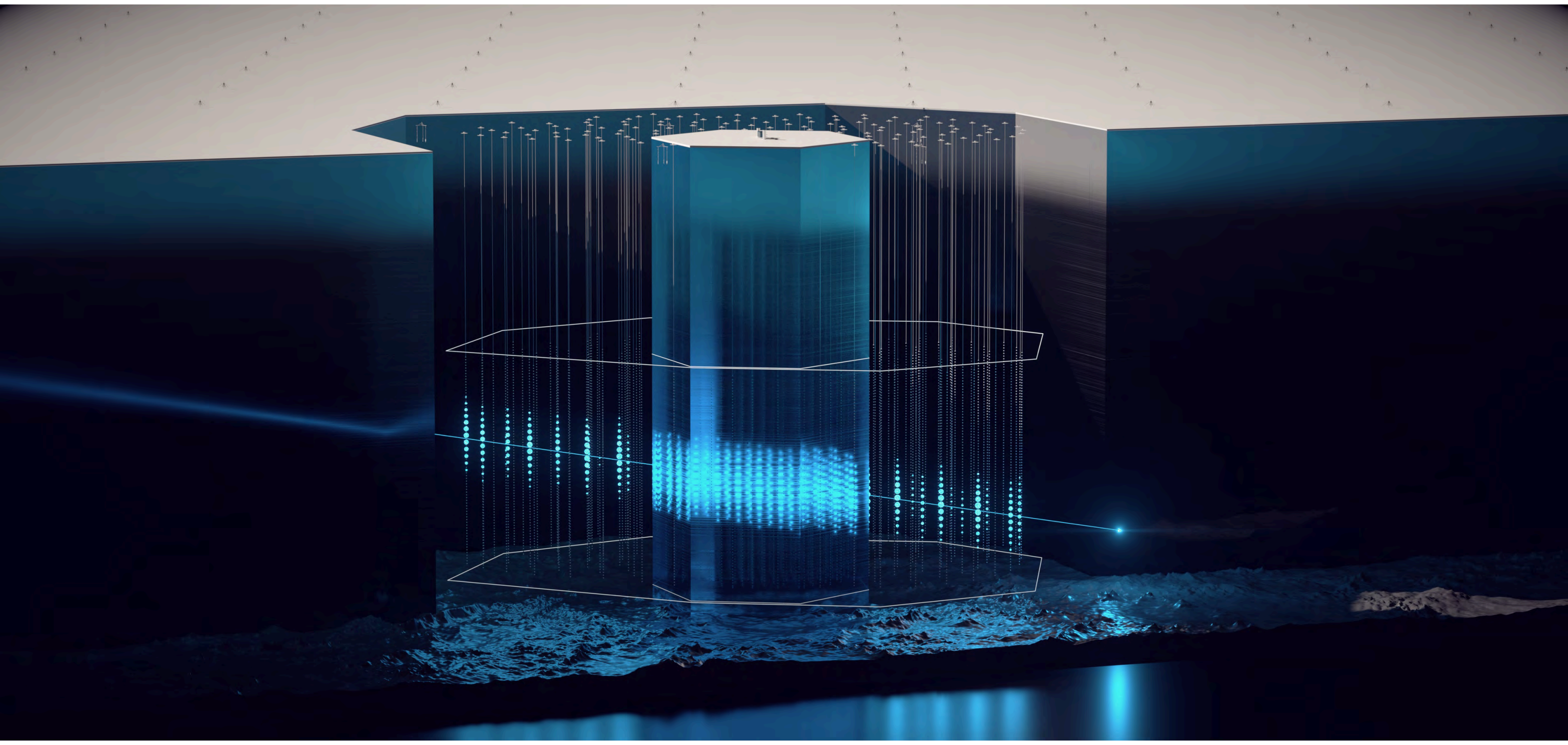
INPUT TO THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS
2026 UPDATE



Expanding the neutrino facility at the South Pole: IceCube-Upgrade and IceCube-Gen2

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Since its completion in 2011, the IceCube Neutrino Observatory has opened a new window to the extreme Universe. Building on its success in multi-messenger astronomy and particle physics, the collaboration is pursuing two major extensions: the IceCube Upgrade, a low-energy addition under construction to enhance studies of neutrino properties and dark matter; and IceCube-Gen2, which is optimized for high energies and which will advance neutrino astronomy from discovery to precision science. European institutions play a key role in both international projects.

I Introduction and Scientific context

With the first detection of high-energy neutrinos of extraterrestrial origin (1; 2) the IceCube Neutrino Observatory opened a new window to some of the most extreme regions of our universe. Neutrinos interact only weakly with matter and therefore escape dense astrophysical environments that are opaque to electromagnetic radiation. In addition, at PeV (10^{15} eV) energies, space becomes opaque to electromagnetic radiation even for galactic distance scales due to the scattering of high-energy photons (γ-rays) on the cosmic microwave background and extragalactic background light. This leaves neutrinos as unique messengers to probe the most extreme particle accelerators in the cosmos - the sources of the ultra-high-energy cosmic rays (CR). There, CRs with energies of more than 10^{20} eV are produced, which is 10^7 times higher than the particle energy reached in the most powerful terrestrial particle accelerators.

