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NEUTRINO FLOOR CALCULATION: A BACKGROUND FOR THE DIRECT DETECTION OF WIMPS

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"Physics is really nothing more than a search for ultimate simplicity, but so far all we have is a kind of elegant messiness."

Bill Bryson, A Short History of Nearly Everything

Abstract

Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) is a process that constitutes an important background source for the direct detection of WIMPs, one of the most attractive dark matter candidates. In this work, our goal is to study minima of the cross sections for WIMP-Nucleus collisions that would stand out over the neutrino floor, focusing on detectors that include Liquid Xenon Time Projection Chambers. We present the CEνNS mechanism, and explain why it produces a signal that can be confused with the one expected from WIMPs. Then, we examine the neutrino sources in our universe, and the fluxes of neutrinos that each of them produce in order to determine the background they constitute for WIMP detection. To compare the number of events expected from neutrinos with the number of events that WIMPs could provide, we calculate the neutrino-nucleus and WIMP-nucleus cross-sections and collision rates. Lastly, we compute the WIMP-nucleus cross-section to WIMP mass relation, for several energy thresholds that a detector may have, that would be needed to successfully detect dark matter with a 90% confidence level.

Acknowledgments

First of all, I would like to thank my family. They have provided everything I have ever needed, and they raised me to be a very curious person, which finally led to my interest in studying science. If my parents had not answered my many questions throughout my childhood with the greatest patience there has ever been, or had not encouraged me to learn about and understand the world around me, I would not have decided to study physics. They also raised me in a home full of love, they were present in every single one of my accomplishments, and still are to this day. They were a huge support in the making of this research, lifting me up when I did not feel like getting anything done and reminding me why I chose this path. I am also thankful of my amazing sister, who has always been my biggest fan. She reminds me that it is okay to feel down sometimes, and she has my back whenever I have to fight anyone or anything.

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Chapter 1

Introduction

In humanity's constant efforts to understand our universe, we have come across an important yet difficult to solve problem: we do not really know what it is mostly made of. Ordinary matter and energy, which is everything we actually know and see in our everyday lives, only accounts to less than 5% of the total mass-energy content of our universe [1]. The rest is what we call "Dark matter" and "Dark energy".

Dark matter is still a hypothetical form of matter, which we think constitutes about 27% of our universe. It does not interact with the electromagnetic field, making it really hard to detect, but we believe it must exist, because if it did not, our universe would be a very different place.

Real evidence of dark matter was first discovered in 1933, when Fritz Zwicky [2] measured the visible mass of a cluster of galaxies. He found that the mass he calculated was much too small to provide the centripetal forces for such fast orbits, meaning that, if the cluster only had that amount of mass, the gravitational pull of the cluster would not be enough to keep it together, the cluster would be ripped apart and the galaxies inside of it would escape. He therefore concluded that something else was needed to keep the cluster together, something that contributed to the gravity pull of the cluster but that could not be seen or measured through our usual methods. He called that substance "dark matter".

Since that discovery there have been many more to prove the existence of dark matter. An example of that is the rotation curves of galaxies. Using Newton's law of gravity, we will find that, the further away we move from the center of a galaxy the slower the stars in that region should be moving. That is because, from what we can see, the majority of stars in a galaxy is found near the center, and there are far less stars as we move away from it. But when, in the 1970s, Vera Rubin and Kent Ford measured the velocity of stars in the Andromeda galaxy [3] [4], they found out they were not rotating as they should be. It turned out that stars at the edges of the galaxy were moving at the same speed as stars near the center, instead of at decreasing velocities as they expected to find. This discovery could only be explained if the amount of matter in that galaxy was more than what they had been able to measure, and if it was distributed differently than what they could see. We now believe that there is more and more dark matter as we move away from the center of galaxies, in order to keep the high velocities far away from the center.

There are many more phenomena that could only be explained by the existence of dark matter, from gravitational lensing [5] to the CMB itself [6]. We cannot deny the existence of dark matter any more, so what we must do next is to understand what dark matter is really made of, and in order to achieve that, we must first be able to detect it in other forms besides its gravitational effects.

In this project I will be studying one method of detection of dark matter, and the background that neutrinos may produce in it. I will consider different sources of neutrinos in order to find the total flux that we receive here on Earth, and with that find out what the characteristics of dark matter should be in order for us to be able to measure it, and for the observations to not be completely covered by neutrino noise.

1.1 Weakly Interacting Massive Particles

Although we know for sure that dark matter must be out there, we have no clarity of what it is. It is obvious that the observations we have made put some constraints on what it can and what it cannot be. The first and most obvious constraint is that it cannot interact with the electromagnetic field, because if it did then it would not be dark. Another thing we know about dark matter is that it interacts with gravity, because that is the thing that made us detect it in the first place. But there are other, more interesting characteristics we know it must have, and that gives us an idea of what it could resemble.

For instance, we know that dark matter must be cold, which means that it travels at non-relativistic speeds. We know this because one of the observations leading to the idea of dark matter was that galaxies have less stars at the edges, but all the stars forming the galaxies are rotating at the same speed. That led us to conclude that dark matter must be accumulating in the form of halos around galaxies and other forms of ordinary matter, and that immediately tells us that it must be cold. If dark matter were hot (moving at relativistic speeds), then after the Big Bang it would just have kept moving away, and it would not have been able to form halos. That would mean galaxies would have different structures and behaviours from the ones we observe. The truth is, a small portion of dark matter could be hot, but the majority of it must be cold in order for everything to add up.

The other interesting fact we know about dark matter is that it must be stable, or with lifetimes at least of the age of the Universe. That is because if it decayed, we would not measure it in such big amounts as we do today. So, with that in mind, we can have some theoretical models of what dark matter could look like.

There are a lot of theories about the nature of dark matter, one of them being primordial black holes (black holes that formed in the early universe) as dark matter providers [7]. Another option is that dark matter is not really "matter", but rather an effect or a manifestation of gravity itself (which would requiere us to modify the current theory of gravitation) [8]. However, of the most likely, and that is of my particular interest, is dark matter being some kind of particle.

The first thing that comes to mind is that if it is a particle, and it interacts with gravity, then it must have a non zero mass (although there are some theories that consider zero mass particles, like the so-called "dark photon", see [9]). There are mainly two candidates for a massive dark matter particle: axions and wimps. Axions are particles that were proposed as a way to solve the strong CP problem, and it was later discovered that they could also be a solution to the dark matter interrogant [10]. They are particles with very little mass, of around $10^{-5}[\text{eV}/c^2]$ to $10^{-3}[\text{eV}/c^2]$ [11], have no electric charge and very little interaction cross-sections with ordinary matter.

The other candidate for a dark matter particle is the WIMP, which stands for Weakly Interacting Massive Particle. "Weakly Interacting" because it interacts with ordinary matter via the weak force, or some other new interaction beyond the Standard Model but with a similar or lower magnitude; and "Massive" because it has a non-zero mass (and, in almost every model, very large compared to axions or other particles, and therefore WIMPs would be travelling at speeds considerably smaller than the speed of light).

WIMPs are actually one of the most accepted hypotheses in this area, and they are being searched in experiments such as LUX [12] and, most recently, XENON1T [13] and in the ATLAS detector at the LHC [14]. Their existence is a really attractive idea for various reasons, the first of them being that WIMP-like particles are predicted in many theoretical models, arising naturally from them. Examples of such models are Supersymmetry theories [15] and models that include universal extra dimensions [16]. Another reason why WIMPs are one of the leading candidates for dark matter is that they are testable by experiment, which has to do with their predicted mass and cross-section range being within reach of current detectors, or of detectors that are now being made or planned to be made in the near future. And it is always good to be able to look for new physics right away.

Nonetheless, one of the most interesting reasons why WIMPs are so popular is that, if you calculate the mass that a WIMP particle should have in order for it to interact weakly with ordinary matter (knowing that the weak force can be characterized by a cross-section range), and plug it into early universe models (to find out how it interacted with matter through time), what you get is the abundance of dark matter that we can see today. Of course, that is under some assumptions (for instance, that WIMPs were thermally produced), but those assumptions are the most accepted ones anyways. This coincidence is called the "WIMP miracle" [17], as it makes WIMPs able to account for all the dark matter content of our universe.

It is important to note that WIMP is more like an umbrella term or a category, and it includes a wide variety of particles. Of course, we do not know what dark matter really is, and because it is so abundant, the most sensible thing to believe is that dark matter is not a single kind of particle, but is rather composed of many different kinds. So we must not think that only one type of WIMP is the right one, and see others as rivals; we should rather keep an open mind and be aware of all the possibilities there are.

One of the most studied WIMPs is called the Neutralino, a hypothetical particle from supersymmetric models. Other supersymmetric candidates include de Sneutrino and the Gravitino, although they do not work as well as the first one. If the theories of supersymmetry are proven to be wrong, we are still left with WIMP candidates, as are the sterile neutrinos, the Lightest Kaluza-Klein Particle (LKP), and many more. Further information about the different types of WIMPs can be found at [18] and [19].

All that being said, in this study I will stick with the WIMP model of dark matter, in its most general form: I will just assume dark matter is a type of massive particle, that interacts weakly with ordinary matter, with a spin-independent cross section. I will look for the minimum cross section for WIMP interactions that generates a signal strong enough not to be confused with the one generated from neutrinos that naturally reach the Earth.

1.2 WIMP detection methods

There are generally three methods to detect WIMPs: direct detection, indirect detection, and production at colliders. Direct detection is based on the idea that WIMPs, although weakly, interact with ordinary matter, and thus we could build detectors that are sensitive to those interactions. WIMPs would scatter with the nuclei of the atoms in the detector, and we would try to measure the recoil energy of those nuclei to then estimate the mass of WIMPs and the scattering cross-section.

Indirect detection, on the other hand, assumes that dark matter must do one of the following: it either decays, or it annihilates with itself. Either way, it is called indirect detection because we do not look for WIMPs, but rather the products of their annihilation or decays, coming from regions of the cosmos where the dark matter density is particularly high, such as the Sun. The most common products studied by this method are photons, whose trajectory can be easily tracked but that have a very large background; neutrinos, which have also a clear path and not a very large background, but are very hard to detect; and charged particles, that are very hard to track because they interact with almost everything on their way to Earth.

