Strategies and Prospects for High Energy Astrophysical Neutrino Detection

Alexander L. Machtay

The Ohio State University
Department of Physics
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Committee Members:
Prof. Amy Connolly
Prof. John Beacom
Prof. Kaeli Hughes
Prof. Yuri Kovchegov

Abstract

Neutrinos are an increasingly useful messenger in astronomy and high energy physics. They're small cross-sections and lack of charge make them unique carriers of information from distant events in the cosmos at a wide range of energy scales and distances. The discovery of High Energy (HE) neutrinos has (together with Gravitational Waves) heralded the era of multi-messenger astronomy, adding another tool in astronomers' toolbox of signal carriers. The search for Ultra-High Energy (UHE) neutrinos promises to uncover the nature of the most energetic distant events in the universe. The discovery of such high energy neutrinos would not only unveil regions of the universe currently invisible to astronomers, but would also give physicists direction in the pursuit of physics beyond the Standard Model (SM) and provide data to answer outstanding questions in particle physics. In this paper, I will discuss the current state of HE and UHE astrophysical neutrino observations and detail the existing and upcoming experiments aimed at detecting them.

Contents

1 Introduction

Neutrinos are notorious for being one of the most challenging particles in the SM to study. At low energies, their cross-sections cause them to interact so rarely that they can hardly be detected at all. While their interaction cross-sections steadily increase with energy, leading to a plethora of different experiments that focus on specific energy ranges and sources, they once again become extremely difficult to study at high energies because of the limits of human built colliders and the extremely low flux from cosmic accelerators [1]. Nevertheless, a long list of sophistricated experiments and observatories have been constructed and planned to push the limit of the highest energy neutrinos detected ever higher.

The intense focus on neutrinos by physicists has always been motivated by their significance to our fundamental understanding of the universe. First postulated by Wolfgang Pauli in the 1930s, neutrinos have played an important role in the development and scrutiny of the SM. Their very small (but decidedly non-zero [2, 3]) mass has helped convince physicists that the SM is incomplete. HE neutrinos and UHE neutrinos can provide more tests of physics beyond the SM.

While physicists are interested in neutrinos for their implications on the fundamentals of physics, astrophysicists are interested in the ability to use neutrinos to observe and explain phenomena in the cosmos. Despite their low cross-sections, neutrinos can have substantial effects on the most extreme events in the universe; for example, 99% of the binding energy released in a type II supernova is released in the form of neutrinos, which contribute to the explosion itself [4]. Much of the universe is also hidden from us because of the limitations of photons as signal carriers. Because of this, neutrinos can give astronomers a complementary lense through which to view objects otherwise obscured by dust or too distant for high energy photons.

In the following section, I will detail the significance of HE and UHE neutrinos to fundamental physics and astrophysics. Some details will be left to later sections, where I will discuss the specifics of different neutrino observatories and the methods they employ to detect the signals from the rare interactions between neutrinos and other baryonic matter.

1.1 Neutrino Interactions at the HE and UHE Regimes

Because neutrinos interact only through the weak force (and gravity), their interactions with matter are rare. At low energies, neutrino detectors observe the interactions between neutrinos and nucleons or nuclei (for example, through the excitation of a nucleon to a higher state, which is followed by a characteristic decay). Above $\sim 1\,GeV$, however, neutrinos can begin to interact with the quarks inside of a nucleon directly. This is called Deep Inelastic Scattering (DIS), and is the dominant interaction mode at the HE and UHE scale [1].

These interactions can be seen in Fig. 1, which shows the two tree-level DIS modes. The Charged Current (CC) interaction occurs when an incoming neutrino exchanges a $W^{\pm}$ with the quark and results in a lepton and a hadronic shower. The Neutral Current (NC) interaction involves the exhange of a Z^0 boson, resulting in the same neutrino (at lower energy), as well as a hadronic shower. Neutrino observatories look for the signature of the hadronic shower (as well as the daughter lepton, in the CC case) to search for neutrino interactions.

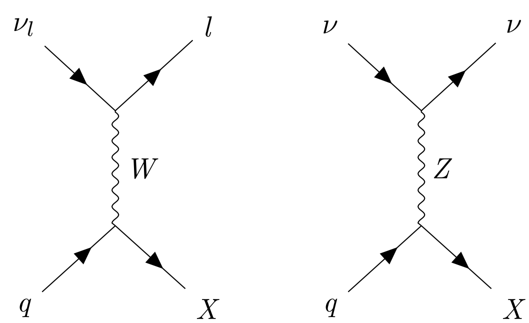

Figure 1: The two tree-level modes of DIS. Left shows the Feynman diagram for CC interactions between a nucleon and an incoming neutrino. The outgoing lepton l corresponds to the neutrino flavor. Right shows the Feynman diagram for the NC interaction between the same incoming particles. The "X" represents a hadronic shower. While the diagram shows an individual quark, it should be noted that the quark is contained within a nucleon.

1.2 Physics Goals

HE and UHE neutrinos are of interest to physicists for a variety of reasons. First, measurements of the neutrino-nucleon cross-section at high energies can act as a test of the SM and hint at Beyond Standard Model (BSM) physics. For example, EeV neutrino observatories will be able to make measurements of $\sigma_{\nu N}$ [5]. This can confirm expectations from the SM, but could also point to deviations, such as those expected from models with extra dimensions that seek to explain the heirarchy problem [6]. In such theories, $\sigma_{\nu - N}$ is enhanced as a function of the number of added dimensions [7]. At existing energy scales, experiments have already begun making observations and measurements of expected SM interactions at the HE scale (see Section 2.1).

