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Monte Carlo simulation of dark matter annihilations in the Sun using PYTHIA and Geant4

Bachelor's thesis

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Introduction

When it comes to understanding the Universe, the precise determination of all the Standard Model (SM) building blocks and the energy budget of the Universe are probably the greatest scientific achievements of the last decade. Just last year the particle physics experiments at the Large Hadron Collider (LHC) reported the discovery of the Higgs boson - the last missing ingredient of the SM [1, 2]. On the other hand, just a few months ago the Plack collaboration published its the latest measurements of the Cosmic Microwave Background (CMB) and determined that only 5% of the mass in the Universe is in the know visible form of baryonic matter. The rest of the Universe is made out of dark energy (DE) (69%) and dark matter (DM) (26%) [3]. Evidence for them is so far purely gravitational and their exact nature remains elusive. Therefore, the origin of DM is the next big question in particle physics and is one of the most important fundamental scientific questions to be answered in this decade.

However, studying the nature of dark matter is not an easy task. In order to observe the particles, describe their interactions, figure out their origins and distribution in the Universe, a global multidisciplinary approach is required. There exist direct detection experiments that are trying to directly observe DM collisions with ordinary matter, such as the DAMA, CoGeNT and CDMS II. For example, latter recently reported an observation of three possible DM collisions [4]. That result, on the other hand, is in tension with the previous negative results by XENON100 [5]. Collider experiments, such as the LHC, are looking for missing energy in their measurements, which would indicate the presence of DM particles, although so far nothing significant has been observed. Cosmic rays are also being studied for potential signatures of dark matter annihilation in the form of excess particles or antiparticles (e.g. the PAMELA, Fermi, HESS, MAGIC and VERITAS experiments). Finally neutrino telescopes, such as IceCube and ANTARES, are improving our ability to detect high energy neutrinos, which could also be used to detect dark matter annihilation.

In this work we study the flux of neutrinos from hypothetical annihilation of DM particles in the core of the Sun. Our motivation is twofold. On the experimental side, modern neutrino detectors will be reaching much lower fluxes and new energy regions in the near future. On the theoretical side, much effort has been put into understanding the solar absorption of DM particles and the annihilation rate of DM in the core of the Sun. Having the annihilation rate of DM and a particle physical model in hand, one can easily estimate the primary flux of neutrinos from the Sun at the location of the Earth. The calculation of secondary flux, however, involves complications. The modelling of particle cascades produced by high energy SM particles in the environment of the solar core is challenging theoretically and computationally. It is important to note, that a few preliminary studies have pointed out that the secondary flux gives additional observables for indirect detection of DM [6, 7]. In our study, we focused on the full-scale simulations of the secondary radiation. We used the PYTHIA8 software [8] for primary radiation and the Geant4 toolkit to model the matter effects [9, 10]. At the present time, it is the first full-scale study of the secondary neutrino radiation.

The thesis is divided into two parts. In the first chapter we give an overview of the topic's background. We will discuss the nature of dark matter, historical developments, latest results and theories. In addition to that we review the basics and some results that are directly related to detecting dark matter annihilations in the Sun. In the second part of this thesis, we describe the software that we created during the course of this work, which can be used to calculate the neutrino spectra from DM annihilations in the Sun. We discuss the structure of the program, validation and present example results.

Chapter 1

Background

In this chapter we give an overview of the theoretical underpinnings and previous results that are related to this thesis. In the first section we discuss dark matter in general and give an overview of both historical developments and latest results and theories relating to it. The second section is devoted to the theoretical basis of the phenomenology of dark matter annihilations in the Sun.

1.1 Dark matter

The key idea motivating this thesis is the concept of dark matter (DM). In a nutshell, DM is a proposed explanation that is able to consistently explain a wide set of astrophysical and cosmological anomalies and phenomena, such as the rotation curves of stars in galaxies, the large scale structure (LSS) formation of the Universe, features in the angular power spectrum of cosmic microwave background (CMB), Big Bang Nucleosynthesis (BBN), gravitational lensing, baryonic oscillations, effects at galaxy cluster collisions etc.The DM hypothesis says that most of the gravitationally interacting matter (about 80%) in the universe is in some non-luminous and weakly interacting form which we have so far only observed indirectly. The know observable baryonic matter (i.e. matter that makes up the stars, planets etc.) accounts for only about 20% of total matter that is out there. In this chapter we give a very short overview of the historical developments, evidence and theories relating to dark matter.

This overview is based on several reviews [11–14]. Some important primary sources and facts not covered in those articles are cited separately.

1.1.1 Origins and astronomical evidence

The story of dark matter begins with the measurments of stellar motion on the 1930s by J.H. Oort. He was studying the velocities of stars near the Milky Way's galactic plane by analyzing their Doppler shifts [15].

Using classical mechanics and making the reasonable assumption that the stellar mass is distributed more or less radially symmetrically in the galactic plane, we can find that the velocity $v(r)$ of a star at a distance r from the galactic center and on a circular orbit, should be following:

$$v(r) = \sqrt{G\frac{m(r)}{r}}$$

where G is the gravitational acceleration and $m(r)$ is the total mass within the radius r. The function $m(r)$ can be independently measured by simply counting all the stars (where most of the mass was assumed to be) and adding together the masses of all the stars that are within the radius. The mass of each star itself can be calculated via astrophysical considerations from the measured value of luminosity.

What Oort observed was that the stars were orbiting faster than the theory predicted. The stars were actually moving so fast that they could escape the gravitational pull of galactic luminous mass. Based on these observation Oort postulated that there has to be some missing mass that we are unable to observe. He did note however that there were possible alternative explanations, such as dust obscuring the light from the galactic center and therefore the luminous mass distribution was not correct or that there were errors in the velocity measurements [15].

Around the same time, independently from Oort, another astronomer made similar observation, but on a larger scale. The swiss astronomer F. Zwicky was studying the Coma galactic cluster (322 million lightyears from Earth) and used the observed Doppler shifts to calculate the velocity dispersions of the galaxies in the cluster. Using the dispersions and the virial theorem [1], he was able to estimate the mass of the cluster to be $M_{\text{cluster}} = 4.5 \times 10^{13} M_{\odot}$, where $M_{\odot}$ is the mass of the Sun. His results were in grave disagreement with measurements based on the standard luminous mass - he found that only roughly 2% of the cluster's mass is from luminous matter [16, 17]. It was later found that approximately 10% of the cluster's mass is contained in the intracluster gas, but this only slightly alleviates the problem of missing mass.

[1] The virial theorem provides a general equation that relates the average over time of the total kinetic energy $\langle K \rangle$ of a stable system consisting of N particles, bound by potential forces, with that of the total potential energy $\langle U \rangle$ of these forces.

$$\langle T \rangle = -\frac{1}{2} \langle U \rangle$$

These results were also confirmed more than forty years after Oort and Zwicky by an extensive study of rotational curves by V. Rubin. He and his collaborators performed a careful analysis of more than 60 isolated galaxies where they again used Doppler shift to measure the velocities of matter at different distances from the center of the galaxy. Instead of seeing an expected Keplerian curve, where the velocity starts falling off after some distance, the measurements instead showed that the curve remained flat. The result is illustrated by the figure 1.1, where we see the Keplerian and the measured rotational curve. Based on these results Rubin summarized: “The conclusion is inescapable: mass, unlike luminosity, is not concentrated near the center of spiral galaxies. Thus the light distribution in a galaxy is not at all a guide to mass distribution.” [18, 19]

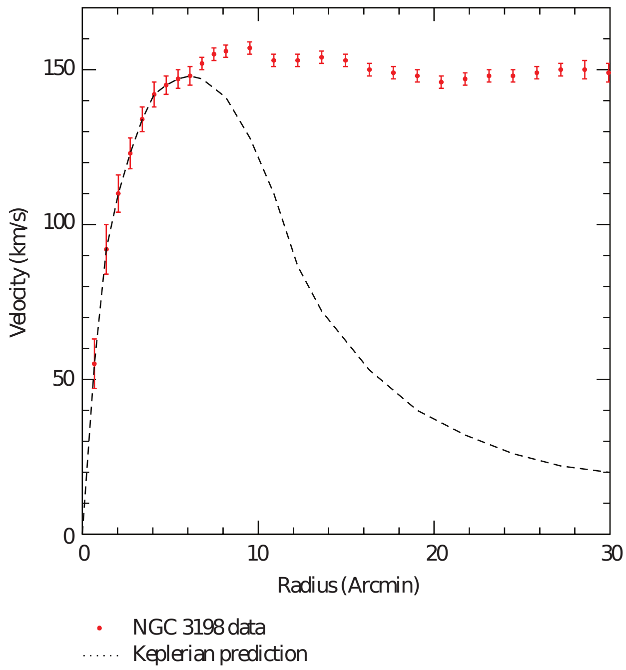

Figure 1.1: Measured rotational velocities of HI regions in NGC 3198[20] compared to an idealized Keplerian behavior. *(Source: [11])*

Gravitational lensing

In the 1970s an alternative way of estimating the distribution and amount of dark matter was proposed, that uses gravitational lensing. It is based on the idea that gravitational fields (i.e. massive objects) also affect the trajectory of light travelling through space.

The basic idea that light could be bent by gravitation was proposed already proposed by Newton and Laplace among others. The first quantitative calculations describing the bending of light by the Sun were made by Soldner in 1804 and the result was rederived by Einstein in 1911. In 1915 Einstein applied the full field equations of General Relativity and derived a more accurate result, which was subsequently confirmed by observing the effect during a solar eclipse. [21, 22]

The basic idea is that the light from a source that is hidden behind a massive object, will be bent around the massive object and will be visible for the observer in the form of a ring. If the light source is directly behind the massive object, we would observer a complete ring, also know as a "Einstein's ring". Since in reality most objects are not exactly behind the massive object, we usually observe only partial Einstein rings or "arclets". Figures 1.2 and 1.3 illustrate the bending mechanism and show and observed example.

