Snowmass2021 - Letter of Interest

IceCube-Gen2: The Window to the Extreme Universe

Thematic Areas:

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
■ (NF6) Neutrino cross sections
■ (NF08/TF11) Theory of neutrino physics
■ (NF10) Neutrino detectors
■ (CF7) Cosmic Probes of Fundamental Physics

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Abstract:

The discovery of cosmic neutrinos, announced by IceCube in 2013, has opened a new window to the high energy Universe. The observations made to date have already brought us one step closer to answering key questions, such as: what are the sources in the PeV sky and how do they drive particle acceleration; where are cosmic rays of extreme energies produced and on which paths do they propagate through the universe; and are there signatures of new physics at TeV–EeV energies? IceCube-Gen2, a next generation neutrino observatory, is designed to address these questions. In conjunction with continued progress in multi-messenger astrophysics, IceCube-Gen2 promises to elevate the cosmic neutrino field from the discovery realm to the precision era and to a survey of the sources in the neutrino sky. IceCube-Gen2 will enhance the existing IceCube detector at the South Pole. It will increase the annual rate of observed cosmic neutrinos by an order of magnitude compared to IceCube, and will be able to detect sources five times fainter than its predecessor. Furthermore, through the addition of a radio array, IceCube-Gen2 will extend the energy range by several orders of magnitude compared to IceCube. The design of IceCube-Gen2 greatly profits from the available experience gained through IceCube and from additional improvements in technology. Despite the large increase in sensitivity, the projected budget for IceCube Gen2 is comparable to that of IceCube.

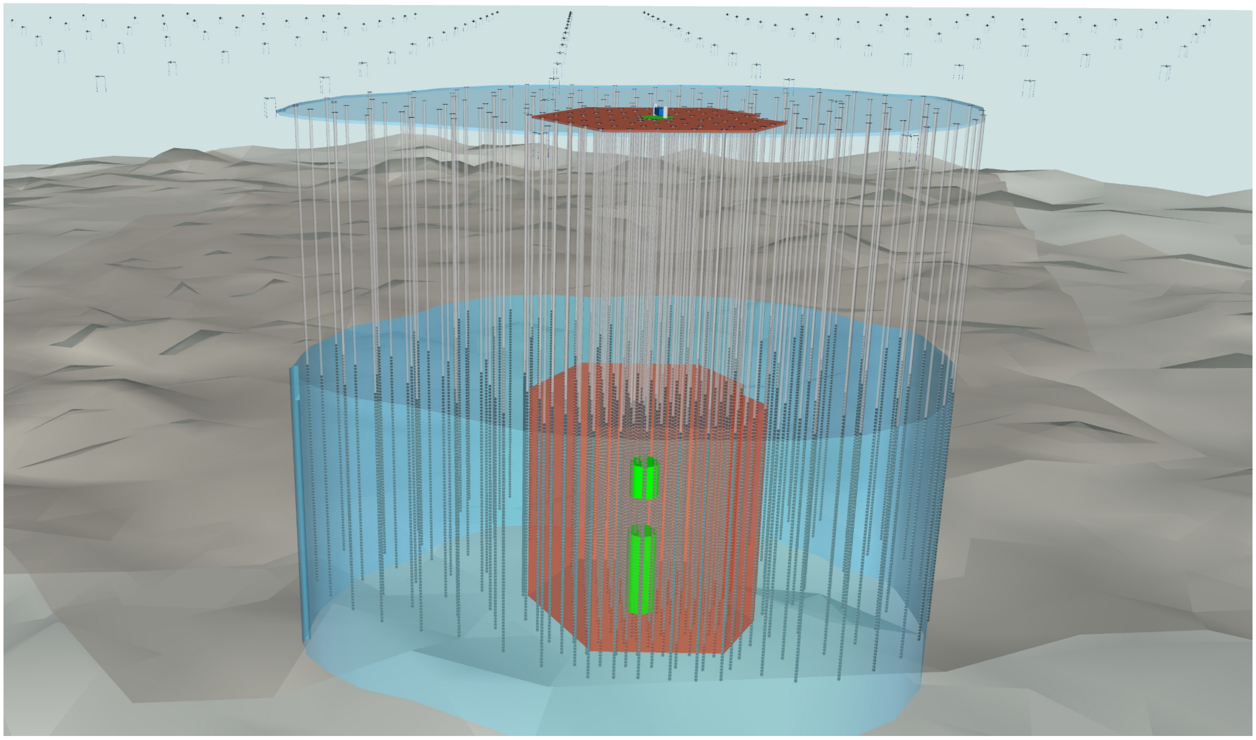

Figure 1: Schematic drawing of the IceCube-Gen2 facility including the optical array (blue shaded region) that contains IceCube (red shaded region) and a densely instrumented core installed in the IceCube Upgrade (green shaded region). A surface array covers the footprint of the optical array. The stations of the giant radio array deployed at shallow depths and the surface extend all the way to the horizon in this perspective.