Of particular interest is the search for the Greisen-Zatsepin-Kuzmin (GZK) effect [8, 9]. The GZK effect is the predicted cut off in the Ultra-High Energy Cosmic Ray (UHECR) spectrum above $50EeV$ as a consequence of interactions with the CMB. The relevant branch of the GZK process is $p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$, which proceeds with the pion decaying, overwhelmingly by $\pi^+ \rightarrow \mu^+ + \nu_\mu$ [10]. These "cosmogenic" neutrinos would be evidence of the GZK process, which acts as a test of SM predictions at energies far out of reach of collider experiments. Additionally, although UHECR events above the GZK cutoff have been observed [11], the measured flux of CRs does show a decline in events above the threshold energy [12]. Detecting the corresponding cosmogenic neutrinos would provide evidence that this decline is caused by the GZK process.

1.3 Astronomy Goals

Perhaps of broader interest in the HE and UHE neutrino community is the use of neutrinos as a tool for observing astrophysical phenomena. The field of multi-messenger (MM) astronomy has developed rapidly over the past decade, in particular with the first observation of gravitational waves by LIGO [13] and the discovery of potential astrophysical neutrino sources by IceCube [14, 15, 16].

Neutrinos are an especially powerful tool for observing astrophysical phenomena because of their small cross-sections, allowing them to pass through matter unimpeded. Neutrinos are also uncharged, meaning that they are not deflected by the large magnetic fields of galaxies they'd fly through en route from distant sources. As discussed above, UHECRs become attenuated above the GZK threshold, and at any rate are charged and therefore deflected by galactic magnetic fields, meaning that they don't reliably point back to extragalactic sources. Similarly, high energy photons become attenuated beyond because of the Breit-Wheeler process and pair production interactions with the CMB [17]. Overall, this makes neutrinos the *only* particle messenger that can probe otherwise hidden regions in the energy-distance parameter space of the universe. Several classes of sources have been suggested as sources of cosmic rays (CRs), but the expected distances and energy scales of those sources makes these theories difficult to test.

1.4 Quantifying Sensitivity

With many experiments probing a wide range of energies [1], it's important to understand the sensitivities of each experiment in the targeted energy ranges. This sets the scale for the potential science output; some experiments may be designed to find events predicted to exist, while others may be designed to constrain fluxes in a given energy range, acting as pathfinders for future projects.

Since the goal of HE and UHE neutrino observatories is to make a count of the number of neutrinos observed at each energy given a model for the neutrino flux, one way to quantify the sensitivity of an experiment is by the number of events it expects to observe in a given time. The number of neutrinos passing through a unit of area per unit time from a differential solid angle is given by

$$dN = F(E)dEdAd\Omega dt. \tag{1}$$

Neutrino observatories often report a quantity called the "effective area" or "effective volume," which combines the area or volume to which the experiment is sensitive with the directions in the sky it can observe. For example, a $1\,km^3$ scale experiment might be expected to be sensitive to $4\pi km^3 sr$, assuming that it can observe events coming from all directions. However, the Earth is opaque to HE neutrinos, meaning that the field of view of these experiments does not include the entire celestial sphere.

The effective area or volume is generally calculated using Monte-Carlo simulations designed to model the specifics of the experiment. Neutrino interactions and the signals they produce are simulated along with the detectors of the experiments. Events are weighted by their probability of reaching the simulated interaction vertex and whether or not they were detected by the trigger simulation. For example, the effective volume would be computed by [18]

$$V_{eff} = 4\pi \frac{V_{det}}{N} \sum_{i=1}^{N} \omega_i, \tag{2}$$

where V_{det} is the physical (fiducial) volume of the detector, N is the number of simulated events, and ω_i is a weight given to the event to signify the probability of the interaction occurring (i.e. accounting for attenuation through the Earth), and is set to zero if the event would not be detected.

In the limit that interaction lengths are much greater than the detector size, the effective area can be related to the effective volume by

$$A_{eff} = \frac{V_{eff}}{l_{int}}, \tag{3}$$

where l_{int} is the interaction length. The interaction length depends on the number density of nucleons and the cross-section of the interaction (which depends on the energy):

$$l_{int} = \frac{m_N}{\sigma(E)\rho}. \tag{4}$$

More generally, the *counting rate*, the number of events observed given the flux, is given by [19]

$$\begin{aligned} C = \frac{1}{T}\int_{t_0}^{t_0+T} dt \int_S \mathbf{d}\sigma \cdot \hat{\mathbf{r}} \int_\Omega d\omega \int_{E_0}^{E_0+\Delta E} \\ \times dE F(E) \varepsilon(E, \sigma, \omega, t), \end{aligned} \tag{5}$$

where $\varepsilon(E, \sigma, \omega, t)$ is the efficiency as a function of the energy, direction, solid angle, and time. Simulations necessarily include the efficiency, so it is accounted for in the effective volume or effective area. In practice, neutrino experiments use their simulated effective area and the number of events they observed to measure the flux $F(E)$. Projections can also be made by assuming a number of observed events and using the sensitivity to set limits on the flux.