The last option is to search for WIMPs in particle colliders, which aim at producing new particles out of high energy collisions of protons or electrons and positrons, or at generating heavy particles which decay into new particles. However, we cannot forget that WIMPs only interact weakly with ordinary matter, which means detectors in particle colliders cannot detect them. Therefore, what we must do is look for final states with missing energy, which is generated by the produced dark matter particles that escape undetected. Of course these searches depend strongly on the discovery of new physics, or at least new particles that could decay and produce WIMPs.

More information on each detection method can be found in Refs. [20] and [21], but, for the purpose of this investigation, I will be focusing on the direct detection method for WIMPs.

There are many different ways in which one could measure the recoil energy of a nucleus. For example, if we use a semiconducting crystal as a detector, we can search for dark matter-induced charge signals via the generation of an electron-hole pair. Or, we could measure the temperature increase that a WIMP-nucleus interaction produces in a detector. Another, more extravagant idea is to use liquids which are kept at a temperature just below their boiling point, and when a WIMP hits the liquid, it transfers energy into it and produces a local phase transition, forming a bubble. Although these are all very good options (see Ref. [22] for details), this study is done for a Xenon target, which is used in noble liquid detectors.

Noble liquid detectors use noble gases, like xenon or argon, that are liquefied to form dense and compact dark matter targets. In order for the detector to work, these materials must be kept at very low temperatures, lower than -108°C for the case of a xenon target. One of the most important experiments for WIMP direct detection, the XENON1T, uses this method, so I have chosen to explain it further.

The XENON1T is what we call a dual-phase time projection chamber detector, which means it can detect two kinds of signals. It is basically a big tank full of liquid xenon (more than 3 tons), and at the top of it there is a thin layer of xenon in its gaseous phase. This tank is inside a larger tank full of water, which is used to identify charged particles (mainly muons) and rule them out, because charged particles produce Cherenkov radiation, but uncharged particles, like WIMPs, do not. The Liquid Xenon Time Projection Chamber (LXeTPC) sits within a cryostat, which allows the xenon to be cold enough to be liquid, without having to freeze the water in the outside tank. And of course, the XENON1T detector is covered by 1400 meters of rock (it is installed inside the Gran Sasso underground laboratory (LNGS) in Italy), which provides shielding from cosmic rays.

The process goes like this: first, a WIMP reaches the detector and, hopefully, interacts with one of the xenon atoms in it. The case I am interested in is the WIMP hitting the xenon nucleus, in what is called an elastic scattering (in some models, dark matter collides with electrons around the nucleus and produces electron recoils, which can also be detected in liquid xenon experiments). The elastic nuclear scattering results in a recoil of the xenon nucleus, which can produce excited and ionized atoms. An excited atom Xe* combines with a neutral one forming a xenon excimer (which is short for excited dimer). It should be noted that xenon, being a noble gas, does not form molecules because it has its valence shell completely filled with electrons. However, when xenon is in an excited state, it can form a two-atom molecule composed of a neutral Xe and an excited Xe*, which we call an excimer state. These molecules have a very short lifetime, decaying after a few nanoseconds. This decay is what the detector "sees", and the whole process can be summarized by the following formula:

$$Xe^* + Xe \longrightarrow Xe_2^* \longrightarrow 2Xe + h\nu \tag{1.1}$$

Meanwhile, an ionized atom is a xenon atom missing one or more electrons. These electrons could be reabsorbed by the detector and form excited xenon atoms, which would eventually decay and emit light. This can be avoided by submitting the detector to a strong electric field, which is done in detectors that have TPCs. By orienting the electric field in the right direction, detectors can get rid of electrons, but what is more important is that they can measure them by leading them to the gaseous xenon that sits on top of the liquid phase. Electrons collide with these xenon atoms, creating more light signals. If a charged particle were to interact with the electrons in the liquid Xe atoms and produce electronic recoils, these electrons would be directed to the gaseous Xe too, but the photons they produce have a very different energetic profile, and therefore these two processes, electronic and nuclear recoils, can be distinguished from one another.

In order to measure all of this, the chamber has photomultiplier tubes (PMTs) at the top and bottom, which are responsible for detecting the scintillation that each interaction produces. The signal produced by photons that come from the decay of xenon dimers in liquid xenon is called S_1, and the one produced by electrons in the gaseous xenon is called S_2. A dual-phase TPC can measure both signals, and reconstruct the initial interaction by putting all the information together. It is called time projection chamber because, by measuring the time it takes for the electrons to get to the gaseous xenon, the detector knows the location of the interaction with mm-precision. The following diagram, which I took from Ref. [22], may be useful to picture the detection process:

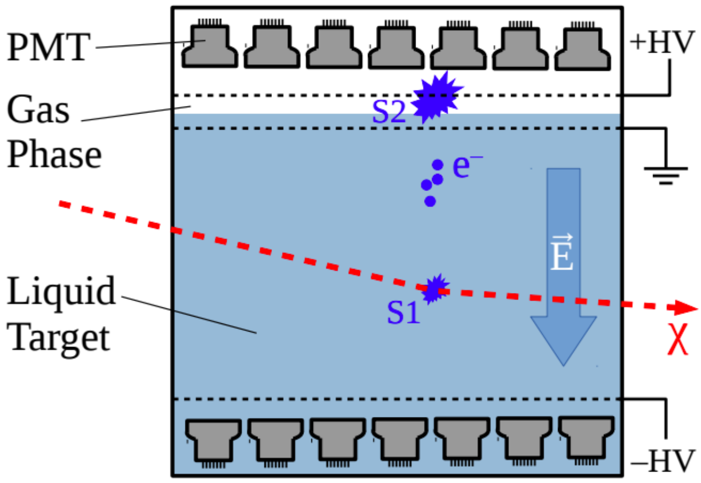

Figure 1.1: Detector using Xenon as WIMP target detect the primary scintillation light (S_1) as well as the ionization signal (S_2) in a dual-phase time projection chamber (TPC). (Image taken from Ref. [22])

More detailed information about the operation of detectors that use noble gases as targets can be found at [23]. To know more about the XENON1T experiment, see [24] and [25].

That is the direct detection of WIMPs in a nutshell. Because we know so little about dark matter, the experiments that we use to detect it are looking for rather ambiguous signals. All we know is that WIMPs may transfer energy to a target nucleus, and the detectors aim at measuring that energy. However a nucleus recoil can be produced by almost any particle of the Standard Model, which is a problem when we want to be sure that we have found evidence of WIMPs. The problem is partially solved by all the mechanisms we mentioned, such as submerging the detector in water and installing it under a mountain. With those techniques one can block the majority of the particles that could produce a signal in the detector. But there is a particle that can pass through all of these walls: the neutrino. The neutrino has no electric charge, and thus does not produce Cherenkov radiation, so the water tank does not detect it. And even going underground, there is little chance that neutrinos will interact with the Earth, as they are known to interact with almost anything. So the amount of neutrinos reaching the detector is non negligible, which leads me to study them and see how much "noise" they make in the direct detection of dark matter.

1.3 Coherent elastic neutrino-nucleus scattering

Whenever we hear about neutrinos, the first thing that comes to our minds is that they interact very little with matter. They are particles with almost zero mass, and therefore travel close to the speed of light. When neutrinos were first theorized, scientists thought they would never be able to detect them, because the interaction cross-section with any other particle was way smaller than the ones they were used to, and they would need gigantic detectors in order to measure neutrino interactions. But eventually, neutrinos were discovered, and since then, we know much more about them and the Standard Model of particles.

In 1973, a huge discovery was made regarding neutrinos: the discovery of a weak neutral current in neutrino interactions [26]. This implied that neutrinos could interact through neutral Z bosons, and therefore collide elastically with quarks. Soon after that, Daniel Z. Freedman proposed that, if a weak neutral current existed in neutrino interactions, it would mean that there should be flavor independent, coherent interactions between neutrinos and atomic nuclei [27]. This idea was a true game-changer, but of course it had its constraints. First of all, coherent interactions with an atomic nucleus are only possible when the incoming particle has a relatively small energy, in fact, we know that $qR << 1$ is required, where q is the momentum transfer and R is the nuclear radius. This condition is equivalent to say that the wavelength of the mediating particle must be larger than the size of the nucleus [28]. This is a rather intuitive constraint because a particle that collides with a nucleus at very high energy is able to tear the nucleus apart, while at low energy, the long wavelength implies that the whole nucleus feels the same force everywhere and therefore has a chance of remaining intact after the collision.

Another important thing to have in mind is that neutrinos have little mass and consequently the kinetic energy they transfer to the atomic nucleus is not very large. There is a compromise in this whole process, because from one point of view, one would want a really heavy nucleus as a target, because the probability of coherent interaction scales with the square of the number of nucleons in it [29]. But, on the other hand, the heavier the nucleus, the less it recoils and the harder it is to detect that recoil. So of course, the detection of coherent elastic neutrino nucleus scattering (also called CEνNS) would be a challenge. But it was also a very attractive idea, because it was found that the cross-section of this interaction was considerably larger than other neutrino related cross-sections. In fact, as shown in Figure 1.2 (which I took from [30]), this new interaction has a cross-section more than two orders of magnitude larger than the Inverse Beta Decay (IBD) cross-section, the mechanism employed for neutrino discovery. This was actually amazing news, because it meant that detectors aiming to see CEνNS did not need to be as big as the ones used to discover neutrinos. This of course meant that less money and resources were needed to prove that the CEνNS process exists, which made everyone really happy.

