PROCEEDINGS OF SCIENCE

Exploring the High Energy Universe with IceCube

Jim Madsen, for the IceCube Collaboration[a,*]

[a] *Wisconsin IceCube Particle Astrophysics Center*
University of Wisconsin-Madison
Suite 500
222 West Washington
Madison, WI 53703 USA

E-mail: jim.madsen@icecube.wisc.edu

The IceCube Neutrino Observatory, running in its present configuration since 2011, has realized the dream of capturing neutrinos to explore the high energy universe. A cubic kilometer of South Pole ice at depths between 1.5 and 2.5 kilometers has been transformed into a versatile instrument capable of seeing neutrinos with energies spanning more than 10 orders of magnitude. The annual data set includes roughly 10^{11} cosmic ray events, 10^5 neutrinos created by cosmic ray interactions in the Earth's atmosphere, and hundreds of neutrinos at the highest energies (>100 TeV) from astrophysical sources. The search for the origins of astrophysical neutrinos is challenging both because of the low number of neutrinos that interact and the large background signal. Improvements in event selection and reconstruction have enabled the first steady-state high energy neutrino sources to be identified—NGC1068 and the Milky Way Galaxy. An overview of these recent results together with a survey of the IceCube science scope will be provided along with a summary of the low-energy extension IceCube Upgrade underway, and of IceCube-Gen2, a high energy extension in the planning stage.

High Energy Astrophysics in Southern Africa 2023 (HEASA 2023)
September 5 - 9, 2023
Mtunzini, KwaZulu-Natal, South Africa

*Speaker

PoS(HEASA2023)005

1. Introduction

The high energy universe is both a promising and formidable frontier for exploration. More than six decades ago, the first extremely high energy cosmic ray was detected providing proof that nature was capable of producing particles with energies greater than 10^{20} eV [1]. Subsequent studies established that the cosmic ray flux can be approximated by a power law over from 10^{10} to 10^{20} eV but the origins and acceleration mechanism(s) remain a mystery for the most part. Except at the very highest energies, the direction determined from the final stages of their journey through the detector does not point back to their source because the path of the cosmic ray is altered when magnetic fields are encountered. Fortunately other particles, produced when cosmic rays interact with matter and radiation, can also provide information.

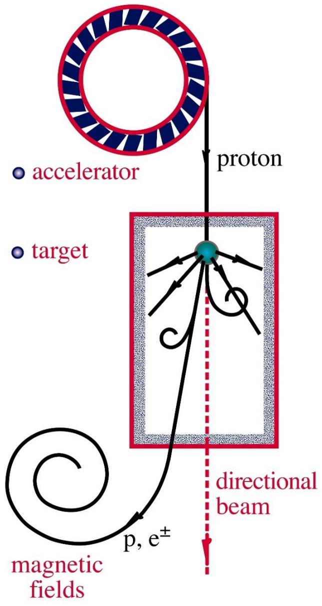


Figure 1: High energy particles, protons and heavier nuclei, accelerated at astrophysical sources produce secondary particles if they interact with a target (radiation or matter). The neutral particles (photons, neutrinos, neutrons) provide a directional beam.

The entire production, interaction and propagation process is represented in Fig. 1. Some of the cosmic rays with interact with radiation or dust (target) that could be within the same environment where the acceleration took place, or somewhere along the cosmic journey. The interaction produces secondary mesons; the charged mesons decay producing neutrinos and neutral mesons decay producing gamma rays. For example, neutral pions decay as $\pi^0 \longrightarrow \gamma + \gamma$ and create a flux of high-energy gamma rays; the charged pions decay into three high-energy neutrinos (ν) and anti-neutrinos ($\bar{\nu}$) via the decay chain $\pi^+ \longrightarrow \mu^+ + \nu_\mu$ followed by $\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$, and the charge-conjugate process. The gamma rays are are not deflected by magnetic fields but have a decreasing reach starting at TeV energies and above, with a minimum range of about the distance to the Galactic center at ~PeV energies.

Neutrinos are unique high energy cosmic messengers, traveling nearly unhindered and maintaining information about their origins. The trade off for these desirable properties is the need for a cubic-kilometer scale detector to capture sufficient number of neutrinos to do astronomy. In the next section, the design and operation of the South Pole IceCube Neutrino Observatory is presented along with an overview of its signals, identified astrophysical sources, and the science scope. This is followed by a section describing the IceCube enhancements. The Upgrade project underway will more densely instrument the central portion of the existing array to improve the low-energy performance, better characterize the optical ice properties to improve signal fidelity, and serve as a test bed for sensor research and development. IceCube-Gen2 is a proposed high-energy extension that would instrument about 8 times more ice to better resolve exiting sources and detect fainter ones. The last section provides a summary.

