PROJECT DESCRIPTION

1 Introduction: The Upgrade for IceCube

The IceCube Neutrino Observatory at the South Pole station is one of the two dozen major research facilities operated by the US National Science Foundation (NSF). The IceCube detector comprises 86 strings each with 60 deep-ice digital optical modules (DOMs) deployed between 1450 m and 2450 m depth along with 81 surface stations each containing four DOMs frozen in shallow ice tanks. The deep array detects the faint Cherenkov light of neutrino-induced muons and electromagnetic and hadronic particle showers. It encompasses 1 Gton of optically transparent glacial ice, which serves simultaneously as a massive target for neutrinos of atmospheric and astrophysical origin and as a Cherenkov radiator medium. The surface array complements the deep detectors by providing sensitivity to cosmic ray air showers; composition above the knee and vetoing downgoing cosmic ray activity above 1 PeV in the deep ice are among its contributions to IceCube science.

IceCube was designed to detect high-energy neutrinos ($E_\nu > 1$ TeV) from astrophysical sources and atmospheric neutrinos and to search for dark matter. Its physics potential at energies as low as $E_\nu \simeq 10$ GeV is made possible by its DeepCore subarray comprising the seven innermost IceCube strings and augmented by eight additional strings in the clearest ice below 2100 m [1]. DeepCore provides a densely instrumented region of the detector with higher sensitivity to dimmer, lower-energy events, while the outer IceCube strings provide an extremely effective active veto against the downgoing cosmic ray muon background. This has opened up a range of exciting, high-impact physics studies in this energy realm.

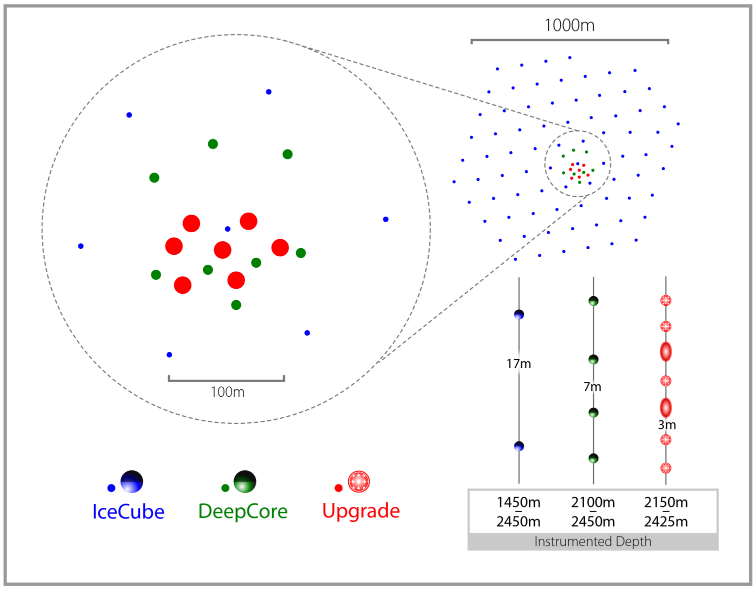

Figure 1: Top and partial side views of the seven additional strings for the IceCube Upgrade array, with neighboring IceCube and DeepCore strings shown for reference. The area of each circular marker is proportional to the PMT density on the corresponding string in the region below 2100 m. The side view shows the relative vertical spacings.

In 2018, an award was made to support the installation of seven additional strings of optical sensors in the bottom center of IceCube's DeepCore region that pushes the energy threshold of the facility an order of magnitude below that of DeepCore. This project, the IceCube Upgrade, will enable us to measure additional physics that no other detector, including DeepCore itself, can reach, while at the same time magnifying the high-quality physics that DeepCore will continue to deliver. Neutrino oscillations have been well measured by particle astrophysics experiments such as Super-K [2, 3], SNO [4], and KamLAND [5, 6], and although dedicated accelerator-based neutrino oscillation experiments, such as MINOS [7], T2K [8], NOνA [9, 10] and OPERA [11], have numerous proven experimental advantages, particle astrophysics experiments continue to make important contributions to the field. DeepCore follows in this tradition [12], bringing several enticing new features to the table. Its sheer size provides a neutrino data set of enormous statistical power: with a fiducial volume of 10 Mton at 10 GeV, DeepCore collects more than 130,000 atmospheric neutrino events per year.

The dense instrumentation of the Upgrade takes a first step in the direction focusing on oscillation measurements unique to the atmospheric neutrino beam. The new strings will use multi-PMT digital optical modules, providing better directionality and more than double the photocathode area per module, at lower cost per unit area, than traditional IceCube DOMs. By lowering the energy threshold to below 5 GeV, increasing the photocathode area in the DeepCore region, and improving reconstruction resolutions, the new strings will dramatically improve IceCube's neutrino oscillation physics reach. The strings will contain additional calibration instruments described in §2.2. A small portion of the sensors will be deployed at shallower and deeper depths for calibration, vetoing, and high-energy reconstruction purposes. The sensors will be fully integrated into the IceCube DAQ system. Every string will contain as many as 100 sensors at depths from 2150 m to 2450 m. For comparison, an IceCube string contains 60 sensors over a length of 1 km. The density of instrumented sensors equals five 10-inch-diameter PMTs per Mton in IceCube. The PMT coverage of the Upgrade is 140 times larger than IceCube with 700 equivalent PMTs/Mt. Figure 1 shows the envisioned Upgrade layout which is held under engineering change control.

1.1 Neutrino Oscillation Physics with Atmospheric Neutrinos

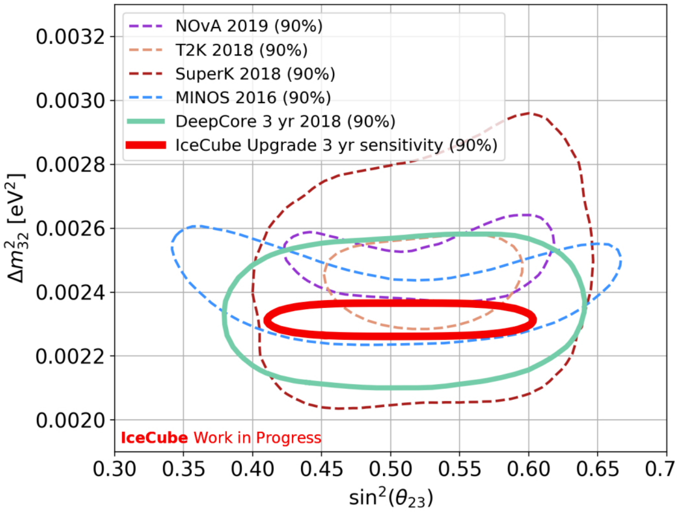

Figure 2: Contours of allowed regions (90% CL) for atmospheric mixing parameters from ν_μ disappearance for DeepCore and Upgrade (expected). See reference [13] for further details.

