Measurement of Astrophysical Events in IceCube and the Implications for Ultra High Energy Neutrino Astronomy

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Abstract

Since the discovery of ultra-high energy (UHE) cosmic rays with energies greater than 10^{18} eV, scientists have theorized about their source. UHE neutrinos provide a promising tool to probe these highly energetic hadronic accelerators at the far reaches of our universe. The discovery of astrophysical neutrinos by the IceCube Neutrino Observatory opened the door to neutrino astronomy and helped motivate the search for ever higher energy neutrinos. IceCube is a neutrino telescope using a cubic kilometer of Antarctic ice to detect Cherenkov radiation from neutrino interactions. This paper will present the evidence that IceCube has detected astrophysical neutrinos will be presented. This evidence hints at the existence of even higher energy neutrinos that have yet to be detected. Consequently, a review of potential UHE neutrino sources will be discussed. In its current state, IceCube alone does not have the fiducial volume to detect the sources of UHE neutrinos. However, the observation of astrophysical neutrinos by IceCube laid the groundwork for future UHE neutrino astronomy, including experiments detecting Askaryan radio signatures. The final section of this paper will discuss the implications of IceCube's observations on the future of UHE neutrino detection and on fundamental aspects of physics.

Contents

1 Introduction

Throughout the past century, scientists have used ultra-high energy (UHE) particles to explore the most extreme events in the distant universe. These events likely accelerate hadronic matter to relativistic speeds leading to the production of three main UHE particles that can be detected on Earth: (1) cosmic rays (CRs), (2) gamma rays, and (3) neutrinos. Each of these have both advantages and disadvantages for probing the distant corners of the universe. As charge carrying particles, cosmic rays are bent by galactic magnetic fields making it difficult to retrace their origins. UHE cosmic rays have been detected, but no sources have been found. Further, at energies above $\sim 10^{19.5}$ eV, cosmic rays are attenuated by the GZK process [3]. Gamma rays are uncharged and can carry information apropos their origin; however, the gamma-ray signal leaves an ambiguity between signal creation from leptonic versus hadronic processes that has yet to be solved [17]. Only gamma-ray signals produced from hadronic processes originate from these extra-galactic phenomena of interest that would produce UHE cosmic rays. Furthermore, interstellar objects are opaque to gamma rays and high energy gamma rays above 100 TeV are absorbed by cosmic radiation [20], [31]. This leaves the highest gamma ray energy sources hidden from telescopes. The third particle, neutrinos, do not carry electric charge, and are only subject to the weak interaction and the force of gravity. This makes them distance resilient communicators, since their direction is not influenced by galactic magnetic fields and they very rarely will interact with matter.

Neutrinos are exceptional extra-galactic messengers. Born from violent events such as blazars, active galactic nuclei (AGN), gamma ray bursts (GRBs) and starburst galaxies, neutrinos are plentiful in the universe and, as elementary particles, play a significant role in understanding the fundamental questions of astrophysics. With neutrino astronomy, we can expand our understanding of the most powerful particle sources in the universe. UHE neutrino astronomy (above 10^{18} eV) seeks to provide new information in the highest energy regimes where other particles are inadequate. There are two main theories behind the origin of UHE neutrinos: (1) direct production, wherein the UHE neutrinos are coming straight from point sources, and (2) indirect production through CR interactions with the cosmic microwave background (CMB).

1.1 Production of Neutrinos

Many theories regarding the origin of UHE neutrinos are based off of extragalactic sources, which are capable of accelerating hadrons (likely protons or possibly heavier nuclei such as iron) to speeds much higher than man-made accelerators on earth [10]. These UHE hadrons interact with gas near the source or with ambient radiation, producing kaons and charged pions which subsequently decay into neutrinos and anti-neutrinos [19]. An example process can be seen below:

$$p_{uhe} + \gamma_{bg} \rightarrow n + \pi^+$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

1.2 GZK Neutrinos

At above 5×10^{19} eV, cosmic rays interact with the CMB through the delta resonance, producing neutrinos and allowing reconstruction back to the source due to the observation distance being relatively short on a cosmological scale. This process is called the Greisen-Zatsepin-Kuzman (GZK) process and is outlined below.

$$\gamma_{\text{CMB}} + p \rightarrow \Delta^+ \rightarrow p + \pi^0$$

$$\gamma_{\text{CMB}} + p \rightarrow \Delta^+ \rightarrow n + \pi^+$$

The neutral pion will decay into photons, but the charged pions will decay into UHE neutrinos called cosmogenic or BZ neutrinos (after Berezinksy and Zatsepin) [16]. The GZK process promises that as long as UHECRs above the threshold energy of 5×10^{19} eV exist, there will be the production of UHE neutrinos.

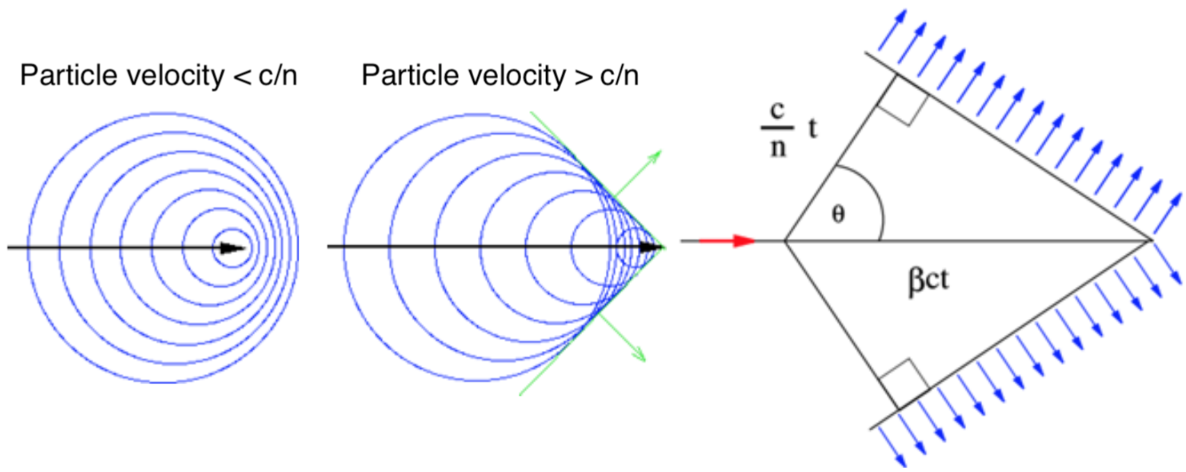

Figure 1: Illustration of the Cherenkov Effect. If the particle velocity is less than c/n, the resulting electromagnetic radiation does not constructively interfere (left). When the particle velocity is greater than c/n, the radiation constructively interferes (center). This produces a cone of light (right) [37]

1.3 Detection of Neutrinos Through The Cherenkov Effect

High energy neutrinos interact with a nucleus primarily through deep inelastic scattering through the weak interaction. There are two types of interactions that neutrinos experience: (1) neutral current (NC) which is mediated by a Z boson, and (2) a charged current (CC) which is mediated by a W boson [19]. These interactions can be seen below [15], [34]:

$$\overset{(-)}{\nu}_l + N \rightarrow \overset{(-)}{\nu}_l + X \qquad (NC)$$

$$\overset{(-)}{\nu}_l + N \rightarrow l^{\pm} + X \qquad (CC)$$

Where N is the nucleus, l is the lepton flavor and X is a hadronic shower. Most current neutrino detection techniques are focused on an indirect method of searching for the remnants of these two types of weak interactions. One major technique is through the detection of optical Cherenkov radiation from the products of these neutrino interactions. Cherenkov radiation occurs when a charged particle propagates through a medium faster than that of the speed of light in the same medium. Radiation is given off by individual atoms as the particle passes nearby. The radiation then constructively interferes, producing a cone of optical light (Figure 1 above).