2 Optical Neutrino Observatories

The most common and well known method used to detect HE neutrinos is the optical Cherenkov technique. Cherenkov radiation occurs when a charged particle moves in a medium faster than the medium's speed of light. The number of photons emitted is given by [20]

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha z}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right), \tag{6}$$

where λ is the wavelength of the emitted photon, α is the fine-structure constant, z is the charge of the moving particle, and $\beta = \frac{v}{c}$. The first important note to make is that the number of particles emitted is inverse with λ^2, making the signal stronger at higher frequencies. However, the scattering and absorption length of dense media means that it is difficult to observe Cherenkov radiation at frequencies higher than the optical spectrum.

Cherenkov radiation occurs because of constructive interference of photons emitted by the moving particle. This occurs at a specific angle relative to the particle's direction of propagation, forming the Cherenkov cone. The angle is related to the medium's index of refraction by

$$cos(\theta) = \frac{1}{\beta n}. \tag{7}$$

For experiments in ice, which is the most commonly used medium for HE neutrino detection and has an index of refraction of 1.78, and with highly relativistic particles, the opening angle is approximately 56°. However, as discussed later, Cherenkov radiation can also occur in air, which results in a much narrower Cherenkov cone of just 1.39°.

Neutrino observatories take advantage of the Cherenkov effect by instrumenting large volumes of dense media where Cherenkov radiation can readily take place, most commonly water and ice. It's necessary to have a large volume in order to detect the rare interactions of low flux neutrinos. These media also need to be sufficiently dense as to make the $\nu - N$ interactions frequent enough to be detected in a reasonable time. Additionally, the medium must be transparent to optical light over distances that can reasonably be instrumented. Because of this, experiments often take place in large bodies of water or in the Artic or Antarctic ice.

2.1 IceCube Observatory

The IceCube Observatory is a neutrino detection experiment located at the geographic South Pole (SP). IceCube currently consists of 86 boreholes drilled deep in the ice. IceCube's 5160 detectors lie between $1450\,m$ and $2450\,m$ below the surface of the ice. The principle detector component in IceCube is called the Digital Optical Module (DOM). DOMs consist of a Photomultiplier Tube (PMT) and a circuit board, which generates the high voltage needed for the PMT and assists in recording and transfering data and in calibration [21]. When a DOM detects a photon, it begins recording the waveform at the PMT and the time of detection. In addition to the DOMs placed in the ice, 81 boreholes also have a pair of stations consisting of two additional downward facing DOMs, called IceTop. IceTop acts as a veto for high energy events, detecting Cosmic Rays at energies between $300\,TeV$ and $1\,EeV$.

DOMs are attached to cables (often called "strings") and lowered into the boreholes, which go as deep at $2.5\,km$ below the surface of the ice. Most DOMs are separated vertically from one another by $10\,m$, with each borehole containing 60 DOMs. These boreholes are separated from their nearest neighbors on a hexagonal grid by $125\,m$. However, eight of these strings comprise the "DeepCore", a region at the center of the grid that is more densely instrumented. DOMs in the DeepCore are separated vertically from one another by $7\,m$ and each borehole is separated from its neihbors by $70\,m$. The added density of detectors in DeepCore allows for lower energy searches.

There are two primary types of events IceCube observes: cascades and tracks. Cascades are events which activate many DOMs in a small, approximately spherical region. Tracks are long paths of DOM activation. Both CC and NC events can cause cascades, since both produce hadronic showers. However, only CC interactions cause tracks, since they can produce a long lived lepton (specifically, the lepton must be a muon, since electrons and taus can't travel long distances in ice). Examples can be seen in Fig. 2 and 3. NC interactions can also be identified by characteristic "double bangs," where a second cascade is seen due to a second interaction from the neutrino produced from the first NC event.

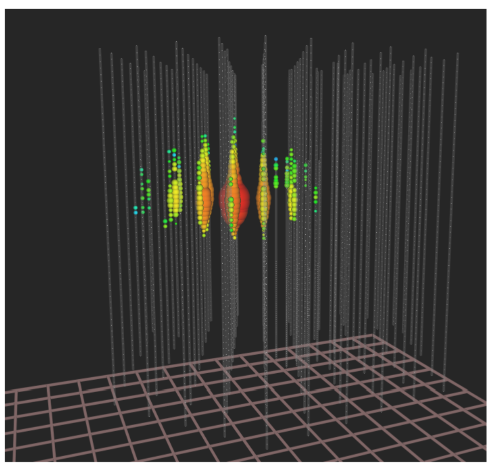

Figure 2: An example of a cascade event from the IceCube HESE sample (taken from [22]).