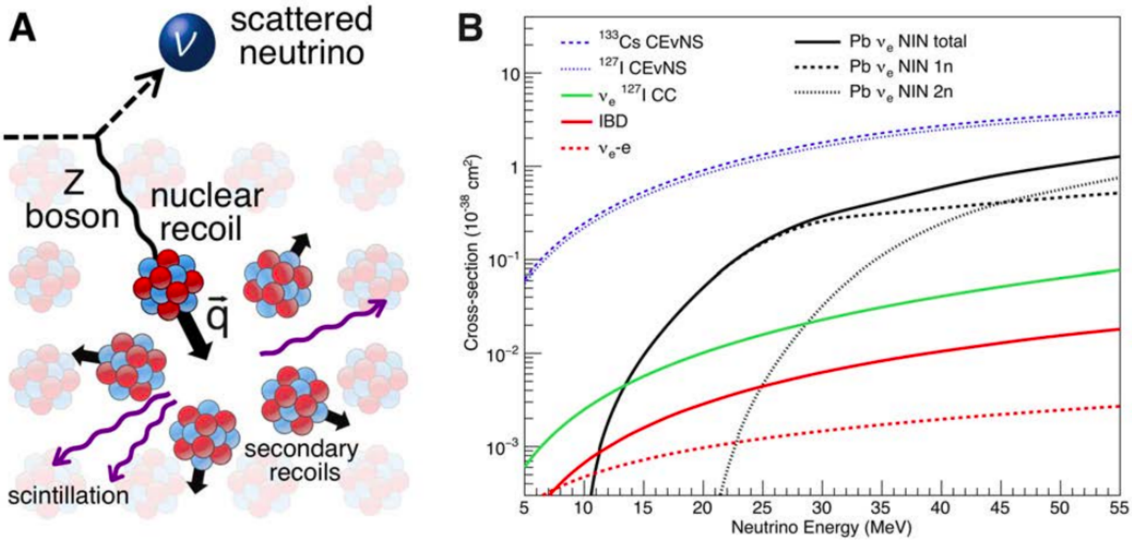

Figure 1.2: (**A**) Coherent Elastic Neutrino-Nucleus Scattering, mediated by a neutral Z boson. (**B**) Total cross-sections from CEνNS and some known neutrino couplings: neutrino-electron scattering, charged-current (CC) interaction with iodine, inverse beta decay (IBD), and neutrino-induced neutron (NIN) generation. (Image taken from Ref. [30])

Even considering the large cross-section of the CEνNS, the measurement of this process was a huge challenge to the scientific community, mainly because of the smallness of the nucleus recoil energy it produces. Since its theoretical prediction in 1973, the CEνNS evaded detection for more than 40 years, until it was finally discovered and precisely measured in 2017 by the COHERENT collaboration [30]. This has brought and will continue to bring new ways of studying the Standard Model and searching for physics beyond it. Examples of that are the study of weak interaction parameters (such as the electroweak mixing angle [31] or the nuclear form factors [32]) and the search for electromagnetic neutrino properties [33].

Now, from the dark matter point of view, the importance of the discovery of CEνNS is that we now have the most important source of background in direct detection of WIMPs: neutrinos. We are now certain that neutrinos are able to produce the exact same signal that WIMPs are expected to produce in a detector, which is a simple nucleus recoil. So naturally, our main interest now is to know everything about this background: how many neutrinos reach the Earth, how much energy they carry, how likely is it that they interact with our WIMP detector, how much sensitivity is needed for a detector to measure those interactions, and most importantly, if we will be able to see WIMPs and tell their signal apart from other sources.

1.4 Neutrino sources in the universe

If we want to correctly identify and characterize the neutrino background for direct detection of WIMPs, the first thing we need to know is which neutrinos are actually reaching the detectors and interacting with them. The neutrinos that we can "see" here on Earth come from many different sources, and depending on the process that produces them, how far away it takes place and how common it is, we know how many neutrinos we will measure and in what range of energy they'll come.

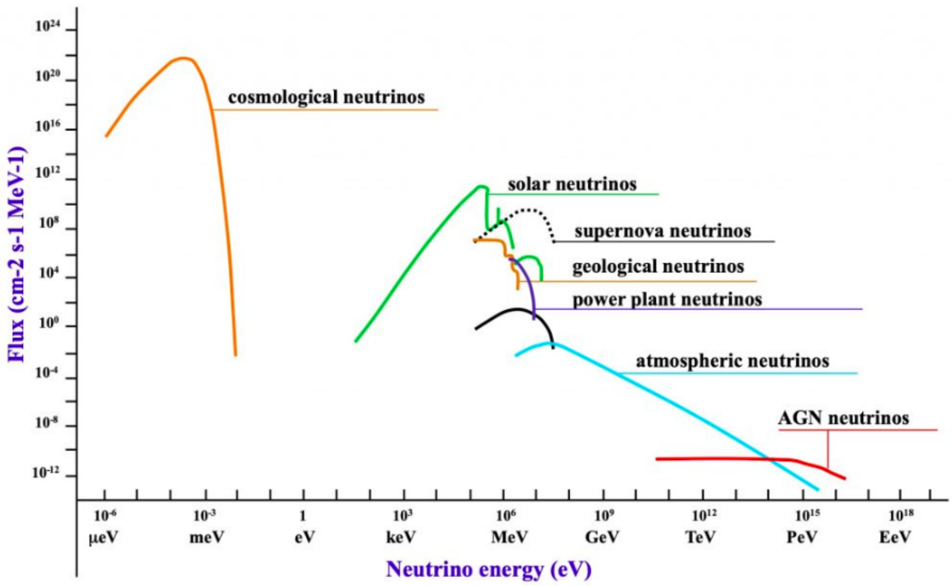

Figure 1.3: Predicted spectral neutrino flux (number of neutrinos per unit area per unit time and per energy) as a function of the neutrino energy, in logarithmic scale. Each color represents a different source. (Image taken from Ref. [34])

Figure 1.3, taken from Ref. [34], includes the main neutrino sources and the expected neutrino fluxes they produce. It is clear that neutrinos cover a vast range of energies, but of course WIMP detectors are not sensitive to all of them. But before I start to discriminate which sources are important and which are not, let's take a brief look of what the sources are.

The least energetic neutrinos we can see in Figure 1.3 are cosmological neutrinos, which are neutrinos that come from the early universe. These neutrinos are predicted to be as abundant as the photons in the CMB, so their flux is very intense. However they have so little energy (less than the mass of an electron) that they are, at least with our current technology, very difficult to detect. Of course, the energy of these neutrinos is far too small to produce any kind of measurable nuclear recoil, so we immediately rule them out from our background. To learn more about them, see [35].

Next in the picture come solar neutrinos, which are produced in fusion processes which fuel the Sun. These neutrinos have the perfect range of energy to interact with our detectors and produce nuclear recoils, and they are also the most abundant in that energy range, so we will study them in subsection 1.4.1.

Supernova neutrinos come from supernovae, the explosion of massive stars. These events are amongst the most violent in the universe, and radiate as much energy in a week as the sun radiates in 10 million years. They also produce a lot of neutrinos, and they can be very useful because, as they interact very little, they can escape the supernova faster than other particles, such as photons. Because of that, these neutrinos could tell us much about what happens in a supernova, and could also alert us to direct our telescopes to the region of the sky where the explosion is happening, for us to be ready when the light arrives. But for this particular study I will not consider them mainly because solar neutrinos and atmospheric neutrinos cover the majority of the energy range we are interested in, and the contribution of supernova neutrinos is not as important. Although other studies do, because their energy range matches the one WIMP detectors are sensitive to. More information about this source of neutrinos can be found in Ref. [36].

Geological neutrinos, often called geoneutrinos, are those that come from the decay of radioactive elements inside the Earth. We know a lot about the Earth's crust, but very little about its interior. This translates into an important uncertainty about how much radioactive material is in the core of the Earth, and subsequently, how many geoneutrinos are actually produced. Thus, if we are able to measure the geoneutrino flux precisely, we will collect information about the Earth's core (learn more in Ref. [37]). Once again, I am excluding these neutrinos from my study, because of the uncertainty in the flux predictions, alongside the reasons I mentioned for the supernova neutrinos.

Nuclear plants also produce neutrinos (actually anti-neutrinos) as a by-product of nuclear fission, making power stations a location of interest for scientists to set up neutrino experiments. An example of this is the Double Chooz experiment [38], which is working on measuring a fundamental parameter in the context of neutrino oscillations, the mixing angle θ_{13}. Although this is an effective way of studying neutrinos in a controllable enviroment, I am disregarding them as well, assuming the experiment is far away from nuclear reactors.

Atmospheric neutrinos are produced by cosmic rays interacting with the Earth's atmosphere, and they are an important source of high energy neutrinos. I will consider the neutrinos produced by this source in this study, so I have dedicated subsection 1.4.2 to them.

Lastly, AGN neutrinos are high-energy neutrinos produced at Active Galactic Nuclei (AGN). AGNs are compact regions at the center of some galaxies, and the most powerful emitters of radiation in the known universe. That is why they are thought to produce high-energy neutrinos, but this is yet to be discovered [39]. Nevertheless, neutrinos from these sources are way out of the energy range that could produce CEνNS, so they do not constitute a background for WIMP direct detection.

Now that we know what each line in Figure 1.3 represents, I will focus on the two main background sources for CEνNS detection: solar neutrinos and atmospheric neutrinos.

1.4.1 Solar Neutrinos

The Sun, just like any other star, produces energy via nuclear fusion. Protons interact with each other to form deuterium, which are then combined to form helium, which then combines into beryllium, and so on. Several of these processes have byproducts, and the one that is of our particular interest is, of course, the neutrino.

The Sun generates energy via two fusion chains, known as the pp (proton-proton) chain and the CNO (carbon-nitrogen-oxygen) cycle. The pp chain is responsible for 98.4% of the total solar output, while the CNO chain, also called CNO cycle, accounts for the remaining 1.6%. A diagram of the main reactions that occur in each chain is shown in Figure 1.4 ([40]). The branching percentages (called branching ratios when divided by 100) indicate how likely each reaction is. Take, for example, one of the first reactions in the pp chain: two protons interact and form a deuterium nucleus, emitting a positron and an electronic neutrino.