Cherenkov light from neutrino interactions in a medium can produce either track or cascade signatures. Tracks are the byproduct of a CC interaction involving a muon neutrino with the ice, which results in the production of a muon. Due to its relatively long lifetime of 2.197×10^{-6} s, the muon propagates producing Cherenkov radiation with line-like features (i.e. tracks), leaving a cascade only in the initial interaction region (Figure 2 left). Due to the short propagation distances of the tau and electron a CC interaction generates a cascade containing light from the superposition of the hadronic shower and the produced lepton (Figure 2 right). NC interactions are similar for all three flavors of neutrinos, producing only a hadronic cascade with the neutrino product likely propagating undetected.

2 The IceCube Neutrino Observatory

2.1 Introduction to IceCube

The IceCube Neutrino Observatory is a cubic kilometer, optical Cherenkov detector located in Antarctica. IceCube aims to measure signals created from particles – such as neutrinos and cosmic rays – emitted from astrophysical sources with hopes of gathering information about their origin [39]. With ice as a medium, neutrinos interact with nuclei, producing Cherenkov radiation. An enormous volume of ice is necessary for detection due to the extremely small interaction cross-section of neutrinos, as well as the low flux expected. Antarctica's three

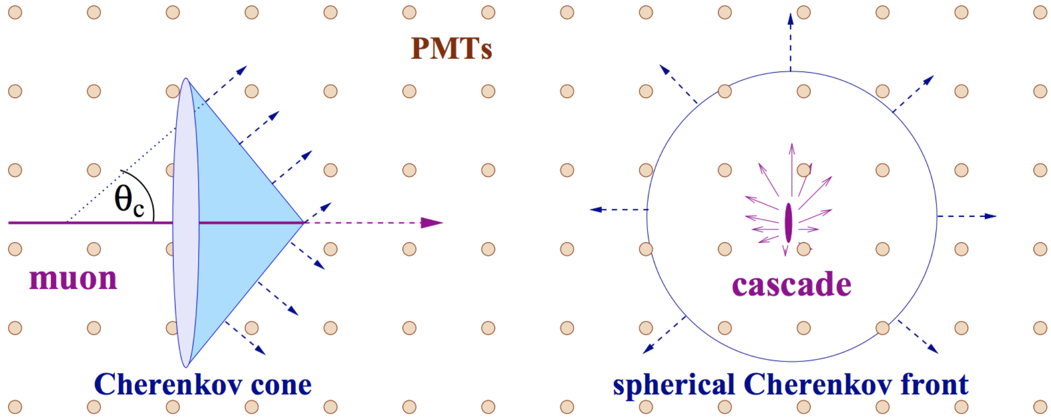

Figure 2: Possible Cherenkov light signals in IceCube. Muons produce a track (left), while hadronic showers from other neutrino interactions produce a short burst of spherical light (right). The tan circles represent Photo-Multiplier Tube (PMT) light detectors. [11]

kilometer thick ice cap provides a large and optically transparent interaction medium [31].

2.1.1 Astrophysical Neutrinos

At energies greater than 10 GeV, there are three main relative energy groups of neutrinos detected by IceCube: high, very-high, ultra-high. High energy neutrinos have energies of about 10^6 eV (1 MeV) to 10^{13} eV (10 TeV) and the main expected sources are individual supernova, supernovae remnants (the Diffuse Supernova Background), and most commonly atmospheric cosmic ray interactions. Neutrinos originating in the atmosphere are within IceCube's designed range of energies and are commonly detected. Atmospheric neutrinos occur from interactions between cosmic rays and particles in the earth's atmosphere. The interactions produce a shower of particles, some of which decay into neutrinos with energies ranging from 10^7 (10 MeV) to 10^{14} eV (100 TeV). Very-high energy neutrinos have energies ranging from about 10^{13} eV (10 TeV) to 10^{17} eV (100 PeV). Atmospheric neutrinos could fall into the lower aspect of this range, although at a very low flux. In the ultra-high energy range, neutrinos would have energies greater than 10^{17} eV. Very-high and ultra-high neutrinos could originate directly from a variety of possible point sources including Active Galactic Nuclei. These sources could also produce neutrinos indirectly from UHE cosmic rays interacting with the CMB through the GZK interaction to produce neutrinos as described above.

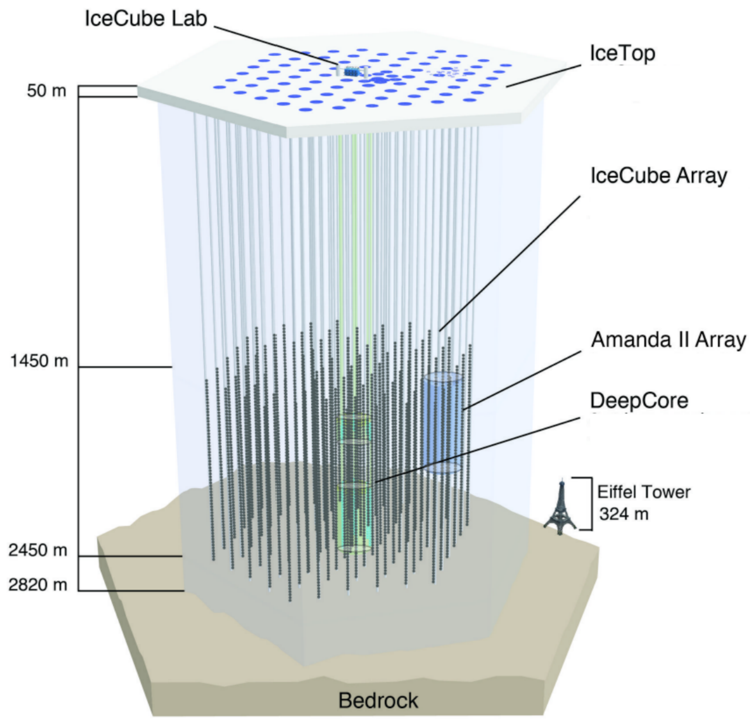

Figure 3: Schematic of IceCube Neutrino Observatory [10]

2.2 Instrumentation

IceCube consists of a lattice of photo-multiplier tubes (PMTs) buried over 1 km deep in Antarctic ice to detect Cherenkov radiation (Figure 3. IceCube's instrumentation allows for the detection of both tracks and cascades, and the estimation of the parent neutrino's energy and direction [8]. The number of photons produced is directly proportional to the energy of the parent neutrino [7]. For both tracks and cascades, the energy of the parent neutrino can be calculated from the deposited energy within 15%. Since muons of high energy can travel distances larger than that of the detector's dimensions, the energy has to be calculated indirectly [24]. The energy loss of the muon throughout the detected track is used to estimate the parent neutrino's energy [2]. In addition, tracks allow for a better directional reconstruction within $<1^\circ$ of the parent neutrino compared to $\sim 15^\circ$ for cascades.