IceCube has made substantial discoveries in the HE neutrino regime. IceCube made the first detection of HE neutrinos in 2013, finding two events with energies just above $1\,PeV$ [23, 24]. A subsequent analysis [25] of 988 days of data found an additional event at roughly $2\,PeV$ and reported a 5.4σ significance, confirming the existence of HE neutrinos. This analysis was extended to include 7.5 years of High Energy Starting Events (HESE) data [26], but no additional HE events were observed. At least one possible cause for this is an updated ice model, which is important for

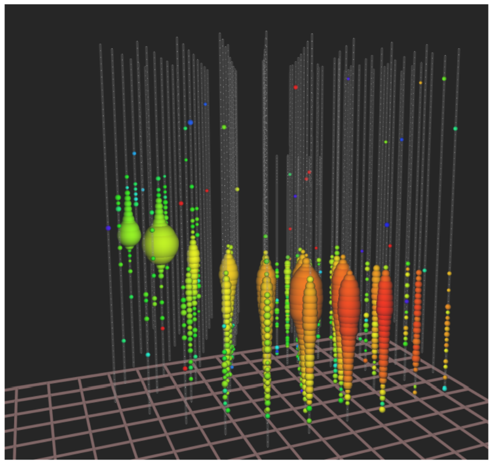

Figure 3: An example of a track event from the IceCube HESE sample (taken from [22]).

energy reconstruction. As discussed below, however, PeV neutrinos were seen again with improved veto techniques.

In addition to the HESE analysis, IceCube also conducts searches for neutrino interactions that occur outside of the actual instrumented volume. While starting events can have either cascade or track morphologies (or both), through-going events provide a way to expand IceCube's volume of sensitivity by searching for the muons produced by CC interactions outside of IceCube's instrumented volume. Among these events, IceCube detected a muon with a corresponding reconstructed neutrino energy of $4.4\,PeV$ [27, 28].

These analyses (which are mostly comprised of events below the HE regime) allowed IceCube to report measurements of the astrophysical neutrino flux. The astrophysical muon-neutrino flux was measured to fall off according to $E^{-2.37}$ [28], while the total neutrino flux was observed to decline according to $E^{-2.87}$ [26]. It's important to note that these are two different analyses, with each looking at a different class of events. One goal of HE and UHE neutrino observatories is to test if the single power law fits consistent with IceCube data remain valid at higher energies.

IceCube's sensitivity to HE neutrinos allows it to robustly test SM physics at high energies. For example, IceCube made the first observation of the Glashow resonance [29]. The Glashow resonance [30] occurs when the center of mass energy of an incoming anti-neutrino and an electron is near the mass of the W boson, and occurs at $6.3\,PeV$ (as measured in the "lab" frame, that is, in the rest frame of the electron). The Glashow resonance contributes multiple orders of magnitude more than DIS interactions at energy scales near the peak [1, 31, 32]. This result was made possible by implementing a different veto technique to use the entire IceCube fiducial volume (IceCube previously used an outer layer veto to decrease noise from atmospheric muons). The event, which had an energy of $6.05 \pm 0.72\,PeV$, was previously vetoed because of its vertex position in IceCube.

The discovery of the Glashow resonance is significant for two reasons. First, it is the first Glashow resonance candidate (though the significance was only 2.3σ), making it an original test of the SM. Second, the Glashow resonance is the only method available to IceCube for differentiating between neutrinos and anti-neutrinos. Collider experiments can distinguish between leptons and anti-leptons using magnets to deflect the two in different directions due to their opposite charge. HE neutrino experiments cannot measure the charge of the lepton produced by a CC interaction. Since the Glashow resonance involves anti-neutrinos and never neutrinos, it is the only type of interaction where HE anti-neutrinos can be confirmed.

2.2 KM3NeT: ARCA

The Cubic Kilometre Neutrino Telescope (KM3NeT) is a network of three deep site observatories being constructed in the Mediterranean Sea [33]. Like IceCube, KM3NeT also uses the optical Cherenkov technique to search for HE neutrinos. KM3NeT has two components, the Oscillation Research with Cosmics in the Abyss (ORCA) and the Astroparticle Research with Cosmics in the Abyss (ARCA) [34]. ORCA is designed to study neutrino oscillations and uses a dense spacing of optical modules to search for low energy neutrinos (similar to the IceCube deepcore).

ARCA is located $90\,km$ off the shore of Italy at a depth of $3500\,m$ [35]. Like IceCube, ARCA uses strings of DOMs arranged in a grid. Currently, 28 strings are deployed, with plans for 230 total strings with a total of 4140 DOMs by the end of construction [36]. DOMs are separated vertically along strings by $36\,m$ and strings are separated by $90\,m$. Unlike IceCube, which used DOMs with a single PMT, ARCA's DOMs have 31 PMTs. This mitigates the effects of failing PMTs on ARCA's performance and makes each DOM sensitive to the direction of arriving photons [37]. An image of an ARCA DOM is shown in Fig. 4. Once completed, ARCA will have an instrumented volume slightly larger than IceCube's [36].

Unlike the IceCube DOMS, which are held in position by refrozen ice in the boreholes, the KM3NeT DOMs are free to translate and rotate in the water. This presents challenges to reconstruction, since the precise location of detectors is needed to point back to a reliable interaction vertex position. KM3NeT tracks the relative positions of the DOMs using an acoustic position system with a precision of $20\,cm$ [38]. To do this, a long baseline (LBL) of acoustic transmitters

Figure 4: A picture of the KM3NeT DOM. Each bronze circle is an exposed photocathode from one of the 31 PMTs. The small circle just left of the center is the DAR. Image and description adapted from [37].

are placed on the seabed. Each DOM contains a Digital Acoustic Receiver (DAR) that detects signals from the transmitters on the seabed. The time between transmission and reception is used to measure the position of the DOM [39, 40]. The orientation of a DOM is measured using an accelerometer and magnetometer installed in the DOM and is accurate to 3.5° [38].

