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High-Energy Neutrinos from the Cosmos

Francis Halzen

The IceCube project transformed a cubic kilometer of transparent natural Antarctic ice into a Cherenkov detector. It discovered PeV-energy neutrinos originating beyond our galaxy with an energy flux that is comparable to that of GeV-energy gamma rays and EeV-energy cosmic rays. These neutrinos provide the only unobstructed view of the cosmic accelerators that power the highest energy radiation reaching us from the universe. The results from IceCube's first decade of operations, foremost the measurement of the diffuse neutrino flux from the universe using multiple techniques is reviewed. The multimessenger data that identified the supermassive black hole TXS 0506+056 as a source of cosmic neutrinos is subsequently reviewed and attention is drawn to accumulating indications that cosmic neutrinos are associated with gamma-ray-obscured active galaxies, that is, the energy in gamma rays that accompanies cosmic neutrinos emerges at MeV energies, or below. Reaching beyond 10 PeV energy, cosmic neutrinos provide a natural beam to study neutrinos themselves.

1. Neutrino Astronomy: A Brief Introduction

The shortest wavelength radiation reaching us from the universe is not radiation at all; it consists of cosmic rays—high-energy nuclei, mostly protons. Some reach us with extreme energies exceeding 10^8 TeV from a universe beyond our Galaxy that is obscured to gamma rays and from which only neutrinos reach us as astronomical messengers.[1] Their origin is still unknown but the identification of a supermassive black hole powering a cosmic-ray accelerator[2,3] represents a breakthrough toward a promising path for resolving the century-old puzzle of the origin of cosmic rays: multimessenger astronomy.

The rationale for searching for cosmic-ray sources by observing neutrinos is straightforward: in relativistic particle flows near neutron stars or black holes, some of the gravitational energy released in the accretion of matter is transformed into the acceleration of protons or heavier nuclei, which subsequently interact with ambient radiation or dust, hydrogen, and dense molecular clouds to produce pions and other secondary particles that decay into neutrinos. For instance, when protons interact with intense radiation fields near the source via the photoproduction processes

$$p + \gamma \to \pi^0 + p \text{ and } p + \gamma \to \pi^+ + n \quad (1)$$

both neutrinos and gamma rays are produced with roughly equal rates; while neutral pions decay into two gamma rays, $\pi^0 \to \gamma + \gamma$, the charged pions decay into three high-energy neutrinos (ν) and antineutrinos ($\bar{\nu}$) via the decay chain $\pi^+ \to \mu^+ + \nu_\mu$ followed by $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$. The fact that cosmic neutrinos are inevitably accompanied by high-energy photons transforms neutrino astronomy into multimessenger astronomy.

A main challenge of multimessenger astronomy is to separate these photons, which we will refer to as pionic photons, from photons radiated by electrons that may be accelerated along with the cosmic ray protons. Another challenge is to identify the electromagnetic energy associated with the pionic photons because they do not reach our telescopes with their initial energy but after suffering losses in the extragalactic background light (EBL), predominantly in interactions with microwave photons via the process $\gamma + \gamma_{cmb} \to e^+ + e^-$. Importantly, they may also lose energy in the source. As is the case for constructing a neutrino beam in a particle physics laboratory, neutrinos are produced in a so-called beam dump with a target transforming the energy of the proton beam into neutrinos. Powerful neutrino sources within reach of IceCube's sensitivity require a dense target that is likely to be obscured to pionic gamma rays. Additionally losing energy in the source, these may reach Earth with MeV energies or below; we will refer to them as gamma-obscured sources. We will review the accumulating evidence that this is indeed the case, with multimessenger signals emerging below the detection thresholds of high-energy gamma-ray satellites and ground-based TeV gamma-ray telescopes.

After collecting 10 years of IceCube data, the emergence of active galaxies as sources of cosmic rays was not unexpected.[4,5] The detailed blueprint for a cosmic-ray accelerator must meet two challenges: the highest energy particles in the beam must reach energies beyond 10^8 TeV for extragalactic sources, and their luminosity must accommodate the observed flux. Both requirements represent severe constraints that have guided theoretical speculations toward active galaxies; for a recent review see ref. [6]. In contrast with our own galaxy hosting a black hole at its center that is mostly dormant, in an active galaxy the rotating supermassive

F. Halzen
Department of Physics and Wisconsin IceCube Particle Physics Center
UW-Madison
Madison, WI 53706, USA
E-mail: halzen@icecube.wisc.edu

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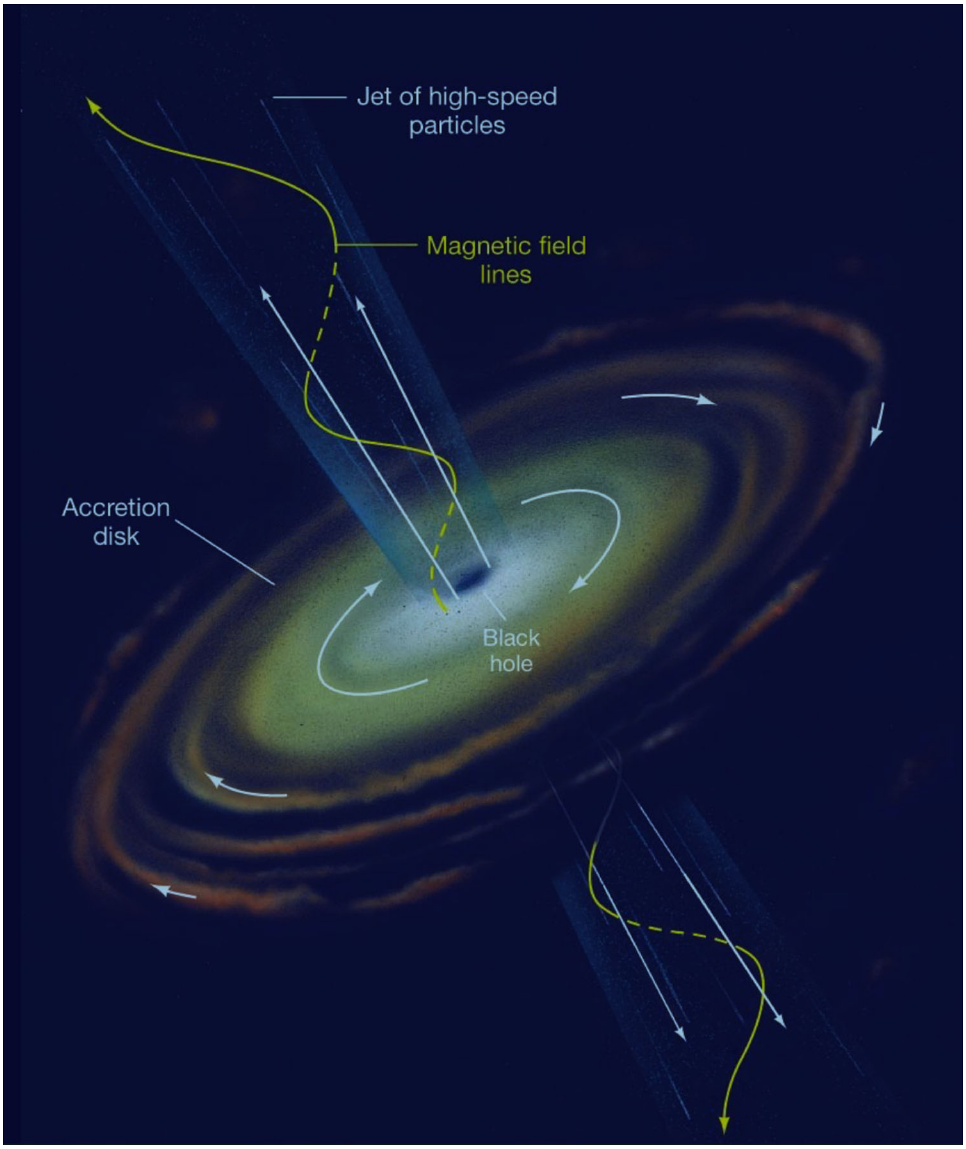

Figure 1. The accretion disk meets the spinning black hole that winds up the disk's magnetic field lines. Reproduced with permission (2010). Pearson Education, Inc.

black hole absorbs the matter in the host galaxy at a very high rate. Fast spinning matter falling onto the active galactic nucleus (AGN) swirls around the black hole in an accretion disk, like the water approaching the drain of your bath tub. When the accretion disk comes in contact with the rotating black hole, its space-time drags on the magnetic field, winding it into a tight cone around the rotation axis into a jet of particles; see **Figure 1**. Not just particles but huge "blobs" of plasma from the accretion disk are flung out along these field lines. It is not clear whether it is the rotation energy of the black hole or the magnetic energy in the rotating plasma that powers the accelerator. The radio emission reveals that the plasma in the jets of active galaxies flows with velocities of 0.99 c. A fraction of a solar mass per year can be accelerated to relativistic Lorentz factors of order 10, leading to a luminosity of 10^{46} erg s^{-1}, close to the Eddington limit where the force of radiation acting outward interferes with further accretion on the black hole.

When the jet runs into a target material, for instance the ubiquitous 10 eV ultraviolet photons in some galaxies, neutrinos can be produced. Production of high-energy neutrinos in the cores of the active galaxy may also result from the acceleration of cosmic rays in the high field regions associated with the accretion disk or the corona surrounding it; for a recent review, see ref. [7].

Two general scenarios have been invoked to accommodate the level of diffuse cosmic neutrino observed by IceCube: protons accelerated near the core interact with high-density targets or strong fields in the vicinity of the black hole,[8,9] or, alternatively, diffuse through the galaxy to produce neutrinos in collisions with interstellar matter.[10] We will return to these speculations after reviewing the status of the neutrino observations.