The main volume of IceCube is an array of 5160 digital optical modules or DOMs (each containing a PMT) installed below the ice top between 1450 m and 2450 m on 86 strings [8]. Each string holds 60 DOMs, which reside along a single cable. For the In-Ice array, each vertical string has a separation of 17 m per DOM. The strings are arranged over a volume of one cubic kilometer of ice in a hexagonal pattern on a triangular grid with a 125 m horizontal spacing [8]. Note that depths between 2000 m and 2100 m are not instrumented due to a "dust layer" where the ice contains impurities resulting in optical scattering and absorption. DeepCore is a denser central region of DOMs beneath 1750 m that provides insight into lower energy neutrinos. IceTop is an array of DOMs on the surface of the ice with the main goal of detecting secondary particle showers resulting from interactions of high-energy cosmic rays in the atmosphere. The instrumentation of IceCube allows identification of both tracks and cascades caused by neutrino interactions as seen in Figure 4.

3 Analysis

IceCube detects more than 3,000 events per second, with the vast majority being atmospheric muons (not to be confused with muons produced from neutrino interactions). Therefore, the challenge of IceCube's cosmic neutrino analysis is to differentiate the hundred thousand atmospheric neutrinos per year from the billions of muon events per year and search the neutrino events to find the tens of astrophysical neutrinos [4]. IceCube overcomes this challenge in two main ways: (1) only utilizing events that originate in the detector, and (2) using the earth as a filter of atmospheric muons, thus only examining upward and horizontal going events [9]. Overall, the IceCube analysis is based on demonstrating that the probability of

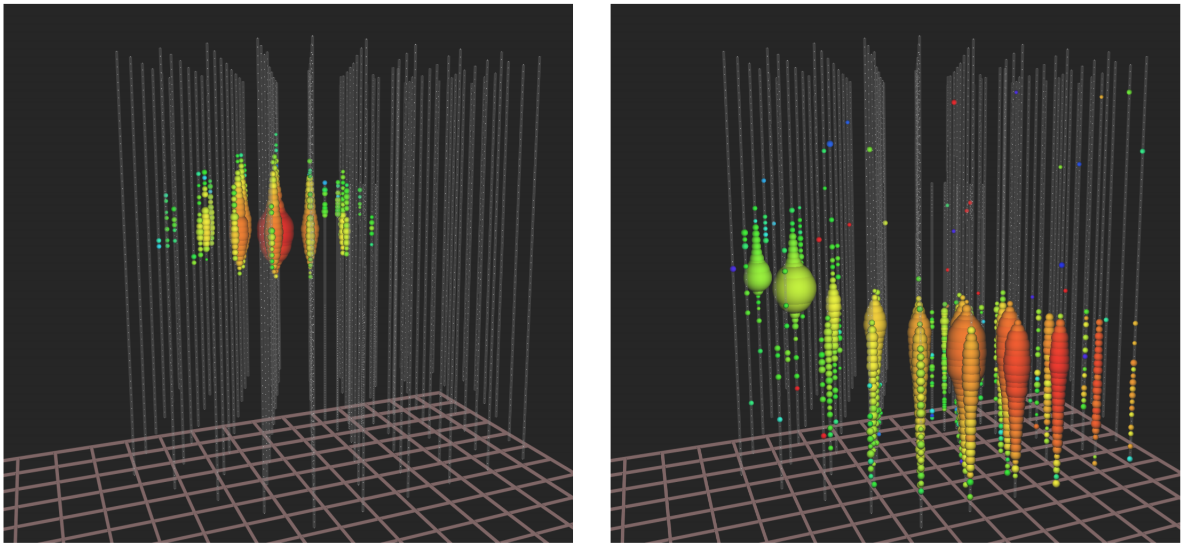

Figure 4: Representations of two high energy neutrino events detected by IceCube. Each faint vertical white line represents a string of detectors with white dots representing DOMs that did not detect any photons. The color illustrates the arrival time of the signal, with red being the earliest and blue being the latest. The larger the sphere, the more photons detected. On the left, a spherical cascade from an electron or tau neutrino is shown with a deposited energy of 1.16 PeV. On the right, an upgoing muon track from a neutrino is shown with a deposited energy of 2.6 PeV [10]. These events can be compared to the drawings in Figure 2. Every high energy event can be seen in 3D at `icecube.wisc.edu/viewer/he_neutrinos`

a group of high energy filtered events originating from only atmospheric origins is extremely small. In 2013, IceCube presented results describing a flux of neutrinos unlikely to be from atmospheric origins, and thus became the first experiment to provide evidence of a very-high energy extraterrestrial flux of neutrinos. The analysis identified 28 very-high energy neutrinos that rejected purely atmospheric origins at a 4σ level [1]. Since that initial discovery, IceCube has continually improved the analysis using more years of data and refined analysis techniques.

3.1 Methods of Analysis

3.1.1 High Energy Starting Events Analysis

In order to properly eliminate atmospheric muon background, one type of IceCube analysis, called High Energy Starting Events (HESE), only uses events that originated within the detector [4]. To accomplish this, the outer layers of DOMs are considered a veto layer, while interior DOMs are considered the active fiducial volume [10].

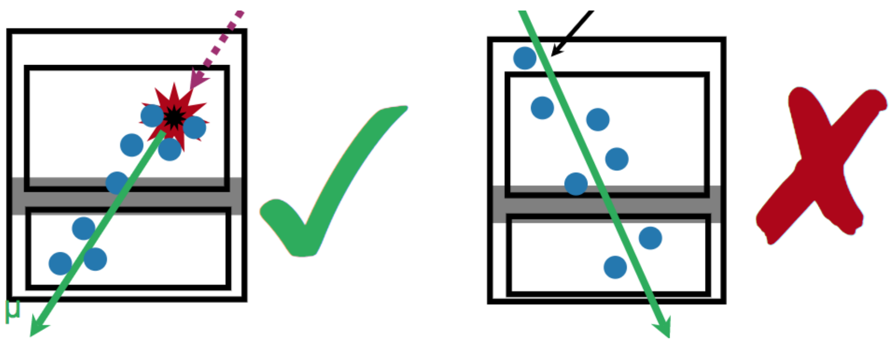

Figure 5: Drawing of how events can be eliminated through the use of a veto layer. The outer boundary represents the entire detector volume, while the inner boundaries represent the fiducial volume. On the left, the neutrino interacts within the fiducial volume and thus no light is initially registered in the veto layer. On the right, however, the muon enters the detector by first passing through the veto layer and thus the event can be eliminated. The grey region is the dust layer. [26]

Atmospheric muons that create Cherenkov light during their entire flight through the ice are the main source of background. This means if an atmospheric muon enters the IceCube detector, it will create light from edge to edge as it passes through. By eliminating events whose first signal occurs within the veto layer (an indication that a particle produced light before entering the detector), atmospheric muon events can be eliminated. Notably, this technique will also eliminate muons from a muon neutrino CC interaction that began outside the detector before crossing into the fiducial volume. Since low energy muons produce less Cherenkov radiation, it is possible for them to slip through the veto layer undetected. Thus, the IceCube collaboration set a minimum threshold energy to eliminate atmospheric muons that could have travelled past the veto layer [4].

Specifically, the cuts are defined so that fewer than 3 of the first 250 photoelectrons may be on the outer boundary of the detector (veto layer) and that there must be a minimum of at least 6000 photoelectrons – corresponding to about 30 TeV [32].

