

The IceCube-Gen2 Project

The IceCube-Gen2 Collaboration

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Since its completion in 2011, the IceCube Neutrino Observatory has opened a new window on the extreme Universe. Building on its success in multi-messenger astronomy and particle physics, the collaboration is now pursuing a major extension: the IceCube-Gen2 facility. IceCube-Gen2 will be a unique wide-band neutrino observatory (MeV–EeV) that employs two complementary detection technologies for neutrinos, optical and radio, in combination with a surface detector array for CR air showers to exploit a large range of scientific opportunities. This contribution provides an introduction to the project as well as a status report.

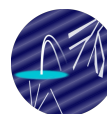
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1. Introduction

The beginning of high-energy neutrino astronomy dates back to the discovery in 2013 of a cosmic neutrino flux in the $10^{13}\text{eV} - 10^{16}\text{eV}$ energy range by IceCube, shortly after its construction was completed in 2011. In 2018, coincident observations of neutrinos and gamma-rays from the blazar TXS 0506+056 identified the first extra-galactic neutrino source [1, 2]. The next breakthrough followed in 2022 with the detection by IceCube of high-energy neutrinos from NGC 1068, one of the closest and brightest Active Galactic Nuclei [3]. Most recently, IceCube has provided evidence for high-energy neutrino emission from our galaxy, the Milky Way [4]. These breakthroughs, together with other recent advances in multi-messenger studies, map out a comprehensive path to study the extreme universe.

Furhermore, the IceCube detector has collected neutrino-induced events with energies from several GeV to beyond 10 PeV, opening new scientific avenues not just for astronomy but also for particle physics. Within the sample of high-energy events, IceCube has identified the first high-energy tau neutrinos [5, 6] and also identified the resonant production of the W boson in anti-electron neutrinos collisions, $\bar{\nu}_e + e^-$, at $E_\nu \approx M_W^2/2m_e = 6.3\text{ PeV}$ energies [7]. At lower energies, IceCube has accumulated more than one million atmospheric neutrinos that are being used to constrain the properties of neutrinos, ranging from measurements of neutrino interactions [8] and neutrino mixing parameters [9] to searches for sterile neutrinos [10–14] and signals of dark matter [15, 16].

To fully exploit these science opportunities an increase of sensitivity at both low and high energies is required. The extension of IceCube is planned in two steps, the IceCube Upgrade targeting lower energies and IceCube-Gen2 tailored to higher energies. The IceCube Upgrade project [17], which also serves as a technology pathfinder for IceCube-Gen2, is under construction with completion expected in 2026. When operational, it will lower the energy threshold of IceCube to a approximately 1 GeV, and significantly improve sensitivity to dark matter and neutrino oscillations.

With IceCube-Gen2, we propose a detector of sufficient volume to increase the rate of high-energy cosmic neutrino events and likely source discovery by an order of magnitude [18]. IceCube-Gen2 will be a unique wide-band neutrino observatory (MeV–EeV) that employs two complementary detection technologies for neutrinos, optical and radio, in combination with a surface detector array for cosmic ray air showers to exploit a large range of scientific opportunities. A complete overview of the project is provided in the Technical Design Report¹ (TDR).

In this contribution, we provide a status update of the IceCube-Gen2 project. Specific developments are further showcased in a number of IceCube-Gen2 related contributions at this conference, including the perspectives for EeV neutrino detections with the radio array (PoS-1045), cosmic-ray physics in the PeV to EeV energy range (PoS-387), sustainability and environmental impact considerations (PoS-1159), first prototypes for in-ice optical sensors (PoS-1072) and surface stations for IceCube-Gen2 (PoS-428) as well as machine learning tools used for improved reconstruction of neutrino (PoS-1201) and cosmic ray air shower events (PoS-309).

¹<https://icecube-gen2.wisc.edu/science/publications/tdr/>, Part I focuses on the science and conceptual design, Part II on the detector and performance, and Part III on the construction and logistic needs.