The indirect observation of neutrino mass through the phenomenon of neutrino oscillations requires additional physics beyond the Standard Model. The lower energy threshold afforded by DeepCore has enabled studies of neutrino oscillations using the copious flux of atmospheric neutrinos produced in cosmic ray air showers in the Earth's atmosphere. Charged mesons produced in these air showers decay, emitting neutrinos that can easily pass through the full diameter of Earth at GeV-scale energies.[1] As they travel, the neutrinos *oscillate* as differences in phase accumulate between their mass and flavor eigenstates. Oscillation probabilities depend on the ratio $\frac{L}{E}$, giving a very wide band of parameter values to explore over large energy scales. Published results on ν_μ disappearance [12] as well as ν_τ appearance [14] from IceCube DeepCore demonstrate the neutrino oscillation physics potential of the massive fiducial volume available inside IceCube as well as the background reduction offered by the surrounding IceCube sensors, which form a strong veto for the cosmic ray muon background. Figure 2 shows the anticipated ν_μ disappearance measurements of the atmospheric oscillation parameters for three years of IceCube Upgrade exposure, compared to existing IceCube DeepCore measurements as well as other astrophysical and accelerator measurements. Moreover, the Upgrade is a significantly more sensitive instrument relative to DeepCore for confirmation of the unitarity, or demonstration of the nonunitarity, of the neutrino mixing matrix, the PMNS matrix. After one year of operation, the Upgrade will measure the ν_τ normalization to 10%, a factor of 3 better than any other current experimental constraint, including DeepCore's. It should be noted that these results do not leverage cut-

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[1] Earth "shadowing," or absorption of neutrinos, does not become important until $E_\nu \gg 1\,\mathrm{TeV}$.

ting edge techniques being concurrently developed with IceCube and DeepCore, principally using AI/ML techniques, that are certain to elevate the ultimate performance of the Upgrade beyond what is estimated here.

1.2 Improving IceCube Through Precision Calibration

Increasingly, systematic uncertainties are becoming a limiting factor for determining angular resolution. The accuracy of our event reconstruction is limited by our knowledge of the optical properties of the bulk ice and refrozen hole ice and of the *in situ* response function of the sensors themselves. The Upgrade presents an opportunity to apply the knowledge gained after 15 years of operating IceCube and making progressive refinements to numerical models of the ice and the detector. These range from an understanding of nonuniformity in the depth structure of regions of differing ice clarity—dust layer tilt as it is commonly called, to directional optical anisotropy along glacial flow lines, to birefringence, to a fundamentally different image, literally from cameras deployed in IceCube, of how bubble columns form as the once liquid instrumentation holes refreeze and herd undissolved gas in a more orderly fashion than previously thought. The high density of optical instrumentation in the Upgrade will be ideal for probing scattering in the deep ice for the first time over distance scales shorter than the scattering length. Each module, as in IceCube, features LED flashers for building better scattering maps but, unlike for IceCube, will also contain camera modules to confirm the hole ice refreeze behavior observed previously with a few cameras is generally true. Steerable, collimated "pencil-beam" lasers deployed in several locations along each string will reveal scattering behavior on short baselines.

The goals of the calibration subsystems are: a determination of module optical efficiency to within 3%, a halving of the ice model fitting errors associated with hole ice, a detailed understanding of optical anisotropies, and a measurement of ice properties below the instrumented volume of IceCube. With the Upgrade, the calibration of IceCube will be significantly improved allowing for a (re-)analysis of IceCube's unique $\sim$10 km^{3}yr exposure data set.

1.3 Research and Development

A third high-level goal of the IceCube Upgrade is to serve as a research and development platform for a potential high-energy extension of the IceCube Neutrino Observtory, the IceCube-Gen2 detector [15]. Advances being made for the Upgrade are assessed for their applicability for a future larger extension. Additionally, promising novel in-ice optical module designs will be included in small quantity R&D ("special devices") deployments on the Upgrade strings. A deployment of instruments in ice offers a rare opportunity to validate technology. These new detector elements include the WOM (wavelength-shifting optical module), a revolutionary step in gaining effective collecting area without increased photocathode size and cost; the FOM (fiber optical module), a similar cost-saving strategy that deploys fibers into the drill hole; the LOM (long optical module), a more evolutionary module based on the mDOM construction (Sec. 2.1) but elongated to fit into a smaller diameter cylindrical or egg-shaped housing that could dramatically reduce drilling costs; and test deployments of fiber optic cables to serve as an alternative to copper wires for communicating with the in-ice electronics.

2 Technical Scope

2.1 Optical Sensors

The two primary optical sensors for the Upgrade are the mDOM and the D-Egg (Fig. 3). The mDOM contains 24 3-inch-class PMTs housed in a glass pressure sphere. The PMT signals are individually digitized and read out by a central electronics mainboard, providing time and amplitude information for detected

Figure 3: Photos of an mDOM (left) and a D-Egg (right).

photons. The D-Egg contains two 8-inch high-quantum-efficiency PMTs facing in opposite directions; as in the mDOM, the PMT signals are digitized by onboard electronics. Both sensors provide increased photocathode area and angular sensitivity compared to Gen1 DOMs, and the use of multiple PMTs adds additional directional information that can improve event directional reconstruction. Quality and reliability of all produced sensors is ensured through a rigorous final acceptance testing (FAT) procedure. A total of 402 mDOMs and 277 D-Eggs will be installed on the seven strings.

The core "physics region" of the array, located between 2,150 to 2,425 meters below the surface (Fig. 4), will be used to perform precision measurements of neutrino properties and tau appearance. It is densely instrumented with 90 devices (on average, 50 mDOMs, 36 D-Eggs, and 4 others, per string; 3 m vertical spacing) forming a detector volume of about 5 Mt of the clearest ice. The photocathode coverage per unit volume will be about 2 orders of magnitude higher than in IceCube. Note: The mDOMs and D-Eggs are in-kind contributions of collaborating institutions in Germany and Japan, respectively.

