IceCube
South Pole Neutrino Observatory

Michigan State University

Forecasted Sensitivity of IceCube-Gen2 to the Astrophysical Diffuse Spectrum

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ECRS, July 25th, 2022

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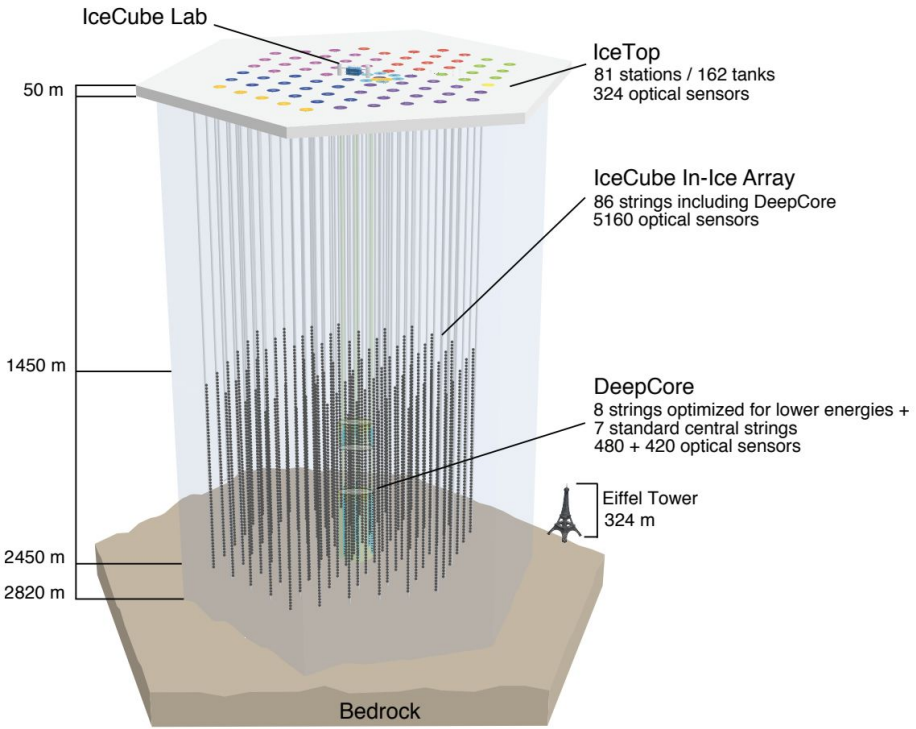
IceCube Neutrino Observatory History and Operation

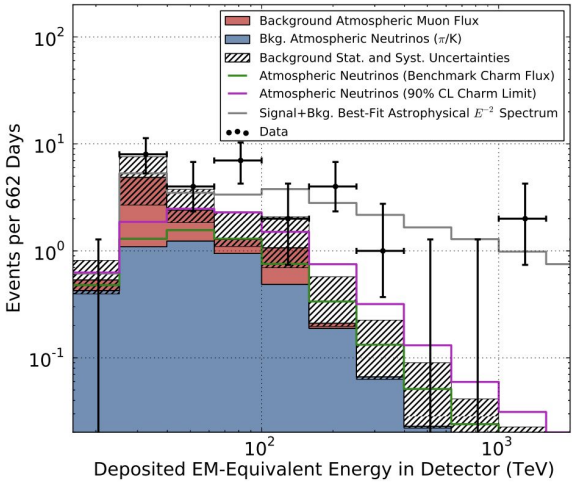
- A cubic kilometer of instrumented Antarctic ice
- Completed deployment of first 86 detector strings (2010)
- Electron, muon and tau neutrinos interact in the local medium, producing charged leptons and detectable radiation
- Light depositions within the detector: both extended ‘track-like’ events, and point-like ‘cascades’
- Low-energy IceCube Upgrade to begin deployment soon (2023-)

