IceCube's Neutrinos: Galactic or Extra-Galactic?

Natasha Jade Atkins

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Principal Supervisor: Associate Professor Gary Hill

Co-Supervisor: Doctor Benjamin Whelan

The University of Adelaide

School of Physical Sciences

Department of Physics

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Contents

Abstract

The exact origin and production method of the astrophysical neutrino, a subatomic particle that is very difficult to detect, is yet to be confirmed. Here, two source scenarios for the origin of the neutrino are considered: Galactic and extra-galactic. In the Galactic scenario, neutrinos are searched for from the disk and the halo of the Milky Way, whereas in the extra-galactic case neutrinos might be coming from Active Galactic Nuclei, Starburst Galaxies and other highly energetic regions of the Universe. The IceCube Neutrino Observatory has detected an astrophysical neutrino intensity which may reveal the origin of these neutrinos.

The Milky Way is not a unique galaxy. If it were to produce some fraction of the neutrinos that IceCube detects then there must be other similar spiral galaxies in the Universe also contributing to the intensity. This could create a contradiction of how many other Milky Way-like galaxies there would be allowed in the rest of the Universe if the assumption is made that the Milky Way produces nearly all of IceCube's neutrinos. The overall number density of Milky Way-like objects in the Universe can be calculated for different Galactic source distributions. The neutrino sources could be distributed throughout the halo of the Galaxy or confined to the Galactic disk. By considering various models and calculating the number density of equivalent Milky Way-like galaxies in the rest of the Universe, constraints are placed on the fraction of the IceCube intensity that could be coming purely from the Milky Way. According to the results of this research it is ultimately found that, under the simplifying assumption that the halo is spherical, the halo of the Milky Way cannot account for all of IceCube's neutrinos and under certain assumptions the disks of Milky Way-like galaxies cannot be the sole origin of neutrinos in light of experimental observations.

Declaration of Originality

I, Natasha Atkins, certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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Chapter 1

Neutrinos

1.1 Background and Discovery

The neutrino, denoted by the Greek letter ν, is a subatomic particle of the Standard Model that belongs to the lepton family. They have a very small mass and only interact via the weak force. Neutrinos do not possess electric or colour charge which prohibits them from interacting via the electromagnetic and strong forces. Neutrinos come in three different flavours: electron neutrino (ν_e), muon neutrino (ν_μ) and tau neutrino (ν_τ), corresponding to the electron (e), muon (μ) and tau (τ) leptons. Each neutrino also has an associated antineutrino, denoted by a bar above the Greek letter, $\bar{\nu}$.

The neutrino was postulated by Pauli in 1930 to explain the conservation of energy, momentum and angular momentum during beta (Eq. 1.1) and beta plus (Eq. 1.2) decay. In the process of beta decay a neutron transforms into a proton as a result of an unstable nucleus. In beta plus decay the proton will transform into a neutron. The electron and the positron (anti-electron) created in these processes conserve the original charge and are known in this context as the β^- and β^+ particles respectively.

$$n \to p + e^- + \bar{\nu}_e \tag{1.1}$$

$$p \to n + e^+ + \nu_e \tag{1.2}$$

Prior to the postulation of the neutrinos, Ellis and Wooster performed an experiment in 1927 in which the total energy released in the decay of $^{210}\text{Bi} \to {}^{210}\text{Po}$ was measured [1]. An unexpected result was found which showed that the initial energy was not conserved. In 1930 this experiment was repeated by Meitner and Orthman again resulting in an unexpected final energy. Pauli made postulations on why the energy, momentum and angular momentum of the reaction was not conserved within the observed proton and electron or the neutron and the positron during this decay. This led to the theory that the missing energy, momentum and angular momentum were being carried away by some, at that time, undetected particle. It was theorized that this particle must be electrically neutral due to charge already being conserved in beta decay, but it also had to have a very low interaction probability in order to explain its lack of detection.

For many years the neutrino remained completely undetectable and it wasn't until 1953 that a tentative identification was made by Cowan and Reines at Hanford in an experiment involving a nuclear reactor [2]. In this experiment the neutrino flux from a fission decay was incident on a detector containing a hydrogenous liquid scintillator. Since the incident neutrino flux was intense and the detector had many target protons the occurrence of the reaction in Eq. 1.3 increased. Once an anti-neutrino interacts with a proton, the products are a neutron and a positron:

$$\bar{\nu}_e + p \to n + e^+ \tag{1.3}$$

The positron will annihilate with an electron in a very short amount of time, creating two gamma-rays each with approximately the rest mass of an electron (511 keV) that travel in the opposite direction. The neutron was captured in dissolved cadmium within the scintillator. These two reaction products were detected as a delayed pulse pair, however, the detection alone did not confirm that the reaction was neutrino induced. The energy of the pulses, their time delay spectrum and the dependence of the signal rate on reactor power were used to rule out the reaction being neutron or gamma-ray induced. Although a large background was experienced due to the reactor and to cosmic radiation, the detection of a free neutrino was probable.

In 1956 another revised experiment was performed by Cowan, Reines, Harrison, Kruse, and McGuire at the Savannah River Plant of the U.S Atomic Energy Commission [3] to confirm the findings of the original reactor experiment in 1953 by checking each term in Eq. 1.3. This time the experiment consisted of a multiple-layer arrangement of scintillators and target tanks which were located underground to provide shielding from neutrons and gamma-rays from the reactor on the surface and also from cosmic rays. The two pulses, detected by photomultiplier tubes within the tanks, were confirmed to be from electron-positron annihilation and from neutron capture. This experiment was able to more reliably reproduce the result from the original experiment and hence verify the products of Eq. 1.3 and confirm the detection of the anti-neutrino. The detection of the anti-neutrino was then able to verify the original neutrino hypothesis made by Pauli and encourage work in neutrino astronomy.

1.2 Interactions

Neutrinos can interact weakly via neutral current or charged current interactions. Neutral current interactions involve the exchange of a Z^0 boson between particle pairs. Fig. 1.1 shows a Feynman diagram of the neutral current interaction. In this case, if the neutrino were to be detected, it would leave the detector having transferred some of its energy and momentum to some target particle without leaving behind neutrino flavour information. Consequently, the detector would not be able to determine the initial flavour of the neutrino.

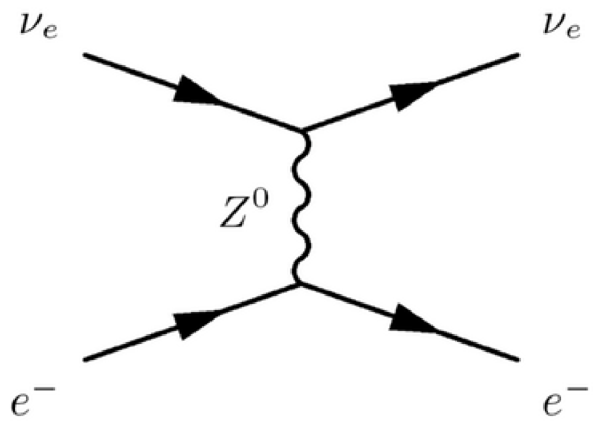


Figure 1.1: A Feynman diagram of a neutral current interaction.

The charged current interaction involves the exchange of a W^+ or a W^- boson. A neutrino with sufficient energy transforms into its partner lepton and hence detectors can determine the initial flavour of the neutrino. Fig. 1.2 shows a Feynman diagram of the charged current interaction. In this reaction a charged lepton is produced which is more easily detected than a neutrino.

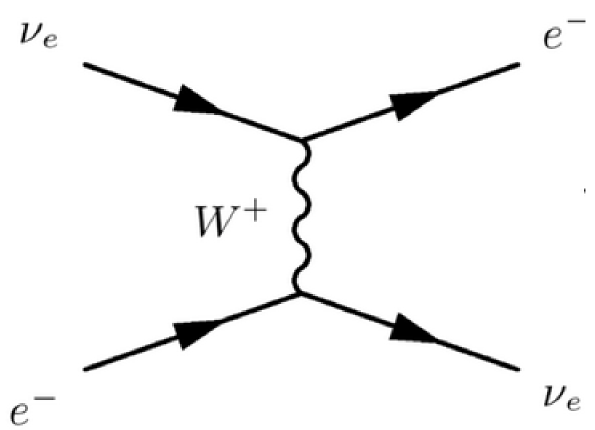


Figure 1.2: A Feynman diagram of a charged current interaction.

All three neutrino flavours can participate in both of these interactions. The neutral current interaction has a probability of approximately a third relative to the charged current interaction.

1.3 Oscillations

In 1998 an experiment called Super-Kamiokande, which is a 50 kilotonne water Cherenkov detector containing over 11,000 photomultiplier tubes and a 22.5 kilotonne inner fudicial volume of ultra-pure water, measured a deficit in the flux of atmospheric neutrinos from 535 days of exposure [4]. At the time, the predictions of the neutrino flux were unable to explain the observed data. This experiment was the first to show neutrino oscillations. A similar deficit in solar neutrinos was detected by the Sudbury Neutrino Observatory (SNO), also a water Cherenkov detector, using ultra-pure heavy water contained within a transparent acrylic spherical shell of 12 m diameter to detect ^{8}B solar neutrinos with over 9000 photomultiplier tubes through a range of interactions [5]. The unexpected results of a solar neutrino deficit from this experiment also showed the concept of neutrino oscillations.

The neutrino is thought to oscillate between the different flavours as it propagates through space. Given enough time, a neutrino of a particular flavour can transform into a neutrino of a different flavour depending on neutrino mass difference and mixing parameters. After propagation and oscillations, a possible combination of relative ratios of neutrino flavours detected at Earth for some starting mixture at their origin is $\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$. The fact that neutrino flavours are thought to change on the journey from origin to detection contributes to the concept that each neutrino flavour has a different mass. This is due to the difference between the mass eigenstates and flavour eigenstates. The mass differences between the three flavours themselves are very well known theoretically, although the absolute mass values of each flavour are still unknown since the mass of the neutrino is too low to be resolved. These mass oscillations are thought to be the most likely sources of the tau neutrinos which theoretically have not been detected at Earth.

1.4 High Energy Neutrinos

Very high energy neutrinos could have energies anywhere above E $\sim 10^{14}$ eV. Most of these neutrinos are believed to be astrophysical in origin, originating from cosmic ray interactions in the most active regions of the Universe. In these regions, there are objects, such as different classes of galaxies, that produce very energetic radiation and particles, such as cosmic rays and gamma-rays. These other high energy particles and photons are detected at Earth with various experiments including the Pierre Auger Observatory [6] and the High Energy Stereoscopic System (H.E.S.S) [7, 8]. The detection of neutrinos, cosmic rays and gamma-rays allow for a better understanding of the objects creating them and hence the most violent regions of the Universe.

1.4.1 Cosmic Rays

Cosmic rays (CRs) are high energy protons or heavier nuclei whose origin remains an important question in modern astrophysics. The very high energy CRs (E $> 10^{18}$ eV) are observed at Earth indirectly through extensive air showers of secondary particles with detectors such as the Pierre Auger Observatory. Low energy CRs (E $\sim 10^{12}$ eV), however, can be detected directly using high altitude balloons. Cosmic rays have been detected with energies up to and even exceeding 10^{20} eV [9].

Acceleration

Cosmic rays are believed to be accelerated by some mechanism at their source. Originally it was believed that cosmic rays might be accelerated by a process called

Fermi acceleration, proposed by Enrico Fermi in 1949 [10]. Fermi's original theory for cosmic ray acceleration says that a CR enters a magnetized cloud near the origin of the CR and scatters off the magnetic irregularities tied to the cloud. This scattering is collisionless which means that the energetic particles do not collide with atoms or ions directly due to low number density and cross section. However, this is not the likely mechanism for CR acceleration since the clouds are too slow. An energy gain ($\Delta E/E$) for different types of collisions can be calculated. The directly trailing collisions (where the CR and the cloud are both moving in the same direction) have a negative energy gain ($\Delta E/E < 0$) and hence energy of the CR is lost, whereas the head-on collisions (where the CR and the cloud are moving in opposite directions) have a positive energy gain ($\Delta E/E > 0$). Statistically, there are only just slightly more head-on collisions than there are directly trailing collisions which means that after many interactions, the net energy gain of the CR is very small and thus insufficient to explain the observed CR energies. This process is now referred to as the "second-order" Fermi mechanism [11] because the fractional energy change is proportional to the square of the velocity of the cloud relative to its local galactic arm. Another disadvantage to this mechanism is that Fermi acceleration fails to simplistically explain heavier nuclei CRs. For heavier nuclei the injection energy is very high and hence the injection mechanism must be equally efficient [10].

A more likely mechanism for the acceleration of CRs is shock acceleration, commonly known as the Diffusive Shock Acceleration (DSA). This is based on "first-order" Fermi acceleration [11] in which the fractional energy gain is proportional to the relative velocity of the shock front. An external shock can be created within a supernova where ejected material is blown out at speeds much greater than the local speed of sound, creating a shock with different speeds on either side for the CR to accelerate across. The CRs scatter off magnetic turbelence that is on either side of the shock, much like in Fermi acceleration. The main difference is that each time the

CR passes over the shock, it gains energy very efficiently. The CR will eventually escape the shock with very high energies. The differential energy spectrum which then predicts the CR intensity emitted from the source is then given by:

$$\frac{dN}{dE} \propto E^{-2} \tag{1.4}$$

where E is the energy of the CR and dN/dE is the differential energy spectrum of the CR.

Propagation

Cosmic rays do not make the ideal astrophysical messenger particle because of their various interactions as they propagate through the Universe. One of these interactions is with the cosmic microwave background (CMB) radiation. This is a low energy, dense photon field left over from soon after the beginning of the Universe. If a CR proton has energy greater than $\sim 7 \times 10^{19}$ eV [12] then it can interact with a CMB photon to produce a pion (see Eq. 1.6). The CR proton loses energy each time it repeats this process until its energy drops below 7×10^{19} eV. This cutoff energy is known as the Greisen-Zatsepin-Kuzmin (GZK) limit which puts an upper limit on the energy of cosmic rays from very distance sources that can be detected at Earth.

Since CRs are charged particles, they are deflected by interactions with inter-galactic and galactic magnetic fields as they travel through the Universe (Fig. 1.3). These deflections mean that the arrival directions of CRs at Earth are not expected to point to their origin, except possibly at the highest energies.

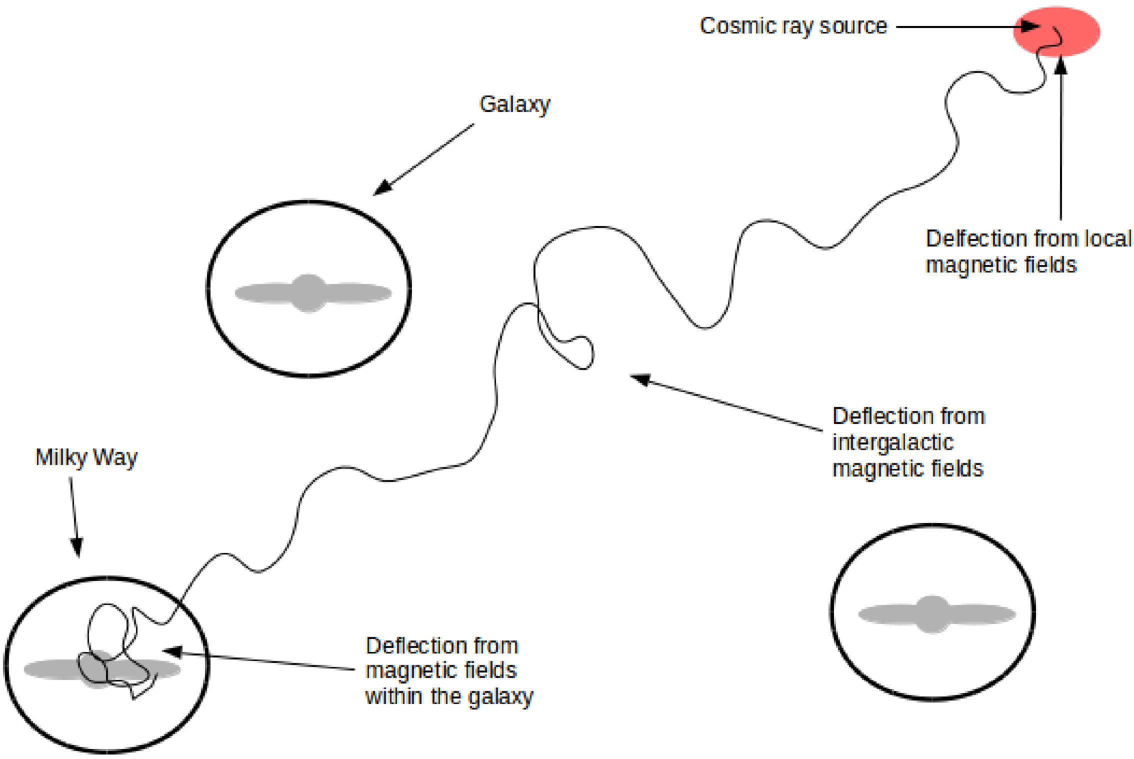


Figure 1.3: Schematic representation of magnetized regions which interfere with CR propagation through the Universe.

There has been a lot of progress made in recent years on the structure and strength of the Galactic magnetic field [13] and its effect on high energy CR propagation. However, very little is understood about inter-galactic magnetic fields and there are many models and theories to predict their effect on CRs. For a CR of energy 10^{20} eV, deflections could be on the order of $10° - 20°$ [14] or $< 1°$ [15], which shows that the deflection is very model dependent because it relies on the choice of magnetic field shape and strength.

1.4.2 Production

It is believed that interactions between CRs and other particles at the source produce high energy astrophysical neutrinos. The CRs can interact with matter (protons or neutrons) or photons in what are commonly called *pp* interactions (Eq. 1.5 & 1.6) or $p\gamma$ interactions (Eq 1.7 & 1.8) respectively. Both of these processes produce charged and neutral pions. In the $p\gamma$ interaction, the proton is excited to the Δ^+ state which then decays to a proton or neutron.

$$p + p \rightarrow p + p + \pi^0 \tag{1.5}$$

$$p + n \rightarrow p + n + \pi^+ \tag{1.6}$$

$$p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0 \tag{1.7}$$

$$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \tag{1.8}$$

The pions produced in these interactions are very unstable, each decaying in a different way. The neutral pions decay into two gamma-rays (Eq. 1.9) on a time scale of $\sim 10^{-17}\,$s, while the positively and negatively charged pions decay into an anti-muon and a muon neutrino and a muon and an anti-muon neutrino respectively (Eqs. 1.10-1.11).

$$\pi^0 \rightarrow 2\gamma \tag{1.9}$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \tag{1.10}$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \tag{1.11}$$

The positively and negatively charged muons produced in these interactions are also unstable (lifetime $\sim 10^{-6}\,$s) and will decay into a positron and electron respectively with corresponding neutrinos:

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \tag{1.12}$$

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \tag{1.13}$$

The interactions between CRs and their surroundings can happen within the region of their source which suggests that since neutrinos can only be produced by hadronic interactions, they also come from the same regions as CRs. Since CRs are largely affected by magnetic fields and other particle interactions, they are less likely, especially at lower energies, to accurately point back toward their source by the time they reach Earth. On the other hand, neutrinos travel almost completely undeflected which means they should point directly back toward their source. Due to this, neutrinos provide a means to discover the origin of CRs and even gamma-rays, exploring some of the biggest mysteries of the Universe.

