*, the one at Cortez inaugurated in 2015. If successful, this effort could help solve possible future shortages of ^{3}He [122], a very rare isotope that finds applications in nuclear fusion and neutron detection.

The noble gas radioisotope ^{37}Ar is of great interest in 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 provides a signature for large numbers of neutrons interacting with the soil [123]. As a noble gas, ^{37}Ar is expected to migrate to the surface following an underground nuclear test, without chemical effects, and can then be studied to understand the testing that had occurred. The chemistry of argon recovery and purification is important for preparing the soil-gas samples for this type of measurement, overlapping 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 radiotracer isotopes. This is one of the most sensitive methods for routine assay of challenging radionuclides like tritium [124] and ^{39}Ar for the age-dating of water [125]. As with dark matter detection, the ^{39}Ar background in atmospheric-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 low-level measurements, allowing for example studies of effects on the time-scale of impacts expected due to modern climate change patterns. Geologic argon samples from the DS Collaboration R&D effort have been recently used at Pacific Northwest National Laboratory to characterize ultra-low-background proportional counter backgrounds.[126, 127] The UAr development work central to the physics reach of DS will significantly enhance the ability of researchers worldwide to employ ^{39}Ar as an environmental radiotracer for hydrologic transport.

As detailed in Sec. III 2, 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 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) [128], a glucose analog with replacement of a hydroxil group with ^{18}F. This is the most common radiopharmaceutical used in medical imaging by PET, TOF-PET, and PET/CT [129, 130]. ^{18}F-FDG also plays an important role in neurosciences [131]. ^{13}C is a marker used in thousands of stable isotope labeled, custom synthesized organic compounds with applications. Its traceability by nuclear magnetic resonance allows applications such as the ^{13}C-Urea breath test to replace gastroscopy for identifying infections from Helicobacter pylori [132], the ^{13}C-Spirulina platensis gastric emptying breath test [133]. 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 of IV Generation nuclear reactors, due to its superior thermal and mechanical properties [134–136]. The main drawback is that uranium nitride must be synthesized from ^{15}N with purity greater than 99 %, to avoid neutron absorption on ^{14}N and obtain an overall optimal neutron economy. The advantage of uranium nitride fuels is that they allow a decreased frequency of refueling shutdowns and thus higher up-time and greater economy. The higher density, higher melting temperature, better thermal conductivity, and lower heat capacity [137, 138] compared with, *e.g.,* oxides, help improve the safety margin in reactor design [139]. 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 National Academies' report, "Rising Above the Gathering Storm," stated that the most consistent and powerful predictor of student achievement in science and mathematics is a teacher who is fully certified and has at least a bachelor's degree in the content area. Teachers of physics at high-poverty schools are less likely than the (already low) national average to have a degree in physics or physics education, and such schools are less likely than average to offer physics courses, especially advanced physics. The diverse composition and experience of the DS Collaboration team affords a unique opportunity to advance not only public understanding of the DS Project and its goals, but also to serve as a platform for broader STEM eduction opportunities to reach a diverse cohort of under represented students. For example, team members Augustana, BHSU, and Fort Lewis College (a Native American Serving institution) are regionally connected to populations of rural, first-generation immigrant, and low-income students. This complements the diverse, urban opportunities afforded from our larger-institution team members, who may also be minority serving (Houston is a Hispanic and Asian serving institution). Unique to this project is ability to directly impact large populations of underrepresented students at all education levels, and create opportunities for underrepresented students to be part of a world-wide collaboration to detect dark matter.

To date, the DS Collaboration conducted educational outreach to local public schools (K-12) and in some cases, engaged high school and undergraduate students in meaningful research related to DS science. Many of these activities are outlined in the prior work section. The present project has the opportunity to expand upon, integrate, and make more deliberate all of those efforts to reach a larger, more diverse, population of students. In doing so, we promote the science of DS to a broader audience and build a cadre of scientists and engineers prepared to further their educational opportunities or enter the STEM workforce. For example, undergraduates at Augustana, BHSU, and Fort Lewis College will participate in summer research at a collaborating institutions and on-site at the UAr extraction facility and various labs around the world conducting research for DS-20k. These summer experiences fold into senior-capstone projects or internships at a National Laboratory.

