Neutrinos: Physics Beyond the Standard Model Through Multi-Messenger Astronomy and Lessons from IceCube

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Abstract

Neutrinos, a class of nearly massless elementary particles interacting with only the weak nuclear and gravitational forces, can traverse enormous distances without interference. Originating from processes like nuclear fusion in stars, supernova explosions, supermassive black holes, and radioactive decay, neutrinos are unique in their capacity to journey through space largely undisturbed. This characteristic helps answer some of the most fundamental questions about the universe, such as the inner workings of astrophysical bodies and potentially matter-antimatter asymmetry. By reviewing data from IceCube, the world's largest optical Cherenkov telescope, this paper critically evaluates the information from a major identified source of astrophysical neutrinos: Blazars. This paper also evaluates and discusses the importance of multi-messenger astronomy and the need to go beyond the standard model to understand the complex nature of neutrino emissions, antineutrino characteristics, and blazars.

Keywords

Physics and Astronomy; Nuclear and Particle Physics; IceCube; Neutrinos; TXS 0506+056

Introduction

Neutrinos are part of the standard model, a theoretical framework for particle physics (Figure 1). The model consists of fermions (leptons and quarks), bosons, and the Higgs boson.[1] Fermions are matter-carrying particles of two subclasses: quarks and leptons.[1] The particles in the class of leptons include the electron, muon, and tau particles and the electron neutrino, muon neutrino, and tau neutrino.[1] Bosons, on the other hand, are force-carrying particles and include the photon, gluon, W boson, and Z boson.[1] The Higgs boson is a particle that creates the Higgs field, which fermions such as electrons and quarks interact with to obtain mass.[1]

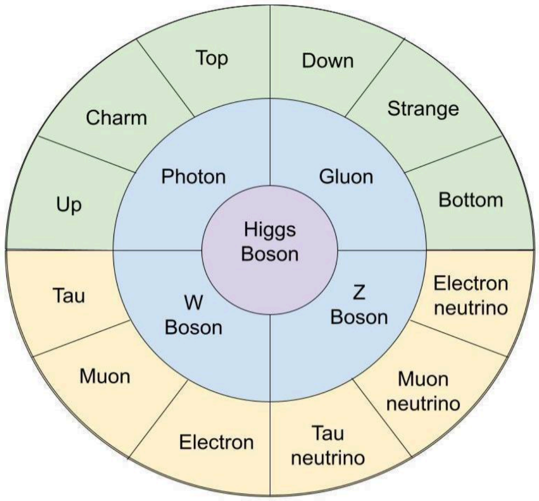

Figure 1. A simplified representation showing matter-carrying particles (leptons: yellow; quarks: green) and force-carrying particles (bosons: blue; Higgs boson: innermost circle). (Created by author)

Neutrinos

For neutrinos, the standard model has generated limited theories. Initially, scientists postulated, based on the standard model, that neutrinos possess no mass and consequently do not engage with the Higgs Boson in the same manner as other fermions.[2] A second hypothesis was that neutrinos travel at the speed of light, indicating they are massless.[2] However, Super-Kamiokande and the Sudbury Neutrino Observatory conducted experiments proving neutrinos have mass. However, it is very close to zero and was also shown to oscillate between 3 known flavors, the muon neutrino, tau neutrino, and electron neutrino, respectively, oscillating into a muon, tau, or electron upon interaction with matter.[2] These discoveries provide the foundation for exploring neutrinos from astrophysical sources.

Neutrinos are unique as they have a neutral charge, almost no mass, and travel close to the speed of light.[2] Though neutrinos rarely interact with matter and only via weak or gravitational forces, they are the most abundant particle with mass in the universe.[2] They are produced during nuclear fission, fusion, and radioactive decay.[2]

Despite being the most abundant particles in the universe, detecting a neutrino is extremely rare. This makes them a challenge to study, and for years, the astrophysical sources of these high-speed neutrinos still need to be determined. Astrophysical neutrinos are of relevance due to their exceedingly high energies. These extreme-energy neutrinos are produced only from interactions near supermassive black holes, which is why they provide insight into the unique processes within them.[3]

CP Violation

Another major question within neutrinos and astrophysics is why the current universe has abundant matter over antimatter. Scientists' current model of the Big Bang includes matter and antimatter being formed in equal amounts.[4] This also suggests that all the matter and antimatter annihilate each other, leaving nothing but light and radiation. [4]

However, we know the universe contains an abundance of matter in comparison to antimatter. Charge-parity symmetry is when the charge can be inverted and coordinate directions mirrored without altering other properties. Charge-parity violation, or CP violation, is a phenomenon where a particle and an antiparticle differ in their fundamental characteristics.[4] This is a key pathway to explain why matter can outweigh antimatter.

While scientists explore CP violation within quarks and their antiparticles, understanding neutrinos is also essential to this mystery. Their very low mass indicates that they might be the relatives of heavy particles that formed near the Big Bang: undiscovered, right-handed particles that obtained mass from a method other than the Higgs field.[4] Right-handed particles are those whose spin, or amount of angular momentum, aligns with their direction of motion.[4] The disintegration of these particles may have led to CP violation that should be observed in neutrinos and antineutrinos today. The hypothesized process that neutrinos went through to cause an excess of matter over antimatter is known as leptogenesis. [4]

By studying neutrinos and antineutrinos, scientists hope to understand more about CP violation and the matter-antimatter imbalance in the universe.

Why Neutrinos Are Key

Particle physics encompasses 36 different fundamental particles, but neutrinos, especially astrophysical neutrinos, are unique to our understanding of the universe.

Astrophysical neutrinos are released in the decay process of particles ejected by blazars. They are key in providing information about blazars because they only interact with gravity and the weak force, traveling large distances without being affected by magnetic fields.[5] Astrophysical neutrinos provide a major source of information to answer key questions about the universe because of the large distance in space and time they travel. Once traced back to their sources, they inform scientists about processes within blazars and these cosmic bodies' characteristics.[5]

Background

Sources of Astrophysical Neutrinos

Possible sources of cosmic neutrinos include black holes, pulsars, supernovae remnants, energetic explosions called gamma-ray bursts, and active galactic nuclei (AGNs).[6] Blazars are this paper's main source of interest as they are a primary source of astrophysical neutrinos.