1.5 Summary

The neutrino is electrically neutral and only interacts with matter via the weak force in neutral and charged current interactions. Since it possesses no charge, the neutrino acts as a very good cosmic messenger being a particle that travels in a straight line, undeflected by magnetic fields, thus preserving information relating to its source [16]. However, a disadvantage of the neutrino as a messenger particle is its extremely low interaction probability, making it very difficult to detect. Neutrinos, CRs and gamma-rays are all complementary messengers, capable of being detected at Earth, which could lead to the determination of their origin in the high energy Universe.

Chapter 2

The IceCube Neutrino Observatory

2.1 Introduction

The neutrino is undeflected by magnetic fields and at low energies, has a very small interaction cross section and hence travels virtually undetected through ordinary matter, making them a promising astrophysical messenger. However, at the highest energies, the Earth becomes opaque to neutrinos, also making them difficult to detect. Although it is hard to detect the presence of neutrinos, they are everywhere in the Universe, being the second most abundant particle after photons. They can travel cosmic distances to reach Earth from wherever their source may be, whether Galactic or extra-galactic. Neutrino detectors such as IceCube aim to detect the Cherenkov light produced by the secondary particles that are produced as a result of very rare neutrino interactions. IceCube is the first kilometer scale detector that was built and is currently the largest neutrino detector in the world (see Fig. 2.1). It is located at the geographic South Pole and was constructed in seven Antarctic seasons with construction only taking place in the summer. The detector has been in full physics operation since May 2011 [16].

2.2 Detector Layout

IceCube consists of 86 strings on a hexagonal base spaced 125 m apart with 60 digital optical modules (DOMs) on each string, totalling 5160 DOMs. Each DOM is equipped with a 10 inch photomultiplier tube (PMT) which is able to detect light and hence create an electrical current which is measured and counted as photoelectrons. The vertical separation of the DOMs is 17 m. The DOMs begin at a depth of 1450 m and end at a depth of 2450 m [16]. DeepCore is a smaller section within IceCube at the bottom of the detector which consists of 8 strings with a smaller spacing (70 m) and a shorter vertical DOM separation (7 m). This section lowers the IceCube threshold energy to 10 GeV which is suitable for the study of neutrino oscillations.

There is an array on the surface of the ice called IceTop which contains 81 stations each with two water Cherenkov tanks with two DOMs per tank. One DOM operates at high gain while the other operates at low gain [17]. The tanks that make up IceTop contain ice and also collect Cherenkov light. IceTop mainly acts as an air shower detector, observing cosmic rays. The data aquisition system of IceCube digitizes waveforms (time varying number of photoelectrons) in each of the DOMs and sends the information over copper wire to computers for processing. The IceTop array is fully integrated with the IceCube DAQ system which means that cosmic ray events observed by IceTop in coincidence with neutrino events observed in IceCube can be identified and reconstructed [17]. The depth of IceCube helps to filter out other atmospheric signals via attenuation outside the detector.

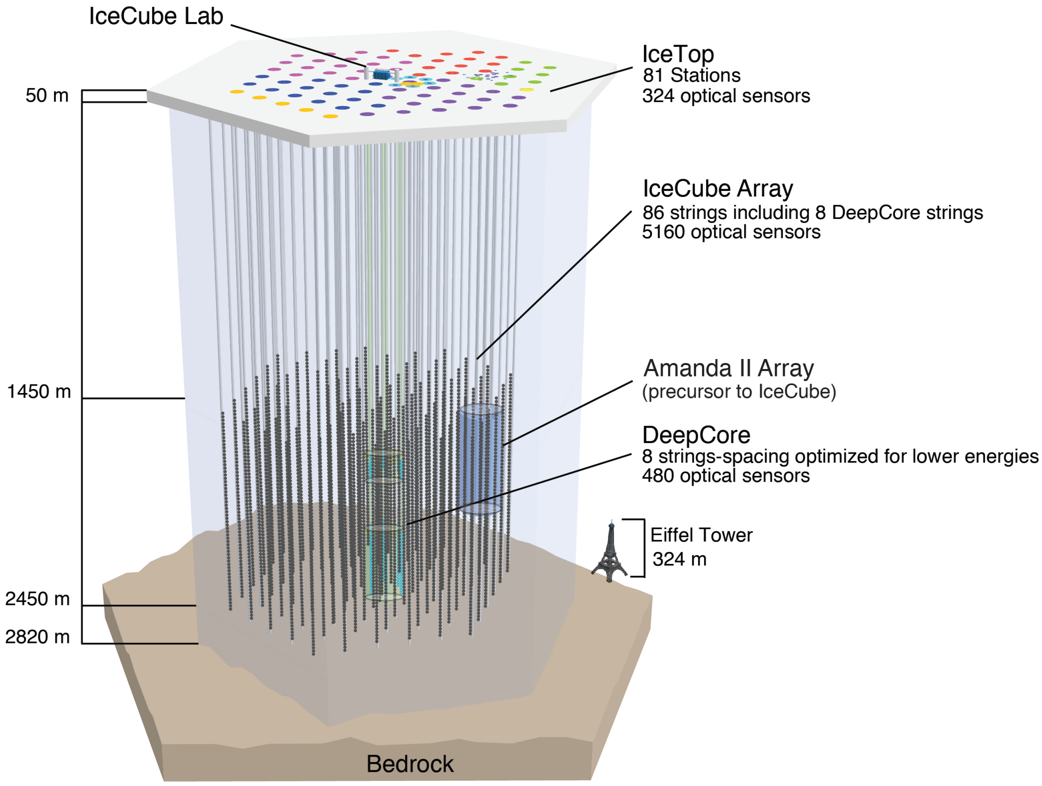


Figure 2.1: The IceCube Neutrino Observatory shown to scale with the Eiffel tower [18].

2.2.1 AMANDA Neutrino Detector: The Past

The predecessor of IceCube was the Antarctic Muon and Neutrino Detection Array (AMANDA) which is now decommissioned. The DeepCore component of IceCube was built to replace AMANDA. Construction on AMANDA began in 1995 when an array of 80 optical modules were deployed on 4 strings at depths between 1.5 km and 2 km (AMANDA-B4). AMANDA was upgraded in 1996 and again in 1997 with more optical modules and strings (AMANDA-B10). As a means of testing the way light traveled within the ice, a shallower array (AMANDA-A) was deployed first in 1993 which determined the presence of air bubbles which greatly scattered light, making detection difficult. For this reason, AMANDA was deployed deeper in the ice where these air bubbles were less of a concern. The AMANDA collaboration both simulated and reconstructed muons while including cuts for events that were not well reconstructed. AMANDA was designed to demonstrate the feasibility of muon track reconstruction in Antarctic ice rather than be a full-fledged neutrino detector. It was determined from AMANDA that the Antarctic ice is an adequate medium for neutrino astronomy [19] and hence the construction of larger neutrino detectors such as IceCube.

2.2.2 IceCube-Gen2: The Future

The next step for the IceCube Neutrino Observatory is *IceCube-Gen2*. While IceCube was a one cubic kilometer detector, *IceCube-Gen2* is planned to cover 7.9 cubic kilometers, nearly ten times larger than IceCube. With the increased volume, *IceCube-Gen2* will also deliver a substantial increase in sensitivity of astrophysical neutrinos of all flavours above $\sim 10\,\mathrm{TeV}$. The design of *IceCube-Gen2* would build upon the existing IceCube detector infrastructure and include 120 new widely-spaced strings. The new strings will be spaced 240m apart and be instrumented with 80 DOMs over a vertical length of 1.25 km. Overall, *IceCube-Gen2* will provide a facility capable of detecting neutrinos from several GeV to hundreds of PeV [20].

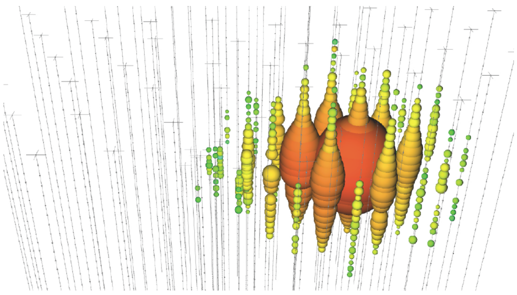
2.3 Light and Signals

2.3.1 Detection of Cherenkov Light

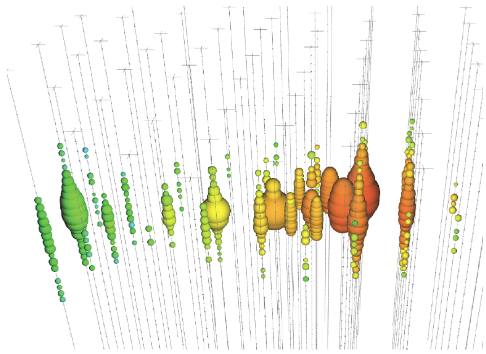
IceCube was designed to detect the products of various neutrino interactions, namely the muons, electrons and hadronic showers. The photomultiplier tubes within the DOMs are designed to detect Cherenkov light which is produced when a particle travels faster than the phase speed of light in that medium. The signal that each DOM receives after an event depends on the location and type of interaction. The signal and spatial distributions corresponding to the activated DOMs are used to reconstruct important properties such as the energy and direction of the event.

2.3.2 Flavour Signals

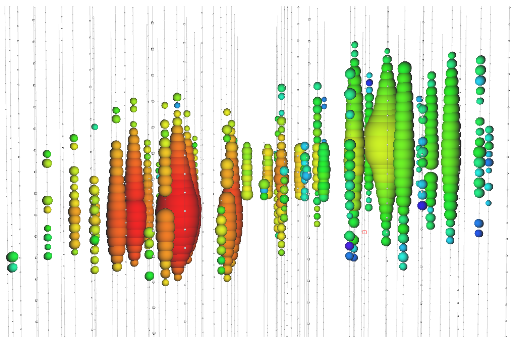
There are three main types of neutrino event that IceCube can detect: cascade (Fig. 2.2a), track (Fig. 2.2b) and "double bang" (Fig. 2.2c). Exemplary visualisations of each topology are shown in Fig. 2.2 where the DOMs are shown as black dots and the light signals (strength and timing information) as coloured spheres. The size of the coloured spheres reflects the amount of light detected and the colour indicates the arrival time, where red is early and blue is late.



(a) A cascade event.



(b) A track event.



(c) A double bang event.

Figure 2.2: Visualization of the three main event topologies expected to be observed at IceCube [21].

A cascade event occurs for neutral current interactions of all flavours and charged current interactions with electron neutrinos [16]. Events having cascade topology come from showers of electrons, taus that decay to hadrons or electrons and the primary production of hadrons. Here, the electron readily interacts with the ice within the detector due to it having the lowest mass of all three leptons. The electron will lose its energy in an electromagnetic shower of particles (a "cascade") that moves in the forward direction while the light is emitted at the Cherenkov angle (direction that the wavefront travels). The direction of the cascade is difficult to determine without exact knowledge of the complex properties of the ice. There are deposits of minerals, soot and ash within the ice that have accumulated over hundreds of thousands of years. This causes the absorption and scattering lengths of particles traveling through the ice to vary greatly with depth. There are also local changes in the hole ice properties caused by melting and re-freezing during the deployment of the DOMs. [16].

A track event can occur for charged current interactions of all flavours [16], however, it is unlikely for an electron neutrino since the range and mass of the electron is too low, and hence the electron will stop before reaching the next DOM. A track is more likely for a muon or tau neutrino event because the corresponding leptons have a much larger mass and scatter less as they travel. As it travels, it produces a track of Cherenkov light, providing a longer lever arm that makes it easier to determine the direction the particle is travelling.

Theoretically, a double bang event (two consecutive cascades) is produced by the tau neutrino, which IceCube has not yet clearly identified, although it is thought that the tau should be somewhere in the neutrino flux due to neutrino oscillations during flight from a distant neutrino source. Not all double bang events can be distinguished from a cascade because in some cases the distance between the bangs will be too small to resolve. The tau neutrino interacts with the ice creating a hadronic shower, which is the first (red) cascade in Fig. 2.2c, and a tau lepton. The lifetime of the tau is approximately $3 \times 10^{-13}\,\mathrm{s}$ and hence decays almost immediately to an electron

(18%), a muon (18%) or a hadron (64%) because it is very unstable, creating a second shower of particles, seen as the secondary (green) cascade in Fig. 2.2c. There are a whole range of signatures that could come from a tau neutrino in the form of a double bang based on distances between decays and other properties. An average tau decay length is 5 cm/TeV. At energies above a few hundred TeV, the tau lepton produced in a tau neutrino charged current interaction would have a decay length sufficiently long such that IceCube can resolve both particle showers and hence observe the "double bang" [22].

It is theorized that the detector would see a very faint track-like structure between the two cascade-like structures as the tau moves through the detector before decaying. The distance that the tau would travel before decaying is, however, energy dependent.

2.4 Discovery of Astrophysical Neutrinos

Detecting muons that come from astrophysical neutrinos is not easy. First, any background signal must be subtracted in order to obtain a significant excess. IceCube's main background comprises muons that are produced in extensive air showers when cosmic rays interact with the atmosphere. These muons do not come from neutrinos of an astrophysical origin. Instead, they are known as atmospheric muons, which have the signature of a down-going event. A down-going event comes from the sky above IceCube (Southern Hemisphere). An up-going event comes through the Earth from the Northern Hemisphere. The up-going events have an advantage in that a muon produced in an air shower in the Northern Hemisphere will not survive a trip through the Earth, so if an up-going muon is observed, it must have come from a neutrino interaction in close proximity (possibly several kilometers away) to the detector.

Atmospheric neutrinos have a steeply falling spectrum (i.e. large power law index) which is steeper than those that can be expected from astrophysical neutrinos. Therefore, signal-background separation can use the spectral information to discriminate. IceCube is interested (although not exclusively) in up-going neutrinos, because they are the most powerful detection channels. In 2012, two cascade-like events that started within the detector were discovered with energies in the PeV range. These events were observed in the 2010-11 and 2011-12 data. This discovery led to a dedicated search in the same two year data for other similar events which are now called high energy starting events (HESE). These events are specifically high energy astrophysical neutrino down-going events that start inside the detector. The containment of HESE, compared to other types of events, allows much better understanding and measurement of the neutrino event. A sample of HESE events was produced that included 28 events, the original two of which were of PeV ($1\,\mathrm{PeV}=10^{15}\,\mathrm{eV}$) energies [17]. The spectrum of this sample was studied and it was discovered that there was an excess at energies that could only be explained by astrophysical neutrinos. HESE event selection allows observation of neutrinos from all directions and the criteria are as follows [23]:

- they must start in a fiducial volume surrounded by a veto region
- they must deposit a large amount of light within the detector

The background must be estimated by looking at how often atmospheric muons pass through a suitably defined inner veto volume that originally starts inside the fiducial volume and pass through the original veto region. Here, the veto region is a layer at the boundary of the detector which excludes muon events which pass through it from the outside and the fiducial volume is a volume within the detector where majority of events are accepted. The position of an interaction that produces a muon outside the detector is unknown, however, the Cherenkov light from a muon that forms within the volume of the detector can indicate the position of the neutrino interaction.

Fig. 2.3 shows a sky map with arrival directions of HESE events in galactic coordinates, presenting no significant clustering. Some of the events appear to be near the Galactic plane while others are far from it. There is also a statistically insignificant cluster near the Galactic center. There have been proposed Galactic and extragalactic models to explain the IceCube HESE neutrino excess above the background and there are many point source searches being conducted to discover the origin of these neutrinos.

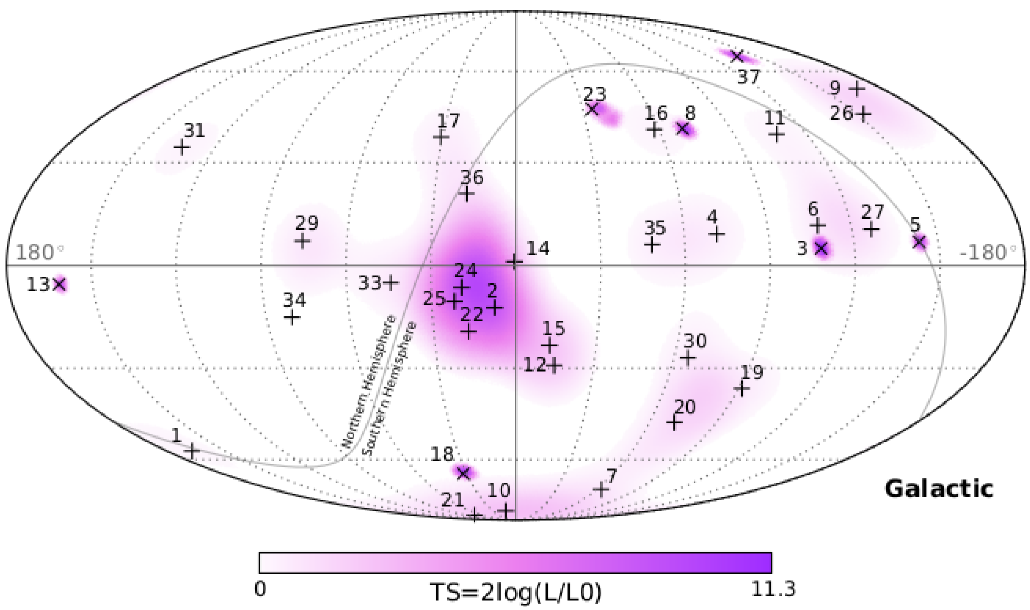


Figure 2.3: Arrival direction of events in Galactic coordinates. Cascades are denoted by a + whereas muon tracks are denoted by a ×. The grey line is the equatorial plane and the colours show the test statistic (logarithm of the ratio between the best-fit likelihood and null hypothesis likelihood) for the point source clustering at each location [23].

