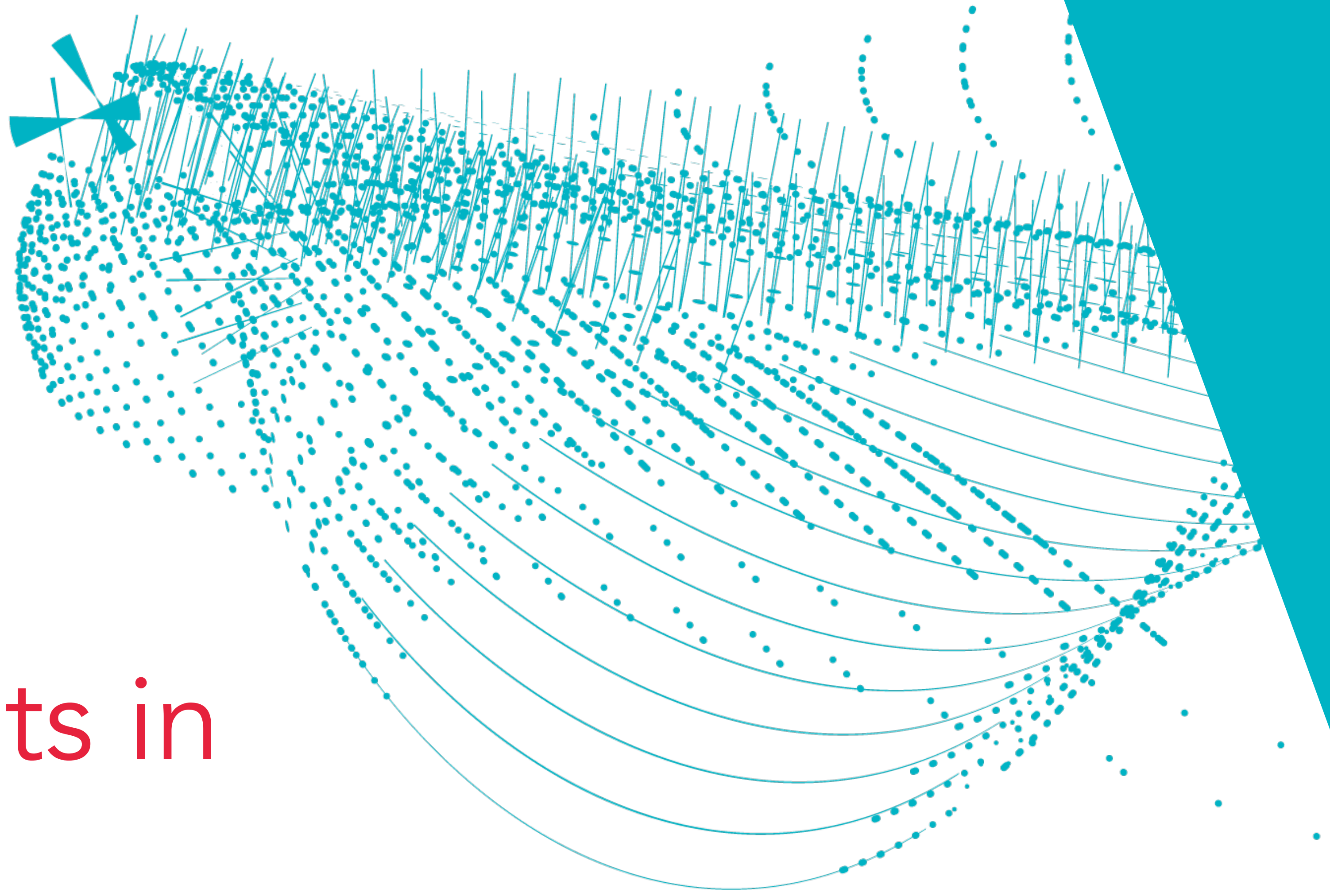
Nikhef

Daan van Eijk

A Search for IceCube Events in the Direction of the Anita Anomalous Events

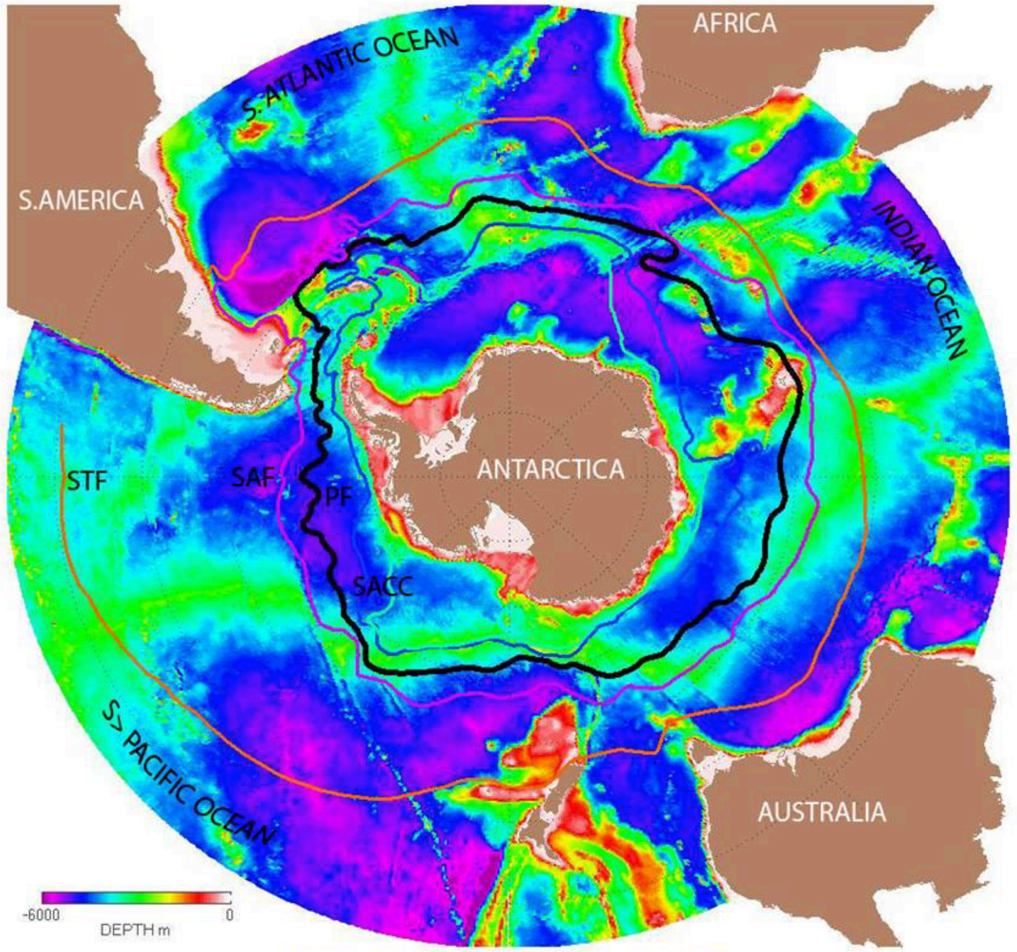


Journal Group Meeting
February 20 2020

an array of radio antennas suspended from a helium balloon flying at a height of about 37,000 meters.

ANITA

The Antarctic Impulsive Transient Antenna (ANITA) experiment is a balloon experiment, designed with the primary purpose of detecting the UHE cosmogenic neutrino flux (Gorham et al. 2009; Hoover et al. 2010; Gorham et al.



ANTARCTIC CIRCUMPOLAR CURRENT
SEAWATER DENSITY FRONTS (FROM ORSI et al, 1995),
AND *BATHYMETRY* OF THE SOUTHERN OCEAN (UP TO LATITUDE 25 S)