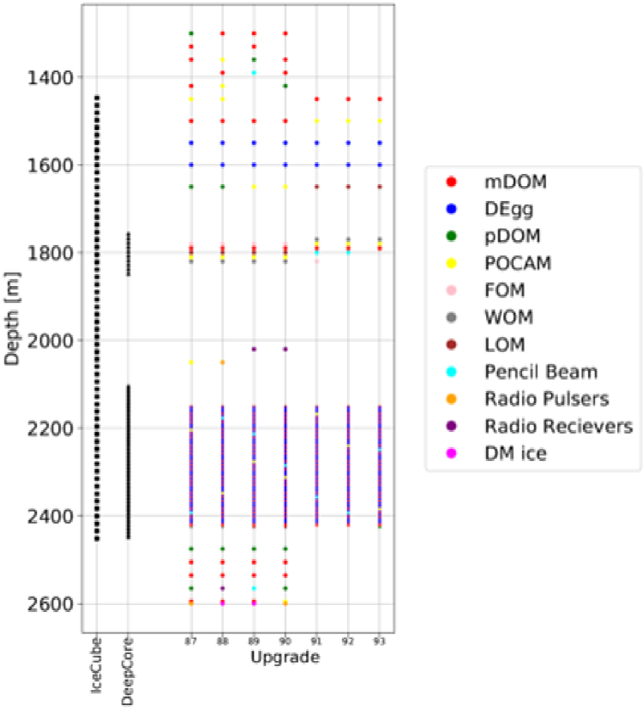

Figure 4: Schematic view of IceCube Upgrade strings and vertical layout of instruments.

2.2 Calibration and R&D Devices

At shallower and deeper depths (down to 2,600 meters below the surface), a smaller number of optical modules (the mDOMs, D-Eggs, and pDOMs, which are similar to Gen1 DOMs) and calibration sources (POCAM and pencil beam for precision ice measurements and radio pingers for geometry) are deployed primarily for calibration purposes. The original IceCube Gen1 extends from 1,450 to 2,450 meters and surrounds these strings. Additional research and development of various types of modules (including the LOM, FOM, and WOM) to study potential sensor technologies for a possible high-energy IceCube-Gen2 extension are also deployed above the primary physics region. Note: R&D modules are not in the budget.

2.3 Power and Communications

The cabling architecture for the Upgrade (Fig. 5) is very similar to that used in IceCube, in which DOMs and other devices connect to copper wire pairs that supply power, communications, and precision timing. Up to three devices per wire pair are supported as part of a larger downhole cable assembly. The downhole cable connects via a passive surface junction box to a surface cable, which is routed into the IceCube Lab (ICL) using an existing cable tower and connects to custom rack-mount readout electronics (FieldHubs). Note: cable systems are largely an in-kind contribution from MSU.

Power delivery, communications, and timing use proven techniques from IceCube. DOM power is delivered via DC voltage on the wire pairs from power supplies in the ICL. Digital communications for DOM data readout and control is via a custom signaling protocol on top of the DC voltage; the cable data rate has been increased by a factor of two from the Gen1 protocol to 2 Mbps. Module timing synchronization to the $O(\mathrm{ns})$ level is achieved using IceCube's reciprocal pulsing technique (RAPCal) [16].

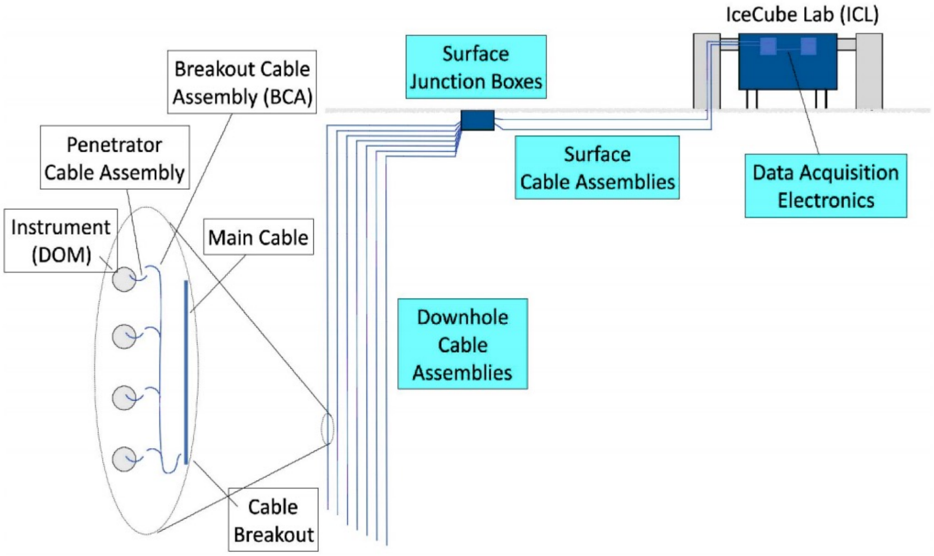

Figure 5: The Upgrade cabling architecture. Power, communications, and precision timing are supplied using copper wire pairs from the DOMs to the readout electronics in the ICL.

2.4 Drilling and Installation

The implementation of the seven strings of optical sensors in the ice is the largest effort for which support is requested. A challenging task is the drilling of the holes of 0.6 m diameter to a depth of about 2,600 m. The drilling will be performed using the IceCube Enhanced Hot Water Drill (EHWD), which produces a jet of hot water (200 gpm, 1,000 psi pressure) of about 5 MW thermal power to drill at a speed of 130 m/hour. The drill, in storage since 2011 (Fig. 6), was excavated from a deep snowdrift in the first field activity of the IceCube Upgrade project in 2019–20. Significant components of the drill need to be replaced entirely, including the drill hose, drill cable, generators, and the complex control system. Other parts such as the main heating plant, high pressure pumps, water tanks, tower operations structures, and hose reel need maintenance and/or refurbishment.

The requirements for the IceCube Upgrade holes are more demanding than for IceCube. The required diameter is larger and the water-filled holes are required to stay open for a longer period of time (50 h vs. 35 h) to ensure that strings can be deployed safely. The Upgrade strings are populated with almost twice as many instruments as regular IceCube strings. In addition, the mDOM optical sensors are larger in diameter and heavier and there is a larger variety of sensors and devices that need to be accommodated. All factors included, the drill time per hole is projected to be about 53 hours, compared to a full production IceCube hole drill time of 34 hours. The preparation for drilling can be categorized in three major tasks: a) planning, rebuilding and in some cases (control system) redesign of subsystems in the North, b) shipping of equipment, and c) refurbishing of subsystems, recommissioning of the drill, and finally drilling operations on the ice. The drill control system includes more than 300 sensors that get read out to a central control center that includes complex safety functions and an emergency stop that can be initiated from any subsystem. Approximately 75% (by weight) of the drill equipment has been shipped as of February 2022.