The distribution in energy for events spanning six years of up-going muon data (2009-2015) is shown in Fig. 2.4. The data in the IceCube six year analysis [24] were analysed using a likelihood approach based on the reconstructed muon energy and zenith angle. The data follow an isotropic, unbroken power law flux and do not follow the softer ($\phi \propto E^{-3.7}$) spectrum of atmospheric or background neutrinos, where ϕ is a neutrino flux, such as in previous IceCube analyses with lower energy thresholds. The data have instead a harder spectrum with $\phi \propto E^{-2.13}$, which might indicate a break in the astrophysical neutrino spectrum of unknown origin. This leads to an excess flux with a significance of 5.6σ above the atmospheric background which can be explained by high energy neutrinos of astrophysical origin and excludes a pure atmospheric origin. The IceCube astrophysical diffuse neutrino intensity per flavour is:

$$E^2\phi(E) = 0.9 \pm 0.3 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}} \tag{2.1}$$

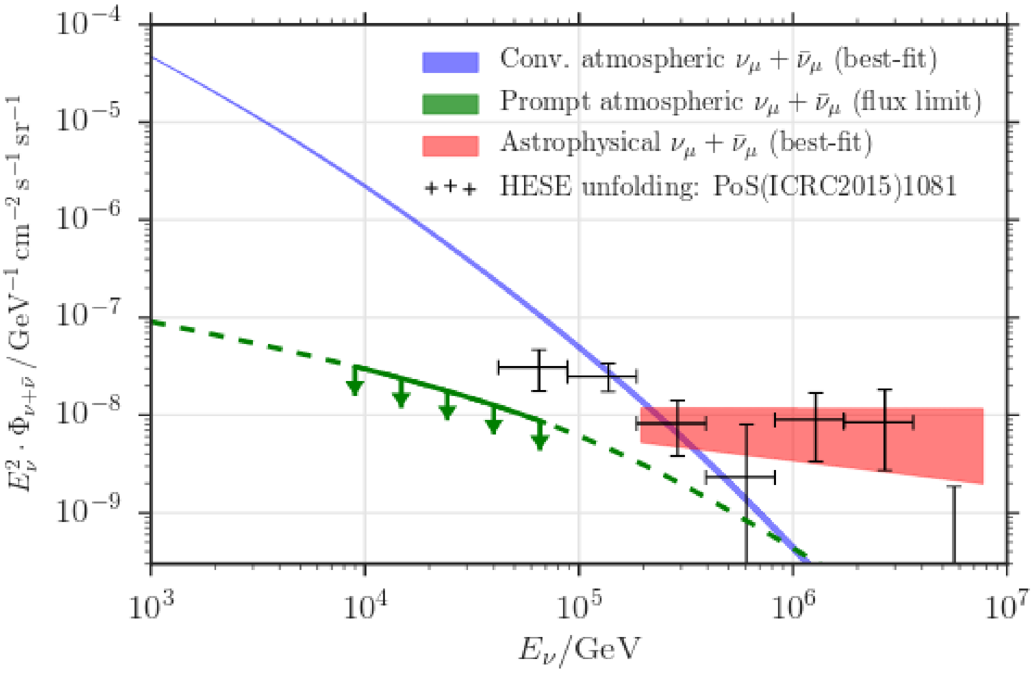


Figure 2.4: Energy distribution of events in 6 year IceCube analysis. The black crosses show the HESE data from IceCube. The conventional (blue) and astrophysical (red) flux curves show best fits to the data and the atmospheric (green) data is a limit on the flux [24].

2.5 Summary

The IceCube Neutrino Observatory at the South Pole is the largest neutrino detector in the world. It contains over 5000 DOMs which detect Cherenkov light from secondary particles produced in neutrino interactions. There are two types of neutrino signals that IceCube has observed: the cascade and the track resulting from an electron and a muon respectively, and one as-yet unobserved event: the double bang, that is expected from tau interactions for PeV energies and above. IceCube observes many atmospheric neutrinos as the result of air showers in the atmosphere, however, analyses have confirmed an excess flux of neutrinos that is believed to be astrophysical in origin.

Chapter 3

Origins of Astrophysical Neutrinos

Presently, one of the most active research areas in neutrino astronomy is the origin of high energy astrophysical neutrinos. Experimental and theoretical results generally suggest a combined origin of these neutrinos: Galactic and extra-galactic. There are many different constraints on the fraction of neutrinos from either origin that are consistent with the observed IceCube intensity.

3.1 Extra-Galactic Origins

The origin of IceCube's neutrinos is still unknown, however, there are many extra-galactic source classes that are suspected to be the production site of high energy astrophysical neutrinos, CRs and gamma-rays. These sources are often related to cataclysmic cosmis events that release large amounts of gravitational binding energy such as Active Galactic Nuclei (AGN) [25], Starburst Galaxies (SBG) [26], Gamma Ray Bursts (GRBs) [25] and Blazars [27]. All of these models use the idea that ultra high energy cosmic rays (UHECR) are undergoing pp or $p\gamma$ interactions near their acceleration sites (Eqs. 1.4-1.5) which produce the high energy neutrinos.

The lack of anisotropy in the observed neutrino events suggests that the neutrinos may come from distant sources beyond the Milky Way [28]. Cosmological sources are also expected to produce a diffuse isotropic neutrino intensity, which is consistent with IceCube's observations [29]. There are various source classes, seen in Fig. 3.1 (from [30]), thought to possibly produce or contribute to the IceCube intensity. This plot shows the relation between luminosity [ergs^{-1}] and number density [Mpc^{-3}] of various source types. This plot was created with constraints on the number densities by requiring that the considered source classes produce the entire neutrino intensity detected by IceCube, which is displayed with the coloured stars on the plot. The constraints applied are quite sensitive to redshift evolution which describes source distributions throughout the Universe as a function of redshift. The solid red IceCube lines represent the diffuse intensity where the upper line is the model for no redshift evolution ([30]), the middle line is the model for evolution following the star formation rate (SFR) ([31]) and the bottom line is the model for evolution following AGN ([32]). The dashed IceCube lines show the limit for point sources under the assumption that they produce the IceCube diffuse intensity. These dashed lines are also constrained by the non-detection of point sources. These lines exclude all combinations in the grey shaded area. Many of the coloured stars appear to be within, or close to, the grey shaded exclusion area which suggests that if these source classes were the source of IceCube's astrophysical neutrinos, a point source would be visible in the sky. Since no point sources have been observed, this plot effectively rules out the possibility that one of these source classes alone are producing all of the IceCube intensity. However, it is still possible that some combination of different source classes could make up the IceCube intensity. This includes a combination of neutrinos from the Milky Way and from various extra-galactic sources which will be discussed in Chapter 5.

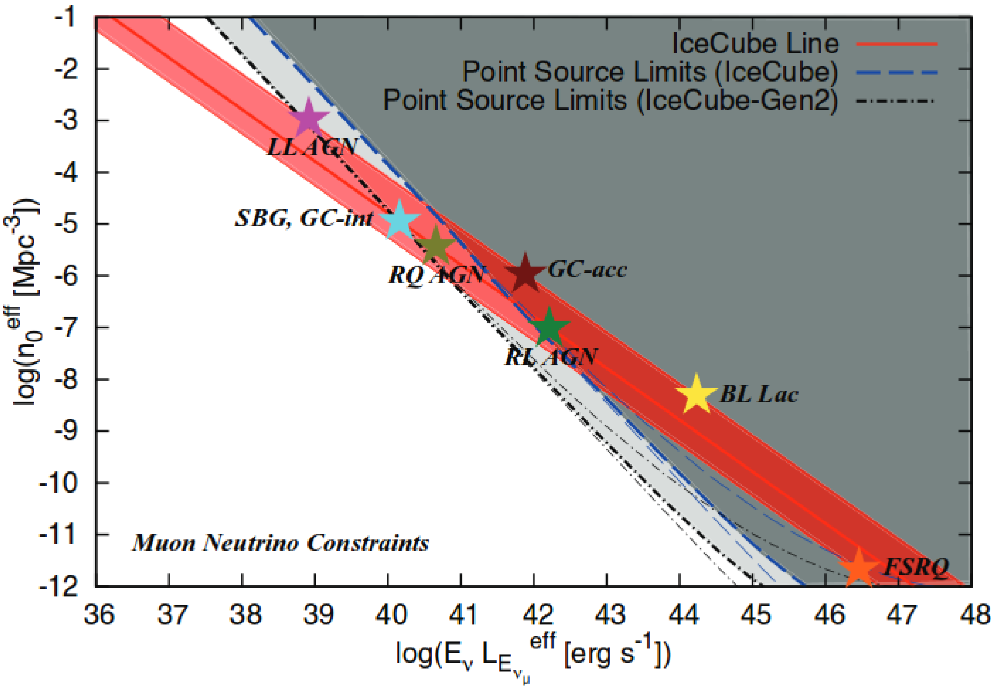


Figure 3.1: A plot of local source number density (n_0) vs. source luminosity ($E_\nu L^{eff}_{E_{\nu_\mu}}$). Solid red lines represent the IceCube diffuse intensity for no redshift evolution, evolution following the SFR and evolution following that of AGNs (from top to bottom) while the blue dashed line is a point source limit derived from a combination of the IceCube diffuse intensity and the non-detection of point sources. The black dash-dotted line is also an expected point source limit based on the design of Gen2. The grey shaded region shows the excluded parameter space (combinations of source luminosity and local number density that are not allowed by the point source limits) and the coloured stars are the combination of luminosity and number density of various source classes if they produce all of the IceCube intensity [30].

In all of the mentioned source classes, the acceleration of cosmic rays is the natural explanation for high energy neutrino production. The energy flux of neutrinos ($E_\nu^2\Phi_\nu(E_\nu)$) related to $p\gamma$ interactions (Eq. 3.2) can be derived from the cosmic ray injection rate:

$$E_\nu^2 \Phi_\nu(E_\nu) \sim \frac{3}{8}\epsilon_\pi \xi_Z t_H \frac{c}{4\pi} E_{CR}^2 \frac{d\dot{N}_{CR}}{dE_{CR}} \tag{3.1}$$

$$\sim 2.3 \times 10^{-8} \epsilon_\pi \xi_Z \, \mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}} \tag{3.2}$$

Here, $d\dot{N}_{CR}/dE_{CR}$ is the cosmic ray injection spectrum, E_{CR} is the energy of the cosmic ray, t_H is the Hubble time, ϵ_π is the fraction of the injected proton's energy lost in $p\gamma$ interactions, c is the speed of light and ξ_Z is a quantity that accounts for the effects of redshift dependent source evolution. The factor of 3/8 comes from the fact that approximately half of the pions produced in $p\gamma$ interactions are neutral and 3/4 of the energy of charged pion decays (Eqs. 1.9-1.10) go into neutrinos. If the parameters $\xi_Z = 5.75$ for star formation rate (SFR) evolution and $\epsilon_\pi = 1$ to satisfy the Waxman-Bahcall Bound are substituted into Eq. 3.2, then the resulting flux is [33]:

$$E_\nu^2 \Phi_\nu(E_\nu) \sim 1.3 \times 10^{-7} \, \mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}} \tag{3.3}$$

Here, the Waxman-Bahcall (WB) bound is an upper bound on the intensity of high energy neutrinos produced by photo-meson interactions in sources that are within the size of the mean free path of proton photo-meson. The WB bound is calculated using CR observations. Based upon the assumption that accelerated cosmic rays are producing the astrophysical neutrinos in these extra-galactic source classes and hence using the cosmic ray injection rate, the resulting neutrino flux (Eq. 3.3), for sources evolving as the SFR, is 4.3 times larger than what is observed by IceCube (three times Eq. 2.1) and thus could be a promising source of astrophysical neutrinos.

3.1.1 Starburst Galaxies

A starburst galaxy is a galaxy that has a very high star formation rate (SFR) compared to the average SFR seen in most galaxies. It is believed that high energy (TeV-PeV [33]) neutrinos could be produced from sources within these galaxies. It is assumed in this case that CR production is proportional to star formation activity. A high SFR means many massive stellar births and deaths which leads to the production of active objects such as supernova remnants (SNRs) capable of accelerating CRs to produce high energy astrophysical neutrinos.

The observed SFR density can be seen in Fig. 3.2 where the different colours and shapes indicate measurements from various experiments. The SFR can be approximated by three power laws as a function of redshift (z) [31]:

$$\mathrm{SFR(z)} = \begin{cases} (1+z)^{3.4} & z \leq 1 \\ (1+z)^{-0.34} & 1 < z \leq 4 \\ (1+z)^{-3.5} & z > 4 \end{cases} \tag{3.4}$$

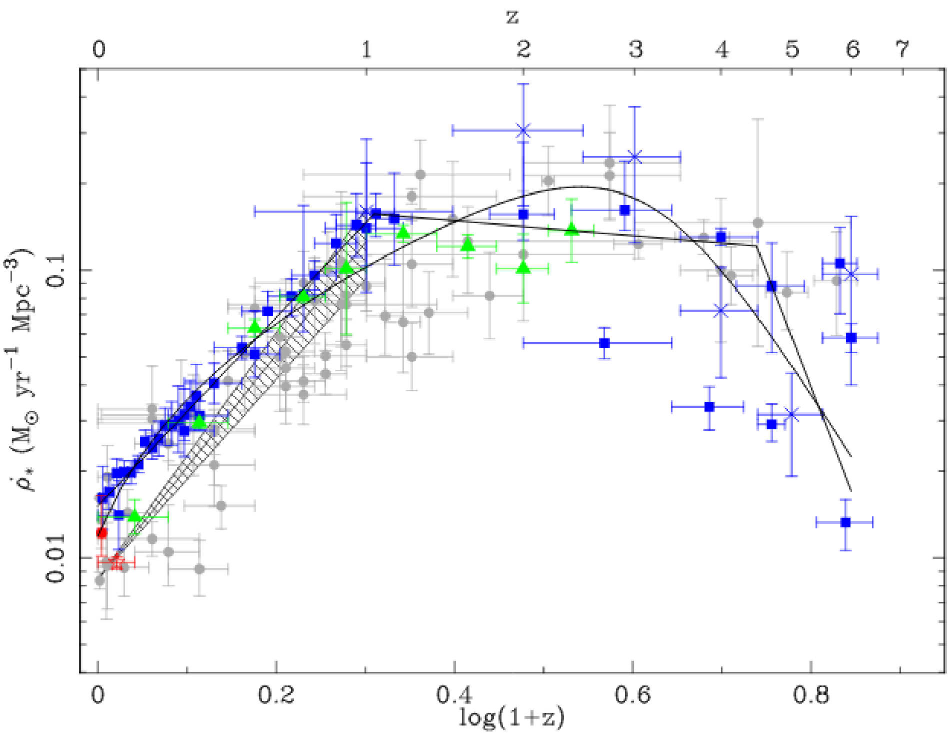


Figure 3.2: The SFR density as a function of redshift. The colours indicate measurements from different experiments. The solid lines are the best fitting parametric forms [31].

The energy spectrum of the high energy extra-galactic component of the CR flux is consistent with a cosmological distribution of sources thought to have a redshift evolution following the SFR [26]. The energy production rate of the observed CRs sets a model-independent upper limit given in Eq. 3.5, known as the Waxman-Bahcall (WB) upper bound [34], to the neutrino intensity of sources (per flavour).

$$E_\nu^2 \Phi_\nu < 2 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}} \tag{3.5}$$

The fact that the IceCube intensity (Eq. 2.2) is within the WB upper bound is compatible with an extragalactic origin of the IceCube neutrinos, possibly within SBGs and related to the acceleration of high energy CRs [26].

3.1.2 Active Galactic Nuclei

An active galactic nucleus has a super-massive black hole at the centre of its host galaxy surrounded by a very hot accretion disk which emits thermal radiation. For about 10% of AGN, perpendicular to the accretion disk are two jets which are thought to accelerate particles, such as protons, to very high, relativistic energies [35, 36]. Diffusive shock acceleration could be the process by which high energy protons are accelerated within the jet of an AGN. These protons interact with photons, which are also produced within the jet, to produce high energy neutrinos. It is believed that AGN are good candidate sources for high energy neutrinos because of the hard GeV gamma-ray spectrum observed from them that could be evidence of hadronic processes [37] or inverse-Compton (leptonic) processes.

Blazars

Blazars are AGN with one of the relativistic jets pointing within a few degrees along the line of sight to Earth [33]. There are two main sub-classes of blazars: BL Lacertae (BL Lac) objects and Flat Spectrum Radio Quasars (FSRQs), differing mostly in their optical spectra. FSRQs have strong, broad emission lines while the spectra of BL Lacs are characterised by optical spectra with very weak emission lines or no features at all [35].

The spectral energy distributions of BL Lacs display a low energy peak at X-ray energies and a high energy peak at γ-ray energies. The low energy peak is due to the synchrotron emission of energetic electrons while the high energy peak is due to several competing interactions and radiation processes of energetic electrons and nuclei. BL Lacs can further be divided into Low (LSP), Intermediate (ISP) and High (HSP) synchrotron peaked sources based upon the frequency of the low energy synchrotron peak [27, 38].

IceCube performed a likelihood analysis which searched for cumulative emission from blazars in the second *Fermi*-LAT AGN catalogue (2LAC) using a three year neutrino dataset that was optimised to detect individual sources [38]. No excess was observed and it was found that the maximum contribution to the astrophysical neutrino flux from 2LAC blazars is no greater than 27% for neutrino energies between 10 TeV and 2 PeV. This result assumes the neutrino flavour ratio to be equal at Earth and for the signal to have a power law spectrum with a spectral index of -2.5. However, a contribution of up to 50% from blazars has not been excluded for a power law spectrum with spectral index as hard as -2.2 in the same neutrino energy range.

3.1.3 Gamma-Ray Bursts

Gamma-ray bursts provide an energetic and highly variable source of gamma-rays. This suggests that they are also powerful particle accelerators. The coincident detection of high energy neutrinos will be the conclusive evidence for the acceleration of CR protons in GRBs [39]. GRBs are a promising candidate for the acceleration of high energy cosmic rays due to their large energy release over short time scales. The popular model for GRBs is the fireball model [40]. In this model, gamma-rays are produced when kinetic energy is dissipated in an ultra-relativistic fireball which flows outward from a stellar collapse or merger. If GRBs are able to accelerate protons with the same efficiency with which they accelerate electrons, then they could account for almost the entire high energy CR flux. The associated neutrinos from GRBs should be detectable with kilometre scale detectors, however, IceCube has not observed any associated neutrino signal [7].

IceCube performed a study [41] to determine if there was any coincident neutrino emission from GRBs. The background neutrino signal was separated from neutrino events that might correlate with GRBs using reconstructed energies and considering the spatial and temporal correlation with a GRB. The data are fitted to expected energy distributions of combined signal and background. Any excess seen after the fit indicates a signal that is not part of the expected background. The analysis includes 506 GRBs, selected by the time of gamma-ray emission and the location in the sky of the burst. In four years of IceCube data, only a single neutrino event that corresponded to a GRB was found, yielding a significance of $p = 0.46$. This event had a neutrino energy greater than 10 TeV with 16° angular separation from the observed GRB.