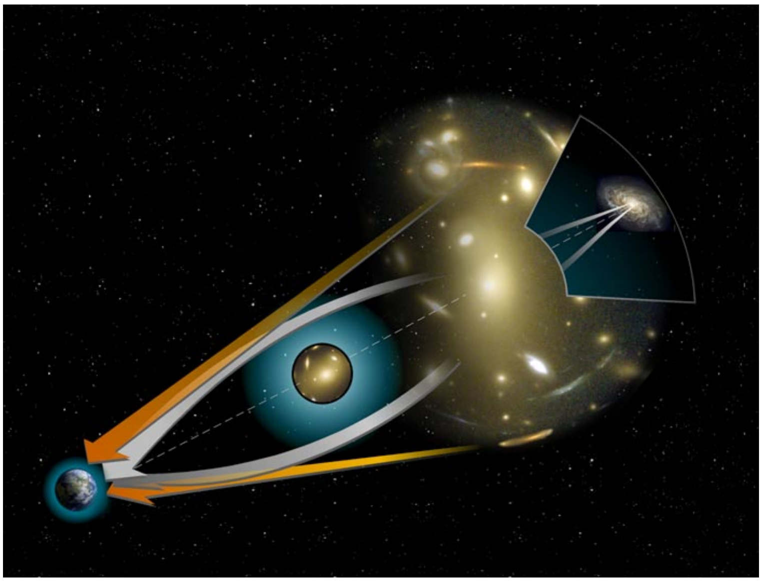

Figure 1.2: An illustration of a gravitational lens. *(Source: NASA)*

While the bending of light by the Sun was observed as early as in the 1919, bending of light from distant galaxies was not observed until the 1970s. In 1979 D. Walsh and others were working in the Kitt Peak National Observatory and they found two distant objects with very similar redshifts, magnitudes and spectra. Since that would have been an unlikely coincidence, they concluded that they were actually observing the same object twice due to the lensing caused by a closer massive object.[23] Since then the effect has been observed numerous times and even near-perfect Einstein's rings have been observed.

We can calculate the "Einstein radius" θ_E (the radius of an arclet in radians) is given by the following formula

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{d_{LS}}{d_L d_S}}$$

where G is the gravitational constant, M is the mass of the lens and d_{LS}, d_L and d_S are the distance between the lens and source, distance to the source and distance to the lens

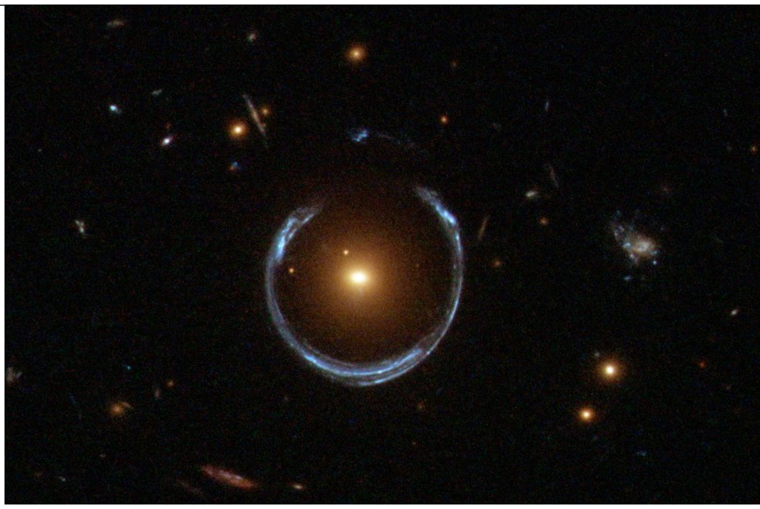

Figure 1.3: Image taken by the Hubble space telescope of a horseshoe shaped Einstein's ring. *(Source: NASA)*

respectively. [2].

It has been found that the mass of the cluster calculated from this is much larger than the mass that can be inferred from the cluster's luminosity. For example, for the lensing cluster Abell 370, it was found that the M/L ratio is about $10^2 - 10^3$ solar units [3]. This again necessitates the existence of large amounts of dark matter that we are not able to observe.[24]

Modern understanding

Although there are a lot of unanswered questions about dark matter, our understanding has evolved a lot since the 1930s. Many different ideas about dark matter have The idea of dark matter has become an integral part of modern cosmology and

The first attempt to explain dark matter was to posit that it was made of ordinary baryonic matter (i.e. the matter we see all around and is made up of fundamental particles called quarks). In accordance with the idea that dark matter is "dark" (i.e. not luminous and not directly detectable through telescopes), numerous possible candidates were proposed - brown dwarves, neutron stars, black holes, unassociated planets etc. All of these candidates are usually classified under a single name - the massive compact halo objects, or MACHOs in short.

Several collaborations, such as the MACHO Collaboration, EROS-2 Survey, MOA, OGLE and SuperMacho have tried to find evidence for these objects by searching for

[2]These distances d_{LS}, d_L and d_S are angular-diameter distances which differ from our "ordinary" notion of distance, called the proper distance, due to the expansion and curvature of the universe.

[3]M/L refers to the mass-luminosity ratio an astrophysical object, which is usually measured in solar units – i.e. in the units of $M_\odot/L_\odot$, where $M_\odot$ and $L_\odot$ are the mass and luminosity of the Sun respectively.

gravitational microlensing (i.e. the brightness variations of distant objects caused by by a nearby massive objects) in the Milky Way halo. The MACHO collaboration analyzed nearly 12 million stars with only 13-17 possible lensing events detected. In 2007, the EROS-2 Survey reported that after studying 7 million bright stars, they found only a single possible lensing event. This extremely low number of lensing events means that MACHOs could explain only a tiny fraction of the non-luminous mass in our galaxy. This implies that most of dark matter is not strongly concentrated nor exist in the form of baryonic astrophysical objects.

Although we know that dark matter is not clumped together, perhaps it is possible that some other forms of baryonic matter would make up the bulk of dark matter? According to the theory of Big Bang Nucleosynthesis (BBN), the answer is no. BBN is a period from a few seconds to a few minutes after the Big Bang in the early, hot universe when neutrons and protons fused together to form deuterium, helium, and trace amounts of lithium and other light elements. In fact, since basically all of the deuterium produced in stars is almost immediately fused into He-4, BBN is the largest source of deuterium in the universe. Therefore the present amount of deuterium we observe can be considered as a lower limit on the amount of deuterium created by the Big Bang. It is possible to estimate the D/H abundance directly, by measuring it primordial-like areas with low levels of elements heavier than lithium (an indication that these areas have not changed significantly since the Big Bang). According to theoretical models, the D/H ratio in the early universe is strongly tied to the overall baryon abundance. Based on these observations it has been calculated that baryonic matter only accounts for about 20% on the total matter density.[25]

Yet another way to estimate the composition of the universe is by studying the Cosmic Microwave Background (CMB). It turns out that the fluctuations in the CMB are indications of both the initial density perturbations that allowed for the formation of early gravitational wells as well as dynamics of the photon-baryon fluid. However, the experiments, such as COBE's Differential Microwave Radiometer (DMR) and the Wilkinson Microwave Anisotropy Probe (WMAP) have shown that the fluctuations are very small. So small in fact they could not explain the structure of the universe we observe today. These results also necessitate the need for an electrically neutral form of matter that played a major role in the formation of the universe's structure. The most recent results in this area are from Plack telescope, that determined that the universe is 59% dark energy, 26% dark matter and only 5% baryonic matter. [3]

Finally, the N-body simulations of the Large Scale Structure of the universe have demonstrated the need for dark matter. Simulations without dark matter do not form the observed filament and void-type structures of the universe.

1.1.2 Particle candidates

Based on the astrophysical and cosmological evidence the existence of dark matter is well motivated. However, its exact nature remains a mystery. The dark matter particle candidates are generally referred to as Weakly Interacting Massive Particles, or WIMPs for short. Based of the observed evidence we assume that these particles are electrically neutral, massive and interact weakly. We will now give an overview of the particle candidates for dark matter that have been proposed in particle physics. We begin with, however, with a quick overview of the Standard Model of particle physics.

The Standard Model (SM) is a quantum field theory that can with very high accuracy, describe three of the four fundamental forces – the electromagnetic force, the weak force and the strong nuclear force. Gravitation is not described by the standard model, since we have not been able to incorporate that into the SM without running into problems. However that is not a problem, since at energies below the Planck scale, gravity is not important at the atomic level.

The standard model describes a total of seventeen particles. Eight of them were predicted by the theory before being experimentally observed. The Standard model has six quarks (up, down, charm, strange, top, bottom), six leptons (charged electron, muon, tau and the corresponding neutrinos) and five force carriers (gluons, photons, W and Z bosons and the Higgs boson). The quarks and leptons all have a half integer spin and are therefore classified as fermions. These are the particles that make up the matter all around us. The force carriers all have an integer spin and are therefore bosons. These particles mediate all the fundamental forces (gluons - strong force, photons - electromagnetic force, W and Z gauge bosons - weak force) and in the case of the Higgs particle, facilitates the mechanism that gives particles mass.

The Standard Model has proven to be a hugely successful theory. By now, all of the predicted particles have been observed in experiment. The latest particle to be found was the elusive Higgs boson which was discovered in the Large Hadron Collider in CERN, Geneva in 2011[1, 2]. In addition to being able to predict several new particles, the theory also allows unprecedented precision in its predictions.

