Search for Neutrinos from Annihilation of Dark Matter in the Galactic Center with IceCube–79

Von der Fakultät für Mathematik, Informatik und Naturwissenschaften der RWTH Aachen University zur Erlangung des akademischen Grades eines Doktors der Naturwissenschaften genehmigte Dissertation

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The search for a comprehensive theory of dark matter is one of the major fields of activity in particle astrophysics, cosmology and particle physics. After more than 80 years of research since the first evidence for its existence, much has been learned, yet the nature of dark matter is unknown. It is clear, that a non-baryonic, non-radiating kind of matter makes up more than 25% of the energy density of the Universe. The gravitational interaction of dark matter with the visible Universe allows for a spatial mapping of the dark matter distribution on different scales, ranging from galaxies to clusters and large-scale filaments. However, dark matter has so far eluded a detection beyond inference from gravitational interaction.

Indirect searches for dark matter attempt to detect a flux of messenger particles from dark matter annihilation or decay, originating from regions of increased dark matter density. This thesis describes the search for a flux of neutrinos from dark matter annihilation in the Galactic center with IceCube–79.

The dark matter density is expected to peak in the Galactic center region, thus yielding the highest expected flux of final state particles. However, for IceCube the Galactic center is located in the Southern Hemisphere, thus the background of atmospheric muons from that direction provides a major challenge for this analysis. Dedicated techniques to veto this background are developed and discussed. Finally, a likelihood analysis is performed, that exploits the spatial shape of the expected flux. The result is compatible with the null hypothesis, and limits are set on the self-annihilation cross-section, $\langle \sigma_A v \rangle$, for a mass range from 100 GeV to 10 TeV, and several benchmark annihilation channels. The most constraining limit for direct annihilation to neutrinos reaches down to $\langle \sigma_A v \rangle \simeq 10^{-23} \text{cm}^3\text{s}^{-1}$ at a mass of 100 GeV. Finally, the limits are compared to other experimental results, and possible improvements to this analysis are discussed.
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This chapter presents a brief overview over the observational evidence for the existence of dark matter. The introduction is followed by a discussion of possible candidates. Finally, alternative scenarios are discussed.
CHAPTER 1. DARK MATTER

1.1 Introduction

One of the major fields of research in physics is the search for dark matter, which began in the 1930s when Fritz Zwicky performed his by-now famous study of the Coma cluster [1]. Contemporary measurements of the redshift of galaxies in the cluster implied a surprisingly large velocity dispersion. Zwicky applied the virial theorem to the galaxy velocity distribution, estimating the bound mass from the amount of luminous matter. His calculations resulted in a typical velocity dispersion of about 80 km/s, while redshift measurements implied values as large as 1000 km/s. Zwicky came to the conclusion, that the total amount of mass in the Coma cluster had to be higher than the amount of measured luminous mass by about a factor of 400. He called this missing mass Dunkle Materie, or dark matter. More recent measurements imply a higher fraction of luminous matter, but the bottom line remains unchanged; the majority of mass bound within the Coma cluster appears to be non-luminous. Zwicky concluded, that the large observed velocity dispersion and the resulting discrepancy between observed and calculated mass was an unsolved problem. Strangely, in the following years this mystery received not as much attention from the research community as could be expected. Nevertheless, the search for this elusive dark matter gained momentum in the decades to come.

This chapter attempts to give a brief overview over the evidence for dark matter. Further, potential dark matter candidates are presented, and the distribution of dark matter in the Galaxy is discussed.

1.2 Evidence for the Existence of Dark Matter

Evidence for the existence of dark matter is found on different scales, ranging from galactic scales to cosmological scales. The following sections present evidence from observation of galaxies, galaxy clusters, the Cosmic Microwave Background (CMB), and the formation of large-scale structures in the Universe.

1.2.1 Galaxy Cluster Surveys

Following Zwicky’s study, the ratio of luminous mass to total mass has been investigated in other clusters. Usually, this quantity is expressed as the total mass-to-light ratio, $M/L$, given in units of the solar mass and solar luminosity $M_\odot/L_\odot$.

The applied measurement methods may differ, but the general principle is the same: the luminosity represents the luminous mass component of a cluster, while the total mass is inferred from a complementary method. This method may be a measurements of the line-of-sight velocities of galaxies within the cluster, based on redshift measurements, or mass reconstruction from gravitational lensing.

Following [2], application of the virial theorem

$$2T + V = 0$$

(1.1)

\footnote{Note that $M_\odot/L_\odot$ may deviate from unity without implication of a mass discrepancy because the Sun, though a fairly common main sequence star, is not representative of the population of stars forming galaxies and clusters.}
relates the kinetic energy $T$, and thus the velocity, to the potential energy $V$ of the total mass bound in the cluster.

The kinetic energy of the total mass $M$ is

$$T \simeq \frac{M}{2} \langle v^2 \rangle,$$

where $v$ is the mass-weighted velocity dispersion. The potential energy can be expressed as

$$V \simeq -\frac{1}{2}GM^2 \langle \frac{1}{r} \rangle,$$

where $G$ is the gravitational constant, $M$ the total mass and $\langle \frac{1}{r} \rangle$ the mean inverse distance between galaxies in the cluster. Applying equation (1.1), the cluster mass is estimated by

$$M \simeq M_{\text{vir}} = \frac{2\langle v^2 \rangle}{G\langle \frac{1}{r} \rangle},$$

where $M_{\text{vir}}$ is the virial mass.

In [3], the authors report on a survey of 16 clusters with high X-ray luminosities at redshifts between 0.17 and 0.55. Using the virial mass estimate, they find an average value of $M_{\text{vir}}/L = (295 \pm 53) h M_\odot/L_\odot$, where $h$ is a dimensionless parameter, such that the Hubble parameter can be written as $H_0 = 100 h \text{km s}^{-1}\text{Mpc}^{-1}$, with $h = 0.673 \pm 0.012$ (latest measurement by Planck [4]). The reported value of $M_{\text{vir}}/L$ was later reduced to $(213 \pm 59) h M_\odot/L_\odot$ [5].

A more recent survey [6] of 459 clusters selected for robust velocity dispersion yields an average value of $M_{\text{vir}}/L = 348 h M_\odot/L_\odot$. However, using X-ray fluxes as a mass tracer, the mass-to-light ratio is reduced to about 200 $h M_\odot/L_\odot$.

Although the exact values differ significantly and have relatively large uncertainties, the message remains:

- All surveyed galaxy clusters seem to have a dominant mass component of non-luminous matter much larger than expected from the mass-to-light ratio in the Solar neighbourhood of 1.2-1.5 [7]
- This matter only reveals itself through gravitational interaction
- The exact nature of this matter is unknown

1.2.2 Rotation Velocity Curves in Galaxies

Unlike in galaxy clusters, the mass-to-light ratio of galaxies is - within observational uncertainties - almost compatible with the total mass being luminous matter. However, in the 1970s Vera Rubin performed measurements of the rotational velocity curves of the Andromeda galaxy (M31), finding unexpected behavior [8]. From Newtonian dynamics one would expect the velocity beyond the central bulge to follow

$$v(r) = \sqrt{\frac{GM_{\leq r}}{r}},$$

(1.5)
where \( M_{\leq r} \) is the mass enclosed in the sphere of radius \( r \). Rubin found that instead of the predicted \( 1/\sqrt{r} \)-behavior, the velocity curve of M31 remained nearly flat (and unexpectedly high) at large radii. More recent measurements [9] on a sample of galaxies selected such that the velocity curves should represent the mass distribution, e.g. using only well-isolated galaxies with as smooth as possible gas distributions extending far beyond the optically visible disc. Figure 1.1 shows an example of a resulting rotation curve. In general, the shape of rotation curves is not flat, but almost all observed galaxies deviate from the \( 1/\sqrt{r} \)-expectation [10].

![Figure 1.1: Black data points represent the measured rotation curve of NGC 6503 versus radial distance from the center. The visible component (dashed), the gas (dotted), and the dark halo (dashed-dotted) are shown separately. Figure from [9].](image)

Neither the optically visible disc, nor the gas component can explain the velocity curves within the framework of Newtonian dynamics. However, adding a spherically-symmetric component of non-luminous dark matter results in a model which provided good fits to the observed data.

### 1.2.3 Cluster Mergers

One of the most impressive pieces of evidence for the existence of dark matter may be the Bullet Cluster (1E0657-56) at a redshift of 0.296 [11]. It consists of two galaxy clusters after a collision, moving away from each other. Figure 1.2 shows a superposition of X-ray measurements of the hot gas component and the reconstructed total mass distribution from gravitational lensing [12]. There is a clear separation of the gas distribution and the reconstructed total mass, which can
be explained by dynamical friction of the gas components, while the majority of mass passed through the collision point, interacting only gravitationally. Since compact objects, like stars or planets usually contribute less than the gas component to the total mass budget of galaxy clusters [13], most of the mass has to be made up of non-baryonic dark matter.

Figure 1.2: Multi-Wavelength observations of the bullet cluster. The blue-shaded map corresponds to the distribution of (hot) gas, measured by the Chandra X-ray telescope. The black contours depict the mass distribution, as reconstructed from weak-lensing data [12]. Input data for this figure taken from [14].

A further piece of evidence is the discovery of a ring-like structure [15] in the galaxy cluster Cl 0024+17. This structure is most likely caused by a collision of two clusters, similar to the Bullet Cluster, but observed along the collision axis. The reconstructed mass does not trace the intra-cluster medium, which should be the case if no dark matter exists. The observed structures can also be reproduced by dedicated computer simulations of this system, that include dark matter.

Several such cluster mergers have been discovered [16, 17], but the Bullet cluster exhibits the strongest displacement between baryonic and dark matter, remaining one of the most compelling pieces of evidence for dark matter.
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<td>Dark Energy density parameter</td>
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<td>$\Omega_m$</td>
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<td>Matter density parameter</td>
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<tr>
<td>$\Omega_b$</td>
<td>0.0490</td>
<td>Baryon density</td>
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<td>$\Omega_c$</td>
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<td>Cold dark matter density</td>
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<tr>
<td>$t_0$</td>
<td>13.8242</td>
<td>Age of the Universe/Gyr</td>
</tr>
<tr>
<td>$H_0$</td>
<td>67.04</td>
<td>Hubble parameter today/km s$^{-1}$ Mpc$^{-1}$</td>
</tr>
</tbody>
</table>

Table 1.1: Excerpt of a few cosmological parameters extracted from combined Planck and WMAP data [4].

### 1.2.4 Cosmic Microwave Background and Cosmology

The anisotropy of the cosmic microwave background (CMB) on different angular scales provides one of the best probes of cosmology. This heavily red-shifted remnant light from the recombination era permeates the Universe, and is one of the best representations of a blackbody spectrum observable in nature. The CMB has a temperature of about 2.73 K [18] and is nearly isotropic with temperature fluctuations on the $10^{-5}$-level.

Earth-based telescopes like ACT [19] as well as satellite-born experiments like WMAP [20] and most recently Planck [4] performed precision measurements of the CMB. Fits of multi-parameter cosmological models to the data yield precise values for e.g. the density parameters $\Omega_{r,m,k,\Lambda}^2$, the number of relativistic species or the Hubble constant. These parameters define the $\Lambda$-CDM - or concordance - model of cosmology, where $\Lambda$ stands for the vacuum energy and CDM for Cold (\(\hat{=}\) non-relativistic) Dark Matter. Planck’s measurement of the model parameters is summarized in table 1.1, and represent the currently best knowledge of the Universe’s setup. The measurement confirms at an unprecedented accuracy that dark matter accounts for the majority of the matter content of the visible Universe.

Basic assumptions within the framework of Big-Bang cosmology allow the calculation of relative abundances of light elements in the Universe [21], which is referred to as Big-Bang-Nucleosynthesis (BBN). The governing free parameter is the baryon-photon-ratio, or the more convenient rescaled quantity $\eta_{10} = 10^{10} n_b/n_\gamma$. This parameter can be estimated from modeling the conditions (e.g. expansion rate, temperature) a few minutes after the Big Bang, or it can be extracted from measured relative abundances of light elements$^3$. Using $5.7 \leq \eta_{10} \leq 6.5$ [21], the baryon density parameter can be constrained to

$$0.021 \leq \Omega_b h^2 \leq 0.024,$$

where $h = H_0/100$ is kept to reduce dependence on the measurement of $H_0$. With current values of $h$, this translates to a baryonic matter density fraction of about 5%, which is in reasonable agreement with CMB results and again stresses the fact, that baryonic matter alone is not sufficient to account for the total matter in the Universe.

$^2$A brief introduction to cosmology and the density parameters can be found in appendix A.

$^3$The inverse procedure of measuring $\eta_{10}$ from $\Omega_b$ and $\Omega_c$ is used to test non-standard BBN scenarios.
1.2.5 Structure Formation

Another piece in the picture of dark matter is the support for Λ-CDM cosmology from simulations of structure formation. Structure formation in the Universe is assumed to originate in primordial density fluctuations. Following the hierarchical collapse scenario described by the Press-Schechter formalism [22], structures grew from gravitational instabilities caused by these fluctuations, similar to e.g. star creation from gas clouds [23]. First, smaller structures formed, which consecutively merged to finally form the largest observable structures like galaxy clusters or even larger filaments [24].

Assuming Λ-CDM initial conditions, simulations which trace the distribution and dynamics of N-body systems under self-gravity should yield structures that are comparable to observations. The finite resolution and limitations in the number and mass of simulated particles makes it impossible to trace the evolution of N-body-systems on all interesting scales within one simulation, thus large-scale structure formation simulations do not resolve the central regions of galactic haloes.

The Virgo consortium\footnote{http://www.virgo.dur.ac.uk/}, among others, performed a series of N-body simulations known as the Millennium simulations (e.g. [25]) under Λ-CDM initial conditions. Large-scale structures, as well as the timescales for the formation of such structures are compared to actual observations form redshift surveys like SDSS [26] or 2dFGRS [27]. Figure 1.3 shows an illustrative comparison of mock catalogues drawn from simulation data with actually observed structures [28]. The striking similarity is a further confirmation of dark matter as a driving force behind large-scale structure formation, and Λ-CDM cosmology in general.

1.3 Dark Matter on Galactic Scales

Simple spherical infall scenarios lead to self-similar collapsed overdensities on different scales, which are reasonably well-described by radially symmetric isothermal ($\rho(r) \propto \frac{1}{r^2}$) power-law density profiles. These overdensities are called haloes, though the term has it’s origin in the galactic halo; the distribution of stars, globular clusters and gas, which extends beyond the visible galactic disk.

N-body simulation is a powerful tool to examine the density distribution and dynamics of dark haloes from such collapse scenarios. These simulations hint at a generalized density profile [29] which is valid over a large halo mass range. The generalized shape is a consequence of halo self-similarity. However, such simulations do not reproduce the $\rho(r) \propto \frac{1}{r^2}$ behavior at small radii, as implied by simple infall calculations.

A frequently used spherically symmetric parametrization of such universal density profiles is the $(\alpha, \beta, \gamma)$-profile, given by [30]

$$\rho_{DM}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^{\gamma}} \cdot \left(1 + \left(\frac{r}{r_s}\right)^{\alpha}\right)^{(\beta-\gamma)/\alpha}, \quad (1.7)$$

with the radial distance $r$ from the halo center, a scale radius $r_s$ to accommodate dark haloes on different scales and mediate between different inner and outer steepness, and a set of parameters...
(α, β, γ) which describe the steepness of the density profile at different radii. For example, γ corresponds to the steepness in the central halo region. The halo profile is normalized via $\rho_0$. For the Milky Way $\rho_0$ has to be chosen such that the local dark matter density at the radius of the Solar orbit, $R_{SC}$, is $\rho_{SC} = \rho(R_{SC} \approx 8.5\text{kpc})$, and is in agreement with observations of e.g. the local rotation velocity. Due to halo self-similarity, equation (1.7) can describe a cluster-scale halo profile just as well as a galactic halo or the galactic sub-structure, though the scaling parameters are different.

The model parameters can be either determined from simulation or fitted to observational data, e.g. based on star tracing in low-surface-brightness galaxies or dwarf galaxies, which are expected to be dominated by dark matter [31]. In general, the halo models have to comply with

- Observed rotation velocity curves, obtained from velocity tracers over a wide range of
galactocentric distances

- 21 cm radiation from interstellar hydrogen (HI)
- Maser velocities from star-forming regions
- Outer halo stars, used as velocity tracers

- Total halo masses (often as boundary conditions for scaling parameters)
- For the Milky Way: the local dark matter density

A widely used halo profile is the NFW model, proposed by Navarro, Frenk, and White, and described by the parameters \((\alpha, \beta, \gamma) = (1,3,1)\) and \(r_s = 20\text{kpc}\) at galactic scales [29].

While the behavior of density profiles at large radii is reasonably well-understood, there is still tension between different profiles in the description of the central region. A shortcoming of the NFW profile as well as other profiles described by equation (1.7) is the prediction of too much mass content in the central region. N-body simulations usually result in haloes with sharp central cusps, often described by a divergent density towards the center. Density profiles derived from observation exhibit a rather flat core region. This disagreement cannot be resolved easily, both due to limited resolution of simulations on one side and large observational uncertainty on the other side. This is referred to as the cusp-core problem [32, 33]. While this aspect is essentially unresolved, many mechanisms have been proposed to ease the tension, usually based on gravitational interaction of compact massive objects (e.g. subhaloes, star clusters), or interaction with baryonic matter (e.g. energetic feedback from stars or supernovae) [34, 35, 36].

A purely phenomenological halo profile was proposed by Burkert [37], which reproduces the dynamics of dwarf galaxies and does not exhibit a divergent behavior for \(r \to 0\). It is convenient to extend the general parametrization given in equation (1.7) to

\[
\rho_{\text{DM}}(r) = \frac{\rho_0}{\left(\delta + \frac{r}{r_s}\right)^\gamma \left(1 + \left(\frac{r}{r_s}\right)^\alpha\right)^{(\beta - \gamma)/\alpha}},
\]

where \(\delta = 0\) for all \((\alpha, \beta, \gamma)\)-profiles, but \(\delta = 1\) for the Burkert case, which is then described by \((\alpha, \beta, \gamma, \delta) = (2,3,1,1)\). The choice of \(\delta = 1\) introduces an extended core of finite size \(r_s\) and central density \(\rho_0\).

Due to the large variety of proposed models, a complete overview is far beyond the scope of this section. However, one further case should be mentioned, namely the Einasto profile, initially reported in [38], but later restated with focus on dark haloes [39, 40] to

\[
\rho_{\text{DM}}(r) = \rho_s \cdot e^{-d_n ((r/r_s)^{1/n} - 1)} \quad (1.9)
\]

with \(r_s\) being the radius which contains half of the total mass, \(\rho_s = \rho(r_s)\), and \(d_n\) a dimensionless normalization constant to enforce that \(M_{<r_s} \simeq M_{\text{tot}}/2\), which is given by

\[
d_n = 3n - \frac{1}{3} + \frac{1}{1215n} + \mathcal{O}(n^{-2}) \quad (1.10)
\]

\[
n = 4...7 \quad (1.11)
\]
CHAPTER 1. DARK MATTER

The Einasto profile proved successful in describing a wide mass range of dark haloes, often in better agreement than the NFW profile.

Table 1.2 gives an overview over a few frequently used models, including normalization parameters for Milky-Way-sized galaxies.

A recent thorough investigation of the local dark matter density, $\rho_{SC}$, and the dark matter density profile of the Milky Way has been performed [47]. Global fits of the Burkert profile and the NFW profile to various velocity tracer data for a wide range of galactocentric distances are compared. While the NFW profile is not excluded, the cored Burkert profile is favored. The results from [47] are used as baseline for the analysis presented in this thesis, where the NFW profile is presented for comparability to other experiments, and the Burkert profile is considered the best-motivated result.

Figure 1.4 shows some of the considered halo models. A broader comparison of halo models can be found in [48].

1.4 Dark Matter Candidates

While there almost certainly is more gravitationally active mass than visible mass in the Universe, the question about the nature of this mass is open: Is it simply non-luminous, but baryonic matter, or is it a new kind of particle? If the majority of dark matter would consist of massive non-luminous astronomical objects, called MACHOs (MAssive Compact Halo Objects), the abundance could be estimated from gravitational lensing experiments. MACHOs can be anything from the extremely faint brown dwarfs to stellar black holes with masses ranging from $0.1 M_\odot$ to $1 M_\odot$. The EROS collaboration determined the MACHO-fraction of haloes from micro-lensing to be less then 25% at a confidence level of 95%, being sensitive to masses from $2 \cdot 10^{-7} M_\odot$ to $1 M_\odot$ [49].

It became apparent, that dark matter has to be a new kind of matter, which also should fulfill the following conditions

- non-baryonic ( $\Omega_q$-determination from BBN, $\Omega_{m,b}$ determination from CMB)
- neutral, no electromagnetic interaction (e.g. mass/gas-displacement in Bullet Cluster)
1.4. DARK MATTER CANDIDATES

![Graph showing the density of dark matter candidates at different radii.]

**Figure 1.4:** Some of the halo models described in section 1.3, the parameters are listed in Table 1.2 (Einasto parameters: equation (1.10 - 1.11)). The different models show reasonable agreement in the outer region, but differ at smaller radii.

- non-relativistic (cold or warm) particles (large-scale structure formation would be washed out otherwise)
- stable or extremely long-lived (relic form the Big Bang)

### 1.4.1 The Usual Suspect: Neutrinos

Looking at the Standard Model, neutrinos seem to be viable dark matter candidates. Given their small but non-zero mass, they are considered a relativistic species, making them a candidate for hot dark matter. However, hot dark matter has a different effect on the cosmic evolution than cold dark matter. The formation of large-scale structures takes longer, compared to Λ-CDM time-scales, and small-scale structures (small in a cosmological sense can mean Mpc-scales) are smoothened. This is in tension with observed structures, which were obviously formed within the age of the Universe of about 13.8 Gyr. A comparison of large-scale structures in the Universe to large-scale structure formation in N-body simulation is shown in figure 1.3). Further, the hierarchy of structure formation would be inverted due to smoothing on small scales.

The Planck collaboration measured the effective number of neutrino-like (relativistic) species to be $N_{\text{eff}} = 3.36 \pm 0.34$, with an upper limit on the summed mass of $\Sigma m_\nu \leq 0.66 \text{ eV}$ [4]. The
neutrino abundance can be estimated by
\[ \Omega_\nu h^2 \simeq \Sigma m_\nu / 93.04 \text{eV} \simeq 0.007, \]
yielding a value of \( \Omega_\nu \simeq 0.015 \) (assuming \( h = 0.673 \)) which is much smaller than \( \Omega_m \). Note that this estimate is valid for any relativistic species, rather than only neutrinos, thus hot dark matter in general is disfavored, if not ruled out. This does not necessarily apply to heavy sterile neutrinos; in fact keV-range sterile neutrinos are intriguing candidates for warm dark matter [50].

1.4.2 WIMP Dark Matter

The favored class of candidates for cold dark matter are Weakly Interacting Massive Particles (WIMPs), a blanket term spanning a wide range of actual underlying theories. Assuming weak-scale interaction strengths and a mass in the GeV–TeV range, WIMPs naturally yield a relic abundance expected of thermally produced dark matter [51].

In order to estimate the relic abundance of a WIMP species, one has to consider all processes which create or destroy particles of that species. Here, the most relevant processes are pair-production, annihilation, and the expansion of space. Initially, WIMPs are pair-produced and annihilate, which leads to an equilibrium density that depends on the temperature. The pair-production rate decreases due to the expansion, and the associated decreasing temperature of the Universe. Similarly, annihilation processes become rarer due to the dilution associated with expansion. At some point the temperature falls below the pair-production threshold \( k_b T \simeq m c^2 \), and WIMPs are no longer produced efficiently. Annihilation reduces the WIMP density exponentially, until the annihilation rate matches the expansion rate. At this point the WIMP population is too diluted to further annihilate efficiently. The WIMP density stabilizes, which is referred to as “freeze-out”.

The time evolution of the density \( n \) of a WIMP species is described by the Boltzmann equation, which for WIMPs is simplified to

\[
\frac{dn}{dt} = -3Hn - \langle \sigma_A v \rangle (n^2 - n_{eq}^2).
\]

Here, \( H \) is the Hubble parameter, and \( n_{eq} \) is the density in thermal equilibrium. The first term corresponds to the expansion of space, the second describes the decrease in density due to self-annihilation.

Figure 1.5 illustrates solutions of equation (1.13), where the time evolution of the WIMP density is shown as a function of increasing time, or increasing inverse temperature \( 1/T \). The equilibrium line is shown, as well as freeze-out plateaus for several assumed annihilation cross-sections.

Although equation (1.13) has no analytical solution, a simple order-of-magnitude estimation of the WIMP relic density \( n_\chi \) and the associated density parameter \( \Omega_\chi \) was derived in e.g. [53, 52] to be

\[
\Omega_\chi h^2 = \frac{3 \cdot 10^{-27} \text{cm}^3 \text{s}^{-1}}{(\sigma_A v)_\chi},
\]

where \((\sigma_A v)_\chi\) is the annihilation cross-section of the WIMP.

\[
\langle \sigma_A v \rangle \simeq \frac{m_\chi}{2 \cdot 10^{-27} \text{cm}^3 \text{s}^{-1}} (\sigma_A v)_\chi.
\]
1.4. DARK MATTER CANDIDATES

Figure 1.5: The relative density fraction is shown as function of the inverse temperature, with different freeze-out scenarios for weak-, strong- and electromagnetic-scale interaction cross-sections. Assuming weak-scale interactions, WIMPs have the right relic abundance, as determined from e.g. CMB measurements. Figure taken from [52].

with the WIMP mass $m_\chi$, the WIMP density $n_\chi$, and the critical density $\rho_c$.