In a more recent study [42], IceCube performed an all sky search for muon neutrinos produced from γ-ray emission in 1172 GRBs. The analysis consisted of an extension to three more years of data of previous track analyses in the Northern Hemisphere. It also consisted of an additional search for tracks in the Southern Hemisphere in five years of IceCube data to improve sensitivity to the highest neutrino energies of around a few PeV. There is no significant correlation observed between neutrino events and GRBs in this new data. Both studies show that no more than 1% of the astrophysical neutrino flux could be produced from the observed GRBs.

Limits from the Diffuse Gamma-ray Background

The diffuse gamma-ray background can be used to put limits on the distance of the neutrino sources [28] based on the concept that the neutrinos are produced in the same sources as the gamma-rays. There is a limit because the gamma-rays that travel from extragalactic sources are attenuated by photon fields such as the cosmic microwave background (CMB), whereas the very small cross section of a neutrino means they are not significantly attenuated over cosmological distances. Therefore, if the sources are too far away, the gamma-rays produced by them would not be detectable at Earth. The study conducted by Chang *et. al.* [28] suggests that the neutrinos must come from large distances (redshift $z > 0.5$) and the evolution of the source with redshift must be at least as steep as the SFR in order to explain that the diffuse extra-galactic TeV gamma-ray flux as measured by *Fermi* is much lower than the flux expected to accompany IceCube's neutrinos [28].

3.2 Galactic Origins

Although an extra-galactic origin of neutrinos is generally favoured, some still accept that at least a small fraction (4 - 8%) of IceCube's diffuse neutrinos are being produced from within the Milky Way from CR propagation [43]. Many analyses search for a Galactic component of the astrophysical flux of neutrinos where the total flux includes an extra-galactic component, generally larger than the Galactic one. However, it has been theorized that all of the observed astrophysical neutrinos could be produced within the Milky Way. In particular, extended regions for neutrino production within the Galaxy are the disk, the halo and the Fermi bubbles. The Galactic neutrinos could all come from one of these locations or, more likely, a combination. As a Galactic model, the Fermi bubbles, which are giant structures that extend outside the Galactic plane [44], are slightly more accepted. However, in general, Galactic models have a tendency to be disfavoured since there are far more active regions in the Universe which are more likely to be producing most of IceCube's neutrinos.

3.2.1 Outline of Work

The extended Galactic halo model suggested by Taylor, Gabici and Aharonian [44] described in section 3.2.3 of this chapter was the main motivation for the research presented in this thesis. The objective of this research is to put a constraint on the fraction of neutrinos that can come from the Milky Way. Firstly, it is shown that there is a contradiction between the actual number density of Milky Way-like galaxies observed in the Universe and the calculated number density under the assumption that all of IceCube's astrophysical neutrinos are produced in the Milky Way. In this model, statistically - assuming that IceCube has observed no neutrinos from the rest of the Universe - extra-galactic sources can only produce an intensity compatible with an upper limit of 0.4% of the IceCube intensity. A range of "allowed" combinations of distance to neutrino source and fraction of neutrinos for suitable number densities in the rest of the Universe can be calculated, as well as an allowed combination of luminosity and fraction. These calculations are then repeated, now assuming that the Galactic disk produces 14 % [45] of IceCube's neutrino intensity.

3.2.2 Galactic Disk

The Galactic disk contains many possible neutrino sources including supernova remnants (SNRs), pulsar wind nebulae (PWN), binary systems and unidentified sources in the Galactic Ridge and Centre [46]. It is believed that these objects are capable of producing high energy CRs which then interact with the interstellar medium in the Galaxy to produce comparable diffuse neutrino and gamma-ray fluxes.

The Galactic disk dominates the high energy sky in diffuse gamma-ray emission produced in pion decay after interactions between CRs and ambient gas within the disk. Since it is believed that these gamma-rays are hadronic in origin then it is expected that neutrinos as a result of these same interactions should be seen as a diffuse flux correlating with the plane of the Galaxy [45]. In studies to date, due to the lack of exposure time, the neutrino emission along the Galactic plane could also be from individual point sources [47].

In a recent study performed by IceCube [45], a constraint on the fraction of the diffuse astrophysical flux from the Galactic plane is calculated. It was concluded that less than 14% of the isotropic diffuse neutrino flux comes from the Galactic plane for a power law spectrum with a spectral index of -2.5. The analysis focussed on SNR and PWN catalogues from gamma-ray observatories. Two methods, which both use muon neutrinos, are used in the analysis with slightly overlapping data sets. The first method is an extension on the point source search (unbinned maximum likelihood analysis). The second is an extension of the method used to measure the diffuse astrophysical neutrinos. The analysis tests three diffuse emission models describing the origin of the neutrinos: the *Fermi*-LAT π^0-decay template [48], the KRA-γ (50 PeV cutoff) model [49] and a smooth parameterization of the Galaxy from [50].

Additionally, if the assumption is made that some fraction of the neutrino intensity is not diffuse on a large scale and actually originates from the Galactic plane region, then, using the gamma-ray flux from this region, the expected neutrino detection rate in IceCube can be calculated to be approximately one event per year [44]. Under certain assumptions, the ratio of the number of neutrinos coming from the disk compared to the number of neutrinos coming from the halo has been calculated and it follows that the neutrinos coming from the disk would dominate unless the Milky Way has a very extended halo [44].

3.2.3 Extended Halo Model

IceCube has observed a neutrino intensity that is statistically consistent with isotropy in the distribution of astrophysical neutrinos. One way that this could be explained is to have the neutrinos originate from PeV CR interactions with the ambient gas in the halo after their escape from the Galactic disk. Taylor, Gabici and Aharonian [44] investigated this possibility and their conclusions were the main motivation for this research. They concluded that on dimensional grounds the halo could be a potentially significant source if sufficient gas exists at large radii and the neutrinos were a result of an outflow of CRs into the halo region.

Assuming that the origin of the IceCube diffuse neutrino intensity comes from a region of average distance of 100 kpc [44], the observed intensity translates to a source luminosity of

$$\begin{aligned} L_\nu &= 4\pi d^2 E_\nu F_\nu && (3.6)\\ &= 4\pi d^2 \Omega E_\nu^2 \frac{dN}{dE_\nu} && (3.7)\\ &= 4\pi \times (3.086 \times 10^{23}\mathrm{cm})^2 \times 4\pi\mathrm{sr} \times 4.81 \times 10^{-11}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,sr^{-1}} && (3.8)\\ &= 7.23 \times 10^{38}\,\mathrm{erg\,s^{-1}} && (3.9) \end{aligned}$$

Here, d is the distance to the edge of the spherical halo, $E_\nu F_\nu$ is the neutrino energy flux, Ω is the solid angle and $E_\nu^2 dN/dE_\nu$ is the neutrino energy flux within an energy interval of 0.1 - 1 PeV for all three flavours. In this model, it is assumed that the emission surface density is from hypothetical sources that are spread out on the surface of a sphere at 100 kpc, which is within the extended halo of the Milky Way. This model is slightly unrealistic since it is more likely that the emission surface density would actually just be an emission density where the hypothetical sources have some distribution through the entire halo. However, for a simple calculation, this model suffices. The corresponding CR luminosity required to power such a system is $L_{CR} = L_\nu/f \sim 10^{39}\,\mathrm{erg\,s^{-1}}$ where f is a scaling factor that is dependent on the fractional energy passed on to the neutrino population through pp interactions, the escape time of CRs, the energy loss time, the process of inelastic pp collisions and whether or not the CRs follow diffusive or advective transport [44].

The Galactic halo model could be a potentially significant source of high energy neutrinos provided that sufficient target material exists out at these large distances.

The extended Galactic halo model cannot currently be ruled out if the neutrino emission is connected to an advected (physically transported) CR population. Here CR transport in the outflow environment must be different to transport within the Galactic disk. The GC would have to accelerate CRs to trans-"knee" (i.e. $\sim 10^{15}\,\mathrm{eV}$) energies before their escape into an outflow to the halo. This would violate the usually adopted uniform CR hypothesis, however, note that there are other CR hypotheses that can be adopted, such as non-uniform [44]. Although, if the extended halo is considered, then the CR hypothesis is still valid. It has been argued that a Galactic origin of neutrinos is possible if they are produced by CR interactions with the gas in the Galactic halo after the CRs have escaped the Galactic disk [44] where they were originally produced by sources still unknown. However, it is assumed here that the CRs are accelerated to energies on the order of $10^{15}\,\mathrm{eV}$ by activity in the GC before their escape into an outflow in the Galactic halo region. In this model, the intensity of the CRs is assumed to be constant throughout the entire Galaxy [44]. A large reservoir of gas in an extended halo is required to adequately explain this model. A similar halo model is proposed in [51] where they describe the neutrino flux for a spherical and arbitrary halo shape under the assumption that the neutrinos are produced by interactions between the CRs and hydrogen within the Galactic halo.

3.2.4 Fermi Bubbles

The Fermi Bubbles (FB) are two large globular shaped structures above and below the Galactic plane stretching to latitudes of $\pm 55°$ [43] or distances of approximately ± 9 kpc, and were discovered in 2009 by the *Fermi*-Large Area Telescope (*Fermi*-LAT) [29]. There are two possible scenarios for the origin of the Fermi Bubbles: leptonic and hadronic. The hadronic case is where neutral pions decay to produce two gamma rays (Eq. 1.9) whereas the leptonic case is where gamma rays are produced from inverse Compton scattering.

If the FB, which were originally observed in gamma-rays, have a hadronic origin, then they could act as candidates for extended neutrino sources in the Milky Way [43]. This is because the hadronic process that produces neutrinos (see Eqs. 1.4-1.10) also produces gamma-rays which means a neutrino counterpart of approximately the same flux [29] is expected to be observed from the FB. For a leptonic origin of the FB, an associated neutrino counterpart is not expected [52]. However, the origin of the FB and the gamma-ray production mechanism (hadronic or leptonic) is yet to be confirmed. Fig. 3.1 shows the geometry of the FB along with the location of IceCube events.

A neutrino counterpart should be detectable in events at IceCube. High energy astrophysical neutrino events have been spatially correlated with the FB where up to approximately five of IceCube's events, with energies between approximately 100 TeV and 1 PeV, have arrival directions consistent with the FB. It is possible that the FB could be the first objects to be observed in both gamma-rays and neutrinos [53]. On the contrary, it has been discussed that measurements of the diffuse gamma-ray flux from the FB region by the *Fermi* satellite are insufficient to account for the excess of neutrinos observed by IceCube [44]. Also, the particles that are reponsible for the gamma-ray and netrino fluxes should differ in energy by a factor of ~ 1000. Thus, there may be considerable differences in the parameters relating the two particle populations.

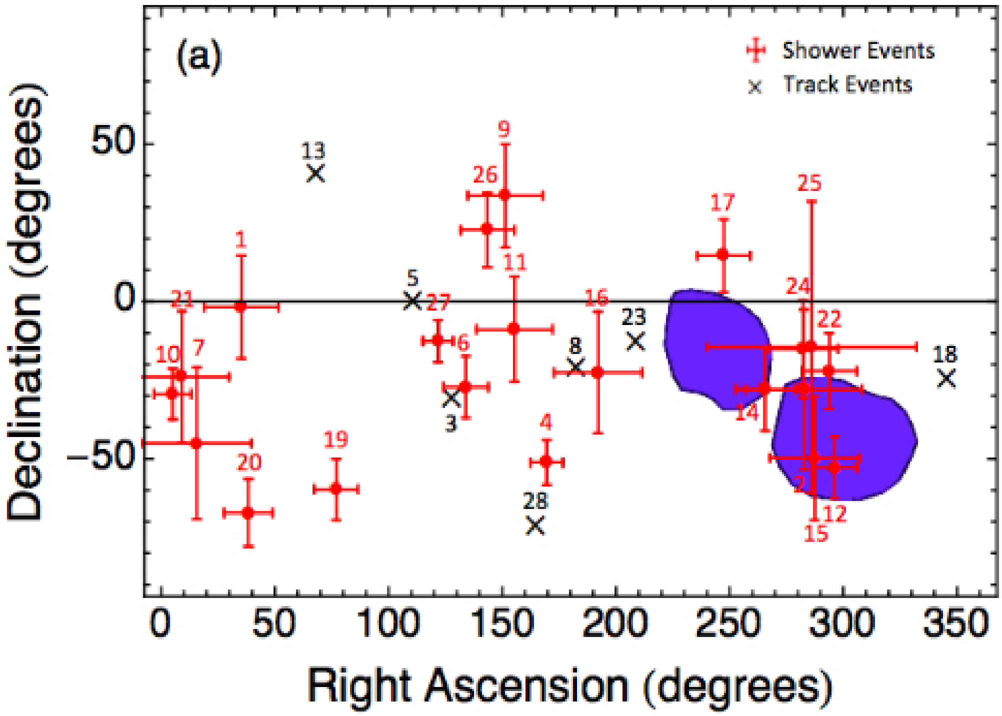


Figure 3.3: Plot showing the contours of the Fermi Bubbles (blue shaded regions) and the equatorial coordinates of IceCube events from [54] with their median angular errors [29].

3.3 Summary

An extra-galactic origin of high energy astrophysical neutrinos is favoured in the absence of strong anisotropies in the neutrino arrival directions. The detection of a neutrino flux from extra-galactic sources such as AGN, GRBs and SBGs would confirm these objects as accelerators of high energy CRs and quite likely gamma-rays. There have been many analyses that search for neutrino events observed by IceCube that correspond with very active astrophysical sources, however, as of yet, no studies have shown any statistically significant correlation. Despite the lack of exposure time, extra-galactic sources still seem to be the most promising candidates to explain most of the IceCube astrophysical neutrino flux. However, that is not to say that a Galactic origin of at least some of IceCube's neutrinos has not been proposed.

A purely Galactic origin of IceCube's astrophysical neutrinos is not favoured by experimental and theoretical constraints. However, it is widely believed that at least a small fraction of IceCube's astrophysical neutrino intensity could come from various sources within the Milky Way such as the Galactic plane region, an extended Galactic halo or the Fermi Bubbles. For the work in this thesis, the focus will mainly be placed on an extended Galactic halo and the Galactic disk to put further contraints on what fraction of the IceCube intensity can come from these areas based on various models.

Chapter 4

The Neutrino Luminosity of the Milky Way Halo

The Milky Way is not a unique galaxy in the Universe. There are many other spiral galaxies contributing to a number density of $10^{-3} - 10^{-2}\,\mathrm{Mpc}^{-3}$ [25, 55]. Assuming that all neutrinos observed by IceCube are produced within the halo of the Milky Way, then, since the Milky Way is not unique there must be other similar galaxies producing neutrinos at a similar rate. In this scenario the rest of the Universe must be producing an at-Earth intensity of neutrinos compatible with zero events consistent with IceCube level statistics. Although the rest of the Universe is predicted to produce such a small fraction of all the neutrinos observed by IceCube, all other spiral galaxies are still expected to produce neutrinos at the same rate as the Milky Way, regardless of the Milky Way's contribution to the astrophysical neutrino flux observed at Earth. To satisfy both of the conditions it is possible that the number density of Milky Way-like galaxies in the rest of the Universe will be outside the accepted range. This in turn would suggest that it is unlikely that all of IceCube's neutrinos are coming from the halo of the Galaxy.

This analysis involves calculating a neutrino luminosity of the Milky Way assuming that all of the neutrinos are coming from the halo. It is assumed both that the emission density is either uniform throughout the volume of the halo or is a surface density that is evenly spread along the surface of the halo [44]. A neutrino luminosity is calculated for both of these instances. It is assumed that the Milky Way-like galaxies in the rest of the Universe will also have the same neutrino luminosity which will allow the calculation of the number density of these galaxies in the rest of the Universe and a comparison to the accepted number density.

4.1 Deriving Equations for the Flux and Luminosity of the Halo Model

To begin the analysis on the extended halo model discussed in the previous chapter a neutrino luminosity expected from the Milky Way must be calculated. The most computationally simple version of the extended halo model is where the halo emission surface density is from a spherical shell with radius equal to the assumed radius of the halo. It can be shown (see Appendix A) that the flux from a single point source of luminosity L is the same as the flux of multiple point sources evenly spread over the surface of the sphere each with individual luminosity $l_i = L/n$, for n sources. L is the combined luminosity of the Milky Way Galaxy coming from the point source distribution assumed, which is defined by requiring the at-Earth neutrino flux to equal the experimental IceCube flux, denoted F.

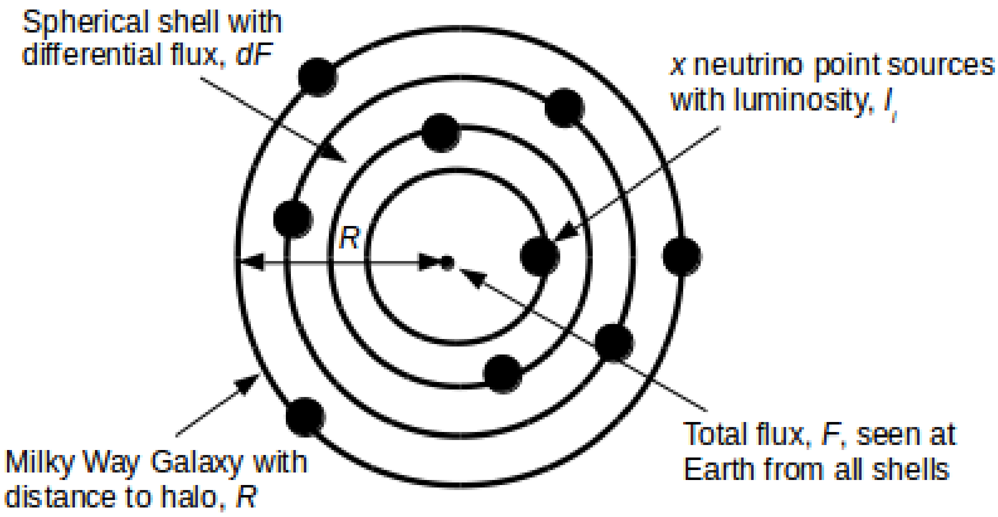


Figure 4.1: Flux and luminosity of many sources spread throughout the volume of a sphere.