2. IceCube Neutrino Observatory

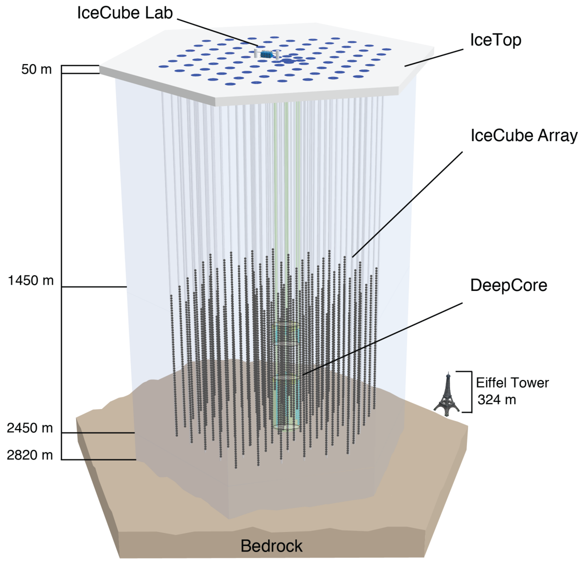


Figure 2: The IceCube Neutrino Observatory.

The IceCube Neutrino Observatory transformed a cubic kilometer of ice into a multipurpose particle detector [2]. Together with a square kilometer surface array, IceTop, it records light from high energy particles produced by cosmic ray and neutrino interactions. The in-ice component consists of 86 strings of light sensors that were deployed in water-filled holes, 60 cm in diameter, bored 2450 m deep. Seventy-eight of the strings are arranged on a hexagonal grid with horizontal spacing of 125 m with 60 light sensors 17m apart starting 1450 m below the surface. In the center of the array there are 8 strings also with 60 light sensors that are more closely-spaced vertically and along the each string to create a smaller volume with increased sensitivity at lower energies. After deployment, the water refroze, locking the light sensors in place. The ice serves as both the detector medium and support structure for the facility. The seven year construction phase was completed in the austral 2010-11 summer as shown in Fig. 2.

The light sensors are 10" diameter photo multiplier tubes (PMTs) enclosed in the lower half of a glass hemispherical pressure vessel. The upper half of the sphere contains electronics power the PMT and digitize the pulses, a clock with ~ns accuracy, and LEDs that can be flashed to measure the optical properties of the ice. Light sensors, operating independently, send a time-stamped digitized pulse when they detect a signal to computers on the surface. A variety of trigger conditions are checked to see if a sufficient number of light sensors report a signal within a sliding time window, typically around 20 μs wide.

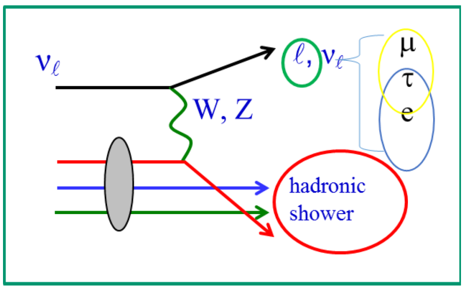


Figure 3: Charged- (W-boson) and neutral-current (Z-boson) neutrino interactions.

Icecube events can be sorted into three categories—tracks, cascades and double pulses. Tracks are roughly cylindrical, and produced by muons whose range increases with energy. Cascades are roughly spherical in shape with a diameter that increases with energy. Double pulses are produced by tau neutrino charged-current interactions—the first pulse corresponding to the hadronic cascade coinciding with the production of the tau, and the second pulse to the tau decay. Since the separation between production and decay is ~50m/PeV, the two pulses are only resolvable at very high energies. Only charged-current muon neutrino interactions can produce tracks. Electron and low energy tau charged-current interactions and all neutral-current interactions produce cascades. A summary of these neutrino interactions is shown in Fig. 3.

2.1 Signals

The main IceCube data channels are shown graphically in Fig. 4. Down-going muons (atmospheric), produced when cosmic rays interact with the Earth's atmosphere in the southern hemisphere, are recorded at a rate of ~2600/second or ~ 10^{11}/year, and are the dominate signal. Up-going muons that originate from the northern hemisphere range out before reaching IceCube. Cosmic ray interactions also produce neutrinos (atmospheric) which are seen at a rate of ~12/hour or ~ 10^5/year. High energy neutrinos that originate from extreme environments outside solar system (astrophysical) are identified at a rate of 10s per month or 100s per year. All data channels in combination allow us to address a wide scope of scientific questions as described in the next section.