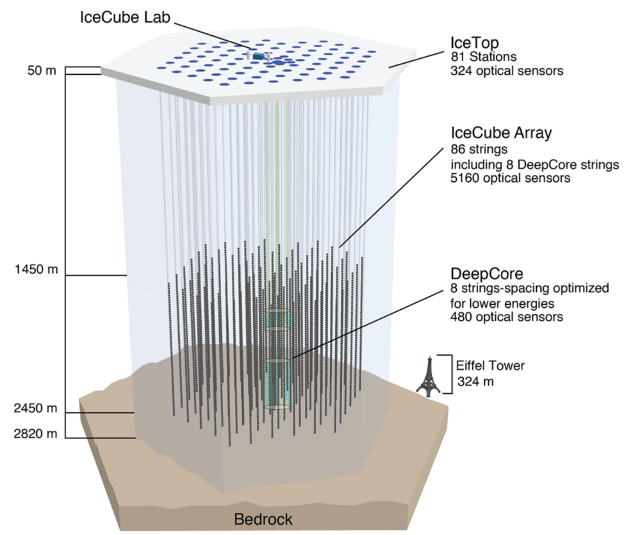

Figure 2. Architecture of the IceCube observatory.

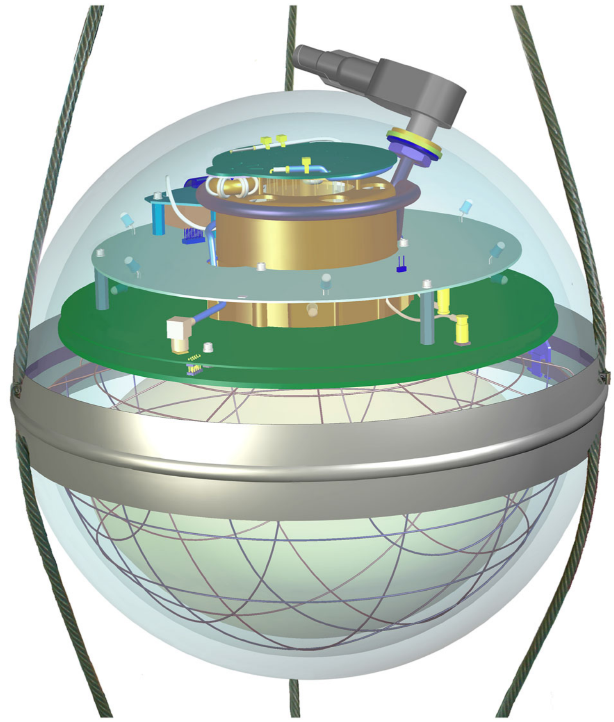

Figure 3. Digital optical module showing the down-facing 10 in. photomulitplier and the associated electronics that digitize the light signals.

2. The Discovery of High-Energy Cosmic Neutrinos

Close to the National Science Foundation's research station located at the geographical South Pole, the IceCube project[11] transformed one cubic kilometer of natural Antarctic ice into a Cherenkov detector. The deep ice of the Antarctic glacier constitutes the detector, forming both support structure and Cherenkov medium. Below a depth of 1450 m, a cubic kilometer of glacial ice has been instrumented with 86 cables called "strings," each of which is equipped with 60 optical sensors; see **Figure 2**. Each digital optical module (DOM) consists of a glass sphere containing a photomultiplier and the electronics board that captures and digitizes the signals locally using an onboard computer; see **Figure 3**. The digitized signals are given a global time stamp with residuals accurate to 2 ns and are subsequently transmitted to the surface. Processors at the surface continuously collect the time-stamped signals from the optical modules, each of which functions independently. The digital messages are sent to a string processor and a global event trigger. They are sorted into the Cherenkov radiation patterns that are emitted by secondary muon tracks produced by muon neutrinos interacting in the ice, or by particle showers for the case of electron and tau neutrinos. These reveal the flavor, energy, and direction of the incident neutrino.[12] Constructed between 2004 and 2010, IceCube has now taken 10 years of data with the completed detector.

The arrival direction of a secondary muon track and of an electromagnetic shower initiated by an electron or tau neutrino is determined by the arrival times of the Cherenkov photons at the optical sensors, while the number of photons is a proxy for the energy deposited by secondary particles in the detector. Although the detector only records the energy of the secondary muon inside the detector, from Standard Model physics we can infer the energy spectrum of the parent neutrino.

Tracks resulting from muon neutrino interactions can be pointed back to their sources with a $\leq 0.4°$ angular resolution for the highest energy events. In contrast, the reconstruction of cascade directions, in principle possible to within a few degrees, is still in the development stage in IceCube, achieving 8° resolution.[13,14] On the other hand, determining their energy from the observed light pool is straightforward, and a resolution of better than 15% can be achieved. For illustration, we contrast in **Figure 4** the Cherenkov patterns initiated by an electron (or tau) neutrino of 1 PeV energy (top) and a neutrino-induced muon losing 2.6 PeV energy while traversing the detector (bottom).

IceCube identifies cosmic neutrinos in a background of muons and neutrinos produced by cosmic rays interacting in the atmosphere. For neutrino astronomy, the first challenge is to select a pure sample of neutrinos, more than 100 000 per year above a threshold of 0.1 TeV, from a background of ten billion atmospheric cosmic-ray muons. Neutrino energies cover more than six orders of magnitude, from ≈ 5 GeV in the highly instrumented inner core, labeled DeepCore in Figure 2, to extreme energies beyond 10 PeV. The second challenge is to identify the small fraction of these neutrinos that is astrophysical in origin. Atmospheric neutrinos are a background for cosmic neutrinos, at least at neutrino energies below ≈ 100 TeV. Above this energy, the atmospheric neutrino flux reduces to a few events per year, even in a kilometer-scale detector, and thus neutrinos well above that energy are cosmic in origin.

Soon after the completion of the detector, with 2 years of data, IceCube discovered an extragalactic flux of cosmic neutrinos[1] with an energy flux, $E^2\, \mathrm{d}N/\mathrm{d}E$, in the local universe that is, surprisingly, similar to that in gamma rays.[15,16] Two principal methods are used to separate neutrinos of cosmic origin from the background of atmospheric neutrinos. The first method reconstructs upgoing muon tracks reaching the detector from directions below the horizon, the second identifies neutrinos of all flavors that interact inside the instrumented volume of the detector;

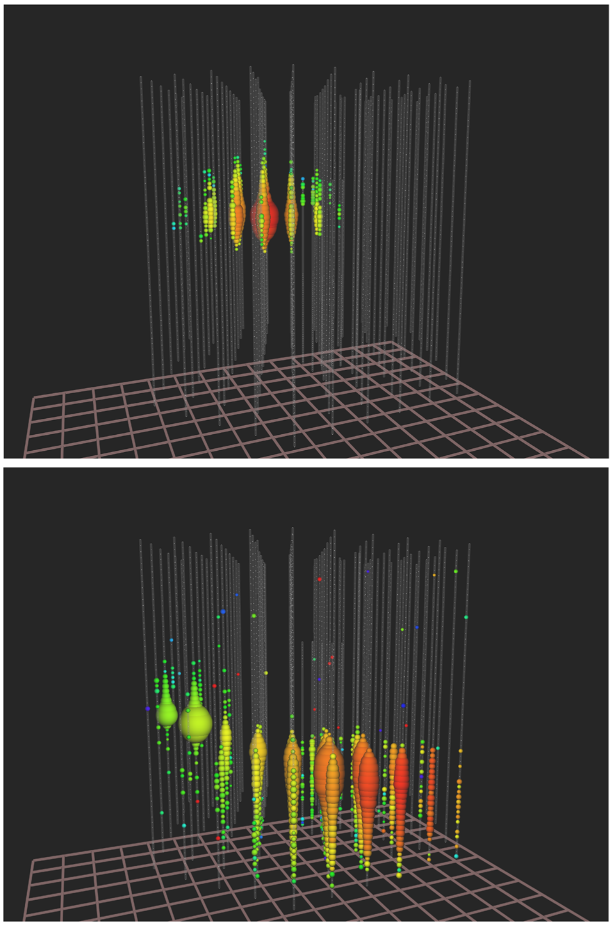

Figure 4. Top panel: Light pool produced in IceCube by a shower initiated by an electron or tau neutrino of 1.14 PeV, which represents a lower limit on the energy of the neutrino that initiated the shower. White dots represent sensors with no signal. For the colored dots, the color indicates arrival time, from red (early) to purple (late) following the rainbow, and size reflects the number of photons detected. Bottom panel: A muon track coming up through the Earth, traverses the detector at an angle of 11° below the horizon. The deposited energy, that is, the energy equivalent of the total Cherenkov light of all charged secondary particles inside the detector, is 2.6 PeV.

examples are shown in Figure 4. We will describe these methods in turn.

Detecting particles from directions below the horizon has the immediate advantage of eliminating the overwhelming background of cosmic-ray muons that reach the detector from above. IceCube thus collected samples of muon neutrinos with high purity, often above 99%, and measured the atmospheric neutrino flux over more than five orders of magnitude in energy with a result that is consistent with theoretical calculations. The tracks can be well reconstructed and separated from the background of atmospheric muons using the Earth as a filter. Muon neutrinos can be detected even when interacting outside the detector because of the kilometer range of the secondary muons. More importantly, IceCube also observes an excess of neutrino events at energies beyond 100 TeV[17–19] that cannot be accounted for by the atmospheric flux. A recent measurement of the energy flux covering 9.5 years of data was performed on a sample of 650 000 neutrinos with 99.7% purity (see **Figure 5**). The excess cosmic neutrino flux (red) over the atmospheric background (blue) is well described by a power law with a spectral index of -2.37 ± 0.09 and a normalization at 100 TeV neutrino energy of $(1.36^{+0.24}_{-0.25}) \times 10^{-18}\,\text{GeV}^{-1}\text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}$.[20] The residual atmospheric muon background is small (yellow). For more details, see ref. [21].