The observation of electromagnetic radiation from radio to γ-ray wavelengths has provided a wealth of information about the universe. However, at PeV (10^{15} eV) energies and above, most of the universe is impenetrable to photons. New messengers, namely cosmic neutrinos, are needed to explore the most extreme environments of the universe where black holes, neutron stars, and stellar explosions transform gravitational energy into non-thermal cosmic rays. These energetic particles have millions of times higher energies than those produced in the most powerful particle accelerators on Earth. As neutrinos can escape from regions otherwise opaque to radiation, they allow an unique view deep into exploding stars and the vicinity of the event horizons of black holes.

The discovery of cosmic neutrinos with IceCube in 2013 [1;2], has opened a new window on the universe. In 2018, IceCube has found the first evidence for cosmic particle acceleration in a Blazar, an active galactic nucleus with a powerful jet pointing at Earth [3;4]. Yet, ultimately, its sensitivity is too limited to firmly detect even bright neutrino sources in larger numbers, or to detect populations of less luminous sources. Furthermore, the sources of the bulk of the cosmic neutrino flux observed by IceCube remain unresolved. The list of candidates is long; transients such as supernovae (SNe), neutron star mergers, or low luminosity Gamma Ray Bursts (GRBs) — or steady sources such as Active Galactic Nuclei (AGN) or starburst galaxies — are all very well motivated. In addition, IceCube detects neutrino induced events with up to 10^{16} eV in energy, corresponding to the highest energy leptons ever observed and opening new scientific avenues not just for astronomy but also for probing physics beyond the Standard Model of particle physics (see, e.g., [5;6]).

Here we present the next-generation instrument IceCube-Gen2, which will sharpen our understanding of the processes and environments that govern the universe at the highest energies, as well as probe fundamental physics through observations of high-energy neutrinos on cosmic baselines. IceCube-Gen2 will be a unique wide-band neutrino observatory (MeV–EeV) (see Figure 1 for a schematic overview) that employs two complementary detection technologies for neutrinos — optical and radio, in combination with a surface detector array for CR air showers — to exploit the enormous scientific opportunities (for a comprehensive overview, see [7]).

IceCube-Gen2 is designed to: 1) resolve the high-energy neutrino sky from TeV to EeV energies, 2) investigate cosmic particle acceleration through multi-messenger observations, 3) reveal the sources and propagation of the highest energy particles in the universe, 4) probe fundamental physics with high-energy neutrinos. With IceCube-Gen2 we propose a detector of sufficient volume to increase the neutrino collection rate by an order of magnitude, and a sensitivity to point sources at least a factor five better than that of IceCube. This is possible by optimizing the new deep, optical array for higher energies, where the astrophysical flux is more prominent, and by adding a radio-detection component to Gen2, with sensitivity at energies above 10^{16} eV.

The proposed Gen2 instrument conceptually utilizes the same approach as IceCube, where the Antarctic ice is the target and detection medium, but with more advanced detector technology. The optimization of the deep optical detector array to higher energy implies in particular a larger string spacing of 240 m compared to 125 m in IceCube. A total of 4 times as much photodetection area instrumented over 8 times the volume provides the basis for the required increase in sensitivity. IceCube-Gen2 will leverage advances in a number of additional key areas. The IceCube Upgrade project[8], consisting of 7 additional strings to be deployed in 2022, is currently underway and has been a key platform for developmental activities towards the Gen2 preliminary design. This includes the reference design of the Gen2 optical sensors that provides significantly higher effective area, an omni-directional sensitivity, and directional information obtained from multiple PMT "pixels" per sensor. The sensors, to be deployed in deep holes to a depth of up to 2600 m, are also being designed for smaller diameter, thus requiring narrower boreholes and therefore reducing the anticipated amount of fuel needed for drilling deployment. The existing IceCube detector has been operating with extremely high stability (uptime of 99.7% and only 0.05% loss of sensors in the past five years) and will remain a fully functional component of the completed IceCube-Gen2 observatory.