2.2 Science Scope

IceCube data enables a broad and growing scope of science including astrophysics, fundamental physics, neutrinos physics, Earth sciences, beyond Standard Model searches and more. At the lower end of the energy range, the in-ice array functions as supernova detector that would see the ~MeV neutrinos produced by a galactic supernova as an increase in the noise rate in the light sensors. This would give valuable insight on neutrino production but no directional information. The threshold for resolving individual neutrino events that provide energy, direction, and some flavor information is ~ 10 GeV. IceTop can reconstruct individual air showers from cosmic ray interactions starting at a few hundred TeV. The upper end of the energy range of events detected so far, which is limited by the flux and the size of the arrays, is ~ 10 PeV for neutrinos and ~ EeV for cosmic ray showers.

Three examples that demonstrate the capabilities of IceCube are the detection of high energy tau neutrinos, identifying a neutrino event associated with the Glashow resonance, and measurements of neutrino properties using oscillation analyses. A clear signature for tau neutrino interactions are the observation of two pulses of light, either at the same light sensor, or above PeV energies,

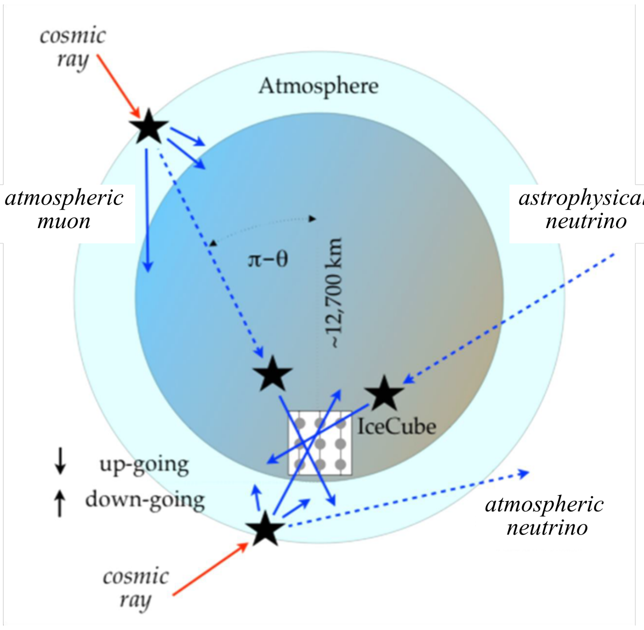


Figure 4: The geometry (not to scale) for describing IceCube signals; up and down are defined relative to the South Pole. Cosmic rays (red lines) interacting (stars) in the Earth's atmosphere produce muons (solid blue lines) and neutrinos (dashed blue lines). Neutrinos also originate from high energy galactic and extragalactic sources (astrophysical). Muons from charged-current muon neutrino interactions (stars) are shown; hadronic showers from all flavors of neutral-current interactions and electron and tau charged-current interactions are not shown.

at adjacent sensors as well. The first pulse is from the hadronic shower from the charged-current interaction and the second from the decay of the tau lepton. The timing and size (# of photons detected) of the pulses depend on the location of the light sensor(s) relative to the interaction and decay, and the initial energy of the tau neutrino. IceCube identified 2 likely tau events out of the sample of 60 "high energy starting events" sample [3]. This translates into the presence of an astrophysical flux of tau neutrinos at a level of 2.8σ and an overall detected flavor ratio consistent with the (1,1,1) for electron, muon, and tau neutrinos predicted by most source production models after accounting for oscillations that occur during propagation.

The Glashow resonance is a novel channel for astrophysical neutrinos [4]. An IceCube event was observed with a measured shower energy of 6.05 ± 0.72 PeV (the predicted resonance peaks at 6.3 PeV) and a light pattern consistent with the production of muons from the hadronic decay of a W^- boson [5]. Detection of a neutrino event consistent with the Glashow resonance confirms the existence of astrophysical electron anti-neutrinos, provides a test of the IceCube energy calibration, and definitive flavor identification. The ability to identify both the flavor and charge (neutrino or antineutrino) for an individual event increases the discrimination power for understanding the production mechanisms for astrophysical neutrinos.

One promising way to probe the properties of the neutrinos is to measure the rate at which neutrinos change flavor between production and detection. The probability of oscillation depends on the length and type of material traversed, neutrino energy, and initial flavor. In contrast to reactor or accelerator oscillation programs, where the neutrino production energy, flavor, and path are well defined, and the beam timing can be controlled, the production state of the IceCube atmospheric neutrino beam is not known for each individual event but can be modeled. Since production occurs when a cosmic ray interacts in the Earth's atmosphere, the path length and the material traversed can be inferred from reconstructed zenith angle for each event. The energy and final flavor and their uncertainties are also determined from the amount and timing of the collected light respectively.