3.1.2 Upgoing Muon Analysis

Muons are unable to travel significant distances through the Earth because they lose energy from multiple radiation processes as they propagate. This grants IceCube the ability to utilize the Earth as a filter against upgoing atmospheric muons, only needing to remove the background from muons coming from above. Even the most energetic muons can only travel a few kilometers through the ice, with a 10^{13} eV (10 TeV) muon traveling 6.09 km-water equivalent [27]. If the zenith angle of an event in IceCube is any larger than $\sim$85 degrees, virtually all atmospheric muons will have been absorbed and thus signals are likely from neutrinos, even if the neutrino interaction occurred outside the detector [7]. Therefore, IceCube can say with a high degree of statistical certainty that all horizontal or upgoing events are from neutrinos. This technique allows for all of the detector to be used as the fiducial volume, but only uses neutrinos with directions from horizontal to upgoing through the northern hemisphere [4]. Using this technique, IceCube has accurately measured the flux of lower energy atmospheric neutrinos and also detected astrophysical neutrinos.

3.2 IceCube Astrophysical Neutrino Results

3.2.1 Astrophysical Neutrinos

IceCube has used the two aforementioned different background rejection methods to identify events that likely originated in extragalactic sources. In order to achieve statistical significance, these events have been compared to the expected background flux extrapolated to high energies. The combined resulting astrophysical fluxes can be seen in Figure 6.

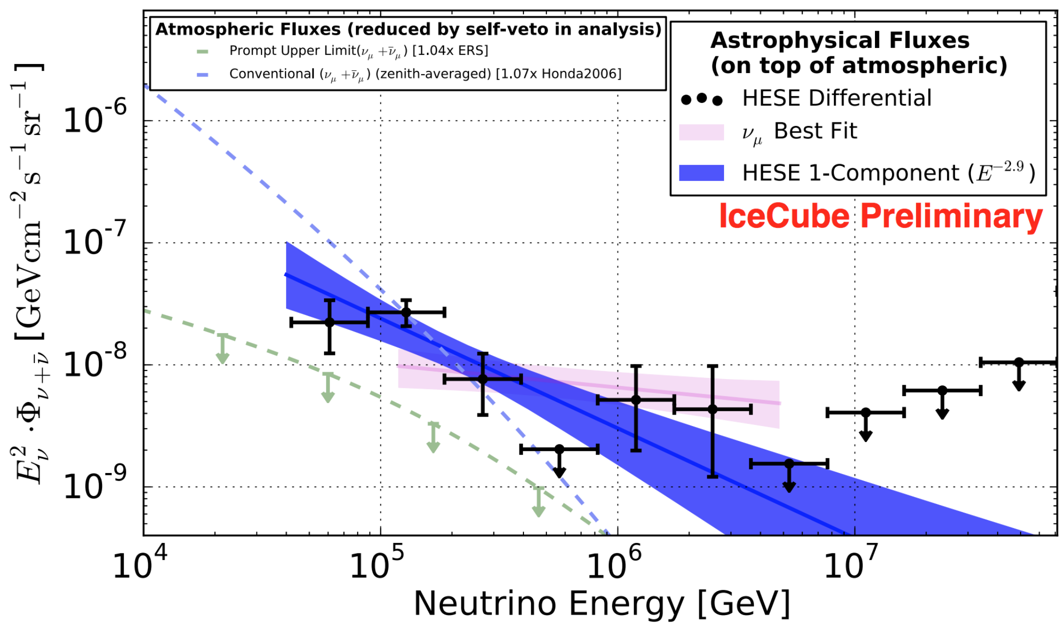

Figure 6: Results from HESE (Blue, $\Gamma = 2.92$, Figure 7) and Upgoing Muon neutrino fluxes (Pink, $\Gamma = 2.19$, Figure 8). The bands show 1σ uncertainties. [32]

3.2.2 HESE Results

The HESE analysis predicts a neutrino flux based on a likelihood of the expected background components (atmospheric muons, atmospheric neutrinos and prompt charm decay) and compares it to the detected flux. It is possible, although very unlikely, that a muon can pass through the outer veto layer and appear as a starting event, especially those near the lower energy regime [32]. Using upper limits of 95% confidence levels predicted for background events, the six year HESE analysis predicted 25.3± 7.3 false neutrinos detected from these muons. Another potential source of false extragalactic neutrinos is from the decay of charm-containing mesons produced by cosmic ray interactions. This so called prompt (from the quick decay) component was estimated to produce at most $15.6^{+11.4}_{-3.9}$ events over the 6 years [32]. This resulted in a upper estimate of 59.6 atmospheric events detected over six years in the very high energy range, that were not removed from the various vetoes. The background and data can be seen in Figure 7. Compared with the detection of 82 total

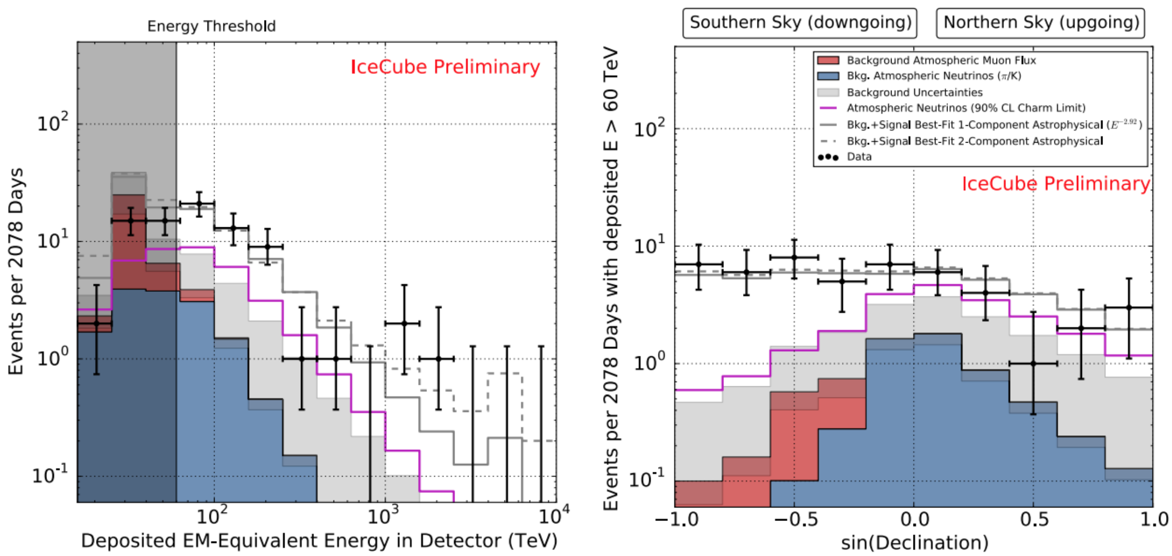

Figure 7: Culmination of six years of HESE data. On the left, the deposited energy is compared to the number of events. The gray region shows uncertainties on the sum of all backgrounds. The background fluxes are determined from past measurements and simulations. The predicted astrophysical flux is well defined by a power law with a spectral index of $\Gamma = 2.92$. On the right, a histogram of the declination ($\delta = \theta - \pi/2$ where θ is the zenith angle) is shown for events greater than 60 TeV. Of particular note, the muon background only occurs in the southern hemisphere (this can be used for analysis as demonstrated in the next section. Also, the astrophysical events are flat in the southern hemisphere, indicating a isotropic flux. [32]

events above 30 TeV suggests a high likelihood that the excess is caused by a astrophysical neutrino flux at 8σ. The best fit flux is given in Equation 1.

