

THESIS TITLE  
SECOND LINE IF NECESSARY

by

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## **Abstract**

This is my abstract.

## Acknowledgments

Blah blah blah.

## **Statement of Originality**

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# Chapter 1

## Introduction

The cosmic sky has entranced humans for as far as recorded history can trace. As technology evolved, so too did the observation of the universe around us; from the naked eye to primitive telescopes, and eventually to present day space telescopes, like the Hubble Space Telescope and the upcoming James Web Space Telescope (**NEED TO CITE THESE**). These growing technological leaps have also resulted in the exploration of the incredibly small and eventually resulted in the discovery of the neutrino [46]. It was perhaps inevitable that these two seemingly separate areas of physics would eventually meet.

Will need to make this a general introduction to the topics, and less like the background.

# Chapter 2

## Background

### 2.1 Neutrinos

The neutrino is a fundamental particle first proposed by Wolfgang Pauli [17], and then later discovered in 1956 using the byproducts of  $\beta^-$  decay [46]. As research continued into the elusive neutrino, another flavour of neutrino was discovered in 1962 called the muon neutrino ( $\nu_\mu$ ) [21] and eventually the final flavour of the tau neutrino ( $\nu_\tau$ ) [35].

#### 2.1.1 Oscillations

Alongside the discovery of the neutrino and their flavours, another problem arose in the field of neutrino physics: the solar neutrino problem [38]. During the 1960's, an experiment was proposed by Bahcall and Davis to measure the solar neutrino flux, referred to as the Homestake experiment [22, 10]. This was a tank of  $^{37}\text{Cl}$ , built underground to avoid cosmic backgrounds, and used the simple reaction[22, 10]



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to measure the expected solar neutrino flux from the sun.

Solar neutrinos originate from nuclear processes that occur in the sun, such as the PP chain, or the CNO cycle, and can be detected in experiments on Earth [29]. Depending on the energy and process in producing the neutrino, we can expect to detect particular flavours of neutrinos in experiments like the Homestake experiment. In particular, using the predicted distribution of the internal electron density of the Sun, and a spectrum of the produced electron flavours, one could predict the expected flux of solar neutrinos [29]. In particular, one could predict the influx of electron neutrinos, as was exactly done for the Homestake experiment. It was found that the measured flux was consistently around 30% the theoretical amount [22, 10, 29], and hence was coined the solar neutrino problem.

Neutrino detectors continued to be constructed to research and understand these fundamental particles, such as Super-Kamiokande [55], the collaboration of Kamiokande [31] and the IMB [18] experiments. Another class of solar neutrino detectors were those that used the Gallium chain



such as GALLEX [53]. Regardless, the same issue persisted as there continued to be a distinct dissonance between the theoretical expectations of solar neutrinos and the observed experimental results. That was, until the Sudbury Neutrino Observatory (SNO) made a distinct change in their approach to solar neutrino detection compared to predecessors by using heavy water [11]. This allowed for the following interactions

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[11],

$$\nu_e + d \rightarrow p + p + e^- \quad (2.3)$$

$$\nu_l + d \rightarrow p + n + \nu_l \quad (2.4)$$

where we have the Charged Current (CC) interaction in equation 2.3 and the Neutral Current (NC) interaction in equation 2.4. This meant that all flavours of neutrinos could be detected, and using it to detect solar neutrinos showed the theoretical flux originally predicted [11].

This result had an astounding implication; the neutrinos were changing on their journey from the Sun [11]. In the Standard Model, all the neutrino flavours have masses that are identically zero, and this would mean that there is no possible way for the neutrinos to somehow change flavour on their journey to the detectors [29]. Clearly there was a change in flavour, and thus the Standard Model must be incorrect about the masses of the neutrinos.

The classic demonstrative method to see this is to consider the mixing of two neutrino flavours (like  $\nu_\mu$  and  $\nu_e$ ) [29]. In analogy to quark flavour mixing [23], we know the mixing of the flavours occurs in the transformation from the mass to the flavour basis. In particular, for two mass and flavour states one can find [29],

$$P(\nu_e \rightarrow \nu_\mu, ct) = \sin^2 2\theta \sin^2 \left( \frac{\pi c t}{L} \right) \quad (2.5)$$

where  $\theta$  is the mixing between the two flavour states,  $L = \frac{4\pi E}{\Delta m^2}$  is the vacuum oscillation length, and  $\Delta m^2 = m_2^2 - m_1^2$ . Here it is easy enough to see that the oscillation probability vanishes if the masses are identical, and this naturally extends into the

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three flavour case. The vacuum oscillation length,  $L$ , is an important and useful quantity as it describes the distance a neutrino must travel before an oscillation is expected [29]. Experiments like the long–baseline neutrino oscillation experiment Tokai–to–Kamioka (T2K) attempt to use this length to probe the mixing angles of the three neutrino flavours.

Similar to the CKM matrix for quark mixing [23], the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix [41] gives a relation between the mass and flavour states:

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \quad (2.6)$$

and we see that

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\text{CP}}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\text{CP}}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\text{CP}}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\text{CP}}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\text{CP}}} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (2.7)$$

where  $s_{ij} = \sin \theta_{ij}$ ,  $c_{ij} = \cos \theta_{ij}$ ,  $\delta_{\text{CP}}$  is the Charge–Parity violation phase [41], and  $\eta_i$  are the Majorana phases. If neutrinos are not their own anti–particles, or in other words are Dirac fermions, we can expect  $\eta_i = 0$ . If they are their own anti–particles, also knowns as Majorana, then the phases  $\eta_i$  play a more imoprant role [28].

### 2.1.2 Interactions

Neutrinos are neutral and interact only through the Weak interaction. The Weak interaction is a force that is mediated by the  $W^\pm$  and  $Z^0$  massive bosons, and is the

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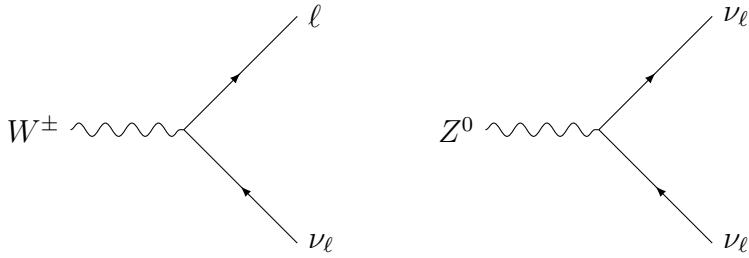


Figure 2.1: The Feynmann diagrams for the vertices that would be included in neutrino interactions using the charged  $W^\pm$  boson on the left and the neutral  $Z^0$  boson on the right.

force responsible for decays. The main vertices involved in neutrino interactions are shown in Figure 2.1, where the interacting lepton corresponds with the interacting neutrino flavour.

All interaction involving neutrino production or detection utilize these vertices in some shape or form. We refer to interactions that use the  $W^\pm$  boson as the Charged Current (CC) interaction [27], and those that use the  $Z^0$  boson as being Neutral Current (NC) interactions [27].

It is natural to notice that these interactions require something to interact with, or in other words, the neutrinos must propagate through non-vacuum media and hit targets. We have up to this point only considered oscillations of neutrinos in vacuum, and another imorant aspect is to consider the effect interactions could have on these oscillations. In particular, it is noted that certain flavours of neutrinos can be more strongly influenced by media than others [29, 44]. In particular, electron neutrinos ( $\nu_e$ ) being first generation and majority of regular everyday matter being first generation would result in this stronger coupling [29, 44]. This difference in coupling would result in changes in the oscillation that could be complex.