The more than 10^5 atmospheric neutrino events collected annually provide a unique data set to explore neutrino properties. The wide span of baselines probes a higher energy energy range than possible with accelerator and reactor experiments, complimenting their results. IceCube has competitive measurements of the 3-flavor properties (Δm^2 and θ_{23}, see Fig. 5) and world-leading

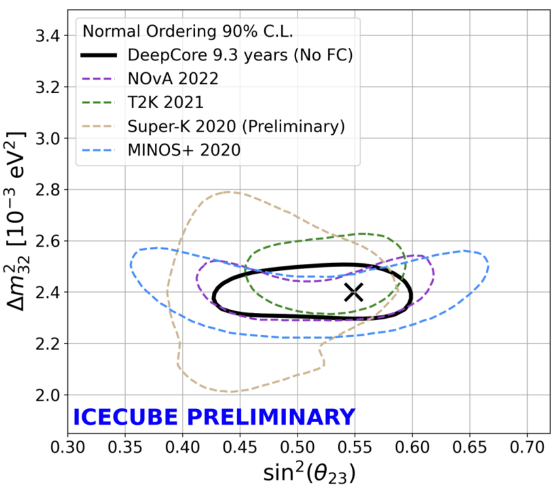


Figure 5: The IceCube DeepCore 90% confidence level contour (black) calculated assuming normal mass ordering and best-fit parameters of the oscillation parameters indicated by the black x compared to results from the listed experiments (details in [6]).

results for searches for sterile neutrinos and other beyond Standard Model physics. Promising progress has also been made on the possibility to use this data channel for Earth tomography [7]. At higher energies, where oscillation effects become negligible, the attenuation of the neutrino beam as a function of energy and path length can be used to study the neutrino interaction cross section [8].

2.3 Sources

The search for astrophysical neutrino sources is one of the prime science IceCube drivers. It is motivated by the likely connection between high energy cosmic rays and neutrinos as shown in Fig. 6. The first step in the search is to find discriminators to identify likely astrophysical neutrinos from the overwhelming background of atmospheric neutrinos and, in the southern hemisphere, atmospheric muons. Above ∼100 TeV, it becomes increasingly likely that the pions created in cosmic ray collisions interact before they can decay so the flux of atmospheric neutrinos is strongly suppressed. Down-going neutrino events where the first light is detected inside the array (starting events) have no accompanying muon, which indicates the neutrino astrophysical origin. Sky maps can be explored independently or by comparisons to catalogs of hypothesized sources to look for hot spots or significant associations. Neutrinos that arrive in time and spatial coincidence with flaring or other time dependent observations from astronomical telescopes are also likely astrophysical in origin.

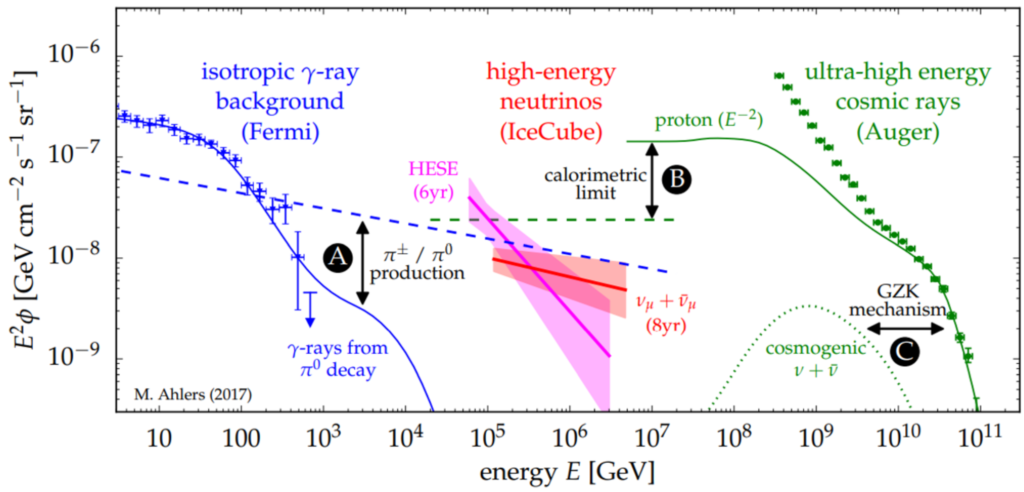


Figure 6: The energy densities in gamma rays, neutrinos and cosmic rays are similar [9]. A: Calculated neutrino flux (dashed blue line) from Fermi data fit (solid blue line) assuming both are from cosmic ray interactions. B: Calculated neutrino limit (dashed green line) from Auger data fit (solid green line) assuming all cosmic rays convert to neutrinos. C: Calculated cosmogenic flux (dotted line) from Auger data fit assuming protons to the highest energy.