However, the Standard Model does not have a candidate for a dark matter particle. The only particles that satisfy the requirements of being a WIMP are the neutrinos. Although the neutrino has the "undisputed virtue of being known to exist"[26], there are two major reasons why they can account for the majority of dark matter. The first is that the due to their low mass, neutrinos are relativistic particles and therefore a neutrino dominated universe would have inhibited the formation of structure and would have caused a "top-down" formation (larger structures first)[27]. However observational evidence (galaxies existing less than a billion years after the big bang) and simulations

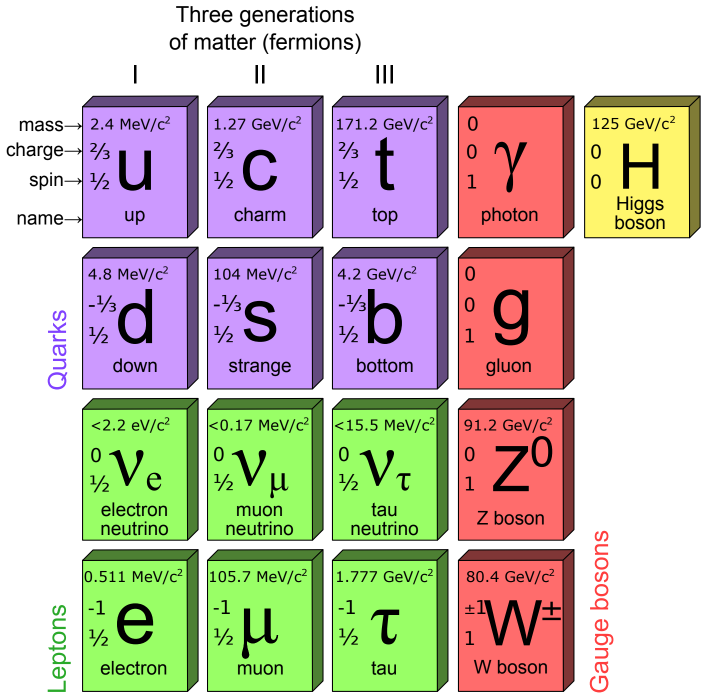

Figure 1.4: The elementary particles of the Standard Model. *(Source: Wikipedia)*

both indicate that our universe formed "bottom-up"[28]. The second reason is that studies have constrained the neutrino mass to be $m_\nu < 0.23$eV, which means that the density of these particles can only account for a fraction of dark matter. Therefore, although neutrinos do account for a small fraction of dark matter, it is not the only and primary source.

The fact that the Standard Model can not provide a viable candidate for dark matter does not invalidate the theory. Instead it means that the theory should be supplemented some physics beyond the Standard Model. The inability to explain dark matter is not the only shortcoming of the Standard Model. Completely independent of that are the hierarchy problem and the fine tuning problem. There are proposed theories that try to solve these issues, the most promising one probably being Supersymmetry. We will now explore possible particle candidates for dark matter that arise from such proposed theories.

In order to address the shortcomings of the Standard Model, Supersymmetry loosens some restrictions on symmetries of the quantum field theory. By doing this, the new theory predicts a superpartner for each Standard Model particle - a superpartner boson for each fermion and a superpartner fermion for each boson. Out of all the new particles, there are several that could act as dark matter - the neutralinos (a particle that is a superposition of the natural superpartners of Higgs and gauge bosons), the sneutrino (the superpartner of a neutrino) and the gravitino (the superpartner of a graviton, that would arise from a quantum theory of gravity). All of these particles are weakly interacting and massive and therefore ideal candidates for dark matter. However, the sneutrinos annihilate rapidly in the early universe and therefore the relic densities are cosmologically significant and it could not contribute much to dark matter[29, 30]. Gravitons would on the other hand act hot dark matter[31, 32]. That only leaves neutralinos as viable candidates for dark matter from supersymmetry.

Although supersymmetric dark matter is arguably currently the most popular model for DM particle candidates, there are many other models and proposed particles, such as the Light Scalar Dark Matter , Axions , Kaluza-Klein dark matte and many more. We will not cover them in detail here, but there are excellent reviews that give an overview.[12, 14]

1.1.3 Detection

If there are dark matter particles out there, then there are several ways we should be able to detect them. There exist numerous experiments that are either specifically designed to detect dark matter of should be able to see it as a side products. So far, no conclusive evidence of dark matter has been observed, but the experiments are ongoing and new ones are being designed and constructed. We will give an overview of different methods that could be used do detect dark matter particles.

Production in accelerators

The most straightforward way to see dark matter particles would be to create them in particle accelerators, such as the LHC. The exact signatures we would expect to observe in an accelerator depends heavily on the particle that we are searching. However, since dark matter particles are weakly interacting, it would be unlikely that we could observe and actual particle. Instead, we expect to see missing energy from particle collision, hinting that there is a particle that we were not able to detect. In addition to that, many measurements that can be performed with accelerators would be able to set limits on theories predicting new particles and through that on dark matter candidates.

So far we have not seen any direct evidence of particles beyond the Standard Model. In addition to that if should happen to discover a new particle, it would not automatically imply that that particle is responsible for the bulk of dark matter.

Direct detection

There are numerous experiments that are designed to detect dark matter particles directly, by observing their elastic scattering with nuclei. These are know as "direct" detection methods since they try to observe a direct effect on ordinary matter by DM particles, as opposed to observing some indirect secondary effects. Examples of such experiments include the XENON, CDMS and DAMA, but there are several others.

The basic idea behind a direct detection experiment is very simple. One has to set up a very sensitive device which can detect the tiny motions and interactions of the atoms that an interactions with a DM particle would create. Even though DM particles are weakly interacting, they may from time to time still bump into the nuclei of the detector and deposit some energy. A crude estimate gives that the upper bound on the deposited energy is in the keV range[11]. Since natural radioactivity is in the MeV range, it means that the detectors have to clean of radioactive elements and well shielded in order for them to be able to detect such low energies.

The latest report from the CDMS II detector announced that they had observed three possible candidates for DM-detector collisions[4]. On the other hand the previous negative result from the XENON100 experiment is in tension with that and other results[5]. DAMA experiment also detected an annual modulation of 7% in scattering events[33], which would be consistent with dark matter. However that result remains controversial, since other experiments have not seen such a signal. All in all, direct detection experiments so far have not seen any conclusive evidence of dark matter.

Indirect detection

If we make the reasonable assumption that dark matter particles can annihilate, then that opens up possibilities for indirect detection by observing the particles created in the annihilation and their decay products. Since we would not observe dark matter directly, we call this technique "indirect detection". However, an observation of a phenomena that can be explained with dark matter annihilation would be a good indication of dark matter and would allow us to form a good hypothesis about its properties. If that observation could be coupled with another observation from a different source but explained again using dark matter with the same properties, then we would have strong evidence that we have annihilating dark matter particles with particular properties floating around.

At first it might seems a bit far-fetched to assume that we could observe dark matter particles annihilate at all - after all, since we do not have normal antimatter flying around in large quantities and annihilating all the normal matter around us, why should this be any different for dark matter? This changes, however, if we consider that prime candidates for dark matter particles - the supersymmetric neutralinos - are classified as Majorana particles (i.e. they are their own antiparticles) and may annihilate if they get close to each other .

An important point is to figure out where this annihilation can take place. While dark matter should be everywhere around us, we have not observed spontaneous annihilations. That however does not mean that annihilation does not take place. The annihilation rate of dark matter is proportional to the square of its density ($\Gamma_A \propto \rho_{DM}^2$). Therefore it would make sense to search for annihilations in places that would have very high dark matter density - such as the sun, earth and galactic center. Due to the already high mass of normal matter, dark matter will be gravitationally attracted to those objects and will fall towards them. Since the particles will occasionally interact with matter through the weak interaction and therefore over time lose energy, they will eventually be captured by these massive objects and will settle down in the center.

The possible annihilation products that interest us the most (due to the possibility of experimentally observing them) are gamma rays, neutrinos and antimatter and we will investigate them in turn:

Gamma rays

Majority of gamma rays from DM annihilation that we expect to observe would originate from the galactic center . The most obvious way they can be generated is when DM particles would directly annihilate into gamma-rays (or Z bosons). This way we should observe gamma-rays that have energies proportional to the mass of the DM particles involved (a "gamma-ray line"). Since we expect the DM particles to have masses on the order hundreds of GeVs, they would be extremely high energy gamma-rays. Even with small flux, an observation of such a gamma-ray line would be a clear indication of dark matter annihilation and its mass.

Another way gamma-rays could be produced is when the annihilation yields a quark-antiquark pair. Those quarks will then hadronize and produce a jet of particles, which among other things, would release a whose spectrum of gamma-rays. This quark-antiquark fragmentation has been well studied in particle accelerators and is well understood . In addition to that, the propagation of gamma rays through space is a predictable process (as opposed to the "random walk" of charged antimatter) which also makes it easier to analyse these processes.

An example of a gamma-ray detection experiment is the Fermi satellite, which is gathering data on gamma-rays that could originate from DM annihilations or decays in and outside our Galaxy [34]. The smoking-gun signal of DM would be a line-like excess in the expected power-law-like spectrum [35, 36]. Surprisingly, last year a line-like (or a double-line) excess was discovered at $\sim$130 GeV in the Fermi measured gamma-ray data of the Galactic Centre [37–40] and at galaxy clusters [41]. Naturally, independent confirmation from experiments other than Fermi is needed, but should that be the case, the most natural explanation would be that the line is caused bu DM annihilation[42, 43].

Antimatter

The second good indicator of DM annihilation would be the observation of antimatter in space. That is because antimatter is quite rare in astrophysics and the astrophysical processes producing it are believed to be well-understood. Therefore any anomalies would be again good indications of dark matter.

The antiparticles that can be produced in DM annihilations and we would be able to detect are antiprotons and positrons. For example, antiprotons can be produced via qq through hadronization and positrons through secondary products of the annihilations W^+W^- and ZZ, where W or Z decay into positron and the corresponding neutrino. Since these particles are charged, their trajectories would be affected by magnetic fields and they would lose energy through inverse Compton and synchrotron processes. Because of that we can not conclude where the annihilations occurred and therefore we must study this flux of antiparticles from the galactic halo as a whole instead of expecting to find them in DM dense areas of the galaxy.

Neutrinos

As we explained before, DM particles would collect in the centres massive objects, such as the Sun or the Earth. The amount of DM in such a massive object would continue to build up until the annihilation rate equals half of the capture rate (you need two DM particles for a single annihilation). According to several models , the capture and annihilation should by now be in equilibrium in the sun - an object that is conveniently close to study. The equilibrium implies that we should be able to observe a constant flux of neutrinos emanating from within the sun. We do not care about other annihilation products, because they are not able to escape the sun (unlike neutrinos, which only interact weakly and therefore easily escape the sun).

The center of the Earth, which is even closer than the Sun, would also seem to be a good candidate to study the neutrinos from DM annihilations. However, according to most models, the DM capture/annihilation has not reached equilibrium yet and therefore Earth does not produce a good flux of neutrinos . Neutrino telescopes therefore usually focus on the flux of neutrinos coming from the Sun .

Since the production of neutrinos in the Sun from DM annihilations is the core idea motivating this thesis, it will be studied more thoroughly in the next section.