This phenomena comes to a head with the Mikheyev–Smirnov–Wolfenstein (MSW)

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effect. The mixing angle and oscillation length vary with the electron density in the medium which varies the rate at which these neutrinos mix [29, 44]. In particular there is a resonance mixing angle (and hence resonance electron density) at which the mixing is maximized [29, 44]. The electron density in the sun at the center starts far above the resonance and ends below the resonance at the edge, hence the produced electron neutrinos experience this resonance oscillation along their path out of the solar center [29, 44]. The MSW effect is currently understood to be the reason for the solar neutrino problem [29].

### 2.1.3 Production & Sources

As was discussed in subsection 2.1.2 and 2.1.1, neutrinos produced in the fusion process hold great historical significance, and in the attempt to resolve the solar neutrino problem we have come to better understand neutrinos and their processes. The leading reaction chain is the *pp* chain [28, 29], which is given by [28]

$$p + p \rightarrow d + e^+ + \nu_e . \quad (2.8)$$

All other chains that fall under the *pp* chain follow a similar idea; through the charged current interaction, there is the production of an electron neutrino during the fusion of two reactants [28].

Another site where we can observe neutrino production is in the atmosphere [25, 28, 54]. These neutrinos are primarily produced by the decay of pions and muons [28],

$$\pi^+ \rightarrow \mu^+ + \nu_\mu , \quad (2.9)$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \quad (2.10)$$

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and the charge conjugate  $\pi^-$  [28]. The production of these decaying pions and muons is initiated by cosmic rays interacting with the nucleons in the atmosphere [25, 28, 54]. Looking at the inciting interactions, a natural and useful ratio is

$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \quad (2.11)$$

of the number densities [28]. It is also useful to note that atmospheric neutrinos can be both downward heading and upward heading, as they can travel through the earth. These two different directions will experience different travel lengths and can be used to probe neutrino oscillations [28]. There have been studies done on the atmospheric neutrino flux with experiments across the globe [28, 54].

Neutrinos can also be generated by the natural decay of rare elements in the Earths crust [12]. In particular, the main source is of  $\beta^-$  decays in elements like  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  [12]. Measuring the geo-neutrino flux holds interesting consequences in the Geology and Physics community, for example predictions of the radiogenic contributions by neutrino producing processes can be predicted [12].

Production of neutrinos by  $\beta^-$  decay also occurs in reactors [45]. The fission process involving  $^{235}\text{U}$  uses a chain reaction of neutron production to fuel more fissions [45], and this neutron rich environment promotes the classic bound neutron decay,

$$n \rightarrow p + e^- + \bar{\nu}_e . \quad (2.12)$$

The benefit of using reactor neutrinos lies in the flavour purity; the production mechanism promotes the creation of electron anti-neutrinos [45].

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Accelerator neutrinos are produced by firing a beam of protons at a target to produce secondary mesons that decay and produce neutrinos [36]. This process is similar to the atmospheric neutrino production process as the idea is similar: secondary mesons produced by high energy primaries that then decay and produce neutrinos. The benefit of this production method is they are generally produced in a collimated beam within some angular error due to the momentum based production [36]. This effectively produces a neutrino beam that can then be used in later processing.

Supernovas can produce high energy neutrinos that can travel thousands of years before reaching detectors on earth [40]. These provide both unique insights into the universe, as they will leave a higher energy signature [40] and the vast distance travelled allows for the neutrino to arrive at the earth in a mass eigenstate. The reason for arriving in the eigenstate occurs as a result of the large distance allowing for the competing mass states to decouple [40].

Another proposed galactic source of high energy neutrinos are Active Galactic Nuclei (AGN) which are potentially the most powerful producers of radiation in the universe [16]. AGNs are known for accelerating protons up to  $10^{20} - 10^{21}$  eV, and provide a potential pathway for producing incredibly high energy neutrinos [16].

### **2.2 Detection Techniques**

With a plethora of neutrino sources, some of which have been discussed, the method of detection becomes increasingly important. For the purposes of this text, we only consider a couple of techniques that are of interest. To begin, we can consider the GALLAX type experiments that use the chain identified in equation 2.2. These are blind to the other flavours of neutrinos, as was already discussed, but they did

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motivate using Germanium as a potential neutrino detection method. In particular there are propositions that these detectors may provide  $\mathcal{O}(1\text{kg})$  modular mass,  $\mathcal{O}(100\text{eV})$  threshold and  $\mathcal{O}(1\text{kg}^{-1}\text{keV}^{-1}\text{day}^{-1})$  background experiments [49]. In particular, detectors like these could be sensitive to low energy solar neutrinos through neutrino–nucleus elastic scattering [14] where the lower energy neutrinos can have an amplified signal through internal charge amplification [14].

Another class of neutrino detectors use calorimeters as a method of detecting energy deposits from secondaries in neutrino producing processes [24, 37]. These signals can then be used to reconstruct the neutrino flavour and energies [24, 37]. Two examples of such detectors are MINOS [24] and ICAL [37]. The former uses a proton beam on a graphite target to produce showers of hadrons that are then focused by two magnetic horns in a calorimeter [24]. These hadron showers consist of pions and, at higher energies, kaons which produce our neutrinos in their decays [24]. ICAL is a calorimeter array located at the India–based Neutrino Observatory [37] that can use external sources of neutrinos (atmospheric) to probe the mixing angles [37]. In particular ICAL can be particularly sensitive between neutrinos and anti–neutrinos [37].

### 2.2.1 Vavilov–Cherenkov

Now that we have an appreciation for some novel techniques in detecting neutrinos, we discuss one that is of particular interest for the purposes of this thesis: Vavilov–Cherenkov (VC) Radiation. VC Radiation was discovered in 1934 by Vavilov [52] and Cherenkov [19] and then later in 1937 explained by Tamm and Frank [50]. In essence, VC Radiation is the emmission of electromagnetic radiation due to a charged particle

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traveling in a medium at a velocity,  $v$ , that exceeds the phase velocity,  $v_p$ , of light in that medium [26]. In particular, if we suppose the velocity of light in vacuum is  $c$ , then VC Radiation will occur if

$$v > v_p = \frac{c}{n(\omega)}, \quad (2.13)$$

where  $n(\omega)$  is the frequency dependent index of refraction in that medium [26]. In particular, if the light is emitted along a wave-vector  $\vec{k}$  from a charged particle traveling with velocity  $\vec{v}$ , then the angle between the two vectors is  $\theta_0$  and can be described by

$$\cos \theta_0 = \frac{c}{n(\omega) \cdot v} \quad (2.14)$$

where  $v = |\vec{v}|$  [26]. Due to the electromagnetic radiation wavefront being a result of spherical emissions [26], the process is very similar to that of the acoustic sonic boom for macroscopic objects [26] which serves as an excellent analogy.

This particular form of radiation is incredibly useful for neutrino detection. We can use the secondary leptons produced in CC interactions, like those in Figure 2.1, to produce VC Radiation that can be detected by ultra sensitive photon detectors.

### 2.3 Neutrino Telescopes

Generally one considers only Telescopes as those that utilise the visible part of the electromagnetic spectrum, and in general this is true, but as technology has advanced we have found that using even other wavelengths of light has resulted in different information to be gained from the imaging of the universe. This idea can be extended to include other sources or even particles to image with, like the neutrino. Due to

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the weakly interacting nature of the neutrino it can travel great distances before interacting and can provide direct sources where cosmic rays may be ambiguous about their source. Neutrino Telescopes use exactly this principle to reconstruct neutrinos from cosmic sources with the potential to image the sky one day in an entirely different lens.