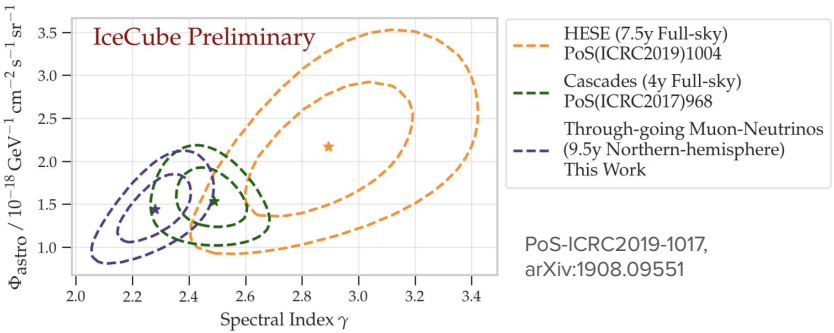


Over a Decade of Astrophysical Discoveries

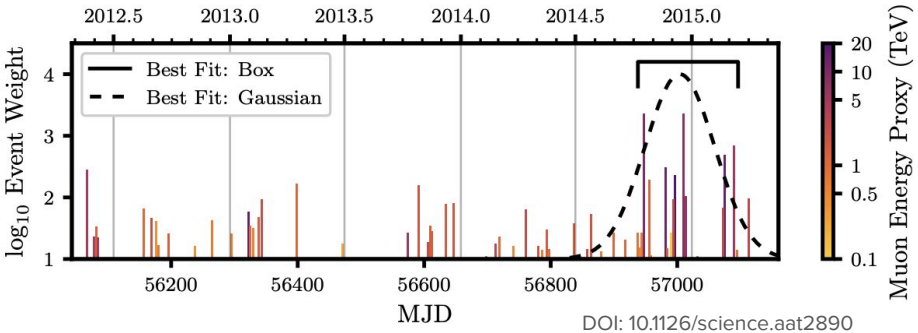
- IceCube established the existence of a diffuse, astrophysical neutrino spectrum, right (2013)
- Observation of transient neutrino emission from blazar TXS 0506+056, bottom right (2017/2018)
- Possible tension with an isotropic power-law flux, bottom left (2019-)
- Source searches place strong limits on correlation with gamma-ray production, other favored signatures

DOI: 10.1126/science.1242856





PoS-ICRC2019-1017,
arXiv:1908.09551



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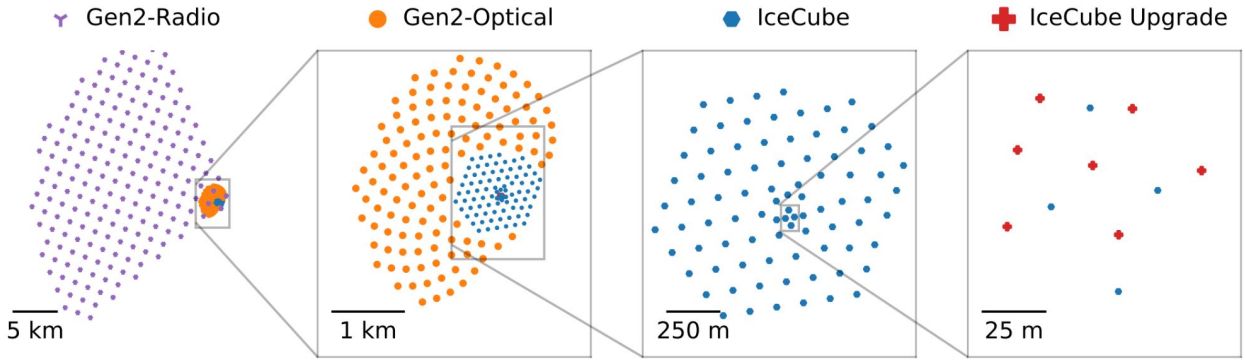
A Next-Generation Neutrino Observatory: IceCube-Gen2