1.2 DM neutrino detection

Out of all the possible detection mechanism of dark matter, we will concentrate on solar neutrinos. That is the idea that the annihilation of dark matter particles, that have concentrated in the Sun, will annihilate and produce neutrinos in the process. In principle, by measuring the flux and energy distributions of these neutrinos, we should be able to make claims about the nature of dark matter and its properties.

The key idea here is that the Sun is the closest massive object where, according to most models, the capture and annihilation of dark matter particles should in an equilibrium. Another, even closer massive object would the Earth itself, but in most models the annihilation and capture are not in equilibrium here[11]. In the case of non-equilibrium, the prediction of neutrino flux has large uncertainties.

1.2.1 Detection and results

On earth we can measure neutrinos using massive neutrino telescopes. The early telescopes were designed to measure low energy neutrinos from either the cosmic background or from nuclear reactions within the Sun or the Earth. These experiments mainly confirmed the existence of neutrinos and determined their basic properties. Probably one of the most important discoveries were the neutrino oscillations - the phenomena needed to explain the discrepancy between the observed neutrino flux and the theoretical predictions based on the models of nuclear reactions taking place within the Sun. The experiments were able to observe only roughly one thirds of the electron neutrinos predicted (the early experiments were sensitive only to electron neutrinos). The widely accepted explanation is that the neutrinos have mass (which is not what the Standard Model predicts) and therefore the particles are able to transform into one another when travelling through the space.

Modern neutrino telescopes, however, are mostly designed to measure high energy neutrinos. One of the goals for doing that is to use those measurements for solving the dark matter mystery. It is exactly because we do not believe that the dark matter capture rate has reached an equilibrium in the Earth, most neutrino telescopes are tuned to measuring solar neutrinos.[11]

The basic principle of operation behind a high energy neutrino telescope is to detect photons from high energy particles using photo-multiplier tubes (PMTs). When a high energy neutrino passes through matter it may interact with the nuclei via charged or neutral current weak interactions and through that generate muons or other particles. These highly energetic particles will then travel through the medium and may create showers of particles and radiation, either directly or through Cerenkov radiation (since the particles will have high enough energy to be travelling through the medium at a speed faster than light in that medium). The radiation can the be captured using the PMTs, analyzed and used to reconstruct the muon's track and ultimately the neutrino that created it.[44]

In order to detect these muons, which are very rare events due to the weak nature of neutrino-nuclei interactions, the detectors need to be large and in low-background environments (i.e. shielded from cosmic rays). Also, since the detectors detect light from the muons tracks and particle showers, the detectors need large volumes on transparent medium. The most obvious way of achieving that is to build a large tank of highly purified water that will act as the medium, as was done in the case of the Super-Kamiokande. An alternative is to look for suitable naturally occurring volumes of transparent material. In the case of AMANDA and IceCube, the transparent media is the several kilometers thick sheet of ice in the South Pole. The ANTARES experiment will use seawater and is currently under construction on the Mediterranean.[12]

Early pioneers of high energy neutrino astronomy were the DUMAND collaboration and the Lake Baikal experiment. Neither of these experiments were able to observe any extraterrestrial neutrinos, although they did see neutrinos created in the atmosphere from cosmic rays. Newer experiments include the MACRO, Super Kamiokande and AMANDA experiments. Most recently the IceCube detector (which extends the AMANDA experiment) was completed and started operations in 2011. Prospective future experiments are the ANTARES experiment, currently under construction in the Mediterranean and the proposed Hyper Kamiokande.[45, 46]

1.2.2 Phenomenology of dark matter solar neutrinos

The exact flux of neutrinos produced is highly model dependent. The annihilation fractions (branching rations) vary a lot from model to model and in addition to that, the energy spectra also depend on the mass of the dark matter particle. However, in order to interpret experimental data (e.g. to verify or rule out theories or models), we need to be able calculate the theoretical flux of neutrinos. It turns out we can do most of that work in a completely model independent way.

The phenomenology of solar neutrino can be though of as a string of operations that have to be done in order to figure out what a detector would see. We will now describe it, starting from the end - the detector effects. Once we know which neutrinos reach the detector, we can use simulations and theoretical calculations to figure out what kind of a signature a particular neutrino would leave in the detector. This information can then be used to determine the energy, angle and flavour of the neutrino that are actually observed in the experiment. It also determines the detector's sensitivity to a specific neutrino. These things are specific to a particular experiment and is the responsibility of the experimentalists to account for these.

Another effect that has to be taken into account is neutrino oscillations – i.e. the fact that in vacuum and in the atmosphere, neutrinos can change flavour. This substantially changes the spectra of neutrinos that reach earth compared to the spectra at creation. The probability of finding a neutrino in a particular flavour depends on its energy, initial flavour and the distance travelled. However, once these parameters are know, it boils down to a quite straightforward calculation.

One of the most difficult parts is to figure out which neutrinos get created at all. However, due to the properties of the annihilation process, the kinematic properties of created particles are independent of the particles annihilating. We can therefore use known Standard Model physics to calculate which neutrinos get created, when the annihilations products decay and travel through the Sun. These calculations are non-trivial, but can be done using, for example, Monte Carlo methods. The effects that have to be taken into account include the decay of unstable particles, Bremsstrahlung, hadronization of strongly interacting particles, energy losses due to collisions with the nuclei of the sun, annihilation of decay products etc.

Spectra for each of channel can be calculated without making any assumptions about the properties of dark matter. After that, the spectra can be simply be scaled by the corresponding annihilation fraction and added together to get the total flux of neutrinos eliminating from the sun due to dark matter annihilations.

The final part of determining the neutrino flux involves figuring out the annihilation rate of dark matter particles.

There have been previous studies that have studies this phenomenology from model independent perspective. The one by M. Cirelli, N. Fornego et al. is probably the most comprehensive one. It uses Monte Carlo simulation to calculate the spectra at the Sun and then also discuss the effects of neutrino oscillations and detector effects.[45] There have also been others who have use Monte Carlo simulations to put constraints on the properties of dark matter[6, 7].

Chapter 2

Solar neutrino spectra

In this chapter we present the work done on calculating the spectra of neutrinos from dark matter annihilations in the core of the Sun. The investigation of DM annihilations is one the primary methods currently employed to discover its nature. Figuring out the initial spectra of neutrinos neutrinos as they are leaving the core of the Sun is an important part of the dark matter phenomenology.

In order to calculate these spectra, we created a program based on the PYTHIA8 and Geant4 tookits [8–10]. We will now describe the work done and present results.

2.1 Physical framework

We will start by giving an overview of the physics we are trying to achieve. Since we do not have a "dark-matter-neutrinos-from-the-sun" calculator available, we first have to first have to figure out how to make due with the tools that do we have. The basic principle is that once we have Standard Model particles, then the rest is easy. Although the physics and mathematics may get quite complicated, we know that the theories describing these particles are accurate, experimentally verified and we have methods to apply them and get accurate results.

The interesting part is to figure out how can we say anything useful about dark matter if we only have Standard Model physics at our disposal. The key here is that we are studying only the annihilation of dark matter particles. Although we can not make any assumptions about the physics governing the dark matter particles, it does not matter. Once you know the masses of the annihilating particles and the particles created (the annihilation channel), then the rest of the annihilation process is physics we understand and can evaluate quantitatively. By realizing this we have solved the problem of analysing the annihilation process of dark matter particles with the fact that we can simply postulate the end result of that process.

That now leaves only two "loose ends" - i.e. things that depend specifically on the properties of dark matter itself - the mass of the dark matter particles and the branching ratios of the annihilation process (i.e. the probabilities of annihilating to a particular channels). These are both parameters that can not be determined from Standard Model physics. However, this is not an issue, since our goal is not to calculate the spectra for specific values, but instead, we want to investigate all possible annihilation channels and energies. These spectra can then later, when coupled with experimental data, used to either verify or rule out areas of that parameter space.

Those facts now set our ultimate goal – given an annihilation channel and the mass of the DM particle, calculate the neutrino spectra. The annihilation channels are limited to elementary standard model particles (i.e. quarks, leptons and bosons), which means it is not a problem to study all these. On the other hand, the energy range seems infinite and continuous. However, we do not have to calculate the spectra for every value of energy for them to be useful. The intermediate energies can simply be interpolated. The lower and upper bounds of the energy are limited also – for lower bounds it has been shown that due to the effect of evaporation (as opposed to capture) of dark matter particles, the flux of neutrinos from the Sun can not be used to set constraints on DM scattering cross sections for DM particles with lower mass than about 4 GeV [47]. In addition to that, on energies of about or less than 10 GeV the QCD calculatons in PYTHIA8, become inaccurate. Similarly, for high energies, the simulations also become inaccurate

2.2 Technical details

In order to calculate the neutrino energy spectra, we implemented a computer program that uses Monte Carlo methods to simulate elementary particle processes (e.g. decays, hadronization) and particle-matter interactions in the Sun (e.g. collisions, captures). From a users perspective, the program simply takes the important parameters (mass of the DM particle and the annihilation channel) as input and then, based on that input, produces, after calculating for a while, the energy distributions of the neutrinos in the form of histograms – one histogram for each neutrino flavour. One can think of the program as the following function:

$$f : \text{DM mass} \times \text{Annihilation channel} \to \text{Neutrino energy spectra}$$

This gives a basic idea of what the program does, although in reality the situation is slightly more complicated. The program actually takes more than two parameters in order to have an easy way of changing the programs exact behaviour (e.g. for validation, optimization, debugging). The output is also slightly more verbose than that - it also includes some extra information that is useful for debugging.

From a technical standpoint the simulation program is a piece of computer software, written in C++, that links to Geant4, PYTHIA8 and ROOT libraries. The source code consists of a main program (main.cc) and numerous extra classes that are used by that main program. In addition that that particular program, we have also implemented utility scripts (written in Python and bash) for extra analysis, plotting, handling the SLURM cluster job submission and to automate some repetitive tasks. The total amount of code written is around 2000-3000 lines of code and is publicly hosted on lab's GitHub [1].

2.2.1 PYTHIA and Geant4 configuration

In order for the Monte Carlo simulators to do something useful, we must configure them first. For the PYTHIA primary generator it was very easy. We simply instructed it to create a custom resonance with energy $E = 2m_{DM}$ and then only allow it to decay into the a particular channel we are interested in. Everything else was handled by PYTHIA automatically.