$$F(E) = \left(2.46 \pm 0.8\right) \cdot \left(\frac{E_\nu}{10^{14} eV}\right)^{-2.92} \cdot 10^{-27} eV^{-1} cm^{-2} s^{-1} sr^{-1} \tag{1}$$

3.2.3 Upgoing Muon Results

The most recent analysis of upgoing muons was done using eight years of data from 2009 to 2017 and detected over 500,000 neutrinos with approximately 1000 astrophysical neutrino events. Through a likelihood analysis that compared the data to a Monte-Carlo simulation that calculated the expected events for each type of background in bins of zenith angle and

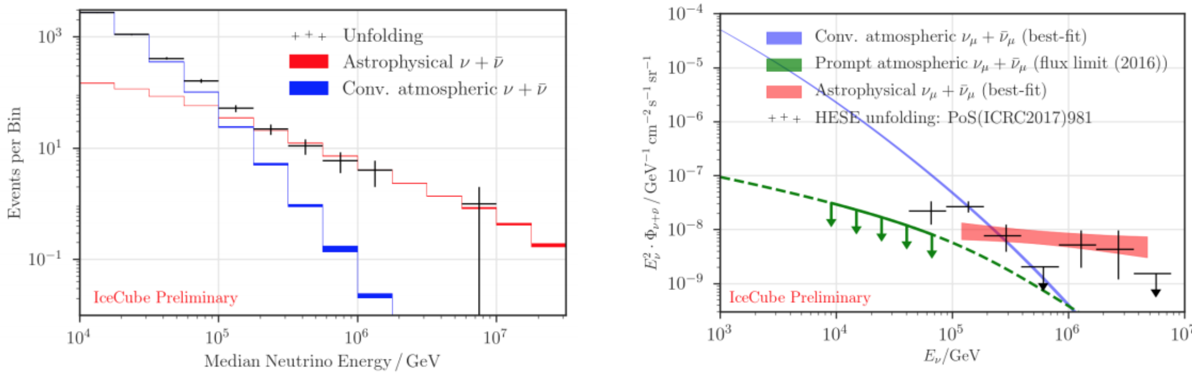

Figure 8: Measured astrophysical flux from upgoing muons over eight years. Left: Unfolded neutrino energy spectrum in comparison to the best-fit fluxes. Right: Uncertainty range of the observed astrophysical per-flavor flux (spectral index $\Gamma = 2.19$), in comparison with the best fit atmospheric background and the results from the HESE analysis. [23]

energy, the flux is determined at energies above 200 TeV. The results can be seen in Figure 8 and rejects a purely atmospheric only hypothesis at 6.7σ. In total there were 36 events detected above energies of 200 TeV with the highest energy detected event to date with median predicted energy of 7.8 PeV. The best fit flux is given in Equation 2.

$$F(E) = \left(3.03 \pm \begin{matrix} 0.26 \\ 0.23 \end{matrix}\right) \cdot \left(\frac{E_\nu}{10^{14} eV}\right)^{-2.19 \pm 0.10} \cdot 10^{-27} eV^{-1} cm^{-2} s^{-1} sr^{-1} \quad (2)$$

3.2.4 IceCube's Search for Potential Sources

Additional IceCube analysis searches for the existence of anisotropies, as well as directional coincidence of both neutrino signals and known point sources [33]. In the search for anisotropies, the astrophysical neutrino events can be plotted, depicting their arrival directions. Figure 9 below shows the combined events from both the upgoing muon analysis and the HESE data set and the probabilities of point sources.

When the predicted absorption rates of the Earth are taken into account, the arrival of astrophysical neutrinos is isotropic and shows no correlation to potential sources [7], [10], [40]. This is seen on the right in Figure 9, which shows the probability that the detected astro-

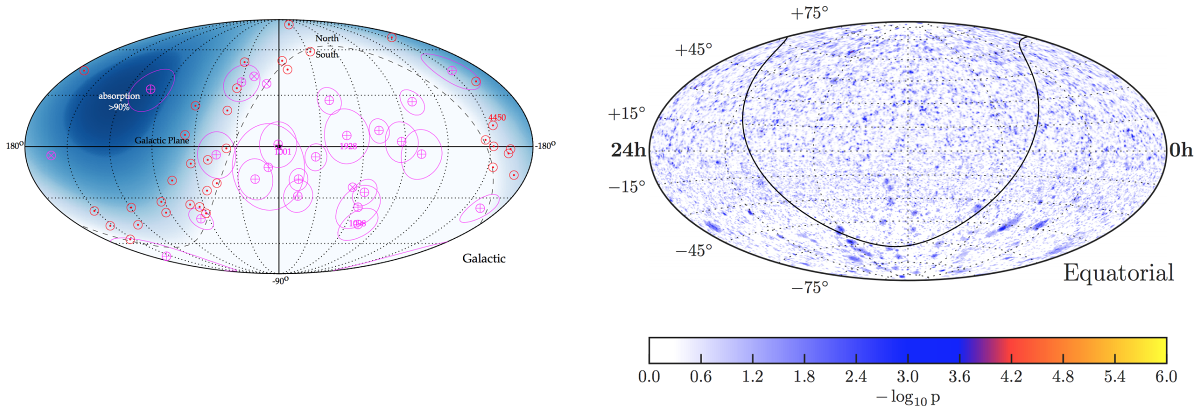

Figure 9: Left: A map showing the directions of astrophysical neutrino events from both HESE and upgoing Muon analysis. HESE events are shown in magenta, with tracks indicated by ⊗ and cascades indicated by ⊕. Upgoing muon events are indicated by a red ⊙. The outer circles indicate the directional uncertainty. The blue shading represents the likelihood of absorption by the earth prior to reaching the detector. The circles around each event represent the uncertainty in the direction [7]. Right: A map showing the p-values that an excess of events is due to a fluctuation of the expected background. No clustering was significant to indicate a specific source and thus an isotropic flux is seen. [10]

physical neutrino excess is a fluctuation of the background, and further supports a diffuse background of astrophysical neutrinos [7]. The result of an isotropic diffuse neutrino flux suggest that astrophysical neutrinos detected most likely originated in many weak sources that are below the point source sensitivity limits for detection [7]. More events are needed to differentiate a particular point source from the currently detected diffuse flux and overcome the poor angular resolution of cascade events. Another technique to find the origin of high energy neutrinos is to compare the locations of known potential point sources to astrophysical neutrino events. No potential candidates have been found with an excess of neutrino events in the same direction [7]. The following section will highlight some potential sources and the results of any examination of known sources.

4 Theoretical Sources

The isotropic neutrino arrival direction implies that it is improbable that galactic sources are major contributors to an astrophysical neutrino flux as there is no concentration of events in the galactic plane [10]. On the other hand, the demonstrated isotropic neutrino arrival direction provides a boon to theories of some extragalactic sources, whose source populations would interact with earth from all directions. Some models that have been proposed are: cosmogenic BZ neutrinos, active galactic nuclei (including blazars), starburst galaxies and various types of gamma ray bursts [7], [9].