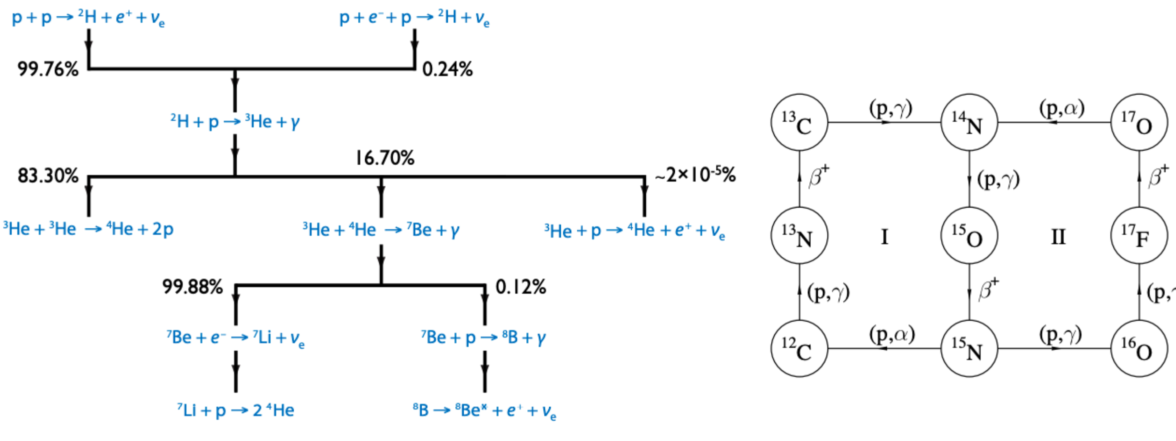

Figure 1.4: pp chain (left) and CNO cycle (right). (Images taken from [40])

There are several reactions involved in the pp chain and CNO cycle, and Figure 1.4 only shows the most important ones. But it is clear that not all the reactions happen with the same frequency, and neither do they produce the same neutrinos. So, one could sense that not all of them constitute an important background in direct WIMP detection. Figure 1.5 ([41]) includes some of the main reactions in the pp and CNO chains, and the neutrino fluxes they produce as a function of neutrino energy.

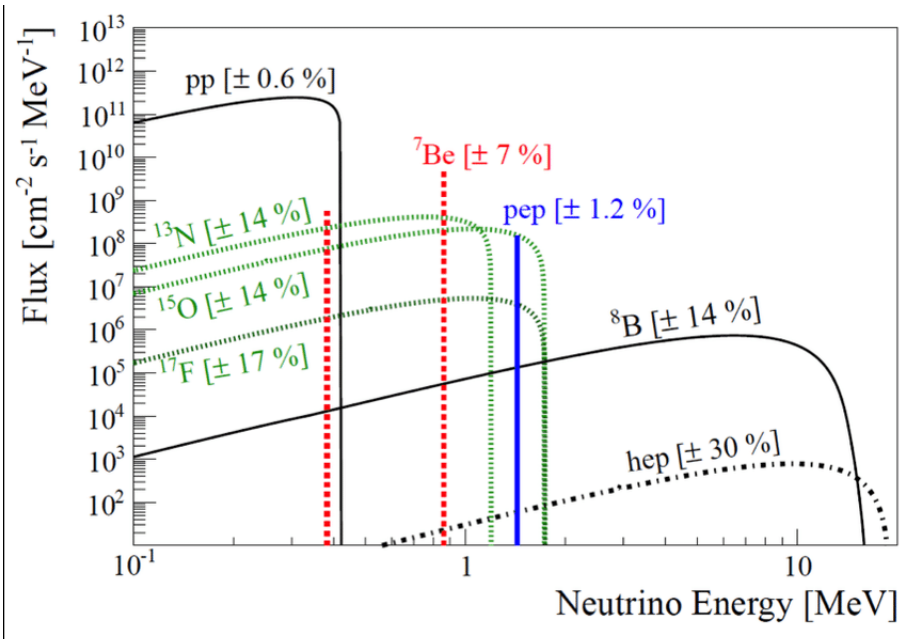

Figure 1.5: Solar neutrino spectrum. In green, the main contributions from the CNO cycle, and in other colors the ones from the pp chain. (Image taken from [41])

In this study, I will only consider the following reactions: ^8B, pp, hep, ^{15}O, ^{17}F and ^{13}N. As for the flux normalization, I will use the values in Table 1.1, following the recommendations from [42].

^8B	$5.25 \cdot 10^6$ [cm^{-2}s^{-1}]
pp	$5.98 \cdot 10^{10}$ [cm^{-2}s^{-1}]
hep	$7.98 \cdot 10^3$ [cm^{-2}s^{-1}]
^{15}O	$2.05 \cdot 10^8$ [cm^{-2}s^{-1}]
^{17}F	$5.29 \cdot 10^6$ [cm^{-2}s^{-1}]
^{13}N	$2.78 \cdot 10^8$ [cm^{-2}s^{-1}]

Table 1.1: Normalization values for solar neutrino fluxes.

1.4.2 Atmospheric Neutrinos

The Earth is constantly being bombarded by cosmic rays, which are high-energy particles or clusters of particles that come from space. The sources of these particles are of course the Sun, distant galaxies, and astronomical objects inside our own galaxy. The most common form of cosmic rays are protons (95%), but there are also alpha particles, electrons and heavier nuclei. When cosmic rays reach the Earth, they interact with nuclei in the atmosphere, creating what we call "showers", cascades of hadrons, electrons, positrons and neutrinos produced by the succesive collisions of the particles created and the atmospheric nuclei. Figure 1.6 ([43]) shows a very detailed example of a cosmic ray shower.

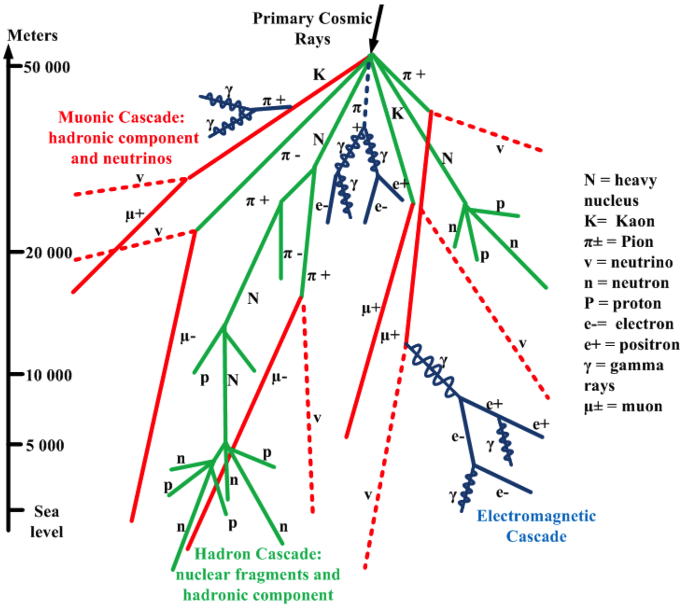

Figure 1.6: Cosmic ray shower. (Image taken from [43])

Although the background from this neutrino source is not as large as the one coming from solar neutrinos, it is important to consider it because atmospheric neutrinos have higher energies, and they cover a different part of the energy range that detectors are sensitive to. In Figure 1.7 (taken from Ref. [44]), there is a summary of the neutrino fluxes from the backgrounds that I will consider for this study. It can be noted that, while solar neutrinos are clearly more common than atmospheric neutrinos, they are only present in an energy range below 20[MeV]. From 20 to 40[MeV], there is a little portion of the spectrum that is dominated by supernova neutrinos (which I will not be considering), and for energies above 40[MeV] atmospheric neutrinos dominate. In Figure 1.7, there are four different sources of atmospheric neutrinos, depending on the flavour (electronic neutrinos, electronic antineutrinos, muonic neutrinos and muonic antineutrinos), but almost all of the lines are overlapping, and telling them apart is not really necessary.

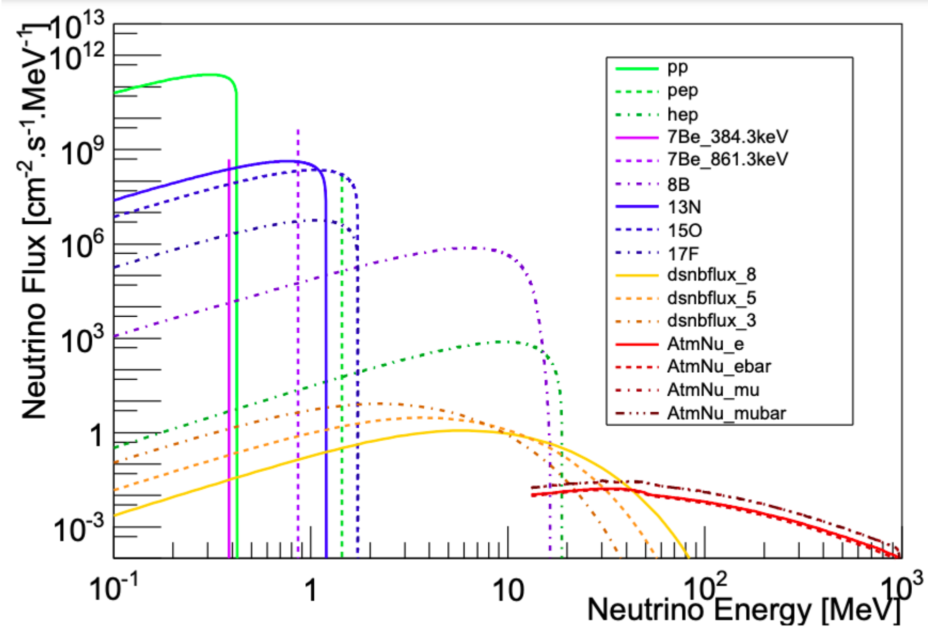

Figure 1.7: Relevant neutrino fluxes which are backgrounds to direct WIMP detection. (Image taken from Ref. [44])

I will not go into the details of the interactions happening in cosmic ray showers, because I am going to work with all of the atmospheric neutrino sources as if they were a single source, not caring whether the neutrinos are electronic or muonic, or which cosmic ray they come from. This is validated by the similarities between all of the sources shown in Figure 1.7, the fluxes that they generate are all the same shape, and lie in the same order of magnitude. The normalization factor I will use for the atmospheric neutrino flux as a whole, which also comes from Ref. [42], is 10.5 [$\text{cm}^{-2}\text{s}^{-1}$]. It can be noted that, in that paper, the authors also treat atmospheric neutrinos as if they came from a single source, and it is usually done when investigating the background sources for direct WIMP detection.