In case of Geant4 it was slightly more complicated. Since it designed to simulate real world objects, its setup is relatively complicated. There were three most important things we had to configure.

First was world geometry. This configuration tells Geant4 what the world looks like where it will simulate the particles. In principle very complicated geometries could be configured, but we used the simplest - in our case the world is a homogeneous sphere with a radius of $1km$. The solar matter is dense enough that all particles (except the neutrinos we are interested of course), will remain within that geometry. Whatever energy they might have, they will lose it to collisions with solar matter and therefore will never reach the world border. On the other hand, at such small scales, the matter near to core of the Sun is indeed homogeneous to a very good approximation.

Second thing we had to configure was the material. This was quite straightforward. We used values published in the literature.[48] The parameters used are also presented in table 2.1. We did not include the minor isotopes, since their abundance is too low and at such temperatures would not matter much anyway.

Final thing we had to configure were the event generators. This basically means we had to set up the initial particles. For that we took the output from PYTHIA and simply placed the particles near the center of the sphere with the correct energy. It should be noted that since we do not care about the angular distribution of the esacaping neutrinos

[1] The source code for the program created for this thesis and more additional code is available the NICPB-HEP GitHub: `https://github.com/HEP-KBFI/genSun/`

Table 2.1: Parameters of the materials used in the Geant4 simulation. The Sun's parameters are based on actual values [48] and the vacuum is based on Geant4 recommendation on interstellar space.

	Sun's core	vacuum	unit
density	160	10^{-25}	g/cm^3
pressure	10^9	10^{-24}	atm
temperature	15×10^6	0.1	K
hydrogen abundance	73.46	100	%
helium abundance	24.85	0	%

or something similar, the exact initial position and direction of the momentum vector also do not matter.

2.3 Program flow

We will now describe the idealized structure of the program and the main loop. A single loop is a single annihilation event and we will run the loop as many times as necessary to get the amount of statistics we need. Before the main loop we set up the necessary variables and configure PYTHIA and Geant. We set up the configuration described in the previous section.

After we are done configuring the program, we start the main loop. The first thing in the main loop is to run PYTHIA, which starts off by creating and decaying the resonance specified. After that it simulates all the necessary physics processes, including Bremsstrahlung, hadronization and decays. Eventually all but handful particles have decayed. The ones that do not decay a the stable particles (such as gammas, neutrinos, protons) and the metastable particles we have specified that have long enough lifetimes so that they will interact with the matter in the Sun (such as muons, neutrons, pions). The list of these stable and metastable particles, including their location, energy and momentum, is the information we receive as output from PYTHIA.

The PYTHIA output is then fed to Geant4 which, uses that information to create the particles in its simulation. It then runs the simulation and calculates the passage of these particles through the solar matter. During this Geant4 simulates the interactions (scatterings, annihilations) with the solar matter and through that properly accounts for energy losses and neutrinos generated from these secondary interactions. Geant simulates the particles until the particle can be discarded. The most obvious for this is that the particle decays or annihilates with the environment – this means that the original particle ceases to exist and it is removed from the simulations.

The second possibility is that the particle's energy becomes so low that nothing interesting happens any more and we can safely discard that particle. Geant has lower limits built in for stable particles such as the photons. This is a very important point since in principle the simulation could otherwise produce effectively an infinite amount of particles, which would then be impossible to simulate. This effect is also know as the infrared divergence . We also introduce additional cuts that are based on the idea that we do not have to simulate particles that do not produce any neutrinos. These optimizations are described in more detain in the chapter 2.5. In any case, once we have decided that we do not care about a particular created particle, we simply ignore it.

The final possibility is that the particle reaches the edge of the world. As was mentioned, our geometry is a finite sphere of solar matter. This means that particles can, in principle, reach the end of the world. Once a particle reaches the edge, it thrown out of the simulation. We check for those events and log all the particles we find there. We should only see neutrinos there, since all other particles should either decay or lose energy and therefore be discarded before reaching there. Neutrinos, however, are so unlikely to interact with matter across these relatively small scales (1 km for our sphere) that effectively all of them reach the border. On the other hand, with vacuum simulations, all stable particles reach the border, since in that case they cant lose energy or otherwise interact with the environment.

The final part is to store all the interesting data. The particles that reach the world edge are the ones that interest us. These events are used to create the histogram of neutrino energy distributions. An example of such a histogram is presented in figure 2.1. We also store additional information - such as the count of all particles reaching the world border, for debugging purposes.

From a technical standpoint we use ROOT files to store our data. In the ROOT file we create a directory structure and then store the information as histograms. Since the possible values for neutrino energy span several orders of magnitude, we store the logarithm of the energy instead (i.e.: $x = \log_{10}\left(\frac{E_\nu}{m_{DM}}\right)$).

2.4 Validation

An important part in developing this simulation is to verify that the results we are getting are actually correct. We do trust that PYTHIA8 and Geant4 work correctly and therefore all the physics is done correctly. However, they both have to be configured, which is a non-trivial process, and it is always possible that there might be some mistakes with interpreting their input and output (for example units or precise physical meanings of different variables). With the following validation we ensure that we have configured the Monte Carlo simulations correctly and there are no obvious programming errors.

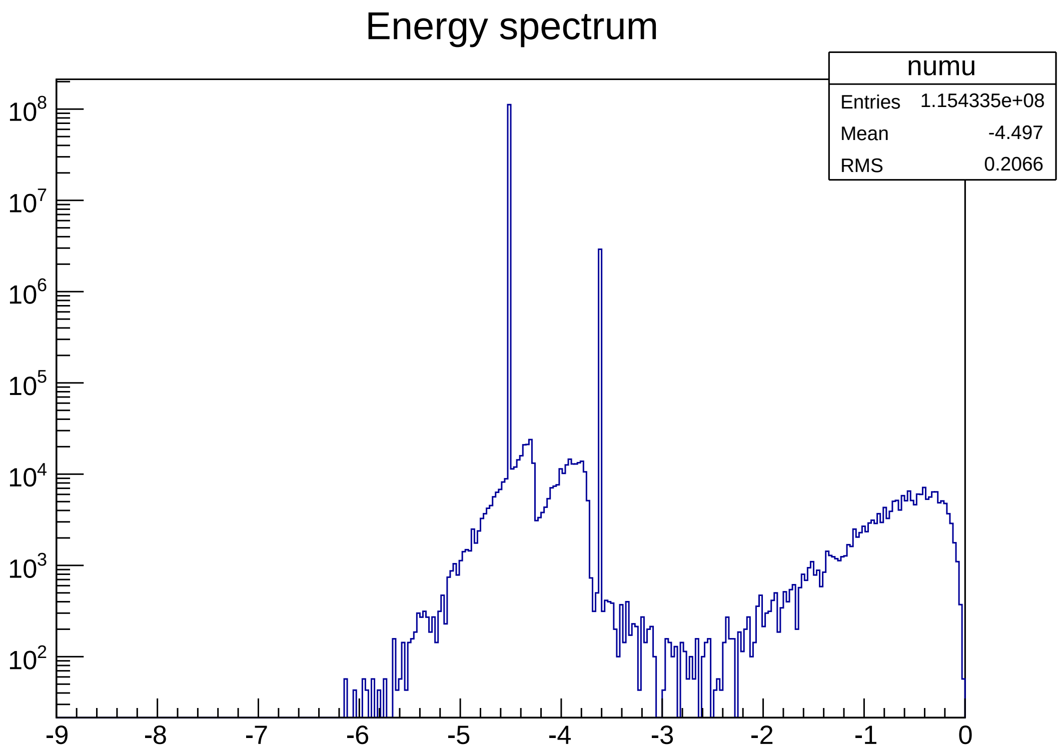

Figure 2.1: An example of a raw spectrum created by the simulation program. Note that no labels or other decorative information has been added. The histogram has 300 bins from -9 to 0. The x-axis is the logarithm of neutrino's energy to dark matter mass ratio.

For validation we simply compare our output spectra with other results that we know are correct. As comparison spectra we chose the spectra that Joosep Pata has independently calculated using also Monte Carlo simulation but a different method. His implementation uses only PYTHIA8, which is used for both primary event generation and to account for energy losses. The energy losses are accounted for by using analytical approximations.

Unfortunately we can not use the final spectra with energy losses, since the independent methods behind the implementation are too different. It might very well be that our results will contradict the results from the other implementation not because our implementation is wrong, but because the other methods are not accurate enough or fail to account for some effects.

However, we can compare the two implementations if we make the process take place in vacuum. In case of Pata's implementation this simply means that the energy loss mechanisms have to be turned off. That is because there is no matter in vacuum with which the particles could interact and therefore all particles should simply decay freely without any energy losses. In our Geant4 simulation we did that by simply setting the material to effectively vacuum (precise parameters are given in table 2.1). From a technical point of view nothing else was changed – the particles were still created using PYTHIA8, feeded to Geant4 where they decayed (if unstable) and were then captured at the world border.

Only two other small details were modified. Since there are no matter-particle interactions energetic metastable particle (such as the muons, i.e. particle with a long-enough lifetime) can reach the world border and therefore not decay. In order to prevent that the radius of the world was increased to 10^9m.

However, this does not stop neutrons and antineutrons, since compared to other particles they have a very long lifetime (880 ± 1.1s[49]) and therefore would still survive long enough to reach the world border and not decay. However, in comparison spectra the neutrons also decayed and therefore we must make sure that they do too in this case. One way of doing that would be to simply set the world large enough to allow the particles to decay. However, a larger volume takes a longer time to simulate due the way simulation is handled in Geant4 and therefore the simulation would become quite slow. Instead, an easier solution was to simply set the neutron lifetime to a microsecond. This is short enough to cause all neutrons to decay somewhere within the world geometry. Since there are no interaction if vacuum and we do not care where exactly decays take place, then this modification does not the observables (neutrino energies) we are interested in.