4.1 UHECR and GZK Events

After more than 7 years of data collection, IceCube has never seen a neutrino in the energy range expected of GZK generated cosmogenic neutrinos. The limits set by the lack of events has excluded multiple UHECR scenarios [7]. Furthermore, using combined results from UHECR detectors, the flux of UHECR can be compared to astrophysical neutrinos events. However, as seen in Figure 10, no correlation was found.

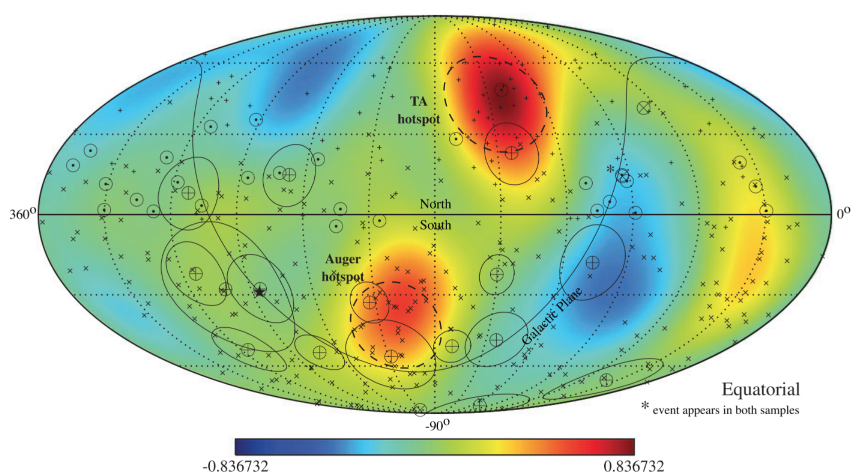

Figure 10: A map of the anisotropy of cosmic rays superimposed on the isotropic neutrino events. There is no statistically significant relation between the two fluxes [9], [36].

4.2 AGN/Blazars

An Active Galactic Nucleus (AGN) is a particular type of compact galactic nucleus that emits electromagnetic radiation with an exceptionally high luminosity. This radiation is likely caused by the accretion disc of a supermassive black hole in the center of the galaxy [36]. Some models predict the emission of gamma rays from AGNs is due to hadronic acceleration with subsequent $p\gamma$ or pp interactions leading to pion production. One particular subclass of AGN, blazars, have shown significant promise to be a major source of astrophysical neutrinos [28]. Blazars are described by the relativistic jets shooting out from the accretion disk containing extremely high energy particles that are pointed toward the earth. Current IceCube analysis comparing blazars identified by Fermi LAT (a gamma ray telescope) to astrophysical neutrinos yields that their contribution is at most 20% of the observed flux [7], [36], [40]. There is, however, some anecdotal evidence that has yet to be statistically significant. One of the highest energy ($\sim$2 PeV) astrophysical neutrinos was detected in the direction of a gamma ray flare from blazar PKS B1424-418 in December of 2012 [29]. More recently, in September 2017, a 0.3 PeV neutrino was found to be within 0.1 degree of a flaring blazar [10]. However, both these events still do not overcome a background excess and remain statistically insignificant.

4.3 Gamma Ray Bursts

Gamma Ray Bursts (GRBs) are extremely bright flashes of gamma rays lasting from less than a second to more than ten minutes [31]. Currently theories predict they are caused by the collision of two compact objects or the core collapse of a massive star. Similar to the diffuse neutrino flux, they are distributed isotropically; however, a search of the prompt emission of 807 GRBs found no coincident neutrinos above background [5]. These results constrain bright GRBs to less than 1% of the observed cosmic neutrino flux [5], [40]. However, GRBs can not be completely eliminated, as Lower Luminosity GRBs (LL GRB), also known as choked-jet

GRBs, could contribute a larger fraction of the observed neutrino flux [7]. The dimness of LL GRBs ensures that they have only been observed at very close distances [36]. Choked-jet GRBs occur when the electromagnetic emission (including gamma rays) are blocked by an opaque external material, but neutrinos could proceed through this uninterrupted [38]. More clustered neutrino events could signal the existence of such choked GRB sources.

4.4 Supernovae

Similar to GRBs mentioned above, Supernovae could create jets that are choked by the envelope of the star with only neutrinos escaping [7]. Although supernovae can be seen optically, deep space observation is only available in limited regions. To overcome this, the IceCube collaboration reversed the point source investigation by having other telescopes explore particular neutrino event directions. Thus far, no distant supernovae have been found to cause the astrophysical neutrinos detected by IceCube [7]. Of course, the 1987 Supernova produced many detected neutrinos, but unfortunately, no similarly close supernova has occurred since the construction of IceCube. A false positive occurred when two upgoing track signatures were detected within 1.6 seconds and the Palomar Transient Factory found a supernova compatible with the neutrino directions. However, further investigation found the supernova was more that 160 days old and thus unlikely to have produced the neutrinos [7]. Another supernova has been found to coincide (1.2 σ) with 4 low energy events, but with poor directional resolution of the cascade events, the result is not significant [35].

5 Implication of Results

5.1 Introduction to the radio technique

The discovery of astrophysical neutrinos by IceCube has opened the door to a new field of neutrino astronomy capable of probing the most distant and violent events of the universe.

However, the extremely low flux of astrophysical UHE neutrinos means that other experiments will need to take over the investigations into higher energies [33]. Despite IceCube's massive size, much larger detectors are needed to detect enough astrophysical neutrinos to make more confident claims on their sources and flux. Recognizing this, the IceCube collaboration is working toward a second generation detector, that will increase the fiducial volume by a factor of ten. To be cost effective, the experiment aims to increase the spacing of strings to allow more volume at a manageable price [30]. Nonetheless, a number of newer experiments have arisen hoping to record the Askaryan radio signature from neutrino interactions with Antarctic ice [12].

5.1.1 Askaryan Radiation

Askaryan radiation occurs when a neutrino traveling faster than light through a dielectric interacts with a nucleus and produces a hadronic shower. As previously outlined, this shower emits Cherenkov radiation; however, due to a 20% negative charge anisotropy of the hadronic shower (from Compton Scattering and positron annihilation with electrons in the medium), a coherent cone of radiation in the radio regime is also emitted if the net charge propagates faster than light in the medium [20]. This radio signal can be detected using properly designed antennas. Similar to how IceCube uses PMTs to detect the light from Cherenkov radiation from a neutrino interaction, experiments can use antennas to detect the radio waves from Askaryan radiation from the same interaction. The benefit of detecting Askaryan radiation is that the radio signal in ice has a much larger attenuation length (up to 1600 m) than that of optical radiation (100 m) which allows for a greater detection volume [20].

