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Forecasted Sensitivity of IceCube-Gen2 to the Astrophysical Diffuse Spectrum

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IceCube-Gen2-Optical is a planned, large-scale upgrade to the existing IceCube Neutrino Observatory. This ~8 cubic kilometer in-ice detector is optimized for point-source science, yielding integer-factor improvements to angular resolution, and increased sensitivity to higher energies. Here, its impact on future study of the diffuse astrophysical spectrum is considered. New analyses of up-going muon neutrino tracks and of all-sky cascade events are performed by adapting standard IceCube selection and analysis methods to this proposed configuration. Improvements to sensitivity of both analyses are presented, along with the combined result. The all-sky cascade analysis excludes a majority of the parameter space allowed by the same period of IceCube observation. The work explores the impact of leading atmospheric systematics on IceCube-Gen2 diffuse sensitivity, and on that of similar, future experiments. A characterization of the Gen2-Optical diffuse program, and implications for our understanding of astrophysical sources in this coming era of next-generation, volumetric neutrino experiments, are provided.

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1. Introduction

In over a decade of livetime, the South Pole IceCube Neutrino Observatory has established a sky bright in high-energy, extraterrestrial neutrinos [1]. This astrophysical diffuse flux follows an approximate power law to PeV energies, potentially surpassing diffuse gamma rays in intensity [2, 3]. The blazar AGN TXS 0506+056 is found as a contributing, transient point source [4]. With suggested gamma-ray or radio correlation, the mechanism of particle acceleration and production at this source remains unclear [4, 5]. Recently, the Seyfert galaxy NGC 1068 has been identified with a steady-state flux at lower energies, further diversifying the set of known source classes [6]. Resolving the remaining 99% of the astrophysical flux would provide insight into the environments of the universe's highest-energy accelerators. Transition from this discovery phase to a new era of precision astronomy requires a next-generation observatory.

1.1 The IceCube-Gen2 Observatory

The IceCube-Gen2 Observatory constitutes a large-scale extension to the existing IceCube experiment at the South Pole. The in-ice optical component would span ~8 cubic kilometers, incorporating 120 new strings of photosensitive modules around IceCube's footprint. The air shower surface array, IceTop, would be extended to cover this new profile. An accompanying radio array will instrument the surrounding 450-600 square kilometers. Vastly increasing sensitivity to atmospheric, astrophysical, and cosmogenic neutrinos, IceCube-Gen2 will open a unique window to the high-energy universe [7].

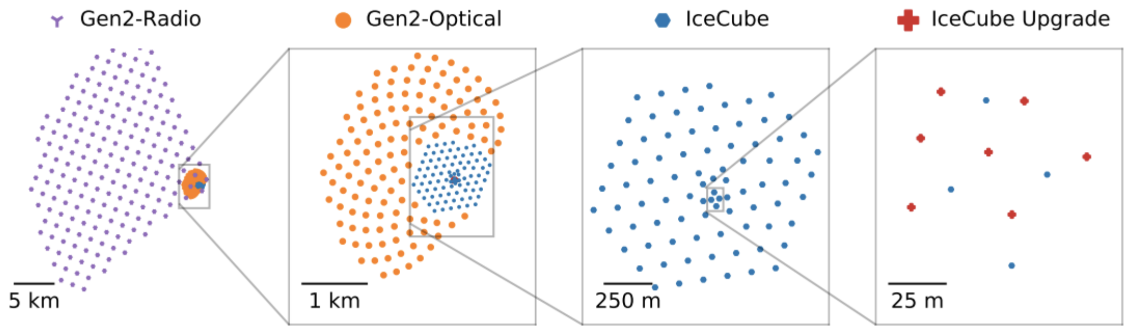

Figure 1: Baseline Layout of the IceCube-Gen2 Observatory. This schematic shows the suggested, face-down layout of radio stations (purple), newly-instrumented optical strings (orange), and existing IceCube optical strings (blue) [7]. Each of the 120 Gen2 strings will deploy 80 optical modules. The expanded surface array is not shown. Strings representing the IceCube Upgrade are pictured for reference.