For validation we compared various annihilations channels and energies. At first this process revealed several bugs in our implementation (unit conversion errors and that

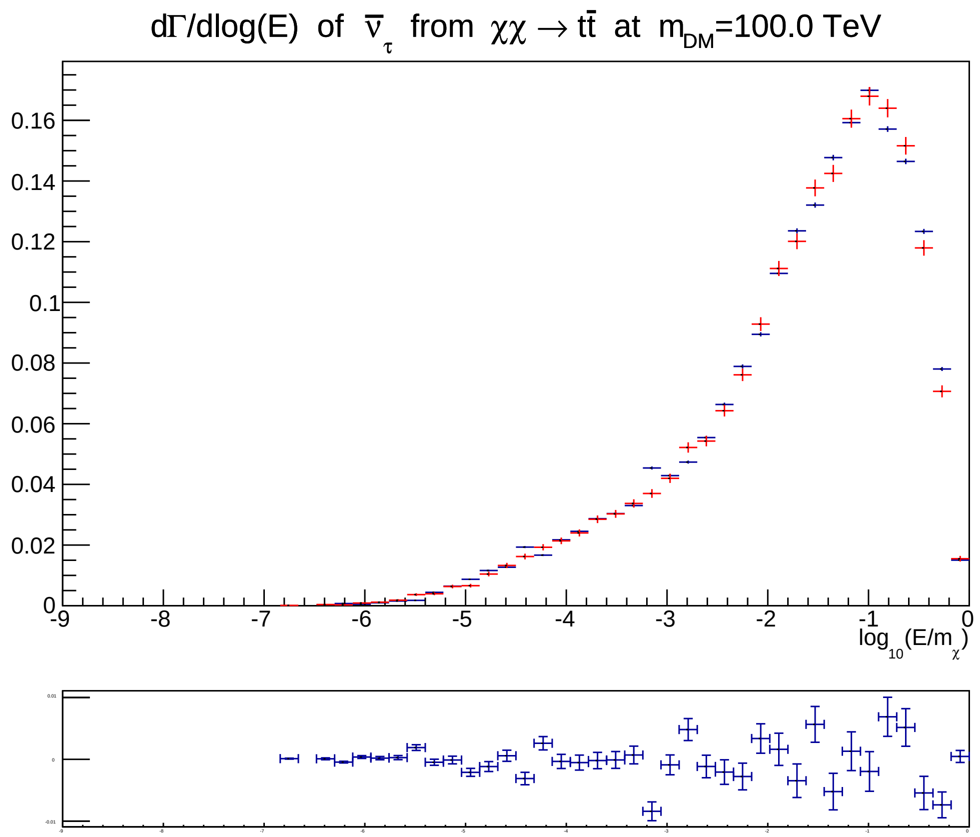

Figure 2.2: Example validation spectra of the spectral flux of tau-neutrinos from a $\chi\chi \to t\bar{t}$ process at $m_{DM} = 10\text{TeV}$. On the y-axis we see the spectral flux of the neutrino. The blue histogram is the spectra calculated by this program and red histogram is from the independent implementation. The graph below the main plot displays the difference between the two implementations.

particles were reaching the world border), which were then promptly fixed. After those fixes the spectra from our and the alternative implementation match very well. An example spectrum if presented in figure 2.2. Additional validation spectra are given in appendix A.

2.5 Optimization

One thing that quickly became apparent when we started simulating particle tracks through the sun was that it was dead-slow. Due to the exponentially high number of particles generated when high energy particles interacted with the environment, the simulation of a single event could take minutes. Since our goal was to simulate millions of events, this was not acceptable, even with the possibility to parallelize. Something had to be done in order for the simulations to be feasible.

The issue arose because through various processes (such as ionization), energetic long-lived particles that travel through the Sun create a lot of secondary particles (mainly electrons and photons). Although these secondaries usually have low energy, there are exponentially many of them created and they themselves can generate secondaries also. Ultimately this means that Geant4 has to simulate simply too many particles and it makes the simulation run slow.

The solution to this problem is based on the observation that if our particles have low enough energies, they will not generate any neutrinos and therefore are not of interest to us. Since our ultimate goal is to simply get the neutrino spectra (as opposed to simulating energy deposition etc.), there is nothing wrong with simply ignoring (i.e. not simulating at all) any particle that was created with energy below some threshold value.

In order to determine that threshold value we investigated the particles of interest at low energies. Instead of using PYTHIA8 to create these particles through annihilation, we we placed a particle with a particular energy directly into Geant4 simulation and then ran the simulation. Like usual, we stored the particles found and their spectra and the summary of the results are presented in table 2.2.

What we see from that table is that gammas and electrons below certain energy do not produce any neutrinos (with a reasonable probability anyway). Based on this data we imposed 100 MeV energy cutoff on both electrons and gammas for simulations - i.e. any electron or gamma that is created and has energy equal or below 100 MeV is automatically discarded. It should be noted that this gave under some circumstances a several hundred fold speed increase.

Table 2.2: Neutrino yields from optimization runs. For every particle and energy we simulated $N_0 = 10^7$ (10^6 for the proton) and we report the number of neutrinos observed (N_ν) and the average number of neutrinos per event (N_ν/N_0). The number reported in the header is the particle's PDG ID for Monte Carlo simulations[49].

E (MeV)	γ (22)			e^- (13)			p (2212)		
	N_0	N_ν	N_ν/N_0	N_0	N_ν	N_ν/N_0	N_0	N_ν	N_ν/N_0
10	10^7	0	0.0	10^7	0	0.0	-	-	-
50	10^7	0	0.0	10^7	92	9.2×10^{-6}	-	-	-
100	10^7	8	8.0×10^{-7}	10^7	52	5.2×10^{-6}	-	-	-
150	10^7	48	4.8×10^{-6}	10^7	177	1.8×10^{-5}	-	-	-
200	10^7	1962	2.0×10^{-4}	10^7	214212	2.1×10^{-2}	-	-	-
500	10^7	202117	2.0×10^{-2}	10^7	450072	4.5×10^{-2}	-	-	-
1000	10^7	635412	6.4×10^{-2}	10^7	918162	9.2×10^{-2}	10^6	5642529	5.6

2.6 Example spectra

Finally we provide some example output from the program. On figures 2.3 and 2.4 we have two sample spectra, that were produced using this program. Unlike the validation spectra, these are full simulations (i.e. with solar matter). In both cases we can easily observe the effects of energy losses. The sharp cutoffs are an indication of a three or more body decay from a particle that has been stopped by the interactions with the solar matter. The mass of the decaying particle is proportional to the cutoff value.

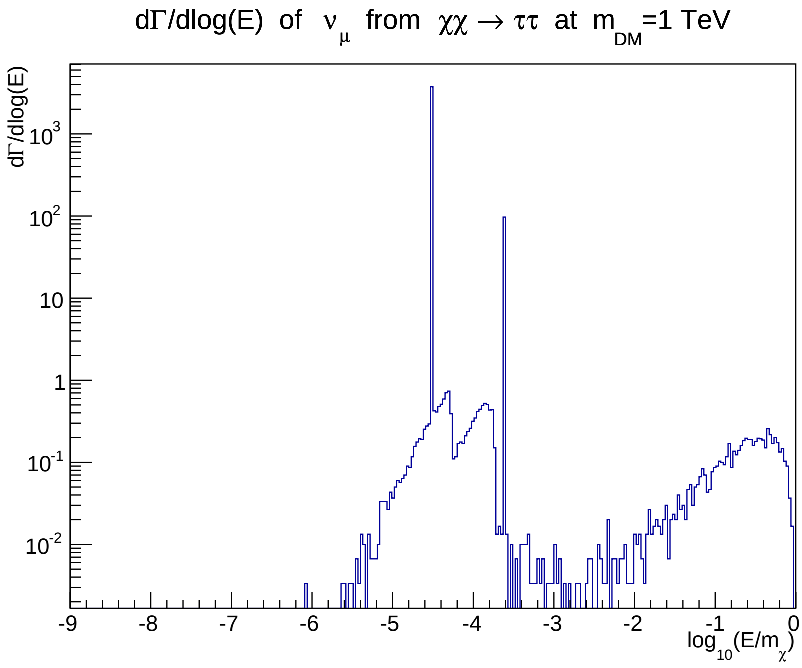

Figure 2.3: An example of the full spectral flux of mu-neutrinos from a $\chi\chi \to \tau^-\tau^-$ process at $m_{DM} = 1\text{TeV}$.

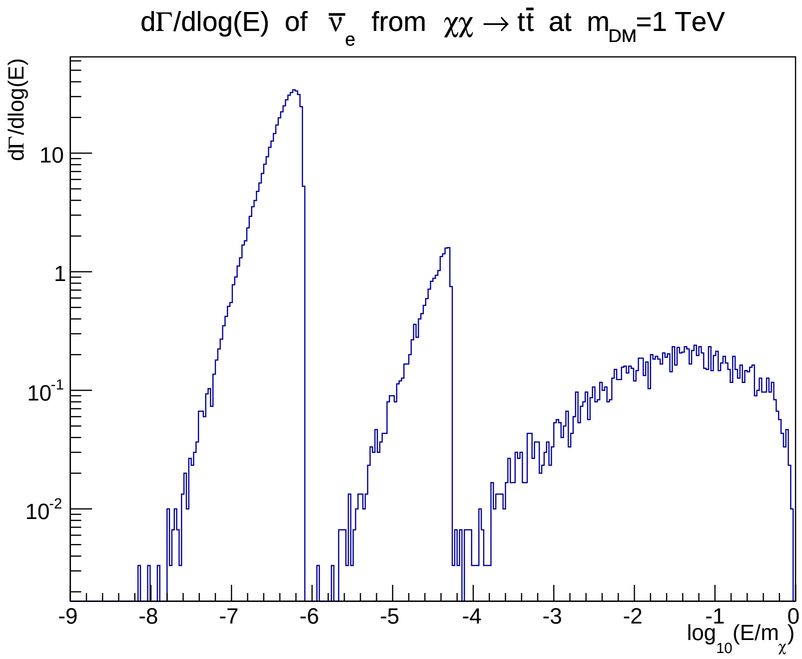

Figure 2.4: An example of the full spectral flux of electron antineutrinos from a $\chi\chi \to t\bar{t}$ process at $m_{DM} = 1\text{TeV}$.

Summary

The evidence that most of the Universe around us is made out of stuff we are unable to see is extensive. Thousands of scientists around the world are working on unravelling that mystery by building experiments, creating new theories or coming up with better and better phenomenological models. Even though this work has been going on for over eighty years, we still do not understand the nature of dark matter.