The annihilation cross-section of a 100 GeV particle with weak-scale interactions can be estimated to $\langle \sigma v \rangle_{\text{weak}} \simeq \alpha^2/m^2 \simeq 10^{-25}\text{cm}^3\text{s}^{-1}$, with $\alpha \simeq 10^{-2}$. With this value, equation (1.14) results in $\Omega_\chi h^2 \simeq 0.03$. This simple estimate yields about the right order of magnitude to explain most if not all of the dark matter content of the Universe. Note that the underlying assumptions on $\langle \sigma v \rangle_{\text{weak}}$ come from particle physics, the necessary value of $\Omega_\chi$, however, is derived from cosmology. Due to this remarkable coincidence, the term “WIMP miracle” was coined.

There are several theoretical frameworks which yield a natural particle candidate for the WIMP class. Two such theoretical frameworks are presented below:

- **Lightest Supersymmetric Particle (LSP)** Supersymmetric extensions (SUSY) to the Standard Model postulate the existence of super-partners to SM particles, boson super-partners to fermions and vice versa. Non-observation of such particles at collider experiments implies, that these super-partners have higher masses (TeV-scale). Assuming that R-parity is conserved, the lightest supersymmetric particle (LSP) is stable\(^5\), and

\[^5\] $R = (-1)^{(B-L)+2s}$, with Baryon number $B$, lepton number $L$, and spin $s$
presents a viable dark matter candidate. This assumption is justifiable, since otherwise couplings may occur, which would lead to baryon number violation [54]. The lightest neutralino, a mass eigenstate of SUSY partners of the Higgs bosons and the electro-weak gauge bosons, is a prominent WIMP candidate.

- **Kaluza-Klein dark matter**
  Kaluza-Klein theory [55] attempts a unification of gravity and electro-magnetism by extending general relativity to 5 dimensions. Models of universal extra-dimensions, where SM particles may propagate in compact additional dimensions, offer a viable lightest Kaluza-Klein particle (LKP) [56], if KK-parity is conserved, which is a similar concept to R-parity. KK-states of the photon or neutrino represent such LKP candidates with masses in the TeV-range.

### 1.4.3 Other Dark Matter Candidates

Currently, there is no lack of dark matter candidates. Rather, a plethora of possible candidates has been proposed from different theories. A complete overview is beyond the scope of this thesis. However, figure 1.6 shows a few classes of candidate particles like neutrinos, axions, q-balls, or black hole remnants in the \( \sigma_{\text{int}} - m_{\text{WIMP}} \)-plane. It is clear, that these candidates span a wide range of cross-sections and masses, and make the design of experiments as well as analyses within a single experiment particularly difficult.

### 1.5 Criticism and Alternative Scenarios

Many questions in the field of dark matter remain open. Be it the nature of dark matter itself, or discrepancies in observation and simulation or analytical descriptions of the dark matter distribution on different scales. As an example for criticism of the \( \Lambda - \text{CDM} \) paradigm, the missing satellite problem should be mentioned [59].

The halo-mass function describes the number density of haloes per mass interval and co-moving volume \( \left( \frac{dn}{dM} \right) \). It can be extracted from analytical calculations within the Press-Schechter formalism [22], fitted to N-body simulations [60], or extracted from weak lensing observation. The number of subhaloes in the Milky Way, which are believed to be seeds for dwarf spheroidal galaxies, should follow the halo-mass-function, and thus the number of satellites should be predicted as well. In [61], the authors first reported that the actually observed number of satellites is a factor of about 10 below the expectation. The exact numbers may vary with new discoveries of faint satellites, but the discrepancy remains unresolved.

One of the first attempts at resolving the missing-mass problem without postulating a new kind of matter was the modification of Newtonian dynamics (MOND\(^6\)), proposed by Milgrom in 1983 [62], and recently summarized in [63]. A modification of the form

\[
F = m \mu \left( \frac{a}{a_0} \right) a,
\]

Figure 1.6: Overview over the vast range in predicted interaction cross-sections and masses for various dark matter candidates. Figure with data from [57, 58].

with

$$
\mu(a/a_0) \approx \begin{cases} 
1 & a/a_0 \gg 1 \\
\frac{a}{a_0} & a/a_0 \ll 1
\end{cases},
$$

was supposed to alter large-scale behavior at low accelerations ($< 10^{-10} ms^{-2}$) only. An extended Lagrangian-based formulation was published by Bekenstein and Milgrom [64], a further relativistic extension followed [65].

These approaches have been applied quite successfully to the usual dark matter test cases, for example ring and shell structures in mass distributions (e.g. 1E0657-56, Cl 0024+17), which are attributed to dark matter [66]. However, while modified gravity theories do explain one or several phenomena, they fail to explain the full picture; dark matter still seems to deliver the best explanation for most phenomena from cosmological scales to galactic and sub-galactic scales, though not without tension.
Evidence for the existence of dark matter has been discussed in section 1.2, with the main theme being inference from gravitational interaction. However, from the point of view of particle astrophysics, dark matter would not be experimentally accessible, if it would not take part in at least weak interactions. In such a case direct and indirect searches can be conceived. In fact, complementary detection channels are absolutely necessary to resolve ambiguities of possible single-detection interpretations, and to close in on the exact nature and properties of dark matter. For example, the detection of missing mass in a collider experiment may be a hint for dark matter, but is it stable? Or is the life time long enough on cosmological scales? This chapter discusses the main classes of dark matter searches.
2.1 Detection Methods Beyond Gravitational Inference

If dark matter interacts with the Standard Model (SM) sector, searches may be conducted, which make use of one of the following processes:

- Production at colliders, leading to a missing-mass signature (s. section 2.1.1).
- Scattering of dark matter on target nuclei in Earth-based detectors (s. section 2.1.2).
- Annihilation of dark matter to SM particles may lead to an observable flux of cosmic messenger particles (s. section 2.1.3).

Figure 2.1 shows a schematic overview over these processes, which can be depicted by similar Feynman graphs, depending on the choice of direction of the time axis.

![Diagram](image)

**Figure 2.1**: Schematic depiction of dark matter interaction with Standard Model particles. Depending on the direction of the time axis, the three major search strategies are shown.

2.1.1 Dark Matter Production in Collider Experiments

Dark matter may be pair-produced in particle collisions at collider experiments, if the dark matter mass is less than half of the center-of-mass energy $\sqrt{s}$ per parton. Since such particles would leave the detector undetected, the main signature of dark matter searches at colliders is missing energy, or more specifically monojets from initial state interaction, accompanied by missing transversal energy [67]. Another signature is the production of heavier parent particles, that in turn decay to dark matter particles and further SM particles in one or more jets.

Figure 2.2 shows exclusion limits on the spin-independent WIMP-nucleon scattering cross-section from an analysis of CMS data, in comparison to current direct search (s. section 2.1.2) experiments.
2.1. DETECTION METHODS BEYOND GRAVITATIONAL INFERENC 

2.1.1 Indirect Detection

The movement of Earth through a dark matter halo at estimated velocities ranging from 200 km/s to 250 km/s [68] would lead to a flux of dark matter particles through Earth-based detectors. Thus, the expected signature is a WIMP-nucleus scatter events with recoil energies in the keV range. The significance of such a signature may be further enhanced by annual modulation of such events due to Earth’s rotation around the Sun [69], as well as a forward-backward anisotropy, if directional reconstruction of recoiling nuclei is possible.

The expected event rates are extremely low, depending on the WIMP velocity distribution, scattering cross-section and WIMP mass, but are typically significantly lower than 1 event/year/kg. Thus the ambient background has to be understood precisely.

In addition to a typical rock overburden of a few kilometers (water-equivalent), dark matter detectors have to be encased in multi-component shields to reduce ambient radiation from e.g.

---

**Figure 2.2:** Limits from the search for monojets accompanied by missing transversal energy at the LHC, and comparison to direct search limits. Figure taken from [67].

However, the detection of missing energy in a collider experiment is not a clear detection of dark matter. While such a measurement would yield information about the production and interaction mechanisms, as well as e.g. the mass of dark matter particles, it is inherently impossible to test the stability of such-produced particles. Any interaction product leaves the detector and may decay on a time scale, that disqualifies the particle as a stable or extremely long-lived dark matter candidate.

2.1.2 Direct Searches

Direct searches for dark matter aim at measuring WIMP-nucleon interactions in extremely radio-pure and background-free Earth-based underground detectors.

The movement of Earth through a dark matter halo at estimated velocities ranging from 200 km/s to 250 km/s [68] would lead to a flux of dark matter particles through Earth-based detectors. Thus, the expected signature is a WIMP-nucleus scatter events with recoil energies in the keV range. The significance of such a signature may be further enhanced by annual modulation of such events due to Earth’s rotation around the Sun [69], as well as a forward-backward anisotropy, if directional reconstruction of recoiling nuclei is possible.

The expected event rates are extremely low, depending on the WIMP velocity distribution, scattering cross-section and WIMP mass, but are typically significantly lower than 1 event/year/kg. Thus the ambient background has to be understood precisely.

In addition to a typical rock overburden of a few kilometers (water-equivalent), dark matter detectors have to be encased in multi-component shields to reduce ambient radiation from e.g.
radioactive decays, $(\alpha,n)$-reactions, and neutrons that are produced by nuclear interactions of atmospheric muons.

Further background reduction can be achieved by pulse-shape discrimination or construction of detectors which combine two detection techniques with different light yields for different interaction types to suppress the remaining background on a per-event basis. The most important detection techniques are:

- Ionization
- Scintillation
- Heat deposition/phonon excitation

**Figure 2.3**: Overview over the major detection techniques, and experiments.

Figure 2.3 presents an overview over experiments, which rely on one or two of the above-mentioned methods. Currently leading experiments are the dual-phase liquid/gaseous xenon time projection chambers LUX [70] and Xenon–100 [71], as well as the cryogenic detector CDMS–II [72]. The latest results from LUX are compatible with the null hypothesis, thus resulting in exclusion limits on the spin-dependent (SD) and spin-independent (SI) WIMP-nucleon interaction cross-section, $\sigma_{SD}$ and $\sigma_{SI}$. Figure 2.4 shows SI-limits along with the previously most constraining upper limits from the CDMS–II final run, and the latest Xenon–100 results.

Despite non-detection of dark matter in current state-of-the-art experiments, there is a long-standing claim of discovery of an annual modulation signal by the DAMA/Libra collaboration [73] at a significance of more than 8$\sigma$. Though the modulation is beyond doubt, the
interpretation as dark matter signal is heavily disputed. Nevertheless, the potential discovery of low-mass WIMPs ($\leq 10\,\text{GeV}$) gained footing due to similar, if more cautious, claims from the CoGeNT collaboration [74], as well as ensuing investigation of low-threshold Si-only data from CDMS–II [75], and results from CRESST [76].

A comparison of allowed regions in the $m_\chi$–$\sigma$ plane from CoGeNT and DAMA/Libra to the current best exclusion limits can be found in figure 2.4. Most parts of the allowed low-mass regions are excluded, making a WIMP interpretation rather challenging.

![Figure 2.4: Latest exclusion limits on the spin-independent WIMP-nucleon scattering cross-section from LUX [70], CDMS–II [72], and Xenon–100 [71]. The shaded regions represent allowed parameter ranges, based on discovery claims from DAMA/Libra [77, 73], and CoGeNT [74]. Data taken from the DM-Tools archive (http://dmtools.brown.edu:8080/).](image)

2.1.3 Indirect Searches

Dark matter particles may (self-)annihilate or decay to Standard Model particles, e.g. $\gamma$, $e^\pm$, or $\nu$, which would lead to a flux of detectable messenger particles. One branch of indirect searches is aimed at the detection of this flux in Earth-based or satellite-based detectors.

For example, an excess of cosmic positrons can be a signature of annihilating dark matter.
Due to propagation/diffusion effects, any positron signal from such annihilations would have to stem from the Solar vicinity with a diffusion radius of a few kpc. The PAMELA collaboration reported such an excess in the positron fraction [78], with support for the claim from recent AMS-2 measurements [79]. Though, the origin of additional positrons can be attributed to the existence of a nearby source [80], e.g. a pulsar [81], the interpretation in context of a diffuse flux of dark matter annihilation products is possible [82]. However, a missing signature in the anti-proton measurement proves challenging from a theoretical point of view, since any viable dark matter candidate would have to be leptophilic, i.e. favoring leptonic annihilation channels.

A very promising approach is the search for a flux from targets or regions which are expected to have a higher-than-average dark matter density and/or a comparatively low foreground radiation. Examples of such regions are the Galactic center, galaxy clusters, dwarf spheroidal galaxies or the outer Milky Way halo.

The advantage of galaxy clusters searches is a potentially high flux expectation due to the large cluster mass, and boosting from substructures. Dwarf galaxies on the other hand offer an astrophysically more simple environment; they are usually dominated by dark matter, host few background sources for e.g. gamma-ray detectors, and can be considered point-like for most instruments.

Among the galactic targets, the Galactic center is the most prominent one, both because of the relative proximity and high dark matter density. One disadvantage of the Galactic center is the large halo-profile-specific uncertainty on the density in the central region. Figure 1.4) shows the dark matter density profile as function of galactocentric radius. The uncertainty translates to an uncertainty on the flux expectation, spanning orders of magnitude among different models. The flux expectation is discussed in section 2.2 with focus on neutrinos as messenger particles.

Searches for an expected large-scale anisotropy of a flux from the Galactic halo offer the advantage of relatively small model-dependence, at the expense of a lower expected flux. However, this disadvantage is mitigated by the significantly larger solid angle, which is usually only constrained by the instrument’s field of view. Due to the distances involved, such searches have to rely on stable messenger particles with a sufficient pointing accuracy, mostly photons and neutrinos.

A very different approach makes use of the assumption that dark matter annihilation in the early Universe would leave an imprint on the CMB due to the injected additional energy [83, 84] during recombination. This method is less prone to uncertainties in structure formation (halos, clusters), but suffers from uncertainties in the energy deposition mechanisms and cosmological evolution.

Figure 2.5 presents a comparison of some of the different presented searches. Such a comparison, however, should be done with caution, since key assumptions among the methods differ. For example, all presented results constrain $\langle \sigma_A v \rangle$, but the velocity distribution in galactic halos is different to the relative velocities during the recombination phase, which is relevant for constraints derived from CMB anisotropy. Further, figure 2.5 shows the natural scale for WIMPs being thermal relics from the Big Bang [52], and the unitarity bound [85]. The
latter is an upper limit on $\langle \sigma_A v \rangle$ and the maximum WIMP mass, assuming s-wave annihilation of elementary particles. Note that both the natural scale and the unitarity bound, while well-motivated, are not carved in stone. For example, the unitarity bound for p-wave annihilation may be very different. A more comprehensive comparison of limits from this analysis to other results is presented in section 6.4.

![Graph](image_url)

**Figure 2.5:** A small subset of experiments yielding constraints from complementary indirect searches for dark matter. The constraint labeled as “CMB” is based on a search of a possible imprint on the CMB [84]. Further, two limits from IceCube searches for dark matter in the Galactic halo (IC22 GH) and dwarf spheroidal galaxies (IC59 dwarfs) are shown [86, 87]. The Fermi limit is obtained from a search for dark matter annihilation in dwarf spheroidal galaxies [88]. The green-shaded region is a preferred region based on the Pamela excess, along with further constraints from Fermi as interpreted by Meade et al. [82]. The upper dotted line represents the unitarity bound [85], the bottom shaded region is the natural scale for WIMPs as thermal relics [52].

## 2.2 Neutrinos from Dark Matter Annihilation in the Galaxy

Neutrinos are ideal messenger particles in astrophysics in general, and for probing the Galactic center region in particular. They can escape the astrophysically complex environment unimpeded because of their low interaction probability. Moreover, there is no known background source of neutrinos from that direction, which is a major source of uncertainty for gamma-ray searches, along with propagation uncertainties.
Further, following [89], a constraint on dark matter annihilation to neutrinos offers a conservative upper bound on the self-annihilation cross-section to Standard Model particles. Neutrinos are the least “visible” Standard Model messenger particles because of the low interaction probability. Further, annihilation to all other final states leads to an associated gamma-ray flux. If a search for annihilations to neutrinos yields an upper bound on $\langle \sigma_A v \rangle$, and the branching ratio $B(\chi \chi \rightarrow \nu \nu)$ deviates significantly from 100%, searches for e.g. a gamma-ray flux from dark matter annihilation would provide stronger constraints on $\langle \sigma_A v \rangle$, or even detect a flux. In [89], the authors derive such a conservative upper bound by comparing the cosmic diffuse neutrino flux from dark matter annihilation in all halos to the flux of atmospheric neutrinos. For example, assuming a WIMP mass of 1 TeV, the such-obtained limit is on the order of $\langle \sigma_A v \rangle \approx 10^{-21}$ cm$^3$s$^{-1}$.

A potential flux of final-state neutrinos from dark matter self-annihilation in the Milky Way depends on the squared density integrated along a line of sight, defined by an opening angle $\Psi$ with respect to the Galactic center. The line-of-sight integral $J_A(\Psi)$ is also referred to as “prompt emission factor”, or simply $J$-factor, and is given by

$$J_A(\Psi) = \int_0^{l_{\text{max}}} dl \, \rho^2(\Psi, l) = \int_0^{l_{\text{max}}} dl \, \rho^2(\sqrt{R_{\text{SC}}^2 - 2lR_{\text{SC}} \cos \Psi + l^2}), \quad (2.1)$$

where $l$ is the integrand along the line of sight, and $R_{\text{SC}}$ the radius of the Solar orbit around the Galactic center. Figure 2.6 shows a schematic depicting quantities that are relevant for this calculation. The $J$-factor is often rescaled to a dimensionless quantity, by dividing the line-of-sight integral from equation (2.1) by the squared local dark matter density $\rho_{\text{SC}}$ and the radius of the Solar orbit $R_{\text{SC}}$:

$$J_A(\Psi) = \int_0^{l_{\text{max}}} dl \, \frac{\rho^2(\sqrt{R_{\text{SC}}^2 - 2lR_{\text{SC}} \cos \Psi + l^2})}{R_{\text{SC}} \rho_{\text{SC}}^2}. \quad (2.2)$$

Removing the normalization emphasises the model-dependence of e.g. the inner slope, and allows for a qualitative comparison of different halo profiles. The upper integration limit $l_{\text{max}}$ is given by

$$l_{\text{max}} = \sqrt{R_{\text{MW}}^2 - \sin^2 \Psi R_{\text{SC}}^2} + R_{\text{SC}} \cos \Psi, \quad (2.3)$$

where $R_{\text{MW}}$ is the assumed radial extension of the Milky Way. The choice of $R_{\text{MW}}$ is somewhat arbitrary, since a dark matter halo blends smoothly into the intergalactic environment, however, contributions to $J_A$ from distances larger than a few halo scale radii $r_s$ (s. section 1.3) are negligible. For this analysis, a value of $R_{\text{MW}} = 60$ Mpc was adopted.

Further, it is convenient to calculate the average $J$-factor for a given solid angle,

$$J_{\triangle \Omega} = \frac{1}{\Delta \Omega} \int_0^{\Psi} d\Psi' 2\pi \sin (\Psi') J_A(\Psi'), \quad (2.4)$$

to compare the expected fluxes from different on-source regions. Here, the solid angle is defined by the half opening angle $\Psi$:

$$\Delta \Omega = 2\pi (1 - \cos \Psi). \quad (2.5)$$
2.2. NEUTRINOS FROM DARK MATTER ANNIHILATION IN THE GALAXY

Figure 2.6: Schematic overview over the line of sight from the position of the Sun at an observation angle, $\Psi$, with respect to the Galactic center (GC). $R_{SC}$ is the radius of the Solar orbit, and $R_{MW}$ is the assumed radial extension of the Milky Way, which is needed to determine $l_{\text{max}}$ for the integration.

Figure 2.7 shows a comparison of $J_A(\Psi)$ for different halo profiles from section 1.3 along with the corresponding average $J$-factors.

The calculation of all $J$-factors is performed with a dedicated software package, which was written for this analysis, and is described in appendix B.

The large variation of the predicted density in the central halo region translates directly into a variation of the $J$-factor for small values of $\Psi$, thus making searches for dark matter annihilation in the Galactic center more model-dependent than searches for a large-scale anisotropy in the galactic halo. Note that the results from this analysis depend on the total amount of dark matter in the observation solid angle, thus the extreme variation of $J_A(\Psi)$ for $\Psi \to 0$ is not a measure of the model dependence of the here-obtained results; the average value of $J_A$ over the observation solid angle exhibits smaller variation.

The neutrino flux from annihilating WIMPs is given by

$$\frac{d\phi_{\nu}}{dE} = \frac{\langle \sigma_A v \rangle}{2} J_A(\Psi) \frac{R_{SC} \rho_{SC}^2}{4\pi m_X^2} \sum_i B_{\nu}^i \frac{dN_i}{dE_\nu}, \quad (2.6)$$

where $\langle \sigma_A v \rangle$ is the product of self-annihilation cross-section and velocity, averaged over the velocity distribution of a WIMP population, $m_X$ the WIMP mass, $B_{\nu}^i$ the branching ratio of annihilations to intermediate species $i$, which can further decay to neutrinos, and $\frac{dN_i}{dE_\nu}$ the energy-dependent neutrino yield for each intermediate species $i$.

Since the nature of dark matter particles is unknown, it is useful to assume a few benchmark annihilation channels with 100% branching ratio into one intermediate species, which
encompass the range of more realistic mixed scenarios, and simplify equation (2.6) to
\[
\frac{d\phi_\nu}{dE} = \frac{(\sigma_A v)}{2} J_A(\Psi) \frac{R_{\text{SC}} \rho_{\text{SC}}^2}{4\pi m^2_\chi} \frac{dN_\nu}{dE_\nu}. \tag{2.7}
\]

In analogy to equation (2.7), a flux from decaying dark matter is given by
\[
\frac{d\phi_\nu}{dE} = \frac{1}{\tau} J_D(\Psi) \frac{R_{\text{SC}} \rho_{\text{SC}}}{4\pi m^2_\chi} \frac{dN_\nu}{dE_\nu}. \tag{2.8}
\]

Here, \(\tau\) is the life time of the decaying dark matter particles, and \(J_D\) is the line-of-sight integral for decay,
\[
J_D(\Psi) = \frac{l_{\text{max}}}{\int_0^{l_{\text{max}}} dl \frac{\rho(\sqrt{R_{\text{SC}}^2 - 2lR_{\text{SC}} \cos \Psi + l^2})}{R_{\text{SC}} \rho_{\text{SC}}}}. \tag{2.9}
\]

The spectra from dark matter annihilation are “source spectra”, lacking any interaction effects during propagation. For neutrinos, impact of propagation on galactic scales is negligible. However, neutrino oscillations have to be taken into account via vacuum oscillations in the long-baseline limit. The probabilities \(P_{\nu_i \rightarrow \nu_\mu}\) for a neutrino of species \(i\) to be detected as a muon neutrino at Earth are given in Table 2.1. The muon neutrino flux is then given by
\[
\Phi_{\nu_\mu} = \sum_{i=1}^{3} P_{\nu_i \rightarrow \nu_\mu} \cdot \Phi_{\nu_i}. \tag{2.10}
\]

The importance of muon neutrinos for IceCube is discussed in chapter 4.

<table>
<thead>
<tr>
<th>Initial flavor</th>
<th>(P_{\nu_i \rightarrow \nu_\mu})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(e)</td>
<td>0.255</td>
</tr>
<tr>
<td>(\mu)</td>
<td>0.370</td>
</tr>
<tr>
<td>(\tau)</td>
<td>0.375</td>
</tr>
</tbody>
</table>

Table 2.1: Neutrino long-baseline oscillations lead to a mixing of the neutrino flavors. This table shows the probability of any produced flavor to be detected as a muon neutrino at Earth. All values calculated by [90].

The neutrino yields were generated with Pythia 6.154 [91] which is integrated in the DarkSUSY package [92], and are normalized to a neutrino yield per two annihilating dark matter particles. Figure 2.8 shows examples of the neutrino yields as function of neutrino energy for a 1 TeV WIMP annihilating to \(b\bar{b}\), \(W^+W^-\), or \(\mu^+\mu^-\) pairs, respectively. The smoothly decreasing spectra are multiplied by \(E_\nu^2\) to approximate the spectral shape of detected neutrinos; the first power of \(E_\nu\) stems from the energy-dependence of the interaction cross-section, the second power of \(E_\nu\) comes from the muon range. Both effects are discussed in section 3.2.1 and 3.2.2.

Direct annihilation to neutrinos results in a line spectrum at the WIMP mass. All shown spectra include neutrino oscillations, as described above.
(a) Line-of-sight integral $J_\Psi(\Psi)$ (solid) and corresponding $J_{\Delta \Omega}$ (dotted) for a few halo profiles from section 1.3.

(b) Skymaps of $\log_{10}(J_\Psi)$ for the NFW profile.  

(c) Skymaps of $\log_{10}(J_\Psi)$ for the Burkert profile.