It is hard to overstate the importance of the field experience of IceCube construction for the planning and the eventual execution of the Upgrade field seasons. The drill refurbishment and the redesign and fabrication of the control system is all done at UW–Madison's Physical Sciences Laboratory, which designed and constructed the drill for IceCube and largely lead the drilling operations. Similarly, the installation effort relies on the collective experience and records of deploying 86 strings during IceCube construction.

The field effort in this project is planned for three seasons, which typically run from mid-November to the end of January. The main tasks by field season are:

- Field season 1 (2023–24): Repair and refit EHWD subsystems. Commission independent firn drill (IFD) and Antarctic Rodwell apparatus (ARA Drill). Set up seasonal equipment site (SES).
- Field season 2 (2024–25): Complete seasonal equipment site (SES) set-up and remaining interconnects. Integrate and test subsystems, including generator and power distribution module, system integration, verification, and testing. Perform control system testing and "wet-testing" of EHWD subsystems. Firn drill all holes. Install surface cables.
- Field season 3 (2025–26): Deep drill all seven holes. Install all seven detector strings. Commission the new strings and integrate them into data acquisition and data handling. Drill system decommissioning and storage/retro.

2.5 Logistics

A detailed logistics plan is crucial to the successful execution of the field program. Even though the largest part of the drill is already at the South Pole, a substantial amount of cargo needs to be shipped to the Pole to support project requirements. A total of 528,500 lbs of cargo will need to be moved between FY23-FY26. While the majority of transport can be accomplished overland with the South Pole Traverse, environmentally sensitive cargo, totalling 117,500 lbs, must be shipped by air (LC-130) due to temperature/shock concerns associated with overland travel and heated warehousing limitations at the South Pole. Overland asset constraints necessitate that project fuel, 95,361 gallons or roughly 667,500 lbs, also be transported by LC-130 aircraft from McMurdo Station to the South Pole.

The coordination of annual cargo shipments and personnel deployments to and from the South Pole will be done in close coordination with the United States Antarctic Program (USAP). It also includes the management of international and domestic shipping schedules to mesh with USAP flights from Christchurch to Antarctica. The logistics requirements and the schedule have been reviewed in a dedicated logistics

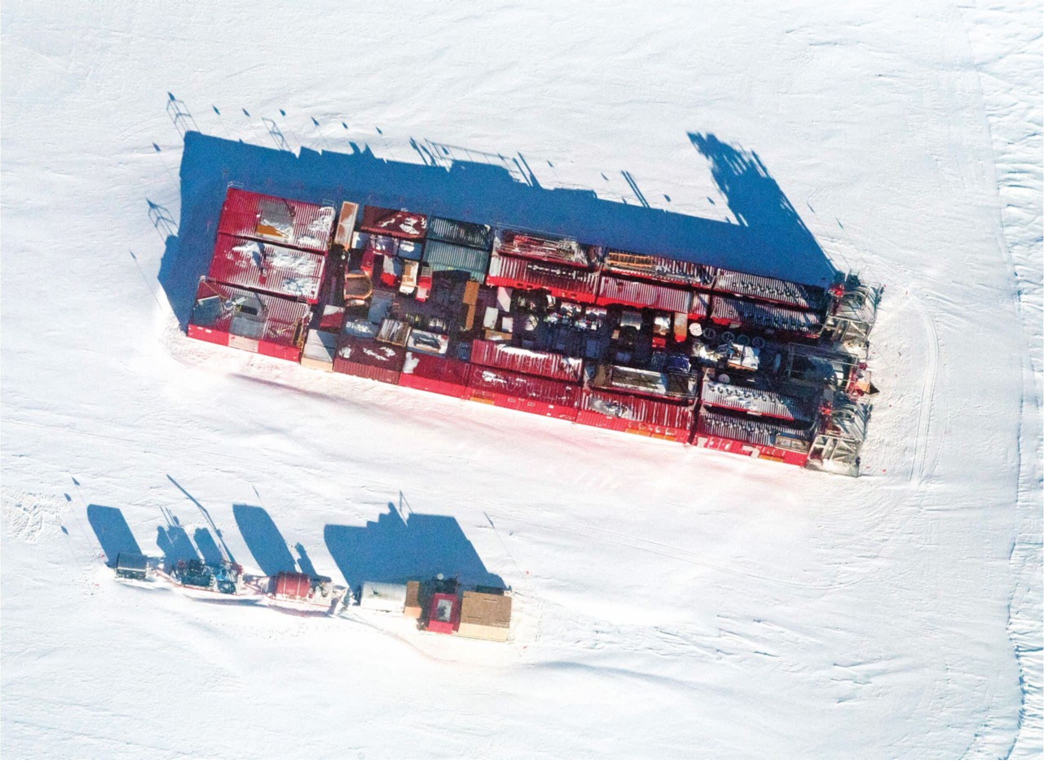

Figure 6: The drill was mothballed for storage at the South Pole in 2011.