The model that uses the halo emission surface density is very simple and so a more complex assumption would be to have an emission density that is uniform throughout the volume of the Milky Way (Fig. 4.1). Within this volume there are x spherical shells on which the individual sources sit. This model will result in a flux that is a factor of three larger from the flux derived in Appendix A for a given luminosity. To calculate this flux, use the volume of a sphere in integral form:

$$V = \int_0^R 4\pi R'^2 dR' \tag{4.1}$$

and the number density of neutrino sources, n:

$$n = \frac{N}{V} \tag{4.2}$$

to write the total number of neutrino sources, N:

$$N = n \int_0^R 4\pi R'^2 dR' \tag{4.3}$$

throughout the volume.

Each spherical shell will have some individual differential luminosity

$$dL = 4\pi R^2 n l_i dR \tag{4.4}$$

based on how many sources are on that shell at that distance. However, each shell will produce the same flux at Earth to contribute to the overall flux. This is because as each shell increases in size, the area of the shell increases by R^2, while the luminosity decreases by R^2. In Eq. 4.4, l_i gives the luminosity of a single source on a shell.

The total flux can be found by integrating the differential flux:

$$dF = \frac{dL}{4\pi R^2} \tag{4.5}$$

$$F = \int_0^R \frac{4\pi R'^2 n l_i}{4\pi R'^2} dR' \tag{4.6}$$

$$= n l_i \int_0^R dR' \tag{4.7}$$

$$F = n l_i R \tag{4.8}$$

To write a more familiar expression for the flux to compare to Eq. A.1 (Appendix

A), substitute the source number density (Eq. 4.2):

$$F = \frac{Nl_i R}{V} \tag{4.9}$$

$$= \frac{Nl_i R}{\frac{4}{3}\pi R^3} \tag{4.10}$$

$$= \frac{Nl_i}{\frac{4}{3}\pi R^2} \tag{4.11}$$

$$F = \frac{3L}{4\pi R^2} \tag{4.12}$$

The l_i becomes an L in Eq. 4.12 because the total number of sources, N, multiplied by the luminosity of a single source will give the total luminosity of all of the sources together and this must be equal to the original point souce luminosity, L. Hence Eq. 4.12 is used to calculate the luminosity of the Milky Way assuming that Earth is in the centre of the Milky Way and the emission density is uniform throughout a spherical volume out to the assumed distance of the halo. Hence Eq. 4.13 can be used to calculate the neutrino luminosity (also seen in Fig. 4.2) of the Milky Way provided the sources are uniformly distributed throughout the volume of the galaxy and halo.

$$L = \frac{4}{3}\pi R^2 F \tag{4.13}$$

The luminosity of the Milky Way with uniform emission density throughout the volume of the halo differs to the luminosity of the Milky Way if the surface emission were from the sphere surface by a factor of three. Fig. 4.2 shows a schematic of the Milky Way with an extended halo at 100 kpc as well as the CRs escaping the disk to interact with ambient halo gas to produce high energy neutrinos.

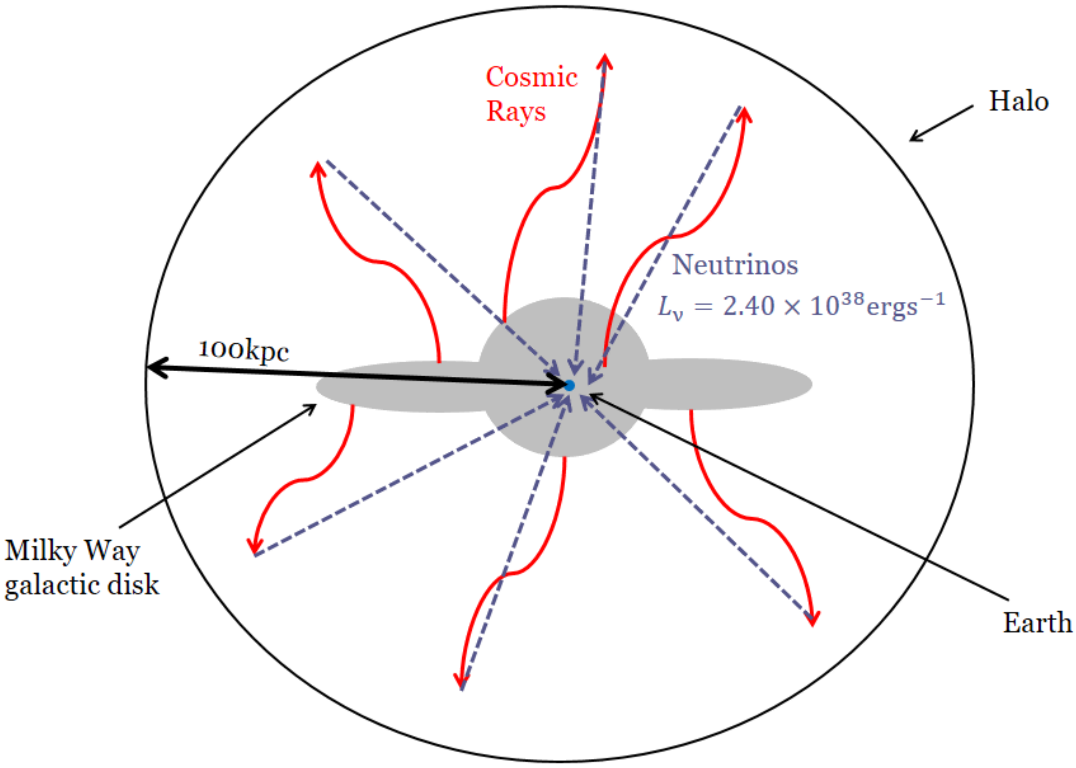


Figure 4.2: Schematic of neutrino production within the halo (black solid line) of the Milky Way (grey shaded area) showing the calculated neutrino luminosity for sources distributed uniformly throughout the volume of the Galaxy. The solid red lines show the CRs escaping from the disk of the Galaxy and interacting with ambient halo gas to produce neutrinos (blue dashed lines).

Although a neutrino source distribution throughout the volume of the Milky Way halo would be more complex and perhaps more realistic, the study that motivated this research [44] assumed that sources were distributed evenly over the surface of the sphere for simplicity. Hence, a neutrino luminosity will be calculated for both scenarios and compared to one another throughout the rest of the research to remain consistent with the original motivation.

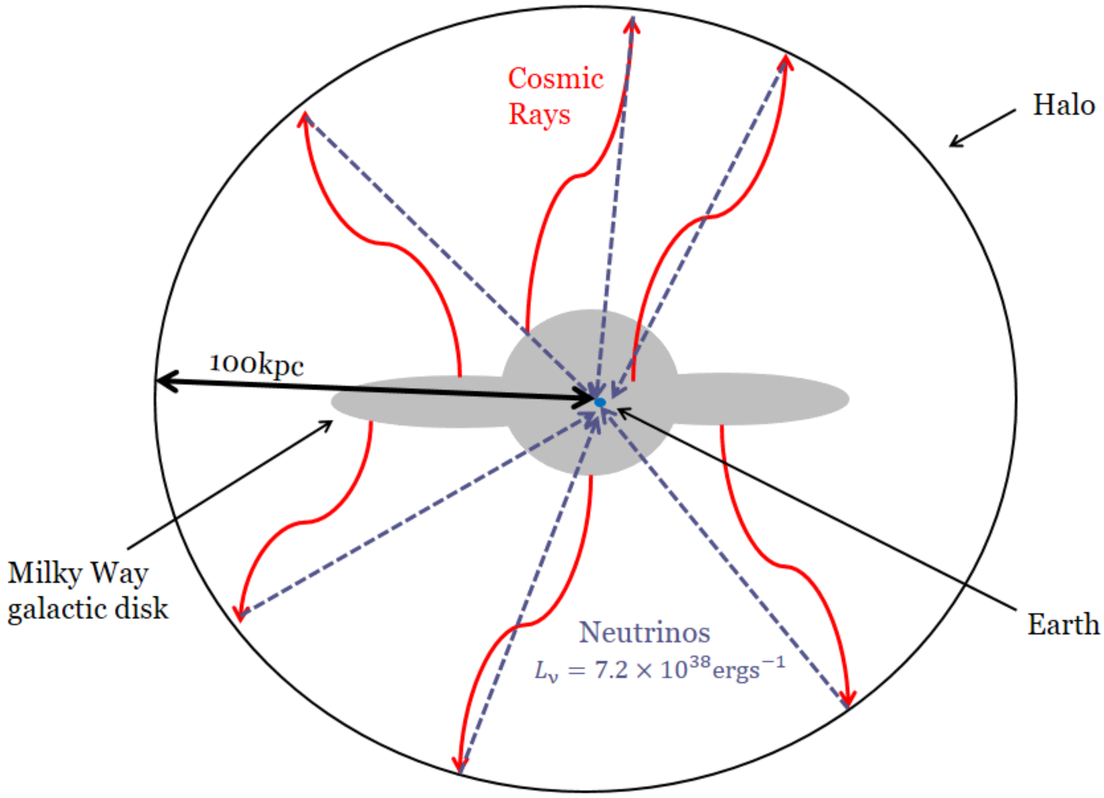


Figure 4.3: Schematic of neutrino production within the halo (black solid line) of the Milky Way (grey shaded area) showing the calculated neutrino luminosity for an emission surface density over the surface of the sphere. The solid red lines show the CRs escaping from the disk of the Galaxy and interacting with ambient halo gas to produce neutrinos (blue dashed lines).

Following Taylor, Gabici and Aharonian, assuming a halo distance of $R = 100\,\mathrm{kpc} = 3.08 \times 10^{23}\,\mathrm{cm}$ and sources following a uniform distribution throughout the volume of the Milky Way, the neutrino luminosity of the Milky Way is given by

$$L_{\nu,vol} = 1.50 \times 10^{41}\,\mathrm{GeVs}^{-1} \tag{4.14}$$

$$= 2.40 \times 10^{38}\,\mathrm{ergs}^{-1} \tag{4.15}$$

Now assuming that the emission surface density is only over the surface of the sphere

(Fig. 4.3) the neutrino luminosity of the halo is given by

$$L_{\nu,surf} = 4.51 \times 10^{41}\,\mathrm{GeVs^{-1}} \tag{4.16}$$

$$= 7.23 \times 10^{38}\,\mathrm{ergs^{-1}} \tag{4.17}$$

which is consistent with the result derived from [44] in Chapter 3.

4.2 Statistical Upper Limit on Neutrino Luminosity of the Rest of the Universe

Based on the assumption that all of IceCube's observed neutrinos come from the Milky Way, statistically there must be an upper limit on the number of neutrinos that could come from the rest of the Universe given the assumption that zero have been observed.

In six years of data, IceCube has detected 350,000 neutrino events in the Northern sky, most of which are atmospheric. There are approximately 500 astrophysical-weighted neutrinos in this data set [24] which come after best fits have been made for atmospheric and astrophysical neutrinos. Based on the study done by Taylor, Gabici and Aharonian [44], assume that all 500 non-atmospheric neutrinos are coming from the Milky Way. Statistically, at the 90% confidence level, at most 2 neutrinos can come from extra-galactic sources if zero are actually observed. Hence, approximately 2 in every 500 neutrinos are coming from extra-galactic sources which translates to 0.4%. However, it is important to note that there is actually no way for IceCube to distinguish between emission from the Galactic halo and that from extra-galactic sources. In this analysis, it is assumed that the neutrino flux from non-Milky Way sources is equal to an intensity compatible to an upper limit of 0.4% of the IceCube intensity.

4.3 Summary

The original extended halo model [44] used the simplistic distribution of an emission surface density from the spherical shell defined as the outer limit of the halo of the Milky Way to calculate the neutrino luminosity of the Milky Way (Eq. 3.8). In this analysis, the emission density is uniform throughout the volume of the Milky Way and halo in order to calculate the luminosity. Since these two luminosities only differ by a factor of three, there is no significant difference between each source distribution.

Chapter 5

Constraining the Fraction of Neutrinos from the Galactic Halo

Given the assumption that the rest of the Universe is only producing an intensity consistent with an upper limit of 0.4% of the IceCube intensity, ultimately, the number density of equivalent Milky Way-like objects in the rest of the Universe can be calculated. The chosen accepted range of local number density of spiral galaxies is between $10^{-3}\,\mathrm{Mpc}^{-3}$ and $10^{-2}\,\mathrm{Mpc}^{-3}$ [25, 55]. Firstly, the equivalent number of Milky Way-like sources allowed in the rest of the Universe must be calculated under the assumption that they can only produce 0.4% of the IceCube intensity. It will be shown that the number density of sources in the rest of the Universe would be significantly below the range of the accepted densities. This would suggest that the Galaxy could not be producing a significant component of the IceCube intensity.

Given an accepted galaxy number density range, constraints can be placed on the neutrino luminosity of the Galactic halo and also the ratio of IceCube's neutrinos that can realistically come from the Milky Way halo and extra-galactic sources. It is found that if the halo were to produce all of the neutrinos, the sources on the halo would have to be less luminous and very close to Earth. In contrast, if most of the neutrinos were to be extra-galactic the sources would have to be more luminous and at a greater distance.

5.1 Number Density of Sources in the Rest of the Universe

IceCube observes a diffuse astrophysical neutrino intensity, I_{IC}, at Earth which would likely be composed of some intensity from Galactic sources and some intensity from extra-galactic sources. The combinations of intensities from Galactic and extra-galactic sources must combine in such a way as to produce the observed IceCube intensity. This means that the parameters that describe the Galactic and extra-galactic intensities must be limited by model assumptions. The equation that describes the IceCube intensity is given by

$$I_{IC} = (1-f)\frac{1}{4\pi}\frac{L_{MW}}{4\pi d^2} + \int_0^z \frac{1}{4\pi}\frac{c}{H_0}\frac{z}{E(z)}\frac{1}{(1+z)^2}\rho_{z=0}g(z)(1-f)L_{MW}d\log z \quad (5.1)$$

which is a combination of a Galactic term and an extra-galactic term. The $L_{MW}/4\pi d^2$ in the first term is derived from assuming that the Milky Way is producing all of the IceCube intensity and hence can be written using the luminosity of the Milky Way (L_{MW}) if it is the origin of all astrophysical neutrinos observed. To be able to include an extra-galactic term and hence have a combination of Galactic and extra-galactic intensities equal the IceCube intensity, the Milky Way part of the Galactic term must be scaled to only produce some fraction of the IceCube intensity ($(1-f)$, where f is the fraction of neutrinos that the rest of the Universe produces). It is important to also describe the behaviour of the near edge cases and realise that the only other changing parameter is the local density. The luminosity of each source is taken as the value $(1-f)L_{MW}$, which is the luminosity of the Milky Way if it produces a fraction $(1-f)$ of the total IceCube intensity. When f is approaching one, the fraction of neutrinos that the rest of the Universe produces is approaching 100%. The $(1-f)L_{MW}$ term approaches zero, and the local density $\rho_{z=0}$ increases to compensate. When f is approaching zero, the fraction of neutrinos that the Galaxy produces is approaching 100%. This requires the density of sources in the rest of the Universe to approach zero as the luminosity of the sources is approaching L_{MW}.

The second term describes the intensity from the rest of the Universe. It is an integral across the Universe, taking into account cosmological factors: $1/(1+z)^2$, which accounts for time dilation and the redshifting of energies, and $E(z)$, which describes the redshift evolution of the Hubble parameter (also discussed in Appendix B). It is important to note that the luminosity of the Milky Way assumes an E^{-2} energy spectrum. It is defined as the energy per time for a logarithmic energy interval. Since a power law was assumed, this allows the shifting of energies to be equivalent to a down-scaling which explains one of the factors of $1/(1+z)$ in Eq. 5.1, which is true for any power law.

The integral also uses the luminosity density of sources, $\rho_{z=0}g(z)(1-f)L_{MW}$ where $\rho_{z=0}g(z)$ describes the number density of sources throughout the rest of the Universe. The local number density of sources in the rest of the Universe is $\rho_{z=0}$ and is the factor that normalises $g(z)$ which describes the shape of the density distribution. When $z = 0$, $g(z) = 1$. For example, the number density could follow a uniform distribution or the SFR, as previously discussed.

Since all other parameters have already been determined in Eq. 5.1, the only free parameter left to vary, to determine a combination of Galactic and extra-galactic intensity that give the IceCube intensity, is the local number density, $\rho_{z=0}$, which is the parameter that normalises the density across the whole Universe. This can be calculated to compare to the accepted number density of Milky Way-like sources

($10^{-3} - 10^{-2}\,\mathrm{Mpc}^{-3}$) and is found by rearranging Eq. 5.1:

$$\rho_{z=0} = \frac{I_{IC} - (1-f)\frac{1}{4\pi}\frac{L_{MW}}{4\pi d^2}}{\int_0^z \frac{1}{4\pi}\frac{c}{H_0}\frac{z}{E(z)}\frac{1}{(1+z)^2}g(z)(1-f)L_{MW}\,d\log z} \tag{5.2}$$

To find an expression for $\rho_{z=0}$ that is independent of the Milky Way luminosity (L_{MW}), take the relationship originally defined between the IceCube inteisty, I_{IC} and the luminosity of the Milky Way, L_{MW}

$$I_{IC} = \frac{1}{4\pi}\frac{L_{MW}}{4\pi d^2} \tag{5.3}$$

and substitute this into Eq. 5.2

$$\rho_{z=0} = \frac{\frac{L_{MW}}{4\pi d^2} - (1-f)\frac{1}{4\pi}\frac{L_{MW}}{4\pi d^2}}{\int_0^z \frac{1}{4\pi}\frac{c}{H_0}\frac{z}{E(z)}\frac{1}{(1+z)^2}g(z)(1-f)L_{MW}\,d\log z} \tag{5.4}$$

$$= \frac{f}{(1-f)4\pi d^2 \int_0^z \frac{c}{H_0}\frac{z}{E(z)}\frac{1}{(1+z)^2}g(z)\,d\log z} \tag{5.5}$$

This implies that this particular model results in a purely geometric argument, meaning that the actual neutrino intensity measured is irrelevant because it later cancels between Eq. 5.4 and Eq. 5.5. This implies that the results are geometrical, so that this model can be applied to any neutrino intensity observed at Earth.

Appendix C shows calculations for an integral that describes the luminosity and intensity of an arbitrary Universe, which will need to be scaled to describe the luminosity and intensity of the actual Universe depending on how much of the IceCube intensity it produces. In this case, the rest of the Universe is responsible for producing an intensity equivalent to 0.4% of the IceCube intensity, however, the fraction coming from the rest of the Universe can be extended to include all possible combinations of the IceCube intensity from the Galaxy and the rest of the Universe (see Section 5.2). Once the luminosity of an arbitrary Universe has been correctly scaled, the luminosity of the Galaxy (in this case assuming that all of the neutrinos are produced across the spherical halo) can be used to calculate the number of equivalent Milky Way-like sources in the rest of the observable Universe permitted to make up the remaining intensity.