The DUMAND experiment [9] was the first to propose the use of large photo-multiplier tubes in deep ocean to detect high energy neutrinos. Though it was never brought to fruition, it was the first of its kind and paved the way for future VC Radiation based neutrino telescopes such as Baikal [13], AMANDA [8], ANTARES [6], and IceCube [4]. We will discuss a few of these that are relevant.

### 2.3.1 IceCube

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector built in the Antarctic ice [4]. Its primary scientific goal was the detection and characterization of astrophysical neutrinos along with their sources [4], but also has many other scientific goals including indirect detection of dark matter, exotic particle searches, neutrino oscillations, and supernova neutrinos [4].

Neutrino detection occurs through VC Radiation of charged particles from neutrino interactions traveling through the ice [4]. IceCube has the advantage of having a very large volume coverage in order to compensate for the small neutrino cross-section and low astrophysical sources flux [4]. The detection is done through the Digital Optical Module (DOM) consisting of 10" Photo-Multiplier Tubes (PMTs) which are sensitive to the VC photons [4]. The full array is has 5160 DOMs on 86 vertical strings where each string consists of 60 DOMs [4]. The array sits between

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1450 meters and 2450 meters below the surface of the ice [4].

The detection medium of ice is novel in the neutrino telescope field and offers both advantages and disadvantages over water [34]. Ice that has been undisturbed, like that in the Antarctic, offers pure conditions and is stationary when compared with the flow of most large bodies of water [34]. However, equipment that is used in the ice is not recoverable [34] and hence difficult to repair. Moreover, ice offers a shorter scattering length than one would expect in water [34] and due to the ice being layered this effect is layer dependent and was studied in detail to build reference tables [34].

IceCube has been successful in its original physics goal [4] and in 2017 detected a high energy neutrino estimated to have an energy of 290 TeV [3]. This was coincident in direction and time with a gamma-ray flare from blazar TXS 0506+056 [3]. Studying previously collected data in search for more high energy events of the same caliber from the same direction supported the claim that blazars can be a source of high energy neutrinos [3]. IceCube is continuing to collect data and explore more of its physics goals.

#### **2.3.2 ANTARES**

The ANTARES Neutrino Telescope is the first operational Neutrino Telescope in the Mediterranean Sea [6] adopting heavily from DUMAND [9] and Baikal [13]. Similar to other Neutrino Telescopes, the main method of neutrino detection arises from V<sub>C</sub> Radiation from secondary leptons produced in neutrino interactions [6]. The array is composed of 12 mooring lines lined with 25 Optical Modules (OMs) that contain PMTs for a total of 885 OMs (the 12<sup>th</sup> line has a different number of OMs) [6].

Compared to the experiments that use ice, like Icecube [4, 3, 34] and AMANDA [8],

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ANTARES uses ocean water as the medium of VC Radiation from high energy neutrino induced leptons [6]. The benefit over ice is that the attenuation/scattering length is longer, and the lack of layering reduces the reconstruction difficulties [6, 34]. The difficulties are that the water shifts, and hence can both rotate the detectors slightly and move their relative positions [6, 34]. To account for this shifting, ANTARES uses a High Frequency Long Base Line (HFLBL) acoustic system providing 3D positions of hydrophones positioned along the mooring lines [6]. To account for the tilting, each OM is given a set of tiltmeter–compass sensors giving the local tilt angles of each OM structure [6]. Moreover, there are backgrounds from  $^{40}\text{K}$  decay and bioluminescence to consider [34].

ANTARES was finished construction in 2008 and has been collecting data since [6]. They have achieved their design goals and are able to achieve a positional accuracy better than 20 cm for each OM with the expected time resolution of 1 ns [6]. This experiment shows the feasibility of water based Neutrino Telescopes and opens the doors for future Ocean Neutrino Telescopes.

#### **2.3.3 KM3NET**

## Chapter 3

### The Pacific Ocean Neutrino Explorer

The Pacific Ocean Neutrino Explorer (P–ONE) is a proposed Neutrino Telescope planned to run in the Pacific Ocean near the West Coast of Vancouver Island, Canada [7]. As with other Neutrino Telescopes, P–ONE hopes to detect and characterize astrophysical neutrinos from galactic and extra–galactic sources for extremely high energy neutrinos [7]. In particular, due to the planned multi–cubic kilometer coverage, it would be suitable for neutrinos from sources such as Blazars [3]. Moreover P–ONE hopes to provide an avenue for research in exotic particle searches, dark matter, neutrino oscillations, supernova neutrinos, and tau neutrino studies ( $\nu_\tau$ ) [7].

#### 3.1 Geometry

The geometry of the detector is incredibly important, as the layout and positions of the detectors can drastically change the results and the sensitivities [4]. The first proposed Explorer phase for P–ONE corresponds to the first 10 string–segment to be deployed [7]. Each string will be composed of 20 photo–sensors and atleast two calibration modules [7], with the strings organized in an array similar to that of IceCube [7, 4]. In order to avoid using thousands of strings to get a larger coverage,

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it can achieve a similar amount of information using a segmented approach where 6 more arrays similar to those of the Explorer are added around it [7]. This design is drawn in Figure 3.1.

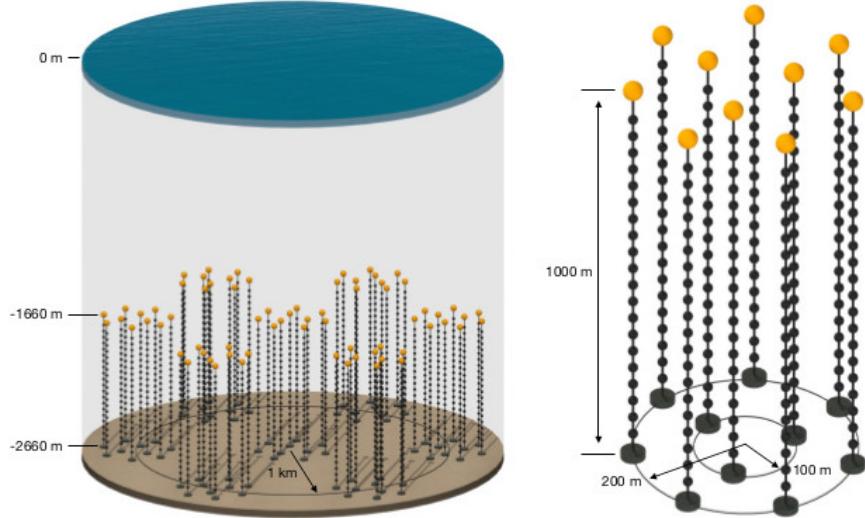


Figure 3.1: Left: Proposed full detector of the P-ONE detector. Right: Proposed array for the Explorer deployment of P-ONE.

With the current proposed geometry, the detector will be incredibly sensitive to horizontal incoming high energy muons from neutrino astrophysical neutrino sources [7].

### 3.2 Detectors

Similar to previously constructed Neutrino Telescopes, P-ONE will primarily use Vavilov–Cherenkov Radiation from leptons produced through neutrino interactions. This electromagnetic radiation is then detected through highly sensitive optical modules that consist of Photo–Multiplier Tubes (PMTs).