Blazars are the active cores, or black holes, of giant galaxies. We can see them at very great distances because they are so bright.[6] Thus, we can also see far back in time because it takes light to travel from a faraway source to our detectors. The difference between blazars and other active galactic nuclei is that the jets of particles (cosmic rays) ricocheting from the blazar are directed toward Earth.[6] These jets are formed as gasses around the active black hole rub against each other, losing kinetic energy.[6] This causes them to fall into the black hole and release visible heat and light. As the plasma moves faster, less space is available, resulting in a crowding effect that causes the plasma to ricochet away from the black hole.[6] Blazars open the door for multiwavelength astrophysics due to the irradiation of radio, optical, x-ray, gamma-ray, and neutrino emissions.[7]

As explored in more detail later in this paper, two major subclasses of blazars have been identified: Flat-spectrum radio quasars (FSRQs) and Broad-line Lacertae Objects (BL Lac Objects). FSRQs are characterized by powerful GeV gamma rays and strong emission lines (radiation lines produced by highly excited electrons).[19] Emission lines are typically made in the broad-line region (BLR) of a blazar, a region of dense gas and dust close to the supermassive black hole at the center of the blazar.[19] Conversely, BL

Lac Objects are less powerful with weaker emission lines. However, the presence of Radiatively Inefficient Accretion Flows (RIAFs) near their nuclei causes them to be a point of intrigue for astrophysical neutrino sources.

Neutrino Fluxes - Photohadronic and Hadronuclear Interactions

Understanding the photohadronic and hadronuclear interactions that produce neutrinos is crucial to understanding more about the role of blazars in neutrino production, which will be covered later in this paper.

When cosmic rays from blazars interact with gasses or photons, they generate high-energy neutrino and gamma rays.[7] Both hadronuclear (interaction with ambient matter in gasses) and photohadronic interactions (interaction with photons) produce charged and neutral pions (particles made up of a quark and antiquark), which play a significant role in the strong nuclear force. [8]

Neutral pions decay into two gamma-ray photons, contributing to the gamma-ray flux.[8] Charged pions (π) produce neutrinos (n) along their decay chain.[8] Neutrino flux refers to the rate at which neutrinos pass through a unit area. It is essentially a measure of the number of neutrinos per unit area, per unit time. Gamma rays are produced alongside high-energy neutrinos (ν or $\bar{\nu}$) and cascade down to lower energies.[8] These gamma rays then lose energy over time, undergoing a process known as 'cascading,' ultimately producing lower-energy photons.[8] These equations explain these:

Photo Hadronic interactions:

p + γ --> n + π(+ or -)

A high-energy proton (p) collides with a photon (γ), typically a gamma-ray photon. This interaction creates a neutron (n) and a charged pion (π+, if the original proton was positive or π- if the proton was negative).

π(+ or -) --> μ(+ or -) + ν (or anti-neutrino $\bar{\nu}$))

A charged pion (π+) or (π-) undergoes a process known as pion decay. The charged pion transforms into a muon (μ) of the same charge, along with the corresponding neutrino (ν) or antineutrino ($\bar{\nu}$).

Hadronuclear interactions:

$$p + p \rightarrow \pi^{0} \rightarrow \gamma + \gamma$$

Two protons interact to form a neutral pion cascading into two gamma-ray photons.

$$p + p \rightarrow \pi^{+} \rightarrow \nu_{\mu} + \mu^{+} \rightarrow \nu_{\mu} + e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$

Since a pion comprises three particles: neutral, positively charged, and negatively charged, the pion produced decays in three stages. The first, as shown above, eventually releases a muon neutrino, positron, electron neutrino, and muon antineutrino.

$$p + p \rightarrow \pi^{-} \rightarrow \bar{\nu}_{\mu} + \mu^{-} \rightarrow \bar{\nu}_{\mu} + e^{-} + \bar{\nu}_{e} + \nu_{\mu}$$

The third stage results in a muon antineutrino, electron, electron antineutrino, and muon neutrino.

Compton and Synchrotron Scattering

Along with neutrino emissions, photons of various frequencies are emitted. Two main processes contribute to the energy of photons released by blazars:

First, Inverse Compton scattering occurs when a high-energy charged particle, usually an electron, interacts with a photon and transfers its energy to the photon (typically X-rays or gamma rays), resulting in a recoiling electron with diminished energy.[9] Second, synchrotron radiation occurs as magnetic fields accelerate a charged particle in a circle. The charged particle, usually an electron again, releases a photon.[10] Detecting these photons in parallel with neutrino emissions allows scientists to correlate wavelengths such as X-rays, gamma rays, and radio waves with neutrino fluxes.

Glashow Resonance

Glashow Resonance is tied together by astrophysical sources' concepts of neutrinos, antineutrinos, and neutrino production. This concept has more implications and is covered later in the paper.

Glashow resonance is a phenomenon predicted 60 years ago by Nobel laureate physicist Sheldon Glashow.[11] It explains that a high-energy electron antineutrino, with an estimated energy above 6.3 PeV, can produce a W- boson when interacting with an electron.[11] No terrestrial accelerators can accelerate neutrinos to such high energies. This resonance is significant in neutrino detection from BL Lac and FSRQ blazars due to the potential production of these high-energy antineutrinos in such environments. This means that only astrophysical neutrinos, such as those created by blazars, are capable of causing Glashow resonance. Secondary muons that cascade from the W- boson are what IceCube detects after Glashow resonance.[11]

Glashow resonance validates the standard model, can distinguish neutrinos from antineutrinos, and can identify astronomical accelerators that produce neutrinos via hadronuclear or photohadronic interactions, with or without strong magnetic fields.

IceCube - The World's Largest Cherenkov Telescope

Detecting neutrinos is a complex feat. This is where the IceCube Detector comes in, the world's largest optical Cherenkov telescope. It is located in the Amundsen-Scott South Pole Station, made of one cubic kilometer of Antarctic ice. [12] IceCube is designed to detect astrophysical and atmospheric neutrinos. Neutrinos must interact with matter to be detected, a rare phenomenon, given that neutrinos do not interact with electromagnetic and strong force.[12] To maximize the chance of a neutrino interacting with matter, IceCube encompasses a huge area of 250 acres. A billion metric tons of clear ice with 5000 detectors allows huge amounts of light to be taken in.[12]

To ensure that sunlight cannot reach the sensors and prevent photon interference from any light that does not come from neutrinos, IceCube is also drilled 2.5 km deep. It comprises 86 strings, 60 phototubes, and 5160 optical sensors. [12]