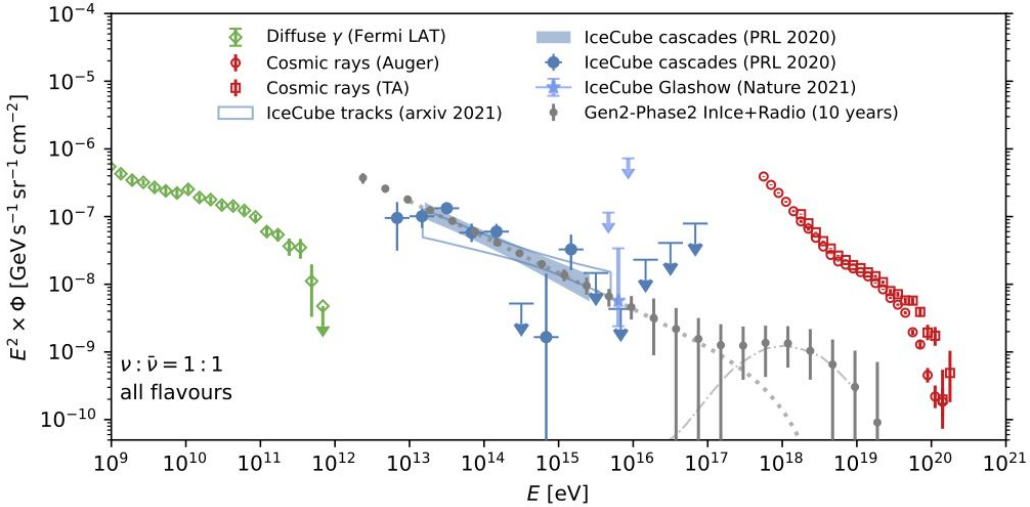


J.Phys.G 48 (2021) 6, 060501

- IceCube-Gen2-Optical, an eight cubic kilometer detector designed in part to answer questions regarding the largely unexplained diffuse spectrum:
  - 120 additional strings, optical module design gives 3x increase to active area
  - Factor of two improvement to track angular resolution, increased event rate (PoS-ICRC2021-1186)
  - Improved cascade statistics driven by detector volume, enhanced ability to probe spectral structure at highest energies
  - Synergy with Gen2-Radio and Gen2 Surface Array provides a unique high-energy observatory for atmospheric, astrophysical and cosmogenic neutrinos

Exploring Diffuse Science w/ Gen2-Optical

- The diffuse spectrum yields insights into its component source populations:
  - Structure in energy spectra relate to source type and energy budget
  - Comparisons of diffuse spectra with Fermi gamma-ray predictions suggestive of opaque source population
  - Potential anisotropy could indicate galactic contributions
- Increases to high-energy cascade and track statistics target a diffuse science program optimal to the neutrino astronomy community



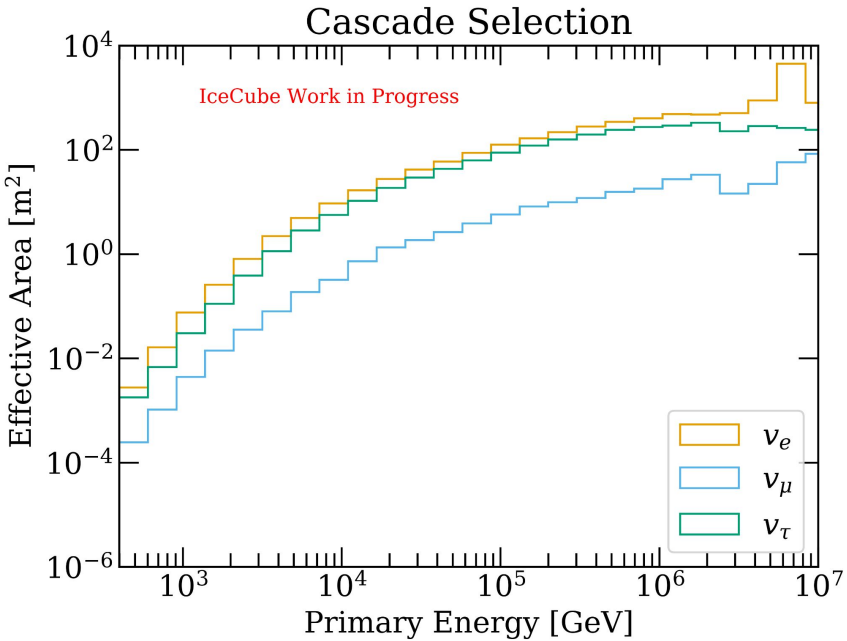
IceCube-Gen2 is a necessary extension, completing the multi-messenger picture, offering a new window into production at the most energetic sources