With this in mind, the Gran Sasso-Princeton Summer School will be restarted by the DS Collaboration in cooperation with the Gran Sasso Science Institute (GSSI), giving an opportunity for rising high-school seniors and/or rising freshman undergraduate students to go to LNGS and at least one other DS-collaborating institutions for a week each during the summer to participate in learning and research activities related to the DS program. With this proposal we request funding for participation in the program of three students each from the regions of Mesa Verde in Colorado, Gran Sasso, and Sardinia, namely locations of the major DS infrastructure and supporting underground laboratories, as well as funding for two chaperones. We will also work with LSC and SNOLab to possibly include students from the respective regions. To further support this effort, the DS Collaboration intends to coordinate with the Davis-Bahcall Scholar Program, the Sanford Laboratory multi-week program for first or second year undergraduates to explore the world of modern scientific research at leading national and international laboratories and universities.

The DS team has a broad set of skills and experience in building compelling narratives around the DS project as well as the science and engineering challenges involved therein. These narratives form the basis of a curriculum that may be used by the DS team to conduct outreach to both local and regional communities. This curriculum may also be shared with K-12 educators to complement the science classroom and adds context and applications that are locally and regionally relevant. For example, science teachers in the Montezuma-Cortez, CO school district will be encouraged to use DS-supplied materials to motivate students and help them to understand the argon extraction happening in their local region. Similar activities may take place in the Sulcis-Iglesiente district of Sardinia in the context of the Aria project.

The Matters of the Sky program is a new outreach effort proposed to address physics instruction shortcomings in low-income-area Philadelphia schools. Ongoing programs at Temple University already exist providing Continuing Professional Education (CPE) for in-service and pre-service STEM teachers from low income schools, but up to now these programs have not included physics content. The proposed outreach will take advantage of DS PIs' in-depth content knowledge, alongside its established practice framework, to devise and add CPE specifically for physics. The content will relate Dark Matter and other DS-related topics which are known to have great popular appeal, to appropriate curricular concepts. Pre-service teachers from the Temple TUteach program will work alongside the in-service teachers, attending a series of workshops devised and presented by DS PIs and others. Popular engaging topics (dark matter, the big bang, asteroid impacts, elementary particle constituents of the universe) will be linked to curricular topics like gravity, orbital motion, Doppler shift, energy, and so forth. Products of the program will include engaging lesson plans for classroom use, initially by the participating teachers. The lesson plans will then be tested through the existing STEM-UP program run by Temples College of Science and Technology, which already delivers project-based classroom instruction in mathematics, computer science and chemistry to ninth through eleventh grade students from North Philadelphia schools. Once field-tested, the lesson plans will be disseminated through presentation at professional meetings and through the STEM Ed Network of Temple's Allegra Family Math and Science Teacher Education Center [140]. The program as a whole will therefore benefit in-service teachers, pre-service teachers, and current

Temple undergraduate students awareness of and interest in physics.

Expanding upon outreach, the DS Collaboration also has the ability to improve undergraduate research opportunities, both in terms of course curriculum, student independent research, and summer activities. This effort expands upon and further formalizes existing collaborations between the partner institutions and increases opportunity for meaningful undergraduate research. Through partnerships in this collaboration, opportunities for undergraduate students range from local, on-campus projects based on problems presented by the DS program to structured summer research opportunities. The proximity of team campuses to, for example, the argon extraction portion of this effort, offers unique, hands-on experiences which will be taken advantage of by groups participating in this proposal. Capstone projects will be crafted not only to give students exposure to problems relevant to DS, but also to improve opportunities for graduate school or industry jobs.

The DS team is uniquely positioned to broadly tell the narrative of the scientific, engineering, and societal value of the DS project and to reach a diverse cohort of our population as well as future scientists and engineers. Again, not only do we create opportunity for the urban population served by our larger University partners, but also the populations of under-served, under-represented students from the rural and regional areas served by our entire DS team.

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