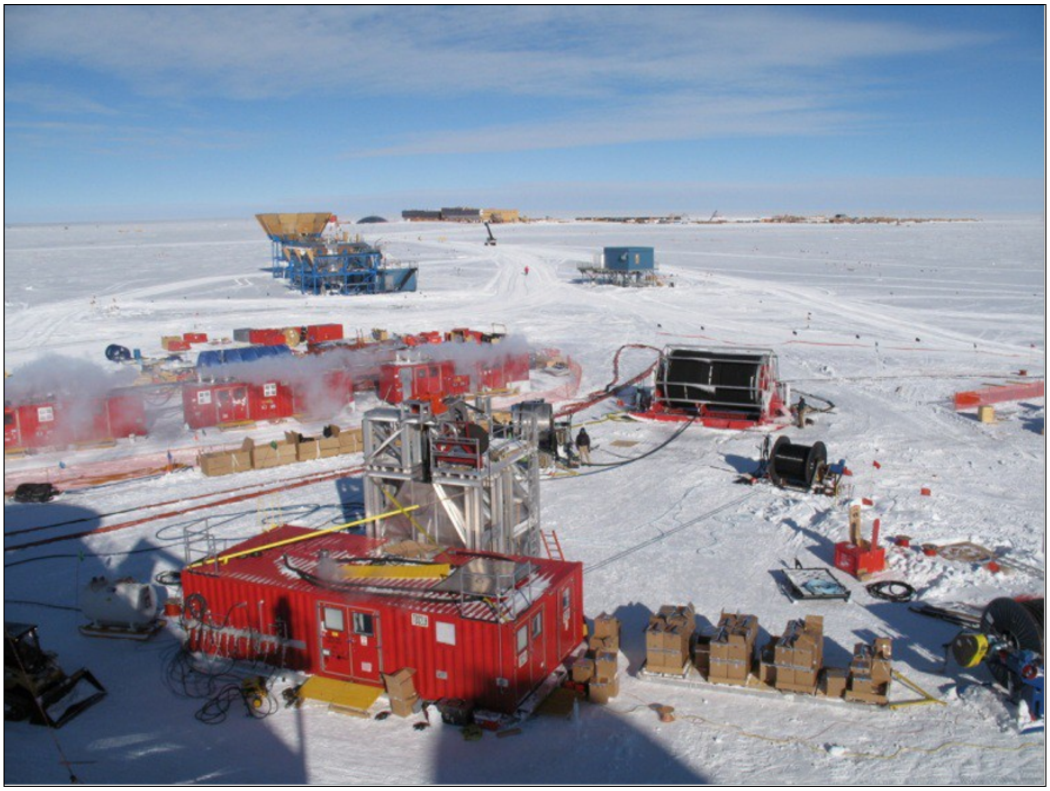

Figure 7: The drill is shown in operation during IceCube construction. A drill tower (one of two) is shown in front. The heating plant in the background. In the far background one can see the South Pole station.

review that was conducted by the NSF in November 2021. The findings and recommendations of the review were positive and have informed the final planning assumptions that served as a basis for the rebaseline plan presented here. The carefully developed and documented logistics plan includes a cargo master plan spreadsheet and a population master plan spreadsheet planned out for all field seasons.

2.6 Integration of Upgrade strings into IceCube

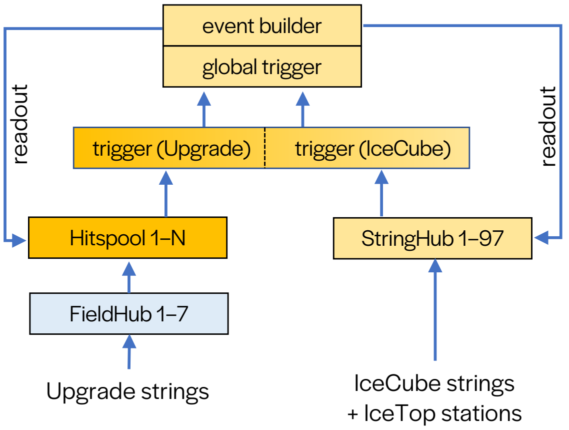

Figure 8: Trigger-level integration of the Upgrade strings into the existing IceCube DAQ software.

In order to leverage IceCube's existing, well-developed data-taking systems at the South Pole, the Upgrade strings will be tightly integrated into the existing online systems at a low level. The data acquisition (DAQ) software will be expanded to integrate the Upgrade DOMs into the detector global trigger (Fig. 8). The DAQ event builder will provide combined events that integrate all IceCube components, including the Upgrade modules; this allows higher-level reconstruction and analysis software, such as the online processing and filtering system (PnF), to be used with only modest changes to support the new module designs and facilitates integrated analyses of both Upgrade and Gen1 data. Furthermore, the control of all calibration devices will be integrated into the DAQ, and special calibration data will either be routed to PnF or to "secondary" data streams for special sensors such as cameras. Monitoring of the Upgrade will be incorporated into the existing IceCube Live software. IceCube's existing data archive and transfer software can be used as-is to manage all data products.

This integration strategy also ensures an efficient transition to operations. IceCube operations will naturally expand to include the Upgrade strings, since data taking, data processing, and detector monitoring will be unified. All custom electronics in the ICL will be installed in existing rack space, by consolidating other hardware and removing unused legacy equipment. The additional power usage expected for the Upgrade is approximately 12 kW, which can be accommodated within the existing ICL power delivery systems with only minor modifications. Because the additional Upgrade trigger rate will be low compared to the current array, the increase in satellite data rates is expected to be modest ($\sim$15%).

3 Project Rebaselining — Completing the IceCube Upgrade

The original IceCube Upgrade project was baselined as a five-year project, starting in FY19 and completing in FY23, with a baseline cost of $22.983M. Unfortunately, the COVID pandemic closed most areas of research in the US and impacted our international partners, starting in the spring of 2020 (middle of PY2). This significantly delayed hands-on technical work. In addition, on-ice field seasons were cancelled starting in FY21 and are not planned to resume until FY24. Since 2020, the project has attempted to replan around the field cancellations and cargo pipeline stalls with the aim to reduce overall project cost. A rebaseline review was conducted in spring 2021, ultimately unsuccessful due to remaining uncertainties in field support. In early 2022, NSF/OPP/AIL provided the Upgrade with a field support profile that included planning capacities for personnel and cargo, both inter- and intra-continental. This has allowed the project to establish a definitive plan for completion at full scope. Descoping options have been considered and are part of the project scope management plan; however, the organization of the project, namely a small number of instrumentation strings deployed in a single field season with instrumentation largely provided in-kind, renders it difficult to realize large cost savings.

3.1 COVID Impact

COVID has impacted both the on-project and in-kind deliverables of the project. The major on-project deliverable is the Enhanced Hot Water Drill (EHWD), designed and built at the University of Wisconsin–Madison's Physical Sciences Laboratory. The EHWD uses much of the drill from the original IceCube project, but requires repair and upgrades to the motor control and monitoring subsystems. In order to assess the state of the EHWD, drill experts deployed to the South Pole in FY19 and FY20. Using the information gathered at that time, a detailed plan for refurbishment and for the final three field seasons was made. Unfortunately, directly after the FY20 deployment, the pandemic forced closure of both UW–Madison and the Physical Sciences Laboratory. Many of the engineers and technicians needed for carrying out the required work were not able to perform hands-on assignments, which put the drill refurbishment behind schedule. The pandemic additionally forced NSF to cancel field seasons and other support for all nonessential science events. For the Upgrade, this has meant that cargo placed into the USAP logistics stream after the early days of 2020 did not move forward for nearly two years and the planned remaining field seasons in FY21 (drill repair), FY22 (integrated drill system verification testing and firn drilling), and FY23 (deep ice drilling and installation of the sensors) have been delayed by three full years.

Finally, collaboration partners contributing in-kind resources also suffered COVID-induced delays in their deliverables. Again, supply chain shortages and workplace population constraints affected the major areas of main cable assemblies and mDOM sensor electronics.

3.2 Project Accomplishments PY1–PY4

Figure 9: Test article of the main downhole cable being fabricated.