Chapter 2

Collision rate calculations

2.1 Neutrino-nucleus collision rate

Let us start with a simplified model:

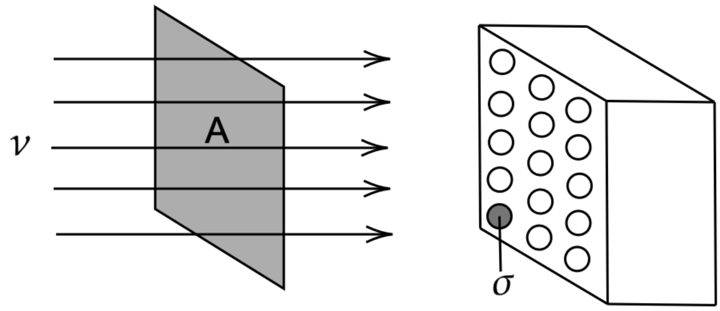

Figure 2.1: Diagram of a neutrino flux going towards a detector.

Let j be the incident neutrino flux, which is valid in a region of area A, such that the number of incident neutrinos N_ν is $N_\nu = j \cdot A \cdot \Delta t$. These neutrinos are colliding into a detector, a piece of material of cross-sectional area A, which contains a total of N_N nuclei, but is thin enough that those nuclei do not overlap. Each nucleus has a cross-section σ. Therefore, the total collision area will be equal to $N_N \cdot \sigma$, and the number of collisions per unit time will be:

$$\frac{N_{coll}}{\Delta t} = N_N \cdot j \cdot \sigma \Longrightarrow N_{coll} = N_\nu \cdot \frac{N_N \cdot \sigma}{A} \tag{2.1}$$

Note that we can write the number of nuclei in the detector as a function of the mass of material in the detector, as $N_N = \frac{M}{m_N}$, where M is the total mass of the material and m_N is the mass of a single nucleus. Furthermore, it should be noted that the expression above can be written as a differential quantity, because we are interested in the number of collisions per unit time, per unit detector mass, and per recoil energy. This is because we can specify σ in a differential form $\frac{d\sigma}{dE_r}dE_r$ as the cross section for a given range of recoil energy. Knowing that the neutrino flux depends on the incident neutrino energy, Equation 2.1 turns into:

$$\frac{dN_{coll}}{M \cdot dt} = \frac{1}{m_N} \frac{dj}{dE_\nu} dE_\nu \frac{d\sigma}{dE_r} dE_r \tag{2.2}$$

Which we can write as follows (where R stands for the collision rate, that is, number of collisions per unit time per unit mass):

$$\frac{dR_\nu}{dE_r} = \frac{1}{m_N} \cdot \int_{E_\nu^{min}} j_\nu(E_\nu) \frac{d\sigma(E_\nu, E_r)}{dE_r} dE_\nu \tag{2.3}$$

The differential neutrino-nucleus cross section is defined as [45]:

$$\frac{d\sigma(E_\nu, E_r)}{dEr} = \frac{G_F^2}{4\pi} Q_w^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F^2(q^2) \tag{2.4}$$

Where G_F is the Fermi coupling constant [46], $Q_w = N - (1 - 4\sin^2\theta_w)Z$ is the weak nuclear coupling (with N and Z the number of neutrons and protons, respectively, and θ_w the weak mixing angle), and $F(q^2)$ is the nuclear form factor for coherent scattering. The latter is an important part of this analysis, because it determines at which energies the scattering stops being coherent.

The nuclear form factor describes the effective spatial extension of a nucleus. It considers the nucleus as an extended object, rather than treating it as if it were point-like. The form factor is the Fourier transform of the nuclear density, having to do with the charge distribution of the nucleus, its radius and other parameters. Although there are many studies and calculations of the form factor, I will work with the one that is commonly used in dark matter searches: the Helm Form Factor [47] [48] [49]:

$$F(q^2) = 3\frac{J_1(qR)}{qR} e^{-(qs)^2/2} \tag{2.5}$$

Where $J_1(qR)$ is the spherical Bessel function of the first kind for $n = 1$, q is the transferred momentum $\left(q = \sqrt{2m_N E_r}\right)$, R is the effective nuclear radius, and s is the nuclear skin thickness. I will use $s = 0.9$[fm], as suggested in ref. [49], and an approximation for the nuclear radius $R = A^{1/3}r$ (where A is the atomic mass number and $r \approx 0.84$[fm] is the charge radius of one proton). This comes from considering the nucleus' volume as the volume of a nucleon times the number of nucleons it contains. Assuming the proton and neutron radii are the same, and taking the nucleus and nucleons as solid spheres, we are left with Equation 2.6. For a xenon detector, $m_N = 1.23 \cdot 10^2[\text{GeV}/c^2]$ and $R = 131^{1/3} \cdot 0.84 = 4.28$[fm].

$$\frac{4}{3}\pi R^3 = A \cdot \frac{4}{3}\pi r^3 \tag{2.6}$$

With this, the form factor for a xenon nucleus looks as follows:

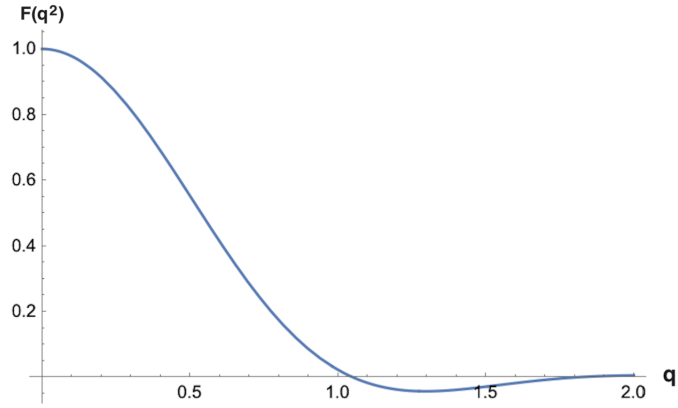

Figure 2.2: Nuclear form factor for a xenon nucleus, $R = 4.28$[fm].

From Figure 2.2 we can see that, when $q \gtrsim 1$, the form factor fades and the coherent collision rate (Equation 2.3) goes to zero. We can therefore calculate which recoil energy turns the transferred momentum q into 1:

$$q = \frac{1}{[\text{fm}]} = 0.198[\text{GeV}] = \sqrt{2m_N E_r} = \sqrt{2 \cdot 123[\text{GeV}] \cdot E_r} \tag{2.7}$$

Which yields $E_r \approx 159$ [keV]. This means we cannot expect to measure nuclear recoil energies above that number, because such a collision would cause the nucleus to break apart.

The last parameter involved in Equation 2.3 is the lower integration limit, E_ν^{min}. In order to understand what this parameter represents, one must comprehend why there is an integral over the energy at all.

If we go back to the scattering kinematics, we should recall that the recoil that a neutrino produces on a nucleus depends not only on the kinetic energy that the neutrino carries, but also on the scattering angle. If a neutrino collides head-on with a nucleus, the transferred momentum is maximum, and so is the recoil energy of the nucleus. But this is not always the case; in fact, neutrinos come from all directions, so we must consider a whole spectrum of energies that an incident neutrino might have in order to produce certain nuclear recoil energy.

Equation 2.3 is an equation for the neutrino event rate as a function of the nuclear recoil energy. In other words, how many CEνNS events are taking place per unit mass per unit time, in which the detector measures a certain nuclear recoil. So in order to consider all the scattering possibilities, we integrate over the incoming neutrino energies, where the lower limit of the integral represents the lowest energy that a neutrino must have in order to produce a given nuclear recoil. As I said before, the maximum transferred momentum is found at a head-on collision, which means that the minimum neutrino energy E_ν^{min} can be obtained from the kinematics of this type of collision:

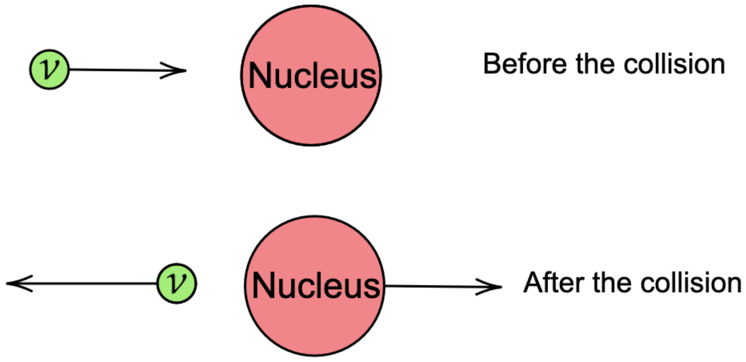

Figure 2.3: Diagram of the CEνNS in the lab frame.

Let E_ν and E'_ν be the energy of the neutrino before and after the collision, respectively. The nucleus is at rest before the collision, so its energy is equal to its mass (taking $c = 1$), and let E_N be its energy after the collision. As energy must be conserved, the first equation we obtain is:

$$E_\nu + m_N = E'_\nu + E_N \tag{2.8}$$

And, following the same notation, from conservation of momentum we get:

$$p_\nu = -p'_\nu + p_N \tag{2.9}$$

Using that $E^2 = p^2 + m^2$ is true for all the momenta involved, we are left with the following system of equations:

$$\begin{cases} E'_\nu = E_\nu + m_N - E_N \\ \sqrt{E'^2_\nu - m_\nu^2} = \sqrt{E_N^2 - m_N^2} - \sqrt{E_\nu^2 - m_\nu^2} \end{cases} . \tag{2.10}$$

Which yields:

$$E_N = m_N + \frac{2E_\nu^2}{2E_\nu + m_N} = m_N + E_r \tag{2.11}$$

From Equation 2.11, we can obtain the neutrino energy as a function of the recoil energy, and because we derived that equation from a head-on collision, the result will correspond to E_ν^{min}:

$$E_\nu^{min} = \frac{1}{2}\left(E_r + \sqrt{E_r^2 + 2E_r m_N}\right) \tag{2.12}$$

With that, everything is ready to compute the CEνNS event rate as a function of the nuclear recoil energy. To summarize, Equation 2.3 can be written as follows:

$$\frac{dR_\nu}{dE_r} = \int_{\frac{1}{2}\left(E_r+\sqrt{E_r^2+2E_r m_N}\right)} j_\nu(E_\nu)\frac{G_F^2}{4\pi}Q_w^2\left(1-\frac{m_N E_r}{2E_\nu^2}\right)F^2(q^2)dE_\nu \tag{2.13}$$

With

$$F(q^2) = 3\frac{J_1(R\sqrt{2m_N E_r})}{R\sqrt{2m_N E_r}}e^{-(s\sqrt{2m_N E_r})^2/2} \tag{2.14}$$

And the parameters for a xenon detector are the following:

m_N	$1.23 \cdot 10^2$[GeV/c^2]
R	4.28[fm]
s	0.9[fm]
G_F^2	$1.36 \cdot 10^{-34}$[keV^{-4}]
Q_w^2	5282

Table 2.1: CEνNS parameters.

