ICECUBE NEUTRINO OBSERVATORY (ICNO) — $7,660,000
+$580,000 / 8.2%

IceCube Neutrino Observatory Funding
(Dollars in Millions)

FY 2021 Actual	FY 2022 (TBD)	FY 2023 Request	Change over FY 2021 Actual: Amount	Change over FY 2021 Actual: Percent
$7.08	-	$7.66	$0.58	8.2%

Brief Description

The IceCube Neutrino Observatory (ICNO) cubic-kilometer detector has delivered world-leading scientific results—from measuring previously unexplored atmospheric neutrino oscillations to observing cosmic neutrinos with energies exceeding 10 peta-electron volts (PeV). The discovery of these cosmic neutrinos establishes ICNO's role in multi-messenger astrophysics for observing the extreme Universe. ICNO is the world's first gigaton, and largest high-energy, neutrino detector, comprising 5,160 digital optical modules (DOMs) deployed deep within the ice cap under the U.S. Amundsen-Scott South Pole Station in Antarctica. ICNO will continue to undergo an evolution in its scientific mission as it is upgraded with an additional 700 DOMs in the coming years.

Scientific Purpose

ICNO was designed to observe neutrinos from the most violent astrophysical sources in the Universe. Neutrinos—almost massless particles with no electric charge—can travel from their sources to Earth with essentially no attenuation and no deflection by magnetic fields.

In 2013, ICNO observed the first high-energy (over 100 tera-electron volt (TeV) and up to 10 PeV) astrophysical (cosmic) neutrinos—key messengers revealing an unobstructed view of the Universe at wavelengths where it is opaque to photons. In 2017, new data obtained by ICNO revealed some answers to a more than century-old quest for the origins of high-energy cosmic rays, tracing the path of a single, very high-energy neutrino back to a previously known but little-studied blazar—the nucleus of a giant galaxy that fires off massive jets of elementary particles, powered by a supermassive black hole at its core. While this evidence of the first known source of high-energy neutrinos and cosmic rays is compelling, more data are now

The IceCube Laboratory building at South Pole where all data-collecting computer servers are located. *Credit: USAP Photo Library, Sven Lidstrom, NSF.*

sought from similar or other sources. The ICNO results opened a new window to the Universe, providing novel insights into the engines that power active galactic nuclei and generate high-energy cosmic rays, gamma ray bursts, and other violent and energetic astrophysical processes. ICNO's exploration of scientific frontiers has already changed and expanded our understanding of the Universe.

Inquiries are underway concerning science questions that may arise from the study of neutrino properties, especially at the lower energies to which ICNO's Deep Core strings have enabled access. For example, to fill in the blanks of the Standard Model of particle physics, scientists have been conducting diligent searches with ICNO data for a hypothesized particle known as the "sterile neutrino." None of the searches found evidence for the eV-mass sterile neutrino hinted at by other experiments.

In the ten years since its completion, ICNO has isolated more than 150 high-energy cosmic neutrinos, with energies between 100 TeV and 15 PeV, from more than a million atmospheric neutrinos and hundreds of billions of cosmic-ray muons.[1] Among them is the first detection of a Glashow resonance event—one of the highest energy particles (6.3 PeV) was observed while distinguishing a cosmic antineutrino for the first time. These PeV neutrinos, the highest energy neutrinos observed to date, have a thousand times the energy of the highest energy neutrinos produced with earthbound accelerators and a billion times the energy of the neutrinos detected from supernova SN1987 in the Large Magellanic Cloud, the only neutrinos that had been detected on Earth from outside the solar system prior to the ICNO breakthroughs. However, the most surprising property of these cosmic neutrinos is their large flux rather than their high energy or their origination outside our galaxy.

Status of the Facility

ICNO operations include two staff members who carry out "winter-over" duties at the South Pole where the ICNO data are collected and transmitted daily to the University of Wisconsin (UW). These data are then managed and served to the IceCube Collaboration[2] by the UW staff, operating remotely. The summer crew is typically five to six members to complete more extended maintenance activities.