The Upgrade project is now in the middle of PY4. All major subsystems have progressed to final design phase or beyond. The 310 D-Egg sensors contributed by collaborators in Chiba, Japan, were produced by industrial partner Nippon Marine Enterprises in Yokohama, finishing November 2021. The mDOM sensors completed their final design review in April 2022. All 10,000 photomultipler tubes were manufactured by Hamamatsu, who additionally manufactured and attached the HV bases designed with project-supported engineering (UW–Madison). The mDOM mainboards have completed design verification; however, lack of availability of Spartan-7 FPGAs from AMD/Xilinx is holding up further production. All sensor modules share a common piece of hardware, the ice comms module, or ICM, to effectuate the custom communication protocol exchanged between all instruments in the ice and surface readout electronics. These modules have all been produced. The D-Egg ICMs have already been integrated as part of the D-Egg production. Fail-safe, low-level firmware has been completed. Finally, initial functional firmware

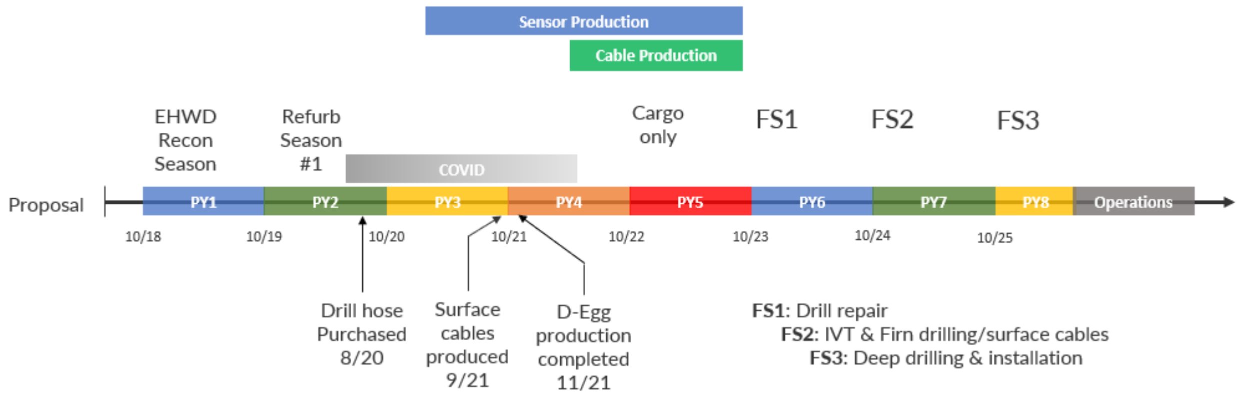

Figure 10: The high-level schedule showing field seasons (FS) for Antarctic work and project years (PY). Three consecutive field seasons are needed: FS1-complete the drill repairs; FS2-drill integration, verification and testing (IVT), firn drilling, and placing the surface cables; FS3-deep drilling and instrumentation installation and verification.

and software for module testing and for data acquisition in the installed detector array has been delivered.

Procurement of the main downhole raw cables was delayed as the IceCube supplier sold off the machinery needed to produce the IceCube cable design. A redesigned cable has been engineered, a test article has been produced (Fig. 9), and mechanical verification is underway. Electrical verification of the quad substructure was completed in PY3. Additionally, surface cables carrying the signals into the ICL were delivered early in PY4.

As mentioned in the previous section, due to COVID cancellation of the FY21-FY23 Antarctic field seasons, the two successful recon and repair deployment seasons were the only opportunities drill personnel had to accomplish necessary field repair of the hardware at the Pole (the towers, workshops, heaters, and pumps) and at McMurdo (generators and power distribution modules). Nonetheless, off-ice accomplishments include inserting the majority of the remaining large cargo items into the cargo stream (firn drill, refit containers) and successful large capital procurements of a new drill hose from Italian supplier IVG ($1M) and drill cables from Fibron ($300k).

3.3 Completing the IceCube Upgrade Project

NSF AIL has taken stock of the current state of the logistics chain after more than two years of very little movement due to COVID and has advised the project of logistics capacities that can be allocated in the field seasons FY24–FY26. The IceCube Upgrade project has been communicating regularly with NSF and the Antarctic contractor in order to plan cargo movement to the South Pole that optimizes the work done in each of these field seasons. The Upgrade project has implemented the logistics capabilities within a complete bottom-up estimate for cost and schedule taking stock of the current state of work. A high-level schedule is shown in Fig. 10.

The major in-kind work to be done includes the mDOM and D-Egg production and the main cable assemblies. While there are some supply chain issues, these productions should be completed next year. All of the PMTs for the mDOMs have been bought and tested, and risks for remaining parts supplies are being mitigated.

For the on-project work, the major cost driver is the drill refurbishment and support for the on-ice seasons. Having been able to review the status of the drill at the South Pole earlier in the project was invaluable; most of the large items needed for refurbishment have been bought. The critical area remaining is the drill control system, as this requires some retrofitting of obsolete hardware and replacing the obsolete software and computing used to drive the drill and ensure safe operations. A test bed at PSL is being used to test and commission the new monitoring hardware in order to minimize any inefficiency during the on-ice seasons.

Additional on-project work includes data acquisition software, firmware, and hardware; calibration software and hardware; and the overall coordination of the project logistics, installation, and field season planning.

3.4 Project Management and Organization

The IceCube Upgrade project organization down to Level 2 in the Work Breakdown Structure is shown in Figure 11. The organization is embedded in the Wisconsin IceCube Particle Astrophysics Center (WIPAC) at the UW–Madison. The project structure is similar to the original IceCube project.