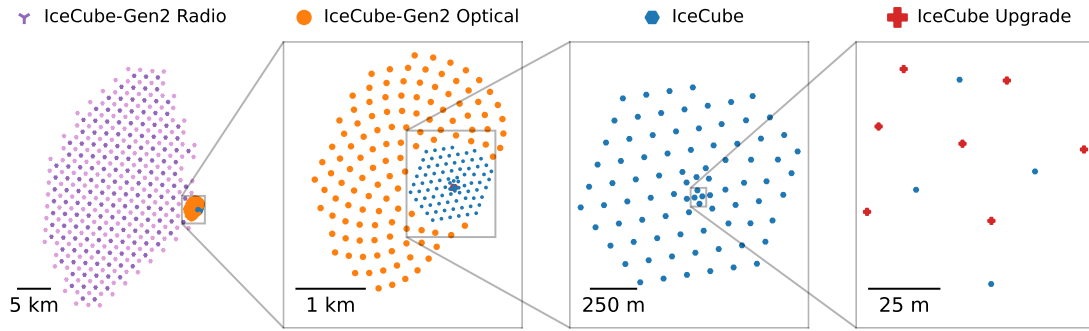


Figure 1: Top view of the envisioned IceCube-Gen2 Neutrino Observatory at the Amundsen-Scott South Pole Station, Antarctica. From left to right: The Radio Array consists of 361 stations with a spacing of 1.75 km. The optical high-energy array features 120 new strings (shown as orange points) that are spaced 240 m apart and instrumented with 100 newly developed optical modules each, over a vertical length of 1.25 km. The total instrumented volume of the optical detector in this design is 7.9 times larger than the current IceCube detector array (blue points). On the far right, the layout for the seven IceCube Upgrade strings relative to existing IceCube strings is shown.

2. IceCube-Gen2: The high-energy extension

IceCube-Gen2 [19] is a third-generation neutrino observatory at the South Pole that is currently in the design phase. It consists of three components: an *in-ice optical array* to expand the detection volume of IceCube for 10 TeV–1 PeV neutrinos, an *in-ice radio array* for the detection of ultra-high-energy neutrinos above 10 PeV, and a *hybrid surface array* for precision measurements of cosmic rays between 0.1 PeV and 100 EeV.

In-ice Optical Array: The in-ice optical array consists of 120 new strings spaced approximately 250 m apart (see Fig. 1), each instrumented with 100 multi-PMT digital optical modules [20] between 1325 and 2575 m below the surface of the ice sheet. The pressure housing of the optical module is narrower than that of the IceCube Upgrade module, requiring smaller holes, and thus less fuel for construction. The wider string spacing increases the effective area of the detector at the expense of a higher energy threshold. This is somewhat compensated by the multi-PMT optical module design, which allows for more photon collection area per module at a lower cost than large-area PMTs, while also delivering richer information that enables more precise event reconstruction.

Hybrid Surface Array: Each of the 120 new strings will be equipped with a surface station consisting of 8 scintillator detectors and 3 radio antennas. This design is based on the 32 surface enhancement stations to be deployed in the IceCube Upgrade. In addition, 20 more stations will be used to fill the gaps between strings in order to uniformly cover the surface with detectors. Small imaging Cherenkov telescopes placed near the center of the Surface Array will lower the energy threshold even further, allowing comparisons with direct measurements of cosmic rays. This design will increase exposure to cosmic rays by a factor 8 and extend the energy range to above 1 EeV.

In-ice Radio Array: The in-ice and hybrid surface arrays are complemented by an in-ice radio array that will increase the detection volume for neutrinos above 10 PeV by a factor ~ 100 . The radio

array consists of 361 stations spaced 1.24 km apart (see Fig. 1, left panel), building on experience gained from RNO-G [21], ARA [22] and ARIANNA [23]. Each of these stations is capable of triggering on and reconstructing neutrino events on its own; the station spacing was chosen such that 10% of events will be detected in at least two stations, maximizing the total effective volume while preserving a subset of events with significantly improved reconstruction quality. 197 of the stations have their antennas just below the surface, while the remaining 164 stations include antennas up to 150 m below the surface. The shallow antennas are simpler to construct and deploy, while the deep antennas can monitor a larger volume of ice, at the expense of deployment complexity, lower gain, and less directionality.

2.1 Science goals of IceCube-Gen2

IceCube-Gen2 is designed to observe the neutrino sky from TeV to EeV energies with a sensitivity to individual sources at least five times better than IceCube. It will collect at least ten times more neutrinos per year than IceCube and enable detailed studies of their distribution on the sky, energy spectrum, and flavor composition, as well as tests of new physics on cosmic baselines.

More specifically, the scientific goals can be grouped according to the following topics:

1. Resolving the high-energy neutrino sky from TeV to EeV energies: What are the sources of high-energy neutrinos detected by IceCube? The IceCube-Gen2 sensitivity will allow identifying realistic candidate source populations.
2. Understanding cosmic particle acceleration through multi-messenger observations: This involves studying particle acceleration and neutrino emission from a range of multi-messenger sources (e.g., AGN, GRBs, TDEs, SNe or kilonovae). Fig. 2 shows an example for the GRB sensitivity. Constraints on the physics within these sources will also come from measurements of the spectrum and flavor composition of the astrophysical neutrino flux.
3. Revealing the sources and propagation of the highest energy particles in the Milky Way and the Universe: This includes studying Galactic and extragalactic cosmic ray sources and their neutrino emission, cosmic ray interactions in the interstellar medium, the properties of cosmic rays in the galactic-extragalactic transition region above 100 PeV, as well as the propagation of extragalactic cosmic rays through the measurement of cosmogenic neutrinos.
4. Probing fundamental physics with high-energy neutrinos and cosmic rays: This entails studying hadronic interactions in the PeV domain, measuring neutrino cross sections at energies beyond the reach of terrestrial particle accelerators (see e.g. Fig. 3), searching for new physics from neutrino flavor mixing over cosmic baselines (see e.g. Fig. 4), and searching for heavy dark matter particles, monopoles and other particles predicted by SUSY or theories with extra dimensions.