CRs produce high-energy neutrinos through the interaction with ambient matter or radiation fields, either in the sources or during propagation in the interstellar and intergalactic medium. Unlike the charged CRs, neutrinos are not deflected by magnetic fields on the way to the Earth, but point back to their source, thus resolving the long-standing question of CR origin(s).

The start of high-energy neutrino astronomy might best be associated with the first discovery of a cosmic neutrino flux in the 10^{13}eV –10^{16} 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 presented evidence of the first extra-galactic neutrino source (3; 4). The next breakthrough followed in 2022 with IceCube's detection of high-energy neutrinos from NGC 1068, one of the closest and brightest Active Galactic Nuclei (5). Most recently, it has provided evidence for high-energy neutrinos emission from our galaxy, the Milky Way (6).

These breakthroughs, combined with other recent advances in multi-messenger studies, point to a comprehensive path to study the extreme universe. In this document, we focus however on the potential of astrophysical neutrinos as a probe of physics beyond the Standard Model of particle physics (7).

IceCube instruments a gigaton of the very deep and clean South Pole ice. After initial deployment, the failure rate of sensors is currently less than 0.1% per decade, with an average uptime of the detector of 99%. The 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 (8; 9) and also identified the resonant production of the W boson in anti-electron neutrinos collisions, $\bar{\nu}_e + e^- \to W^-$, at $E_\nu \approx M_W^2/2m_e$ = 6.3 PeV energies (10). At lower energies, IceCube has accumulated more than one million atmospheric neutrinos that are being used to constrain the properties of neutrinos, ranging from highly competitive measurements of neutrino mixing parameters (11) to searches for sterile neutrinos (12; 13; 14; 15; 16; 17; 18). It has also produced world leading constraints on dark matter annihilation or decay (19; 20), dark matter-nucleon scattering (21; 22), and dark matter-neutrino interactions (23)

In addition, IceCube's low detector noise make it a valuable asset to search for and detect the MeV energy neutrinos from a Galactic supernova, thus providing a >99% uptime alert system for what is expected to be a once-in-a-lifetime event. If detected, it would lead to e.g. the determination of the mass ordering (24). Finally, the IceTop array, located on the surface, detects particles from cosmic-ray-induced air showers when they first hit Earth, while the high-energy muon components are detected by the in-ice IceCube detector. This combination allows for unique measurements of cosmic-ray spectrum and composition with great accuracy.

The extension of IceCube is in full swing. The IceCube Upgrade project (25) provides a low-energy in-fill array. Construction has started with completion expected in 2026. Once completed, it will lower the energy threshold of IceCube to a approximately 1 GeV, and significantly improve detection prospects for dark matter and neutrino physics. The IceCube Upgrade will also enable a precision calibration of the existing IceCube detector. With IceCube-Gen2, we propose a detector of sufficient volume to increase the rate of high-energy cosmic neutrino events and source discovery by an order of magnitude (26). 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. Meanwhile, the KM3NeT and GVD detectors under construction in the Mediterranean Sea and in Lake Baikal respectively, target the size of one cubic kilometer. They will complement IceCube-Gen2 in terms of sky coverage (27; 28). Elaborate multi-messenger studies that combine information from other observatories, ranging from γ-rays to radio and also including gravitational waves, continue to provide opportunities for more associations of high-energy neutrinos with their sources.

In this document, we provide a status update of the IceCube Upgrade and IceCube-Gen2 projects, as well as summarize their scientific opportunities, focusing only on those connected to particle physics.

II Objectives related to particle physics

II.I IceCube Upgrade: The low-energy extension

The IceCube Upgrade increases the sensitivity to low-energy neutrinos in IceCube. The enhanced multipixel optical module technologies of the Upgrade (see Section III) deployed in a much denser configuration than the current IceCube detector lead to a higher neutrino detection efficiency, more than 5-fold below 10 GeV, and improved event reconstruction. We take advantage of these improvements to make precision measurements of the atmospheric neutrino spectra from approximately 1-100 GeV and search for new physics phenomena.

Cosmic-ray air showers in the Earth's atmosphere produce pions and kaons that decay to provide an abundant source of ν_μ and ν_e (and antineutrinos) with a broad energy spectrum. At low energies, ν_τ production in these air-showers is suppressed by many orders of magnitude due to the mass of charmed mesons from which they would be produced. The composition of the atmospheric neutrino flux is well-known with uncertainties on the $\nu_\mu + \overline{\nu}_\mu$ flux and flavor ratio ν_μ/ν_e ratio at the level of 1-2% below 100 GeV (29).