2.3.1 Flaring Source: Blazar TXS 0506+056

The IceCube data stream is monitored in real time to identify highly likely astrophysical neutrinos. On 9/22/2017, a track event with a reconstructed neutrino energy of 290 TeV was recorded and an alert was posted within 43 seconds. A wide-range of telescopes, from radio to gamma ray, subsequently identified a flaring blazar coincident with the reconstructed angular direction of the IceCube high-energy neutrino event [10]. The chance coincidence of detecting a neutrino in the direction of such a blazar is estimated to be 3σ. An archival search of IceCube data revealed a ~ 150 day period with a 3.5σ neutrino flare over background expectation centered around December 2014 [11]. The measured flux during this period is consistent with an $E^{-(2.1\pm0.3)}$ power law.

2.3.2 Steady State Source: Active Galaxy NGC1068

IceCube searches for steady state sources by looking for hot spots in neutrino sky maps. To identify a source, a statistically significant excess number of IceCube neutrino events must be detected. The backgrounds are atmospheric neutrinos and misreconstructed atmospheric muons.

A persistent hot spot consistent with the location of active galaxy NGC1068 that increased in significance with time but never exceeded the 3σ level, appeared in IceCube sky maps constructed from muon neutrino events. Reprocessing of a uniform data set from 13 May 2011 (when IceCube was fully configured) to 29 May 2020 with improved event reconstruction and uncertainty estimates identified 79^{+22}_{-20} neutrinos at tera–electron volt energies, with a global significance of 4.2σ, consistent with the location of NGC1068 as shown in Fig. 7 (Left) [12]. The measured flux during this period has an $E^{-(3.2\pm0.2)}$ energy dependence, Fig. 7 (Right).

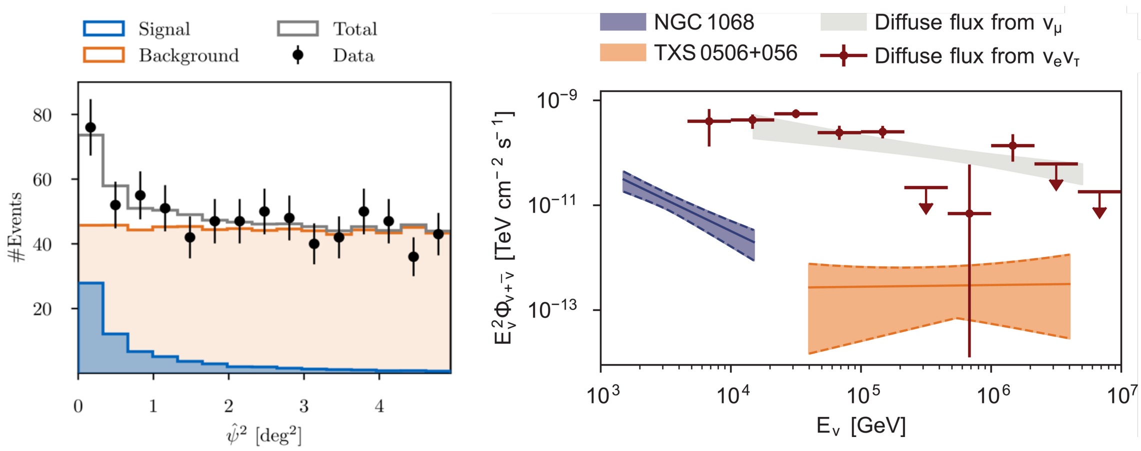


Figure 7: Left: The spatial distribution of neutrino events in the vicinity of NGC1068. **Right:** The energy dependence of the measured neutrino flux for NGC1068 and TXS0506+056 compared to the diffuse flux determined from track(ν_μ) and cascade events ($\nu_e\nu_\tau$).

2.3.3 Extended Steady State Source: Milky Way Galaxy

It is perhaps counter intuitive that the closest potential neutrino source, our own Milky Way Galaxy, would not be the first to be identified. The galactic plane is presently not a statistically significant source using only the muon neutrino events that found NGC1068. Two key advances using machine learning made it possible to resolve the Galactic plane. The first increased the data sample by a factor of more than 20 compared to the previous IceCube cascade Galactic plane analysis. The second produced significantly better angular resolution for reconstructed cascades. These resulted in evidence for neutrino emission from the Galactic plane with a global significance