A full review of the science capabilities of IceCube-Gen2 is beyond the scope of this document and we are referring to the Technical Design Report (Part I) for a detailed overview.

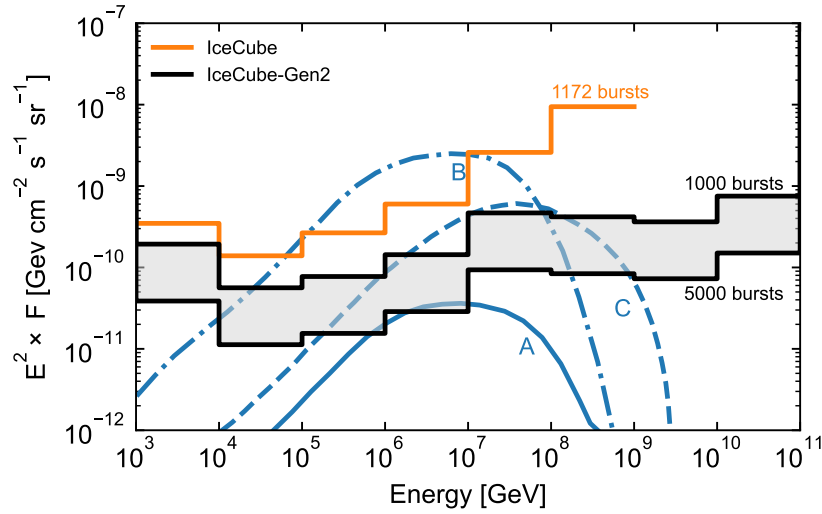


Figure 2: Upper limits from IceCube (rescaled to one energy bin per decade from [24]) and sensitivity of IceCube-Gen2 to the diffuse neutrino flux from GRB. Also shown are three scenarios from [25] in which GRBs produce the UHE cosmic rays (see also [26–29]). The figure also illustrates the large range in energies that Gen2 is sensitive to.

2.2 Readiness and timeline

The IceCube Upgrade, essential to test new sensor and drill technology relevant to IceCube-Gen2, is fully funded and will be deployed into the ice during the winter season 2025/26.

IceCube-Gen2 is still in the planning phase. Currently, the project has passed the conceptual design stage, as documented in the detailed Technical Design Report. IceCube-Gen2 can draw on the model of IceCube, a project of very similar (inflation-corrected) cost as IceCube-Gen2 that was delivered on-time and on-budget. Key components of the IceCube-Gen2 facility, such as the optical sensor and the hot water drill exist as fully functional prototypes as part of the IceCube Upgrade. The final design phase will allow us to incorporate the experience from the IceCube Upgrade and other on-going developments.

The construction schedule estimate spans 10 years and is based on the IceCube experience with drilling and installing optical strings, on IceTop regarding the installation of the surface detector, and from the RNO-G experience with drilling and installing radio stations.

IceCube, IceCube Upgrade and IceCube-Gen2 are international interdisciplinary flagship projects with extensive science cases in both multi-messenger astrophysics and particle physics. Over 400 scientists from 63 institutions in 15 countries work together to run IceCube and make the new extensions a reality.

The interdisciplinary character of the science of IceCube-Gen2 is underlined by the top rankings it received in the two most important project prioritization panels in the US, the Decadal Survey on Astronomy and Astrophysics 2020², which considered planned projects in astrophysics, as well as in the Particle Physics Project Prioritization Panel (P5)³ which evaluates particle physics projects.