When high-energy particles interact with the ice, they create a shower of particles that travel faster than the speed of light in ice, though slower than the speed of light in a vacuum.[13] Like a supersonic spacecraft emitting a sonic boom, these electrically charged particles release a cone of light known as Cherenkov radiation. This radiation is useful as it tells how much energy was deposited, which indicates how much energy the particle had, roughly where the particle came from, the type of particle, and possibly even the type of collision.[12] In the ice, digital optical molecules (DOMs) designed as strings form much of the detector. With a photomultiplier and electronics, the DOMs detect Cherenkov light. Sensors collect the light, which is digitalized and time-stamped.[12]

The surface array of IceCube, called IceTop, is made up of a veto and calibration detector. IceTop detects neutrino air showers from cosmic rays ranging from 300 TeV to 1 EeV.[12] Eight DOM strings packed more compactly within the ice are known as DeepCore. This component lowers the neutrino energy threshold to 10 GeV for closer atmospheric neutrinos. The IceCube lab processes data from the DOMs for information on where the neutrinos arrived.[12]

IceCube is not designed for low-energy neutrinos such as those from the radioactive decay of rock, sun, and supernovae explosions.[12] These all fall in the energy spectrum of thousandths GeV to a few hundredths GeV. Instead, IceCube commonly observes atmospheric neutrinos created by high-energy particles that collide with nuclei and generate a shower of hadrons that decay into neutrinos, as well as astrophysical neutrinos.[12]

To contribute to multi-messenger astrophysics and validate the discoveries of IceCube, other telescopes are used to detect optical, radio wave, or gamma ray fluxes while an astrophysical neutrino is detected. IceCube's most important collaborations include Laser Interferometer Gravitational-wave Observatory (LIGO), NASA's Fermi-gamma telescope, Major Atmospheric Gamma Imaging Cherenkov Telescope (MAGIC), Max Planck Institute for Radio Astrophysics (MPIfR) in Germany, and Tracking Active Galactic Nuclei with Austral Milliarcsecond Interferometry (TANAMI).[13]

IceCube Historical Data

Since 2010, IceCube has made several groundbreaking discoveries in neutrino physics. Between 2010 and 2012, IceCube detected 26 high-energy particles.[14] Their energies were more than one million times greater than those from supernovae in the Magellanic Cloud detected in 1987. [14] These particles first indicated the possibility of neutrinos from outside the solar system.[14]

Soon after, in April of 2012, a pair of neutrinos nicknamed Bert and Ernie were detected. Each one had an energy of above one PeV.[14] This confirmed neutrinos outside the solar system and earned the Physics World 2013 Breakthrough of the Year.[14]

In December of 2012, Big Bird was detected: a neutrino with less than a millionth the mass of an electron but energies a million million times that of an X-ray. [14] With the energy of 2 quadrillion EeV, Big Bird was the highest energy neutrino of its time and still stands as the second most energetic.[14] IceCube collaborated with scientists from the Fermi-Gamma ray telescope to connect Big Bird to the blazar PKS B1424-418. Observations showed that the blazar shone 15 to 30 times brighter than normal during the neutrino flare.[14]

In July 2018, IceCube, for the first time, confirmed the source of a high-energy neutrino.[14] By turning telescopes to observe the unusually bright bursts of energy from the blazar TXS 0506+056, scientists tied this blazar to the high-energy neutrino event named IceCube-170922A.[14]

Results and Discussion

In this section, we discuss more specific data from IceCube and other multi-messenger sources that demonstrate the importance of blazars in neutrino physics and the implications of the data we receive from them.

Proof that Neutrinos Originate from Blazars

On September 22, 2017, IceCube detected a high-energy neutrino (estimated to be ~290 tera-electron volts (TeV) and sent messages to other observatories around the globe.[15] The Fermi Large Area Telescope Collaboration observed and identified a gamma ray source 0.1 degrees from the neutrino's direction. The source, blazar TXS 0506+056, was observed to be flaring. (The emission of neutrinos can be linked to gamma-ray radiation, as explored later in this paper).[15]

The MAGIC Telescope Collaborations observed that the gamma-ray flux reached 400 GeV at times. TXS 0506+056 has a redshift of 0.34[14]. As depicted in Figure 2, the regions containing 50% and 90% of the neutrino event IceCube-170922A (indicated by dashed red and solid gray contours, respectively) are superimposed on an optical V-band sky image.[14] Known gamma-ray sources within this area, previously identified by the Fermi spacecraft, are denoted by blue circles. The size of the circles corresponds to the 95% positional uncertainty of each source, and they are labeled with their respective names.

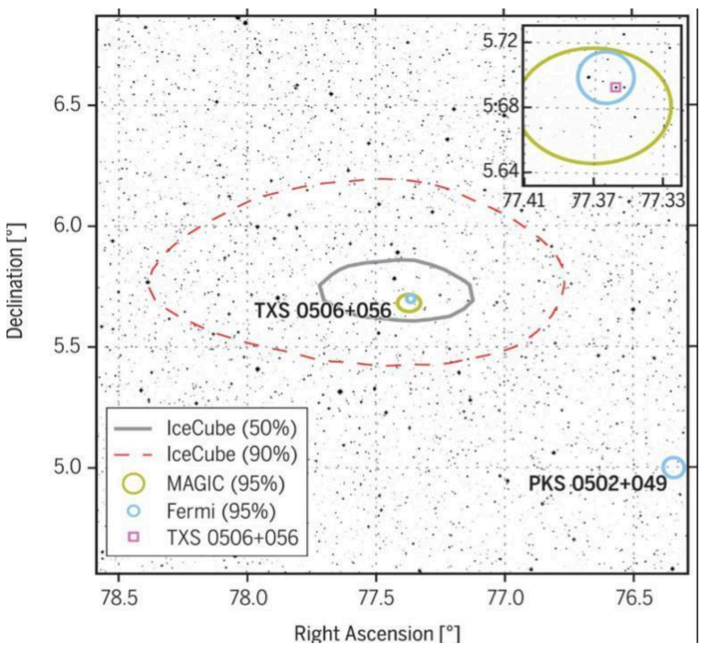

Figure 2. Circles represent positional uncertainty of previously detected gamma-ray sources, enabling multimessenger astrophysics to hone in on TXS 0506+056.[14]

The IceCube neutrino event aligns with the blazar TXS 0506+056, indicated by the pink square. The yellow circle represents the 95% positional uncertainty of very-high-energy γ-rays detected by the MAGIC telescopes during the subsequent observation campaign.[14] Inset is a zoomed-in view of the region around TXS 0506+056, superimposed on an R-band optical sky image.[14]

Scientists Gao et al., 2019 employed redshift as a basis to calculate the muon-neutrino luminosity (the rate at which muon neutrinos are emitted from a source, measured in units of muon neutrinos per unit of time) and found that it matched the luminosity of the observed gamma-rays from that source.[16] These findings attribute the high-energy neutrino to the blazar TXS 0506+056 with a statistical significance of 3 sigma, or 99.7% confidence level.[16]

Motivated by this discovery, the IceCube collaboration examined lower-energy neutrinos detected over the previous several years, finding an excess emission at the blazar's location. To understand this, we will next explore the two subclasses of blazars: BL Lac Objects and Flat-Spectrum Radio Quasars (FSRQs).