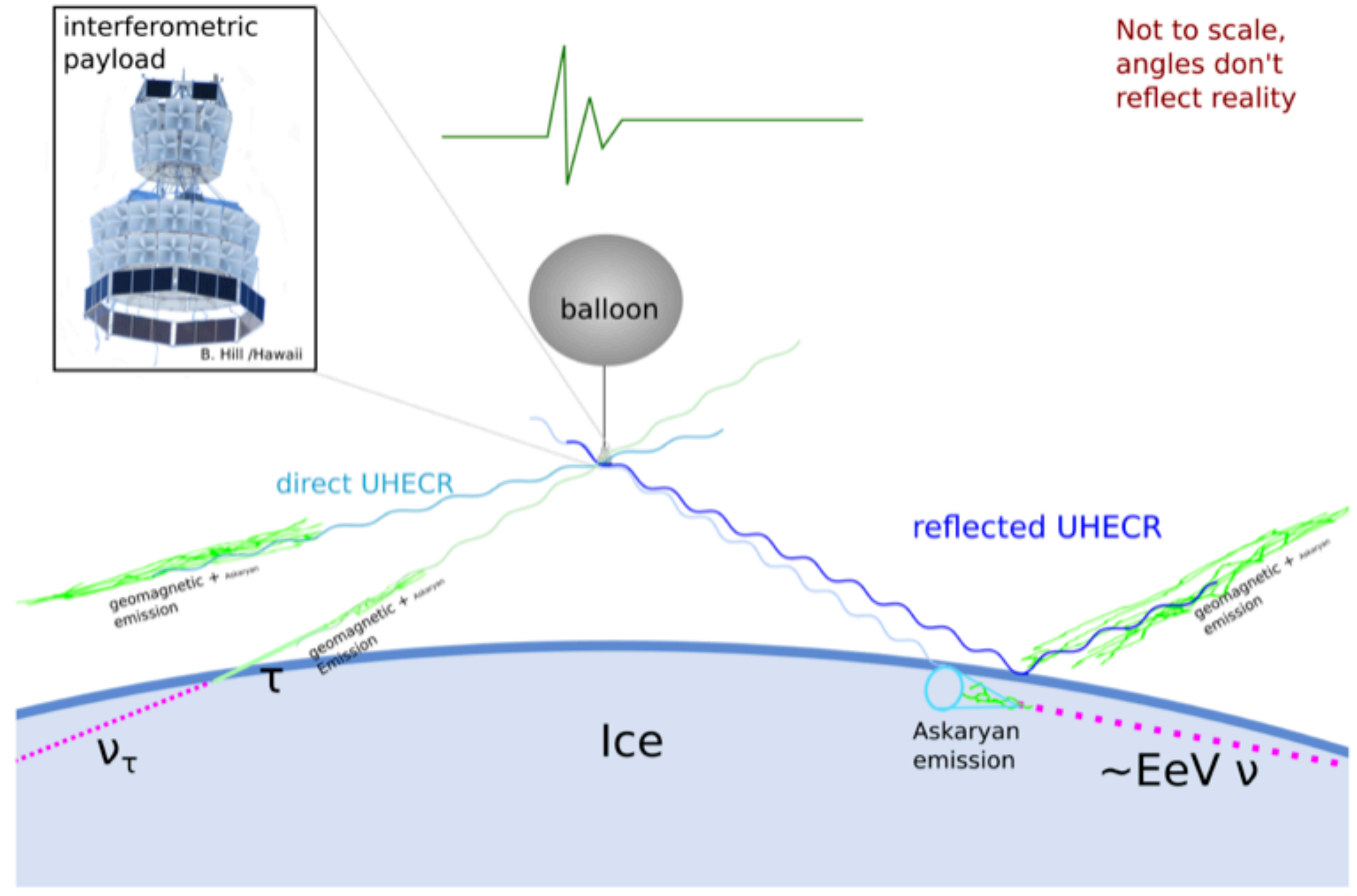
neutrinos, with energies on the order of 10^{18} eV, produce radio pulses in the ice because of the Askaryan effect.

The **Askaryan radiation**[1][2] also known as **Askaryan effect** is the phenomenon whereby a particle traveling faster than the phase velocity of light in a dense dielectric (such as salt, ice or the lunar regolith) produces a shower of secondary charged particles which contain a charge anisotropy and thus emits a cone of coherent radiation in the radio or microwave part of the electromagnetic spectrum. It is similar to the Cherenkov radiation. It is named after Gurgen Askaryan, a Soviet-Armenian physicist who postulated it in 1962.

The radiation was first observed experimentally in 2000, 38 years after its theoretical prediction. So far the effect has been observed in silica sand,[3] rock salt,[4] ice,[5] and Earth's atmosphere.[6]

ANITA Detection Modes: Geomagnetic and Askaryan

for isolated non-anthropogenic events [4]. ANITA observes UHECR via radio impulses that occur when geomagnetically-induced charged-particle acceleration occurs in the propagation of an extensive air shower in the atmosphere. Conventional down-going ultra-high energy cosmic-ray (UHECR) air showers produce downward-propagating radio impulses that are observed in reflection off the surface of the ice, leading to phase inversion of the signal. UHECR events detected by ANITA also include a subset of horizontally-propagating stratospheric air showers seen just above the horizon, which point directly at the payload, and show no phase inversion of the signal [5]. These observations have established a baseline for identification of events of UHECR origin in ANITA data.



The ANITA detection concepts, figure from ***Cosmin Deaconu****.*

From https://arxiv.org/pdf/1803.05088.pdf

The Anita Anomalous Events

these analyses. ANITA also reported two additional events, each consistent with an astrophysical ν_τ emerging from the Earth (Gorham et al. 2016, 2018b). In this scenario, a ν_τ undergoes a charged-current interaction (CC) with a nucleus in the Earth. The τ-lepton produced in this interaction subsequently decays in the atmosphere, producing an extensive air shower (EAS). The polarity of the radio signal makes it possible to identify and reject downward moving cosmic-ray induced EAS, as the radio signals of these EAS acquire a phase reversal (opposite polarity) from reflection off the Antarctic ice, while an upgoing τ induced EAS does not acquire this phase reversal. For a complete list of details of these events,