The Galactic halo model has a number of assumptions that can be altered to calculate slightly different number densities in the rest of the Universe. The distribution of neutrino emission densities within the Galactic halo can be changed from uniform throughout to evenly spaced on the surface of the halo sphere at 100 kpc. As well as this, the distribution of sources in the rest of the Universe can be constant or follow the SFR. Table 5.1 shows all the possible combinations of these assumptions and the number densities that result. The densities in this table are the local number densities at $z = 0$, $/rho_{(}z = 0)$. This results in the number densities for sources distributed according to the SFR being lower than those for a uniform source distribution in the rest of the Universe because the SFR becomes larger further out.

Source Type	d [kpc]	N_{SFR}	ρ_{SFR} [Mpc^{-3}]	N_{NOZ}	ρ_{NOZ} [Mpc^{-3}]
Galactic Halo (volume)	100	2.1×10^{8}	1.1×10^{-5}	1.8×10^{8}	5.1×10^{-5}
Galactic Halo (surface)	100	7.1×10^{7}	3.8×10^{-6}	6.2×10^{7}	1.7×10^{-5}

Table 5.1: Distance to halo boundary (d), number of equivalent sources (N) and number densities (ρ) of Milky Way-like objects in the rest of the Universe. The number of equivalent sources is the number of equivalent Milky Way-like galaxies in the rest of the Universe. Note that the number densities are local at $z = 0$ and come from Eq. 5.5 with the appropriate choice of $g(z)$. The subscript SFR means the sources are distributed according to the SFR throughout the rest of the Universe and the subscript NOZ means the sources have a uniform (with respect to redshift) distribution throughout the rest of the Universe.

Consider the case where the neutrino sources in the rest of the Universe have a distribution that follows the SFR while the neutrino sources in the Milky Way are evenly spread across the surface of the spherical halo. The density, for this specific case, of equivalent Milky Way-like sources in the rest of the Universe is $3.8 \times 10^{-6}\,\mathrm{Mpc}^{-3}$ (Table 5.1). It can be seen that, for the same distribution of sources in the rest of the Universe, but a uniform distribution of sources throughout the Galaxy, the number density is $1.1 \times 10^{-5}\,\mathrm{Mpc}^{-3}$ (Table 5.1). These results show the factor of three difference which was discussed in Chapter 4.

Again consider the case where the neutrino sources are evenly spread across the surface of the spherical halo, but now assume the distribution throughout the Universe changes with redshift. The number densities for a SFR distribution and a constant redshift distribution are $3.8 \times 10^{-6}\,\mathrm{Mpc}^{-3}$ and $1.7 \times 10^{-5}\,\mathrm{Mpc}^{-3}$ respectively (Table 5.1). It should be noted that these two densities vary by a factor of approximately 4.5. This is not very significant and hence, in this particular model, it can be concluded that the distribution of Milky Way-like galaxies throughout the rest of the Universe does not greatly affect the number density calculated. A radically different distribution would be required in order to make up the required difference.

Regardless of which model details are considered, the resulting number densities of equivalent Milky Way-like galaxies in the rest of the Universe still falls outside the accepted range of $10^{-3} - 10^{-2}\,\mathrm{Mpc}^{-3}$. This implies that whether the neutrino sources are on or within the spherical halo or whether the Milky Way-like galaxies are uniform throughout the Universe or follow the SFR distribution, there would always be too few to adequately explain experimental observations of spiral galaxy number densities. Since the Milky Way is not a unique galaxy, other spiral galaxies can be expected to be producing neutrinos in a similar manner to the Milky Way, regardless of the amount of neutrinos the Galaxy is producing. These results suggest that the majority of IceCube's neutrinos cannot come from the halo of the Milky Way because there would not be enough other spiral galaxies in the Universe. It should be noted that even with modifying details within the model such as choosing a source distribution of objects likely to produce neutrinos within the Galaxy (as is later done in Chapter 6), the results would not change by the several orders of magnitude required to meet the accepted number densities.

5.2 Constraints on Luminosity and Number of Neutrinos from the Galactic Halo

The original model to explain the entire diffuse flux observed by IceCube adopted for this part of the analysis is the extended Galactic halo at 100 kpc with the neutrino sources situated on the surface of the spherical halo. So far it has been shown that one combination of source luminosity and fraction of neutrinos from an extended Galactic halo of fixed radius is not likely consistent with the known number density of other equivalent Milky Way-like galaxies in the rest of the Universe. Using the same analysis method, it is possible to compare all the combinations of source luminosity and fraction of neutrinos produced at the source and hence varying radii. Many combinations can be ruled out since they are not consistent with the density constraints that can be applied. The lower limit for the number density has been chosen as $10^{-3}\,\mathrm{Mpc}^{-3}$ [55] while the upper limit for the number density has been chosen as $10^{-2}\,\mathrm{Mpc}^{-3}$ [25]. These both describe a local number density at $z = 0$ which can be compared to the local number density calculations made here.

Every possible combination of distance to the extended halo boundary (d) and fraction of neutrinos from the rest of the Universe (f) results in a corresponding number density of equivalent Milky Way-like sources allowed in the rest of the Universe. The opposite is also true where every combination of Milky Way luminosity (L) and f results in a number density. In both of these cases, the equivalent Milky Way-like galaxies can be assumed to be uniformly distributed throughout the Universe or to have a distribution following the SFR. Hence there are four separate ways to show the density constraints which can be seen in Figs. 5.1, 5.2, 5.3 & 5.4 as plots of $rho_{z=0}$ (Eq. 5.5).

The densities calculated in Table 5.1 clearly do not lie within the accepted density region. They all lie toward the middle and upper left areas of Figs. 5.1, 5.2, 5.3 & 5.4. This implies that the halo of the Milky Way is unlikely to produce all of IceCube's neutrinos and hence this particular combination of Galactic and extra-galactic neutrino sources is not supported. It might also suggest that there is room to alter the chosen model by changing the geometry of the Milk Way neutrino sources.

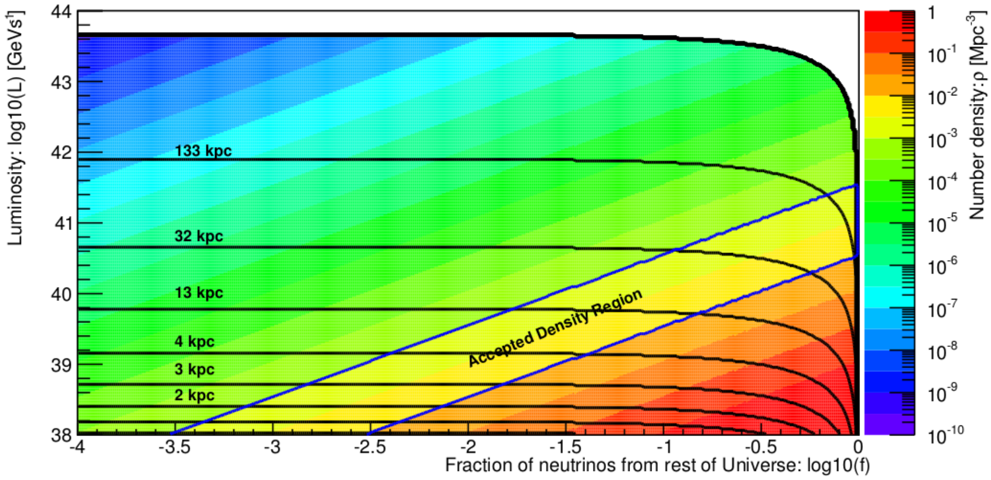


Figure 5.1: Possible combinations of luminosity and fraction of neutrinos from the rest of the Universe (f from Eq. 5.5) for a source constrained by the number density (colour scale) of spiral galaxies in the Universe ($\rho_{z=0}$ from Eq. 5.5) for a source distribution consistent with no redshift evolution. The black contour lines show the distance to the halo boundary (d from Eq. 5.5) for each combination of luminosity and fraction. Note that the neutrino sources are on the sphere of the halo. The diagonal blue lines show the accepted range of densities ($10^{-3} - 10^{-2}\,\mathrm{Mpc}^{-3}$).

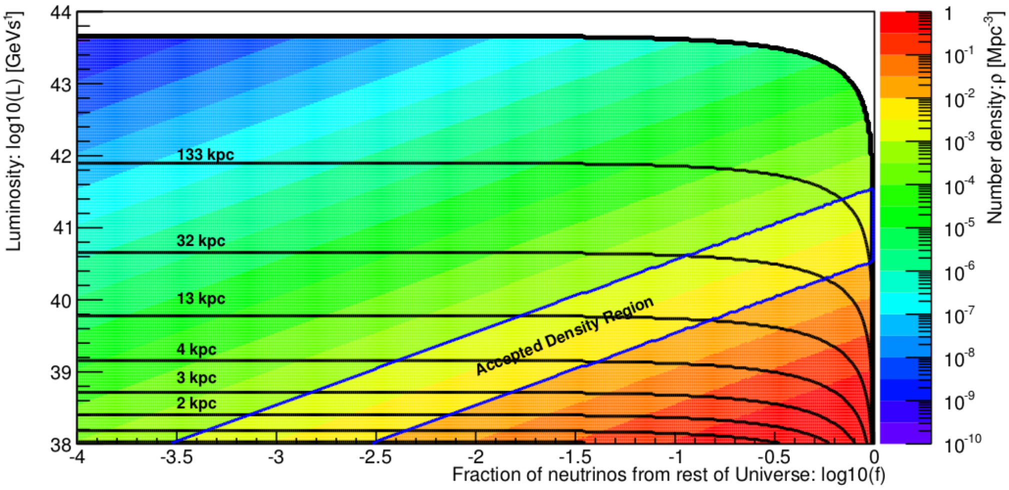


Figure 5.2: The same as Fig. 5.1, but for sources in the Universe distributed according to the SFR.

As an example, Figs. 5.1 & 5.2, when $\log f = -4$ (i.e $f = 10^{-4}$), the Galaxy produces almost all of the IceCube intensity. In the area defined by the blue lines (accepted area) the luminosity of the Galaxy (and hence the individual sources in the rest of the Universe) is lower ($< 10^{38}\,\mathrm{GeVs^{-1}}$) than the original luminosity calculated for the Milky Way ($4.5\times10^{41}\,\mathrm{GeVs^{-1}}$) (Eq. 4.16). The distance that this corresponds to is also much lower than the originally assumed 100 kpc, shortening to a few parsecs.

When $\log f \sim 0$ (i.e almost $f = 1$), the rest of the Universe produces almost all of the IceCube intensity. In the accepted density region, for the number density to be accepted, the halo radius must be higher than the original value of 100 kpc, while the resulting luminosity remains the same. Toward the bottom of the plot for the same fraction, the halo radius and hence the resulting luminosity are now in the red region and are smaller than the original values. This combination of a smaller halo radius for $\log f \sim 0$ is not supported since the number density would be much higher than the accepted range.

A very similar comparison can be made for Figs. 5.3 & 5.4 which show the same information in a different visualisation in which the distance is plotted against the fraction of the neutrinos from the rest of the Universe and luminosity contours over the top.

Overall, if the halo of the Milky Way were to produce all of IceCube's neutrinos, the combination of distance (luminosity) and the fraction of neutrinos from extra-galactic sources would have to fall within the accepted (blue line) region of the previous four plots. This would imply that the luminosity (distance) would have to be small and hence the neutrino sources within the Milky Way would have to be very close to Earth (or very dim). It is possible that individual neutrino sources might be dim, however, if sources within the Galaxy were that close to Earth, they possibly should have been detected as a point source, however, none have been observed.

In a study done by Kalashev and Troitsky (2016) [56], they calculated the neutrino contribution to the IceCube intensity from the corona of the Milky Way out to a radius of 250 kpc. Note that their corona was equiavlent to the halo of the Milky Way used in this study (however, recall the radius here was 100 kpc). They used equations and models of the density, spectrum and transport of CRs within the corona to estimate the neutrino contribution from the corona of the Milky Way. They also consider an extragalactic corona contribution to the IceCube intensity. To do so, they assume that the number of CRs in other corona is proportional to the total stellar mass within the corona and use transport equations to estimate the extragalactic component and normalise it to the contribution from the corona of the Milky Way. This is combined with the Milky Way's contribution to find that it would make up $< 1\%$ of the IceCube intensity, which is a negligible contribution. These results agree with the general result of the study done in this thesis that the halo of the Milky Way cannot account for all of IceCube's intensity.

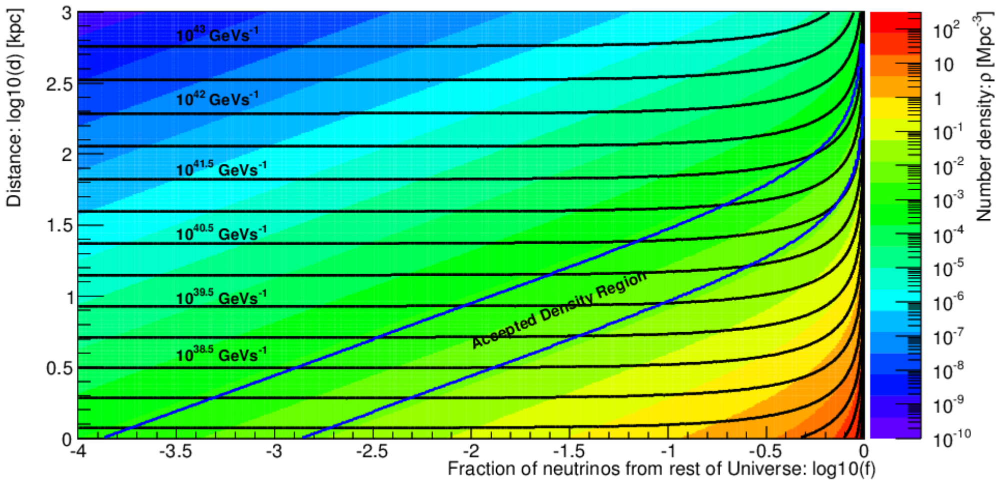


Figure 5.3: Possible combinations of distance (d from Eq. 5.5) and fraction of neutrinos from the rest of the Universe (f from Eq. 5.5) for a source constrained by the number density (colour scale) of spiral galaxies in the Universe ($\rho_{z=0}$ from Eq. 5.5) for uniform source distribution. The black contour lines show the luminosity for each combination of distance and fraction. Note that the neutrino sources are on the sphere of the halo. The diagonal blue lines show the accepted range of densities ($10^{-3} - 10^{-2}\,\mathrm{Mpc}^{-3}$).

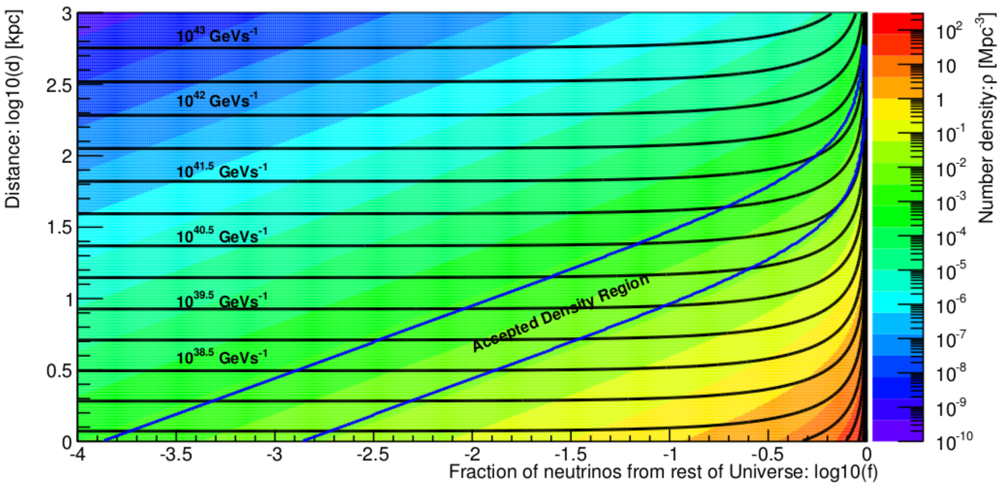


Figure 5.4: The same as Fig. 5.4, but for sources in the Universe distributed according to the SFR.

5.3 Summary

If the assumption is made that the Milky Way produces the majority of IceCube's astrophysical neutrinos (using the model that the neutrino sources are on the surface of the spherical halo) and the rest of the Universe only produces an intensity compatible with an upper limit of 0.4%, the number density of Milky Way-like galaxies in the Universe is $3.8 \times 10^{-6}\,\mathrm{Mpc}^{-3}$ and $1.7 \times 10^{-5}\,\mathrm{Mpc}^{-3}$ for SFR and no redshift evolution respectively. This is below the accepted number density range of $10^{-3}\,\mathrm{Mpc}^{-3}$ to $10^{-2}\,\mathrm{Mpc}^{-3}$. This implies that the rest of the Universe would have to be lacking in spiral galaxies if all of the observed neutrinos came from the extended Galactic halo and hence this is an unlikely explanation of the origin of IceCube's astrophysical neutrinos. A similar result is obtained when larger local volume regions are considered, implying that IceCube's neutrinos are more likely to come from regions of the Universe with $z \gg 1$, with still some smaller fraction coming from within a redshift of $z = 1$. According to the chosen density limits, if all of IceCube's neutrinos were to come from the Galaxy, then the sources would have to be very close to Earth with a low luminosity. Then, the idea that the sources are evenly distributed on the surface of the sphere becomes unrealistic. Sources within the Galactic disk then need to be considered which is the subject of the next chapter.

Chapter 6

Neutrinos from the Galactic Disk

IceCube recently published a paper that put a constraint on the fraction of the observed astrophysical neutrino intensity that could come from the Galactic disk [45]. This was an upper limit of 14% of the diffuse IceCube intensity. A different study by external authors yielded a very similar result of 9.5% [57]. Now that a very recent, experimental upper limit is available, the Galactic disk can be included in the previous analysis from Chapter 5. The same calculations of neutrino luminosity and number density of equivalent objects in the rest of the Universe can be made assuming that the disk is a neutrino source in addition to the MIlky Way halo.

6.1 Defining the Model of the Disk

Firstly, a simple model of the Galactic disk must be developed. Assume that a top down view of the disk is circular and two-dimensional for the sake of it being geometrically simplistic (Fig. 8.1) and define a distance, l, from Earth to any arbitrary point on the circumference of the disk. Also define an angle, θ, from the plane that the Earth is on to any point on the circumference of the circle with length defined as l. These two parameters allow the entire disk to be described by a function $l(\theta)$.