²<https://www.nationalacademies.org/our-work>

³<https://www.usparticlephysics.org/2023-p5-report/>

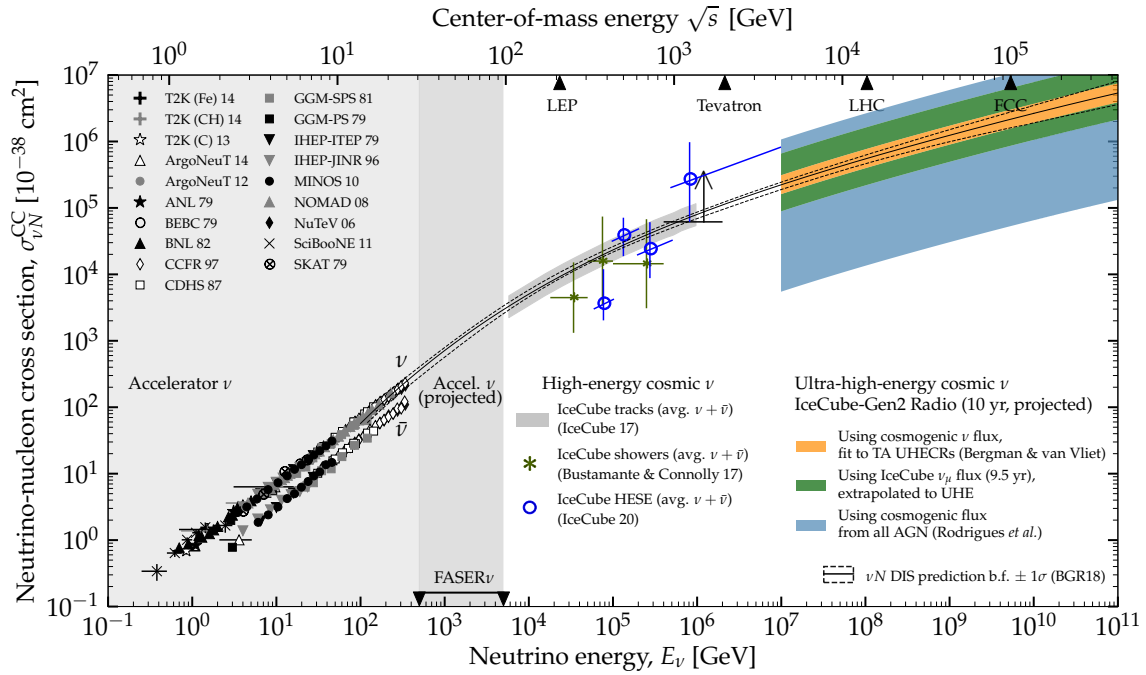


Figure 3: Neutrino-nucleon cross section measurements, compared to the deep-inelastic-scattering (DIS) cross section prediction from [30] (BGR18). The forecasts at ultra-high energies are for the radio component of IceCube-Gen2 only, and for three different assumptions of the UHE neutrino flux. For each choice of flux, the cross-section sensitivity forecast accounts generously for the uncertain normalization of the flux prediction. The assumed resolution in shower energy is 10% and the resolution in zenith angle is 2°. Figure adapted from [31].

In Europe, IceCube-Gen2 is on the roadmap of the Astroparticle Physics European Consortium (APPEC)⁴ and in Germany, IceCube-Gen2 has been a part of Helmholtz roadmap process since 2022. In both Sweden (as research infrastructure of national interest) and Belgium, IceCube-Gen2 has received positive funding to advance the project to the next stage of maturity. Similarly, the Japanese ministry of research (MEXT) continues to support development towards IceCube-Gen2, having funded the first critical prototype of the optical sensors.

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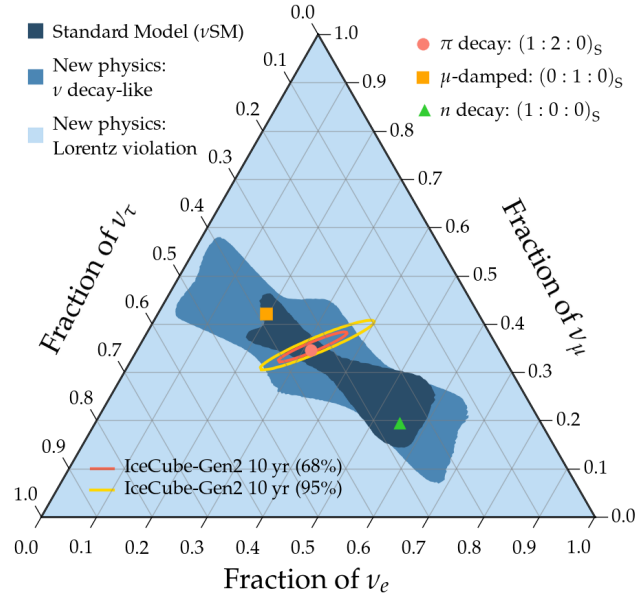


Figure 4: Flavor composition at Earth of high-energy cosmic neutrinos, indicating the “theoretically palatable” [32, 33] regions accessible with standard oscillations only (including 3σ uncertainties in the mixing parameters), and with new physics similar to neutrino decay and Lorentz-invariance violation [34, 35]. The colored contours indicate the expected constraints from IceCube-Gen2, if the source flavor ratio is $(\nu_e : \nu_\mu : \nu_\tau) = (1 : 2 : 0)$ and assuming standard neutrino oscillations.

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