As atmospheric neutrinos travel through the Earth, the flavor composition of the beam is modulated through neutrino oscillations as a function of *L/E*, where *L* is the distance traveled and *E* is the neutrino energy (30; 31). The dominant effect observable with the IceCube is the oscillation of $\nu_\mu \to \nu_\tau$, where the amplitude and frequency of the oscillation pattern is driven by the atmospheric neutrino oscillation parameters θ_{23} and Δm^2_{32}, respectively (11). By measuring the disappearance of muon neutrinos as a function of *L/E*, the IceCube Upgrade will measure these parameters with unprecedented precision as shown in fig. 1 (left). The expected sensitivity is shown assuming three years of live time from the IceCube Upgrade (**IC93**) combined with twelve years of live time already available from IceCube (**IC86**). A significant improvement is expected compared to the current experimental landscape.

In addition, the IceCube Upgrade will be able to study the ν_τ flux arising from oscillated atmospheric neutrinos and thereby probe the unitarity of three-flavor neutrino oscillations and the ν_τ cross-section (32; 33). The Upgrade is expected to collect over 3×10^3 ν_τ interactions every year, providing a rich statistical sample for such studies. Figure 1 (right) shows the uncertainty on the ν_τ normalization as a function of live time with the IceCube Upgrade. A precision of 5% is expected after only three years of operation.

Another strength of the IceCube Upgrade is the capacity to determine the neutrino mass ordering (NMO). It remains unclear whether the ν_3 mass eigenstate is heavier or lighter than the ν_1 mass eigenstate. These two scenarios are referred to as the normal and inverted mass ordering, respectively, and whichever scenario is realized in nature has profound implications for neutrino oscillation measurements, neutrinoless double-beta decay, and cosmology (34; 35). The sensitivity to the NMO leverages the matter effects felt by ν_e and $\overline{\nu}_e$ as they traverse the variable density profile of the Earth (36). Figure 2 (left) shows the sensitivity of the Upgrade to the determine the NMO as a function of detector live time for the scenario where the normal ordering is realized in nature. A significance of up to 3σ can be achieved after four years of data taking, depending on the true value of θ_{23}. The sensitivity can be markedly enhanced by combining Upgrade data with measurements of other experiments such as JUNO (37) or with other atmospheric neutrino experiments (38).

Compared to contemporary long-baseline accelerator neutrino experiments, the IceCube Upgrade measurements employ neutrinos with much higher energy that have traveled over significantly longer baselines through matter. By probing a different region of the *L/E* phase space, the IceCube Upgrade

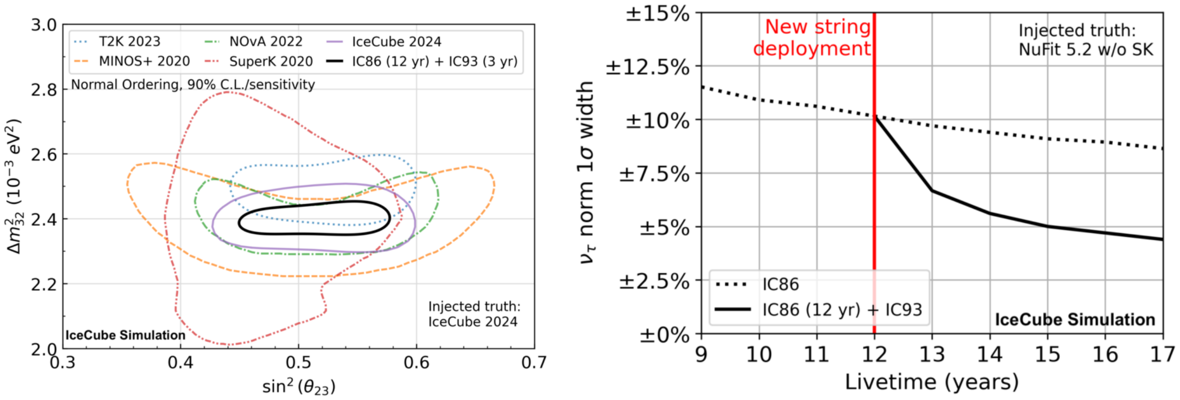

Figure 1: ***Precision measurements of neutrino oscillations.*** *Left*: Sensitivity to the atmospheric neutrino oscillation parameters for the IceCube Upgrade (black, solid line) compared to current leading experiments. *Right*: Constraint on the tau-neutrino normalization as a function of exposure, which tests unitarity of 3-flavour neutrino oscillations and neutrino interactions.

measurements are subject to distinct flux and cross-section modeling uncertainties, offering complementary insights to long-baseline accelerator measurements of neutrino oscillations with different systematic uncertainties (39).