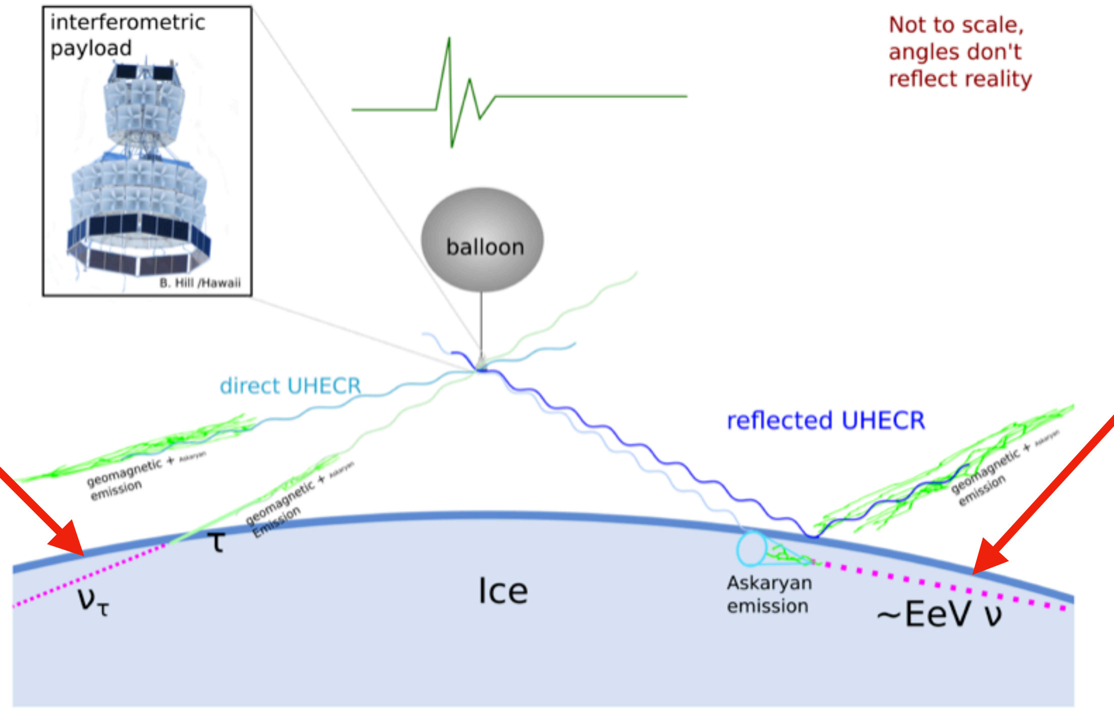
Table 1. Properties of the neutrino candidate events from the first three flights of ANITA, from (Gorham et al. 2018a, 2016, 2018b). The two Anomalous ANITA Events (AAE) are those consistent with a steeply upgoing ν_τ interpretation.

	AAE-061228	AAE-141220	AAC-150108
Event, Flight	3985267, ANITA-I	15717147, ANITA-III	83139414, ANITA-III
Detection Channel	Geomagnetic	Geomagnetic	Askaryan
Date, Time (UTC)	2006-12-28, 00:33:20	2014-12-20, 08:33:22.5	2015-01-08, 19:04:24.237
RA, Dec (J2000)[1]	282°.14, +20°.33	50°.78, +38°.65	171°.45, +16°.30
Localization Uncertainty[2]	1°.5 × 1°.5, 0°.0	1°.5 × 1°.5, 0°.0	5°.0 × 1°.0, +73°.7
Reconstructed Energy (EeV)	0.6 ± 0.4	$0.56^{+0.30}_{-0.20}$	≥ 10
Earth Chord Length (km)	5740 ± 60	7210 ± 55	-

[1] Sky coordinates are projections from event arrival angles at ANITA

[2] Expressed as major and minor axis standard deviations, position angle. This angle describes the rotation of the major axis relative to the North Celestial Pole turning positive into right ascension.

dates". In the third flight, one Askaryan neutrino candidate (AAC) event was simultaneously identified in one analysis searching for Askaryan emission (Askar'yan 1962) and was found to be subthreshold in another. This Earth-skimming event has a signal shape consistent with impulsive broad-



The ANITA detection concepts, figure from **Cosmin Deaconu**.

Why are They Anomalous?

The interpretation of these events as extremely high energy upgoing neutrinos poses many challenges under Standard Model assumptions. First, from the observation angles and reconstructed energies of the ANITA events, neutrinos are extremely unlikely to traverse the long chord lengths (Gorham et al. 2016), even after accounting for the probability increase due to ν_τ regeneration. Second, if these events are of cosmogenic origin, they would imply fluxes that are in severe tension with limits set by multiple experiments (Aab et al. 2015; Zas 2018; Aartsen et al. 2016a) as well as a self-inconsistency from ANITA data alone. For an isotropic flux of cosmogenic neutrinos ANITA should have detected many more events at other elevation angles than those of the anomalous ANITA events (AAE) as the detector differen-

On the other hand, if the origin of ANITA events is considered to be from individual cosmic accelerators there is no inconsistency with diffuse extremely-high-energy flux limits. This is especially true for accelerators with short char-