Gen2 Sensitivity for Benchmark IceCube Diffuse Studies

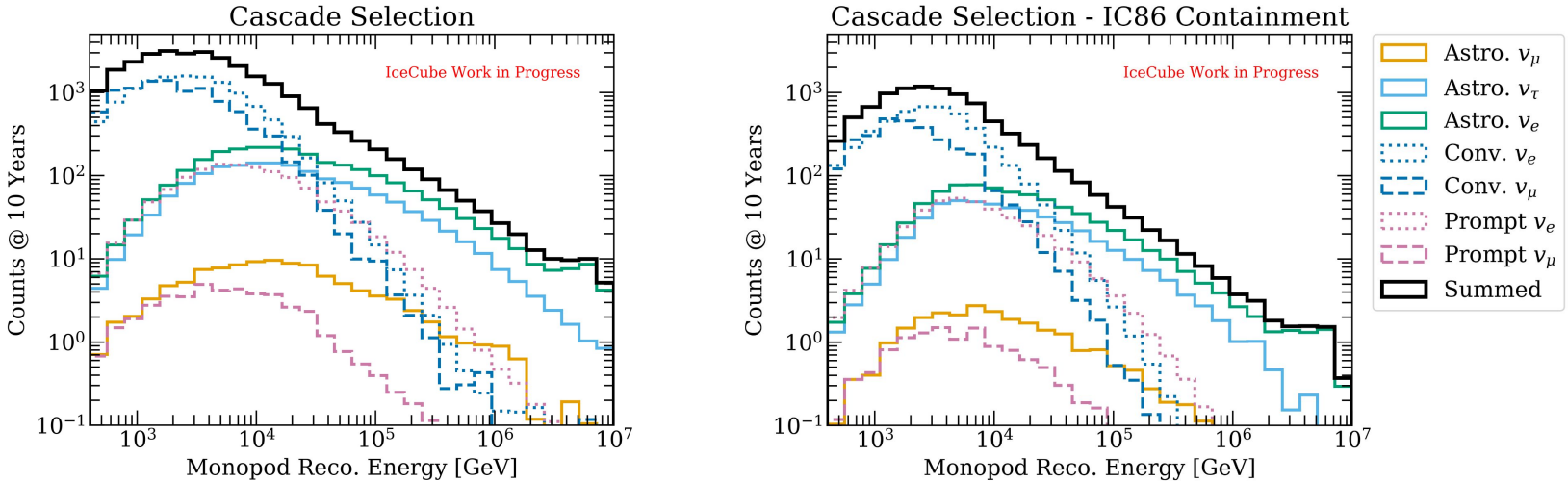
- IceCube observes shower muons, conventional and prompt neutrinos, as well as the astrophysical
- This work focuses on sensitivity to a standard power law astrophysical spectrum, and the impact of leading order systematics. Prompt and conventional normalizations left free in fit
  - Astrophysical index: 2.37, normalization: 1.36×10^{-18} GeV^{-1} cm^{-2} s^{-1} sr^{-1}
  - Atmospheric contributions follow Sibyll2.3c interaction model, Gaisser-Hillas H4a primary spectra
- A diffuse cascades analysis and northern tracks analysis are performed
  - Both studies use optical modules similar in performance to those of IceCube for 120 new strings
  - Will compare Gen2-Optical sensitivity (86 + 120 strings) at ten years of livetime, with the (ten year) IceCube (IC86) diffuse Monte Carlo study: PoS-ICRC2021-1129, arXiv:2107.10003

The Gen2 Cascades Diffuse Selection

- An all-flavor neutrino and muon background event set are simulated
- Quality cuts relating to containment, brightness, proximity to the dust layer, and reconstruction quality are applied
- A gradient boosted decision tree (GBDT) trained on event topology (starting, through-going tracks, and cascades) is used to identify an analysis-level selection of cascades. The resulting Gen2 effective areas are pictured
- Approximate order of magnitude increase to cascade effective areas at highest energies