The measured arrival directions of the astrophysical muon tracks are isotropically distributed over the sky. Surprisingly, there is no evidence for a correlation to nearby sources in the Galactic plane; IceCube is recording a diffuse flux of extragalactic sources. Only after collecting 10 years of data[22] did the first evidence emerge at the 3σ level that the neutrino sky is not isotropic. The anisotropy results from four sources—TXS 0506+056 among them (more about that source later on)—that emerge as point sources of neutrinos above the 4σ level (pretrial); see **Figure 6**. The strongest of these sources is the nearby active galaxy NGC 1068, also known as Messier 77, which, interestingly, also happens to be the most significant source in a list of about a hundred candidates that were preselected as potential neutrino sources.

The second method for separating cosmic from atmospheric neutrinos exclusively identifies high-energy neutrinos interacting inside the instrumented volume of the detector, so-called starting events. It divides the instrumented volume of ice into an outer veto shield and a $\approx$ 500-megaton inner fiducial volume. The advantage of focusing on neutrinos interacting inside the instrumented volume of ice is that the detector functions as a total absorption calorimeter,[13] allowing for a good energy measurement that separates cosmic from lower-energy atmospheric neutrinos. In contrast to the first method, neutrinos from all directions in the sky and of all flavors can be identified, including both muon tracks and secondary showers produced by charged-current interactions of electron and tau neutrinos and neutral current interactions of neutrinos of all flavors. A sample event with a light pool of roughly one hundred thousand photoelectrons extending over more than 500 m is shown in the top panel of Figure 4.

The starting event samples revealed the first evidence for neutrinos of cosmic origin.[1,23] Events with PeV energies and with no trace of coincident muons that reveal either the accompanying decay products or the parent atmospheric shower of an atmospheric neutrino are highly unlikely to be of atmospheric origin. The present 7 year data set contains a total of 60 neutrino events with deposited energies ranging from 60 TeV to 10 PeV that are likely to be of cosmic origin. The deposited energy and zenith dependence of the high-energy starting events[19,24] is compared to the atmospheric background in **Figure 7**. A purely atmospheric explanation of the observation is excluded at 8σ.

The flux of cosmic neutrinos has by now also been characterized with a range of other methods. Their results agree, pointing at extragalactic sources whose flux has equilibrated in the three flavors after propagation over cosmic distances,[26] with $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$. **Figure 8** shows the results of a search exclusively identifying showers that have been isolated from the atmospheric background down to energies below 10 TeV.[27] The energy spectrum of $E^{-2.5}$ agrees with the measurement using upgoing muons with a spectral index of $E^{-2.4}$ above an energy of $\approx$ 100 TeV.[19] In general, analyses reaching lower

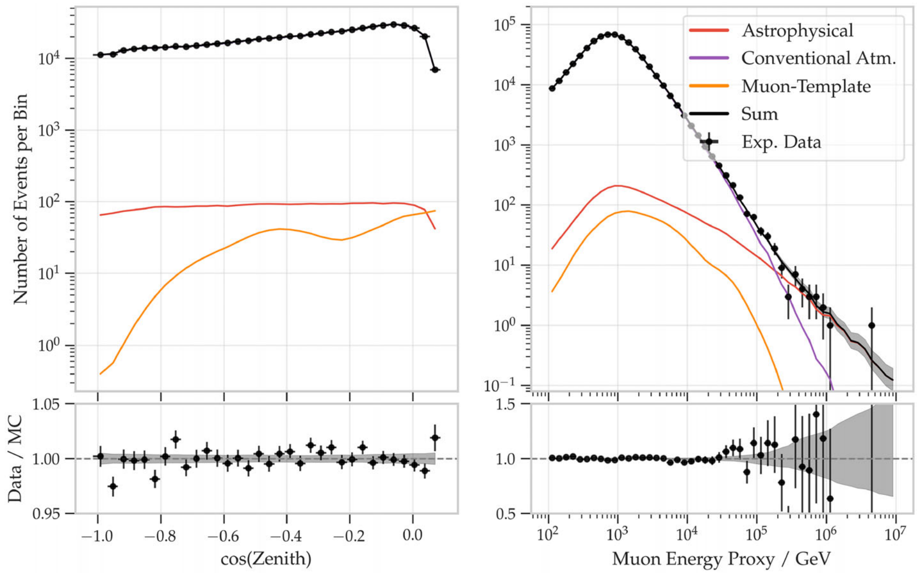

Figure 5. The distributions of muon tracks arriving from the Northern Hemisphere, that is, with declination greater than −5°, for the period 2010-2018,[20] are shown as a function of reconstructed zenith (left) and muon energy (right). The full data set consists of about 650 000 neutrino events with a purity of 99.7%. Best-fits to the low-energy atmospheric and high-energy astrophysical components of the neutrino flux are superimposed. Statistical errors are shown as crosses, the gray bands in the ratio plots show an estimate of the systematic error obtained by varying all fit-parameters within their uncertainties.

energies exhibit larger spectral indices with the updated 7.5 years starting-event sample [24] yielding a spectral index value of -2.87 ± 0.2 for the 68.3% confidence interval.

We should comment at this point that there is yet another method to conclusively identify neutrinos that are of cosmic origin: the observation of very high energy tau neutrinos. Tau neutrinos are produced in the atmosphere by the oscillations of muon neutrinos into tau neutrinos, but only for neutrino energies well below 100 GeV. Above that energy a tau neutrino must be of cosmic origin, produced in cosmic accelerators whose flux will be approximately one third neutrinos of tau flavor. Tau neutrinos produce two spatially separated showers in the detector, one from the interaction of the tau neutrino and the second from the decay of the secondary tau produced.[28] The mean decay length of the tau lepton is $\lambda_\tau = (E_\tau/m)\, c\,\tau \approx 50\ \text{m} \times (E_\tau/\text{PeV})$, where m, τ, and E_τ are the mass, lifetime, and energy of the tau, respectively. Two such candidate events have been identified.[29] An event with a decay length of 17 m and a probability of 98% of being produced by a tau neutrino is shown in **Figure 9**. The energies of the two showers are 9 and 80 TeV.

Yet another independent confirmation of the observation of neutrinos of cosmic origin appeared in the form of the Glashow resonance event shown in **Figure 10**. The event was identified in a dedicated search for partially contained showers of very high energy. The reconstructed energy of the shower is 6.3 PeV, which matches the laboratory energy for the production of a weak intermediate W^- in the resonant interaction of an electron antineutrino with an atomic electron[30]: $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow q + \bar{q}$. Given its high energy, the initial neutrino is cosmic in origin; it represents an independent discovery of cosmic neutrinos at the level of 5σ. Assuming the Standard Model cross section, we expect 1.55 events in the data sample searched, assuming an antineutrino:neutrino ratio of 1:1 characteristic of a cosmic source producing an equal number of pions of all three electric charges. Taking into account the detector's energy resolution, the probability that the event is produced off resonance by deep inelastic scattering is only 0.01, assuming a spectrum with a spectral index of $\gamma = -2.5$. Furthermore, the presence of both muons and an electromagnetic shower is consistent with the hadronic decay of a W^- produced on the Glashow resonance.

The observation of a Glashow resonance event indicates the presence of electron antineutrinos in the cosmic neutrino flux. Its unique signature provides a method to disentangle neutrinos from antineutrinos; their ratio distinguishes accelerators that produce neutrinos via pp and $p\gamma$ interactions and is also sensitive to their magnetic field.[30]

Finally, data from the ANTARES experiment are consistent with the observation of a flux of cosmic origin although with limited statistical significance.[31]

3. Multimessenger Astronomy

The most important message emerging from the IceCube measurements may not be apparent yet: the prominent role of neutrinos relative to photons in the extreme universe. To illustrate this point, we show in **Figure 11** the energy fluxes, $E^2\, \mathrm{d}N/\mathrm{d}E$, of neutrinos and gamma rays in the universe. Clearly, the energy flux of cosmic neutrinos is comparable to the one for gamma rays observed by the NASA Fermi satellite.[15] This may point at a common origin but, in any case, indicates a more prominent role of hadronic processes than routinely anticipated. It definitely creates excellent opportunities for multimessenger studies.