The Observatory includes a Deep Core Array (DCA) to detect low to medium energy neutrinos. A mid-scale research infrastructure award was issued in 2019 to upgrade the DCA with 700 new sensors that will measure the properties of tau neutrinos, the least understood fundamental particles discovered to date. As neutrinos travel through space, they change from one type to another—a quantum-mechanical process known as neutrino oscillation. The IceCube Upgrade will provide the first precision measurement of the number of tau neutrinos appearing due to these oscillations.

<u>Summary of COVID-19 Impacts</u>

During the COVID-19 pandemic, limitations on the number of personnel who could be deployed to Antarctica restricted the ICNO staffing primarily to two winter crew members, who were rotated during the Antarctic summer season. There were no additional summer crew in 2020 and only one in

[1] Neutrinos are now known to exist over a broad range of energies described in electron-volts, or eV; their energy range spans from well below 1 eV to 10 EeV (1 GeV = 10^9 eV; 1 TeV = 10^{12} eV; 1 PeV = 10^{15} eV, and 1 EeV = 10^{18} eV). Neutrinos with energies between 100 GeV and 100 TeV are referred to as medium range, and those over 100 TeV are referred to as high-energy neutrinos, which generally originate outside the Solar system.

[2] https://icecube.wisc.edu/collaboration/meet-the-collaboration/

2021 and 2022. The summer crew size for 2022/2023 season is yet to be determined. These crew size limitations have caused at least a three-year delay to the DCA upgrade project, which was originally targeted to start in the 2022-23 austral summer season. Options for initiating field work are being evaluated, and a new project baseline will be developed for consideration in FY 2022.

Meeting Intellectual Community Needs

More than 300 physicists from 52 institutions in 12 countries make up the IceCube Collaboration. Of these, about 130 are U.S. scientists supported by OPP and MPS Division of Physics (PHY). This international team is responsible for the ICNO scientific program, and many of the collaborators contributed to the design, construction, and now operation of the detector.

The ongoing DCA upgrade will extend ICNO's overall sensitivity to a lower energy range which will provide a bridge to studies at other neutrino observatories such as the Super-Kamiokande detector in Japan and other similar (much smaller than IceCube) detectors across the world. The DCA upgrade will also provide enhanced calibration capabilities to improve the pointing of neutrino events to astrophysical sources and improve the existing 10+ year data set.

Governance Structure and Partnerships

NSF Governance Structure

The ICNO facility is managed at NSF by an Integrated Project Team consisting of program directors and staff from OPP, MPS, BFA's Large Facilities Office, the Cooperative Support Branch in the Division of Acquisition and Contract Support, and others in BFA.

External Governance Structure

The ICNO facility is governed by the lead institution, UW-Madison, and its sub-awardee institutions: University of Maryland College Park, University of Delaware, Michigan State University, Pennsylvania State University, University of Alabama, and Lawrence Berkeley National Laboratory.

ICNO is managed by UW and includes a broad science collaboration, currently consisting of 54 institutions worldwide (North America - 30, Europe - 20, Asia and Pacific - 4) in 13 countries (Australia, Belgium, Canada, Denmark, Germany, Japan, New Zealand, South Korea, Sweden, Switzerland, the United Kingdom, and the United States).

Partnerships and Other Funding Sources

Full O&M in support of scientific research began in FY 2011. The associated costs are and will continue to be shared by the partner funding agencies—U.S. (NSF) and non-U.S.—roughly in proportion to the number of Ph.D. researchers involved in the Observatory's maintenance and operations (in 2020, this ratio was about 51perceent U.S. and 49 percent non-U.S.). The NSF support for O&M, research, and education and outreach is shared by OPP (lead) and PHY, as well as by other in-kind contributions from participating institutions.