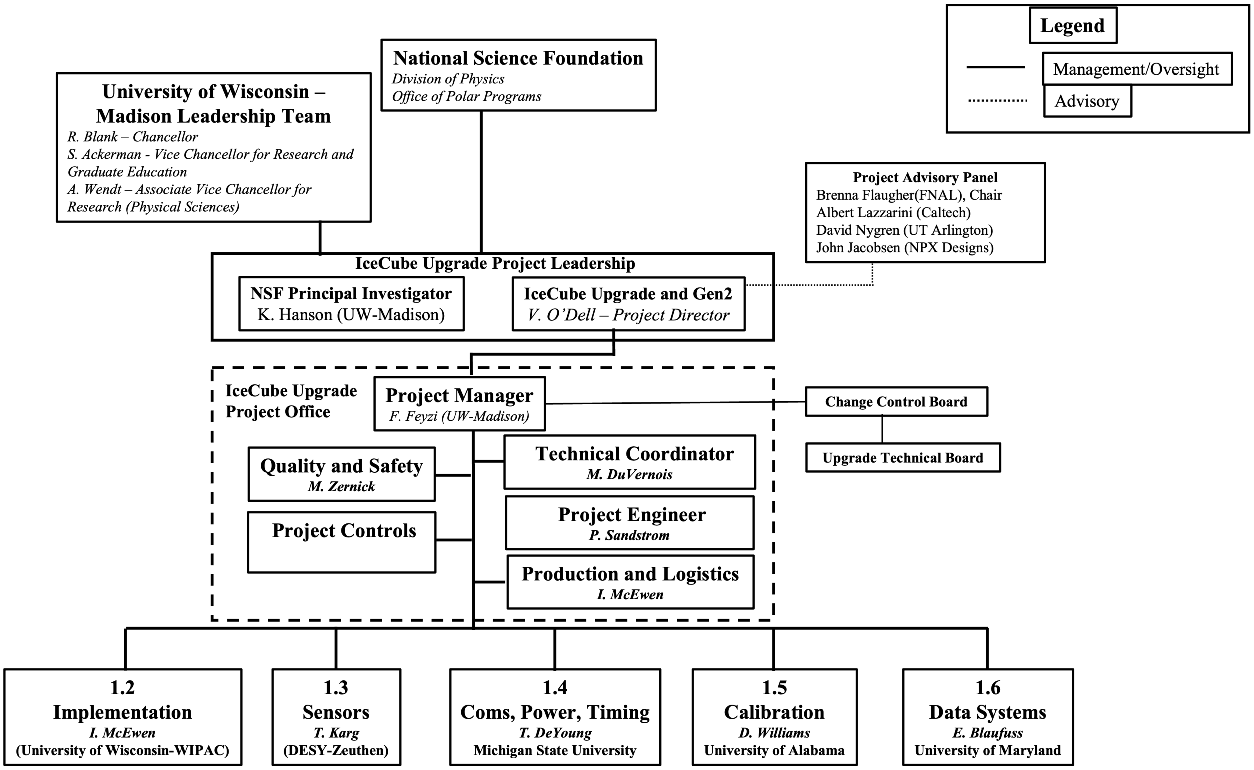

Figure 11: Diagram of the IceCube Upgrade project organization. Solid lines indicate management and oversight, and dotted lines are advisory.

The University of Wisconsin–Madison is the host institution for the project, and the Vice Chancellor's office has formal authority over the project and ensures that the project is well governed and appropriately staffed. The Office of the Vice Chancellor oversees regular reviews of the project.

The **Principal Investigator (PI)** is ultimately responsible to NSF for the financial and scientific oversight of the project. The PI appoints and oversees the project director in the execution of the project.

The **Project Director (PD)** is the primary contact to NSF. The PD is responsible for completing the project within the budget and schedule agreed upon by NSF. The PD delegates the responsibility of running the project to the **Project Manager (PM)**, but tracks the progress of the project, reports the progress to

NSF, and has authority to bring in additional resources or reallocate resources as needed for the successful execution of the project.

The PM runs the project, chairs the Change Control Board, and appoints key management positions in the project in consultation with the PD. The **Project Advisory Panel** participates in regular reviews of the project and advises the project.

NSF is responsible for oversight of the project, which is shared between the NSF Division of Physics and Office of Polar Programs.

The PM, in consultation with the PD, appoints the WBS Level 2 managers and approves the WBS L3 managers. WBS Level 3 managers may choose to appoint, in consultation with the WBS L2 managers and the PM, WBS Level 4 managers and delegate some responsibility to them as appropriate. The WBS Level 2 managers oversee and direct their subareas and report to the PM. They are responsible for generating and maintaining the cost estimate, schedule, risks, and resource requirements and providing regular status reports for their areas. They are responsible for meeting the goals of their area within the accepted baseline cost and schedule.

All **WBS Level 3 and some Level 4 managers** will also be designated as control account managers (CAMs). They are responsible for earned value management on their assigned control accounts.

The **Technical Board** is chaired by the technical coordinator and includes the Level 2 and Level 3 managers and technical support staff. The PI, PD, and IceCube Collaboration spokesperson are ex officio members. The Technical Board meets once per week, via conference call, to discuss project progress, problems, interfaces, potential changes, risk and risk mitigation strategies, and technical requirements, and convenes in person as needed. The Technical Board also provides recommendations to the Change Control Board and maintains the technical issue tracker.

The **Change Control Board (CCB)** reviews and approves or rejects all changes to the technical, cost, and schedule baselines, as documented in the IceCube Upgrade Configuration Control process. The CCB is chaired by the PM and consists of the technical coordinator, the project engineer, the quality and safety manager, the project controls manager, the L2 managers, the IceCube associate director for science and instrumentation, and the PD. The PI is an ex officio member. The CCB is an executive decision-making body convened when the level of a proposed change to the budget, schedule, or scope of the project demands approval of this body as defined in the Configuration Management Plan.

Entities external to the project, with lines of authority, responsibility, and communication are also shown in Figure 11 and described below.

The **IceCube Neutrino Observatory (ICNO)** and **IceCube Upgrade collaboration** serve as advisors to the project. Additionally, the ICNO Project Advisory Board consists of a group of external senior advisors with collective expertise in the science, technology, and management of the project. The ICNO meets regularly at the request of the PD and the PI.

The **University of Wisconsin–Madison** is the host institution for the IceCube Upgrade project and the home university of the NSF IceCube Upgrade PI. The responsibilities of the host institution include providing internal oversight for the project, appointing the PD (subject to concurrence of the NSF and of the IceCube Collaboration Board), ensuring that the project office has adequate staff and support, ensuring that the management structure is established for managing the project and monitoring progress, ensuring that accurate and timely reports reflecting full transparency of the project are provided to the NSF, IOFG, and IceCube Collaboration, developing subawards with other U.S. collaborating institutions and providing appropriate funding, and establishing MoUs between UW–Madison and non-U.S. collaborators that define the non-U.S. institutional responsibilities.

The **Wisconsin IceCube Particle Astrophysics Center (WIPAC)** is a scientific center within the Office of the Vice Chancellor for Research and Graduate Education at the University of Wisconsin–Madison, with researchers based in the Departments of Physics and Astronomy, and encompasses a range of particle astrophysics research interests. WIPAC manages the IceCube Neutrino Observatory and related projects.

The IceCube Upgrade project is embedded in and endorsed by WIPAC.

The IceCube Upgrade project office is headquartered at WIPAC. WIPAC is the primary interface to the university administrative and support systems to coordinate the multiple roles of the university, such as lead and host institution for the IceCube construction projects, and for IceCube maintenance and operations. WIPAC provides administrative services such as accounting, purchasing, and human resources, coordinates education and outreach activities, and collaborates with the largest participating research group. It also supports engineering and computing needs for these projects.