BL Lac Objects vs. Flat-Spectrum Radio Quasars

FSRQs contain bright optical and UV emission lines, whereas BL Lac Objects lack these. FSRQs have a very high luminosity but low source density (Figure 3).[17]

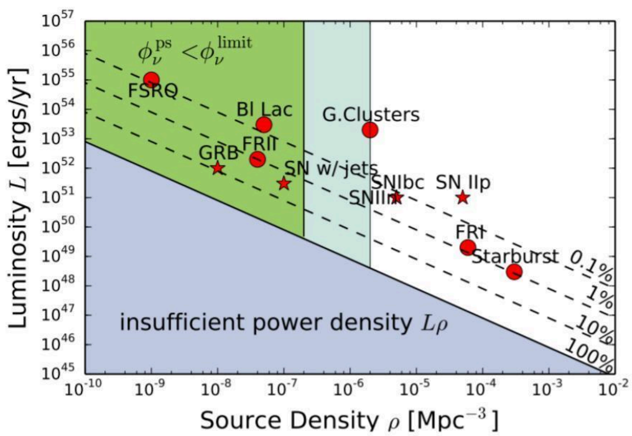

Figure 3. FSRQs are located in the upper left corner of this density-luminosity graph, illustrating that they are the highest in luminosity but lowest in source density of possible neutrino sources.[17]

Given the relatively small number of FSRQ sources close to each other, detecting multiple neutrino samples from a single FSRQ source is a reasonable expectation. However, this has not been detected, which indicates that FSRQs are likely not strong neutrino emitters.

This makes it unlikely for FSRQs to be strong neutrino emitters because, with such high power and low amount of FSRQs, one would expect to find multiple neutrino samples from a single FSRQ in the current data. However, since this is not the case, it seems unlikely that FSRQs would be strong neutrino emitters.

The FSRQ jet composition is also primarily comprised of electrons and positrons (the antiparticles of electrons). In contrast, BL-Lacs are primarily electrons and protons, allowing for protons to be accelerated in BL Lacs.[18] Protons are necessary for photohadronic interactions. Furthermore, neutrinos from astrophysical sources are expected to fall between 0.1 -10 PeV, based on known relationships between the target photons, protons, and neutrinos.[18]

However, the proton frequency of FSRQs corresponds to very high energies of protons and, therefore, high energies of neutrinos above the PeV threshold.[18] This provides another possible reason for a lack of neutrino emission from FSRQs.

Radiatively Inefficient Accretion (RIAF) flows and Blazars

All supermassive black holes have an accretion flow of particles around them. The accretion rate (the rate at which matter falls into the black hole) determines the properties of this accretion flow.[19]

A radiatively efficient flow has an accretion rate greater than 10^{-2} Eddington units.[19] This standard accretion disk is geometrically thin, optically thick (emits a wide range of electromagnetic radiation), and radiatively efficient.[19] However, radiatively inefficient accretion flow is produced when the mass accretion rate is less than 10^{-2}. In a radiatively inefficient accretion flow (RIAF), proton temperatures remain much hotter than in standard accretion disks.[19] This high temperature causes the electrons to be stripped from the atoms, which creates a plasma. Plasma is very good at scattering photons, so the photons can travel through the RIAF without interacting with the matter, thus making RIAF geometrically thin and optically thick.[19]

The Spectral Energy Distribution (SED), or the range of energies emitted by the object at different wavelengths, of RIAFs is much broader than that of standard accretion flows.[19]

The SED of FSRQ and BL Lacs is measured as how much energy is emitted at different wavelengths due to both the jet and the accretion process. RIAFs are considered target photon sources for accelerated protons in these jets, producing neutrinos (proton collisions with photons result in neutrinos), thus making BL Lac Objects strong candidates for neutrino emissions.[19] Moreover, BL Lac objects are subdivided into three classes:

First, Low-Synchrotron-Peak BL Lacs (LBLs), such as TXS 0506+056, have a high density of RIAF photons in the soft X-ray range. This allows the neutrino luminosity of LBLs to be 4 orders of magnitude larger than HBLs.[19] In this class, the external RIAF photons are completely dominant. Second, in Intermediate-Synchrotron-Peak BL Lacs (IBLs), external RIAF photons are still more important than internal photons, though internal photons have a presence.[19] Third, in High-Synchrotron-Peak BL Lacs (HBLs), internal photons are the most significant, while external RIAF photons have little contribution.[19]This means HBLs have a very low neutrino production efficiency. Figure 4 illustrates the contribution of internal and external photons for each subclass.[19]

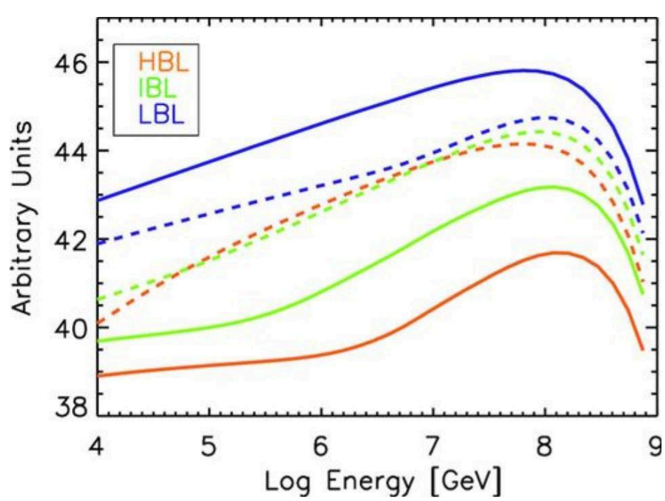

Figure 4. Internal photons (solid lines) and external photons (dashed lines) contribute differently to their photon target fields in neutrino-creating photohadronic processes.[19]

BL Lac objects, especially LBLs, with weak emission lines and a lack of external radiation fields, were originally thought to be less likely to be high-energy neutrino candidates.[19] However, the high-energy neutrino from TXS 0506+056 came from a LBL. Despite HBLs emitting stronger X-rays, high-energy neutrinos have not been detected from them.[19]

With evidence of RIAFs allowing for neutrino production and the previously mentioned characteristics that prevent FSRQs from being strong neutrino emitters, the BL Lacs are much more likely to be a major source of astrophysical neutrinos.