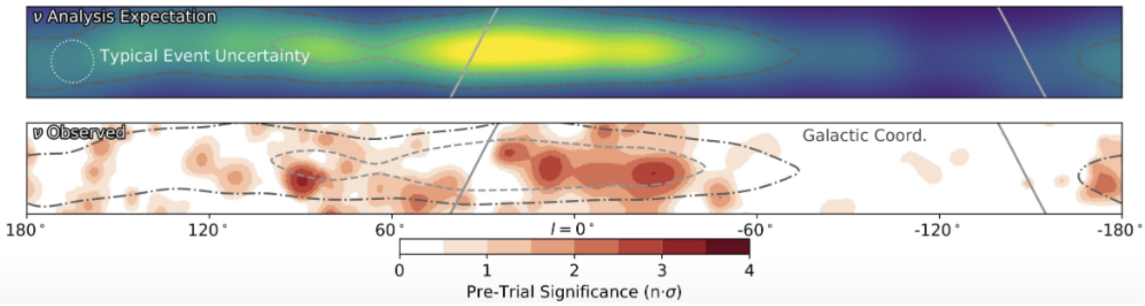


Figure 8: The predicted IceCube neutrino signal (upper panel) and the pre-trial significance of the all-sky search for point-like sources using a cascade neutrino event sample [13].

of 4.5σ, the first time the Galactic plane has been imaged (Fig. 8) without using photons [13]. The calculated flux shown in Fig. 9 is ∼10% or less than measured diffuse neutrino flux. A relatively poor source of high energy neutrinos, the "neutrino luminosity of the Milky Way is one-to-two orders of magnitude lower than the average of distant galaxies" [14]

3. IceCube Enhancements

Improvements in event reconstruction, higher yield event selections and other efforts to optimize IceCube analyses are ultimately limited by the physical hardware deployed in the ice. The spacing of the light sensors together with the optical properties of the ice determines the low energy threshold. The event rate is proportional to the overall volume of instrumented ice. The next two sections describe the IceCube Upgrade that is underway to more densely instrument the central region of the existing array, and the vision for IceCube-Gen2 [15], a high energy extension to instrument roughly 8 times more ice together with an expansive radio array as shown in Fig 10.

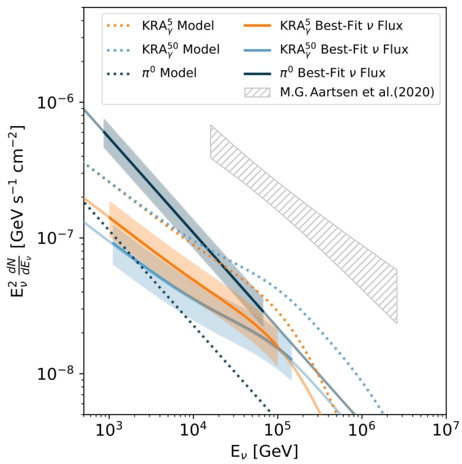


Figure 9: The energy dependence of the neutrino flux for events associated Galactic plane. For details, see [13].

3.1 IceCube Upgrade

The IceCube Upgrade project will add seven more densely instrumented, more closely spaced strings in the 2025-26 austral summer season near existing DeepCore strings as shown on the left in Fig. 11. One goal of the Upgrade project is to lower the energy threshold and improve the quality of the detected low energy events (Fig. 11 above). This will significantly reduce the uncertainty contours in the prior oscillation analysis as shown in Fig. 12, provide sensitivity to probe the mass ordering and tau neutrino sector, improve low energy searches for beyond Standard Model physics, and aid efforts to image the Earth using neutrino tomography.

The two other major Upgrade project goals are to deploy more calibration devices to improve the modeling of the optical properties of the ice and to serve as a test bed for research and development

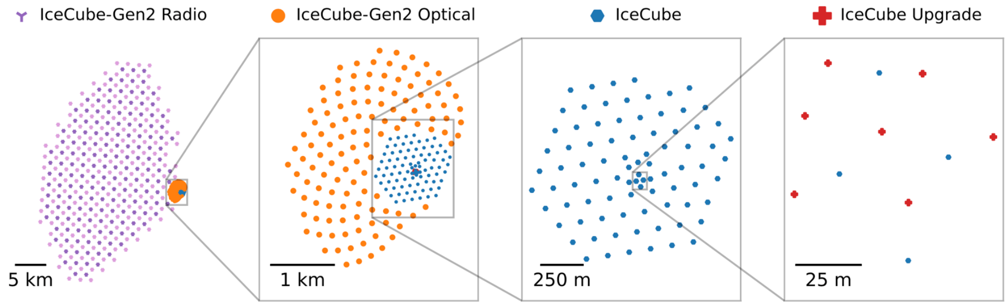
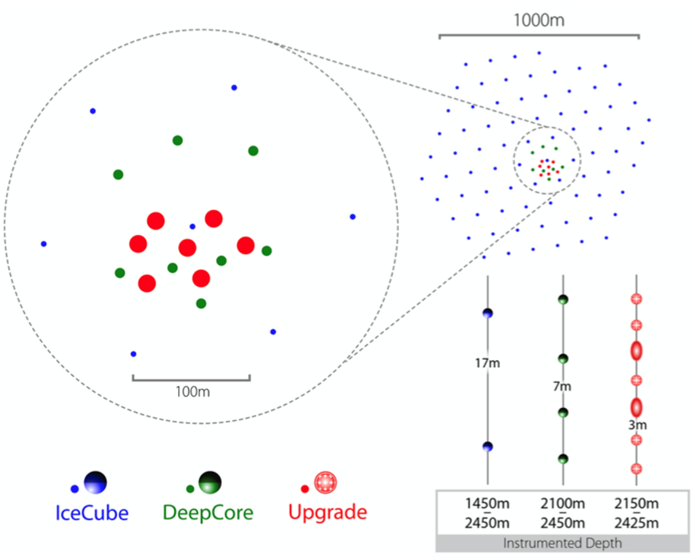