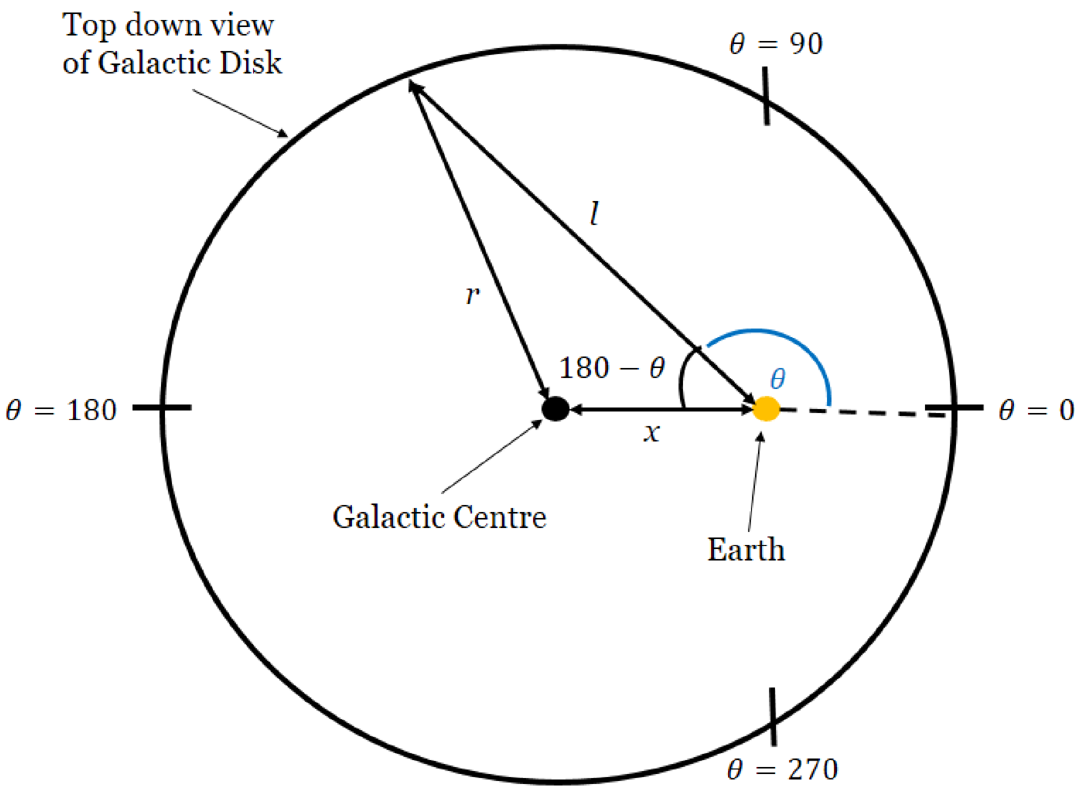


Figure 6.1: A top down view of the Galactic disk showing the relative positions of the Galactic Centre (GC) and Earth. Here, r is the radius of the disk, x is the distance from the GC to Earth, l is the distance from Earth to any arbitrary point on the circumference of the disk and θ is defined as the angle from the plane of the Earth to a point on the circumference of the circle with length l. The origin of θ and the triangle rxl have been defined.

A function $l(\theta)$ that describes the distance from the Earth to any point on the circumference of the circle can be calculated using trigonometry relations (shown in Appendix D) and is given by

$$l(\theta) = \frac{-2x\cos(\pi - \theta) - \sqrt{(-2x\cos(\pi - \theta))^2 + 4(r^2 - x^2)}}{-2} \tag{6.1}$$

6.2 Flux and Luminosity of the Galactic Disk

The function $l(\theta)$ is able to describe every point on the two-dimensional disk. This can be used to write an equation for the flux of the Galactic disk (Eq. 6.2). The basis of Eq. 6.2 is the standard equation for flux (Eq. A.1), however, this time a double integral must be taken to include the entire disk:

$$F_{disk} = \frac{L_{disk}}{4\pi} \int_0^{2\pi} \int_{l_0}^{l(\theta)} n \frac{l'(\theta)}{l'(\theta)^2} dl' d\theta \tag{6.2}$$

Here, L_{disk} is the luminosity per source of the Galactic disk and n is the number of sources per area. For simplicity, n is taken to be constant which corresponds to a uniform distribution of sources throughout the disk. The choice of a uniform distribution for n is not very realistic and hence a more reasonable model, where it is assumed that the neutrino sources follow the distribution of supernova remnants, is later used. The extra factor of $l'(\theta)$ in the numerator is included to take into account the fact that as an integral is taken over a circle, the area increases since the area of a segment is given by

$$A = l' d\theta dl' \tag{6.3}$$

where $d\theta$ is the angle of the segment, l' is the radius of the circle and dl' is the small increment along the radius.

The flux can be simplified and integrated:

$$F_{disk} = \frac{L_{disk}}{4\pi}\int_0^{2\pi}\int_{l_0}^{l(\theta)}\frac{1}{l'}dl'd\theta \tag{6.4}$$

$$= \frac{L_{disk}}{4\pi}\int_0^{2\pi}\ln\,[l']_{l_0}^{l(\theta)}d\theta \tag{6.5}$$

$$= \frac{L_{disk}}{4\pi}\int_0^{2\pi}\ln\,[l(\theta)] - \ln\,[l_0]d\theta \tag{6.6}$$

$$= \frac{L_{disk}}{4\pi}\left(\int_0^{2\pi}\ln\,[l(\theta)]d\theta - \int_0^{2\pi}\ln\,[l_0]d\theta\right) \tag{6.7}$$

$$= \frac{L_{disk}}{4\pi}\left(\int_0^{2\pi}\ln\,[l(\theta)]d\theta - 2\pi\ln\,[l_0]\right) \tag{6.8}$$

The lower limit of the integration across l is set as l_0 which is the minimum distance a source is allowed to be from Earth. The minimum distance cannot be zero otherwise the integral does not converge. Instead, choose the starting point of the integral to be the distance to the closest supernova remnant, Vela, ($\sim 0.25\,\mathrm{kpc}$). This is reasonable since the SNR density within the disk is used to describe the distribution of sources and SNRs are considered as a possible source of astrophysical neutrinos due to their proton accelerating environments.

To calculate the number density of sources in the rest of the Universe, the luminosity of the Galactic disk (Eq. 6.9) must first be calculated by rearranging Eq. 6.8. The IceCube result that claims the Galactic disk should only produce an intensity consistent with a statistical upper limit of 14% of the diffuse astrophysical intensity will be utilised where F_{disk} will be taken to be 14% of the all flavour IceCube diffuse neutrino intensity (Eq. 2.1 is the per flavour intensity).

$$L_{disk} = \frac{4\pi F_{disk}}{\int_0^{2\pi}\ln\,[l(\theta)]d\theta - 2\pi\ln\,[l_0]} \tag{6.9}$$

The integral over θ of the distance $l(\theta)$ is numerically evaluated and hence, the luminosity of the Galactic disk using Eq. 6.9 is given by

$$L_{disk} = 1.8 \times 10^{38}\,\mathrm{GeV s^{-1}} \tag{6.10}$$

$$= 2.9 \times 10^{35}\,\mathrm{erg\,s^{-1}} \tag{6.11}$$

The distribution of sources chosen for this model was uniform throughout the disk and perhaps not very realistic. Instead, take the density distribution of SNRs within the Galaxy, $n(r)$ [58], since they could be production sites of astrophysical neutrinos:

$$n(r) = A \sin\left(\frac{\pi r}{r_0} + \theta_0\right) \exp\left(-\beta r\right) \tag{6.12}$$

where $A = 1.96\,\mathrm{kpc^{-2}}$, $r_0 = 17.2\,\mathrm{kpc}$, $\beta = 0.13\,\mathrm{kpc}$ and $\theta_0 = 0.08$ are all best fit constants and r is the distance from the GC to the edge of the disk, which can be written in terms of $l(\theta)$. This distribution is valid for $r < 16.8\,\mathrm{kpc}$ which is not problematic since the chosen disk model only has a maximum radius of $r = 15\,\mathrm{kpc}$. The SNR density distribution has a minimum at the GC and peaks at 5 kpc (Fig. 6.2). Now the flux is given by

$$F_{disk} = \frac{L}{4\pi} \int_0^{2\pi} \int_{l_0}^{l(\theta)} n(l', \theta) \frac{1}{l'(\theta)} dl' d\theta \tag{6.13}$$

The neutrino luminosity of the Milky Way, if the sources within the disk followed the distribution of SNRs given in Eq. 6.12, is then

$$L_{disk} = 1.3 \times 10^{38}\,\mathrm{GeV s^{-1}} \tag{6.14}$$

$$= 2.2 \times 10^{35}\,\mathrm{ergs^{-1}} \tag{6.15}$$

When the distribution of SNRs is incorporated into the model of the Galactic disk, the neutrino luminosity of the disk is smaller. On average, the sources are more concentrated toward the Earth, and thus the luminosity is smaller.

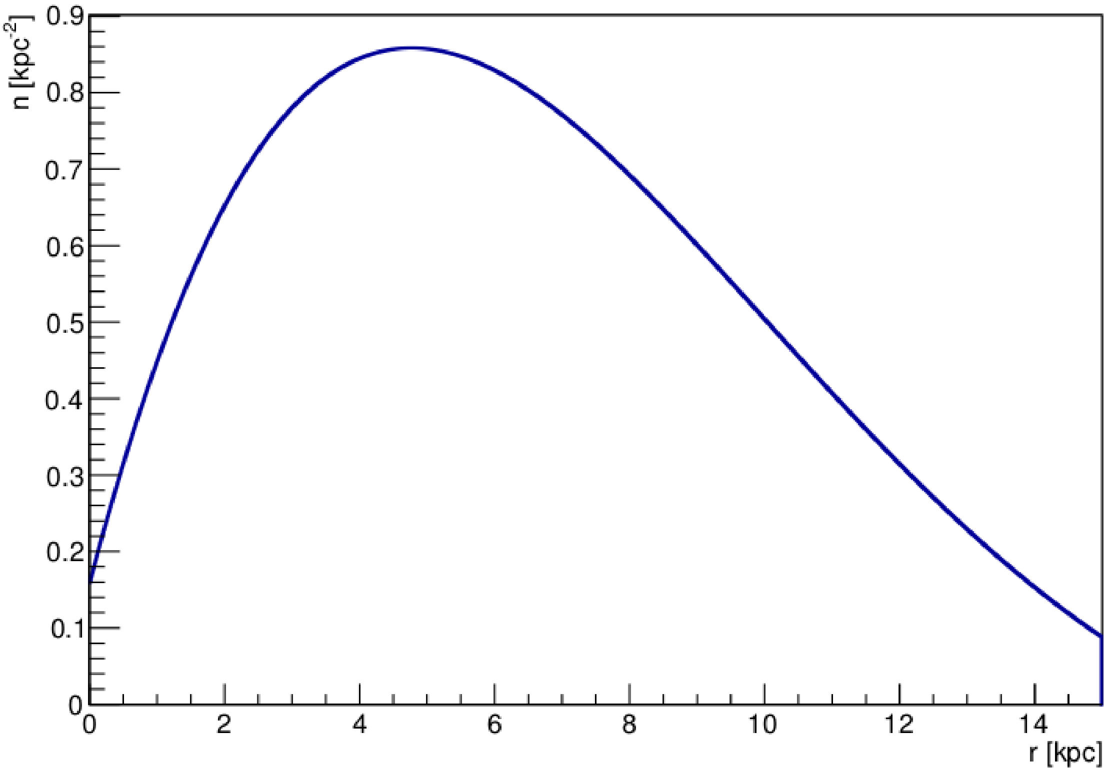


Figure 6.2: The number density of SNRs within the Galactic disk per area, as a function of the radius of the disk from the Galactic Center (from equation given in [58]).

6.3 Number Density of Equivalent Disks in the Rest of the Universe

A recent study by IceCube [45] found that the upper limit of neutrinos potentially produced within the Galactic disk is 14% of the diffuse astrophysical neutrino intensity (see Chapter 3). As a result, assume that the remaining 86% of the IceCube intensity is coming from the rest of the Universe. Using the same method that was used for the density of sources calculation when considering a Galactic halo neutrino origin, the number density of sources in the rest of the Universe, for the Galactic disk model with uniform source distribution, can be calculated for a uniform source distribution in the rest of the Universe (Eq. 6.16) or a distribution that follows that SFR (Eq. 6.17).

$$\rho_{NOZ} = 7.5\,\mathrm{Mpc}^{-3} \tag{6.16}$$

$$\rho_{SFR} = 1.7\,\mathrm{Mpc}^{-3} \tag{6.17}$$

The same calculation can be made for a distribution of Galactic neutrino sources that follows the distribution of SNRs within the Milky Way. The densities of equivalent Milky Way-like sources in the rest of the Universe for uniform source distribution in the rest of the Universe (Eq.6. 18) or a distribution that follows the SFR (Eq. 6.19) are:

$$\rho_{NOZ} = 10.4\,\mathrm{Mpc}^{-3} \tag{6.18}$$

$$\rho_{SFR} = 2.3\,\mathrm{Mpc}^{-3} \tag{6.19}$$

Note that the only difference between the density for a uniform source distribution in the Universe and one that follows the SFR is a factor of approximately 4.5 which was already discussed in Chapter 5.

The results for a Galactic source distribution following the distribution of SNRs in the disk is obviously too large in comparison to the accepted number density of spiral galaxies in the Universe which is $10^{-3}\,\mathrm{Mpc}^{-3} < \rho < 10^{-2}\,\mathrm{Mpc}^{-3}$. The number densities for a non-realistic uniform distribution of Galactic neutrino sources also still fall outside of the accepted range, and are still too large to be reasonable. For the uniform Galactic distribution, the results would suggest that there would be up to about ten equivalent Milky Way disks every cubic megaparsec in the rest of the Universe which is much greater than the observed number of galaxies. With the

SNR density distribution included there is an even higher density of Milky Way-like galaxies in the rest of the Universe. If the Galactic disk were to produce 14% of IceCube's neutrinos, these results suggest that the distribution of sources in the disk could not be uniform and even less so follow the distribution of known SNRs in the disk. By adding in a physical and realistic source distribution throughout the disk, it shows that even modifications to the disk model, whether they are more simple or more complex, do not change the density sufficiently to allow it to fall within the accepted range.

To get a lower number density, the fraction of neutrinos that the disk is producing needs to increase, however, this would violate the experimental constant of 14% of the IceCube intensity. This would create a contradiction since anisotropy in the neutrino flux has not been observed and if all neutrinos came from the disk, there would be a distinct anisotropic signal across the sky following the shape of the disk according to the matter distribution.

6.4 Summary

The Galactic disk is another potential source for IceCube's diffuse astrophysical neutrinos. Assume that the disk can be modelled as a circle with the Earth in the approximate location of 8 kpc from the Galactic Centre (Fig. 6.1). The Galactic disk can be described by a function $l(\theta)$ that can be integrated over to obtain the flux, and then after rearranging, the luminosity of the disk. For the number density calculation, assume that the Galactic disk is producing 14% of IceCube's neutrinos while the rest of the Universe is producing the remaining 86%. This returns a number density of equivalent disks in the rest of the Universe that is too large compared to the accepted number densities of spiral galaxies in the Universe. If the distribution of sources within the disk is changed to follow the distribution of

Galactic SNRs, the density is even larger and hence does not fall within the accepted range. These results suggest that the Galactic disk alone would have to be responsible for more than 14% for the number density of Milky Way-like galaxies in the rest of the Universe to significantly decrease to allowed levels, however, this would violate the recent experimental limit from IceCube. Thus, it can be concluded that Milky Way-like spiral disks cannot be the sole source of astrophysical neutrinos.

In reality, were the sources in such close proximity to Earth, non-uniformities in their distribution would likely appear as point sources aligned with the Galactic plane, which have not been observed in IceCube data. If all of the neutrinos came from the rest of the Universe, the sources would have to be very distant with a high luminosity, which is a more likely scenario in light of experimental results of arrival directions, which show no evidence of correlation with the Galactic plane.

Chapter 7

Conclusions

7.1 IceCube's Neutrinos are not likely of Galactic Origin

In this work, the possibility of the Galactic halo and the Galactic disk being responsible for certain percentages of the IceCube diffuse astrophysical neutrino intensity was investigated. The possible neutrino sources are separated into Galactic and extra-galactic. This research mainly focuses on showing that a purely Galactic origin of neutrinos, whether it be from the halo or disk, is not favoured in light of experimental observations. Extra-galactic sources still seem to be the most promising candidates to explain most of the IceCube astrophysical neutrino intensity.

Initially, the assumption was that the Universe, outside of the Milky Way, only produces an intensity compatible with the 90% upper limit of 0.4% of the observed IceCube flux. This limit comes from an assumption that the Milky Way Galaxy produces all of the IceCube neutrinos. Slightly different models were considered when distributing the neutrino sources throughout the halo of the Milky Way (uniform throughout the volume and even over the sphere surface), however, very little difference emerged in the results. These assumptions and model choices then allowed for a calculation of the number density of Milky Way-like galaxies in the rest of the Universe, given that it is assumed to only be responsible for a very small fraction of the astrophysical neutrino intensity. The number densities were $3.8 \times 10^{-6}\,\mathrm{Mpc}^{-3}$ and $1.7 \times 10^{-5}\,\mathrm{Mpc}^{-3}$ for extra-galactic sources that had a distribution following the SFR and a uniform distribution (which corresponds to no redshift evolution) respectively. This result is significantly below the accepted number density range of $10^{-3}\,\mathrm{Mpc}^{-3}$ to $10^{-2}\,\mathrm{Mpc}^{-3}$ which implies that the rest of the Universe would have to be lacking in spiral galaxies if all of the observed neutrinos came from the extended Galactic halo. To produce densities consistent with experimental observations, the Milky Way would have to be responsible for a much smaller fraction of the astrophysical neutrino intensity and therefore violate the initial assumption. Therefore, this is an unlikely explanation of the origin of IceCube's astrophysical neutrinos.

The initial results only considered one possible combination of neutrino production between the Galaxy and the rest of the Universe. The same analysis was extended to all possible combinations that lie outside the accepted number density range. Through this, constraints were able to be put on the distance to or the luminosity of sources given the fraction of neutrinos the local source produced. If all of IceCube's neutrinos were to come from the Galaxy, then the sources would have to be very close to Earth with a low luminosity, which is disfavoured by experimental evidence since IceCube has not detected any point sources, whereas if all of the neutrinos came from the rest of the Universe, the sources can be very distant with a high luminosity, which cannot be ruled out. They can also be very distant, with low luminosity, and high density.