Spectral Energy Distribution (SED) of Blazars

All blazars' Spectral Energy Distribution (SED) comes in two categories. The low-energy category, from radio to UV is likely due to synchrotron radiation by relativistic electrons (electrons that approach the speed of light).[19] The high-energy category, from X-rays to gamma rays, results from the same relativistic electrons undergoing inverse Compton scattering off target photons or other hadronic processes.[19] Dividing the broadband SED into two categories, the low-energy and the high-energy, is called the leptonic model for modeling electromagnetic radiation from blazars.[19]

Blazars are subdivided into three classes depending on the highest point of synchrotron emission: low-synchrotron peaked, intermediate-synchrotron peaked, and high-synchrotron peaked. While FSRQs only fall under the low-synchrotron peaked class, BL Lac objects can fall under any of the three classes.[19]

As we have previously seen in this paper, the production of neutrinos requires hadronic processes, thus causing the leptonic model to be modified. The hadronic model for electromagnetic radiation describes how cosmic-ray nucleons at energies ~ 10 PeV interact with UV photons to produce charged and neutral pions.[19] Neutral pions decay into gamma-ray photons, charged pions decay into a muon and electron, and neutrinos that travel to Earth.[19]

However, this hadronic model only partially matches scientific observation. X-ray emissions by the secondary electrons predicted in the model overshoot the observed X-ray flux. This means the ideal model for electromagnetic radiation from blazars should differ from the hadronic model. A hybrid model was proposed to allow neutrino emission but constrain the X-ray flux.[16] This hybrid model says that most photons are of leptonic origin, and any contribution by the hadronic processes is limited so that there are not so many X-rays produced that they overshoot the flux constraints. The hybrid model is shown in Figure 5.

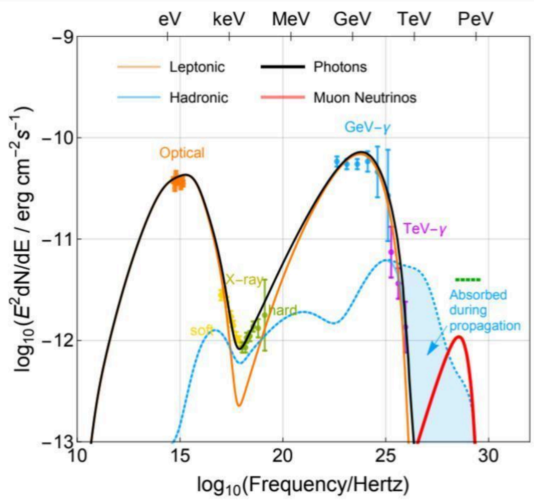

Figure 5. A hybrid model of neutrino production incorporating leptonic and hadronic parts without overshooting the observed X-ray flux.[16]

Another constraint put on this model includes the Eddington limit, meaning that radiation from the blazar cannot be so powerful that it counteracts the force of gravity and blows away surrounding matter.[16] The maximum contribution from photohadronic interactions is constrained by efficient neutrino production, which requires high-energy photons, electrons, and positrons.[16] This means the electromagnetic cascade must be visible as X-rays and TeV gamma rays.

As shown in Figure 6, Time-dependent modeling of emissions before, during, and after the injection boost of a blazar indicates a sharp increase in the amplitude of hard X-rays and gamma-rays during the neutrino flux.

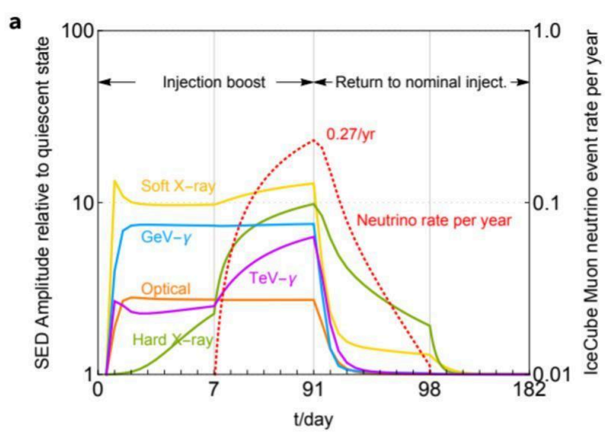

Figure 6. Relationship between hard X-rays, gamma-rays, and neutrinos underscoring the importance of multiwavelength astrophysics.[19]

Multiwavelength Astrophysics

In multimessenger or multiwavelength astrophysics, studying all the processes contributing to the overall observed electromagnetic spectrum is significant. Information from IceCube led to a spur in multimessenger astrophysics as other detectors sought to correlate neutrino emission with other types of radiation. Scientists can better understand the astrophysical phenomena and the underlying physical processes at play by studying the emissions across different wavelengths such as gamma rays, X-rays, radio waves, etc.

Radio Waves

The Owens Valley Radio Observatory (OVRO) further analyzed radio data from blazars, detecting a long-term outburst of radio waves before reaching a peak during neutrino emission for both PKS 1502+106 and TXS 0506+056. Based on this and other studies, the correlation between IceCube neutrinos and radio-bright blazars has been quantified at a p-value of 0.002, indicating that the correlation between IceCube neutrinos and radio-bright blazars has a 0.2% probability of being due to pure chance.[20]

Despite this statistical significance, observations from OVRO still did not indicate a strong correlation between radio emission and neutrinos since this was only two out of the five sources observed by OVRO. A third source was observed only 70 days after the arrival of the neutrino.[20] Though all five sources are monitored in radio, none demonstrated long-term radio wave activity, indicating that more observation is needed to correlate them to the emission of high-energy neutrinos. [20]

On the other hand, a more recent study found that in recent years, an increasing number of neutrinos detected can be correlated to radio blazars.[21] It was found that radio blazars significantly correlated with the entire 7-year dataset from IceCube, including radio waves from lower energies as low as a few TeV range.[21] Combined with other analyses on independent data, the correlation of neutrinos with radio waves below and above 200 TeV was significant at 4.3 standard deviations, indicating that the differences between data groups are large enough for statistical significance. [21] This means there was enough variability in the evidence that the correlation was strong enough to overcome external factors.