Though ARCA is still under construction, it may already be making discoveries in the HE regime. Preliminary results from the existing ARCA detector show an event originating from roughly 1° below the horizon at $\sim 10\,PeV$ [41]. The direction is consistent with expectations, since at these energies the cross-section is sufficiently high as to be attenuated by the Earth from below and the volume above is too low to make interactions likely. This would be the highest energy neutrino detected to date, and would be close to the $100\,PeV$ UHE regime threshold. However, the KM3NeT collaboration has yet to officially publish the result, as a full analysis still needs to take place.

2.3 Earth-skimming Optical Detectors

As discussed in the next section, tau neutrinos at the highest energies can produce air showers that can be detected through radio emission. Air showers also produce optical light through Cherenkov radiation. While some experiments are already beginning to target the radio signal from air showers produced by the resulting lepton of neutrino interactions, some proposed experiments will target the optical emission. These experiments focus on neutrinos which narrowly graze the Earth, called

Earth-skimming neutrinos.

The Probe of Extreme Multi-Messenger Astrophysics (POEMMA) observatory is one such example. POEMMA will consist of two identical Earth-pointing satellites in low Earth orbit [42] with optical telescopes for detecting fluorescence and Cherenkov radiation from EAS. POEMMA will be sensitive to neutrinos above $20\,PeV$. POEMMA will have two operational modes in its mission. First, it will observe optical fluorescence in "stereo" mode, where both satellites point down at Earth with significantly overlapping fields of view. This will be primarily sensitive to UHECRs. The other mode, however, is called "limb" mode, in which the satellites point toward the horizon to search for skimming neutrinos. In limb mode, POEMMA will observe an area of over $10^6 km^2$.

2.4 Other In-Situ Optical Detectors

Several other experiments are underway to search for HE neutrinos using optical Cherenkov light. Like ARCA, the Baikal Gigaton Volume Detector (Baikal-GVD) uses water as its detector medium. Once completed, it will have a detector volume similar to that of IceCube and ARCA, around $\sim 1km^3$. By the end of 2024, it will have a volume of $0.75\,km^3$ [43]. The most recent analysis reported an effective volume of $0.6\,km^3$ at PeV energies and reported the detection of one event at just over $1\,PeV$ [44].

Additionally, a new experiment has been proposed that would seek to construct a multi-cubic kilometer neutrino observatory. The Pacific Ocean Neutrino Experiment (P-ONE) would have a similar design to ARCA and Baikal-GVD and would be optimized for energies from $10\,TeV$ to $10\,PeV$ [45]. The first strings for P-ONE are set to be deployed in 2025 [46].

3 Radio Neutrino Observatories

While the optical Cherenkov technique has been the most commonly used strategy for observing neutrinos, HE and UHE observatories seek to make use of radio emission from interactions at the highest energies to be able to search even larger volumes for rarer signals. Two mechanisms of energy loss due to interactions with a medium at high energies are responsible for the processes discussed below: bremsstrahlung, the emission of photons by charged particles, and pair production, the conversion of high energy photons into electron-positron pairs [47].

At high energies, bremsstrahlung is the dominant form of energy loss by charged particles in matter. This primarily occurs due to scattering off of the atomic nuclei in the material. We can characterize this process by the radiation length, which is the mean free path of the *energy* of the initial electron. Photons have a mean free path for pair production of $\frac{9}{7}X_0$.

The photons and $e^{\pm}$ produced in these processes can continue to generate more $e^{\pm}$ and photons so long as the energy of the charged particles remains in the regime dominated by bremsstrahlung. With each radiation length, an additional electron-positron pair is created, meaning that the number of charged particles on average doubles with every X_0 traversed.

This particle shower also broadens in time, since the particles produced in each interaction don't propagate exactly in the direction of the original particle. A characteristic radius of the shower is given by the Molière radius, $21\,MeV\frac{X_0}{E_c}$, where E_c is the critical energy below which ionization effects become significant. In ice, the Molière radius is approximately $10\,cm$ and the radiation length is $40\,cm$ [20].

Radio signals produced by this process can travel further in dense media than optical light and can even be produced in the atmosphere. In this section, I'll detail the two primary radio signatures used by neutrino observatories to probe the UHE regime.

3.1 Askaryan Radio Technique

Just as optical experiments use Cherenkov radiation to search for HE and UHE neutrinos, radio observatories also make use of the radio Cherenkov effect. Called Askaryan radiation [48, 49], this effect occurs when many particles of the same charge emit radiation while moving in the same direction. Typically, this doesn't occur in Cherenkov radiation because both electrons and positrons are present in the shower. However, once the energy of particles in the shower drops below the critical energy, an excess of electrons (compared to positrons) can develop. This is caused by Compton scattering by photons adding electrons to the shower and annihilation with the medium subtracting positrons. The result is that the electrons not only move faster than the speed of light in the medium, but also produce radiation coherently.