Photons are inevitably produced in association with neutrinos when accelerated cosmic rays produce both neutral and charged pions in interactions with target material in the vicinity of the accelerator. While neutral pions decay into two gamma rays, $\pi^0 \rightarrow$

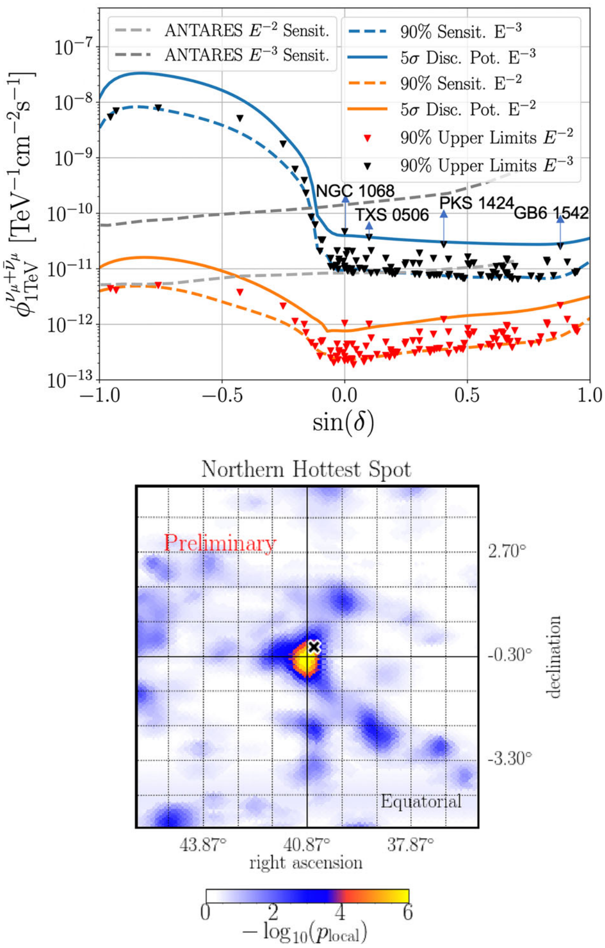

Figure 6. Top panel: Upper limits on the flux from candidate point sources of neutrinos in 10 years of IceCube data assuming two spectral indices of the flux. Adapted with permission.[22] Copyright 2020, American Physical Society. Also shown as triangles are limits on a preselected list of about 100 candidate sources. Four sources exceed the 4σ level (pretrial) and collectively result in a 3σ anisotropy of the sky map. Bottom panel: Association of the hottest source in the sky map as well as in the list of preselected candidate sources with the active galaxy NGC 1068.

$\gamma + \gamma$, the charged pions decay into three high-energy neutrinos (ν) and antineutrinos ($\bar{\nu}$) via the decay chain $\pi^+ \rightarrow \mu^+ + \nu_\mu$ followed by $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$ and the charged-conjugate process. On average, the four final state leptons equally share the energy of the charged pion. With these approximations, gamma rays and neutrinos carry on average 1/2 and 1/4 of the energy of the parent pion.

The neutrino production rate Q_{ν_α} (with typical units $\text{GeV}^{-1}\text{s}^{-1}$ and with the subscript α labeling the neutrino flavor) can be related to the one for charged pions Q_π by

$$\sum_\alpha E_\nu Q_{\nu_\alpha}(E_\nu) \simeq 3\left[E_\pi Q_{\pi^\pm}(E_\pi)\right]_{E_\pi \simeq 4E_\nu} \quad (2)$$

while, similarly, the production rate of pionic gamma rays is related to the one for neutral pions by

$$E_\gamma Q_\gamma(E_\gamma) \simeq 2\left[E_\pi Q_{\pi^0}(E_\pi)\right]_{E_\pi \simeq 2E_\gamma} \quad (3)$$

Pion production in the interactions of cosmic rays with photon fields proceeds resonantly via the processes $p + \gamma \rightarrow \Delta^+ \rightarrow \pi^0 + p$ and $p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$. These channels produce charged and neutral pions with probabilities 2/3 and 1/3, respectively. However, the additional contribution of non-resonant pion production changes this ratio to ≈1/2 and 1/2. In contrast, cosmic rays interacting with matter produce equal numbers of pions of all three charges: $p + p \rightarrow n_\pi\,[\pi^0 + \pi^+ + \pi^-] + X$, where n_π is the pion multiplicity. We thus obtain a charge ratio $K_\pi = n_{\pi^\pm}/n_{\pi^0} \simeq 2$ and 1 for pp and $p\gamma$ interactions, respectively.

Equations (2) and (3) can now be combined to obtain a direct relation between the gamma-ray and neutrino production rates:

$$\frac{1}{3}\sum_\alpha E_\nu^2 Q_{\nu_\alpha}(E_\nu) \simeq \frac{K_\pi}{4}\left[E_\gamma^2 Q_\gamma(E_\gamma)\right]_{E_\gamma = 2E_\nu} \quad (4)$$

where the factor 1/4 accounts for the fact that two gamma rays are produced in the neutral pion decay with twice the energy of the accompanying neutrino, $\langle E_\nu \rangle / \langle E_\gamma \rangle \simeq 1/2$. Note that the relative production rate of gamma rays and neutrinos only depends on the ratio of charged-to-neutral pions produced without any reference to the cosmic-ray beam that initiates their production in the target. This powerful relation follows from the fact that pion production conserves isospin, and nothing else.

Before applying this relation to data, one must recall that the universe is not transparent to PeV gamma rays. These will interact with microwave photons and other components of the EBL to initiate an electromagnetic cascade that reaches Earth in the form of multiple photons of lower energy. The electromagnetic shower subdivides the initial PeV photon energy, resulting in a shower of multiple photons with GeV to TeV energies by the time it reaches Earth.[32,33] If the source itself is opaque to gamma rays, the high-energy gamma rays will lose energy even before reaching the EBL to possibly emerge at Earth below the threshold of Fermi, at MeV energies and below.

As discussed in the introduction, production of neutrinos requires a beam and a target, and a powerful neutrino source requires a dense target that will render the source opaque to high-energy gamma rays. While the beam loses energy in the target producing high-energy neutrinos, the energy of the accompanying photons may be spread over a wide range of the electromagnetic spectrum before reaching our telescopes. This is very likely to be the case for the most powerful neutrino sources, which exceed the sensitivity of IceCube at this time. The energy of the photons associated with cosmic neutrinos may thus emerge below the threshold of our gamma-ray instruments, for instance the NASA Fermi gamma-ray satellite; we refer to these as gamma-obscured sources.

In order to underscore the power of the multimessenger connection between photons and neutrinos, we calculate the gamma-ray flux accompanying the diffuse cosmic neutrino flux observed by IceCube, which we describe by a power law with spectral index of −2.15, consistent with the neutrino data above an energy of 100 TeV. The result is shown in Figure 11 assuming transparent sources and equal multiplicities of all three pion charges, that is, $K_\pi = 2$. The cascaded gamma-ray energy flux resulting from the pionic photons accompanying the neutrino flux matches the energy flux of extragalactic gamma rays measured by Fermi. This exercise illustrates that, rather than

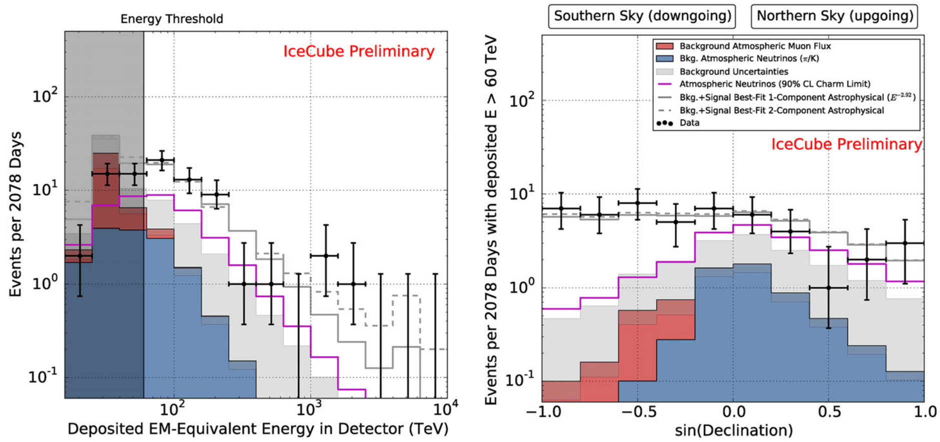

Figure 7. Left panel: Deposited energies, by neutrinos interacting inside IceCube, observed in 6 years of data.[19] The gray region shows uncertainties on the sum of all backgrounds. The atmospheric muon flux (blue) and its uncertainty is computed from simulation to overcome statistical limitations in our background measurement and scaled to match the total measured background rate. The atmospheric neutrino flux is derived from previous measurements of both the π, K, and charm components of the atmospheric spectrum.[25] Also shown are two fits to the spectrum, assuming a simple power-law (solid gray) and a broken power-law (dashed gray). Right panel: The same data and models, but now show the distribution of events with deposited energy above 60 TeV in declination. At the South Pole, the declination angle δ is equivalent to the distribution in zenith angle θ related by the identity, $\delta = \theta - \pi/2$. It is clearly visible that the data is flat in the Southern Hemisphere, as expected from the contribution of an isotropic astrophysical flux.