Figure 10: The surface projection showing the progression in spacing from the IceCube Upgrade to IceCube-Gen2. Increasing spacing allows a greater volume of ice to be instrumented for the same cost with a trade off of a higher minimum energy threshold.

of next generation light sensors and calibration devices. Improvements in modeling the optical properties of the ice translate directly into better event reconstruction, improving the fidelity of future and and archived data.

3.2 IceCube-Gen2

Neutrinos have demonstrated their potential to probe the a wide-range of physics and, as cosmic messengers, to learn about the high energy Universe in fundamentally new ways. IceCube has established there is a large astrophysical neutrino flux, and that it is possible to identify sources. Continued progress requires a next generation instrument to get a larger ensemble of sources. Adding 120 more widely-spaced strings will increase the number and likely the variety of new sources. The improvement is illustrated in Fig. 13 which shows the significance that would have been achieved for a flaring source like TXS 0506+056 and a steady state source like NGC1068 if IceCube-Gen2 was operational.



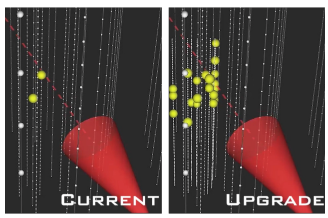


Figure 11: Left: The placement of the IceCube Upgrade strings and sensors shown relative to the existing IceCube and DeepCore strings. **Right:** A simulated 3.8 GeV neutrino event with current IceCube array and with the planned Upgrade layout. Larger colored circles indicate sensors that detected light.

The science case for IceCube-Gen2 is strong and growing. The Astro 2020 panel report, Pathways to Discovery in Astronomy and Astrophysics for the 2020s [17], identified IceCube-Gen2 in the New Messengers and New Physics Priority Area: New Windows on the Dynamic Universe and a key activity in a related field (Astronomy). The recently released report from the Particle Physics Project Prioritization Panel (P5) identified IceCube-Gen2 as one of the top 5 priorities for the field over the next decade and beyond [18].

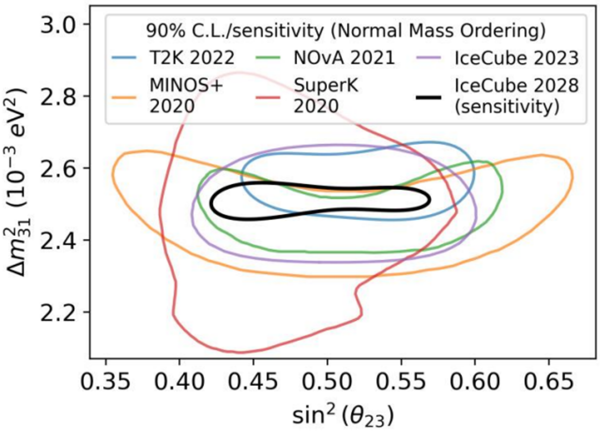


Figure 12: A comparison of expected IceCube Upgrade results with currently operating neutrino experiments. For detials, see [16]