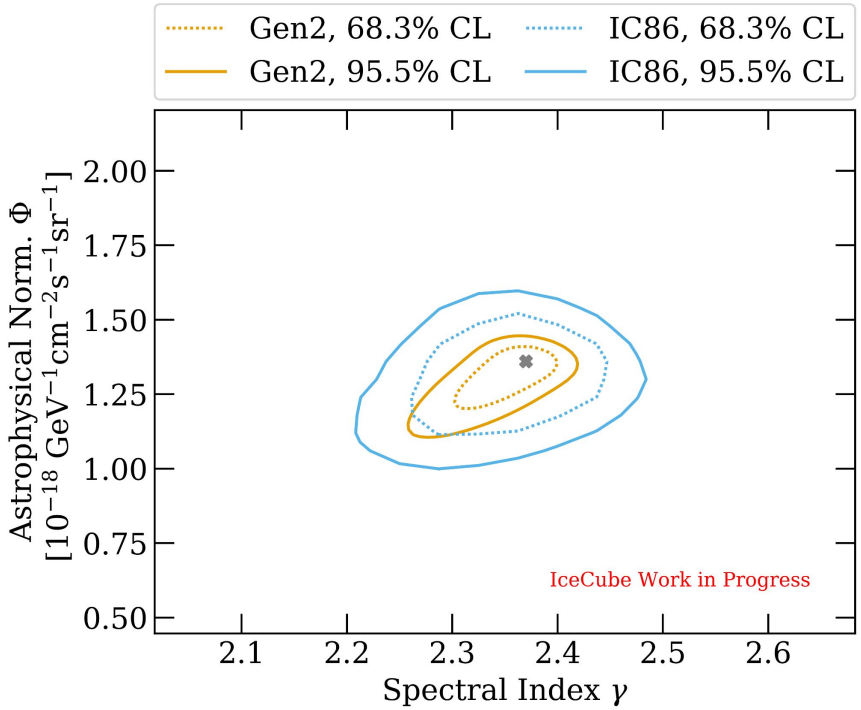
Gen2 Cascades Selection Spectra



- Spectra at ten years of livetime. IceCube-Gen2 (86 + 120 strings) at left, and events with reconstructed vertex within IC86 plotted at right
- Insufficient statistics to properly model muon passing spectra. Normally constrained with a control population of through-going events. Incorporated only in selection process
- 120 Gen2 strings provide order of magnitude increase to ~PeV statistics

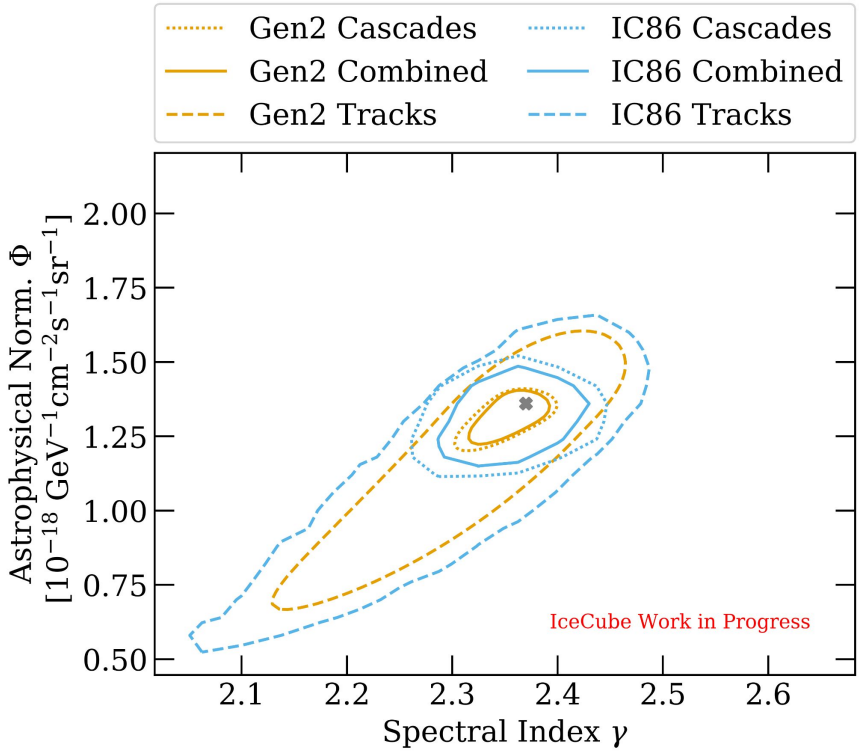
Gen2 Cascades Selection Likelihood Scans

- The cascades likelihood scan uses two spatial bins (IC86 sub-array contained events, and Gen2 sub-array contained events), 40 bins in energy (2.6 < log(reconstructed energy) < 7.0), and three bins in cos(zenith) angle (-1.0, 0.2, 0.6, 1.0)
- Ten year sensitivities for the selection are pictured at right. Comparable IceCube MC sensitivity also shown
- Angular resolution *very* conservative (to be fixed)