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### 3.2.1 Photo-Multiplier Tubes

A key part of any neutrino telescope is the detection mechanism, and in this community the Photo-Multiplier Tube (PMT) is synonomous with detector. The PMT is a vacuum-sealed photocathode with dynode and anodes above connector pins [30]. The primary mechanism of a PMT is the photoelectric effect from a photon hitting the photocathode resulting in a cascade of electron showers along the dynodes and anodes amplifying the signal before it reaches the connector pins [39]. Through this method the PMT can produce large signals at the single photon level, but is for the same reason sensitive to a particular range of frequencies/wavelengths of light [39].

In particular, PMTs are generally sensitive to wavelengths anywhere as low as 100 nm to as high as 500 nm depending on the material of the photochathode [30]. Another property of PMTs to note is the Quantum Efficiency (QE), which is defined as the ratio of photoelectrons emitted by the photocathode to the number of incident photons [30]. Thus, QE defines how much photon information a PMT will transmit. The QE is dependent upon the photocathode and varies with the incident photons wavelength, as different wavelengths carry different energies [30].

In contrast to QE, the Dark Current (Dark Noise) is the reporting by PMTs of light even in completely dark environments [30]. According to the HAMAMATSU handbook [30], a number of reasons can be the cause for this misfiring in PMTs including (but not limited to) thermionic emissons, internal current leakage, scintillation from glass envelope and radiation sources. One can minimize the effect from these sources, such as reducing the temperature to limit the thermionic emissions [30].

The final aspect of PMTs we discuss is after pulsing, the small pulses observed

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after the arrival of a signal [30]. The quick afterpulses (within nano–seconds) can usually be attributed to scattering of electrons on the first dynode [30], while later afterpulses (within microseconds) can be the result of positive ions from the ionization of residual gases in the tube [30].

The PMT is an incredibly technical piece of hardware, and characterizing each PMT becomes important to understanding the detector as a whole.

### 3.2.2 Digital Optical Modules

In IceCube, the Digital Optical Module (DOM) is a module containing a ten–inch PMT supported by coupling gel, the high voltage generator, an LED flasher board for calibration, and the mainboard used for analog and digital signal processing [5, 4]. P–ONE will be adopting this approach for detector construction.

What else to add here?

### 3.2.3 mDOMs

A proposed redesign of the IceCube DOM to increase the granularity of light detection is the multi–DOM (mDOM). In place of one large PMT, multiple smaller PMTs can line the same space and coverage at the cost of gaps between detectors. The benefit being that individual hits on the smaller PMTs can provide extra information using the acceptance angle and directionality of that particular PMT [20]. Moreover, in theory this can also reproduce the standard DOM data as the signal collected by a single PMT in the array can be collected and treated as a hit for the entire DOM. This gives the mDOMs a flexibility that isn’t present for standard DOMs. In IceCube the standard DOMs use a ten–inch diameter PMTs [4], where the mDOMs would use

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up to 24 three-inch diameter PMTs [20].

#### **3.3 Strings for Absorption length in Water**

The Pathfinder mission for P-ONE is the STRings for Absrption length in Water (STRAW) and its follow up STRAW-b, which were deployed in 2018 and 2020 respectively. The purpose of these missions was to test the technical details of running an experiment like P-ONE, such as the hardware limitation, to provide data to measure the Attenuation length of light in water for light in wavelengths between 350 nm and 600 nm, characterize the bioluminescence of deap-sea living organisms and the  $^{40}\text{K}$  dissolved in the salty water [15].

### 3.3. STRINGS FOR ABSORPTION LENGTH IN WATER

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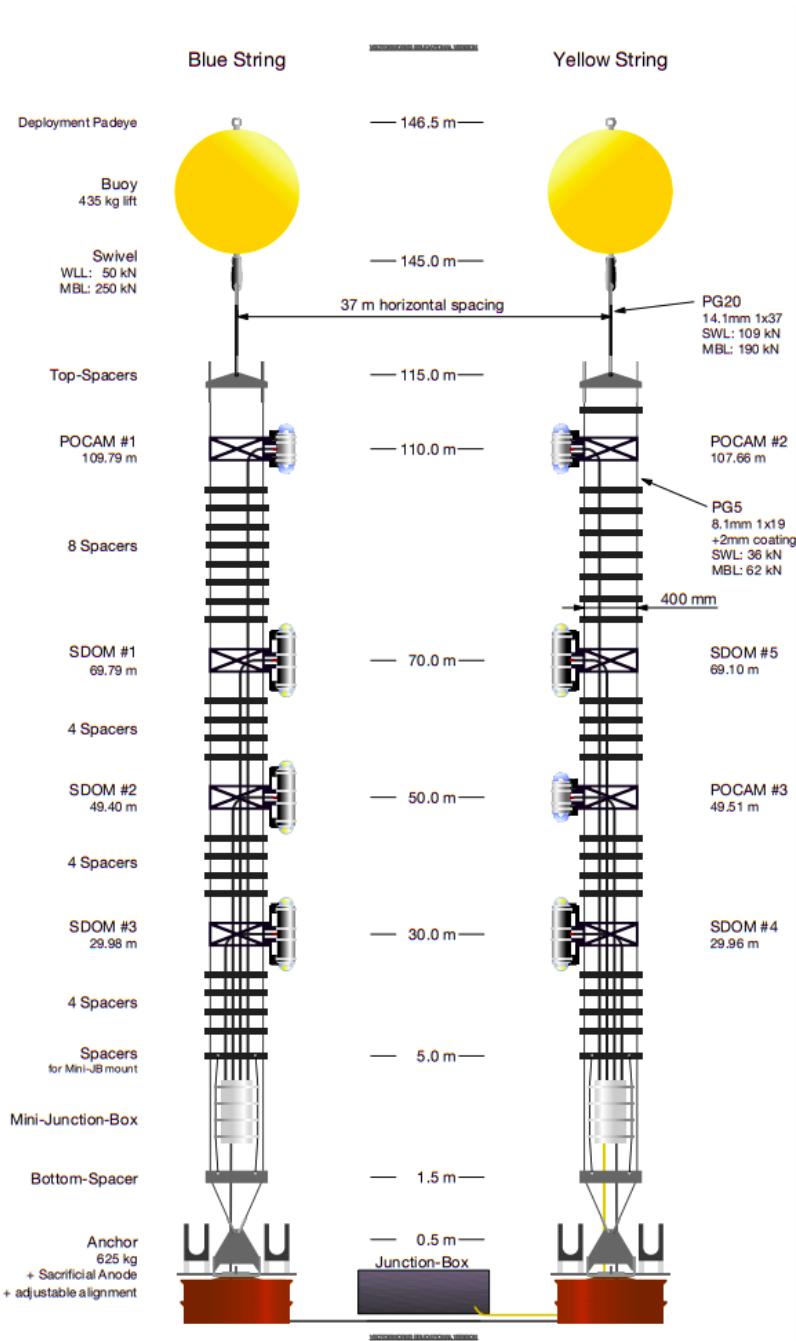


Figure 3.2: A diagram of the full STRAW setup including distances [15].

The basic design of STRAW, as shown in Figure 3.2, is the same as that of standard

### 3.4. OCEAN NETWORKS CANADA

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Neutrino Telescopes; using PMTs for detecting photons and calibrating light emitting sources on mooring lines to collect data [15]. In this particular case STRAW uses two vertical mooring lines with 3" PMTs and Precision Optical Calibration Modules (POCAMS) for the calibration sources [15], which provide isotropic and short pulsed flashes of light. The attenuation length  $L_T$  in water can be realized using the known photon intensity  $N_0$ , the wavelength from the POCAM flashes and the distance  $r$  to each particular PMT with effective collection area  $A_{\text{det}}$  measuring an intensity  $N(r)$  [15]. This yields

$$N(r) = \frac{N_0}{4\pi r^2} \exp\left(-\frac{r}{L_T}\right) A_{\text{det}}. \quad (3.1)$$

The expected maximum value of absorption length is around 50 meters, so the STRAW geometry has been chosen to cover the ranges between 20 m and 90 m [15]. Some of the geometry choices were purely due to technical limitations, such as the maximum safe cable lengths to minimize data loss [15], while others were to preserve some form of symmetry between modules [15].