The work in support of facility operations is performed by students, postdocs, and senior researchers, who are also participating in research using the data produced by ICNO.

Funding

Total Obligations for ICNO
(Dollars in Millions)

	FY 2021 Actual	FY 2022 (TBD)	FY 2023 Request	ESTIMATES[1] FY 2024	FY 2025	FY 2026	FY 2027	FY 2028
Operations and Maintenance (GEO)	$3.56	-	$3.83	$3.83	$3.83	$3.83	$3.83	$3.83
Operations and Maintenance (MPS)	3.53	-	3.83	3.83	3.83	3.83	3.83	3.83
TOTAL	**$7.08**	**-**	**$7.66**	**$7.66**	**$7.66**	**$7.66**	**$7.66**	**$7.66**

[1] Outyear estimates are for planning purposes only. The current cooperative agreement ends March 2026.

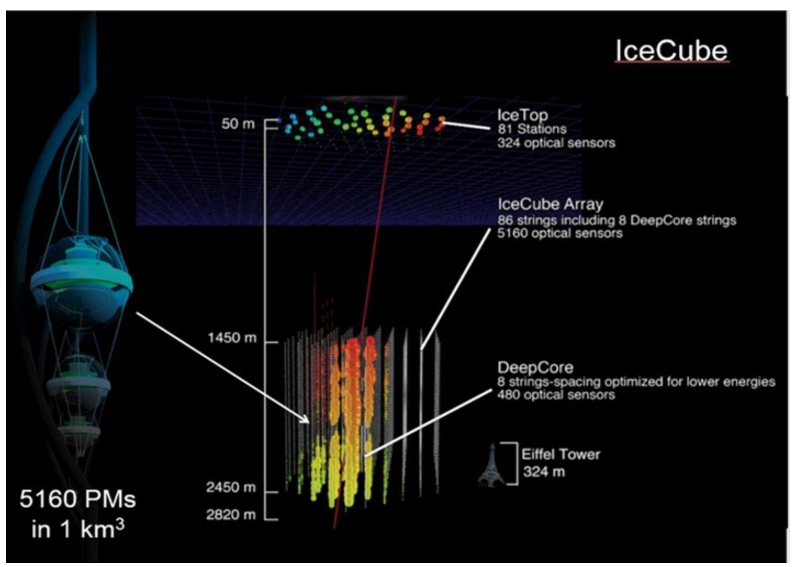
A new five-year cooperative agreement was awarded in 2021. The award increase reflects the higher cost to operate the larger number of strings in the sensor array.

Reviews

The previous cooperative agreement with UW required reviews of the ICNO O&M activities after the second and fourth project years. The mid-term O&M panel review was held (in person) in March 2019, and the second, NSF's staff "site visit" review was held virtually in March 2020. These reviews found that ICNO continues to be a very important element of the OPP and PHY programs, rated the O&M activities as excellent, and recommended continuing operation of ICNO for the remaining period of the previous cooperative agreement. However, with the severe COVID-19 pandemic impacts to the U.S. Antarctic Program operations, the IceCube Upgrade project was halted, and its re-baselining options were reviewed in March and November 2021. The most significant re-baselining review of the Upgrade project is now scheduled for April 2022.

Renewal/Recompetition/Termination

The ICNO full operation began in 2011 with an anticipated lifetime of the detector of 25-30 years. In anticipation of the ICNO O&M support cycle completion in 2021 and according to the LFO/SOP guidance, the O&M renewal proposal was solicited from the IceCube leadership. It was received in Summer 2020 and fully reviewed according to the NSF standard practice. In April 2021, the UW's ICNO O&M cooperative agreement was renewed for the next five years, 2021-2026. Currently there are no plans for divestment of this facility.



IceCube graphical diagram showing how neutrino's interaction within an ice sheet is developed and captured by detector strings. *Credit: IceCube/NSF photo*