As for the spectral functions for solar neutrinos, they can be found in Ref. [50], and those for atmospheric neutrinos can be found in Ref. [51]. The normalization factors are given in subsection 1.4.1 and subsection 1.4.2.

2.2 WIMP-nucleus collision rate

We will now focus on the behaviour of WIMPs. The WIMP differential recoil spectrum, that is, number of WIMP-nucleus collisions per unit time per unit mass per nuclear recoil energy is given by [49]:

$$\frac{dN_{coll}}{M \cdot dt \cdot dE_r} = \frac{dR_\chi}{dE_r} = \frac{\rho_0 \sigma_0}{2 m_\chi m_r^2} F^2(q^2) \int_{\vec{v}_{min}} \frac{f(\vec{v})}{v} d^3v \tag{2.15}$$

Where ρ_0 is the local halo dark matter density, σ_0 is the assumed WIMP-nucleus cross section, m_χ is the WIMP mass, and m_r is the WIMP-nucleus reduced mass, given by:

$$m_r = \frac{m_\chi m_N}{m_\chi + m_N} \tag{2.16}$$

It is important to mention that I will be using the same form factor as I did for the neutrino-nucleus collision (see Equation 2.5). For the final part of Equation 2.16, what we have is an integral over all possible WIMP velocities that could produce a nucleus recoil of energy E_r. The function $f(\vec{v})$ is the velocity distribution of dark matter in our galaxy. I will use the Gaussian model for the velocity distribution, which is a relatively simple and often used model. Nevertheless, recent studies have found that the velocity distribution of dark matter in galaxies may be more complicated [52]. That being said, the velocity distribution is the following[49]:

$$f(\vec{v}) = \begin{cases} \frac{1}{N_{esc}(2\pi\sigma_v^2)^{3/2}} \exp\left[-\frac{(\vec{v}+\vec{V}_{lab})^2}{2\sigma_v^2}\right] & \text{if } \left|\vec{v}+\vec{V}_{lab}\right| < v_{esc} \\ 0 & \text{if } \left|\vec{v}+\vec{V}_{lab}\right| \geq v_{esc} \end{cases} \tag{2.17}$$

Where $\sigma_v = v_0/\sqrt{2}$ (v_0 being the average velocity of dark matter), $\vec{V}_{lab}$ and v_{esc} are the laboratory and the escape velocities with respect to the galactic rest frame, and N_{esc} is a normalization factor. We will use the following values for the dark matter parameters [53]:

Dark matter parameters		
ρ_0	0.3 [GeV/c^2/cm^3]	
N_{esc}	0.993	
v_0	220 [km/s]	$7.338 \cdot 10^{-4}$ [c]
V_{lab}	232 [km/s]	$7.738 \cdot 10^{-4}$ [c]
v_{esc}	544 [km/s]	$1.815 \cdot 10^{-3}$ [c]

Table 2.2: Values for the average, laboratory and escape velocities along with the dark matter density used in the calculations of the WIMP-nucleus collision rate.

Using that $\sigma_v = v_0/\sqrt{2}$, and that v_0 is a positive number, Equation 2.17 can be simplified into:

$$f(\vec{v}) = \begin{cases} \frac{1}{N_{esc}\pi^{3/2}v_0^3}\exp\left[-\frac{(\vec{v}+\vec{V}_{lab})^2}{v_0^2}\right] & \text{if } \left|\vec{v}+\vec{V}_{lab}\right| < v_{esc} \\ 0 & \text{if } \left|\vec{v}+\vec{V}_{lab}\right| \geq v_{esc} \end{cases} \tag{2.18}$$

we can write $(\vec{v}+\vec{V}_{lab})^2 = (v^2 + 2vV_{lab}\cos\theta + V_{lab}^2)$, where $\vec{v}$ is the velocity of WIMPs. With this, we can re-write the integral in Equation 2.15 as follows:

$$\int_{v_{min}}^{\infty}\int_{-1}^{1}\int_{0}^{2\pi}\frac{1}{v}\frac{1}{\pi^{3/2}v_0^3}\exp\left[-\frac{(v^2+2vV_{lab}\cos\theta+V_{lab}^2)}{v_0^2}\right]v^2 d\phi\; d(\cos\theta)\; dv \tag{2.19}$$

Where we have not considered the velocity cutoff v_{esc} because the integration limits get too complicated. This does not change much, because N_{esc}, the normalization factor that makes the velocity distribution's integral be equal to 1, takes the value 0.993. This means that the integral, instead of being equal to 1, is equal to 0.993 without the normalization factor. 0.993 is really close to 1, so if we take the distribution without the velocity cutoff, the results will remain within what is expected. With a little algebra, Equation 2.19 turns into:

$$\int_{v_{min}}^{\infty}\frac{2v}{\sqrt{\pi}v_0^3}\exp\left[-\frac{(v^2+V_{lab}^2)}{v_0^2}\right]\int_{-1}^{1}\exp\left[-\frac{2vV_{lab}\cos\theta}{v_0^2}\right]d(\cos\theta)\; dv \tag{2.20}$$

And by solving the second integral, we are left with:

$$\int_{v_{min}}^{\infty}\frac{1}{\sqrt{\pi}v_0V_{lab}}\exp\left[-\frac{(v^2+V_{lab}^2)}{v_0^2}\right]\left(\exp\left[\frac{2vV_{lab}}{v_0^2}\right]-\exp\left[-\frac{2vV_{lab}}{v_0^2}\right]\right)dv \tag{2.21}$$

The meaning of v_{min} comes from the same analysis made in section 2.1, where we established that a head-on collision is the one that produces the largest nuclear recoil. So v_{min} is the lowest speed that a WIMP must have in order to produce a nuclear recoil of a certain energy E_r, corresponding to a head-on collision. However, when we integrate over the velocities, we are considering that v_{min} is a head-on collision and all the other velocities are higher, meaning they represent collisions with other scattering angles. Therefore, what one should do is to derive an expresion for v_{min} that depends on the scattering angle θ (not to be confused with the angle between $\vec{v}$ and $\vec{V}_{lab}$).

I began this part of the work doing that, but it introduces a new variable, the scattering angle, which makes the calculation of the integral far more complicated. So, what I will do instead, is consider that all collisions are head-on, and integrate over the velocities without taking into account the scattering angle. It is clear that this is not perfectly accurate, but it is a good approximation that will let me compute the expressions with less obstacles.

That being clarified, we can find an expression for the minimum velocity by studying the kinematics of a head-on WIMP-nucleus scattering:

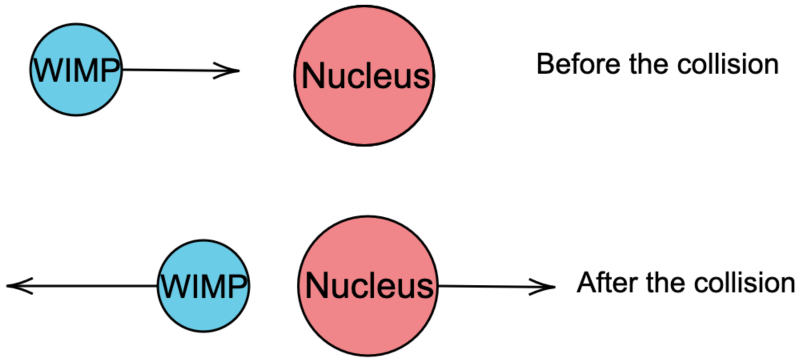

Figure 2.4: Diagram of the WIMP-nucleus scattering in the lab frame.

Let m_χ, p_χ and E_χ be the mass, momentum and energy of the WIMP before the collision, repectively. The energy of the nucleus before the collision is equal to its mass m_N (when we take $c = 1$). After the collision both masses remain the same, the WIMP carries a momentum p'_χ and an energy E'_χ, and the nucleus has an energy E_N. As energy is conserved, we can write:

$$E_\chi + m_N = E'_\chi + E_N \tag{2.22}$$

And, as momentum is conserved too, we also get:

$$p_\chi = -p'_\chi + p_N \tag{2.23}$$

We can conveniently write the energy of the WIMP as the sum of its mass and its kinetic energy, $E_\chi = m_\chi + Ek_\chi$ as well as $E'_\chi = m_\chi + Ek'_\chi$. At the same time, we know that WIMPs are heavy (I specified that this work would be focused on that model), so we know they are not travelling at relativistic speeds. Therefore, we can use the non-relativistic expression for momentum, $p = \sqrt{2mEk}$, where k is the kinetic energy. We can then write Equation 2.22 and Equation 2.23 as follows:

$$\begin{cases} Ek'_\chi = Ek_\chi - Ek_N \\ \sqrt{2m_\chi Ek_\chi} = -\sqrt{2m_\chi Ek'_\chi} + \sqrt{2m_N Ek_N} \end{cases} . \tag{2.24}$$

Which yields:

$$Ek_N = E_r = \frac{4m_\chi m_N}{(m_\chi + m_N)^2} Ek_\chi \tag{2.25}$$

We can then write the kinetic energy explicitly, $Ek_\chi = m_\chi \cdot v^2/2$, where v is the WIMP velocity. With that, we can find v_{min} as a function of the nuclear recoil energy:

$$v_{min} = \sqrt{\frac{E_r(m_\chi + m_N)^2}{2m_\chi^2 m_N}} \tag{2.26}$$

With this, the initial expression Equation 2.15 takes the form:

$$\frac{dR_\chi}{dE_r} = \frac{\rho_0\sigma_0}{2m_\chi m_r^2} F^2(q^2) \int_{v_{min}}^{\infty} \frac{1}{\sqrt{\pi} v_0 V_{lab}} \exp\left[-\frac{(v^2 + V_{lab}^2)}{v_0^2}\right] \left(\exp\left[\frac{2vV_{lab}}{v_0^2}\right] - \exp\left[-\frac{2vV_{lab}}{v_0^2}\right]\right) dv \tag{2.27}$$

2.3 The neutrino floor

What I have done so far is to derive the expressions for the event rates of WIMP-nucleus and neutrino-nucleus interactions. Now comes the important question: will WIMP events, if detected, be enough to stand out over the neutrino events? In order to answer that question, we must analyze how a detector works.