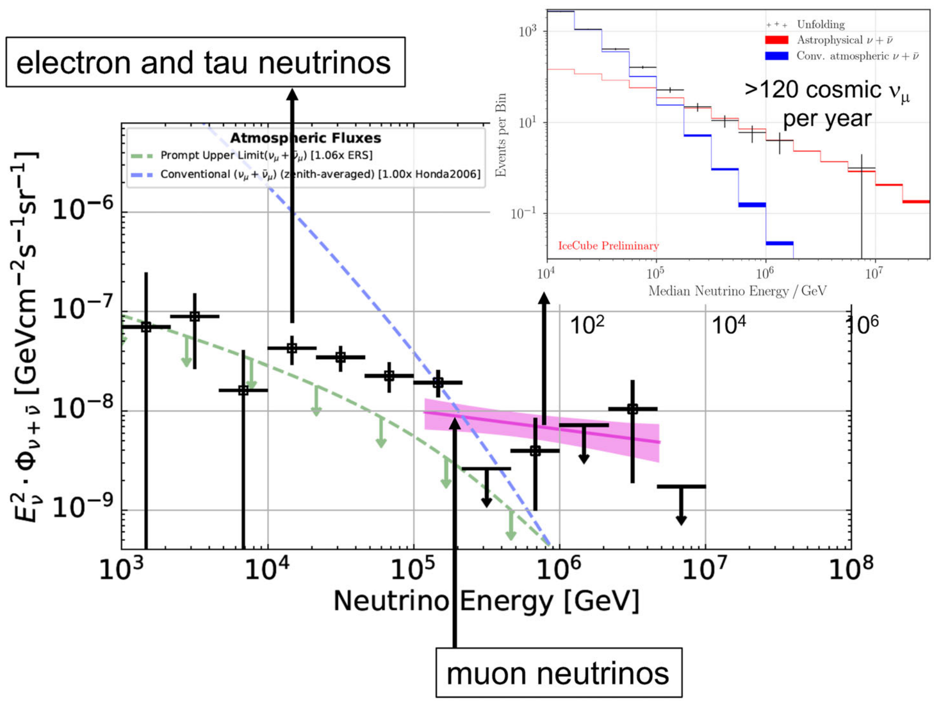

Figure 8. The flux of cosmic muon neutrinos[19] inferred from the 8 year upgoing-muon track analysis (red solid line) with 1σ uncertainty range (shaded range; from fit shown in upper-right inset) is compared with the flux of showers initiated by electron and tau neutrinos.[27] The measurements are consistent assuming that each neutrino flavor contributes an identical flux to the diffuse spectrum.

detecting some exotic sources, IceCube observes to a large extent the same universe astronomers do. The finding implies that a significant fraction of the energy in the nonthermal universe originates in hadronic processes, indicating a larger role than previously thought.

Clearly, in this exercise, the slope and overall normalization of the neutrino spectrum has been adjusted to not exceed the isotropic extragalactic gamma-ray background observed by the Fermi satellite. We conclude that the high-energy cosmic neutrino flux above 100 TeV shown in Figure 11 saturates the Fermi measurement for the highest photon energies; higher normalization and larger spectral index of the neutrino flux will result in a gamma-ray result that exceeds the Fermi data as shown in **Figure 12**. Fitting the IceCube data with a $E^{-2.5}$ spectral index,

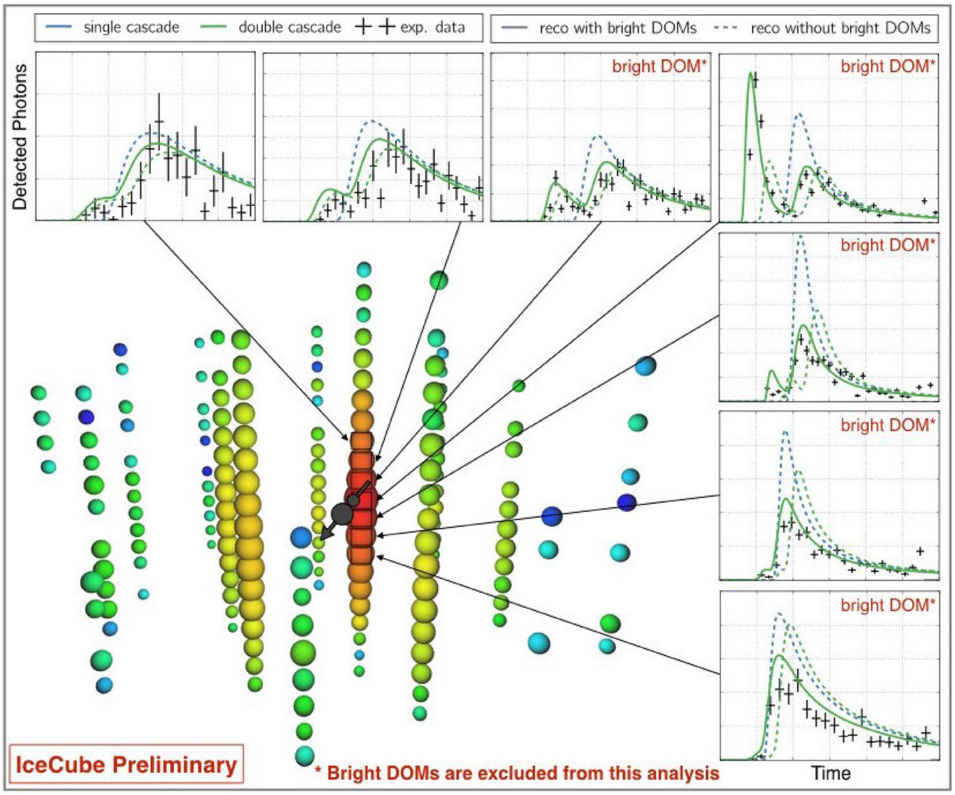

Figure 9. Event view of a tau neutrino.[29] The Cherenkov photons associated with the production and subsequent decay of the tau neutrino are identified by the double-peaked photon count as a function of time for the bright DOMs, for instance, the one shown in the top-right corner. The best fit (solid line) corresponds to a 17 m decay length and is far superior to fits assuming a single electromagnetic or hadronic shower (dashed lines).

closer to the present observations, results in larger neutrino energy fluxes at energies below 100 TeV for both neutrinos and their accompanying photons. After cascading in the EBL, the latter exceeds the Fermi observations. There is no conflict here, we conclude that the assumption that the sources are transparent is untenable. The resolution is that the sources themselves are opaque to photons that lose energy in the source even before entering the EBL and, as a result, reach Earth with energies that are below the detection threshold of the Fermi satellite, at MeV energy or below.

Alternatively, the target for producing the neutrinos may be photons. This changes the value of K_π and, more importantly, the shape of the energy spectrum; for a detailed discussion see, for instance, ref. [37]. Yielding an energy spectrum that peaks near PeV energies as shown in **Figure 13**, the contribution to the Fermi flux is suppressed at lower energies relative to the power law assumed in Figures 11 and 12. However, as was the case for *pp* interactions, fits that do not exceed the Fermi data tend not to accommodate the cosmic neutrino spectrum below 100 TeV. This is shown in Figure 13 where a neutrino spectrum below the Fermi observation fails to describe the neutrino data. If sources of the TeV–PeV neutrinos are transparent to gamma rays with respect to two-photon annihilation, tensions with the isotropic diffuse gamma-ray background measured by Fermi seem unavoidable, independently of the production mechanism.[36]

The conclusion is inescapable that the energy fluxes of neutrinos and gamma rays in the extreme universe are qualitatively the same. To the extent that the IceCube observations favor steeper energy spectra than $E^{-2.15}$, we anticipate contributions to the diffuse flux from gamma-hidden sources. Interestingly, the common energy density of photons and neutrinos is also comparable to that of the ultra-high-energy extragalactic cosmic rays.[38] We therefore anticipate that multimessenger studies of gamma-ray and neutrino data will be a powerful tool to identify and study the cosmic ray accelerators that produce cosmic neutrinos. Accordingly, IceCube developed methods, most promising among them real-time multiwavelength observations with astronomical telescopes, to identify the sources and build on the discovery of cosmic neutrinos to launch a new era in astronomy.[39,40]

An important lesson for multiwavelength astronomy is that strong high-energy gamma-ray emitters may not be the best candidate neutrino sources. For instance, IceCube does not observe neutrinos from gamma-ray bursts, but it has exclusively followed up long bursts that emit gamma rays.[41] A handful of gamma-ray bursts have been identified that are obscured in gamma rays and may instead provide the key to detecting a neutrino signal.

4. Identifying Neutrino Sources: The Supermassive Black Hole TXS 0506+056

Phenomenological studies[42,43] and recent data analyses[44–46] have converged on the fact that Fermi's extragalactic gamma-ray flux shown in Figure 11 is dominated by blazars, AGN with jets pointing at Earth. It is tempting to conclude, based on the

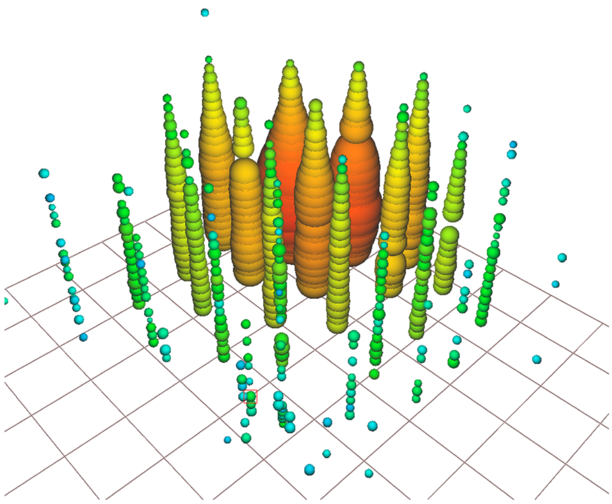

Figure 10. Particle shower created by the Glashow resonance.[30] Its energy is reconstructed at the resonant energy for the production of a weak intermediate boson W^- in the interaction of an antielectron neutrino with an atomic electron in the ice. The properties of the secondary muons produced in the particle shower are consistent with the hadronic decay of a W^- boson.