Cosmogenic

Additionally, another population of neutrinos could exist at extremely high energies. Cosmogenic neutrinos are believed to be the result of interactions between ultra-high energy (UHE) cosmic rays with the cosmic microwave background (CMB) (Greisen 1966; Zatsepin & Kuzmin 1966). This population is expected to manifest as an isotropic flux at Earth, as cosmic ray primaries can travel outside of the vicinity of their accelerators before interacting with the CMB.

ultra-high-energy (10^{20} eV) cosmic rays

Astrophysical

origins. The bulk of these astrophysical neutrinos are believed to be created in hadronic interactions between cosmic rays and ambient matter or radiation fields in the vicinity of cosmic accelerators (Gaisser et al. 1995) and their detections can be used to point back to the acceleration sites. Although the first evidence of a neutrino point source, the blazar TXS 0506+056, was reported in 2018 (Aartsen et al. 2018c,b), the overwhelming majority of the measured neutrino flux remains unexplained.

Cosmogenic vs Astrophysical Neutrinos

Cosmogenic

Additionally, another population of neutrinos could exist at extremely high energies. Cosmogenic neutrinos are believed to be the result of interactions between ultra-high energy (UHE) cosmic rays with the cosmic microwave background (CMB) (Greisen 1966; Zatsepin & Kuzmin 1966). This population is expected to manifest as an isotropic flux at Earth, as cosmic ray primaries can travel outside of the vicinity of their accelerators before interacting with the CMB.

ultra-high-energy (10^{20} eV) cosmic rays

Astrophysical

origins. The bulk of these astrophysical neutrinos are believed to be created in hadronic interactions between cosmic rays and ambient matter or radiation fields in the vicinity of cosmic accelerators (Gaisser et al. 1995) and their detections can be used to point back to the acceleration sites. Although the first evidence of a neutrino point source, the blazar TXS 0506+056, was reported in 2018 (Aartsen et al. 2018c,b), the overwhelming majority of the measured neutrino flux remains unexplained.

EeV tau-neutrinos through long chord lengths. The events are known to be inconsistent with a cosmogenic interpretation, but could have been produced by cosmic accelerators, specifically those with short characteristic timescales. We

What can IceCube Do?

changes throughout the detector's flight. If we assume that ANITA detected single events of 1 EeV from a comic accelerator with a $E^{-\gamma}$ emission power-law spectrum, then one should expect also a larger flux of neutrinos at TeV - PeV energies, where IceCube will be sensitive. Significant correlation between IceCube and ANITA data would not only provide evidence for a neutrino point source, it would also eliminate non-astrophysical explanations of the AAE, such as background and systematics or non-astrophysical models which invoke physics beyond the Standard Model.

The focus of this work is to use IceCube to investigate the hypothesis that the ANITA events were from neutrino point-sources, considering several neutrino emission time profiles.

(The short answer is no)

The Analysis

Can be a number or a function

Anita spatial PDF

$$\mathcal{L} = \lambda \prod_{i=1}^{N} \left(\frac{n_s}{n_s + n_b} S(\mathbf{x}_i, \mathbf{x}_s, \alpha) + \frac{n_b}{n_s + n_b} B(\mathbf{x}_i, \mathbf{x}_s) \right) P_A(\mathbf{x}_s),$$

IC signal PDF

IC background PDF

IC signal PDF

$$S = S^{space}(\mathbf{x}_i, \mathbf{x}_s, \sigma_i) \cdot S^{energy}(E_i, \delta_i, \gamma) \cdot S^{time}$$

S^{space}, two-dimensional Gaussian functionwith angular resolution σ_i.

S^{energy}, the probability of obtaining an event with reconstructed energy E_i given a declination δ_i under the hypothesis of an $E^{-\gamma}$ power-law energy spectrum, which helps differentiate signal from the known atmospheric backgrounds in our event selec-

S^{time} tion. The time term, S^{time} describes the time PDF of events observed from the source. While the spatial term is shared

Anita spatial PDF

P_A 2D Gaussian in prompt and steady analysis, uniform in search region in rolling analysis

IC background PDF

B describes the energy and declination PDF of our background, which is parameterized from data and is the same among all analyses. Temporal terms in B are described in sections 3.1

Prompt, Rolling and Steady Analysis

observed from the source. While the spatial term is shared between all analyses, the energy and temporal term is unique to each individual analysis. This joint likelihood procedure is carried out in three complementary search strategies: *prompt*, *rolling*, and *steady*.

- Prompt: on-time, constant emission over time windows of 10, 10^3 and 10^5 seconds
- Rolling: Gaussian emission time dependence
- Steady: Uniform time PDF over entire data collection period

- Three different test statistics, depending on lambda, the energy and temporal terms for signal PDF and the assumption for the ANITA spatial PDF

Results

> No significant correlation is found in any of the analyses above the expectation from background. In order to calculate p-values, results are compared against pseudo-experiments from time-scrambled data (Aartsen et al. 2015b). The most significant observation results from the steady search for AAE-141220, with a p-value of 0.08, which we find to be consistent with background.