In addition, many Beyond Standard Model (BSM) theories that propose new interactions or particles in the neutrino sector predict effects that grow stronger with energy (40; 41). Even subtle effects can accumulate to produce significant modifications to the atmospheric neutrino oscillation pattern due to the extremely large distances these neutrinos travel through the Earth, including its dense core. IceCube has already conducted searches for such BSM effects, such as sterile neutrinos (12; 17; 42), non-standard interactions (43), and Planck-scale sensitivity to space-time quantum fluctuations (44) and Lorentz invariance violation effects (45), using atmospheric neutrinos. The IceCube Upgrade will significantly enhance the sensitivity of these searches and therefore provide an excellent probe of many BSM theories.

The nature of dark matter is one of the biggest problems in fundamental physics. In many theories beyond the Standard Model, dark matter candidates appear at the electro-weak scale (46), making searches in IceCube, sub-TeV sample very important. One way in which we can look for dark matter is by searching for an excess of event in the direction of the Sun (47; 48; 49). This is a unique gateway to neutrinos, since gamma-rays or other particles produced in the annihilation or decay of dark matter cannot leave the dense solar core. Neutrinos produced from dark matter annihilation in the Sun are able to exit the dense solar medium essentially unperturbed so long as their energy is below 200 GeV (50). The production rate of neutrinos is thereby determined by the capture rate of dark matter and its annihilation channels (51). This implies that measurements by IceCube constrain the dark matter proton scattering cross section, thus being complementary probes to direct dark matter searches. Figure 2 (right) shows the expected sensitivity of the IceCube Upgrade to this cross section. Beyond models of dark matter, searches for neutrinos from the Sun in this mass range are also motivated by neutrino mass-generation models (52), where the coupling of dark matter produces neutrino masses. The IceCube Upgrade will probe this exciting parameter space (53).

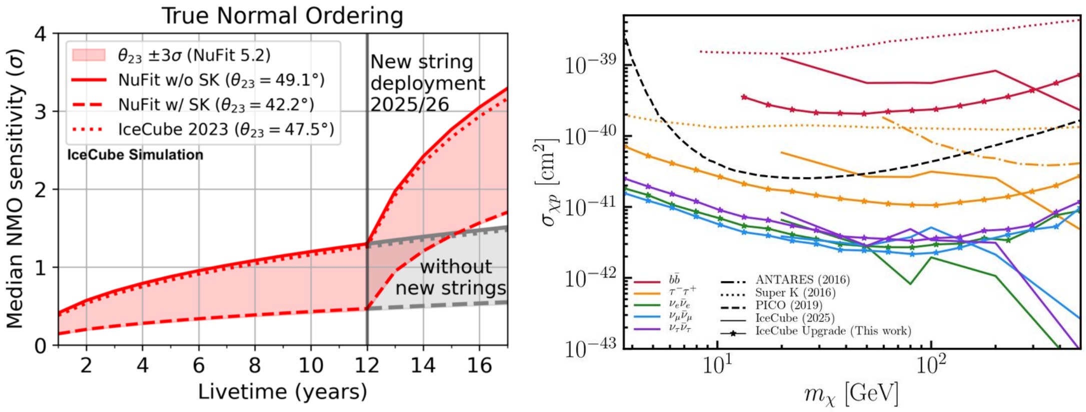

Figure 2: ***Precision particle physics measurements.*** *Left*: Determination of the neutrino mass ordering as a function of exposure assuming normal ordering is true. *Right*: Expected sensitivity to the dark matter proton cross section from solar neutrino measurements compared to other experiments.

II.II IceCube-Gen2: The high-energy extension

IceCube-Gen2 will have an order-of-magnitude larger in-ice volume instrumented with optical sensors as compared to IceCube, and also feature an in-ice radio component. This unique combination will increase the statistics of PeV-energy neutrinos ten-fold, and smoothly extend the detector's reach into the EeV energy range, where IceCube is simply too small. Thus, IceCube-Gen2 will have unparalleled sensitivity to high-energy particle and BSM physics involving neutrinos, which we outline below.

The prompt atmospheric neutrino component stemming from the decay of charm mesons (produced by cosmic-ray interactions in the atmosphere) has thus far eluded detection. Studies of neutrinos from charm meson decays at the Forward Physics Facility (FPF) at the LHC (56; 57) can be used to improve theoretical modeling of the prompt atmospheric fluxes. In turn, a measurement of the prompt neutrino flux may lead to a better understanding of the proton structure (58; 59; 60; 61; 62). IceCube-Gen2 will greatly improve the sensitivity to the prompt neutrino flux, which is the dominant background to astrophysical neutrinos in the energy range 100 TeV$< E_\nu <$1 PeV.