The Gen2 Combined Diffuse Analysis

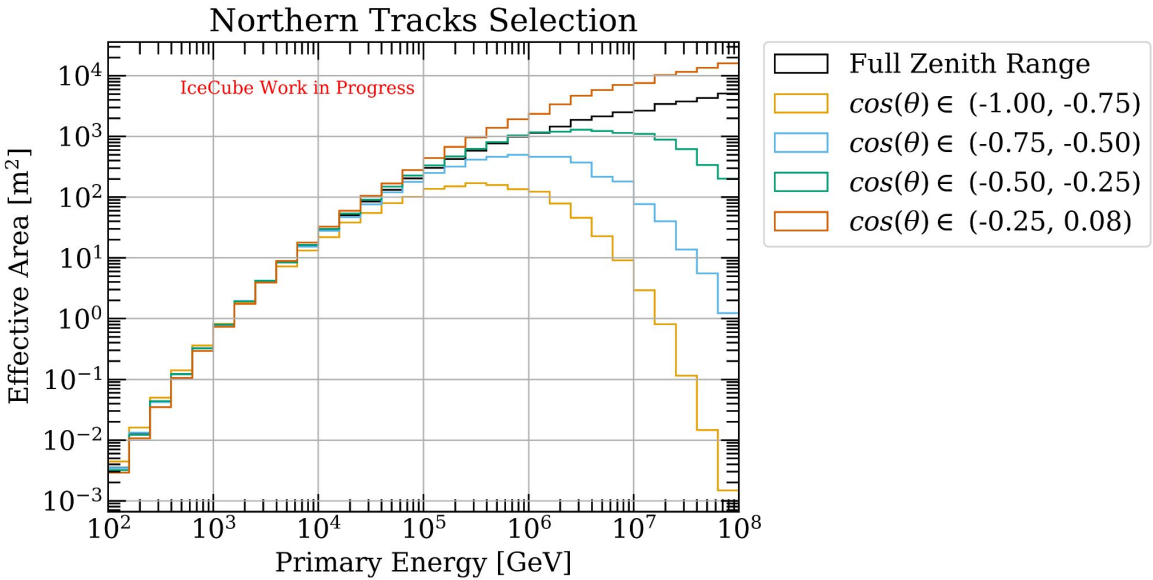
- Shown is the combined diffuse sensitivity
- Northern tracks analysis uses muon neutrino/anti-neutrino charged current events (missing a 15-20% contribution from tau-induced tracks)
- Potential for improvement to the tracks sensitivity from further optimized quality cuts
- When cascades angular resolution is corrected, zenith dependence introduced by the self-veto of prompt and conventional events will help constrain background contributions



Outlook and Future Work

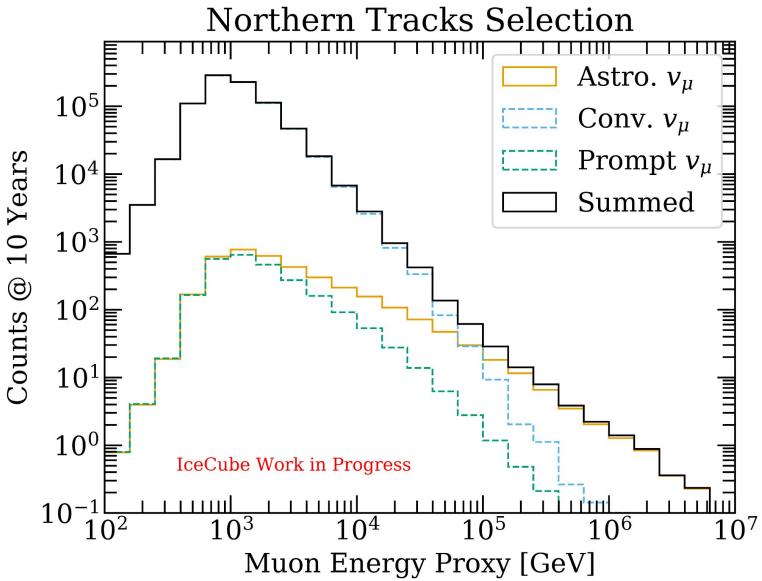
- Present results give initial estimates for diffuse sensitivity in a ~10 cubic kilometer scale neutrino observatory
  - Improvements are driven by increased cascade statistics beyond ~1 TeV
  - After cascade angular resolution is made better performing (more realistic), expect approximate order of magnitude reduction of contour space
- Gen2 will offer a precision measurement of the diffuse energy spectrum, with increased high-energy statistics giving new insights into spectral structure, and the characteristics of IceCube's point-source populations
  - Measurement of such structure will be the focus of future work, extending the reach of Gen2's diffuse program beyond IceCube benchmark analyses