The second measure is the introduction of a large radio detector array to complement the optical detector at high energies. The radio component will allow to measure the extension of the neutrino flux observed by IceCube to higher energies and explore the origin of the flux. For generic E^{-2} source spectra, the sensitivity of the radio array at EeV energies will match that of the optical array at PeV energies. While the radio component is a small fraction of the instrumentation cost, it is the system that makes IceCube-Gen2 a true wide band observatory.

The gain in sensitivity by IceCube-Gen2 allows detection of any of the main candidate source classes considered to explain the diffuse flux observed by IceCube. It allows for the observation of high-energy cosmic neutrinos with an order of magnitude higher statistics over an increased energy range, enabling a range of studies, e.g. from neutrino flavor physics and astronomy, to that of neutrino cross-sections. In addition, its high up-time and low detector noise make it a valuable asset to search for and detect the MeV energy neutrinos from a Galactic supernova, thus providing a unique alert system for what is expected to be a once-in-a-lifetime event.

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[9;10], and will achieve astrophysical neutrino detection rates comparable to the present IceCube. With its optimization towards high energies, IceCube-Gen2 will play an essential role in shaping the new era of multi-messenger astronomy, fundamentally advancing our knowledge of the high-energy universe. This challenging mission can be fully addressed only through the combined measurements of neutrino, electromagnetic, and gravitational wave emission, a prospect that will be further improved in the coming years through a new generation of observatories across the multi-messenger spectrum. In concert, they will provide enormous opportunities for detecting and studying the sources of high-energy neutrinos.

The discovery of the cosmic neutrino flux and the first astrophysical source of high energy neutrinos is the culmination of a 30 year effort. The envisaged IceCube-Gen2 observatory is the premiere next-generation instrument to realize world-leading sensitivity for astrophysical, high-energy neutrinos. Given the established existence of a strong cosmic neutrino signature, IceCube-Gen2 presents a timely opportunity to build on the investments to move this rapidly emerging field from the era of discovery to precision neutrino astrophysics and astronomy. Construction of IceCube-Gen2 will take 8 years and cost about $350M. The goal is to have IceCube-Gen2 fully operational by 2033.

References

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Cross-references to related Snowmass 2021 LOIs:

Frontiers in Neutrino Physics

- Monitoring Near-Galactic Core Collapse Supernovae with IceCube and IceCube-Gen2 — Segev BenZvi et al.
- BSM Neutrino Oscillation Searches with 1-100 TeV Atmospheric Neutrinos at IceCube — B. Jones et al.
- New physics with astrophysical neutrino flavour — T. Katori et al.
- Neutrino cross-sections and interaction physics — S. Klein et al.
- Neutrino oscillations with IceCube-DeepCore and the IceCube Upgrade — T. Stuttard et al.

Cosmic Frontier

- Observing the High-Energy Sun — C. Arguelles et al.
- The IceCube Neutrino Observatory — D. Grant et al.
- Highest Energy Galactic Cosmic Rays — A. Haungs et al.
- Searches for exotic particles with the IceCube Neutrino Observatory — A. Pollmann et al.
- Letter of Interest in Dark Matter Physics with the IceCube Neutrino Observatory — C. Rott et al.
- Radio Detection of Cosmic Rays — F. Schroeder et al.
- IceCube and Cosmic Rays — D. Seckel et al.
- Studies of the Muon Excess in Cosmic Ray Air Showers — D. Soldin et al.

- Opportunities for multi-messenger observations with neutrinos and tests of fundamental physics over the next decade — I. Taboada et al.
- Cosmic neutrino probes of fundamental physics — M. Bustamante et al.

Computational Frontier

- IceCube and IceCube-Gen2: Quantum computing applications — C. Arguelles et al.
- IceCube and IceCube-Gen2 Long Term Preservation — P. Desiati et al.
- IceCube and IceCube-Gen2 Simulations — J. C. Diaz Velez et al.
- IceCube and IceCube-Gen2 Machine Learning — C. Kopper et al.
- IceCube and IceCube-Gen2 User Analysis Computing — K. Meagher et al.
- IceCube and IceCube-Gen2 Storage and Processing Resources — B. Riedel et al.
- IceCube and IceCube-Gen2 Event Management Service — B. Riedel et al.
- IceCube and IceCube-Gen2 Experimental Algorithm Parallelization — A. Olivas et al.

Instrumentation Frontier

- IceCube-Gen2: the next generation wide band neutrino observatory — A. Karle et al.