Should I talk about POCAMS in detail? [32]

### 3.4 Ocean Networks Canada

The construction and implementation of P-ONE is supported by Ocean Networks Canada (ONC), an oceanography observatory with a vast network monitoring the west and east coasts of Canada along with the arctic [2]. Situated at the University of Victoria, ONC uses cabled observatories, remote control systems and interactive sensors for data collection and evidence-based decision-making [2].

The west coast observatory, as seen in Figure 3.3, is comprised of the 800-km

### 3.4. OCEAN NETWORKS CANADA

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Figure 3.3: A diagram of the Ocean Networks Canada Western Infrastructure for monitoring the Pacific Ocean. This contains the NEPTUNE and VENUS observatories. Source [2].

NEPTUNE observatory and the nearly 50-km VENUS observatory [2], with the NEPTUNE observatory housing the proposed site of P-ONE at the Cascadia Basin. The Cascadia Basin, as seen in Figure 3.4, is a heavily sedimented abyssal plain located 2660 meters below sea level [2]. Though the environment seems inhospitable, with temperatures below 2°, high-pressure, and a distinct lack of light, one can still find organisms highly adapted to the extreme environment [2].

This biodiversity results in the potential background of bioluminescence [7, 2, 56, 43]. Bioluminescence is the emission of visible light by living organisms due to natural chemical processes used by a wide range of species [56]. Some studies show that 75% of all organisms larger than 1 cm occurring between the surface down to 4000 m depth are capable of bioluminescence [43]. Due to evolutionary advantages, most bioluminescent organisms emit light between 440 nm and 540 nm, which also has the

### 3.4. OCEAN NETWORKS CANADA

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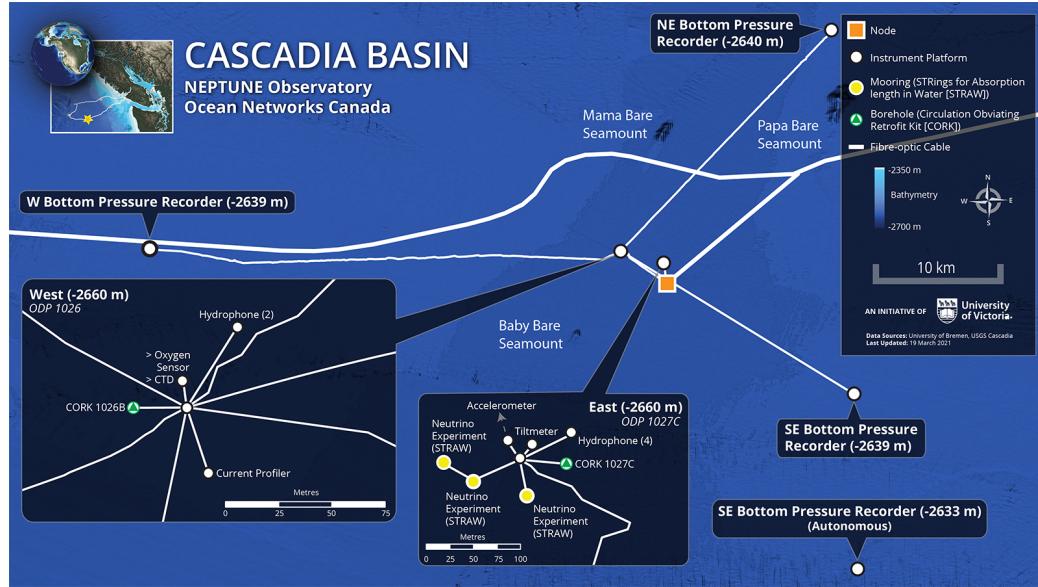


Figure 3.4: Diagram of the Cascadia Basin, the site of the upcoming P-ONE experiment and current site of the pathfinder STRAW. Source [2].

largest absorption length in water [56]. The amount of photons emitted can also vary significantly from  $10^3$  for bacterium to  $10^{12}$  photons from some fish [56]. There are efforts being put together to understand and characterize this background in order to be better prepared for when the detector is installed.

# Chapter 4

## Simulation

As P–ONE has only deployed the Pathfinder missions thus far, including STRAW and STRAWb, the data used in this thesis is primarily simulated. In particular, the data needs to be usable to test and build a reconstruction algorithim for muon–neutrinos. This means simulating muon tracks. For this reason, we lightly cover the simulation process used to produce data including the pre-existing IceCube Framework, Simulating Neutrinos, Simulating Muons and the Detector Response.

### 4.1 IceCube Framework

The software framework already exists from IceCube, and in order to minimize the amount of new code needed to simulate P–ONE it is simplest to use the IceCube software. In particular, the software documentation is readily available [1] and referred to as IceTray. This is meant to be a full framework capable of simulating, reconstructing and analysis all in one [1]. For the purposes of P–ONE, we wish to only use the simulation subset of the framework as it is primarily made using open-source software, and hence can avoid potential proprietary issues.

The bulk of the code is written in C++ with the goal of being modular. This means

## 4.2. SIMULATING NEUTRINOS

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that rather than writing scripts that call functions or classes that are pre-existing, the code is designed so that there is a single steering script that calls modules to run tasks including the simulation of muons or neutrinos, and including geometry files. Modules can be added by users as well to then be included in the steering scripts. The code has also been wrapped using Python so that modules can be reached via python scripts, and hence steering scripts can be written in Python. For this reason, Python is the language of choice for the purposes of this work.

### 4.2 Simulating Neutrinos

The software used to generate neutrinos is the very aptly named Neutrino-Generator (NuGen) [1]. This is code written in IceTray based off of the All Neutrino Interaction Generator (ANIS), a high energy neutrino generator used for neutrino telescopes. NuGen has the capabilities of preparing and injecting a neutrino and interacting along the way if they so happen, and then forcing an interaction in the detector. NuGen can also produce secondaries. However, NuGen does not propagate photons nor charged leptons. This is saved for PROPOSAL and CLSim, where the former is used to propagate charged leptons and the latter is used to produce and propagate photons in a parallel manner (if using GPUs).

### 4.3 Simulating Muons

The module used to generate muons is the MuonGun that exists in GEANT4. This can be used to inject muons based on some sampling surface dependent upon a given flux model [1]. Muon Gun is versatile as it can be easily modified to produce muons using a variety of sampling surfaces, and can even be modified to be energy dependent

#### 4.4. DETECTOR RESPONSE

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[1].

In particular, the MuonGun works by drawing samples from a parameterization of the atmospheric muon flux [1]. This is parameterized in the same manner as described in [42]; it depends on the water depth ( $h$ ), zenith angle ( $\theta$ ), multiplicity, and energy. In particular, the energy spectrum of single muons is described by

$$\frac{dN}{d(\log_{10} E_\mu)} = G \cdot E_\mu e^{\beta X(1-\gamma)} [E_\mu + \epsilon(1 - e^{-\beta X})]^{-\gamma}, \quad (4.1)$$

where there are multiple fit parameters described more in [42]. The energy loss due to water interactions also have to be added and are also discussed in [42]. These parameterizations are great for fast generation of muons [42], which is important for understanding the background of cosmic ray muons common in most neutrino telescopes [4, 6, 8, 7, 42].