The **National Science Foundation** is the U.S. source of funding for IceCube, the IceCube Upgrade, and the ongoing IceCube maintenance and operations program. The NSF oversees the project and holds line management and financial oversight for the NSF awards/subawards. The NSF has a special role in the IceCube Upgrade because of its host laboratory responsibilities in managing the logistical operations of the Amundsen-Scott South Pole Station. These responsibilities include safety; physical qualification of project staff; environmental protection; transport of personnel, fuel, and equipment; and the provision of housing, food service, support personnel, logistical support, IT support, and general infrastructure support.

The **International Oversight and Finance Group (IOFG)** is a group chaired by the NSF IceCube program managers and comprises representatives of all funding agencies engaged in IceCube Upgrade construction and operation. The IOFG provides oversight, financial support, and sets policies for reporting and external reviews.

NSF principal investigators and non-NSF partners contributing significant resources to the project constitute the scientific leadership of the project and ensure that technical decisions are made in a manner that preserves the scientific viability of the instrument. IceCube Maintenance and Operations ensures compatibility with the existing infrastructure. The IceCube Collaboration Board ensures that the project efforts are transparent to IceCube collaborators.

The project relies substantially on **in-kind contributions** from international collaborators. The mDOM optical sensors are being contributed by Germany: The largest contribution is from the DESY (Deutsches Elektronen Synchrotron) with additional contributions on design and testing from several Universities. All the photomoltipliers for the mDOMs are contributed by KIT (Karlsruhe Institute of Technology). Specialized calibration devices are contributed from TU Munich (POCAM), Aachen University (radio pingers) and from University of Stockholm (”Swedish Camera”). All the D-Egg optical sensors are contributed from Chiba University, Japan. The project office coordinates and oversees the integration of all activities in the project.

4 Broader Impacts

The broader impacts program will build on the expertise developed during IceCube’s nearly 20-year history. We will leverage efforts in the current IceCube E&O and communication programs and continue facilitating access to IceCube data for other communities and disciplines. In the IceCube Upgrade, we will work with the IceCube-Gen2 Collaboration to integrate the testing of prototype instrumentation for a full-scale development of the large IceCube-Gen2 array. We will also strengthen partnerships with the dark matter and glaciology communities to open up opportunities for future experiments in these fields. Finally, we will increase our efforts in the development of a diverse and skilled STEM workforce. Details about specific activities, including some metrics and outcomes, are given below.

4.1 Education and Outreach

Design and construction of new instrumentation at facilities distributed worldwide opens up unique possibilities for training the next generation of researchers, including the participation of students and postdocs on medium-scale production and testing of detector hardware. The Upgrade E&O program will continue Ice-

Cube efforts on intensive undergraduate research experiences and research-based activities for high school students. We will address NSF broader impact priorities to integrate research and formal and informal education and to reach communities that are underrepresented in STEM fields by pursuing multiple paths:

1. Developing an online platform allowing both novice and expert users to analyze IceCube data, using tools such as sky maps or advanced computer-based algorithms to explore data
2. Engaging high school students and teachers through the IceCube Masterclass, a one-day research-based learning program hosted at IceCube institutes that utilizes online data tools
3. Providing summer research experiences for undergraduates at IceCube institutions, with an annual commitment that at least three of the six positions go to underrepresented students

4.2 Fostering a Strong, Diverse, and Skilled STEM Workforce in the US

IceCube has recently launched a task force to foster a more diverse and skilled team of researchers and technicians as well as to broaden the participation of underrepresented audiences in E&O programs. Upgrade recruiting efforts will benefit from this initiative and will contribute to a targeted steady increase in the diversity of IceCube staff and collaborators.

4.3 Engaging All Audiences

IceCube communication activities will also support Upgrade efforts, providing consolidated formats and audiences all over the US and around the world. Information about this project will be published in press releases, news articles, IceCube social networks, and a devoted minisite on IceCube's main site. We will also produce a series of videos and podcasts about this project.

5 Summary

The Upgrade was originally a five-year, $23M project with an approximately $14M addition of in-kind contributions. We are now in year 4 of the project. COVID impacts, both external and within, will extend the project to a total of 7.6 years. We have done a complete bottom-up replan, taking stock of where we are now, the work to go, and external realities using commonly accepted and recommended methods and assumptions as detailed in our Cost Estimating Plan and Key Assumptions sections. We have a solid plan, cost, and schedule as well as an experienced team to execute the project that has benefited from multiple internal and external reviews over the last two years.

REFERENCES CITED

References

[1] M. G. Aartsen et al. (IceCube), Nucl. Inst. Meth. **A711**, 73 (2013).

[2] Y. Fukuda et al. (Super-Kamiokande), Phys. Rev. Lett. **81**, 1562 (1998), `hep-ex/9807003`.

[3] M. Nakahata (Super-Kamiokande), PoS **NEUTEL2015**, 009 (2015).

[4] Q. R. Ahmad et al. (SNO), Phys. Rev. Lett. **89**, 011301 (2002), `nucl-ex/0204008`.

[5] S. Abe et al. (KamLAND), Phys. Rev. **C84**, 035804 (2011), `1106.0861`.

[6] T. Araki et al. (KamLAND), Phys. Rev. Lett. **94**, 081801 (2005), `hep-ex/0406035`.

[7] P. Adamson et al. (MINOS), Phys. Rev. Lett. **110**, 251801 (2013), `1304.6335`.

[8] K. Abe et al. (T2K), Phys. Rev. Lett. **112**, 181801 (2014), `1403.1532`.

[9] P. Adamson et al. (NOvA), Phys. Rev. Lett. **116**, 151806 (2016), `1601.05022`.

[10] P. Adamson et al. (NOvA), Phys. Rev. **D93**, 051104 (2016), `1601.05037`.

[11] N. Agafonova et al. (OPERA), Phys. Lett. **B691**, 138 (2010), `1006.1623`.

[12] M. G. Aartsen et al. (IceCube), Phys. Rev. **D91**, 072004 (2015), `1410.7227`.

[13] T. f. t. I. C. Stuttard (IceCube), PoS **NuFACT 2019**, 099 (2019).

[14] M. G. Aartsen et al. (IceCube), Phys. Rev. D **99**, 032007 (2019).

[15] M. G. Aartsen et al., J. Phys. G **48**, 060501 (2021), `astro-ph.HE/2008.04323`.

[16] M. G. Aartsen et al. (IceCube), JINST **12**, P03012 (2017), `1612.05093`.