Figure 2.7: Line-of-sight integral as one-dimensional function of the opening angle $\Psi$, and skymaps depicting $\log_{10}(J_\Psi)$ for the two baseline halo profiles in equatorial coordinates.
Figure 2.8: Examples of neutrino yields generated for a 1 TeV WIMP annihilating to different benchmark channels. The $E^2_\nu$ weighting is motivated in the text. The yields are computed with Pythia 6.154 [91] which is integrated in the DarkSYSY package [92].
In this chapter, the principles of neutrino detection are discussed, beginning with an overview over detection techniques. Further, neutrino interactions in matter are discussed, as well as energy deposition mechanisms of particles that are produced in such interactions. Finally, the production mechanism and characteristics of Čerenkov radiation are discussed.
3.1 An Incomprehensive Overview of Neutrino-Detection Techniques

Neutrino detection provides challenges due to extremely low interaction probabilities, e.g. the inelastic scattering cross-section at 100 GeV is on the order of $10^{-37}\text{cm}^2$ (s. also figure 3.1b). Thus, neutrino detectors necessarily have large detection volumes. Methods for neutrino detection include

- **Chemical detection** via e.g. $\nu + ^{\text{A}}\text{Z} \rightarrow e^- + ^{\text{A}}\text{Z+1}X$ (Homestake [93], GALLEX [94], SAGE [95])
- **Liquid scintillators** (BOREXINO [96], JUNO [97], LENA [98], LSND [99])
- **Liquid-Argon Time Projection Chambers (LAr–TPC)** (ICARUS [100], LBNE [101], Mini/Micro–BooNE [102, 103])
- **Iron calorimeters** (Soudan [104])
- **Detection of Čerenkov light** from charged secondary particles
  - Small-scale Čerenkov-ring imaging detectors (e.g. Super-Kamiokande [105])
  - Sparsely instrumented large-scale arrays (DUMAND [106], Baikal [107], ANTARES [108], IceCube (s. section 4.1), KM3NeT [109])
- **New techniques under development**
  - **Radio-detection** of neutrinos via the radio-Askaryan effect [110]. Similar to the Čerenkov effect, coherent emission of radio signals may occur through medium polarization by the net charge of cascades. The larger wavelength, when compared to Čerenkov light, is explained by the coherent emission of the full spatially extended particle cascade. (ARA [111], ANITA [112])
  - **Acoustic detection** via the acoustic Askaryan effect [113]. Neutrino-induced hadronic cascades may locally heat up the detector medium, causing the medium to expand and contract temporarily. This creates pressure (and in solid media shear) waves, which can be detected by means of hydrophones in water, or acoustic detectors in ice, e.g. based on robust piezoceramics. (SPATS [114], AMADEUS [115])

Chemical detection played an important role in the early days of neutrino physics for the detection of Solar neutrinos, and the discovery of the Solar neutrino deficit [93]. Čerenkov detectors are the current state of the art in neutrino astronomy. Smaller detectors like Super-Kamiokande have the advantage of a dense instrumentation, which allows for a low energy-threshold and sampling of the Čerenkov-ring. The latter provides means for particle identification ($\nu$-flavor identification) and excellent direction reconstruction. Large-scale volume arrays feature a sparser instrumentation, which allows for larger detector volumes and thus higher event rates. This comes at the expense of a higher energy-threshold and lower sampling density of Čerenkov light, which impacts the event reconstruction quality.
At highest energies ($≥1$ PeV) the expected event rates of current detectors are of the order of $1/a/km^3$, and provide difficulties for statistically meaningful interpretation. Given current Čerenkov-based technology, a significant expansion of detector volumes comes at high costs, therefore new techniques are investigated. Radio-detection and acoustic detection may provide the means for cost-efficient expansion of detector volumes by factors of 10–1000, due to simple and cheap detector units, like radio antennas and acoustic sensors. Both techniques offer the prospect of low per-unit costs, compared to light detection via photomultiplier tubes (PMT).

3.2 Principle of Čerenkov-based Neutrino Detectors

Čerenkov detectors measure neutrino interactions indirectly through the measurement of light. This light is caused by charged particles from neutrino interactions and secondary interactions, passing through a dielectric and transparent medium, like water or ice. The following sections describe neutrino interactions, energy deposition processes of produced particles, and finally the generation of Čerenkov light. The resulting experimental signatures are discussed in section 4.4.

3.2.1 Neutrino Interaction with Matter

Neutrinos are subject to gravitational and weak interactions. The latter makes them experimentally accessible via interaction products.

Neutrino interactions are mediated by $Z^0$ and $W^\pm$ bosons, leading to neutral-current (NC) and charged-current (CC) interactions, respectively. For sufficiently high neutrino energies of roughly $> 10$ GeV, deep inelastic neutrino-quark scattering (DIS) is dominant\footnote{An exception is the Glashow-resonance; resonant $W^-$-production in $\bar{\nu}_e - e^+$ scattering \cite{116, 117}. However, the resonance energy of $E_{\text{res}} = 6.3$ PeV is well above the range of this work.} \cite{118}. At energies below 10 GeV, (quasi)-elastic scattering of neutrinos off nucleons and resonance production gains importance. However, for the analysis presented here, these contributions are negligible. The contribution of interaction types to the cross-section is shown in figure 3.1a. Figure 3.1b shows the energy-dependence of DIS cross-sections for neutrino and anti-neutrino CC and NC interactions, using data taken from \cite{119}.

The relevant reactions are described by

\begin{align}
\text{NC} & : \nu/\bar{\nu} + N \rightarrow \nu/\bar{\nu} + X \\
\text{CC} & : \nu/\bar{\nu} + N \rightarrow l^-/ + X. \quad (3.2)
\end{align}

Here, $N$ is a nucleus of the target material, and $X$ encompasses collectively remaining products like nuclear fragments, and in both cases a hadronic shower\footnote{Hadronic showers also have electromagnetic components, e.g. from pion decays. Also, neutrinos may be produced and carry away energy.}. In the CC-case, charged leptons, $l^-/ +$, are produced corresponding to the respective neutrino flavor. The energy threshold for lepton production, and thus for the CC interaction, is given by

$$E_{\text{th}} \geq \frac{m_l^2 + 2m_l m_n}{2m_n},$$

(3.3)
where $m_L$ is the lepton rest mass and $m_n$ the nucleon mass. The highest lepton mass is $m_{\tau} = 1776.82 \pm 0.16$ MeV [120], which yields a threshold energy of about 3.5 GeV for $\tau$ production.

The products of neutrino interactions, mostly hadronic and electromagnetic showers and charged leptons, propagate through the detector medium and are subject to energy loss, which is discussed in the following section.

### 3.2.2 Energy Deposition of Charged Particles Passing Through Matter

There are several continuous and stochastic energy-loss processes of charged particles passing through matter, that are relevant for Čerenkov-detection of neutrinos, because they may produce light or particles that in turn lead to light emission. Ionisation and Čerenkov-emission are two continuous processes, while radiative processes like bremsstrahlung, pair production and photo-nuclear interaction are mostly stochastic in nature. This section first introduces these processes, then discusses their impact on the behavior of electrons, muons, and tauons passing through matter.

#### Energy Deposition Processes

**Ionization loss** of relativistic heavy particles in a medium is described by the Bethe equation [120]:

\[
\left( \frac{dE}{dx} \right) = Kz^2 Z A \frac{1}{\beta} \left( \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\text{max}}}{I^2} - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right),
\]  

(3.4)
where \(Z\) and \(A\) are the charge and atomic number of the target material respectively, \(\beta = \frac{v}{c}\), the Lorentz factor \(\gamma\), \(m_e\) the electron mass, and \(c\) the speed of light. Further, \(I\) is the mean excitation energy of the target medium, \(K = 4\pi N A r^2 m_e c^2 \approx 0.307\) MeV mol\(^{-1}\) cm\(^2\) a constant, and \(W_{\text{max}}\) the maximal energy transfer per collision. \(\delta(\beta\gamma)/2\) is a correction for the density-effect.

**Bremsstrahlung** is emitted when charged particles are deflected in the electric field of a nucleus. The corresponding energy loss \(\frac{dE}{dx}\) is proportional to the particle energy [121]

\[
- \left\langle \frac{dE}{dx} \right\rangle = \frac{E}{X_0},
\]

where the radiation length \(X_0\) is a constant determined by the material.

**Pair production** of \(e^+e^-\) pairs from (virtual) photons may occur in the vicinity of a nucleon. The nucleon’s Coulomb field allows for momentum conservation. The energy loss is linear in energy [121]:

\[
- \left\langle \frac{dE}{dx} \right\rangle \propto E.
\]

**Muon** Photo-nuclear interaction gains significance particularly for muons at energies above 10 GeV, where a muon interacts with a nucleus via virtual photons at high momentum transfer [122]. The nucleus is destroyed, resulting in a hadronic cascade. The energy loss is given by:

\[
- \left\langle \frac{dE}{dx} \right\rangle \propto E.
\]

Energy loss of charged particles through Čerenkov radiation, or rather the underlying polarization processes, is negligible compared to the aforementioned processes. The relative contributions of these processes to the total energy loss depend on the detector material (ice in this case), and the particle’s type and energy. The most relevant particle types for Čerenkov-based detection of charged-current neutrino interactions are electrons, muons, and tauons, which are discussed below.

**Energy Deposition of Charged Leptons**

**Electrons** The energy loss of electrons is dominated by bremsstrahlung, and ionization is negligible. In [123], Tsai calculated a radiation length in water of \(X_0 = 36.0823\) g/cm\(^2\). Bremsphotons pair-produce further positrons and electrons, leading to the development of an electromagnetic cascade. Given a density for water or ice of about 1 g/cm\(^3\), electrons are stopped within a few meters. The full cascade has a similar extension, since MeV-photon radiation lengths are \(\leq 10\) g/cm\(^2\) [120].
However, at energies above $\simeq 100 \text{TeV}$ the cross-section for bremsstrahlung and pair-production is suppressed due to destructive interference of scattering sites in multiple scattering [124, 125, 126]. This is referred to as the LPM effect, and spatially extends electromagnetic cascades significantly. In [127] the authors state a threshold energy for the LPM effect in water of $278 \text{ TeV}$.

**Muons**  The muon energy loss in the energy region relevant for current Čerenkov detectors is more complex than for electrons. Following [128, 120], the energy loss can be parametrized by

$$- \left\langle \frac{dE}{dx} \right\rangle = a(E) + b(E) \cdot E.$$  \hspace{1cm} (3.8)

The first term, $a(E)$, describes the energy loss through ionisation, and depends logarithmically on the particle energy. Therefore, at sufficiently high energies $a$ can be approximated as a constant since the logarithmic increase as function of the particle energy is small compared to the linear term:

$$a \simeq 2 \text{ MeVcm}^2\text{g}^{-1}$$  \hspace{1cm} (3.9)

Radiative processes like bremsstrahlung, muon photo-nuclear effect and pair production comprise the second term $b(E) \cdot E$, which scales linearly with muon energy. Again, $b(E)$ can be approximated as constant:

$$b(E) \simeq b \simeq 3.5 \cdot 10^{-6} \text{cm}^2\text{g}^{-1}.$$  \hspace{1cm} (3.10)

The relative contribution of both terms is shown in figure 3.2a. A cross-over from dominant ionisation to dominant radiative loss is seen at the critical energy $E_c = a/b$.

Using equation (3.8), the average muon range $R$ at energy $E$ is given by

$$R_\mu = \frac{1}{b} \ln \left(1 + \frac{Eb}{a}\right),$$  \hspace{1cm} (3.11)

and shown in figure 3.2b for water. Given the extremely large range at high energies, the muon provides a particularly interesting detection channel for muon neutrinos. It allows for good reconstruction due to the long track, and significantly increases the effective detection volume of open, large-scale detectors, because the initial neutrino interaction is not required to be contained within the detector.

On macroscopic scales, the various processes exhibit different “smoothness” in energy loss for a propagating muon, e.g. ionization leads to a rather continuous energy loss, while bremsstrahlung interactions lead to few catastrophic energy losses. Such catastrophic losses lead to secondary cascades along the muon trajectory.

The final energy deposition of a muon is decay to an electron (and neutrino).

**Tau leptons**  Compared to muons, tau leptons are heavier and have a shorter life-time of about $2.9 \cdot 10^{-13} \text{s}$ [120]. The higher mass suppresses radiative losses compared to muons, while the ionisation loss is similar. Due to the extremely short life-time, tau leptons most likely decay, predominantly to hadronic final states, however, leptonic decay modes to muons or electrons happen at branching ratios of about 17% each [120].
3.2. PRINCIPLE OF ČERENKOV-BASED NEUTRINO DETECTORS

![Graphs showing relative contributions of ionization and radiation losses to the total energy loss for muons (a), and average muon range as function of energy (b).]

Figure 3.2: Relative contributions of ionization and radiation losses to the total energy loss for muons (a), and average muon range as function of energy (b)

The only terrestrial sources of τ neutrinos are appearance due to neutrino oscillation, and decay of $D_{(s)}^+$ mesons. Thus, a detection of tau neutrinos is a strong hint on an astrophysical origin. The short life-time of tau leptons gives rise to intriguing τ-neutrino signatures which are discussed in section 4.4, and are well-distinguishable from experimental backgrounds.

3.2.3 Emission of Čerenkov Light

Čerenkov radiation occurs, when charged particles propagates through a dielectric medium [129, 130]. The medium is polarized, and relaxation leads to radiation emission. If the particle moves at a speed $v$ above the speed of light in the medium, $v > c_M$, constructive interference of elementary waves emitted along the trajectory of the particle is possible. This leads to coherent emission of Čerenkov light under a characteristic angle with respect to the particle trajectory $\theta_c$ given by

$$\cos \theta_c = \frac{1}{\beta n}, \quad (3.12)$$

with $\beta = v/c$ and the phase refraction index $n$. The produced Čerenkov light then propagates at the group velocity $v_g = c/n_g$ through the medium, where $n_g$ is the group refractive index. The emission is illustrated in figure 3.3. The phase refractive index for light in ice as function of the wavelength $\lambda$ can be parametrized as [131]

$$n(\lambda) = 1.55749 - 1.57988(\lambda/\mu m) + 3.99993(\lambda/\mu m)^2 - 4.68271(\lambda/\mu m)^3 + 2.09354(\lambda/\mu m)^4. \quad (3.13)$$

This parametrization is valid in the relevant wavelength range from 0.3 $\mu$m to 0.6 $\mu$m. The refractive index and corresponding Čerenkov angle in this range are shown in figure 3.4. For ice, the Čerenkov angle is about 41°.

The threshold condition for Čerenkov emission is $\beta_{th} = 1/n$, or in terms of the particle’s
Figure 3.3: Schematic of Čerenkov radiation. A muon traveling faster than $c_M$ emits coherent radiation at a characteristic angle $\theta_c$ with respect to the propagation direction.

kinetic energy:

$$E_k \geq m \left( \frac{1}{\sqrt{1 - \frac{1}{n^2}}} - 1 \right).$$  \hfill (3.14)

The threshold energy for (relativistic) electrons, muons, and tau leptons in water or ice ($n \simeq 1.32$) is about 0.26 MeV, 55 MeV, and 918 MeV respectively.

The double-differential photon yield per unit track length and wavelength has been calculated by Frank and Tamm to [132]

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi \alpha z^2}{\lambda^2} \left( 1 - \frac{1}{\beta^2 n^2(\lambda)} \right).$$  \hfill (3.15)

Here, $\lambda$ is the photon wavelength, $z$ the particle charge, $\beta = v/c$, and the fine-structure constant $\alpha \simeq 1/137$. Equation (3.15) is divergent for $\lambda \to 0$, however this macroscopic description breaks down at too small wavelengths.

The relevant wavelength range for IceCube is roughly between 300 nm–500 nm. Adopting the integration boundaries, one can calculate the photon yield for a muon track in water or ice to about 250 cm$^{-1}$ [133].

The strong directionality and prompt emission of Čerenkov light lead to a very clear signature, since Čerenkov photons should be the earliest signal from a charged particle in the detector; the dispersion is small, and the medium response time is negligible. The directionality allows particle track reconstructions even in sparsely instrumented volume arrays. However, the simplistic assumption of a single muon emitting Čerenkov radiation does not hold; a realistic muon produces secondary particles, which are boosted in the propagation direction, and thus emit Čerenkov photons at roughly the same angle. This light is accompanied by light produced in hadronic and electromagnetic cascades from catastrophic energy losses in pair-productions, and brems- and photo-nuclear interactions along the track.
Figure 3.4: Value of $\theta_c$ as function of refraction index $n$ at $\beta = 1$. The relevant range of $\theta_c$ and $n$ for wavelengths between 0.3\(\mu\)m and 0.6\(\mu\)m is marked by gray-shaded area.
Chapter 4

The IceCube Neutrino Observatory

This chapter introduces the IceCube neutrino observatory. An overview over the hardware setup is given. The data processing chain is explained, including low-level DAQ, triggering, online filtering and reconstruction of events. Finally, different classes of events in IceCube, and the corresponding physics cases, are discussed.
40  

CHAPTER 4. THE ICECUBE NEUTRINO OBSERVATORY

Figure 4.1: Overview of the components of the IceCube Neutrino Observatory, including IceTop, IceCube and DeepCore. The color-code on the surface depicts the string configurations of the different geometries during the construction phase. Image from [135].

4.1 Description of the Detector Setup

The currently largest neutrino detector, the IceCube Neutrino Observatory [134], is located at the geographic South Pole. The observatory consists of two major components; the IceTop air-shower detector on the surface, and an in-ice part for neutrino detection, usually referred to as IceCube. Figure 4.1 shows an overview over all facilities of the IceCube Neutrino Observatory.

IceCube has been completed in December 2010, and the final detector is composed of 5160 digital optical modules (DOMs) attached to 86 cables (strings), with each string holding 60 DOMs. The strings are deployed with two spacings. 78 strings (4680 DOMs) are deployed between 1450 m and 2450 m below the ice surface, and have a horizontal inter-string spacing of about 125 m and a vertical DOM-spacing along each string of about 17 m.

Of the remaining 8 strings (480 DOMs), 6 are arranged in a denser spacing such that the average inter-string distance (including neighbouring conventional strings) is reduced by a factor of two to about 75 m. The vertical placement is split into two groups. Fifty DOMs are arranged on the lower half of each string, and have a vertical spacing of 7 m, followed by a gap of about 260 m. The remaining 10 DOMs are placed above that gap, and have a vertical
4.2. OPTICAL ICE PROPERTIES

The gap is motivated by a layer of increased dust density in the ice, which
increases the absorption of light, labeled “dust layer”, and discussed in section 4.2. The last
two strings are in-fill strings in the more densely instrumented volume, and have a similarly
reduced vertical DOM spacing.

The 8 densely-spaced strings (referred to as DeepCore strings) together with the lower half
of the adjacent 7 conventional IceCube strings compose the sub-array DeepCore. It serves as a
low-energy extension for IceCube, lowering the neutrino energy threshold from about 100 GeV
for IceCube to about 10 GeV. The top 10 DOMs above the dust layer serve as a veto cap.

All DOMs on the 6 densely instrumented strings, as well as about 12 DOMs on the central
IceCube string and the in-fill strings hold PMTs with a higher quantum efficiency with respect
to standard IceCube PMTs [136].

IceCube construction began in austral summer 2004/2005 with the deployment of one
string, and the full detector was finished in December, 2010. However, also the intermediate
string configurations were taking data. Analyses and data from these intermediate detectors
are designated by IceCube–(number of string).

The analysis presented in chapter 5 uses data taken with the 79-string configuration,
IceCube–79, consisting of 73 IceCube strings and 6 DeepCore strings. Here, the DeepCore
array is defined as the 6 DeepCore strings plus the adjacent 7 IceCube strings. Figure 4.2
shows a top view of IceCube–79.

4.2 Optical Ice properties

Neutrino detection in IceCube is based on detection of Čerenkov light, thus the understanding
of optical ice properties is crucial for direction- and energy-reconstruction of recorded events,
as well as for simulation.

Optical properties of ideal, homogeneous and isotropic bulk ice can be described by two
parameters; the absorption length \( \lambda_a \), and the effective scattering length \( \lambda_{eff} \), given by

\[
\lambda_{eff} = \frac{\lambda_s}{1 - \langle \cos(\theta_s) \rangle}.
\]  (4.1)

Here, \( \lambda_s \) is the scattering length, and \( \langle \cos(\theta_s) \rangle \) is the mean of the cosine of the scattering
angle [137]. Both scattering and absorption have an impact on the amount and arrival (or
propagation) time of photons in ice.

The main effect of scattering is a delay of photon arrival times, while absorption leads to a
decreased survival probability at larger propagation distances, and thus late times. Knowledge
of the shape of arrival time distributions is e.g. used in the direction reconstruction of muons,
which is discussed in section 4.5.4.

IceCube is embedded in the glacial ice sheet at the South Pole, a natural medium, grown
over a time period of about a hundred thousand years [138]. Near the surface, the ice is
extremely diffuse due to enclosed air bubbles. With increasing depth, and thus pressure, solid
air hydrates (or clathrate hydrates) are formed and incorporated into the surrounding ice such
that the ice becomes transparent. The ice sheet grows through snow accumulation, which,
Figure 4.2: Top-view of IceCube-79 with conventional IceCube-strings marked in green, and the DeepCore strings marked in red (coordinates taken from detector geometry file).

given the long accumulation time and varying environmental conditions, results in layers of varying density of dust, salts, or minerals. Therefore, optical ice properties exhibit a strong depth-dependence. Further, bedrock topology and horizontal drift at velocities on the order of 10 m/a cause a tilt of isochronic layers with respect to the surface, and thus the vertical alignment of IceCube strings.

A realistic description of optical ice properties has to model the depth-dependence of absorption and scattering lengths for different wavelengths. These dependencies are shown in figure 4.3. For clean ice at depths between 1.5 km and 2.5 km, the absorption and effective scattering lengths are on the order of

\[
\lambda_a \approx 100 \text{ m} \quad \text{(4.2)}
\]

\[
\lambda_{\text{eff}} \approx 25 \text{ m}, \quad \text{(4.3)}
\]
4.3 Sources of Background in IceCube

There are two sources of background, that are relevant for this analysis; muons and muon neutrinos from cosmic-ray interactions in Earth’s atmosphere. Both backgrounds are discussed in the following two sections.

4.3.1 Cosmic Rays - An Interlude

The Earth’s atmosphere is exposed to a flux of high-energy particles, labeled as cosmic rays. The discovery of cosmic rays is attributed to Victor Hess, based on his measurements of the ambient radiation at different altitudes using balloons. Contrary to expectation, the radiation level increased with altitude, which was interpreted as evidence for a flux of ionizing particles of extraterrestrial origin.

The cosmic ray spectrum, shown in figure 4.4, spans several orders of magnitude in energy and flux. The shape of the spectrum is described by a power law

\[ \frac{dN}{dE} \propto E^{-\gamma}, \]  

Figure 4.3: Depth-dependence of the absorption (a) and scattering (b) coefficients at a wavelength of 400 nm, for the optical ice models SPICE-Mie and SPICE-Lea in units of \( m^{-1} \) [139]. The right axis shows the inverse values.

with more or less distinct structures. The most prominent feature is an increase in absorption and scattering caused by increased dust density at a depth of about 2 km. This roughly 200 m thick dust layer is caused by increased volcanic activity about 60,000-70,000 years ago [138].

Ice-model parameters are determined from flasher data, where light is emitted by LEDs incorporated into the DOMs, and recorded by neighbouring DOMs. The ice model used in this analysis is called SPICE-Mie [140], and incorporates both the depth dependence, and isochron tilt. An updated version of the ice model, called SPICE-LEA, also incorporates a horizontal anisotropy of \( \lambda_a \) and \( \lambda_{\text{eff}} \) [139].
with a spectral index $\gamma$, which is not constant over the full energy range. At a primary energy of about $3 \cdot 10^{15}$ eV, the spectral index changes from 2.7 to about 3, leading to the first feature in the spectrum: the knee \cite{141}. A second feature at about $10^{19}$ eV, called ankle, is a further transition of $\gamma$ back to 2.7 \cite{142, 143}. Both features can be seen in figure 4.4.

The knee may be explained by galactic sources reaching a maximum energy, with the region between knee and ankle being a transition region from dominance of galactic sources to extra-galactic sources. At highest energies, a cut-off is predicted by Greisen, Zatsepin, and Kuzmin (GZK cut-off \cite{144, 145}) due to photo-pion production in cosmic-ray interactions with CMB photons and an associated energy loss per interaction, rendering the Universe essentially opaque beyond propagation lengths of $\simeq 100$ Mpc for protons at energies above $\simeq 10^{20}$ eV\cite{146}.

The composition of cosmic rays varies with energy. Below the knee, the composition is dominated by protons. With increasing energy above the knee, the contribution of heavier nuclei is expected to increase due to a smaller gyro-radius and thus lower escape probability from the Galaxy, compared to lighter nuclei of the same energies. However, due to the power-law behavior of the spectrum, the total flux of cosmic rays is dominated by the low-energy region, consisting of about 90% proton primaries, 9% $\alpha$-particles \cite{147}.

The large range in energy and flux makes the measurement of the full spectrum with only one instrument effectively impossible. At lower energies, the flux is relatively high, and the spectrum is measured by balloon-borne or satellite-based experiments.

With increasing primary energy, and thus steeply falling flux, larger detector areas are necessary for statistically meaningful measurements. This proves challenging for e.g. satellites...
due to inherent limitations in size and mass, and at primary energies of about 100 TeV such measurements become impracticable [142].

Large, ground-based detectors like KASCADE-Grande [148], the Pierre Auger Observatory [149], TUNKA [150], or IceTop [151] use Earth’s atmosphere as a giant calorimeter to measure cosmic rays via extended air showers. This indirect detection method poses challenges for particle identification, and thus the chemical composition at high energies is not well known.

4.3.2 Cosmic-Ray-Induced Atmospheric Muons and Neutrinos in IceCube

Cosmic ray primaries, mostly protons, interact with nuclei in Earth’s atmosphere, and produce secondary particles, which in turn may interact or decay. Such consecutive interactions lead to particle showers, containing several $10^6$ particles, depending on the primary energy. Air showers consist of three distinct components; hadronic, electromagnetic, and muonic [147].

Due to the low mass, pion production is dominant, but also kaons are produced via

$$p + N \rightarrow \pi^{0,\pm}, K^{0,\pm}, X,$$

where $N$ is any nucleus in Earth’s atmosphere, and $X$ represents further products like nucleons and nuclear fragments. The produced particles decay, unless they interact again with other nuclei.