Do we talk about Muon Gun or Cosmic Muons? Currently only Cosmic Muons are being used but both could be used.

#### 4.4 Detector Response

The choice of geometry is incredibly important, as varying the position and number of detectors can, as one would expect, result in large changes in the performance of the detector (**WHERE TO CITE THIS FROM?**). The current proposed first stage of P-ONE is to be a pair of nested circles with the inner containing three strings and the outer containing 7 [7], as we can see in Figure 3.1. The simulated geometry is based off of this first design and held in a “.gcd” file which is used by IceTray [1]. **GET IMAGE OF GCD HERE SOMEHOW**. If we wish to see how the potential detector performance is affected by varying the geometry, we can change

#### **4.4. DETECTOR RESPONSE**

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this geometry file and measure parameters such as the effective area to see how well it compares.

One of the most useful and widely used methods of measuring a neutrino detectors performance at a glance is the effective area. For a given particle of interest with some flux, the effective area is defined as the area of the detector scaled by the efficiency of the detector in measuring this particle [33]. Another way of phrasing this is that the effective area is that which detects perfectly the particles entering it for a given number of detections. Computing the effective area is non-trivial, as it is particle, flavour, energy, and direction dependent.

This has to include the detector geometry (GCD) files, the DOMs, and efficiency...?

# Chapter 5

## Reconstruction

A telescope is only as good as its ability to identify distinct sources. In the case of a neutrino telescope this translates directly to how well observed events can be reconstructed for the direction of high energy events. IceCube uses several reconstruction methods [4] and has several data quality checks it must go through before a result is given any weight. Similarly, ANTARES has had years of work put into the reconstruction software in order to reach the accuracies it can now [6]. To set the context for reconstructions, we need to first understand the data that is collected and how it appears.

### 5.1 Geometry of a Single Hit

At first thought, it may sound simple to try and reproduce the tracks that produce the light one would observe in neutrino detectors, but upon considering the data that is acquired the true complexity is revealed. To see this, we consider first the geometry of a single hit to see what the data would look like. Referring to Figure 5.1, we consider a muon track that is infinite in length, which is a safe approximation assuming a sufficient energy of the neutrino relative to the size of the detector. Specifically we

## 5.1. GEOMETRY OF A SINGLE HIT

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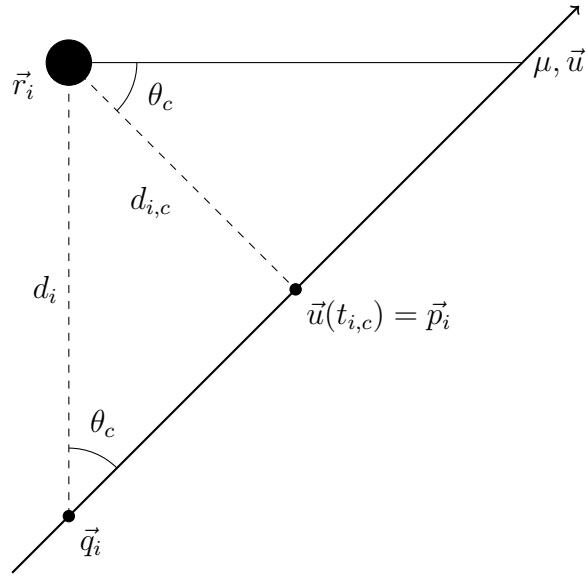


Figure 5.1: Drawing of muon track and Vavilov-Cherenkov Radiation hitting a single DOM.

can parameterize the track with

$$\vec{u}(t) = \vec{x} + ct\vec{v}, \quad (5.1)$$

where  $\vec{x}$  is the vertex,  $\vec{v}$  is the direction the muon is travelling in,  $t$  is the time parameter, and finally  $c$  is the speed of light, which again for sufficiently high energy muons is a good approximation for the speed. Looking at the  $i^{\text{th}}$  DOM located at a position  $\vec{r}_i$ , it is easy to see there must be a closest approach position for the track,  $\vec{p}_i$ , and emission point of a photon given there is a direct hit on the DOM, located at  $\vec{q}_i$ . The photon is emitted at a cherenkov angle of  $\theta_c$ , which is as described in equation 2.14.

## 5.1. GEOMETRY OF A SINGLE HIT

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The next step is to consider the information we know about the DOMs. In particular, the direction of the DOM will determine its angular acceptance giving information on whether or not particular photons can actually reach the DOMs, and the time at which photons are detected. Moreover, light can scatter and may not travel a direct path, so the distance  $d_i$  also becomes an important parameter to consider. Any sophisticated reconstruction technique will require these parameters to produce reliable results, and hence are important to both understand and compute given a track. Hence, we first attempt to discuss the method for computing these parameters given a DOM position and track.

Assuming a track as given in equation 5.1, and that we know the closest approach position at  $\vec{p}_i$  for a DOM at  $\vec{r}_i$ , then we can easily compute  $d_{i,c} = |\vec{p}_i - \vec{r}_i|$ . Then, using the closest approach distance,

$$d_i = \frac{d_{i,c}}{\sin \theta_c} \quad (5.2)$$

will describe the distance the photon travels. To get the emission point of the photon  $\vec{q}_i$ , we know that  $s_i = d_i / \tan \theta_c$  and that the corresponding time would be  $t_s = s/c$ . Then we see that

$$\vec{q}_i = \vec{p}_i - ct_s \vec{v} = \vec{p}_i - s \vec{v}, \quad (5.3)$$

where  $\vec{p}_i = \vec{u}(t_{i,c}) = \vec{x} + ct_{i,c} \vec{v}$ , and so

$$\vec{q}_i = \vec{x} + (ct_{i,c} - s) \vec{v}. \quad (5.4)$$

It is important to note that the distance term  $s$  is negative in equation 5.4 due to the photon being emitted before the track will be closest to the DOM.

## 5.1. GEOMETRY OF A SINGLE HIT

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Now, we know where the emission point is and we know the distance  $d_i$  from equation 5.2. Now, we want to compute the geometric time, as in the time we would expect the photon to arrive at the DOM from our proposed track. To predict this time, we need a reference along the track, and the vertex  $\vec{x}$  is a natural choice for this. Then, we know that

$$t_{\text{geo}} = t_d + t_x \quad (5.5)$$

where

$$t_d = \frac{d_i}{c_n}, \quad \& \quad t_x = \frac{(\vec{q}_i - \vec{x}) \cdot \vec{v}}{c}. \quad (5.6)$$

The former is the time it takes for the emitted photon to travel directly to the DOM, with  $c_n$  being the group velocity of light in water, and the latter is the time it takes for the muon to travel from the vertex to the emission point. It is important to note that in the second term of equation 5.6, the numerator makes sure that the travel time has the correct value. Since the vertex  $\vec{x}$  is not physical, and is merely a reference point for the purposes of this thesis, it is possible for this to be after the emission point. In that case, the value  $t_x$  would have to be negative, and this projection onto the direction vector of the track ensures this. Now, given that we know the time at which the muon is at the vertex, we can shift this travel time accordingly to a shifted  $t_{\text{geo}}$  that will now be comparable to the time that the DOM reports,  $t_{\text{obs}}$ . The parameter of importance then is the residual time, defined as

$$t_{\text{res}} = t_{\text{obs}} - t_{\text{geo}}, \quad (5.7)$$

as it will vaguely inform of the difference between the geometric guess track and the true track.