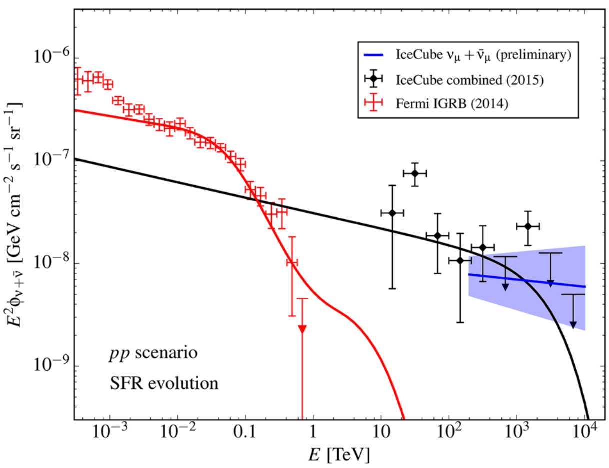

Figure 11. An early calculation illustrating that the photon flux that accompanies the neutrino flux (black line) measured by IceCube matches the gamma-ray flux (red line) observed by Fermi. We assume a $E^{-1.5}$ energy spectrum, star-formation redshift evolution and, importantly, gamma-ray transparent sources, that is, pionic photons cascade in the EBL only. The black data points are early IceCube measurements[34,35] and the blue band is a best fit to the flux of high-energy muon neutrinos.[17–19] The result suggests that the decay products of neutral and charged pions from *pp* interactions may be significant components of the nonthermal radiation in the extreme universe.[36] (Introducing the cutoff on the high-energy flux, shown in the figure, does not affect the result.)

matching energy fluxes of photons and neutrinos discussed in the previous section, that the unidentified neutrino sources contributing to the diffuse neutrino flux have already been observed as strong gamma-ray emitters. This is not the case. A dedicated IceCube study[47] correlating the arrival directions of cosmic neutrinos with Fermi blazars shows no evidence of neutrino emission from these sources. The limit leaves room for a contribution

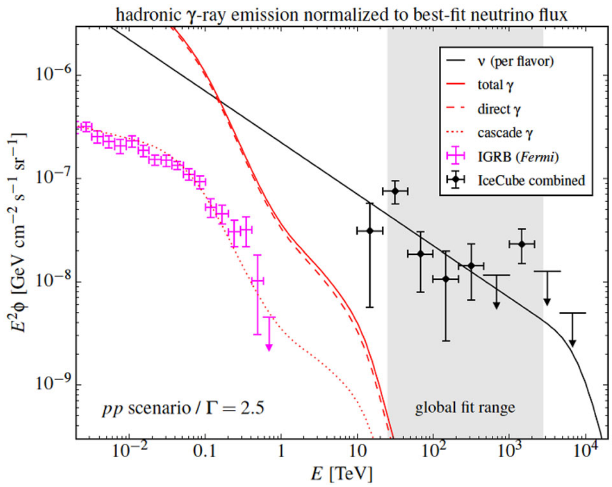

Figure 12. Same calculation as in Figure 11 with the spectral index of −2.15 replaced by −2.5, closer to what is suggested by the present IceCube measurements. The predicted gamma ray flux exceeds the Fermi observations implying that the assumption that the sources are transparent to $\gamma\gamma$ interactions is not tenable. The excess flux is shifted below the Fermi threshold, to MeV energies or below, by cascading of the pionic gamma rays in the source before reaching the EBL. (Introducing the cutoff on the high-energy flux, shown in the figure, does not affect the result.)

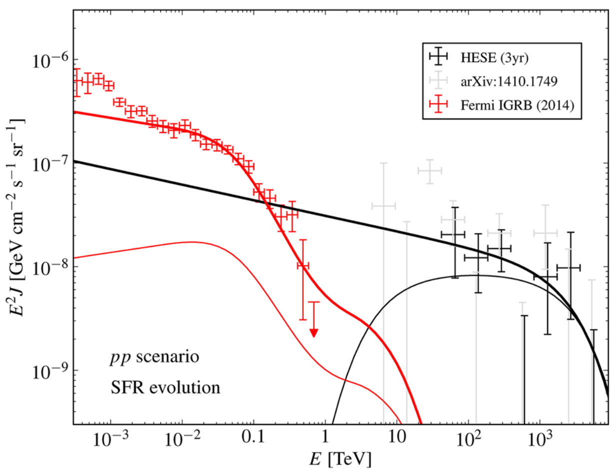

Figure 13. The calculation in Figure 11 is compared to an identical calculation adopting a spectral shape characteristic for the production of cosmic neutrinos on a gamma ray target in the source. While the pionic gamma ray energy flux is now suppressed relative to the Fermi observations, the neutrino energy spectrum does not fit the IceCube observations and the conclusion that the sources are likely obscured is recovered after correct normalization to the most up to date measurements.[36]

of Fermi blazars to the diffuse cosmic neutrino flux below the 10% level. Surprisingly, the multimessenger campaign launched by the neutrino alert IC-170922A[2] identified the first source of cosmic neutrinos as a Fermi "blazar;" we will discuss how the multiwavelength data shed light on the apparent contradiction.

Since 2016, the IceCube multimessenger program has grown from issuing Galactic supernova alerts[48] and common data analyses matching neutrinos with early LIGO/Virgo gravitational wave candidates to a steadily expanding set of automatic filters that selects in real time rare, very high energy neutrino events that are likely to be cosmic in origin.[49] Within less than a minute of stopping in the instrumented Antarctic ice, the arrival directions of the neutrinos are reconstructed and automatically sent to the Gamma-ray Coordinate Network for potential follow-up by astronomical telescopes.

4.1. Observation of a Cosmic Neutrino Source: TXS 0506+056

On September 22, 2017, the tenth such alert, IceCube-170922A,[50] reported a well-reconstructed muon that deposited 180 TeV inside the detector, corresponding to a most probable energy of the parent neutrino of 290 TeV. Its arrival direction was aligned with the coordinates of a known Fermi blazar, TXS 0506+056, to within 0.06°. The source was “flaring” with a gamma-ray flux that had increased by a factor of seven in recent months. A variety of estimates converged on a probability on the order of 10^{-3} that the coincidence was accidental. The identification of the neutrino with the source reached the level of evidence, but not more. What clinched the association was a series of subsequent observations, culminating with the optical observation of the source switching from an “off” to an “on” state 2 h after the emission of IC-170922A, conclusively associating the neutrino with TXS 0506+056.[51] The sequence of observations can be summarized as follows:

1) The redshift of the host galaxy, a known blazar, was measured to be $z \simeq 0.34$.[52] It is important to realize that nearby blazars like the Markarian sources are at a distance that is ten times closer, and therefore TXS 0506+056, with a similar flux despite the greater distance, is one of the most luminous sources in the universe. This suggests that it belongs to a special class of sources that accelerate proton beams in dense environments, revealed by the neutrino. That the source is special eliminates any conflict between its observation and the lack of correlation between the arrival directions of IceCube neutrinos and the bulk of the blazars observed by Fermi.[47] Such limits implicitly assume that all sources in an astronomical category are identical, and this is a strong, unstated assumption as underscored by this observation.
2) Originally detected by NASA’s Swift[53] and Fermi[54] satellites, the alert was followed up by ground-based air Cherenkov telescopes.[55] MAGIC detected the emission of gamma rays with energies exceeding 100 GeV starting several days after the observation of the neutrino.[56] Given its distance, this establishes the source as a relatively rare TeV blazar.
3) Informed where to look, IceCube searched its archival neutrino data up to and including October 2017 for evidence of neutrino emission at the location of TXS 0506+056.[3] When searching the sky for point sources of neutrinos, two analyses have been routinely performed: one that searches for steady emission of neutrinos and one that searches for flares over a variety of timescales. Evidence was found for 19 high-energy neutrino events on a background of fewer than six in a burst lasting 110 days. This burst dominates the integrated flux from the source over the last 9.5 years of archival IceCube data, leaving the 2017 flare as a second subdominant feature.

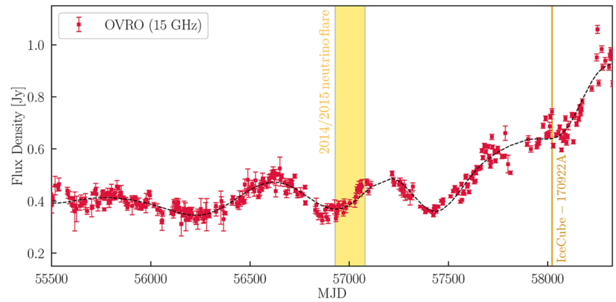

Figure 14. TXS 0506+056 radio light curve from Owen Valley Radio Observatory (OVRO) at 15 GHz (red). The dashed line illustrates the pattern of the radio flux density. The 2014/15 110-day neutrino flare (yellow band) and the IceCube-170922A episodes are shown. Radio data suggest that the neutrinos arrive during extended periods of enhanced radio emission.

We note that this analysis applied a published prescription to data; no new data analysis was involved, and thus the chance that this observation is a fluctuation is small.
4) Radio interferometric images[57,58] of the source revealed a jet that loses its tight collimation beyond 5 milliarcseconds running into material or intense radiation fields that are likely to be the target for producing the neutrinos. The nature of the target is still a matter of debate. Speculations include the merger with another galaxy that may supply plenty of material to interact with the jet of the dominant galaxy. Alternatively, the jet may interact with the dense molecular clouds of a star-forming region or simply with supermassive stars in the central region of the host galaxy.[57,58] Also, in a so-called structured jet, the accelerated protons may catch up and collide with a slower moving and denser region of jetted photons. Additionally, the VLBA data reveal that the neutrino burst occurs at the peak of enhanced radio emission at 15 GHz, which started 5 years ago; see **Figure 14**. The radio flare may be a signature of a galaxy merger; correlations of radio bursts with the process of merging supermassive black holes have been anticipated.[59]
5) The MASTER robotic optical telescope network has been monitoring the source since 2005 and detected its strongest time variation in the last 15 years to occur 2 h after the emission of IC170922, with a second variation following the 2014-15 burst.[51] The blazar switches from the “off” to the “on” state 2 h after the emission of the neutrino. After an episode of monitoring the uniformity of their observations of the source in the first quarter of 2020, they argue that the time variation detected on September 22, 2017 conclusively associates the source with the neutrino.[51]

Additionally, it is important to note the fact that the high-energy photon and neutrino spectra covering the 2014 burst are consistent with a hard E^{-2} spectrum, which is expected for a cosmic accelerator. In fact, the gamma-ray spectrum shows a hint of flattening beyond E^{-2} during the 110-day period of the 2014 burst.[60,61]

In summary, both the multiwavelength campaign[2] and the observation of an earlier burst of the same source in archival neutrino data provide statistically independent[3] evidence for TXS

0506+056 as a source of high-energy neutrinos. When combined, the two observations reach a statistical level of 4.4σ. It is however challenging to evaluate the final combined significance because of the a posteriori nature of some considerations, but we conclude that the association of neutrinos with the source summarized above is totally compelling. However, the significance contributed by the optical and TeV associations on timescales of hours and days, discussed above, are not taken into account in this estimate.