What is the criterium?

No Signal, so Set Limits

steady analyses (Figure 2). To calculate upper limits, locations are sampled according to the per-event PDFs reported by ANITA, injecting the same level of flux at each sampled location, and running each iteration through the full analysis procedure which maximizes the joint likelihood at all locations on the sky. This allows us to place upper limits on point-sources whose locations are distributed according to the per-event PDF reported by ANITA. We set these limits for an assumed spectrum given by

$$\Phi(E,t) = \frac{dN_{\nu_\mu+\bar{\nu}_\mu}}{dE\, dA\, dt} = \Phi_0 \left(\frac{E}{E_0}\right)^{-2}, \quad (8)$$

where Φ_0 is a normalization constant on a point-source flux, which carries units of $\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. We constrain the time-integrated muon neutrino flux, E^2F, where

$$E^2F = E^2 \int \Phi(E,t)\, dt\,. \quad (9)$$

Prompt limits are placed at the specified time windows for emission centered on the ANITA event times, whereas limits from the steady analysis are for emission over the livetime of our data sample. This hard spectrum was chosen conserva-

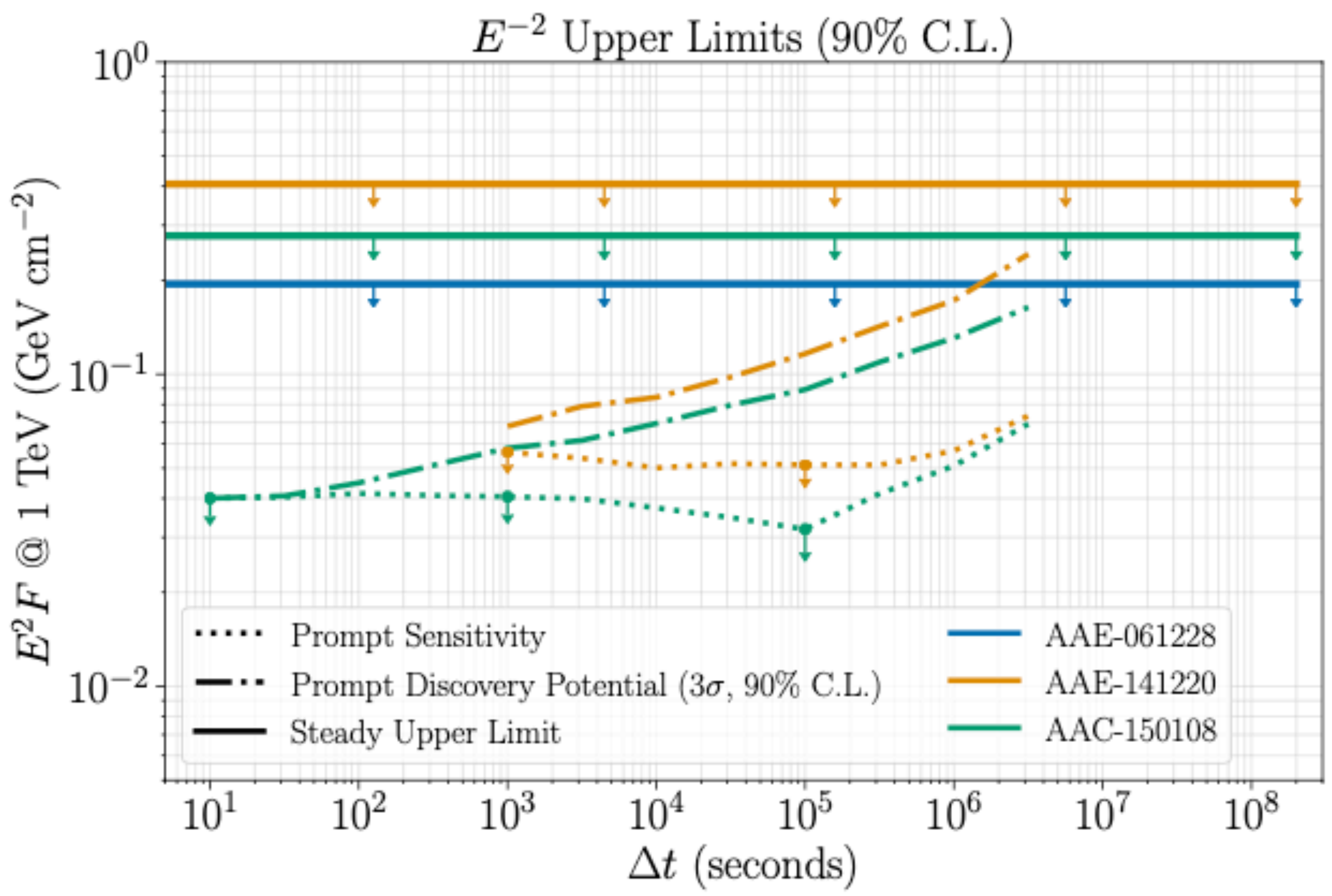


Figure 2. Sensitivity (dotted) and upper limits (arrows) (90% confidence level) on the time-integrated $\nu_\mu + \bar{\nu}_\mu$ flux normalization for an E^{-2} source spectrum as a function of Δt from the prompt analysis, compared to the upper limits (solid) from the steady analysis. The central 90% intervals of the expected neutrino energies for these spectra are 1TeV-1PeV.