## 5.1. GEOMETRY OF A SINGLE HIT

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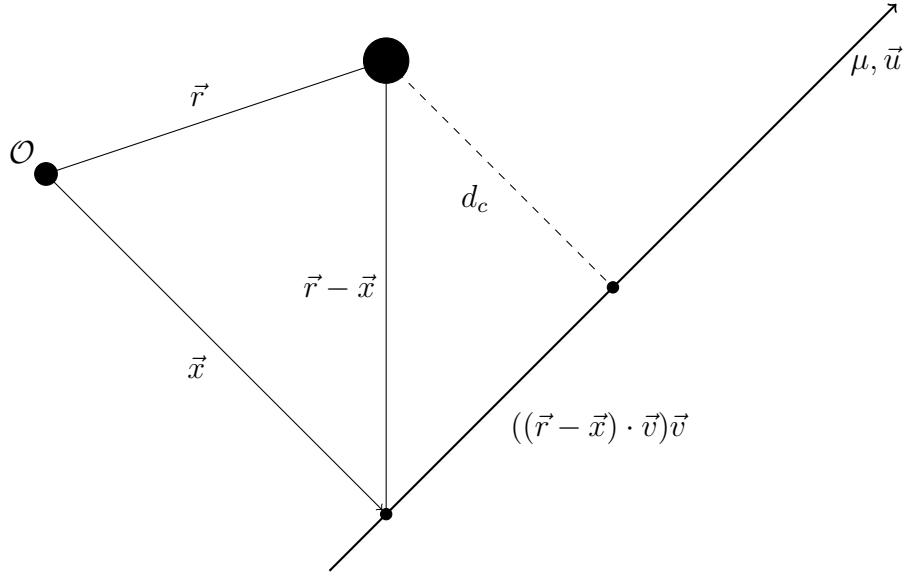


Figure 5.2: Drawing of a track with vertex and DOM labeled. The origin here is also marked to emphasize the vector notation and algebra. It is easy enough to see the vector algebra required to get the distance of closest approach through this diagram.

The next step is to recall all these prior computations rely on the distance of closest approach ( $d_{i,c}$ ) being known. To compute this, we need some geometric considerations with the vectors of the track, the DOM and the vertex. To visualize the vector algebra, we can introduce an origin from which the vectors can be drawn, in which case we get Figure 5.2. We see that the vector pointing to the vertex is  $\vec{x}$  and the vector pointing to the DOM is  $\vec{r}$ , where the indices are dropped for convenience. Then, we see that a vector pointing from the vertex to the DOM can be defined by  $\vec{r} - \vec{x}$ . Next, we can find the projection of this vector along the track direction (which is already a unit vector) as being  $(\vec{r} - \vec{x}) \cdot \vec{v}$ . Then, we see that we have two sides of a right angle triangle with the third missing side being the length  $d_c$ , so

$$d_c = \sqrt{|\vec{r} - \vec{x}|^2 - |(\vec{r} - \vec{x}) \cdot \vec{v}|^2}. \quad (5.8)$$

## 5.2. LINEFIT

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We now have a method of computing  $d_{i,c}$ , and thus computing  $d_i$  and  $t_{\text{res}}$  for each DOM given a proposed track  $\vec{u}(t) = \vec{x} + ct\vec{v}$ . It is important here to note the degrees of freedom that parameterizing a track have. The vertex provides four as it is a position in 3-dimensional space with a time attached. The direction provides two degrees of freedom, as it is a unit vector and can be parameterized using two angles and a unit length radius in spherical coordinates. This gives us six parameters in total that need to be computed to uniquely define an infinite track.

We are now ready to consider different methods for computing these parameters. There are several software techniques that need to be applied before a result can be taken seriously, and usually this pipeline begins with a simple and quick initial guess fit.

### 5.2 Linefit

Any robust reconstruction method requires an initial guess (generally referred to as a seed) in order to be used, but getting this first guess can be non-trivial. Moreover, reconstruction pipelines can be incredibly sensitive to the initial guess and ensuring the quality of this fit is difficult in its own right. The standard method for a first guess in such situations is the linefit/linear fit. This is a simple track fit that minimizes the  $\chi^2$  on the observed hits given in an event. As such, this fitting technique assumes that all hits on the DOMs are directly on the path of the muon track, which is a decent first approximation.

Under these approximations, we assume each spatial coordinate independent from the others. Then we can fit linearly in the projected two dimensional spaces of position and time:  $x - t$ ,  $y - t$  and  $z - t$ , where  $t$ , the time of the corresponding

## 5.2. LINEFIT

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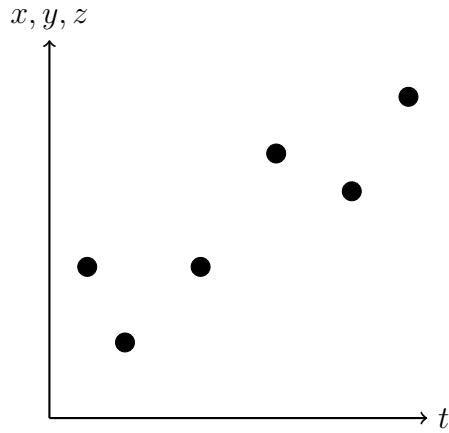


Figure 5.3: Drawing of the position and time space with possible points  $(x_i, y_i)$  that would be fit.

hit, is the independent variable. This way, the problem is reduced to fitting the equation  $y = c_1x + c_0$  in each position and time space as seen in Figure 5.3. From here, we need only apply  $\chi^2$  minimization, which in the case of linear data fitting is exactly the method of least squares. In this scenario, if the data points are defined as  $(x_1, y_1), \dots, (x_m, y_m)$ , then the solution that minimizes the  $\chi^2$  will be

$$\vec{c} = (X^T X)^{-1} X^T \vec{y}, \quad (5.9)$$

where

$$\vec{c} = \begin{bmatrix} c_0 \\ c_1 \end{bmatrix} \quad \& \quad X = \begin{bmatrix} 1 & x_1 \\ 1 & x_2 \\ \vdots & \vdots \\ 1 & x_m \end{bmatrix} \quad \& \quad \vec{y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix}. \quad (5.10)$$

Once  $\vec{c}$  is computed for each position and time space, the vertex position is estimated

### 5.3. LIKELIHOOD

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to be at  $(c_{0,x}, c_{0,y}, c_{0,z})$  with direction  $(c_{1,x}, c_{1,y}, c_{1,z})$ , where the second subscript denotes the spatial component of the data that was used in the fit.

#### 5.3 Likelihood

A more robust technique for reconstructing potential muon tracks is a Maximum Likelihood Estimate [47]. In essence this is a statistically driven parameter fitting technique that allows for more complex modelling, such as the inclusion of the VC emissions. Specifically, if a single DOM observes data  $\vec{x}_i$ , then the probability of observing this data given track parameters  $\vec{\theta}$  is described by a probability distribution  $p(\vec{x}_i|\vec{\theta})$ . Since this is true for each DOM in a given event, the likelihood distribution is defined as

$$\mathcal{L}(\vec{\theta}) = \prod_{i=1}^n p(\vec{x}_i|\vec{\theta}), \quad (5.11)$$

where the indices are over all  $n$  DOMs. The data,  $\vec{x}$ , can carry information such as the times, charges, and directionality of the hits. The varied parameters,  $\vec{\theta}$ , carry the information about the track including the direction, the vertex, the vertex time, and the energy. The parameters that maximize the distribution  $\mathcal{L}(\vec{\theta})$  are the best guess for the track given this method.