A very similar analysis method was applied to a model for the Galactic disk. Initially the disk was assumed to be two-dimensional with uniformly distributed neutrino sources. This was made more realistic by changing the distribution of sources within the disk to follow that of Galactic SNRs. Calculating an intensity and luminosity for the Galactic disk allowed the calculation of a number density of equivalent disks in the rest of the Universe to compare to the allowed range (as for the halo model). A recent experimenal result by IceCube [45] claims that the Galactic disk alone can produce an intensity compatible with an upper limit of 14% of the current diffuse astrophysical neutrino intensity. For the number density calculation, it was assumed that the Galactic disk is producing 14% of IceCube's neutrinos while the rest of the Universe is producing the remaining 86%. This returns a number density of equivalent disks in the rest of the Universe of $7.5\,\mathrm{Mpc}^{-3}$ and $10.4\,\mathrm{Mpc}^{-3}$ for uniform source distribution and SNR distribution within the disk respectively. These obviously do not fit into the accepted range of number densities of spiral galaxies in the Universe. Just by considering the resulting density, for that to be acceptable, the fraction of the neutrino intensity the disk was producing would have to be significantly increased. This, however, does not agree with experimental observations which shows a lack of anisotropy. Based on the chosen model and analysis method, this result suggests that Milky Way-like Galatic disks cannot be the sole sources of astrophysical neutrinos.

Overall, based on the chosen assumptions and simplified models, whether the neutrino production is occuring in the Galactic disk or halo, not all of the neutrinos observed by IceCube can be produced in a Galactic origin. The resulting number densities of Milky Way-like galaxies in the rest of the Universe as well as experimental evidence disfavours a purely Galactic origin of astrophysical neutrinos.

7.2 Future Work

The model, in terms of neutrino source distribution, for the Galactic halo and the Galactic disk used in this work have been very simplified with a uniform distribution and a SNR distribution considered for the disk. The same analyses could be extended to consider a more diverse range of source distributions, not only within the disk, but within the halo as well. For example, as well as catalogues of known sources such as SNR, there are, for example, Pulsar Wind Nebula (PWN) catalogue that might be reasonable to use as a proxy for a neutrino source population. Another possibility for distributions of neutrino sources is to consider the distribution of matter within the halo and the disk. If non-uniform distributions are used, a combination of neutrinos from the halo and disk could be used as an assumption to calculate a luminosity to then use in the calculation of the number density of equivalent galaxies in the rest of the Universe. The distribution of dark matter within the Galaxy could also be used to model a possible source distribution of IceCube's astrophysical neutrinos. Here, neutrino might be produced through possible WIMP (weakly interacting massive particles) annihilation into neutrinos. It is possible that the dark matter has a uniform distribution throughout the halo of the Galaxy and hence the calculations done in this research may be similar for dark matter.

The *Fermi* Bubbles could also be explored as a potential Galactic origin of IceCube's neutrinos. The same analysis could be applied to this choice of origin where a certain number of neutrinos are assumed to be produced within the FB to then constrain the number density of similar structures in the rest of the Universe if it produces the remaining fraction of the diffuse astrophysical intensity. A combination of neutrinos from the FB, the Galactic halo and the Galactic disk could have the same analysis applied.

Not only can the distributions of neutrino sources within the Milky Way be altered, the distribution of Milky Way-like galaxies in the rest of the Universe could also follow a different source distribution. It could be assumed that the galaxies follow a distribution similar to that of AGNs or some other galaxy type. Then comparisons and possibly constraints could be made on the type of galaxies that are more likely to be producing neutrinos. Given a more complex source distribution, a tighter constraint could be placed on the fraction of IceCube's astrophysical neutrinos that are allowed to come from somewhere within the Milky Way.

The original model and Eq. 5.1 assumes that the neutrino contribution from the Milky Way is continuously injected over its lifetime and similarly for the Milky Way-like galaxies producing neutrinos in the rest of the Universe. However, it is well known that the Milky Way's central black hole might have been more active in the past (10^6 years ago) [59]. This may lead to the idea that the current neutrino flux could have partly resulted from an episodic injection of CRs. For example, Eq. 5.1 could be altered to include the duty cycle of the CR injection rate versus the lifetime of the Milky Way and the effect that this would have of the results could be explored. Another idea that arises from the central black hole in the Milky Way being more active in the past is that the Milky Way is currently in a period of high activity (based on how long it takes CRs to diffuse throughout the Galaxy and reach the halo) or in a period of low activity (if it is assumed that the Milky Way was more active in the past). This would have implications on what is assumed to be the intensity contribution from other Milky Way-like galaxies in the rest of the Universe based on whether they are in a period of high or low activity.

7.3 Summary

It is unlikely that the majority of IceCube's astrophysical neutrinos are produced within the Milky Way Galaxy. The implied number density of equivalent Milky Way-like sources in the rest of the Universe would not be consistent with the accepted range, indicating that there would be very few galaxies in the Universe under the assumptions that were made, when this is not what is observed. Given various model assumptions, it is also unlikely that a uniform distribution of neutrino sources or one that follows that of SNRs in the Galactic disk is responsible for producing an experimental upper limit equivalent to 14% of IceCube's neutrinos.

Appendices

Appendix A

Calculation of Fluxes for a Point Source and a Sphere

Consider a neutrino point source (blue dot, Fig. A.1) with luminosity, L, at a distance, R, from Earth. The isotropically emitted neutrinos from this point source will spread out onto a sphere. At any point on the sphere, the flux (Eq. A.1) is the always the same. This gives the flux units of luminosity per area as

$$F = \frac{L}{4\pi R^2} \tag{A.1}$$

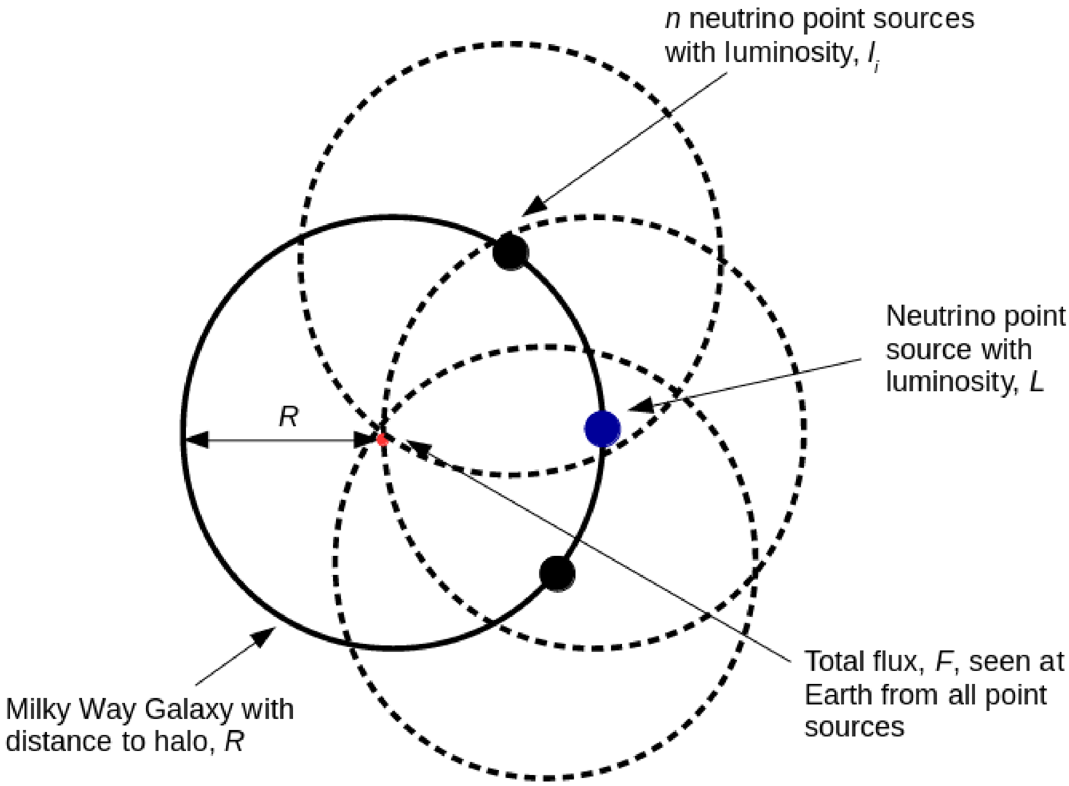


Figure A.1: Flux and luminosity of many sources on the surface of a sphere. The blue dot represents the original point source and the red dot is the simplified position of the Earth.

To keep the simplicity in this model, consider the Milky Way as a sphere with the Earth at the centre. The initial model with a single point source is too basic and should at least be adjusted to have multiple neutrino sources that are evenly distributed along the surface of the spherical shell. This slightly more realistic model is also shown in Fig. A.1 where the individual luminosities of the neutrino sources (l_i) now add up to the original luminosity:

$$L = \sum_{i=1}^{n} l_i \tag{A.2}$$

Because of this property, the new flux seen at Earth as a result of having multiple sources is the same as the flux seen at Earth with only a point source (given in

Eq. A.1).

The luminosity from each individual source on the sphere around Earth will spread out onto an individual sphere of radius, R, and each will produce a flux:

$$F_i = \frac{l_i}{4\pi R^2} \tag{A.3}$$

Hence, the total flux, F, is calculated by summing the individual fluxes over the sphere:

$$\begin{aligned} F &= \sum_{i=1}^{n} F_i &\text{(A.4)}\\ &= \sum_{i=1}^{n} \frac{l_i}{4\pi R^2} &\text{(A.5)}\\ &= \frac{1}{4\pi R^2} \sum_{i=0}^{n} l_i &\text{(A.6)}\\ F &= \frac{L}{4\pi R^2} &\text{(A.7)} \end{aligned}$$

It should be noted that Eq. A.7 and Eq. A.1 are equal, which shows that having the neutrino sources uniformly distributed over the surface of the sphere at the halo distance returns the same flux as having one point source at the same halo distance.

Appendix B

Volume of the Universe

Various cosmological quantities including volume, intensity and luminosity are required in this analysis. The volume of the Universe (out to a redshift of $z = 10^5$) can be calculated via an integral. Once a redshift of $z = 10^5$ is reached, the volume of the Universe begins to change very slowly and hence this can approximately be taken as the volume of the whole Universe. This volume integral will be the basis of all other integrals of quantities relating to the rest of the Universe. The dependent variable for all of these integrals will be co-moving distance, d_{cm}, in terms of redshift, z. Ultimately each quantity will be integrated with respect to the logarithm of redshift.

The volume of the Universe, V, (Eq. B.1) can be written as the standard volume of a sphere. Currently, Eq. B.1 is in terms of co-moving distance, but for simplicity will be transformed into terms of redshift. Eq. B.1 can be re-written in integral form (Eq. B.2) then split into two differentials to include a term for redshift (Eq. B.3).

$$\begin{aligned} V &= \frac{4}{3}\pi d_{cm}^3 && \text{(B.1)} \\ &= \int_0^z \frac{dV}{dz} dz && \text{(B.2)} \\ &= \int_0^z \frac{dV}{dd_{cm}} \frac{dd_{cm}}{dz} dz && \text{(B.3)} \end{aligned}$$

The differentials in Eq. B.3 can be replaced with the area of a sphere and the definition of co-moving distance in terms of redshift:

$$d_{cm} = \frac{c}{H_0} \int_0^z \frac{dz}{E(z)} \tag{B.4}$$

Here, the constants are the speed of light, c, and the Hubble constant, H_0. A function $E(z) = \sqrt{\Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\lambda}$ is defined such that it uses the density parameters ($\Omega_M = 0.3, \Omega_k = 0, \Omega_\Lambda = 0.7$). This then gives the volume integral in terms of redshift:

$$V = \int_0^z 4\pi d_{cm}^2 \frac{c}{H_0} \frac{1}{E(z)} dz \tag{B.5}$$

Eq. B.5 is now an integral that calculates the volume of the Universe. However, it needs to be modified slightly to deal with the fact that our code uses the logarithm of the redshift to integrate over rather than just redshift. Hence the dz term in Eq. B.5 needs to become a $d\log z$ by using a logarithmic relationship (Eq. B.6).

$$d\log z = \frac{1}{z} dz \tag{B.6}$$

The code used to calculate these integrals does so within a histogram and hence a factor of $\ln 10$ is required in Eq. B.5 because of the change in bin sizes between a histogram over z and a histogram over $\log z$. Hence the final integral that calculates the volume is given by

$$V = \int_0^z 4\pi d_{cm}^2(z) \frac{c}{H_0} \frac{z}{E(z)} \ln 10 d\log z \tag{B.7}$$

For purposes in the code, $d \log z$ is written as the step size used in the calculation:

$$dlogz = \frac{d \log z_{hi} - d \log z_{lo}}{N_{steps}} \tag{B.8}$$

$$= \frac{5 - (-4)}{500} \tag{B.9}$$

$$= 0.018 \tag{B.10}$$

The final integral calculates the volume of the observable Universe (out to a redshift of $z = 10^5$) to be

$$V = 3.34 \times 10^{86}\,\mathrm{cm}^3 \tag{B.11}$$

$$= 1.14 \times 10^{13}\,\mathrm{Mpc}^3 \tag{B.12}$$

This volume was confirmed by calculating the volume of the Universe using the standard spherical equation. Confirming that this volume integral was working and producing the correct answer is important for future calculations involving the number of galaxies within the observable Universe. Now this integral can be used to find the luminosity and the flux of the observable Universe.

Appendix C

Intensity and Luminosity of the Rest of the Universe

The intensity and luminosity of the rest of the observable Universe are relevant quantities that are also calculated using integration. The volume integral (Eq. B.7) is the basis of both of these integrals. Once the intensity and luminosity of some arbitrary Universe is calculated, it can be scaled to the IceCube intensity to aid in the calculation of the number density of allowed sources in the rest of the Universe.

An important part of the analysis is how the neutrino sources are distributed throughout the Universe in terms of redshift. A function *L(z)* (units $\mathrm{GeV s^{-1}\, cm^{-3}}$), which describes the luminosity per volume of the neutrino sources throughout the Universe, is incorporated into the volume integral.

$$L = \int_0^z L(z) 4\pi d_{cm}^2(z) \frac{c}{H_0} \frac{z}{E(z)} \ln 10 \, d\log z \tag{C.1}$$

In this analysis two options are chosen for the luminosity per volume function. The first is $L(z) = constant$ for no redshift evolution, where the sources are distributed uniformly throughout the volume of the Universe, and secondly, *L(z)* is assumed to follow the star formation rate (Eq. 3.3, Fig. 3.2) as discussed in Chapter 3. Eq. C.1 has units of luminosity ($\mathrm{GeVs^{-1}}$) regardless of whether the sources are either uniform throughout the volume of the observable Universe or distributed according to the SFR. A similar process can be used to calculate the intensity of the Universe:

$$I = \int L(z) \frac{1}{4\pi} \frac{c}{H_0} \frac{z}{E(z)} \frac{1}{(1+z)^2} \ln 10 d \log z \tag{C.2}$$

There are additional factors present in Eq. C.2 to transform the luminosity into an intensity. Firstly, to find a flux, the luminosity must be spread out onto a sphere at some co-moving distance which means dividing by the area of the sphere ($4\pi d_{cm}^2(z)$). This cancels out the original spherical area in the volume integral to eliminate the co-moving distance term. The flux is an energy per area per time from the entire sky and must be transformed into an intensity which is a flux per solid angle, to be comparable and later scaled to the IceCube intensity. This results in the factor of $1/4\pi$. The factor $1/(1+z)^2$ comes from the cosmological effects of time dilation and the redshifting of energies that must be taken into account after considering co-moving distances further than a redshift of $z = 1$, since Euclidean calculations are no longer valid. The luminosity used is the energy per logarithmic interval for an E^{-2} spectrum. This means the red-shifting of energy to lower values is equivalent to a simple down-scaling of the spectrum and thus the luminosity which justifies one of the factors of $1/(1+z)$.

Even with *L(z)* incorporated into the luminosity and the intensity, these calculations are still only for an arbitrary Universe. Once *L(z)* is normalized according to the observed IceCube intensity, the luminosity and intensity will be that of our observable Universe and can be used to determine the number density of the Milky Way-like galaxies in the rest of the Universe.

Appendix D

A Function to Describe the Galactic Disk

In section 6.1 a two dimensional model of the Galactic disk is discussed as the source of 14% of IceCube's astrophysical neutrinos. Fig. 6.1 shows the geometry used to describe the disk in terms of a length from the Earth to any point on the circumference of the circle, $l(\theta)$, and an angle, θ, from the horizontal line Earth is on to the distance $l(\theta)$. To calculate the function $l(\theta)$ start by drawing a triangle (between the vertices r, x and l, Fig. 6.1). This triangle now only has two unknown parameters: l and θ. The radius of the Galactic disk is taken to be $r = 15\,\text{kpc}$ while the distance from Earth to the GC is taken to be $x = 8\,\text{kpc}$. To write an equation in terms of l and θ use the cosine rule (Eq. E.1) for an arbitrary triangle (Fig. E.1). In Eq. E.1, the side lengths are a, b and c and the opposite angles are A, B and C respectively.

$$c^2 = a^2 + b^2 - 2ab\cos(C) \tag{D.1}$$

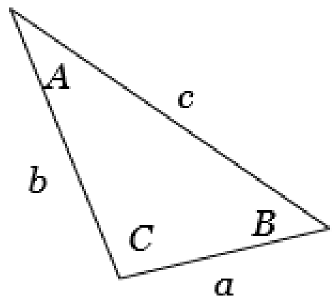


Figure D.1: An arbitrary triangle with side lengths a, b and c and opposite angles A, B and C.

For the triangle present in Fig. 6.1, Eq. E.1 can be used to write an equation for r in terms of all the other parameters as a consequence of how the angle was defined (Eq. E.2). This can then be re-arranged to form a quadratic equation for l in terms of θ:

$$r^2 = l^2 + x^2 - 2lxcos(\pi - \theta) \tag{D.2}$$

$$-l^2 - 2lxcos(\pi - \theta) + (r^2 - x^2) = 0 \tag{D.3}$$

This equation can be solved for $l(\theta)$ (Eq. E.4) using the quadratic formula. Since the values of r and x are known and chosen to be 15 kpc and 8 kpc respectively, Eq. E.4 can be reduced to Eq. E.5 with the only unknown parameter as θ and with units of kpc.

$$l(\theta) = \frac{-2x\cos(\pi - \theta) - \sqrt{(-2x\cos(\pi - \theta))^2 + 4(r^2 - x^2)}}{-2} \tag{D.4}$$

$$= 8\cos(\pi - \theta) - \sqrt{(8\cos(\pi - \theta))^2 + 161} \tag{D.5}$$

An example that shows that $l(\theta)$ describes the distance from the Earth to any point on the circumference of the disk is the trivial case where $\theta = \pi$ and showing that Eq. E.5 reduces to Eq. E.6 which is trivial to write using the model defined in

Fig. 6.1.

$$l = r + x \tag{D.6}$$

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