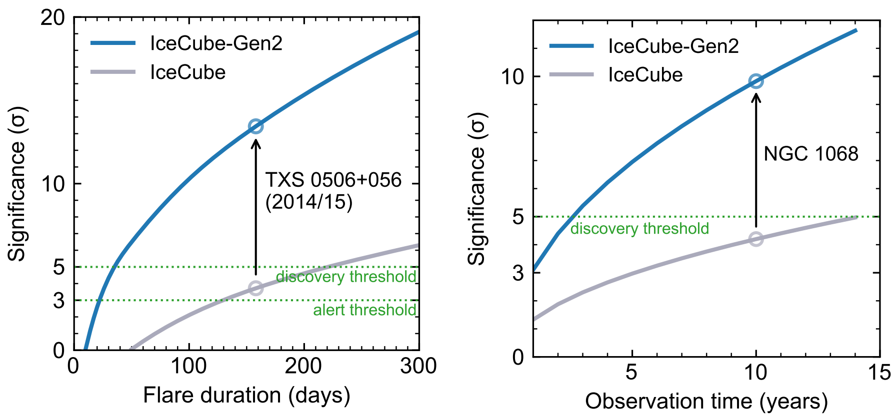


Figure 13: For IceCube-Gen2, the instrumented volume of ice would increase by a factor of 8 making it possible to identify more and fainter flaring (left) and steady state sources (right).

4. Summary

IceCube has established the viability of operating a neutrino observatory at the South Pole, and demonstrated the value of neutrinos to explore the high energy universe. Motivated by the success so far, the capabilities of the facility will be enhanced in a two phases. The first phase, IceCube Upgrade is underway and on track to install seven more strings of instruments primarily to improve low energy performance. Phase two, IceCube-Gen2, has received strong support from the community, and has a mature reference design that will support a growing, exciting science scope.

References

[1] J. Linsley, *Evidence for a primary cosmic-ray particle with energy* 10^{20} *ev*, Phys. Rev. Lett. **10** (1963) 146.

[2] M. Aartsen, M. Ackermann, J. Adams, J. Aguilar, M. Ahlers, M. Ahrens et al., *The icecube neutrino observatory: instrumentation and online systems*, Journal of Instrumentation **12** (2017) P03012–P03012.

[3] I.C. https://icecube. wisc. edu/analysis@ icecube. wisc. edu, R. Abbasi, M. Ackermann, J. Adams, J. Aguilar, M. Ahlers et al., *Detection of astrophysical tau neutrino candidates in icecube*, *The European Physical Journal C* **82** (2022) 1031.

[4] S.L. Glashow, *Resonant scattering of antineutrinos*, Phys. Rev. **118** (1960) 316.

[5] IceCube collaboration, *Detection of a particle shower at the Glashow resonance with IceCube*, Nature **591** (2021) 220 [2110.15051].

[6] S. Yu and J. Micallef, *Recent neutrino oscillation result with the icecube experiment*, 2023.

[7] A.K. Upadhyay, A. Kumar, S.K. Agarwalla and A. Dighe, *Locating the core-mantle boundary using oscillations of atmospheric neutrinos*, Journal of High Energy Physics **2023** (2023) .

[8] R. Abbasi, M. Ackermann, J. Adams, J. Aguilar, M. Ahlers, M. Ahrens et al., *Measurement of the high-energy all-flavor neutrino-nucleon cross section with icecube*, Physical Review D **104** (2021) .

[9] M. Ahlers, *Neutrino sources from a multi-messenger perspective*, EPJ Web of Conferences **209** (2019) 01013.

[10] IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift NuSTAR, VERITAS, VLA/17B-403 collaboration, *Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A*, Science **361** (2018) eaat1378 [1807.08816].

[11] IceCube collaboration, *Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert*, Science **361** (2018) 147 [1807.08794].

[12] IceCube collaboration, *Evidence for neutrino emission from the nearby active galaxy NGC 1068*, Science **378** (2022) 538 [2211.09972].

[13] R. Abbasi, M. Ackermann, J. Adams, J.A. Aguilar, M. Ahlers, M. Ahrens et al., *Observation of high-energy neutrinos from the galactic plane*, Science **380** (2023) 1338–1343.

[14] K. Fang, J.S. Gallagher and F. Halzen, *The milky way revealed to be a neutrino desert by the icecube galactic plane observation*, Nature Astronomy (2023) .

[15] R. Abbasi, M. Ackermann, J. Adams, S. Agarwalla, J. Aguilar, M. Ahlers et al., *The next generation neutrino telescope: IceCube-Gen2*, PoS **ICRC2023** (2023) 994.

[16] P. Eller, K. Leonard DeHolton, J. Weldert, R. Orsoe, R. Abbasi, M. Ackermann et al., *Sensitivity of the IceCube Upgrade to Atmospheric Neutrino Oscillations*, *PoS* **ICRC2023** (2023) 1036.

[17] N.A. of Sciences, Engineering, and Medicine, *Pathways to Discovery in Astronomy and Astrophysics for the 2020s*, The National Academies Press, Washington, DC (2023), 10.17226/26141.

[18] “Pathways to innovation and discovery in particle physics, report of the 2023 particle physics project prioritization panel.” https://www.usparticlephysics.org/2023-p5-report/, 2024.