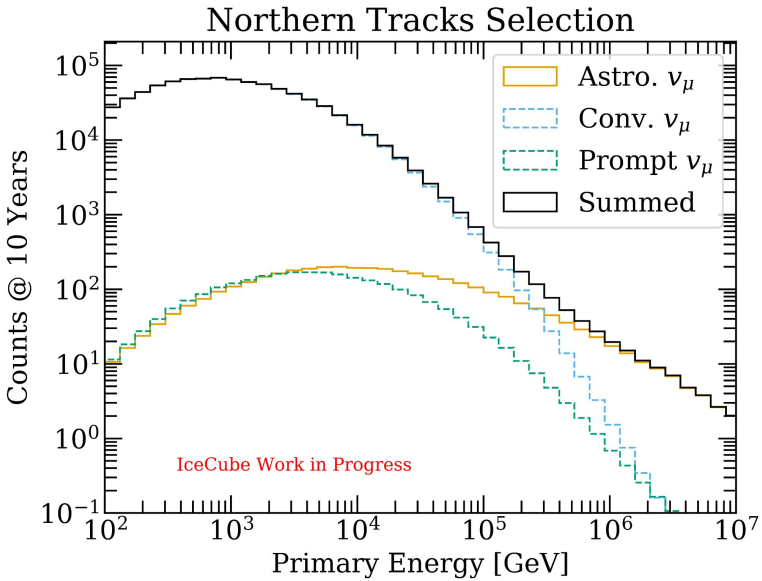
Backup: Effective Areas for Gen2 Northern Tracks



- Pictured at left are effective areas as a function of zenith and energy
- At trigger level, successfully reconstructed events show a factor of 4-6 improvement over IC86 at high energies, heading upwards

Backup: Gen2 Northern Tracks Diffuse Selection Spectra

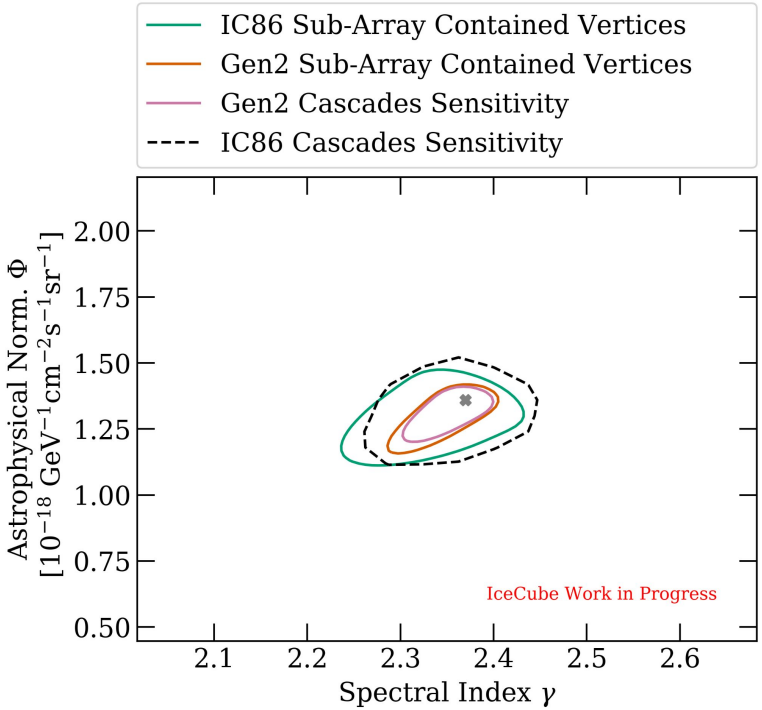




- Spectra for the northern tracks diffuse selection are shown at left in reconstructed muon energy proxy, and at right in true neutrino energy. Improvements to high-energy statistics are likely as new reconstruction methods are adapted to the Gen2 string spacing