The neutrino-nucleon cross section in the TeV–PeV range was measured for the first time using astrophysical and atmospheric neutrinos in (63; 64; 65) and found to agree with high-precision Standard Model predictions (66). Each year of data from IceCube-Gen2 will yield roughly one order of magnitude more statistics than used in (63), enabling the study of the cross-section with significantly higher precision and to energies beyond 10 PeV. It would also probe the QCD parton distribution functions (PDFs) at large momentum transfers Q^2 ($Q^2 \approx M_W^2$) and Bjorken-x values down to $\sim 10^{-4}$ (66; 54; 67). This data will complement results from the FASER$_\nu$ experiment at CERN, which will use forward neutrinos from LHC interactions to measure neutrino cross-sections at energies centered around 1 TeV (68). Future measurements in the EeV range could probe BSM modifications of the cross section at center-of-momentum energies of up to 100 TeV (69; 70; 71; 72; 73; 74; 75; 76; 77; 78; 79) and test the structure of nucleons with a sensitivity comparable with colliders (80; 81; 82).

For a given production scenario, the neutrino flavor ratio observable at Earth are expected to be confined to small regions in parameter space (see Figure 4), even after accounting for uncertainties in the neutrino oscillation parameters (83; 84). Thus, precise measurement of the astrophysical neutrino flavor ratio can provide insights into the production mechanism in extreme high-energy environments and coherent interactions between neutrinos and matter (87). However, mixing remains untested at high energies and over cosmological propagation baselines (88). Even small BSM effects could affect flavor mixing, vastly expanding the allowed region of flavor ratios at the Earth and making the flavor ratio measurement a very sensitive probe of BSM physics (89; 90; 91; 92; 93; 83; 85; 94; 95; 86; 96; 97; 98; 99). In Figure 4 this is shown for two scenarios (ν-decay (83) and Lorentz invariance violation (85; 86)). The figure also shows the expected constraints from IceCube-Gen2 on the flavor composition of cosmic neutrinos, assuming standard neutrino oscillations and a 1:2:0 production ratio at the sources. IceCube-Gen2 will allow substantially more sensitive searches for, and constraints on, BSM effects

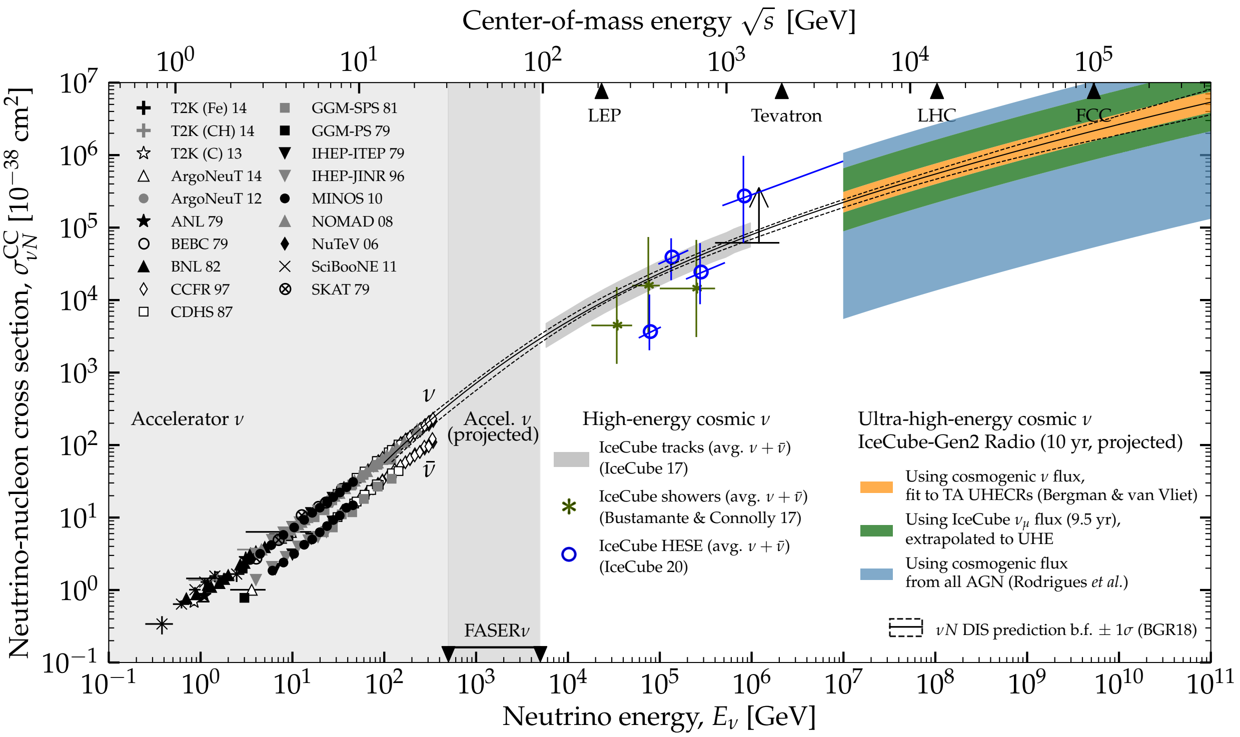

Figure 3: Neutrino-nucleon cross section measurements, compared to deep-inelastic-scattering (DIS) cross section prediction from (54) (BGR18). The forecasts at ultra-high energies are for the radio component of IceCube-Gen2 only, and for three different assumptions of the UHE neutrino flux. For each 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 (55).