Neutral pions mostly decay to photon pairs\(^1\),

$$\pi^0 \rightarrow \gamma + \gamma,$$

which in turn may pair-produce $e^\pm$,

$$\gamma + N \rightarrow e^+ + e^- + N,$$

which generate more photons via bremsstrahlung. Particles from these processes are the dominant contribution to the electromagnetic component of air showers.

Charged pions almost exclusively decay to muons\(^2\), which may reach the surface due to Lorentz-boost and a relatively long life-time of about 2.2 $\mu$s, or further decay to electrons:

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

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu.$$  \hspace{1cm} (4.8)

Atmospheric muons and muons from atmospheric neutrinos are the most common type of events detected by IceCube. The muon component of atmospheric showers can reach IceCube at a depth of 1.5 km – 2.5 km. The zenith spectrum cuts off at roughly 87°; at larger zenith angles, and associated larger slant depths, muons are absorbed by the ice.

Atmospheric neutrinos are detected at a rate about 5 orders of magnitude below the atmospheric muon detection rate. The energy spectrum is roughly approximated by a power law with spectral index 3.7 [152]. The steeper shape, compared to the primary cosmic ray spectrum, is explained by the interplay of decay and interaction of pions and kaons, which leads

\(^1B(\pi^0 \rightarrow 2\gamma) = 0.98823\) [120]

\(^2B(\pi^\pm \rightarrow \mu^\pm + \nu_\mu) = 0.9998770\) [120]
to energy-dependent suppression. Atmospheric neutrinos feature a distinct zenith spectrum over the full zenith range, since Earth is mostly transparent at lower neutrino energies. The spectrum is peaked at the horizon due to the interplay between energy-dependent decay length and zenith-dependent interaction length [153].

At higher neutrino energies (above a few 100 TeV), a harder component of “prompt” neutrinos is expected to contribute to the energy spectrum; more massive charmed and strange mesons decay instantly, rather than interact [154].

Most IceCube analyses consider both of the above-mentioned event types as background, with the exception of e.g. measurements of atmospheric neutrino-oscillations, or of course precision measurements of the atmospheric muon spectrum. These backgrounds impose the main experimental challenge for the here-presented search for neutrinos from dark matter annihilation, and are discussed in sections 5.1, and 5.2. The event rate at trigger-level is dominated by atmospheric muons, and the zenith-dependence of the rate is shown in figure 5.1.

4.4 Neutrino Signatures in IceCube

Neutrino interactions produce secondary particles, which deposit energy as discussed in section 3.2.2, and thus produce light in the detector. Every interaction leads to a hadronic shower at the interaction vertex. In case of neutral-current (NC) interactions the neutrino leaves the detector and carries away part of the initial energy. Charged-current (CC) interactions produce a lepton in addition to the hadronic shower. The lepton flavor determines the event topology, giving rise to distinct event signatures in IceCube. Such an event topology may be characterised as either track-like, or shower-like, depending on the shape of the hit pattern of optical modules. The following paragraphs present the expected neutrino signatures in IceCube. Figure 4.5 shows a schematic overview of the discussed neutrino signatures.

**Hadronic showers** are stopped within a propagation distance of the order of 10 m, depending on the shower energy. This is small compared to the instrumentation density of IceCube, thus the shower development is not resolved. Also, Čerenkov light is emitted by particles, which propagate in all directions, though a general boost in the initial neutrino direction is present. Thus, the light pattern of hit optical modules is nearly spherical, with some energy-dependent elongation due to a boost in the neutrino flight-direction. This signature is also referred to as cascade-like.

The nearly spherical hit pattern of light from such showers imposes limitations on the accuracy of direction reconstruction, however, at sufficiently high energies, the median angle between neutrino and reconstructed propagation direction is of the order of 15° and less, depending on the neutrino energy and event selection [157].

**Electrons** from CC-interactions are stopped within a distance of a few meters. Similar to hadronic showers, such electromagnetic showers are small compared to the instrumentation density of IceCube. Therefore, the hit pattern is also spherically symmetric, with some elongation due to boost, and the event signature is cascade-like. Since both the hadronic
4.4. Neutrino Signatures in IceCube

![Diagram of neutrino signatures in IceCube](image)

**Figure 4.5:** Schematic of neutrino signatures in IceCube. The first three signatures from the left depict CC-interactions, the last is a NC-interaction. Muonic $\tau$ decay is not shown. Figure taken from [155, 156].

and electromagnetic shower from $\nu_e$-CC-interactions can be contained in IceCube, calorimetric measurement of the neutrino energy is possible with the highest precision among the three flavors. Similar to hadronic showers, the median angle between the neutrino and the reconstructed direction is on the order of 15°, at least below energies where the LPM effect becomes relevant.

**Muons** from CC-interaction may produce km-scale tracks in ice (s.figure 3.2b), depending on the muon energy, extending the effective detection volume of IceCube well beyond the instrumented volume.

The long, track-like hit pattern consists of Čerenkov light from the bare muon, as well as hadronic and electromagnetic showers from catastrophic energy losses along the track. The latter cause light patterns similar to those described above. Depending on the neutrino interaction vertex and muon energy, such tracks can either appear as incoming tracks into the IceCube volume, starting tracks, leaving tracks, or even fully contained tracks. There are two signatures that identify muons from neutrino interactions over atmospheric muons. The Earth can be used as a shield against atmospheric muons, thus upwards moving muons from the Northern Hemisphere most likely originate in CC-interactions of neutrinos. Further, a starting track is a signature of neutrino interactions, since muons entering the detector may also originate from pion/kaon decay in the atmosphere.

Given the length of muon tracks, and the directionality of the Čerenkov emission, the muon direction can be reconstructed reasonably well, depending on muon energy. At muon energies of a few TeV, the median angle between muon and reconstructed track is below 1°. Due to boosting, the neutrino direction is correlated with the muon direction, thus making directional neutrino astronomy possible. However, there is a limitation given by the kinematic scattering
angle between the neutrino and the muon. The mean angle between the neutrino and the muon as function of neutrino energy can be parametrized as [152]

\[
\langle \Psi(\nu, \mu) \rangle \simeq \frac{0.7^\circ}{(E_\nu/\text{TeV})^{0.7}}.
\] (4.10)

The muon range, though an advantage for directional reconstruction, provides challenges for the reconstruction of the neutrino energy. The longest diagonal through IceCube is roughly 1.5 km. Using equation (3.11), this corresponds to a muon energy of at least 400 GeV. Muons above that energy will most probably not be contained in IceCube, thus a fraction of the deposited energy is undetected. As a consequence, the detected deposited energy is only a lower bound for the muon and neutrino energies, and can be inferred from \(\frac{dE}{dx}\)-measurements [158].

For tracks which are contained in IceCube, the muon track length can be used as energy estimator.

**\(\tau\) leptons** have a short life-time of \(2.9 \cdot 10^{-13}\) s and a rest mass of 1776.82 MeV [120]. The decay length is energy-dependent due to time dilation, and is given by

\[
L_{\text{dec}} = \beta c t \gamma = ct E/m \simeq 50 \text{ m} \frac{E_\tau}{\text{PeV}}.
\] (4.11)

Depending on the energy of the produced \(\tau\) lepton, this gives rise to several classes of event signatures for \(\tau\)-neutrinos in IceCube.

First, the \(\tau\)-lepton is subject to energy loss as described in section 3.2.2. Due to the relatively high mass, the energy deposition, and thus the light yield is lower than for muons, leading to tracks that appear faint compared to muons.

Second, the \(\tau\) lepton has leptonic and hadronic decay modes, where leptonic decays occur at a branching ratio of about 17% to muons and electrons each. The complementing branching ratio to hadronic final states is about 66%. Hadronic decay, or decay to electrons give rise to shower signatures, while decay to muons adds a track-like signature. The \(\tau\)-neutrino signature is determined by the \(\tau\) energy. At low energies, e.g. below 10 TeV, the decay length is less than 1 m, and thus the initial hadronic shower and the shower from decay is overlapping, leading to a shower-like signature.

With increasing \(\tau\) energy, and thus increasing decay length, the separation between the two showers becomes larger. Initially, this leads to consecutive double-pulse structures in the PMT waveforms. With further increasing \(\tau\) energies in the PeV-region, the cascade separation is large enough to be resolved as two showers. If both showers are contained within IceCube, this is referred to as a “double-bang” event. If only one of the showers is contained, the signature is labeled “lollipop”, or “inverted lollipop”, with the \(\tau\)-track entering or leaving the detector, respectively. Beyond \(\simeq 10\) PeV, double-bang events are usually too large to be fully contained in IceCube [159].

### 4.5 Data Acquisition and Event Processing

So far, the deposition of energy and ensuing light generation within IceCube has been discussed. The recording of the generated light, and further processing of the collected data are handled
4.5. DATA ACQUISITION AND EVENT PROCESSING

by the IceCube data acquisition system (DAQ), and the online\(^3\) event processing chain.

The IceCube DAQ is responsible for recording the full event information, beginning with low-level capture of PMT waveforms in the DOMs, signal digitization, timing calibration, and the combination of information from all DOMs. Global trigger algorithms are then applied on the combined data. The DOM-level DAQ and trigger algorithms are discussed in sections 4.5.1 and 4.5.2.

Triggered events enter the online event processing chain, which is performed in a computing cluster at the surface. The online processing chain is responsible for extraction of high-level information like, like calibrated waveform, pulse extraction, reconstruction of arrival direction and energy of the triggered events. Finally, the events have to pass through a set of online filters, which select events based on requirements for specific physics cases. The event processing is discussed in sections 4.5.3, 4.5.4, and 4.5.5. The filters that are used for this analysis are discussed in section 5.4.2.

The simplified workflow of the DAQ system and processing chain is shown in figure 4.6, both for simulated and experimental data. The single steps are explained in the following sections.

\(^3\)Here, “online” means the processing is performed directly at the South Pole.
CHAPTER 4. THE ICECUBE NEUTRINO OBSERVATORY

4.5.1 DOM-Level DAQ

Each of the 5160 DOMs is a nearly autonomous data collection unit, consisting of a 25.4 cm diameter Hamamatsu type R7081-0 photomultiplier tube (PMT), high voltage supply, the DOM mainboard [160, 161], and a dedicated LED board. The DOM mainboard hosts readout and digitizer electronics [162], and the LED board is used for calibration purposes. The components are enclosed in a glass pressure housing. Each DOM is connected to its four adjacent neighbours, to allow local inter-DOM communication, and the DOM hubs at the surface. A DOM hub is a commercial computer in the surface computing facility, responsible for communication to all DOMs of a string through 8 custom DOM Readout (DOR) cards.

The PMT signal is alternatingly digitized by one of two fast custom ASICs (Analog Transient Wave Digitizer, ATWD), as well as a slower Flash Analog-Digital Converter (FADC). The ATWD takes 128 samples at a sampling rate of roughly 300 MS/s, and is thus capable of digitizing a roughly 426 ns long waveform. This corresponds to a time discretization of about 3.3 ns. This sampling rate corresponds to a pulse time resolution on the order of 1 ns. The full digitization process takes about 29 µs, leading to a small dead time if both ATWD chips are busy.

The continuous FADC readout is constrained to a time window of 6.4 µs, and the time discretization is about 25 ns. The FADC allows for capture of longer physics signals, or light delayed by scattering.

If the measured PMT anode voltage surpasses a threshold of ≃ 0.25 photoelectrons (pulse height equivalent), a DOM-Launch is initiated, starting the ATWD and FADC signal capture. In addition, the DOM sends a local coincidence (LC) signal to the four adjacent DOMs. If any of these DOMs also detects a signal above threshold within a time window of 1 µs, the pair of DOMs fulfills the Hard Local Coincidence (HLC) criterion, and forms an HLC pair. An HLC readout contains the full available waveform information from the whole readout window of

\footnote{Application-Specific Integrated Circuit}
4.5. DATA ACQUISITION AND EVENT PROCESSING

6.4 µs.

In case of no LC signal, the DOM readout is still initiated, but only reduced information from the FADC is stored; the time and charge stamp of the three highest FADC samples. The DOM-Launch is then aborted after about 1 µs.

The local coincidence criterion is a simple method for noise reduction; HLC pairs have an increased probability of being caused by signal events, rather than being noise. The main cause of noise launches in IceCube DOMs are radioactive decays in the DOM material, and faint untriggered atmospheric muons. The anode voltage threshold is chosen sufficiently high to suppress launches from electronic noise, and thermally emitted photons from dark noise are strongly suppressed because of the low ambient temperature. The observed in-situ launch rate per DOM is about 600 Hz [136].

If a trigger condition is fulfilled (s. section 4.5.2), the data transfer to the surface facility is initiated. The hit information from all DOMs and strings is combined and arranged in hit maps, or DOM-Launch maps, where each read-out DOM key is associated with a series of digitized HLC or SLC readouts.

### 4.5.2 Event Triggering and Filtering

IceCube triggers are based on HLC hits only. The main trigger type is a simple multiplicity trigger (SMT), demanding a certain amount of HLC hits in a given time window on a given set of DOMs. A further trigger requires at least 5 out of 7 adjacent DOMs on one string to register HLC hits within 1.5 µs. Table 4.1 presents a summary of the most important “in-ice” triggers for IceCube–79; “in-ice” here refers to IceCube and DeepCore, as opposed to IceTop, which is part of the same DAQ chain.

<table>
<thead>
<tr>
<th>Name</th>
<th>HLC Multiplicity</th>
<th>Time Window/µs</th>
<th>Rate/Hz</th>
<th>DOM-Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMT-3</td>
<td>3</td>
<td>2.5</td>
<td>183-219</td>
<td>DeepCore DOMs</td>
</tr>
<tr>
<td>SMT-8</td>
<td>8</td>
<td>5.0</td>
<td>1984-2260</td>
<td>all in-ice DOMs</td>
</tr>
<tr>
<td>String</td>
<td>5 out of 7</td>
<td>1.5</td>
<td>2112-2428</td>
<td>conventional IceCube strings</td>
</tr>
<tr>
<td>total (in-ice)</td>
<td></td>
<td></td>
<td>2206-2520</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1: Inclusive trigger rates for the main trigger algorithms in IceCube–79, taken from the internal monitoring website [163]. Some triggers run only on subsets of DOMs, e.g. the DeepCore subset consists of DOMs below the dust layer on any of the 13 strings of the DeepCore sub-array, while the IceCube DOM-set consists of all “in-ice” DOMs. The range of rates shows the variation of the trigger rate between summer (higher rate) and winter (lower rate), which is caused by the seasonal variation of the rate of atmospheric showers.

For each trigger the time window is extended by a pre-trigger and post-trigger readout window to ascertain that the full event information is recorded. Then, a global trigger algorithm is applied to merge single triggers into one DAQ-event if the end of one trigger and the start of the following trigger fall in an overlap time window of 10 µs. The trigger time for each
DAQ-event is defined as the start time of the first HLC DOM-Lauch contributing to the trigger. Once any of the described trigger conditions is met, the full information from HLC launches and the reduced information from SLC launches is transmitted to the surface, and the DAQ-event is propagated to the event processing chain. Due to the size of IceCube, such DAQ-events may consist of several coincident atmospheric showers.

IceCube is triggered by a large number of down-going atmospheric showers, which are considered background in most analyses. The total IceCube–79 trigger rate was about 2.3 kHz, and the dominant fraction of events at trigger level are atmospheric muons. The data has to be transferred from Pole to the storage facility via satellite, which had a bandwidth limitation to roughly 90 GB/day during the IceCube–79 season. In order to reduce the amount of data, a set of online filters is applied to select event topologies according to specific physics cases, e.g. upwards-going particles, contained events, extremely high-energetic events, or special target filters.

The two filter streams contributing to this analysis are the DeepCore filter and the Galactic center filter, and are presented in section 5.4.2.

4.5.3 Hit-Cleaning

The collection of hits from each event consists of the set of HLC hits accompanied by a set of SLC hits, which have a higher noise hit fraction. Calibration and feature extraction algorithms are applied to extract time and charge of pulses, which are related to the registered photons. In addition to the HLC cleaning, two major hit-cleaning algorithms are used to reduce the noise content of DOM-Lauch maps or pulse maps.

The **Classic R-T-Cleaning (CRT)** algorithm checks for each hit, if another DOM within a sphere of radius $R$ and a time $\Delta T$ registered a hit as well. If this is the case, both DOMs and the associated hits are added to the cleaned hit map. This cleaning accepts all HLC hits by definition of the HLC criterion, as well as causally connected SLC hits.

The **Seeded R-T-Cleaning (SRT)** algorithm is seeded by a pulse map of nearly noise-free HLC hits, and searches for hits in the full pulse map in a $R\Delta T$ range (as in the CRT case). This is done iteratively, with the output of one iteration as seed for the next.

For this analysis, values for the above-mentioned hit-cleaning algorithms are $R=150\,\text{m}$ and $\Delta T=1\,\mu\text{s}$. The maximal spatial distance corresponds to about one string layer.

The two algorithms serve different use cases. The first algorithm retains a slightly higher fraction of physics hits, at the cost of a higher noise contamination. The second algorithm retains less noise hits, while keeping almost as many signal hits. Thus, the first algorithm is used for veto purposes against a dominant muon background, since keeping hits is more important than noise reduction. The second algorithm delivers pulse maps of higher purity, and is used for directional reconstruction. Table 4.2 lists the signal retention and noise rejection for the above-mentioned values of $R$ and $\Delta T$ for IceCube–79.
4.5. DATA ACQUISITION AND EVENT PROCESSING

<table>
<thead>
<tr>
<th></th>
<th>HLC</th>
<th>SRT</th>
<th>CRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of kept noise hits in %</td>
<td>3.0</td>
<td>5.2</td>
<td>17.8</td>
</tr>
<tr>
<td>Kept fraction of signal-related hits in %</td>
<td>72.7</td>
<td>95.2</td>
<td>95.9</td>
</tr>
</tbody>
</table>

Table 4.2: Efficiencies of SRT and CRT hit cleaning algorithms [164]. Here, signal hits are defined as hits associated with secondary particles (mostly muons) generated by an atmospheric muon-neutrino.

4.5.4 Direction Reconstruction of Track-Like Events

The arrival direction of muon neutrinos in IceCube is approximated by the reconstructed muon track direction, in case of charged-current interactions. Muon tracks are reconstructed based on the set of locations and hit times, \( \{t_i, \vec{r}_i\} \), of registered photons.

A very fast first-guess track approximation, the Linefit, is used to seed more elaborate and time-intensive likelihood-based direction reconstruction [165].

The Linefit does not model Čerenkov emission or ice properties, and simply assumes that the detected light propagates along a straight line at a speed \( \vec{v} \), which is not required to be the speed of light. This allows for a definition of a least-squares optimization problem

\[
\chi^2 = \sum_{i=1}^{n_{\text{hit}}} \rho_i(t_0, \vec{r}_0, \vec{v}_0)^2
\]

\[
\rho_i(t_0, r_0, v_0) = (\vec{r}_i - \vec{r}_0 - \vec{v}_0 t_i),
\]

where \( \vec{r}_0 \) and \( \vec{v}_0 \) are fit parameters.

This track approximation can be calculated analytically and succeeds for nearly all events. However, outliers like noise hits, or hits at larger distances exert a strong pull on the fit result, since neither noise nor 3D-effects are modeled correctly.

The use of robust statistics allows for an improvement of this first-guess algorithm [166]. The impact of outliers is reduced by switching from the ordinary least-squares penalty function to a more robust one which applies a linear penalty for hits that are classified as outliers based on an empirically determined metric, which is calibrated on simulated data.

The resulting track approximation is used for event pre-selection, and as seed for a likelihood-based reconstruction, which takes into account the geometry of Čerenkov light emission (see [165] for details). Figure 4.8 illustrates a muon track and a hit pattern in a stylized DOM geometry. Given a track hypothesis \( a \), which consists at least of a fix point and a direction, and a hit collection \( \{\vec{r}_i, t_i\} \) one can calculate the time residual, defined by

\[
t_{\text{res}, i} = t_i - t_{\text{exp}},
\]

where \( t_i \) is the measured arrival time, and \( t_{\text{exp}} \) is the expected arrival time, assuming Čerenkov geometry and no scattering. In an ideal case, unscattered light from the correct track hypothesis should lead to time residuals of zero.

For the reconstruction, a likelihood function \( L \) is defined by

\[
L = \prod_{i=1}^{n_{\text{hit}}} p(t_{\text{res}, i}|a),
\]

(4.15)
where \( p(t_{\text{res},i}|a) \) is a probability density function (pdf) for the time residual \( t_{\text{res},i} \). The reconstructed track is the result of maximization of expression (4.15) under variation of \( a \). A useful estimate of the reconstruction quality is given by the reduced log-likelihood value

\[
\nu \log L = -\frac{\log(L_{\text{max}})}{n_{\text{dof}}},
\]

with the maximal absolute likelihood value \( L_{\text{max}} \) divided by the number of degrees of freedom. For a track reconstruction this corresponds to \( n_{\text{dof}} = n_{\text{hits}} - 5 \), with \( n_{\text{hits}} \) being the number of hits considered by the reconstruction. The number of fit parameters is subtracted; here the 5 fit parameters are the reference point \( \hat{r}_0 \), and the direction \( (\theta, \phi) \).

In an ideal case, the pdf \( p(t_{\text{res}}|a) \) would be given by a gaussian distribution \( G(t_{\text{res}}) \), reflecting the time resolution of the detector. The time resolution depends on several factors, like e.g. the geometrical size and spread in transit times of the PMTs, time calibration accuracy, impact of photon dispersion, and the accuracy of the DOM placement geometry. However, there are several effects, which alter the pdf:

- Scattering in the ice leads to delayed photons which create a tail in the pdf
- Late light from stochastic losses and bremsstrahlung along the muon track produces a tail in the pdf
- Uncorrelated noise hits add a constant noise floor to the pdf

Figure 4.8: Muon track through a stylized DOM geometry. DOMs are marked by circles, red circles are hit DOMs.
Figure 4.9: Impact of several broadening effects, like jitter, late and delayed photons, and noise hits on the time-residual pdf. Figure from [165].

Figure 4.9 shows the impact of these effects on the pdf.

There are two frequently used pdfs for the photon arrival times, or rather the time residuals. The Single Photo-Electron (SPE) pdf describes the probability for a time residual \( t_{res} \) for any hit in a series. A parametrization of this pdf is called “Pandel-function” [167, 165], and is given by

\[
\begin{align*}
PP_{\text{Pandel}}(t_{\text{res}}) &= \frac{1}{N(d)} \cdot \frac{\tau^{-(d/\lambda)} \cdot t_{\text{res}}^{(d/\lambda-1)}}{\Gamma(d/\lambda)} \cdot e^{-(t_{\text{res}}(\frac{1}{\tau} + \frac{c_m}{\lambda a}) + \frac{d}{\lambda a})}, \\
N(d) &= e^{-\frac{d}{\lambda a}} \cdot \left(1 + \frac{\tau c_m}{\lambda a}\right)^{-d/\lambda a}.
\end{align*}
\] (4.17) (4.18)

Here, \( \lambda_a \) and \( c_m \) are the absorption length and the speed of light in the medium, and \( \lambda \) and \( \tau \) are functions of the distance \( d \) of the registered hit to the track and further geometrical parameters. The functions \( \lambda \) and \( \tau \) are parametrized based on photon propagation simulations in AMANDA. Further, \( \Gamma \) is the gamma function, and \( N(d) \) normalizes the pdf.

The such defined pdf describes the ice by \( c_m \) and \( \lambda_a \), and thus neglects depth-dependence of ice parameters, but offers the advantage of analytical integrability. The final pdf is obtained by convolution with a gaussian function, and the addition of a noise term.

An improvement of the SPE pdf is the Multi Photo-Electron (MPE) pdf, which makes use of the excellent timing quality of the earliest, and thus unscattered hits. The reconstruction quality is improved at higher muon energies, since low-energy tracks tend to produce about one hit per DOM.

A further improvement is the SplineMPE, which takes ice properties into account, based on spline representations of photon arrival probabilities, which are directly obtained from photon propagation simulation.
Figure 4.10: Muon track starting at the interaction vertex marked by the green star. DOMs are represented by circles, red circles are DOMs with registered hits. The projected position of the first hit DOM along the track can be interpreted as reconstructed interaction vertex, marked by a black star.

4.5.5 Reconstruction of the Neutrino Interaction Vertex

A method for the rejection of background events especially from the Southern Hemisphere is the selection of events which appear to be starting within the IceCube volume. Muons from atmospheric showers, being the dominant background, enter the detector from outside.

A simple reconstruction method (called FiniteReco) for the interaction vertex has been developed in [168]. A robust and fast first-guess algorithm projects all hits of a pulse map within a perpendicular distance of 200 m to a reconstructed muon track on the track, respecting the Čerenkov angle, as shown in figure 4.10. The spatially first projected position on the track is then interpreted as the interaction vertex. For stopping muons, the stop point can be calculated in a similar fashion. A more exact reconstruction of the interaction vertex is achieved by likelihood-based reconstruction, taking into account DOMs without hits along the track. Incoming tracks will have reconstructed vertices clustering on a shell outside the instrumented volume, while clearly starting tracks should have a vertex inside IceCube.

A drawback of this reconstruction method is that the hadronic shower from the initial neutrino interaction is not modeled, thus high-energy events with large energy transfer to the cascade will have a large systematic shift backwards along the track. An improvement can be achieved by only considering hits that have small time residual values, and thus are likely caused by the muon track [169].
4.6. EVENT SIMULATION CHAIN

![Graphs showing vertex resolution in x-y-plane and along z-axis.](image)

Figure 4.11: Vertex resolution for two signal assumptions in the x-y-plane, and along the z-axis. Splitting the resolution is motivated by the different vertical and horizontal DOM spacings in IceCube. The low-energy signal is better resolved, than the high-energy signal. The reason is that triggering dim tracks associated with low energies are biased to start closer to DOMs.