With contrasting data from multiple analyses, more data must be collected to confirm a correlation between radio and neutrino emissions. Recent data may be more accurate using Very Long Baseline Interferometry (VLBI). This process compares the distances traveled by light to each telescope in a system of telescopes placed far from each other. This allows for highly accurate astronomical data, especially when focusing on radio blazars to relate them to neutrino emission. The evidence indicates a high likelihood of neutrinos originating from radio blazars. However, more monitoring by observatories such as OVRO needs to be done to identify the chance of a flux of radio waves during a single high-energy neutrino event.

Gamma rays

Gamma rays were also correlated with neutrino emission. The first likely extragalactic neutrino counterpart is the gamma-ray blazar TXS 0506+056, identified on September 22, 2017. The gamma-ray blazar was found to be flaring in spatial and temporal coincidence with the arrival of the 290 TeV neutrino event IC- 0722A.[20]

Since TeV and PeV photons are quickly absorbed through photon-photon annihilation and cascade down to lower energies, GeV gamma-rays are the closest in energy to high-energy neutrinos, making them important to neutrino detection.

In the study of gamma rays from astrophysical bodies, there were two neutrino observations from the same source.[22] The source emitted a 160-day-long neutrino flare in 2014 and again in 2015. It was not accompanied by increased gamma-ray, optical, or radio wavelength activity. It was discovered that the gamma-ray spectrum hardened, but the discovery was not statistically significant.[22] One study found that the hardening of the gamma-ray spectrum was statistically compatible at less than 2 standard deviations with the average spectrum, meaning there was likely no significant increase of the gamma-rays due to neutrino events. [22]

Follow-up studies were initiated to discover other neutrino sources. However, while only measuring neutrino data and ignoring multiwavelength data, flares were not detected above the expected atmospheric background.[22] This suggests that neutrino emission from these sources may be accompanied by emission at other wavelengths, such as radio waves, gamma rays, or X-rays. The neutrino emission from these sources could be stronger and easier to detect.

The Fermi-LAT telescope is sensitive to gamma rays, making it a crucial collaborator with Ice Cube in detecting astrophysical neutrinos. The study of more blazars, focusing on multi-wavelength data, reveals more information about gamma rays. Below is the analysis of data from two blazar neutrino sources.[22]

The study of the blazar 1H 0323+342 reveals that this source has a p-value of 0.08 for gamma-ray fluxes during neutrino flares, whereas other sources show p-values from 0.17 to 0.92.[21] The neutrino from 1H 0323+342 came during a small increase in the gamma-ray flux, while an increase in UV, X-ray, and optical emission came one month earlier.[21]

The blazar PKS 1502+106, a possible neutrino source for the neutrino event IC-190730A, is particularly interesting to scientists because it is extremely gamma-ray bright: it is the 15th brightest out of 2863 in terms of gamma-ray luminosity.[21] The gamma-ray emission from this blazar has been explained to be from interactions between jet electrons and photons from the broad line region. This information indicates that the BLR photons could provide a target photon field for hadrons in the jet, allowing neutrino production. [22]

Over 11 years, the gamma-ray emission from PKS 1502+106 has been studied, identifying periods of quiet and flaring states. Altogether, two hypotheses are consistent with the observed data. The first is that the gamma-ray brightness of blazars is linearly correlated with neutrino emission[20] This is supported by the neutrino event IC-170922A being associated with a bright gamma-ray flare from TXS 0506+056.[20]

However, blazar stacking analyses show that if the neutrino spectrum follows an $e^{-2.5}$ power law, the gamma-ray blazar contribution is limited to less than 27%. If the neutrino follows a steeper power law of e^{-2}, the stacking analysis shows that the contribution from the gamma-ray blazars expands to 40-80%.[20] Figure 7 illustrates the difference between these power laws.

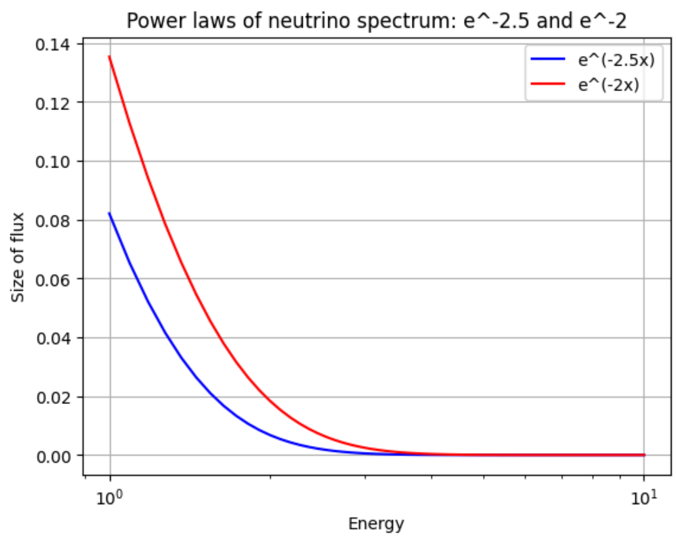

Figure 7. The graph shows the two possible power laws that the neutrino spectrum can follow: $e^{-2.5}$ and e^{2}. (Author).

The power law determines the relationship between the flux of neutrinos at different energies and the output of the neutrino's energy. Stacking analyses show that if the neutrino flux follows a e^{2} power law, the contribution by gamma-ray blazars expands to 40-80%.[20] Note that this applies to neutrinos between the 10 TeV to 100 TeV range, while this graph only depicts the general pattern of these two power laws.

The second hypothesis, the background hypothesis, is that neutrino emission is not correlated to gamma-ray emission.[20] There are a few possible reasons for this. The gamma-ray flux identified a few times with neutrino emission could be coincidental.[20] Scientists might conclude that neutrino emission does not correlate with gamma rays because gamma rays from some neutrino sources are produced in optically thick regions so that gamma rays can be absorbed and then cascade down to X-rays.

If the first hypothesis is true, gamma-ray flare coincidences can be used to study neutrinos and cosmic-ray acceleration. This also allows us to associate high-energy neutrino sources with more distinct properties. Since it would be impossible to detect the production of gamma rays beyond the optically thick regions, more observations would be needed to collect data points of various blazars with gamma-ray emission. IceCube-Gen2 will be especially useful as it is much more sensitive to weaker neutrino sources.