5.1.2 ARA, ANITA, and ARIANNA

A number of experiments have been developed in order to detect the Askaryan radiation from UHE neutrinos, including ANITA, ARA and ARIANNA [20]. The ANtarctic Impulse Tran-

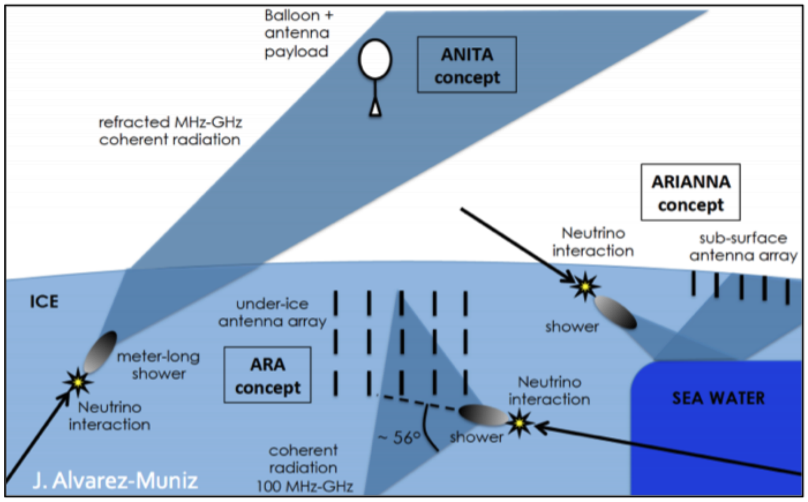

Figure 11: A illustration of three Antarctic based neutrino radio telescopes discussed in this section: ANITA, ARA and ARIANNA.

sient Antenna (ANITA) is a UHE neutrino experiment that flies an array of horn antennas 37,000 meters above the Antarctic ice to detect Askaryan pulses from neutrinos interacting with the ice [22]. There have been four flights of ANITA with the first in 2006 and the most recent in late 2016. The Askaryan Radio Array (ARA) is a radio Antarctic telescope analogous to IceCube. ARA uses a hexagonal array of antennas buried in the ice to detect the radio pulse from neutrino interactions [13]. The large distance that the Askaryan radio waves travel in ice allows individual detector stations to be spaced 2 km apart apart which massively increases the potential fiducial volume compared to IceCube. The Antarctica Ross Ice-Shelf Antenna Neutrino Array (ARIANNA) is another Antarctic based radio neutrino telescope. ARIANNA consists of antennas buried in the ice of the Ross Ice-shelf. When a Askaryan radio pulse hits the water beneath the shelf it is reflected back toward the antenna array [14]. This increases ARIANNA's effective area because the experiment can observe neutrinos whose radio pulses are both directed toward the volume and reflected off the water. The current published limits of these radio based experiments can be seen in Figure 12, along with any published limits for future expansions.

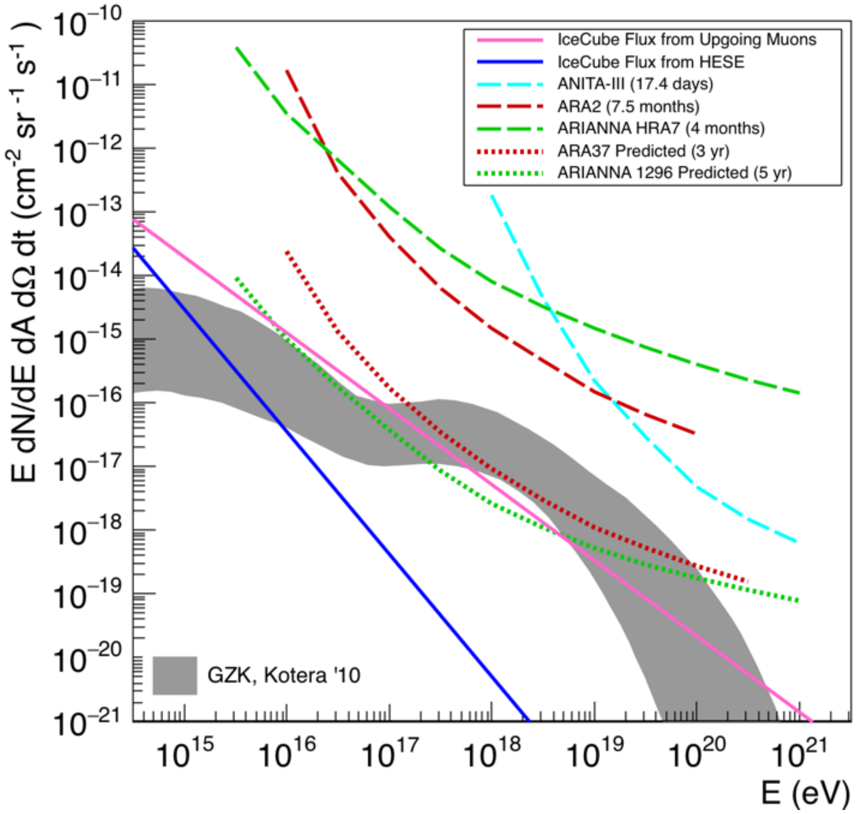

Figure 12: Current and Predicted UHE Neutrino Limits from Radio Telescopes. The IceCube astrophysical flux used in this analysis is shown in black. Adapted from [12], [14], [20], [22].

5.2 Estimation of UHE events detected by radio experiments

To date, no neutrinos have been detected in the ultra-high energy regime. Consequently, our understanding of this region is based on three techniques: theoretical predictions (based on the energies of other detected particles), limits set by neutrino experiments, and the astrophysical flux determined by IceCube. In the following sections, the IceCube fluxes will be used in conjunction with information from radio experiments to predict the number of UHE neutrino events future radio experiments could detect.

5.2.1 UHE Neutrino Flux

Since the initial discovery of astrophysical neutrinos, IceCube has proposed an ever evolving list of models to describe the flux. The simplest expression for neutrino flux is given by an isotropic power law:

$$F(E) = \Phi_0 \cdot \left(\frac{E_\nu}{100TeV} \right)^{-\gamma_{astro}} \tag{3}$$

Where the flux has been normalized at 100 TeV and γ_{astro} is the spectral index (also written as Γ). For the proceeding analysis, an astrophysical neutrino flux was chosen from the IceCube collaboration's recent analysis on HESE in Equation 1 and on upgoing muon neutrinos, given in Equation 2. These fluxes can be seen in pink and blue respectively in Figure 6 and Figure 12. Equation 1 and Equation 2 can be extrapolated to the ultra high energy regime to be used as a rough estimate of the flux at ultra-high energies.

5.2.2 Derivation of the number of events

The flux is a measurement of the number of neutrinos per energy per effective area per solid angle per second. This can be mathematically expressed as:

$$F(E) = \frac{dN}{dE_\nu \ dA_{eff} \ d\Omega \ dt} \tag{4}$$

Where N is the number of particles, A_{eff} is the effective area, t is the time and Ω is the fractional sky coverage or solid angle [21]. The differential can then be separated and integrated to find the number of particles. This is done under the assumption that the effective area is constant over each energy bin and that each variable is independent of their relationships known [21].

$$dN = F(E) \ dE_\nu \ dA_{eff} \ d\Omega \ dt$$

$$\int dN = \int F(E)\ dE_\nu \int dA_{eff} \int d\Omega \int dt$$

$$N = F(E) \cdot \Delta E \cdot T \cdot \left[\Omega A\right]_{eff} \tag{5}$$

Where ΔE is the energy bin, T is the operational time of the experiment, and $\left[\Omega A\right]_{eff}$ is called the acceptance. Therefore, in order to predict the number of events a particular experiment will detect at a given energy range and time frame, the flux and acceptance must be substituted into Equation 5. As the flux that will be used is given in Equation 1 and 2, the only remaining variable is the acceptance of the radio detectors. The acceptance of the current radio experiment detectors was found in the literature and can be seen in Table 1.