Finding this maximum is generally non-trivial and a difficult problem. Computational limits motivate using more robust maximization techniques than full parameter searches, and generally these are techniques that use gradient driven methods. Due to this methodology, generally the solution proposed by the MLE is not the global maximum, and is usually a local maximum. The result of the maximization is thus heavily dependent upon the initial conditions and the exact method of fitting.

## 5.3. LIKELIHOOD

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### 5.3.1 Likelihood Function

Though we understand the general theory for how the likelihood function will turn out, we still need an explicit form for  $p(\vec{x}_i|\vec{\theta})$ . This probability function could be made arbitrarily complex by attempting to account for every little physical detail, so we need to state the assumptions and physical processes that will be modeled. Using the fact that we know how to get the geometric time and direct distance that the emitted photon would travel before hitting the DOM given a guess track, the next step would be to account for the scattering and absorption of light. This seems like a small change, but has large repercussions in the probability distribution describing the data given a hypothesis track. IceCube uses the Podel function [48], which explicitly takes the following form,

$$p(t_{\text{res}}|\vec{\theta}) = \frac{1}{N(d)} \frac{\tau^{-d/\lambda} \cdot t_{\text{res}}^{d/\lambda-1}}{\Gamma(d/\lambda)} \cdot \exp\left(-t_{\text{res}} \cdot \left(\frac{1}{\tau} + \frac{c_{\text{medium}}}{\lambda_a}\right) - \frac{d}{\lambda_a}\right),$$

$$N(d) = e^{-d/\lambda_a} \cdot \left(1 + \frac{\tau \cdot c_{\text{medium}}}{\lambda_a}\right)^{-d/\lambda}, \quad (5.12)$$

where  $d$  is the photon travel distance,  $\lambda$  is the scattering length,  $\lambda_a$  is the absorption length,  $\Gamma(x)$  is the Gamma function,  $c_{\text{medium}}$  is the speed of light in water, and  $\tau$  is an inverse time parameter for fitting [48]. Given these parameters, which are physically motivated or fit using simulated data, the Podel function gives the probability of observing a residual time for a hypothesis track. It is important to note here that  $\vec{\theta} = (\vec{v}, \vec{x}, t_{\text{vertex}})$ , where we have the track direction, vertex position and vertex time respectively.

The Podel function favours positive residual times, so much so the probability has varying behaviours as  $t_{\text{res}} \rightarrow 0$ . Figure 5.4 shows this behaviour over three different

### 5.3. LIKELIHOOD

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distances over a domain for 300 nanoseconds in residual time. As the distance is increased for the emission point, the probability of observing a photon later than expected increases. This is consistent with the concept of the probability of light being absorbed or scattering increasing as you increase the distance.

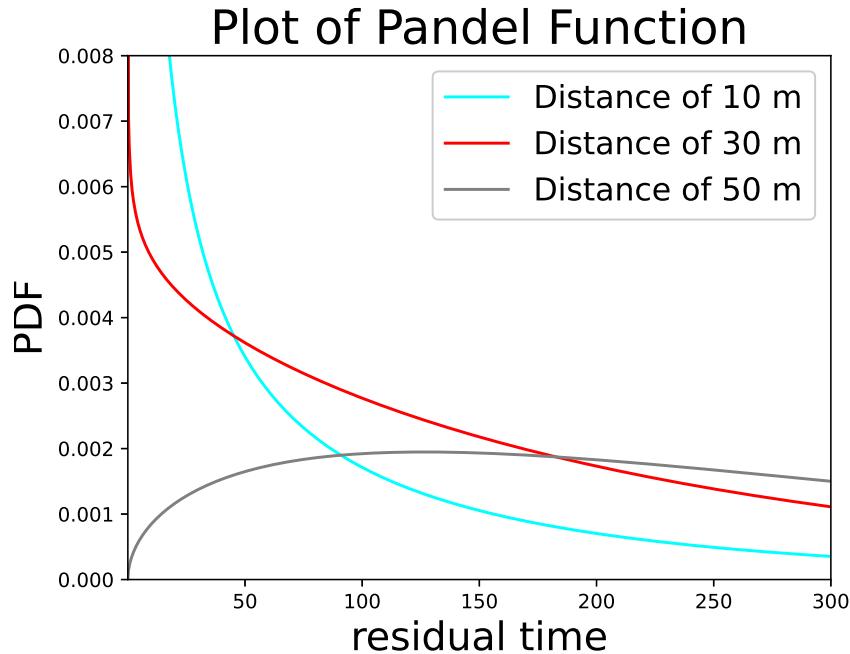


Figure 5.4: A figure showing a plot of the podel function over 300 nanoseconds with 10 meters, 30 meters and 50 meters of travel distances for the emitted light. The fit parameters, including  $\lambda_a$  and  $\lambda_s$ , are fit according to the IceCube parameters as described in [48].

Theoretically this probability distribution should describe the behaviour of light in water, once the parameters have been fit accordingly. This, however, is not the case practically. The issue arises particularly with the behaviour around  $t_{\text{res}} = 0$ , since in real data there are statistical fluctuations due to detection capabilities. By ignoring the detection step of the process, the Podel function can't effectively model the data as one would actually observe it, and for this reason the detector error needs to be

### 5.3. LIKELIHOOD

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folded into the Pandel function.

The simplest model for detector error is a gaussian, and a known method of folding this error into the Pandel is a convolution, as done here [51]. The gaussian width can then be fit and altered to account for any time jittering caused by detection limitations and will allow for negative time residuals. If, as in [51], the pandel function is reparameterized as  $p_{\text{pandel}}(\rho, \xi, t)$ , then the convolution with a gaussian of mean zero and standard deviation  $\sigma$  is given by

$$\mathcal{F}_\sigma(\rho, \xi, t) = \int_0^\infty \frac{dx}{\sqrt{2\pi\sigma^2}} p(\rho, \xi, x) e^{-(t-x)^2/2\sigma^2}. \quad (5.13)$$

This integral has an exact form [51],

$$\mathcal{F}_\sigma(\rho, \xi, t) = \frac{\rho^\xi \sigma^{\xi-1} e^{-t^2/2\sigma^2}}{2^{(1+\xi)/2}} \left[ {}_1F_1\left(\frac{1}{2}\xi, \frac{1}{2}, \frac{1}{2}\eta^2\right) - \sqrt{2}\eta \frac{{}_1F_1\left(\frac{1}{2}(\xi+1), \frac{3}{2}, \frac{1}{2}\eta^2\right)}{\Gamma(\frac{1}{2}\xi)} \right], \quad (5.14)$$

where

$$\eta = \rho\sigma - \frac{t}{\sigma} \quad (5.15)$$

and  ${}_1F_1$  is the confluent hypergeometric function [51]. Fortunately  ${}_1F_1$  is available in multiple computing languages and allows for numerical evaluation of  $\mathcal{F}_\sigma(\rho, \xi, t)$  [51]. This is still non-trivial due to convergence bounds on  ${}_1F_1$ , and as in [51] approximations for different domains must be used in order to accurately be able to use the entire distance and time domain.

# **Chapter 6**

## **Results**

### **6.1 Likelihood**

# **Chapter 7**

## **Summary and Conclusions**

**7.1 Summary**

**7.2 Future Work**

**7.3 Conclusion**

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