IceCube-Gen2-Optical has been optimized for point-source science. This layout will improve the angular resolution of track-like events, muons generated in charged-current neutrino interactions and those of atmospheric origin, by a factor of two; The expanded optical array will increase the observable lever arm, enhancing pointing ability. A modernized optical module, the Long Optical Module, will bring pixelated sensors, discerning photon directionality, and increasing active sensor area by a factor of three. Additionally, the larger instrumented volume will substantially increase the rate of tracks above 10 TeV. Sensitivity to cascades, the nearly-spherical event topology associated with neutral-current and electron neutrino interactions, will also improve. As the interactions yield calorimetric depositions, the observed rate increases with detector volume. While this extended optical array will help localize and identify astrophysical point sources [7], it's also worth considering the impact of these improvements on diffuse science.

1.2 Modern Diffuse Science with IceCube

Study of the astrophysical diffuse spectrum began with the observation of anomalous, high energy events. This excess over the expected atmospheric background triggered a first search for a diffuse flux of astrophysical neutrinos [1]. Today, a power-law astrophysical spectrum is detected at high significance with both track and cascade event selections [8, 9]. Potential deviations from this spectral shape may indicate galactic contributions or relate to the method of neutrino production and acceleration at our astrophysical sources. IceCube remains systematically limited below a few-hundred TeV, and statistically limited at PeV-energies, impacting our ability to discern these spectral signatures.

A typical analysis relies on the energy, zenith, and topology-dependence of observed events. Cosmic-ray air showers create dominating backgrounds of through-going muon bundles, single muons, atmospheric electron and muon neutrinos. Filters are introduced to reduce the rate of passing air showers. Further selections focus on event topology, creating separate selections of cascades and track-like events. Atmospheric spectra dominate at lower energies, leaving the harder astrophysical spectrum observable beyond. The dependence of atmospheric rates on zenith angle provides an additional discrepancy from the isotropic, astrophysical intensity. In a track analysis, the dominating flux of southern, atmospheric muons is commonly excluded by considering only the northern hemisphere.

2. Diffuse Selections for IceCube-Gen2-Optical

This work considers the impact of leading-order systematics on IceCube-Gen2-Optical diffuse, astrophysical sensitivity. Two benchmark analyses are performed, one based on a previous IceCube selection of cascades [9], the other of northern-hemisphere tracks [10].

2.1 Northern-Hemisphere Tracks

Typical IceCube analyses achieve a high-efficiency, high-purity sample of northern muon neutrinos. In this study, perfect selection efficiency for track-topology events, rejection of cascades and atmospheric muons, is assumed. Two major backgrounds remain in the selection, conventional and prompt atmospheric muon neutrinos. Conventional neutrinos produced in the decays of pions and kaons contribute at low energies, becoming subdominant to the flux of charm-induced prompt neutrinos at higher energies. To model both signal and background, a set of muon neutrino and antineutrino charged-current events has been simulated with the package LeptonInjector [11]. As a simplification, the optical modules of the 120 proposed strings are modeled after existing IceCube sensors. A 17% contribution to the astrophysical channel from tau-induced tracks is neglected.

A number of quality cuts are applied to select well-reconstructed, identifiable tracks. After noise cleaning, photoelectron pulses must be observed on at least 6 optical modules. Additionally, the reconstructed track speed is required to be less than twice the speed of light, a common veto for the misreconstructed activity of coincident, atmospheric muons. As the 86-string IceCube array observes a higher density of deposited charge, further cuts depend on whether the reconstructed track intercepts IceCube, or is only observed on the 120-string Gen2 array. The latter requires more stringent cuts on reconstructed track length and best-fit likelihood, maintaining the quality of dimmer events at lower energies.

2.2 All-Sky Cascades

An all-flavor set of neutral- and charged-current neutrino interactions has been generated to model both signal and atmospheric backgrounds [11]. Additionally, a set of single, through-going muons has been simulated to approximate the leading contributions of misclassified air showers.

Initial quality cuts are applied to identify well-reconstructed cascades. This selection is modeled after a previous IceCube cascade analysis [9]. The log-likelihood of a simple cascade reconstruction is used to identify such topologies. An additional cut is placed on the reconstructed interaction vertex, ensuring the event is well contained in the Gen2-Optical array. Last, events reconstructed within a certain depth range of the ice, known for increased photon scattering and absorption, are removed from the set.