The first advantage of using Askaryan radiation for HE and UHE neutrino detection is that the radio signals travel larger distances in media. For example, P-ONE measured a scattering distance of roughly $30\,m$ for $450\,nm$ light in ocean water [46]. By contrast, polar ice has been measured to have an attenuation length of $\mathcal{O}(1\,km)$ for $380MHz$ radio signals [50]. This is crucial for UHE neutrino experiments, which need to instrument much larger volumes to be able to detect the extremely low flux of neutrinos at the highest energies [51]. In-situ radio experiments can be more sparsely instrumented than optical observatories because the radio signals travel longer distances.

Additionally, Askaryan radiation is coherent for frequencies less than $1\,GHz$ (a result of the spread of the charges, the Molière radius). The power of Cherenkov radiation is proportional to the number of particles in the shower, N, which is set by the shower energy E_{sh}. Since Askaryan radiation is coherent, it scales like N^2, so above a threshold energy it becomes a stronger signal than optical Cherenkov radiation [52].

Despite the advantages of Askaryan radiation as a strategy for detecting, it is difficult to sufficiently instrument the large volumes ($\mathcal{O}(10\,km)$ required to detect UHE neutrinos. Experiments seek to use the same media as optical experiments, either by sparsely instrumenting the medium or using air born observatories.

3.2 Air Shower Technique

Another way that neutrinos can produce radio signals is through geomagnetic radiation caused by particle showers resulting from interactions in the atmospherei [20]. This technique is used for detecting cosmic rays. When a CR interacts in the atmosphere, it produces an Extended Air Shower (EAS) that propagates forward along the direction of the incoming CR. The shower is comprised of charged particles, which feel a Lorentz force from Earth's magnetic field perpendicular to the shower axis. Electrons and positrons in the shower are accelerated in opposite directions, which amounts to the formation of a current transverse to the direction of the shower's motion. As the positrons and electrons interact with air molecules, however, the current changes. The change in the current results in radio emission. Since the EAS moves close to the speed of light, the radio emission is beamed along the direction of travel into a narrow cone [53, 54, 55].

This effect has been used to observe CRs [56] and is proposed as a method for detecting incoming neutrinos [57, 58]. Incoming UHE neutrinos will produce a charged lepton in CC interactions in a dense medium, which can propagate into the air and would further interact to produce showers like those observed in CR interactions. Just as in the case of CRs, the radio signals would be beamed into a small cone around the traveling direction. These events require very specific geometries, however, since the neutrino must interact at a grazing incidence and the signal will be tightly beamed along the incoming direction.

Air shower techniques are sensitive to tau neutrino interactions coming from near the horizon. The electrons produced from ν_e interactions are too light to travel long distances, and thus can't produce EAS. Muons are longer lived, but their light mass still prohibits long travel distances. In optical experiments, muons are the only lepton to produce tracks because they are sufficiently massive and long lived enough to traverse long distances relative to the detector volume. However, at high enough energies, tau particles can travel long distances within their lifetime [57]. This technique is sensitive to neutrinos at the highest energies, since they need to interact shallowly in the dense media, requiring high cross-sections to occur.

3.3 In-Situ Radio Observatories

Like optical experiments, the most straightforward way to use radio signals to search for HE and UHE neutrinos is to instrument the medium directly. These primarily use polar ice, drilling holes in the ice just like IceCube. Instead of optical modules with PMTs, however, radio antennas are used.

Two large scale radio neutrino observatories exist in Antarctica. First, the Askaryan Radio Array (ARA) sits near IceCube at the south pole [59, 60]. ARA has a similar design to IceCube, with stations arranged in a hexagonal grid. To take advantage of the radio properties of ice, however, stations are separated by $2\,km$. Stations contain 16 receiving antennas arranged in four boreholes, with two vertically (VPol) and horizontally (Hpol) polarized antennas on each string [18]. The target frequency band for ARA is $150 - 850\,MHz$. While Askaryan radiation can be coherent up to $1\,GHz$, the thickness of the Cherenkov cone falls with frequency, meaning that targeting frequencies below the limit promises better results.

ARA's antennas are lowered to roughly $200\,m$, where the ice is clearer (compared to closer to the surface). Signals are expected to be predominantly vertically polarized because of the constraints on possible event detection geometries due to the large cross-sections of UHE neutrinos. However, HPol antennas are still important for reconstruction, especially if the effects of birefringence in the ice substantially affect the signal polarization as it travels from the shower to the detectors [61, 62].

Analysis of two stations over four years is competitive with previous balloon borne experiments (discussed below) at the low end of the UHE regime. With five stations currently deployed, ARA will set the strictest limits on the neutrino flux at energies above $10\,EeV$ in advance of next generation radio neutrino observatories [63]. To improve its sensitivity and to inform future radio experiments, ARA deployed a phased array antenna system in the fifth station [64]. The phased array contains seven VPol and two HPol antennas, and the spacing between them is reduced to just $1\,m$. This allows for a lower threshold to be used, and is a strategy adopted by RNO-G and IceCube-Gen2. An analysis using all five stations is currently underway. With the full 37 station array, ARA would cover an area of $200\,km$.