using the flavor ratio than the current generation of neutrino telescopes, including searches for a potential energy dependence of mixing (93; 83). The observation of non-zero neutrino masses opens the possibility of neutrino decay. Due to their extremely long travel distances astrophysical neutrinos can place strong constraints on decay scenarios (100; 101; 102; 103; 104; 105). Neutrino decay imprints a specific correlation between the energy distribution of the events and the flavor composition (94), making it a very predictive signature of new physics. The IceCube-Gen2 flavor composition measurement will be competitive with and complementary to terrestrial high-precision oscillation experiments searching for sterile neutrinos (98). Finally, the extremely long-baselines of astrophysical neutrinos makes them sensitive the Dirac-nature of neutrino masses. If neutrinos are quasi-Dirac particles, then oscillations from left to right-handed neutrino are observable at extremely long baselines (106). The study of high-energy astrophysical neutrinos can thus provide a unique insight into the nature of neutrino masses (107; 108; 109; 110; 111; 112; 113; 94; 114; 115; 116; 117). Specifically, the observation of disappearance of neutrinos from astrophysical neutrino sources (115) or oscillatory features in the diffuse spectra (118) would provide a smoking-gun signature of the quasi-Dirac-nature of neutrinos. Thus, IceCube-Gen2 provides a unique opportunity to discovery the nature of neutrino masses.

In IceCube-Gen2, new signatures of heavy sterile neutrino decay become accessible. An active, light neutrino might scatter off a target nucleon producing a heavy, sterile neutrino (119). These heavy neutrinos can be detected by observing displaced vertexes in the detector instrumented volume (120) for bright-enough events. Another signature is di-muon production from the decay of the heavy neutrinos, when they are either produced from meson decay in the atmosphere (121) or when they are produced through neutrino upscattering. Double muon tracks are also formed in neutrino trident interactions (122; 123; 124), though typically at rates below di-muons from neutrino-nucleon production. This very rare process is mediated by the W, Z, or a virtual photon in the Standard Model, but could additionally be mediated by a new vector or scalar boson (125).

Lorentz invariance violation (LIV) (126) can be detected in a neutrino telescope as an anomalous

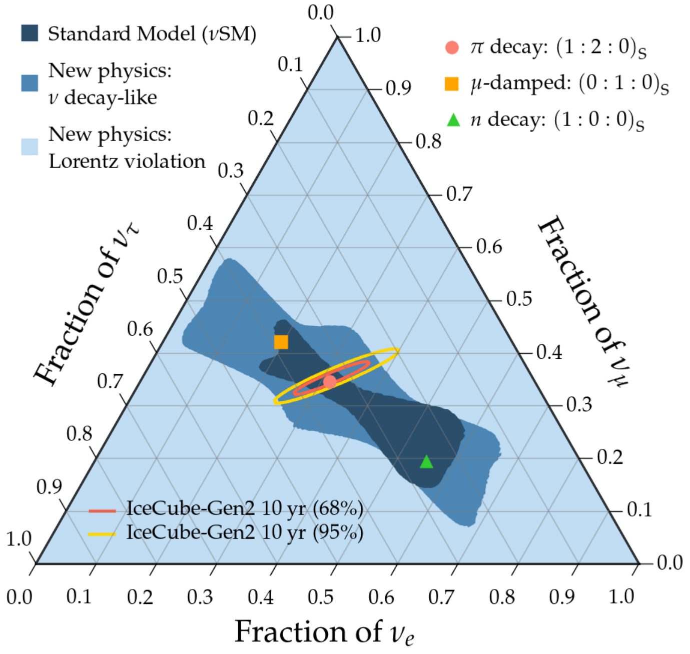

Figure 4: Flavor composition at Earth of high-energy cosmic neutrinos, indicating the "theoretically palatable" (83; 84) regions accessible with standard oscillations only (including 3σ uncertainties in the mixing parameters), and with new physics similar to neutrino decay and Lorentz-invariance violation (85; 86). 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.

oscillation effect (127; 128; 129; 130; 131; 132; 133; 134; 135; 136; 137; 138). Currently, the strongest constraints on LIV with neutrinos come from IceCube (139). Further, neutrino flares in cosmic sources, with additional assumptions of the mechanism of neutrino emission, can be used as precise time-of-flight measurements, leading to strong constraints on LIV as obtained in the neutrino candidate source TXS 0506+056 (140; 141). The higher statistics and expected discovery of more high-energy neutrino sources with IceCube-Gen2 will significantly improve those bounds.