Given the sparse spacing of IceCube, low-energy muons of lower brightness may deposit no hits on the outer strings or enter the detector through the dust layer. Also, the DOM spacing in IceCube and DeepCore is a limiting factor in obtainable resolution. The actually achieved resolution strongly depends on the event selection and energy region, and will be discussed in the analysis section. Figure 4.11 shows the spatial vertex resolution of FiniteReco for events from the final sample from this thesis.

4.6 Event Simulation Chain

Data simulation in IceCube relies on a chain of tools which can be roughly split into three categories:

- Generators
- Propagators
- Detector Simulation

At the end of the last step, the simulated data is fed into the processing chain (s. section 4.5), and treated like experimental data. The above-mentioned categories are shown in figure 4.12, and will be discussed briefly in the following sections.

4.6.1 Generators

Atmospheric Muons from cosmic-ray induced showers are simulated within the CORSIKA framework [170], where cosmic-ray primaries are generated according to their chemical...
compositions and energy distributions. The primary interaction, as well as the full shower development is simulated down to configurable observation levels, taking into account an atmospheric model defined by chemical composition, depth/temperature-dependent density, and curvature. CORSIKA offers the possibility to configure the composition, primary spectrum, interaction models, and atmospheric parameters individually.

Only the muon- and neutrino-components of atmospheric showers reach IceCube, the hadronic and electromagnetic showers are absorbed in the atmosphere or the ice overburden of at least 1.5 km. The minimal primary energy required to generate muons which are capable of reaching IceCube is of the order of 1 TeV. The muon component, a bundle of high-energy muons at surface, is passed on to the propagation tools.

Given the large instrumented volume of IceCube, about 10% of the triggering events are expected to be coincident; two or more atmospheric showers overlapping in the DAQ-event readout window.

The standard CORSIKA datasets for IceCube–79 are generated in an energy range from 600 GeV to $10^{11}$ GeV, with the lower bound being well below the minimal energy required to reach IceCube. The energy spectrum and composition is based on the poly-gonato model by Hörandel [141]. The zenith range of simulated events is constrained to $0^\circ \leq \theta \leq 90^\circ$. In order to account for the seasonal variation of experimental data, four atmospheric models (March, July, October, December) are simulated.
Neutrino events are generated by the Neutrino Generator [171], a tool based on the ANIS package [172]. The neutrino energy is sampled from a power-law with configurable index. The geometry of event generation is shown in figure 4.13. Neutrino arrival directions are sampled uniformly in azimuth and the cosine of the zenith. The impact parameter with respect to the center of IceCube is randomized on a circular plane perpendicular to the flight direction. In the standard IceCube–79 neutrino dataset production, the injection radius of the circular plane is 1200 m, extending beyond the projected area of the detector. Propagation through Earth is performed analytically, and an interaction is enforced in the vicinity of IceCube. The interaction point is randomized along the propagation path with a configurable maximal distance to the detector. The maximal distance is automatically extended to the energy-dependent maximal muon range in case of charged-current interactions. In case of CC-interactions, the angle between incident neutrino and produced muon is given by [172]

$$\cos(\Psi) = 1 - \frac{xy}{1 - y} \frac{m_N}{E_\nu}. \tag{4.19}$$

Here, $m_N$ is the nucleon mass, and $x$ and $y$ are the Björken variables

$$x = \frac{Q^2}{m_N(E_\nu - E_l)}, \tag{4.20}$$
$$y = 1 - \frac{E_l}{E_\nu}, \tag{4.21}$$

where $E_l$ and $E_\nu$ are the lepton and neutrino energies, respectively, and $Q$ is the invariant momentum transfer. The Neutrino Generator samples a large set of pregenerated and tabularized $(x,y)$-pairs representing final states of neutrino interactions at different energies.

The interaction probability is taken into account by use of event-specific weights, which also allow for reweighting to a different energy spectrum, such that the datasets are usable for different analyses. The weights are given by

$$\omega_i = \frac{p_{int} A \Omega}{p_{gen}}, \tag{4.22}$$

with the generation area $A = 2\pi r^2_{injection}$, $\Omega$ the simulated solid angle ($4\pi$ for standard datasets), and $p_{int}$ and $p_{gen}$ the total interaction probability and generation probability, respectively. Using $\omega_i$, the datasets are weighted to a target spectrum $\phi(E)$ by weights $w$ given by

$$w = N \cdot \omega_i \cdot \phi(E), \tag{4.23}$$

where $N$ is a dataset-dependent normalization constant incorporating the number of generated files, and the number of generated events per file.

The standard IceCube–79 datasets for low-energy analyses are generated according to a power law $\frac{d\sigma(E)}{dE} \propto E^{-2}$, in the full zenith and azimuth range, over an energy range from 10 GeV to $10^9$ GeV. The neutrino interaction cross-sections are based on [173], and include only deep inelastic scattering, which is sufficient for the here considered neutrino energies above $\simeq 10$ GeV (s. section 3.2.1).

All particles produced in the interaction are passed on to the particle propagation tool chain.
Figure 4.13: Schematic of a charged-current event generated by Neutrino Generator. The arrival direction is generated isotropically on a sphere (black, solid line), the injection radius (impact parameter with respect to the center of IceCube) is randomized (green, dotted line). The propagation is performed analytically, and an interaction is enforced randomly within a cylinder along the propagation axis. The cylinder length is configurable, but is automatically extended to the maximal muon range in case of high-energy charged-current interactions of muon neutrinos.

4.6.2 Propagation of Particles and Generated Čerenkov Light

Following the event generation stage, all produced particles are propagated through the vicinity of IceCube, using the MMC package (Muon Monte Carlo) [174]. The MMC propagation volume is defined by a cylinder around the detector with a radius of 1200 m, and height of ±850 m. The cylinder extends far beyond the instrumented volume to ensure that all light from energy depositions outside the detector is properly simulated.

MMC simulates the energy loss from particle interactions, secondary particle production, and potential decay of electrons, muons, and tauons, and calculates the Čerenkov light produced by these energy losses. The energy loss of secondaries below a threshold of 500 MeV is approximated as continuous loss, and the light yield per track length is parametrized based on Geant4-simulations [133]. Energy losses at higher energies than the threshold of 500 MeV are traced individually.

The light produced in the vicinity of IceCube has to be propagated to the DOMs, taking into account scattering and absorption in ice. At high neutrino energies, and thus high photon densities this is achieved by the Photonics package [175], which relies on look-up tables to calculate the arrival probability and time distribution of photons in dependence of the photon wavelength and incident angle at a DOM position with respect to the photon emission point.
4.6. EVENT SIMULATION CHAIN

The Photonics tables also incorporate the angular acceptance of DOMs. The simulation of systematics datasets with varied optical efficiency is possible; the photon arrival probabilities can be simply rescaled with a relative optical efficiency factor.

At lower neutrino energies, and thus lower photon densities, individual photon propagation by e.g. the photon propagation code [176, 177] (ppc) yields more exact results. The ppc tool treats the angular acceptance of DOMs, the wavelength acceptance of DOMs, and effects of the hole ice effects. Variation of the optical efficiency for systematics datasets is possible by assuming a very high initial optical efficiency, and thinning out the hits produced by photons according to the desired efficiency. The time-consuming photon tracking became feasible with the advent of low-cost graphics processor units (GPU), which allow a massive parallelization, and speed-up factors of the order of 100 [177].

4.6.3 Detector Simulation

The result of the photon propagation is a map of DOMs, and associated series of hits that were produced by the photons, which already include a part of the detector simulation, like e.g. the angular efficiency of DOMs. The next step is the generation and inclusion of noise hits, which are merged with the physics hits maps. These maps are then passed on to the PMT simulation. The simulated waveforms are further processed to simulate the DOM digitizers, leading to digitized waveforms, which are then similar to experimental data. The individual hit information is storage-space consuming, and thus is only kept in 1 out of 10 simulated events.

In the final step, the simulated data is adjusted to the experimental configuration; e.g. the information in DOM-Launches which do not fulfill the HLC criterion is reduced to SLC-only, removing the full waveforms (s. section 4.5.1). Further, the time information of all generated Monte Carlo particles is synchronized to the DAQ trigger time. The events are then passed on to a standard processing chain that resembles the experimental data processing at the South Pole (s. section 4.5).
Chapter 5

Analysis

The following chapter describes a search for neutrinos from WIMP annihilations in the Galactic center, starting with a description of signal and background characteristics, and the ensuing challenges for such an analysis. The event selection is motivated and explained, and finally a likelihood analysis of the obtained data is described.
5.1 Experimental Challenge

This analysis targets the Galactic center to search for a flux of messenger particles from dark matter annihilation. The Galactic center is defined by the center of rotation and coincides with the radio source Sgr A*. It is located on the Southern Hemisphere at equatorial coordinates \((\alpha, \delta) = (17^h 45^m 40.04^s, -29^\circ 00' 28.1''\) (J2000). This declination corresponds to a local zenith in IceCube’s coordinate system of about 61°, and is 29° above the horizon. The Southern Hemisphere is challenging for analyses of IceCube data, since the vast majority of triggering events are atmospheric muons.

Usually, this background is reduced by constraining the analyses to the northern hemisphere, or applying a high energy threshold, since the atmospheric muon energy spectrum is dropping steeply, compared to the harder neutrino and thus muon energy spectrum expected from extraterrestrial neutrinos.

However, for a search for neutrinos from dark matter annihilation both approaches are not viable. The target region is above the horizon, and the here investigated WIMP masses range from 100 GeV to 10 TeV; these energies are low compared to conventional searches for a generic astrophysical \(E^{-2}\)-flux.

The approach adopted for this analysis is a search for events, which start within IceCube, and thus are caused by neutrino interactions within the detector; incoming tracks are most likely caused by atmospheric muons. The selection of starting tracks is achieved by splitting IceCube into an outer veto region against incoming muon tracks, and a fiducial core region. However, unlike a DeepCore-focused analysis, this analysis attempts to retain as much of the inner parts of IceCube beyond the DeepCore sub-array as fiducial region, as possible. The advantage of the additional IceCube volume is a higher sensitivity, especially at energies larger than the trigger threshold associated with the conventional IceCube string spacing and trigger configuration of about 100 GeV neutrino energy. This comes at the cost of veto efficiency; while bright incoming tracks may be vetoed with a comparably small outer veto, the majority of atmospheric muon events are relatively dim and may pass several string layers undetected.

5.2 Definition of Signal and Background

The dominant background for this analysis are atmospheric muons for cosmic ray interaction with the atmosphere. Figure 5.1 shows the reconstructed zenith distribution of events at trigger level in IceCube–86\(^1\). At the zenith of the Galactic center of about 61°, the muon background is about 5 orders of magnitude above the level of atmospheric neutrinos. Atmospheric muons enter the detector in bundles, or as single muons, since many muons produced in the atmosphere range out or are absorbed in the ice sheet.

Reduction of this background is achieved by selecting events, which start within a fiducial volume in IceCube. Neutrinos may interact within that volume, leading to starting muon tracks. Atmospheric muons have to enter from outside. However, this background reduction comes at a cost. The large effective detection volume associated with the muon range is reduced

\(^1\)The 86-string configuration is very similar to IceCube–79, and well comparable at trigger level.
Figure 5.1: Reconstructed zenith (Linefit) of events at trigger level [178]. The rate of atmospheric muons is about 5 orders of magnitude higher than the rate of atmospheric neutrinos in the Southern Hemisphere. Both components are considered a background for this analysis. The location of the Galactic center is indicated by the vertical dashed line.

for such veto analyses.

The signal for this analysis is a flux of neutrinos from dark matter annihilation from the direction of the Galactic center. The flux is peaked in that direction, but the signal is extended rather than not point-source like. Halo profiles are described in section 1.3). This analysis considers the NFW and Burkert profiles. Although initially optimized for the cuspy NFW profile, the Burkert profile is favored by current observational data. The results are presented for both profiles, with the NFW results being presented for comparability, and the Burkert results presented as best physically motivated results.

Several annihilation channels are considered:

\[
\chi\chi \rightarrow b\bar{b} \\
\rightarrow W^+W^- \\
\rightarrow \tau^+\tau^- \\
\rightarrow \mu^+\mu^- \\
\rightarrow \nu\bar{\nu}
\]

A realistic signal should be bracketed by the extreme choices of such channels; a soft spectrum from annihilation to \(b\bar{b}\), and a hard spectrum from direct annihilation to \(\nu\bar{\nu}\).

The investigated WIMP masses range from 100 GeV up to 10 TeV, with the main focus being on masses between 500 GeV and 1 TeV. The wide mass range and variety of energy
spectra from various annihilation channels lead to a plethora of possible event topologies, providing challenges to find an effective event selection for low-mass and high-mass WIMPS. The event selection was optimized on a signal assumption of 1 TeV WIMPs annihilating to $\mu^+\mu^-$, if not mentioned otherwise.

5.3 Analysis Outline

This analysis relies on two online filter streams for initial event selection; the DeepCore filter, and the Galactic center filter (s. section 5.4.2). The former is a general-purpose pre-selection filter for low-energy events, which start within DeepCore. The latter is a dedicated region of interest (RoI) filter, targeting the Galactic center.

The two input streams are transmitted to the data storage facility in Madison, Wisconsin, and reprocessed in a collaboration-wide effort. The complete processing chain beginning with calibration and feature extraction from raw data (labeled level 1) is repeated, and CPU-time-consuming reconstruction algorithms are applied (labeled level 2). The such processed experimental and simulated data from the two filters is used in this analysis.

There are three major processing levels, shown in the simplified flow chart in figure 5.3. First, basic quality cuts are applied, and a simple starting track selection is applied. Second, more elaborate veto algorithms are developed and applied. Third and last, a boosted decision tree (BDT) is trained to further reduce the remaining background.

The background expectation is determined from experimental data. The signal flux is peaked towards the Galactic center. This allows for the definition of an on-source and off-source region in a declination band around the Galactic center. Due to IceCube’s location at the South Pole, the coordinate transformation of equatorial declination $\delta$ to local zenith $\theta$ is given by

$$\theta = \delta + \pi/2,$$

while the right ascension transformation to local azimuth depends on the event time. However, azimuthal distances are equal to distances in right ascension.

For this analysis, the considered declination band has a width of $\pm 15^\circ$ around the Galactic center declination. The on-source region in this declination band is $\pm 15^\circ$ wide in right ascension with respect to the Galactic center. Further, there are two $15^\circ$ wide buffer zones around that on-source region, and the remaining declination band is used for background estimation. The buffer zones are introduced to reduce any possible effects caused by the transition zone from full acceptance to prescaled acceptance in the Galactic center filter (s. section 5.4.2). All regions are shown in figure 5.2.

For background estimation, the prescaling by a factor of $1/3$ of off-source events in the Galactic center filter has to be taken into account by applying a weight $w_i$ to each event:

$$w_i = \begin{cases} 3 & \text{if off-source and not DC} \\ 1 & \text{else} \end{cases} \quad (5.2)$$

All coordinate transformations are performed using the coordinate-service package from the IceCube software framework, which relies on SLAlib [179].
Further, to calculate the expected number of on-source background events, the solid angle of both regions has to be taken into account. In right ascension, the on-source region extends to 30°, and the off-source region extends to 300°. Thus, the scale factor is 1/10, and the number of expected on-source background events \( \langle n_{\text{bg,on}} \rangle \) is given by

\[
\langle n_{\text{bg,on}} \rangle = \frac{\Omega_{\text{on}}}{\Omega_{\text{off}}} \cdot \sum_{i}^{\text{off}} w_i = 0.1 \cdot \sum_{i}^{\text{off}} w_i, \tag{5.3}
\]

where only off-source events are considered in the sum, and \( w_i \) is defined in equation (5.2).

Finally, the analysis is performed in a blind fashion. The Modified Julian Date (MJD) of events is randomized, thus the angular distance of neutrino arrival directions with respect to the Galactic center position is scrambled. Further, events from the on-source region are not considered during cut optimization and background estimation.

## 5.4 Event Selection

The large amount of experimental data is dominated by background events at trigger level. Depending on the actual event topologies, some of this background can be reduced comparatively simple, while other event topologies require more elaborate and time-consuming methods. Therefore, the background reduction is split in several major processing levels, which are described in the following sections.

Throughout the selection process, different veto algorithms are applied based on different veto definitions. These definitions are shown in figure 5.4, and are referred to in the following sections.

All distributions of the used observables are shown in the appendix (D, E, F), and the signal efficiencies for all cut levels are summarized in section 5.4.6.
CHAPTER 5. ANALYSIS

Figure 5.3: This analysis flowchart shows the input data streams for this analysis, as well as the three major processing levels.

5.4.1 Experimental Data Run Selection

IceCube data taking is performed in runs designated by a run number. These runs are usually 8 hours long. Although the IceCube detector uptime is close to 100%, not all runs pass all quality criteria, but are labeled as bad runs. Some such runs may be aborted early, or be calibration runs. Another class of bad runs are partial runs, where not all DOMs or strings were operating properly. These runs are removed especially from veto-based analyses.

The list of good runs consists of non-partial, non-calibration runs, where the rate per run does not deviate more than 5σ from the expectation. Here, the expectation is determined by fitting a 5-th order polynomial to the experimental data to account for the annual modulation of the cosmic ray muons. The full good run selection was performed on cut level 3, which is explained in section 5.4.3. However, all numbers, optimizations, and distributions shown in the following sections are based on data from good runs.

The total IceCube-79 live-time is 340.9 days. After applying the strict quality requirements, 312.6 days of live-time remain.
5.4. EVENT SELECTION

5.4.2 Online Event Selection Filters

The DeepCore filter is a general-purpose low-energy filter [180, 181], and selects events which trigger the DeepCore array (SMT-3, s. section 4.5.2). The filter algorithm selects upgoing or starting tracks over the background of incoming atmospheric muons, and uses the surrounding IceCube detector as veto.

The veto algorithm consists of the following steps. First, DeepCore hits are extracted from the hit map, and a simple cleaning is applied, which keeps only hits within one standard deviation in $\delta t$ of the average hit time. Second, the geometrical Center Of Gravity (COG, $r_{COG}$) is calculated based on these hits. Third, an averaged vertex time$^3$, is calculated by

$$t_{\text{vertex}} = \frac{1}{N} \sum_{n} t_n - \frac{D_n}{c_{\text{ice}}}, \quad (5.4)$$

where $t_n$ are the hit times, $D_n$ is the distance of the COG to each hit DOM, and $c_{\text{ice}}$ is the speed of light in ice.

The such obtained vertex time and location is used as reference to search for causally connected hits on IceCube DOMs in the veto region. For each such hit, a particle speed is calculated by

$$v_i = \frac{|r_i - r_{COG}|}{|t_i - t_{\text{vertex}}|}, \quad (5.5)$$

Figure 5.6 illustrated the filter principle.

$^3$Here, the term vertex does not refer to the interaction vertex. In this case it is just a reference time.
Figure 5.5: Good-run selection, where runs are accepted if they do not deviate more than 5σ from the expected rate. The expectation is derived from a fit to the experimental data as function of the run number. Only the burn sample (1 out of 10 runs) is plotted for better readability.

If a hit is caused by an atmospheric muon rather than noise, the speed should be close to the vacuum speed of light. Causally unconnected hits would lead to uniformly distributed values of \( v \) within the bounds of the readout time windows. Figure 5.7 shows the distribution of \( v_1 \) for simulated signal and background events.

Finally, hits in a velocity range between 0.25 m/ns and 0.4 m/ns are considered causally connected, and events with at least one hit in this velocity range are discarded. The DeepCore filter reduces the data rate by about one order of magnitude from 183 Hz at trigger level to about 18 Hz (full sky). The event rate in the zenith band of ±15° around the Galactic center zenith is about 4.46 Hz.

The dedicated Galactic center filter [182] was developed and implemented at the South Pole for this analysis. The filter selects events from the ±15° wide declination band centered at the declination of the Galactic center. A ±20° wide on-source region in right ascension is defined within this declination band around the Galactic center. One out of three events outside this on-source region is kept for background estimation from experimental data, and all of the on-source events are kept. Note that the filter’s on-source region is wider than the region used for the analysis. Finally, the filter applies a starting-track criterion; the earliest HLC hit must not be registered on any of the upper 5 DOMs on a regular IceCube string, or any of the outer strings. Compared to the DeepCore filter, the Galactic center filter offers the advantage of a significantly larger fiducial volume. The experimental data rate is reduced from about 2.2 kHz to about 40 Hz.

The combined data rate from both filters within the declination band defined by the Galactic center filter is about 43.02 Hz. The expected signal rate depends strongly on the considered
5.4. **EVENT SELECTION**

![Figure 5.6](image-url)

**Figure 5.6:** Illustration of the DeepCore filter principle. The color-coding corresponds to hit times, with early hits being red, and late hits being blue. Vertex time and COG are marked (s. description in text), and the cut region on the velocity axis is shown. Figure taken from [180].

annihilation channel, WIMP mass, and halo profile, but is below $\lesssim 1\mu$Hz for all here-considered cases.

### 5.4.3 Level 3

The cut level 3 is the initial cut level of this analysis after the online filter selection and the reprocessing of all transmitted experimental data from Pole. First, quality cuts are applied on the number of hit strings

$$n_{\text{String}} > 2,$$

and the number of hit DOMs

$$n_{\text{Channel}} > 8.$$

The first cut removes events with ambiguous reconstructed azimuth values. The second cut removes events which have barely enough hit DOMs to allow for a reliable likelihood reconstruction.
Further, a quality cut is applied on $r \log L$ (s. section 4.5.4):

$r \log L < 18$.

Second, starting tracks are selected based on the interaction vertex reconstruction FiniteReco (s. section 4.5.5). The main background rejection power comes from a cut on the $z$-component of the reconstructed vertex position in detector coordinates,

$z_{fr} < 300 \text{ m}$,

removing events which are reconstructed to start within the upper 200 m of instrumented volume, or above the detector. The detector coordinates are shown in figure 5.4.

Further, due to the hexagonal string arrangement, a cut on the position in the $x$-$y$-plane is applied, where the reconstructed vertex is required to be inside a polygon, defined by the outer corner strings, and a scale factor

$scale = 0.75$

The scale factor, shown in figure 5.8, reduces the polygon size relative to the outer strings, and allows for a continuous cut, while respecting the detector geometry.

To preserve tracks which start deep within the detector, and may have an interaction vertex in the veto region, then leave the detector, the above-described polygon cut is applied with an additional OR-condition. Events, where the vector from the center of the detector to the interaction vertex, and the direction vector of the reconstructed track enclose an angle of $\gamma > 90^\circ$, are kept. Here, $\gamma$ is calculated in the $x$-$y$-plane only, ignoring the $z$-component.

The reconstructed vertex distribution for background, as well as several signal assumptions is shown in figures 5.9 and 5.10.
Figure 5.8: This figure illustrates the scale factor for the vertex cut. A scale factor of 1 corresponds to the full detector contour. For values smaller than 1 the contour is scaled down, reducing the fiducial volume. The contour is scaled with respect to the center of gravity of the outer strings to ensure a veto region of uniform thickness.

The cut values are set based on a desired rejection factor of about $10^{-1}$, rather than an optimization. The fiducial volume definition is arbitrary, but driven by the necessity to identify incoming faint tracks. The cut values are summarized in table 5.1. The experimental data rate after these cuts is 4.5 Hz. The signal efficiency as function of neutrino energy is shown in the cut summary in section 5.4.6

<table>
<thead>
<tr>
<th>Observable</th>
<th>Cut value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{\text{Channel}}$</td>
<td>$&gt; 8$</td>
</tr>
<tr>
<td>$n_{\text{String}}$</td>
<td>$&gt; 2$</td>
</tr>
<tr>
<td>$r_{\log L}$</td>
<td>$&lt; 18$</td>
</tr>
<tr>
<td>$z_{\text{tr}}$</td>
<td>$&lt; 300 \text{ m}$</td>
</tr>
<tr>
<td>$scale$</td>
<td>0.75 ($\text{OR}_\gamma &gt; 90^\circ$)</td>
</tr>
</tbody>
</table>

Table 5.1: Summary of level 3 cut values.

5.4.4 Level 4

The cut level 4 consists of two complementary veto methods:

- **Causality Veto**: A causality-based veto algorithm that does not rely on track reconstructions

- **Punch-Through Veto**: A veto cut that relies on a track reconstruction
Both veto methods are required to retain the maximal amount of starting tracks from the direction of the Galactic center. Therefore, the signal sample is defined by the following pre-selection cuts on true Monte Carlo information to define a clear signal signature:

- The interaction has to be a charged-current interaction
- The neutrino zenith lies within 10° of the Galactic center zenith
- The produced muon has an interaction vertex
  - \( z < 300 \text{ m} \) (corresponding to a top-veto of 200 m, or 12 DOMs)
  - within the outer two string layers

These values are motivated by the level 3 cuts on the reconstructed vertex.

**Causality Veto**

The **Causality Veto** is a likelihood-ratio test for light in the veto to be causally connected to a fiducial event. Here, the veto consists of all DOMs on the outer two string layers, and the upper 12 DOMs on all regular IceCube strings, as illustrated in figure 5.4. Since the inter-string spacing is significantly sparser, compared to the inter-DOM spacing on a string, the **Causality Veto** is split in a top and side veto. The top veto consists of the upper 12 DOMs on all IceCube strings. The side veto consists of all DOMs on the two outer string layers that are not part of the top veto. The motivation for removal of the 12 upper DOMs from the side veto is to avoid double-counting of hit DOMs in the overlap region.