A gradient boosted decision tree is then trained on the three topologies remaining in the selection: cascades, through-going tracks, and starting muon tracks. Training features and model hyperparameters are adapted from an earlier IceCube analysis [9], with changes to accommodate the extended Gen2 optical array and altered string spacing. A final analysis-level cascade selection is chosen to admit an integral rate of weighted atmospheric muons similar to that of the atmospheric neutrinos. Due to resource constraints, the simulated atmospheric muon set had limited ability to model the energy and zenith dependence of these rare passing events. As these events are known to contribute at lower energies, where the astrophysical spectrum is already dominated by the flux of conventional neutrinos, the atmospheric muon sample is used only in the selection process, and is not included in the final likelihood analysis. Generally, the comparable contributions of passing atmospheric muons and conventional neutrinos can be constrained by examining starting and through-going control samples [9]. As the conventional spectrum can be well measured at low energies within this signal sample, only this final-level cascade selection is considered.

3. Projecting Sensitivity to the Astrophysical Diffuse Spectrum

3.1 Signal Modeling

This work considers sensitivity to a power-law astrophysical spectrum, with parameters taken from a recent IceCube analysis of northern track data [10]. The astrophysical flux is assumed as isotropic, and equal in flavor. The form is taken as,

$$\Phi_{\nu,\bar{\nu}} = \Phi \times \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-\alpha} \times 10^{-18}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}. \tag{1}$$

Here, $\Phi_{\nu,\bar{\nu}}$ describes the astrophysical flux of a given flavor and energy, E, from both neutrinos and antineutrinos. The models used to weight the contributing spectra are further described in Table 1.

Channel	Parameterization	Model Parameter	Value	Bounds
Astrophysical	Power Law	Index, α	2.37	$[0.0, \infty)$
Astrophysical	-	Norm., Φ	1.36	-
Conventional	Gaiser-Hillas H4a, Sibyll 2.3c	Scale Factor	1.0	-
Prompt	-	-	0.0	-
Single Atm. Muon Flux	-	-	1.0	N/A

Table 1: Spectral Parameterizations. This table shows the spectral models used in this work. The conventional and prompt atmospheric spectra have been modeled with the package MCEq [12]. Here, the Gaiser-Hillas H4a primary cosmic-ray spectrum is assumed [13], with interactions governed by the Sibyll 2.3c hadronic interaction model [14]. The flux of single atmospheric muons follows a similar description, used only in the selection process. The value of each parameter describes the Asimov spectra assumed in this work. Bounds considered in the likelihood analysis are also provided.

At Earth, atmospheric and astrophysical fluxes experience a number of matter effects, impacting both flavor and intensity. The propagation of muons through the Earth is handled by PROPOSAL, a particle simulation package catering to high energies [15]. Neutrino Earth absorption, tau regeneration, and oscillations are modeled with the nuSQuIDS software package [16].

The effect of self-veto on the prompt and conventional fluxes is also incorporated. As an atmospheric neutrino is produced with an accompanying muon bundle, such events may be removed based on this bundle visibility. This decreases the passing rate of bright, atmospheric events at high energies, and from zenith, where muons travel through a decreased overburden relative to those from the horizon. While the prompt and conventional spectra in this work are represented by single neutrinos, the diminished event rate can be parameterized with the nuVeto package [17]. Generally, the passing fraction of neutrinos is set by the minimum muon energy for rejection. In this work, events of true direction intercepting the 86-string IceCube array are described with an efficient muon rejection energy of 250 GeV. Similarly, events intercepting only the new, 120-string IceCube-Gen2 array have a minimum muon rejection energy of 1 TeV. The resulting, weighted spectra are shown for the cascade selection in Figure 2.