Dark matter searches with IceCube have focused on *Weakly Interacting Massive Particles* (WIMPs), by looking for neutrinos from annihilations (or decays) of dark matter captured in the Sun, Earth, or in the Galactic halo or galaxy clusters (142). Neutrinos offer many advantages to search for annihilation or decays of heavy dark matter with masses beyond about 100 TeV (143; 144; 145): The neutrino interaction cross section increases with energy (66) keeping event rates predicted for heavy decaying dark matter constant as function of the particle mass. IceCube-Gen2 is expected to significantly improve upon the current strongest limits on the dark matter lifetime above 100 TeV at the level of 10^{28} s (146), obtained with IceCube's highest energy neutrinos. With the improved characterization of the astrophysical diffuse flux and observation of new neutrino sources, IceCube-Gen2 will improve sensitivity to dark portal scenarios (147). The dark sector could couple to the Standard Model either via kinetic mixing or neutrino mass mixing, leaving an imprint on the diffuse astrophysical neutrino spectrum (148), as well as on the expected attenuation from single neutrino sources (149). Further interesting BSM scenarios are coherent interactions between neutrinos and dark matter (148; 150; 151; 152; 153; 154; 155); neutrinos and dark energy (156); very-long-range $L_e - L_\mu$ and $L_e - L_\tau$ gauged interactions sourced by the universe's electron content (157; 158; 159; 97); and new interactions between high-energy cosmic neutrinos and low-energy relic neutrinos (160; 161; 162; 163; 164; 165; 149; 166).

IceCube-Gen2 will allow unique tests of BSM physics involving extra dimensions, leptoquarks or sphalerons (167; 168; 169; 170; 77; 171; 172). Searches for relativistic magnetic monopoles look for large, but roughly constant dE/dx, without large stochastic fluctuations (173).

The interaction of a high-energy CR with a nucleon in the atmosphere can take place at a much higher center-of-mass energy than that achievable in man-made accelerators, and the in-ice and sur-

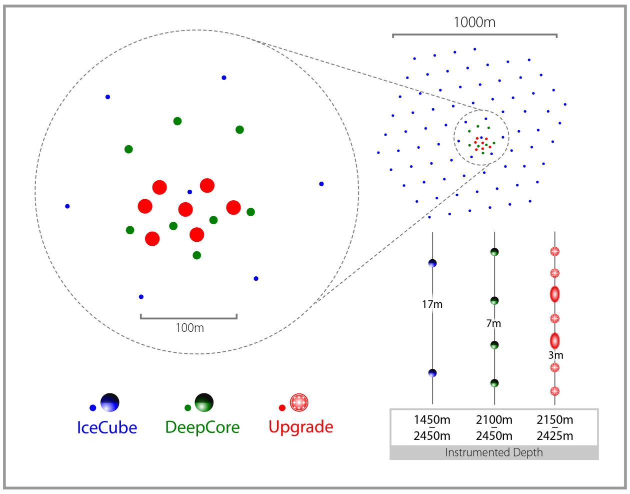

Figure 5: Top view of the IceCube Upgrade as it will be deployed in 2025-26. The locations of the 7 new strings are shown in red, while the blue (green) points show the locations of the existing IceCube (DeepCore) strings.

face arrays will provide an opportunity to study them in detail. For example, supersymmetric particles can be produced in pairs and, even if unstable, they can reach the depths of the detector. If charged, they would give rise to Cherenkov light as they traverse the array. The signature in IceCube-Gen2 would be two minimum ionizing, parallel, coincident tracks separated by a distance of over 100 meters (174).

By combining a large air-shower detector at the surface with a deep detector in the ice, IceCube and IceCube-Gen2 enables unique, high-precision measurements of cosmic rays (175). Ultra-high-energy air showers remain poorly understood, particularly regarding muon production and associated atmospheric neutrinos. Current hadronic interaction models predict fewer muons than observed, a discrepancy unexplained by standard physics (176). Competing hypotheses suggest differences in the energy evolution of GeV muons and varying GeV-to-TeV muon ratios, requiring more precise testing. IceCube's surface array, IceTop, combined with other experiments, indicates that this muon deficit may emerge at 10 PeV cosmic-ray energy. IceCube-Gen2 will extend measurements to several 100 PeV, overlapping with the Pierre Auger Observatory. By correlating GeV muons from the surface array with TeV muons detected in ice, we can refine hadronic interaction models via muon spectroscopy. Additionally, IceCube-Gen2 will uniquely probe PeV forward muon fluxes. The flux of leptons from prompt decays remains highly uncertain, dependent on mass composition and hadronic interactions at multi-PeV energies. These measurements will enhance understanding of prompt atmospheric neutrino production, reducing flux uncertainties at PeV scales and beyond. The measurements will be complementary to the studies at the proposed Forward Physics Facility (FPF) at CERN (56).