Also in Antarctica is the Antarctic Ross Ice-Shelf Antenna Neutrino Array (ARIANNA). In contrast to other in-situ neutrino experiments, ARIANNA places its detector elements in shallow ice. Four log-periodic Dipole Antennas (LPDAs) are placed at roughly three meters below the surface, pointing downward [65]. LPDAs allow for a large bandwidth, with ARIANNA being sensitive to signals from $100\,MHz$ to $1\,GHz$. Seven ARIANNA stations, separated from neighbors by $1\,km$, are commissioned at the Ross Ice-Shelf. This lets ARIANNA detect radio signals reflected from the ice-water interface, giving it a broader view of the southern hemisphere. A total of 200 stations are proposed, which would give [66, 67, 68]. Additionally, future designs of ARIANNA stations will include upward facing LPDAs to detect and veto CR air showers [69, 70].

The Radio Neutrino Observatory in Greenland (RNO-G) promises to provide a complement to ARA and ARIANNA in the northern hemisphere [71]. RNO-G is being constructed at Summit Station in Greenland and currently has seven stations separated by $1.25\,km$ in a square grid, with a total of 35 planned [72]. The design of RNO-G combines features of ARA and ARIANNA; each station has three deep boreholes ($100\,m$) housing VPol and HPol antennas as well as six downward facing and three upward facing shallow LPDAs. Like ARIANNA, the upward facing LPDAs are sensitive to air showers, and so far three CR detections have been reported [73]. An image of the station design can be seen in Fig. 5.

Finally, an expansion to IceCube in the coming years will add a radio array component to expand IceCube's sensitivity into the UHE regime [74]. IceCube-Gen2 will include the largest in-situ neutrino radio array, with an intended area of $500\,km^2$ The radio array will be placed adjacent to the (expanded) optical array, which may allow for events to be seen in both optical and radio. For example, a hadronic shower can be observed in the sparsely instrumented radio component, followed by the detection of an outcoming lepton seen as a track in the optical component. The design of the radio stations would be similar to that of RNO-G, with both deep VPol and Hpol antennas and surface level LPDAs.

In addition to the observation of radio signals in ice produced directly from the products of neutrino interactions, it may be possible to detect the particle cascade from neutrino interactions in

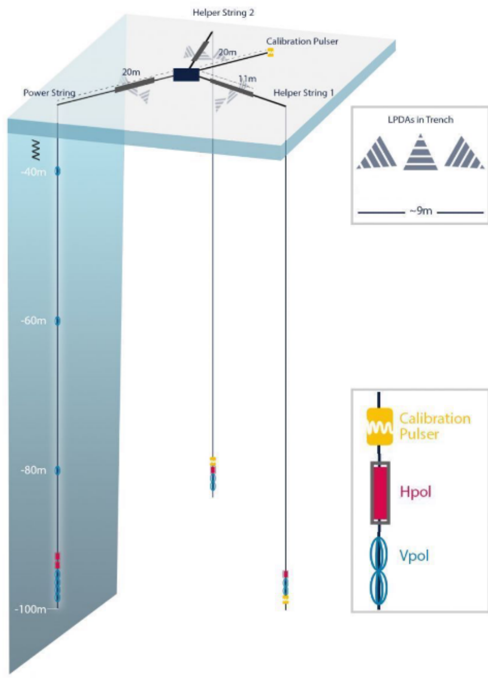

Figure 5: The design of the RNO-G station. The power string contains a phased array of VPol and HPol antennas, while the helper strings assist in reconstruction by adding directional sensitivity. Image taken from [72].

dense media using a *transmitted* radio signal [75]. The Radar Echo Telescope (RET) is investigating using a radar based system to detect CR induced EAS [76] as a test of radar as a method for observation. Radio emission from a transmitting antenna can reflect off of the wide particle shower and be detected with a receiving antenna. An observatory using the radar technique can instrument large volumes because of the relatively little components needed.

3.4 Air-Borne Observatories

While Askaryan radiation in dense media makes large scale in-situ experiments easier to construct than if only optical techniques were used, instrumenting the vast volumes required for finding events at the highest energies is still a challenge. Air-borne experiments are an alternative to in-situ observatories. By flying high above a dense medium, balloon experiments can view more km^2 than any experiment has instrumented. Additionally, these experiments are sensitive to events occurring in the air, providing access to EAS induced by tau neutrinos. However, since balloon experiments only fly for a limited time, they sacrifice livetime for the increased effective volume they observe.

The ANtarctic Impulsive Transient Antenna (ANITA) was a balloon experiment that flew over Antarctica in four iterations [77, 78, 79, 80]. Balloons flying nearly 40 km above the surface can view $\sim 10^6\,km$ of ice. ANITA consisted of a cylindrical array of quad-ridge horn antennas (see Fig. 6) with a frequency band of $200 - 1200\,MHz$. The two vertically oriented ridges are electrically connected and act as a VPol channel, while the other two act as an HPol channel. Arranging the antennas in a cylinder give a full azimuthal view. ANITA-IV consisted of 48 antennas, each tilted 10° below the horizon to be able to observe the ice.

Figure 6: The ANITA-IV payload prior to launch. Picture taken from [80], credit Luke Batton.

ANITA was sensitive to both Askaryan radiation produced from neutrino interactions in ice and to cosmic ray interactions in the atmosphere. ANITA's dual-channel antenna design allows it to distinguish between these signals because of the different polarizations. Since Earth's magnetic field is close to vertical at the south pole, signals from EAS are horizontally polarized. However, Askaryan radiation passing from within the Antarctic ice into the air is mostly vertically polarized [80]. This is important for ANITA to be able to confirm events as neutrino interactions as opposed to CRs.