Table 1: Acceptances of some radio neutrino experiments [14], [22]

	Acceptance ($cm^2 sr$)		
Energy (eV)	ANITA III	ARA 37	ARIANNA
10^{16}	-	1.08×10^{7}	1.49×10^{7}
10^{17}	-	1.84×10^{8}	2.84×10^{8}
10^{18}	3.80×10^{6}	2.33×10^{9}	5.35×10^{9}
10^{19}	3.10×10^{9}	1.03×10^{10}	2.99×10^{10}
10^{20}	1.40×10^{11}	3.02×10^{10}	1.11×10^{11}
10^{21}	1.09×10^{12}	-	-

Inserting the IceCube flux and acceptance into energy bins centered at each decade as well as a time of one year, Equation 5 becomes:

$$N = \left(3.03 \cdot 10^{-27}\right) \cdot \left(\frac{E_\nu}{10^{14} eV}\right)^{-2.19} eV^{-1} cm^{-2} s^{-1} sr^{-1} \cdot \Delta E \cdot 1\ year \cdot \left[\Omega A_{eff}\right]$$

$$N/yr = \left(9.55 \cdot 10^{-20}\right) \cdot \left(\frac{E_\nu}{10^{14} eV}\right)^{-2.19} \cdot \frac{\Delta E}{eV} \cdot \frac{\Omega A_{eff}}{cm^2 sr} \tag{6}$$

The resulting number of events per year for each experiment is given in Table 2. Muon Refers to flux determined in the upgoing muon analysis. HESE refers to the flux determined from the High Energy Starting Event Analysis

Table 2: Predicted astrophysical neutrino events for some radio neutrino experiments

Energy (eV)	Binned Number of Events per year					
	ANITA III		ARA 37		ARIANNA 1296	
	Muon	HESE	Muon	HESE	Muon	HESE
10^{16}	-	-	0.12	3.4×10^{-3}	0.56	4.8×10^{-2}
10^{17}	-	-	1.35	7.1×10^{-3}	0.69	1.1×10^{-2}
10^{18}	1.8×10^{-3}	1.7×10^{-6}	1.10	1.1×10^{-3}	0.84	2.5×10^{-3}
10^{19}	9.5×10^{-2}	1.7×10^{-5}	0.31	5.7×10^{-5}	0.30	1.7×10^{-4}
10^{20}	0.27	9.3×10^{-6}	5.9×10^{-2}	2.0×10^{-6}	7.2×10^{-2}	7.4×10^{-6}
10^{21}	0.14	8.7×10^{-7}	-	-	-	-
Total:	0.51	2.9×10^{-5}	2.95	1.1×10^{-2}	4.81	0.12

5.3 Discussion of Predicted Events

This analysis also exemplifies the limitations of using the IceCube astrophysical fluxes to predict UHE events. First, many current UHE neutrino theories predict that the flux of cosmogenic BZ neutrinos to be higher than what the IceCube flux predicts in UHE ranges. This is illustrated in Figure 12 above, which illustrates that GZK models exceed the extrapolated IceCube fluxes. Consequently, the model used in this investigation likely underestimates the actual flux of UHE neutrinos because it fails to account for these BZ neutrinos, validating the relatively low numbers of predicted events. Note that Figure 12 has different livetimes for each experiment and from the above analysis. Furthermore, as noted above, these fluxes are centered at 100 TeV and are explicitly restricted to less than 10 PeV. While the two fluxes are similar around 100 TeV (see Figure 6), the HESE flux is dramatically smaller at higher energies. Ergo, a seemingly small difference in spectral index at 100 TeV, is manifested by significantly fewer UHE events detected as demonstrated in Table 2, which shows a 17500, 268, 40 times fewer total events for ANITA III, ARA 37 and ARIANNA respectively.

Finally, this model gives the number of events in one year, a practical estimate for long term experiments such as ARA and ARIANNA which hope to run for many years in the footsteps of IceCube; however, ANITA typically runs for only about one month at a time (with less than one run per year), meaning that the above ANITA numbers should be divided by 12 to give a more accurate per run result for these fluxes.

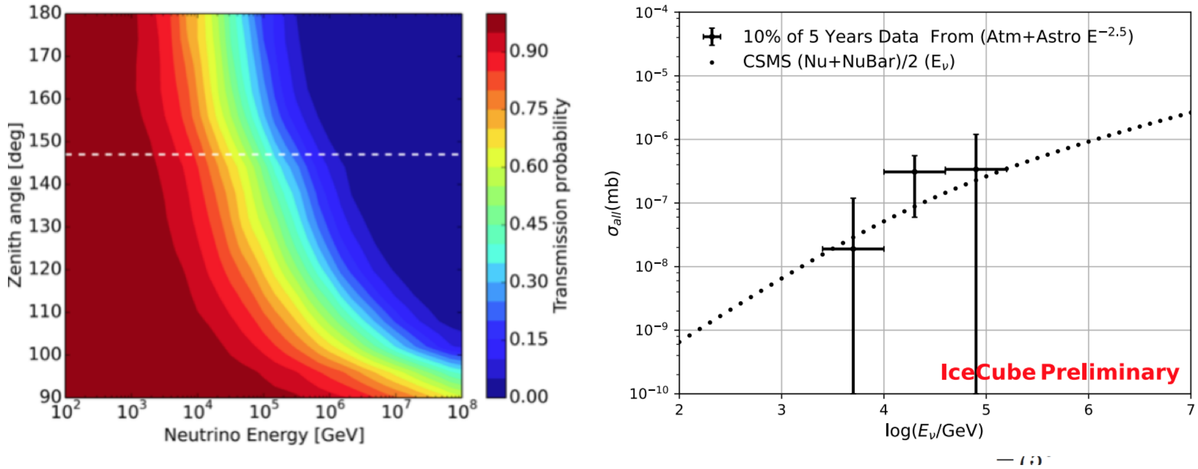

Figure 13: Left: the transmission probability predicted by the Standard Model for neutrinos to transit the Earth as a function of energy and zenith angle. The horizontal dotted white line shows a neutrino trajectory (and zenith angle) that just passes through the core-mantle boundary [6]. Right: Preliminary results showing measured neutrino energy vs cross section using 10% of 5 years experimental data [40].

5.4 Implications on fundamental physics

Beyond simply discovering the presence of astrophysical neutrinos, IceCube has been able to investigate various areas of fundamental physics. For example, current theory predicts the neutrino-nucleon cross section at energies far past what has been confirmed in accelerator experiments. It had been postulated that by comparing the number of upgoing and downgoing events, one could determine the cross section of high energy neutrinos given the density of the earth [25]. This analysis has recently been performed examining the directions of IceCube neutrinos in different energy bins [6], [18], [40]. Using 10,784 upgoing neutrinos with energies between 6.3 TeV to 980 TeV, IceCube measured the neutrino cross section to be $1.3 \pm .61$ of the standard model predictions [6]. Additional investigation using HESE events found cross sections within 1σ of predictions [18].

6 Conclusion

The IceCube Neutrino Observatory has with high confidence detected astrophysical neutrinos, thus ushering in a new era of neutrino astronomy. Yet, the incredibly small flux prevents a satisfactory understanding of the source of these neutrinos. As IceCube continues its search for higher energy neutrinos, radio based Antarctic experiments have emerged in an effort to maximize available detector volumes and detect UHE neutrinos. Using IceCube astrophysical fluxes extrapolated to ultra-high energy ranges, the effectiveness of these radio experiments can be evaluated. It is only a matter of time before the detection of UHE neutrinos and we gain a better understanding of their sources in the universe.

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