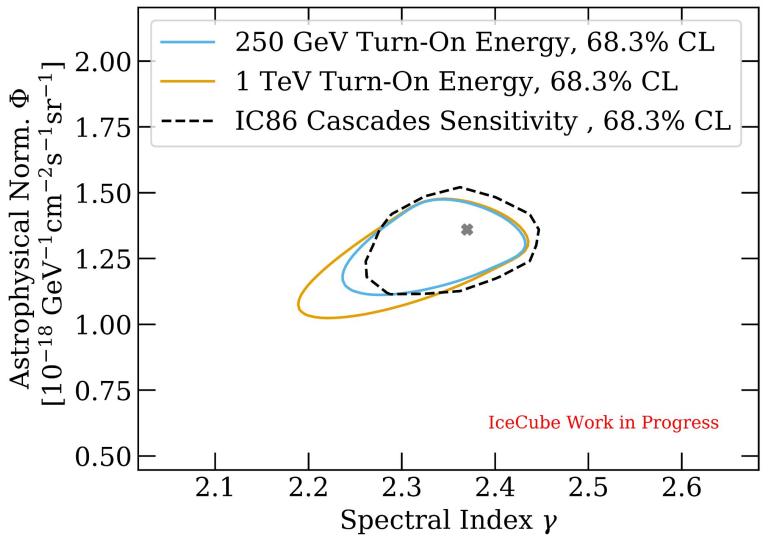
Backup: Diffuse Contours of Gen2 Sub-Arrays

- Pictured is the cascades likelihood scan decomposed into sensitivity contributions from events of reconstructed vertices within the Gen2 sub-array (120 new strings), and IC86
- Analysis of IC86-contained events roughly approximates modern IceCube performance (black)
- Combined cascades result (120 + 86 strings) shown in pink
- Sensitivity along the positive diagonal is largely controlled by parameterization of the self-veto effect, the rejection of atmospheric events based on the presence of detectable shower muons

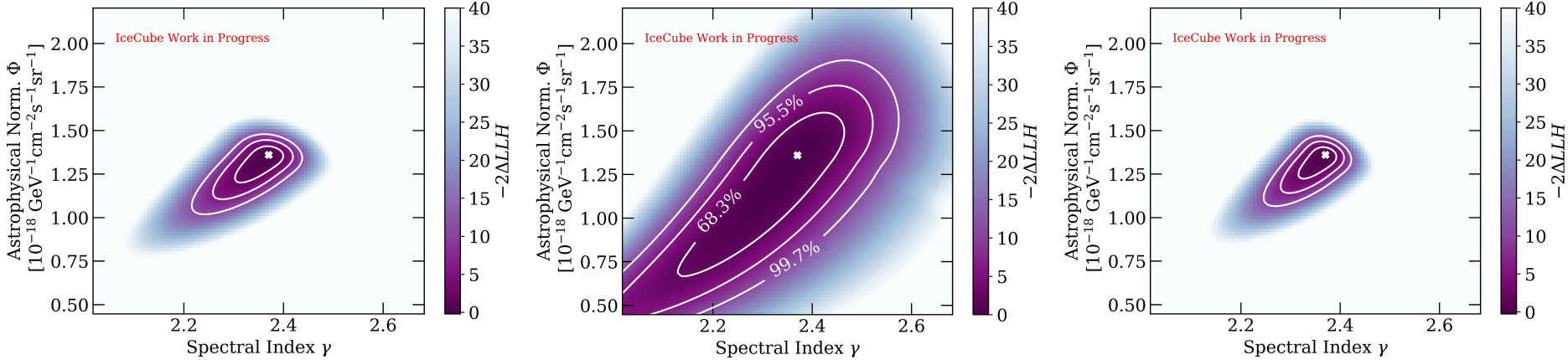


Backup: Effect of Muon Veto Turn-On Parametrization

- Cascades selection diffuse sensitivity at ten years for events of reconstructed vertex within IC86
- Previous IceCube MC analysis shown in black dashed line
- Result from present work shown in orange (blue) for 1 TeV (250 GeV) muon-veto turn-on energies
- Modeling the self-veto effect relies on this minimal muon energy (JCAP07(2018)047)
- Inclusion of this effect adds zenith-dependence to the prompt spectra, breaking degeneracy with the astrophysical



Backup: Contours with Confidence Levels



- Contour levels (68.3, 95.5, 99.7%) at ten years of livetime from the cascades diffuse analysis (left), tracks analysis (center), and combined sensitivity (right)
- Astrophysical parameters are tightly constrained by the cascades analysis, a likely underestimate as shown