ANITA's sensitivity to air showers also provides an opportunity for it to search for neutrino interactions in the atmosphere. Neutrinos at the highest energies cannot pass through substantial layers of the Earth. Because of how tightly beamed the signal from a neutrino induced air shower is, ground based detectors would likely miss neutrinos interacting in the atmosphere [58]. ANITA may be sensitive to tau neutrino interactions near the horizon because of its position high in the atmosphere.

Indeed, in addition to CRs, ANITA has reported "anomalous" events that appeared to be CRs but with incorrect polarity [81, 82, 83]. Since ANITA flies high in the air, most of the signals from CRs that it sees are reflections from the ice. The polarity of these signals should flip from the reflection. In these anomalous events, the polarity appears to be unflipped. This is consistent with the expectated signal from EAS induced by skimming tau neutrino interactions. However, the direction of these events (which would require an UHE neutrino passing through a substantial portion of the earth) and the CR and neutrino fluxes measured from other experiments [84, 85, 86] makes it unlikely that a tau neutrino hypothesis can explain the anomalies.

ANITA will be succeeded by the Payload for Ultrahigh Energy Observations (PUEO). PUEO will target the UHE regime, with the best sensitivity to date for neutrinos above $1EeV$ [87]. Like ANITA, PUEO will be sensitive to EAS from tau neutrinos. PUEO will improve on ANITA's sensitivity in part by employing a phased array trigger, as used by ARA and RNO-G. In addition to the Main Instrument (MI), which targets $300-1200\,MHz$, a Low Frequency instrument will be deployed to be sensitive to signals between $50\,MHz$ and $300\,MHz$. By increasing the minimum frequency of the MI, the sensitivity is improved by decreasing the size of the antennas, allowing more to be used. The LF, on the other hand, will improve sensitivity to air shower events, since the signal they produce is strongest at lower frequencies [88].

4 Sensitivity Comparisons

As stated in Section 1.4, one of the primary goals of HE neutrino observatories is to measure the flux of neutrinos at the highest energies. Since HE neutrinos are rare and none have been discovered in the UHE regime, experiments report contraints they place on the HE and UHE neutrino flux based on the number of neutrinos they detect and their sensitivity (that is, their effective area). Experiments also *project* the constraints that they will place given a number of observed events.

This can be seen in Fig. 7 and Fig. 8. Neutrino fluxes are commonly shown in two ways. One is to plot the EdN/dE flux. This is a number count of events at each energy. The other is to plot the *energy* flux, E^2dN/dE. Each of these figures shows models (shaded) for the possible HE and UHE neutrino flux, along with curves representing the upper limits on the flux placed by various experiments. Experiments need to push the upper constraints they set further down the flux axis so that there is overlap between the experimental limits and the models. Both RNO-G and PUEO project sensitivities that can probe the cosmogenic neutrino flux. Additionally, the ongoing five station analysis being conducted by ARA will also be sensitive to the cosmogenic flux [89].

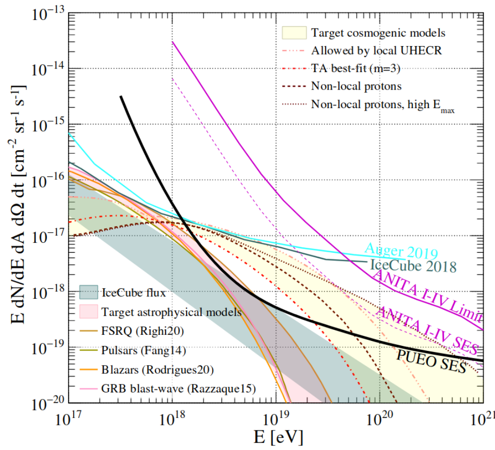

Figure 7: Constraints anticipated by PUEO and set by ANITA, IceCube, and Auger. SES refers to "single event sensitivity," indicating the constraint put on the flux by observing a single event during the experiment's livetime. Figure taken from [90]

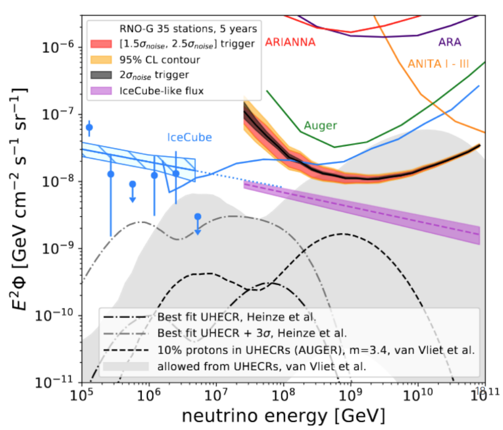

Figure 8: Constraints anticipated by RNO-G and set by other in-situ radio experiments. Figure taken from [91]

5 Conclusion

The landscape for HE and UHE neutrino detection has been rapidly growing in the past two decades. Proof from IceCube that neutrino observatories can act as discovery level experiments and the advent of MM astronomy with gravitational waves, CRs, and neutrinos is motivating the community to develop new strategies to make the first UHE neutrino observations. Despite decades of exciting science using neutrinos from astronomical sources, there is still clearly a rich unexplored region of the parameter space at the highest energies that promises to tell us more about fundamental physics and reveal the furthest reaches of the cosmos.

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