The signal sample by definition consists of noise in the veto region, thus it is used for both the top and side veto optimization. The background sample, however, is split in a top- and side-veto sample. This split is based on the point of entry (PoE) of the muon into the detector volume; events with a PoE above \( z=300 \text{ m} \) comprise the top-veto sample, the remaining events comprise the side-veto sample.

The **Causality Veto** procedure consists of several steps which are outlined below, and then further elaborated.

1. First, identify the earliest HLC hit in the fiducial volume, and use it as reference point \( \vec{x}_{\text{ref}} \) in space and time.

2. Second, calculate the distance in space \((\Delta r_i)\), and time \((\Delta t_i)\) to the reference point for each hit in the veto:

\[
\Delta r_i = \sqrt{(x_{\text{ref}} - x_i)^2 + (y_{\text{ref}} - y_i)^2 + (z_{\text{ref}} - z_i)^2}
\]

\[
\Delta t_i = t_{\text{ref}} - t_i
\]

Note that the time distance carries a sign to identify early veto hits.

3. Third, define a region on the \(\Delta r-\Delta t\)-plane to look for veto hits, and calculate the number of such veto hits, \(n_{\text{hit}}\).
5.4. EVENT SELECTION

4. Fourth, use the number of hit DOMs, as well as the space- and time-distance information to construct pdfs for the background and the above-defined signal sample.

5. Finally, calculate the likelihood ratio for each event, given by

\[ R = \log \left( \frac{p_n(n_{\text{hit}} | S)}{p_n(n_{\text{hit}} | B)} \cdot \prod_i p_r(\Delta r_i | S) \cdot p_t(\Delta t_i | S) \right) \cdot \prod_i p_r(\Delta r_i | B) \cdot p_t(\Delta t_i | B) \),

(5.8)

where the first ratio corresponds to a Poisson term, but is based on histogrammed data. The second ratio consists of the 2-dimensional space-time pdfs \( p_{r,t} \). The product runs over all hits within the veto region on the \( \Delta r - \Delta t \)-plane, as defined in step 3.

Figure 5.11 shows the \( \Delta r - \Delta t \)-plane for background as well as a signal sample for the top-veto. The features are explained in the following paragraphs.

Incoming background events cause hits that are consistent with the speed of light with respect to the reference point, and thus cluster at early (negative) times along the red-dashed line, defined by \( \Delta r_i = c_v \Delta t_i \). This feature is clearly visible in figure 5.11a.

Starting signal events do not produce any early hits. Noise hits are distributed uniformly in time, as can be seen in figure 5.11b. The \( \Delta t \)-distribution shows only two features. First, a cut-off at \(-4\mu s\), which is caused by different pre-trigger read-out windows (s. section 4.5.2) of the two major triggers. Second, hits appear at late times along the red-dashed line. These hits are caused by light from the hadronic cascade at the neutrino interaction vertex, which propagates back into the veto region.

Finally, the broad horizontal feature along the \( \Delta r \) direction that can be seen in figure 5.11a and more distinctly in figure 5.11b is caused by noise. If one calculates the DOM-to-DOM distance for all combinations of one veto DOM and one fiducial DOM, a broad peak appears at about 700 m. For signal and background data, the peak position in figures 5.11a and 5.11b is shifted due to the position distribution of the reference point. This noise peak is more pronounced in the signal case, since only noise hits are expected.

The pdf construction is challenging due to limited statistics especially for the noise level of the signal sample, which is shown in figure 5.11b. Therefore, the 2-dimensional pdfs \( p_{r,t} \) are decorrelated and split in two separate 1-dimensional pdfs \( p_r, p_t \). A decorrelation in the 2-dimensional plane corresponds to a rotation, where the rotation angle is the angle between the \( \Delta r \)-axis and the line of expected veto light \( \Delta r = c_v \Delta t \); in the \( \Delta r - c_v \Delta t \) plane the angle is \( 45^\circ \).

The such obtained top-veto and side-veto pdfs for incoming background and two (fiducial) WIMP signal assumptions are shown in figure 5.12. The signal pdfs do not vary much despite large differences in the underlying signal assumptions, since they contain only noise hits.

Using the 1-dimensional pdfs, the likelihood ratio can be written as

\[ R = \log \left( \frac{p_n(n_{\text{hit}} | S)}{p_n(n_{\text{hit}} | B)} \cdot \prod_i p_r(\Delta r_i | S) \cdot p_t(\Delta t_i | S) \right) \cdot \prod_i p_r(\Delta r_i | B) \cdot p_t(\Delta t_i | B) \),

(5.9)

with the hit multiplicity pdf \( p_n \), and the spatial and time distance pdfs \( p_r \) and \( p_t \), respectively.
Based on the top-veto and side-veto pdfs, the likelihood-ratio is calculated for the top-veto and side-veto individually, such that for each event there are two ratios: \( R_{\text{top}} \) and \( R_{\text{side}} \). Large positive values of \( R_{\text{top}} \) and \( R_{\text{side}} \) correspond to signal-like events, large negative values correspond to background events. A muon track that enters the detector through the top part has only noise hits in the side-veto, and thus appears signal-like in the side-veto (\( R_{\text{side}} \)), but should appear background-like in the top-veto (\( R_{\text{top}} \)), and vice versa. Therefore, both likelihood-ratios are used as cut observables, where each event is required to fulfill both cut criteria in a logical AND-cut.

The signal assumption for pdf generation is chosen as 600 GeV WIMPs annihilating to \( \mu^+\mu^- \)-pairs. The resulting distributions of the likelihood-ratios are shown in figure 5.13. As stated previously, the difference in horizontal and vertical spacing has a large impact on the veto capability; this is clearly visible in the likelihood-ratio distributions. Further, the distribution of likelihood-ratios for the full sample shows signal-like and background-like features in both veto cases. This is a consequence of a lack of e.g. top-veto hits (beyond noise) in the side-veto sample and vice versa.

The cut values for the two likelihood-ratios \( R_{\text{top}} \) and \( R_{\text{side}} \) are optimized individually by maximization of the significance defined by \( S/\sqrt{B} \) for fiducial signal (\( S \)) and the corresponding top-veto and side-veto background (\( B \)) sub-samples. Figure 5.14 shows the background passing fraction as function of signal efficiency for the corresponding background sub-sample as well as the full background sample.

The such determined cut values are

\[
R_{\text{top}} > 0.0 \quad (5.10)
\]
\[
R_{\text{side}} > 0.2. \quad (5.11)
\]

**Punch-Through Veto**

In contrast to the Causality Veto the Punch-Through Veto makes use of well-reconstructed events to set a hard cut on a sharp veto signature. The Punch-Through Veto consists of the following steps:

1. First, calculate the point of entry (PoE), \( \vec{x}_{\text{PoE}} \), of the reconstructed track into the detector. The detector boundaries are defined by the top and bottom caps at about \( \pm 500m \), and the side planes defined by the outer string layers.

2. Second, apply a noise cleaning (CRT) to the full pulse map (s. section 4.5.3) to reduce most of the noise hits, and calculate the position of the earliest hit DOM, \( \vec{x}_{\text{early}} \).

3. Third, calculate the distance between the two positions in the \( x-y \)-plane, and the signed distance along the \( z \)-axis:

\[
\rho = \sqrt{(x_{\text{PoE}} - x_{\text{early}})^2 + (y_{\text{PoE}} - y_{\text{early}})^2} \quad (5.12)
\]
\[
z = z_{\text{PoE}} - z_{\text{early}} \quad (5.13)
\]
The motivation for calculating two distances is similar to the motivation for separate top and side vetoes; the difference in horizontal and vertical DOM spacing. Figure 5.15 shows the distributions of fiducial signal and background events in the $\rho$-$z$-plane.

The very clean background feature of incoming tracks in this plane is caused by well-reconstructed tracks from a relatively narrow declination band of $\pm 15^\circ$ around the Galactic center. Fiducial signal illuminates the detector more uniformly, and in general the earliest hit of the signal sample is more distant than in the background case. The contribution of noise in the narrow veto region is small due to the CRT cleaning.

A box cut is defined around the veto feature, that removes about 50% of the remaining background. The fiducial signal retention is about 90% for 600 GeV WIMPs annihilating to $W^+W^-$-pairs. For DeepCore-dominated signal samples, like 100 GeV WIMPs annihilating to $b\bar{b}$-pairs the signal retention is up to 99%.

All level 4 cut values are summarized in table 5.2. The experimental data rate after these cuts is 0.45 Hz. The signal efficiency for this cut is summarized in section 5.4.6.

<table>
<thead>
<tr>
<th>Observable</th>
<th>Cut value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{top}}$</td>
<td>$&gt; 0.0$</td>
</tr>
<tr>
<td>$R_{\text{side}}$</td>
<td>$&gt; 0.2$</td>
</tr>
<tr>
<td>$z$</td>
<td>$&lt; -400 \text{ m or } &gt; 0 \text{ m}$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>$&lt; 200 \text{ m or } &gt; 280 \text{ m}$</td>
</tr>
</tbody>
</table>

Table 5.2: Summary of level 4 cut values. The motivation for the $z$ and $\rho$ cut values is the box cut on a clear veto signature.

### 5.4.5 Level 5

The final event selection is performed by means of supervised machine learning, using the Boosted Decision Tree (BDT) implementation from the TMVA package [183]. The BDT method is briefly described in appendix C.

The BDT is trained for the final event selection, using the following signal and background definitions:

- **Background**: the remaining simulated atmospheric muon sample (CORSIKA)
- **Signal**:
  - 600 GeV WIMPs, annihilating to $W^+W^-$-pairs
  - starting events
  - $J_A(\psi)$-weighted, where $\psi$ is calculated using only the declination distance to the Galactic center

The motivation to use only declination distance for the halo-shape weight is to avoid a modification of the right ascension distance distribution of events to the Galactic center; the
Figure 5.9: Reconstructed vertex projection on the $p_{T}$-$z_{T}$-plane for experimental data, simulated background, and a soft and a hard WIMP channel.
Figure 5.10: Reconstructed vertex projection on the $x_H$-$y_H$-plane for experimental data, simulated background, and a soft and a hard WIMP channel.
Figure 5.11: The $\Delta r$-$\Delta t$-plane for simulated background (CORSIKA), and a signal assumption of 600 GeV WIMPs annihilating to $\mu^+\mu^-$-pairs. The red-dashed lines correspond to the vacuum speed of light. The red-solid boxes define the region to look for veto hits (s. text for full explanation). The angle between the red-dashed line and the $z$ axis correspond to $45^\circ$ in the $\Delta r$-$c$,$\Delta t$-plane.
Figure 5.12: Hit multiplicity pdf, and decorrelated 1-dimensional pdfs for the likelihood-ratio calculation. Top-veto pdfs are on the left side, side-veto pdfs are on the right side.
Figure 5.13: $R_{\text{top/side}}$ distributions for the top-veto (left) and side-veto (right), using a signal assumption of 600 GeV WIMPs, annihilating to $\mu^+\mu^-$ pairs. All distributions are normalized individually. Events without any hits in the veto region are not shown, but retained in a signal-like error bin for normalization and cut optimization.
5.4. EVENT SELECTION

Figure 5.14: Background passing fraction as function of signal efficiency, based on the $R_{\text{top/side}}$ distributions from figure 5.13. The optimal cut values are found based on maximization of $S/\sqrt{B}$. The blue lines represent the subsamples used for optimization of each veto. The dotted line shows the same calculation for the full simulated background sample (CORSIKA).

Figure 5.15: Distance of the earliest hit DOM to the point of entry (PoE) of reconstructed tracks into the detector volume. The PoE is at (0,0). The deeper the event starts within the detector, the farther the earliest hit DOM is located from the PoE at (0,0). The vertical stripes correspond to string locations. The narrow and clear signature in both the signal and background case is caused by the zenith cut.
background is estimated from the off-source declination band. Furthermore, the final likelihood analysis will make use of the full shape information.

The 13 observables for event classification are roughly grouped into the following categories:

- **event quality**
- **event topology in the detector**
- **WIMP/halo-related**

The category of **quality-related observables** consists of the Linefit velocity $v_{\text{linefit}}$ (s. section 4.5.4), the number of direct DOMs $n^D_{\text{dir}}$, and the number of direct strings $n^S_{\text{Dir}}$. Here, the direct observables are defined by the number of DOMs and strings, that registered a hit in a time-residual window\(^4\) of $[-15 \text{ ns}, 125 \text{ ns}]$.

The category of **topological observables** is mainly intended as a measure of where and how deep the event starts within the detector.

For this purpose the reconstructed vertex positions in $x$, $y$, and $z$ from FiniteReco (s. section 4.5.5) are used. Further, the algorithm yields likelihood values for the track to be a starting, stopping, or infinite (through-going) track, using information from all DOMs, including not hit DOMs. The likelihood ratio $R_{\text{start} - \text{inf}}$ of the two hypotheses is a measure for the track to start within the detector. The algorithm calculates the total possible length of the track in the detector, as well as the reconstructed length. This allows for a definition of $L_{\text{start}}$ and $L_{\text{stop}}$. $L_{\text{start}}$ is the length of the track in the detector before the reconstructed vertex, that is not covered by hit DOMs. On the other hand, $L_{\text{stop}}$ is the length of the outgoing track that is not covered by hit DOMs. The motivation for the latter observable is that many atmospheric muons get absorbed within the detector.

A further set of topological observables are the $x$, $y$, and $z$ coordinates of the center of gravity (CoG) of the 25% of earliest hit DOMs. These quantities are a simple and robust first-guess for an interaction vertex without using any reconstruction information.

The last topological observable is $z_{\text{travel}}$, which is the difference of the average $z$-position of all hit DOMs and the average $z$-position of the earliest 25% of hit DOMs.

Finally, the reconstructed zenith is used to exploit the difference between the spiked halo shape and the zenith distribution of background events, which is steeply falling with increasing zenith (and decreasing declination).

All distributions of the observables that are used in the BDT selection are shown in appendix F. The BDT settings are summarized in table 5.3.

Following the BDT training, the resulting classifier is used to assess simulated and experimental data, assigning a BDT score to each event. The BDT score distribution for simulated signal and background samples, and experimental data are shown in figure 5.16. The BDT score distribution is shown both for the signal assumption used for training, as well as a soft annihilation channel of 100 GeV WIMPs annihilating to $b\bar{b}$-pairs.

Figure 5.17 shows the significance $S/\sqrt{B}$ as function of the BDT score. The BDT has sufficient discrimination power to remove almost all of the remaining simulated background.

\(^4\)See likelihood-based track reconstruction in section 4.5.4
5.4. **EVENT SELECTION**

<table>
<thead>
<tr>
<th>Option</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of trees</td>
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<tr>
<td>Depth</td>
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</tr>
<tr>
<td>Separation Type</td>
<td>Misclassification error</td>
</tr>
<tr>
<td>Adaptive boost factor</td>
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</tr>
<tr>
<td>Prune Method</td>
<td>Expected error</td>
</tr>
<tr>
<td>Pruning</td>
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</tr>
<tr>
<td>nCuts</td>
<td>50</td>
</tr>
<tr>
<td>nMin</td>
<td>100</td>
</tr>
</tbody>
</table>

**Table 5.3**: BDT setup in the TMVA framework.

Events near the optimum cut value for the training sample, thus the optimization curve suffers from insufficient statistics near the optimal value. Further, the same BDT scoring for the previously mentioned soft channel of 100 GeV WIMPs annihilating to $b\bar{b}$-pairs shows a lower optimal cut value than for the signal assumption used for training.

A cut value of

\[
\text{BSTScore} \geq 0.1
\]

is set on the BDT score to accommodate both the decreasing statistics and the retention of low-energy signal. The experimental data rate after this cut is about 0.11 Hz.

### 5.4.6 Summary

The event selection reduces the amount of background from $\simeq 43\text{Hz}$ at filter level to about 11 mHz at final level. Table 5.4 summarizes the data rate at each level.

<table>
<thead>
<tr>
<th>Level</th>
<th>rate/Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger level</td>
<td>$\simeq 2350$</td>
</tr>
<tr>
<td>Filter level</td>
<td>43.02</td>
</tr>
<tr>
<td>Level 3</td>
<td>4.50</td>
</tr>
<tr>
<td>Level 4</td>
<td>0.45</td>
</tr>
<tr>
<td>Level 5</td>
<td>0.011</td>
</tr>
</tbody>
</table>

**Table 5.4**: Experimental data rates at different selection levels. The signal efficiency strongly depends on the WIMP mass and annihilation channel, but in general is between 0.5 and 0.8 per cut level for levels 3 to 5.

The signal efficiency for all cut levels depends on the considered annihilation channel and WIMP mass, and is best shown in terms of the effective area $A_{\text{eff}}$ in figure 5.18; All effects of neutrino propagation through the Earth, neutrino interaction, light generation and propagation, as well as detection efficiency are taken into account. Thus the effective area is a measure of the performance of the detector, but also of the selection efficiency of a sample, and satisfies
Figure 5.16: Level 5 BDT score distributions for the signal sample used for training, and a soft channel for comparison. The background score distribution for the full CORSIKA sample, and single showers are shown and compared to experimental data from the burn sample (1 out of 10 runs).

the equation

\[ \Gamma = \int d\Omega \int dE A_{\text{eff}}(E) \phi(E), \]

where \( \Gamma \) is the event rate, and \( \phi(E) \) an assumed differential flux.

Figure 5.18 also shows the ratio of effective areas as function of neutrino energy for each level. These ratios correspond directly to the signal efficiencies for annihilation to neutrinos as function of neutrino energy, and thus WIMP mass.

Figure 5.19 shows the relative contributions of the DeepCore filter and the Galactic center filter to the signal efficiency.

Prior to dataset unblinding the expected number of on-source background events is determined. The total number of off-source events in the full sample is 228,983. Using the weighting scheme from equation (5.2, 5.2) to correct for the on-source and off-source region sizes and the off-source pre-scaling, the expected number of on-source events is 36,806. This number is used for sensitivity studies and background expectation in the likelihood analysis.

5.5 Outline of Likelihood Analysis

A likelihood-based analysis of the data at final level is performed to determine or constrain the number of signal events in the on-source region. The code for the likelihood analysis was developed in Stockholm for a similar analysis focusing on DeepCore [184].
Figure 5.17: Level 5 BDT score optimization based on data from figure 5.16. The black line indicates the optimal cut value for the signal assumption. For the harder signal assumption, the optimal cut value lies in a region where the background statistic is insufficient for a reliable determination, thus the spike in the $S/\sqrt{B}$-curve.

Figure 5.18: Effective area at different filter levels, and the relative signal efficiencies as function of neutrino energy. The efficiency is mostly flat, with a bump below 100 GeV.
Figure 5.19: Relative contribution of the two used filter streams to the signal efficiency, and the contribution of events from both filter streams. With increasing neutrino energy the Galactic center filter contributes more to the sensitivity, and becomes more important than the DeepCore filter at energies above 100 GeV. The rising flank at about 100 GeV is a consequence of the sparser spacing and the higher trigger threshold of IceCube over DeepCore.
The on-source region is defined by

\begin{align}
|\delta - \delta_{GC}| & \leq 15^\circ \tag{5.15} \\
|\alpha - \alpha_{GC}| & \leq 15^\circ, \tag{5.16}
\end{align}

where \(\alpha\) is the right ascension, and \(\delta\) is the declination of events. The likelihood approach exploits the different shapes of the distributions of background and signal events in the on-source region, thus an optimization of the on-source region size is not necessary.

![Image](image.png)

**Figure 5.20:** A schematic overview of the HEALPix ordering principle of bins on a sphere. Each bin number corresponds to a grey-shade value, and represents a pair of coordinates \((\alpha, \delta)\).

The underlying 2-dimensional pdfs for the expected background are constructed from skymaps of scrambled off-source data. The signal pdfs are constructed from simulated neutrino datasets which include the halo shape and the annihilation channel weights.

The sky pixelization is performed using the HEALPix\(^5\) package [185], which divides the sky into bins that cover equal solid angles. The HEALPix ordering principle of bins on a sphere is explained in figure 5.20.

Figure 5.21 shows examples of a signal and a background skymap. The full skymap consists of 49,152 bins, and the number of on-source bins is 1009. Rather than using the 2-dimensional pdfs for the likelihood analysis, the internal HEALPix mapping

\[(\alpha, \delta) \rightarrow b_i \tag{5.17}\]

is used to define 1-dimensional pdfs that depend only on the bin number \(i\) of the HEALPix bin denoted by \(b_i\). The such mapped 1-dimensional representation of the pdfs are shown in figure 5.22. Off-source bin numbers are omitted in the incremental bin counting, thus the shown pdfs have 1009 bins.

The peculiar pdf shape is caused by the ordering of HEALPix bins. The increasing bin number corresponds to right ascension scans, with breaks at the on-source region boundary.
where the bin location jumps to the next declination band. The background, being distributed uniformly in $\alpha$, has constant plateaus for each declination band. The different plateau heights are the result of the initial background declination distribution, convolved with the declination-dependent acceptance of the BDT selection which already exploits the distance in declination of events to the Galactic center. The signal is peaked in the direction of the Galactic center, thus the pdfs show a fast oscillation for each right ascension scan in addition to the envelope shape caused by the declination distribution.

(a) Background skymap from scrambled experimental off-source data.  
(b) Signal skymap assuming 10 TeV WIMPs, annihilating to $\mu^+\mu^-$-pairs. The halo profile is NFW.

Figure 5.21: The background skymap and an example of a signal skymap that are used for the likelihood analysis (equatorial coordinates). The number of on-source bins is 1009. The features are explained in the text.

Based on the above-explained mapping, a 1-dimensional likelihood function is defined as

$$
L(n_{\text{sig}}) = \frac{(n_{\text{bkg}} + n_{\text{sig}})^{n_{\text{obs}}}}{n_{\text{obs}}!} \cdot e^{-\left(n_{\text{bkg}} + n_{\text{sig}}\right)} \cdot \prod_i \left( \frac{n_{\text{sig}}}{n_{\text{bkg}} + n_{\text{sig}}} p(b_i|S) + \left(1 - \frac{n_{\text{sig}}}{n_{\text{sig}} + n_{\text{bkg}}} \right) p(b_i|B) \right)
$$

(5.18)

Here, $n_{\text{sig}}$ is the number of signal events, $n_{\text{bkg}}$ the number of expected background events, and $n_{\text{obs}}$ the number of observed events. The (first) poissonian term considers the probability to measure a number of on-source events, $n_{\text{obs}}$, given an expectation $n_{\text{bkg}}$ and signal $n_{\text{sig}}$. The second term is the shape likelihood, that makes use of the above-described pdfs for signal (S) and background (B).

The analysis is performed using a background pdf from scrambled data, and one signal pdf. The signal pdf is generated from a cuspy signal assumption; 10 TeV WIMPs annihilating to $\mu^+\mu^-$-pairs in an NFW halo. The other pdfs are only used for sampling of signal events for pseudo-experiments. The motivation to use only one pdf for hypothesis testing is to avoid penalty factors from testing many signal assumptions; the analysis is performed for 15 mass points, 5 annihilation channels and two halo profiles, which would lead to 150 signal assumptions.
Figure 5.22: 1-dimensional pdfs extracted from skymaps as shown in figure 5.21. The bin number $b_i$ corresponds to mapping of equatorial coordinates to HEALPix-internal bin numbers. Off-source bins are skipped in the incremental counting. The number of bins is 1009, and corresponds to the number of on-source bins in the skymap. The features are explained in the text.

5.5.1 Confidence Belt Construction

The confidence intervals are constructed following the Feldman and Cousins prescription [186]. The likelihood ratio

$$R(n_{\text{sig}}) = \frac{\mathcal{L}(n_{\text{sig}})}{\mathcal{L}(n_{\text{sig}}^{\text{max}})}$$

is used for ranking, where $n_{\text{sig}}^{\text{best}}$ maximizes the likelihood.

For each $n_{\text{sig}} \in [0, n_{\text{obs}}]$ 10,000 pseudo-experiments are conducted by drawing $n_{\text{sig}}$ events from the signal sampling pdf and $n_{\text{obs}} - n_{\text{sig}}$ events from the background pdf. As described in section 5.5, $R(n_{\text{sig}})$ is calculated using one analysis pdf. The critical value $R_{\text{crit}}(n_{\text{sig}})$ is determined by

$$\frac{N(R(n_{\text{sig}}) < R_{\text{crit}})}{N(R(n_{\text{sig}}))} = 1 - \alpha,$$

where $N$ is a fraction of pseudo-experiments, and $\alpha$ is the confidence level (C.L.). For a 90% C.L. sensitivity the critical value is determined by the lower 10% quantile of the $R(n_{\text{sig}})$ distribution. The confidence belt consists of intervals $[n_{90}^{\text{lower}}, n_{90}^{\text{upper}}]$ where $R(n_{\text{sig}}) > R_{\text{crit}}(n_{\text{sig}})$.

The confidence belt construction is performed for all 150 hypotheses.

5.5.2 Sensitivity Towards $n_{\text{sig}}$ and $\langle \sigma_A v \rangle$

The sensitivity of this analysis towards the number of signal events in the sample is computed for each considered halo profile, mass point and annihilation channel. Following the confidence
belt construction described in section 5.5.1, the null hypothesis is sampled 10,000 times. The sensitivity is the median upper limit, given by the median of $n_{90}^{\text{upper}}$.

Examples of the such-obtained sensitivities are shown in figure 5.23. The data is grouped into sensitivity curves as function of mass for one channel and one halo profile. There is no strong variation of $n_{90}^{\text{upper}}$ for different signal assumptions. The sensitivities for all channels and both halo profiles are presented in appendix G.

![Diagram](image)

(a) NFW profile, $\chi \chi \rightarrow b\bar{b}$.  
(b) NFW profile, $\chi \chi \rightarrow \nu\bar{\nu}$.