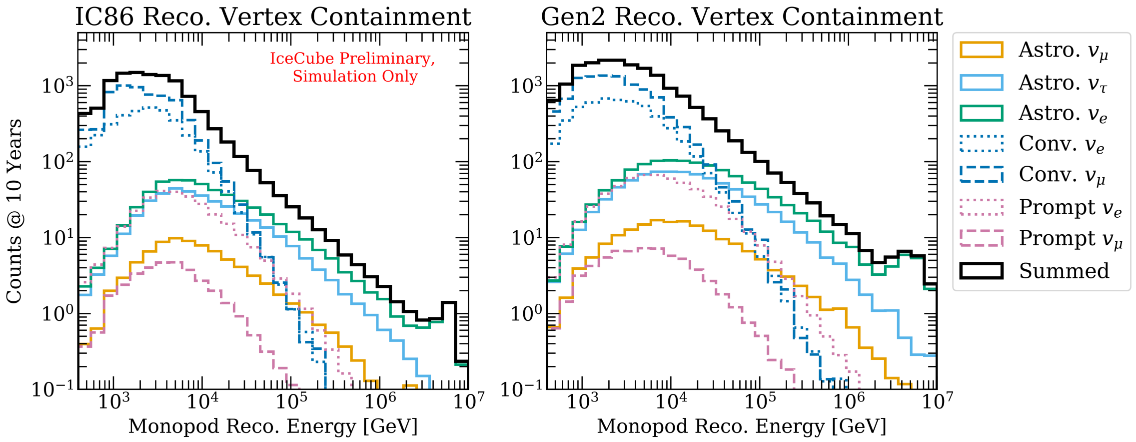

Figure 2: Analysis-Level Spectra of the Cascade Selection. The plot above represents the spectra of events in the final cascade selection, separated by the reconstructed location of the interaction vertex. Events with reconstructed vertices within the parameterized volume of the original 86-string IceCube array are represented on the left, while those contained on the surrounding, 120-string array proposed for IceCube-Gen2 are shown right.

3.2 Likelihood Formulation

In this work, a forward-folding analysis of an Asimov data set is performed. The astrophysical spectral index and normalization, and the conventional and prompt neutrino flux scales, are taken as free parameters. The assumed values and bounds are described in Table 1. A Poisson likelihood is optimized in terms of reconstructed values for event zenith angle, position, and energy. The binning scheme is described in Table 2.

This work introduces an additional binning parameter for the cascade likelihood analysis, the position of reconstructed interaction vertices. As events contained on the 86-string IceCube array (IC86) may have energy and zenith resolution different from those on the 120 proposed strings, this differentiation is added.

A combined analysis of cascade and track selections has also been performed. This study shows the combined sensitivities of both event sets.

Selection	Cosine of Zenith, $\cos(\theta)$	Energy Index, $\log_{10}(E)$	Vertex Position
Cascades	[1.0, 0.6, 0.2, -1.0]	22 bins $\in$ [2.6, 7.0]	IC86, Gen2 120-string array
Northern Tracks	10 bins $\in$ [0.1, -1.0]	25 bins $\in$ [2.0, 7.0]	N/A

Table 2: Binning Used in Likelihood Construction. The above table describes the binning of reconstructed quantities adopted for the two selections of this work. Choices reflect those of previous IceCube analyses. Reconstructed energy is represented in GeV. If not written explicitly, zenith binning is assumed equally spaced in the cosine of the angle, and energy bins equal on a logarithmic scale.

4. Results

Sensitivity to the diffuse astrophysical spectrum is shown in Figure 3. One-dimensional, 68.3% confidence-level uncertainties for the astrophysical parameters are summarized in Table 3. The track, cascade, and combined sensitivities of this work are compared to similar projections from a recent IceCube study [18]. This work has used the same parameterization of the astrophysical spectrum, similar atmospheric spectra, selections and likelihood binning. Each result reflects ten years of livetime. Performance of the IceCube-Gen2-Optical array represents only the final, composite configuration, and does not model preexisting observations from IceCube or a partial detector. It is worth noting the IceCube study used for comparison incorporates additional nuisance parameters modeling uncertainty in the optical description of the ice, and the structure of the atmospheric neutrino spectra.