X-rays

The association of X-rays with neutrino producers is the most statistically significant compared to the other correlations discussed thus far. As explained in the previous section, broadband SED modeling suggests that X-ray photons from the corona (the outer edges of the blazar) could make up a target photon field for photohadronic interactions that produce high-energy neutrinos. Figure 8 shows a time-dependent model of the different parts of a Spectral Energy Distribution that shows an increase in the flux of Hard X-rays and TeV gamma rays. At the same time, there is a flux in muon neutrino events.[19]

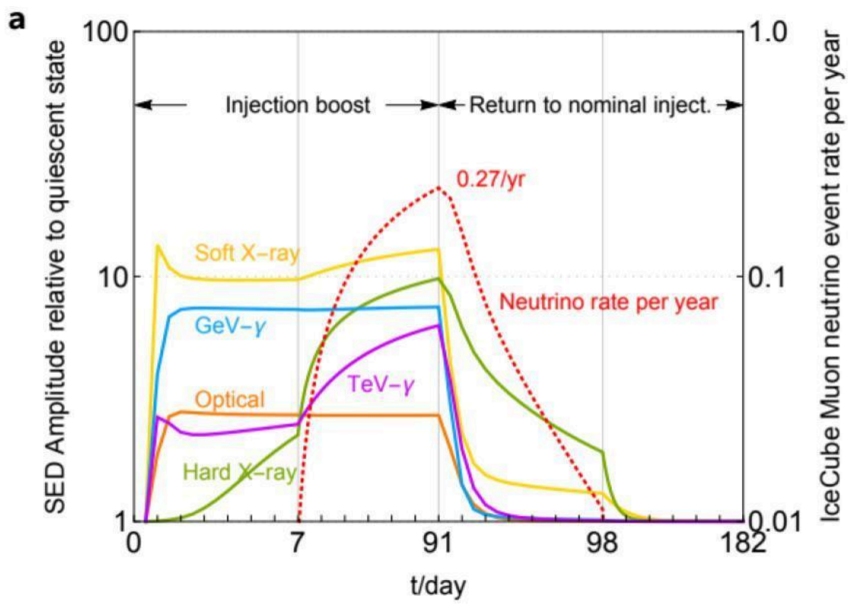

Figure 8. The time-dependent model of the Spectral Energy Distribution (SED) reveals a concurrent increase in the flux of Hard X-rays and TeV gamma-rays, coinciding with flux in muon neutrino events.[19]

X-ray coronal photons also explain the steepening of the graph of the gamma-ray spectrum because they absorb gamma rays through pair production.[19]

X-ray neutrino sources were analyzed by cross-matching with a sample set of Very-Long-Baseline-Interferometry (VLBI) bright sources, primarily blazars. If telescopes detected X-ray emission within a certain threshold of a VLBI source, it was named an X-ray source.[20] Then, an analysis was completed that counted the matches between neutrinos and X-ray VLBI blazars. This was compared to a count of the random expectations of the matches. For one sample, the SRG/ART-XC catalog, the statistical significance of neutrinos correlated to X-ray VLBI blazars was 0.5%. The hard X-ray catalogs studied, SRG/ART-XC, Swift/BAT, and INTEGRAL/IBIS, reveal a correlation with IceCube neutrinos. [21]

However, there was no correlation within the ROSAT catalog, a set of soft X-ray blazars. Thus, it was found that blazars that emit neutrinos likely have the characteristic of X-rays above 10 keV.[20]

X-rays are found to make up the target-photon field for photohadronic interactions responsible for neutrino emission, given that they are produced in the jet.[21] Thus, the emission of hard X-rays also explains the correlation of radio waves with neutrino emission because the number of synchrotron-self-Compton photons is proportional to the amount of radio waves emitted by the photons. These synchrotron-self-Compton photons are located in the jetstream of a blazar.

Additionally, higher energies of GeV gamma-ray photons are found to interact with low-energy photons and produce electron-positron pairs that cascade down to lower energies, which lose efficiency in the GeV range.[21] So, although gamma-ray photons may accompany neutrinos in production, observing X-rays is more reliable to trace neutrino production.

X-ray flares are important for neutrino emission because they can produce pions that decay into neutrinos. Pions are produced when high-energy protons interact with photons, and X-ray photons are energetic enough to produce pions. Additionally, X-ray fluxes are often optically thick, which means there is a high probability of protons interacting with photons. One model explains why focusing on X-ray flares is important. Since X-ray photons are energetic targets for photomeson interactions (interactions between high-energy protons and photons), they reduce the energy required of protons for pion production.[24] Pions are unstable particles that decay into other particles, including neutrinos.[24] Thus, X-rays have the highest statistical significance in correlating with neutrino emission based on observational analysis because they explain crucial production processes for neutrinos.

Therefore, as this paper analyzed thus far, multiwavelength data is crucial to understanding neutrino production from blazars.

Neutrinos, Antineutrinos, and Glashow Resonance

Much is still unknown about astrophysical neutrinos. Certain neutrino events have been traced to their sources, allowing for more data on blazars and neutrino production processes. However, other neutrino events are not associated with a specific astrophysical source but still provide crucial information. In 2016, IceCube measured a shower of particles with energies 6.05 ± 0.72 PeVas, determined by Cherenkov radiation.[12] Antineutrinos interacting with electrons in the ice form a W boson, which decays into secondary muons. The detection of these secondary muons by IceCube indicated the occurrence of Glashow Resonance.[12]

The huge number of electrons located on Earth allows for an increased chance of Glashow resonance occurring. This is significant as it distinguishes antineutrinos within the neutrino flux. Glashow resonance can occur between a neutrino and a positron (antielectron) or an antineutrino and electron. However, the neutrinos will rarely hit a positron because the Earth is made of matter, not antimatter.[24] However, as electrons are abundant in everyday environments, some antineutrinos will hit electrons. So, if evidence of Glashow resonance is detected, scientists can be reasonably certain that this is evidence of an antineutrino.