(c) Burkert profile, $\chi \chi \rightarrow b\bar{b}$.  
(d) Burkert profile, $\chi \chi \rightarrow \nu\bar{\nu}$.

Figure 5.23: Sensitivity towards the number of signal events, including the 1-σ and 2-σ contours. The markers indicated tested mass points. The hard and soft benchmark annihilation channel is shown for the cuspy NFW and the cored Burkert profile.

The number sensitivity can be converted to the sensitivity on the self-annihilation cross-
5.5. OUTLINE OF LIKELIHOOD ANALYSIS

section $\langle \sigma_A v \rangle$ by

$$\langle \sigma_A v \rangle = n_{90}^{\text{upper}} \frac{8\pi m_\chi^2}{R_{SC} \rho_{SC} T_{\text{live}}} \cdot S_{\text{eff}}$$

(5.21)

$$\frac{1}{S_{\text{eff}}} = \int d\Omega \int dE J(\psi) A_{\text{eff}}(E) \frac{dN_\nu}{dE},$$

(5.22)

where $A_{\text{eff}}(E)$ is the effective area, $J(\psi)$ is the line-of-sight integral, $m_\chi$ the WIMP mass, $T_{\text{live}}$ the live time, $R_{SC}$ is the radius of the Sun’s orbit around the Galactic center, and $\rho_{SC}$ is the local dark matter density. The integral $\int dE A_{\text{eff}} \frac{dN_\nu}{dE}$ carries the detector efficiency for the considered WIMP masses and channels.

Figure 5.24 shows the resulting $\langle \sigma_A v \rangle$-sensitivity for four benchmark channels for the NFW profile, as well as the $\langle \sigma_A v \rangle$-sensitivity for the neutrino channel and two halo profiles.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{sensitivity.png}
\caption{Sensitivity towards the self-annihilation cross-section, $\langle \sigma_A v \rangle$, for the considered mass range of 100 GeV to 10 TeV assuming different benchmark annihilation channels and halo profiles. The black-dashed line is the unitarity bound [85, 187], and the grey-shaded region indicates the cross-section for WIMPs to be thermal relics [52].}
\end{figure}

Despite the flat $n_{90}^{\text{upper}}$ sensitivity curves, the $\langle \sigma_A v \rangle$-sensitivity varies by orders of magnitude among channels, as well as within a channel. This is caused by the energy dependence of the neutrino detection efficiency, incorporated in the effective area $A_{\text{eff}}(E)$. The variation among channels for a single mass point is caused by the different shape of neutrino energy spectra $\frac{dN_\nu}{dE}$. The shape of the sensitivity curves as function of WIMP mass is best understood considering the neutrino channel. The sensitivity is

$$\langle \sigma_A v \rangle \propto m_\chi^2 \cdot S_{\text{eff}},$$

(5.23)

where $S_{\text{eff}} \propto A_{\text{eff}}(E = m_\chi)$. The effective area, and thus the detection efficiency is proportional to the neutrino cross-section, and, in case of charged current interactions, the muon range.
Both are roughly proportional to the neutrino and muon energy, respectively. Thus, the limit curve would be flat until at a few 100 GeV the muon’s stochastic energy losses would become dominant.

However, the starting event selection necessitated by the incoming muon background removes the advantage of the muon range. Thus, the limit curves increase with increasing WIMP mass.

Direct annihilation to neutrino pairs yields the best sensitivity. The annihilation channel to $b\bar{b}$-pairs has the lowest fraction of high-energy neutrinos, and thus yields the weakest sensitivity of all considered channels. The cuspy NFW profile yields a better sensitivity compared to the flat-cored and currently favored Burkert profile, which represents the physically best-motivated case.

The most optimistic scenario for this analysis is a WIMP at a mass of a few 100 GeV, annihilating directly to neutrinos in an NFW halo profile. The best-case sensitivity on $(\sigma_A v)$ is more than two orders of magnitude above the natural scale.
This chapter presents results from the analysis of the un-blinded dataset. The likelihood analysis results, and a cut&cut comparison are shown, and the results in terms of the self-annihilation cross-section are presented. Finally, the results are discussed in context of other experiments, and systematic effects are addressed.
6.1 Unblinded Experimental Dataset

The full dataset was unblinded with respect to the right ascension of events. A skymap of these events is shown in figure 6.1, and the results are summarized in table 6.1.

![Unblinded experimental skymap.](image)

**Figure 6.1:** Unblinded experimental skymap.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live-time</td>
<td>$T_{\text{live}}$</td>
<td>312.6 days</td>
</tr>
<tr>
<td>Total number of events</td>
<td>$n_{\text{tot}}$</td>
<td>293,043</td>
</tr>
<tr>
<td>Number of off-source events</td>
<td>$n_{\text{off}}$</td>
<td>228,983</td>
</tr>
<tr>
<td>Number of events in buffer zone</td>
<td>$n_{\text{buffer}}$</td>
<td>29,399</td>
</tr>
<tr>
<td>Number of expected on-source background events</td>
<td>$n_{\text{exp}}$</td>
<td>36,806</td>
</tr>
<tr>
<td>Number of observed on-source events</td>
<td>$n_{\text{on}}$</td>
<td>36,969</td>
</tr>
<tr>
<td>Number of events after background subtraction</td>
<td>$n_{\text{on}} - n_{\text{on}}^{\text{exp}}$</td>
<td>+163</td>
</tr>
</tbody>
</table>

**Table 6.1:** Dataset statistics after unblinding.

The number of expected background events in the on-source region is 36,806, and the observed number of events is 36,969. The overfluctuation of 163 events corresponds to 0.44% of the expected number of events, and is a deviation of $\sim +0.85\sigma$ from the expectation value. This corresponds to a single-sided p-value of 19.8%, assuming gaussian statistics. The result is compatible with the background-only hypothesis.
6.2 Results of the Likelihood Analysis

The likelihood analysis was performed on the unblinded dataset, using the analysis pdf constructed from the assumption of 10^7 TeV WIMPs annihilating to $\mu^+\mu^-$-pairs. The best fit value for the number of signal events is

$$n_{\text{sig}}^{\text{best}} = 0.$$ \hfill (6.1)

The result is tested against $R_{\text{crit}}$ for the two considered halo profiles, all masses and channels. The obtained values of $n_{90}^{\text{upper}}$ for each tested point are grouped to $n_{90}^{\text{upper}}(m_\chi)$ limit curves for each halo profile and annihilation channel. The neutrino-channel limits for both halo profiles are shown in figure 6.2, together with the median upper limits, and the 1-$\sigma$ and 2-$\sigma$ contours. The median upper limits and contours are obtained from 10,000 pseudo-experiments. The figures for all other annihilation channels can be found in appendix G.

![Figure 6.2: Sensitivities (dashed lines) and limits (solid lines) on the number of signal events, including the 1-$\sigma$ and 2-$\sigma$ contours. The direct annihilation channel to neutrinos is shown as an example for two halo profiles. The markers indicated tested mass points. Other annihilation channels show similar behavior.](image)

The likelihood analysis result is a slight underfluctuation of less than 0.5$\sigma$. The overfluctuation from the cut&count estimate in section 6.1, and the underfluctuation in the likelihood analysis are statistically compatible.

6.3 Limits on $\langle\sigma_A v\rangle$

The limit on $\langle\sigma_A v\rangle$ is calculated according to equation (5.22), and shown in figure 6.3 for both halo profiles, and four annihilation channels. The shape of the limit curves is the same as for the sensitivity curves, and is qualitatively explained in section 5.5.2.
Figure 6.3: Limits on the self-annihilation cross-section, $\langle \sigma v \rangle$, assuming different benchmark annihilation channels and halo profiles. The black-dashed line is the unitarity bound [85, 187], and the grey-shaded region indicates the self-annihilation cross-section for WIMPs to be thermal relics [52].
6.4 Comparison to Other Results

The results of this analysis are compared to other experimental results. The limits obtained with the NFW profile are used, since many experiments choose this profile as baseline. In some cases the results need to be rescaled to the same local dark matter density \( \rho_{SC} \). In case of \( \langle \sigma A v \rangle \)-limits the rescaling is straightforward; the rescale factor \( s \) is

\[
s = \left( \frac{\rho_{SC}^{\text{old}}}{\rho_{SC}^{\text{new}}} \right)^2
\]

and the modified limit curves are given by

\[
\langle \sigma A v \rangle^{\text{new}} = s \cdot \langle \sigma A v \rangle^{\text{old}}.
\]

All figures that contain rescaled data state the rescale factor in the corresponding figure caption. In the following sections, the here-obtained limits are compared to

- Other IceCube Galactic center analyses
- IceCube searches for dark matter in the Galactic halo and dwarf galaxies
- Dark-matter-interpretations of excesses above expected background in electron, positron and gamma-ray data
- Best limits from gamma-ray and CMB observations

6.4.1 The IceCube Galactic Center Results

First, the results of this analysis are compared to the predecessor analysis of IceCube–40 data [188]. Compared to IceCube–79, the IceCube–40 detector was smaller by a factor of 2 in terms of string numbers, and the string configuration was flattened such that the fiducial volume was relatively small. Further, IceCube–40 lacked the low-energy extension DeepCore. Figure 6.4a shows a comparison of the limits for the annihilation channels to \( b\bar{b} \)-pairs, \( W^+W^- \)-pairs, \( \mu^+\mu^- \)-pairs and direct annihilation to \( \nu\bar{\nu} \)-pairs. In all cases, the limits are improved, with improvement factors ranging from more than four orders of magnitude at low WIMP masses and soft annihilation channels, and a factor on the order of 2 for 10 TeV WIMPs and direct annihilation to \( \nu\bar{\nu} \)-pairs. The reason for the comparatively small improvement at high WIMP masses is the optimization on TeV-scale WIMPs.

Further, another analysis of IceCube–79 data was performed with focus on the DeepCore array and low-mass WIMPs down to WIMP masses of 30 GeV. The results are compared to results from the here-presented analysis in figure 6.4b. The low-mass analysis is labeled “GC-LE”, as opposed to the here-presented analysis, which is labeled “GC-HE”. The event selection was developed independently, and the overlap of the samples is on the few-% level. The result was an underfluctuation of about 2\( \sigma \), and thus compatible with the null hypothesis. Since the underfluctuation leads to limits that are about a factor of 4 more constraining than the sensitivity, both the sensitivities and limits are presented, as suggested by Feldman
and Cousins [186]. The results from both the “GC-LE”- and the “GC-HE”-analyses will be published together. The limit curves from both analyses will be combined based on the best sensitivity for each channel and mass point.

6.4.2 ANTARES Limits for the Galactic Center

The ANTARES neutrino detector in the Mediterranean Sea offers the advantage over IceCube, that the Earth can be used as shield against atmospheric muon background. Therefore, the detector benefits both from a better background rejection, and an increased effective volume due to the muon range at higher energies. The muon-range advantage vanishes at lower energies, and thus shorter muon tracks, due to the fact that IceCube is larger than ANTARES, even with the constraint of a starting-event analysis. This is reflected in the preliminary ANTARES result presented in figure 6.5, which was obtained from an analysis of approximately 1300 live-days of the final ANTARES dataset. The reason for the point-to-point variation in the ANTARES limit is the optimization of the analysis for each signal assumption. This comparison shows that dark matter searches in the Galactic center with the next-generation detector KM3Net can be expected to be very sensitive, reaching almost down to the natural scale for massive WIMPs annihilating in an NFW profile.
6.4. COMPARISON TO OTHER RESULTS

![Graph showing comparison of ANTARES results to other results](image)

Figure 6.5: Comparison of ANTARES results from a multi-year analysis of the final dataset of approximately 1300 days live-time [189] to the here-presented results. The annihilation channel to \( \tau^+\tau^- \) pairs is shown. No profile-related rescaling is applied, as the reference does not state the profile parameters.

6.4.3 The IceCube Galactic Halo Results

Second, the limits from this analysis are compared to limits on \( \langle \sigma_A v \rangle \) from two searches for dark matter annihilation in the Galactic halo with the 22-string [86] and 79-string [190] configurations of IceCube.

A flux of final state particles from dark matter annihilation in the halo would lead to a large-scale anisotropy on the Northern Hemisphere.

Figure 6.6 shows a comparison of limits from this analysis to the two halo analyses. At low WIMP masses the Galactic center limits are more constraining, since the halo searches do not gain significantly from the muon range, and the flux expectation from the Galactic center is higher. Further, the event selection used in the halo searches is optimized for higher neutrino energies. At higher masses the halo searches are more constraining. Further, the IceCube–22 halo limits are more constraining in the high-mass range than the IceCube–79 halo limits. The cause is the comparably high selection efficiency for low-energy events in the IceCube–79 halo sample; low-energy neutrinos are a background for high-mass WIMPs.

As explained in section 2.1.3, the Galactic center limits are subject to large uncertainties from the choice of halo profile. On the other hand, the Galactic halo limits are relatively model-independent. Figure 6.7 shows the \( \langle \sigma_A v \rangle \)-limit range between the NFW profile and Burkert profile from the IceCube–79 halo and center searches.

Despite the lower flux expectation from the Galactic halo, these limits are competitive to the
Figure 6.6: Comparison of limits from this analysis to limits from searches for dark matter in the Galactic halo, performed using data from IceCube–22 [86] and IceCube–79 [190], respectively. The IceCube–22 limits were rescaled to a local dark matter density of $\rho_{SC} = 0.471 \text{ GeV/cm}^3$ ($s = 0.41$).

Galactic center limits, especially at high WIMP masses. The reason is the better background rejection, and the muon-range advantage, since no fiducial-volume requirement is imposed.

6.4.4 Results from the IceCube Dwarf-Galaxy Analysis

Dark matter annihilation in dwarf galaxies would lead to a point-source-like flux of messenger particles. A search for such a flux was performed using IceCube–39 data [87]. The stacking analysis of the two dominant dwarf galaxies, Segue 1 and Ursa Major II, yields the most stringent constraints. A comparison of the limits for the annihilation channels to $b\bar{b}$-pairs, and $\tau^+\tau^-$-pairs is shown in figure 6.8.

The astrophysical $J_3$-factors for both galaxies are obtained from observational data, thus the limits are not rescaled, but shown as published. While the sensitivity to dark matter annihilations in dwarf galaxies is not really competitive to the sensitivity for the Galactic center or Galactic halo, the astrophysical uncertainties on e.g. the $J$-factor or any foreground sources are very different, making such an analysis a complementary method to probe dark matter annihilation.

6.4.5 The PAMELA/Fermi/HESS Dark-Matter-Interpretation

The PAMELA collaboration reported an excess in the positron fraction [191], compared to expectations from standard diffusive models. Further, the Fermi and HESS collaborations reported a deviation from expectation in the $(e^+ + e^-)$-flux [192, 193, 194]. A possible explanation for an additional electron and positron component may be dark matter annihilation in Earth’s vicinity [82], where the excess is interpreted as a flux of annihilation products orig-
6.4. COMPARISON TO OTHER RESULTS

Figure 6.7: The shaded regions show the model dependence of the Galactic center (GC, red) and halo (GH, blue) limits, obtained from analysis of IceCube–79 data. The variation of the Galactic halo limits is negligible on a logarithmic scale.

nating from a diffusion volume with a radius of about 4 kpc around Earth. The such-obtained regions in the \( \langle \sigma_A v \rangle - m_\chi \) plane are shown in figure 6.9, along with IceCube limits from this analysis, the two halo analyses, and the dwarf stacking analysis.

However, the dark-matter-interpretation of these excesses is not favored; such measurements may well be caused by astrophysical objects like nearby pulsars [81, 195].

The applied rescaling of the region data is justified, since the lepton flux from annihilation within the Milky Way scales in the same way as the here-obtained indirect limits on \( \langle \sigma_A v \rangle \). The annihilation channel to \( \tau^+\tau^- \)-pairs is presented as best-case scenario for exclusion of the PAMELA/Fermi/HESS excess, since the preferred regions are higher on the \( \langle \sigma_A v \rangle - m_\chi \) plane than for the \( \mu^+\mu^- \) case.

The best-case scenario cannot be ruled out by the Galactic center-results, but the halo limits start to cut into the Fermi region. However, improved future IceCube Galactic center and Galactic halo searches focusing on the high-mass region around a few TeV may well be able to exclude a dark matter origin of the positron excess.

6.4.6 The Fermi Gamma-Ray Excess

The 1 GeV-3 GeV gamma-ray excess measured by Fermi at the Galactic center is a very promising hint at dark matter beyond inference from gravitational interactions [196]. The signal extends up to 10° beyond the Galactic center, thus, given Fermi’s angular resolution, it does not originate from a point source. Further, the inner slope is incompatible with diffuse emissions
Figure 6.8: Comparison of limits from this analysis to limits from the IceCube–59 dwarf stacking analysis [87], for a soft and a hard channel. The direct annihilation channel to $\nu\bar{\nu}$-pairs is not available for the dwarf analysis.

from the gas component. Template fits based on background modeling and a flux of annihilation products from dark matter annihilation yield an inner slope parameter $\gamma = 1.1$-1.3, and good agreement with the data assuming 31 GeV–40 GeV WIMP's annihilating to $b\bar{b}$-pairs.

Figure 6.10 shows the 3-$\sigma$ contour for this channel, as well as limits from this analysis and the “GC-LE”-analysis.

The Fermi gamma-ray preferred region in the $\langle \sigma v \rangle$-$m_X$-plane lies below the natural scale, and far beyond the current reach of IceCube. The $b\bar{b}$ annihilation channel is the best-case scenario for gamma-ray observation, and the worst-case scenario for IceCube due to the huge fraction of low-energy neutrinos. The IceCube limits for this channel are not competitive, and the prospects for a future detection or constraint of this possible signal with IceCube or DeepCore are very limited. This is also the case for the possible future low-energy extension Precision IceCube Next Generation Upgrade (PINGU) [197]. A preliminary 1-year sensitivity of a Galactic center analysis is included in figure 6.10, assuming the most optimistic direct annihilation channel to $\nu\bar{\nu}$-pairs. The shaded region spans the sensitivity range given current veto, reconstruction, and analysis techniques, and an optimistic sensitivity for a perfect veto.

The currently most promising way to probe the Fermi GC excess in a relatively complementary way is by Fermi itself, and a search for a gamma-ray flux from dwarf satellites.
6.4. **COMPARISON TO OTHER RESULTS**

![Graph showing comparison of limits from this analysis to preferred regions in the $(\sigma_A v) - m_\chi$-plane for a dark-matter-interpretation of the excesses in the positron fraction reported by PEMELA (3-$\sigma$, green-shaded), and the $(e^+ + e^-)$-flux reported by Fermi and HESS (5-$\sigma$ in light red, 3-$\sigma$ in dark red) [82]. Further, the IceCube–22 [86] and IceCube–79 [190] halo analyses, and the IceCube–59 dwarf analysis [87] are shown. The regions and the IceCube–22 limit were rescaled to a local dark matter density of $\rho_{SC} = 0.471$ GeV/cm$^3$ ($s = 0.41$).](image)

**Figure 6.9:** Comparison of limits from this analysis to preferred regions in the $(\sigma_A v) - m_\chi$-plane for a dark-matter-interpretation of the excesses in the positron fraction reported by PEMELA (3-$\sigma$, green-shaded), and the $(e^+ + e^-)$-flux reported by Fermi and HESS (5-$\sigma$ in light red, 3-$\sigma$ in dark red) [82]. Further, the IceCube–22 [86] and IceCube–79 [190] halo analyses, and the IceCube–59 dwarf analysis [87] are shown. The regions and the IceCube–22 limit were rescaled to a local dark matter density of $\rho_{SC} = 0.471$ GeV/cm$^3$ ($s = 0.41$).

### 6.4.7 Currently Best Limits from Gamma-Ray and CMB Observation

Some of the currently most constraining limits on $(\sigma_A v)$ are obtained from gamma-ray observations of dwarf spheroidal galaxies. Two examples are the deep observation of Segue 1 by the ground-based imaging air Čerenkov telescope VERITAS [198], and a combined analysis of observational data of 25 dwarf galaxies by Fermi-LAT [88]. The advantage of dwarf galaxies as target for gamma-ray dark matter searches is a low background, unlike in the case of large observation regions in the Milky Way or the Galactic center.

A different approach to searches for dark matter is the analysis of CMB data; dark matter annihilation in the early Universe would release energy, and thus alter the characteristics of the CMB. Combined data from Planck, WMAP, and other CMB telescopes was analysed and yields very constraining limits on $(\sigma_A v)$ [84]. However, this analysis method relies on several assumptions, like e.g. the energy deposition and absorption efficiency in the early Universe, or the relative WIMP velocities. Since the expected relative velocity distributions during recombination and in cold dark matter halos are very different, a direct comparison of these limits should be interpreted with caution, and different values of $(\sigma_A v)$ are not necessarily directly related to different self-annihilation cross-sections, thus similar limits (or measurements) have different implications for the underlying dark matter particle.
Figure 6.10: Comparison of limits from this analysis (red shades) to the “GC-LE”-analysis (cyan shades), and the 3-σ region in the $\langle \sigma v \rangle$-$m_A$-plane for a dark-matter-interpretation of the gamma-ray excesses at the Galactic center in Fermi data ($b\bar{b}$, red region, bottom left) [196]. The solid lines are limits, the dotted lines are sensitivities. The light-blue shaded region indicates a preliminary 1-year sensitivity projection for the (optimistic) direct annihilation channel to $\nu\bar{\nu}$-pairs with PINGU [197]. The Fermi and PINGU regions were rescaled to a local dark matter density of $\rho_{SC} = 0.471$ GeV/cm$^3$ ($s = 0.41$).

Figure 6.11 shows a comparison of the above-described constraints to limits from this analysis.

6.4.8 Summary of Comparisons

The Galactic center limits from this analysis are complementary to limits from the Galactic halo analyses. They provide more stringent constraints in the low-mass region, e.g. below 600 GeV for the neutrino channel. The dependence on the halo profile is strong compared to the halo analyses, due to the astrophysical uncertainty on the dark matter density in the Galactic center. However, this may prove an advantage in case of a positive discovery in one of the analyses, allowing for a differentiation between halo profiles.

In a global comparison, the IceCube limits are not very competitive due to the low neutrino interaction cross-section, and the huge background of down-going muons. Further, the low-mass region is affected by mediocre accuracy of the track reconstruction algorithms, especially in case of starting tracks.

The limits are about three orders of magnitude above the natural scale for WIMPs to be thermal relics. However, the neutrino limits provide a conservative upper limit on $\langle \sigma v \rangle$. If
6.5. DISCUSSION OF UNCERTAINTIES

Figure 6.11: Comparison of limits from this analysis (red shades) to limits derived from gamma-ray observations of dwarf galaxies by VERITAS [198] and Fermi [88], and a combination of various CMB measurements [84]. The CMB-limit is not channel-specific.

WIMPs annihilate with a branching ratio $B(\chi \chi \rightarrow \nu \bar{\nu})$ significantly lower than 100% with a $\langle \sigma v \rangle$ on the level of the here-presented limits, gamma-ray searches in dwarf satellites or the Galactic halo would have detected them by now, or yield more constraining limits. This conservative constraint is complementary to the unitarity bound, which is easily circumvented, e.g. in case of p-wave annihilation.

6.5 Discussion of Uncertainties

This analysis is subject to different sources of uncertainties. The optical ice properties and optical efficiency of DOMs are the major contributors to systematic effects. These uncertainties are discussed in section 6.5.1.

Further, the impact of astrophysical uncertainties on the limit on $\langle \sigma v \rangle$ is evaluated. The impact of the halo profile was already shown in direct comparison to the IceCube–79 halo limits. The model-intrinsic uncertainties on the scale-radius $r_s$ and the local dark matter density $\rho(R_{SC})$, and the resulting impact on the astrophysical $J_A$-factor are evaluated in section 6.5.2.

6.5.1 Uncertainties from Systematic Effects

The background for this analysis is estimated from experimental data, thus e.g. preferred reconstructed arrival directions of events may give rise to systematics. Due to the hexagonal string structure there are preferred directions in detector-fixed coordinates. However, these
are averaged out due to the rotation of the Earth. Further, the Galactic center has a constant
declination, and the final dataset has an even exposure in right ascension. Therefore, systematic
effects of the data-driven background estimate are negligible, and are not considered.

The conversion of the limit on the number of signal events to the limit on $\langle \sigma_A v \rangle$ is based
on the detector acceptance for each channel and WIMP mass. The acceptance is determined
from simulated neutrino datasets, thus systematic uncertainties of the signal simulation are
directly propagated to uncertainties on $\langle \sigma_A v \rangle$.

The main sources of systematic effects are the uncertainty on the optical properties of
Antarctic ice and the optical efficiency of DOMs. Therefore, dedicated systematics datasets
are generated, where parameters like the optical ice model (s. section 4.2), the optical DOM
efficiency, or the absorption and scattering coefficients are modified by up to 10%, and are
expected to encompass the true values. For this analysis the variation of the optical DOM
efficiency is simply a threshold effect; the higher the efficiency, the less light is needed to fulfill
trigger conditions. The variation of the absorption coefficient has a similar impact on the
detection threshold. The variation of the scattering coefficient also impacts threshold events;
since the DOMs are looking downwards, low-energy down-going muons have a higher detection
probability due to increased scattering.

A list of all systematics datasets and the changes with respect to the baseline is shown
in table 6.2. All datasets were generated with the baseline Spice-Mie optical ice model [176],
except dataset 8421, which was simulated with an alternative optical ice mode; Water Hardened
Antarctic Measurement!, or WHAM! [199]. These datasets are produced at reduced statistics
of about 10% of the baseline datasets.