III Methodology - new detector components for low and high energies

IceCube Upgrade

The IceCube Upgrade consists of 7 densely-instrumented strings to be deployed as an infill to the existing IceCube detector in the austral summer of 2025-26. The aims of the Upgrade are twofold: first, to lower the energy threshold to below 10 GeV, and second, to provide a precision calibration of the existing IceCube detector.

The main IceCube Upgrade instrumentation consists of two new optical module types. The DEgg (177), developed and produced in Japan, contains two 10" PMTs, one upward-, one downward-facing, in a novel catenary pressure housing. Its effective isotropic photon collection area is approximately 1.5 times that of the current IceCube Digital Optical Module (DOM). The majority of the sensors are mDOMs (178), developed in Germany and produced in Germany and the US. These modules use 24 3" PMTs to achieve a total effective isotropic photon collection area approximately 2.2 times greater than that of

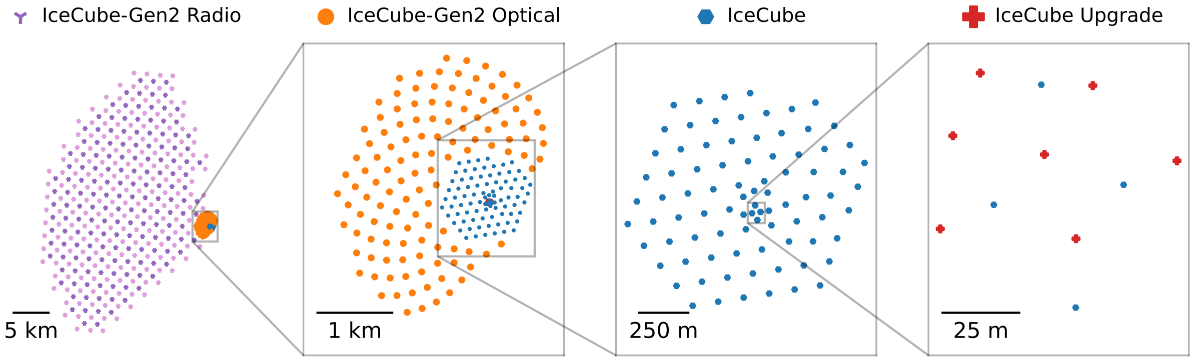

Figure 6: Top view of the envisioned IceCube-Gen2 Neutrino Observatory at the Amundsen-Scott South Pole Station, Antarctica. From left to right: The Radio Array consists of 361 stations with a spacing of 1.75 km. The optical high-energy array features 120 new strings (shown as orange points) that are 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.

the IceCube DOM. While the different module types have different on-board readout electronics, they use a common module to communicate with the unified Icecube/IceCube-Upgrade data acquisition system. The Upgrade strings are spaced $\sim$ 20 m apart, inside the existing DeepCore low-energy subdetector (see Fig. 5). The optical modules on each string are spaced 2.4 m apart, and only within the depth region with the most transparent ice, in order to minimize the energy threshold and maximize reconstruction quality for a fixed number of sensors.

In addition to the main instrumentation, the IceCube Upgrade strings host prototype optical modules for IceCube-Gen2 as well as standalone calibration devices that will enable precise in-situ measurements of the ice optical properties as well as the response of the existing IceCube detector. These include, for example, the Precision Calibration Optical Module (POCAM) (179), an absolutely calibrated, isotropic light source for determining the absolute sensitivity of the optical modules, as well as pencil-beam devices for precisely characterizing how photons scatter in the ice

IceCube-Gen2

IceCube-Gen2 (180) 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. 6), each instrumented with 100 multi-PMT digital optical modules (181) 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. 6, left panel), building on experience gained from RNO-G (182), ARA (183) and ARIANNA (184). 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.

IV Readiness and timeline

The IceCube Upgrade is fully funded. The development of the instrumentation, as well as most of the pre-assembly work in the North has been completed. Preparation of the South Pole site has been ongoing since the winter season 2023/24. The full detector will be deployed into the ice during the winter season 2025/26, with the commissioning following in spring 2026.

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[1] (TDR). 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. It can be completed as early as 2027/28, at which time the project can move into the construction phase.

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 outstanding 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 2020[2], which prioritizes planned projects in astrophysics, as well as in the Particle Physics Project Prioritization Panel (P5)[3] which evaluates particle physics projects. 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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[1] `https://icecube-gen2.wisc.edu/science/publications/tdr/`, Part II focuses on the detector

[2] `https://www.nationalacademies.org/our-work`

[3] `https://www.usparticlephysics.org/2023-p5-report/`

[4] `https://www.appec.org/roadmap/`

Endorsers

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