Other IceCube alerts have triggered intriguing observations. Following up on a July 31, 2016, neutrino alert, the AGILE collaboration, which operates an orbiting X-ray and gamma-ray telescope, reported a day-long blazar flare in the direction of the neutrino one day before the neutrino detection.[62] A tentative but very intriguing association of an IceCube alert[63] has been made with a tidal disruption event, an anticipated source of high-energy neutrino emission. Even before IceCube issued automatic alerts, in April 2016, the TANAMI collaboration argued for the association of the highest energy IceCube event at the time, dubbed "Big Bird," with the flaring blazar PKS B1424-418.[64] Interestingly, the event was produced at a minimum of the Fermi flux,[65] as expected for a neutrino source and as was also the case for PKS 1502+106, which we will discuss further on. AMANDA, IceCube's predecessor, observed[66] three neutrinos in coincidence with a rare flare of the blazar 1ES 1959+650 detected by the Whipple telescope in 2002.[67] However, none of these identifications reach the significance of the observations triggered by IC-170922A.

4.2. The Blueprint of the TXS 0506+056 Beam Dump?

The gamma ray community has developed a routine procedure for modeling the spectrum of blazars with two contributions: a lower energy component produced by synchrotron radiation by the electron beam and a high-energy component resulting from the inverse Compton scattering of (possibly the same) photons by accelerated electrons; for a recent discussion see ref. [68]. This model cannot accommodate the TXS observations for two reasons: an electron beam does not produce pions that decay into neutrinos and, even in the presence of a proton beam, a target is required to produce the parent pions. It is evident that a source that emits high-energy gamma rays is transparent to $\gamma\gamma$ absorption and is unlikely to host the target material to produce neutrinos. The opacity for $\gamma\gamma$ interactions to absorb photons is typically two orders of magnitude larger than the one for $p\gamma$ interactions to produce pions and neutrinos.[69] The photon spectra themselves strongly indicate that TXS 0506+056 is not a high-energy photon blazar at the times of neutrino emission. It belongs to a special class of sources, is reinforced by the fact that attempts at conventional blazar modeling of the multiwavelength spectrum have been unsuccessful despite the opportunity for tuning 14 free parameters; see for example, refs. [68, 70].

In what follows, we will scrutinize the multiwavelength data rather than try to match it to, or model it as, a known class of astronomical objects. Our conclusion will be that the source is special, with properties unlikely to match any astronomical classification, which should not be surprising[69] given that it emits neutrinos. Astronomical data catalogues accelerators, not neutrino "beam dumps."

First, we would like to draw attention to a more recent alert, IC-190730A, sent by IceCube on July 30, 2019. A well-reconstructed 300-TeV muon neutrino was observed in spatial coincidence with the blazar PKS 1502+106.[71] With a reconstructed energy just exceeding that of IC-170922A, it is the highest energy neutrino alert so far. OVRO radio observations[72] show that the neutrino is coincident with the peak flux density of a flare at 15 GHz that started 5 years prior,[73] matching the similar long-term radio outburst of TXS 0506+056 at the time of IC-170922A; see Figure 14. Even more intriguing is the fact that the gamma-ray flux observed by Fermi shows a clear minimum at the time that the neutrino is emitted; see **Figure 15**. We infer that at this time the jet meets the target that produces the neutrino. Inevitably, the accompanying high-energy gamma rays will be absorbed and their electromagnetic energy cascade down to energies below the Fermi threshold, that is, MeV or X-rays. For a discussion, see ref. [65], where we argue that cosmic neutrinos are produced by temporarily gamma-suppressed blazars, or, more likely, any other category of AGN. In fact, this is also the case for TXS 0506+056, with no flaring activity coincident with the 2014-15 neutrino burst and IC170922 produced at a local minimum of the gamma ray flux.[74]

The coincidence of the two highest energy alerts to date with extended periods of radio emission has led to the speculation that all [75], or at least some,[76] cosmic neutrinos originate in radio-bright radio galaxies. The significance of the correlation and its physical origin, if any,[77] are hotly debated.

We have already pointed out that the large distance of TXS 0506+056 suggests that the source is special. So does the large neutrino flux observed: we will underscore this by showing that a subset of $\approx 1-10\,\%$ of sources with a density similar to blazars, bursting at the level of TXS 0506+056 in the period of 10 years covered by the IceCube observations, is sufficient to accommodate the total diffuse flux observed by IceCube.

The diffused neutrino flux from a population of neutrino sources with source density ρ and neutrino luminosity L_ν, is given by [69,78]

$$E^2\frac{\mathrm{d}N}{\mathrm{d}E} = \frac{1}{4\pi}\int d^3r\,\frac{L_\nu}{4\pi r^2}\rho \tag{5}$$

which can be simplified to

$$E^2\frac{\mathrm{d}N}{\mathrm{d}E} = \frac{c}{4\pi}\,t_{\mathrm{H}}\,\xi\,L_\nu\,\rho \tag{6}$$

where ξ is the result of the integration over the redshift history of the sources and t_{H} is the Hubble time corresponding to a Hubble distance $R_{\mathrm{H}} \simeq 4.3$ Gpc. For instance, for a spectral index of $\gamma \simeq 2$ and no source evolution in the local universe, $\xi_z \simeq 0.5$, while for sources following the redshift history of star formation, $\xi_z \simeq 2.6$.[78] The above relation can be adapted for the case of sources that flare for a duration Δt in a total time of observation T_{obs}:

$$E^2\frac{\mathrm{d}N}{\mathrm{d}E} = \frac{c}{4\pi}\,t_{\mathrm{H}}\,\xi\,L_\nu\,\rho\,\frac{\Delta t}{T_{\mathrm{obs}}}\,\mathcal{F} \tag{7}$$

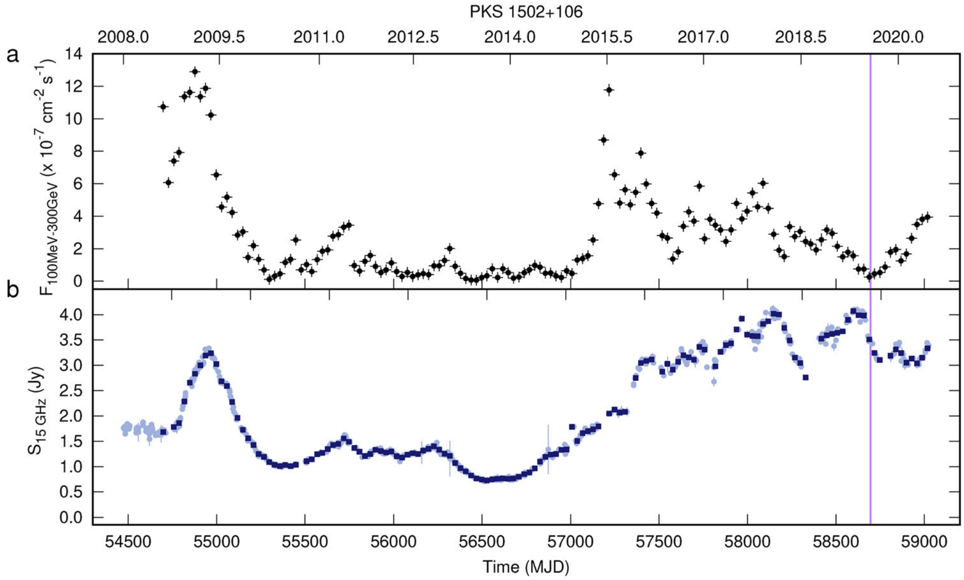

Figure 15. Temporal variation of the γ-ray and radio brightness of PKS 1502+106. Top panel: Fermi-LAT likelihood light curve integrated between 100 MeV and 300 GeV (marked by black dots with error bars). Bottom panel: OVRO flux density curve of PKS 1502+106 plotted with light blue dots, which are superimposed by the radio flux density curve binned to the Fermi-LAT light curve (marked with dark blue squares). The detection time of the neutrino IC-190730A is labeled by a vertical purple line.

Assuming that blazars are the sources of the diffuse flux we conclude that

$$3\times10^{-11}\,\mathrm{TeV cm^{-2}s^{-1}sr^{-1}} = \frac{\mathcal{F}}{4\pi}\left(\frac{R_{\mathrm{H}}}{3\,\mathrm{Gpc}}\right)\left(\frac{\xi}{0.7}\right)\left(\frac{L_\nu}{1.2\times10^{47}\,\mathrm{erg\,s^{-1}}}\right) \times\left(\frac{\rho}{10^{-8}\,\mathrm{Mpc^{-3}}}\right)\left(\frac{\Delta t}{110\,\mathrm{d}}\frac{10\,\mathrm{yr}}{T_{\mathrm{obs}}}\right) \tag{8}$$

which results in $\mathcal{F}=0.05$, where $\mathcal{F}$ is the fraction of some astronomical category of sources that emit neutrinos. We here normalized $\mathcal{F}$ to the density of blazars, but we could have normalized to a smaller fraction of all AGNs. Clearly, if TXS 0506+056 were a source typical of all blazars, it would overproduce the diffuse flux observed by IceCube. Attempts by IceCube and others to find a correlation between the directions of high-energy neutrinos and all Fermi blazars must inevitably be unsuccessful, as was the case in ref. [47].