In a nucleon (the collective term for protons and neutrons), valence quarks are the primary ones that contribute to its composition and are involved in the strong force interactions that hold nucleons together (akin to valence bonds in atoms). For example, a proton comprises two up-quarks and one down-quark. A neutron is made of two down and one up-quark.[26]

Valence quarks are distinct because they are the only particles within a nucleon that are unpaired with an antiquark.[26] Antiquarks are the antimatter counterparts of quarks. Also, valence quarks are left-handed (their spin is aligned to their momentum), and the weak force acts on left-handed particles and right-handed anti-particles.[26] In particle physics, quarks come in left- and right-handed versions. Only the left-handed ones can interact with W bosons because they have weak isospin, similar to electric charge for electromagnetic interactions.[26] Due to this, valence quarks are more likely to engage with neutrinos and antineutrinos than other quarks within the nucleon. In other words, nucleons serve as interaction targets for neutrinos and antineutrinos in astrophysical contexts.

However, at higher energies, the ratio of other quarks to valence quarks becomes high enough that valence quarks become lost in the noise. This is why in high-energy neutrino interactions, Glashow resonance, primarily driven by interactions with valence quarks, becomes increasingly important, thus proving high-energy electron antineutrino collisions.

Before the new analysis of neutrinos and antineutrinos, studies of the astrophysical neutrino flux assumed an equal contribution of neutrinos and antineutrinos, and they focused only on a three-flavor composition.[25] The three-flavor composition assumes that there are three types of neutrinos: electron neutrinos, muon neutrinos, and tau neutrinos. The ratio of these three flavors is given by (f_e : f_μ : f_τ) = (1:2:0), meaning that there is one electron neutrino for every two muon neutrinos and no tau neutrinos.[25]

However, this assumption was shown to be incorrect. Liu et al. showed that neutrino production by high-energy sources results in an asymmetry between the particles, necessitating a six-flavor composition. The six-flavor composition includes the three neutrino flavors and their corresponding antineutrino flavors.

This asymmetry is caused by the different ways that different hadronuclear and photo-hadronic interactions produce positively charged pions and negatively charged pions.[25] Positively charged pions decay to produce electron neutrinos and muon neutrinos, while negatively charged pions decay to produce electron antineutrinos and muon antineutrinos.

As a result of this asymmetry, the ratio of neutrinos to antineutrinos in the astrophysical neutrino flux is not equal. New ratios for the photo-hadronic scenario and the hadronuclear scenario were calculated. This ratio is given in the from of ({f_e, $-v_e$} : {f_μ,$-v_\mu$} : {f_τ, $-v_T$}), with $-v_e$ representing an electron antineutrino, $-v_\mu$ representing a muon antineutrino, and $-v_T$ representing a tau antineutrino. The photohadronic ratio is ({1, 0} : {1, 1} : {0, 0}), and the hadronuclear ratio is ({1, 1} : {2, 2} : {0, 0}).[25]

Glashow resonance is a unique interaction between a high-energy electron antineutrino and an electron. It results in the creation of a W- boson. This significant resonance process differentiates neutrinos and antineutrinos in the astrophysical flux. [27-28] Liu's work highlights the necessity of a six-flavor model to account for the intrinsic asymmetry between neutrinos and antineutrinos produced by high-energy sources interacting with earthly electrons. This six-flavor model encompasses neutrino and antineutrino counterparts of the original three flavors (electron neutrinos, muon neutrinos, and tau neutrinos). This is significant as the processes by which neutrinos were produced, photoadronic or hadronuclear, can be distinguished based on the ratios of the neutrinos and antineutrinos detected in a flux.

This research unveils the underlying mechanisms that lead to an imbalance between neutrinos and antineutrinos, which is possible evidence of CP violation. Glashow resonance complements this understanding by providing a means to identify electron antineutrinos, which are vital components of this newly recognized asymmetry. The resonance process, occurring due to the presence of electrons, allows for the discrimination between neutrinos and antineutrinos, thus enriching our insights into astrophysical neutrino production processes. This begins a deeper exploration of how neutrinos can provide evidence of CP violation.

Conclusion

This review paper critically examines various hypotheses regarding neutrino physics and provides insights into the most promising ones. It also highlights existing experiments' limitations and underscores the standard model's inadequacy in addressing fundamental questions about the universe, particularly concerning neutrinos.

IceCube has been the first neutrino detector to relate a neutrino to an astrophysical source, opening the realm of multimessenger astrophysics.

IceCube has answered key questions about high-energy neutrinos. It correlates neutrinos to blazars as sources with a statistical significance of 3.5 σ. The Radiatively Inefficient Accretion Flow (RIAF) that likely exists in the nucleus of a BL Lac Object provides a strong region for neutrino production compared to a standard accretion flow of FSRQs.

Neutrinos provide crucial information about astrophysical bodies. Because neutrinos can be associated with blazars, we can give specific characteristics. Photohadronic and hadronuclear interactions, crucial in neutrino production, require accelerated protons and a photon target field. As this paper shows, blazars must provide these components as jet streams, RIAFs, and possibly X-ray target photon fields from the jet stream.

IceCube data reveals that hard X-rays are key to identifying neutrino emissions from astrophysical objects. The correlation between neutrinos and gamma rays or radio waves is yet to be statistically significant, and more data needs to be collected. X-rays provide an ideal target photon field for neutrino production.

IceCube is beginning to answer questions about how CP violation can explain the matter-antimatter imbalance in the universe. Glashow resonance provides a way to distinguish between neutrinos and antineutrinos originating from astrophysical sources, but more data needs to be collected to see if this explains CP violation.

Improvements on IceCube are planned to be completed by 2032 to create IceCube-Gen2. With the installation of 750 advanced photodetectors and calibration devices, IceCube-Gen 2 will increase the volume of IceCube by tenfold, expanding it to 10 cubic kilometers. Its higher sensitivity and sharper focus will allow it to measure super PeV events and above 100 TeV astrophysical flux. It will be the first to measure neutrino cross sections at PeV and EeV energies, well beyond the capabilities of particle accelerators.

Regarding multi-messenger astrophysics, data collected by IceCube-Gen2 will help answer some of the uncertainties presented in this paper, such as the correlation of neutrino emission with radio and gamma-ray fluxes. IceCube-Gen2 will be able to cover a range of energies, with optical and radio detectors providing continuous coverage of emissions across the spectrum. This will provide more data that can then be used to correlate radio waves and gamma rays to neutrino events. IceCube-Gen2 will also be much more sensitive to weaker neutrino sources, up to five times fainter, than what could be detected with IceCube. As a result, it will be sensitive to hidden sources in optically thick environments where only neutrinos escape.

Analyzing this multimessenger information from high-energy astrophysical neutrinos is a vital tool that IceCube provides to understand key processes in the universe.

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