As discussed in section 1.2, what a detector measures is the recoil that a collision produces on the nuclei of the atoms in the detector. However, just like any other experiment, detectors have a range in which they can successfully measure a signal. For example, the XENON1T works with PMTs, which measure the photons emitted by excited and ionized xenon atoms. If a particle with very little kinetic energy collides with a xenon nucleus, the photons emitted will also have low energy, and the PMTs will not detect them.

It is therefore useful to introduce the concept of "energy threshold". The energy threshold in this context is the lowest recoil energy that a nucleus must have in order to be measured by the detector. The energy threshold depends on the detector, so we will take it as a parameter.

Going back to Equation 2.13 and Equation 2.27, one can notice that they express the rate of events as a function of the recoil energy. However, a detector does not only measure one value of energy recoil, it measures any recoil that is above the energy threshold. Consequently, we should integrate the event rates over the recoil energy, taking the energy threshold as the lower limit of the integral. Thus,

$$R_\chi = \frac{dN_\chi}{Mdt} = \int_{E_{thr}} \frac{dR_\chi}{dE_r} dE_r \tag{2.28}$$

$$R_\nu = \frac{dN_\nu}{Mdt} = \int_{E_{thr}} \frac{dR_\nu}{dE_r} dE_r \tag{2.29}$$

Equation 2.28 and Equation 2.29 are the rates of WIMPs and neutrinos for a given energy threshold, respectively. Nonetheless, one should be aware that both of these interactions (WIMP-nucleus and neutrino-nucleus) will be measured in the same detector, in other words, M and dt will be the same for R_χ and R_ν. When we integrate over a period of time, we call $\varepsilon = MT$ the "exposure" of the experiment (do not forget that M is the detector mass). So we can say that both the neutrino and the WIMP measurements will be taken under the same exposure.

We can reformulate our question: how many WIMP events would be enough to stand out over the neutrino events? Or, even better: how many WIMPs should collide with the detector, for each neutrino collision there is, for us to be sure that we are detecting WIMPs? This might sound confusing, but one can think about it this way: if, for every neutrino colliding and producing a nuclear recoil, there are 0.01 WIMPs doing the same, then the signal is not clear. This would mean that, when we expected to measure 100 recoils (for 100 neutrino-nucleus interactions), we would measure 101 recoils. That could clearly be confused with a statistical fluctuation, we could not affirm the existence of WIMPs with such a low number of them being detected. So, how many would be enough?

In Ref. [44], the authors find that 2.3 WIMP events for each neutrino event yield a 90% confidence level, which means that there is a 90% certainty that WIMPs are being detected. This means that we are expecting to find:

$$R_\chi = 2.3 R_\nu \tag{2.30}$$

Being able to measure such amount of events depends on the two unknown quantities there are in the WIMP event rate: WIMP mass and WIMP-nucleus cross-section. Therefore, we are interested in finding a relation between these two parameters, which can be done by taking Equation 2.27 and putting it into Equation 2.30:

$$\int_{E_{thr}} \frac{\rho_0 \sigma_0}{2 m_\chi m_r^2} F^2(q^2) \int_{v_{min}}^{\infty} \frac{1}{\sqrt{\pi} v_0 V_{lab}} e^{-\frac{(v^2+V_{lab}^2)}{v_0^2}} \left(\exp\left[\frac{2vV_{lab}}{v_0^2}\right] - \exp\left[-\frac{2vV_{lab}}{v_0^2}\right] \right) dv\ dE_r = 2.3 R_\nu \tag{2.31}$$

Which, solving for σ_0, yields:

$$\sigma_0 = 2.3R_\nu \left(\int_{E_{thr}} \frac{\rho_0}{2m_\chi m_r^2} F^2(E_r) \int_{v_{min}}^{\infty} \frac{1}{\sqrt{\pi} v_0 V_{lab}} e^{-\frac{(v^2+V_{lab}^2)}{v_0^2}} \left(e^{\frac{2vV_{lab}}{v_0^2}} - e^{-\frac{2vV_{lab}}{v_0^2}} \right) dv \; dE_r \right)^{-1} \tag{2.32}$$

Equation 2.32 connects the WIMP mass m_χ and WIMP-nucleus cross-section σ_0. These are unknown quantities, however we have no control over them, it is not like we can manipulate a particle's mass. Equation 2.32 should not be misinterpreted; the goal of this relation is to know under which conditions we will be able to detect WIMPs. If the relation does not hold, it does not mean that WIMPs with those values of mass and cross-section do not exist, but rather that they could not be detected in these kind of experiments. That is why we call it neutrino floor: neutrinos are a signal these detectors cannot escape from, so they constitute a background in direct detection of dark matter. When detectors look for WIMPs, they will inevitably measure neutrino-nucleus interactions, which translates into constraints for WIMPs.

Our goal is to compute Equation 2.32 for different values of m_χ and E_{thr}, and plot the results in order to visualize the neutrino floor.

Chapter 3

Results

By computing Equation 2.13 for different values of E_r, we find the coherent neutrino-nucleus spectral collision rate per detector mass:

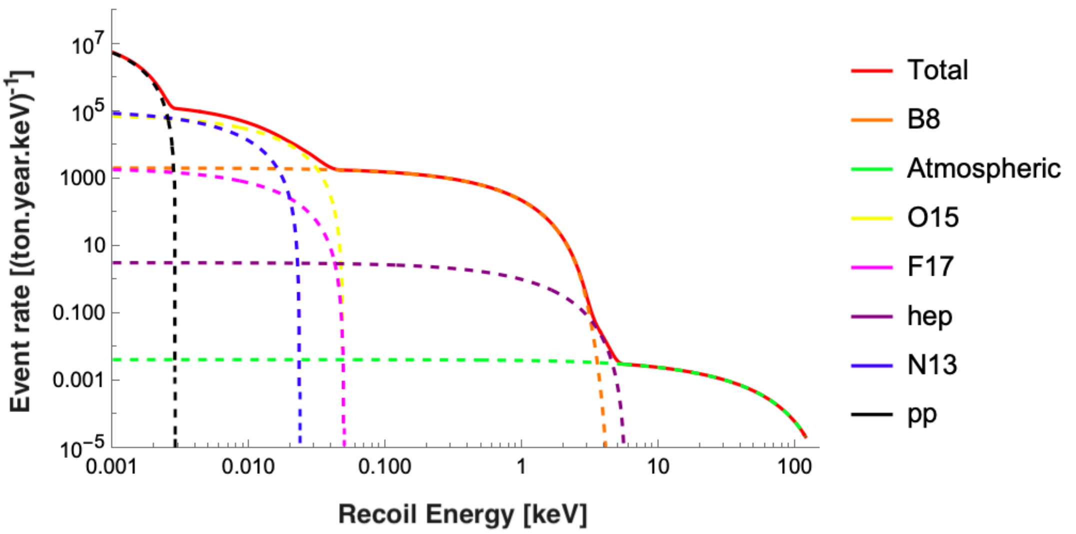

Figure 3.1: Neutrino-induced nuclear recoil spectra for the different neutrino sources, for a Xe target.

From Figure 3.1 we can see that, as we predicted, the main contribution at low recoil energies comes from solar neutrinos, while at energies above [keV] atmospheric neutrinos dominate. Among solar neutrinos, the one source that stands out is Boron8, which dominates the event rate from 0.05 to 4 [keV]. All the other solar neutrinos are at very low recoil energies. We computed the event rate in $[(ton \cdot year \cdot keV)^{-1}]$, as detectors usually work for around 3 years, and direct detectors such as the XENON1T contain about 3 tons of liquid target material.

By integrating the recoil energies above a given threshold, as shown on Equation 2.29, we obtain the following plot:

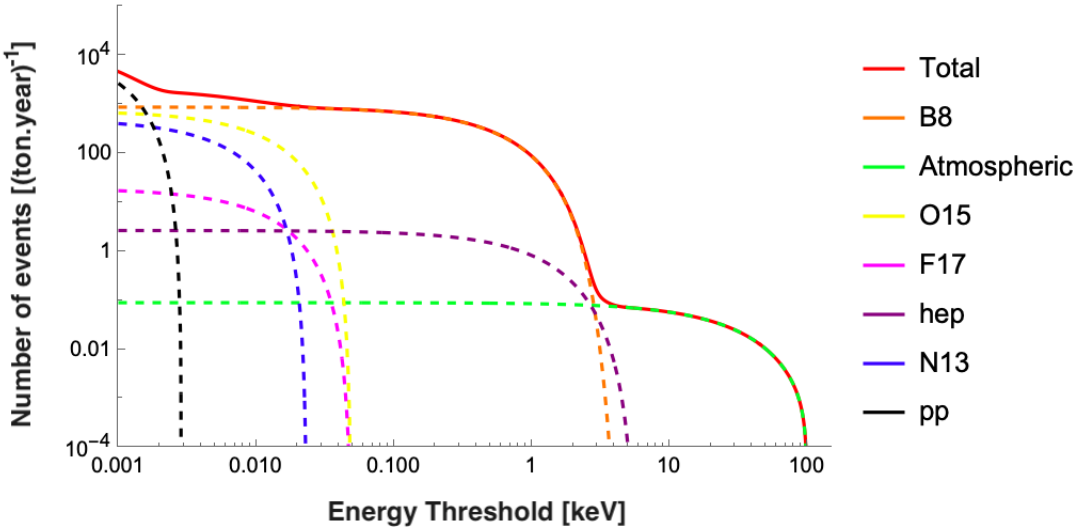

Figure 3.2: Number of neutrino-induced nuclear recoils per ton-year for a Xe target as a function of the energy threshold.