our data sample. This hard spectrum was chosen conservatively because with the observation of EeV events by ANITA, if the underlying spectrum is softer, then the expected number of observable neutrinos for IceCube would increase. As

Nikhef

Discussion

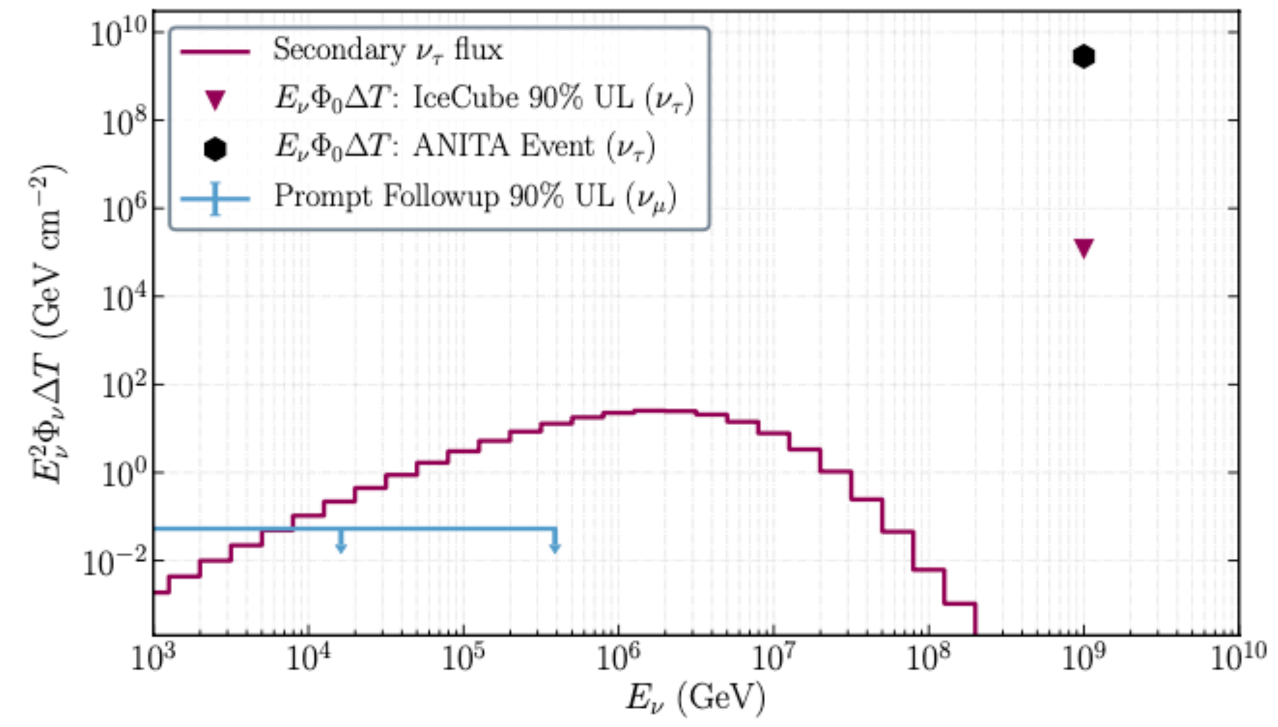
ever, for the ANITA events, interpolating a power law between the energy range at which IceCube is sensitive to the best-fit ANITA event energies could pose a problem. For soft spectra, events detected by ANITA would suggest that many events would be detectable at IceCube. For hard spectra, extrapolating between IceCube and ANITA would imply dramatic bolometric neutrino luminosities for any point source.

I'm not sure I fully understand this statement

trinos with EeV energies. As has been shown in (Safa et al. 2020), any incident flux with an EeV ν_τ component that traverses large Earth chord lengths will result in a secondary flux of lower energy neutrinos, to which IceCube would be sensitive. We use the same prescription here to analyze how constraining our limits are on a generic point source flux that includes EeV neutrinos.

sion, the limits we can set on muon neutrinos in the TeV-PeV energy range can constrain generic fluxes of incident tau neutrinos with EeV energies. As has been shown in (Safa et al.

cident on IceCube. As we observed 0 coincident events in the time window of 10^3 s around AAE-141220 in the prompt analysis, we calculate the maximum allowed flux normalization (at 90% confidence level) on the primary flux that would evade this non-observation. The results are displayed in Figure 5.