In the first part of this thesis we present the evidence, best theories and therefore motivation for studying dark matter. In the second part we describe the novel software that was created to simulate dark matter annihilations in the Sun and calculate the energy spectrum of neutrinos from these processes. During the course of this work, the computer program that performs these simulations was created from scratch using the PYTHIA8 and Geant4 particle physics Monte Carlo simulation libraries. In addition to creating the the software, it was necessary to verify that the program works correctly and to time-optimize it.

The motivation of this software is to provide a critical link to the phenomenological analysis of dark matter, which tries to determine its nature by measuring the solar neutrinos that reach the Earth. In order to interpret the experimental data we need some theoretical baseline and these spectra provide exactly that. There have been a few similar studies before but this is the first time that the simulation has been done on this level on generality. Our simulation is able to account for both primary and secondary spectra.

As a final note, the author would like to thank his supervisor Andi Hektor whose guidance and enlightening discussions made doing this work a fun experience. In addition to that he would like to thank Joosep Pata, whose assistance, on both technical and conceptual matters, proved to be invaluable. Finally he would like to acknowledge professor Martti Raidal and the High Energy and Computational Physics Laboratory at the National Institute of Chemical Physics and Biophysics of whose support and resources made this work possible and enjoyable.

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Tumeaine annihilatsiooni modelleerimine Päikeses Monte Carlo meetoditega PYTHIA ja Geant4 abil

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Kokkuvõte

Täpne arusaam ja kinnitused selle kohta, millised on universumi ehituskivid ja milline on nende osakaal, on kahtlemata viimase dekaadi üks suurimaid teaduslikke läbimurdeid. Alles äsja avaldatud Plancki kosmoseteleskoobi tulemused, mis määratlesid enneolematu täpsusega ära kosmilise taustkiirguse ning kinnitas, et me elame universumis, kus ainult 5% ainest on nähtav. Ülejäänud moodustab tume energia (69%) ning tumeaine (26%). Hoolimata nendest tulemustest on tumeaine täpne loomus siiski veel teadmata ja see on käesoleva dekaadi üks olulisimaid teadusküsimusi.

Tumeaine uurimine ei ole lihtne ülesanne ning vajab multidistsiplinaarset lähenemist. Käesoleva töö esimeses osas kirjeldame tumeaine ajalugu, vaatluslikke tõendeid, viimaseid teooriaid, uurimismeetodeid ning muud seonduvat. Siiani oleme tumeainet detekteerinud ainult kaudselt läbi gravitatsioonilise interaktsiooni. Väga oluline oleks saada tumeainele kinnitust ka muude otseste või kaudsete eksperimentide kaudu.

Käesoleva töö põhiline osa keskendub hüpoteetilise tumeaine annihilatsiooni uurimisele Päikese tuumas. Töö eesmärgiks oli koostada arvutiprogramm, mis oleks võimeline arvutama annihilatsiooniprotsessidest tekkivat neutriinovoogu. Nende teoreetiliselt arvutatud neutriinode energiaspektrite võrdlemine eksperimendist mõõdetuga lubaks teha väiteid tumeaine olemuse kohta – kas välistades või kinnitades vastavaid hüpoteese.

Neid spektreid on modelleeritud ka varem, aga kunagi pole täies mahus arvesse võetud sekundaarseid neutriinosid, mis tekivad osakeste-aine vastasmõju tõttu. Seega on antud raames tegu täiesti uudse uuringuga. Töö praktiline osa koosnes tarkvara arendamisest kasutades PYTHIA8 ja Geant4 osakestefüüsika teeke, programmi töö valideerimisest ning kiiruse optimeerimisest.

Kuna antud teema on hetkel väga aktuaalne, siis plaanime tulemused publitseerida võimalikult kiirest ning jätkata tehtud tööd.

Appendix A

Validation spectra

Here we present the validation spectra that were used to validate the program. These are normal spectra, but calculated in vacuum. They are validated against an independent implementation of the same annihilation process using only PYTHIA8.

On the y-axis we see the spectral flux of the neutrino. The blue histogram is the spectra calculated by this program and red histogram is from the independent implementation. The graph below the main plot displays the difference between the two implementations.

For presentation we chose four different annihilation channels at different energies, so that we could be as general as possible. In all cases we observe very agreement between the implementation, which means that the program is free of any obvious bugs. The are some small discrepancies but these can be explained with statistical fluctuations and by the fact that the two programs use slightly different methods. Similar agreement can also be observed in other channels and other energies.

A.1 Muon-antimuon channel

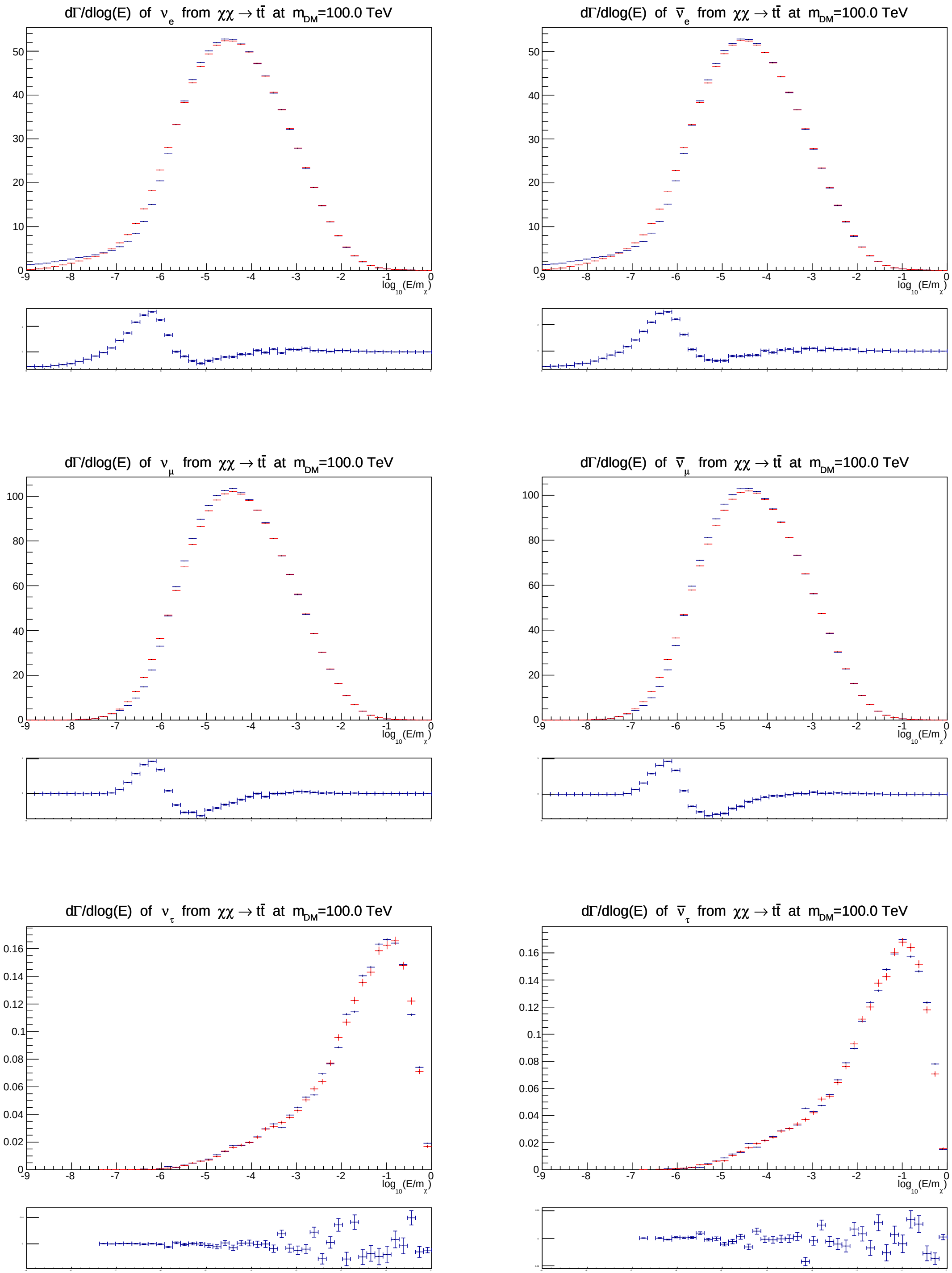

Figure A.1: These are the neutrinos from the $\chi\chi \to \mu^-\mu^+$ process, calculated at the $m_{DM} = 100\text{GeV}$.