In Figure 3.2 the importance of Boron8 contributions becomes much more evident, as well as the dominance of atmospheric neutrinos for energy thresholds above 4[keV]. Note that both Figure 3.1 and Figure 3.2 are in log-log scale, only because it is the usual display method when working with neutrinos and WIMPs, and that way we can compare with previous researches. In fact, we can see that our results are in agreement with those presented in Ref. [44].

As for the most important calculation, the neutrino floor, we computed Equation 2.32 for different WIMP masses in the range 0.5 to 1000 [GeV/c^2], and then interpolated the data to get a continuous distribution. This process was made several times for different energy thresholds from 0.01 to 99[keV]. The results can be seen in Figure 3.3, where each line represents a different energy threshold.

The results in Figure 3.3 correspond to a xenon target, however, the neutrino floor is a background for any direct detector, and we are interested in computing that background in its most general form. So, what we do is write the WIMP-nucleus cross section in terms of the WIMP-nucleon cross section, σ_n [54]:

$$\sigma_{WIMP-nucleus} = \sigma_0 = \frac{m_r^2}{\mu^2} A^2 \sigma_n \tag{3.1}$$

where μ is the WIMP-nucleon reduced mass, and A is the atomic mass number (131 for xenon).

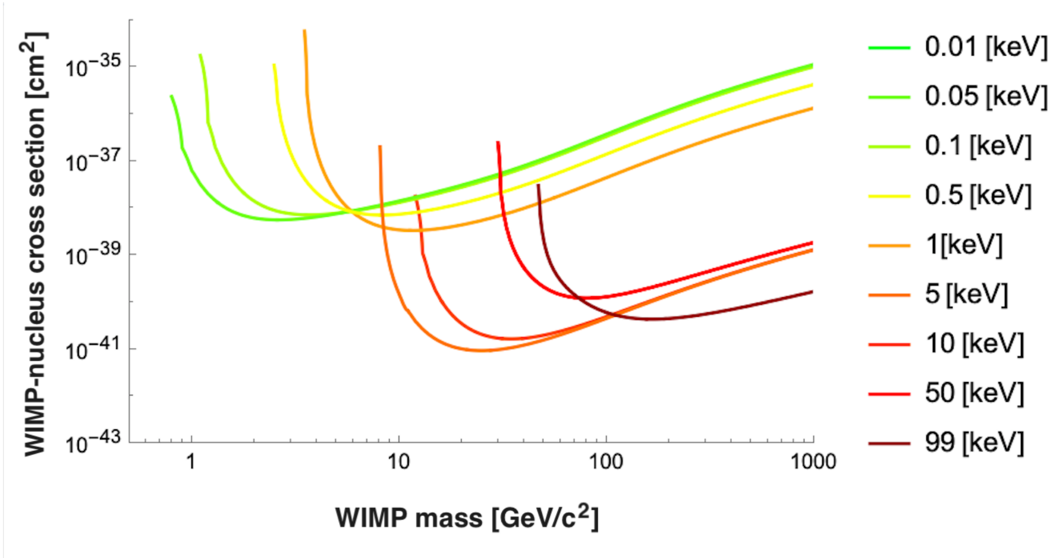

Figure 3.3: WIMP-nucleus cross section (for a Xe nucleus) as a function of WIMP mass that a WIMP must have in order to produce 2.3 collision events for each neutrino event. Each line represents a different energy threshold.

We can put Equation 3.1 into Equation 2.32 and solve for σ_n, and following the same procedure we followed to plot Figure 3.3 (computing σ_n for different values of WIMP mass, and for various threshold energies), we get the most important result of this work, Figure 3.4.

Figure 3.4 is the famous neutrino floor. If we compare this result with the neutrino floor in Ref. [44], we can see that, even though we made some assumptions and approximations along the way, these do not differ much from the original ones. We could examine the WIMP-nucleon cross section from characteristic WIMP mass and energy threshold; a very common WIMP mass to expect is 6 [GeV/c^2], and a respectable threshold would be around 0.1[keV]. So, from the lime green curve in Figure 3.4, we can see that σ_n takes the value $1.0 \cdot 10^{-44}$ [cm] (I obtained the exact value from the code), which is a number that is within the expected for a neutrino-nucleon cross section.

We can see some subtle differences between our results and the ones from Ref. [44], for example, we have no possible value of cross section for WIMP masses below 0.8 [GeV/c^2], whereas the authors of that paper do. This is probably because of the velocity distribution. For a given recoil energy, when the WIMP mass is lower, the minimum velocity increases. If the minimum velocity reaches the end of the Gaussian distribution, the WIMP-nucleus events go to zero because the cross section has to be extremely big in order to produce any events. Therefore, as we used a slightly different distribution from the one used in Ref. [44], it is reasonable to have gotten some differences in the plots.

An interesting thing to note, both from our results and the ones from Ref. [44], is that the curves diverge for low WIMP masses. Take, for example, the 5[keV] curve in Figure 3.4. For WIMP masses below 10[GeV/c^2], there are no allowed values for the cross section. This can be understood by looking at Equation 2.32, where the WIMP event rate R_χ (divided by σ_0 because we solved for that variable) is in the denominator. This means that, when R_χ/σ_0 is zero, the cross section goes to infinity. That seems obvious, but it is not so clear when one only looks at the plot. So this means that, for a given energy threshold, there is an explicit lower limit on the WIMP mass. This is because v_{min} (Equation 2.26) is inverse to m_χ. For m_χ too small, v_{min} grows. When $v_{min} > v_{esc}$, $R_\chi \to 0$, meaning there are no WIMP-nucleus events.

An extreme case would be trying to measure a 2[keV] WIMP with a detector that has a threshold of 0.5[keV]. Even though the threshold is pretty decent, such a small WIMP mass is just not enough. The neutrino floor makes up a background that is too big for such a detector to measure WIMPs with enough confidence level.

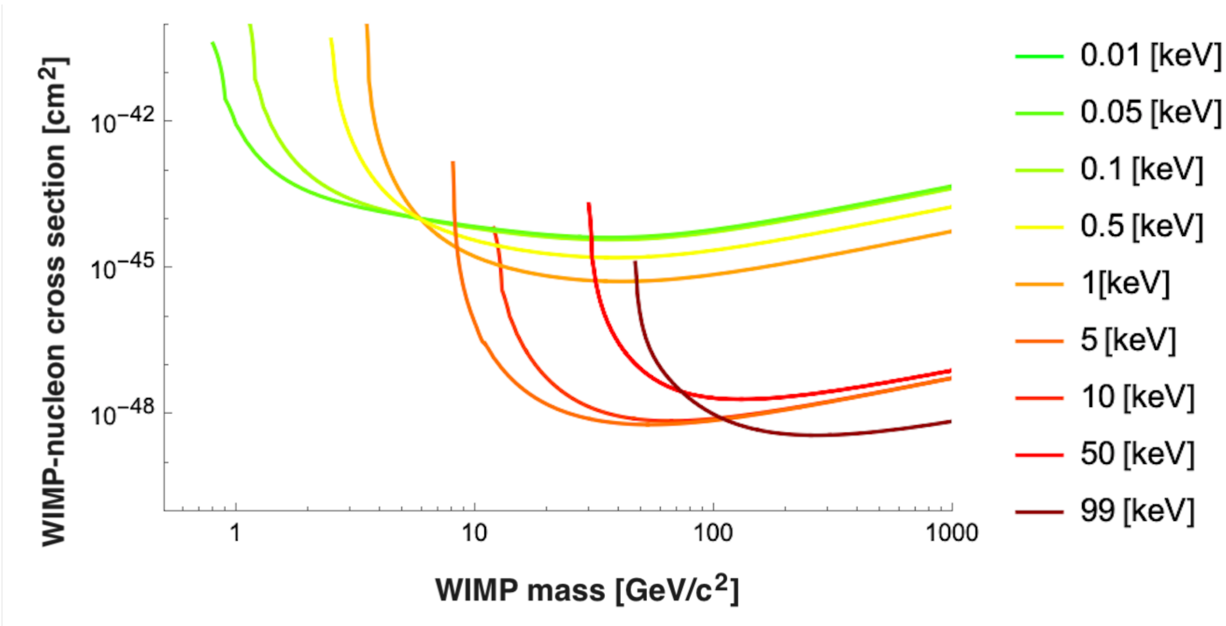

Figure 3.4: WIMP-nucleon cross section as a function of WIMP mass that a WIMP must have in order to produce 2.3 collision events for each neutrino event. Each line represents a different energy threshold.

Chapter 4

Conclusions and future work

In this research, we established the importance of detecting dark matter and learning more about its nature. We reviewed the state-of-the-art, showing some of the evidence for dark matter existence and examining some of the theories about its nature, as well as the most used detection methods in the present. In the context of direct detection of dark matter, we realized neutrinos constitute an important background for the experiments, which could be one of the reasons why dark matter has not been detected yet (aside from its gravitational effects). We were also able to replicate the calculations of the neutrino floor, getting results that are very similar to the ones in literature.

From the neutrino floor calculations, we can conclude that detecting WIMPs that have little mass and WIMP-nucleon cross sections is not possible with the direct detection methods we studied. When we reach the point where detector sensitivies are very high, WIMP measurements will be inevitably covered by the neutrino floor, and new methods for WIMP detection will be needed.

The neutrino floor has been recently renamed "neutrino fog", in order to clarify that it is not an unbreakable barrier [55]. Future work includes exploring this possibility by investigating other, more precise methods for direct detection of WIMPs. An example of that is including directionality in the experiments, which would allow us to know the direction incoming particles came from. This would let us discriminate between neutrinos and WIMPs more easily, which is one way of getting past the neutrino floor.

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