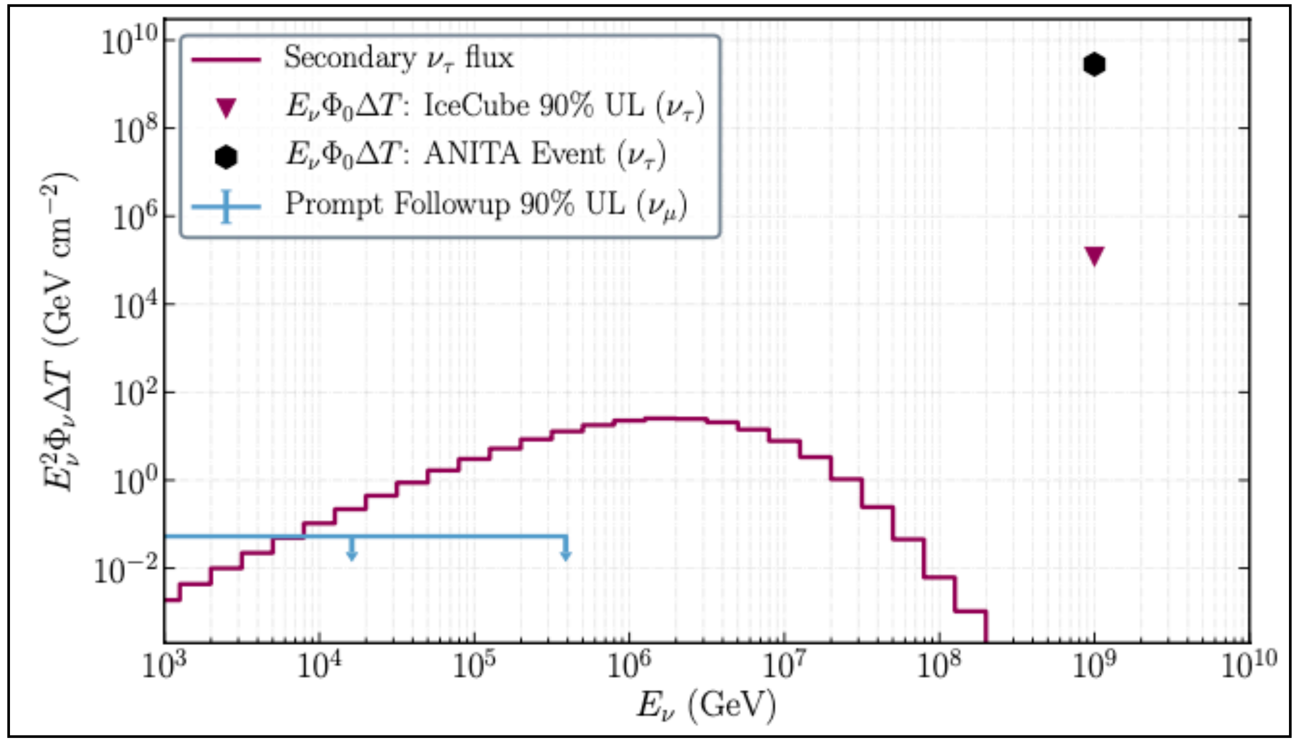


Discussion (II)

the Standard Model. However, it has been shown that these events can be explained using physics Beyond the Standard Model, as many models suggest that the AAE lend support for axionic dark matter, sterile neutrinos, supersymmetry, or heavy dark matter (Cherry & Shoemaker 2019; Anchordo-

cently been suggested that the AAE could be explained by downward-going CR-induced EAS that reflected off of sub-surface features in the Antarctic ice (Shoemaker et al. 2019). Another possible explanation could be coherent transition radiation from the geomagnetically-induced air shower current, which could mimic an upgoing air shower (de Vries & Prohira 2019). Explaining these anomalous events with systematic effects or confirming the need for new physics requires a deeper understanding of ANITA's detection volume. Efforts such as the HiCal radio frequency pulser, which has flown alongside ANITA in the last two flights (Prohira et al. 2018), are already underway to try to characterize the various properties of the Antarctic ice surface.

Conclusion



specifically those with short characteristic timescales. We show here that for timescales as small as 10^3 s, assuming AAE-141220 as originating from a neutrino source, limits set using IceCube data are more than four orders of magnitude in tension with the point source flux required to detect one event at ANITA. These limits are constraining for a va-

In addition to the anomalous events, we also find no evidence for a neutrino source in the direction of the neutrino candidate event from a search for Askaryan emission during ANITA-III. These new limits, in conjunction with the incon-

Nikhef