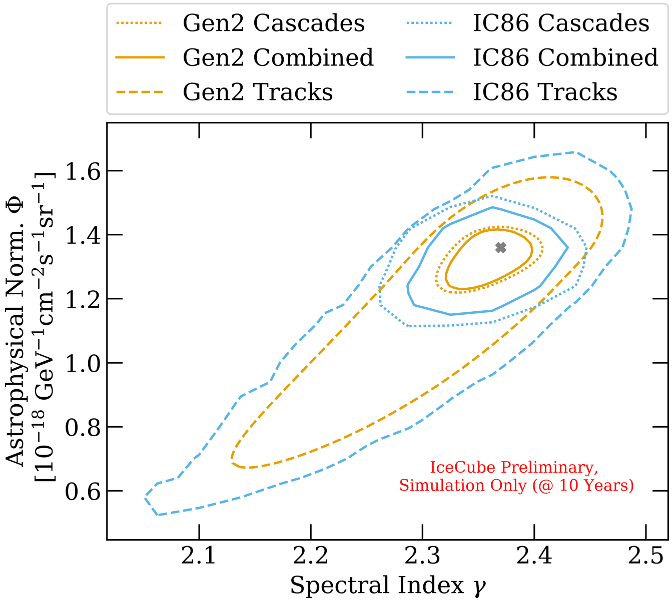

Figure 3: IceCube-Gen2-Optical and IceCube Sensitivity of Benchmark Diffuse Analyses. The plot above shows 68% confidence-level sensitivities for a power-law astrophysical spectrum at ten years of livetime. The results of this work are shown in orange, reflecting IceCube-Gen2-Optical. The blue contours represent a similar analysis with the present-day, 86-string IceCube configuration [18].

Selection	Normalization, Φ	Index, α
Northern Tracks	$1.36^{+.22}_{-.68}$	$2.37^{+.09}_{-.24}$
Cascades	$1.36^{+.07}_{-.14}$	$2.37^{+.04}_{-.06}$
Combined	$1.36^{+.06}_{-.13}$	$2.37^{+.03}_{-.05}$

Table 3: Astrophysical Uncertainties. The above table shows the 68% confidence-level uncertainties for a power-law astrophysical spectrum. This sensitivity reflects ten years of Gen2-Optical livetime.

5. Conclusions

This work has considered sensitivity of the proposed IceCube-Gen2-Optical array to the diffuse, astrophysical, neutrino spectrum. Two standard analyses were performed – one focusing on track-like event topologies, the other on contained cascades. This study mirrors a previous work performed for the existing, 86-string IceCube configuration [18]. The most substantial improvement comes from the increased statistics of the cascade selection. While the expected rate of PeV-energy events has increased by a factor of ten, the rate of ~30 TeV selection-level cascades has also tripled, the energy at which the astrophysical flux overtakes background contributions. In the same period of livetime, there is a factor-of-three improvement in our ability to constrain a power-law astrophysical spectrum.

The degeneracy of the astrophysical spectrum with the prompt atmospheric neutrino flux is the limiting factor for cascade-selection sensitivity. The prompt atmospheric spectrum can be described as an approximate power law with an index of ~2.7, bearing similarity to the harder astrophysical flux. As the prompt flux is dominated at low energies by conventional atmospheric neutrinos, and at high energies by the astrophysical, the component remains poorly constrained. Degeneracy with the astrophysical neutrino spectrum creates extension along the positive diagonal in the cascade-selection, likelihood-scan contour (Figure 3). Sensitivity to this prompt component is driven by its zenith dependence – introduced from the veto of accompanying, visible muons. Lowering the minimum muon rejection energy increases the parameterized impact of the self-veto effect, and variance in the atmospheric zenith spectra. Additionally, cascade angular resolution controls our ability to recover structure within these spectra. Future work may explore these implications for IceCube and other volumetric neutrino observatories.

IceCube-Gen2 will revolutionize our understanding of diffuse science. The high-statistics cascade selection will measure energy dependence of the astrophysical spectrum at unrivaled precision. This improved sensitivity to spectral structure at both medium and high energies will help identify the neutrino production and acceleration mechanisms of our source populations. Aside from the significant improvement to angular resolution expected of IceCube-Gen2, this next-generation observatory will bring substantial changes to diffuse sensitivity, an essential tool in revealing the nature of our astrophysical sources.

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