<table>
<thead>
<tr>
<th>Generator</th>
<th>Dataset Number</th>
<th>Generation Spectrum</th>
<th>Settings</th>
</tr>
</thead>
<tbody>
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<td>CORSIKA</td>
<td>7444</td>
<td>$E^{-2.7}$</td>
<td>baseline, photonics</td>
</tr>
<tr>
<td>Nugen</td>
<td>6467</td>
<td>$E^{-2}$</td>
<td>baseline, ppc</td>
</tr>
<tr>
<td>Nugen</td>
<td>8421</td>
<td>$E^{-2}$</td>
<td>WHAM!, ppc</td>
</tr>
<tr>
<td>Nugen</td>
<td>8508</td>
<td>$E^{-2}$</td>
<td>opt. efficiency 110%</td>
</tr>
<tr>
<td>Nugen</td>
<td>8591</td>
<td>$E^{-2}$</td>
<td>opt. efficiency 90%</td>
</tr>
<tr>
<td>Nugen</td>
<td>9407</td>
<td>$E^{-2}$</td>
<td>opt. absorption +10%</td>
</tr>
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<td>Nugen</td>
<td>9405</td>
<td>$E^{-2}$</td>
<td>opt. scattering +10%</td>
</tr>
<tr>
<td>Nugen</td>
<td>9408</td>
<td>$E^{-2}$</td>
<td>opt. abs. and scatt. -7.1%</td>
</tr>
</tbody>
</table>

Table 6.2: Overview over the datasets used in this analysis. The first two datasets are signal
and background baseline datasets. Below the separation line is a list of systematics datasets.
All neutrino datasets are generated with an $E^{-2}$ primary neutrino energy spectrum. The
optical efficiency is a convolute term that may encompass e.g. the PMT’s photon detection
efficiency, impact of refrozen hole ice, and shadowing by cables, and is applied as global scaling
factor with respect to the baseline.

Figure 6.12 shows the neutrino effective area $A_{\text{eff}}(E)$ for the baseline and systematics
datasets, as well as the ratios of each systematics dataset to the baseline dataset. The ratio
reaches up to 30% in the extreme cases. At the high-energy end of the figure, the starting-
6.5. DISCUSSION OF UNCERTAINITIES

<table>
<thead>
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<th>Profile</th>
<th>$(\alpha, \beta, \gamma, \delta)$</th>
<th>$\rho(R_{SC})$/GeVcm$^{-3}$</th>
<th>$r_s$/kpc</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFW</td>
<td>$(1, 3, 1, 0)$</td>
<td>$0.471^{+0.048}_{-0.061}$</td>
<td>$16.1^{+17}_{-7.8}$</td>
</tr>
<tr>
<td>Burkert</td>
<td>$(2, 3, 1, 1)$</td>
<td>$0.487^{+0.075}_{-0.088}$</td>
<td>$9.26^{+5.6}_{-4.2}$</td>
</tr>
</tbody>
</table>

Table 6.3: Halo parameters for the NFW and Burkert profile [47].

track selection removes a large fraction of events due to the muon range, and thus reduces the statistics. This leads to fluctuations of the ratio curves in the highest-energy bin, which are not significant, and dominated by few events with large individual weights.

The variation of the optical efficiency has a stronger impact than the variation of optical ice parameters. In general, the impact of systematics is larger in the low-energy region, than in the ≃TeV-region, and increases towards the high-energy side of figure 6.12. The reason is the detection threshold, which has a higher impact in the low-energy region, as seen for e.g. the optical efficiency datasets.

The increasing variation in the high-energy region is dominated by the impact of optical ice properties on events interacting near the causality-veto surface. For example, a higher optical efficiency increases the veto probability of incoming tracks, but also the veto probability of starting tracks (false-positives). The latter effect is explained by the fact, that the causality veto does not make use of reconstructed arrival directions, and the proximity of veto DOMs and fiducial DOMs at the veto surface; light from the hadronic cascade at the interaction vertex (near the veto surface) is more likely to by falsely identified as incoming veto light.

The impact of systematics on each annihilation channel and mass point is computed by convolution of the effective area with the neutrino energy spectrum for the respective mass and channel. Figure 6.13 shows an example of the variations of $\langle \sigma_A v \rangle$ for each systematics dataset for the annihilation channel to $W^+W^-$-pairs, considering both the NFW and Burkert profiles. Similar figures for all annihilation channels can be found in appendix H.1.

The variation of simulation parameters propagates approximately linearly to the final results, leading to variations of $\langle \sigma_A v \rangle$ with respect to the baseline of up to 30%, though mostly below 15%.

6.5.2 Halo Profile Uncertainties

A consequence of the largely unresolved cusp-core problem, as described in section 1.3, is the uncertainty on the expected flux of annihilation products from the direction of the Galactic center. The NFW and Burkert profiles yield limits that differ by up to an order of magnitude. Furthermore, the profile parameters are also subject to uncertainty. Table 6.3 lists the key profile parameters and respective uncertainties based on an analysis of observational data [47].

These uncertainties are propagated to the limit on $\langle \sigma_A v \rangle$; for each combination $\rho(R_{SC})$ and $r_s$ the limit curve is recalculated. The results are shown in figure 6.14 for annihilation to $W^+W^-$-pairs, and both halo profiles. The remaining channels are shown in appendix H.2.

A direct comparison of both the Burkert and NFW profiles is shown in figure 6.15, where
Figure 6.12: $A_{\text{eff}}$ for different systematics datasets listed in table 6.2. In general the shape of the effective area is very similar among different systematics datasets. The ratio plot shows deviations of up to 30%. At the high-energy edge, the limited statistics of the systematics datasets lead to fluctuations (see text). The statistical uncertainty on the ratio is shown to increase towards higher energies. The error bar x-locations are shifted for each dataset for better visibility.

The lines indicate the baseline halo parameters, and the bands indicate the total envelope obtained from parameter uncertainties within each profile.

The limit on $\langle \sigma A v \rangle$ varies by factors of [0.3, 2.5] for the NFW profile, and [0.25, 1.8] for the Burkert profile. Thus, the astrophysical uncertainty on the expected flux is by far the dominant uncertainty, when compared to the uncertainty from systematic effects of the detector simulation, as discussed in the previous section.
6.5. DISCUSSION OF UNCERTAINTIES

Figure 6.13: Variation of limits on $\langle \sigma v \rangle$ for the two halo profiles for a variation of detection uncertainties. The baseline (black) and varied parameters (colored) are explained in the text, and listed in table 6.2.

Figure 6.14: Limits on $\langle \sigma v \rangle$ for the two halo profiles with baseline values (black lines), and limits when one of the parameters is varied within the uncertainty given in table 6.3 (shaded lines). The legend order and color intensity is arranged by limit strength.
Figure 6.15: Limits on $(\sigma_A \nu)$ for the two halo profiles. The shaded regions show the envelope of the maximal variation within one profile, when changing any of the two parameters given in table 6.3 within the stated uncertainties.
This chapter summarizes the challenges, methods, and results of this analysis. Further, based on the lessons learned from this analysis, possible improvements for follow-up analyses are discussed.
7.1 Summary

This thesis describes the search for a flux of neutrinos from the direction of the Galactic center, that originate from annihilations of dark matter. The Galactic center, for IceCube about 30° above the horizon, is a promising target region for dark matter searches; the flux expectation from this direction is large due to the peaked dark matter density profile. This analysis is the first search for dark matter in the Galactic center, that makes use of the nearly fully-deployed IceCube detector in the 79-string configuration, which allows for the definition of a large fiducial volume. Beginning with the design and implementation of an online-filter, the event selection is motivated and explained, and the likelihood analysis of the final sample is presented.

The advantage of neutrinos as messenger particles is the lack of extraterrestrial astrophysical background. No extraterrestrial source of neutrinos has been identified at the here-considered neutrino energies above $\gtrsim 100$ GeV, however the foreground of atmospheric muons in the Southern Hemisphere is challenging. One goal of this analysis was to make the Southern Hemisphere accessible to a search for low-energy neutrinos in the GeV-TeV range.

Atmospheric muons dominate the IceCube data at trigger level by about five orders of magnitude. Usually, for sources in the Southern Hemisphere this background is reduced by imposing high threshold requirements on the deposited energy of the event. For WIMP-searches, or other analyses with focus on low-energy neutrinos ranging from about 10 GeV (trigger threshold) to well into the TeV-range, such an energy-threshold requirement cuts deep into the signal region, and yet proves inefficient against background muons. The approach adopted in this analysis is a search for tracks that start within IceCube, as opposed to atmospheric muons which enter the detector. This removes the advantage of a large effective volume due to the range of muons from CC-interactions, at least for long tracks from high-energy muons. However, it allows a selection of low-energy neutrinos at a relatively high efficiency on the order of 10% with respect to trigger level. Some of the veto methods against incoming muon tracks were developed specifically for this analysis, and tuned to the declination of the Galactic center. In contrast to DeepCore analyses, this analysis attempts to keep large parts of IceCube fiducial, resulting in a higher sensitivity above a few 100 GeV.

The final sample is still dominated by atmospheric muons. The background of atmospheric neutrinos is almost irreducible at the here considered neutrino energies. Self-veto methods by identification of atmospheric muons associated with an atmospheric neutrino require the atmospheric muons to pass through at least 1.5 km of glacial ice.

A further challenge is the broad spectrum of possible signal assumptions, which is best illustrated considering the direct annihilation to $\nu\bar{\nu}$-pairs. When covering WIMP masses ranging from 100 GeV to 10 TeV, the event selection has to be efficient for neutrinos at 100 GeV, as well as 10 TeV, while maintaining a good background suppression. However, suppression of atmospheric background is significantly easier, assuming 10 TeV signal events, e.g. by imposing fiducial charge thresholds. Such an approach led to the discovery of a diffuse extraterrestrial high-energy neutrino flux [200]. A low-energy event selection, however, accepts also down-going muons, which lead to dim tracks. These tracks may pass undetected through several
string/DOM layers, and mimic starting neutrino events. Figure 7.1 shows a remaining simulated background (CORSIKA) event, which is representative of the main class of remaining background events.

The event selection was optimized on signal assumptions that yield neutrinos predominantly in the energy range from 500 GeV to 1 TeV (trigger level). The final event selection was based on a BDT, and the cut on the BDT score was set below the optimal value for the training channel in order to not over-specialise on the energy range specific to the training assumption. The final-level analysis was performed using a shape-likelihood approach, that includes the halo shape according to the astrophysical $J_A$-factor. The $J_A$-calculation for different halo profiles was performed with the HaloTools package for line-of-sight integration, that was developed for this analysis, and is briefly described in appendix B.

The likelihood-analysis result is compatible with the null hypothesis, and limits are set on the self-annihilation cross-section $\langle \sigma v \rangle$, reaching down to $10^{-23} \text{cm}^3\text{s}^{-1}$ for the NFW halo profile, and $10^{-22} \text{cm}^3\text{s}^{-1}$ for the Burkert halo profile. The final limits for four annihilation channels are shown in figure 6.3. These results are discussed in a global context in section 6.4. The impact of astrophysical uncertainties, as well as systematic simulation uncertainties is discussed in section 6.5, where the astrophysical uncertainty on the halo profile parameters is found to be dominant.

While the here obtained limits are not competitive compared to the very constraining experimental limits from photon searches, they represent conservative upper bounds; models with a self-annihilation branching ratio to other SM particles than neutrinos would, at a self-annihilation cross-section of the order of the here-presented limit for the $\nu \bar{\nu}$ channel, be visible in e.g. gamma-rays, or otherwise be more constrained.

### 7.2 Outlook on Possible Improvements

Throughout the online-filter design study, event selection, and final-level analysis several lessons were learned, that led or may lead to improvements in the Galactic center WIMP search.

Computationally inexpensive parts of the level 3 starting-track selection, based on the FiniteReco tool [168], were incorporated into the Galactic center online-filter for the following seasons of data taking. The reduction in filter rate reduced the bandwidth consumption, and simplified further data handling.

The lack of clear signal definition due to different WIMP masses and annihilation channels proved challenging throughout the event selection process. A uniform set of cut observables and cut values is not easily found due to the plethora of possible signal event topologies, and associated background topologies. E.g. a starting track at a few 100 TeV muon energy requires a comparatively small veto because an incoming track at similar energies would deposit a large amount of charge in DOMs in a veto region, while veto charge of dim tracks has to be discerned from noise.

Therefore, one improvement to this event selection may be to split the data sample into subsamples according to event topologies, e.g.

- fully contained events
Figure 7.1: Display of a typical background event (CORSIKA), passing all veto cuts. The color-code represents hit times, from early times in red to late times in blue. The charge information is encoded in the size of the spheres. Only HLC pulses are shown. The muon passes by several DOMs on several strings without registering any hits.
7.2. OUTLOOK ON POSSIBLE IMPROVEMENTS

- starting but outgoing DeepCore events
- very bright events starting in IceCube above the dust layer
- bright events starting in IceCube below the dust layer

Such a subdivision would allow for the definition of cut observables that are tailored to the underlying background topologies, and would increase the overall signal efficiency after merging of the subsamples. This has been demonstrated to some extent with the DeepCore-focused low-mass Galactic center WIMP search developed by the Stockholm group, and discussed in section 6.4.1; the obtained sensitivity from the low-mass search is better up to a WIMP mass of $\simeq 200$ GeV for the $\nu\bar{\nu}$-channel.

A final event-selection stage using common BDT implementations is a very efficient method to remove the remaining background in a final optimization step. A drawback is, that the efficiency is best for the signal assumption used for training, while other signal may well be classified as background, e.g. high-mass WIMPs being scored by a BDT trained on low-mass WIMPs predominantly starting within DeepCore. This can be circumvented by training the BDT on a mixture of signal assumptions covering different topologies. A better approach to reduce the impact of BDT over-specialisation on one signal assumption may be the implementation of BDT algorithms that have a uniform selection efficiency in an energy proxy observable [201], or even the true neutrino energy from Monte Carlo information.

Finally, even an ideal event selection that removes most of the atmospheric muons and results in a pure atmospheric neutrino sample provides challenges for the final analysis due to the range of signal assumptions. Considering, again, the direct annihilation channel to $\nu\bar{\nu}$-pairs, it becomes apparent that low-energy neutrinos are signal for low-mass WIMPs, and background for high-mass WIMPs, and vice versa. The introduction of an energy term into the likelihood analysis would ameliorate this aspect.

The above-described improvements should increase the sensitivity especially in the high-mass region above $\simeq 1$ TeV, partly due to higher signal efficiency, but especially due to better background suppression. The prospects for low-mass WIMPs, which are of particular interest due to the low-energy gamma-ray excess at the Galactic center (s. section 6.4.6), are rather poor. The result of the low-mass WIMP search performed by the Stockholm group is compared to results from this analysis, the projected PINGU sensitivity and the preferred region for the Fermi Galactic center excess in figure 6.10.

A different, intriguing approach to a search for dark matter in the Galactic center is the search for cascades rather than muon tracks. This approach, while not intuitive, has the advantage, that the main background consists of down-going track-like events. The selection of cascade-like events allows for excellent background suppression, which has been demonstrated for low-energy [202] and high-energy neutrino samples [200]. While the impact of poor angular reconstruction quality needs to be investigated, the Galactic center as source of neutrinos form dark matter annihilation is not a point source; the flux drops to 10% of the maximum for an opening angle of $20^\circ$ for the Burkert profile. Thus, the pointing accuracy is not as essential for this analysis as for a point-source search. Further, a cascade event selection is complementary to the here presented selection.
Looking beyond the current state of the art, the discovery of a diffuse astrophysical neutrino flux with IceCube motivated investigations of possibilities to increase the sensitivity in the Southern Hemisphere. One such possibility is the construction of a surface veto detector. Given a sufficiently low energy threshold, such a veto would significantly increase the effective volume for high-energy neutrinos, and thus high-mass WIMPs due to the associated range of multi-TeV muon tracks.
Appendices
Appendix A

Cosmology

The evolution of the Universe is described by Einstein’s field equations. However, assuming a homogeneous and isotropic Universe, a metric was defined by Robertson and Walker metric (RWM) in spherical coordinates:

\[ ds^2 = -c^2 dt^2 + R(t)^2 \frac{dr^2}{1 - kr^2} + R(t)^2 r^2 d\theta^2 + R(t)^2 r^2 \sin^2(\theta) d\phi \]  
(A.1)

Here, \( R(t) \) is a spherically symmetric expansion parameter that carries the time-dependent expansion of space-time, \( k \) is a curvature parameter, \( s \) is the metric, and \( r, \theta, \) and \( \phi \) are fixed coordinates. The RWM simplifies Einstein’s equations to the Friedmann-Lemaître equations (FLE),

\[ H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3} \rho - \frac{kc^2}{R^2} + \frac{\Lambda c^2}{3}, \]  
(A.2)

\[ \dot{H} + H^2 = \frac{\ddot{R}}{R} = -\frac{4\pi G}{3c^2} (\rho c^2 + 3p) + \frac{\Lambda c^2}{3}, \]  
(A.3)

with the Hubble parameter \( H \), the gravitational constant \( G \), the cosmological constant \( \Lambda \), and a pressure term \( p \).

Using the pressure equations for the matter \( (p_m) \), radiation \( (p_r) \), and vacuum \( (p_\Lambda) \) components,

\[ p_m = 0, \]  
(A.4)

\[ p_\Lambda = -c^2 \rho_\Lambda, \]  
(A.5)

\[ p_r = c^2 / 3\rho_r, \]  
(A.6)

and the corresponding density functions,

\[ \rho_m \propto R^{-3}, \]  
(A.7)

\[ \rho_\Lambda \propto R^{-4}, \]  
(A.8)

\[ \rho_r = \text{const}, \]  
(A.9)

the FLE can be stated as

\[ \frac{H^2}{H_0^2} = \Omega_r R^{-4} + \Omega_m R^{-3} + \Omega_k R^{-2} + \Omega_\Lambda, \]  
(A.10)
with the density parameters $\Omega_r$, $\Omega_m$, $\Omega_k$, and $\Omega_\Lambda$. The density parameters are densities in units of the critical density,

$$\rho_c = \frac{3H^2}{8\pi G},$$

and

$$\Omega_i = \frac{\rho_i}{\rho_c},$$

where $\rho_i$ is any of the considered densities.

Various measurements that are sensitive to some of these density parameters yield a concordance model of cosmology. Figure A.1 shows measurements of cosmic acceleration from Supernova observations (Sn), Baryon Acoustic Oscillations (BAO), and CMB anisotropy.
Appendix B

Halo Tools

As discussed in chapter 1.3, the neutrino flux from dark matter annihilating in the Galactic halo depends on the density squared along the line of sight. For this analysis, the value of $J_a$ has to be calculated for each event to make use of event-level Monte Carlo, rather than relying on calculations using the effective area and average values $J_\Omega$ for an on-source region defined by the solid angle $\Omega$.

A software package was developed for this analysis to combine the calculation of J-factors for annihilation and decay of dark matter in a Galactic halo. The package is written in python, and relies on numpy\(^1\) and scipy\(^2\).

![Diagram of line-of-sight integration package work flow.](image)

**Figure B.1:** Line-of-sight integration package work flow.

The package is organized as shown in figure B.1. The main parts are the halo profile wrapper class, that provides a method that returns the dark matter density $\rho$ at radius $r$, and holds all necessary parameters, like e.g. the cut-off radius of cuspy profiles, or the Milky Way radius $R_{MW}$. The wrapper class internally handles halo profile classes, like the isothermal profile or generalized $(\alpha, \beta, \gamma, \delta)$-profiles of the form given in equations (1.8). Thus the package handles many profiles without the necessity to duplicate or change code, and is easily

\(^{1}\)http://www.numpy.org/

\(^{2}\)http://www.scipy.org/
extended to handle halo profile types without modification of the main integration engine, with
the restriction to spherically symmetric profile types.

The integration engine is a class that is initialized with a halo profile wrapper instance. It
internally handles integration limits, and provides derived methods to calculate the density at
a line-of-sight opening angle $\Psi$, and distance parameter $l$. Further, a numerical integration of
the average $J_{A,D}$-factor for a solid angle $\Omega$ is provided.

The numerical integration of equations (2.9, 2.2) is performed with scipy, which is partly
implemented in FORTRAN to increase performance as compared to pure python methods. All
figures of dark matter density profiles, as well as $J_{A,D}$-factors in this thesis rely on this package.
Appendix C

Boosted Decision Trees

Boosted Decision Trees (BDTs) are a method of supervised machine learning for binary classification of data, e.g. “signal-like” and “background-like”. The TMVA\textsuperscript{1} toolkit implementation was used for this analysis [183].

A BDT is trained on data samples labeled as signal or background, using a set of observables (or features) to distinguish between data from these samples.

The BDT consists of an ensemble of binary decision trees, which are trained iteratively. The training of each tree consists of the following steps. At the main node, the observable with the strongest discrimination power between signal and background is determined based on a predefined metric (e.g. statistical significance, or the here used misclassification error). Then the samples are split in two subsamples, based on a binary decision on this observable, creating two new nodes on a lower depth. The separation procedure is repeated on all nodes at that depth. This iterative process is aborted if a certain purity criterion is fulfilled or the maximum depth of a tree is reached. The final nodes are called leafs. Figure C.1 illustrates this process.

After each decision tree training, misclassified events get a higher importance (e.g. increased event weights) in the next training process to reduce misclassification errors, thus the term “boosted”. The boost algorithm used in this analysis is AdaBoost, which stands for adaptive boost. Weights of misclassified events are multiplied by a global factor

\[ \alpha = \frac{1 - r_{err}}{r_{err}}, \]  

where \( r_{err} \) is the misclassification rate. The final BDT then classifies events according to

\[ D_{\text{boosted}}(\{O_i\}) = \frac{1}{N} \cdot \sum_{i=1}^{N} \ln \alpha_i \cdot D(\{O_i\}). \]

A BDT in the TMVA implementation is defined by several parameters. The most important parameters are summarized in table C.1, and described in the TMVA manual [183].

\textsuperscript{1}Toolkit for Multivariate Analysis
Figure C.1: Outline of a decision tree training. The inputs at the main node are a signal (S) and background (B) sample, and a set of observables. The observable with the highest discrimination power is determined, and a binary split on both samples is performed. The split value for observable $O_i$ is $C_1$, optimized for e.g. maximal statistical significance.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ntrees</td>
<td>Number of trees used</td>
</tr>
<tr>
<td>Depth</td>
<td>Number of decision layers</td>
</tr>
<tr>
<td>AdaBoost factor</td>
<td>A boosting factor, determining the strength of the importance weighting of misclassified data</td>
</tr>
<tr>
<td>nCuts</td>
<td>Number of bins of data to find split observable and split value (granularity)</td>
</tr>
<tr>
<td>nMin</td>
<td>Minimal number of events in a leaf</td>
</tr>
<tr>
<td>Separation type</td>
<td>Method to determine the observable and cut value at each node (e.g. significance)</td>
</tr>
<tr>
<td>Prune method</td>
<td>Method to determine and remove statistically insignificant nodes</td>
</tr>
<tr>
<td>Prune strength</td>
<td>Fudge factor to influence the impact of pruning, and thus the amount of pruned nodes</td>
</tr>
</tbody>
</table>

Table C.1: BDT parameter explanation.
Observable distributions used for cuts at level 3 are shown in this appendix.

Figure D.1: Observable distributions used for Level 3 cuts - Panel 1.
Figure D.2: Observable distributions used for Level 3 cuts - Panel 2.

(a) $\gamma$.

(b) $\theta$.

Figure D.3: Observable distributions used for Level 3 cuts - Panel 3.

(a) $n_{\text{Channel}}$.

(b) $n_{\text{String}}$. 
(a) $\nu Log L$.

(b) $\theta$.

Figure D.4: Observable distributions used for Level 3 cuts - Panel 4.
Appendix E

Level 4 Observable Distributions

Observable distributions used for cuts at level 4 are shown in this appendix.

Figure E.1: Observable distributions used for Level 4 cuts - Panel 1.
Figure E.2: Observable distributions used for Level 4 cuts - Panel 2.
Appendix F

Level 5 Observables for BDT optimization

Observable distributions used for BDT training on level 5 are shown in this appendix.

Figure F.1: Observable distributions for BDT training - Panel 1.
Figure F.2: Observable distributions for BDT training - Panel 2.

Figure F.3: Observable distributions for BDT training - Panel 3.
Figure F.4: Observable distributions for BDT training - Panel 4.

Figure F.5: Observable distributions for BDT training - Panel 5.
Figure F.6: Observable distributions for BDT training - Panel 6.

Figure F.7: Observable distributions for BDT training - Panel 7.
Figure F.8: Observable distributions for BDT training - Panel 8.
Appendix G

Sensitivity Towards, and Limits on $n_{90}^{\text{upper}}$

This appendix contains all of the limits and sensitivity curves as well as 1-\(\sigma\) and 2-\(\sigma\) regions obtained in this analysis. The halo profile and annihilation channel can be found in the figure titles.

Figure G.1

Figure G.2
Figure G.3

Figure G.4

Figure G.5
Appendix H

Uncertainties

This appendix contains all the figures showing the impact of systematic effects, as well as halo parameter uncertainties.

H.1 Detector Systematics

This section contains figures, that show the impact of systematic variations of simulation parameters on the limit on $\langle \sigma A v \rangle$.
Figure H.2

Figure H.3
Figure H.4

Figure H.5
H.2 Halo Parameters

Figure H.6

Figure H.7
Figure H.8

Figure H.9
Figure H.10


[163] IceCube Live Monitoring Website (internal). URL: https://live.icecube.wisc.edu/.


First and foremost, I would like to thank Prof. Christopher Wiebusch for the opportunity to be a part of the IceCube–Aachen group. During my time with the group, I had the opportunity to do research on dark matter, a topic that captured my interest quite a while ago, and already accompanied me during my diploma thesis on the Xenon–10 experiment.

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