It is interesting that the energy flux in neutrinos is consistent with their production by the sources of the highest energy cosmic rays with[69]:

$$E^2\frac{\mathrm{d}N}{\mathrm{d}E}\simeq\frac{c}{4\pi}\left(\frac{1}{2}(1-e^{-\tau_{p\gamma}})\,\xi\,t_{\mathrm{H}}\frac{\mathrm{d}E}{\mathrm{d}t}\right) \tag{9}$$

a relation referred to as the Waxman–Bahcall "bound"[79,80] in the limit $\tau_{p\gamma}\to1$. From the total cosmic ray injection rate $\mathrm{d}E/\mathrm{d}t=\approx(1-2)\times10^{44}\,\mathrm{erg\,Mpc^{-3}yr^{-1}}$ of extragalactic cosmic rays into the universe, we can determine the average opacity of the neutrino producing sources to protons $\tau_{p\gamma}$ that matches the observed diffuse neutrino flux: Equation (8)

$$\left(\frac{L_\nu}{1.2\times10^{47}\,\mathrm{ergs^{-1}}}\right)\left(\frac{\rho}{10^{-8}\,\mathrm{Mpc^{-3}}}\right)\left(\frac{\Delta t}{110\,\mathrm{d}}\frac{10\,\mathrm{yr}}{T_{\mathrm{obs}}}\right)\left(\frac{\mathcal{F}}{0.05}\right) \simeq\frac{1}{2}(1-e^{-\tau_{p\gamma}})\,\frac{\mathrm{d}E/\mathrm{d}t}{(1-2)\times10^{44}\,\mathrm{erg\,Mpc^{-3}yr^{-1}}} \tag{10}$$

We find that $\tau_{p\gamma}>0.8$. This can be achieved with a proton beam with low boost factor interacting with the intense photon fields near the core of an active galaxy. With the opacity to photons about two orders of magnitude larger, the target producing the neutrinos is not transparent to TeV photons, only to photons with tens of GeV energy, and that is indeed what is observed by Fermi at the time of the 2014 flare.

There is also evidence that, temporarily, TXS 0506+056 was a gamma-ray-obscured source at the time the IC-170922A neutrino was emitted; see ref. [74]. Recall that the optical observations show a dramatic transition of the blazar from the "off" to the "on" state 2 h after the emission of the neutrino, resulting additionally in the doubling of its total optical luminosity.[51] Also, the atmospheric gamma-ray telescopes observe rapid variations in the flux around the time of the neutrino emission,[2] with the gamma-ray emission observed by MAGIC only emerging after several days.[56]

The observation that the energy flux in neutrinos and very high energy cosmic rays are similar supports the fact that the cosmic rays must be highly efficient at producing neutrinos, requiring a large target density that renders them opaque to high-energy gamma rays. A consistent picture emerges with the source opacity $\tau_{p\gamma}$ exceeding a value of 0.8,[69] resulting in a gamma-ray cascade where photons lose energy in the source before cascading to yet lower energies in the extragalactic background light. Some of their energy emerges below the Fermi threshold by the time they reach Earth. This is consistent with the discussion in the previous section that the multimessenger relation between neutrinos and gamma rays points at obscured sources.

The nature of this special class of sources has not been settled. One straightforward explanation could be that a subclass of blazars or, more likely, a smaller fraction of all AGNs, selected by redshift evolution, are powerful proton accelerators producing neutrinos in the past but are no longer active today. This accommodates the large redshift of TXS 0506+056, which would be the closest among a set of sources that only accelerated cosmic rays at early redshifts.[81]

Alternatively, in merging galaxies there is plenty of material for accelerated cosmic rays to interact with the jet of the dominant galaxy. Merger activity in active galaxies in not uncommon. The fresh material provides optically thick environments and allows for rapid variation of the Lorentz factors. A cursory review of the literature on the production of neutrinos in galaxy mergers is sufficient to conclude that they can indeed accommodate the observations of both the individual sources discussed above and the total flux of cosmic neutrinos.[82–84] Besides mergers, some form of structured jet where the accelerated protons collide with a slower moving and denser region of jetted photons is a possibility. The jet could also interact with dense molecular clouds of a star-forming region or simply with supermassive stars near the central region of the host galaxy.[57,58]

We previously mentioned the evidence emerging from 10 years of IceCube data that the arrival directions of cosmic neutrinos are no longer isotropic.[85] The anisotropy results from four sources—TXS 0506+056 among them—that show evidence for clustering above the 4σ level. The strongest of these sources is the nearby active galaxy NGC 1068. There is evidence for shocks near the core and for molecular clouds with column density reaching $\approx 10^{25}$ cm^{-2}.[86] Similar to TSX 0506+056, a merger onto the black hole is observed — either with a satellite galaxy or, more likely, with a star-forming region[87] accounting for the molecular clouds. This major accretion event may be the origin of the increased neutrino emission.

Although it is obviously challenging to provide a final conclusion on the origin of neutrinos and cosmic rays, we should not lose sight of the fact that high-energy neutrino astronomy exists and that IceCube has demonstrated it has the tools to reveal the extreme universe with more data, or, more realistically, with a larger detector.

5. From Discovery to Astronomy: Larger Neutrino Telescopes with Better Angular Resolution

Following the pioneering work of DUMAND,[88] several neutrino telescope projects were initiated in the Mediterranean Sea and in Lake Baikal in the 1990s.[89–92] In 2008, the construction of the ANTARES detector off the coast of France was completed. It demonstrated the feasibility of neutrino detection in the deep sea and has provided a wealth of technical experience and design solutions for deep-sea components. An international collaboration has started construction of a multi-cubic-kilometer neutrino telescope in the Mediterranean Sea, KM3NeT.[93] They developed a digital optical module that incorporates 31 3-inch photomultipliers instead of one large photomultiplier tube; see **Figure 16**.

Figure 16. The KM3NeT optical module.[93] The optical module consists of a glass sphere with a diameter of 42 cm, housing 31 photosensors. The glass sphere can withstand the pressure of the water and is transparent to the faint light that must be detected to see neutrinos.

The advantages are a tripling of the photocathode area per optical module, a segmentation of the photocathode allowing for a clean identification of coincident Cherenkov photons, some directional sensitivity, and a reduction of the overall number of penetrators and connectors, which are expensive and prone to failure. KM3NeT in its second phase[93] will consist of two units for astrophysical neutrino observations, each consisting of 115 strings carrying more than 2000 optical modules.

A parallel effort is underway in Lake Baikal with the construction of the deep underwater neutrino telescope Baikal-GVD (Gigaton Volume Detector).[94] The first GVD cluster was upgraded in the spring of 2016 to its final size: 288 optical modules, a geometry of 120 meters in diameter and 525 meters high, and an instrumented volume of 6 Mton. Each of the eight strings consists of three sections with 12 optical modules. At this time, seven of the 14 clusters have been deployed, reaching a sensitivity close to the diffuse cosmic neutrino flux observed by IceCube.

IceCube itself is deploying seven new strings at the bottom of the detector array that have been designed as an incremental extension of the DeepCore detector and as a test bed for the technologies of a next-generation detector. The new instrumentation will dramatically boost IceCube's performance at the lowest energies, increasing the samples of atmospheric neutrinos by a factor of ten. New calibration devices will advance our understanding of the response of the light sensors in both current and new strings, resulting in improved reconstructions of cascade events, better identification of tau neutrinos, and an enhanced pointing resolution of muon neutrinos that could approach the 0.1 degree level for the highest energy events of cosmic origin. The improved calibration of the existing sensors will also enable a reanalysis of more than 10 years of archival data and significantly increase the discovery potential for neutrino sources before the construction of a second-generation instrument.

Further progress requires a larger instrument. Therefore, as a next step, IceCube proposes to instrument 10 km^3 of glacial ice at the South Pole, capitalizing on the large absorption length of light in ice to thereby increase IceCube's sensitive volume by an order of magnitude.[95] This large gain is made possible by the unique optical properties of the Antarctic glacier revealed by the construction of IceCube. Exploiting the extremely long photon absorption lengths in the deep Antarctic ice, the spacing between strings of light sensors will be increased from 125 to close to 250 m without significant loss of performance of the instrument at TeV energies and above. The instrumented volume can therefore grow by one order of magnitude while keeping the instrumentation and its budget at the level of the current IceCube detector. The new facility will increase the rates of cosmic events from hundreds to thousands over several years. The superior angular resolution of the longer muon tracks will allow for the discovery of cosmic neutrino sources, currently seen at the $\approx 3\sigma$-level in the 10-year sky map; see Figure 6.

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Conflict of Interest

The author declares no conflict of interest.

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Francis Halzen is a theoretician studying problems at the interface of particle physics, astrophysics, and cosmology. His earlier career overlapped with the development of the Standard Model. He coauthored a textbook on the subject "Quarks and Leptons" (Wiley 1984). Since 1987, he has been working on the concept of transforming natural Antarctic ice into a Cherenkov detector. First realized with the AMANDA experiment, a first-generation neutrino telescope at the South Pole, which represented a proof of concept for IceCube, a kilometer-scale observatory completed in 2010. In 2013, it revealed a flux of high-energy neutrinos reaching us from the cosmos.