A.2 Electron-positron channel

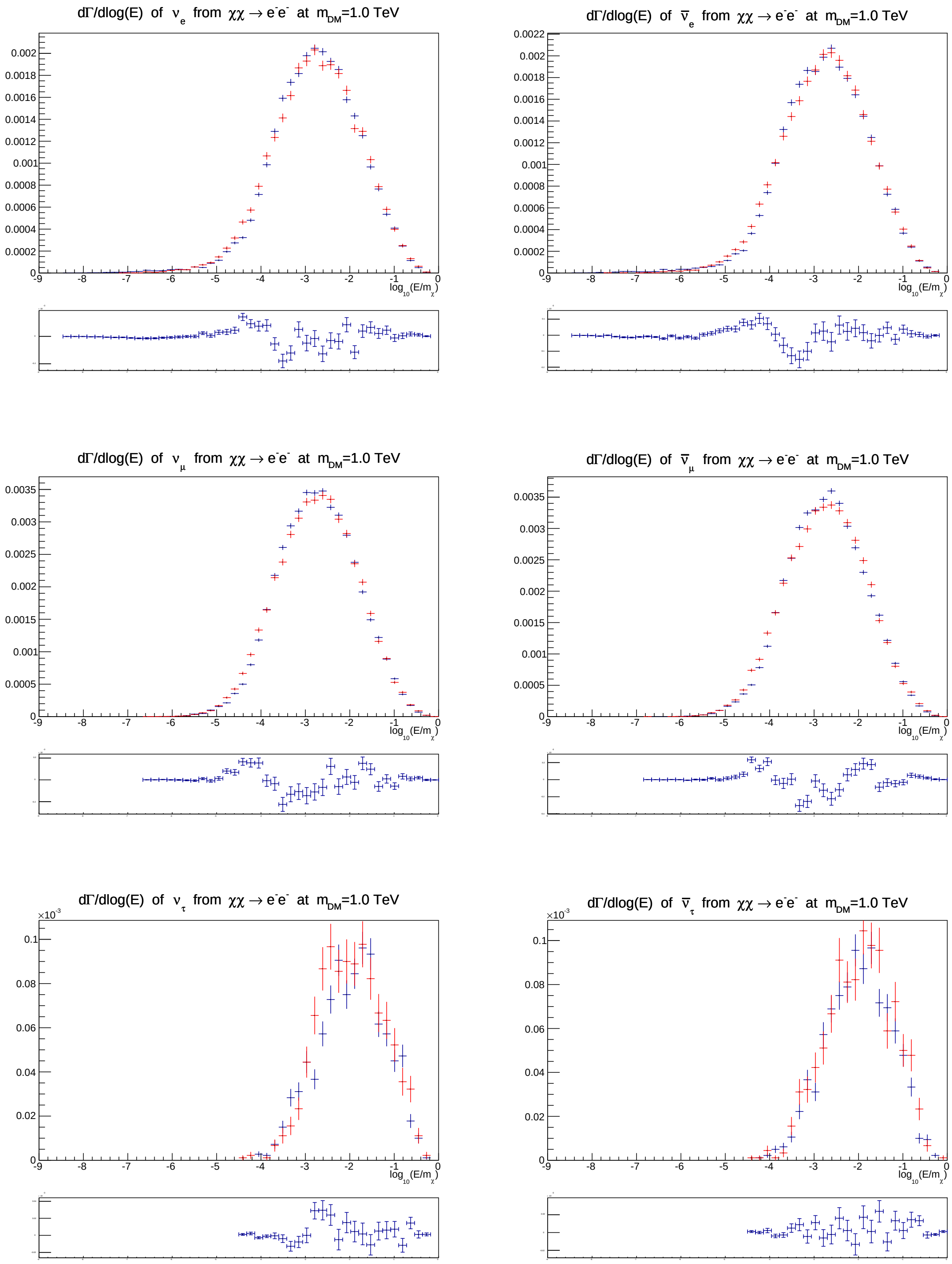

Figure A.2: These are the neutrinos from the $\chi\chi \to e^- e^+$ process, calculated at the $m_{DM} = 1000\text{GeV}$.

A.3 Gamma-gamma channel

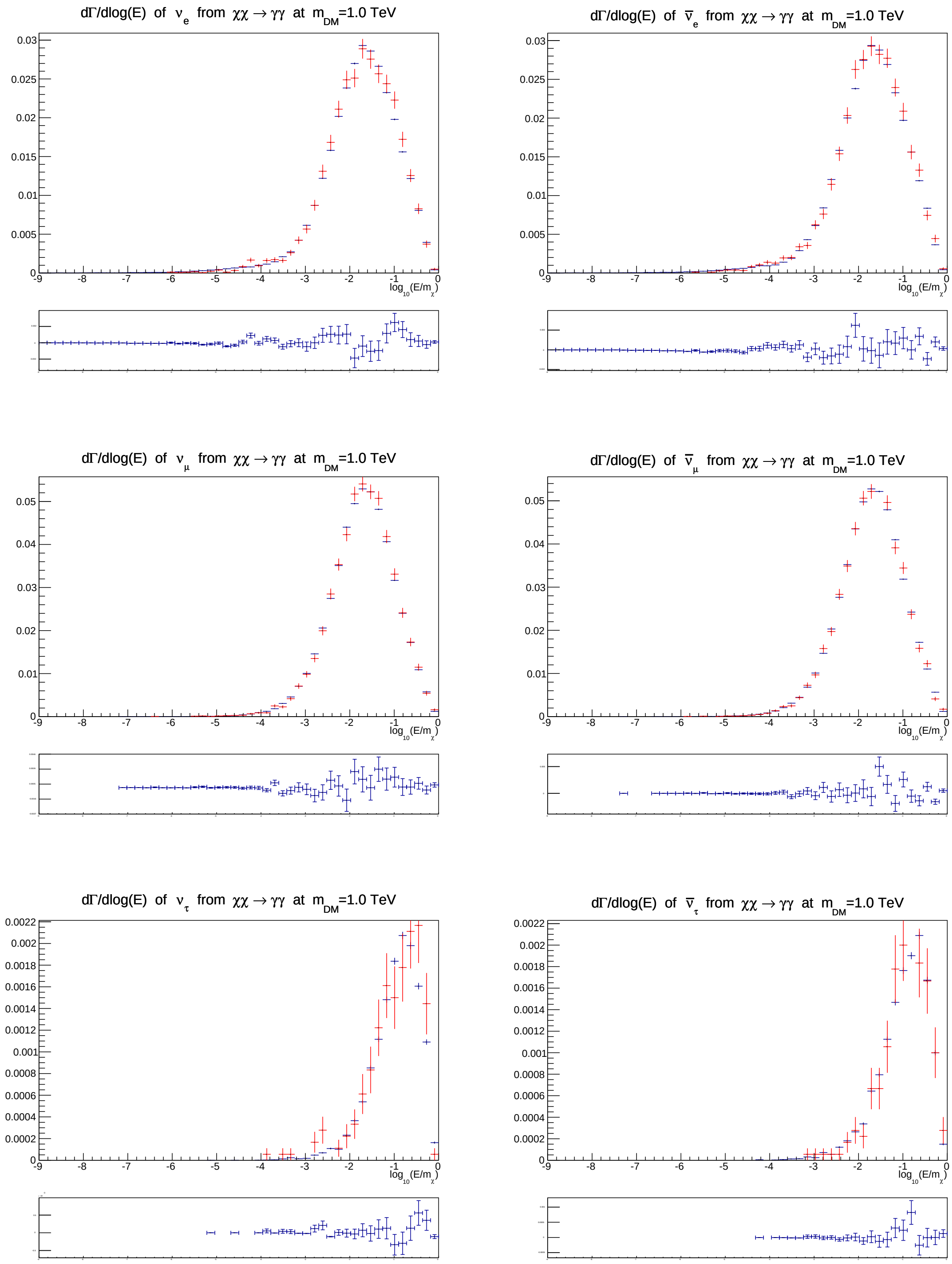

Figure A.3: These are the neutrinos from the $\chi\chi \rightarrow \gamma\gamma$ process, calculated at the $m_{DM} = 1000\text{GeV}$.

A.4 Top-antitop quark channel

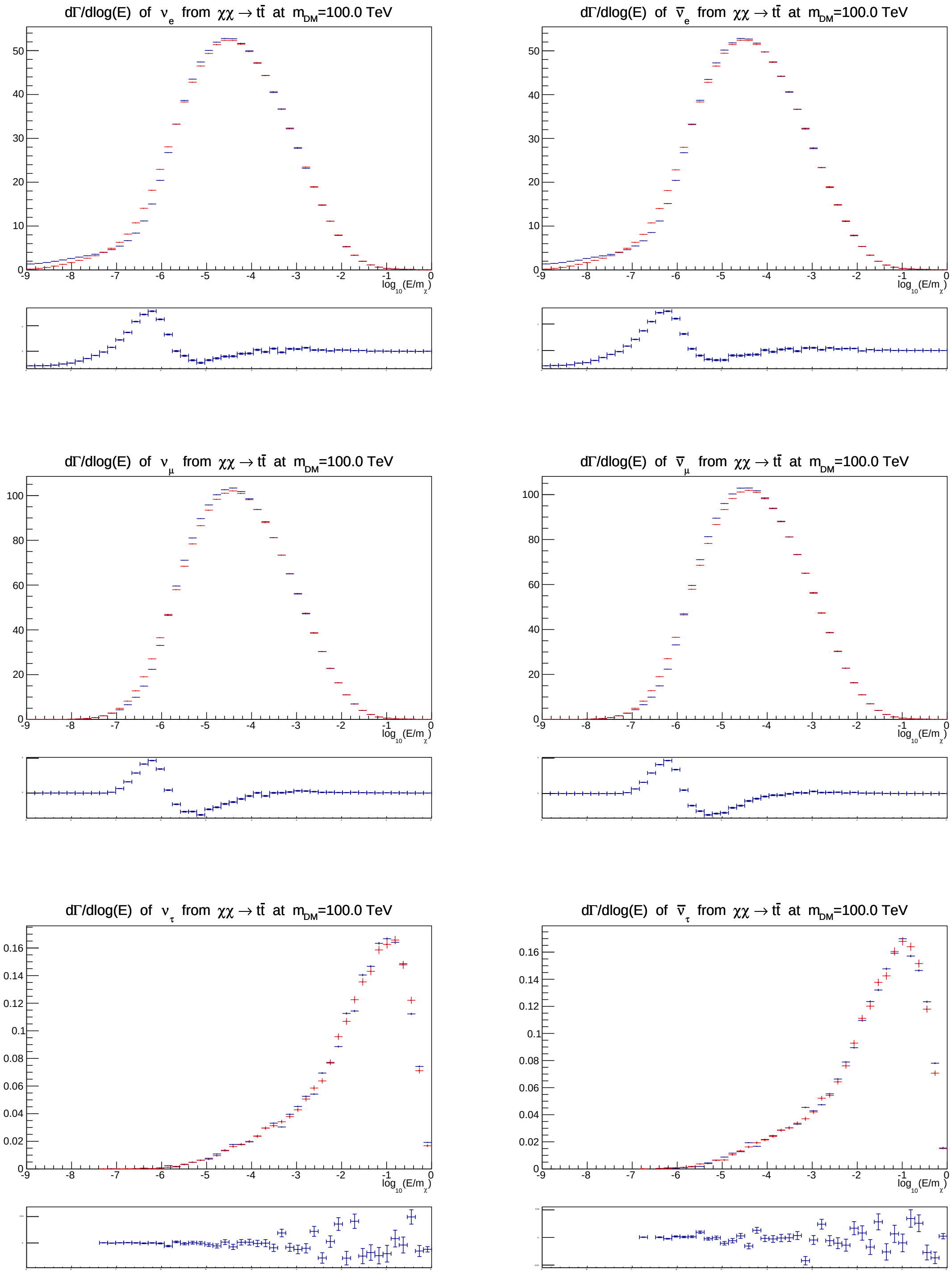

Figure A.4: These are the neutrinos from the $\chi\chi \to t\bar{t}$ process, calculated at the $m_{DM} =$ 100TeV.